Advanced optical filters with coupled Sagnac loop waveguide reflectors

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ABSTRACT

We present theoretical designs of high performance optical filters in integrated silicon photonic nanowire resonators. We use mode interference in formed by zig-zag waveguide coupled Sagnac loop reflectors (ZWC-SLRs), tailored to achieve diverse filtering functions with good performance. These include compact bandpass filters with improved roll-off, optical analogues of Fano resonances with ultrahigh spectral extinction ratios (ERs) and slope rates, and resonance mode splitting with high ERs and low free spectral ranges. The analysis verifies the feasibility of multi-functional integrated photonic filters based on ZWC-SLR resonators for flexible spectral engineering in diverse applications.

Keywords: Integrated optics, resonators, Fano resonance, mode splitting, classical filters.

1. INTRODUCTION

Micro/Nano-scale integrated photonic resonators enable a wide variety of optical functions in photonic integrated circuits [1-6]. Optical bandpass filters (BPFs) are core components in wavelength division multiplexing (WDM) optical communication systems [7]. To date, various types of photonic resonators have been designed to improve the roll-off of optical filters for achieving quasi flat-top spectral responses, which are highly desirable in WDM optical communication systems [8, 9]. However, these structures usually achieve flat-top spectral responses via cascading many subunits. This results in a bulky device footprint and, in addition, it is challenging to maintain the desired spectral response given the unequal wavelength drifts for different sub-components induced by the thermo-optic effect [10].

Fano resonances are fundamental physical phenomena exhibiting a distinctly asymmetric resonant lineshape profile arised from the constructive and destructive interference of a narrow discrete resonance with a broad spectral line or continuum [11-13]. Optical analogues of Fano resonances have been hot research topics in recent years and have found many applications[11, 14].

At the same time, resonance mode splitting is also a fundamental phenomenon in photonic resonators that occurs when two or more mutually coupled modes co-exist in the same resonant cavity [15, 16]. Recently, many applications based on mode-split resonators have been introduced due to their capability of providing a reduced free spectral range (FSR) and an increased quality (Q) factor while maintaining a small physical cavity length [17-19]. This yields a compact device footprint, low power consumption, and versatile filter shapes for dense WDM (DWDM) and microwave photonics applications [20, 21].

Recently, we demonstrated multi-functional integrated photonic filters based on cascaded Sagnac loop reflectors (SLRs) [22] formed by self-coupled silicon-on-insulator (SOI) nanowires. Here, we theoretically investigate advanced filter structures based on zig-zag waveguide coupled Sagnac loop reflectors (ZWC-SLR) [23, 24], that yield greatly enhanced performance together with additional versatile filtering functions. The ZWC-SLR resonators can be considered to be hybrid filters consisting of both finite-impulse-response (FIR) and infinite-impulse-response (IIR) filter elements as well as standing-wave (SW) and travelling-wave (TW) filter elements that provide more versatile mode interference and significantly improved flexibility for spectral engineering [25-30]. Combining this approach with highly nonlinear thin films [30-39] would offer exciting possibilities for advanced nonlinear integrated devices.
2. DEVICE CONFIGURATION

The schematic configurations of two and three ZWC-SLR resonators are illustrated in Figs. 1(a) and (b), respectively. To model the ZWC-SLR resonators based on the scattering matrix method [22, 23, 25], the waveguide and coupler parameters are defined in Table 1. To simplify the comparison, we assume that the two and three SLRs are identical in each ZWC-SLR resonator, i.e., \( L_{\text{SLR}}(i = 1-3) = L_{\text{SLR}} \), \( t_b(i = 1-3) = t_b \), and \( t_b(i = 1-3) = t_b \).

![Schematic diagram](image)

Figure 1. Schematic configuration of (a) two and (b) three ZWC-SLR resonators, respectively. The definitions of \( t_b(i = 1, 2, 3) \), \( t_b(i = 1, 2, 3) \), \( L_{\text{SLR}}(i = 1, 2, 3) \), and \( L_i(i = 1, 2, 3, 4) \) are given in Table 1.

In the following sections, mode interference in the ZWC-SLR resonators is tailored to achieve high-performance filtering functions, including compact BPFs (Section 3), optical analogues of Fano resonances (Section 4), and resonance mode splitting (Section 5). In our design, we use values attained from our previously fabricated SOI devices [22, 26] for the waveguide group index \( n_g = 4.3350 \), transverse electric (TE) mode, and the propagation loss \( (\alpha = 55 \text{ m}^{-1}, \text{i.e., } 2.4 \text{ dB/cm}) \). The devices are designed based on but not limited to the SOI integrated platform.

