Tunable photonic circuits: a leap toward system-on-a-chip optical integration

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Tuning and trimming technologies are key to raising photonic integration from today’s single-device level to future optical architectures.

Recent progress in photonic integration on the generation, manipulation, and detection of light in miniaturized optical chips has contributed to fostering great interest in photonics for many applications, such as data transmission (telecoms, optical interconnects), (bio)sensing, metrology, and quantum computing. However, recent work has given rise to doubts as to which applications could actually benefit from photonic integration. The suggestion is that the main advantages are likely to be found in applications requiring the aggregation of many devices into complex systems, as in microelectronics. This would imply a radical change of thinking from the roadmap followed so far in photonics, where pushing the performance of single devices to the limit has largely prevailed over the search for technological solutions enabling the manufacturing and control of complex on-chip systems.

Moving from research on a single-device level to a system-on-a-chip level gives rise to new issues. First, any single device embedded into a much more complex system needs certain flexibility in its characteristics (e.g., time or frequency domain response). This is essential to make photonic systems reconfigurable, that is capable of adapting themselves to different requirements and operating conditions. Second, when many optical elements are integrated together, the effects of fabrication tolerances, functional drifts, and mutual crosstalk become much more relevant, and must all be accurately counteracted to set and maintain the desired system functionality.

Reconfigurability, adaptivity, trimming, and ultimately programmability, are rather new concepts in photonics, but they are already credited as enabling factors for the ascent of photonics to the system level. A common answer to these requirements is provided by tunable photonics, that is by the use of photonic integrated circuits whose response can be modified within a certain range by means of controllable actuators. Here, we briefly summarize recent progress we have achieved in this field, in working toward tunability for flexibility and trimming to counteract imperfections.

A first example of a tunable photonic device is the integrated variable bandwidth filter of Figure 1(a), consisting of an

Figure 1. Photograph (a) and spectral transmission (b) of an integrated variable bandwidth filter: the bandwidth can be continuously tuned from 23 to 173 GHz by thermally controlling the resonances of the two rings. Photograph (c) and tunability range (d) of a variable delay differential phase-shift keying receiver: the delay of the longer arm (red circles), that is, the baud rate of the receiver (blue squares), can be continuously changed from 66 ps (15 Gbaud) to 102 ps (9.85 Gbaud) by properly setting the resonant wavelength of the rings.

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unbalanced Mach-Zehnder interferometer (MZI), loaded with two identical ring resonators coupled to the shorter arm of the interferometer. The wavelength domain transmission of the filter, shown in Figure 1(b) for one of the two output ports, can be modified by controlling the resonant frequency of the two rings. In our fabricated device, realized on a silicon-on-insulator (SOI) platform, tunability is accomplished by locally heating the circuit through metallic electrodes placed on top of the waveguide. A large bandwidth tunability from 23GHz, less than one-tenth of the 200GHz free spectral range (FSR), to 173GHz (85% of the FSR), is achieved with no appreciable increase of the device insertion loss and keeping an off-band isolation higher than 20dB.

As a second example, Figure 1(c) shows a variable delay MZI receiver for differential phase-shift keying (DPSK) modulation formats. Here, a continuously tunable delay line, consisting of a coupled resonator optical waveguide (CROW) in a reflective configuration, is used to modify the mutual delay between the two arms of the MZI. Each resonator provides a delay between 0 (off-resonance condition) and \( T_{\text{max}} = \frac{2\pi}{B} \), where \( B \) is the CROW bandwidth.\(^6\) Figure 1(d) shows the tunable delay (red circles) and the corresponding baud rate (blue squares) of an SOI DPSK receiver, including a thermally actuated two-ring CROW. The device can be used to optimally detect a DPSK signal with a baud rate spanning from 15Gbaud (66ps delay) to 9.85Gbaud (102ps delay). In both devices, full tunability is achieved with less than 30mW power consumption.

CROWs are a valuable test bed for showing the sensitivity of complex photonic circuits to fabrication tolerances. Consequently, we have employed them in work using trimming to counteract imperfections. In the device shown in Figure 2(a), propagation from the In port to the Drop port is allowed only if all the resonators share the same resonant wavelength. In high index contrast waveguides, deviation of a few nanometers in the waveguide width randomly shifts the rings' resonances and hinders effective light transmission through the resonators' chain. As an example, Figure 2(b) shows in blue dashed lines the In–Drop transmission of a four-ring CROW filter fabricated by using arsenic sulfide (As\(_2\)S\(_3\)) chalcogenide glass waveguides.\(^7\) To counteract fabrication imperfections, we exploited the photosensitive properties of this material, whose refractive index can be permanently modified after chip fabrication by means of visible light exposure.\(^8\) By individually trimming each resonance to the same wavelength (1555.15nm), the transmission of the filter (red solid lines) was restored in very good agreement with theoretical results (black dashed curve).\(^7\) Compared to thermal tuning, after trimming the performance of the device is preserved with no need for continuous power dissipation. The use of As\(_2\)S\(_3\) or other photosensitive materials embedded into conventional waveguides is being explored to extend the potential of the trimming procedure to other photonic platforms, such as SOI.

In summary, we have shown that tunable photonic integrated circuits are key to fulfilling the emerging needs of system-on-a-chip applications, which require greater flexibility, adaptive reconfigurability, improved performance, and a high fabrication yield. However, advanced circuit architectures assisted by tuning/trimming technologies are not yet sufficiently developed to reliably control complex photonic integrated systems. An open issue to solve is how to locally inspect the status of a circuit without perturbing the circuit itself. Such ‘hitless probing’ is still a weak point of photonics compared to electronics. A solution to the problem is one of the main targets of our research in the field.

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**Figure 2.** (a) Schematic of the selective photoinduced trimming technique applied to coupled ring-resonator circuits. (b) Normalized spectral response of a four-ring arsenic sulfide filter at the Drop port: measurement before (dashed blue lines) and after (red solid lines) photoinduced trimming are compared with theoretical curves (dashed black lines).
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