Toward feedback-controlled integrated photonics

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***Abstract*—The evolution of photonic technologies from current device level toward complex, adaptive and reconfigurable photonics integrated circuits pass through the monitoring, stabilization and feedback control loop of each single element. Hitless optical probes, sophisticated algorithms imparting intelligence to the photonic layer, and the realization of more energy efficient optical actuators are the enabling factors for the future of the software defined photonics. The potential of arbitrarily reconfigurable photonics and the enabling conditions at which it can be realistically achieved have been recently envisioned in literature and will be here reviewed and discussed.**

Keywords—Photonics integration; silicon photonics; feedback and control

I. 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), 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 the recent years on the monitoring, tuning and stabilization of integrated optical devices. 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.

II. STATE OF THE ART OF 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 and 2014, there have been 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 [4] applied to the resonator to produce a small modulation of the optical signal. 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 [5]; 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 [6] or through an additional microheater [7]. Error free modulation was demonstrated at 10

Gbit/s by using an external photodiode (against 8 K fluctuations at 5 KHz speed) [6] and at 5 Gbit/s with an integrated defect enhanced silicon photodiode (3 K fluctuations at 10-100 Hz) [7]. An alternative wavelength locking method was proposed in the work by Zortman et al. [8], 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 [9].

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 solution 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.

III. Recent Result on Feedback-Controlled Photonic Devices at Politecnico di Milano

One of the best achievement in the field is the monitoring of the light intensity through a ContactLess Photonic Integrated Probe (CLIPP) [10]. The CLIPP realizes an in-line transparent detector that is here exploited to enable wavelength tuning, locking and swapping of thermally tuned Si microring resonators with negligible perturbation of the optical field.

A CLIPP integrated inside a microring provides information on the resonant wavelength, linewidth, quality factor and field enhancement in the resonator. Figure 1(a) shows the optical intensity versus wavelength measured by the CLIPP for different voltage V_h applied to the thermal actuator. The resonator has linewidth 10.8 GHz, free-spectral-range FSR = 138.6 GHz, and quality factor Q = 18000. As the heater voltage is increased from 0 to 3 and 4V, the spectrum of the resonator red-shifts accordingly.

Here we show the feedback stabilization of a Si microring, by locking its resonant wavelength λ_R to that of an external laser λ_L [Fig. 1b)] thanks to the efficient power monitoring enabled by the CLIPP. A small dithering signal is applied by means of the integrated thermal actuator that provides the control signal able to drive the feedback loop. The normalized optical intensity, measured by the CLIPP inside the resonator as a function of time is reported in Fig. 1b), when the feedback loop is enabled (red line) and disabled (green line), in presence of a continuous detuning of λ_L by 50 pm, corresponding to about 98% of the resonator linewidth.

As λ_R and λ_L shift away from each other, the intensity in the resonator drops if the feedback loop is disabled. On the contrary, when the feedback loop is switched on, no significant variation in the resonant optical power is observed, thanks to the continuous compensation is provided by the feedback loop through the voltage V_h applied to the heater. The error signal is shown in the inset of Fig. 1b), for a sinusoidal dithering with various amplitudes V_d and frequency f_d = 160 Hz. The error signal has an antisymmetric shape, a maximum value along the resonant slope, and vanishes at λ_R and outside the full linewidth of the microring.

Further, we demonstrate that the CLIPP is able to discriminate and monitor various optical signals at different wavelengths, simultaneously. To this aim two signals with wavelengths λ_1 = 1549.5 nm and λ_2 = λ_1+120pm have been injected at the input of the resonator [Fig. 2(a)]. In order to distinguish between λ_1 and λ_2, a weak modulation signal at the frequency f_T=10 KHz, has been added to the optical carrier by means of an external modulator. When the CLIPP read-out system performs the lock-in detection at frequency f_e =1MHz, the CLIPP is unable to identify λ_1 and λ_2. This is shown in Fig. 2(b). However, when the CLIPP performs the electrical demodulation at frequency f_e+f_T, it is straightforward to identify distinctively the two signals. For instance, Fig. 2(b)

