Engineered Reflections in Silicon Ring Resonator: A New Degree of Freedom for Design

A. Li[1,2], and W. Bogaerts[1,2]

[1] Photonics Research Group, Ghent University-Imec, 9000 Ghent, Belgium.
[2] Center for Nano- and Biophotonics (NB-Photonics), 9000 Ghent, Belgium.

Traditional ring resonators can be manipulated through two factors: the coupling coefficients and the optical roundtrip length. These two factors determine the most important performance parameters of the ring resonator such as the Q factor, the free spectral range (FSR) and extinction ratio (ER). But there is another important factor that plays an important role: the internal reflection(s). In this paper, we systematically discuss and experimentally demonstrate our manipulation of reflections in silicon ring resonators by introducing one or two integrated tunable reflectors. Various applications and phenomenon can be generated by these structures, including backscattering compensation, ultra wide FSR, Fano resonance and Electromagnetically induced transparency (EIT).

Introduction and background

When people discuss microring resonators, the expected behavior does not consider any reflections inside the ring. For example, in an add-drop ring resonator the output spectra are expected to be: a series of Lorentzian shaped peaks at the *drop* port;a series of Lorentzian shaped notches at the *through* port; No transmission to the *add* port and no reflection to *in* port. In such an ideal ring resonator, the response is purely dependent on two physical parameters, namely the roundtrip length L and field coupling coefficient κ in the directional couplers. Together they determine the Q factor, the *free spectral range* (FSR) and the *extinction ratio* (ER) of a ring resonator. However, in a real high-contrast system such as silicon photonics, there is no such thing as an ideal ring resonator, especially in terms of internal reflections. Due to the inevitable sidewall roughness of silicon waveguides, stochastic reflections are always present in the ring waveguide [1]. Mostly, the effects of reflections are detrimental, as they will cause peak splitting at the *drop* and *through* ports, introduce leakage to the *add* port and reflection to the *in* port [2]. All of these effects degrade to a certain degree the performance of the ring resonator in most applications. However, under specific conditions, it can also be utilized to enhance ring resonator's performance [3]. Therefore we can state that, besides L and κ, internal reflections can be treated as additional design parameters in a ring resonator that can be used to influence the performance.

Different approaches have been tried to manipulate the reflections in a ring resonator, such as Bragg gratings. Metal nanodisks have also been theoretically proposed to achieve a larger FSR. While these demonstrations show the importance and novelty of manipulated reflection in a ring resonator, the poor tunability and control limits the applicability, and the reflections introduced are actually non-predictable at the design stage and can not be tuned after fabrication.

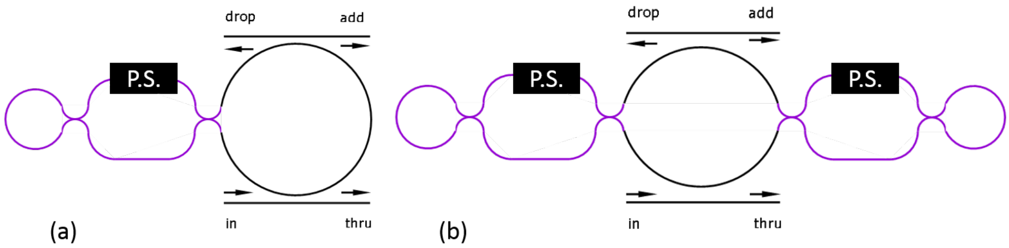

Figure 1: Schematic for a ring with (a) one reflector and (b) two reflectors.

In this paper we propose and demonstrate our way of manipulating reflections in silicon ring resonators. We implement one or two tunable integrated reflectors inside the ring cavity and the reflectivity of such reflectors can be efficiently tuned over a wide range (from 0 to almost 100%) through thermo-optic phase shifters (heaters). This allowed us to observe very diverse phenomena and demonstrate different applications.

