

Editorial Review: Group IV Photonics—Advances and Applications

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1. Introduction

Group IV photonics has emerged as a cornerstone of modern integrated photonic technologies, driven by the convergence of silicon-compatible materials, scalable fabrication processes, and the rapidly growing demand for high-performance optical systems across communications, sensing, computing, and energy applications. Leveraging group IV elements and their compounds—such as silicon, germanium, silicon–germanium alloys, and related heterostructures—this field offers a unique pathway toward large-scale photonic integration that is fully compatible with mature CMOS manufacturing ecosystems. As a result, Group IV photonics plays a critical role in bridging the gap between electronic and photonic integration, enabling compact, low-cost, and energy-efficient devices for next-generation technologies.

The Special Issue “Group IV Photonics: Advances and Applications” brings together six research articles that collectively highlight recent progress across materials, devices, and system-level applications. The selected contributions reflect both the depth and breadth of current research, spanning fundamental photonic device physics, novel modulation and detection mechanisms, advanced integrated architectures, and emerging application domains such as optical communications, sensing, and energy harvesting. Together, these works demonstrate how Group IV photonics continues to evolve beyond traditional silicon photonics, incorporating new material platforms, innovative device designs, and interdisciplinary approaches that expand the functional landscape of integrated photonics.

In this editorial review, we provide a comprehensive overview of the six papers included in this Special Issue. We contextualize each contribution within the broader research landscape, highlight their key technical innovations, and discuss their collective impact on the advancement of Group IV photonics. By synthesizing the insights from these studies, we aim to offer readers a coherent perspective on current trends, remaining challenges, and future opportunities in this rapidly advancing field.

2. Scope of the Special Issue Contributions

1. *Bandwidth-Tunable Optical Amplifier with Narrowband Filtering Function Enabled by Parity-Time Symmetry at Exceptional Points* [1]

Integrated optical amplifiers constitute fundamental building blocks of on-chip photonic systems and are typically combined with narrowband filtering elements to suppress amplified noise. Accordingly, the realization of a bandwidth-tunable optical amplifier with intrinsic narrowband filtering capability is of critical importance for integrated photonic circuits and radio-frequency photonic systems. In conventional resonator–waveguide configurations, however, the achievable bandwidth is fundamentally constrained by intrinsic losses and coupling coefficients.



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Parity–time (PT) symmetric coupled microresonators operating at exceptional points (EPs) offer a powerful mechanism to overcome these limitations, enabling the formation of ultra-narrow spectral responses approaching zero bandwidth. In this work, a PT-symmetric coupled-resonator system operating near an EP is proposed and demonstrated to achieve a bandwidth as narrow as 46.4 MHz—substantially smaller than the 600.0 MHz and 743.2 MHz bandwidths obtained from two conventional all-pass resonators with identical gain–loss coefficients. In addition to amplification, the system inherently functions as a bandwidth-tunable optical filter, with the passband continuously adjustable from 175.7 MHz down to 7.8 MHz as the gain coefficient is varied from 0.2 dB/cm to 0.4 dB/cm.

This approach provides a distinctive route for realizing ultra-narrow bandwidth responses using coupled broadband resonators and establishes a versatile platform for optical bandwidth tuning. More broadly, it opens new opportunities for exploiting non-Hermitian physics in integrated photonic devices, enabling advanced light manipulation in fully on-chip, all-optical systems.

2. *Silicon Optical Phased Array Hybrid Integrated with III–V Laser for Grating Lobe-Free Beam Steering [2]*

Silicon photonics-based optical phased arrays (OPAs) represent a highly promising approach for achieving compact, solid-state beam steering systems. In this work, a 1×16 silicon optical phased array hybrid-integrated with a III–V laser source is proposed and experimentally demonstrated. The III–V laser chip is vertically coupled to the silicon OPA chip using a chirped grating coupler with broad operational bandwidth, enabling efficient optical power transfer. By incorporating a metal reflector beneath the silicon oxide layer, a coupling efficiency of up to 90% is achieved.

The one-dimensional antenna array, formed by silicon waveguides with half-wavelength spacing, supports beam steering across a wide angular range while effectively suppressing higher-order grating lobes, enabling a theoretical 180° field of view. Experimentally, the hybrid-integrated OPA exhibits beam steering over $\pm 25^\circ$ without observable grating lobes. Furthermore, after phase calibration, the sidelobe suppression ratio exceeds 9.8 dB, confirming the effectiveness of the proposed integration scheme for high-quality beam steering applications.

