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WP1

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(WP Leader WWU)

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Contributors: WWU (Wolfram Pernice, Johannes Feldmann) UOXF (Harish Bhaskaran, Wen Zhou)
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Summary

Photonic integrated circuits offer the capability to realize complex optical functionality in a chipscale framework. In analogy to electrical integrated circuits, optically integrated devices can be combined into advanced circuit architectures which deliver a desired optical response. Using established fabrication recipes developed for integrated electrical circuits, many optical components can be efficiently prepared and assembled on chip. This way scalable design routines can be used to fabricate next-generation photonic components. Particularly attractive about integrated photonic devices is their inherent broadband optical response. Photonic waveguides support a broad wavelength spectrum and are thus able to operate on many wavelengths in parallel. These wavelengths can be individually addressed using wavelength division multiplexing (WDM) techniques which can be seamlessly integrated into photonic circuits. In the Fun-COMP project we employ microring resonators coupled to photonic bus waveguides as frequency selective filters to implement compact WDM multiplexing devices on chip. By tailoring the geometry of the ring resonators desired wavelengths can be conveniently selected and be used to add or subtract wanted wavelengths onto common broadband bus waveguides. We employ these concepts to create interference-free on-chip power adders needed for the optical implementation of photonic spiking neurons, as well as a convenient tool for addressing photonic memories in an integrated framework. We also use WDM techniques to carry out matrix-vector multiplication optically.

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1. Introduction and background

Top-down nanofabrication with reproducible recipes enables realizing the optical analogue of electrical integrated circuits on chip. In photonic integrated circuits, suitable optical elements are joined into complex circuits using nanophotonic waveguides as connecting elements. These waveguides do not show strong wavelength selectivity and thus support a broad spectrum. In order to separate desired wavelengths from a large signal bandwidth wavelength, selective elements are needed. In order to realize a small device footprint, microring resonators are an attractive choice. These devices can be efficiently coupled to broadband waveguides, as shown in Figure 1 and provide sharp resonances when optical resonance conditions are fulfilled. Ring resonators come in many forms (e.g. rings or racetracks).

Figure 1. (a) Top-view SEM image of a fabricated racetrack resonator, side coupled with a bus waveguide. The focusing grating couplers are used for light coupling with optical fibres. (b) Measured transmission spectrum of the entire device.

Figure 1(a) shows a top-view scanning electron microscope (SEM) image of a racetrack resonator, which is side coupled to a bus waveguide. Figure 1(b) shows measured transmission spectrum of the entire device. There are 4 prominent resonant dips with well-defined separation, i.e., free spectra range. If the optical round trip length of a ring is an integral number of wavelengths, a resonance can be formed with enhanced light intensity. The ring/racetrack resonator functions as a wavelength filter due to the destructive interference between the incident light in the bus waveguide and resonant light coupled from ring to bus waveguide in the evanescent coupling region. On resonance, completely destructive interference can be obtained, with nearly zero transmission when the critical coupling condition is satisfied, i.e., coupling coefficient in the coupling region equals the round trip loss in the ring resonator. This makes the optical ring resonator an ideal notch filter, blocking transmission of light at the resonant wavelength. The over (under) coupling condition is satisfied when the coupling coefficient is larger (smaller) than the round trip loss, which reduces extinction ratio of the resonant dips. The performance of a ring resonator can be conveniently accessed through the quality factor which is defined by the ratio of resonant wavelength and 3-dB bandwidth, i.e., the narrower the dip, the higher the quality factor. High quality factors are useful in sensing, light modulation, and transduction applications. Traditionally such resonators are passive elements and therefore their resonance condition cannot be modified after fabrication. In the Fun-COMP project we employ phase-change materials (PCMs) as an active medium to alter the filter response of ring resonators dynamically, after fabrication. These PCMs can be switched all-optically and thus do not require electrical connections on chip. Through this approach, tunable WDM elements can be realized in a compact format. Because the ring resonators can be realized by scalable
2. Result and discussion

Active tuning of WDM elements on chip is often required after fabrication in order to adjust the wavelength response dynamically. Particularly attractive are tuning solutions which remain even after removing power input (i.e. are non-volatile). Such non-volatile tuning mechanisms can be achieved by combining passive photonic devices with active materials. When deposited onto nanophotonic waveguides, thin film active elements interact in the evanescent near-field with propagating optical modes. This way light guided on chip can be used conveniently both for carrying out the tuning operation, as well as the optical readout with the same device.

