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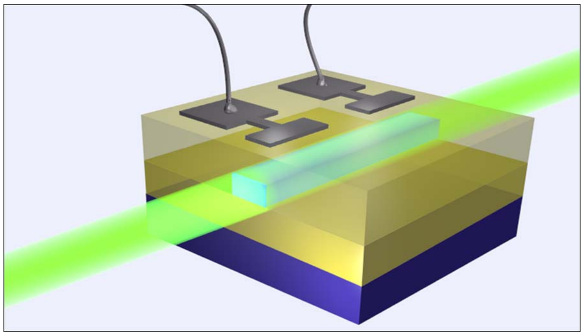

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Breakthroughs in Photonics 2013: Toward Feedback-Controlled Integrated Photonics

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Abstract: We present an overview of the main achievements obtained in 2013 on the monitoring, stabilization, and feedback loop control of passive and active photonic integrated circuits. Key advances contributed to the evolution of photonic technologies from the current device level toward complex, adaptive, and reconfigurable integrated circuits.

Index Terms: Optical waveguides, photonic integrated circuits, silicon photonics, photodetectors, microring resonators.

1. Introduction

The extreme device miniaturization reached by state-of-the art photonic technologies now enables the realization of hundreds or even thousands of photonic elements in a footprint of less than 1 mm^2 [1]. Although a large number of building blocks potentially provides the required degrees of freedom to realize flexible and arbitrarily complex photonic architectures, reconfigurable optical circuits aggregating many different functionalities are still encountering strong difficulties to emerge. The reason is that in photonics, similarly to electronics, device miniaturization is not synonymous with large scale of integration, and some keys still need to be found to make photonics step up from the current device level to complex, adaptive and reconfigurable integrated circuits.

The potential of arbitrarily reconfigurable photonics and the enabling conditions at which it can be realistically achieved have been recently envisioned by Miller [2]. He demonstrated that a set of optical elements, like the arrangement of Mach–Zehnder interferometers (MZIs) shown in Fig. 1(a), can self-configure to perform any linear function between input and output ports [3]. Feedback-control is mandatory to steer and hold the entire system to the desired functionality, and make it immune to fabrication tolerances, functional and environmental drifts, and mutual crosstalk effects. Local feedback loops, setting individual optical elements within the circuit, appear a more viable route than global multiparameter optimization of the entire system, yet requiring multipoint monitoring of the circuit status through transparent on-chip detectors.

The vision of “self-configuring” integrated photonics timely and nicely meets key advances that have been reported in 2013 on the monitoring, tuning and stabilization of integrated optical devices.

