Silicon ring resonator with phase-change material as a plastic dynamical node for scalable all-optical neural networks with synaptic plasticity

Alessio Lugnan[1], Santiago Garcia-Cuevas Carrillo[2], Junchao Song[2], Samarth Aggarwal[3], Frank Brückerhoff-Plückelmann[4], Wolfram H. P. Pernice[4], Harish Bhaskaran[3], C. David Wright[2], Peter Bienstman[1].

1. Photonics Research Group, INTEC Department, Ghent University – imec, Ghent 9052, Belgium
2. University of Exeter, Department of Engineering, Exeter EX4 4QF, UK
3. University of Oxford, Department of Materials, Parks Road, Oxford OX1 3PH, UK
4. University of Münster, Department of Physics, CeNTech, Heisenbergstraße 11, 48149 Münster, Germany
E-mail: alessio.lugnan.1@unitn.it

ABSTRACT

Synaptic plasticity, that is the ability of connections in neural networks to strengthen or weaken depending on their input, is a fundamental component of learning and memory in biological brains. We present a numerical and experimental investigation of an integrated photonic plastic node, consisting of a silicon ring resonator enhanced by phase-change materials (GST). This all-optical device is capable of dynamical nonlinear behaviour, multi-scale volatile memory, non-volatile memory and multi-wavelength operations. We propose its employment as a building block in scalable all-optical dynamical neural networks that can adapt to their input via synaptic plasticity.

Keywords: Integrated photonics, neuromorphic computing, all-optical artificial neuron.
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1. INTRODUCTION

Spurred by the considerable progresses in artificial neural network (ANN) research, the recent upsurge in Artificial Intelligence (AI) applicability has given rise to a rapidly expanding AI market, whose contribution to the global economy is projected to grow tremendously by the next decade. However, because of the inherently low energy efficiency of the computers and data centers that host today's AI software, such a growth risks to become unsustainable, e.g. causing a serious increase in worldwide CO_2 emissions. In this context, the photonics platform is particularly promising thanks to inherent parallelism, low-power data transmission and high-speed linear operations [1]. Moreover, the silicon photonics platform allows to fabricate neuromorphic photonic integrated ciruits (PICs) employing existing and mature semiconductor fabrication techniques and facilities, therefore enabling low-cost mass production.

In comparison to today's AI state-of-the-art, the human brain is incomparably more powerful and energy efficient. Inspired by this fact, the related scientific community and industry are struggling to develop hardware-based neuromorphic computing systems that can efficiently address real-life problems [2]. In particular, synaptic plasticity is known to play a fundamental role in memory and learning of biological brains, allowing both temporary and permanent complex adaptation to sensory inputs [3]. Hence the motivation in developing and investigating scalable hardware ANNs featuring complex and dynamics-based plasticity.

In this work, we discuss the employment of a silicon RR with a short GST patch (length ≤ 1 μm) as an all-optical neuron with the property of plasticity. When fed with a powerful enough optical pulse at a resonant wavelength, silicon RRs show a nonlinear response due to the increase of free carriers concentration and temperature in the ring waveguide. In particular, free carriers blue-shift the resonant wavelength within a faster timescale (few nanoseconds) but more weakly w.r.t. the red-shift effectuated by heating (time scale of around 1 μs). Exploiting these nonlinear effect, neuron-like dynamics have been demonstrated in different works [4][5]. Moreover, very complex dynamics can be achieved by networks of coupled silicon RRs operating in a nonlinear regime [6].

On the other hand, phase change materials, and in particular $Ge_2Sb_2Te_5$ (GST for short), have been deposited on the waveguide of RRs so to build a device featuring all-optical non-volatile memory [7][8]. In particular, powerful and short optical pulses (generally few mW with a duration of few tens of nanosecond) can switch part of the GST from the crystalline state to the amorphous state. This effect can be reversed by optical pulses with a less abrupt decay in time, thus giving the time to the GST to crystallize after being melted. Here, we focus on obtaining an all-optical cascadable plastic node, that can be easily employed as a building block to build scalable and plastic neural networks based on silicon RRs and PCM.