Table 1. Definitions of structural parameters of the ZWC-SLR resonators

| Waveguides                                      | Length | Transmission factor | Phase shift |
|------------------------------------------------|--------|---------------------|-------------|
| Bus waveguides between SLRs \((i = 1, 2, 3, 4)\) | \( L_i \) | \( a_i \)          | \( \phi_i \) |
| Sagnac loop in SLR \((i = 1, 2, 3)\)          | \( L_{\text{SLR}} \) | \( a_i \)          | \( \phi_i \) |
| Directional couplers                           | Field transmission coefficient | Field cross-coupling coefficient |
| Coupler in SLR \((i = 1, 2, 3)\)               | \( t_b \) | \( k_b \)          |             |

\(^a a_i = \exp(-\alpha L_i/2), a_i = \exp(-\alpha L_{\text{SLR}}/2), \alpha \) is the power propagation loss factor.  
\(^b \phi_i = 2\pi n_g L_i/\lambda, \phi_i = 2\pi n_g L_{\text{SLR}}/\lambda, n_g \) is the group index and \( \lambda \) is the wavelength.  
\(^c t_b^2 + k_b^2 = 1 \) and \( t_b^2 + k_b^2 = 1 \) for lossless coupling are assumed for all the directional couplers.

3. COMPACT BANDPASS FILTERS WITH IMPROVED ROLL-OFF

In this section, we tailor the mode interference in the two ZWC-SLR resonator to realize compact BPFs with improved roll-off. Figures 2(a) and (b) show the power transmission spectrum and corresponding group delay response of the two ZWC-SLR resonator from Port 1 to Port 2 in the wavelength range of 1548.9 nm – 1551.2 nm, respectively. There are wide-flat stopbands and a passband with improved roll-off, arising from coherent mode interference within the two ZWC-SLR resonator. The structural parameters are \( L_{\text{SLR}} = L = 100 \text{ µm}, t_b = t_b = 0.78 \).

To quantitatively analyze the improvement in the filtering roll-off, we further compare the 3-dB BW of the BPF based on two ZWC-SLRs (2-ZWC-SLRs) with BPFs considering other types of integrated photonic resonators, including a single add-drop MRR (1-MRR) [27, 28], two cascaded SLRs (2-C-SLRs) [29], three cascaded SLRs (3-C-SLRs) [22], and two parallel coupled MRRs (2-MRRs) [27, 28]. In comparison, the above filters were designed based on the same SOI wire waveguide (i.e., with the same \( n_g = 4.3350 \) and \( \alpha = 55 \text{ m}^{-1} \)). Figure 3(a) shows the normalized power transmission spectra of the BPFs considering the various types of integrated resonators mentioned above. The filtering spectra of all the
devices were normalized to have the same ER (~10.36 dB) and full width at minimum (~230.6 GHz) as those of the BPF in Fig. 2(a). The corresponding 3-dB BWs are given in Fig. 3(b). It is clear that the BPF based on the two ZWC-SLRs resonator has the largest 3-dB BW and the best roll-off, reflecting enhanced mode interference in this compact device consisting of only two SLRs.

4. ULTRA-SHARP FANO RESONANCES

In this section, we tailor the spectral response of the three ZWC-SLR resonator structure to realize optical analogues of Fano resonances with high ERs and SRs. The power transmission spectrum from Port 2 to Port 4 of the three ZWC-SLR resonator is depicted in Fig. 4(a). One can see that there are periodical Fano resonances with identical asymmetric resonant line-shapes in each period. The device structural parameters are \( L_{\text{SLR}} = L_{1,2,3,4} = 115 \ \mu\text{m}, t_s = 0.743, \) and \( t_b = 0.994 \). The FSR is about 200 GHz, which equals the sum of the two wavelength spacings (\( W_{S1} \) and \( W_{S2} \)). The two \( W_{S}s \) are very close to each other (\( W_{S1} = 101.71 \ \text{GHz} \) and \( W_{S2} = 98.88 \ \text{GHz} \)), reflecting the high SR of the Fano resonances.

Figure 4(b) shows a zoom-in view of Fig. 3(a) in the wavelength range of 1549.8 nm – 1550.65 nm, which shows a Fano resonance with an ultra-high ER of 76.32 dB and an ultra-high SR of 997.66 dB/nm. The ER is defined as the difference between the maximum and the minimum transmission, and the SR is defined as the ratio of the ER to the wavelength difference between the resonance peak and notch (i.e., \( \Delta\lambda \) in Fig. 4(b)). The high ER and SR reflect the high performance of the Fano resonances resulting from strong coherent optical mode interference in the compact resonator with only three SLRs. Further, the periodical filter shape of the zig-zag 3WC-SLR resonator is also useful for applications in WDM systems.
Figure 4. (a) Power transmission spectrum of the three ZWC-SLR resonator from Port 2 to Port 4 when \( L_{\text{SLR}} = L_{1, 2, 3, 4} = 115 \mu \text{m}, t_s = 0.743, \) and \( t_b = 0.994. \) (b) Zoom-in view of (a) in the wavelength range of 1549.8 nm –1550.65 nm. WS: wavelength spacing. ER: extinction ratio. \( \Delta \lambda: \) wavelength difference between the resonance peak and notch.

