
THE FUTURE

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Far Future of Fibers

Philip Russell

Over the next century it seems likely that glass optical fibers, in many as-yet-uninvented forms, will continue to penetrate more and more deeply into science, technology, engineering and their applications.

Ultra-Low-Loss Fiber

Perhaps there will be hollow-core photonic crystal fibers, with specially treated ultra-smooth internal surfaces, that offer transmission losses of 0.001 dB/km in the mid-infrared. Such ultra-low loss will allow extremely long repeaterless communications spans (perhaps more than 20,000 km) and greatly simplify long-haul communications by rendering the ubiquitous Erbium-doped fiber amplifier, with its thirst for expensive pump lasers, largely redundant. All the world's oceans may then be spanned by single continuous lengths of such fiber: Sydney to Los Angeles, Auckland to Lima, or Sao Paolo to London. The resulting greatly reduced cost of long-haul communications will make access to the World Wide Web a realistic and cost-friendly possibility for all the world's populations. Of course, this may also entail the development of a range of new sources, modulators, and detectors for the mid-infrared, but semiconductor science and technology will certainly meet this challenge.

The extremely low loss of these fibers and the lack of optical damage in the empty core might also allow them to be used in power distribution systems. They will thus replace old-fashioned electrical power lines, which will vanish from the landscape in many countries, replaced by underground fiber optical power cables carrying light generated by the highly efficient laser “power stations” of the future. These high-power fibers will be so ultra-lightweight (a 100 km length with the newest high-strength carbon fiber coatings will weigh only 10 kg and have a transmission loss of 0.1 dB, i.e., a loss of 1%) that they could be suspended vertically in the atmosphere using computer-controlled balloons placed at regular intervals. Spiraling up into the sky, they will deliver megawatts of optical power to the Earth's surface from Sun- or fusion-driven lasers in space.

Domestic power outlets of the future may also be based on light, delivered via low-loss optical fibers. Such a power socket might consist of a low-loss optical fiber that, when a plug is inserted, sends a signal to a computer-controlled network specifying the amount of power required. Fiber power delivery to remote devices, using highly efficient laser diodes, will have become ubiquitous, providing an elegant and cost-effective replacement for awkward and often-unreliable electrical supply cables and batteries.

Sensing Systems

In an exotic sensor system of the future, a small “sensing” particle is picked up using laser tweezers and propelled into a length (which might be kilometers long) of hollow-core optical fiber. Enclosed and protected by the glass sheath, the particle can be propelled along a flexible path even through harsh environments. It can be held stationary or moved backward and forward by varying the power ratio between counterpropagating optical modes, and its position

monitored using time-domain reflectometry or (to interferometric precision) using laser Doppler velocimetry. It can also be optically addressed in many different ways, permitting sensitive measurements of external parameters with high spatial resolution. A further exotic particle type, made possible by future advances in semiconductor nanofabrication, is a micrometer-scale optoelectronic “microbot” that is powered by the propelling light and capable of sending signals back to the fiber input using light of a different wavelength or perhaps via a radio signal. It will be designed to sense many different physical quantities, including acting as a small microphone for detecting vibrations in inaccessible or harsh environments, as a point source for illumination or probing, as a light detector, or as a probe for local oscillating electric or magnetic fields. Perhaps the microbot could, by varying its orientation (if non-spherical) or its reflection coefficients against the incoming light, “swim” freely to and fro in the optical field upon instructions coded into the counterpropagating laser fields.

In the future it may be essential to monitor radiation levels and other parameters close to the core of a nuclear fusion reactor. Electronics cannot be used and solid-core fibers darken rapidly upon exposure to high levels of radiation. Flying particle sensors in hollow-core fibers will provide a solution: light generated by a radioluminescent particle is relayed back to the fiber input, providing a direct measure of radiation level, as well as other parameters.

