Phase change materials for reconfigurable photonic integrated circuits

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Pierre Noé, Benoît Cluzel, Stéphane Malhouitre, and Benoît Charbonnier, discuss phase change materials for reconfigurable photonic integrated circuits

Phase-change materials (PCMs) have gained increasing interest over the past decade for their potential in photonic applications. This article reviews their properties, key advantages over competing reconfigurable photonic technologies, and the challenges limiting their widespread adoption.

It also highlights potential solutions currently being researched in the NEUROPULS European project.

Reconfigurability in integrated optics

Reconfigurable photonic devices, such as Mach-Zehnder (MZ) and ring resonator (RR) modulators, are crucial components in integrated optics, allowing both the amplitude and phase of optical signals to be manipulated, a key operation in future High-Performance Computers for data transmission and calculation. The choice of reconfiguration mechanisms depends on factors such as power consumption, compactness, losses, non-volatility, and CMOS compatibility.

Standard mechanisms include the thermo-optic effect (micro-heaters), free-carrier effects (e.g., electro-absorption, Pockels effect, and quantum-confined Stark effect), and plasmonic effects. However, these methods suffer from limited refractive index contrast (Δn), necessitating long device lengths to achieve substantial phase shifts. Additionally, most standard approaches are volatile, requiring continuous power input, which is inefficient for applications with long reconfiguration time intervals, such as optical routers and photonic neural networks.

PCMs, particularly chalcogenide-based materials, offer solutions to these limitations due to their non-volatile nature and high refractive index contrast.

Optical and material properties of PCMs

Chalcogenide materials are widely studied for their electronic, structural, and optical properties, making them suitable for photonic applications. Conventional PCM alloys, such as $Ge_2Sb_2Te_5$ (GST225) and GeTe, have been extensively used in optical data storage (e.g., CD-RW, DVD-RAM). These materials exhibit large refractive index contrasts between their amorphous and crystalline phases, enabling effective optical modulation.

However, at telecom wavelengths (1.55 μm), these materials are highly absorbing, limiting their use in integrated optics. The extinction coefficient (k) increases significantly upon crystallisation, leading to optical losses. Therefore, new PCMs with high Δn but low Δk are desirable for low-loss photonic platforms.

A simple figure of merit (FOM = Δn/Δk) is often used to evaluate PCMs. Standard GST225 and GeTe have FOM values of 2.2 and 6.2, respectively, while newer compounds such as Ge2Sb2Se4Te1 exhibit FOM ≈ 4.2 at 1.55 μm. More recently, GeSe-based alloys (GeSexTe1-x) have demonstrated significantly improved FOMs due to their tunable properties. By adjusting the Te/Se ratio, these materials balance transparency and phase-change efficiency, making them promising candidates for low-loss phase shifters. Other ultra-low-loss PCMs, such as Sb2S3 and Sb2Se3, have also been introduced.

PCM-based optical devices and applications

One major project, NEUROPULS, is developing ultra-low-loss non-volatile phase shifters and Mach-Zehnder interferometers (MZIs) using GeSe-based PCMs, which exhibit extremely small optical absorption pushing their FOM in excess of 100.

A key challenge for PCMs in photonics is their integration into CMOS-compatible silicon photonics platforms. Research efforts in the NEUROPULS project focus on integrating thin-film PCMs (≤100 nm) onto silicon waveguides alongside III-V materials. These PCMs act as perturbations, modifying the effective refractive index of the waveguide mode.

In photonic computing, the precise control of light interference allows weighted sums to be calculated. Such devices can also be used as programmable weights in photonic neural networks, enabling low-power inference without continuous energy input.

Another promising application is photonic memories, where the PCM state determines optical attenuation levels. By carefully controlling input power during the writing phase, multi-level optical storage (e.g., 8-level, 3-bit memories) can be achieved with minimal energy consumption. Recent demonstrations have shown switching speeds in the GHz range, with energy consumption as low as 13.4 pJ per switching event. The NEUROPULS project aims to model these memories in a full computing framework, assessing trade-offs against electronic memory technologies.

Current challenges

Despite their advantages, several challenges hinder the widespread adoption of PCM-based photonics:

1. Integration in standard photonic platforms –
   PCMs are not yet included in multi-project wafer (MPW) runs, limiting their accessibility to the broader research community. Their integration into CMOS-compatible platforms remains a work in progress.
2. Limited data resolution –
   The number of discrete levels in standalone PCM patches is still low, restricting their use in high-bit-resolution applications such as photonic memories and neuromorphic computing.
3. Scalability of optical read/write operations –
   Optical addressing of PCM devices at scale remains complex due to the large size of photonic components. Future solutions may involve 3D integration with multiple guiding layers and wavelength-division multiplexing (WDM) to optimise read/write processes.

Ongoing research efforts

The NEUROPULS project is actively addressing these challenges by:

- Integrating PCMs into mature silicon photonics platforms.
- Developing PCM devices with improved bit resolution for enhanced data encoding.
- Exploring 3D waveguide integration to enable higher component densities and optimized optical interconnects.

PCMs hold great potential for reconfigurable photonic applications due to their non-volatility and high refractive index contrast. Se-based PCM thin films, in particular, offer superior optical properties compared to traditional GST225-based materials. Their integration into silicon photonics platforms is progressing, with applications in neuromorphic computing, photonic memories, and optical switches.

However, challenges such as CMOS integration, limited bit resolution, and scalability of optical addressing remain. Research efforts, particularly through the NEUROPULS project, aim to overcome these hurdles and unlock the full potential of PCMs in next-generation photonic technologies.

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