

# ENERGY EFFICIENT PHASE-CHANGE MATERIAL BASED SLOT WAVEGUIDE DEVICES IN SOI PLATFORMS

Clément Zrounba<sup>1</sup>, Raphael Cardoso<sup>1</sup>, Mohab Abdalla<sup>1</sup>, Sebastien Cueff<sup>1</sup>, Alberto Bosio<sup>1</sup>, Sébastien Le Beux<sup>1,2</sup>, Xavier Letartre<sup>1</sup>, Ian O'Connor<sup>1</sup>, Fabio Pavanello<sup>1</sup>

<sup>1</sup> 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

<sup>2</sup> 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 demonstrate a novel design for energy-efficient phase-change material-based devices using Si slot waveguides. A figure-of-merit based on programming energy and transmission change is introduced to demonstrate the proposed design benefits compared to previous implementations.

**MOTS-CLEFS :** *phase-change materials ; slot waveguide ; silicon photonics ; non-linear losses*

## 1. INTRODUCTION

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 short optical pulses down the waveguide 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 benefits offered by other waveguide configurations.

In particular, slot waveguide geometries where the PCM patch is above a vertical dielectric slot (see Fig. 1(b)) are yet to be investigated despite being inherently suited for these devices. Indeed, slot waveguides possess two key characteristics that can improve the efficiency 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, allowing 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 for discrete multi-level memories [5].

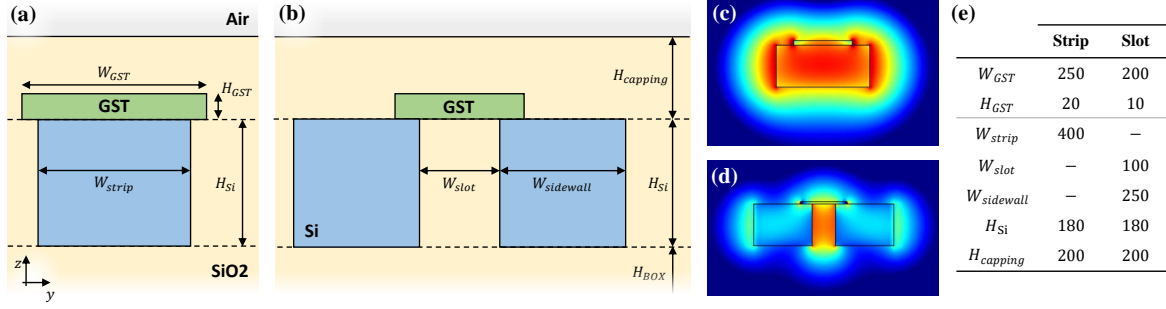


FIGURE 1 : Investigated cross-sections for (a) strip and (b) slot waveguides ; (c), (d) their respective squared E-field amplitude 50nm into the patch ; (e) geometrical parameter values (in nm).

## 2. DEVICE DESCRIPTION

Here, 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.

Before analyzing the performance of the devices, we performed an initial optimization of the geometries based on optical simulations (optical efficiency and fully crystalline vs. fully amorphous contrast) and thermal simulations. For both waveguide types, we observed that the absorbed power density in the PCM is highest in its first 200nm along the propagation direction. We thus considered only very short patch lengths. Optically, thinner patches minimize the energy lost by scattering and reflection. However, the top and bottom facets of the patch experience rapid cooling according to thermal 3D FEM simulations using parameters from ref. [4], thus imposing a constraint on the minimum patch thickness, if energy efficiency is to be maximized. Finally, the slot waveguide patches are set to be 100nm wider than the slot to limit the impact of fabrication misalignment on the device behavior. This was found to be unnecessary for strip waveguide patches, which are less sensitive to a lateral offset. Fig. 1(e) summarizes the dimensions that were used for the results shown here.

## 3. FIGURE-OF-MERIT AND SIMULATION FRAMEWORK

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  $\Delta T$  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.

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.

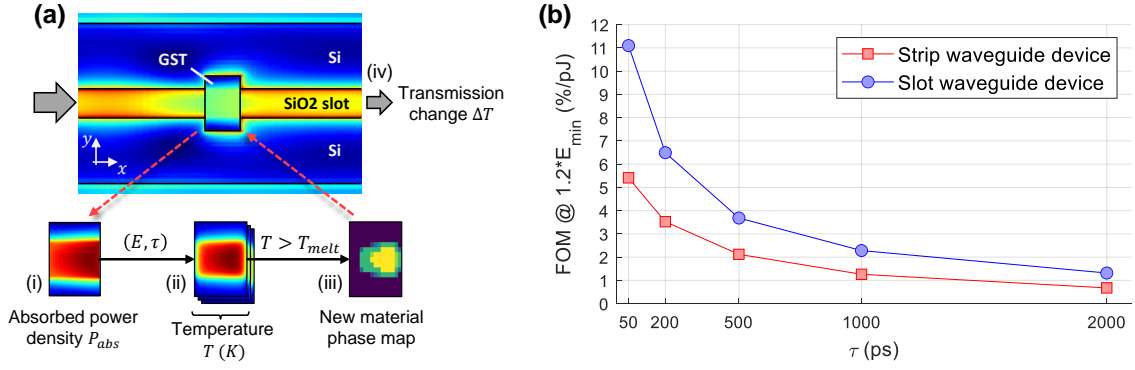


FIGURE 2 : (a) Description of the simulation process ; (b) FOM versus pulse duration for  $E_{in} = 1.2E_{min}$ .

#### 4. RESULTS AND DISCUSSION

The resulting FOM values for the devices are shown in Fig. 2(b), against the pulse duration  $\tau$  and for a programming energy of  $E_{in}(\tau) = 1.2E_{min}(\tau)$ . For a pulse duration of  $\tau = 200$ ps, slot devices yield a FOM improvement factor of 1.84 compared to strip devices. This improvement can be attributed to two main factors. First, the absorbed power density is greater in the slot-based device, likely due to the greater lateral confinement of the field and to the higher index difference between the PCM and the propagation medium (SiO<sub>2</sub> vs. Si). Second, the lower thermal conductivity of SiO<sub>2</sub> compared to Si means that the heat dissipation is lower in the slot-based device; this effect is more prevalent for long pulse durations.

It is clear from the graph that, in both cases, shortening the pulse duration leads to better performances. Indeed, it reduces how much heat is dissipated before reaching phase-transition temperatures (as already reported by [2]). The programming energy is majorly defined by this simultaneous heat dissipation, and it is thus essential to minimize it in order to boost the energy efficiency of the devices. A more intuitive approach consists in reducing the pulse as much as possible.

Non-linear effects are not accounted for in our simulations. However, transmission in Silicon strip waveguides is known to saturate due to two-photon absorption and the free-carrier absorption it induces[6]. In the studied configuration, non-linear losses become non-negligible when the guided power exceeds about 30mW. Yet strip-based devices require such programming powers as soon as the pulse duration goes below 200ps, and 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 are thus able to be operated using much shorter pulses than previously reported devices.

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