3. *Design and Simulation of a High-Responsivity Dielectric Metasurface Si-Based InGaAs Photodetector [3]*

Silicon-based photodetectors are core components of optical interconnect systems, with material quality and device performance serving as key factors that limit their further development. This work presents a theoretical investigation addressing two major challenges in silicon-based InGaAs photodetectors operating in the 1550 nm optical communication band: lattice mismatch arising from heterogeneous material integration and limited device responsivity. The lattice mismatch issue is mitigated through the use of a high-aspect-ratio trapping (ART) epitaxial technique, enabling the integration of high-quality III–V materials on silicon substrates.

To further enhance device performance, a dielectric metasurface is introduced into the top layer of the photodetector structure to improve light–matter interaction and optical absorption efficiency, enabling broadband absorption enhancement. The study focuses on optimizing the geometric parameters of the dielectric metasurface using finite-difference time-domain (FDTD) simulations to achieve high responsivity at 1550 nm. Theoretical results indicate that the proposed metasurface-enhanced photodetector achieves a quantum efficiency of up to 88.8% and a responsivity of 1.11 A/W, representing a 2–16% improvement over the unetched structure across the operating bandwidth.

These findings offer new design strategies for the realization of compact, high-performance silicon-based photodetectors and provide a solid theoretical foundation for future silicon-based optical interconnect technologies.

4. *Advancements in CMOS-Compatible Silicon Nitride Optical Modulators via Thin-Film Crystalline or Amorphous Silicon p–n Junctions [4]*

This work proposes two electro-refractive optical modulator architectures as fully CMOS-compatible alternatives to conventional tuning approaches in silicon nitride photonic platforms. The proposed modulators exploit the electro-optic properties of amorphous (upper) and crystalline (lower) silicon films integrated around silicon nitride waveguides operating in the C-band at a wavelength of 1550 nm. A range of device configurations is investigated with the goal of matching or exceeding the performance of thermal tuners, which remain the dominant tuning mechanism in silicon nitride integrated photonics.

Both vertical and lateral p–n junction modulator designs incorporating amorphous or crystalline silicon layers are proposed and numerically analyzed. For lateral p–n junction configurations, π -phase-shift lengths below 287 μm for the TE mode and below 1937 μm for the TM mode are achieved. In particular, optimized designs employing fully p-doped regions positioned above or below the waveguide yield π -phase-shift lengths as short as 168 μm for the TE mode and 1107 μm for the TM mode. Power consumption is mode-dependent, with values below 23 mW for TE polarization and approximately 100 mW for TM polarization.

Compared with crystalline silicon, modulators incorporating amorphous silicon exhibit higher optical losses, with insertion losses remaining below 10.21 dB and 3.2 dB for amorphous and crystalline implementations, respectively. Vertical p–n junction modulators generally require larger device footprints—approximately 5.03 mm for TE and 38.75 mm for TM polarization—while maintaining low losses of less than 3.16 dB (TE) and 3.95 dB (TM) in crystalline silicon devices. The corresponding power consumption is approximately 21 mW for TE operation and 164 mW for TM operation.

Overall, these results demonstrate that electro-refractive modulators based on CMOS-compatible amorphous and crystalline silicon films offer a viable, energy-efficient alternative to thermal tuning in silicon nitride photonic circuits, particularly for applications requiring fast response and reduced thermal crosstalk.

5. *Simulation and Analysis of a Near-Perfect Solar Absorber Based on SiO₂-Ti Cascade Optical Cavity [5]*

Improving optical absorption efficiency and long-term stability remains a primary objective in the development of advanced solar and thermal energy technologies. To address these challenges, this work proposes a novel absorber–emitter architecture composed of two multilayer disc stacks with different radii: one capped by a TiO₂ disc and the other by a cascaded SiO₂–Ti disc stack. The structure is designed for dual functionality as both a solar absorber and a thermal emitter.

