Integrated Phase-change Photonics: A Strategy for Merging Communication and Computing

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Abstract: Driven by the rise of silicon-photonics, optical signaling is moving inexorably from the domain of long-distance communications to chip-chip and even on-chip application. If we are to have on-chip signals that are optical, an obvious question is to ask is whether we can do more than simply communicate with light. Could we, for example, store and process information directly in the optical domain, rather than having to go through time and energy consuming optical-electrooptical conversions? It is just such capabilities that we demonstrate here, using a novel integrated photonics platform that embeds chalcogenide phase-change materials into standard silicon photonics circuits. Specifically we show that our phase-change photonics platform can deliver binary and multilevel memory, arithmetic and logic processing, as well as synaptic and neuronal mimics for use in neuromorphic, or brain-like, computing, and all working directly in the optical domain.

1. Introduction

Chalcogenide-based phase-change materials (PCMs), such as the ternary alloy $Ge_2Sb_2Te_5$ (or GST for short), are well-known for their use in non-volatile memory applications. In recent years, their use as electrical memories, as a possible replacement of, or complement to, conventional silicon CMOS Flash and DRAM devices, has been actively pursued by academic and industrial researchers alike (the recent 3D-xpoint memory from Intel and Micron is purported to be phase-change material based). PCMs have also been used for many years (since the 1980s) in the optical storage field, for example to provide re-writable CD, DVD and Blu-ray optical disk formats. However, with the dawn of the so-called silicon photonics revolution, in which chip-to-chip and even on-chip signals are routed optically instead of electrically, the question naturally arises as to whether phase-change materials can be used to deliver a new generation of optical storage technologies – not one based around mechanically rotating disks, but one compatible with, and able to take advantage of, the ever-increasing capabilities of integrated photonic systems. In this paper we show that this is indeed possible, by embedding phase-change cells into standard integrated photonic devices and circuits (waveguides, resonators etc.). Moreover, we show that such integrated phase-change photonic devices can provide a plethora of functionality extending beyond simple memory. They can, for example, carry out arithmetic computation directly in high-order bases (e.g. base-10) and perform logic operations, so offering the exciting prospect of integrated photonic ALUs. They can also provide hardware photonic mimics of brain neurons and synapses, that can potentially be connected together to deliver brain-like processing systems working directly in the optical domain.

2. Results and discussion

The basic configuration for an integrated phase-change photonic memory cell is shown in Fig. 1(a). Here, a GST cell is deposited on top of a linear Si or SiN ridge waveguide. The GST cell can be switched between its amorphous and crystalline phases using light pulses sent down the waveguide, and the phase-state of the GST cell determines the degree of light transmission when the read pulse is launched down the waveguide. Hence, a re-writable, non-volatile memory functionality is provided. Indeed, both binary and multilevel memory can be realized, as shown in Fig. 1(b) and 1(c) [1, 2]. Since a multi-level memory facility can also be used to provide arithmetic, logic and neuromorphic (i.e. brain-like) processing capabilities, it might be expected that our integrated photonic memory concept can also be extended into these areas. This is indeed the case, and in Fig. 2 we show, by way of an example, the operation of an integrated phase-change arithmetic unit carrying out the direct base-10 subtraction of the numbers 79 and 14 (Fig. 2(a)) [2], the provision of AND, OR and NAND logic (Fig. 2(b)) [3], and the results of implementing an integrated phase-change photonic synapse in which the synaptic weight can be generated by a sequence of identical pulses with the number of such pulses determined by a simple conversion of the pre-post neuron spiking delay [4]. Moreover, by embedding phase-change cells into micro-ring resonators, wavelength division multiplexed memories and all-optical network switches can be obtained (see Fig. 3). Thus, integrated phase-change photonics may offer a route for merging of two currently disparate fields, optical communications and optical computing.

