Guest Editorial: Nanophotonics for Communications

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The communication industry has been the major driving force behind the extraordinary progress made in photonics that contributed to an age of information explosion over the past two decades. In the recent past, scientific breakthroughs have brought tremendous momentum to this field of research and we have observed an outbreak of interest in nanoscale materials and devices with revolutionary applications in both electronics and photonics. Enormous progress has been made in the field of nanophotonics based on high-index contrast waveguides, photonic crystals, plasmonics, nanoheteroepitaxy, and low-dimensional materials and devices. Extremely sharp curves and bends along with sophisticated splitters have also been demonstrated, thereby allowing a high level of device integration. Different materials have been explored ranging from polymers to semiconductors on a variety of substrates for both passive and active photonic devices. Applications for these devices include telecom, sensing, on-chip and chip-to-chip interconnects, and Si photonics, among others. Subsequent to more than a decade of research, the applications of nanophotonics in communications are progressively becoming a technological challenge rather than a field of fundamental research. Therefore, it is not an overstatement that nanophotonics is now becoming ubiquitous in the field of computer and communication technologies.

This special section, with seven invited papers, attempts to highlight some of the significant popular topics in nanophotonics for communication and has contributions from several renowned experimentalists as well as theorists, who have presented the necessary physical understanding along with the state-of-the-art review of active and passive nanoscale materials and devices for communication applications.

In the first paper, Gerken and Nazirizadeh address the use of one-, two-, and three-dimensional photonic crystals and related structures to engineer the spontaneous emission-radiation pattern as well as the relaxation time. The authors focus on enhancing the performance of LEDs, lasers, and single-photon sources that may be applied in future communication devices. The performance of these optoelectronic devices is largely governed by the spontaneous emission properties, which are not inherent to an emitter but may be engineered to improve device performance [1]. The far-field radiation pattern of LEDs, for example, may be designed to funnel more than 80% of the generated photons into a divergence angle of just ±30 deg by using defects in two-dimensional photonic crystals [2]. Photonic crystal defect-based lasers exhibit far increased modulation speeds with response times on the order of a few picoseconds [3], and single quantum dots in two-dimensional photonic crystals are applicable as efficient single-photon sources [4].

The current size of optoelectronic circuits is several orders of magnitude larger, in physical dimensions, than their ordinary electronic counterparts. State-of-the-art commercial electronic devices are fabricated with feature sizes in the range of tens of nanometers. On the other hand, optical devices can reach a theoretical size limit on the order of the wavelength, if sophisticated techniques, such as those based on photonic crystals, are used. Thus, the packing density of optical devices remains low. Another notable difference is the difficulty in designing optical devices with dimensions much smaller than the wavelengths involved.

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Electronics can offer single-electron transistors and quantum devices with diminishingly small dimensions. In the optical domain, plasmonic devices and circuits offer the potential to manipulate and carry optical signals through thin subwavelength metallic structures.

Many modern communication technologies rely on light as the information carrier. Their scaling often proves difficult due to the finite wavelengths of light. Nanoscale apertures are of fundamental importance in near-field optics and nanophotonics that underlie such technologies [5]. They may hold the key to squeezing more light into smaller places. It is well established that light transport in apertures strongly varies depending on whether they allow or prohibit propagating modes. A widely held belief is that subwavelength and nanoscale cylindrical holes do not support propagating modes. Following Ebbesen et al.'s pioneering experiments [6], extraordinary optical transmission has commonly been associated with the excitation of surface-wave resonances on interfaces of metallic films and an evanescent tunneling process through the holes. It has become clear now that there are, in fact, other pathways by which extraordinary transmission can occur [7]. The complete control of light transport in nanoscale apertures requires detailed knowledge of all these pathways including their interaction.

In the second paper, Catrysse and Fan study the interference of different pathways by which extraordinary transmission through subwavelength aperture arrays arises. They provide a complete physical picture that incorporates all previously reported pathways and unifies them in a comprehensive framework based on the analysis of their respective dispersion relations. They show that the transmission behavior is qualitatively different, depending on the number of transmission pathways present in the regime of operation. If only one pathway is present, it gives rise to extraordinary transmission. When multiple pathways are present simultaneously, their coupling mechanism must be studied to understand the rich and complex transmission behavior. They further demonstrate that the frequency range of these pathways can be controlled by varying the geometry of the structures. In addition, they identify several regimes of operation for subwavelength aperture arrays, including the regime probed by Ebbesen et al. [6], a regime previously reported by Shin et al. [7], and a newly identified regime. For devices in each of these different regimes, a dispersion analysis of the supported modes reveals all of the intricacies of subwavelength light transport.