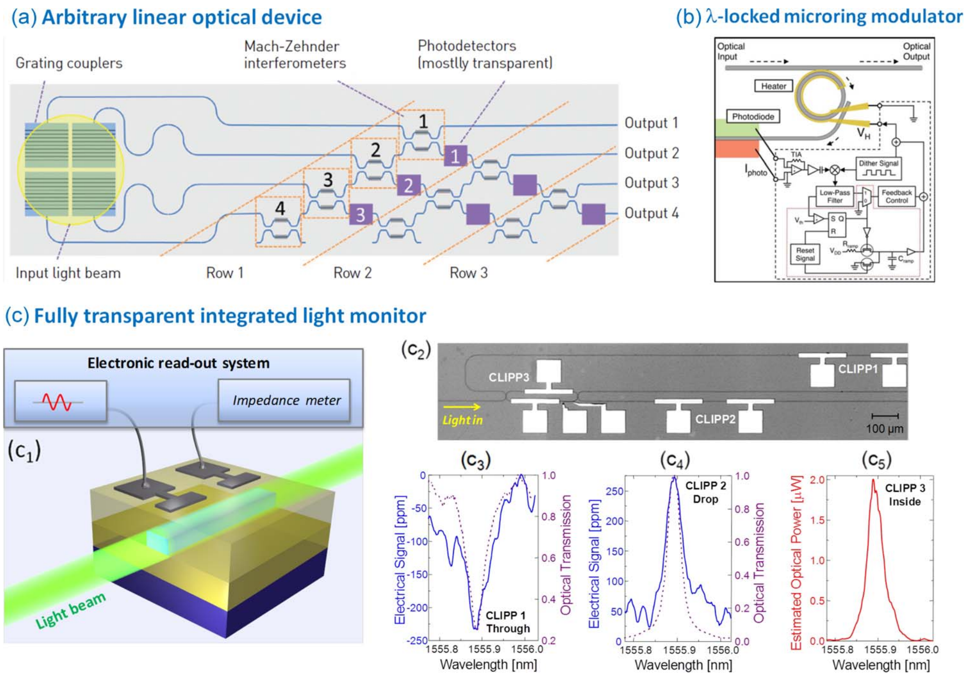

Fig. 1. (a) Schematic of a self-configuring linear optical component (reproduced from 2013 OSA [3]); (b) Schematic of a thermally stabilized microring resonator exploiting a low-speed integrated photodetector and dithering signals for automated locking of the microring resonant wavelength (reproduced from 2014 IEEE); (c) Fully transparent integrated optical monitor. (c_1) Schematic of the CLIPP concept; (c_2) Top-view photograph of a racetrack microresonator with CLIPPs integrated at Through port (CLIPP1), at the Drop port (CLIPP2), and inside the resonator (CLIPP3); (c_3) Through and (c_4) Drop port transmission measured with an external OSA (purple dashed curves) and with the on-chip CLIPPs (blue solid curves); (c_5) Optical power inside the resonator estimated from the electric signal of CLIPP3 (adapted from 2014 IEEE [30]).

Recent developments demonstrate that keeping photonics under control is a common goal targeted by many research groups. Research efforts in this field have been mainly focused on the mitigation of temperature sensitivity of optical waveguides and circuits, on feedback locking and stabilization of passive and active devices, and on the development of non-invasive techniques for on-chip light monitoring. The most relevant results are briefly summarized in this review.

2. Athermal Photonic Waveguides and Circuits

Sensitivity to temperature fluctuations is one of the strongest limiting factors to the exploitation of integrated optical devices. This effect is particularly relevant in silicon photonics, where the large thermo-optic coefficient (TOC) of silicon $(k_{\mathrm{th,Si}} \sim 1.8 \times 10^{-4}\ \mathrm{K}^{-1})$ is responsible for a wavelength shift of any interference-based device of about 10 GHz K^{-1}.

Three main approaches can be followed to counteract thermal effects in integrated photonics circuits: athermal optical waveguides, thermally self-compensating passive optical circuits and active thermal compensation by means of actuated waveguides. The main achievements reported in 2013 on these three techniques are here briefly summarized:

i) *Athermal optical waveguides*. Temperature sensitivity in optical waveguides can be mitigated by cladding the waveguide core with a material with a negative TOC [4]. Polymer materials were extensively investigated in the past, but they were addressed to suffer from chemical instability, mechanical weakness, and poor compatibility with CMOS process. In 2013, many research efforts were focused on the use of TiO_2 as a cladding material of silicon waveguides [5], [6], because it is one of the few CMOS compatible materials exhibiting negative TOC $(k_{\mathrm{th,TiO2}} \sim -1 \times 10^{-4}\ \mathrm{K}^{-1})$. By suitably engineering the mode confinement in the waveguide,

TiO_2-cladded microring resonators with a resonant shift as low as -1.6 pm K^{-1} (over a range of 5 K) for TE polarization [5] and a comparable shift for TM polarization [6] were demonstrated at 1550 nm. The price to be paid is the increase of the waveguide propagation loss (up to 8 dB/cm [5] and 16 dB/cm [6]), which is expected to decrease by reducing the scattering at Si-TiO_2 interface [7]. By following the same approach, the temperature dependent wavelength shift of hybrid SiN-TiO_2 microring resonators was reduced down to 0.073 pm K^{-1}, which is almost two orders of magnitude lower than that of the uncladded SiN resonator [8]. Advantageously, this method can be applied to different waveguide technologies, including plasmonic waveguides [9], and to generic optical circuits. However, recent investigations pointed out that thermo-stress-optic effects can suppress the large negative TOC of TiO_2 (by more than two orders of magnitude) if the material is not allowed to thermally expand [10], this effect constraining the design of the waveguide.