Tunable non-volatile WDM devices

Non-volatile photonic switching and light routing can be realized by combining the ring resonators and phase change materials. Specifically, the resonance with initially critical coupling is shifted in wavelength, along with a change in extinction ratio, when the phase change material (Ge\(_2\)Sb\(_2\)Te\(_5\), or GST for short, in the examples shown here) is switched from amorphous to crystalline states. This is due to the refractive index contrast (different \(n, k\)) between the states, a contrast that is maintained over a broad spectral range covering visible and infrared wavelengths. Examples of such tuning effects are shown in Figure 2, for racetrack resonators with various sizes of GST cells (note that these results were obtained by Fun-COMP partners prior to the start of the Fun-COMP project itself).

Figure 2. (a) Optical microscopic image of an array with 25 different ring (racetrack) resonators elements. (b) Comparison between resonances of the devices with the GST cell in the crystalline and amorphous states, for different GST cell sizes. The relative shift of the central wavelength can be observed, as well as the reduction of the \(Q\)-factor when peaks get broader. Switching and “inversed switching” were observed in the highlighted regions in green and yellow, respectively.

Ring resonators of the type shown in Figures 1 & 2 are, within Fun-COMP, fabricated in either SiN or Si waveguides. For the case of the devices of Fig. 2(a), for example, we used silicon nitride-on-insulator substrates with 330 nm stoichiometric Si\(_3\)N\(_4\) on 3300 nm buffered SiO\(_2\), which allow us to obtain high-quality nanophotonic components with low propagation loss at telecom wavelengths. Photonic circuitry was defined using a combination of electron-beam lithography and reactive ion etching. Using a lift-off procedure, a section of each waveguide was covered with a 10 nm thick GST cell, realized after a second lithography step and sputtering in argon atmosphere. In order to prevent oxidization of the GST, it is capped with a thin layer of indium tin oxide (ITO). ITO is optically transparent for the entire visible spectrum and provides...
moderate loss at near-IR wavelengths, which allows optical access to the active phase-change material layer with the added advantage of being highly conducting, paving the way for future work on electro-optical mixed-mode devices.

**WDM-enabled non-volatile integrated photonic memories**

The use of wavelength division multiplexing (WDM) to potentially increase the storage capacity of integrated phase-change photonic memories was demonstrated (by project partners) prior to the start of the Fun-COMP project. We give brief details of that approach in *Figure 3*, in order to provide useful background to the general reader. In the approach of Fig.3, multiple microring resonators, each tuned to a different wavelength and each having its own integrated phase-change cell, were used to store data sent using WDM techniques along a common coupling waveguide.

![Figure 3](image)

**Figure 3** WDM-enabled all-optical memory. (a) Schematic of a WDM-enabled memory device. (b) Actual fabricated device of the type shown in (a). (c) Readout pulses from the device shown in (b), as the GST cell in each microring is selectively written and erased. [(b) and (c) taken from C. Ríos et al., *Nat. Photon.* 9, 725 (2015)].

**WDM-enabled matrix vector multiplication**

Having demonstrated, prior to the start of Fun-COMP, the basic resonant properties of interated phase-change ring and racetrack resonators, and their use for WDM-based photonic memory, initial WDM-related work within the project focused on an exploration of WDM techniques for processing applications. In particular, we investigated the possibility of carrying out matrix-vector multiplications using integrated phase-change photonic devices and WDM techniques. Matrix-vector (MV) multiplication is a key operation underpinning much of modern ‘data science’, from image processing to machine learning, data analytics etc. At the heart of MV operations is the scalar multiplication, \( c = a \times b \). We can perform this multiplication directly using a single phase-change cell. We do this by coding the multiplier, \( a \), into the transmission state of the cell (i.e. by setting the cell to a particular multilevel state) while the multiplicand, \( b \), is coded into the (optical) power, \( P_{in} \), of the readout pulse. The result of the multiplication, \( c \), is thus calculated directly and appears as the power, \( P_{out} \), of the readout signal, see *Figure 4*(a).

