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Simulation-based Comparison of the Performance of Various Phase-Change Materials on a SiN-based Photonic Platform

C. Zrouba^{1*}, F. Bentata^{1,2,3}, R. Cardoso¹, A. Bosio¹, S. Le Beux^{1,4}, P. Genevet², S. Monfray³,
L. Berguiga¹, X. Letartre¹, I. O'Connor¹, S. Cueff¹ and F. Pavanello¹

¹Univ. Lyon, Ecole Centrale de Lyon, INSA Lyon, Université Claude Bernard Lyon 1, CPE Lyon, CNRS, INL, UMR5270, 36 avenue Guy de Collongue, 69130 Ecully, France

²Université Côte d'Azur, CNRS, CRHEA, Rue Bernard Gregory, Sophia Antipolis 06560 Valbonne, France

³STMICROELECTRONICS, 850 Rue Jean Monnet, 38920 Crolles, France

⁴Dept. of Electrical and Computer Engineering, Concordia University, 1455 Blvd. de Maisonneuve O, Montréal, Canada

*corresponding author: clement.zrouba@ec-lyon.fr

Abstract: We present a simulation-based performance assessment of various phase-change materials (PCMs) in the context of photonic integrated circuits. We study a device consisting of a thin rectangular patch of PCM deposited on a silicon nitride waveguide. This device is programmed using guided optical pulses to alter its optical transmission by partially changing the phase of the PCM. Using two application-aware figures of merit, we evaluate the programming efficiency for each PCM considered.

As CMOS scaling reaches physical and economical limits, emerging technologies are poised to take over some of the workload and functionality required in tomorrow's chips. Silicon photonics has emerged as a robust and versatile supplement to conventional electronic circuits, in part thanks to its high compatibility with existing CMOS processes [1]. To improve and extend the capabilities of photonic circuits, a number of materials are being investigated, including III-V semiconductors, 2D materials, and phase-change materials (PCMs).

PCMs are an emerging class of materials whose properties can be reversibly modulated by crystallographic control (i.e., gradually switching between two stable or metastable states – often between crystalline and amorphous states). Their most defining feature is the large change in refractive index when switching from one state to the other. Additionally, they must be capable of fast and reversible switching. Most PCMs can be switched in multiple ways (electrically, thermally, and optically), and can be integrated into CMOS processes. PCMs have already been employed in silicon and silicon nitride (SiN) photonics platforms to create optical devices for a wide range of target applications spanning memory, optical routing, and computing [2].

The integration of PCMs in photonic devices and circuits requires substantial work to (i) enhance the optical response of devices through careful design optimization, (ii) engineer materials to achieve high index contrast and switching capabilities, and (iii) efficiently exploit these characteristics by optimizing programming schemes and architectures. Traditionally, each of these problems has been studied independently, with materials in particular being studied irrespective of the target device/application. Now, as potential applications become more defined, it is essential for designers to start resorting to application-aware co-optimization using meaningful device-level figures of merit (FOM).

In this work, we consider a simple building block for PCM-based devices: a thin patch of PCM deposited over a SiN waveguide, as illustrated in Fig. 1(a). Depending on the state of the PCM, varying degrees of attenuation and/or phase delay can be applied to the signals passing through the structure. This building block can, for example, be embedded in a micro-ring resonator, allowing the latter's characteristics to be adjusted in a very efficient manner by limiting the amount of static power needed for tuning [3].

For several commonly studied PCMs (GST, GeTe, VO₂, GSST, Sb₂Se₃...), we calculate the efficiency of programming this building block optically with a single pulse scheme. An optical pulse at carried by the waveguide heats the PCM patch and partially switches its state. The resulting change in transmission of the device can then be leveraged by sending signals through the same waveguide, possibly at a different wavelength, depending on the material and application. The programming scheme is illustrated in Fig. 1(a).

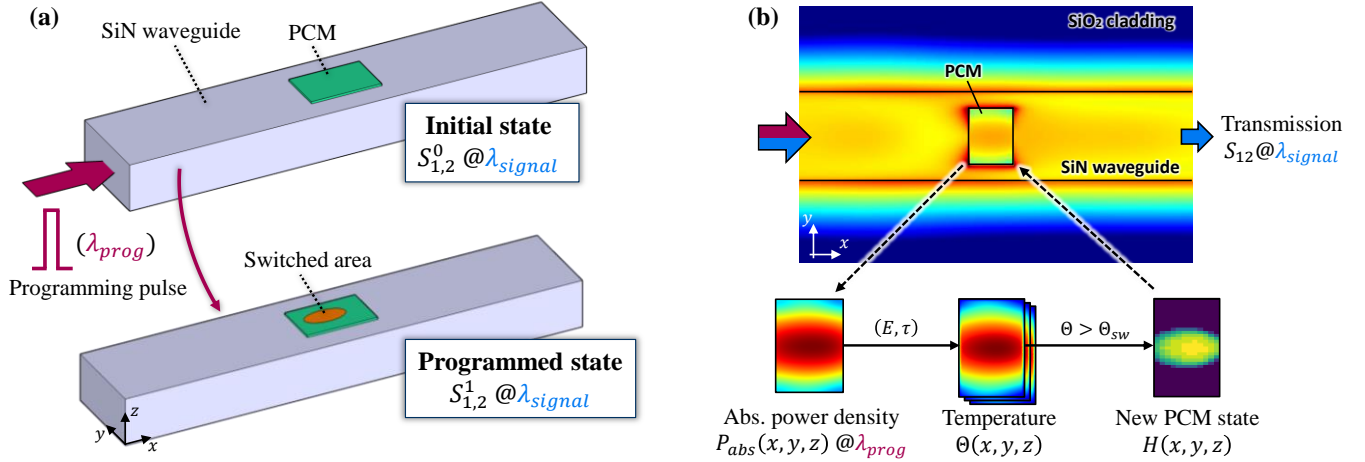


Fig. 1 (a) Device under study and programming process; (b) illustration of our simulation flow.

Our simulation flow is summarized in Fig. 1(b). We perform a 3D finite-difference time-domain (FDTD) optical simulation and 3D heat diffusion simulations to obtain the temperature profile within the patch following the absorption of the programming pulse. This result is used to estimate the new state of the PCM. Finally, the transmission of the signal in the initial state and after programming (resp. S_{12}^0 and S_{12}^1) are calculated using 3D FDTD simulations at λ_{signal} . From these, we extract ΔT the change in transmission intensity, and $\Delta\phi$ the change in phase-delay after programming.

Since the concept of device performance depends heavily on the target application, we propose two key figures of merit (FOMs) which relate the optical characteristics to E the energy of the programming pulse:

$$FOM_1 = \Delta T / E \quad (1a)$$

$$FOM_2 = \Delta\phi \cdot \min(|S_{12}^0|, |S_{12}^1|) / E \quad (1b)$$

These FOMs give an indication of how efficiently the device can be programmed, and allow materials to be compared. They cover two classes of applications: FOM_1 is suited for transmission gating applications, such as memory cells, and FOM_2 makes sense in interference-based applications such as optical computing or routing.

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