Executive summary of the "Towards quantum-secured wireless networks" project

Challenge

The dramatic progress of quantum computing capabilities poses a real threat to conventional RSA asymmetric encryption in communication. Quantum computers will be able to break encryption algorithms securing the transfer of data. Low-power devices, such as the Internet of Things that can be responsible for transferring sensitive information may lack the computational resources to maintain security against upcoming threats. Finding new ways to safeguarde information transferred over radio frequency (RF) and wireless networks in general is crucial.

Proposed Project

Within this project, we aim to build a quantum key distribution (QKD) system with auto-tracking capability. The QKD system will be used to secure indoor RF communication links established using universal software radio peripherals (USRPs). The system will use infrared sources (1370 nm) to limit the effect of artificial lighting and ambient sunlight. We will further explore incorporating the orbital angular momentum (OAM) degree of freedom of light to boost the QKD key transfer rate. Other methods to secure RF communication beyond using the shared keys will be explored. Theoretical physical layer security channel modeling will be conducted.

Intended Outcomes

There has been little work on indoor QKD and very little on integrating QKD to secure wireless communication. A successful first demonstration on the topic will lead to further studies that will involve securing THz and even free space optical communication signals. Our main initial focus is to use the QKD system indoors, but further experiments upon successful project completion will involve outdoor tests. We aim to openly share the system design and the generated data to serve as a starting point for other researchers in the field. Any theoretical codes and analysis will be shared with the public.

<u>**Executive summary for**</u>

Dynamic nanophotonic trap-release for in-situ regenerative biosensing

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The scope of this research proposal is to design and implement a *dynamic biosensing strategy* that leverages highly sensitive plasmonic devices. The concept relies on dynamic trapping of *functionalized carriers that serve as transient affinity hotspots for in-situ biosensing*, which are subsequently reagent-free eluted via trap release. This approach would permit the prompt sensor regeneration and re-functionalization on demand, with same or different affinity, which are the key ingredients for continuous biosensing.

Biosensing is the fundamental step for interrogating the state of a biological system, including human health. Whether it is a biomarker that indicates the state of a disease, infection, or chronic pathology, or the detection of an infection that can threat the individual or the surrounding population's health. Furthermore, in-line and real time biosensing has been a sought-after technology for biological reactors, such as organs on chip, where not only the sensing of ions is important but cellular byproducts such as proteins, enzymes, antibodies, and other relevant biomolecules indicates the health of the biological model, or which serve as parameters for closed-loop feedback.

Plasmonic devices that support localized plasmonic resonance modes have been extensively studied as potential ultra-sensitive biosensors. Colleagues in the field have demonstrated the *detection of almost any imaginable biomarker of interest to human health* even in scenarios where the concentration suggests an early onset of an acute disease, infection, or chronic pathology. However, the covalent nature of the affinity surfactants limits the use of these *plasmonic biosensors to a single sensing event*. On top of this, high-quality plasmonic biosensors use noble metals and expensive nanofabrication processes, which results as financial burdens that hinders mass production for statistical and clinically relevant validations and its eventual commercial translation.

The solution proposed here aims to develop a strategy that employs the concept of surface trapping and release of off-line functionalized functional carriers (FCs). Using a capture and release approach the high quality plasmonic chips trap and hold the FCs in place using, providing a temporary affinity functionalization. Biosensing occurs via localized plasmonic resonance spectroscopy while the optical trap is still active. Then, the optical trap is released allowing the sensor to elute the FCs without involving harmful reagents that might degrade the quality of the device or the supporting infrastructure. Therefore, multiple sensor regenerations, even with different affinity, will be possible.

Although plasmonic biosensors have found a great appeal as potential biosensing technology for clinical and commercial use, the translation of the technology as continuous or universal sensing platform requires to address a *perennial problem that has prevailed in the field: surface regeneration*. If successful, this proposed research will open the opportunity to translate plasmonics biosensing technologies into practical applications. The direct impact is in applications that require on-demand continuous biosensing such as ions/metabolites in bioreactors, biomarkers at the bedside or operating-room settings, or as a universal sensing platform for points of care/detection solutions at remote locations.

The high-risk factor that this proposed work accompanies makes funding from external sources a challenge, especially in the context of a junior assistant professor. The proposed work seeks to establish the foundations for an active research program in novel nanophotonic biosensing, which leverage the PI's experience in plasmonic biosensing, nanoimprinting technology for mass production of high-quality plasmonic devices, microfluidics integration, and integration with optoelectronic and spectroscopic system. Most importantly, it will reiterate the solid strength of optical technologies as potential disruptors in the market of ultra-sensitive optical biosensors.

Quantifying gold nanoparticle uptake and aggregation in live cells using nanoparticle plasmon coupling and deep learning.

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Challenges: Gold nanoparticles (AuNPs) have recently become widely used in cellular imaging, single particle tracking, photothermal cancer therapy, surface plasmon resonance based biosensing, disease detection, and drug transport. However, determining AuNP uptake and aggregation without destroying the cell is challenging. The early and critical processes of EGF-induced signal transduction are dimerization and phosphorylation of the epidermal growth factor (EGF) receptor (EGFR). The mechanism by which EGFR ligands cause dimerization and phosphorylation, however, remains unknown. In search of higher-level ordering of receptor clusters, we require a technique that can probe the size regime in 10 –100 nm. Direct microscopic observation of such cluster oligomerization on cell membrane is difficult, because of the resolution limit of light microscopy (250 nm). To address this, we propose to use nanoparticle plasmon coupling and deep learning-based image segmentation technique in human cervical carcinoma (HeLa) cells. Recently Artificial Intelligence (AI) and deep learning methods play a crucial role in understanding, diagnosing, and treating diseases and analyzing cell images. For microscopic image segmentation, Generative Adversarial Networks (GANs) [26] and other image segmentation technique such as UNet, SegFast etc. has been applied to image segmentation, disease detection, cell, or nuclei detection, counting numbers of cells, and cell structure analysis for cancer detection [27]. Plasmonic nanoparticles will be used as multifunctional probes and nano-spacers in a model cell system to investigate the organization of membrane proteins and how receptor spatial arrangement influences cell behavior.
Aim & Objectives The aim of the project is to determine the role of spatial organization on the function of membrane proteins. The objective of the project is as follows: **(a)** Investigate the light matter interaction and determine nanoparticle (NP) Uptake mechanism **b)** Probe the spatial organization of membrane proteins (EGFR). (c)Control the spatial organization of membrane proteins**.** **(d)** Determine how receptor spatial arrangement influences cell behaviour.
Expected Outcome: Expected outcome from aim 1: Investigate the light matter interaction of single particle and cluster on the 10-100 nm scale. We will provide evidence of how the shape, size and geometry of the particle influence NP uptake. **Likely Impact from aim 1:** The results will be useful to investigate monomer-dimer transitions at the molecular scale. **Expected outcome from aim 2:** We will probe the spatial organization of membrane proteins (EGFR) using nanoparticles as a probe or nanospacer. We will demonstrate perturbation of spatial organization through the creation of clusters of different size, spatial extent, and geometry. **Likely impact from aims 2:** The impact from this study will be high because it will address the issues of creating clusters with defined size and geometry directly. **Expected outcome from aim 3:** We will determine how cellular function is linked to spatial organization of membrane proteins. **Likely impact from aims 3:** The concept of spatial organization appears to be important for polyvalent ligand-receptor interactions where ligand-mediated receptor cross-linking brings components into molecular contact. Additionally, the proposed project will help to address SDG 3 (Good Health and Wellbeing), SDG 4 (Quality Education), and SDG 9 (Industry, Innovation, and Infrastructure), as well as produce a competent workforce to meet the challenges posed by Industry 4.0.

S/L	Task	Facility at BracU	Collaborator
1	Bioconjugation: Nanomaterial & EGF Antibody	Wet chemistry & cell culture laboratory (pharmacy dept.)	Monash University Australia, Swinburne University Australia, Kind Saud University, UAE, University of Central Florida, USA, Coppin State University, USA, Pharmacy, CSE and Biotechnology Dept BracU, BUET, Bangladesh
2	Numerical Simulation-FDTD	Workstation available with Lumerical software	
3	Confocal Scattering Microscopy & Spectroscopy	Fluorescence and Darkfield Confocal Microscopy and Spectroscopy laboratory	
4	Live cell imaging	Biological cell imaging facility	
5	Deep learning	High computing workstation	

The findings of this study will be helpful in spatial structuring, receptor organization and cellular function and drug delivery. Most importantly, we will utilize our expertise and existing microscopy, spectroscopy, and wet chemistry laboratory available at BracU. If needed, we will seek assistance from our collaborators in the United States, Australia, and the United Arab Emirates.

Structured light generation and sensing with metasurfaces for THz communications

Optica Foundation Challenge: Information

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Introduction: The global free space optical (FSO) communications market is projected to reach 7 billion USD by 20230 with CAGR of 30%. Terahertz (THz) radiation, located in the wavelength range from 3 mm to 30 µm, between the microwave and infrared, holds the promise of hosting a wide range of new communications protocols. It provides larger bandwidth than current microwave wireless standards such as IEEE 802.11b WiFi while imposing minimal effects on the human body (as it is non-ionizing in nature) making it ideal for indoor and short-haul communications. Besides FSO communications, THz waves have been widely utilized in non-invasive imaging, remote sensing, and material identification. However, the widespread use of THz waves has been hindered by the shortage of affordable cameras at room temperature with high sensitivity, fast speed, and broadband operation. Moreover, current THz camera sensors can primarily detect intensity information without retrieving phase and polarization — missing two rich information carriers of light. The goal of this project is to develop efficient schemes for sensing and generating THz beams in order to facilitate their use in free space communications and beyond.

Objective: We propose the use of metasurfaces to convert any 1D THz power detector array to a full 2D wavefront camera. Metasurfaces refer to flat optics made of subwavelength-spaced arrays of patterned structures which can control the phase, amplitude, and polarization of incident light, point-by-point. Our proposed system is composed of a static metasurface and a power detector array (for e.g., Schottky diodes or bolometers). The metasurface performs a discrete set of operations on incoming light and projects the result into diffraction orders which can be captured by the detector. From this discrete set of intensity measurements, the full wavefront of the incident THz beam can be fully retrieved including its 2D intensity, phase, and polarization profiles over a broadband. Besides their use at the receiver end, our metasurfaces can be deployed at the source as a wavefront shaping platform to generate light with complex spatial structures such as vortex and vector beams, unlocking a gamut of structured light modes in the THz regime.

Plan: The duration of this project is 12 months. It combines concepts from signal processing, holography, and nanophotonics. We will utilize the recently developed THz laser source by the group of Prof. Federico Capasso at Harvard University. The wide tunability of this source in the 0.25-0.955 THz range (and beyond) makes it ideal for free space communications. The experiment will be performed in collaboration with Dr. Paul Chevalier who built this laser. The metasurfaces will be fabricated at the Center for Nanoscale Systems (CNS) at Harvard University following standard lithography, deposition, and etching protocols. To build and characterize our setup, we will purchase Schottky diodes, lens kit, polarization optics, and a THz camera. The project will also involve a collaboration with the group of Prof. Nader Engheta from the University of Pennsylvania who will contribute expertise in electromagnetic wave modelling at THz.

Impact: Efficient and versatile detectors and generators of THz waves will facilitate their widespread use in a variety of applications such as free space communications (including 6G and IoT), remote sensing, and non-invasive imaging. Furthermore, owing to their lightweight, our metasurfaces can address many challenges in drone-based sensing and space domain awareness. Lastly, given their CMOS compatibility and compact footprint, our flat optics enable a direct route to integration and large scale. With the abundance of efficient and compact THz sensors and modulators, we will take a key step towards solving one of the open challenges in optics related to affordable, secure, and fast information processing.

Multilayer holographic augmented reality with digital micromirror devices: content pipeline and system implementation

Executive summary

Most augmented and virtual reality devices currently available rely on stereoscopy to present 3D information to users. However, stereoscopy has certain limitations, including the issue of vergence-accommodation conflict. On the other hand, holographic displays have the potential to fully control the amplitude and phase of a light field, allowing for visualizations that closely resemble natural vision. Additionally, holographic displays can project multiplane scenes, where different information is presented to the user's eyes depending on their focus position. However, there are several challenges that need to be addressed in order to fully realize this potential.

The main challenges are related to the need for fast and accurate methods to encode a target scene into a hologram, as well as the availability of suitable devices to modulate a light field with the resulting holograms. Current high-performance holographic displays use phase-only holograms combined with liquid crystal on silicon spatial light modulators (LCOS-SLM). However, these devices are expensive and limit the potential applications of holographic display techniques. An alternative option is the use of digital micromirror devices (DMD), which are more affordable but limited to binary amplitude modulation. Due this limitation, most existing high-performance hologram generation methods were developed for phase only holographic displays and are not suitable for projection using a DMD. Despite these limitations, recent advances in fast propagation methods and binary amplitude hologram generation with binarized neural networks show promise in overcoming these challenges.

In this project, we aim to leverage the latest advancements in hologram generation to develop a holographic display based on a digital micromirror device, as well as a binary amplitude hologram generation pipeline that takes advantage of the high speed offered by DMDs compared to LCOS-SLMs. Specifically, our intention is for the prototype system developed during the project to serve as a test platform to demonstrate the capabilities of new binary amplitude hologram generation methods, as well as the potential of holographic augmented reality in general. Moreover, by highlighting the potential of digital micromirror technology in holographic displays, we hope to lower the entry barrier for many applications, such as optogenetics, superresolution microscopy, and holographic tweezers, which have traditionally relied on expensive LCOS-SLM-based solutions.

<u>Executive summary</u>

Optica Foundation Challenge – 2023 (Category – Environment)

Sensing trace gases by speckle correlations and adaptive random laser spectroscopy

Sensing of trace gases is crucial for safe and secure environment. Presence of the trace gases above the permissible limit increases the green-house effect and causes serious health risk such as lunge, kidney, and mental diseases. Methane and ammonia are two of the well-known trace gases that have significant contribution in air pollution and are of major concern. Methane is one of the fastest growing green-house gases and has a contribution of around 30% of global warming. Moreover, it has thirty times more potential in global warming than carbon-di-oxide and is responsible for half a million premature death annually due to the air pollution. Most of the developed nations have also acknowledged ammonia as an air pollutant and implemented restrictive measures to control its emission. Ammonia is highly reactive and can form aerosols that contribute in the green-house effect. These two trace gases have a wide range of sources such as agricultural sector, decomposition of manure from wildlife and plants, motor vehicles and fossil fuel, chemical industry, and mining. Optical gas sensors are widely used to detect and monitor the concentration levels of these gases in the environment. However, most of the optical sensors available today for sensing these gases have low sensitivity and gas selectivity. Moreover, the infrared absorption bands of these gases are targeted to detect them and hence, sensing different gases requires sources of corresponding wavelengths. Furthermore, the existing optical gas sensors are complex and expensive. Therefore, developing a chip-scale gas sensor to detect these trace gases is highly demanding, but possess several difficulties due to their small interaction length/area and poor signal to noise ratio. In this respect, a random laser based and laser speckle correlation-based sensing technologies can provide the possible solutions to overcome this problem. Both of these techniques utilize multiple scattering of light in a disordered material: the former uses an active disordered medium, whereas the latter utilizes a passive disordered system. Any change in the scattering environment due to interaction between the analyte trace gases and the selected disordered material alters the random lasing properties and also the speckle pattern which can be exploited to detect and monitor these trace gases.

Therefore, in the proposed project, to the best of our knowledge, we target to develop, for the first time, an adaptive random laser-based ammonia sensor and a speckle cross-correlation based methane gas sensor. Polymer based planar waveguide diffuser will be fabricated to build both of these sensing systems. Adaptive optic control of random lasing modes by wavefront shaping of the excitation beam will be employed for detecting the ammonia gas and measuring its concentration level in the environment. Random lasing in the disordered material will also enhance the gas detection sensitivity. In methane gas sensor, the change in the speckle pattern due to the interaction between the methane gas and a conductive polymer diffuser will be monitored to sense and evaluate the gas concentration. Both of these sensors will work at visible wavelength range. Additionally, these compact, portable, lab-on-a-chip trace gas sensors will find applications in agriculture sector, mining, fertilizer and automobile industries, and disease control in biomedical field. Moreover, they will have less response time, improved sensitivity and gas selectivity compared to the existing optical gas sensors. Precise detection of ammonia and methane gases in the local atmosphere would help to control their possible origins and also save the human and animal lives from the possible health risk. We believe that these new gas sensing technologies can further be used for sensing other trace gases as well and will open up the possibility of remote and real-time sensing. Hence, this work will contribute in detecting the concentration levels of the trace gases in local atmosphere, controlling their emission sources and reducing the green-house effect.

Executive Summary of Proposal

Miniaturization of Laser Speckle in Application for Non Invasive Intraocular Pressure (IOP) Monitoring for Glaucoma

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Intraocular pressure (IOP) is a physiological parameter that eye care providers measure to monitor and assess the progression of glaucoma, a leading cause of blindness that affects over 100 million people in the world. Since early treatment is imperative to prevent irreversible vision loss, the primary goal behind early glaucoma management is to reduce and control a patient's IOP level using prescribed eye drop medications for an indefinite period. Additionally, patients exhibit diurnal fluctuations of IOP, making the timing and close monitoring of the medication's effects essential to treatment efficacy. Without an optically-based, non-invasive technique to develop a portable solution that captures true IOP, current methods limit the frequency and accuracy of IOP measurement and thus prolongs the treatment process resulting in untimely treatment, disease progression, and financial burdens.

Elevated IOP is characterized by a buildup of aqueous humor in the anterior chamber of the eye due to increased resistance to fluid outflow. Several non-invasive optical techniques have been developed to probe the anterior chamber and extract information from aqueous humor for biomedical diagnostics and monitoring, with laser speckle imaging (LSI) being the most prominent. However, current LSI techniques are unable to measure IOP independent of measuring for the indirect effect of ocular blood flow. As a result, many LSI instrumentations either have not been developed for commercial use or optimized for precisely imaging the anterior chamber. The presence of the light scattering particles in blood also found in aqueous humor allow for the potential to use laser speckle to characterize fluid activity relating to IOP.

In this proposal, we will use optoelectronics such as laser diodes and photodetectors to develop and test an innovative, portable LSI system for measuring changes in IOP in an experimental model of ocular hypertension. The optical components are integrated and miniaturized into a benchtop headset prototype used to control, focus, and align the laser path corresponding to the anterior chamber. We consider that changes in fluid activity from outflow resistance causing pressure differences in the eye will directly impact the observed random interference pixel intensity pattern and generate repeatable speckle behavior related to IOP. As such, our approach involves generating a computational model from a series of speckle contrast values instead of determining conventional 2D maps of fluid flow. To validate this, an *ex vivo* study on enucleated rabbit eyes will be performed to establish technical feasibility followed by an *in vivo* study on live rabbits to demonstrate the accuracy and repeatability of a laser speckle-based method of measuring IOP.

Beyond demonstrating technical feasibility and validation, the proposed project will lead the innovation of traditional IOP monitoring systems and allow further research and development towards a commercially viable product. Our findings will advance the scientific understanding and engineering capabilities of laser speckle technology, broadening perspectives on ocular diseases such as glaucoma. LSI has the potential to extend clinical knowledge by revealing more about the properties of aqueous humor flow that relate to IOP levels. The proposed technology will extend applications towards at-home, remote patient monitoring devices that increase accessibility to eye care, elevate quality of life, and offer peace of mind by limiting the extent of disease progression towards blindness.

Fully-integrated implantable light-sheet microscope
PI: Aseema Mohanty, Tufts University

Challenge: Health Category
High-resolution microscopy currently relies on table-top optics which are large, bulky, slow, and expensive. Light-sheet microscopy belongs to a class of microscopy techniques that decouple the light excitation from the optical readout gaining significant resolution in the axial dimension, less photodamage, and faster imaging of large volumes. However, these techniques require large objectives and beam shaping apparatus including spatial light modulators and galvo-mirrors that ultimately prohibit their use in practical or mobile settings that require portability and lower costs. In addition, these techniques are limited by optical scattering at visible wavelengths which limits specimen that can be studied to transparent, artificially cleared, small volumes and short depths (typically <100 μm). For eventual point-of-care use for medical diagnostics, these systems should ideally be handheld and not rely on expensive, bulky table-top optics and powerful lasers while being compatible with larger scattering tissues.

Objective and Outcomes:
Here we propose a fully-integrated light-sheet microscope based on a hybrid platform combining visible wavelength photonic integrated circuits (PIC), an integrated laser, and 3D polymer micro-optics to extend imaging depths by up to 100 times in scattering tissue. Recent advances in silicon nitride PICs have shown operation down to 400 nm and active control of optical modulators, switching networks, and phased arrays for beam routing and beamsteering. This platform can be thinned down to thicknesses below 50 μm and has been demonstrated for implantable neural probes. Combined with a tunable self-injection locked microresonator-assisted diode laser, we will demonstrate an actively switched light-sheet for multi-plane excitation and detection through a 3D polymer waveguide and lens system all fabricated on the same chip. The implantable microscope will be mechanically and optically tested in brain phantoms of fluorescent bead embedded agarose to demonstrate readiness for scattering brain tissue and in-vivo neuroscience experiments. There will be several key outcomes with the success of the project: 1) fully-integrated biocompatible visible PIC with laser and electrical control, 2) implantable microscope reaching depths beyond multiphoton imaging, 3) low-power optical switching at visible wavelengths, 4) novel device structures for beam shaping.

Capabilities and Applications:
The implantable microscope will be able to measure down to depths of approximately 1 cm, which is 100 times that of a traditional light-sheet microscope in scattering tissue. The chip-generated light-sheet allows for cellular-scale axial sectioning that can be scanned in depth at kHz speeds. The device can be used for time-multiplexed multi-plane imaging. Short-term applications of the device will be for in-vivo deep brain imaging with neuroscience collaborators at Tufts University School of Medicine to study neural circuit dynamics related to mood disorders, epilepsy, and other neuropsychiatric diseases. Many of these disorders are studied in a mouse model, but the brain regions involved lie below what can be reached with multiphoton imaging (<1 mm). The device will be compatible with the open-source Miniscope allowing fast adoption within the neuroscience and biomedical imaging communities. Long-term applications of this type of device will be for point-of-care imaging. Currently, high resolution imaging involves taking a biopsy and sending it out to an imaging specific lab. However, with the move towards portable, handheld, and low-cost technologies such as the proposed device, these imaging devices could be made more accessible to medical facilities and be used in real-time with patients. This would be transformative for healthcare, taking a technique that is typically used in research to understand disease to real-world heath monitoring potentially for medical diagnostics.

Executive Summary

Asymmetric wavefront manipulation through all-dielectric passive metasurfaces

Asymmetric transmission (AT) is the intrinsic limitation of electromagnetic waves due to the time reversal property. To address this problem Junus subwavlength engineered structures (metasurface) are explored by stacking the multiple metallic layers. However, they are configured with multi-layered metallic transmissive layers structures for shorter wavelengths. These structures have limitation in higher frequencies due the fabrication difficulties of stacked subwavelength structures as well as ohmic losses. Additionally, the usage of external beam reconfiguration techniques contributes to efficiency loss and difficulty of device integration. Therefore, there is need to realize to subwavelength structures which can realize asymmetric wavefront manipulation in optical frequency regime. In this project, passive dielectric structure will be studied with minimal stacking layers (maximum two) without external parameters (electrical gating, temperature etc.) to realize asymmetric wavefront manipulation such as asymmetric holography, asymmetric orbital angular momentum generation, and asymmetric beam steering. The enhanced signal isolation, increased data capacity, reduced crosstalk, enhanced security, and compatibility with existing infrastructure assisted by AT through ultrathin platform will significantly benefit the several practical fields such as imaging, data storage and communication.

The specific objectives are to realize and **solve following key scientific problems**:

- **AT through Non-interleaved wavefront engineering:** To achieve multiple functionalities by using single cell design meta-structures is key scientific issue to be solved. In multifunctional meta-designs, interleaved meta-design refers to metadesign where one column or row performs one function, and the neighboring column/row/elements performs different function which takes extra space on the metasurface. In this project, by studying the propagation phase and geometric phase simultaneously this issue will be resolved which will lay a foundation to achieve multiple functionalities without using extra space on metasurface.
- **Spin to orbital momentum converter (SOC) assisted by AT:** This project will realize SOC design to decode different orbital angular momentum (OAM) "l" values from back and front side of the metasurface.
- **Information encryption/decryption by utilizing all the transmitted channels for circularly input light:** For circularly input light we have four transmitted channels, however, normally only two channels are utilized. This research problem of utilizing of all the four transmitted channels will be solved and will apply for dynamic holographic display. A unique design by using non-interleaved metasurface will be realized, where for circular polarized input light, both the co and cross polarization transmitted channels will be utilized for holographic images encryption. Specific input polarizing light which will work as an encryption key.
- **Expand the use of Janus metasurfaces in optical frequency regime:** The project will be expanding the utilization of directional metasurfaces to explore the wavefront engineering applications in optical frequency regime through dielectric subwavelength structures.
- **High efficiency:** Efficiency is a key issue at shorter wavelengths e.g., visible and Infrared therefore dielectric metasurfaces will be utilized for our design which exhibit high efficiency.
- **Low fabrication cost:** The non-interleaved metasurfaces designs will not only reduce the complexity but also the cost of microwave systems.
- **Simple compact structure:** In order to easily fabricate, the target metasurfaces aimed to have a simple rectangular structure. Further, the project will not include any active component such as gating which will make the design compact and less complex.
- **Scalability:** As EM characteristics of light are scalable. Therefore, the approach adopted for AT in this project is extendable to any frequency of EM waves spectrum by using dielectric structures.

It is also expected that, upon completion of the project, the future career prospects of the participants will be enhanced. The project is expected to train two (2) MSc and one (1) PhD students. The research team will participate in scientific conferences, symposia and patent submission, publish research findings in peer reviewed journals. Further, the outcome of this project will benefit whole electromagnetic community and will play a vital role to design ultrathin smart optoelectronic devices.

Executive Summary for: **A Holographic Quantitative Phase Imaging Approach to Mapping the Biochemical Pathway for Synaptic Vesicle Fusion and Neurotransmitter Release**

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Challenge. Many processes in biology require the assembly of multiple proteins; however, challenges in characterizing the identity, structure, role, and the dynamic assembly of such heterogeneous protein aggregates poses a severe limitation to our understanding of a wide range of biological processes. As an example, consider information transfer in neurons, where calcium mediates the release of neurotransmitters stored in synaptic vesicles. [1-3] In this case, the key proteins involved in the process of anchoring the vesicle to the target bilayer and inducing fusion in the presence of calcium are known.[1-3] Moreover, a variety of fluorescence-based assays have identified some of the roles that the proteins may play, and electron microscopy-based characterization has identified critical structures[3] that are thought to mediate this biochemical pathway. Nevertheless, ***there is no existing method by which to identify and monitor the dynamics of such large protein clusters*** as they alter the relative position of a synaptic vesicle with respect to a bilayer to ultimately induce vesicle fusion, content release, and therefore enable neuronal information transfer.

Solution. Quantitative phase imaging (QPI) techniques, such as interferometry and holography, enable a label-free, non-destructive approach for studying biological systems. Current state-of-the-art technologies enable vesicle tracking[4] and both custom-built as well as commercially available QPI and holotomography microscopes can be used to monitor refractive index changes in cells and vesicles as well as the self-assembly of high refractive index proteins in solution.[5-8] Herein, I aim to build upon these established technologies to assemble ***a holography system capable of z-resolution ~ 10 nm*** by maximizing the ratio of signal-to-noise and leveraging known geometric constraints to more accurately determine the center of mass and thus the relative position of the point spread function for the scatterers in our system. After assembling the holographic QPI (HQPI) system, I aim to establish, for the first time, a standard method for spatially calibrating the HQPI and other QPI systems. Then, I aim to ***apply HQPI to resolve the biochemical pathway by which synaptic transmission occurs*** with the goal of ultimately being able to monitor the step-by-step proteomic changes that occur between a synaptic vesicle and bilayer during vesicle docking and subsequent fusion. Furthermore, by combining the HQPI system with spectroscopic modalities (*e.g.*, Raman/electrochemical impedance spectroscopy) I aim to provide a more localized understanding of the chemical changes that occur in the active zone of synapses. Altogether, the successful development of the HQPI system will broaden the scope of holography within the context of biological research and for the first time provide an easy-to-translate platform for studying dynamic protein assembly *in vitro* and *in vivo*.

Impact. By leveraging existing technologies, this proposal aims to design a microscopic modality that is able to address a critical need in biomedical research – a way to directly study protein dynamics under conditions that reconstitute the native structures of interest. Moreover, we specifically chose to study synaptic vesicle fusion because the fundamental understanding of this biological phenomenon will not only answer questions in neuroscience but will also provide ***a new basis for understanding information transfer in the brain*** and will likely also lead to significant advances in our understanding and treatment of the severe, often lethal, pathologies caused by key proteins involved in the fusion process[9-11]. Furthermore, given the similarity in the component proteins for neurotransmission, optical signaling in the eye, insulin secretion, as well as cellular signal transduction via exosomes, extracellular vesicles, and multi-vesicular bodies, it is indubitable that the successful utilization of the HQPI system in one field may directly lead to new findings in adjacent fields. Such findings could completely alter our understanding of how our body communicates with itself so rapidly and efficiently, which is ultimately critical for medical, scientific, and technological advancement. Taken together, the development of the HQPI microscope could ***provide a broadly applicable technology that addresses a critical need in biomedical research***.

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NONLINEAR INTERFEROMETRY FOR ENHANCED OPTICAL SENSING

Metasurfaces have the potential to become the key building block of smart, multi-functional sensing devices. Once integrated with microfluidic technologies, they can be engineered (via geometry) and functionalized (with surface chemistry) to target a broad variety of analytes and address various properties such as concentration, refractive index, chirality. etc. **Plasmonic** metasurfaces (Fig. 1, left) are a particularly attractive platform, due to the ease of functionalization and the strong confinement of the electric field at the surface, enabling **ultra-sensitive** detection of a targeted molecular species with very **small sample volumes**. Most often, sensing relies on the spectral shift of a plasmonic resonance induced by the modification of the local environment of the metasurface upon binding of the target analyte to the metal surface. While in conventional implementations resonances are monitored via refractometry, lately it has been proposed to rely on **nonlinear optical processes**, to benefit from their enhanced surface sensitivity and superlinear dependence on local perturbations of the electric field due to the binding analytes. In principle, this was expected to yield sizable improvements in sensitivity, but in practice such gains have been hindered by the low efficiency of nonlinear conversion, which leads to small signals affected by a comparatively large noise.

In this project, I aim to demonstrate a **phase-sensitive interferometric detection** scheme capable of circumventing the noise limitations of previous reports of static nonlinear sensing. Specifically, I will exploit a **dual-wavelength illumination** scheme whereby a pulse at the telecom frequency ω and the externally-generated replica at the double frequency 2ω excite the metasurface simultaneously. Due to the coherence of the second harmonic generation process, the direction of the energy flow between the two frequencies depends on the relative phase of the two pumps. **High-frequency phase modulation** of one pump has already been shown to implement a phase-sensitive imaging modality. A balanced detection of any two opposite diffraction orders of the metasurface (Fig. 1, right) will also implement a homodyne detection with effective rejection of common-mode laser noise. Application of this innovative nonlinear interferometry to sensing will boost the sensitivity of the plasmonic platform, abating the noise limitations that have so far prevented translating these assets into technology.

The benchmark of the proposed sensing platform will be the label-free detection of small amounts (<pM concentration) of **insulin-autoantibodies**, which are the very first blood indicator of the insurgence of **type 1 diabetes**, a non-preventable autoimmune disease which frequently has its offset during childhood. Such sensitivity is key to an early diagnosis, enabling effective therapeutic interventions, but is hardly achieved with standard immunoassay techniques, such as radioactive tagging or enzyme-linked immunosorbent assays.

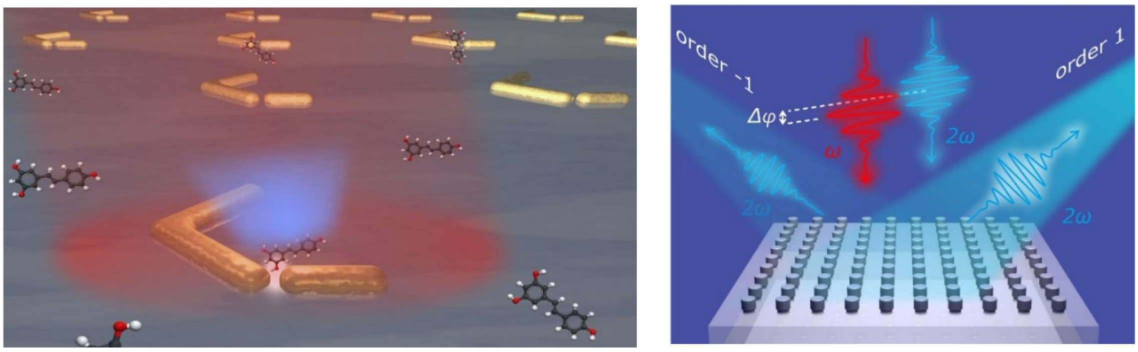


Figure A Artist's impression of the proposed sensing concept. (Left) **Sample**: a plasmonic metasurface whose optically resonant response at ω brings about an enhanced sensitivity to the local chemical environment. (Right) **Experiment**: controlling the relative phase Δφ between pump pulses modulates the nonlinear emission at 2ω, enabling phase-sensitive high-frequency demodulation with balanced photodetection of opposite diffraction orders.

EXECUTIVE SUMMARY

Integrated photonics has led to revolutionary advances in communications, computing, and information processing; however, there is an ever-increasing Challenge to densely encode, manipulate, transmit, and process even more information on a chip. Achieving such integrated photonic devices while maintaining a small size, weight, and power (SWaP) would further augment communications and computing, both classically and in emerging quantum computing and networking infrastructures. The underutilized transverse spatial degree of freedom of multimode waveguides provides a potential route to encoding more information, which can multiplicatively increase the number of information channels carried by a photonic link, i.e., beyond polarization- and wavelength-division multiplexing (WDM). Such mode-division multiplexing (MDM) using just 4 modes has shown promise to massively increase the data capacity of silicon photonic interconnects beyond terabits per second (Tb/s). For example, an MDM x WDM link with 20 wavelengths near 1550 nm, 10 spatial modes per wavelength, and QPSK modulation @ 50 GHz, can achieve high bit rates greater than 20x10x50 = 10 Tb/s, which can be further increased using coherent modulation formats.

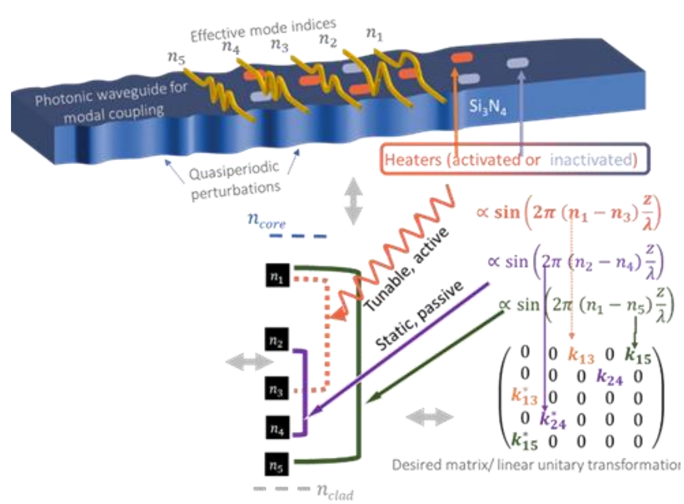


Fig. 1: Multimode photonic waveguide (top) with passive quasi-periodic perturbations and tunable heaters. Bottom: arbitrary engineering of target matrix's coupling amplitude and phase is possible by superimposing subwavelength nanopatterned

However, traditional mode-division multiplexing (MDM) uses each transverse mode as a different information channel, and interference or crosstalk between them is undesirable, hence suppressed. The overarching goal of this Optica Challenge proposal is to explicitly leverage interference between many transverse spatial modes of high-confinement multimode waveguides to build arbitrary scalable photonic circuit topologies for dense classical and quantum information processing with small footprint. This is in striking contrast to existing work which focus on mode conversion, multiplexing and demultiplexing between few modes. A high-contrast multimode waveguide can accommodate many transverse modes (N>10) yet occupy a much smaller footprint than N single-mode waveguides, while still maintaining low-power operation due to SiN's high spatial confinement and ultralow-loss (0.01~0.1 dB/cm), thus improving SWaP. By precisely engineering the amplitude and phase of subwavelength quasiperiodic perturbations to simultaneously couple higher-order modes, we will dramatically scale up the number of modes that can be encoded and processed within a desired footprint, especially within CMOS-compatible silicon-based photonics. In comparison to the predominant technique of creating arbitrary linear transformations or matrix vector multiplications using Mach-Zehnder meshes, our proposal has substantially better scaling with loss, number of modes N, and spatial footprint, especially since it can couple far-off modes in a single shot. If successful, the advance here will be substantial in integrated photonics, comparable to the manipulation and control of free-space orbital angular momentum (OAM) modes through spatial light modulators, but now miniaturized to the chip-scale. Additionally, since our proposed platform uses ultralow-loss silicon nitride waveguides, they are fully quantum-compatible yet possessing low size, weight and power (SWaP). Lastly, since we use high-confinement silicon nitride waveguides for our demonstrations, the proposed approach should be scalable to a wide range of high-confinement platforms like silicon, lithium niobate, diamond and silicon carbide, thus providing a universal tool for ultracompact, dense information processing for emerging technologies such as quantum computing and machine learning hardware.