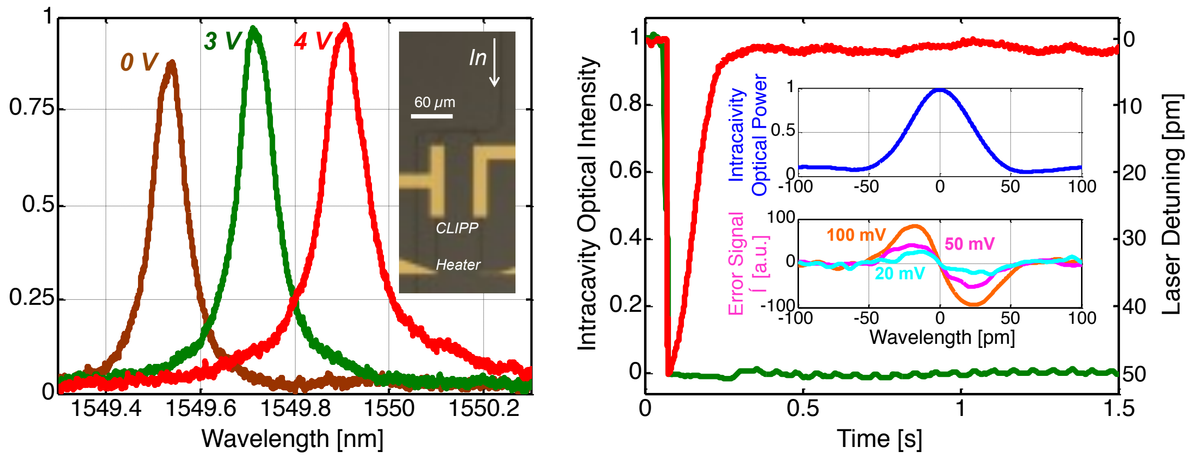

Fig. 1: (a) Tuning of the ring. Normalized optical power inside the resonator measured by the CLIPP integrated in the microring for voltage V_h = 0, 3, 4 V applied to the thermal actuator; (b) Locking. Optical power measured by the CLIPP inside the resonator versus time when the feedback loop is active (red line) and then switched off (green line), in presence of a detuning of the laser by 50 pm. The inset shows the resonator spectral intensity and the error signal δ measured by the CLIPP inside the resonator.

reports the optical intensity in the resonator versus the heater power when the modulation signal f_T is added to the signal at wavelength λ_1: the typical resonant peak is clearly recorded by the CLIPP and the λ_1 signal can be easily identified. Similarly, the case where the modulation tone is added to λ_2 is reported too.

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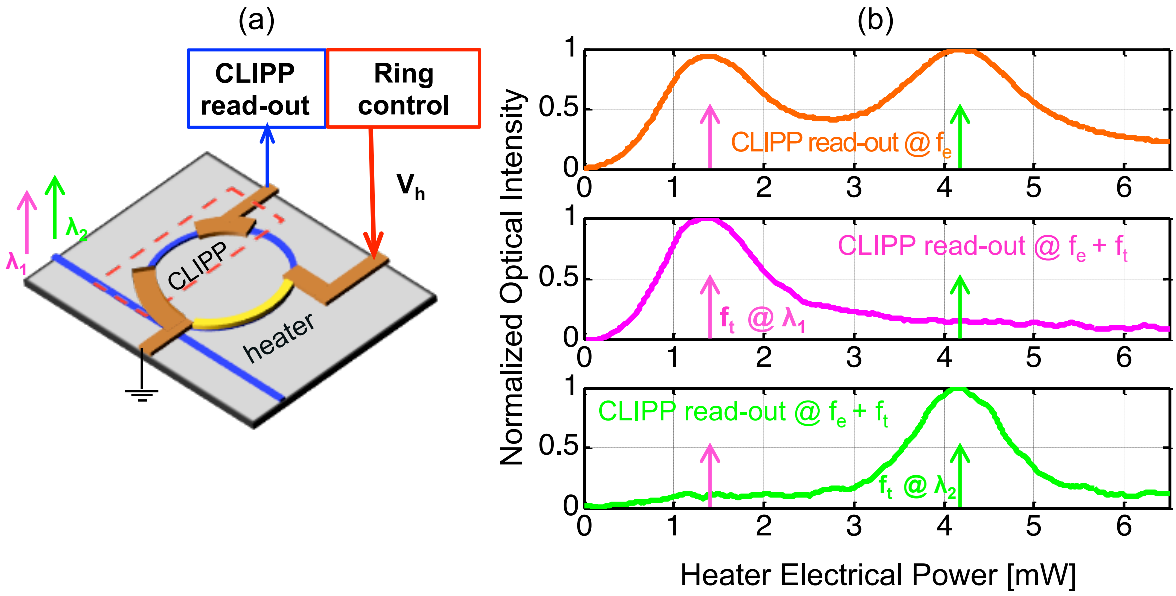

Fig. 2: (a) The ring with the heater and the CLIPP embedded and the readout and control units; (b) Detection of two different signals by the CLIPP with pilot tones.