Programmable Integrated Photonics via Phase-Change Materials

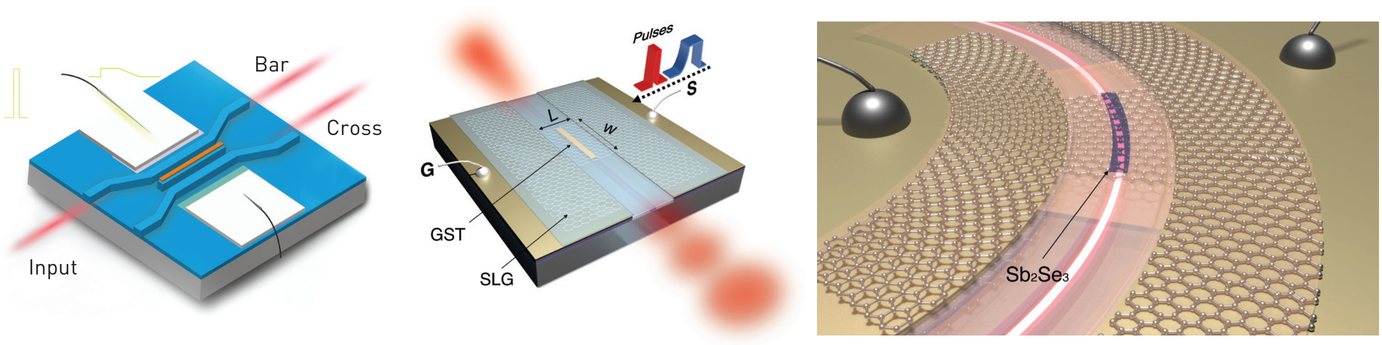
Programmable photonic integrated circuits (PICs)[1] composed of arrays of tunable phase shifters and beam splitters are expanding their application from traditional optical communications to optical signal processing, computing and even quantum information processing. However, traditional tuning methods, such as thermo-optic and electro-optic effects, are weak, power hungry and volatile. The resulting devices usually feature a large footprint (greater than 100 μm) and require a constant power supply of around 10 mW. This significantly limits the integration density and energy efficiency of the PIC.

Chalcogenide-based phase-change materials (PCMs) offer a promising platform to circumvent these limitations. Switching the PCMs between their optically different phases results in a significant and nonvolatile refractive-index change (Δn>1), enabling a compact footprint and low power consumption thanks to the PCM's zero static energy. We recently demonstrated that both doped silicon[2,3] and graphene[4] could be harnessed as external heaters to electrically actuate PCM phase transitions. These electrically controlled devices create new opportunities for large-scale, nonvolatile, programmable PICs.

We mitigated the high loss in the traditional PCM $Ge_2Sb_2Te_5$ (GST) by leveraging a three-waveguide geometry and device engineering.[3] The compact 2×2 tunable beam splitter (around 64 μm long) showed a low insertion loss (less than 2 dB) and high extinction ratio (greater than 8 dB) across the entire C-band (1530–1565 nm). We switched the beam splitter with on-chip silicon PIN micro-heaters via electrical pulses.[2] After more than 2,800 switching cycles, little performance degradation was observed.

One limitation of the silicon PIN heater is the high switching energy density (around 200 aJ/nm^3 for amorphization), due to the large amount of energy wasted in heating large volumes of silicon. We recently showed that atomically thin graphene heaters can ensure minimal heat dissipation. The graphene heater allows most of the heat to go directly to the PCMs, and the programming energy density is reduced to only roughly 8.7 aJ/nm^3, approaching the fundamental thermodynamic limit. Using graphene heaters, we demonstrated a broadband amplitude-programmable unit based on GST and a phase shifter using the emerging wide-band-gap PCM Sb_2Se_3. These programmable units exhibit excellent endurance over 1,000 cycles.

We believe that these electrically controlled, nonvolatile PCM-based photonic programmable units can transform the current landscape of reconfigurable PICs. With the potential to harness mature foundry processes and packaging techniques, our work should open a new avenue toward large-scale and ultra-power-efficient programmable PICs.[5] OPN



Schematics for electrically controlled phase-change-material integrated-photonic devices. Left: Tunable beam splitters using doped silicon PIN heaters. Center and right: Amplitude- and phase-programmable units with graphene heaters.

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