Self-coupled microring resonator with multiple split resonances

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Abstract: We propose and experimentally demonstrate a self-coupled microring resonator with multiple split resonances at certain wavelengths. By changing the phase shift along the feedback loop, variable numbers of split resonances can be obtained.
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1. Introduction

Silicon photonics have attracted a lot of research interests in the past two decades, and various silicon-based integrated optical devices have been investigated [1–3]. By employing these devices with diverse spectral responses, agile applications in optical signal processing were realized, such as fast and slow lights [1], temporal arithmetic computing [2], and optical reconfigurable filter [3].

Waveguide mutual-coupling and self-coupling can be used to tailor the spectral responses and dispersion characteristics of optical devices. With mutually-coupled waveguides such as microring resonators (MRRs) , optical resonances at certain wavelengths were obtained. On the other hand, optical resonances were achieved by self-coupled waveguides [4], whose resonances have two degenerate modes circulating in opposite directions, thus resulting in split resonances in the transmission spectra.

Optical resonators with spilt resonances have been theoretically analyzed based on the temporal coupled mode theory [5]. When two or more mutually-coupled modes coexist in the same system, the resonance at a certain wavelength splits into several resonances. Mode-split optical resonators have found various applications in wavelength division multiplexing (WDM) systems [6], optical buffers [7], and nano-particle detections [8].

In this paper, silicon MRR with a self-coupled region in a resonance loop is theoretically and experimentally investigated. Multiple split resonances are achieved at certain wavelengths, which are verified by the measured transmission spectra of the fabricated devices. By changing the phase shift along the straight waveguide in the feedback loop, variable numbers of split resonances in the transmission spectrum can be obtained. Due to the narrow interval between split resonances in the transmission spectra, the designed device with diverse split resonances may find potential applications in dense wavelength division multiplexing (DWDM) systems.

2. Device Structure and Operation Principle

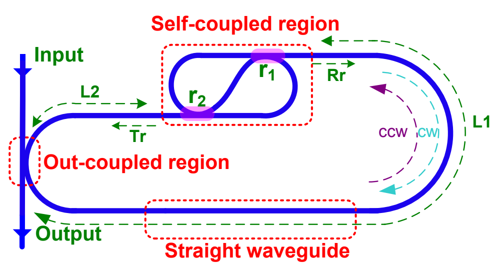

Fig. 1. Schematic diagram of the proposed self-coupled microring resonator.

Fig. 1 illustrates the schematic of the proposed self-coupled microring, with a self-coupled waveguide embedded in a MRR. A bus waveguide side-coupled to the MRR acts as the system input and output. There are three regions in the proposed configuration, i.e., straight waveguide along the feedback loop, self-coupled region, and out-coupled region, with two different coupling mechanisms, i.e., self-coupling in the self-coupled region and mutually coupling in the out-coupled region.

For the self-coupled region, light travels back and forth. There are two degenerate resonance modes, one circulates clockwise (CW) and the other transmits counterclockwise (CCW). Self-coupling is induced between the CW and CCW modes. When the coupling coefficients of the two couplers are close, there is a narrow transparency peak in the middle of a broad resonance range at the transmission port, which is analogous to an electromagnetically induced transparency (EIT) spectrum, as shown in Fig. 2(a). The self-coupled region and the straight waveguide of L1 and L2 compose the whole resonance loop. The light travelling through the whole resonance loop interferes at the out-coupled region and produces resonances. Since the straight waveguide is part of the whole resonance loop, the phase shift in this region will result in resonance shift induced by the whole resonance loop at the system output.

By using scattering matrix method [9], we obtain the transfer function of the proposed configuration as follows:

$$T = \frac{(T_r^2 - R_r^2)a_1^2a_2^2 \cdot r - T_r a_1 a_2 e^{i(\phi_1+\phi_2)} \cdot (1+r^2) + e^{2i(\phi_1+\phi_2)} \cdot r}{(T_r^2 - R_r^2)a_1^2a_2^2 \cdot r^2 - 2T_r a_1 a_2 e^{i(\phi_1+\phi_2)} \cdot r + e^{2i(\phi_1+\phi_2)}}, \quad (1)$$

where T_r and R_r represent the transmission and reflection functions of the self-coupled region, respectively [6]. They are determined by the transmission coefficients of r_1 and r_2 and the round-trip length of the self-coupled region. $\Phi_{1,2} = \kappa L_{1,2}$ are the phase changes along the waveguides of $L_{1,2}$, with κ representing the vacuum wave number; $a_{1,2} = exp(-\alpha L_{1,2}/2)$ are the single pass attenuations associated with $L_{1,2}$, respectively, with α denoting the attenuation coefficient; r is the transmission coefficient of the coupler in the out-coupled region.