Medicine

Endoscopy systems of the future will be multi-functional, enabling surgeons to carry out keyhole diagnosis, treatments, and surgery using a thin flexible cable containing a multi-core microstructured optical fiber with many advanced functions built into it. Such a fiber will be able to deliver drugs (perhaps photo-activated for treating all kinds of conditions including invasive cancer) in precise amounts through a hollow channel, transmit many different wavelengths of light appropriate for diagnosing the health of tissue, deliver selectable wavelengths of high-power laser light for tissue cutting and blood coagulation, and produce deep-UV light for killing cancerous cells. Each system is likely to have as standard a multi-mode fiber microscope for high-resolution “structured light” imaging of tissue at many different wavelengths. It will also have a built-in distributed electrically controllable transducer system (with feedback provided by optical bend and twist sensors) that will allow the fiber to be twisted, turned, coiled, and bent at the surgeon’s command.

So there you have it—a future where glass fibers will play an ever-increasing role in society and everyday life. Do some of these applications seem outrageous? Just think what has been achieved over the past half century in optical fiber communications. Maybe they are not outrageous enough

View of the Future of Light

Steven Chu

Niels Bohr, the great Dane wisely noted, “Prediction is very difficult, especially about the future,” while the American philosopher of the twentieth century, Yogi Berra quipped, “You can observe a lot by just watching.” To be asked to write seriously about what we can expect from light-based technologies over the next hundred years is serious foolishness. With this caveat, here are some predictions of what light will allow us to see and do in that future.

The interferometers of Michelson of 100 years ago are superseded by matter interferometers that use light as beamsplitters and mirrors to measure the interference of atom matter-waves. The precision of the Michelson–Morley experiment 100 years ago saw no measurable shift of distances $\Delta l / l \sim 3 \times 10^{-9}$ parallel and perpendicular to the motion of the Earth. With atom interferometers, the precision improves by 19 orders of magnitude—the equivalent of measuring a change in the distance to the nearest star 3 light years away to one millionth of the width of a human hair. Gravity-wave astronomy becomes a reality, and space–time distortions due to quantum fluctuations of the vacuum enlarged during the epoch of inflation are mapped directly.

Photostable, near-infrared optical probes smaller than the average protein are routinely used to label and observe the molecular interactions of RNA strands and dozens of proteins simultaneously with sub-millisecond time resolution. While tissue is relatively transparent at these wavelengths, light is strongly scattered. Adaptive optics using multi-megapixel arrays and ultrafast correction methods are used to restore full optical resolution, peering centimeters into tissue. Voltage-sensitive versions of these probes record the real-time individual firing of billions of synapses in the human brain. Coupled with full knowledge of the Human Connectome, we now understand, at the circuit wiring level and at the molecular level, human consciousness and self-awareness. This understanding has allowed us to significantly slow the progression of various forms of dementia.

Optical probes allow us to track the expression levels and location of the full suite of RNA expression in time and space within individual cells in live tissue. DNA sequencing identification methods based on optics help us identify many diseases and greatly reduce misdiagnoses. Optical methods of understanding the genetic mutations that cause many cancers are routinely used to develop targeted drug therapies and in helping recruit the human immune system to cleanse the body of oncogenes with minimal side effects.

To handle the stupendous computing needs of the achievements listed above, quantum computers, quantum simulators, and nanoscale memory are widely used. We use them to simulate complex systems with sufficient detail to discover improved room temperature superconductors. We use this computational prowess to understand how our brains perceive and how we analyze and respond to stimuli, as well as to perform massive simulations that reliably predict climate change caused by human-generated greenhouse gas emission.

Solar power is the lowest-cost source of energy in many parts of the world. This energy is beginning to be distributed across oceans via ultra-high DC voltage lines in undersea cables capable of moving tens of gigawatts of power greater than 4000 km with less than 5% loss. Regions of the world with poor solar irradiation and reduced winter solar generation are supplied with clean energy.

Unfortunately, the integrated carbon emission by 2065 was not reduced quickly enough. With our deeper understanding of climate change, the errors of not heeding early warning signs are starkly seen. The advanced visible and infrared Earth monitoring sensors and orbiting

atom-wave gravity gradiometers allow us to measure with remarkable precision how the climate is changing. The demonstration of reliable long-term weather predictions allows us to forecast with confidence the climate of 2100 and 2200. Just as exposure to carcinogens such as asbestos or cigarette smoke can trigger a series of multiple mutations that lead to cancer many decades later, we now realize that greenhouse gas emissions put our world on an extremely disruptive and destructive course for a significant fraction of the population.