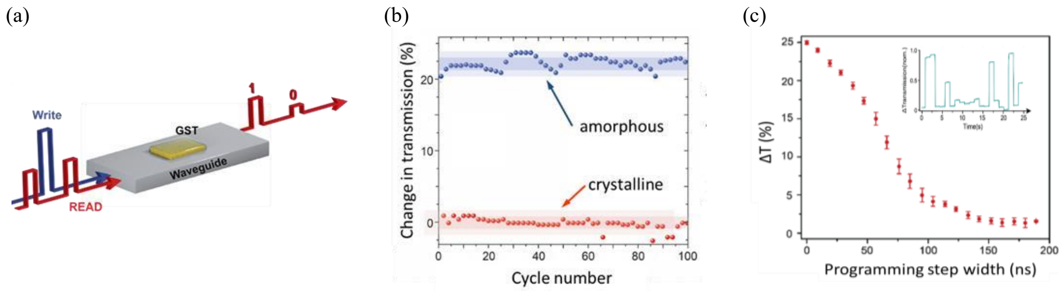

Fig. 1: (a) Schematic of integrated phase-change photonic memory and write/read pulses. (b) Binary integrated photonic memory switched over many cycles. (c) Provision of multi-level (here 20-level) memory by control of write pulse shape and duration.

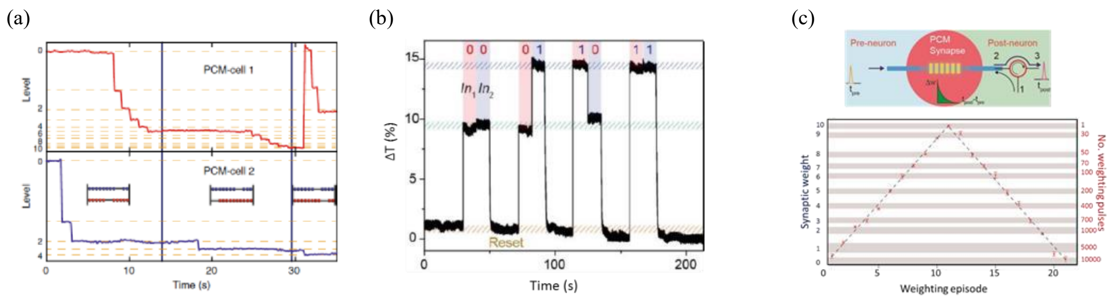

Fig. 2: (a) Subtraction of two base-10 numbers using an integrated phase-change photonic arithmetic unit, here operating in nines-complement mode. Also shown analogy to operation of an abacus. (b) Non-volatile logic functionality achieved using a single phase-change photonic cell. (c) Schematic of an integrated phase-change photonic synapse, in which the synaptic weight depends on the pre-post neuron spike time delay (top).

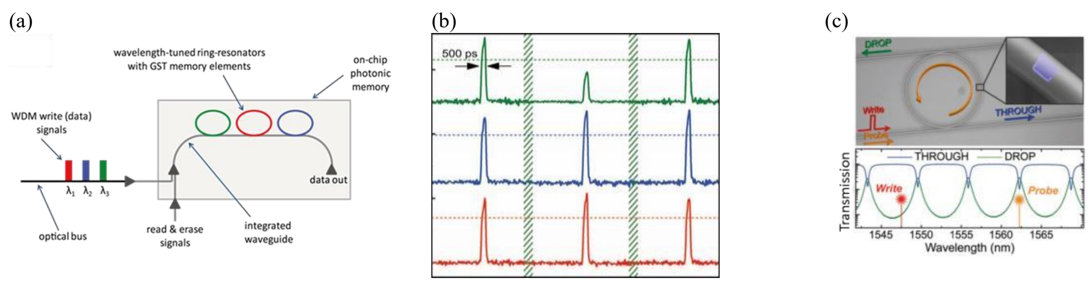

Fig. 3: (a) Schematic of a wavelength division multiplexed (WDM) integrated optical memory. Pulses at specific wavelengths couple preferentially into specific resonators and write, erase and read phase-change cells embedded into such resonators. (b) Experimental operation of the WDM memory. Here we show the readout of each cell before and after the writing and erasing of only one of the 3 cells (green pulses). (c) Optical micrograph of an integrated all-optical switch (top). The GST (inset) is embedded in a ring resonator which is evanescently coupled to two waveguides. Depending on the laser wavelength, all optical power is fully directed to the THROUGH port (off-resonance) or divided between DROP and THROUGH port (on-resonance).

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4. References

[1] C. Rios et al., "Integrated all-photonic non-volatile multi-level memory" Nature Photonics **9**, 725 (2015)
[2] X. Li et al., "Fast and reliable storage using a 5-bit, non-volatile photonic memory cell" Optica, in press (2018)
[3] J. Feldmann et al., "Calculating with light using a chip-scale optical abacus", Nature Communications **8**, 1256 (2017)
[4] Z Cheng et al., "Device-level photonic memories and logic applications using phase-change materials", Science Advances **3**, e1700160 (2017)