2. RESULTS

2.1 Simulation of a small RR network: self-pulsing properties depend on GST non-volatile state.

In out previous work [9], we have shown via simulations that a silicon RR with a short GST patch (0.7 μm) allows for substantial improvement in energy efficient and speed of memory operations with respect to a straight silicon waveguide with a GST cell. Even if the optical contrast (i.e. the transmission relative difference between a device with minimum and maximum GST amorphization level) is relatively low in the linear steady-state regime, that is up to 15%, it can be considerably increased by driving the RR in a suitable nonlinear dynamic regime. In particular, the self-pulsing regime, that is when a silicon RR responds with periodic pulses to an input with constant optical power due to the silicon nonlinear effects, is especially interesting as it can make a silicon RR a spiking neuron. Here we show that a simulated small photonic ANN (Fig. 1 a), comprising two RRs with GST and two without, presents complex self-pulsing dynamics, where the delay, the timing and the shape of the pulses considerably change by switching the GST memory elements (Fig. 1 b-f). (The employed simulation approach, model and parameters are the same as in [9].) Such an effect is particularly interesting for two different neuromorphic computing approaches: when the delay and timing of spikes in a photonic spiking ANN are to be optimized via external tuning by a training algorithm; or to obtain a plastic photonic spiking ANN where the spiking properties are permanently changed via autonomous adaptation of the network to its input.

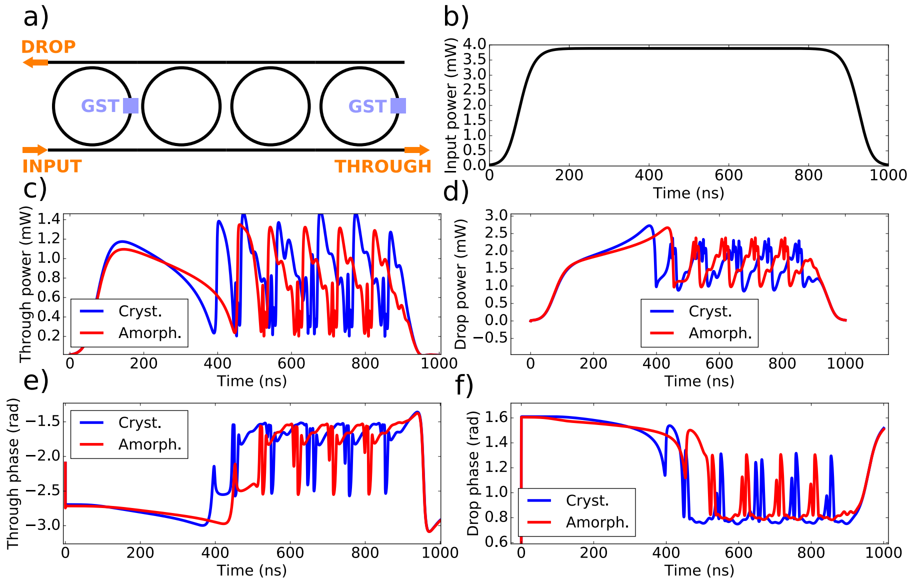

Figure 1: a) Schematic of the simulated RR network. b) Input optical waveform employed to trigger self-pulsing behaviour. c), d) Power of the optical waveform at the two output ports, for minimum (blue) and maximum (red) GST amorphization level. e), f) Phase shift, w.r.t. the input phase set to 0, of the optical signal at the two output ports.

2.2 Experiment

In this section we present the experimental characterization of a plastic node (silicon RR with PCM cell) similar to the one simulated and investigated in [9]. The photonic integrated circuit was fabricated through e-beam technology, using shallow-etched waveguides. The considered RR has a radius of 15 μm and a coupling gap of 350 nm. In order to investigate the energy efficiency and the contrast of memory operations (both of GST amorphization and recrystallization), we inserted a series of short optical pulses into the RR input port, so to trigger changes of the solid-state phase of the GST cell. In particular, a single optical pulse of 10ns duration was employed for GST amorphization, while for recrystallization we used a sequence of 100 pulses of the same duration, each separated by time intervals of 10ns, with total length of 2μs. It should be stressed that we considered this type of recrystallization waveform, instead of the double-step pulse usually employed [8], so to demonstrate that the repetition of the same type of pulse used for amorphization (although possibly with different peak power) can reverse the memory state as well. This is particularly important to achieve the plastic behaviour of the node, whose memory states need to be fully accessible employing the same input signal shape.

By suitably setting the peak power of the input optical pulses we could achieve different GST amorphization levels, i.e. intermediate memory states, each showing a different resonance dip in the acquired RR spectrum at the THROUGH port (Fig. 2 a). The chosen pulse wavelength is 0.06 nm larger than the resonance wavelength (corresponding to the minimum spectrum point) when the GST is fully crystalline. In accordance with the RR theory, we ascribe the resonance dip changes in width and depth to variations in the GST cell absorption: a higher GST crystalline fraction implies a higher optical absorption, and thus a larger width and smaller depth of the resonance dip. Moreover, the GST solid-state phase also affects the effective refractive index of the corresponding waveguide segment, which in turns modifies the resonance wavelength. In particular, a larger crystalline fraction implies a larger effective refractive index and thus a larger resonance wavelength. Importantly, this effect further increases the achievable optical contrast due to different memory states, and therefore represents an additional advantage of employing a GST cell on a RR rather than on a straight waveguide, whose transmission is much less affected by variations in effective refractive index. It should be stressed that we achieved a significantly higher optical contrast due to memory operations when experimentally investigating our plastic node w.r.t. what we previously predicted through simulations [9].

