Fast, low-power, and high-resolution meta-reflect-arrays for massive space-division-multiplexing

Lawrence, WUSTL

With the age of zetta-scale computing rapidly approaching, humanity's thirst for high-speed digital communication shows no sign of slowing. Increased bandwidth is needed on all scales, whether to cope with exponential growth in internet traffic flowing through data centers, to increase global equity by providing broadband internet access to remote or under-developed regions or provide higher cloud connectivity to ever smaller consumer electronic devices. Free-space optical telecommunication offers a unique opportunity to address these challenges, as highlighted by forecasts suggesting that this market will be worth $2 billion by 2027. Not only is the density of free-space information channels much greater than in optical fibers, but the topology of a free-space optical information network need not be fixed. A network that can adapt to changing patterns of data traffic can reduce congestion without needing to boost the capacity of any single channel. In data centers, for example, where resources utilized at any moment can drop as low as 15%, power consumption could be drastically reduced simply by spreading out that load. Even when data traffic patterns are stable, reconfiguration is vital in environments with fast moving agents, such as fleets of autonomous vehicles or surveillance drones and crowds of people sporting wearable devices. Of course, as bandwidth is always tied to the transmitted signal to noise ratio, the benefit of any reconfiguration strategy is constrained by the cost incurred in term of power consumption***. Targeting the Optica 20th Anniversary Challenge in <u>information</u>, here, we propose to solve a key bottle neck towards realizing dynamic free-space optical systems by building extremely energy-efficient infrared wave shaping technology that can update on microsecond timescales and with spatial resolution approaching the diffraction limit***.

Two established solutions exist for reconfiguring free-space optical networks: liquid crystal spatial light modulators and micro-electro-mechanical mirror arrays. While both have been deployed in specialized applications, material constraints limit their widespread use. Liquid crystal only allows switching on millisecond timescales and micromechanical devices require large drive voltages which hinders efficient tuning. Emerging platforms based on carrier injection or phase change materials look promising for producing high speed modulation with modest electrical biases. However, to be suitable for communication, the vanishingly weak signal strengths, often <1% of the input, must be drastically improved.

This proposal will focus on the design, fabrication, and testing of nanoscale silicon antennas that by virtue of being highly resonant exhibit a strong response to very small changes to their refractive indices. Based on high quality factor-dipolar-guided-mode-resonances (DGMRs) - the nanoantennas will not only be highly responsive but will also couple efficiently to free-space with point dipole radiation patterns, leading to very low insertion loss. To capitalize on the extreme sensitivity, the subtle temperature dependance of silicon's refractive index will be used to dynamically and precisely tune the resonant frequencies and therefore scattered phases of each element. Temperature control will be delivered by nanoscale resistive heating elements which can be very efficient due to their small size. By developing nanofabrication procedures that optimize both the optical and electrical properties of the nanoantennas, we seek to demonstrate dynamic light wave shaping with speeds at the limit of thermal tuning, ~100kHz, and with low power operation <1mW/pixel. Importantly, sub-λ pixel pitch will unlock an unprecedented number of modes.

While ~100kHz wave shaping will open many exciting doors for free-space optical communication, the proposed project is the first step towards operation at much higher speeds. The key enabling concept is subwavelength pixels that are nevertheless highly sensitive. Mechanisms such as carrier injection in 2D materials and the Pockels effect produce index modulation 1-2 orders of magnitude smaller than for thermo-optic tuning in silicon. With further refinements to our nanofabrication procedure which will unlock even higher Q factors, steering rates at 10s to 100s of GHz should be possible. Such performance would allow for network reconfiguration at the scale of a single data packet.