The key innovation lies in exploiting multiple Fabry–Perot resonances within the SiO₂–Ti cascaded optical cavities to significantly broaden the absorption bandwidth while maintaining high absorption efficiency. Using finite-difference time-domain (FDTD) simulations, the proposed design achieves an average absorption of 96.68% across an ultrabroad bandwidth of 2445 nm ($A > 90\%$) spanning the 280–3000 nm solar spectrum, with an even higher weighted average absorption of 98.48% under AM1.5 solar illumination. Analysis of the electric-field distributions at four dominant absorption peaks reveals that the exceptional absorption performance arises primarily from the strong coupling of multiple Fabry–Perot resonance modes within the cascaded cavity configuration.

Beyond spectral performance, the robustness of the absorber under extreme operating conditions is also investigated. The results demonstrate excellent thermal stability, with thermal radiation efficiencies of 96.79% at an operating temperature of 1700 K and 96.38% at 1500 K. In addition, the proposed structure exhibits polarization-independent behavior and maintains high angular tolerance, retaining an absorption of 88.22% for incidence angles up to 60° in both transverse electric (TE) and transverse magnetic (TM) polarizations.

These findings highlight the strong potential of the proposed cascaded cavity design for next-generation solar absorbers and thermal emitters, offering a promising pathway toward high-efficiency, broadband, and environmentally robust energy-conversion devices.

6. *Theoretical and Experimental Study of Optical Losses in a Periodic/Quasiperiodic Structure Based on Porous Si-SiO₂ [6]*

This work examines the reduction in optical losses in periodic and quasiperiodic porous Si-SiO₂ structures through a controlled dry oxidation process. Owing to their distinctive optical properties, such structures are highly attractive for a wide range of optoelectronic applications. By precisely tailoring the material composition and structural geometry, periodic and quasiperiodic multilayer structures are fabricated on quartz substrates using electrochemical anodization, followed by dry oxidation treatments at two different temperatures.

Optical measurements reveal the presence of two localized modes in both the transmission and reflection spectra of the fabricated structures. The complex refractive indices and filling factors of the unoxidized and oxidized samples are determined through a combination of theoretical modeling and experimental characterization. Compared with pure porous silicon, the oxidized porous Si-SiO₂ structures exhibit significantly reduced absorption losses and enhanced optical transmission. Structural and compositional analyses using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) confirm the formation of porous Si-SiO₂ and a corresponding reduction in silicon content.

The results demonstrate that dry oxidation effectively suppresses Rayleigh scattering losses, leading to improved optical performance and increased suitability for silicon-based optoelectronic devices and systems. Moreover, these periodic and quasiperiodic structures offer promising opportunities for future light-emitting applications, where the incorporation of photoluminescent nanoparticles could activate the localized optical modes and enable novel emission functionalities.

3. Summary

The Special Issue “Group IV Photonics: Advances and Applications” offers a timely snapshot of a vibrant and rapidly advancing research landscape that lies at the intersection of materials science, device physics, and integrated system design. The six contributions collected in this issue collectively demonstrate how Group IV photonics continues to evolve beyond conventional silicon photonic paradigms, driven by sustained innovation in material platforms, novel device architectures, and application-oriented engineering. Together, these works highlight the versatility of Group IV materials—including silicon, germanium, and related heterostructures—as a foundation for scalable, CMOS-compatible photonic technologies addressing the growing demands of communication, sensing, energy conversion, and emerging optoelectronic systems.

By addressing challenges across the entire photonic value chain—from mitigating material incompatibilities and optical losses at the device level, to enabling efficient modulation, detection, beam steering, and broadband absorption at the system level—the contributions underscore the critical role of Group IV photonics in bridging fundamental research and real-world deployment. Several papers illustrate how advanced design concepts, such as metasurfaces, non-Hermitian physics, hybrid integration, and resonant cavity

engineering, can be combined with mature fabrication processes to unlock performance regimes that were previously difficult to achieve using traditional approaches.

We hope that this editorial review provides readers with a clear, coherent, and integrative overview of the Special Issue, while also serving as a catalyst for further research and interdisciplinary collaboration within the photonics community. As global demand continues to rise for high-performance, scalable, and energy-efficient photonic technologies—particularly in data-centric computing, wireless communications, and sustainable energy systems—Group IV photonics is uniquely positioned to play a central role in shaping the next generation of integrated photonic platforms. Continued progress in this field will not only expand the functional capabilities of on-chip photonic systems but also accelerate their transition from laboratory demonstrations to widespread technological adoption.

Conflicts of Interest: The author declares no conflict of interest.

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