PHOTONICS Research

Next-generation silicon photonics: introduction

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In the past decade, silicon photonics has been making tremendous progress in terms of device functionality and performances as well as circuit integration for many practical applications ranging from communication, sensing, and information processing. This special issue, including four review articles and nine research articles, aims to provide a comprehensive overview of this exciting field. They offer a collective summary of recent progresses, in-depth discussions of the state-of-the-art, and insights into forthcoming developments that are well poised to drive silicon photonics technology into its next generation.

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Silicon photonics has established itself to be a leading technology for integrated photonics, benefiting from the advanced silicon manufacturing infrastructure and CMOS ecosystem. In the past decade, silicon photonics has been developing at an increasingly fast pace with diversified types of passive and active devices, integrated circuits and systems demonstrated with unprecedented performances. Large-scale and high-density silicon photonic circuits have been realized to cater to a wide spectrum of practical applications ranging from high-capacity optical interconnects to high-precision optical sensing and metrology, plus more emerging ones, such as analog optical computing, quantum photonic communication and computing. Many of these technologies are enabled by leveraging new materials, novel physical mechanisms, advanced fabrication technologies, extended operational wavelength bands, among others. Meanwhile, the continuous performance improvement of the devices and subsystems paves the way to further scaling silicon photonic circuits for photonic-systems-on-chip and other sophisticated and small-form-factor configurations, further penetrating into more application domains in our society. This special issue, consisting of four review articles and nine research articles, aims to provide a comprehensive overview of recent progresses, in-depth discussions of the state-of-the-art, and insights into forthcoming developments that are well poised to drive silicon photonics technology into its next generation.

One of the most important trends for the next-generation silicon photonics is the convergence of photonics, electronics, and mechanics (phononics), all monolithically integrated on state-of-the-art CMOS platforms. Such a convergence is promising to enable the ultimate efficiencies, performance, and scaling of systems-on-chip. H. Gevorgyan *et al.* [1] reported miniature and highly-sensitive ring modulators in a co-optimized monolithic electronics-photonics platform that is compatible with all CMOS manufacturability design rules. They have turned the metal-oxide-semiconductor (MOS) field-effect transistor's basic structure into a novel, highly efficient MOS capacitor (MOSCAP) ring modulator. It has the smallest ring cavity (1.5 μm radius) and record 30 GHz/V shift efficiency in the O-band among silicon photonic modulators demonstrated to date.

Also using a MOSCAP structure, S. Cheung *et al.* [2] have demonstrated ultra-power-efficient (de)interleavers for dense wavelength-division multiplexing (DWDM) optical links. With wafer-bonded III–V/Si MOSCAP structures, they implemented various asymmetric Mach-Zehnder interferometers (AMZIs) and ring-assisted AMZI (de)interleavers operating at O-band wavelengths with 65 GHz channel spacing. The III–V/Si MOSCAP structure facilitates ultra-low-power phase tuning on a heterogeneous platform that allows for complete monolithic transceiver photonic integration, leading to the first demonstration of athermal (de)interleavers with the lowest crosstalk and power consumption for reconfiguration on a silicon platform.

Beyond photonics and electronics, the convergence of mechanics (phononics) with the former two has also rapidly become a promising new direction. The emerging fields of silicon photonic micro–electromechanical systems (MEMS) and optomechanics are anticipated to enable a wide range of novel photonic devices with unique characteristics. In this regard,

G. Jo *et al.* [3] demonstrated wafer-level hermetic sealing of silicon photonic MEMS inside cavities with ultra-thin caps featuring optical and electrical feedthroughs for the first time. Such an elegant, reliable and cost-effective packaging solution clears a significant hurdle for the practical application of integrated silicon photonic MEMS.

Another important topic of the next-generation silicon photonics is the incorporation of materials in addition to the silicon-on-insulator (SOI) platform. C. Xiang *et al.* [4] provided their perspectives on the trends and prospects for large-scale silicon nitride passive and active photonic integrated circuits (PICs), which has rapidly progressed in recent years, enabling versatile functionality. Especially, they highlighted the hybrid and heterogeneous integration of III–V with silicon nitride for electrically pumped soliton micro-comb generation and ultra-low-noise lasers with fundamental linewidths in the tens of mHz range. They also discussed several ultimate limits and challenges of silicon-nitride-based photonic device performance and provided routes/prospects for future development.

In addition to silicon nitride, silicon carbide has also been under extensive investigations in recent years, thanks to its wide bandgap, excellent second- and third-order nonlinear properties, and a variety of intrinsic color centers. However, due to its low refractive index, hence the low waveguide birefringence, it is challenging to design polarization beam splitters (PBSs) in silicon carbide waveguides. To overcome such a challenge, X. Shi *et al.* [5] proposed and experimentally demonstrated a novel compact PBS using vertical-dual-slot waveguides in silicon carbide integrated platforms, featuring broadband operation and a small footprint of 2.2 μm × 15 μm.