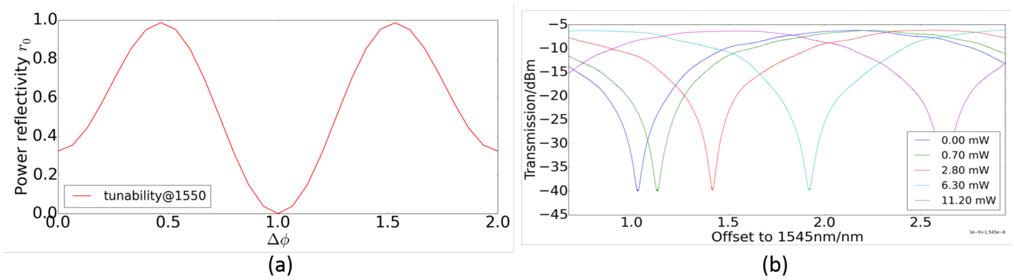

Figure 2: Simulation shows that $\frac{\pi}{2}$ radians added to the phase shifter can generate a reflectivity change from 0 to 100% (a). Measurement proved 6 mW would lead to a 35 dB change in its reflectivity (b).

Ring resonator with one reflector

The schematics of the device with one and two reflectors are shown in Fig. 1. The tunable reflector shown in purple is a loop-ended *Mach-Zenhder interferometer* (MZI), with a thermo-optic phase shifter in one arm. By adding only $\frac{\pi}{2}$ radians to the phase shifter, its reflectivity can be changed from 0 to 100% as shown in Fig. 2 [4]. The measurement result of this reflector confirms this: less than 6 mW tuning power can generate a 35 dB change in its reflectivity, also shown in Fig. 2. This broad tuning range enables various reflection conditions inside a ring resonator.

For the device with a single reflector, the most straightforward application is the suppression of stochastic backscattering originating from sidewall roughness and discontinuities at the directional couplers [4]. From previous research, we concluded that the total backscattering inside a ring cavity can be modelled as a lumped reflector with certain reflectivity and phase [2]. By introducing a controllable reflector inside the ring to compete with the backscattering, we should be able to suppress it. Fig. 3 shows the measurement results of such application. After tuning the reflector to a correct condition, the splitting at *through* and *drop* ports is eliminated. Moreover, the leakage to the *add* port and reflection to the *in* port are also significantly suppressed. This approach can be potentially applied

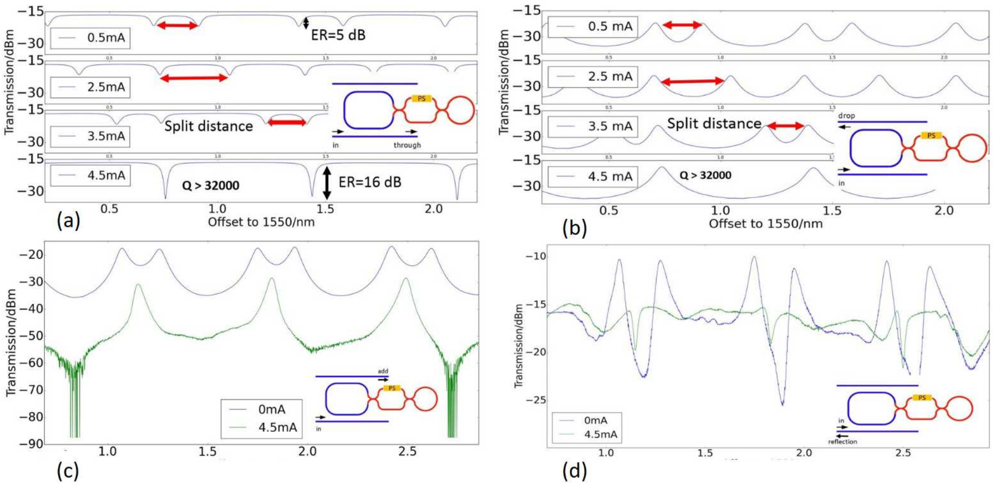

Figure 3: (a) demonstrates the splitting elimination in the *through* port (b) shows the same compensation for the output at the *drop* port, while (c) and (d) show how our device can suppress the unwanted output from *add* and *in* port.

to larger scale PICs with ring resonators in an automatic way by adding integrated photodetectors (PD) at the *add* ports. High transmission to the *add* port is a convincing proof of strong backscattering inside the ring cavity, so the current of the PD can be fed backed to the driver of the reflector in order to minimize the photocurrent in the feedback loop.

