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Comparing Rib and Slot Waveguides for Phase-Change Material Devices in SOI Platforms

Clément Zrounba¹, Raphael Cardoso¹, Mohab Abdalla¹, Sebastien Cueff¹, Alberto Bosio¹, Sébastien Le Beux^{1,2}, Xavier Letartre¹, Ian O'Connor¹, Fabio Pavanello¹

1. Univ. 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

2. Dept. of Electrical and Computer Engineering, Concordia University, 1455 Blvd. de Maisonneuve O, Montréal, QC H3G 1M8, Canada

clement.zrounba@ec-lyon.fr

Abstract: We introduce a novel design for integrated phase-change material devices. A figure-of-merit is introduced to quantify the improvement of the proposed design over previous implementations. Additionally, the significance of non-linear effects is discussed.
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The exponential increase in data processing and communication needs has been a major driver for the last two decades of photonic integrated circuit (PIC) technologies. Specifically, to enable novel functions in PICs, a wide range of materials has been considered, including III-V semiconductors, graphene, and phase-change materials (PCMs) [1]. PCMs are an emerging class of chalcogenide-based materials capable of strong and non-volatile optical and electrical modulation properties, providing key benefits to standard silicon photonics platforms. The modulation of their material properties by optical or electrical stimuli and their potential for integration in CMOS-compatible platforms allowed their use in e.g., multi-level memories and neuromorphic computing systems [2, 3].

A commonly studied PCM-based integrated photonic device is fabricated by depositing a thin rectangular patch of PCM on a waveguide [2, 4], as shown in Fig. 1(a). The state of the PCM patch strongly affects the transmission characteristics (attenuation and/or phase delay) of the device. In an all-optical setup, an initially fully crystalline patch can be programmed by sending it short optical pulses in order to quickly raise its internal temperature above its melting point T_{melt} , and then letting it cool down as fast as possible. Resetting the patch to a fully crystalline state can be achieved by using lower power optical pulses in order to anneal the amorphous regions. In most previous works, such devices almost exclusively employed rib or strip waveguide geometries [2, 3]. While they are the most straightforward configurations to implement, they miss out on some of the benefits offered by other waveguide configurations.

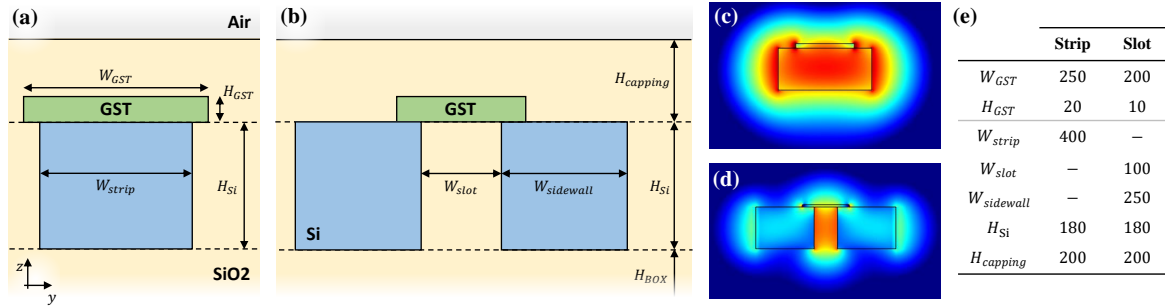


Fig. 1. Investigated cross-sections for (a) strip and (b) slot waveguides; (c), (d) their respective squared E-field amplitude 50nm into the patch; (e) geometrical parameter values (in nm).

In particular, slot waveguide geometries, in which the PCM patch is above a vertical dielectric slot (see Fig. 1(b)) are yet to be investigated. Slot waveguides possess two key characteristics that can improve the performance of the devices. First, the well-known enhancement of the electric field in the slot allows for a stronger interaction with the PCM patch (more efficient heat generation). Second, their low non-linear propagation losses allow for higher optical peak powers to be used for setting/resetting the device compared to rib or strip devices. Using short (and therefore high-power) pulses is particularly important in order to minimize thermal losses and significantly reduce the programming energy. Slot waveguides can be efficiently coupled to strip waveguides with low-loss mode converters [5], making it possible to build complex photonic systems with a large number of such slot waveguide PCM-based devices, e.g., a cascade of such devices in series along a slot waveguide functioning as a discrete multi-level memory cell.