Executive summary

The rise in the rate of plastic waste accumulation currently surpasses the capabilities of recycling technologies and leading towards dangerous concentration of microplastics in the environment. An obvious solution of burning plastics is barred by the toxic chemicals that are produced during the incineration process. The commonly proposed methodologies usually involve large scale and high up-front costs installations, which incentivizes future production of plastics while reduction in plastic consumption is currently promoted. Furthermore, removal of persistent toxic chemicals is an energy intensive process, as high energy bonds must be separated to form new inert compounds. This in turn makes it very efficiency sensitive problem, even more so in face of energy consumption driven climate change. One of the classic approaches to the problem of toxic chemicals is photolysis. However, it is rather limited in terms of energy efficiency due to physical restriction in ultraviolet sources. On the other hand, the efficiency of infrared sources has experienced a steady growth in recent years which has also led to advances of laser sources in this spectral region. If we consider that bond dissociation observed after absorption of ultraviolet photons can also be achieved by simultaneous multiphoton absorption, new possibilities for photolysis arise. Therefore, in this application we propose investigation of laser resonator based nonlinear photolysis as an efficient tool for such toxic molecules accelerated decomposition. However, there is little information on the nonlinear absorption induced dissociation in toxic chemical compounds. Therefore, the investigation begins by characterizing the interaction at various parameters such as incident wavelength, pulse duration, concentration, and intensity. Using this information theoretical design as well as the optimization of the laser resonator and the nonlinear photolysis process will take place. This will be followed by the evaluation of physical as well as economic viability. In case of positive outcome, a construction of a prototype will commence.

Executive Summary of the challenge project

In the low-carbon future, hydrogen plays a vital role as an alternative and sustainable energy carrier that can be stored and used to release its energetic potential, of chemical, electrical, or thermal nature, on demand. Proton exchange membrane water electrolyzer (PEMWE) is the most promising technique for hydrogen production. A variety of different transport processes, such as proton flux and mass (liquid, gas, vapor) diffusion, pressure- or concentration-driven, are involved in the operation of a PEMWE cell; On the anode side, upon applying an electrical current, water is oxidized and releases gaseous oxygen, electrons, and protons; While electrons and protons reach the cathode side, the non-oxidized water and oxygen gas are transferred back to the entrance flow channel; On the cathode side, electrons and protons recombine to form hydrogen. Investigating these processes is crucial for controlling the local concentration and efficient distribution of various species in the reaction sites of the cell.

The PEMWE assembly consists of adjacent compact layers stacked in the cell to provide multiphase (gas, liquid, and ions) permeability, optimize the contact area between the layers, and increase the thermal and electrical conductivity of the device for efficient species transportation. The liquid/gas diffusion layer (LGDL) on the anode side acts as an entrance gateway for controlling the water flow rate from the entrance flow field channel to the rest of the cell while removing the produced oxygen gas bubbles. The access of the reactive sites to the water and the hydration of the membrane while preventing the flooding of the electrodes are crucial for the whole cell's performance. The performance and durability of the cell are also associated with the produced gas density in two-phase regions. For instance, the accumulation of oxygen gas can shield the anode from water and negatively impact cell performance. For these reasons, LGDL significantly influences the performance and efficiency of the PEMWE cell. Therefore, methods that provide new insights into the dynamic behavior and distribution of liquid water as it migrates through LGDL allow an early diagnosis of the faulty states with inefficient access to the water. Moreover, techniques for simultaneous visualization of liquid/gas transfer through this reactive site provide a deeper understanding of the complexity of underlying processes. Particularly, observational methodologies can enable the identification of the connectivity and interdependence of the species in this multiphase region where both the flow field of gas and water need to be analyzed.

Herein, we propose an optical quantitative methodology for the *in-situ* evaluation of water/gas transport in PEMWE cells. The proposed optical system is designed for two-phase visualization of water and gas through LGDL on the anode side of the PEMWE cell. While the available observational diagnostic techniques for PEMWE are mostly *ex-situ,* offering insights into the distribution of the water droplets within the LGDL, our proposed experimental setup allows a simultaneous evaluation of bulk transport of liquid water through LGDL as well as the distribution of oxygen gas bubbles on its surface during the PEMWE operation. Similar to the well-established optical techniques for flow measurements, such as Schlieren Imaging and Mach-Zehnder interferometry, we apply the dependence of the fluid's medium refractive index on its density. The goal is to measure the optical path differences caused by the refractive index nonuniformities due to various water densities through instantaneous recording of the phase variation of the light field as it passes through the LGDL. The recorded interferogram provides spatial information about the water density variation as it flows through different paths in LGDL. In addition, we use the deflection of the light ray traces caused by oxygen bubbles to measure the distribution of gas on the LGDL surface. The present proposal describes in detail the technical and experimental adaptations to apply these concepts for the case of two-phase flow measurement in a PEMWE cell. The viable optical setup will present a diagnostic prototype device capable of simultaneously quantifying the two-phase (gas/water) flow through a delivery channel (LGDL). Ultimately, the results of the experiments provide an in-depth understanding of micro- and macroscale phenomena in the PEMWE cell, helping to develop new materials for multi-phase delivery sites.

Executive summary Optica Foundation Challenge

Applicant: Dr. Carlos Doñate Buendía, University of Wuppertal, Germany

Category: Health **Anticipated total duration of the project: 24 months**

Stereolitography 3D printed custom and low-cost bactericidal dentures by laser generated Ag_2WO_4 nanoparticles additivation

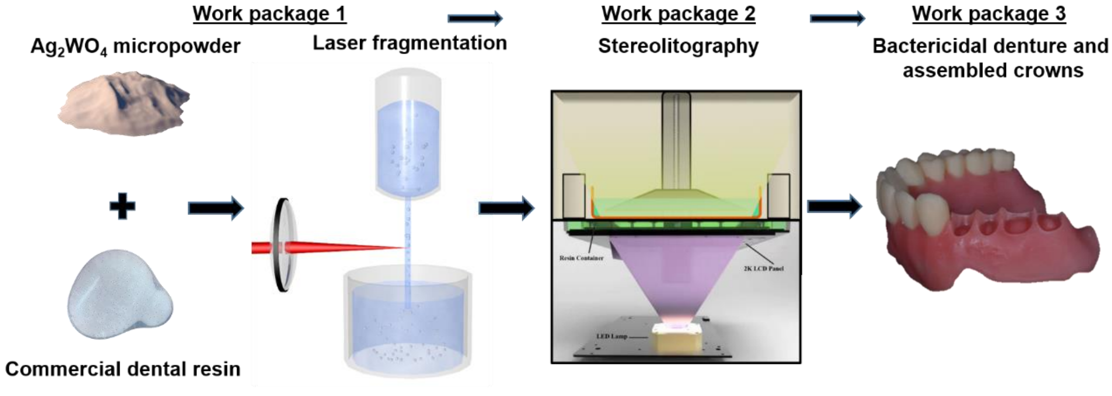
The proposed project addresses a fundamental problem in nowadays society, universal health access. Specifically, **dental health costs limit its access to low-income population and countries**, resulting in reduced well-being, sickness, and even death. Implants, crowns, and dentures costs still represent a barrier for their extended employment. One of the sources of the high costs comes from the necessity of fabricating custom dental prosthetics for each patient, not allowing serial production. To overcome this limit, a **photonics-based 3D printing** technique as stereolitography (SLA) is proposed **to produce dentures** with complex custom geometries and low production costs.

Another problem linked to **dental prosthetic** is the proliferation of bacterias and the **risk of infection**. Dentures represent a reservoir of microorganisms that can derive into stomatitis or infections. In fact, 70% of dentures wearers suffer from denture stomatitis. To treat infection problematics, antibiotic protocols are developed. However, this solution is limited due to the emergence of antibiotic resistant superbugs. To address it, the employment of **laser irradiated Ag_2WO_4 particles to provide them bactericidal properties** is proposed.

Overall, in the current project a complete photonics based approach is proposed to produce dentures with bactericidal properties by the formulation and SLA printing of resins containing laser generated Ag_2WO_4 particles with enhanced bactericidal properties.

The proposed methodology can be explained in three steps, represented in the scheme below. First, the **irradiation of Ag_2WO_4 particles dispersed in the dental resin**, a commercial flexible resin to produce dentures. The irradiation is carried out by laser fragmentation in liquids (LFL), it enhances the Ag_2WO_4 bactericidal effects and facilitates the particle dispersion. Then, the **Ag_2WO_4-resin is employed for SLA** after detailed characterization of the Ag_2WO_4 particle stability in the resin, the viscosity and wettability. Finally, the **produced dentures are characterized by tensile, hardness, bactericidal, and biocompatibility** tests to evaluate their suitability for in-vivo applications.

The proposed approach aims to overcome the current main drawbacks of dental prosthetics. On the one side, high costs that difficult general population access to basic dental health treatments. On the other side, infection and bacteria proliferation and the subsequent loss of patient well-being and extra dental health treatment costs.



Energy-efficient Analog Computing with Simultaneous Photonic and Electronic In-Memory Processing

PI: Carlos A. Rios Ocampo | University of Maryland College Park

Overview

This proposal aims to develop a transformative approach based on optoelectronic multilevel nonvolatile phase-change memories in a co-located photonic and electronic in-memory computing processor. While electronics and photonics have been co-integrated in the same chip die to accelerate digital computing, an analog computing counterpart has not yet been demonstrated, nor is an architecture in which multiplications are also performed in the optical domain, as opposed to only use light for data transfer. This proposal aims to fill this gap by creating an innovative hybrid optoelectronic approach based on photonic integrated circuits (PICs) with embedded phase-change materials (PCMs) and a triple electrical Vertical Interconnect Access (vias) scheme, which enables a fully versatile architecture that can be written and read both optically and electrically. Developing a proof-of-concept computational device with seed funding is the first step towards the long-term vision of building a full in-memory computing processor with dual optical and electrical readout, which we intend to pursue further through NSF or DoD funding. Moreover, this proposal's scope perfectly matches OPTICA's interest in <u>driving new scientific discoveries and breakthroughs to transform our world in the information space</u> by enabling faster and energy-efficient ways to compute large volumes of information.

Problem statement

Unlike current phase-change memory technology operating either optically <u>or</u> electrically, our approach will create innovative systems that **integrate <u>both</u> into a single device**, **merging the best performance metrics from both domains**. Photonic PCM architectures have advantages in bandwidth, throughput, heat dissipation, no drift, and multiplexing over their electronic counterpart. Electronics benefits from mature, scalable, and standardized fabrication and demonstrated memory architectures (exemplified by Micron/Intel's 3D Xpoint), enabling volume manufacturing and interfacing with advanced logic and digital-analog converters inexistent in photonics. This team seeks to validate the central hypothesis by completing three main tasks: **1) optical materials innovation using high-throughput material discovery**: Mapping the Ge-Sb-Te PCMs alloyed with Sn, Ti, or Ag to achieve optimal optical and electrical performance by leveraging the metal content to improve both optical attenuation and electrical conductivity. **2) device engineering, fabrication, and testing:** hybrid memory devices will be home-built using three electrical ports on silicon-on-insulator (SOI) waveguides with embedded PCMs.

Impact

This project pursues a unique cross-disciplinary technology, innovating in fields such as optical material synthesis and processing, device design engineering, system architecture innovation, and photonics manufacturing**.** Our innovation will enable faster and energy-efficient ways to compute large volumes of information by matching the software requirements of the artificial intelligence revolution with hardware that optimizes the arithmetic operation at the core: matrix-vector multiplications. The high-performance computing market is expected to grow from $36.0b in 2022 to $49.9b by 2027, and with that growth also comes a spike in power consumption, already up to 10MW (electricity for ~10,000 homes) per supercomputer. Minimizing energy waste in heat by using hybrid optoelectronic memory while allowing the seamless combination of both domains in a portable device operating in ambient temperature conditions (vs. extreme cold locations) is the major impact we foresee in this critical technology development.

Project Title: Development of a polarization-sensitive holographic microscope for point-of-care diagnosis of Malaria in resource-limited settings.

Category: Health

Summary:

The project addresses the pressing need for accurate and accessible diagnostic tools in resource-limited settings for malaria diagnosis. The project aims to develop a submicrometric-resolution, cost-effective, and portable multiparametric optical microscope incorporating polarization-sensitive holographic imaging techniques. This innovative approach will enable point-of-care diagnosis of Malaria in regions with limited resources, where traditional diagnostic methods face significant challenges.

The project will focus on three key objectives. Firstly, we will design and implement the hardware components of the polarization-sensitive holographic microscope, ensuring high spatial resolution and sensitivity to polarization, optical phase changes, and absorption. This device will involve the development of optimized illumination sources and the integration of polarization-sensitive elements.

Secondly, we will develop computationally efficient software algorithms for reconstructing and analyzing holographic images acquired by the microscope. These algorithms will enable rapid and accurate interpretation of the acquired data, facilitating identifying and quantifying malaria parasites and other microorganisms of interest.

Lastly, we will miniaturize the developed system, leveraging 3D printing technologies and compact designs, to create a portable and user-friendly device suitable for point-of-care settings. This miniaturized microscope will be evaluated and validated with medical experts in malaria diagnosis, ensuring its reliability and usability in real-world scenarios.

The successful implementation of this project will have significant outcomes and impact. Firstly, it will lead to the development of an affordable and portable multiparametric optical microscope specifically designed to detect pollutants and microorganisms, particularly for malaria diagnosis accurately. This innovative technology will improve access to timely and precise diagnostic tools in resource-limited settings, reducing malaria morbidity and mortality rates.

This project represents a significant advancement in optical diagnostics for health applications. By developing an affordable and portable multiparametric optical microscope, we aim to address the global challenge of accurate and accessible diagnosis of diseases in resource-limited settings. The project outcomes will directly impact improving public health, enhancing research capabilities, and fostering innovation in the field of optical technologies for healthcare.

Advancing Cancer Diagnostics: Development of a Non-Contact Viscoelastic Imaging System using Nanosecond Laser Pulse-Generated Photoacoustics with Photorefractive Interferometry

Category: Health

Executive summary

The diagnosis of cancer, a leading cause of mortality worldwide, necessitates innovative and non-invasive imaging techniques to improve early detection and personalized treatment strategies. This research proposal presents the development of a groundbreaking diagnostic imaging system based on viscoelastic contrast for tumor tissues, utilizing nanosecond laser pulse-generated photoacoustics (PA) with photorefractive two-wave mixing photorefractive interferometry (TWMPI). The proposed approach seeks to revolutionize cancer diagnostics by providing a truly remote and non-contact imaging modality capable of visualizing viscoelastic properties of tumors without physical contact with the patient's tissue.

The primary goal of this project is to establish an optoacoustic imaging instrumentation modality for non-contact viscoelastic imaging of tumor tissues. By harnessing the unique viscoelastic contrast between tumor and normal biological tissues, this imaging technique aims to facilitate early-stage tumor detection with high sensitivity and specificity. Moreover, the developed imaging system will enable precision medicine by providing valuable insights into the mechanical properties and heterogeneity of tumors at the molecular level, thus optimizing personalized treatment plans for improved patient outcomes.

The proposed research project will consist of three key tasks. Task 1 focuses on laser photoacoustics of biosamples using low and high excitation lasers, integrating the TWMPI method for non-contact detection of ultrasonic displacements on the specimen surface. Task 2 involves the validation of the results with Brillouin spectroscopy, further characterizing the viscoelastic properties of biomaterials. Task 3 is dedicated to the development of a robust image reconstruction and processing technique to convert photoacoustic signals into viscoelastic images of biological materials ex-vivo. The logarithmic PA-BLS pictures will be obtained by scaling the raw data based on histogram distribution, reducing background noise.

The proposed research project's impacts are multifold, ranging from advancing cancer diagnostics and precision medicine to minimizing patient discomfort and health risks associated with traditional imaging modalities. By bridging the gap between research and clinical practice, the successful development of the remote viscoelastic imaging system can catalyze collaborations and inspire future research in medical imaging and beyond.

In conclusion, this research proposal endeavors to introduce a transformative diagnostic imaging system that capitalizes on viscoelastic contrast for tumor tissues, leveraging nanosecond laser pulse-generated photoacoustics with photorefractive interferometry. With the potential to revolutionize cancer diagnostics and enhance patient care, this non-contact imaging modality holds promise for addressing critical challenges in oncology and shaping the future of biomedical imaging technologies.

Proposal Title: Green and Affordable Energy Harvesting Using Laser Sculptured Moist-Electric Generators

Category: Environment

This research proposal addresses the urgent global energy problems of greenhouse gas emissions and lack of access to energy. By harnessing the abundant moisture in the atmosphere, this project aims to develop green and affordable energy harvesting technology using laser-sculptured moist-electric generators (MEGs). The proposed MEGs will utilize active materials with abundant channels and functional groups, obtained from lab-free materials such as cloth, paper, wood, food, and cork, through a controllable laser sculpture technique.

The research objectives can be summarized as follows:

1. Develop a laser sculpture technique to fabricate active materials with abundant channels and functional groups from lab-free materials, enabling the conversion of these materials into graphene-like nanomaterials for the development of cost-effective and environmentally friendly MEGs.

2. Investigate the interfacial force-electric-thermal coupling process to gain a deep understanding of the moisture-induced electricity mechanism. The study will involve cross-scale dynamic simulations to simulate charge transfer at the water-material interface and explore influential factors on electricity output. Advanced analytical techniques will be used to characterize the active materials and study their interaction with water molecules.

3. Build generators capable of efficiently harvesting green moisture energy using laser-sculptured active materials in large scale. The generators will be tested in various ambient conditions and geographic locations in China, including deserts, forests, and mountains.

The outcomes of this research program are expected to include the development of cost-effective and environmentally friendly MEGs, capable of efficiently harvesting energy from ambient moisture. The controllable laser sculpture technique will enable the fabrication of scalable generators using lab-free materials, contributing to the affordability and accessibility of green energy solutions. The project aims to achieve milliwatt-level electricity output and demonstrate the feasibility of moisture-electric generation in real-world applications.

The broader impact of this research lies in addressing global energy challenges while promoting collaboration among researchers with diverse expertise. By leveraging advanced optics and photonics, this project underscores the potential for international collaboration and collective efforts in finding solutions to urgent environmental issues the world faced today. The outcomes of this study have the potential to revolutionize energy harvesting technologies, mitigate climate change, and improve energy access for underserved communities worldwide.

In conclusion, the proposed research program combines interdisciplinary knowledge and expertise to develop laser-sculptured moist-electric generators for green and affordable energy harvesting. The project aims to provide novel solutions to the pressing energy problems faced globally, emphasizing the importance of international collaboration and the application of advanced optical technologies.

Mid-infrared spectroscopy-based breath analysis tool for mass-screening of early cancer diagnosis

This project aims to develop a non-invasive, compact mid-infrared spectroscopy system with artificial intelligence-based statistical analysis to generate extensive patient data for early-stage cancer detection and treatment. The system will continuously monitor metabolic health, disease progression, disease phenotyping, and pharmacokinetics, among other applications. The main objectives include demonstrating the world's first compact mid-infrared system using cutting-edge fiberized supercontinuum light sources, hollow-core optical fiber technology, and up-conversion detectors for online analysis. It also aims to explore high-resolution mid-infrared spectroscopy (2 to 10 μm) to identify and validate biomarkers in human exhaled breath for detecting oesophageal-gastric cancers, lung cancers, and other diseases. The proposal also focuses on standardizing the compact point-of-care (POC) optical spectroscopy system through clinical trials to gather extensive patient data for early oesophageal-gastric cancer detection and cross-platform validation.

The project shows promising expected outcomes and potential applications. It aims to create a non-invasive, patient-friendly alternative to invasive endoscopy/biopsy tests for diagnosis. Additionally, the project seeks to enable cost-effective mass-scale screening for early detection of various cancers and diseases among the general population, ultimately leading to improved treatment outcomes. Another important aspect of the project is the exploration of mid-infrared spectroscopy to gain insights into the biology of different diseases. The development of a compact spectroscopy system will facilitate its easy integration into diverse medical studies, promoting research across various disease domains. Furthermore, the system's versatility allows for the analysis of different bodily fluids, such as saliva, sputum, urine, and blood, expanding its potential diagnostic capabilities. Notably, the project also contributes to advancements in optical technology through the development of novel fiber designs for mid-infrared range spectroscopy, sensing, and beam delivery. To ensure the field's growth and expertise, the project includes manpower training in mid-infrared spectroscopy and diagnostic tools, fostering knowledge dissemination in this cutting-edge area.

In conclusion, this project holds significant promise in revolutionizing early cancer detection and treatment, enabling more accessible and non-invasive diagnostic tools, and enhancing our understanding of various diseases through the novel application of mid-infrared spectroscopy and artificial intelligence.

Executive summary-health category

Development of an affordable robotic microscope for rapid and stain-free malaria diagnosis

Malaria is one of the most serious public health challenges globally, despite current therapeutics having high efficacy rates when administered timely. Most concerning is that the fight against malaria has stalled. There were 230 million cases in 2015 (the baseline year of the global technical strategy for malaria 2016-2030) and 247 million cases in 2020. The barrier to malaria eradication is the lack of early diagnosis of the infected population. Current malaria diagnostics can be classified into three categories with specific strengths and weaknesses: 1) highly sensitive molecular-based techniques which use PCR. These are slow and demand the use of sophisticated equipment, expensive reagents, and a highly trained workforce; 2) Rapid Diagnostic Tests (RDTs) are relatively fast in comparison to optical microscopy but less sensitive (100-200 parasite μL^{-1}). Besides, the majority of them target the *Plasmodium falciparum* histidine-rich protein 2 *(pfhrp-2)* biomarker, and recent studies have shown the deletion of *pfhrp-2* which causes false negatives and threatens malaria control strategies. 3) Optical microscopy, the gold standard method for diagnosis. This involves examining stained blood smear samples under a microscope. It can detect up to 5-20 parasite μL^{-1}, however, the results vary significantly based on the expertise of the technician or health care provider, and it is labor and time intensive.

None of the three methods offers a definitive solution to early detection. Prompt treatment is crucial in preventing severe illness, complications, and deaths associated with malaria. To boost the fight against malaria, new approaches for diagnostics must be adopted to enhance the sensitivity, accuracy of detection besides being rapid and affordable. While research and development efforts are ongoing to improve and develop these and other malaria diagnostic methods, microscopy is likely to remain a vital tool in malaria diagnosis due to its proven effectiveness, cost-effectiveness, and established specialists in many malaria-endemic regions. Therefore, we think offering a solution within microscopy is key to enhancing early screening and reducing the disease burden.

In this study, we propose to develop an affordable robotic configuration for imaging Malaria by detecting the presence of the parasite waste product, hemozoin (Hz). The affordable OpenFlexure microscope (OFM) will be modified to incorporate polarizing microscopy capability. Leveraging on the magneto-optical physical properties of malaria pigment Hz, we will develop a phase-locked imaging microscope for maximal sensitivity. The microscope will have autofocusing and auto-imaging capability. We will develop a phase-locked mode combining magneto-optical control, thus fully exploiting the Hz features to maximise sensitivity and allow a full automation of the detection assay. We can thus overcome the limitations of traditional microscopy and improve malaria diagnostics in terms of accuracy, efficiency, and accessibility.

e-CoMet: **E**nergy **E**fficient 5G/6G **Co**mmunications with Optically Transparent, Multifunctional **Met**asurfaces

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Executive Summary

This aspiring project will focus on designing and implementing **high-efficiency transparent multifunctional metasurfaces** with particular emphasis on their potential to revolutionize the **environmental impact of 5G/6G telecommunication** technologies.

Our ambitious approach will prioritize the development of transparent, multifunctional, and reconfigurable metasurfaces to overcome the efficiency limitations observed in current examples, where efficiency often falls below 50%. Therefore, the main objective will be **to create (design, implement, and characterize) efficient metasurfaces made from transparent conductors.** To achieve improved efficiency, we will explore innovative design techniques, such as **inverse-design** methodologies, combined with advanced 3D printing approaches fused with **highly efficient transparent conductors**. These will allow us to create **the first-of-its-kind multifunctional transparent metasurface** with **enhanced efficiency**.

Incorporating transparent surfaces into buildings can significantly enhance the energy consumption and efficiency of 5G devices. Meta Materials Inc. and other companies are working diligently to achieve this goal, but producing highly effective transparent metasurfaces is still challenging. Our proposed approach aims to lead the way in achieving groundbreaking advancements in technology, particularly in the field of communication and beyond.

The **e-CoMet** project aims to provide various benefits to both the Optica society and the telecommunications industry, including research innovations and patents. The expected technological advancements can bring advantages with impact in both academic and industrial settings. By improving and extending the concept of transparent metasurfaces concept, we can move closer to a more sustainable and efficient future for telecommunications.

2023 Optica Foundation Challenge
Category: Environment
Title: Spectral radiance mapping to characterize the ecological impacts of light pollution
Name: Dorukalp Durmus
Affiliation: Pennsylvania State University

Executive summary:

The challenge

The accessibility and growing demand for electric lighting have a large-scale impact on natural habitats. Unfortunately, the electric light at night (LAN) can cause negative consequences, such as disrupting ecosystems, confusing migratory patterns, altering predatory-prey relations, causing stress, and interrupting the entrainment of circadian rhythms of many species. The negative effects of LAN (aka "light pollution") is often quantified using photometric and colorimetric measures. Despite the complexity of spectral impact of light sources on the environment, research suggests that light source spectra influences arachnida, aves, instecta, mammalia, and reptiles in predictable manners. However, ecological research studies still use photometric (i.e., illuminance, luminance) and colorimetric (i.e., correlated color temperature) measures, which are based on human visual sensitivity. In addition, photometric and colorimetric measurements are performed using either spot measurements or satellite images. While these measurement methods have merits, they have limitations in accurately evaluating the ecological impacts of light pollution.

Proposed project

Characterizing the impacts of light pollution on several species requires a holistic measurement approach in spectral and spatial dimensions. The proposed research project aims to characterize optical radiation using a spectral imaging radiance colorimeter and assess the outcomes compared to spot (e.g., handheld spectroradiometer) and remote (satellite) measurements. A test field in central Pennsylvania will be identified, and light pollution of a large field of view will be characterized using radiance imaging colorimeter to simulate realistic field conditions. The variation between the traditional and proposed measurement methods will be evaluated, and a new metric for light pollution will be developed using the data generated in this project.

Intended outcomes

The results of this project will help characterize the unintended consequences of light pollution that captures the effects on the environment beyond just humans. New light pollution metric and measurement methods comparison will be disseminated to relevant bodies, such as the Council for Optical Radiation Measurements, the International Commission on Illumination, and International Dark-Sky Association. The project aims to reach a transformative impact on project development where designers and engineers can quantify the impact of lighting systems and mitigate any potential offence. The development of a holistic light pollution metric will also help ecological researchers find acceptability thresholds and guide outdoor lighting standards and recommendations, such as Model Lighting Ordinance (MLO), LEED Sustainable Sites program, the International Commission on Illumination (CIE) recommendations, and standards, such as the Australian New Zealand Standard AS/NZS 4282:2019 Control of the obtrusive effects of outdoor lighting.

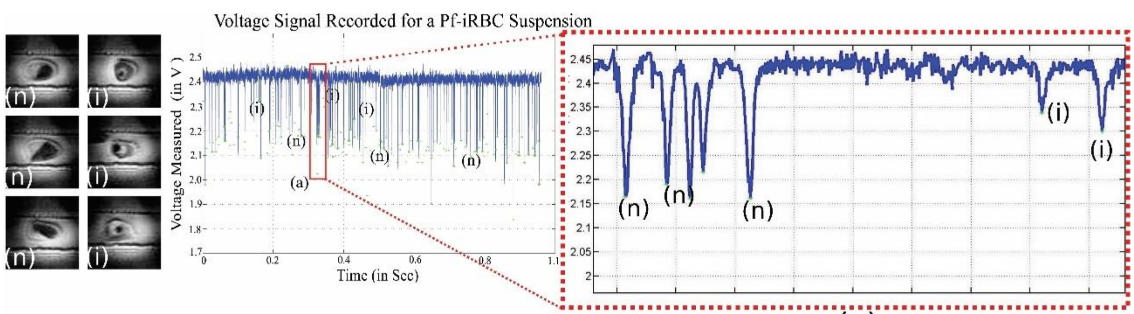
2023 Optica Foundation Challenge

Name of Challenge Project: Artificial Intelligence enabled smart Optical Absorption Point-of-Care device for Malaria screening.

Executive summary:

Background: For the larger interest of the needy design and development of Point-of-Care (PoC) diagnostics is the critical requirement of the health care industry. The requirement of rapid, sensitive detection and reliable solution with minimal human intervention is the front runner objectives of the research and innovation. The aim of the present research proposal is to develop an indigenous smart PoC instrument for screening/ detection of the malaria. The monitoring and screening of malaria transmission is possible with the advancement of the technology in view of malaria eradication.

Scientific Rationale: The microvascular system is responsible for the transfer of oxygen and nutrients and the removal of the waste products generated by the tissue it serves. Here, the main role of the erythrocyte/ Red Blood Cells (RBCs) is the transmission of hemoglobin (oxygenated) and nutrients through microvascular system. As we know that the malarial parasite targets RBCs such as infect inside the RBCs and reduce the hemoglobin concentration by degrading it as hemozyme. As a result, there will be changes in the level of hemoglobin present in normal RBC and malarial infected RBCs. So, this information can be utilized to develop a point of-care device to differentiate between malarial infected and normal RBCs at single-cell high-throughput by differential light absorption in microfluidic channel as observed in any flow cytometry. The proof-of-concept and primary results shown briefly in the figure below.



Novelty: The present malaria diagnosis instruments including clinical microscopy, PoC, Rapid (**qualitative info**.) testing devices use standard signal/image processing algorithms. PoC devices integration with AI models for automatic malaria screening/ testing may give more promising results. Current proposal aims in development of an AI-enabled PoC device for Realtime analysis at single-cell high-throughput (quantitative info.). The primary objective of the study involves development of smart PoC device for malaria screening. The secondary objective of the study includes proper design of experiments for clinical validation and testing, Develop the novel AI based algorithm and comparison with state-of-the-art techniques

Methods: The major principle involved in development of device is to study the light (near UV) absorption properties of malaria infected and healthy/normal blood cells. Predominant features are automatically extracted from the output signal of the sensor using signal processing algorithms and trained with artificial intelligence algorithms for classifying malaria and non-malaria cells. Novel reinforcement learning techniques will be incorporated and further tested.

Expected outcome: Low cost and portable Smart point-of-care Instrument for malaria screening and research publications in high reputed journals along with patents. Custom design and developments of flow-focusing microfluidic devices which are used for identifying cell morphology, deformability, blood flow velocity. Development of GUI based algorithm for malarial parasite detections, finding the stages of infection, quantitative information of infected cells from overall assessed sample. Development of this type of product help in early screening of malaria endemic zone which help towards the eradication of malaria.

Proposal Title: A Laser Helmet Device for Transcranial Infrared Laser Stimulation: A Home-Based Approach for the Treatment of Dementia

Research Category: Biomedical Optics, Therapeutic Laser Applications

EXECUTIVE SUMMARY

A little boy's response to the question, "What is the scariest thing in the world?" was, "The unstoppable nature of time, which slowly leads us all to an inevitable death." Surprisingly, this is quite accurate, despite coming from a little child. Our bodies age and become less functional over time until their ultimate demise. Nonetheless, though the ultimate demise is inevitable, certain comorbidities associated with old age are somewhat avoidable and/or reversible. A considerable proportion of elderly individuals, for instance, are afflicted by a group of disorders that cause progressive deterioration in cognitive function, despite having many more years to live. These disorders, collectively called "dementia," are neurologic dysfunctional diseases characterized by variable degrees of cognitive impairment and other neurologic functional insufficiencies that diminish the quality of life (QoL) in old age. Medical professionals, as directed by allopathic medicine, have sought effective therapies for these conditions for many years with very limited success, and to date, approximately 50 million people are afflicted with dementia on a global scale, with projections indicating that this number will nearly triple by 2025 (Arvanitakis et al. 2019). How, then, can we combat dementia so that our journey through life is enjoyable even in old age?

This work aims to build a home-use-compatible bioactive laser device for transcranial infrared laser stimulation (TILS) as a method of treating dementia. TILS is a form of photobiomodulation in which bioactive, frontal lobe-penetrating lasers are utilized to stimulate the proliferation and regeneration of neuronal cells and neural vascular tissue. It uses near-infrared light to enhance the proliferation of cells, improve circulation, and reduce inflammation (Caldieraro and Cassano 2019). Two arguments support the use of TILS to treat dementia. First, because the various types of dementia involve either one or a combination of cellular degeneration of brain cells, impairment of vascular tissue, and/or the occurrence of diffuse inflammation; and second, because the pathological mechanisms associated with dementia indicate that cognitive decline is acquired rather than developmental. Hence, TILS could efficiently reverse degeneration. In this project, therefore, a laser gadget will be constructed, housed for both clinical and home usage, and utilized in a Johannesburg population of dementia-stricken adults. *In vitro* performance evaluation will be followed by *in vivo* administration of diverse dosages and fluencies of TILS. Measures of brain activity, including the psychomotor vigilance task (PVT) and delayed match-to-sample (DMS) memory task, will be conducted on all experimental and placebo groups after dose administration to determine the effect of this laser device.

This study's primary outcome is a potentially efficacious and cost-effective alternative therapy for treating dementia. The device developed in the study will be patented, and subsequent studies and prospective phases of clinical trials will be done with the ultimate goal of establishing this therapeutic alternative as a clinically authorized treatment. Besides, to ensure accessibility, the design of this product is intended to be convenient for home use, allowing people with dementia to be treated at home without making random visits to a clinic where a stationary laser device is held.

Democratizing Shortwave Infrared Imaging with Avalanching Nanoparticles

Executive Summary – Information Challenge

Emma Xu, Columbia University, NY, emma.xu@columbia.edu

The challenge: Shortwave-Infrared (SWIR) refers to wavelengths between approximately 1 and 2um. Imaging in SWIR can provide crucial information about systems that cannot otherwise be obtained with visible light. Thus, SWIR is vital to many industries, including semiconductor, agriculture, and healthcare.

Despite its wide range of potential uses and impact, commercially available SWIR cameras are extremely costly relative to visible ones ($20k+), dramatically limiting their accessibility. The key component within a SWIR camera is the photodetector (PD). Most of these cameras use Indium Gallium Arsenide (InGaAs) for the PD. While it has very high quantum efficiencies (QE) in the SWIR range, it is expensive, complicated to manufacture, and must be cryogenically cooled to reduce background noise. More recently, Colloidal Quantum Dots (CQD) have been demonstrated as a cheaper alternative PD material system; however, due to difficulties in controlling uniformity during synthesis, their tendency to degrade in air, and low QE, CQDs are still a long way from delivering a robust SWIR solution.

Proposed project: we propose to build a robust, high pixel density, highly sensitive, affordable, easy to manufacture SWIR camera with avalanching nanoparticles (ANPs) and Silicon sensors. Invented during my PhD, ANPs are nanocrystals that exhibit photon upconversion and photon avalanching (PA) phenomena. ANPs can not only convert SWIR photons into ones detectable by Silicon (Si), but the PA property also boosts the QE of this process to up to 40%. The inherent high nonlinearity of this material enables an ultra-high photon sensitivity. Importantly, ANP-based SWIR imaging circumvents the need for InGaAs and is compatible with Si-based complementary metal-oxide semiconductor (CMOS) sensors: a film of ANPs is simply deposited onto a substrate above a Si sensor, which upconverts SWIR light directly to Si-detectable wavelengths. The advantage is multifold: much lower noise can be achieved without cooling, and as a much more mature technology, the manufacturing of Si CMOS is cheaper, the pixel sizes are smaller, and the quality is higher. Compared to CQD, ANPs are also superior because they are extremely air- and photo-stable, and the synthesized uniformity is well-controlled. In terms of fabrication, InGaAs and CQD PDs require 10+ layer semiconductor deposition and lithography processes in the cleanroom. In contrast, ANP-based PDs just require spin-coating a layer of ANP onto a substrate.

	InGaAs	CQD	ANP
Signal-to-noise ratio	Low	Low	High
Uncooled	✗	✗	✓
Pixel density	Low	High	High
Photo- & air-stability	High	Low	High
Quantum efficiency	High	Medium	Medium
Fabrication	Hard	Hard	Easy
Cost	$$$$	$$$	$

Chart: side-by-side comparison of InGaAs, CQD, and ANP-enabled photodetectors across multiple performance factors.

This project has three major tasks: (1) investigate the ANP deposition. Because it is the first of its kind, we will develop a recipe for the concentration and layer thickness of ANPs needed for optimal SWIR photon detection; (2) optimize the coupling of light from the substrate into the Si imager; we will then characterize key performance parameters of this system, including its responsivity, QE, and signal-to-noise ratio; (3) finally, we will retrofit our ANP-based PD into a commercial camera and demonstrate SWIR imaging.

Intended outcomes: My ultimate goal is to commercialize this technology, and my near-term career plan is to graduate with a PhD from Columbia University in the Fall of 2023, and continue to develop this project as an Associate Research Scientist in 2024. The funding of the Optica Foundation Challenge will provide me with the capital needed to develop a first prototype of an ANP-based SWIR camera. This opportunity is pivotal because, with it, I can de-risk this game-changing technology and raise future funds to continue on the commercialization path, thus providing affordable, high-performing SWIR cameras to all.

Volcano-in-a-chip: Simulating CO_2 Uptake of Thermophiles under Extreme Conditions for Industrial Implementation

As carbon dioxide (CO_2) levels in the atmosphere continue to rise, new carbon-negative technologies are required to keep global warming well below the critical 2°C threshold. To achieve net-zero targets and foster circular economies, industries generating flue gases must adopt direct CO_2 capture mechanisms.

While engineered direct air capture system are still under development, natural systems are already well adapted for sequestering CO_2 from the environment, converting it into biomass or minerals. Bioreactors, equipped with precise control over light and CO_2 conditions, have shown potential for achieving high conversion efficiencies required at industrial scales. Nevertheless, existing bioreactors can only operate at ambient conditions, constrained by the requirements of the organisms involved. This limitation becomes apparent when dealing with industrial flue gases, which can reach temperatures as high as 100°C.

Recently, thermophile bacteria have been rediscovered thanks to their exceptional ability to sequester CO_2 at high temperatures. These microorganisms thrive near hydrothermal vents of volcanoes, having evolved to withstand extreme environments. Consequently, their implementation at industrial processing sites holds significant promise.

Incorporating thermophiles into current bioreactor designs presents significant technological challenges due to the need for precise environmental control. Conventional techniques like resistive heating are limited to broad and uniform heating, thus can not realistically simulate dynamic thermal conditions required by such microorganisms. Conversely, light-to-heat conversion offers a fast, easily implementable solution that enables precise localization of thermal conditions, making it a promising approach for addressing this issue.