Is this last prediction too dire? Possibly, but I also believe there is hope. While science alone will not change political policy, the massive use of optical technologies will provide compelling evidence (and compelling predictions) to convince a vast majority of people and governments of the world to make the necessary investments for future generations. In addition, the near future is ripe with the promise of understanding the human brain and body at breathtaking new levels, again with optics-enabled technologies. These advances will not only lead to better health and longer and better life spans. With our optics-enhanced ability see the future, we will likely observe that global altruism and compassion will serve our own self-interest exceedingly well.

Of course, what happens beyond 50 years is very difficult to predict. The first power flight by the Wright Brothers was in 1903, and we landed men on the moon in 1969. All that can be reliably foreseen is that there will be many wondrous surprises in optics in the next 100 years.

The 100-Year Future for Optics

Joseph H. Eberly

The most interesting part of a 100-year future is the last three-quarters of it, following the arrival of the predictable stuff. Even obvious insights can quickly look silly—think of the confident predictions of personal airplanes for commuting to work made in the 1930s and 1940s, while we've managed only bigger highways and longer-lasting traffic jams since then. Meanwhile, entire generations of music playing systems arrived unpredicted, became universally adopted, and are already forgotten. How many futurists imagined xerography, or personal computers, or intelligent telephones that are also cameras and computers, to say nothing of the FANG team—Facebook, Amazon, Netflix, and Google?

What we need is an unconstrained view of the future of optics, and Quantum Optics is nearly ideal for this because we think we know what it is, but it's still far from fully explored. The meaning of quantum mechanics itself is steadily debated while more and more optical processes are being given quantum properties. On the near horizon, and easy to connect to current research themes, one expects to see and possibly benefit from optical control of cars and roadways, photon counting without photon annihilation, wide uses for optical entanglement both quantum and classical, quantum optical networks for secure identity hacking, the development of powerful sources of squeezed light, 4-photon down-conversion crystals and quantum-communicating telescope arrays, in addition to inexpensive consumer items such as invisibility cloaks that will fit in ladies' purses.

Farther out, but inevitable, will be lethal hand-held optical weapons and wide-area satellite monitoring of their use. Entirely speculative, but more fascinating, will be fundamental discoveries employing quantum optical sensitivity, including: (i) experimental proof that a connection between quantum mechanics and gravity cannot exist, (ii) detection of coherent quantum opto-galactic signals pervading space, (iii) discovery of the origin of quantum randomness, (iv) prediction of the longest possible electromagnetic wavelength and its detection, (v) real-time optics for in-vivo whole-body DNA correction, (vi) verification of the macroscopic limit to quantum superposition, and (vii) reliable quantum-optical disassembly and recovery of bio-systems, allowing practical teleportation. In the end, all of these projections will turn out to be too conventional. To reorient a remark attributed to Steve Jobs, and thinking of Marie Curie, the optical scientist doesn't know what she'll be most thrilled to find until she finds it.

Future of Energy

Eli Yablonovitch

Civilization is presently in the hunter/gatherer mode of energy production. Nonetheless, the continual drop in cost of solar panels will lead to an agrarian model in which energy that is harvested from the Sun, optically, will satisfy all of society's needs.

Solar panels are optical. By recognizing the optical physics in solar cells, scientists are, for the first time, approaching the theoretical limit of $\sim 33.5\%$ efficiency from a single bandgap.

At the same time, solar panels have dropped in price by a factor of approximately three times per decade, for the last four decades, cumulatively a ~ 100 -fold reduction in real price. Since solar panels are manufactured in factories under controlled conditions where continuous improvement is possible, these panels will continue to drop in price until solar electricity becomes the cheapest form of primary energy (likely to occur around 2030). At that point, solar electricity will become cheap enough to be converted into fuels, which can be stored summer to winter. The creation of fuel requires panels that are three to four times cheaper than today's already depressed solar panel cost, while maintaining the highest efficiency.

The highly successful petroleum industry is over 150 years old. It has taken advantage of technology, but it appears resistant to disruptive technical changes that could sweep it away, as so many industries have been irrevocably changed or entirely eliminated by the advance of technology. Nonetheless, the application of solar electricity to create fuel could sweep away the petroleum exploration industry, which the author calls the "hunter/gatherer" mode.