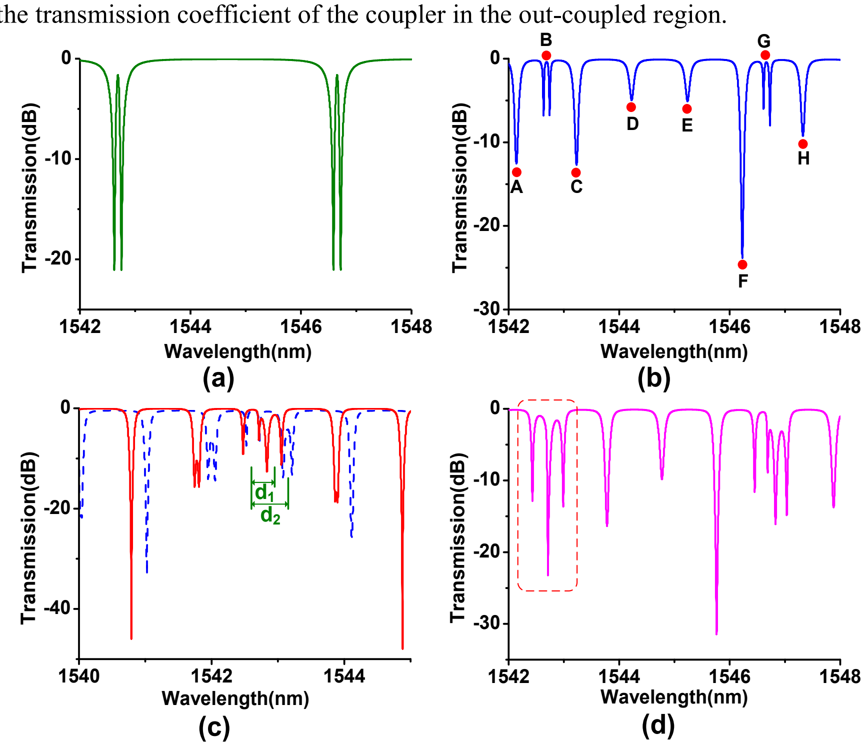

Fig. 2. Simulated transmission spectra of (a) self-coupled optical waveguide (SCOW) and (b) self-coupled microring. (c) Transmission spectrum with L_1 = 220 µm (blue dashed curve), and 220.1 µm (red solid curve), d_1 and d_2 represent the separations between the resonance wavelengths of the whole loop and those of the self-coupled region. (d) Multiple split resonances at different wavelengths.

Fig. 2(b) illustrates the transmission spectrum of the proposed self-coupled microring. The split resonance notches in Fig. 2(b) labeled as B and G have the same resonance wavelengths as the SCOW in the self-coupled region, as shown in Fig. 2(a). They are essentially introduced by the self-coupled region embedded in the loop. While other resonance notches (A, C~F, and H) result from the whole resonance loop. The lights traveling through the two resonance paths interfere at the out-coupled region, and produce multiple resonances. The separations between the resonance wavelengths of the whole loop and those of the self-coupled region change with various phase shifts along the straight waveguide. Fig. 2(c) shows the normalized transmission-intensity spectra with two different lengths of the straight waveguide in the feedback loop. One can see that there are different numbers of split resonance notches. In detail, when the self-coupling induced resonances and the mutual-coupling induced resonances approach each other, further mode splitting along the resonance loop occurs, and there would be more split resonances, as shown by the red dashed curve in Fig. 2(c). When the two resonances overlap, the number of the split resonances becomes three, as illustrated in frame in Fig. 2(d).

3. Device Fabrication and Measured Spectrum

Fig. 3(a) is a micrograph of the fabricated device on a silicon-on-insulator (SOI) wafer with a 220-nm top silicon layer and a 2-µm-thick buried oxide layer. The cross-sectional dimension of the waveguides is 450 nm × 220 nm.

The gap size in the three coupling regions is 180 nm due to fabrication limitation. The layout is defined by 248-nm deep ultraviolet (DUV) photolithography followed by inductively coupled plasma (ICP) etching. It is assumed that the waveguide group index of the transverse electric (TE) mode is $n_g = 4.33$ and the waveguide loss factor is ~5 dB/cm. To couple light in and out of the waveguides, grating couplers are used at each end. The length of L_1 and L_2 are 376.1 μm and 151.3 μm, respectively. The round-trip length of the self-coupled region is 138.9 μm. The transmission coefficients of the couplers are: $r_1 = r_2 = 0.602$, and $r = 0.719$.

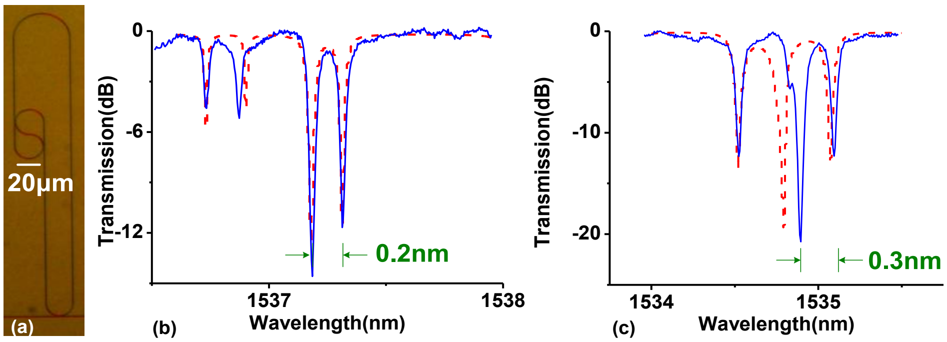

Fig. 3. (a) Micrograph of the fabricated device. (b) and (c) Experimentally measured spectral responses of transmission-intensity (blue solid line) and fitting results (red dashed line) at different wavelengths.

Fig. 3(b) and (c) show the measured transmission spectra. The on-chip insertion loss is ~12 dB. In the measured spectra, four resonances are observed in Fig. 3(b), while the multiple modes nearly degenerate into three in Fig. 3(c), implying that the resonance wavelength of the whole loop almost coincides with that of the self-coupled region. We also note that the separations between adjacent resonances in the measured spectra are smaller than 0.5 nm, as labeled in Fig. 3(b) and (c), which would be more suitable for DWDM systems with closely spaced channels.

4. Conclusions

Self-coupled microring resonator with multiple split resonances has been proposed, fabricated and experimentally demonstrated. Experimental results show that variable numbers of split resonance notches in the transmission spectrum are achieved at different wavelengths. This device with more closely spaced resonances in the transmission spectrum could help to increase the system capacity for DWDM systems.

5. Acknowledgement

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6. References

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