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Tunable photonic integrated toolbox: from realistic models to control algorithm

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The evolution towards complex photonic circuits integrating many building blocks and functionalities poses major issues on the design as well as on the control of the functionality in real operation conditions. Optical and thermal interactions between single devices, spurious effects, drifts, non-idealities and fabrication uncertainties can prevent the realized circuits to work as expected. As a consequence, advanced photonic devices must be considered as a system to control with feedback loops and algorithms, and the above non-idealities must be taken into account also during the early design stages to evaluate their impact on the circuit behavior and perform robust optimizations towards the parameters of interest.
Here, the estimation of the impact of the tolerances on a tunable delay line and a robust optimization of a filter, are reported. Further, the tools needed to monitor and control a complex circuit are described and an example discussed.

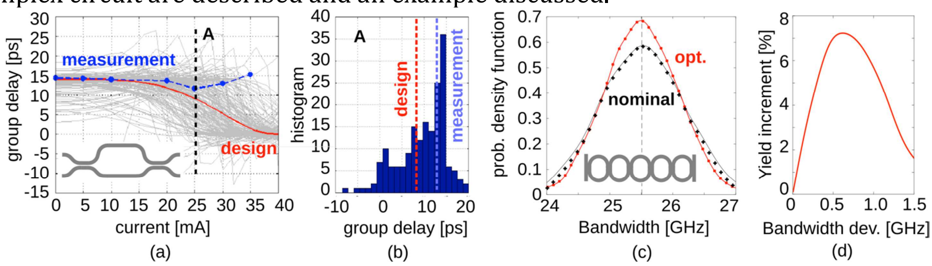

Fig. 1. (a) Group delay of a Mach-Zehnder filter as function of the current fed into the controller of the tunable couplers and (b) histogram at 25 mA. (c) Probability density function of the 3-dB bandwidth of a five-ring-resonator filter for nominal (black curve) and optimized design (red curve). (d) Circuit yield increment for the optimized design.

Circuit simulators enriched by advanced Process Design Kits and complex models are emerging as the right tools to perform this kind of analyses [1,2]. As an example, Fig.1 (a) shows the Monte-Carlo analysis of the group delay of a tunable delay line based on unbalanced Mach-Zehnder Interferometer (MZI) with tunable couplers (realized with two balanced MMI-based MZIs) when exposed to fabrication uncertainties. Group delay is reported as function of the current fed to the thermal actuators used to change the splitting ratio of the two couplers. Simulations were performed with the commercial circuit simulator Aspic [3]. Red curve shows the designed group delay that is expected to drop of about 15 ps applying a current of 40 mA. In order to describe realistic "grand challenge" and a major obstacle to the advent of large-scale photonic integrated systems. The possibility to control the PIC is a key requirement for different reasons and in many applications: i) reconfigurability of circuits to provide the required functionality such as in routers, cross-connects, tunable bandwidth filters, reconfigurable add-drop multiplexers, etc.; ii) adaptive circuits that modify their behavior depending on the state of the system such as signal polarization state, signal to noise ratio, crosstalk, eye aperture, BER, etc.; iii) locking or stabilization of the circuit in a well-defined state independently of the temperature, electrical fluctuations, drifts, stress, aging, etc; iv) compensation of fabrication tolerances and technological non-uniformities. All these requirements become even more critical when dealing with wavelength selective devices, such as microrings resonators, high bit rate signals operating in coherent domain, dense WDM systems and densely integrated PICs realised on semiconductor platforms, such as silicon and indium phosphide InP. Local and global feedback control tools and strategies will soon become the ordinary way to operate even for simple circuits.

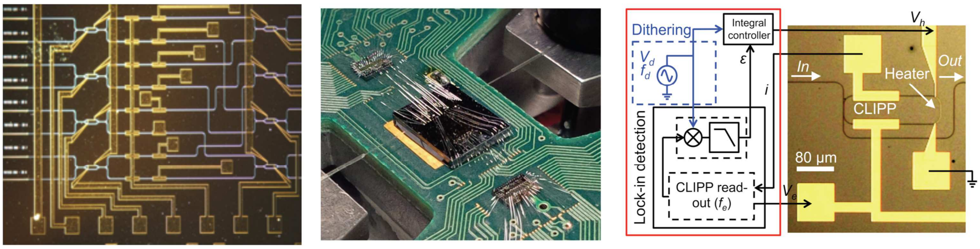

Fig. 2. (from left to right) An 8x8 Silicon Photonic Router with heathers and CLIPPs, mounted on a PCB with two CMOS ASICs for the control and readout and a detail of a ring resonator with feedback control loop.

In order to realize a feedback control loop, light monitors and actuators are required, in addition to an electronic control unit and control strategies. Monitoring approaches based on conventional photodetectors are not effectively scalable to large-scale PICs due to the need for multi-point light tapping. In this work, we report on our recent achievements on the development of an in-line transparent integrated detector, named ContactLess Integrated Photonic Probe (CLIPP) [5,6,7], that can monitor the light intensity in semiconductor waveguides without introducing any photon absorption in excess to the waveguide propagation loss and on the control strategies for PICs. Results shown in this work demonstrate the effectiveness of the non-invasive CLIPP technology for the feedback-control tuning, switching, and locking of silicon PICs. As an example, Fig. 2 shows an 8x8 Silicon Photonic Router with heathers and CLIPPs, mounted on a PCB with two CMOS ASICs for the control and readout and a detail of a ring resonator with feedback control loop. The CLIPPs permits to monitor the circuit in every desired point and control the working points of the various elements individually.

Also, when multiple optical signals are simultaneously injected at different input ports of a circuit, like a switch fabric, CLIPP detectors can be used to identify channels coming from specific input ports regardless of the presence of other concurrent channels injected at the other input ports if these are labelled with a tone with an intensity modulation amplitude of a few percent and a frequency in the order of some

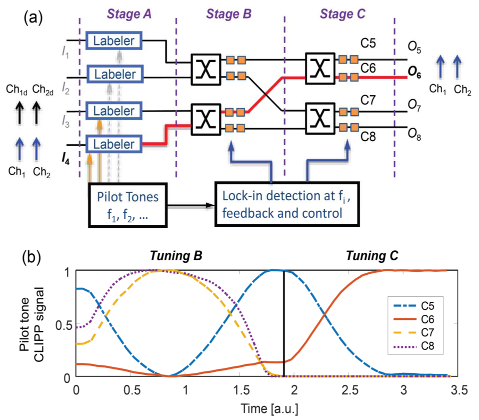

Fig. 3. CLIPP assisted lightpath tracking using on-chip labelling with pilot tones: scheme and CLIPPs signal after the stage B and stage C.

kilohertz. Fig. 3 shows the CLIPP assisted lightpath tracking of concurrent signals distinguished by using on-chip labelling through pilot tones.
In conclusion, we have shown the software tools for the design and analysis of circuits in presence of tolerances, non-perturbative probes for monitoring and feedback algorithms and for locking and control of complex PIC. This toolbox is strategic for a fully exploitation of the capabilities of photonic circuits.

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