Experimental demonstration of loop-coupled microring resonators for optimally sharp optical filters

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Abstract: We present the first experimental demonstration of recently proposed loop-coupled resonator device concepts, with characteristic transmission zeros, enabling optimally sharp passbands for channel add-drop filter applications. Fourth-order SiN-core and Si-core strong-confinement microring-resonator designs are described.

OCIS codes: (130.3120) Integrated optics devices; (230.5750) Resonators; (120.2440) Filters; (230.7370) Waveguides.

Microphotonic circuits have enabled the integrated implementation of flat-top, high-order coupled-cavity filters [1], analogous to thin-film filters available in bulk optics, suitable for chip-scale wavelength routing applications [1-3]. These designs have – because they lack transmission zeros – limitations such as being suboptimally sharp, and being minimum-phase filters so that their amplitude and phase responses are related by the Kramers-Kronig condition. The latter implies that a flat-top-amplitude design is necessarily dispersive [4]. However, planar microphotonic chips accommodate other new device topologies not easily implemented in bulk optics. For example, interferometer-embedded-resonator filters [4] permit responses with transmission zeros, but their extinction ratios are highly sensitive to designing a precise 3dB coupler. Recently, a new class of loop-coupled-resonator optical filters has been proposed that enables the realization of optimally sharp bandpass filters for a given number of cavities, and dispersionless (maximally linear phase) flat-top filters and optical delay lines [5]. These designs are robust, and provide transmission zeros by coupling cavities in a loop as in Fig. 1(a). The four microrings coupled in this case have a layout geometry defined by a 4-side polygon connecting their centers – determined by their four mutual-coupling gaps and the angles of the polygon [Fig. 1(a)]. A new degree of freedom in this geometry is a tilt angle that can be applied to this polygon without changing the chord lengths (coupling gaps). This angle determines a new electromagnetic parameter of loop-coupled resonant structures, the loop-coupling phase (LCP), Φ, which is the phase accumulated by one propagation around the loop [5,6]. The LCP turns out to be directly related to the position of transmission zeros, as shown in Fig. 1(b). Proper choice of LCP allows optimally sharp or non-minimum-phase optimal linear-phase filters. While the present microring structures have analogues in the microwave domain [7,8], they are more general in practice. Standard, reciprocal microwave devices can only have LCP $\Phi = 0$ or π, while the optical microring structures, because they are intrinsically 4-port reflectionless "hybrids" [6], can have arbitrary LCP (in principle reproducible only in non-reciprocal 2-ports). This gives greater control of zero placement and opens the possibility of novel response designs enabled by these geometries, see Fig. 1(b) [6].

In this paper, we show the first experimental demonstration of loop-coupled resonators, designed to provide an optimally sharp 4th-order add-drop filter, including the confirmation of transmission null interference mediated by the LCP. Two designs are used: a static microring filter in Si-rich SiN, and a thermally tunable Si microring filter.

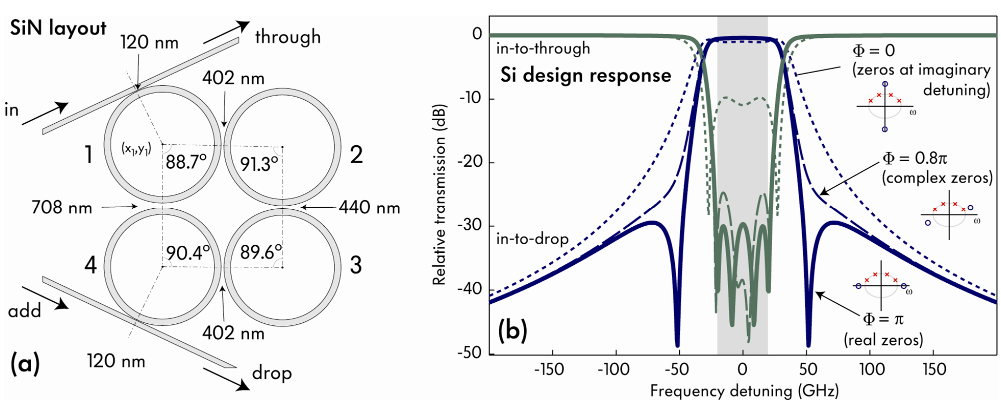

Fig. 1. (a) Layout of a 4th-order SiN loop-coupled-resonator filter, with LCP $\Phi = \pi$ (8 μm microring radius, ring and bus cross-sections same as [2], gaps shown); (b) bandpass response of a Si device (waveguides same as [3]) and pole-zero constellation vs. the LCP, Φ.