In Fig. 4(b) we demonstrate 429 multiplications, choosing arbitrary values for \( a \) and \( b \), with the associated error (difference between the exact and the measured value of \( c \)) shown in Fig. 4(c).
We found good agreement between the exact and the measured value of the multiplication, having an error that spreads as $a$ and $b$ get larger (as shown in the inset of Fig. 4(c)). While the results of the multiplication are not exact, it can still find application in many areas of AI that do not need high-precision. Moreover, in application domains where arbitrarily high accuracy is required, ideas such as mixed-precision computing (see Le Gallo et al., Nat. Electron. 1, 24 (2018)) can be used where the low precision multiply unit is used in conjunction with a high precision unit.

By using multiple cells and appropriate photonic circuit architectures, it is relatively straightforward to extend this approach to deliver direct MV multiplication. An experimental implementation of the multiplication of a $[2\times1]$ matrix by a $[1\times2]$ vector is shown, for example, in Fig. 4(d). Here we use WDM to code the two vector elements ($P_1$ and $P_2$) into the optical powers of pulses sent into the device at two different wavelengths. The matrix elements (here $G_{11}$ and $G_{12}$) are written into the phase-state of the two GST cells integrated with each waveguide. The outputs from the two waveguides separate waveguides are coupled together in the output waveguide and passed to a photodiode whose output is the result of the MV operation.

A major advantage of the use phase-change cells to store the matrix elements is that in applications where the same matrix elements are repeatedly used (e.g. in convolution-based processing), the programming of the matrix values needs to be done only once (since the cells are non-volatile). Thereafter the MV multiplication can be carried out extremely quickly indeed (using short, WDM optical pulses) and with very little energy budget.

![Figure 4](image_url)

**(a)** Direct multiplication using a single photonic phase-change cell. **(b)** Linearity of and **(c)** error in, the resulting multiplication process. **(d)** Experimental implementation of a $[2\times1] \times [1\times2]$ MV multiplier. **(e)** Experimental demonstration of multilevel capabilities and the apparent absence of level drift in the optical memory (the latter in stark contrast to the very significant resistance drift seen in electrical phase-change memories).
Low-loss WDM components using GeSe₃ thin films

The archetypal PCM Ge₂Sb₂Te₅, as used in the devices described above, and commonly used (inside and outside of Fun-COMP) to realize phase-change photonic devices, has a relatively strong optical absorption (high k value), particularly in the crystalline phase. This can limit performance efficiencies in certain applications, and potentially complicates device level integration (e.g. by potentially requiring additional optical amplification stages). ‘Novel’ PCM compositions with lower optical losses, e.g. Se-substituted GST, or GeSbSeTe, have recently been described in the literature (e.g. Zhang et al., Optics Letters Vol. 43, pp. 94-97, 2018), and may be attractive alternatives to GST in certain applications.

Within Fun-COMP, we have also explored alternative, low-loss, materials. One example is the chalcogenide glass GeSe₃; this is not a PCM per se, instead it undergoes thermally-activated structural changes to its amorphous phase which bring about a corresponding change in refractive index (Ghazi et al., Nano Lett. 19, 7377–7384, 2019). GeSe₃ has very low optical absorption, yet tunability in the refractive index (real part) of the material can be exploited in tuning the spectra of ring resonators. For example, Figure 5(a) illustrates an optical racetrack resonator fabricated from Si₃N₄ followed by the deposition of 150-nm GeSe₃ film. The optical and structural changes of GeSe₃ during thermal annealing affect the effective refractive index (nₑffective) of the waveguide region with GeSe₃ on top, as clearly shown in the inset of Fig. 5(a). Comparing with a control device without GeSe₃, the waveguide with GeSe₃ as deposited has a higher nₑffective with the mode centre shifted towards the GeSe₃ cell. This contributes to mode scattering inside the racetrack, affecting the quality factor of the resonator. After annealing, the effective index of Si₃N₄/GeSe₃ decreases, which reduces the mode scattering and results in an increased Q factor. The transmission spectra after different annealing temperatures are illustrated in Fig. 5(b). Using Lorentz function to fit each resonant peak, we obtained the Q factor of the resonator, shown in Fig. 5(c), and find that the Q factor is evidently increased after annealing. Furthermore, the resonance wavelength of the device with GeSe₃ could be tuned step-wisely through annealing. In addition, the free spectral range (FSR) for both devices are very consistent and not affected by annealing. It should be noted that the thermally-induced change in refractive index of GeSe₃ is non-volatile, but, at least at the present time, non-reversible.