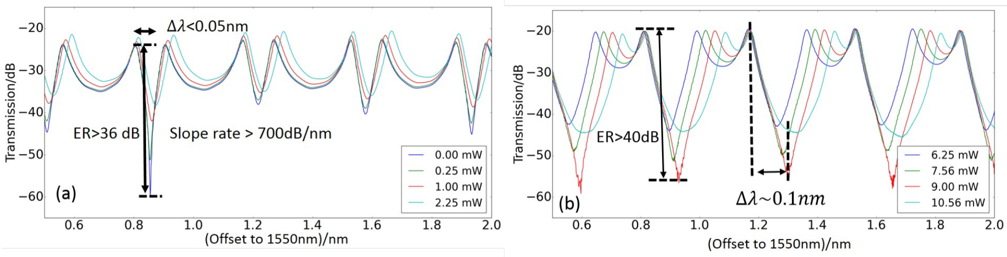

Figure 4: Experimental demonstration of tunable Fano resonances. (a) shows the maximum slope rate over 700 dB/nm and (b) gives the maximum extinction ratio over 40 dB.

Ring resonator with two reflectors

Adding a second reflector to the ring unlocks even more interesting phenomena [5]. The two reflectors will now form an embedded *Fabry-Perot* cavity (FP) inside the ring, whose output mode depends on the two reflectors' phase and reflectivity. Under correct tuning of the two reflectors, where the FP generates a slowly varying mode, the FP mode can serve as a continuum mode interfering with the discrete ring resonances. Consequently, a Fano resonance will emerge and its ER and slope rate can be further tuned as evident in Fig. 4. Our measured results show that a maximum ER larger than 40 dB and a sharpest slope rate over 700 dB/nm can be achieved. Such sharp features make this device a great candidate for highly efficiency sensors, or low power switches.

If we precisely tune of the FP mode until its peak has a good alignment with one of the ring resonance, the conditions are right for *electromagnetically induced transparency* (EIT).

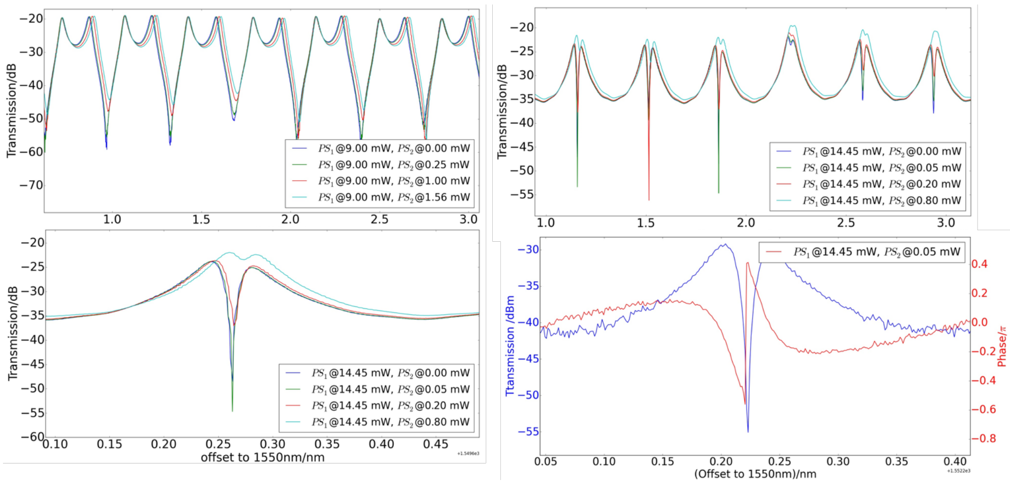

Figure 5: (a) shows the generation of Fano resonance if the FP mode and ring resonance are not perfectly aligned. (b) gives the transition from Fano resonance to EIT when precisely tune the FP mode to make it aligned with ring resonance. (c) provides a zoomed view of one resonance. (d) shows the phase response of such a EIT peak.

This situation is demonstrated in Fig. 5. EIT is a phenomenon originally discovered in atomic physics with multiple energy states. Due to the destructive interference between probability amplitudes of possible transition pathways of electrons among energy states, a transparent window (which is usually ultra narrow) will be generated at the transmission or absorption spectrum of these atomic systems. The importance of demonstration EIT in optics lies in its phase response: we can observe an abrupt phase change within an ultra narrow window. This translates into strong dispersion with a very larger group index and slow group velocity. Such a structure can be used as a tunable optical buffer.

Conclusion

In this paper we demonstrate our way of manipulation of reflections inside silicon ring resonator. Implementing one or two tunable integrated reflectors inside a ring cavity, various applications including backscattering suppression, tunable Fano resonance and EIT have been reported.

References

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