This research project aims to explore the CO_2 sequestration capabilities of thermophiles under extreme conditions within a highly controlled microenvironment. To achieve this, we propose an advanced optofluidic system integrating digital holography, optical diffraction tomography, spatial light modulation and the efficient light-to-heat conversion via plasmonics, into a state-of-the-art optofluidic system with unprecedented thermal control. The system will facilitate precise thermal control, enabling the creation of spatially confined temperature gradients of up to 100°C, which closely mimic the complex environmental conditions encountered near volcanoes and within industrial processes.

By applying specifically designed optical fields on plasmonic nanostructures, we can induce and measure temperatures in situ with high accuracy through tomography. This feature will allow us to fine-tune our experimental protocols to identify the optimal growth conditions for thermophiles. Notably, the extended depth of field provided by digital holographic microscopy will enable us to monitor thermophile movement and growth in 3D while simultaneously measuring the induced temperatures.

Through careful control of the temperature landscape, we will guide thermophiles into desired structures, promote clustering, and thereby stimulate their growth. Further optimization of these protocols could potentially enhance the efficiency of CO_2 sequestration under less-than-ideal environmental conditions.

Assessing CO_2 sequestration of thermophiles under extreme conditions is a crucial first step in evaluating their performance in industrial settings. To achieve this, we will develop a miniature bioreactor prototype that enables exceptional optothermal control while precisely monitoring CO_2 conditions. This on-chip setup will facilitate the measurement of the CO_2 sequestration efficiency and allow for a direct comparison between ideal growth and simulated industrial conditions. The findings from this research will shed light on the potential of thermophiles as a viable solution for CO_2 capture in industrial applications.

This project holds the potential to yield significant insights into CO_2 sequestration using biological systems as an alternative pathway towards climate neutrality. On-site CO_2 capture directly at the site of emissions will provide the industry a quantitative tool for direct sequestration and storage, leading to more sustainable practises.

Advancing our understanding of thermophiles as key species in CO_2 sequestration will provide critical insights into the fundamental carbonic anhydrase process to enhance the efficiency of synthetic biofuel production and foster the development of alternative food and animal feed resources.

The significance of optics and photonics in the sustainable transformation of societies becomes apparent when considering their capacity to control microenvironments of biological systems. By promoting the broader utilization of optical tools across various industries, this research will enhance accessibility to these cutting-edge technologies for an interdisciplinary community, contributing to the broader goal of promoting sustainable solutions.

Low-Cost Stain-free Computational Spectral Fluorescence Imager for Diagnosis of Diseased Tissues

Effective and timely diagnosis is critical for successful disease treatment. Yet, conventional diagnostic methods often involve invasive procedures, high costs, and limited accessibility, particularly in resource-restricted areas. One promising alternative to traditional invasive diagnostic methods is optical biopsy. Unlike conventional biopsy techniques that require tissue extraction, optical biopsy allows for real-time, non-invasive visualization of tissue morphology and pathology. It provides immediate and accurate results, greatly reducing patient discomfort and the risk of complications, as well as overall healthcare costs. However, current optical biopsy methods, reliant on contrast agents and requiring expensive equipment and skilled personnel, are challenged by potential inaccuracies, slow operation speeds, and high costs. Fluorescence microscopy could potentially overcome these limitations. This technique offers high specificity and sensitivity in visualizing cellular components, yet traditional fluorescence microscopy requires tissue labeling with dyes and lacks the necessary spectral information to identify specific disease markers, compromising the accuracy of diagnosis. To address these challenges, we propose the low-cost Computational Spectral Fluorescence Imager. This innovative technology combines the benefits of label-free fluorescence microscopy and optical biopsy, offering three key features:

1. **Multiplex Color Imaging**: The proposed system is designed for direct compressive imaging of multiple fluorescence contrasts, facilitating multiplex color imaging. This design will potentially overcome the limitations of current color imaging techniques, offering the capability to simultaneously image multiple fluorescence contrasts. This feature will greatly enhance the system's ability to differentiate and classify multiple entities in complex tissue environment.
2. **Rapid Optical Biopsy**: The proposed work will also enable rapid compressive imaging of autofluorescence images. By leveraging cutting-edge data compression techniques, we aim to significantly increase the speed of optical biopsy procedures. This will streamline data acquisition and processing, making the procedure more efficient and accessible while maintaining high diagnostic accuracy.
3. **Advanced Signal Analysis**: Lastly, the unique feature of the system will allow for higher-level analysis of detected signals that mix the multidimensional information of the tissue of interest, enabling applications such as classification of tissue types, disease types, and more.

By providing an affordable, non-invasive diagnostic tool, this proposal has the potential to democratize healthcare, particularly in low-resource areas, while serving as a precise, cost effective, and non-invasive imaging tool for broad biomedical research.

Backing this proposal signifies support for meaningful health advancements in underserved areas and for advancing biomedical research. The Computational Spectral Fluorescence Imager, at the intersection of optics, biotechnology, and information theory, is a practical, cost-effective solution to enhance disease diagnostic quality and to catalyze advances in global health.

Proposal title: Development of a clinical multi-excitation optical coherence elastography system to interrogate corneal biomechanics for the detection and staging of normotensive glaucoma.

Category: Medicine

Abstract:

In Peru, Glaucoma is the first cause of irreversible blindness characterized by progressive optic nerve damage and visual field loss. It is estimated that 50% of Glaucoma Peruvian patients are not aware they carry such a disease. The primary risk factor for Glaucoma detection is elevated intraocular pressure (IOP). However, normotensive Glaucoma (NTG) is a form of Glaucoma that develops in the eye despite its IOP being within the normal range of 12 to 21 mmHg. Therefore, early detection of NTG becomes a challenging task and it is crucial for timely intervention and preservation of vision. Currently, NTG diagnosis relies on IOP measurements through the cornea and visual field testing, which may miss the early stages of the disease. Corneas with abnormal (softer) biomechanics and topography (high astigmatism) may lead to inaccurate readings of IOP which, added to the assumptions made by each clinical tonometer, results in high variability in the estimation of IOP. Moreover, there is scientific evidence reporting that patients with NTG tend to have softer corneas compared to control patients. We propose the development of a clinical multi-excitation optical coherence elastography system to interrogate corneal biomechanics for the detection and staging of normotensive glaucoma. This system will be capable of measuring the topography of the cornea (structural B-mode frame information) and the corneal dynamic response (biomechanical information) from two simultaneous excitation sources: air-pulse macro deformation (AP-MD), and air-couple ultrasonic wave excitation (AC-US). The innovative integration of both excitation technologies together with a finite element model (FEM) of the eye will allow us to probe not only the shear modulus of the cornea through the propagation of Lamb waves, but the calculation of a true-biomechanically corrected IOP. The accuracy of the estimations of shear modulus and corrected IOP using measurements from the clinical system and the outcomes of the inverse FEM simulations will be tested using ex vivo animal models of the eye by modulating IOP with an artificial pressure-control system, and corneal stiffness with collagen enzymes. After a safety validation of the system in terms of acoustics, photonics, and air pressure for human use, a preliminary patient study will be carried out with 20 control patients, 20 patients with NTG, and 20 patients with high-tension Glaucoma (HTG). These measurements and estimations will be used to generate biomechanically inspired biomarkers of the corneal to detect early and advanced stages of NTG. We expect that shear modulus and the true-biomechanically correlated IOP can separate NTG from control and HTG patients. The impact of this research on the Peruvian ophthalmology healthcare system is fundamental since our proposed solution could catch NTG earlier and enable patient treatment to avoid further optical nerve damage and vision loss. This represents more than 80% in savings in the application of more invasive (costly) treatments and preserving vision quality. Finally, this technology can be used to understand the impact of unusual corneas (i.e., high astigmatism, low rigidity, and thin corneas) in the estimation of IOP, treatment monitoring, and the evaluation of other ocular diseases such as keratoconus.

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Executive Summary of “Hardware and Software Enablers for Future Optical Access Networks”

Contact: Gaël Simon, Philippe Chanclou

The access network recently witnessed an important increase, through the massive deployment of Fiber To The Home (FTTH). The industry is already working on the definition of the optical technologies which will replace the currently deployed technology, the G-PON (gigabit passive optical network) standard, offering higher than ever throughputs. Those future technologies will enable, beside the throughput increase, to answer the constantly evolving customers’ uses.

The success of G-PON and the coming XGS-PON technologies and similar permitted to imagine new use cases for those technologies, in taking advantage of their robustness, their low energy consumption, or their low-cost for mass production in other network segments. This is the objective of the “ETSI-F5G” organism, which aims to “extend the FTTH paradigm to a Fiber to Everywhere”.

In parallel, the rapid development of mobile networks (5G’s deployment started; 6G’s main directions emerge) requires the fiber infrastructure to evolve toward antenna sites. Mobile network transport and associated specifications induce important constraints on optical segments in terms of throughput (10x more in 6G than 5G), and latency (10x less in 6G than 5G). This is emphasized by the interest in solutions as “Cloud Radio Access Network”. The later splits the radio network functions and creates new interfaces, often requiring high bitrates, as the x-Haul.

The objective of this project is to identify technological solutions allowing to answer to previously presented stakes, and to identify their strength and weaknesses, while insuring interoperability of the future systems working at 100Gbit/s. The current optical transmission technologies for access network employ Non-return to Zero modulation format, for the sake of simplicity and cost. However, the need for high bitrate interface come at a price, which imposes to reevaluate the solutions and to assess the need for a technological rupture. It could mean to choose PAM4, coherent detection “regular” or simplified, the use of Frequency Division Multiplexing, Wavelength Division Multiplexing, NRZ at higher bitrate,… In any case, those solutions must adapt to the multiple access topology of the FTTH. The energy consumption must also be carefully monitored, and so must be the ability to maintain interface’s interoperability, avoid the dependency to a vendor, and make the optical fiber passive infrastructure viable.

PLASMONIC SENSORS FOR MONITORING WATER CONTAMINANTS

In rural zones of Northeast Mexico

Category: Health

The goal of wastewater quality monitoring is to obtain quantitative information about the physical and chemical characteristics of the water, such as color, refractive index, acidity, and salinity, to mention a few. Due to in *rural areas*, especially in the *north of Mexico*, obtaining fresh water is complex and is getting harder to obtain; usually, access to water in these areas is through subsoil water wells and then purified using artisanal water filters. Therefore, to improve human health in the community, it is necessary to monitor the quality of water from these artisanal filters, which are handmade using local resources.

The refractive index (RI) is a generic indicator of water quality, as any substance dissolved in water will change the refractive index of the water matrix. Its advantage is that it includes consistent sensitivity for all substances, response linear with concentration, and high resistance to matrix interference. Surface plasmon resonance (SPR) senses the refractive index changes near the surface layer and is extremely sensitive to detecting minimal refractive index changes. By angular scanning reflectivity, the SPR angle occurs at the minimum reflectivity. The SPR angle changes with the solution's refractive index at the interface, and the latter changes with the mass, density, and refractive index of foreign items attached to the surface of the metallic film. We use the transfer matrix method for a multilayer system to simulate numerically the reflectivity intensity of the p-polarized incident beam.

The general objective is to design and optimize a portable plasmonic sensor in the Kretschmann configuration for monitoring the water quality of artisanal filters in rural zones based on refractive index changes using the matrix transfer method.

Participants will focus activities to achieve the following specific objectives: 1) to achieve the relationship between the ratio of containments presented in a water sample with the refractive index, 2) to prepare solutions for different molarities of different contaminants and measure the refractive index of the solution for each concentration, 3) to propose a n-layers Kretschmann configuration sensitive to water contaminants, 4) to simulate numerically the reflectivity angular scanning for each concentration and achieve the resonance angle, 5) to use the Taguchi´s method to determine the best performance of the sensor from the control factors (wavelength, metal film, thickness) and 6) to implement the experimental prototype for monitoring the quality water from the artisanal filter.

The quality of water for human consumption depends on the area's environmental conditions. In urban areas with seismic fractures, such as Mexico City, wastewater is enriched with sulfates, nitrates, arsenic, manganese, lead, and iron. In contrast, in rural areas in the northeast of Mexico, wells are contaminated with coliform organisms due to fecal contamination of warm-blooded animals. Particularly, in the northeast of Mexico, the presence of dissolved solids is related to the surroundings of the Sierra Madre Oriental, as it comes from the dissolution of minerals that form subsoils and rocks. Along the Santa Catarina River, the concentration varied from 500 to 600 ppm, and this can be attributed to the flow that carries groundwater through the subsoil, dissolving salts such as chlorides, sulfates (CuSO4), and the higher the content of dissolved solids there are, the greater the possibility of taste problems, laxative effects, etc. Thus, preserving and keeping the natural space that provides the water source free of contaminants is necessary. Plasmonic sensors can improve community health through real-time measurements of filtered water quality from subsoil wells and artisanal filters in rural areas.

Background – Quantum information processing (QIP) takes advantage of quantum mechanical resources like superposition and entanglement, leading to groundbreaking advancements in computational efficiency, communication security, and sensing/imaging resolution. Various systems, from single atoms to macroscopic objects such as superconducting circuits, have demonstrated quantum effects. Among the many potential quantum platforms, photon-based optical systems stand out as prime candidates due to their exceptional qualities: ultimate propagation speed, immunity to decoherence and crosstalk, and low power consumption. Despite the recent attention to photonic QIP schemes, there is a fundamental hurdle in achieving scalable photonic QIP. This obstacle arises from the requirement of strongly enhanced photon interaction and/or high nonlinearities, which have proven challenging to attain. Despite efforts to improve nonlinearities in traditional materials, the achieved interaction falls far short of the single-photon nonlinearity necessary for a practical and scalable quantum photonic platform.

Project goals – To address the significant challenges in achieving robust photon-photon interactions at the single-photon level through a scalable approach, our endeavor focuses on developing the first *nonlinear quantum nanophotonics* platform. We will leverage the recently discovered strongly interacting Rydberg excitons in cuprous oxide (Cu_2O) thin films and microcrystals for this innovative platform. By combining nanophotonics as a controllable, low-loss, and scalable foundation with extraordinary quantum properties and strong single-photon level interaction of Rydberg atoms, we aim to create a novel quantum material-based system. Our project will begin by establishing a CMOS-compatible and easily integrable growth method to produce thin films and microcrystals of Cu_2O, a quantum material uniquely known for its highly-excited Rydberg states. Through detailed high-resolution laser spectroscopy, we will thoroughly investigate the properties of these excitonic levels, including their coherence and optical characteristics. The ultimate objective is to realize the Rydberg photonics platform by effectively coupling strongly interacting Rydberg excitons in Cu_2O with specially designed and optimized nanophotonic structures. To achieve this, we will study the mutual coupling between the Rydberg exciton and engineered nanostructures. By examining the dynamics of this hybrid system and assessing the impact of Rydberg excitons in facilitating strong photon-photon interaction and generating substantial optical nonlinearities, we seek to overcome the existing limitations and unlock the potential for scalable quantum nanophotonics.

Broader Impact – By gaining fundamental insights into Cu_2O Rydberg excitons and their exciton-photonic hybrids, we have the potential to usher in the next generation of powerful quantum optics methodologies, which were previously limited mostly to atomic systems. The results of this endeavor will push the boundaries of light-matter interactions in solid states, transcending conventional excitonic schemes that rely on ground-state excitons. The proposed novel platform presents an exciting opportunity to explore quantum optics at the *single-photon level*, capitalizing on the concept of Rydberg blockade and forming strongly interacting photons. They could enable the realization of photonic quantum simulators and facilitate progress in quantum nonlinear optics, nanophotonics, and QIP. The outcomes of this project would not only hold great significance for the fundamental understanding of quantum phenomena but also carry substantial implications for technological applications. This research has the potential to unlock new possibilities in quantum optics and solid-state physics, bringing us closer to the practical implementation of quantum-enhanced technologies and furthering our exploration of the quantum world.

Handheld MEMS-SOA Silicon Based Gas Analyzer for Real-time, Cumulative and Wide-Band Environmental Monitoring in Smart Cities

Assoc. Prof. Dr. Eng. Haitham Omran

Laboratory of Micro Optics, Faculty of Information Engineering and Technology (IET), German University in Cairo, Egypt

Human activities are the main cause of Earth's environmental changes [1]. Effects like global warming caused by increasing carbon dioxide (CO_2) and methane (CH_4) emission from fossil fuel, human waste and agricultural activities have disastrous effect on humankind [1, 2]. Rising see levels and extreme weather triggered by environmental changes affects the existence of many communities and even nations across the globe [3, 4]. Limiting the global warming and pollution to the target levels requires continuous, wideband, cheap and accumulative monitoring solutions for CO_2, CH_4 and other climate forcing emissions [1-4].

This proposal aims at contributing to achieve the global warming 2°C target limit implying a cumulative carbon emission limit of the order of 500 GtC [1]. The target limit is to be achieved by continuous, cumulative and smart monitoring of climate forcing gas emissions (e.g. CO_2, CH_4) using a flexible use case handheld micro-electro-mechanical-system semiconductor-optical-amplifier (MEMS-SOA) Silicon based gas analyzer with cloud connectivity for Internet of things (IoT) smart cities. The analyzer core engine is an experimentally verified MEMS-SOA swept laser source connected to a small gas cell [5-7]. The MEMS is constructed from two deeply-etched Si/Air Bragg mirrors attached to an electrostatic comb actuator allowing the tuning of the swept laser over 100 nm bandwidth with up to 0.2nm resolution depending on sweep speed [6, 7]. The absorption spectrum of gases in the near-infrared is used for quantitative and qualitative monitoring of the environment climate forcing emissions [5]. The device smart IoT and cloud connectivity allow real-time and accumulative monitoring which is crucial for correct environmental assessment and decision-making. The device will have a flexible use case by working in two gas sampling modes; an in-device near gas cell mode and long-fiber far gas cell mode for difficult to access locations (e.g. factories, mining cites and gas pipelines) enabled by a detachable gas cell head.

At the end of the project, the team will demonstrate a working prototype of a packaged handheld MEMS-SOA gas analyzer in the near-infrared spectrum. The package is to include all functional parts including the MEMS-SOA swept laser core module, control electronics, power supply, gas flow control and detachable gas cell head. We will demonstrate practical sensing of climate forcing gas emissions (e.g. CO_2, CH_4) in the range (1500 nm – 1600 nm) with up to 0.2nm resolution. The device will have IoT connectivity for smart cities environmental monitoring. We will develop a mobile app with cloud connectivity allowing device control, real-time monitoring and cumulative data logging for fast and accurate analysis and long-term decision-making based on cumulative sensing in smart cities.

Executive summary of

Scalable room-temperature quantum computing based on nonlinearity in microcavities

Quantum computing promises an exponential speedup on some special tasks over classical computers. However, most of quantum computing systems, such as superconducting qubit, trapped ions, neutral atoms, silicon quantum dots, etc, have to be cooled to cryogenic temperature to reduce the relentless deleterious influence of the environment. Photon, a quanta of light, is naturally decoupled with environment thus provides a promising approach to realize universal quantum computing [1] working at room temperature under atmospheric condition. Nevertheless, the lack of photon-photon interaction at a single-photon level [2] hinders the realization of this enormous goal in the last decades.

In this project, we proposed that a set of coupled optical microcavities with strong $\chi^{(2)}$ nonlinearity provides a solid-state system to implement a high-precision room-temperature quantum computing. Owing to the strong nonlinearity in the materials [2-5], the harmonicity of cavity energy levels can be broken so that all requirements—a well-defined qubit with a long coherent time, initialization of qubit, single- and two-qubit operations, readout of qubit—can be realized with high efficiency and fidelity, simultaneously. This is the first macroscopic qubit working at room temperature, containing more than 10^{10} atoms in a single qubit. This CMOS-compatible scalable scheme can be carried out within next few years in view of rapid development of high-Q cavity fabrication on nonlinear materials.

Given the current state of quantum control technologies, achieving this ambitious goal requires substantial technological accumulation and simplification of theoretical approaches in order to develop this direction into a competitive research field in quantum computing. As this project spans two years, it is expected to achieve two milestone objectives: room-temperature single-photon source based on photon blockade, and strong coupling between microcavity modes.

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Development of Spatial Heterodyne Atmospheric Carbon-Dioxide Spectrometer (SHACS)

Executive Summary

Finding solutions to the continuous concerns over climate change has been of increased interest in recent times with efforts targeted at mitigating its effects. Satellite observations and *in-situ* terrestrial networks play key roles in the understanding and management of the problem. Whilst detecting carbon-dioxide (CO_2) optically is relatively straightforward, and has been achieved with small satellites, accurate quantitative mapping of CO_2 requires very high precision (~1 ppm uncertainty or better) measurements of the gas concentration. This normally requires high-performance, large and complex instruments whose high cost, mass, volume, and power requirements preclude their use on small satellites.

To provide a low-cost solution for the global monitoring of atmospheric CO_2, we propose the development of a Spatial Heterodyne Atmospheric Carbon-Dioxide Spectrometer (SHACS). SHACS is a robust, no-moving-part, compact precision atmospheric CO_2 monitoring instrument that is suitable for deployment for both space-based and *in-situ*-based observations. It provides a cost-effective and affordable means of monitoring atmospheric CO_2 levels globally. SHACS comprises of two interferometer channels (1 & 2) and an O_2 A-band Channel. Channel-1 was developed and tested during my PhD and Postdoctoral research. Both Channels will be redesigned and developed with improvements for the 2023 Optica Foundation Challenge Program at the Institute of Space Science and Engineering (ISSE) in Nigeria. Due to its compact configuration, the instrument fits into a microsatellite-size platform and is capable of tackling the concerns of climate change by providing high-quality hourly measurements of atmospheric CO_2 concentration when launched in constellation.

It is vital to ascertain the levels of atmospheric CO_2 since it is the most anthropogenic (manmade) greenhouse gas constituent responsible for increase in global temperatures which leads to global warming that causes climate change. Therefore, there is a crucial need for effective monitoring of CO_2 especially along the tropics where there are sparse terrestrial observatories and nondedicated satellites for monitoring CO_2 in the Sub-Saharan African (SSA) region. The ability to effectively monitor CO_2 sustainably in this region, will assist in ascertaining the uncertainty surrounding the annual net increase of global atmospheric CO_2 and provide solutions to Climate Change. This information will enable policymakers to enact policies that promote clean air, good health and wellbeing.

Having a constellation of satellites and a network of cost-effective *in-situ* measurement hubs in Nigeria and across the SSA regions using the SHACS instrument, which is designed for both terrestrial and space-based observations, would vastly promote economic development and welfare of countries across the region through job creation, capacity building, collaboration, innovative solutions, good health and wellbeing, whilst providing carbon flux data to offer solutions to issues surrounding climate change and mitigating its effects.

Apart from benefits obtained from mitigating the effects of climate change, the outcome of this project also features added value through advancement in technology by development of spin-offs. By caring for the environment and combating climate change, investors would be attracted from both local and international communities to utilize our products and services which cuts across key sectors that promote sustainable economic growth such as agriculture (for food security), health and education. Furthermore, the outcome of this project develops knowledge, collaboration and expands its benefits to schools/colleges, higher institutions, research institutes, space-related institutions, government and non-governmental organizations etc. The establishment of regional hubs across Sub-Saharan Africa, would promote regional collaborations, reduced inequalities and provide a platform for technological growth in this region thereby addressing 13 UN Sustainable Development Goals (SDGs).

Jhonattan Cordoba Ramirez

Universidade Federal de Minas Gerais (UFMG)

Highly efficient all-optical isolators on silicon-based Brillouin platform for modern communications systems

The proposed research project aims at addressing the challenges associated with developing highly efficient all-optical isolator systems in integrated photonics. The current state of non-reciprocal devices, particularly optical isolators, has hindered their integration into photonic systems due to limitations such as bandwidth constraints, reliance on magnetic fields, and sensitivity to nonlinear effects. The proposed research presents an innovative approach that harnesses the power of Brillouin scattering, space-time modulation, and waveguide-based designs. In addition, this study explores the vast potential of using highly versatile 2D materials, such as graphene and/or twisted bilayer graphene, to integrate them seamlessly into structures with the previously described characteristics. By leveraging the exceptional physical properties of these proposed materials and structures, we aim to significantly enhance the expected effects, thereby opening new possibilities in the field. The anticipated outcomes of this research include developing highly efficient all-optical isolator systems with broadband operation, reducing power consumption, improving performance compared to existing solutions, reducing signal loss, and increasing network efficiency. Overcoming bandwidth limitations, addressing nonlinear absorption effects, and enhancing conversion efficiencies are among the key goals. This research is significant for advancing integrated photonics by developing more reliable and efficient photonic systems for modern communication networks.

By successfully bringing this proposal to fruition, we aim to significantly contribute to developing this technology, propelling it forward, and pushing the boundaries of the state-of-the-art. The integrated-photonics-based isolators allow the integration of this technology with other integrated photonics components, systems, and technologies. The alignment of this proposal with Sustainable Development Goals (SDG) and Environmental, Social, and Corporate Governance (ESG) principles emphasizes the responsible and ethical advancement that we aim to have in developments related to new technologies based on integrated photonics.

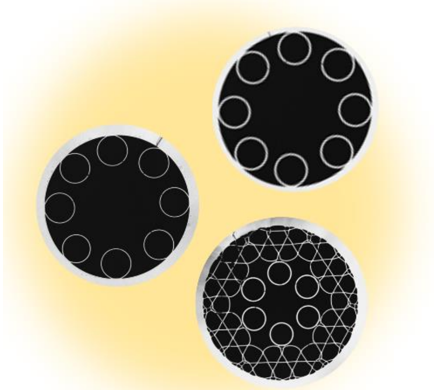
Overall, the proposed research has the potential to significantly impact the field of integrated photonics by advancing optical isolator technology, improving performance and efficiency in communication networks, enabling integration with other photonic components and technologies, and promoting sustainable and responsible practices. The outcomes of this research can benefit various sectors, including telecommunications, data centers, and optical sensing applications, with significant implications for researchers, industry professionals, communication network providers, end users, environmental advocates, and government/regulatory bodies.

Multi-gas sensing with ultralow-loss hollow-core fibers

Jonas H. Osório

Federal University of Lavras, Lavras, Brazil

Category: Environment



Multi-gas sensing with HCPCF
- Greenhouse gas emissions
- Gaseous pollution
- Agriculture and livestock

The development of devices able to monitor multiple gas species is a pressing need in environmental science. Although it motivated the study of a great set of gas sensors, selectively and remotely detecting multiple gas species using a single platform lingers as a challenging task. This project proposes the realization of multi-gas fiber-enhanced Raman spectroscopy (FERS) with newly demonstrated hollow-core photonic crystal fibers (HCPCFs) displaying ultralow loss in the short-wavelength range. Performing FERS with such new fibers, which stand nowadays as the lowest loss fiber optics guiding in the visible range, will allow enlarging the interaction lengths to potentially achieve lower detection limits for greenhouse gases and gaseous pollutants sensing. Additionally, this platform will enable the realization of remote multi-gas sensing as the sensor head can be deployed at the application site while the measurement apparatus can be kept away from the measurement locus.

The outcomes of this project will encompass both scientific and practical achievements. From the scientific viewpoint, the activities to be developed within this project will allow delving into HCPCF properties – modal content, polarization characteristics, and sources of loss –, to identify the most suitable configuration for the sensors' operation. From the practical point of view, the development and application of the sensors will allow demonstrating devices able to detect and quantify greenhouse emissions and gaseous pollutants. This in turn will contribute to the broad community efforts towards a better future for humanity by providing the social actors involved in productive, monitoring, and controlling actions with an effective means for assessing multi-gas environments using a simple and cost-effective configuration.

The development of the proposed multi-gas HCPCF sensors will impact the scenario of environmental monitoring systems and, therefore, significantly contribute to the efforts regarding environment preservation. This, together with other techniques, has the potential of supplying information on the environmental conditions capable of providing guidance for strategic discussions on environmental conservation and climate change assessment.

Additionally, being Brazil, due to its wide availability of natural resources and need for environmental monitoring, a country with strategic importance to world's environmental issues, I highlight that the development of this project has the potential of having amplified repercussions of its gas sensing results, as the developed devices will be, after laboratory characterization, employed in on-the-field applications in areas of interests such as urban and rural environments, plantations, livestock production sites, and forests.

Title: Diffractive Optical-Computational Imaging for Deep Learning-Based Depth Estimation of Skin Chronic Wounds

Abstract: Skin chronic wounds pose a serious health problem, especially in patients with diabetes or Hansen's disease, as their healing capacity is limited, leading to significant healthcare and socioeconomic repercussions. An early treatment of these chronic wounds can prevent up to 80% of amputations. To achieve effective monitoring and control of patients with chronic wounds, it is essential to determine various wound characteristics, such as area, perimeter, and depth. These parameters help to determine the precise amount of medical products needed for treatment in each evaluation and monitor the evolution of skin tissue, being the depth the most decisive parameter. However, current depth calculation methods involve invasive techniques with direct contact with the ulcer, making precise measurement difficult and potentially interrupting the healing process. Therefore, there is a need to develop non-invasive and accurate technological solutions for the depth estimation of skin chronic wounds.

Computer vision systems are experiencing growing popularity in the field of medicine, thanks to image processing and the use of artificial intelligence algorithms, which have enabled the development of various applications in the healthcare sector, such as action recognition, patient monitoring, and hygiene protocol control, among others. However, conventional cameras only capture a 2D spatial projection of scenes, losing depth information. Although techniques such as structured light or stereo vision exist for depth estimation in images, they have limitations for use in healthcare due to high costs, sensitivity to lighting, and adaptation difficulties and calibration. Recently, a new methodology has been proposed that utilizes optical-computational diffractive systems to encode depth optically and subsequently estimate it using computational algorithms. Diffractive elements are optical devices capable of custom encoding the amplitude or phase of light waves passing through them by modifying their height map. The advantage of this methodology is its lower cost compared to structured light and stereo vision systems, as it does not require expensive or complex devices.

The present project, led by researcher Jorge Bacca, aims to address the need for an innovative approach to estimate ulcer depth in images of patients from the Sanatorio de Contratación E.S.E. in Santander, Colombia. The project spans a duration of 2 years and encompasses various stages, starting from establishing the acquisition requirements in Colombian patients, followed by the creation of a dataset using structured light systems used only for training, verification, and comparison. The project further involves utilizing deep learning techniques to develop an optical-computational diffractive system for accurately estimating ulcer image depth. The final stages of the project entail the implementation and validation of the proposed system. Collaboration between Dr. Jorge Bacca, experts from the HDSP research group at Universidad Industrial de Santander, and the Computational Imaging group at Stanford University has contributed valuable knowledge for designing and assembling the proposed diffractive camera, with the potential to significantly enhance ulcer medical diagnosis. By providing healthcare professionals with quantitative criteria, this technology enhances diagnostic accuracy and reduces the burden on the healthcare system.

The intended outcomes of this project are:

1. Development of an optical-computational diffractive system for depth estimation in ulcer images.
2. Construction of a database of ulcer images using structured light systems.
3. Utilization of deep learning algorithms to improve the accuracy of ulcer depth estimation.
4. Enhanced medical diagnosis of ulcers, through training/awareness-raising session with medical staff.

Clinically validated equitable polarization pulse oximetry

Increasing access to reliable pulse oximeters worldwide remains a challenge as there is an unprecedented need for creating new and effective standards and technologies for oximetry validation accounting for all skin complexions. A 2020 retrospective study carried out at the Univ. of Michigan and published in the *N Engl J Med* found that Black patients with critically low SaO_2 levels were 3X more likely than White patients to suffer from *hidden hypoxemia* (SpO_2 of 92 – 96% on pulse oximetry, but an SaO_2 < 88%) [1]. The following year, Wong *et al* determined that all racial and ethnic patient groups with *hidden hypoxemia* experienced higher in-hospital mortality. These shortcomings have been recognized by the FDA and identified as a major issue to address shared during the Pulse Oximetry Forum, a joint meeting of experts and the ISO Oximeters Joint Working Group, held at UCSF by the Open Oximetry project in March.

Today, it is commonly believed that mitigating this problem boils down to incorporating real-time skin-tone detection and by calibrating for a more diverse distribution of skin tones using better instruments and procedures than current practice. However, to-date, there are no published studies showing that spectral calibration procedures improve the accuracy of pulse oximetry, yet alone in a clinical setting. Moreover, the purported model to correct for skin tone still assumes that subsurface optical scattering in skin by melanosomes changes slowly or not at all with respect to wavelength and can be effectively ignored. Crucially, this model has yet to be vetted and is at the crux of purely optical-based approaches by others to arrive at an equitable pulse oximeter.

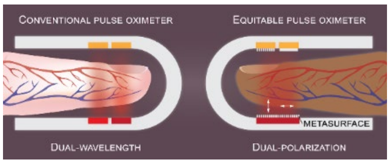


Fig. 1 | Conceptual diagram comparing conventional (left) to a novel single-wavelength (right) pulse

Recently, our group at Brown University led by Prof. Kimani Toussaint has developed an alternative approach based on a novel single-wavelength polarization pulse oximeter (PPO) that has the potential to correct for melanated skin tones (See Fig. 1 for approach comparison) [2]. Following the proof-of-concept demonstration on healthy patients, our team swiftly partnered with expert clinicians and pulmonary physicians to complete a pilot study on critically-ill patients with arterial lines at the Miriam Hospital ICU. With this on-going 24-patient study, we aim to benchmark the PPO accuracy for hypoxic patients representing diverse skin complexions. Our initial results from 12 patients on supplemental oxygen indicate that both the medical-grade pulse oximeter and PPO oximeter fall within 3% of the SaO_2 ranging between 96 – 98%. However, the PPO suffers from limited polarization contrast thus leading to poor signal-to-noise ratio (SNR) below 96%.

The **outcome of this proposal is expected to be an improved portable polarization-based pulse oximeter**. The envisioned <u>compact, single-wavelength, polarization pulse oximeter will feature enhanced SNR and dynamic range of the reflected photoplethysmogram (PPG) signal with extended polarization contrast</u>. This project will evaluate the accuracy of medical grade and polarization pulse oximeters in a clinical study on diverse populations. Importantly, the new reduced fill-form prototype design would account for patient comfortability and clinical accessibility.

Our proposed equitable technology will potentially diminish the global health gap disparity, especially in emerging global economies where there is a growing prevalence of respiratory diseases. By leveraging eccentric degrees-of-freedom of light and novel metasurface platforms, our interdisciplinary team of engineers, physicists, clinicals and statisticians will validate the accuracy of a novel approach for PPG-based sensing technologies and outline a viable path toward commercialization by partnering with companies and under the advisement of local biomedical technology business experts.

[1] Sjoding MW, et al., Racial bias in pulse oximetry measurement. N Engl J Med. 383(25):2477-2478. (2020)
[2] Jakachira, R. et al, "Single-wavelength, single-shot pulse oximetry using an LED-generated vector beam." Opt. Express 30, 27293-27303 (2022).

Name of the project proposal: Development of optical fiber based portable device for drug-free sustainable cancer therapy

Category: Health

Cancer is one of the most serious diseases that is severely threatening the health of human beings. Worldwide, an estimated 19.3 million new cancer cases and almost 10.0 million cancer deaths occurred in 2020, being the first or second leading cause of death before the age of 70 years in 112 of 183 countries. Therefore, the development of novel therapeutic modalities with concurrent high efficacy and largely diminished side effects in combating cancer is urgently required to save millions of lives worldwide. The surgery, radiotherapy and chemotherapy are three main treatment strategies for cancer. There are several limitations to use these three techniques. Surgery is effective only in early stage of cancer when it is very much localized. Radiation therapy is very much slow process to cure cancer. It also damages healthy cells. Chemotherapy is a systemic medication which uses anti-cancer drugs to kill cancer cells. However, the poor aqueous solubility and permeability of these drugs have resulted in low bioavailability and decreased treatment efficiency. Chemotherapy can cause side effects like hair loss and nausea. Recently, a number of emerging therapeutic modalities such as photodynamic therapy and photocatalytic therapy, have shown high performance for cancer treatment, but they are still undergoing basic research and have not been extensively used in the clinic.

To address this serious issue, I am proposing to develop a portable device based on laser or LED coupled optical fiber. The light can be driven to cancer tumor through the fiber. Because of high flexibility and durability of the fiber it can be placed anywhere in the body easily. The end of the fiber will be activated with nano-photocatalysts which will generate ROS on excitation of light and the ROS will kill the cancer cells. There is very less probability that healthy cells are damaged using this technique as the fiber can reach exact location of the tumor or cancer cells. This device may bring revolution in cancer therapy as the proposed device is associated with sustainable, effective and side-effects free cancer treatment. Moreover, the cost to fabricate this device is not expensive and it is reusable after sterilization, and does not require any drugs. Therefore, this device will reduce the cost of cancer treatment significantly and it will prevent the death of a cancer patient because of poverty.

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Excutive Summary: Photonic Quantum Computing and Phase-Sensing Using Ultralow-Loss Silicon Nitride Integrated Circuits

Exploiting the quantum superposition, quantum information processing (QIP) greatly complements the conventional concept of computer and information science, providing computational ability overwhelmingly exceeding state-of-the-art classical computers for specific problems. Among its multiple physical realizations, photonic systems feature extremely weak interaction with environment and are free from decoherence. This unique property allows photon manipulation at room temperature.

As entering the noisy intermediate-scale quantum (NISQ) computing era, manipulation of more than 50 qubits becomes the central goal. For photonic systems, the continuously improving quantum light sources significantly boosts the number of manipulable photons. Combining with state-of-the-art optical interferometers, a large-scale experimental "*Gaussian Boson Sampling*" (GBS) has been reported recently, showing evidence for quantum computational advantages. Meanwhile, there has been equal endeavor on developing quantum sensors using photons, critical to metrology applications and precision measurement. By introducing squeezed light into the interferometer's dark port, one can surpass the quantum noise limit (QNL) of $1/\sqrt{N}$, and potentially achieve Heisenberg scaling of $1/N$ sensitivity, with N being the photon number. Progress has been achieved in designing squeezed light sources and applying them in gravitational wave detection, which ultimately surpasses the QNL and achieves quantum-enhanced sensitivity exceeding 2 dB.

However, currently almost all the high-performance quantum photonic systems are based on bulky, table-top experimental setups. In comparison, chip devices using *photonic integrated circuits* (PIC) can potentially provide a robust way to perform sophisticated and versatile quantum tasks within a much smaller footprint. They can prominently boost the programmability and reconfigurability of photonic systems for QIP.