As a drawback, athermal waveguides cannot be thermally tuned. Therefore, to counteract fabrication tolerances, alternative mechanisms are required to modify the waveguide properties. The first athermal and trimmable waveguide was demonstrated in 2013 by sandwiching a thin layer of photosensitive As_2S_3 chalcogenide glass between the silicon waveguide core and a negative TOC polymer cladding [11]. Resonant wavelength trimming of a microring resonator was achieved over 10 nm (corresponding to about 5 Free-Spectral-Ranges), while maintaining a temperature dependent wavelength shift of less than ±5 pm K^{-1} over a 50 nm wide wavelength range.

ii) *Thermally self-compensating passive optical circuits.* Some interferometric devices, such as MZIs, can be designed in such a way to be robust against temperature fluctuations, even though the waveguide is inherently temperature sensitive. Two different circuit designs were proposed in 2013 where the two arms of the interferometer either have different width [12] or operate on orthogonal polarization states [13] in order to cancel out the temperature dependence of the overall circuit. This technique has the advantage to avoid the deposition of an additional thermally compensating material, but typically results in a larger circuit footprint [14] and is hardly applicable to generic circuits [15].

iii) *Active thermal compensation.* Integrated optical actuators are a largely used approach to compensate thermal fluctuations by keeping the local temperature of the device at a constant value. Silicon waveguides are conventionally actuated by means of microheaters, that are resistive elements realized around the waveguide, or by carrier injection/depletion/accumulation effects in diode junctions embedded into the waveguide. In 2013, Zhou *et al.* demonstrated that the silicon waveguide itself can be effectively used as a resistive microheater by embedding a *p-i-p* junction in the waveguide [16]: a heating time response of 460 ns (1.1 μs cooling time) was demonstrated with a power consumption of 35 mW per 2π-phase shift.

Power dissipation is actually the main drawback of active thermal compensation. Thermal insulating trenches can be realized around the waveguide to increase the power efficiency, yet at the price of a higher response time; resistive heaters with power consumption in the order of 1 mW per π-phase shift and a time response higher than 150 μs were demonstrated in thermally insulated silicon waveguides [17]. Recently, extremely low-power (2 fJ/bit) thermal stabilization over 10 K was achieved by Timurdogan *et al.* in a high-speed (25 Gb/s), low voltage (0.5 V_{PP}) silicon microdisk modulator by exploiting an ultra large electro-optic effect response (250 pm/V) in a vertical p-n junction device [18].

With respect to passive approaches, active thermal compensation requires also a control system to drive the actuator and lock the circuit to the desired working point (see Section 3).

3. Feedback-Controlled Photonic Devices

Feedback control circuits need to extract an error signal, with real-time information on the current status of the photonic circuit, and use it to provide a driving signal to the actuated photonic devices. Conveniently, control systems should be low cost, energy efficient, insensitive to fluctuations of the optical power, applicable to both passive and active devices, and should not require additional photonic structures. In 2013, there were significant advances in the development of feedback loop schemes for the stabilization of active and passive devices, especially focusing on silicon microring resonators.

In passive microrings, the symmetry of the optical response around the resonant wavelength requires efficient methods to remove the ambiguity of the wavelength drift direction. Padmaraju *et al.* proposed to use a small dithering signal [19] applied to the resonator to produce a small modulation of the optical signal [see Fig. 1(b)]. By mixing the modulated optical signal with the driving dithering signal, an anti-symmetric error signal providing a non-ambiguous location of the resonance relative to the optical signal is obtained. This scheme is effectively implemented by means of low-speed photodiodes and low-speed ($<$ 20-MHz bandwidth) energy-efficient analog and digital electronics, thus making this approach scalable to architecture comprising multiple microring resonators. Alternatively, a dither-free technique was proposed where the microring is inserted in an interferometric structure in order to realize a homodyne detection scheme [20]; this solution is simple and effective, but it is hardly scalable to circuits integrating a large number of microrings.

Concerning active devices, Padmaraju *et al.* demonstrated, for the first time, error-free operation of a silicon microring modulator in a thermally volatile environment. The resonator wavelength, monitored by measuring the mean power of the modulated signal through a low-speed photodiode, was adjusted by directly setting the DC bias current of the PIN junction of the modulator [21] or through an additional microheater [22]. Error free modulation was demonstrated at 10 Gbit/s by using an external photodiode (against 8 K fluctuations at 5 kHz speed) [21] and at 5 Gbit/s with an integrated defect enhanced silicon photodiode (3 K fluctuations at 10–100 Hz) [22]. An alternative wavelength locking method was proposed in the work by Zortman *et al.* [23], where the error signal is directly provided by a bit-error-rate measurement; thermal stabilization of a 3.5 Gbit/s silicon microring modulator actuated by a digitally driven micro-heater was demonstrated over 32 K temperature variation. This approach guarantees optimum system performance, irrespective of any aging effects or unpredictable drifts in the entire system, yet at the price of a fast detection system.

