A behavioural model for integrated phase-change photonics devices

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ABSTRACT

The use of phase-change materials in integrated photonics applications has enabled the development of new types of all-optical devices, including multilevel photonic memories, arithmetic and logic processors and synaptic and neuron mimics. In order to design, optimise and understand the performance of large-scale systems, fast and accurate material and device models are needed. Here we present a behavioural model for phase-change photonic devices that can simulate the write, erase and readout operations in timespans compatible with system level performance evaluation.

Key words: photonic memory, neuromorphic computing, behavioural model.

1. INTRODUCTION

Integrated phase-change photonic devices (IPCPDs) have demonstrated outstanding capabilities that allow them to operate as multilevel non-volatile memories [1], non-von Neumann arithmetic computing devices [2] and neuromorphic components and systems [3]. However, the design and development of large-scale systems, such as arithmetic-logic units and neuromorphic processing chips, will require the simulation of the combined operation of a large number of interconnected IPCPDs. As a consequence, for modelling the performance of entire systems, it can be inferred that the time required to simulate the operating characteristics of a single device should be very short, while still maintaining reasonable accuracy (as compared to experimental device performance).

Physically realistic modelling of IPCPDs based on the combination of finite-element (FE) simulations (to simulate the optical and thermal operation) with device-scale phase-change models (such as nucleation and growth, or rate-equation approaches) can provide detailed insights of device behaviour. However, the time required for such physically realistic simulations to simulate even a single write/erase (i.e. amorphization/crystallization) cycle can be many hours, even days (with desktop type workstations). This makes the use of FE based modeling unsuitable in system-level simulations. In this paper, therefore, we present the development of a behavioural model that is able to emulate the write, erase and readout operations in IPCPDs, with simulation times in the order of seconds, while keeping a close correlation to experimentally measured data.

2. MODEL DESCRIPTION AND RESULTS

The behavioural model has been implemented to simulate the operation of two types of IPCPDs. The first is based on a silicon rib-type waveguide with a phase-change material ($Ge_2Sb_2Te_5$, GST) cell deposited on top of it [1], Fig. 1(a). The second comprises a silicon micro-ring resonator with a phase-change cell (also $Ge_2Sb_2Te_5$) deposited on the ring [1,3], and an input/output coupling waveguide, Fig. 1(b). In general, the operation of these kinds of devices is based on modification of the transmitted optical power (amplitude) and optical phase of the mode travelling through the waveguide, caused by interactions between the waveguide mode and the phase-change cell. The transmitted optical power and optical phase can be controlled by changing the state (and hence the complex refractive index) of the phase-change material cell between its amorphous and crystalline phases, and such a phase-change can be induced by sending appropriate optical write/erase pulses along the waveguide.

Here, the operation of IPCPDs of the type shown in Fig. 1 is modelled using three interconnected electromagnetic, thermal and phase-change models. The electromagnetic model uses the effective refractive index to calculate optical power and optical phase, along with the heat source term that feeds the thermal model. Thermal behaviour is approximated with a circuit analogy that uses resistor-capacitor networks to simulate the heat flow in the structure. Finally, the phase-change process itself is modelled using the John-Mehl-Avrami-Kolmogorov (JMAK) model.

The IPCPD behavioural model was validated by comparing simulated results to experimental data consisting of the application of pulses with different amplitudes and durations to a 4 μm cell similar to the one depicted in Fig. 1(a). Exemplar results are given in Fig. 1 (c), where a reasonable degree of agreement between simulation and experiment is seen for the case of excitation pulses of 13.23 mW with durations of 10, 20, 50, 75, 100, 125, 150, 175 and 200 ns.

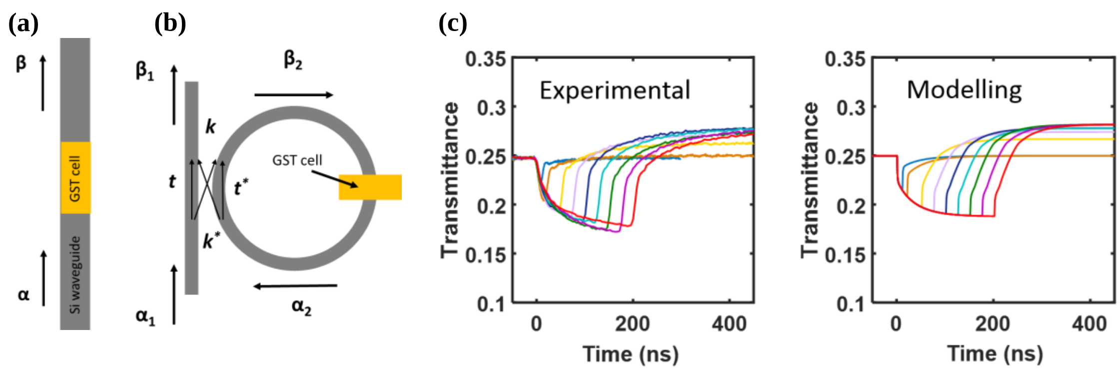

Fig. 1. (a) Schematic representation of the IPCPD composed of a GST cell on top of a silicon waveguide. **(b)** Schematic of the IPCPD composed of a micro-ring resonator with a GST cell on top and an input-output waveguide. The different modes circulating in the structures in (a) and (b) are represented by the labels *α* and *β*. Moreover, the coupling and transmission coefficients in (b) are represented by *k* and *t*. **(c)** Comparison of experimentally measured data (left) with the data produced by the model (right).

3. CONCLUSION

The development of a behavioural model capable of reproducing the operation of integrated phase-change photonic devices has been reported. The model is able to reproduce quite accurately experimental data from real devices, in timescales that are suited for large-scale system simulations.

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