In the last decade, based on PIC, multiple works concerning QIP have been carried out, including high-dimensional quantum state manipulation, chip-to-chip quantum teleportation, and squeezed states generation. However, extensive demonstrations have been performed on the silicon-on-insulator (SOI) platform. Due to the high optical loss in SOI waveguides (>1 dB/cm), the number of useful quantum bit and the squeeze factor of squeezed states are severely limited. To build large-scale quantum PIC of high-performances, programmability, and – particularly – ultralow loss, silicon nitride (Si_3N_4) PIC technology will be the material of choice.

In this proposal, we aim to develop heterogeneous, programmable, ultralow-loss Si_3N_4 PIC for photonic quantum computing architectures and squeezed-light-based sensors with sensitivity beyond the QNL. We will develop an advanced CMOS-compatible Si_3N_4 PIC fabrication technology with optical loss below 0.005 dB/cm – 200 times smaller than that of the commonly employed SOI waveguides. In addition, we will develop a complete Si_3N_4 quantum photonic design kit, numerical simulation models, and a standard set of building blocks. We will apply this Si_3N_4 quantum PIC technology to demonstrate chip-scale GBS and precise phase sensors.

Our proposed research promises to advance integrated quantum processors and sensors, and will open new avenues for quantum computation and precision metrology, as well as other domains such as telecommunications, LiDAR, imaging and environmental monitoring.

Executive Summary

Next-Generation High Throughput Plasmonic Nanotweezers for Nanoplastics Analysis

The contamination of the environment by plastic waste has become a pressing global challenge, with an alarming projection that there will be more plastics in the ocean than fishes by 2050. Understanding the properties and potential health impacts of plastic nanomaterials, specifically nanoplastics (1 nm to 100 nm), is crucial. However, analyzing nanoplastics remains a significant challenge due to their small size. Current analytical tools are limited, hindering our comprehensive understanding of nanoplastic exposure and its consequences.

To address this critical need, this research project aims to develop a groundbreaking technology for the rapid characterization of nanoplastics with single-particle resolution. We propose a high throughput plasmonic nanotweezers approach, merging plasmon-nano-optics and microfluidics, to enable stable trapping and enhanced Raman spectroscopy of individual nanoplastic particles.

Our research objectives are to develop plasmonic optical nanotweezers for high throughput nano-optical trapping (within seconds) and enhanced Raman spectroscopy of single nanoplastics. By controlling the nanogap spacing of the central plasmonic cavities, we will stably trap and analyze a wide range of nanoplastic sizes, from 5 nm to 100 nm.

We will also utilize engineered and natural nanoplastics to experimentally validate the technology's ability to trap and perform enhanced Raman nanoplastics at various concentrations. By analyzing the enhanced Raman signals, we will determine the chemical composition of trapped nanoplastics.

The completion of this research will yield a transformative technology that overcomes the limitations of conventional optical tweezers and current nanoplastic analysis methods. It will allow for rapid and precise characterization of nanoplastics, enabling more comprehensive assessments of nanoplastic pollution levels and potential impacts on ecosystems and human health. The research findings will be shared through scientific publications in leading journals and conferences, facilitating knowledge dissemination, and encouraging the adoption of this technology by other researchers. Moreover, the technology will help offer new insights into nanoplastic degradation and breakdown processes, contributing to effective strategies and policies to combat plastic contamination.

The potential impacts of this research are significant, and they include:

Environmental monitoring: The technology could be adapted to detect nanoplastics at extremely low concentrations, making it ideal for identifying leaching from infant plastic feeding bottles and evaluating suitable materials. It will aid in assessing nanoplastic pollution in water bodies, and air, supporting targeted cleanup efforts.

Industry motivation: The accurate measurement of nanoplastic pollution will incentivize industries to develop sustainable alternatives, fostering innovation in eco-friendly materials and packaging solutions.

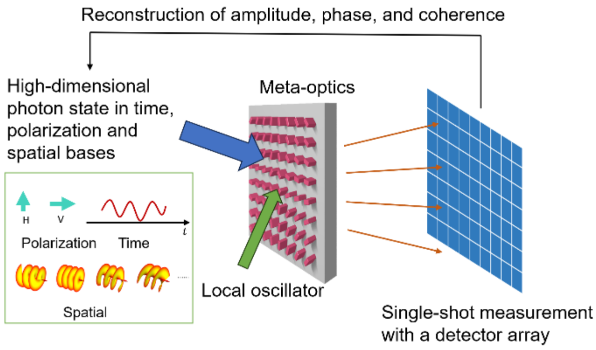
Ecological consequences: The high-throughput detection technology can help assess the ecological impact of nanoplastic pollution, helping conservationists and biologists design appropriate conservation strategies.

In conclusion, our research project holds significant promise for advancing nanoplastic analysis, addressing an important timely grand challenge, and contributing significantly to global efforts to combat plastic pollution and safeguard the health of our planet and its inhabitants.

Meta-optics for high-dimensional coherent detections in optical communications

Traditional incoherent modulation techniques face limitations due to the dispersion of optical fibers, which hinders bandwidth expansion in optical communications. To overcome this bottleneck, people seek to harness the two critical advantages of light: coherence and multiple degrees of freedom. Coherent optical communication enables the transmission of multiple bits per symbol, significantly increasing data capacity. At the same time, mode division multiplexing allows independent data streams to be transmitted through different spatial modes simultaneously, further boosting bandwidth. However, there remain many challenges to the large-scale applications of these techniques.

A key bottleneck is the precise and efficient detection and measurement techniques. Such measurements are highly challenging because they require detection of not only amplitude but also phase and coherence of light across many modes. The number of unknown variables scales quadratically with the mode number. Conventional detection methods, such as direct heterodyne detection, are either unsuitable or limited to very few degrees of freedom. Moreover, the typically used reconfigurable systems are bulky and slow, suffering from poor scalability. New paradigms of coherent measurement devices are thus highly desirable to overcome these challenges and unleash the full potential of these technologies.



This proposal aims to develop inverse-designed nanostructured meta-optics elements and systems to enable coherent, single-shot, and highly efficient measurement of high-dimensional states encoded in various degrees of freedom of classical and non-classical light in optical communication channels. Meta-optics will be used as an unconventional "camera lens" in conjunction with photodiode arrays or image sensors to achieve a massively parallel interferometric measurement at once. The project focuses on highly transmissive meta-optics designs with no moving parts that can efficiently utilize light with no extra post-selection. This approach ensures robust and scalable measurement capabilities while enabling miniaturization of the detection systems.

The key objectives of the project include the **design** and **experimental realizations** of:

- Nonlocal meta-optics structure for efficient single-shot retrieval of spatial states.
- Meta-optics for single-shot imaging-based measurement of polarization & spatial states
- Meta-optics for compressed sensing of high-dimensional states encoded in time, polarization, and spatial modes.

The project's outcomes are expected to have significant impacts on optical communication and quantum communication technologies:

- **Enhanced efficiency and scalability**: The measurement process is highly efficient and scalable by utilizing dielectric meta-optics with optimized diffraction efficiency and no moving parts. The incorporation of compressed sensing approaches further enhances scalability, making it applicable to large-scale communication networks.
- **Single-shot measurement**: The proposed meta-optics designs enable single-shot measurements, eliminating the need for post-selection and improving measurement accuracy and reliability.
- **Miniaturization**: The miniaturization potential of meta-optics elements ensures that the coherent measurement devices can be integrated into compact communication systems, reducing the overall footprint and resource requirements.
- **Straightforward extension to quantum communications**: The proposed project's advancements in coherent measurement techniques promise extensions to quantum communication technologies, enabling high-speed and secure transmission of quantum information.

Overall, the proposed project aims to revolutionize the optical and quantum communication field by developing advanced nanostructured meta-optics for coherent single-shot measurements. The project's focus on efficiency, scalability, and miniaturization will have far-reaching implications for optical communication networks and potential applications in quantum communication.

Immune Cell Tracking with Adaptive Illumination

Highly motile immune cells actively migrate in various organs and tissues in normal and disease states to initiate efficient immune response. Understanding how the immune cells migrate in various organs under various conditions is important for finding disease treatments. The major technology used for immune cell tracking in intact, living tissue is multiphoton fluorescence microscopy. As a nonlinear process, however, multiphoton excitation generates an inherently weaker signal than one-photon excitation, and high excitation power is typically required for fast tracking deep within intact tissues. Because multiphoton microscopes typically operate at the photon shot-noise limit, the maximum number of cells that can be tracked at high spatial and temporal resolution is fundamentally limited by the number of signal photons, which in turn is determined by the maximum permissible average and peak power in biological specimens. Therefore, the fundamental limit for technologies aimed at measuring real-time immune cell migration in intact tissues is the photon budget: the number of signal photons obtainable from the sample within a given period of time. Simply scanning fast, while necessary, is not sufficient for high speed and large volume imaging. This proposal will create new imaging technologies to address this fundamental challenge in dynamic immune cell imaging.

To address the fundamental limit of the photon budget, we will develop adaptive cell tracking (ACT) that will illuminate only the ROIs. A one to two orders of magnitude gain in photon budget can be achieved by ACT because the ROIs usually only occupy a small fraction of the imaging volume (1-10%). This gain in photon budget can directly translate to an increase in imaging volume or imaging speed (or a combination of the two), without increasing the excitation power on the sample or sacrificing signal-to-noise ratio (SNR). (1) To demonstrate the concept of ACT, we will image T cell migration in a live mouse by using 3D ROI localization algorithms and direct modulation of the laser output to illuminate only the ROIs. This demonstration will show how much photon budget can be saved with ACT when compared to that without ACT. However, the direct modulation of the laser output wastes a large fraction of the laser output power and is impossible to achieve the optimum performance when imaging deep. (2) Next, we will combine the ACT with the adaptive excitation source (AES) that reduces the required output power of the excitation source and ensures every photon emitted from the laser is directed towards the ROIs. To do this, we will significantly reduce the time required for the gain equalization in the AES by obtaining a good initial guess of the input pulse train with a machine-learning approach. (3) In addition, we will develop photon efficient scanning and localization algorithms to further reduce the excitation and emission photons required for cell tracking.

Through the development of imaging methods, lasers, photon efficient scanning and object localization algorithms, this work will increase the fluorescence signal by one to two orders of magnitude without increasing the excitation power in the specimen or the laser output power. While we will focus on immune cells, the technologies developed in this program are applicable for tracking any cells or molecules deep within intact tissues. The gain in photon budget will proportionally increase the tracking speed or volume (or a combination of speed, depth and volume), and ultimately enable dynamic, real-time tracking at the cellular and sub-cellular levels deep within intact tissues or organs that are completely beyond the reach of any existing techniques.

Summary:

Time Crystal Dynamics and Entropy in Periodically Driven Quantum Systems

Krzysztof Giergiel
Swinburne University of Technology

Categories:

Quantum Information, Ultracold Quantum Gases, Condensed Matter Physics, Many-Body Physics

Intended Outcomes:

1. **Detection of Momentum Transfer**: The project aims to detect the tiny change in momentum of the Bose-Einstein condensate (BEC) as it bounces on the vibrating atomic mirror in the time crystal experiment.
2. **Understanding Information and Entropy**: The investigation of time crystal dynamics will provide insights into how information and entropy flow in periodically driven closed quantum systems.
3. **Characterization of Periodically Pulsed Quantum Systems**: The research will contribute to characterizing big periodically perturbed quantum systems using ultracold atoms, helping understand macroscopic laws emerging from quantum descriptions. Investigating the back-reaction of time crystals to periodic drives may reveal periodic drives' role as an entropy sink.
4. **Validation of Time Crystal Dynamics**: By observing clean non-dissipative time crystals, the project aims to validate and explore the dynamics of time crystals.
5. **Development of Experimental Techniques**: Techniques to analyze light profiles affected by atom reflection and monitor laser light fluctuations will be developed, aiding future experiments.
6. **Advancement in Optical Fiber Optics**: Collaboration with fiber optics specialists will lead to advancements in storing high-power visible light using hollow-core optical fibers.
7. **Contributions to Scientific Literature**: The project's findings will contribute valuable data and insights to the scientific literature on time crystals, quantum matter, and periodically driven quantum systems.
8. **Importance for General Public**: Working with visible light storage in fiber optics is of general importance and relevant to various technological applications.

The research on time crystal dynamics and entropy has significant implications for the development of future quantum technologies, including quantum computing and quantum communication. By understanding how information and entropy flow in periodically driven quantum systems, the project contributes to the creation of energy-efficient and robust quantum systems. This is of paramount importance as global energy consumption from digital devices continues to rise. The insights gained from this study will contribute to advances in quantum simulation, sensing, and inertial navigation, positioning Australia at the forefront of ultracold quantum gas research. Furthermore, the project's findings will be of broader importance to condensed matter physics and many-body physics, fostering a better understanding of macroscopic laws emerging from quantum descriptions. The potential advancements in fiber optics for storing visible light have practical implications in various fields, including electronics, computing, communications, imaging, sensing, timing, and navigation.

Overall, the research holds significant promise in advancing our knowledge of time crystals and periodically driven quantum systems, while also having broad applications in quantum technologies and related scientific disciplines.

Project Title: "Photonics-Driven Solutions for Sustainable Solar Energy: Research, Education, and Outreach Initiatives"

Category: Environment

This project seeks to establish a state-of-the-art Optics & Photonics Laboratory at NTU "KhPI" focused on advancing sustainable solar energy solutions. By leveraging photonics technologies, the project aims to optimize the conversion of solar energy into electrical and thermal energy, specifically in the context of hybrid solar installations. The project's key objectives include conducting cutting-edge scientific research, fostering the education of students and young researchers, and promoting solar energy awareness through various outreach initiatives. Through the acquisition of necessary equipment, participation in conferences and workshops, and organization of educational events, the project aims to contribute to the growth of solar energy research and its practical implementation, while inspiring the next generation of scientists and engineers in the field of optics and photonics.

My active work is focused on scientific research in the field of solar energy and the use of solar radiation and on their popularization among schoolchildren and young people. For this, the Department of Micro- and Nanoelectronics of NTU "KhPI" was equipped with an Optics & Photonics Laboratory, the equipment of which included optometric devices as well as solar radiation simulators and measuring devices for research aimed at increasing the conversion of solar energy into electrical and thermal energy. In addition to purely scientific research, the laboratory was a base for conducting introductory workshops and STEM events aimed at encouraging school-age children to engage in science. Based on this laboratory, I conducted research in the field of thermophotovoltaic solar energy conversion systems as the basis of my doctoral dissertation. This year, two new post-graduate students are to join the research, whose scientific work is also planned to be aimed at optimizing the processes of simultaneous production of thermal and electrical energy by hybrid solar installations.

However, during the war, Kharkiv suffered significant destruction, in particular, a direct missile hit practically destroyed the educational building in which the department and the actual laboratory are located. The premises were severely damaged; some of the equipment was lost. Currently, we have a new premises and have begun to actively work on the restoration of the laboratory, the purpose of which is aimed at scientific research and raising awareness of the processes related to the production of electricity at photovoltaic power plants, the creation of photovoltaic systems, thermophotovoltaic systems and other design solutions, as well as motivation young people to choose this direction as a future profession and specialty.

The opportunity to equip a new laboratory will be the basis for continuing my scientific work, the work of my graduate students, and conducting activities to popularize solar energy and the physical principles of using solar radiation (trainings, master classes, STEM events).

The importance of my work is due to the fact that in recent years Ukraine has gone through a rapid path of development of alternative energy, business began to rapidly enter the field of renewable energy, due to which large capacities of solar and wind power plants were built. Now the emphasis on the development of alternative energy has changed and the greatest attention has begun to be paid to compact solutions aimed at providing not only electrical energy, but also thermal energy, and optical solutions for such projects are decisive for their success - first of all, we are talking about the study of solar radiation concentration processes in order to reduce the number of used solar cells. Receiving the grant will allow our team to accelerate research into optical elements for such photo-energy systems.

Thanks to the Grant, we will be able to conduct optical experiments involving licensed software packages and accelerate work on equipping the Optics & Photonics Laboratory for the manufacture and testing of experimental samples. As part of the Grant, we will pay attention to marketing research and participation in conferences and workshops, which will ensure active promotion of the results of our research among representatives of the business community. With the involvement of domestic business, we will achieve a truly broad introduction of research results at the Optics & Photonics Laboratory into the life of our country. Particular attention is planned to be given to the participation of the newly equipped laboratory in educational projects such as master classes, STEM events to spread the ideas of renewable energy among schoolchildren and involve young people in research in the field of optics and photonics.

The presence of an Optics & Photonics Laboratory with appropriate equipment on the campus of our university will expand the participation of our team in borderline research of colleagues from other fields in order to strengthen the role of optical sciences in the general spectrum of university research.

Summary: Optical techniques are valuable for diagnosing and treating disease because optical spectroscopic interactions with molecules confer specificity with regard to target biochemical information and quite favorable spatial resolution. Yet, tissues strongly scatter light, making tissue opaque within tens to hundreds of μms of propagation depth, moderating the success of optical biomedical imaging.

Some cancers are very difficult to detect with current technologies. As early detection leads to much better outcomes and lower mortality rates, new diagnostics technologies could profoundly impact our ability to detect and successfully treat disease. I am motivated by ovarian cancer, which is extremely difficult to detect and is usually detected at a late stage where treatments suffer from low efficacy.

I am focusing second harmonic generation (SHG) microscopy which is already established as a powerful tool for biological imaging. SHG has proven diagnostic and prognostic capabilities for a wide range of diseases. Of prominence is the use of SHG imaging to grade cancerous tumors by quantifying the type of organization of collagen around tumors. Moreover, cancers tend to reorganize collagen to present a spiral structure that aids in differentiating healthy tissues, benign tumors, and cancers. Despite this potential, SHG imaging is limited in imaging depth. As a result, non-invasive biological imaging (e.g., optical pathology without the need for surgery) is restricted to superficial tissues or through endoscopy and current SHG microscopy technology is extremely limited in its potential for use with *in-vivo* optical biopsies.

I propose a new approach to rendering opaque tissue effectively transparent using both advanced data science tools and wavefront control to sidestep the current limitations that restrict the SHG imaging depth. This is a radical departure from the conventional paradigm for nonlinear microscopy that relies on scanning a ballistic focus in the specimen and forming an image from the measured power from each focal point. Depth imaging is severely limited because the ballistic light intensity decays exponentially with depth.

This proposal seeks to remedy the deficiency in the limited imaging depth by posing the question: rather than throwing away multiply scattered (MS) light, can we redirect it into image formation? I will explore two methods of harnessing MS light for SHG imaging (e.g., collagen in the extracellular matrix around tumors) at unprecedented imaging depths in tissues. In Aim 1, I will unscramble the SHG light exiting the tissue to remap that information into an image deep within tissue. SHG fields exiting the tissue will be recorded with nonlinear holography. Since the SHG field propagates through tissue, the field is spatially randomized (exits as speckle). The speckle field is a distinct fingerprint of each SHG scattering source point. With a set of measurements that vary the SHG signal brightness spatially, the mapping between the SHG source points and the measured speckle will be uncovered. Armed with the random SHG speckle fingerprint for each point in the object field, the SHG image will be revealed by unscrambling the SHG light that was randomized with propagation through the tissue. Thus, I will break free from relying on image formation by scanning a ballistic focus. In Aim 2, the data will be used to estimate the transmission matrix for the fundamental field. This matrix operator describes the distortion of the input fundamental field at the image plane. This information will be used to focus the wave in the object plane through wavefront shaping to further improve the SHG image quality and enable deeper imaging depths.

This new approach to *in-situ* fundamental transmission matrix estimation opens new avenues of imaging by avoiding the need for a detector in the tissue (not possible) or relying on the accidental existence of a nonlinear guide star. Moreover, the wavefront reshaping increases the SHG signal power, and thus the image quality, and allows for increasing imaging depth. This could change the landscape for deep tissue imaging. Simulations will be employed to study the limits of imaging depth. Data from these experiments will be combined with simulation results to seek additional funding for pushing this new imaging approach to unprecedented imaging depths.

Project outcomes: A) Demonstrate unscrambling of measured SHG speckle fields to obtain an SHG image field deep in tissue. B) Demonstrate estimation of the transmission matrix of the fundamental field to the SHG image plane and use that transmission matrix to generate a brighter focus and a higher quality SHG image. C) Enable deeper imaging by pushing the depth where bright SHG imaging can be accomplished. D) Capture a set of data that will be used for papers, talks, and as preliminary data for future funding.

A low-cost integrated hyperspectral monitoring device for environmental pollution

Category: Environment

Environmental pollution poses serious threats to human health and well-being. It is crucial to assess the health of ecosystems and detect environmental changes for ecological protection and resource optimization. Current methods of monitoring environmental pollution rely on in-situ sampling, which is inefficient and limited in capturing the spatial and temporal variation of pollutants. Therefore, alternative methods are needed to address this global problem.

Hyperspectral imaging acquires spatial, temporal and spectral information of the physical world, characterizing the intrinsic optical properties of each location. It has been widely applied in environmental pollution monitoring which requires lightweight integration and superior spectral imaging performance. Most of the existing hyperspectral imaging systems employ individual optical elements and mechanical components to scan the dense spatial-spectral data cube, resulting in bulky configuration, low resolution, and high cost. The recent trials of on-chip spectral acquisition apply narrow-band filtering on different pixels, suffering from low light throughput, low resolution, and few channels. To sum up, there still exists a gap towards practical applications of lightweight high-resolution hyperspectral imaging.

To monitor the spatial and temporal variation of environmental pollution, we develop a novel on-chip computational imaging device capable of acquiring tens of hyperspectral images with full temporal and spatial resolution over a wide range.

We will report a novel on-chip computational imaging scheme for high-dimensional vision, providing details of hardware fabrication, optical calibration, and computational reconstruction. This technique integrates innovations from multiple fields, including materials, integrated circuit, computer science and optics. It transforms the common challenges of high-dimensional imaging, which are associated with the physical constraints of high-cost optical fabrication and complex system design, into challenges that can be solved by agile computation. Meanwhile, we will conduct a series of application experiments, including regional monitoring of water and air pollution. For the existing version of our device, the spectral response range covers from 400 nm to 1700 nm, with an average light throughput of 71.8%. It outperforms mosaic multispectral cameras and scanning hyperspectral systems in low-light conditions. The device has an average spectral resolution of 2.65 nm (400-1000 nm) and 8.59 nm (1000-1700 nm), with the ability to differentiate monochromatic light with a peak-to-peak spacing of 10 nm. The peak signal-to-noise ratio (PSNR) of spectral reconstruction achieves 32.5 dB tested on the ColorChecker Classic chart. Each channel consists of 2048 $\times$ 2048 pixels at a frame rate of 47 fps, maintaining 3.43 arc minute optical resolving ability at a 39-degree field of view. The high frame rate allows for the capture of fast-moving objects, facilitating dynamic imaging.

The demonstrated hyperspectral imaging sensor maintains great application potentials in off-of-the-shelf platforms such as unmanned aerial vehicle and nano satellite, as well as consumer electronic products such as smart phones and digital cameras. We anticipate that this technique to open a new venue for the next generation imaging sensor with higher information dimension, imaging resolution, and integration level. In this context, we are applying for the 2023 Optica Foundation Challenge to support our work to contribute to environmental protection.

Microcomb-based, energy-efficient optical communication

Optica 20th Anniversary Challenge: Information

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The ever-growing data traffic of the internet, fueled by recent advancements in AI and big data, is imposing significant challenges on optical communication infrastructures. Over the last few years, remarkable efforts have been dedicated to increase the capacity of communication links, particularly exploring the massively parallel wavelength division multiplex (WDM) communications. However, conventional approach employing laser arrays as the light source suffers from drawbacks in stability and coherency, resulting in substantial power consumption in both wavelength multiplexing and digital signal processing (DSP).

Recently, microcomb has attracted a lot of attentions as a promising candidate to overcome this problem. One microcomb can provide hundreds of equally-spaced wavelengths, which can support high-capacity communication. However, previous microcomb-based communications rely on bulky and power-hungry pump lasers, thereby causing a disadvantage in terms of energy efficiency.

In this project, we propose to develop a fully chip-based and power-efficient microcomb to drive communication links. We will leverage self-injection locking technology, which enables coherent microcomb generation by laser-diode pumping, without relying on any bulky equipment or auxiliary electronics. Based on ultra-high Q S_3N_4 microresonators ($Q > 2.6 \times 10^8$) manufactured by CMOS foundry, we can achieve high coherence between each comb line, whose linewidth can reach Hz level. Furthermore, the self-injection locking technique enables the generation of a dark pulse, allowing for a conversion efficiency exceeding 50%, which can overcome the energy efficiency problem of microcombs used in previous communication systems.

At the system level, we propose a novel WDM coherent communication architecture that fully leverages the advantage of microcombs in massive parallelization and high coherence. This communication system will incorporate over 150 channels, with each channel capable of supporting high-order coherent modulation formats, leading to beyond 100 Tbps aggregate data rate. Importantly, such high capacity will be achieved with much lower power consumption: the equal spacing of comb lines eliminates the need for wavelength control; more importantly, the constant phase relation among different comb lines can significantly reduce the requirements for two major parts of DSP, carrier recovery and phase estimation. With these advantages, we envision a high-capacity, power-efficient communication system which should have a profound impact on the future of the telecom and datacenters.

Agriphotonic Technique for Sustainable Agriculture: Reducing Human Footprint through Whitefly Pest Management

Author: Luis Miguel Gomes Abegão, Ph.D. || **Category:** Environment

The use of insecticides and pesticides in crop production can significantly impact environmental pollution. Water pollution, soil contamination, non-target species, residue accumulation, and resistance development are examples of the human footprint consequences of controlling crop pests. This real-world issue is among the highest challenges the science community must solve. On one hand, one must provide food for an increasing world population; on the other hand, humanity must drastically decrease its footprint. A solution for this real-world issue is replacing pesticides with novel biocompatible techniques to control crop pests. An agriphotonic technique, based on laser, able to control crop pests without harming the plant's development or affecting non-target species can help tackle this global problem.

Several species of whiteflies are considered pests in agriculture. For example, the whitefly *Bemisia tabaci* (biotype MEAM1) is one of the most relevant insect pests of crops worldwide once it is present in all continents. *Bemisia tabaci* can colonize plants belonging to many plant families and adapt highly to different environments. Moreover, they have a rapid selection of insecticide-resistant populations, which makes them a threat to food security, especially in developing countries.

The main objective of this proposal is to develop a prototype of a future commercial agriphotonic device for pest control. This device will use a novel biocompatible technique based on a laser. Such a technique has already been tested in the laboratory, showing that it is able to achieve 100% mortality of *Bemisia tabaci* without affecting the plant's development [1].

The proposal's objective will be achieved concurrently by conducting a science investigation and technology implementation, as illustrated in Figure 1. The first will focus on how different optical parameters will affect the mortality of whitefly species not yet studied and the plant's development after laser irradiation, and the latter will focus on the prototype development. It is important to emphasize that the strong collaboration between the author's proposal and the Brazilian Agricultural Research Corporation (Embrapa) will trigger a high-level success for the proposed strategy.

In summary, this proposal intends to develop a prototype of a future commercial agriphotonic device, based on a laser, for whitefly pest management. The success of this proposal will be capable of providing a new biocompatible technique for pest control to small- and large-scale farmers, which can decrease environmental pollution by reducing the usage of conventional pesticides. Moreover, if accepted, this proposal will unlock new possibilities and perspectives, paving the way for a new startup company in Agriphotonics.

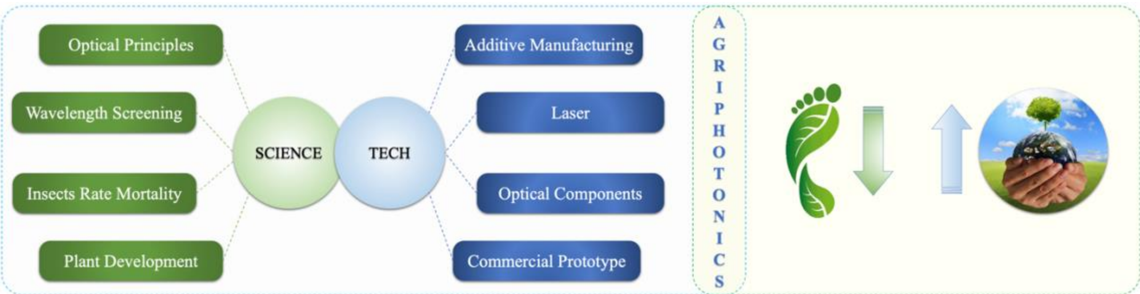


Figure 1. Diagram showcasing the proposal's integration. The left side represents the science and technology elements needed to develop the photonic device prototype. The right side illustrates the proposal's goal, i.e., reducing the human footprint and pursuing a better, more sustainable world using Agriphotonics.

[1] Zaidem, A., Silva, L., Ferreira, A., Carvalho, M., Ragni, M., **Abegão, L.**, & Pinheiro, P. (2023, May). New Biocompatible Technique Based on the Use of a Laser to Control the Whitefly Bemisia tabaci. In *Photonics* (Vol. 10, No. 6, p. 636). MDPI.

Title of the proposal:

3D Optogenetics for Functional Brain Mapping and Parkinson's Disease Therapy

The objective of the research proposal is to develop a new framework of three-dimensional (3D) optogenetics combined with computational modeling for *in vivo* functional brain mapping and to improve the treatments for neurological diseases including the Parkinson's disease.

The field of applied optics in neuroscience has been profoundly influenced by optogenetics. However, there are multiple challenges in optogenetics for the investigations of structural and functional information of brain. **This project aims to develop a next-generation 3D optogenetics tool aiming to overcome the technological hurdles and close all those gaps to enable *in vivo* optical investigations of brain cell morphology and function**, in the following directions:

1. Development of a 3D multi-spot illumination system realizing the computer-generated holograms [**AIM 1**],
2. Functional observation and computational modeling of neural activity [**AIM 2**],
3. Record the activity of the neurons by 3D fluorescence imaging technology based on metasurface systems [**AIM 3**] to collectively generate the 3D brain mapping, and
4. Utilization of the developed system for the improved treatment of Parkinson's disease [**AIM 4**]

Category it seeks to address:

Health

Intended outcomes, capabilities and applications to real-word issues:

This research work will contribute to the development of new research achievements and activities in the field of **3D optogenetics, 3D imaging, and simultaneous investigations of models of neurological disease**. The proposed research proposal could be beneficial for the imaging tool in the field of neuroscience to uncover the fundamental aspects and pathologies that have been beyond reach and reveal useful neural activity and their behavior and mental states. Since different sets of neurons are associated with different functions, and if the activity of each set of neurons is analyzed then it would be possible to understand how they work together. By analyzing the activity of different neurons, various brain disorders such as depression, Parkinson, etc. can be evaluated. **The proposed system would allow modulating, controlling, and monitoring of manifold neuronal activities with cellular and millisecond-temporal precision and resuscitating the physiological patterns of brain activity**. In optogenetics, various systems have been developed for photo-stimulation. However, none of them is capable of simultaneous 3D stimulation and 3D observation of neural activity. Moreover, the system will be developed with single-neuron (cellular) spatial resolution across a large volume without compromising temporal precision. **Such efforts in the field of 3D brain mapping may provide the necessary evolutions and exciting achievements in the field of neuroscience**. As an excellent tool for studying the brain's development, computation, and adaptation, *in vivo* imaging of brain cells is becoming increasingly popular. It would play an important role in a deeper understanding of brain activity, and helps in the improvement of diagnosis by monitoring disease progression. The health care devices and systems will be developed that may promote several collaborations and receive strong interest from research labs, hospitals, and companies. Being a multidisciplinary research proposal, I will work closely with a team of biologists (**Prof. Prof. Mitsuhiro Morita**, Department of Biology, Kobe University),), optical engineers [**Prof. Osamu Matoba** (Kobe University) and **Prof. Yasuhiro Awatsuji** (Kyoto Institute of Technology)], to develop the state-of-art 3D optogenetics tools and use it for the PD therapy and other neurological investigations. **Upon successful completion, this study will generate sufficient data to determine the feasibility of optogenetic therapy as a potential treatment for Parkinson's disease and may facilitate recovery from several neurological diseases**. It is expected that the success of the proposed project will open new research fields in neuroscience and the biomedical imaging field where **watching brain cells in action is possible**.

OPEN-MED-ACT, **O**ptimization of **P**hotonic **E**quipment with **N**ovel **ME**dical **D**evice design based on optical properties: **A**ccelerating **C**linical **T**ranslation of biophotonics

Category: Health

What is the problem? Despite the potential to translate optical technologies, new spectroscopy/imaging systems and accurate treatment approaches have been slow to emerge. This slow uptake is partly due to the lack of tools to design and optimize optical instruments and treatment dosimetry. Designing medical devices starts with simulating potentially captured signals and/or treated tissue volumes based on instrument specifications and light propagation in the targeted samples (e.g., tissues and biofluids). Since simulations provide the **ground work of any medical device design** as well as **device fine tuning during clinical testing**, it is important that optical properties are reliable, accessible to instrument designers and available at wavelengths used by next-generation devices. However, limitations on the availability of optical properties and the disagreement within the research community slows down the development and clinical translation of optical technologies.

What is the solution? This project aims to accelerate the **clinical translation of biophotonics technologies** by providing an open **database** of optical properties of tissues (including skin, oral subsites, teeth, bone, brain, heart, kidney, liver and lung) and biofluids (including saliva, urine, blood) over a **wide range of wavelengths** (from 350-1900 nm and from 2500-25000 nm). For this purpose, we aim to build tools to extract optical properties based on diffuse reflectance, fluorescence, FT-IR and Raman spectra in a **more reliable** way compared to previous studies. The database will be available to the public as a website enabling quick assessment of optimized parameters for optical instrument design for specific applications. Finally, we intend to include Irish and Brazilian populations in our studies.

Why is this important? Until a reliable database of tissue and biofluid optical properties becomes publicly available, the clinical translation of optical technologies will be hindered by research, commercial and clinical barriers. Most industries typically prioritize application-specific research with shorter term outcomes and benefits to particular institutions and/or nations. That makes building an open database unfeasible and hinder international collaborations that are necessary to quantify variations of biological tissues and biofluids across different populations. **Funding the development of such a database is a rare opportunity to bring the biophotonics community together and encourage data sharing with intent of future standardization of optical properties**.

Why should this proposal be granted? By granting the funding to the Applicant, the database can be built in a research group having current and/or past collaborations with prominent MedTech companies such as Stryker, Medtronics, Raydiant and Rockley Photonics, and where expertise to extract tissue optical properties is already well established. Moreover, the development of such a database represents a critical first step to put the Applicant's long-term research vision into practice. Consolidating a basis for biophotonics medical device design would enable him to apply for follow up funding in collaboration with partner institutions of this project, and world-leading MedTech companies.

What is the impact on global challenges? In terms of applied research and commercial perspective, this database is essential for comparability of studies and multicenter initiatives to **translate biophotonics innovations** for **endoscopes, wearable devices, smartphones, imaging devices, personalized medicine devices, implantable devices** and others. The design of novel biophotonics instruments includes those for **real-time disease screening, diagnostics, staging, monitoring, treatment** and p**rediction of treatment outcomes**, as well as **surgical or therapeutic guidance.** From a fundamental research perspective, this database will be useful to evaluate the feasibility of "omics" studies (including **metabolomics, proteomics, lipidomics**, etc) which target the concentration of tissue constituents reported in the database. Since **translating cellular-level research findings to 3D cell culture models/tissues** may be hindered by light scattering and absorption effects, applications include advances in **tissue engineering, pharmacology, treatment dosimetry** and other fields.

Marcelo Saito Nogueira | marcelo.nogueira@tyndall.ie | IPIC & Tyndall, UCC

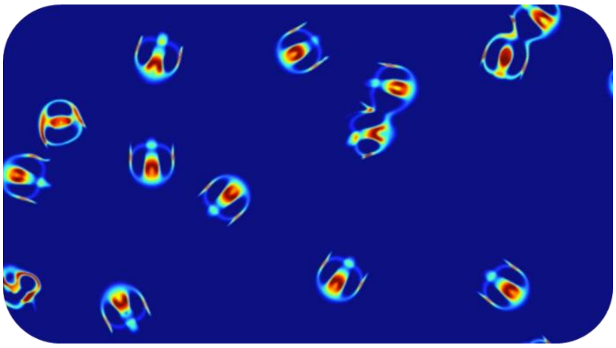
Executive Summary

Artificial Lighfe: Bridging AI and optical lifeforms

Prof. Marco Piccardo
Técnico Lisboa and INESC Microsystems and Nanotechnologies, Portugal
Harvard University, USA

Artificial Intelligence (AI) has revolutionized many areas of information technology, such as data analysis, automation, predictive modeling, and decision-making processes. However, as we continue to generate and process an ever-growing tsunami of data, the global electricity consumption associated with these operations is becoming a significant concern. Photonics, the science of light generation, detection, and manipulation, offers a promising approach to augment or even replace traditional electronic architectures for AI. Photonic systems are renowned for their parallelism, high-dimensionality, and low-power consumption, making them ideal for handling the increasing demands of AI applications. They can help make AI faster, more efficient, and more sustainable, thereby addressing the pressing need for energy-efficient data processing. Despite these advantages, the mutual influence of AI and optics has so far been mainly confined to the realm of deep learning inference in computer vision, microscopy and other visual computing tasks. While these fields have seen significant advancements, there is a vast, unexplored potential for further integration of AI and optics.

This project aims to transcend the boundaries of existing optical architectures and propose a novel optical system rooted in the principles of Artificial Life. This innovative approach opens new horizons in the interplay of AI and optics, pushing the limit of what is currently achievable. Our objective is to implement an analog all-optical system based on continuous cellular automata, which will generate optical lifeforms capable of self-organization, evolution, complex interactions, and dynamic adaptation. We refer to this as "Artificial Lighfe".



Artificial Lighfe represents a natural, eminently scalable form of optical computing, involving recurrent computation performed entirely with light, with no electronic intermediary. This system will diversify AI by opening the possibility of analog implementation of recurrent residual convolutional neural networks, open-endedness, and generative art via optics. Simultaneously, Artificial Lighfe will serve as a playground for AI, providing a unique platform for the deployment of exploratory, genetic and novelty search algorithms, and enabling the testing of pattern recognition, generation and encoding techniques. The computational capacity of the prototype is estimated to be over 5×10^{16} operations/s, with a power consumption of approximately 10 W. This translates to an energy efficiency better than 0.2 fJ per operation, which is about 5000 times better than a GPU.