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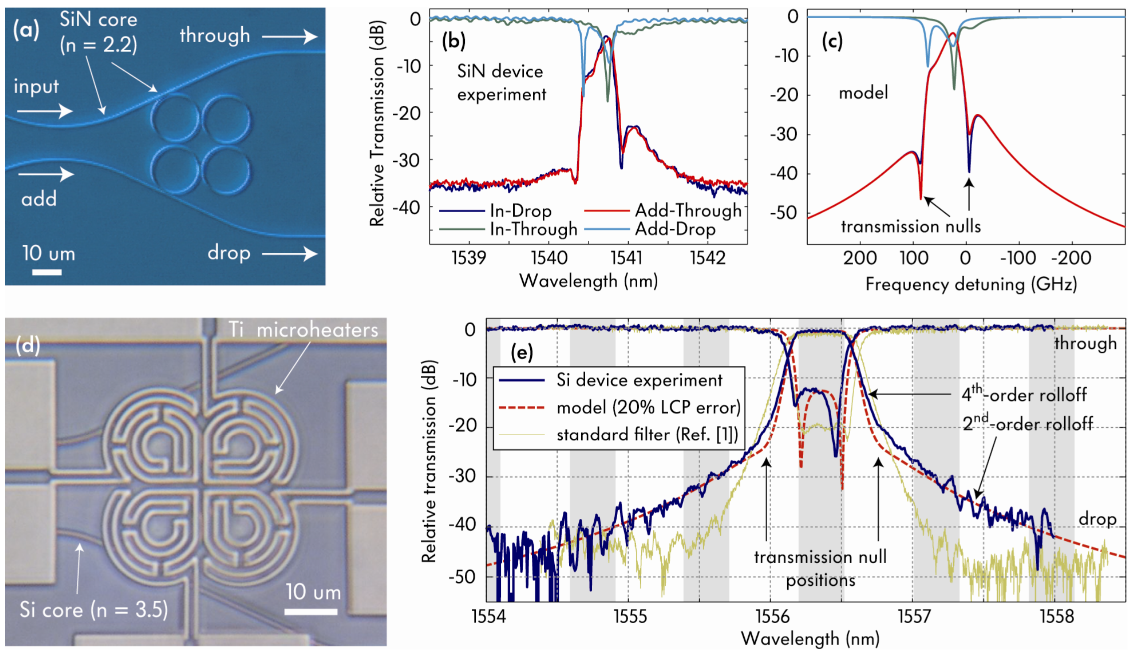

Fig. 2. Experimental devices: (a) optical micrograph of a fixed-frequency device in SiN waveguides (photoresist layer shown), and the (b) experimental transmission responses successfully demonstrating passband transmission nulls due to loop coupling, and (c) model, indicating residual resonance-frequency mismatch between microrings is the cause of the distorted passband shape. (d) Optical micrograph of a tunable silicon microring device with Ti microheaters, and (e) its response showing a flat passband in a loop-coupled device – the design model shows that about 20% error exists in the realized loop-coupling phase.

The Si filter is designed to give a 4th-order optimally sharp response with 2 zeros and a 65GHz 3dB bandwidth, while the SiN design has the same response design but with a 50 GHz bandwidth. The SiN filter, fabricated by the process in [9], is shown in Fig. 2(a), and uses the geometry of Fig. 1(a) and the ring and waveguide cross-section designs in [2]. Fig. 2(b) shows the experimentally measured bar- and cross-state responses from both input ports, clearly demonstrating the sharp nulls on each side of the passband induced by the loop coupling and LCP. The device model in Fig. 2(c) shows that the reason for the distorted shape of the passband is that the ring cavities are misaligned in frequency by about 20 GHz left to right, and 40 GHz up to down in Fig. 1(a). Dose compensation in the electron-beam lithography was used to compensate for the various lithography and electromagnetically induced sources of resonance frequency misalignment. However a lack of time meant that the calibration done for the devices in [2] was used, rather than a specific calibration for the present device. This is the source of the error.

A silicon microring version of the device is shown in Fig. 2(d), thermally tunable by Ti microheaters [3]. The device is not the same as the series-coupled filter in [3], which has no coupling between rings 1 and 4. Fig. 2(e) shows the measured spectral response, showing aligned resonators, a well-formed passband with less than 1dB drop loss. The response deviates from the expected response in that the transmission nulls are washed out and hence the sharpness of the rolloff slightly reduced. As shown by the included model response, this is consistent with an error of 20% in the loop coupling phase [compare Fig. 1(b)]. The reason for the LCP error is suspected to be deterministic nonuniformity in the cross-section of rings 1 and 4 caused by lithographic proximity effects at ring-bus couplers. Further conclusions on the sources of nonideality will be reported in the presentation. These sources are believed to be deterministic and possible to compensate in design with proper advance calibration.

The fundamental performance improvements enabled by the extra degrees of freedom (couplings and loop-coupling phase parameters) in this topology promise an important place for these structures in photonic circuits.

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