Future solar cells will all have direct bandgaps, allowing them to be very thin. The cost of the material elements composing the cell will be small, since a film as thin as 100 nm can fully absorb sunlight using light trapping. Even if the chemical elements were to be expensive, there would be so little material used in such thin photovoltaic films that the cost would be low. Indeed, there are methods to produce free-standing, highest-quality, single-crystal thin films economically.

The key to high performance from a solar cell is external luminescence efficiency, an insight which has produced record open-circuit voltage and power efficiency. This has everything to do with light extraction, in agreement with the mantra "a great solar cell needs to also be a great light emitting diode"—again the application of optics.

Solar electricity in the open field will be brought to nearby locations where it will be used for the recycling and electrolysis of CO_2 solutions. There have been great strides in electrolysis, which can produce various proportions of H_2 , CH_4 , and higher hydrocarbons as products. The carbon-carbon bond is particularly prized, since such compounds can be readily converted into diesel fuel and jet fuel. The study of such selective electro-catalytic surfaces is still in its infancy. Even if only H_2 were ever to be produced, there are industrial methods of using H_2 to reduce CO_2 , and make useful liquid fuels, among many other products.

The ability to create fuels would increase the size of the photovoltaic panel industry at least tenfold, allowing the adoption of new cell technology, which is better than the current outdated 1950s crystalline silicon solar cell technology.

Thus we see that the application of optical science in making solar cells more efficient and lower in cost will produce a revolution in mankind's energy source, playing a role analogous to the agricultural revolution of 10,000 years ago.

Future of Displays

ByoungHo Lee

Displays have been created as a way to convey information. From 2D to 3D, display technology has been evolving to cope with the complexity of the information we try to deliver. But what comes next? Based on current research progress in the field, it is possible to predict that in the next decade we will be reading news from newspaper-like flexible displays with real-time videos (instead of still pictures) and live internet feeds. But if we go even further and predict what displays are going to be like 100 years from now, we can expect that displays will substantially affect the way we live.

The year is 2116, and as his windows turn from opaque to transparent, Mark wakes up feeling the sun in his face. Mark's house already knows that he is awake and the coffee is already brewing. As Mark looks out to an awakening New York, he is presented with the weather forecast as well as a reminder about his dinner with his girlfriend. While taking his shower, Mark likes to read the morning news in the shower-box glass door. In the kitchen Mark is distracted by the football highlights being shown on the table-top display when he gets a call from his mother. It is a hologram call. She is having trouble with the new robot vacuum cleaner she was given for Christmas. Mark then activates the 3D interactions mode, and his 3D image appears in his mother's house where he can show her how to fix her problem. Mark's smartwatch buzzes, telling him that he should leave home if he wants to catch the subway on time. He then transfers the call to his watch and continues to see his mother through his contact lenses. As an architect, Mark has always struggled to visualize and interact with his creations in three dimensions, so he is excited to work on his new interactive desk with a built-in volumetric 3D flexible transparent display. To get a better perspective of what a client's structure is going to look like, Mark uses the virtual reality feature on his contact lenses and walks around the structure fixing the last details. He then invites his boss and clients to his virtual model, where they can look at it together and talk over details using a 3D virtual reality call. The client is happy, and Mark could not be happier. He copies the design documents to his foldable transparent screen. Before folding it, he checks the status of his own house with the display. His house seems a little bit dark. He opens the curtain with the Internet of Things menu of the display and orders his robot cleaner to clean the living room. In addition, since he wants to invite his girlfriend to his home after dinner, he adjusts the temperature of a nice bottle of wine. Now everything is perfect!

Technology development goes faster and faster, and predicting "10 years later" often looks meaningless. However, predicting "100 years later" might be easier because a century is plenty of time to pass through the "trial and error" stage, and we can expect that what we originally imagined as a technology will have come true in real life. The whole idea of displaying information that started from people's imagination will be implemented, and we might hope that all the bugs will be worked out in 100 years. Think of a seamless display technology like perfect, anytime, completely life-like augmented reality, where users see appropriate virtual images overlapped with real scenes at any time and at any place. 100 years is enough to make that possible. The only limitation would be the lack of our imagination rather than an incomplete technology.