By creating a symbiotic relationship between AI and optics, we aim to unlock new possibilities in both fields, paving the way for a more sustainable, efficient, and innovative future in information technology.

Enabling Equitable Communication: Next-Generation Connectivity using Neural Network Trained Reconfigurable Intelligent Surfaces to Bridge Urban-Rural Digital Divide

The global climate change has led to an increase in extreme weather events, disproportionately affecting remote areas with limited internet access. Rural communities in the northern territories of Canada, facing severe weather conditions, struggle with their communication infrastructure during crises. Current communication methods, such as satellite and mobile wireless services, are expensive and insufficient to meet the demands of these challenging environments. This situation calls for improved and resilient communication solutions to bridge the urban-rural digital divide and mitigate the impacts of climate change on vulnerable populations.

The advent of 6G communication promises higher data rates and improved connectivity. To counteract the higher propagation losses of 6G millimeter waves, new transmission technologies are needed. Reconfigurable Intelligent Surfaces (RIS) offer a potential solution. RIS consists of passive reflection elements that can dynamically adjust incident signals, enhancing wireless communication performance. Integrating RIS with neural networks enables intelligent adaptation to changing weather conditions, further optimizing signal propagation.

The challenge’s objectives are threefold: (1) Develop a cost-effective and energy-efficient RIS system using printed electronics for remote and rural areas, with a focus on the northern territories of Canada. (2) Integrate neural networks with the RIS system to optimize its performance in extreme weather conditions, allowing real-time adjustments based on meteorological data. (3) Conduct field tests in harsh weather conditions in Arviat, Nunavut, Canada, to evaluate the RIS system's effectiveness in enhancing communication and maintaining reliable connectivity.

In the first year, the focus will be on fabricating and validating the RIS system. The metasurface, a crucial component of the RIS, will be designed and fabricated using two approaches: conventional lithography (RIS-1) and printed electronics (RIS-2). These prototypes will be integrated with a control board and tested in the lab to evaluate their performance in manipulating electromagnetic waves.

The second year of the project will be centered around integrating neural networks with the RIS system and conducting real-world tests. Data on RIS performance under varying weather conditions will be collected, and relevant features will be extracted to establish the relationship between weather and optimal RIS configurations. A neural network will be trained to adaptively optimize the RIS settings based on real-time meteorological data. The final phase involves deploying the RIS system in Arviat, Nunavut, Canada, to evaluate its effectiveness in maintaining reliable communication in adverse weather conditions.

The expected outcomes include a scalable and innovative RIS system, intelligent and weather-aware through neural network integration for real-world deployment. The project's impact reaches beyond the northern territories, empowering vulnerable communities worldwide with improved communication services during extreme weather events. Through multidisciplinary research and cutting-edge technology, this project strives to bring reliable, energy-efficient, and resilient communication infrastructure to remote and rural areas, contributing to a more equitable and connected global society.

Executive summary

Electro-magnetic information theory of Photonic Integrated Curcuits with Fabrication and environmental UNcertainties (EPIC-FUN)

Applicant:
Metodi P. Yankov
Associate professor, PhD
Department of Electrical and Photonics Engineering, Technical University of Denmark

Photonic integrated circuits (PICs) will be the key enabler of the urgently needed sustainable growth in data rates in worldwide communication networks. PICs have the potential to replace a variety of their electronic counterparts in data centers and communications transceivers by providing *higher throughput and lower energy consumption at the same time.* The energy consumption of a PIC is a function of its physical parameters as topology, material composition and parameters of its active components, e.g. lasers and thermal elements used for stabilization. Unlike digital electronics, variations in these parameters across devices due to fabrication tolerances, as well as within each device due to laser stability and environmental factors inevitably impose a stochastic nature on the PIC as a communication channel and affect its information carrying capabilities.

An information theoretic framework can provide the link between signal uncertainty, information capacity and energy. Optimization of the PIC communication channel using such a framework can make it robust to the uncertainties, thereby decreasing energy consumption, increasing yield, improve reliability and increase capacity. Such a framework, while highly desired for widespread PIC deployment, is currently an open research problem.

In this project, I will lay the ground works for deriving an electro-magnetic information theory of photonic devices and the fundamental relation between the energy consumption and information capacity of PICs. This relation will drive the next generation of research into energy-efficient, PIC-dominated networks.

In particular, we will derive Green's functions of PICs with selected functionality, e.g. a ring resonator, and extend it to the general case of a network of resonators which can potentially serve as a switch. Complimentary to that, we will use data driven and machine learning modeling of components in order to capture their fabrication and environmental uncertainty. This uncertainty will then be translated to statistics of signal waveforms propagating through the component and the network, which allows for the optimization of the waveforms for increased robustness and maximized capacity. Constraining this optimization to the maximum required thermal tuning will result in a Pareto front of the information capacity and energy consumption of the component or the network, which can be used for future designs.

This work has the potential to unify the information theoretical modeling and simulation of discrete photonic components with the general optical communication systems and networks. Ultimately, it carries the key to designing PIC-based devices and networks of high-throughput and low energy consumption to be applied in future telecommunication systems.

Virtual staining of virtually cleared unlabeled tissue images via deep learning and autofluorescence microscopy

Optica Foundation Challenge, Category: Health

Executive Summary

Challenge:

Traditional tissue clearing and staining methods for pathology assessments present several challenges, including long processing times, uneven tissue penetration, alteration of tissue structure, high costs, and labor-intensive protocols. These limitations hinder the acquisition of accurate three-dimensional (3D) visualizations of tissue biopsies, therefore impeding the comprehensive understanding of tissue structure and cellular organization. Moreover, certain diagnostic scenarios often necessitate invasive excisional biopsies due to the limitations of current 2D imaging techniques, consequently leading to increased patient discomfort and potential risks.

Proposed Project:

We propose the development of a cascading, deep learning-based model, called **ClariGAN**, in order to virtually clear and stain tissue samples, therefore bypassing the physical and chemical procedures involved in traditional techniques. ClariGAN can leverage advanced computing and deep learning methods, transforming 3D (~500 µm) scans of unlabeled samples into virtually stained versions that mimic traditional 2D fluorescent stained thin tissue sections. This model will be based on conditional Generative Adversarial Networks (GANs) and trained on paired confocal microscopy images of tissue samples, before (autofluorescence) and after the clearing and staining procedures.

Intended Outcomes:

Enhanced Pathology Assessments: By digitizing the preparatory workflow of pathology specimens, ClariGAN would enable the acquisition of 3D visualizations of tissue biopsies, thereby capturing certain unique features and preserving interconnections among tissue components. This approach provides a more comprehensive understanding of tissue structure and cellular organization compared to traditional 2D histology.

Time and Cost Efficiency: This proposed model offers a time-efficient alternative to lengthy tissue processing methods. It eliminates the need for laborious clearing and staining procedures, accordingly reducing processing times and associated costs.

Minimally Invasive Diagnostics: ClariGAN's ability to obtain virtually stained 3D scans from minimally invasive core needle biopsies could improve diagnostic accuracy and reduce the need for invasive excisional procedures.

Automation and Standardization: The implementation of ClariGAN in standard pathology workflows can streamline and standardize the staining and clearing process, thus reducing manual handling and limiting potential variations between technicians.

Future Adaptability: Once validated for use with human samples, the ClariGAN model can extend its benefits to a broader range of tissue types and applications, further enhancing pathological tissue examination.

Ultra-high Resolution Computational Fundus Camera for Chronic Retinal Disease Detection

Age-Related Macular Degeneration (AMD) is a major issue and the leading cause of blindness in the developed world. According to the World Health Organization, the affected population in 2020 was approximately 200 million people. Limited treatment options, combined with technological barriers against monitoring and early detection of the disease make battling AMD a major challenge.

Early stage AMD is characterized by the gradual deterioration of the retinal pigment epithelium (RPE) layer which sits beneath the photoreceptor cells. As the RPE cells become less efficient in their functions, the photoreceptor cells gradually degenerate, leading to progressive vision loss.

Challenges with imaging the RPE cells are multi-fold: Firstly, the transverse resolution of conventional retinal imaging systems is generally limited to around 20 microns due to intrinsic aberrations of the ocular media (in particular the lens and cornea); second, most of the imaging light entering the pupil is either absorbed or reflected at the interface of photoreceptor segments, overwhelming the weak signal backscattered from the neuronal or RPE cells; and finally, the RPE cells are transparent to visible light, and therefore suffer from low contrast and signal to noise ratio.

To address the limitations in the cellular resolution, the ophthalmic systems have incorporated adaptive optics (AO) techniques which rely on wavefront sensing, and manipulation technologies in order to estimate and correct for optical aberrations. Despite continuous advancements in speed, resolution, and capabilities, conventional AO systems are cumbersome to operate, optically complex, and expensive. Moreover, practical wavefront sensing and correction is only achieved over a very small field of view (FOV) (see Fig. 1 for example).

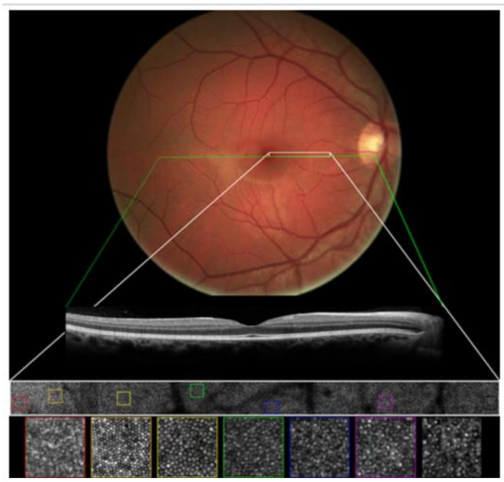


Fig. 1. Sample multi-modal retinal image, demonstrating the trade-off in the FOV, resolution, and information content between wide-field fundus image, OCT B-Scan, and a state-of-the-art, flood illuminated AO retinal image.

In this application, we propose to develop a new class of retinal cameras which we term complex field fundus imager. Our technology which combines advances in Fourier Ptychography, Pupil Modulation, and trans-palpebral illumination ***overcomes the limitations faced by the current state of the art in imaging the sub-surface retinal layers while achieving an order of magnitude improvement in the SBP compared to the existing technologies***.

In order to de-risk achieving the greater goal outlined above, we intend to follow three complementary, yet incremental specific aims:

In **Specific Aim 1**, we design, build and optimize a computational retinal camera that recovers complex field from a series of intensity images of a model eye. One of our primary objectives is to develop a cost-effective solution that can be designed and disseminated in the developing world.

In **Specific Aim 2**, we will leverage multiplexed image acquisition and computational reconstruction in order to improve the SNR, and frame rate of our proposed imager.

Finally, in **Specific Aim 3**, we will carry out *in-vivo* imaging studies in order to validate the system performance in presence of motion artefacts and ocular movements.

Executive Summary - Topic Environment

TITLE: Unveiling Optical Properties and Degradation Mechanisms in Emerging Multijunction Solar Cells through Advanced Spectroscopy

Solar power is crucial for addressing global energy and environmental challenges, and multijunction solar cells have gained attention for their ability to achieve higher efficiencies compared to single-junction cells. Unveiling Optical Properties and Degradation Mechanisms in Emerging Multijunction Solar Cells through Advanced Spectroscopy is a proposal that addresses the challenges in the stability and performance optimization of emerging multijunction solar cells. The proposal focuses on optoelectrical characterization, as understanding the underlying mechanisms is essential for optimizing the performance of multijunction solar cells. Traditional techniques provide limited information, but intensity modulated photocurrent spectroscopy (IMPS) has emerged as a powerful tool for characterizing multijunction solar cells. IMPS involves modulating incident light and measuring the photocurrent response, providing insights into charge carrier dynamics and material properties. IMPS has various applications, including evaluating individual subcells within a multijunction architecture, determining the influence of boundary conditions, and studying the stability and degradation of solar cells. However, IMPS still faces challenges in accurately determining optical properties and extracting key parameters from the data. Additionally, it has limitations in measuring only the stability of small-area devices, up to a few cm^2. Further research is needed to develop robust modeling approaches and analysis methods for both small and large-area (> 400 cm^2) devices.
The proposal highlights the advantages of using IMPS for studying the stability and degradation of emerging multijunction solar cells, particularly perovskite-based or tandem solar cells. IMPS offers non-destructive characterization, sensitivity to interface and bulk properties, fast and efficient measurements, quantitative analysis, versatility and compatibility with other techniques, and real-time monitoring capabilities.
The project has two main objectives. Firstly, it aims to develop an improved IMPS technique for identifying degradation mechanisms in large-area multijunction PV devices. This technique will assess the stability of these devices by monitoring changes in charge carrier dynamics and performance degradation over time. The goal is to create a robust and integrated system capable of accurately assessing the optical characteristics of multijunction solar cells. Secondly, the proposal aims to provide crucial information to develop effective strategies for enhancing the performance of emerging multijunction solar cells. By doing so, the project aims to advance the practical viability of these devices for real-world applications.
To achieve these objectives, the proposal outlines a work plan with several interrelated work packages. These work packages include tasks such as defining and selecting experiment parameters, conducting measurement characterization and validation, developing an enhanced IMPS setup, and optimizing the design and fabrication processes of tandem and perovskite solar cells to achieve high performance and extended lifetime. This last task will culminate into the definition of guidelines for the design of highly efficient, stable and long-lasting multifunction solar cells. As a case study, the clean room of Delft University of Technology's photovoltaic materials and devices group will be used to fabricate tandem/perovskite solar cells following the developed guidelines.
The intended outcomes of the research include (i) the development of an advanced IMPS system, (ii) improved stability and reliability, enhanced performance, cost reduction, and technological advancement in multijunction solar cell technology, and (iii) improvement of perovskite solar cell processes.
The impact of the research is significant and aligns with UN initiatives for sustainable development. The outcomes contribute to the transition towards clean and efficient energy, sustainable cities and communities, and affordable and clean energy. The findings will be disseminated through scientific publications, conference presentations, and engagement with industry stakeholders.
By addressing the challenges in multijunction solar cell characterization, stability, and optimization, the proposal aims to advance the field and contribute to the development of sustainable and clean energy solutions. The research outcomes have the potential to support the widespread adoption of solar energy, reduce greenhouse gas emissions, and promote a cleaner and more sustainable future for society.
In addition to addressing the Challenge, the research results obtained will serve as a catalyst for future research activities. The project will also offer valuable mentorship opportunities for two (2) Master's students and one (1) PhD student. Furthermore, there will be an exploration of collaborations, licensing, and start-up creation to foster development and maximize impact. This includes conducting comprehensive customer analysis, crafting a compelling value proposition, determining market sizing, creating a minimum viable product (MVP), and developing a robust business canvas.

Multimode fibre based “adaptive optic” for long range free-space optical communications

Mitchell A. Cox

Executive Summary

This research project aims to bridge the digital divide in peri-urban areas through innovative free-space optical communication technology. With two-thirds of the world’s population projected to live in urban areas by 2050, improving access to vital resources like internet, education, healthcare becomes crucial. However, rapid urbanisation in developing nations creates informal settlements with limited infrastructure, hindering digital inclusion.

To tackle this pressing issue, our work in general is focused on the development of low-cost free-space optical communication systems which can be used as a form of "fibre", before the fibre in these areas. Low-cost fibre hardware can be used to avoid expensive custom electronics and signal processing, however the challenge is coupling light efficiently into these transceivers, which were not intended for free-space use. Multi-mode fibres (MMFs) can be used at the receiver for efficiency, with two caveats: Light from high order optical modes may still be lost, and modal dispersion limits the possible capacity (speed) of a system.

The focus of this project is thus to thoroughly investigate using a dynamically actuated MMF to "reshape" the incoming, distorted light into a Gaussian, thus increasing the amount of light impinging on the receiver photodiode and possibly even combating the modal dispersion within the fibre. This "MMF-based adaptive optic" has the potential to significantly enhance the range and speed of communication systems in these peri-urban areas while keeping costs to a minimum, ultimately helping bridge the digital divide. The project is organised into five objectives:

1. Design and construct the necessary electronics and 3D-printed components, incorporating stepper or servo motors for dynamic bending of the fibre.
2. Output beam shaping: Demonstrate the generation of structured light beams using the system, verified with modal decomposition and off-axis interferometry to measure output wavefront characteristics in terms of amplitude and phase.
3. The MMF "adaptive optic": Investigate transforming turbulence-distorted beams back into Gaussian-like beams, optimising the number of actuators for cost-effectiveness.
4. Faster optimisation strategy: Explore machine learning and Bayesian optimisation algorithms to towards real-time adaptive optic control, as opposed to slow population based methods (currently used in literature).
5. The effect on modal dispersion: In parallel, we will study the device’s impact on modal dispersion within the multimode optical fibre, crucial for future high-speed optical communication systems.

Throughout the two-year project, we aim to publish at least four journal papers and present our work at local and international conferences. Additionally, we will provide an open-source design on GitHub, ensuring accessibility to the wider scientific community.

The potential impact of this research is substantial. The developed technology can help bridge the digital divide in peri-urban areas, providing longer range and higher speed FSO systems that are still affordable and use predominantly off the shelf hardware. Moreover, the dynamically actuated multimode fiber technology holds promise for ultra-high-speed optical communications using space division multiplexing and all-optical reservoir computing, making it a disruptive advancement for various applications.

With its scientific rigour, societal relevance, and transformative potential, this research project offers an opportunity to leverage optics and photonics to drive impactful scientific discoveries, transforming the way we address global challenges and creating a more inclusive digital society.

Executive Summary

Proliferating Radiative Cooling: From Aesthetics to Nonreciprocal Thermal Emission

Challenge: As the global demand for cooling increases, it becomes imperative to explore sustainable alternatives to traditional compression-based cooling that represent 20% of the total electricity usage in buildings. One such alternative is radiative cooling, an energy-efficient and passive cooling process. However, challenges surrounding its efficiency, cost, aesthetic integration into architectural designs, and limited applicability under diverse environmental conditions hinder its adoption.

Proposed Project: This proposal aims to proliferate the usage of radiative cooling by focusing on enhancing its efficiency, reducing its cost, improving its aesthetics, and broadening its applicability under various environmental conditions. The primary tasks of the project include:

Enhancing Efficiency of Radiative Cooling in Humid Environments through Angular Selectivity: This task will focus on developing and testing angularly selective thermal emitters that can cool efficiently in humid conditions.

Photonic crystal-based radiative air conditioning: We will improve radiative cooling-based air conditioning by utilizing a photonic crystal to reflect the solar spectrum and capitalizing on the intrinsic thermal emissivity of water, the coolant, increasing the overall efficiency. The device design relies on scalable and inexpensive nanofabrication methods.

Structural coloring of thermal emitters using Transverse Kerker Effect: The goal is to color radiative cooling panels to blend into various architectural designs, thereby facilitating their adoption. This task will involve exploiting the transverse Kerker effect in dielectric Mie resonators to introduce a color without degrading the radiative cooling performance.

Nonreciprocal and nonlinear photonic cooling: This task will rigorously study the potential of electromagnetic non-reciprocity in overcoming the limits on passive cooling imposed by Kirchhoff law of radiation. Breaking these limits opens the door towards novel niche applications of radiative cooling. In addition, we will debunk existing claims that simple transmission asymmetry is sufficient to overcome Kirchhoff's law of radiation.

Intended Outcomes: Through these initiatives, we intend to overcome the barriers to the adoption of radiative cooling. By improving the cooling efficiency, reducing the costs, introducing aesthetically pleasing designs, and ensuring performance under diverse conditions, we expect to increase the integration of radiative cooling devices into building designs. This will mitigate the impacts of global warming by reducing reliance on energy-intensive cooling methods. We also anticipate opening novel applications such as passive cooling of high-temperature superconductors, thereby further driving the proliferation of radiative cooling technology.

Optica Foundation Challenge Proposal - Health category

Integration of a microcomb-based mid-infrared spectrometer with microfluidics towards biomedical applications

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Microfluidics technology has become a mature and ubiquitous tool for many fields, including environmental science, analytical chemistry and biomedicine. Despite the significant progress in microfluidics, strategies for analyte detection and quantification that offer high acquisition rates, sensitivity, and selectivity are still scarse. To this end, optical spectroscopy techniques, encompassing fluorescence, Raman, and UV-visible to infrared spectroscopies, are a remarkable solution. The mid-infrared (mid-IR) spectral range, from 2 to 20 μm, is particularly important since most molecules have intense fundamental vibrational bands there, including the biochemical building blocks of life: proteins, lipids and DNA.

One of the most promising techniques for mid-IR spectroscopy is the dual-comb spectroscopy (DCS), which allows to acquire broadband absorption spectra by measuring the time-domain interference between two frequency combs of slightly different line spacings. Unlike a conventional Fourier-transform IR spectrometer, DCS requires no moving parts, which allows for fast acquisition times with high resolution and signal-to-noise ratio using a single photodetector. DCS in the mid-IR have traditionally been realized with bulky setups based on femtosecond mode-locked lasers, and more recently, it has been realized using chip-scale photonic devices. Although there have been some advances on the use of microcomb-based DCS as an analysis tool for microfluidics, their integration on the same chip has not been demonstrated.

In this project, we will design and develop a microcomb-based mid-IR (2 - 4 μm) DCS integrated with a microfluidics system on the same chip. We intend to fabricate the photonic chip, which will be based on silicon photonics materials, through a foundry run. Our major challenge would be to fabricate a microfluidic device that can be directly integrated with the photonic chip. For that, we propose to use the technique of two-photon polymerization (TPP), a laser writing fabrication technique that leverages the nonlinear nature of two-photon absorption to fabricate 3D microstructures with arbitrary geometries and sub-diffraction features. The mild processing conditions of the TPP technique, combined with its geometry flexibility, makes it suitable for this task. By using TPP, we will fabricate a simple microfluidic scheme on top of the photonic chip and characterize the sensitivity achieved in the DCS system by interfacing waveguide structures with microfluidic channels in the hybrid chip. Our proposal may unlock an *in-situ* strategy for the detection and quantification of biochemical materials with a high acquisition rate and sensitivity. Overall, this proposal takes steps towards a fully integrated optofluidic platform that is scalable and readily deployable to needed places outside a controlled laboratory environment, such as medical settings. If successful, this project will benefit various microfluidic applications, especially those in the biomedical field. Examples of applications that can potentially benefit from our proposed technology include the synthesis of nanoparticles for the treatment and diagnosis of cancer and pharmacodynamics studies.

Title: Development of a Wearable Multiwavelength NIR Spectroscopy Module for Diabetes and Cardiovascular Risk Factors Monitoring

Summary:
Diabetes and cardiovascular diseases (CVDs) are two of the most prevalent and significant health challenges facing the global population. Both conditions have reached epidemic proportions, leading to substantial economic burdens, loss of productivity, and increased mortality rates. These diseases are chronic and requires long term monitoring. The proposed project aims to develop a NIR (Near-Infrared) spectroscopy module, wearable and equipped with multiwavelength capabilities, for non-invasive detection of diabetes and cardiovascular diseases. This technology will significantly impact healthcare by enabling mass screening, timely diagnosis, and proactive management of these prevalent diseases.

Objective:
The NIR spectroscopy module will interact with the skin's surface, and underlying tissues and blood vessels. The device will be optimized to capture and analyze the specific spectral patterns indicative of glucose and cardiovascular disease biomarkers. The spectral patterns will be a combination of both chemical changes like glucose, cholesterol levels, etc., and physical changes in blood pressure and heart rate.

Intended Outcomes:

1. **Compact and Wearable Design:** The primary objective is to design a compact and user-friendly NIR spectroscopy module that can be easily worn on the skin and monitor chemical and physical parameters associated with diabetes and cardiovascular diseases. The device will be non-intrusive and comfortable, allowing for continuous monitoring and seamless integration into users' daily lives.
2. **Multiwavelength Functionality:** By integrating multiwavelength capabilities, the module will be able to interact with specific biomarkers relevant to diabetes and cardiovascular diseases. This enhanced specificity will enable accurate detection and differentiation of these conditions, leading to better management and control of the disease. It will also help with incorporating the effects of local environment and skin conditions in the analysis.
3. **Database development:** One of the major challenges with success of such non-invasive devices is unavailability of good reference data. The work will help in creating a database which will be helpful for future researchers.

Applications to Real-World Issues:

1. The device will help end-users with improved diabetes management. It will provide real-time glucose insights, helping users make informed decisions about insulin dosing, diet adjustments, and lifestyle modifications. Timely intervention based on the Cardiovascular risk factor level can prevent or delay the progression of heart-related issues.
2. Overall, the device with help user with enhanced lifestyle choices. Users will be motivated to adopt healthier lifestyle choices based on real-time health data. It also helps with mobile health screening.
3. The portable and user-friendly nature of the wearable module makes it suitable for mobile health screening initiatives. It can be deployed in community health programs to conduct screenings for diabetes and cardiovascular disease risk factors in remote or underserved areas.

Capturing Cancer's in It's Early Glow: Pioneering Early Detection Strategies using Light Based Biomarkers (Health Challenge) – *Executive Summary*

<u>The Challenge</u> – Cancer is unique among all global health challenges as it is one of the only diseases that will become *more common* as biomedical innovations eradicate other diseases and extend lifespan. As a leading cause of death worldwide, 2 in 5 people will develop cancer in their lifetime and most surviving patients will experience life altering, negative side effects from current anti-cancer treatments. One unfortunate consequence of such anti-cancer treatment, like chemotherapy, is a syndrome of cognitive impairment that has been colloquially termed "Chemo-Brain" (CB), which remains as the leading source of decreased quality of life amongst the increasing number of cancer survivors. Without predictive and early-detection diagnostic tools, clinicians cannot anticipate which patients are most at-risk of developing CB, thus delaying mitigating interventions. Like the early detection of cancer, without an early diagnosis of CB, the mental health and quality of life of cancer patients declines insidiously, leaving both patients and clinicians with diminishing options. Unfortunately, current cancer diagnostics rely on costly and invasive assays of molecular biomarkers that are highly variable across individuals and must be sufficiently concentrated to achieve detection thresholds, leading to diagnoses at later stages and increased patient mortality. **Thus, there are two challenges that require immediate attention: *ultra early detection of cancer and the early detection cancer-related cognitive impairments like CB*.** Earlier, non-invasive detection is crucial for improved patient survival as current treatments are proving to be much less effective at later stages with known racial disparities of outcomes. Again, what is urgently needed are safe, affordable, and scalable diagnostic tools to detect cancers at earlier stages and monitor side effects of therapies to enhance patient outcomes and quality of life for survivors.

<u>Proposed Project</u> – The main objective of the project is to develop a novel diagnostic imaging platform and signal classification algorithm to non-invasively detect early-stage cancer and chemotherapy-related cognitive impairments, with the ***ultimate goal of reducing mortality rates and enhancing the quality of life for cancer survivors***. We will realize this vision by isolating and characterizing light-based biomarkers of cancer that are naturally emitted from cancerous tissues. While it is well established that all cells continuously emit low-intensity light (10^{-15} W/cm^2), termed ultraweak photon emissions (UPE), their use in biomedicine and early detection technologies is only now being realized. UPEs are a consequence of cellular metabolism, resulting from the oxidation of biomolecules such as lipids, nucleic acids, and proteins. Our group demonstrated that UPE signatures, which span the visible and near-visible electromagnetic spectrum are linked to molecular activity within the cell and can be used as readouts of cell state and behaviour, especially in dysfunctional states like cancer. Advances in single-photon detectors (SPDs) have enabled the unprecedented measurement UPEs from cancer cells at high spatiotemporal resolutions. Our published research indicates that cancer cells express fingerprint-like UPE patterns, and our preliminary data indicate functional brain states correlate with UPE fluctuations. Therefore, ***light-based biomarkers of cancer and CB could represent major breakthroughs toward ultra-early detection***. In Aim 1, we will use in vitro methods to identify light-based biomarkers of proliferation and migration of brain and breast cancer cells. In Aim 2, we will use an array of head- mounted UPE detectors to establish a novel method ("photoencephalography") of predicting cognitive symptoms associated with CB.

<u>Intended Outcomes</u> – The project will deliver a fully non-invasive and affordable biomedical imaging platform and classification algorithm that passively senses naturally emitted light patterns to detect cancer earlier than molecular tests and predict chemobrain before the onset of cognitive symptoms. Unlike current imaging tools (MRI, PET, CT), UPE-based diagnostics use inexpensive and portable optical sensors to capture light-based biomarkers of cell state and fate without the use of external magnetic fields or ionizing radiation. Light-based biomarkers of breast and brain cancer-related proliferation and migration as well as chemotherapy-related cognitive impairment will be characterized. The techniques that we will develop can be applied to detect stroke, metabolic disorders, and many other medical conditions at earlier stages of disease progression. The novelty of the research and its appeal as a biomedical advance will be an important factor in recruiting highly qualified trainees and driving accessible and inclusive scientific innovation. Our team of world-renowned experts will use this opportunity to train the next generation of frontier-pushing scientists to explore equally exciting questions and innovate toward a better world.

QUARTZ-BASED OPTICAL WAVEGUIDE SENSOR FOR MICROPLASTICS DETECTION IN WATER

PROJECT LEADER

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MEMBER:

- NAZIRAH MOHD RAZALI (Universiti Teknologi Malaysia, UTM)

KEYWORD: Quartz, Optical Waveguide, Optical Sensing and Sensor, Waveguide Sensor, Microplastics, Water

EXECUTIVE SUMMARY

Nowadays, the sizeable number of microplastics pollution has become a global and societal concern that needs to be addressed. Not only does this endanger the ecology and marine animals, but it can also cause health threats to human beings. Moreover, microplastics are optically difficult to be detected especially in water bodies such as rivers, oceans and tap water due to its density, size, shape, morphology, and transparency. This has led to an expansion of studies on microplastics detection methods in water. However, most of the methods introduced to date is rather time-consuming, expensive, and complicated. To overcome this issue, this research aims to develop a compact optical waveguide refractive index sensor by employing the quartz as a main material. In this research, the objectives are to design and model the quartz-based optical waveguide sensor using Ansys Lumerical software for microplastics detection in water as refractive index sensor and to fabricate quartz-based optical waveguide sensor by using moulding and etching fabrication techniques. Note the range of the refractive index used in this research are from 1.30 up to 1.53 which reflect the refractive index of microplastics that commonly found in polluted water. Therefore, to understand the performance of quartz-based optical waveguide sensor, optimisation on the waveguide's geometric parameters will be conducted. These parameters, which include waveguide length and dimension, thickness, refractive index profile as well as variation of coating material will essentially be varied to attain the best sensitivity and linearity performance of the waveguide sensor for microplastics detection in water. Overall, it is believed that this research is beneficial to researchers, government and environmental agencies which provide a better understanding about the technology of microplastics detection in water. With the development of the quartz based optical planar waveguide sensor, new substantial impact could be achieved in water environment sustainability which aligned with SDG 3, SDG 6 and SDG 14 which are good health and wellbeing, clean water, and life below water. The preliminary result from this research will be the early step towards advanced technology in preserving nature.

Executive Summary - Health category

Real-time brain Tumor border visualization with imaging Partial Mueller Polarimetry (TurboPMP)

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Surgery remains the decisive treatment step for most patients with brain tumors, particularly life-threatening gliomas. A visualization of the precise border between a tumor and healthy brain tissue is crucial for the complete excision of the tumor and preservation of neurological function, because not always a neurosurgeon can perform resection with a wide safety margin without damaging eloquent areas of the brain. Despite the recent advances in intra-operative imaging modalities, e. g. the use of ultrasound, ALA-5 fluorescence and magnetic resonance imaging (MRI), tumor tissue shows low contrast compared to white matter of healthy brain tissue during neurosurgery.

The densely packed and highly aligned fiber tracts of the white matter of healthy brain tissue exhibit uniaxial linear birefringence with an optical axis oriented along the direction of fiber bundles. Brain tumor tissue, whose cells grow in largely chaotic way, should lose this optical anisotropy. To address the limitation of current tumor visualization strategies, the IP research group recently proposed to visualize the microstructure of the brain, through its fiber tracts during tumor surgery, since the absence of fiber would imply tumor tissue. The results using the complete multi-spectral wide-field imaging Mueller polarimetry (IMP) system are promising for both ex and in vivo brain tissue differentiation and diagnosis. However, the complete IMP system realies on the sequential acquisition of the intensity images for each pair of probing and analyzing polarization state at each wavelengths. Moreover, the system uses averaging of 8 up to 16 measurements of the intensities for each pair of polarization states to reduce the noise in the images. These limitations are not compatible with the ultimate goal of real-time polarimetric imaging during neuro surgery.

*My TurboPMP proposal suggest a solution to visualize and segment accurately the border between healthy and brain tumor tissue in the polarimetric images acquired under in vivo neurosurgery conditions, using a real-time partial **V**ideo-**R**ate **I**maging **M**ueller **P**olarimeter (VRIMP).* The new method I propose will be based on the measurements of the partial Mueller matrix (MM) at video-rate, while extracting the same diagnostic information as from the complete MM. It will be a significant breakthrough towards the next generation of intraoperative polarimetric imaging, thus paving the way to the implementation of this imaging modality in clinical settings. The TurboPMP project is realistic and interdisciplinary, as this combine two fields, namely, the IMP instrumental development and the intra-operative neurosurgical imaging. Moreover, their merging for brain tumor neurosurgery is completely new and was not achieved yet.

The creation of an ergonomic VRIMP prototype applicable for use in OR and well adapted for clinical practice, will be the main output of the TurboPMP project. The VRIMP system will have integrated polarimetric images post-processing and interpretation algorithms, the latter will be validated for *in vivo* brain tissue imaging and optimized for running real-time measurements. The versatile design of the final VRIMP system allowing its integration in both a standard commercial microscope and an exoscope which could facilitate the implementation of the VRIMP in OR settings

Successful completion of the TurboPMP project will demonstrate the relevance of the partial IMP technique for the i*n vivo* identification of healthy brain fiber tracts and their orientation at crucial time points of brain surgery. I expect that the implementation of the VRIMP system for a non-contact and real-time visualization of fiber tracts in the tissue-at-sight would be a breakthrough for brain tumor surgery. It will reduce postoperative neurological deficits that have devastating effects on the patient's quality of life and survival time. Hence, the TurboPMP project approach has the potential to significantly improve the patients' outcome and reduce surgical morbidity.

Design of an Optical Brain Interface: Bio-Neural Dust

CHALLENGE

The field of optogenetics has undergone significant development in recent years. One of its applications is stimulation of neurons with light. However, when coming to stimulating the actual brain, using optical fiber inserted through the skull is not practical. To achieve neural stimulation wirelessly, the concept of neural dust was introduced. Neural dust is a type of brain-computer interface, which uses devices the size of a millimeter as wireless nerve sensors to remotely monitor neural activity. However, despite of their small size, these devices are still very large compared to the size of a neuron, making it impossible to achieve stimulation and monitoring at the granularity level of a single neuron; it is also impossible to achieve very localized brain stimulation/monitoring. In addition, CMOS technology is reaching its limits in terms of miniaturization due to quantum phenomena, making the control of CMOS sensors at the nano level very challenging. The brain stimulation at a single neuron precision level is faced with two problems; size miniaturization and biocompatibility. In the optogenetics literature, we either find miniaturized systems with no biocompatibility, or biocompatible systems but very large compared to the size of neurons.

PROPOSED PROJECT

One promising solution in designing wireless nanosensors is to use bioluminescence and biological agents such as bacteria and viruses. Besides their biocompatibility inside the human body, bio-inspired systems are stable, inexpensively manageable, their tiny size allows them to be injected noninvasively inside the brain and they are easily controlled with genes and enzymes. The goal of this project is to design and implement bio-nanosensors that can monitor and stimulate neurons at nano level by using optogenetics. The proposed bio-nanosensor contains two biosystems. The first uses the piezoelectric properties of M13 virus to harvest the mechanical energy of ultrasonic waves, converting it to electricity. The second biosystem uses a photo-protein called *Aequorin*, which generates bioluminescent blue light in the presence of Ca^{2+} ions. Both biosystems will be placed inside a transparent nanosphere creating a bio-nanosensor, which detects ultrasonic waves, converts them to electricity, which triggers release of Ca^{2+} ions in the pool where *Aequorin* is located. The reaction generates blue light emission. A network of these bio-nanosensors creates the Bio-Neural Dust that will be used as an optical brain interface to stimulate neurons *in vitro* by using optogenetics.

INTENDED OUTCOMES

The project is divided into an analytical study and an experimental study. The intended outcomes of the analytical study are journals, conference publications and a patent of the designed bio-nanosensor. The intended outcomes of the experimental study are testbed, in vitro prototype and a patent of the constructed bio-optical brain interface. The project will involve 4 graduate students (2 PhD and 2 Master), who will acquire multidisciplinary expertise and research training. We have secured use the laboratories required for our research. This project will have a significant scientific and technological impact, especially in the field of medical applications and neuroscience.

EXECUTIVE SUMMARY

We write to propose the integration of ultraviolet (UV) light sources into compact, energy-efficient devices for water treatment. This innovative approach utilizes optics and photonics to address the global challenge of providing clean and safe drinking water to regions facing water scarcity or contaminated water sources. In underdeveloped nations like Ghana, the majority of the people reside in rural areas where it is challenging to find clean and portable drinkable water. The water is drawn from river water which is contaminated with many dirty particles including animal and human excreta. The river water or contaminated water is infected with dangerous bacteria, protozoa, or viruses, and is highly unhygienic. The issue is that these rural settlers lack a developed infrastructure such as electricity. The continuous drinking of unhygienic has resulted in a lot of infectious ailments among the people in rural areas. The main objective of this research is to find a solution that provides people in deprived nations with portable drinking water. In this regard, it is especially important to design portable and effective water purifying systems for rural residents in selected rural communities in Ghana. The project will be piloted in six (6) communities and thirty (30) households in Ghana. The solution describes the steps involved in the proposed water purification system that uses a UV-LED source as a disinfectant and automated solar energy equipment. The proposed solution will provide users with refreshing clean purified water that has gone through treatment with the UV-LED source and a solar energy system. The system will be named 'nsupa UV-LED water purification system'. The simplified design of the nsupa UV-LED water purification system will allow for easy deployment in remote or disaster-stricken areas, ensuring access to clean drinking water in emergency situations. The treated water would be tested by a qualified microbiology and chemical scientist to confirm the quality of the water to ensure it is good for human consumption. After the successful completion of the pilot, the project could be rolled out in other rural communities and nations.