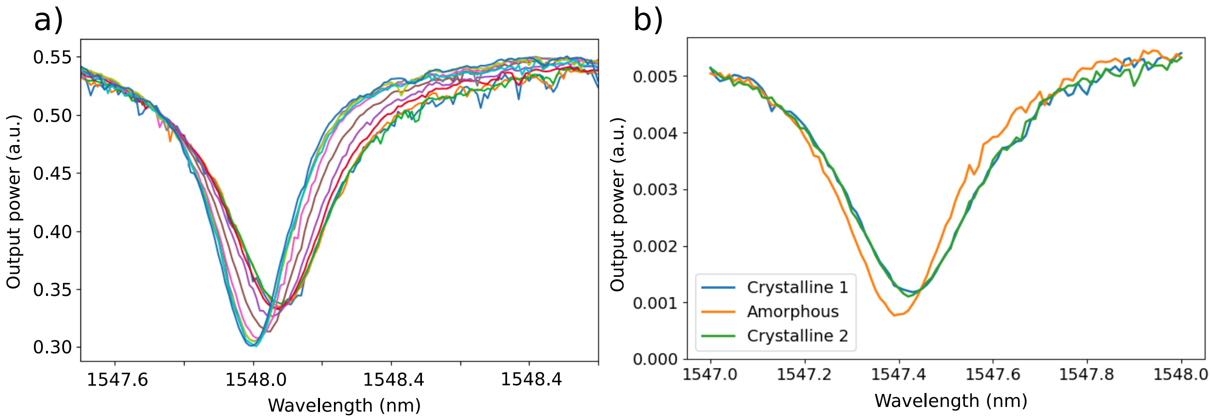

Figure 2: a) Linear response of a plastic node (RR spectra showing resonance dips at the through output port) for different GST crystallinity levels, reached by insertion of a single (amorphization) or multiple (crystallization) optical pulses. b) Resonance spectrum of a plastic node, showing the non-volatile effect of single-pulse amorphization (from "Crystalline 1" to "Amorphous") and single-waveform recrystallization (from "Amorphous" to "Crystalline 2").

Let us now discuss an example of the maximum GST amorphization level, and the corresponding optical contrast, reachable with a single pulse and reversible with a single recrystallization waveform (comprising several pulses). In Fig. 2 b, we can see the resonance spectra of a plastic node, corresponding to the following memory states and operations:

1. Initial crystalline GST state (labelled as "Crystalline 1" in the legend).
2. Partially amorphized GST after the insertion of an amorphization pulse of around 14mW peak power, conveying around 0.14nJ of energy (labelled as "Amorphous" in the legend).
3. Return to initial crystalline state, after the insertion of a recrystallization waveform, consisting of pulses with around 1mW peak power, conveying a total energy equal to around 1nJ (labelled as "Crystalline 2" in the legend).

A reversible optical contrast greater than 40% is achieved. In comparison, to achieve a reversible optical contrast of 15% with a GST cell on a straight silicon waveguide (i.e. without the advantages of exploiting the RR resonant behaviour), an amorphization pulse 100ns long and with 1.6nJ energy is required, and a recrystallization double-step pulse, 530ns long and with 3.6nJ energy. Therefore, our plastic node shows the following improvements w.r.t. its straight waveguide counterpart:

- More than double optical contrast.
- More than a factor 10 in amorphization energy efficiency.
- Almost a factor 4 in recrystallization energy efficiency.
- A factor 10 in amorphization speed.

The considered recrystallization operation, instead, is more than 3 times slower (although we did not try to maximize the speed), but it employs a sequence of single-step pulses, instead of double-step pulses. This aspect is key for the network plasticity property, since we want the same input shape to be able to change the memory states of the plastic nodes in both directions, allowing for a more flexible network adaptability.

3. CONCLUSIONS

In this article we discussed a numerical and experimental investigation of a silicon RR with a short (≤1 μm) GST cell, which can take the role of plastic node (a building block providing the plasticity property) in an all-optical plastic neural network based on silicon RRs. Through numerical simulations, we showed that the GST memory state can modify the timing, delay and shape of pulses generated (via the self-pulsing effect) by a small network of four RRs. This mechanism could be used for on-chip training of all-optical spiking ANNs or to introduce plastic adaptability into such networks. Moreover, exploiting the RR resonance, we experimentally demonstrated significant improvements of memory operations w.r.t. a GST cell on a straight silicon waveguide, in terms of energy efficiency and speed. We argue that these enhancements are key to develop scalable plastic photonic ANNs based on silicon RRs.

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