A novel technique was also proposed to lock a MZI modulator at any desired working point by using as feedback error signal the ratio of first-order harmonic and average output power, thus making the bias control independent of power fluctuations at the input of the modulator [24].

Feedback loop algorithms demonstrated so far can operate at the level of individual devices only and are limited to the control of only one degree of freedom (e.g., the resonance of a microring resonator or the bias point of a MZI modulator). Reconfiguration and stabilization of complex architectures integrating many devices are likely to require many concurrent feedback loops, each one locally controlling a small subset of devices. Local feedback is a promising solutions because it enables to operate on a few degrees of freedom [2], thus reducing the complexity of control algorithms, but it implies the need for local monitoring of the circuit by means of transparent optical detectors [see Fig. 1(a)].

4. On-Chip Transparent Monitoring

Feedback control of photonic integrated devices requires real-time information on the current status of the circuit. In the aforementioned works [19]–[24], this operation is done by tapping a portion of the light from the waveguide and detecting the optical signal with an external or integrated photodetector. In silicon photonics, the waveguide itself can be used as power monitor at 1550 nm, by exploiting photocarrier generation due to two photon absorption (TPA) [25], surface-state absorption (SSA) [26], and defect mediated absorption [27]. Although the loss introduced by these detectors can be relatively low [28], when many devices are integrated in a complex photonic circuit, the number of probing points increases accordingly [2], so that any light attenuation or perturbation should be avoided [29]. The development of transparent waveguide power monitors has been always considered one of the key challenges for integrated optical technology [29].

The first fully transparent integrated power monitor was demonstrated in 2013 by using a ContactLess Integrated Photonic Probe (CLIPP) [30]. The CLIPP monitors the light intensity in silicon waveguides by measuring the variation of the electric conductance of the silicon core due to intrinsic SSA effects. According to the scheme shown in Fig. 1(c_1), conductance measurement is performed through a capacitive access to the waveguide, by means of two electrodes located at suitable distance from the waveguide core. Compared to the bare waveguide, no extra-photon absorption is induced by the CLIPP, the only measurable perturbation being a small phase perturbation (as low as 0.2 mrad), comparable to that that would be induced by thermal fluctuations below 3 mK. This perturbation completely disappears when the CLIPP driving voltage is switched off. Light intensity can be monitored with a sensitivity of -30 dBm, a dynamic range of 40 dB, and a time response of a few μs. Thanks to the inherent CMOS compatibility and non-invasive nature, the CLIPP can be integrated everywhere inside generic photonic devices, including high Q-factor resonators, thus enabling multi-point monitoring, local feedback and tuning of complex integrated circuit [30]. Fig. 1(c_2) shows the top view photograph of a high-Q silicon microring resonator $(Q = 55000)$ with three CLIPPs integrated at the Through port, at the Drop port, and inside the resonator. Fig. 1(c_3)–(c_4) show the comparison between the spectral response of the resonator measured with a CLIPP and with an external optical spectrum analyzer at the Through Port (c_3, CLIPP1) and at the Drop port (c_4, CLIPP2). The CLIPP can also provide the power inside the ring resonator (c_5, CLIPP3), this information being usually not accessible with conventional power monitors without altering the Q factor of the resonator.

Since the working point of an individual device can be monitored regardless of the presence of other cascaded photonic elements, the CLIPP is a promising light observer for the implementation of local feedback loops in complex integrated architectures.

5. Conclusion

Key advances have been achieved in 2013 on the on-chip monitoring, tuning, and feedback control of integrated devices. Novel building blocks have been developed, which are expected to leverage the evolution of photonic integration toward complex reconfigurable architectures. Future research efforts should address the integration of all these elements on a common photonic platform, the development of more sophisticated algorithms imparting intelligence to the photonic layer, and the realization of more and more energy efficient optical actuators. Concerning low-power actuators, a promising route that is being explored makes use of reversible non-volatile switching elements, based for instance on phase change materials [31]–[33], to realize programmable optical waveguides. Finally, the concept of feedback controlled photonics meets the use of photonic devices themselves as optical feedback elements to enhance system performance, for instance, to realize fast tunable light sources with extremely narrow bandwidths [34]. Breakthroughs in these fields are expected over the next few years.

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