The prospect to integrate various low-dimensional materials with silicon photonic waveguides has triggered extensive research efforts in the recent decade, due to their rich physical phenomena for engineering the light-matter interaction. In particular, photodetectors based on two-dimensional (2D) material van der Waals heterostructures have shown high responsivity and compact integration capability. In this regard, C. Patil *et al.* [6] proposed and experimentally demonstrated self-driven highly-responsive p-n junction InSe heterostructure near-infrared (980 nm) light detectors for the first time. The heterojunction is constructed by vertically stacking p-type and n-type indium selenide (InSe) flakes, leading to enhanced responsivity with self-powered photodetection operation.

As a unique type of artificial material, the optical properties of dielectric metamaterials can be versatilely engineered for diverse purposes. Subwavelength gratings (SWGs) are a widely used dielectric metamaterial that is very well suited for silicon photonics. C. Pérez-Armenta *et al.* [7] theoretically proposed and simulated a novel O-band polarization-independent 2 × 2 multimode interference coupler with anisotropy-engineered bricked metamaterial using standard 220 nm silicon thickness. Such an SWG design overcomes the strong birefringence of silicon photonic waveguides, covering a wavelength range of 160 nm with excess loss, polarization-dependent loss and imbalance all below 1 dB, as well as phase errors less than 5°.

Other than the incorporation of new materials, the expansion to new operation wavelength bands can also enhance the functionalities of silicon photonics. Recently, the 2-μm waveband has emerged as a promising new spectral window for fiber optic communication. In their research article, W. Shen *et al.* [8] experimentally demonstrated a record-high-speed silicon microring modulator (MRM) at the 2-μm waveband. A high modulation efficiency of $V_\pi \cdot L$ of 0.85 V · cm and a 3-dB bandwidth of 18 GHz were achieved. Additionally, optical bi-stability has been analyzed theoretically and observed experimentally in the 2-μm-waveband MRM for the first time, which provides important guidance for future investigations.

This special issue also features one review article and two research articles on silicon photonic subsystems, including supercontinuum light sources, beamforming transceivers, and scanning spectrometers. Supercontinuum generation is a nonlinear optical phenomenon responsible for extreme spectral broadening, which may find a wide spectrum of potential applications, including sensing, imaging, and optical communications. With the emergence of silicon photonics, integrated supercontinuum sources on silicon have seen tremendous progress during the past decades. C. Lafforgue *et al.* [9] aimed at giving an overview of supercontinuum generation in three main silicon-compatible photonics platforms, namely, silicon, silicon germanium, and silicon nitride, as well as the essential theoretical elements to understand this fascinating phenomenon.

Integrated photonic active beamforming can significantly reduce the size and cost of coherent imagers for LiDAR and medical imaging applications. To reduce the scaling complexity of current architectures, A. Khachaturian *et al.* [10] proposed and experimentally demonstrated a novel photonic beamforming transceiver architecture based on co-prime sampling techniques that achieves the full grating-lobe-free (radiating-element-limited) field of view (FOV) for a 2D aperture with a single-frequency laser. A silicon photonics implementation of this architecture using two 64-element apertures, one for transmitting and one for receiving, requires only 34 pulse amplitude modulation (PAM) electrical drivers. The system demonstrated a transceiver sidelobe level (SLL) of −11.3 dB with 1026 total resolvable spots, and 0.6° beamwidth within a 23° × 16.3° FOV.

On-chip spectrometers with both wide optical bandwidths and high spectral resolutions are required in applications such as spectral domain optical coherence tomography (SD-OCT). To meet these stringent requirements, Z. Zhang *et al.* [11] proposed and experimentally demonstrated a compact integrated scanning spectrometer by using a tunable micro-ring resonator (MRR) integrated with a single arrayed waveguide grating (AWG) for operation in the 1265–1335-nm range. A 70-nm optical bandwidth and a 0.2-nm channel spacing were demonstrated, which offers a total of 350 wavelength channels with 31-kHz wavelength scanning speed, showing great potential for future applications in sensing and imaging systems.

Furthermore, this special issue features two review articles on the silicon photonics used for data communication and quantum information applications. For high-capacity data communication, Y. Shi *et al.* [12] reviewed recent progresses for silicon PICs including (1) an overview of recent achievements, (2) an introduction of the silicon photonic building blocks, including low-loss waveguides, passive devices, modulators, photodetectors, heterogeneously integrated lasers, etc., (3) a discussion of the recent progress on high-capacity silicon photonic transceivers, and (4) a review on high-capacity silicon photonic networks on-chip. Silicon photonics technology is well poised to overcome the limitations of traditional transceiver technology in high-speed transmission networks to support faster interconnection within and among data centers.

Beyond the classical regime, silicon photonics is becoming a promising platform for complete-integration and large-scale optical quantum information processing. Scalability for quantum information applications requires photon generation and detection to be integrated on the same chip, which has been a crucial goal for recent device development. In this regard, L. Feng *et al.* [13] reviewed the latest research effort and state-of-the-art technologies on silicon photonic chips for scalable quantum applications, covering (1) key technologies for scalability including single-photon sources and detectors, wavelength- and mode-division multiplexing, as well as cryogenic and interconnect solutions, and (2) representative applications including multiphoton and high-dimensional applications, quantum error correction, quantum key distribution, and quantum state teleportation. Furthermore, the authors pointed out the challenges and opportunities in low-loss components, photon generation, deterministic quantum operation, and frequency conversion, for future on-chip scalable quantum information applications.

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