Biomedical Optics—The Next 100 Years

Rox Anderson

The previous century of biomedical optics strongly suggests that our technology and capability will be much improved in the next 100 years. Today we have artificial light sources emitting thousands to billions of watts that are routinely used to treat children; photodynamic therapy drugs designed to hit specific molecular targets; reading an individual person's genetic code using molecular-optical probes; changing brain functions by inserting light-activated genes into mammals; and reading human brain activity with light, to name just a few current capabilities.

But what comes next, next, and next? Some doctors, including this author, have been accused of being “often wrong, but never in doubt.” With that caveat, what follows is certainly what will happen during the next 100 years.

Optical diagnostics will improve, miniaturize, proliferate, become mainstream, replace conventional biopsies, guide medical and surgical therapy in real time, and then be fully integrated via the extension of what we now call robotics. Optical systems already provide an unprecedented combination of high-speed imaging, resolution, point-of-care molecular assays, and minimally invasive access deep inside the body. By 2040, optical diagnostics will be comparably as different as today's smart phones are from the telephones of 1985—an equal time gap. What will drive this? At the least, cancer detection, surgical guidance, instant diagnosis of infections including their antibiotic sensitivity, and the need for common lab tests done quickly on a single drop of blood, probably as a smart phone app. By 2050, user-friendly optical diagnostics will be nearly everywhere in medicine, surgery, school, public, and home. Data and decision analysis will be rapid, highly automated, almost free, and simultaneously personal and widely shared.

Most of our optical treatments using lasers and light-activated drugs aim to destroy some undesirable “target.” But light also stimulates, modulates, heals, controls, or creates. By 2065, the tables will have turned—most of the therapeutic realm of biomedical optics will be non-destructive. An early example now is optogenetics. Rhodopsin genes linked to specific promoter sequences are used to express light-activated action potentials in neuronal systems. The technique started as a way to study brain function. By 2025, it will provide a cure for blindness from the genetic disease retinitis pigmentosa. This is just the first example of a “designer optical interface” with our central nervous system. Other examples will hail from the natural and somewhat enigmatic phenomenon of “photobiostimulation,” in which light activates mitochondria, the cellular power plant that produces ATP. Apparently every cell in our bodies has at least one photoreceptor system, and probably several. During this century, light will be used to activate much more than transfected neurons, mitochondria, or naturally occurring photosystems. There will be a steady trend to use light for controlling biological systems. Microscale implanted optical machines will be developed, powered, and controlled by light. Think, “designer tattoos.”

Optical technology itself will benefit directly and greatly from biology! The first live-cell laser was demonstrated only a few years ago. Useful optical components occur in natural organisms, including waveguides, gain media, energy storage and transfer, charge separation, quantum-level light detectors at body temperature, and narrow-band emitters. We use a lot of optical devices to study biology, but the flow of capability between optics and biology is ultimately a two-way

street. Can you imagine using optical components that respond to their environment, self-align, replicate, and/or repair themselves (because they are alive)? This revolution has already started, by making optical components from natural biomaterials. Some useful optical cyborgs will be around well before 2115.

The past 100 years has seen a steady trend in optics and electronics, toward smaller and smaller devices. Enzymes, RNA, and other macromolecules are incredibly agile nanomachines that specifically manipulate other molecules. Combining three current trends of (a) ever-smaller-devices, (b) designer molecular biology, and (c) near-field optics, one comes up with diagnostic and therapeutic, nanoscale, inside-you, optical robots that work in concert with our natural nanomachinery. This will lead to the design of circulating, biocompatible, harmless, controllable, self-reporting, intervention-capable cyborgic devices that are the size of your cells or smaller. At the end of this century, such things will be in clinical trials. It will be impossible—and irrelevant—to decide if they are devices, drugs, or diagnostics. Eventually, even the FDA will stop caring about that.

Energy, global warming, and environmental change are all, at heart, biomedical optics problems. Evolution came up with photosynthetic algae and forests that are barely 1% energy efficient, yet they are the only power source for life on the planet (except for a few, very weird organisms). Can we do better than photosynthesis? A delocalized, efficient, solar-driven, self-repairing, replicating, energy-generating, non-polluting equivalent of photosynthesis is sorely needed. Like it or not, we have become shepherds of this world. A century ago, Mark Twain famously quoted a friend... “everybody complains about the weather, but nobody does anything about it!” A century from now, global warming may be viewed as an uncontrolled but positive feasibility experiment—yes, we *can* change the weather! Other global challenges will be faced and attacked using biomedical optical technologies. By 2115, people themselves may have the option of being photosynthetic. What if food were plentiful and free? What if people were healthy for a very long time? Traditionally, species populations are controlled by disease, famine, and unfortunately for us, war. Population control is probably going to be an even bigger issue in 2115. Maybe biomedical optics will help that, somehow.