Germicidal UV Dosage Index Levels (GUV-DIL) for UV-C LEDs based Photonic Disinfectants, Sustainable Solution Again Diseases Transitions in Healthcare Facilities on the Hearth now and on the Spaces Villages Tomorrow

Dr. Ing. Pablo Fredes[1]

Executive Summary

Resume

The use of mercury (Hg) free germicidal UV sources are increasing every day. The Hospital Acquired Infections (HAIs) on Hearth and the Infection Prevention and Control during Prolonged Human Space Travels, and inhabiting Spaces Villages is a great challenge, that's we are boarding supporting by the new LEDs germicidal UV sources and the Germicidal UV Dosage Index Levels (GUV-DIL). Our main beneficiaries will be users, professionals and staff of the Healthcare Services now, and the space travelers in the near future, they are hiring us to make improvements in the cleaning and disinfection practices in Healthcare Facilities and in the space shuttles, spatial Stations and in the future Spatial Villages.

Introduction

Of all preventable infections on the Hearth, the one that causes the most concern is the Hospital Acquired Infections (HAIs), there as the eighth leading cause of death in the United States, just after diabetes (79,535 deaths in 2015). The two main causes of the appearance of HAIs have relation with the thoroughness of the cleaning and disinfection processes, applied for the surfaces and the airborne transitions. Every year more and more studies appear providing strong evidence supporting the effectiveness of the Photonic Disinfection (UV disinfection technologies) improving the Indoor Air Quality (IAQ) and the cleaning and disinfection levels of the surfaces. Photonic Disinfectants are being a key tool in the fight against HAIs, especially those caused by Antibiotic Resistant Microorganisms. On the other hand, the UV LEDs based emitters appears as a sustainable and mercury (Hg) free option to provide the appropriated UV light source for the innovative photonics disinfectant systems, that's are an indispensable tool again HAIs, and will be indispensable for the prolonged human spaceflight, and the development and building of the future Space Village Projects. To take optimal advantage of the disinfectant capacity of UV LED based photonic solutions, an Germicidal UV Dosage Index Levels (GUV-DIL) is need. We propose a simple and fast reading dosage scale that's relates the applied photonics dose by the devices (or systems) with the desired sanitation level. The top index level of GUV-DIL will be relate with the Spatial Sanitation index level. This index level of sanitation will be needed in the prolonged human spaceflight, in the Spatial Stations and for the future Spatial Villages.

Outcomes: Germicidal UV Dosage Index Levels (GUV-DIL) and Level of sanitation achieved.

Accurate UV light validation plays a crucial role in effective sanitization practices, particularly in the healthcare industry and in Space travels, Spatial Stations and Spatial Villages. By understanding the importance of UV light in eliminating pathogens, we can ensure a safe environment for the patients, healthcare professionals and spaces travelers. By incorporating Germicidal UV Dosage Index Levels (GUV-DIL) into the sanitization protocols, you can confidently monitor and validate the applied germicidal UV dose, thereby enhancing the safety and well-being of patients, professionals and staff.

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[1]Acknowledgments to: Dr. Ulrich Raff, Prof. Blanca Troncoso form University of Santiago, Chie, and Mr. Cristobal Rios Director of Hydraluvx, Chile to its valuable comments, suggestions and corrections.

NASCENT: **N**on-G**A**us**S**ian **C**ontinuous Variable Quantum N**E**ural **N**e**T**works

Executive Summary – Information Challenge

Despite being extremely promising emerging technologies, quantum computers face significant challenges in their development and implementation. Inter-disciplinary teams worldwide are dedicated to overcoming these hurdles. However, progress is hindered by fundamental issues such as scalability, end-user friendliness, certification of components and algorithms, and the limited applicability to real-world problems. Photonics simulators have emerged as a highly promising candidate in the realm of quantum computing and quantum simulation, drawing significant attention in fundamental and applied physics and engineering. Machine learning (ML), a highly successful technology of the current era, is focused on tasks such as classification, clustering, and pattern recognition for extensive datasets. The performance of deep learning and many ML architectures, is constrained by the available computing power, which, in turn, is restricted by energy consumption. Optics has the potential to enhance neural networks, enabling faster and more efficient operations.

NASCENT aims to combine the two fields and explore how quantum optical phenomena, such as non-Gaussianity, can significantly enhance classical Machine Learning (ML) techniques to address problems in both quantum physics and classical applications. The project has two main objectives. The first objective is to develop and assess continuous variable non-Gaussian variational quantum simulation, demonstrating its utility in studying the static properties of various quantum many-body systems, ranging from quantum chemistry to lattice field theories. The second objective is to leverage entanglement in non-Gaussian systems as a resource to enhance Quantum Machine Learning (QML) models.

To achieve these objectives, the project will be divided into two working packages. The first working package will focus on demonstrating the performance of a variational quantum eigensolver (VQE) in the continuous variable form with non-Gaussian operation. The novelty of this project lies in the variational ansatz that is scalable, hardware efficient, and can be already included in modern-day technology. The VQE will be applied to bosonic systems, relevant for strongly correlated quantum matter physics, and to high-energy physics models, that can be naturally formulated in the Continuous variable formalism. The second working project will focus on the implementation of a Quantum Neural Network in the continuous variable formalism. Quantum photonic systems present promising potential to enhance the performance of ML architectures. This project will investigate how quantum entanglement can provide an advantage in classification tasks for classical and quantum data.

This is an exceptionally thrilling moment to delve into these subjects, given the increasing efficiency and scalability of quantum devices based on photonics. As hardware capabilities advance, it becomes imperative to progress in the algorithmic aspects of quantum computers, particularly focusing on algorithms suitable for near-term devices

Title: **Robust and reliable mid-infrared pulsed fiber laser as a laser scalpel**

Category: **Health**

Lasers are the surgical tool of the 21st century. They are intrinsically sterile, do not blunt or deform tissue, and present an opportunity for inhuman precision in the depth and positioning of cuts. However, current laser technologies still face a number of challenges that limit their widespread adoption as a substitute to the regular scalpel, among them the difficulty of controlling thermal damage, the inconvenience of their maintenance and their limited capabilities in processing hard tissue such as bone and teeth. CO_2 lasers operating near 10 µm are cheap and robust, but their delivery method (articulated arms with guided mirrors), limited tissue absorption and large spot size limit their effectiveness in the operation room. Flash-lamp-pumped Er:YAG lasers at 2.94 µm have higher absorption in biological tissue, but their low repetition rate, limited pulse length control, frequent need for maintenance and poor beam quality make them a slow, rigid platform that cannot be precisely tailored to specific applications. There is a need for a new, 21st-century laser platform that simultaneously addresses all the constraints of legacy laser technologies and opens the way to the democratization of laser surgery: the high energy pulsed mid-infrared fiber laser.

This proposal for the Optica Foundation Challenge in the health category aims to develop a field-deployable gain-switched all-fiber laser that generates pulses shorter than 100 ns with a power density of up to 2 GW/cm² (a fluence of up to 200 J/cm²). The operation wavelength near 2.8 µm, adjustable repetition rate and near perfect beam quality make it suitable for efficient precision surgery on soft and hard biological tissues. The project is divided into two objectives. The first one focuses on developing a gain-switched mid-IR all-fiber laser system that can be industrialized for soft tissue processing such as arteries or cartilage. The second objective is to build an amplified version capable of generating larger energy pulses at higher average power to ultimately deliver efficient ablation of hard biological tissues such as bones and teeth. These new fiber laser systems offer an excellent beam quality and divergence, and shorter pulses to increase the biological tissue ablation efficiency while also reducing the damage to surrounding tissues compared to current Er:YAG and CO_2 lasers. Achieving these performances with a simple and cost-effective design makes this technology appealing for high-volume markets and has the potential to revolutionize the biomedical industry, just as the adoption of the fiber laser did for the material processing industry.

The main outcome expected from this project is the development of a pre-production prototype suitable for the start of clinical trials and experiments by medical device partners. Moreover, the achievement of an all-fiber mid-IR laser system producing highly energetic pulses with durations in the range of a few tens of nanoseconds would represent a scientific advance that would be worth publishing in highly ranked peer-reviewed journals like *Optics Letters* and *Optics Express* as well as in renowned conferences such as *CLEO*. The application of such laser sources as a novel laser scalpel adapted for efficient biomaterial processing will also be investigated by the medical partners of *LumIR Lasers* and will lead to advances in our understanding of laser-tissue interactions.

The impact of the novel biomedical laser system will be to increase the cutting efficiency while also reducing the surrounding area damage to biological tissues compared to the current laser scalpel technologies. Moreover, these improvements will also enhance the healing process and reduce the pain experienced by the patients of such surgery. The CW mid-IR fiber lasers commercialized by *LumIR Lasers* are already making waves in the biomedical industry and a gain-switched fiber laser adapted to cut through harder biological tissues would open a whole new sector of applications for this “cutting edge” technology while also improving the quality of life of many patients worldwide. Given enough time to complete clinical phases, the flexibility and optical properties of this laser technology will allow dramatic improvements to difficult surgical procedures such as for the treatment of endometriosis, ovary cancer and several bone and teeth conditions.

EXECUTIVE SUMMARY

Silicon photonics and printable photonic ink for an affordable medical sensor platform

Optica Foundation Challenge Category: Health

The Challenge: Traditional medical sensors consisting of discrete optics cannot keep pace with patients' needs and the growing demand for wearable sensors. These limitations were highlighted during the COVID-19 pandemic when the standard pulse oximeters used to measure blood oxygen levels yielded incorrect diagnoses for people with dark skin pigmentation. New devices needed to be developed with even more wavelengths (LEDs) at increased cost to reach the required accuracy for all skin colors. The core issue is that traditional devices based on discrete optics require separate components to be sourced from different supply chains and individually packaged, resulting in complex products. While the individual components are sometimes inexpensive, the true cost driver is the required packaging of each LED. As another example, commercial carbon monoxide poisoning detectors made by the company Nonin require eight or more LEDs and are niche as a result. To advance beyond the current state-of-the-art, Iris Light is pioneering the development of an affordable medical sensor platform based on silicon photonic chips (SiP). A SiP chip requires only a single packaging step and can obtain a bounty of data from densely-packed, on-chip integrated components. Based on direct customer contact with leading Fortune 500 medical companies, Iris Light is targeting hydration sensors as the first application. An optical hydration sensor uses near-infrared wavelengths to accurately measure the water content in skin. Our SiP based optical medical sensor platform will enable the collection of more health data per dollar leading to improved patient outcomes. Looking to the future, the $20 billion medical sensor industry needs a way to achieve accuracy, complexity, and versatility while maintaining a low cost to expand global access to healthcare.

Proposed Project: *This Optica Foundation Challenge will provide critical seed funding for demonstrating the viability of optical medical sensors based on SiP*. The specific challenge addressed here is the printing of LEDs directly onto a SiP chip to improve performance compared to the discrete optics approach. To achieve this, our company is pioneering a new class of printed photonic inks for light sources and detectors (actives) based on nanoscale black phosphorus (BP), a material that exhibits desirable opto-electronic properties including direct-gap light emission and high conductivity. BP is a 2D semiconductor that can be tuned to emit over a broad spectrum from visible to infrared based on the number of atomic layers. **Here, we will achieve an electrically driven BP LED emitting at 1450 nm for water absorption measurements in skin.**

Intended Outcomes: This project will leverage key results from our company's work on BP over the last several years including world-record conductivity for semiconductor ink, and demonstration of printed photodiodes with state-of-the-art performance. Here, the main outcome will be an LED consisting of a BP-based P-N junction that emits at 1450 nm. Towards this goal, we recently demonstrated a new nanomaterial *synthesis* recipe where we isolated a single spectral band (monodisperse) for the first time. The specific band we isolated was of 4-atomic layer BP (4L BP) that covers the desired spectral range for this project. Three major milestones are targeted by this proposal: First, we will improve the yield of our 1450 nm ink. Next, we will optimize the ink for emission at 1450 nm. Finally, we will print the ink onto pre-patterned substrates to form the LED and verify emission at 1450 nm. **This advance will represent the first ink-printed light-emitters on silicon chips.**

New Capabilities: The success of this project will illustrate how printed photonic inks can enable SiP to reach its full potential as a transformative technology. A wearable hydration monitor will be a major step toward sophisticated optical medical sensors that will improve patient outcomes. At scale, our new photonic chip medical sensor platform will enable access to affordable, state-of-the-art medical care for people all over the world. More broadly, printable photonic inks solve one of the most important outstanding problems for the entire silicon photonics industry: namely, the need for an on-chip light-source covering multiple spectral bands. Beyond medical sensors, the impact of this new on-chip ink-printed LED platform will enable SiP to expand its reach into applications in environmental monitoring, communications, quantum photonics, and beyond. Further, the photonic inks will foster growth in the *printed electronics* industry to open the way for applications in *printed opto-electronics*.

Pradeep Subedi, Ph.D. Iris Light Technologies, Inc.

Executive Summary for

Compact Computational Flat-Optical Bronchoscopes for Image-guided Cancer Therapies Under Respiratory Deformation of Lungs

Praneeth Chakravarthula
cpk@cs.unc.edu, UNC Chapel Hill, Department of Computer Science

Problem Statement and Objectives

Over 200,000 new cases of lung cancer are diagnosed annually in the United States alone, resulting in about 150,000 deaths, making lung cancer the most lethal of all forms of cancer. Only 1 in 6 lung cancers are diagnosed at an early stage and over half are diagnosed with distant metastasis. For effective and early diagnosis, adequate and representative biopsy sample collection is the key which will help in better management and improve patient outcomes. However, accessing inner nodules of the lung is challenging due to the large size of the bronchoscope compared to the bronchial airways of the lungs. Adding to this, the lungs deform intraoperatively due to respiratory motion making it further difficult to visualize the lesions towards the periphery of the lung. Given that existing solutions do not address this problem and a standard scope can only reach up to 4-5th generation of bronchi – in a typical 23 generation bronchial tree of lung – we aim to develop a compact bronchoscope based on computationally designed flat meta-optical elements that will significantly reduce the size while still allowing for full color real-time imaging and guided therapies.

Impact of Proposed Research

The development and implementation of thin bronchoscopes will have a transformative impact on respiratory medicine. These ultra-compact and agile instruments have the ability to revolutionize the landscape of minimally invasive operations and experimental surgeries, offering improved diagnostic capabilities and therapeutic interventions. The reduced rigid tip length of the proposed bronchoscope allows for enhanced maneuverability, facilitating smoother navigation through narrow and tortuous ducts with minimized patient discomfort and risk of complications. By reaching peripheral lung regions more effectively, the proposed thinner bronchoscope promises to enable more extensive visualization and sampling of lesions that were previously challenging to access, resulting in higher diagnostic yield and more accurate staging of lung cancer. Furthermore, integrating with the computational optimization techniques will improve image resolution thereby improving real-time guidance during procedures. Overall, the proposed research can significantly advance respiratory medicine and interventional pulmonology, enhancing patient outcomes.

Why should this proposal be granted?

The proposed technique represents a significant advancement in imaging optics for respiratory medicine and serves as a crucial initial step towards realizing the PI's long-term research vision. The project’s success is pivotal in establishing the foundation for larger and more extensive grants in the future, which could further support the development of the bronchoscope demonstration over multiple years.

Silicon photonic biosensors for low-cost, portable, data-rich measurements of hormone biomarkers relevant to women's health and the menopausal transition

Executive Summary for Health Challenge

Dr. Samantha M. Grist, The University of British Columbia, Vancouver, Canada

What is the unmet need? There have historically been significant gender inequities in healthcare and medical research, with many women's health issues, including symptoms of the menopausal transition, neglected and underfunded. Women's gonadal (sex) hormones can be key indicators of health and impact many conditions beyond fertility, including cardiovascular conditions and neurological disorders. These hormones also fluctuate significantly during the menstrual cycle, requiring frequent monitoring to fully understand the levels and fluctuations. Gonadal hormones are critical during the menopausal transition, with levels of more than 10 hormones linked with perimenopausal symptoms including sleep and mood disruption, brain fog, and hot flashes. These symptoms present a significant societal burden – 25% of people experiencing perimenopause symptoms consider leaving the workforce – but people experiencing them and the physicians treating them have limited tools and data to understand and predict symptoms or monitor and improve the impact of treatment. To provide insightful, impactful data, the ideal monitoring tool would provide quantitative, accurate, and data-rich measurement of at least 4-10 hormones and hormone metabolites, and it would be able to provide these measurements quickly (in minutes) at low cost, in a form factor suitable for people to conveniently use at home at least multiple times per week. This kind of solution does not currently exist: centralized lab-based assays are expensive, slow, and inconvenient for daily testing, while existing point-of-need solutions like lateral flow assays do not provide the required quantitative, accurate, and multiplexed (measurement of multiple hormones) data.

What is being proposed to meet this need? Silicon photonic integrated circuits containing biosensors are well-suited to performing quantitative, accurate, data-rich measurements, and tens to hundreds of sensors can be integrated on a single millimeter-scale chip for multiplexed measurements. They are fabricated with scalable semiconductor manufacturing technologies, facilitating low costs at high volume. A key limitation of these types of sensors has historically been the size and cost of the readout system (e.g., the Genalyte platform for doctors' offices), because an expensive ($40,000-$100,000), bulky tunable laser and light coupling system are required to read out the data, precluding their use for at-home testing applications like hormone monitoring. We have invented a new sensor architecture that addresses this challenge, allowing us to use a tiny (<1 mm), inexpensive (<$1), fixed-wavelength laser for readout. In this project, we propose to validate this new silicon photonic technology, create a bench-scale portable readout system, and demonstrate urine-based detection of an initial panel of two hormone biomarkers relevant to menopause (expandable to tens in the future).

What are the expected outcomes? Through this work plan we will develop our new silicon photonic sensor and quantify its photonic performance metrics (to provide data-rich measurements at 1000× lower cost than traditional photonic biosensors), compare performance with gold-standard measurements, and also quantify detection of two biomarkers relevant to the menopausal transition: pregnanediol (PdG) and follicle-stimulating hormone (FSH). We will also demonstrate a portable system suitable for demonstration at Optica conferences and to collaborators.

What will be the real-world impact of this project? This project will use innovation in photonics to address a critical unmet need in women's healthcare by validating a portable, low-cost technology for decentralized, multiplexed monitoring of hormone markers in urine. With this project, we will build a tool that has the potential to drastically improve health and quality-of-life during the menopausal transition, and also lay the foundation for future development of tests for additional conditions for broader potential impact of the technology on human health.

Name of the proposal:
Ultra-low loss and broadband all-fiber acousto-optic circulators (FiberCircl)

Category: Information

Applicant: Riccardo Pennetta, Humboldt University of Berlin

Executive summary

The introduction of low-loss optical fibers probably represents the single most important advance in the growth of our current global telecommunication system, which, in turn, fostered the rapid development of all kind of novel and more efficient fiber-based optical components. To meet our growing demand for secure communication and to interconnect future quantum computers, it is likely that our "classical network" will soon operate side by side of a so-called "quantum network", which, extremely sensitive to loss, poses new constraints and challenges to the performance of existing fiber devices. In particular, already demonstrated quantum networks prototypes explicitly pointed out a surprising flaw in our current fiber technology, namely the absence of low-loss non-reciprocal fiber components (i.e., isolators and circulators). To date, the best commercially available fiber-coupled circulators rely on free-space optics and feature high insertion-loss of approximately 1 dB at telecom wavelengths, which only increases for NIR and visible light.

Proposed project

In this project, I propose a solution to this pressing technological challenge by designing and fabricating novel all-fiber non-reciprocal devices based on acousto-optic interaction. These devices will combine ultra-low insertion loss (< 0.1 dB), large extinction ratio (at least 20 dB) and an extraordinary large bandwidth (> 100 GHz), considering the underlying physical mechanisms. They will be built from standard single-mode fiber and therefore could be readily integrated into existing fiber networks. Furthermore, they will be electrically switchable and reconfigurable within a response-time smaller than 100 µs.

The elementary units of my proposal are so-called fiber null-couplers. In brief these are fiber couplers, whose splitting ratio can be controlled via acoustic waves traveling along the coupler waist. It is well known that the acousto-optic effect breaks Lorentz reciprocity if the acoustic frequency is large enough, i.e., greater than 10 GHz for fiber-based devices. However, in practice, it is really challenging (and not yet demonstrated) to excite such high frequency waves in optical fibers via electrical actuation, an imperative requirement for any technologically relevant device. In this proposal, I show that cascading nearly identical null-couplers in a non-linear interferometer would allow us to break Lorentz non-reciprocity with acoustic waves of any frequency. As a consequence, I demonstrate how this concept can be applied to the design of novel electrically-actuated all-fiber circulators with ultra-low loss.

Intended outcomes

The most striking feature of the proposed devices is their ultra-low insertion loss, which is comparable to the one of standard fused couplers (< 0.1 dB). For this reason, these non-reciprocal devices could become a new technological standard for all optical systems in which low-loss are key, as in particular for future quantum networks, for which loss represents a highly undesired source of decoherence. Indeed, after an initial phase of careful design and parameters optimization, the future of these devices could go beyond the pure research environment, due to the relatively simple and potentially low-cost fabrication procedure.

Company Name: **Quanscient**

Challenge:

Simulation of classical fluids is an intensively researched and computationally demanding problem with direct impact on engineering and multidisciplinary fields such as climate modeling and automotive efficient design. We take on the challenge of efficient, low-energy consumption simulations by providing a novel way to provide quantum advantage through the development of quantum algorithms for photonic quantum computers (PQCs).

Proposed Research:

We aim to develop one-year fundamental research in the simulation of classical fluids by discovering and adapting quantum cellular automaton (QCA) models for photonic quantum computers. By enabling quantum speedup for cellular automata models we anticipate, in the long-term, our quantum native approach will revolutionize large-scale classical fluid simulation. We center our research over two main goals:

G1. Establish resources needed (theory and hardware) for implementation of QCA on PQC. Sustain our claim for quantum useful advantage throughout an scaling analysis in the photonic context.

G2. Collaborate with PQCs manufacturers to run on real-devices our developed algorithms obtained in G1. Open a collaborative channel to explore co-design to optimize hardware for algorithms, if possible.

Intended Outcomes:

The intended outcomes of this project are to:

- Research article in collaboration with Quanscient quantum team (7-months)
- Joint research article for the real-device implementation of QCA models (9-months)

Benefits:

The benefits of this project include:

- Attract well-motivated research to quantum cellular automaton models.
- Develop an alternative approach for useful quantum advantage on photonic quantum computers
- Establishing the first demonstration of QCA on photonics quantum computers.
- Produced the first milestone on quantum algorithms research for large-scale multiphysics problems.

Conclusion:

Proof that implementations of simple cellular automata models are valuable and represents a reliable approach for solving diverse real-world problems that can take advantage of increasing capabilities of photonic quantum computers.

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Silicon photonic biosensors for low-cost, portable, data-rich measurements of hormone biomarkers relevant to women's health and the menopausal transition

Executive Summary for Health Challenge

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What will be the real-world impact of this project? This project will use innovation in photonics to address a critical unmet need in women's healthcare by validating a portable, low-cost technology for decentralized, multiplexed monitoring of hormone markers in urine. With this project, we will build a tool that has the potential to drastically improve health and quality-of-life during the menopausal transition, and also lay the foundation for future development of tests for additional conditions for broader potential impact of the technology on human health.

Wafer-scale, transfer-free hetero-integrated photonic circuits using confined growth of single-crystalline 2D materials – Summary

Sang-Hoon Bae, Washington University in St. Louis

The integration of two-dimensional (2D) materials for on-chip photonic applications has attracted immense research interest, thanks to their prominent optoelectronic attributes and the unprecedented degrees of freedom to create heterogeneous integrated photonic layouts and van der Waals (vdW) heterostructures without the lattice-matching constraints that apply to heteroepitaxy. Abundant useful properties are shown in 2D materials of graphene and transition metal dichalcogenides (TMDs), encompassing vital optical functionalities from light emission, modulation, photodetection, and nonlinear optics. However, most reported 2D-materials-based integrated photonic devices to date still largely remain lab demonstrations, far faltering the surging vision of practical 2D-photonics commercialization in real-word.

Before fledging into fully viable technology, 3 long-standing challenges exist for integrated photonics based on 2D materials. (1) Most reported devices use transferred 2D materials. This is because substrates that are suitable for 2D material growth (such as sapphire) cannot be directly used for integrated optical applications (typically require thick SiO_2 BOX layer). Consequently, 2D materials are later transferred to prefabricated photonic templates such as waveguides and micro-cavities using PMMA or metal handler after growth. However, the transfer process inevitably induces residues and defects (cracks, holes, wrinkles) to 2D that significantly deteriorate material optical property and performance. Transfer of delicate 2D films is also incompatible with standard foundry mass-production process. (2) Lack of robust scalable synthesis method of high-quality 2D materials, especially 2D TMDs. Conventional mechanical exfoliation and transfer approaches can produce 2D flakes with high quality, but it remains a trial-and-error process with heavy labor work and extremely low yield. For scalable manufacture methods such as chemical vapor deposition (CVD), it was an open challenge to obtain controlled monolayer-by-monolayer (ML) single-crystalline uniform 2D material growth over wafer-scale, especially for 2D TMDs. (3) Due to the above two reasons, currently reported works are still restrained to single-device demonstration of 2D materials.

Here we propose a novel strategy to simultaneously solve the abovementioned issues, by providing a transfer-free approach to fabricate integrated 2D photonic devise at wafer-scale with high robustness, high throughput, and low-cost. The proposed project will be based on our modified CVD on patterned thin HfO_2/SiO_2 substrates that have judiciously engineered growth pockets to spatially confine the nucleation of 2D materials. Using this confined CVD method with spatial growth selectivity, we have priorly successfully achieved single-crystalline 2D TMD (WSe_2, MoS_2) controlled growth (ML, bilayer/BL, and BL 2D vdW heterostructures) on sapphire or HfO_2/Si templates. Here, we will use optical substrates (2 µm-thick SiO_2/Si) deposited with very thin (< 10 nm) HfO_2 to realize integrated photonic applications including 2D TMD (WSe_2, MoS_2) or quasi-2D metal-halide perovskites-based waveguide-integrated photodetectors and 2D ML-TMDs-based optical modulators. The growth patterns will be re-designed for optical devices followed by re-optimized confined CVD growth conditions. Compared to conventional Si or SiN photonic platforms that either necessitate 2D transfer or can hardly realize good waveguide quality on 2D, we propose a new hybrid bottom-up nanofabrication strategy, by using SU-8 polymer waveguides to directly make the as-grown 2D monolayers into integrated photonic devices without any layer transfer. This method completely solved the residue and defect problems in conventional approaches. The SU-8 polymer waveguides also have the benefit of low-loss (~2 dB/cm), low-cost, and easy-to-fabrication.

Wafer-scale hetero-integrated photodetectors array will be demonstrated without 2D transfer, by first doing confined CVD of ML 2D WSe_2 and/or MoS_2, followed by aligned photolithography and metal lift-off for electrodes and e-beam lithography (EBL) for SU-8 waveguides with high responsivity. Dual confined CVD of ML TMD will be developed to form 2D/HfO_2/2D structure to electrically modulate the absorption of the 2D material for broadband (visible to near infrared) integrated optical modulators. A proof-of-concept demonstration of scalable integrated 2D photonic nano-system with 2D modulators and photodetectors will be delivered as well, following the research steps/schedules detailed in proposal. By simultaneously solving the prior outstanding challenges in 2D integrated photonics community, we envisage this transfer-free scalable strategy to integrate single-crystalline 2D monolayers to photonic chip can offer a crucial leap towards the practical commercialization of 2D photonics into a viable and worthy technology.

Executive Summary:
Quantum-enhanced nonlinear optical learning machine

Category: Information

Saroch Leedumrongwatthanakun
Division of Physical Science, Faculty of Science, Prince of Songkla University, Thailand

In the current information era, the pressing demand for information processing systems with high-capacity, high-speed, and energy-efficient capabilities is of considerable significance. To address this challenge, we propose the development of a programmable optical circuit capable of high-performance computing - the "quantum-enhanced nonlinear optical learning machine". It consists of a sequence of high-dimensional spatially entangled light sources, interspersed with a programmable linear optical circuit and reconfigurable optical phase arrays (see Figure 1).

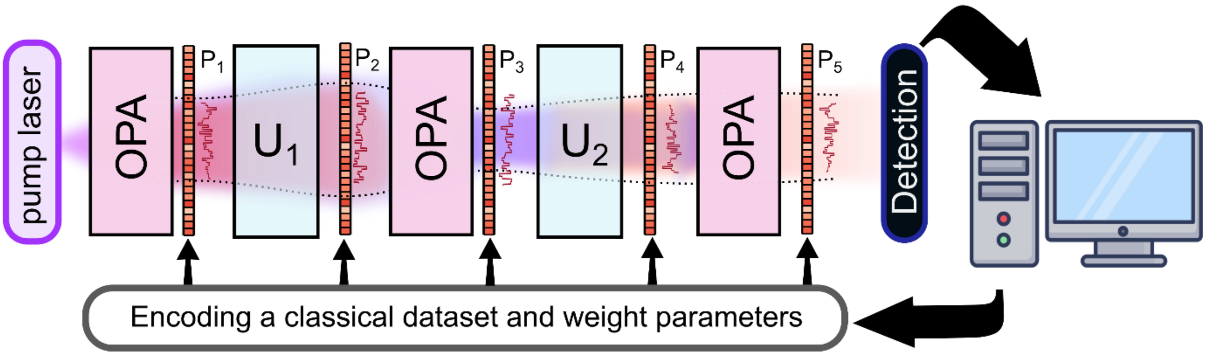

Figure.1 The conceptual schematic of quantum-enhanced nonlinear optical learning machine: It consists of a series of high-dimensional entangled light sources generated from the optical parametric amplification (OPA) process, and a programmable linear circuit, U_i, constructed from a cascade of random unitary transforms and reconfigurable optical phase arrays, P_i. The optical phase arrays, implemented by a spatial light modulator, are used to encode classical data and weight parameters onto the optical circuit where all pump, signal, and idler fields are manipulated to control de/amplification process in the cascade OPAs.

One layer of the optical machine, known as the multimode nonlinear SU(1,1) interferometer, has garnered significant attention for its sensing applications due to its sub-shot-noise sensitivity, even in the presence of external optical loss. Our research further explores the intricate interference between signal and idler radiations, paving the way for computing functionalities. Through the implementation of linear optical circuits, one can adjust the relative phases and amplitudes between the optical pump, signal, and idler fields of each mode of optical parametric amplifiers. This enables us to control the de/amplification and quantum correlation of parametric downconversion light throughout the entire circuit.

By harnessing the quantum optical process, we aim to investigate the learning capability and trainability of the optical machine through statistical learning theory. Additionally, we aspire to showcase its practicality for large-scale real-world data classifications and time-series predictions, all achieved at high speeds while consuming minimal energy. One highlight advantage of the optical machine is its independence from intricate lithography, precise designs of nonlinear optical components, and the requirement for a sophisticated mesh of reconfigurable Mach-Zehnder interferometers. These characteristics simplify the implementation process, making the optical machine more accessible and feasible for practical applications, catering to the ever-increasing demands of the modern information-driven world.

Executive Summary (Category: Information, Period of project: 2 years)

Title: Electrically driven lasers based on two-dimensional materials

Moore's law observes that computing power doubles every 1.5–2 years. This will soon end as we reach the physical limits of traditional computing, yet demand for increased information processing capacity is surging. Researchers are investigating new, atomically thin, 2D materials, which can be used to build very small and highly energy efficient devices.

In the past decade, significant progress has been made in the field of optically driven 2D lasers, with the first successful demonstration occurring in 2015. These lasers have the advantage of being able to operate at room temperature due to the large exciton binding energy. However, there are several challenges that need to be addressed. These include improving the environmental stability of these lasers, expanding their lasing capabilities to the near infrared range, and developing electrically driven devices for 2D lasers.

This proposal aims to fill aforementioned research gap in the field of 2D material photonics. The primary objective is to showcase the first-ever electrically driven laser using 2D materials. Achieving electrically driven semiconductors is crucial but quite challenging. The main hurdle lies in designing electrodes that can efficiently guide electrical current to the specific section of the optical cavity where population inversion occurs. Furthermore, the electrode design should minimize any degradation in the Q-factor. To address these challenges, the project will investigate optical cavity and electrode designs that have proven successful in semiconductor nanolasers.

The proposed optical cavity will be entirely made from 2D materials, where the 2D gain medium is sandwiched between wide-bandgap 2D materials. It is known that a 2D dielectric material, hBN, increase the optical stability of other 2D semiconducting materials due to reduced surface defects, which result in reduced inhomogeneous broadening. This will effectively address the issue of poor instability in 2D material lasers. Additionally, for the first time, this project will utilize GaSe and InSe as the gain materials. These 2D materials maintain a direct bandgap in their bulk form, enabling the design of active material layers with various thicknesses to maximise the confinement factor.

The project's desired outcomes involve gaining valuable research insights in the advancement of integrated photonic circuits based on 2D materials. Through this investigation, we aim to identify the most suitable 2D material for various 2D optical systems and determine whether 2D material lasers can surpass traditional on-chip lasers in performance. The successful demonstration of an electrically driven 2D laser would not only contribute to a prestigious journal publication but also facilitate the practical implementation of 2D materials in on-chip lasers. The applications of 2D material lasers span across various fields, including LiDAR, biosensors, AI, and data centres.

The principal investigator possesses a strong track record and expertise in both 2D materials photonics and semiconductor lasers, as evidenced by her first-authored lasing papers and extensive work with various 2D materials. Her previous research experience at Prof. Yong-Hee Lee's group at KAIST, where they developed the first electrically driven photonic crystal laser, further strengthens her capabilities.

The project is highly relevant and timely, given the emerging field of 2D light sources, evident from the increasing number of publications in this area. A successful application would not only ensure the project's completion but also contribute significantly to the advancement of 2D material photonics. Securing funding for this research topic is critical as this topic currently has no external financial support. If successful, this funding opportunity will be the first external funding for the Principal Investigator, Dr Kim. Additionally, the PI's department has played a vital role in supporting Dr. Kim in establishing her research lab, which is equipped with a comprehensive micro-PL setup featuring various functionalities such as lifetime measurement and photon correlation measurement. The successful completion of this project will realise ultrafast, energy efficient lasers that will be critical for next generation optical computing technology.

Proposal title: Miniature extreme-ultraviolet light sources
Category: Health
Sub-category: Advancing biomedical imaging.

This project aims to develop new light sources with ultra-short wavelengths for next-gen optical diagnostics. The project aims to develop novel approaches to generate high harmonics – source of light in vacuum-ultraviolet and extreme-ultraviolet ranges. Currently, such sources are large and expensive. But recent research suggests practical all-solid-state sources are feasible to develop with the concepts of nanostructured solids. The project intends to develop theory and computation, nanofabrication, and experimental characterisation. Short-term outcomes include demonstrations of vacuum- and extreme-ultraviolet imaging that employs all-solid-state nanoscale sources of high harmonics. Long-term outcomes will be the development of new diagnostics techniques for medical imaging.

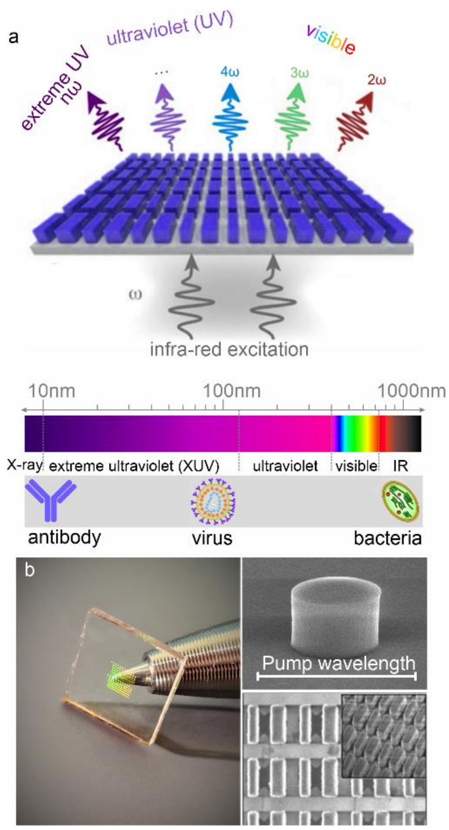

Figure 1. (a) Concept image of a nanostructure generating high harmonics – multiples of the incident frequency of light (top) and the scale of anticipated harmonics wavelength (bottom). (b) Examples of my preliminary nanostructures for harmonics generation [Sci Adv 9, eadg2655 (2023); Zograf, G. et al. ACS Photonics 9, 567–574 (2022)]

The project will facilitate the development of new technology capable of observing tiniest objects in living mater such as individual viruses and organelles inside cells. This will open up new insights into how cells sense, move and self-organize in context to tissue injury, pathogen invasion and cancer metastasis.

High-resolution biological imaging of such small objects is impossible with conventional optical microscopy due to Abbe diffraction limit. Typically, direct observations are done with electron microscopy (EM; TEM or SEM). However, electron microscopes impose substantial limitations: they cannot be used for imaging live cells, require sample fixation and freezing, and they continuously degrade sample during the observation. EMs are large and costly initially and in service and cannot be portable. Another currently available technology is confocal optical microscopy of fluorescent labels attached to sub-cell objects. It is more practical and faster, also being more biologically compatible. However, due to the resolution limitations they yield much less structural information. HHG-based imaging proposed here is poised to occupy the currently unexploited niche between the EMs and confocal microscopy. The EM market is valued at ~AUD 6 billion [Allied Market Research, Report A16756, p204] with a quarter of the market being driven by life and medical science. Confocal microscopy market is valued at ~AUD 1.5 billion, and it is dominated by life science.

The project is at the confluence of nanophotonics with medical imaging, and the research will be supported by a collaboration with the School of Medical Research at the Australian National University.