Nanolithography will enable a variety of new components for optical communication systems, including broadband reflectors [8], polarization elements [9], subwavelength resonant gratings, and plasmonic devices. Until recently, the high cost of nanolithography methods, such as e-beam lithography, had limited the commercialization of these components. Nanoimprint lithography (NIL) has gained acceptance in recent years as a practical low-cost alternative to photolithography. It uses direct contact between the mold (or template) and the thermoplastic or UV-curable resist to imprint the pattern and, unlike photolithography, does not require expensive optics to image subwavelength features. In the third paper, Horsley, Talin, and Skinner discuss the use of NIL in combination with microelectromechanical systems (MEMS) to realize low-cost tunable optical filters. In these devices, wavelength tuning is achieved by means of varying the refractive index on the surface of a nanoimprinted diffraction grating. NIL allows wafer-scale arrays of gratings to be realized, and the simultaneous fabrication of multiwavelength gratings is possible. Nanoimprinted gratings are also considerably easier to integrate with optical MEMS devices than multilayer dielectric mirrors, where stress control problems have limited device yield and performance in the past.

Photonic integrated devices based on planar lightwave circuit (PLC) technology are becoming more and more attractive because of their excellent performances and suitability for mass production. In the past decades, a lot of work has been done on PLCs based on micrometric optical waveguides such as SiO_2 and polymer buried rectangular waveguides. However, the weak confinement of light in these micrometric waveguides requires a large radius (about several thousands of micrometers) for any bending section, which limits the

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integration density of PLCs. In order to achieve a high integration density, one usually has to increase the refractive index contrast while reducing the cross section to satisfy the single-mode condition. Due to the ultrahigh index contrast, silicon-on-insulator (SOI) nanowires of submicron cross sections have now become one of the most attractive candidates for realizing ultrasmall photonic integrated devices with a high integration density. By utilizing SOI nanowires, it is possible to realize large-scale photonic integrated circuits (PICs) for optical communications, optical signal processing, optical sensing, optical interconnects, etc.

However, there are some challenges for SOI-based PICs due to the submicron cross section: for example, very large scattering loss, low coupling efficiency to a single-mode fiber, and a very serious polarization dependency. In the fourth paper, Dai and He discuss the recent progress in solving these issues and review the characteristics of Si nanowires (including the single-mode condition, the birefringence, and the bending loss), the mode converters for the coupling between Si nanowires and single-mode fibers, the novel layouts for AWG (de)multiplexers based on Si nanowires, and the polarization-insensitive Si-nanowire-based PLCs.

Heteroepitaxially grown optically active materials, such as III-V and II-VI, for integration with the mainstream Si technology will enable low-cost and highly integrated ultrafast devices due to their high carrier mobilities and optical absorption coefficients. This development opens opportunities for a wide variety of applications including intrachip, interchip, and free-space communications. The capabilities of generating and detecting photons by direct bandgap materials on Si substrates, which are known for low efficiency in electron-to-photon conversion, will bring about a myriad of challenges along with revolutionary opportunities that will impact a large sector of the high-tech industry [10]. Several barriers remain that impede this technology transition from the laboratory to real-world applications.

Many of the exciting developments are only recent and the basic conceptual issues have now been widely debated and reasonably clarified. At the time of writing this editorial, theoretical fundamentals have been laid and numerous experiments on heteroepitaxy have been performed, placing this field on a sound footing. In the fifth paper, Sarkar et al. study the growth of highly lattice-mismatched InP/Si nanowire heterostructures and present a general discussion on the inherent challenges of nanoepitaxially grown 0-D and 1-D structures [11, 12]. In the context of growth dynamics, they discuss the opportunities and limits of the heteroepitaxial growth techniques and numerically correlate the size (diameter) of nanostructures with dislocation lines formed at the InP/Si heterointerfacial plane, by expanding the proposed model of Ertekin et al. [13]. They also present techniques for nanowire synthesis with large diameters and high aspect ratio, and highlight the associated critical issues.

Silicon has been the material of choice for the microelectronics industry for more than half a century [14], since it is a relatively inexpensive and well-understood material for producing microelectronic devices [15]. The silicon-based electrophotonic integrated circuit is the natural evolution of the microelectronic integrated circuit, with the added benefit of photonic capabilities. Most of these discrete or integrated optoelectronic devices are fabricated using crystalline silicon. Black silicon [16] is a relatively novel material, which is obtained by pulsed laser processing of crystalline silicon surfaces in the presence of a halogen-containing gas such as SF_6 or a variety of ambient gases, or immersed in water, or coated with other group VI elements. In this process, the flat, mirrorlike surface of a silicon wafer is transformed into a forest of microscopic spikes.