Finally, there is optical exobiology. Bioscience has been fundamentally limited by looking at life, well, *here*. Optical telescopes are the tool that recently allowed us to detect many other planets, orbiting many other stars. Exobiology is likely to be a robust science by 2115, and surely it will depend on much better optics. Someone or some team will use optical spectroscopy to probe what’s on those planets. Telescopes now look at a small patch of sky for a small patch of time, with limited spatial and spectral resolution. Why not look at all of it, all the time, with detecting life in mind? If life is found, bioscience will take a giant leap forward thanks to optics.

Lasers and Laser Applications

Robert L. Byer

The year 2015 was declared by the United Nations to be the International Year of Light and light-based technologies. The opening ceremonies not only celebrated the present but also acknowledged the past and hinted at what was in store for the future. In the modern world, 50 years after the demonstration of the laser, light impacts everything we do from communicating, to manufacturing, to health care. This is not surprising, because 50 to 100 years is the adoption cycle of a new technology for widespread use by society. Just think for a moment about railroads, electrification, air transportation, the national highway system, electromagnetic communication from the radio, television, and the Internet.

So what about the future of lasers and laser technology? We are now six years into the x-ray-laser age, and x-ray lasers based on linear accelerators are being constructed around the world. What will the characteristics and applications of the x-ray laser be 50 years from now? We can expect that, like the radio and the laser, in 50 years the x-ray laser will be integrated into wide use by society in applications such as precision medical imaging, protein structure determination, and coherent transmission of information at rates 10^5 times higher than with visible light. We can also expect advances in x-ray power that will allow for controlling matter at the high densities suitable for small-scale inertial fusion power generation. The field of x-ray nonlinear interactions will be extended from x-ray to gamma ray frequencies suitable for probing nuclear energy levels and for pumping gamma ray lasers.

Laser-driven accelerators will open up a host of applications in the future. Going from Klystrons to laser-driven accelerators reduces physical device scale by 5 orders of magnitude. Accelerators could even be made as all-solid-state devices on a wafer scale. For example, a few-centimeter-long accelerator will generate MeV-energy electrons at a mode-locked laser repetition rate of 100 MHz and would be ideal for treating patients. Such an accelerator, if fitted into a catheter, would revolutionize radiation medicine. This same technology could enable an all-solid-state scanning electron microscope of centimeter length that is driven by compact fiber lasers.

A 1-m laser accelerator with 1 GeV electrons of 10-attosec duration at a 100-MHz repetition rate is ideal for driving a free-electron laser (FEL) that operates at x-ray frequencies. The 100-MHz repetition rate allows the consideration of an FEL laser with a resonator to match the 100-MHz period. Using, for example, diamond mirrors, this sync-pumped FEL opens the door to upconverting a comb of modes from the visible to x-ray frequencies. This in turn leads to opportunities for precision clocks, precision spectroscopy, and attosecond-timing resolution measurements in the hard-x-ray region, as well as field strengths adequate to ionize the vacuum. Imagine the vacuum as the ideal nonlinear medium for future experiments.

High-average-power lasers have opened the door to new applications. As the power level increases in the future to approach and exceed the 1-MW level, new and surprising applications are enabled. For example, a laser of 15-MW average power operating at 100 pulses per second, located on the ground, will enable the launching of satellites into low earth orbit, each with a mass of greater than one ton. A laser of 35-MW average power operating at a 15-Hz repetition rate is ideal for driving a laser inertial fusion power plant with a 1-GW electrical output. When that happens, laser energy will become the carbon-free energy of choice: stars burning under control on the surface of the earth.

In the future, if laser propulsion were used to launch hundreds of 2-m-diameter telescopes and the telescopes were directed into formation as a constellation of satellites, then optical

telescopes of 1000-m diameter and greater would be possible. How would these mirrors be aligned? Again the laser offers the solution through the use of precision clocks and precision interferometry to locate each 2-m mirror to better than $1/100$ of an optical wave in space-time. Such a telescope array would enable detailed studies of exoplanets using precision spectroscopy based on laser frequency combs.