2023 Optica Foundation Challenge
Category: Health

Title: Combining Multispectral Imaging with Artificial Intelligence for Technology-driven Cancer Care

One of the major challenges in providing timely, holistic, and personalized care to the growing number of cancer patients around the world is our lack of understanding of how this disease develops, progresses, and alters the body's ecosystem. There are several molecular and physiological changes that together govern the course of the disease. Current clinical approaches rely on the physical changes in cells by investigating biopsy samples, whereas genetic tests rely on the average molecular expression of key biomarkers. None of these technologies captures the simultaneous alterations in the spatial-molecular profile of the disease and the surrounding microenvironment. This is crucial in individualized patient care rather than utilizing a one treatment fits all approach. The underlying mechanisms of the microenvironment (extracellular matrix + stromal cells + immune cells) drive tumor invasion and migratory patterns. We will address this need with a combination of artificial intelligence and multispectral imaging to investigate the structural, molecular, and biochemical signatures of cancer cells and the associated tumor microenvironment. Here, we will focus on breast cancer (the second leading cause of cancer deaths for women in the U.S.). However, this work can be extended to other types of cancers. The work is guided by two specific aims:

Aim 1. Integrating Artificial Intelligence with Multispectral Imaging for Disease Evaluation. Many high-resolution and multispectral tissue imaging technologies have been developed recently, powered by the recent advancements in the field of optics. However, there is a significant gap in integrating artificial intelligence (AI) tools with the emerging tissue imaging techniques that limits their potential for high-throughput diagnostic decision making. In this aim, we will integrate machine learning methods with multispectral images of breast cancer biopsies for high throughput evaluation of molecular markers. Additionally, we will combine information from the Hematoxylin and Eosin (H&E) stained images (most commonly used in clinics for cancer diagnosis) with multispectral imaging to get spatially registered molecular maps. The developed analytical pipeline will spectrally unmix the acquired data, divide tissue into different histological groups, segment cells of interest (tagged molecular markers) and models for diagnostic and prognostic analysis. Further, we will carry out validation and robustness studies to facilitate clinical translation of our developed methods.

Aim 2. Spatial and multiplexed analysis of the tumor-immune-microenvironment complex. It is now well known that the study of just the tumor is not enough to understand the disease profile of a patient and subsequently utilize the emerging treatments in cancer care. In this aim, we will investigate tumor cells along with their immune signatures and alterations in the microenvironment (particularly stromal cells). The underlying hypothesis is that stromal alterations and the different immune networks will elicit a unique tumor-immune signaling, providing new insights into personalized patient assessment. High resolution images along with machine learning models will enable spatial analysis across cell types in a tissue specimen. Abundance and spatial distribution of different immune cells will be correlated diagnostic profile of the tumor.The findings would then be combined across tissue specimens using statistical analysis.

Outcomes: The proposed work will extend our understanding of the tumor-immune heterogeneity with desired molecular and structural resolution. It will provide a pipeline to integrate AI with multispectral imaging for enhanced understanding of breast cancer. This pipeline can then be extended to any other cancers analyzed using multispectral imaging. It will be crucial in understanding tumor outcomes, and tailoring treatment strategies for different patient groups.

Key Deliverables: (1) Digital toolbox for cancer and microenvironment characterization using multispectral images. (2) Data and model standardization across patient samples. (3) All tools, particularly code developed in this proposal will be made open source to the community for further development and use.

Asymmetric Pharmaceutical Synthesis with Molecular Hall Effect

Shoufeng Lan, Texas A&M Engineering Experiment Station, Texas A&M University

Overview: More than 80% of U.S. Food and Drug Administration or FDA-approved commonplace pharmaceuticals such as ibuprofen carry an inherent flaw, pairing the active and beneficial ingredient with an ineffective or toxic counterpart. The underline mechanism is chirality, which discerns the dissimilarities between objects and mirror images. One prominent example is human hands because the left hand is the mirror image of the right hand, but they are not superimposable. Each handedness or so-called enantiomer of chiral objects should have the same probability of occurring, like the left hand and right hand always appearing in a pair. Unfortunately, the pairing of left- and right-handed chiral materials might not be favorable or often detrimental in the pharmaceutical industry, for example, the thalidomide tragedy that led to more than 10,000 birth deformities in the 1960s. Therefore, asymmetric synthesis, or selecting/sorting one enantiomeric handedness over the other, is a pressing need yet a grand challenge for human health and the pharmaceutical industry. According to the symmetry principle, the asymmetric synthesis should have a fundamental force (i.e., electromagnetic, gravitational, strong, and weak) to break the symmetry. The only one that breaks the parity-inversion symmetry is weak interaction. That is why all atoms are slightly left-handed, and indeed it results in enantiomeric excess, however, on the level of thermal fluctuation. Emulating the weak interaction using light and magnetism, we found a new magneto-chiral effect (MChE) that is several orders of magnitude stronger. Although the MChE could lead to enantiomeric excess in principle, implementing it for practical applications in asymmetric synthesis is a daunting task, which is also the challenge we will address. To that end, we have three specific objectives based on our recently published works on the MChE. (**1**) Electromagnetically induce enantiomeric excess by developing a plasmonic magneto-chiral system. (**2**) Dramatically enhance the plasmonic MChE with nanostructures to achieve an unprecedented spatial separation of chiral pharmaceuticals, which we named the molecular Hall effect. (**3**) Obtain enantiopure pharmaceutical molecules with on-demand handedness fully controlled by light and magnetism. Like the electronic Hall effect that lays the foundation of modern electronics, the molecular Hall effect could contribute to asymmetric synthesis, hence the pharmaceutical industry and human health.

Outcomes and Unique Aspects: Our proposed research will produce a universal physical means to separate chiral objects for asymmetric synthesis – in stark contrast to current techniques that use existing chiral objects (e.g., catalysis for the 2001 and 2021 Nobel prizes in Chemistry) to biologically and chemically transfer handedness. These chemical and biological methods are expensive, may only apply to specific molecules near the asymmetric center (proximity effect), or may damage more complex molecules with multiple chiral centers. Due to its physical rather than chemical or biological nature, our proposed method can enable all chiral species to be selectively sorted by their inherent handedness, potentially achieving absolute enantioselectivity. Also, the research will generate a molecular Hall effect from our proposed plasmonic magneto-chiral technique, providing the elusive spatial separation of chiral molecules favorable for asymmetric synthesis in pharmaceutical manufacturing.

Potential Impact: To the scientific community, the proposed research will introduce a relatively unknown phenomenon called plasmonic MChE, enhanced by momentum matching and directionally controlled by the polarization of light. With broader impacts, it can also lead to the cost-effective production of a wide range of enantiopure drugs. As 80% of FDA-approved drugs are chiral, our technique can play a role in the pharmaceutical industry and human health in general. Also, since the predicted global market for asymmetric synthesis is ~133 billion dollars by 2030, our research can contribute to the U.S. and the world economy.

Pushing the limits of live-tissue multiplex imaging

Optica Challenge - Health

Significance and challenge of live-tissue multiplexing

Abnormal cell compositions, reorganization, and interactions play a central role in the initiation and progression of numerous diseases. Current gold-standard methods to evaluate cellular changes include flow cytometry, iterative immunolabeling, and multiplexed confocal laser scanning microscopy. However, these multiplexing (or cell phenotyping) methods are fundamentally limited by their incompatibility with thick and/or living samples. Multiplex (or multicolor, multimodal) multiphoton microscopy (mMPM) circumvents these limitations by its unique combination of deep penetration, 3D subcellular resolution, and relatively low phototoxicity while maintaining multiplexed tissue and cellular contrast. To date, mMPM has played an essential role in mapping neural circuits, immune systems, and tumor microenvironments. However, nontrivial technology limitations have restricted mMPM to few-type cell imaging in the superficial layers of organisms, which hamper its application to studying complex multicellular dynamics in living organisms. There is a significant unmet need for novel mMPM technologies to better understand the multicellular tissue architecture of intact/living organisms.

Multiplexed deep tissue imaging by a programmable, high-power, visible-to-SWIR source

Our preliminary studies achieved label-free cell phenotyping in living tissues by fiber-source-enabled multimodal nonlinear imaging. These studies form the basis for our proposed research to advance the proof-of-concept technology to a more versatile, gentle, and fast working prototype for live-cell multiplexing through innovations in the fiber source, excitation engineering, and demixing strategies. To overcome the limitations of current multiplex imaging technologies and enhance the accessibility and functionality of mMPM in biomedical research, we propose to develop:

Aim 1: Ultrabroadband source for flexible excitation of wide-ranging contrast in deep tissue
Aim 2: Simultaneous mMPM for imaging multicellular dynamics *in vivo* and *in vitro*
Aim 3: High-throughput mMPM for large-volume mapping of multicellular tissue architectures

Outcomes: This project will enable transformative imaging capacities of deep tissue microscopy. It overcomes the limitations of the current state of the art imaging techniques in three ways: 1) by deploying the visible-to-SWIR high-power fiber source, this technique will enable deep excitation of many endogenous and exogeneous contrast, making it an ultra-flexible tool for versatile deep-tissue multiplexed microscopy; 2) by incorporating high-speed spectral shaping devices, we will allow simultaneous and flexible imaging of multicellular dynamics in thick and moving organisms; 3) by joint design of excitation encoding hardware and decoding algorithms, we will enable fast time-lapse imaging, rapid tiling of large areas, and volumetric mapping of multicellular dynamics. Our work will lead to a paradigm shift in a new class of light generation and shaping tools that enables highly multiplexed imaging in deep and living tissues with higher versatility, lower phototoxicity, and greater sensitivity.

Impact: The technology development will have an important *positive impact* on *human health* because it will advance our understanding of complex multicellular processes in deep tissues such as organ functions, disease progression, and therapeutic mechanisms. The light source and imaging platforms developed in this project will enable new research in the broad area of biology, clinical imaging, and tissue engineering. **Application to real-world issues:** The proposed work will provide a new imaging platform for biologists and clinicians to probe and diagnose complex diseases. Specifically, this project will initiate a collaboration with Professor Linda Griffith and Dr. Keith Isaacson on the study and diagnosis of endometriosis. Label-free visualization and differentiation of lesions and glands will be a major advance in understanding of disease mechanism and diagnosis of endometriosis. In addition, our simultaneous label-free imaging platform will initiate a collaboration with Professor Fan Wang on *in vivo* whisker pad imaging for dissecting neural circuits and Professor Roger Kamm on *in vitro* imaging of dense organoids for understanding vascular network dynamics. Visualization of multiple cells noninvasively in dense disease-modeling organoids will be a major contribution to tissue engineering and drug screening.

Scanning probe nano-optical investigation of biomolecule nanoparticle corona

Background & Challenge

The biomolecule nanoparticle (NP) corona is a hybrid structure that emerges when NPs interact with biological environments, leading to the absorption of biomolecules on their surfaces. The composition and conformation of coronas can vary depending on the specific NP properties and the surrounding biological milieu. Remarkably, the corona conformation plays a critical role in shaping the properties of NPs, granting them unique biological identities. As a result, studying coronas presents exciting prospects for a wide range of applications, including drug delivery, precise therapies, disease diagnosis, and environmental remediation. The successful development of corona-based applications necessitates a comprehensive understanding of corona characteristics at the nanoscale, where fundamental physical, chemical, and biological processes take place. However, current infrared (IR) spectroscopy-based analysis of corona composition and conformation, although highly productive, faces a limitation imposed by the diffraction law, which restricts the spatial resolution to > 10 μm. Consequently, a knowledge gap persists regarding the *nanoscale* features of biomolecule NP coronas, hindering a deeper scientific understanding and limiting engineering opportunities at the ultimate length scales.

Research Objectives & Outcomes

We aim to fill the knowledge gap of *nanoscale* characteristics in biomolecule NP coronas by unveiling their composition and conformation at < 50 nm length scales. To this end, we propose s-SNOM nano-imaging, spectroscopy, and manipulation of biomolecule NP coronas. Specifically, we will explore the nanoscale composition and conformation across a wide range of coronas with diverse parameters. These parameters include biomolecules and NP type, size, shape, and ratio, along with time, temperature, and pH during the incubation process. Moreover, we will study local properties and interactions between biomolecules and NPs in the corona, delving into aspects like local conductivity, plasmonic response, and charge transfer. Furthermore, we will manipulate coronas using the scanning probe to engineer on-demand functionalities. Specific objectives and outcomes include:

Objective 1: Unveil the *nanoscale* characteristics of biomolecule NP coronas
Outcomes 1: Unprecedented & comprehensive information on the composition, conformation, and spatial heterogeneity across diverse coronas, with a coverage down to < 50 nm

Objective 2: Study local properties & interactions between biomolecules and NPs in coronas
Outcomes 2: Nanoscale optical, electronic, and mechanical properties, their dynamics, as well as various interactions between NPs and biomolecules in coronas

Outcomes 3: Manipulate & engineer biomolecule NP coronas with scanning probes
Outcomes 3: Novel biomolecule NP coronas with delicately altered and engineered structures and conformations, leading toward desired functionalities

Impact

Unprecedented understanding & insights: Our proposal will uncover the nanoscale composition, conformation, and properties of biomolecule NP coronas. It is transformative since it will revolutionize our fundamental understanding of nano-bio systems, particularly coronas, and inspire nano-engineering of biomedical and healthcare devices from previously unexplored yet ultimate length scales.

Promising biomedical applications: The nanoscale characteristics and manipulation of coronas will facilitate corona nano-engineering for targeted drug delivery and precise immune responses. Revealed local properties and interactions between NPs and biomolecules in coronas offer tremendous potential for tailored therapies and nanophotonic biosensing for early, rapid, and accurate disease diagnosis.

New knowledge: Exploring nanoscale characteristics and manipulation in biomolecule NP coronas will complement current knowledge in nanobiotechnology, optics & photonics, physics, and mechanics with the understanding of corona structure, properties, and biomolecule NP interactions in nanoscales.

Career development: This proposal is a crucial step toward one of the PI's research visions in biophotonics, nano-optical investigation, and engineering biomedical materials and devices. Building upon the nano-optical study of coronas, the PI plans to explore other important biomedical systems and further develop the scanning probe nano-optics for biomedical and healthcare research. The PI envisions promising opportunities in photonic biomedical research leveraging his unique nano-optical expertise.

Compact laser-plasma very high-energy electron (VHEE) accelerator for cancer therapy

Executive summary - Health

According to World Health Organisation, cancer is a leading cause of death worldwide, accounting for nearly 10 million deaths in 2020, or almost one in six deaths. Roughly 60% of cancer patients receive radiation therapy, which is effective at causing remission in specific cancers. More than 90% of radiotherapy, however, is currently performed using megaelectron volt (MeV) X-rays. These sources are highly detrimental as their radiation severely harms healthy tissues on its way while reaching the deep tumor. By contrast, the use of very-high-energy electrons provides a much more uniform dose deposition depth, which could significantly reduce the harmful impact of the radiation on healthy tissues. Protecting healthy tissue is critical to the patient's recovery; thus, using energetic electrons could be a game changer for cancer radiotherapy. The challenge lies in the machinery needed to produce electrons in the energy range of hundreds of MeV suitable for deep tumor treatment. Machines that achieve such energetic electrons with conventional radio-frequency technology are considerably more complex, large, and expensive than the widely used photon guns used to produce MeV photons for standard X-ray radiotherapy. Therefore, access to high-quality radiotherapy for deep tumors is very limited in many parts of the world, especially in low- and middle-income countries.

This project aims to experimentally demonstrate a proof-of-principle of compact laser-plasma accelerator that delivers high-energy electrons up to 100 MeV at a kilo-Hertz (kHz) repetition rate. The accelerator utilizes an intense ultrashort pulse to generate and propel a plasma structure known as a wakefield. While this technology has already shown promise in achieving compact accelerators, it still encounters certain inherent limitations. One significant limitation is the disparity between the group velocity of the laser in the plasma and the relativistic electron bunch, which moves near the speed of light. Consequently, the faster electrons surpass the acceleration structure created by the wake, resulting in a termination of their acceleration. This limitation, known as "dephasing," constrains the maximum energy that can be attained by the electron bunches generated by the accelerator.

Optically shaping the driver laser in space and time at the focus will allow control of the dynamics of laser-plasma acceleration, mitigating the dephasing that limits the final electron energy. I aim to increase the electron energy by one order of magnitude compared to the current state-of-the-art kHz laser-plasma accelerators using the same driver-laser parameters. This source's unique beam properties, high energy, narrow energy spread, and high dose and dose rate will allow for the developing of next-generation radiotherapy treatments with precise dose control.

With current laser technology, the final size of this accelerator could be no larger than an optical table, making it cheap and accessible to many hospitals around the world. Moreover, a radiotherapy unit based on such technology could fit into a truck. This mobility and cost-effectiveness can allow this technology to permeate the economic and geographical periphery. This access will stand in contrast to techniques like proton beam therapy, whose massive sophistication and cost limit its use to the best-funded and most central cancer centers.

In conclusion, the development of this novel laser-plasma electron source technology, which relies on precise optical laser sculpting in space and time, offers promising prospects. It not only enables the creation of innovative and cost-effective radiotherapy sources but also unlocks opportunities for high-energy, high repetition rate table-top electron sources. This advancement holds the potential to drive significant advancements in medicine, biology, chemistry, and physics, which could lead to groundbreaking discoveries and transformative breakthroughs.

Quantum-enhanced Raman imaging of hyperthermia-treated cancer cells

Cancer remains a leading cause of death and a barrier to increasing life expectancy worldwide, despite decades of efforts to develop reliable treatment procedures. According to the Global Cancer Incidence, Mortality and Prevalence report, **the number of cancer cases is expected to reach 28.4 million worldwide in 2040**. Hence, it is of vital importance to develop innovative treatments and investigate new therapeutic targets - which is the focus of this proposal.

Healthy cells become cancerous as a result of mutations accumulated in the various genes responsible for cell proliferation. Various carcinogens can generate reactive oxygen species (ROS) during their metabolism causing a reduction of molecular oxygen. Therefore, it is crucial to define the control mechanisms of ROS production. Throughout this project, I will **develop an innovative approach for quantum-enhanced biosensing of tumour cells aiming to understand the conditions of their vitality. Plasmonic-coupled quantum-enhanced Raman imaging of tumour cells will pave the way for a better understanding of hyperthermia efficiency for cancer treatment.**

The scientific novelty will bring the combination of quantum-squeezed light with surface-enhanced Raman spectroscopy to scan the intercellular environment. I will merge the above-mentioned physical phenomena and boost both sensitivity and Raman imaging to provide a new modality for quantum imaging of cancerous cells. With the outcome of this research, we aim at understanding the mechanisms of hyperthermia in stopping ROS production in tumour cells, thus understanding the not-viable conditions for tumour cells. Beyond cancer treatment, ROS detection and its quantification are critical in cardiovascular diseases, translatology, inflammation, organ injuries, and ageing. Hence, the impact of this research goes well beyond the development of a new quantum imaging modality and will aid in an “all-around” ROS analysis, thus contributing to the increase of our life expectancy.

Teerapat Rutirawut
Suranaree University of Technology, THAILAND

Executive Summary

“On-chip programable/controllable spatial light modulator for the next-generation quantum circuit using silicon nitride platform.”

Quantum circuits are a fundamental concept in quantum computing and are essential as they provide a structured way to represent and manipulate quantum information using quantum gates, similar to classical circuits that use classical gates (like AND, OR, NOT gates) to manipulate classical bits. Quantum circuits facilitate the manipulation and processing of quantum information. They enable the encoding, transformation, and decoding of quantum states, which is crucial for performing quantum computations. The most startling and powerful future quantum technology is a quantum computer, which promises exponentially faster computation for particular tasks.

Spatial light modulators (SLM) are key components in the quantum optical circuit which will be further used to implement the gate in quantum computers. They are used to form optical wavefronts, generate hundreds of individually focused optical tweezers beams, and study new amplitude and phase modulation algorithms. As the quantum information processing tasks requires dense network connectivity, high dimensionality, and the possibility to actively reconfigure the network, nowadays techniques to fabricate the spatial light modulators are limited by the fabrication scalability, non-reconfigurable, and non-controllable.

In this research project, the invention of the optimal design of the programable/controllable SLM and the development of the fabrication process for the MMI and material integration will be performed. Based on the literature, the phase change material (PCM) is the material of use to manipulate the light in MMI showing as a reprogrammable SLM. The PCM reveal a low-power, but it is a passive wavefront shaping which require a reintegrate material to change the new- design wavefront shaping. Thus, in this research the integrated material of choice will be the liquid crystal (LC) with the SiN MMI to function a quantum linear transformation (two inputs to four outputs).

Material=> Liquid Crystal (LC)/Phase Change Material (PCM): Controllable/Programable SLM

=> Active Wavefront Shaping where the wavefront can be shaped real time by electrically changing the optical property of liquid crystal.

Design=> 2x2 MMI equipped with 2D-SLM (scalable up to NxM multiport MMI)

=> High-dimensional quantum operation in a small footprint

=> Easily scalable

Waveguide=> On-chip Silicon Nitride (SiN) MMI and Polarisation Beam Splitter (PBS)

=> Broad wavelength compatibility

=> Low losses and denser component architectures.

The simultaneous factors were established within the last decade which enabled this project in this timeline. (a) Advances in the field of photonics and nanotechnology, that enabled the controllable SLM proposed in this project. (b) The enormous leap in manufacturing techniques which enabled the fabrication of on-chip SLM and material integration to enable the next-generation quantum circuit. The on-chip programable/controllable spatial light modulator proposed in this project offers step change in both physical size, controllability and scalability limitation compared to existing SLM in quantum technology, making it an ideal candidate for SLM device in the next-generation quantum circuit.

The Earth and its inhabitants require darkness

July 16, 2023

Executive Summary
Humans use electric light at night to illuminate our homes, our streets, sidewalks, outdoor sporting events, buildings, facades, landmarks, bridges, parks, parking lots, and commercial and industrial properties. Nearly everything we interact with at night is illuminated. Light at night has become essential to our feeling of security and to our ability to extend our activities into the evening.

But this is not without cost. Outdoor electric light sources placed by humans to illuminate the night—often called *artificial* or *anthropogenic* (i.e., “human generated”) light at night (ALAN)—is seriously eroding natural light-dark cycles across the planet, having marked impacts on the biological functions and rhythms of humans, plants, and animals. This includes impacts on mortality (through light attraction or aversion), disruption of migratory and diurnal patterns, increasing or decreasing population size, altering natural competition, disturbing inter-species communication, and negative impacts on human health and well-being.

A significant portion of the Earth’s population—especially in Europe and the Americas—now experiences light-polluted nights, which creates a sky glow that limits or eliminates our view of the night sky, poses significant problems for amateur and professional astronomical observations, negatively impacts animals in a myriad of ways, and wastes a significant amount of energy at great financial cost. The estimated cost of this wasted energy exceeds USD $7 Billion.

Without serious intervention, the problem is projected to get worse.

The objective of this project is to advance the science in architectural lighting with the goal of developing actionable guidance—for the lighting industry and local legislators—to reduce the negative impacts of ALAN, to disseminate research findings to spread awareness of these negative impacts, and to develop lightings standards and initiatives that minimize the negative impacts of ALAN (especially sky glow).

Corresponding to these objectives, the project will constitute three tasks.

Task 1 | advance research: the goal of this task is to advance research in the field of architectural lighting to provide actionable guidance for lighting professionals and local legislators. The work will study the barriers to use of promising emerging lighting technologies, such as phosphor-converted amber LEDs, and challenges faced by change-makers. The outcome of task 1 is a journal-quality research paper that will be submitted to an Optica journal, likely Optics Express. This work will provide actionable guidance for change-makers and influence standard ordinance language for local legislators being developed by DarkSky (formerly the International Dark Sky Association).

Task 2 | disseminate and advocate: to goal of task 2 is to spread awareness of the negative impacts of light at night by disseminating work at industry and industry-adjacent events. The outcome of this task is a series of educational presentations and scientific reports. The impact of this work is an increased awareness and sensitivity to the impacts of light at night.

Task 3 | reduce light pollution: the goal of this task is to develop new lighting standards and drive important changes to existing lighting standards. This includes an expansion of ANSI C78.377-2017 (an influential LED chromaticity standard) based on my previous research work, additional light pollution mitigation incentives in products from the International WELL Building Standard (where I am the *Director* of the *Lighting Concept*), and updated recommendations and standard ordinance language for local legislators from DarkSky, and organization with whom I liaise.

Thank you for your time and consideration. I am grateful for this potential opportunity. Thank you.

Label-free Widefield Multi-modal Interferometric-Raman Microscope for Exosome Imaging and Early Cancer Detection

Executive Summary:

Cancer remains a global health challenge, leading to the loss of millions of lives each year. Timely diagnosis plays a crucial role in increasing survival rates and improving patient outcomes. This project aims to address the urgent need for early cancer detection through the development of a multi-modal exosome imaging platform for liquid biopsy applications.

Exosomes, nanometer-sized extracellular vesicles found in body fluids, have emerged as potential biomarkers for various types of cancer. They carry a diverse array of molecules, including RNAs, DNA, proteins, and lipids, making them valuable indicators of disease progression. However, the translation of exosome research into clinical practice requires rapid and efficient exosome isolation methods, as well as sensitive and comprehensive characterization tools. Conventional isolation methods, such as ultracentrifugation, are labor-intensive and time-consuming. Standard analytical techniques, such as ELISA and western blot analysis, require large sample volumes and complex labeling procedures. These limitations hinder the development of high-throughput and clinically viable exosome analysis techniques.On the other hand, their heterogeneity requires the detection and analysis of individual exosomes to obtain comprehensive diagnostic information.

In this project, we propose the development of a complete label-free detection and quantification platform for exosome analysis in prostate cancer patients. The proposed platform combines an advanced interferometric microscope and a Raman module to enable label-free detection and quantification of exosomes at the single-particle level. By visualizing and characterizing individual exosomes, the platform overcomes the limitations of conventional ensemble-averaged methods and provides a more accurate representation of the exosome population's heterogeneity.The Interferometric module enables the visualization and size estimation of individual exosomes with high sensitivity and a large field of view. Novel data processing algorithms, including machine learning techniques, will be implemented to enhance resolution and accuracy. The Raman module provides chemical composition analysis, enabling the determination of the cellular origin of exosomes and the identification of tumor-derived exosomes.

The platform's validation will be conducted using clinical samples obtained from both healthy donors and prostate cancer patients. Through the multiparameter characterization of exosomes, including size distribution, concentration, and spectral signatures, we aim to differentiate exosomes derived from healthy cells and tumor cells. This validation process will demonstrate the clinical potential of the developed platform for early cancer detection.

The outcomes of this project will advance our understanding of exosomes as diagnostic markers for cancer, specifically prostate cancer. The label-free platform will provide accurate visualization and chemical characterization of exosomes, leading to improved diagnostic capabilities. By harnessing the power of exosomes, this research has the potential to revolutionize routine cancer patient monitoring, enabling the early detection of cancer-specific biomarkers and reducing the financial and economic burdens associated with advanced-stage treatments.

Moreover, the developed platform's adaptable nature allows for potential applications beyond cancer research. It can be utilized in the study of other diseases and viral infections, such as the detection and characterization of viral particles. This versatility paves the way for efficient virus detection, rapid diagnostics, and the development of targeted therapeutic interventions.

In summary, this project addresses the critical need for early cancer detection by developing a multi-modal exosome imaging platform. By focusing on the detection and analysis of individual exosomes isolated from the body fluids, the platform provides a more accurate representation of their heterogeneity. This advancement in exosome research has significant implications for cancer diagnostics, personalized medicine, and the broader understanding of disease biomarkers. The outcomes of this research will contribute to improved patient outcomes and pave the way for novel therapeutic approaches in the fight against cancer.

Name: Development of low excess noise, ultra-high resolution, OCT system through the development of low intensity noise, continuous-wave, fiber Supercontinuum source.

Category: Health.

Problem: Excess intensity noise of broadband optical sources, such as supercontinuum (SC), used for spectral domain (SD) ultra-high resolution (UHR) Optical Coherence Tomography (OCT) forms the fundamental limitation to achieve shot-noise limited detection. The consequence of this is to lose the capability of early-stage detection of pathologies in ophthalmology, cardiology, cancer diagnosis etc. Existing solutions require either non-standard, complex, bulky sub 50 femtosecond pulse width, shot noise limited pump laser designs, and complex, patent protected optical fiber designs to generate low excess intensity noise supercontinuum. Such methods further elevate the cost and complexity of the already expensive (>100000$) UHR OCT systems that currently are limited to high-income developed countries. Further, the existing solutions fail if there is a small amount of intensity noise (0.5-1%) of pump (which is true with many practical pump lasers) used for SC generation.

Our Solution: The goal is to develop a low excess noise (ideally shot noise limited) UHR OCT system based on low intensity noise, fiber supercontinuum (SC) source. This will be achieved by following the essential requirements of low intensity noise SC generation. They are: 1) Low intensity noise of the pump that generates SC and 2) Low quantum noise amplification in the SC generated. Besides, both the above requirements should be met in a cost-efficient manner. This will be achieved, a) by developing, in-house, a low noise, continuous wave (CW) fiber-based pump laser, and b) by using standard off-the shelf telecom optical fibers for SC generation as shown in figure.

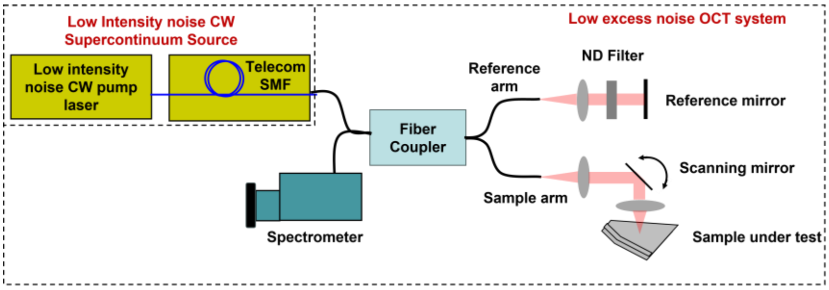

Figure: Schematic of proposed low excess noise SD UHR OCT system

Unique features: CW natures of the pump enable low quantum noise amplification (unlike femtosecond laser pumped SC generated), and the low intensity noise nature enables low intensity noise of the SC generated. Both CW pump and telecom fiber make the system cost-efficient by atleast an order of magnitude compared to the existing systems (based on complex, pulsed pump and, patent protected photonic crystal fibers), without compromising the excess noise performance of OCT. Same technique can be readily transferable to low intensity noise SC generation in other nonlinear optical fiber types such as photonic crystal fibers, highly nonlinear fibers etc., depending on the wavelength region of interest.

Outcomes: Publications and patents on these new methods for low noise nonlinear frequency generation to generate widely tunable wavelength and broadband SC sources in various nonlinear optical fiber media. Tabletop prototypes of low intensity noise widely tunable wavelength, broadband SC sources, and low excess noise OCT system. Technology transfer to a private Indian company for the first realization of UHR OCT system in India. Trained graduate students in research areas of fiber lasers, nonlinear fiber optics and OCT.

Impact: The proposed OCT system enables early-stage detection of multiple diseases in various categories of healthcare diagnostics such as Ophthalmology, Dermatology Cardiology etc. Due to the cost-efficient nature, the developed technology provides wide accessibility of UHR OCT technology to billions of underserved populations in low income developed countries. The SC source developed when used for other low-coherence interferometric applications such as contact-less, non-destructive testing and inspection of processes parameters in industrial manufacturing, oil, and gas sensing, can increase the signal to noise ratio, resolution, acquisition speed and sensitivity.

Name of the project: Design of a Modular system for Measuring Electric Field in plasmas oriented to Fusion (DEMOMEFF)

Category: ENVIRONMENT

Highlights:

- ✓ **Design, characterization, and construction of a modular system for the measurement of the electric field in plasmas oriented to fusion via second harmonic generation.**
- ✓ **Improving the generation of second harmonic generation via the generation of different polarization and optical vortexes, to improve the sensitivity of the electric field measurements.**
- ✓ **Adaptable to different types of discharges and experiments, thus facilitating the diagnosis of this type of devices**.
- ✓ **Generation of a scientific network on the electric filed measurements, that will serve as a consulting service, for the design of new set-ups and for monitoring measurement campaigns.**

This proposal presents the design and construction of a modular system to measure the electric field in plasmas, using the technique known as Electric Field Induced Second Harmonic (E-FISH). This method allows the generation of the second harmonic of a radiation when it passes through an external electric field. The project arises from the urgence of developing a clean source energy, where fusion plasmas play a key role.

Among many other techniques, laser spectroscopy has been a powerful characterization tool, providing a good spatial and temporal resolution. In this project, I propose a modular experiment to optimize the measurement of a crucial parameter when talking about plasmas: the electric field. Here, I propose the optimization of this measurement creating optical vortexes to improve the generation of the second harmonic; and also, to be able to detect the different components and orientations of the electric field.

At the end of the project, the following outcomes are expected:

- The generation of optical vortexes with nanosecond lasers for the detection and measurement of the different components and orientations of the electric field in a discharge.
- An electrical discharge built to simulate discharge conditions oriented to fusion devices, allowing the development of this and other types of photonics-based characterizations.
- Electric field measurements provided, being an important source of data for the scientific community. This data serve as a basis for new experiments, simulations, and development of theoretical models.
- Generation of a consulting network to provide solutions on the design of the electric field installation, and monitoring of electric filed measurement campaigns in real fusion-like devices.

This proposal will provide the community valuable data about fusion-like device behavior via photonic characterization, advancing in the control and knowledge of this technology called to be the source of clean energy the world needs.

Executive summary of:

Stimulated Coherence Tomography for Fluorescent Imaging in Turbid Tissues

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Pontificia Universidad Católica de Chile

Tracking of therapeutic agents inside the human body is a long-sought technology with potential to improve drug targeting and treatment response monitoring. Multiple approaches have been investigated using probably all imaging modalities including PET, MRI, and a variety of optical methods. While label-free optical techniques gather anatomical, dynamical, and spectroscopic information from tissues, they lack therapeutic specificity. Optical detection specificity can be greatly improved by using molecular markers that provide functional insights into biological processes. Fluorescence imaging is particularly effective in detecting both endogenous signals and external contrast agents, which are often clinically beneficial for assessing superficial tissues. Applications in routine clinical use include retinal vasculature angiography, diagnosis of corneal abrasions, and evaluation of cholecystitis and urethral obstructions. Fluorescence imaging is also under investigation in clinical trials for cancer surgery, especially for identifying sentinel lymph nodes and for intraoperative tumor margin delineation.

But the optically accessible region for fluorescence microscopy is fundamentally limited to only about the first tenth of a millimeter from the surface in scattering tissues. As light travels through biological tissues, it gets scattered, and beyond this distance it loses the sharp focusing that is typically necessary for imaging. Because the utility of current fluorescence microscopy is limited by depth, most clinical applications use bulk fluorescence or are applied only in the tissue surface.

In this project, we will develop a new technology to increase 10-fold the optically accessible region for fluorescence imaging, with the goal to expand the clinical utility of fluorescence-based molecular contrast agents. This could be achieved by stimulating fluorescence emission from a chromophore of interest, while using an Optical Coherence Tomography (OCT) system to perform interferometric detection of back reflected light after multiple scattering in tissue. The signal contributed by the fluorophore will be isolated by differentially modulating illumination in the chromophore excitation wavelength, which will be incoherent to the interferometry measurement. The interferometry detection normally isolates the back reflected signals from the randomly scattered light, thus typically imaging up to 10 times deeper than standard fluorescence microscopy. Enabling fluorescence detection by this method would allow fluorescence imaging at OCT depths. This work will build on our previous research developing computational microscopes for sensitive detection of fluorescent reporters and on our previous research investigating OCT contrast generated by multiply scattered light.

The availability of fluorescence contrast at 10-fold increased depths will enable imaging deeper inside tissues to expand the clinical utility of optical interrogation with functional and molecular specificity. New medical applications that could be enabled include precise monitoring of labeled cell therapies and deep tracking of diagnostic contrasts agents.

“ROD - The inclusive retina system”

“Inclusive Low-Cost Retinal Oximetry providing Diagnostic Imaging Systems for Retinopathy - Exploring the Links between Infectious & Non-Communicable Diseases in Limited Resource Settings”

What is proposed?

The proposal aims to create an inclusive low-cost retinal oximeter as a minimal viable product, to enable diagnostic imaging systems for retinopathy in low-resource, under-served community settings in the Global South. The tools will be used to explore the links between infectious & non-communicable diseases including for example diabetic retinopathy and malaria.

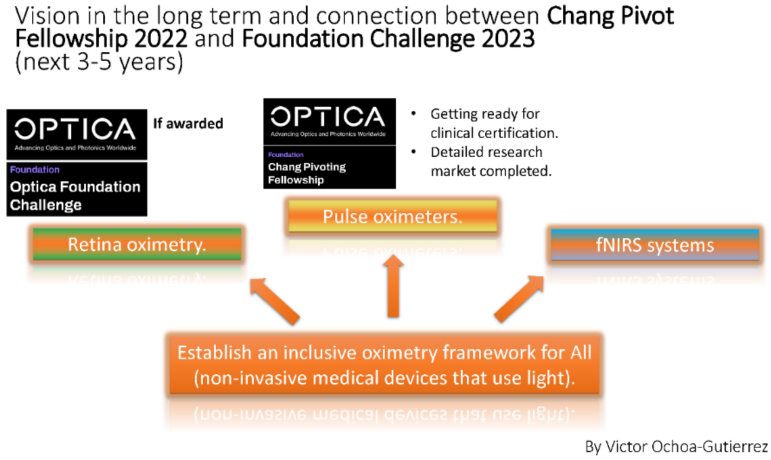
Why is this important? Over the last decades the field of retinal imaging has been under constant progress and improvement. However, under-represented vulnerable communities, with increased levels of melanin, have not been included in the design of such tools. The programme will lead to new optical design, algorithms that can cope with these differences in human biology, enabling the validation of the tool in retinal disease diagnosis amongst people of all skin colours.

What is the problem? There is currently a lack of low-cost retinal diagnostics systems in low resource community settings to identify disease in rural clinics. Exiting instruments are expensive and placed in centralised facilities. New optical retinal systems that work effectively despite pigmentation will in future be used to save lives and prevent loss of sight.

What is the solution? This proposal outlines new solutions based upon novel optical imaging methods and new algorithms to compensate for differences in signals amongst different individuals, and the use of deep-learning as a diagnostic decision support tool. The device itself will be based upon the implementation of a illumination technique, allowing us to obtain high quality images with ultra-low cost designs.

Who cares (impact)? The proposed technique/system will find broad application amongst rural clinics to collect data on different individual retinophathies including those caused by diabetes and by malaria. The tool will also help establish links between these two disparate diseases, developing a new field of clinical and epidemiological research. In the longer term, we aim to develop both industrial and clinical translational pathways such that these low cost sytems will enable such diagnostic data to be collected in community clinics in remote rural areas, guiding care pathways and treatment.