Black silicon has increased light absorbance to approximately 90% from the near-ultraviolet to the near-infrared regimes [17]. This absorbance resulted in high-sensitivity infrared photodetectors [18], high-quantum-efficiency avalanche photodiodes [19], and high-sensitivity infrared photodiodes [20]. Black silicon has potential applications such as magnetizeable biodetectors, superhydrophobic surfaces, and microfluidic devices. Regular

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arrays of black silicon have been produced for other potential device applications. Black silicon also exhibits visible and near-infrared luminescence. Serpengüzel et al. report on the temperature and laser-intensity dependences of the visible and near-infrared photoluminescence from black silicon, in order to fully characterize and optimize the material in the pursuit of obtaining novel nanophotonic devices.

The advancement of enabling photonic components developed for progressive fiber-optic communication systems began nearly 40 years ago, while the advantages of using light-wave communication in computing systems have been discussed for several decades. Following the evolution of microelectronics, the size of required photonic components for future communication systems will certainly need to be scaled down dramatically along a route of exploring higher system performance. Nanophotonics, as it implies a unified scientific and technological field of nanotechnology and photonics, is an emerging field of study built upon modern science and advanced technologies. The number of exotic experimental results and intriguing theoretical analyses in the area of nanophotonics, with the view toward future communication, is growing rapidly while numerous technical challenges are apparently looming on the horizon.

In the last paper of this special section, Kobayashi addresses the following question: How would nanophotonics benefit in the development of future communication systems that utilize light? He reviews recent research activities in nanophotonics. The paper focuses on the recent progress for developing photonic components that would be used in future communication systems. The concept of photonic bandgap crystals has been around for more than two decades. A line-defect within a two-dimensional photonic bandgap crystal provides efficient spatial confinement of light, works as a building block of a variety of routing and processing schemes of light. In contrast, silicon in the form of a complementary metal oxide semiconductor (CMOS) platform has been a core in microelectronics. Silicon nanophotonics that allow CMOS platforms to handle light, thus, would offer a wide range of photonic functions required for CMOS platforms to push further progress. While the photonic bandgap crystal and silicon nanophotonics are still subject to the diffraction limit of light, photonic devices that use surface plasmon polaritons and/or energy transfer mechanisms relying upon optical near-field interactions would pave the road toward ultimate photonic integration beyond the diffraction limit of light.

The main motivation for exploring applications of nanophotonics in enhancing the performance of electronic logic elements, microprocessors, and memory is to continue the exponential progress that industry has been making for more than two decades. A recent trend of using multicore processors is providing a temporary respite from stagnation of microprocessor clock frequencies, but has created daunting challenges to programmability, and ultimately drives today's system architectures towards extreme levels of unbalanced communication-to-computation ratios. Interior heat removal capability compounded with a huge deficit in chip input/output (I/O) bandwidth due to insufficient I/O interconnect density has stalled high performance gains. The excessive access time of a microprocessor for communication with the off-chip main memory is among the major hurdles holding back ultrafast computing. Nanophotonics offers a disruptive technology solution that will not only enhance the performance of communications and future computers but will also contribute to the fundamental transformation in the field of computer architecture. Proven ultrahigh throughput, minimal access latencies, and low power dissipation of nanophotonic devices remain independent of capacity and distance. While, for a distance exceeding a few millimeters, energy efficiency for electrical signaling is typically ~10 pJ/bit (equivalent to ~10 mW/Gb/s) [21], photonic communication links based on nanophotonics have shown the ability to operate at 100 fJ/bit, with potential to reduce the cost to the level of 10 fJ/bit. The application of photonics offers the potential of increasing the DRAM bandwidth by a factor of ~100 on each pin—a revolutionary leap for computing systems. The unique capability of photons for multiwavelength photonic interconnects in the DRAM I/O can continue the

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scalability that the semiconductor industry has become accustomed to in the last few decades, prescribed by Moore's law. The emergence of multicore architectures and ever increasing demand for information processing naturally make room for nanophotonics in the field of intrachip and interchip communications.

Unlike prior generations of optical technologies, nanoscale photonics offers the possibility of creating highly integrated platforms with dimensions and fabrication processes compatible with nanoelectronic logic and memory devices, and is expected to have a great influence on how future computing and communication systems will scale. Challenges such as developing new nanoscale materials, novel devices and ultraminiaturization, and integration are likely to keep the scientific community occupied for some time. A long list of possible opportunities, along with the extraordinary recent progress in the field, will keep the researchers busy for years to come.

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