![Figure 5](image-url)

**Figure 5.** (a) Optical micrograph of a racetrack resonator with a 150-nm GeSe₃ thin film (red dashed box). The input and output grating couplers of the device are highlighted by the yellow arrows. Bottom inset: Simulations of the mode profile (cross-section) of the waveguide with GeSe₃ in the as-deposited and annealed (380 °C) states. (b) The transmission spectrum of the racetrack resonator after annealing at different temperatures. Each curve is normalized to its maximum transmission (RT corresponds to the device before annealing). The arrows show typical resonant peaks of the device with step-wise blue shifts observed as the function of annealing temperature. (c) The calculated Q factor of the device as a function of both the wavelength and annealing temperature.
WDM components in photonic spiking neural networks

The ring resonator approach can also be used to efficiently join, using WDM techniques, desired optical signals on a common bus waveguide. This functionality is essential for carrying out addition of optical signals without interference. Within Fun-COMP we have, for example, used ring resonator devices to carry out weighted addition of input signals for implementing spiking neurons on chip. These devices use WDM ring resonators as multiplexing elements, and tunable WDM resonators for realizing threshold behavior in spiking neurons. An optical micrograph of several such neurons combining both passive and active WDM elements is shown in Figure 6. Each line in the image represents one single neuron with four input ports, and one tunable ring resonator with crossed waveguide on the right side for spike generation. The devices are realized by electron beam lithography and subsequent dry etching and thus employ established nanofabrication routines. The spiking resonator is equipped with a nanoscale PCM element, which is fabricated via sputter deposition and lift-off processing. The input ring resonators multiplex weighted optical driving signals onto the waveguide leading to the spiking neuron, thus superimposing on the input waveguide to the neuron the summed, weighted contributions from the all the pre-neuron (plastic) synapses (which are themselves implemented with a near-field coupled PCM element deposited on the input waveguide to the ring resonators).

Different wavelengths are selected as inputs by varying the radius of the ring resonators. This geometric modification shifts the resonance wavelength of each ring resonator to a desired spectral position, is chosen at the design step. In the telecommunication wavelength range a near-linear relationship between the ring radius and the resonance wavelength exists, and thus allows for convenient selection of the resonance wavelength. Because the fabrication approach is fully scalable, a large number of resonators can thus be realized in each device to embed WDM capability.

![Figure 6](image_url) (a) Optical micrograph of an artificial photonic spiking neuron employing WDM capability. Four ring resonators are used to multiplex optical input signals 1-4 onto a common waveguide leading to a tunable WDM ring resonator which provides spiking capability. The tunable resonator is fabricated with a crossing waveguide and uses an evanescently coupled PCM element for non-volatile reconfigurability.

3. Conclusions and next steps

With both passive and actively tunable WDM integrated phase-change photonic elements now developed within Fun-COMP, advanced photonic neuromorphic and arithmetic processing architectures can be realized. Using top-down fabrication, these individual elements will be joined into larger networks comprising various functional elements. An immediate application
is the implementation of layered spiking neural networks. Having established multi-neuron single layer architectures, the scalable fabrication routines can be directly transferred to the realization of deeper network architectures, capable of processing more complex optical inputs. Arithmetic processing, in particular scalable array-based approaches to matrix-vector multiplication, can also be developed. WDM elements will play an essential role in these architectures, to route and combine optical signals on different wavelengths in a deterministic fashion.