Why should this proposal be granted? The proposed technique advances the state-of- the-art in low-cost retinal imaging systems, that will have the potential to help populations living in remote, rural communities, particularly in Sub-Saharan Africa. The work also represents a critical first step to enable the PI to realise his research vision of creating new diagnostic tools based upon optical systems



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PROJECT NAME: SureVision. CATEGORY: Health.

Refractive errors (myopia, hyperopia, astigmatism, presbyopia) affect up to 67% of the global population, and 100% over 50 years. Furthermore, preventable refractive error affects 1 billion people worldwide, representing the 1st cause of visual impairment and the 2nd cause of visual loss according to WHO (UN), with dramatic consequences at social and economic levels and, impacting life quality for people. The evaluation of refractive error is the basic piece of information about the state of the eye and is the main test performed in eyecare clinics worldwide. The gold standard method for diagnosis is called **subjective refraction** and consists of identifying different letters through different lenses until achieving the best combination of lenses providing the best visual acuity. **This traditional approach is highly variable (0.27 D), time-consuming (>6 minutes), is affected by accommodation, and requires a clinician with years of experience to master the technique.**

We have developed a new method called **Direct Subjective Refraction (DSR)**, which uses a tunable lens to create fast and periodic defocus changes that, combined with the chromatic aberration of the eye and a bichromatic stimulus, creates a chromatic flicker perception which is minimum when the patient is perfectly compensated. The task of the patient in the DSR method is minimizing the chromatic flicker. We showed that the **DSR task is easy, barely requires supervision** (clinicians explains the task and patients perform it autonomously), **decreases measurement time by 5x, and increases precision by 2x compared to the traditional method.**

The first attempt of including this new method in the clinic is **SureVision**, a new ophthalmic device that uses the DSR method as working principle to obtain the visual the prescription of the patient. First clinical measurements have shown the potential of the new device and has allowed to acquire invaluable feedback from the clinicians, the final user. The DSR method brings **a revolution to the eyecare community** as the first subjective method that provides a prescription without identifying letters. The high precision and low measurement time make SureVision a potential candidate for replacing current paradigms, as their advantages overpass current devices and improve the stakeholders experience: patients, clinicians, clinics, manufacturers.

The main goal of this project proposal to the OPTICA Foundation Challenge is to **develop an industrial prototype** that can be used in a clinical environment, which includes the feedback obtained from clinicians. Particularly, the following key steps will be followed:

1. **Scientific advance**. Answer key questions regarding the DSR method such as accommodation response, theoretical simulation, chromatic components, and pupil size.
2. **Industrial prototype**. Refinement of the optical system. Design the prototype. Develop an app for performing measurements. Develop 1st industrial prototype. Reach TRL 8.
3. **R&D activities**. i) Develop a measurement of the angle of astigmatism, ii) including pupil alignment control, iii) design calibration system, iv) conceptualize the inclusion of objective measurement via aberrometer or light reflex, and v) include DSR in a conventional phoropter.
4. **Gather clinical evidence**. Clinical studies in i) general population (Hospital Clinico San Carlos Madrid) and ii) refractive surgery patients (Moorfields Eye Hospital, London).
5. **Business roadmap**. Full business and financial plan. Market study. Develop investment strategy (Caixa Impulse, Healthstart, CSIC Hackaton, FIPSE Estudios Viabilidad, investment forums, startup competitions) and investment pitch. Management and maintenance of IP portfolio.

In the long term, the project will be highly transformative, as it will represent a **disruptive method** to measure the refractive error. It will also serve as an incentive for the ophthalmic industry, as more precise prescriptions will require new expertise and resources. The potential launch of a spin-off company would create an impact in the community, generating value, high-skill jobs, and the return of the investment to society. Members of the SureVision project have already been part of successful spin-off companies, employing PhDs with multi-year post-doctoral international experience. We take this as an example and lesson to learn. Furthermore, given the large size of the market, a prospective license, and to a much larger extent, the success of the company, SureVision will have high business potential and financial viability. Therefore, the **successful completion of the project** (and of subsequent phases towards regulatory process and commercialization) **will bring a positive impact on the community at large, healthcare, economic growth, preventable blindness, and well-being in general**.

Project summary

Challenge: Biomarkers are biological molecules present in the bodily fluids and tissues which provide critical knowledge on human health. Detecting and quantifying biomarkers are useful in disease diagnostics, prognosis, efficacy of therapy and treatment, and drug discovery and development. Current detection methodologies such as enzyme-linked immunosorbent assay (ELISA), polymerase chain reaction, western blotting, and electrochemical sensors lack either low limit of detection (i.e, quantifying attomolar concentrations) or long detection time or combination of both. This limits their use for detecting biomarkers that are found in low concentrations but provide valuable information on human health. Thus, to quantify these biomarkers, it is necessary to develop a new sensing methodology with low limit of detection and faster sensing time, that is also cost-effective and user-friendly.

Proposed project: The overarching goal of this project is to develop a digital, ultra-sensitive, cost-effective, and user-friendly sensor system for biomarkers. We aim to achieve this by employing an *advanced nanophotonic platform called as zero-mode waveguides (ZMWs) in combination with an optical dark-field microscopy*. In this project, we will develop our sensor targeted to Interleukin-6 (IL-6), one of the common cytokines to understand the condition of disease which is associated with several diseases including COVID-19, HIV, Alzheimer's and CAR-T cancer therapy. ZMWs are cylindrical or conical nanopores in a thin metal film (typically 100 – 200 nm) with a bottom pore diameter smaller than the wavelength of visible light, capable of confining excitation radiation within the nanopore with the intensity decaying exponentially along the axial direction. We will exploit this feature of the ZMW to quantify biomarkers with the plasmonic nanoparticle as a scattering readout mechanism. Imaging the ZMW substrate under dark-field mode blocks the trans-illumination but effectively captures the low angle light scattered by the individual nanopores. The inherent light scattering by the nanopore increases with the insertion of a plasmonic nanoparticles such as silver inside the nanopore due to their localized surface plasmon resonance (LSPR) property. Using this principle, we will quantify the biomarker concentration in two ways: 1) Construct molecular architecture to attract and hold IL-6 in the nanopores and use silver nanoparticles to specifically bind to the nanopores containing IL-6. By monitoring and counting the number of nanopores with the nanoparticles, we can quantify the IL6 concentration. 2) Immobilize IL-6 on the surface of silver nanoparticles using molecular architecture followed by releasing silver particles and microscopically counting them on the ZMW substrate and relate to IL-6 concentration. Further, we will improve the limit of detection and detection time by increasing the mass transport of silver nanoparticles inside the nanopores using a voltage gate.

Outcomes: We expect that the proposed nanophotonic based platform, zero-mode waveguides will quantify IL-6 in the atto molar range (~10-18 M) within 30 minutes including assay formation and readout. Naturally, the platform can be extended to quantify other biomarkers by forming suitable assay. Further, the approach can be transformed into multiplex sensing by co-functionalizing nanopores with multiple recognition elements targeting different analytes, which can be sensed by employing different size plasmonic nanoparticle to provide difference in the scattering intensity magnitude. Lastly, the dark-field microscopy can be implemented on a smartphone-based detection setup, making it an easily accessible POC platform.

Executive Summary

Title: Temperature Influence on Integrated Silicon-Germanium Electroabsorption Modulator for Optical Machine Learning Accelerator

PI: Weilu Gao, the University of Utah, Email: weilu.gao@utah.edu

Category: Information

Machine learning (ML) algorithms have seen unprecedented performance in broad applications, including computer vision, the discovery of materials and molecules, and electronic chip design. However, the execution of ML algorithms on hardware requires substantial computation and energy resources. The fundamental quantum mechanics limit leads to a bottleneck of further reducing the energy consumption and simultaneously increasing the integration density of electronic circuits to catch up with the increasing scale of modern large-scale ML models, thus urgently calling for new high-throughput and energy-efficient hardware ML accelerators. Recently, optical systems built upon silicon-on-insulator photonic integrated circuits (PICs) are emerging as high-performance hardware accelerators for executing the most computationally intensive matrix-vector multiplication (MVM) operations in large-scale ML models, thanks to their parallel and speed-of-light processing, and low static energy consumption. In addition, with the continuing advances of semiconductor foundry manufacturing, the integration density of PICs can reach thousands of devices in an area of $\sim$ mm^2 and the cost of PICs has reduced drastically. **The key to high-throughput and energy-efficient optical MVM calculations is the implementation of fast and energy-efficient electro-optic intensity modulators.**

Current modulation mechanisms implemented in the components of foundry Process Design Kits, such as GlobalFoundries and American Institute for Manufacturing Integrated Photonics (AIM Photonics), are mainly based on heat (e.g., thermal shifters) and carrier transport (e.g., *p*-*n* junctions) with limited modulation speeds (hundreds of kHz to a few GHz) and large energy consumptions (pJ to nJ/bit). In contrast, the electric field effects, such as the electroabsorption effects near the band edges of semiconductors including Franz-Keldysh (FK) and quantum-confined Stark effects, are ideal because they can deliver ultrafast response ($>$ 100 GHz) and require little switching energy (10s fJ/bit). In particular, the latest photonics foundry technologies have prepared processes to involve high-speed electronics for high-speed optical modulators. For example, the GlobalFoundries just released its first-of-its-kind SiGe platform, GF Fotonix, laying the ground for the volume manufacturing of semiconductor FK electroabsorption optical modulators.

Despite the readiness of industry technologies and a few but limited prior works, there has been little attention paid to the temperature influence on FK electroabsorption modulators. **The goal of this 15-month project will be analyzing the temperature influence on the behaviors of devices, circuits, and ML systems based on FK modulators, and designing new temperature-insensitive circuits and chip tapeouts ready for future foundry manufacturing and testing**. Specifically, this project will **(i)** create a high-throughput, integrated simulation framework consisting of materials, devices, circuits, and ML systems based on SiGe FK modulators for analyzing temperature influence and **(ii)** design temperature-insensitive circuits and chip tapeouts based on AIM Photonics foundry processes for future manufacturing and testing. The deliverables of this project will have far-reaching implications in various aspects. For example, the developed integrated simulation framework will enable the co-design and end-to-end design of optical materials, devices, circuits, and systems. In addition, the designed temperature-insensitive FK modulators can be applied not only to next-generation high-speed, high-throughput, and energy-efficient optical ML hardware accelerators, but also many other application scenarios, such as optical communications and photonic quantum information processing.

Executive Summary of Proposal:

Real-time quadrupled resolution of ultrafast structured illumination microscopy by multi-constrained learning

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Assistant Professor, School of Instrumentation Science and Engineering
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The emergence of super-resolution (SR) fluorescence microscopy technologies has revolutionized biology and enabled previously unappreciated, intricate structures to be observed. However, many of these earlier experiments were conducted in fixed cells in which the dynamic structural and functional changes of cellular structures were lost. The reachable spatial resolutions of modern live-cell SR microscopes are ultimately limited by the maximum collected photon flux. To meet this challenge, we previously developed a sparse deconvolution algorithm that extends resolution beyond the physical limits posed by the hardware (***Weisong Zhao et al., Nat. Biotechnol. 40, 606–617, 2022***). As a result, sparse deconvolution-assisted structured illumination microscopy (Sparse-SIM) achieves ~60 nm resolution at a temporal resolvability of ~2 ms. However, with multiple constraints involved, the use of sparse deconvolution requires step-by-step parameter adjustment, with considering the experimental conditions and different organelle features. These complexities of use essentially restrict the method dissemination and high-throughput application.

In this proposal, we will use learning-based representations to eliminate the adjustable parameters of sparse deconvolution. A deep-learning engine is used to extract the pattern of parameter selections in a high-dimensional representation, enabling parameter-free and real-time sparse deconvolution reconstruction. Inputting raw SIM images with the optimally reconstructed images as ground-truth, the deep neural networks will automatically learn the complex expressions of low-to-high resolution transformations. Then, the well-trained DNNs can be frozen for direct SR reconstructions. This non-iterative form of reconstruction with the graphics processing unit (GPU) acceleration has the potential to achieve real-time SR imaging.

By integrating of ultrafast SIM imaging system with this real-time SR reconstruction module, we construct a smart bioimaging platform. There are several advantages of this platform. First, our platform has contained all advantages of ultrafast live-cell SIM for 564 Hz maximum imaging speed and is compatible with all fluorescence labels. Second, the spatial resolution is automatically doubled from 120 nm of SIM to 60 nm without parameter-tuning. Last, the SR reconstructions are in real-time at 30 Hz (in full data acquisition, analysis, and saving time), and this feature is particularly valuable for live-cell imaging.

Using this platform, biologists can dissect the sub-organelle interactions in real-time without the need for training or specific experience. It enables biologists to observe the ultra-microstructure and subcellular dynamics of cells, significantly facilitating live-cell imaging research. Beyond that, we also expect our smart platform to break the stereotype that SR microscopes are all difficult to use, making SR imaging easier.

Executive Summary

Cerebral blood flow (CBF) is an important biomarker for brain health which plays a crucial role in regulating oxygen delivery to the brain and facilitating the removal of metabolic waste like carbon dioxide. Alterations in CBF are closely associated with serious clinical conditions such as ischemic stroke, traumatic brain injury, and Alzheimer's disease. CBF can also be utilized to measure brain function due to neurovascular coupling, which has been done in functional magnetic resonance imaging (fMRI). Therefore, monitoring CBF is valuable in physiology and cognitive neuroscience research, as well as in clinical applications. Optics presents a convenient and non-invasive approach to continuously monitor CBF at the bedside. It is especially useful for populations and for studies for which other imaging modalities are limited, e.g. fMRI, including for children, infants, and studies that involve motion and interactions or require high temporal resolution. Diffuse correlation spectroscopy (DCS) is the state-of-the-art optical method that has already been used to measure CBF clinically. However, traditional DCS often has relatively low SNR, restricting the achievable source-detector separation (SDS) to shorter distances (~20 mm). Consequently, the scalp rather than the brain contributes primarily to the measured blood flow at such short SDSs. More temporal averaging can be utilized to improve SNR but at the expense of reduced temporal resolution. DCS also uses relatively expensive single photon counting devices, e.g. single photon avalanche diode (SPAD) detector (>$10,000), thus is financially challenging for wide adoptions.

Recently, we have proposed to use a fiber-based speckle contrast optical spectroscopy (SCOS) to measure human CBF. Compared to DCS, SCOS uses relatively low-cost complementary metal–oxide–semiconductor (CMOS) cameras as detectors. Our recent modeling and experimental work has demonstrated that the performance of SCOS can surpass that of DCS systems for human brain measurements in terms of signal to noise ratio (SNR) by *at least one and up to two orders of magnitude* at a high measurement rate of ~50 Hz with lower cost (~$500). SCOS also measures the optical density (OD) that is linearly related to cerebral blood volume (CBV) that is not measured by DCS. But our prototype SCOS system utilizes lenses and bulky cameras such that it needs to be established on the optical table in the lab environment. Therefore, the development of the next generation miniaturized SCOS system is key to extend its utility for everyday monitoring of brain health. We propose to miniaturize the SCOS system to construct a more portable and wearable device that measures CBF and CBV non-invasively in real time. This will be done by pursuing two specific aims:

Aim 1: Design the optics for the miniaturized SCOS device (Year 1). We will remove the lenses in both the illumination and detection side of the prototype SCOS system to improve wearability. A new cap will be built to hold the source fiber and CMOS detector on the human head.

Aim 2: Develop the hardware and software for real time displaying of brain hemodynamics and function (Year 2). We will improve the portability by connecting the CMOS detector to a mini-computer and develop the software for real time displaying of CBF and CBV time traces.

This success of this project will provide a miniaturized SCOS device to monitor human CBF and CBV in real time. It will provide great clinical values such as to monitor CBF for patients suffering from medical conditions as shock, stroke, cerebral edema, or traumatic brain injury. The portability and affordability also makes it an ideal solution for global health care, especially in rural areas where the access to medical resources, e.g. MRI scanner, is limited. It will also motivate the development of future generations of SCOS devices that feature wireless connections to tablets and cellphones, high density measurements that cover a larger area of the brain, and integration with functional near infrared spectroscopy (fNIRS) to enable measurements of hemoglobin concentrations and cerebral metabolic rate of oxygen ($CMRO_2$). These will shape the future of everyday recording of human brain health that responds to the stated goal of the *Optica Foundation Challenge* that calls for "*innovative and affordable technology solutions*" for the medical community.

Integrated Silicon Photonics with On-chip Quantum Dot Lasers

The rapid growth of artificial intelligence (AI)-driven services has created an unprecedented demand for compute capacity and speed. However, this surge is accompanied by a parallel increase in power consumption [>60 kWh per rack in extremely-dense AI workloads], as well as capital (CapEx) and operational (OpEx) expenditures [$154 billion globally on AI services in 2023]. The rate of progress in electronic hardware, doubling every 18 months, lags behind the doubling of machine learning computational demands every 3.5 months, resulting in a widening gap between compute requirements and hardware capacities.

Photonic integrated circuits (PICs) offer a promising solution by capitalizing on the inherent properties of photons, offering ultra-high bandwidth and processing frequency (>100GHz), ultra-low power consumption (projected sub-pJ/bit), and high parallelism through additional dimensions of division multiplexing. Notably, **optical neural networks (ONNs)** have emerged as hardware accelerators for AI workloads, particularly in matrix-vector-multiplication (MVM), which constitutes >80% of operations in modern AI models. For ONN implementation, **Silicon (Si) photonics** is an appealing platform due to its CMOS compatibility and high-density integration capacity. Prototypes of Si-based ONN hardware have been successfully verified using cascaded Mach-Zehnder interferometers (MZIs) and wavelength division multiplexing (WDM)-based microring resonator (MRR) arrays. However, *the inherent indirect bandgap of Si has impeded the progress of on-chip laser integration, thereby hindering the realization of a fully-integrated ONN system-on-chip (SoC)* that can further enhance system performance and address the computational acceleration demands of edge devices.

Leveraging Intel's silicon photonics platform, our team previously pioneered the heterogeneous integration of **quantum dot (QD) lasers** with Si PICs. In this project, we aim to further advance the development of a volume-manufacturable, fully integrated ONN system with high bandwidth and energy efficiency. We aim to achieve this by implementing QD mode-locked lasers (MLLs) as on-chip embedded sources through wafer-salce heterogeneous integration. This innovative approach deviates from conventional off-chip solutions, which require considerable power (approximately 2dB+6dB) for coupling and modulation. A key innovation also lies in utilizing QDs as active elements in the light sources to replace the commonly used quantum well (QW) active medium. QDs offer several favorable material properties over QW counterparts, including low threshold currents, high thermal durability, and excellent reliability. Moreover, QD-based lasers exhibit isolator-free stability, facilitating higher on-chip integration densities. By implementing QD MLLs as optical frequency on-chip comb sources for the ONN MVM system, our targets include reduced laser thresholds (< 200 A/cm^2), high thermal stability (>100°C), maximized output power (~20 wall-plug efficiency), multiwavelength emission (>8 modes at 25/50/100 GHz spacing), as well as demonstration of an **isolator-free system**.

At the ONN system level, we propose a novel architecture that employs hardware and software co-design approach for full integration on Si. The architecture utilizes an MRR crossbar design, which offers high scalability and parallelism by leveraging both spectral and spatial parallelism in optics, thereby maximizing the advantages of QD lasers. By employing an innovative, hardware-adapted algorithm to address the hardware modulation and operational speed mismatch, we aim to achieve increasingly complex tasks with a small hardware footprint. Initial simulation validation yielded a recognition accuracy of 91.313% on the MNIST dataset with mere 536 model parameters at high-speed (37 GHz) using Intel's standard 65 nm CMOS process line. By incorporating on-chip non-volatile memory and multi-cores scale-out framework, we project our hardware to theoretically increase in computing density by 70 times compared to Google's TPU electronic accelerator while reducing power consumption by 1000 times. Ultimately, the fabricated **QD MLL device and ONN system**, optimized and fine-tuned for this purpose, will be **co-integrated** using the state-of-the-art **heterogeneous integration technology** into a **holistic and isolator-free PIC** as a **compact and efficient SoC**. This transformative development is anticipated to unlock unprecedented advancements in energy efficiency, sustainability, and scalability and create new avenues for commercialization.

Multi-modal photogrammetry for enhanced pathology documentation

Challenge

Contrary to the popular belief that anatomic pathology is primarily dependent on microscopy, many pathology evaluations today are actually performed at the macroscopic level by visual inspection, or "grossing." Grossing can reveal the malignancy or severity of many diseases. It also helps pathologists to identify regions of interest for further microscopic analysis.

Grossing relies on good communication between surgeons and pathologists. Sample origin, orientation, and key landmarks must be explained precisely and accurately. Graphical data like sketches and photography facilitate communication, but tissue landmarks and orientations are still easily misrepresented in 2D images, leading to sampling errors, misdiagnosis, and wrong treatment plans. These shortfalls stress the need for a transition towards more accurate and comprehensive graphical communication methods.

The implications of grossing errors can be severe but are hard to gauge or recover. Surgical samples processed into microscope slides cannot be examined again. 2D images are often the only remaining visual evidence, but they cannot represent the entirety of the specimens in 3D. Sometimes, an image itself could be a source of error if not properly acquired. To prevent and catch errors in grossing, clinicians need a better method to acquire and preserve the graphical data of the specimens.

Proposed Project

Anatomic pathology heavily depends on graphics to document and describe cases, but 2D images miss 3D details and quality to provide complete visuals of surgical specimens. It is the root cause of the problem above. If surgeons can create a detailed 3D visualization of the tissue in the operating room (OR), digitally label and annotate, send it to pathologists, and keep it on record, all problems will be resolved. In fact, recent pilot studies suggested that 3D scans of surgical specimens can improve surgical pathology communication and leave extra evidence for post-surgical reviews. However, existing 3D scanners struggle to handle a large range of sample sizes, record high-resolution details, manage tissue physical properties, and provide a streamlined clinical experience. Clinicians are also concerned with extra costs and training, not to mention regulatory concerns and workflow changes.

In addressing these challenges, we aim to create an optical 3D scanner uniquely tailored to clinical specimens and users. The scanner is intended to be compact and user-friendly, readily adaptable to diverse sample properties such as texture, size, and resolution, and seamlessly integrated into clinical workflow. We determined photogrammetry is the ideal technology to satisfy these specifications and are prepared to tackle inherent technical hurdles, including variations in illumination and deformation during scanning. Integrating photogrammetry with novel optical contrasts, such as fluorescence and luminescence, will simplify illumination design and generate fresh perspectives on pathology. We will also develop a robust photogrammetry 3D reconstruction pipeline, automated 3D model optimization, and a user interface with features designed for medical professionals.

Intended Outcomes

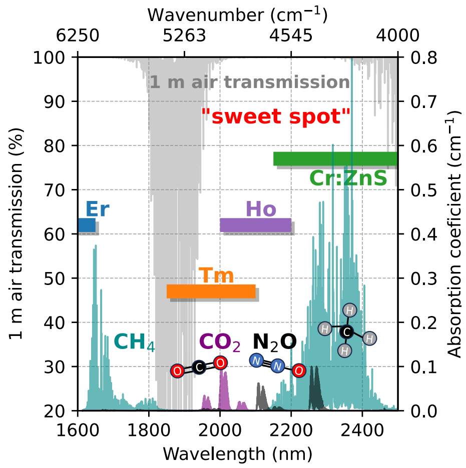
The project will deliver a prototype photogrammetry 3D scanner comprising modules for illumination, imaging, mechanical manipulation, and data handling. This prototype shall let us engage our first users, create strategic partnerships with key stakeholders in academia and hospitals, start initial tests, build feedback channels, and enable continuous improvement of design and user experience. We aim to prove that a tissue 3D scanner is technically and clinically viable. We also anticipate that our work could bolster various medical photonic innovations, such as **enhanced slide-free pathology** and **fluorescence-guided surgery,** and provide new data support for advancements in **personalized medicine, virtual reality medical training, medical robotic applications, and novel AI medical insights**.

High-power 2-µm frequency combs for rapid greenhouse gas sensing

20th Anniversary Challenge OPTICA — Category: Environment

Applicant: Yicheng Wang

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) compose 98% of global greenhouse gas emissions, and significantly contribute to global warming. Despite their importance, effectively understanding and monitoring regional emissions through sensitive remote detection of these gases remains challenging today. Dual-frequency-comb based remote sensing has emerged as a unique tool for this purpose in the 'eye-safe' wavelength range of 1.6 µm. Despite the remarkable progress in Er-fiber-based laser systems at this wavelength for this application, the 1.9-2.4 µm wavelength region offers potential advantages due to stronger absorption lines of the greenhouse gas, making it attractive for sensitive tracking of small concentration variations. I propose here employing a **high-power Ho-laser based frequency-comb system (HoLa-Comb) for rapid greenhouse gas detection**.



Laser emission range (1.6-2.5 µm) illustrated. Ho-laser operates at the 'sweet spot' for max. air transmission, covering both greenhouse gas lines.

The success of 2-µm rapid remote sensing relies on lasers meeting specific requirements: firstly, the air transmission at 2 µm is low due to water vapor in the atmosphere, necessitating **high average power** levels for long-distance remote sensing. Moreover, to cover the absorption band of the greenhouse gas (about 450 cm^{-1} from 2000-2200 nm), a sufficiently **broadband source** is needed. Additionally, **high repetition rate** is beneficial for measurement speed and detection sensitivity in dual-comb spectroscopy.

In this regard, Tm-, Ho-, and Cr-lasers emitting direct broadband pulses at 2-µm are desirable due to compactness, simplicity, and stability without nonlinear conversion stages or amplifiers. However, their average power is typically below Watt-scale, limiting long-distance remote detection. Ho-laser is operating at the "sweet spot" in this wavelength region, where air transmission is maximum, and the emission is possible to cover both gas absorption lines. Recently, we achieved significant milestones with Ho-laser, including a record-high average power mode-locked laser using all commercially available parts, as well as long-term stability and low-noise. Motivated by its outstanding performance and potential applications, I plan to develop a compact high-power single cavity dual-comb based on Ho-laser and polarization-multiplexing, named **HoLa-Comb**, and demonstrate the proof of concept for rapid greenhouse gas sensing.

The project's impact extends beyond greenhouse gas sensing, benefiting various fields such as next-gen MIR-spectroscopy for environmental monitoring and medical diagnostics, exploring the 2-µm waveband for communications, and enhancing GHz-burst fs-laser ablation at 2-µm, advancing precise material processing on silicon and transparent materials. We are currently exploring the option of creating a spin-off with our Ho-laser, and funding from this proposal is crucial to fully explore its commercial potential, establish a strong foundation for market entry, and drive innovative solutions that benefit society.

Monolithic III-V active devices in-plane coupled with Si for integrated Si-photonics

The relentless growth of data traffic is rapidly approaching the communication bottleneck of Si-based integrated circuits and systems, with further scaling down hindered by technological and economic viability. Si-photonics, leveraging the highly successful Si IC infrastructure, is regarded as the enabling technology for new-generation communications as well as emerging fields, including supercomputers, neural and quantum networks, microwave photonics, and sensing. While Si-photonics has been successful with Si-based passive components, integrating III-V lasers on Si has remained the major challenge for Si-photonics. Heterogeneous integration approaches such as wafer-bonding and micro-transfer printing have facilitated the integration of high-performance III-V lasers on Si-photonics platforms. However, their integration density, cost, and manufacturing yield are suboptimal compared to monolithic integration, thereby limiting the broad adoption of Si-photonics. In the past few years, our group, along with a few others worldwide produced III-V lasers on Si by blanket epitaxy of III-V thin films on Si and incorporation of quantum dot active region. Unfortunately, the thick III-V buffer layers for defect engineering severely impede the efficient coupling between III-V active devices and Si passive components. To address this dilemma, we have developed a novel selective epitaxy method named ***lateral aspect ratio trapping (LART)***. The core concept of LART involves the ***in-plane and intimate placement of Si and III-V***, eliminating the III-V buffers and providing an elegant solution for efficient coupling between III-V and Si. The wisdom of LART also lies in the ***unique feature of removing threading dislocations (TDs)***. Traditional blanket epitaxy methods only allow for the reduction of TD density to approximately 10^6 cm^{-2} for GaAs on Si and 10^8 cm^{-2} for InP on Si using 2 to 3 μm thick III-V buffer layers. In contrast, the LART method enables the complete removal of TDs, rendering the entire III-V devices TD-free, a feat not yet achieved on any other platform.

Building upon the LART method, we have achieved TD-free III-V crystals on SOI with excellent uniformity and flexible dimensions of up to hundreds of micrometers. Furthermore, on the versatile III-V/SOI platform, we have realized high-performance photodetectors (PDs), optically pumped lasing of telecom micro-lasers arrays and distributed feedback lasers and Si-waveguide-coupled III-V PDs. In this project, we propose to advance the field by developing monolithic integration of III-V electrically pumped lasers, PDs, modulators, and Si passive devices through efficient and in-plane coupling. This program will leverage our expertise in designing novel metal-organic chemical vapor deposition (MOCVD) growth procedures, as well as laser fabrication and characterization technologies. A primary focus will be addressing the specific challenges associated with coupling high-performance III-V lasers with Si passive components on SOI – a crucial requirement for the realization of Si-photonics that has not yet been achieved on any existing platform.

The results of this project will lead to *the placement of high-performance lasers exactly where they are needed in the photonic integrated circuit in an elegant, efficient, scalable, and low-cost manner*. This unique and versatile technology will significantly contribute to the development of energy-efficient Si-photonics, yielding benefits for both academia and industry. Furthermore, it will enable the integration of cost-effective electronics and power-efficient photonics on the same chip, unlocking the next generation of datacom and telecom, fostering advancements in novel computing systems, microwave photonics, optomechanics, sensing, and LIDAR, creating new opportunities for research and innovation.

Optica Foundation Challenge 2023: Information

Spatiotemporal quantum metasurfaces for high-dimensional information processing

Challenge:

Single-photon sources are crucial for many optical and quantum technologies. Typical stand-alone quantum emitters (QEs) basically feature less brightness, low efficiency, and no polarization and phase priorities that prevent them being directly used in advanced photonic applications. The common way for changing the polarization and phase front of single-photon beams requires the use of bulky and slow-response optical components, unavoidably lowing the efficiency, tunability, and compactness. Alternatively, by carefully engineering the near-field environment around, e.g., coupling with nanocavity, the QE decay rate was domenstrated to be significantly enhanced. The investigation has been extended to modulate the direction, polarization, and phase front with QE coupling with planar surface nanostructures. However, on-chip generation of structured quantum emission, e.g., encoded with composite multichannel SAMs and OAMs, remains challenging. Moreover, most of state-of-the-art single-photon sources are set in stone with fixed modes once constructed, up to now, ***the realization of spatiotemporal single photon sources is still elusive***. Overcoming this challenge can potentially provide more channels for date transmission in optical and quantum information processing.

Proposed project:

In this project, I propose an approach using MEMS- integrated QE-coupled metasurfaces, i.e., spatiotemporal quantum metasurfaces, in a vertical cavity, in which the gap distance between QE-coupled metasurface and optical shaping metasurface is dynamically tunable. Remarkably, right- and left-circular SAM states ($|R\rangle$ and $|L\rangle$) and OAM states ($\pm\ell$) will be dynamically encoded with single photons. The main features of proposed spatiotemporal single-photon sources:

- **a. Structured single-photon beams by QE-coupled metasurfaces (M1).** Solid-state QEs should be first selected and precisely positioned with prefabricated align markers on the substrate. M1 is then designed and fabricated around selected QEs to convert QE-excited surface plasmon polaritons into structured single-photon beams, i.e., with the "doughnut" patterns changing in *z* direction.
- **b. Manipulation SAM and OAM by optical shaping metasurfaces (M2).** M2 have several annular areas, consisting of different azimuthally and radially arranged nanoelements, which can manipulate the polarization and phase of photon emission. With different sizes of emission pattern ("doughnut"), photon beams will interact with corresponding areas and thus will encode different SAMs and OAMs.
- **c. Tunable gap distance of MEMS-controlled vertical cavity (C0).** M1 and M2 forms a vertical cavity. The pattern size of photon emission when arriving M2 is related to the distance between M1 and M2. This gap distance can be dynamically tunable by MEMS with a fast response (~0.1 millisecond) when changing the voltage. This can be viewed as one of the keys of the tunability of the proposed single photon sources.

Outcomes:

The overall goal of this project is to realize for the first time the spatiotemporal single-photon sources with ultrafast tunability. Reaching this goal means a great progress from currently inefficient and static single photon sources to tunable and efficient regime, opening a new perspective for quantum technologies especially with its dynamic tunability. Moreover, the tunability is not only realize on SAM (two states, $|L\rangle$ and $|R\rangle$) but also can be superpositioned with OAM (unlimited states, $\pm\ell$), which is crucial for exploiting full potential and freedom of single photons from QEs.

In the scientific side, one of the significant achievements is the on-chip generation of higher-dimensional structured single photons, beyond the state-of-the-art 2D single photon vortexes. In the technologic side, we will realize the integrated platform consisting of QE, metasurfaces, and MEMS, with scalable on-chip integration of complicated nanostructures around QEs in *x*, *y*, and *z* directions. Overall, we believe this project will provide a new toolkit by making significant impact not only on fundamental understanding of light-matter interactions but also on wide-ranging applications that benefit from ultracompact, ultrahigh-capacity, and ultrahigh-speed single-photon OAM systems-on-a-chip, which is crucial to advanced modern optical and quantum applications.

Executive Summary

Project Title: A New Solution for Microwave Photonic Sensing by Laser Dynamics

Challenge: Microwave photonic (MWP) sensing and measurement are envisioned to be a promising alternate to the conventional pure electronic or optical solutions as MWP overcomes their critical limitations: the requirements of large instantaneous bandwidth and wide frequency coverage may not be achievable by pure electronic schemes or lead to extremely complicated and costly systems, and pure optical schemes are subject to small sensing range and limited by interrogation speed. However, most existing MWP sensing schemes require a microwave signal through an electro-optical modulator (EOM) to modulate an optical source for generating MWP signals, and a measurand is applied to the sensing system through EOM or an optical sensor such as optical interferometry, fibre sensor, etc. This leads to an MWP system that is large in size, making it difficult to integrate all key components onto a single chip, and consequently expensive in terms of cost.

To tackle the challenge, the project proposes a new sensing scheme and provides an innovative solution, where a laser serves as both an MWP source and a sensor, and MWP signals are directly generated by laser dynamics without external modulation (thus electro-optical conversion is not required), which can lead to: highly compact (minimum part-count) and cost effective implementation; a great potential to boost the sensing resolution, sensitivity and measurement range; more functionalities and more practical applications.

Expected outcomes: I, together with my colleagues at the University of Wollongong (UOW), Australia, have been working in the field of the proposed project with a set of findings. Based on the solid research background previously built, this project aims to

- Conduct theoretical investigations on a new MWP generation scheme and its relevant sensing mechanism. New theories on MWP sensing and measurement will be generated.
- Develop advanced signal processing algorithms to exploit the full potentials of the proposed new scheme and to efficiently extract the rich information on measurand contained in the MWP signals, thereby achieving high sensing performance.
- Investigate the mechanism of the generation and control of photonic microwave frequency comb (PMFC) using the new scheme, leading to a number of well-synchronized parallel chirp signals over a wide frequency band. Chirped PMFC will be developed to achieve high resolution and flexibility in microwave remote sensing.
- Develop an integrated sensing platform with optical sensing and microwave remote sensing sharing a common core optical configuration and explore their industrial applications.

The proposed project will be conducted in ‘Sensing, Communications and Control Laboratory’ within the Faculty of Engineering and Information, University of Wollongong, Australia, where I have been working since my PhD study. The research lab will provide both optical and electrical devices, and elements for the relevant experimental investigation.

The proposed project falls within one of the three categories: Information and aligns with Item 4“Exploring high-sensitivity optical sensors and detectors” and Item10 “Exploring new optical sensing technologies to improve various parameter monitoring capabilities”, listed in the **Proposals of interest** of 2023 Optica Foundation Challenge.

Accelerating Optical Edge Sensing with Photonic Deep Learning

PI: Zaijun Chen, University of Southern California, zaijunch@usc.edu

Category: Information

Abstract: Existing optical sensing networks rely on sensors deployed at the internet's edge and processing in the cloud. Data acquisition, transmission, and processing lead to large energy consumption, data traffic, and long latency that are unacceptable in the era of the Internet of Things (a self-driving car would require decision-making within <1 ms). Optical neural networks (ONNs) are emerging to process machine learning tasks with great potential to elevate the electronic bottleneck for both general-purpose computing (Z. Chen, et al, VCSEL-ONN, ***Nat. Photonics*** 2023) and decentralized photonic edge computing (Sludds, et al, ***Science*** 378, (2022)). In particular, incorporating ONN processors with optical sensing would lead to the development of *"smart optical sensors"* that can detect and process optical signals without the need of converting the signal to the electronic domain, thus reducing energy consumption, latency, data traffic, and sensor footprint by orders of magnitude.

Intended outcomes: 1. **first smart optical sensors** incorporating both sensing and processing in a single photonic integrated circuit. 2. **System integration** with laser frequency combs, electro-optic modulators, photonic memories, and long optical waveguides. 3. **state-of-the-art computing performance**: low-energy (10 fJ/MAC), low latency processing (<1 ns), high-density processing chip area 1 cm^2; 4. **On-chip optical sensing** with an optical neural network to retrieve sample information (sample existence, concentration, etc). 5. **Reduced data traffic** with in-sensor processing.

Capability and Impact:

As the global emergence of IoT will continue to explore optical sensing for real-time, high-sensitivity detection, pushing the demands on lower latency, lower energy consumption and footprint, smart optical sensors will play an essential role in addressing the response time, energy cost and data traffic issues, such as in autonomous driving.

For optical sensing, the implementation of neural network hardware (with custom-designed kernels) could enhance the sensitivity of a specific feature that might have been buried in a regular spectral measurement, which would lead to new breakthroughs in biosensing and disease monitoring.

Toward photonic integration, the success of the project will have a profound impact on miniaturized and low-power optoelectronic circuits (frequency combs, photonic memories, coherent detectors) for neuromorphic photonics.

For computing, the architecture allows MAC operations on both amplitude and phase information encoded with hundreds of comb modes in parallel, which might lead to the development of next-generation **ultralow-power optical tensor processors** with high throughput and low computing power in the post-Moore's age.