Silicon photonic integrated circuits based on integrated cascaded Sagnac loop reflectors

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ABSTRACT

Advanced photonic filters implemented by cascaded Sagnac loop reflectors (CSLRs) in silicon-on-insulator (SOI) nanowires are experimentally demonstrated. Based on mode splitting in these standing-wave (SW) resonators, we achieved diverse filtering shapes for spectral engineering showing good agreement with theory.

Keywords: Photonic filters, mode splitting, Sagnac loop reflectors, resonators

1. INTRODUCTION

Along with the advance of micro/nano fabrication technologies, integrated photonic resonators play more and more important role for signal modulation, buffering, switching, and processing in optical communications systems [1]. Mode splitting induced by coherent optical mode interference in coupled resonant cavities is a key phenomenon in photonic resonators that can lead to powerful and versatile filtering functions such as optical analogous to electromagnetically-induced-transparency (EIT), Fano resonances, Autler-Townes splitting, and dark states [2, 3]. Mode splitting can break the fundamental dependence between quality factor, free spectra range, and physical cavity length [4], which is critical for the implementation of integrated photonic resonators with reduced footprints and power consumptions. Moreover, the group delay response and mode interaction are also useful for enhancing light-material interaction and dispersion engineering in nonlinear optics [5].

In this paper, we investigate integrated standing-wave photonic filters formed by cascaded Sagnac loop reflectors (SLRs) [6]. The devices are designed and fabricated on a silicon-on-insulator (SOI) wafer. By changing coupling strengths of the directional couplers and phase shifts along the connecting waveguides, versatile filtering shapes corresponding to diverse mode splitting conditions are experimentally achieved that show good agreement with theory, verifying the effectiveness of the proposed device as a multi-functional filter for spectral engineering.

2. OPERATION PRINCIPLE AND EXPERIMENTAL RESULTS

Figure 1(a) illustrates schematic configuration of the integrated CSLR resonator. It consists of N SLRs ($SLR_1, SLR_2, \dots, SLR_N$) formed by cascaded SLRs. The two adjacent SLRs together with the connecting waveguide form a Fabry-Perot (FP) cavity, thereby N cascaded SLRs can also be regarded as $N-1$ cascaded FP cavities ($FPC_1, FPC_2, \dots, FPC_{N-1}$), similar to Bragg gratings [7]. t_i and κ_i ($i = 1, 2, \dots, N$) are the field transmission and cross coupling coefficients of the directional coupler in SLR_i , respectively. L_i ($i = 1, 2, \dots, N-1$) is the length of the waveguide connecting SLR_i and SLR_{i+1} . L_{ci} ($i = 1, 2, \dots, N$) is the coupling length of the directional coupler in SLR_i . The reflectivity of SLR_i ($i = 1, 2, \dots, N$) can be given by $R_i = (t_i^2 - \kappa_i^2)a_i \exp(j\varphi_i)$, with a_i and φ_i denoting the field transmittance factor and phase along SLR_i , respectively. The high degree of freedom in engineering the transmittance and reflectivity of individual SLRs via changing t_i or κ_i makes the CSLR resonator more flexible for spectral engineering as compared with Bragg gratings. In practical fabrication, different t_i can be achieved by changing the coupling length L_{ci} . The scanning electron microscope (SEM) pictures of the devices fabricated on a SOI wafer are shown in Figs. 1(b)–(d). Electron beam lithography was utilized to define the device layout on a positive photoresist, followed by a reactive ion etching process to transfer the device pattern to the top silicon layer. TE-polarized grating couplers were employed at the ends of ports IN/OUT to couple light into/out of the chip with single mode fibres, respectively. The coupling loss was ~ 6 dB/facet.

Fig. 1. (a) Schematic configuration of integrated cascaded SLRs. (b)–(d) SEM pictures of the fabricated devices.

Fig. 2. (a) Measured (solid curve) and fit (dashed curve) transmission spectra of the fabricated CSLR resonators with three SLRs ($N = 3$). (b) Measured and fit transmission spectra of the fabricated CSLR resonators with four SLRs ($N = 4$). (c) Measured and fit transmission spectra of the fabricated CSLR resonators with eight SLRs ($N = 8$).

For $N > 2$, mode splitting occurs due to coherent interference between the cascaded FP cavities. The measured transmission spectra of the fabricated CSLR resonators with three, four, and eight SLRs are shown in Figs. 2(a) – (c) by the blue solid curves, respectively. The measured spectra are fit by the red dashed curves calculated based on the scattering matrix method [8]. The devices in Fig. 2(a) have the same L_{c1} and L_{c3} , but increased L_{c2} from (i) to (iii), thus resulting in different mode splitting degrees. The filter shapes with multiple transmission peaks in Figs. 2(b-i), 2(b-iii), and 2(c-iii) are useful for signal reshaping and multicasting in dense wavelength division multiplexing (DWDM) systems [9]. The narrow bandwidth between the split resonances is resulting from coherent interference within the CSLR resonator. For ring resonators, such a narrow bandwidth can only be achieved by using much larger loop circumferences, thus leading to much larger device footprints. In addition, the CSLR resonator is a standing-wave resonator, and so the cavity length is nearly half that of a traveling-wave resonator (e.g., ring resonator) with the same FSR, which enables even more compact device footprints. The devices in Fig. 2(b-ii) and Fig. 2(c-ii) are 4th-order and 8th-order Butterworth filters with a flat-top filter shape, respectively. The device in Fig. 2(c-i) is designed for enhanced light trapping by introducing an additional $\pi/2$ phase shift along the centre FPC, i.e., L_4 for $N = 8$. This work also has implications for the integration of highly nonlinear materials [10 – 19] including graphene oxide (GO) for nonlinear optical functions at telecommunication band. These results also have implications for designing advanced photonic circuits for both classical [19] and quantum [20–23] applications.

3. CONCLUSION

Integrated mode-split CSLR resonators have been investigated and exploited for spectral engineering. By tailoring mode splitting in the CSLR resonators, versatile filter shapes for diverse applications are experimentally achieved.

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