It seems appropriate that in 2060, 100 years after the demonstration of the laser, the amazing laser will continue to serve society across multiple dimensions from energy to manufacturing to health and the environment.

Optical Communications: The Next 100 Years

Alan E. Willner

Over the past few decades, the field of optical communications has produced astounding scientific and engineering feats. In addition, it has helped transform the way society functions since the Internet as we know it could not exist without it. Given the exciting nature of optical science and the ubiquity of communications in our world, there is much reason to hope that this rate of technical progress and impactful applications will continue for many decades to come.

The following predictions might capture the future of our field, or just tickle the imagination.

We know that technological advances have made the transmission of enormous amounts of data across the planet commonplace, with the exponential growth in capacity continuing into the future. Many past advances in transmission capacity have utilized the multiplexing of multiple data-carrying optical waves with each beam inhabiting a unique optical parameter, such as is done with different wavelengths. Although recent research experiments have shown significant capacity increases due to space-division multiplexing, we are just scratching the surface. Basic optical science tells us that the spatial domain has an enormous number of orthogonal spatial states, and we will find new ways to exploit space to enable many orders of magnitude improvement. Whatever the technology, we will have an endless cycle of thinking we have enough capacity followed by the panic of needing more, followed by innovation. We will be feverishly following a Moore's Law-like growth, and always worried that we are coming to fundamental physical limits—but not.

We are always intrigued by the single photon itself. Present single-photon systems are fairly limited in terms of data rate, transmission distance, complexity, and cost. However, utilizing future advances in quantum repeaters and high-speed single-photon sources and detectors, we will be able to control and communicate using single photons for many types of low-power, long-distance, and secure systems.

It is quite likely that advances in the coming decades in the performance and mass production of photonic integrated circuits will enable optics to be ubiquitously deployed wherever and whenever it can bring benefit to the system, just as we use electronic integrated circuits today without thought. Furthermore, optics will bring low-loss and high-bandwidth connections between and within computer chips. Furthermore, with future advances in highly nonlinear devices, optics will perform specific signal processing operations and logic functions alongside electronics to enable higher speed and lower power consumption, such that electronics and optics will be used in a hybridized and harmonized fashion. In some applications, optics will not even need electronics to process data.

Optical networks have enabled many users to communicate with each other very efficiently. However, these networks are still made up of discrete nodes, such that data is sent away from one node and independently received by a different node, without different nodes actually interacting as a single unit. Indeed, think of a computer chip. It is a brain, with many operations occurring in parallel but all working toward a single end goal. With advances in highly accurate optical clocks, networks covering large geographic areas will be designed to act like a large computer brain and synchronously communicate and process data efficiently. Distances will truly disappear.

For the past 100 years, radio has been king of the free-space communications world, with optics barely registering an impact. However, with the constant increase in needed capacity, optical links will become commonplace. Indeed, with the future ubiquity of solid-state lighting, almost any bulb can be used for communications.

Sir Charles Kao, the Nobel Laureate credited with proposing that low-loss glass can be used for a communication system, had said that silica might last 1000 years as the medium of choice. So, going out on a limb, is it possible that silica fiber will give way to a new material with lower loss and lower nonlinearity? Such materials have been envisioned, and the economics may one day demand that a new type of fiber be adopted and laid around the world.

Since there has been exponential growth in the fiber transmission capacity and the demand for that capacity, our field is now cemented as being essential for economic and societal growth. For the past few decades, fiber transmission capacity has increased $\sim 100\times$ every decade. We have seen names fly by—Mega, Giga, Tera, and now even Petabits/sec on a single fiber. Will this continue? In 100 years and if—a big “if!”—advances continue at the same pace, we will see words like Exa, Zetta, Zotta, and even Brontobits/sec (10^{27} bits/sec). It is thrilling to imagine the enabling technologies and potential applications for such capacity.

If past is prologue, either the above-mentioned or other transforming advances will occur. If this happens, the exponential growth in the capacity of communication systems will enhance our ability to interact with each other, our environment, and machines in unforeseen ways.