In this work, we compare the performance of $\text{Ge}_2\text{Sb}_2\text{Te}_5$ (GST)-based devices that use either a strip or a slot waveguide geometry at $\lambda = 1.55\mu\text{m}$, as shown in Fig. 1(a,b). In Fig. 1(c,d), we show the squared electric field amplitudes in the cross-section for both geometries, resulting from 3D FDTD simulations. Fig. 1(e) summarizes the dimensions that were used for the results shown here.

To compare the system-level performance achievable based on these devices, we introduce the following figure-of-merit (FOM): $\Delta T / (E_{out} - E_{in})$ where ΔT represents the change in transmission resulting from programming the device with a pulse carrying an energy equal to E_{in} . E_{out} represents the energy still carried by the pulse at the output port of the device. From a system-level perspective, it is important to consider this energy which can still be recycled to program other devices. Thus, this FOM relates the transmission change after a pulse of a given energy and duration to the energy that was effectively removed from the optical signal.

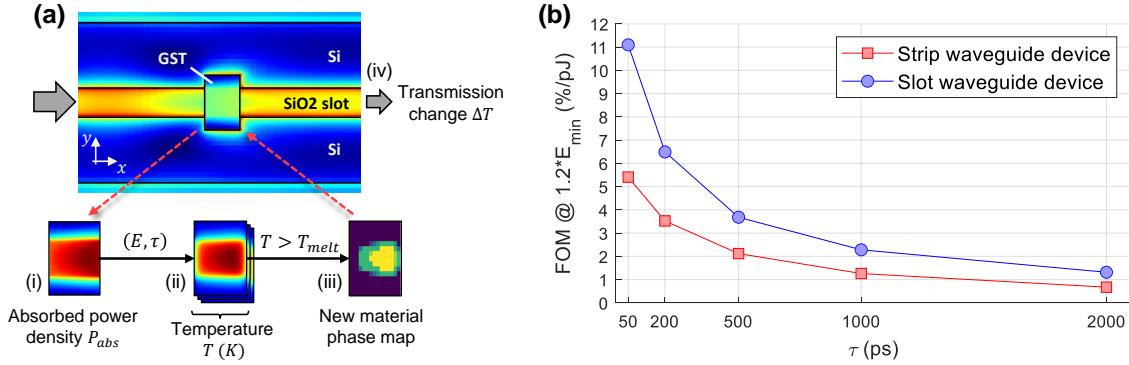


Fig. 2. (a) Description of the simulation process; (b) FOM versus pulse duration for $E_{in} = 1.2E_{min}$.

For each given geometry and pulse duration, we first calculate the minimal programming energy E_{min} , defined so as to bring the maximum temperature in the PCM patch up to T_{melt} . We then calculate the amount of transmission change that is achieved by using programming energies E_{in} close to E_{min} , under the assumption that, during the programming pulse, the phase-transition has little effect on the optical response of the device. In Fig. 2(a) the various phases of our approach are reported: (i) a 3D FDTD simulation yields the optical absorption profile within the patch, (ii) a 3D FEM heat transfer simulation uses this profile as a heat source, scaled to the pulse power, (iii) the resulting temperature map is compared to T_{melt} to define the location of amorphous volumes in the PCM, and (iv) a final 3D FDTD simulation yields the transmission of the programmed device. Fig. 2(b) shows the performances of the devices for several pulse durations and for a programming energy of $E_{in}(\tau) = 1.2E_{min}(\tau)$. For the considered pulse durations, slot devices yield a performance boost between 56.7% and 96.7% compared to strip devices.

Additionally, non-linear effects are known to limit the power that can be transmitted in a single-mode silicon waveguide [6]. In the studied configuration, non-linear losses become significant above about 30mW. Yet, strip-based devices require such programming powers as soon as the pulse duration goes below 200ps. Consequently, their performances deteriorate quickly for shorter pulses. On the other hand, in slot waveguides, most of the light propagates through the dielectric, and these effects can be neglected even for very high peak powers. Slot-based devices can thus be programmed with much shorter pulses, possibly boosting their efficiency beyond what can be achieved with previously reported device geometries.

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