Figure 5(a) compares the power transmission spectra for various \( t_s \) (reflectivity of SLRs), we changed only \( t_s, \) keeping the other structural parameter the same as those in Fig. 4. The corresponding IL and SR are depicted in Fig. 5(b). The IL increases with \( t_s, \) while the SR first increases and then decreases with \( t_s, \) achieving a maximum value of 997.66 dB/nm at \( t_s = 0.743. \) The non-monotonic relationship between the SR and \( t_s \) is a combined result of both a decrease in \( \Delta \lambda \) and a non-monotonic variation in ER. The latter mainly arises from the difference between the internal (transmission) and external (coupling) cavity loss, which is similar to that for different coupling regimes in microring resonators (MRRs) [30].

Figure 6(a) shows the power transmission spectrum from Port 2 to Port 4 of the three ZWC-SLR resonator. The structural parameters are \( L_{\text{SLR}} = L_{1, 2, 3, 4} = 115 \mu \text{m}, t_s = 0.72, \) and \( t_b = 0.99, \) which are designed in order to achieve a WS of about 100 GHz between adjacent split resonances. In Fig. 6(a), \( WS_1 = 98.33 \) GHz and \( WS_2 = 102.26 \) GHz. There are two split resonances within a FSR of ~ 200.59 GHz. Figure 6(b) shows a zoom-in

5. RESONANCE MODE SPLITTING

In this section, we tailor the mode interference in the three ZWC-SLR resonator to achieve resonance mode splitting with high ERs and low FSRs. The resonance mode splitting with multiple densely spaced resonances can break the dependence between the Q factor, FSR, and physical cavity length, thus allowing low FSRs and high Q factors in resonators with a compact footprint. Figure 6(a) shows the power transmission spectrum from Port 2 to Port 4 of the three ZWC-SLR resonator. The structural parameters are \( L_{\text{SLR}} = L_{1, 2, 3, 4} = 115 \mu \text{m}, t_s = 0.72, \) and \( t_b = 0.99, \) which are designed in order to achieve a WS of about 100 GHz between adjacent split resonances. In Fig. 6(a), \( WS_1 = 98.33 \) GHz and \( WS_2 = 102.26 \) GHz. There are two split resonances within a FSR of ~ 200.59 GHz. Figure 6(b) shows a zoom-in
view of Fig. 6(a) in the wavelength range of 1549 nm – 1550.7 nm. The IL, Q factor, ER1, and ER2 of the two split resonances in Fig. 4(b) are ~2.02 dB, ~6.03 × 10^4, ~24.65 dB, and ~27.55 dB, respectively.

![Figure 6](image)

Figure 6. (a) Power transmission spectrum of the three ZWC-SLR resonator from Port 2 to Port 4 when \( L_{\text{SLR}} = L_{1, 2, 3, 4} = 115 \) µm, \( t_s = 0.72 \), and \( t_b = 0.99 \). (b) Zoom-in view of (a) in the wavelength range of 1549 nm –1550.7 nm.

Figure 7(a) shows the spectral response for various \( t_s \), we only changed the reflectivity of SLRs, keeping the other structural parameters the same as those in Fig. 6 (a). The Q factor and ERs (ER1 and ER2) as functions of \( t_s \) are depicted in Fig. 7(b). As \( t_s \) increases, the Q factor slightly decreases while the ER1 and ER2 change more dramatically, resulting in a change in the spectral response towards that of the Fano resonances in Fig. 4(a). The non-monotonic change in ER2 with \( t_s \) follows the trend of the SR in Fig. 5(b) for similar reasons. In particular, ER1 equals to ER2 when \( t_s = 0.7177 \). Under this condition, the Q factor and effective FSR are ~6.06 × 10^4 and ~100.30 GHz (i.e., half of the FSR in Fig. 6(a)), respectively.

![Figure 7](image)

Figure 7. (a) Power transmission spectra of the three ZWC-SLR resonator for various \( t_s \) for input from Port 2 to Port 4 when \( t_b = 0.99 \) and \( L_{\text{SLR}} = L_{1, 2, 3, 4} = 115 \) µm. (b) Calculated Q factor and ERs (ER1 and ER2) as functions of \( t_s \) for the transmission spectra in (a).

To achieve the same FSR, the circumference of a comparable MRR (with the same waveguide geometry and loss) is 690 µm, which is 6 times the length of the SLRs. This highlights the reduced cavity length enabled by the mode splitting in the 3WC-SLR resonator. On the other hand, the Q factor of a comparable MRR with the same FSR and ER is ~6.08 × 10^4 – almost the same as that of the zig-zag 3WC-SLR resonator. This indicates that the reduced cavity length did not come at the expense of a significant decrease in Q factor.
The number of split resonances can be changed by varying the length of the connecting bus waveguides. Figure 8(a) shows the power transmission spectrum from Port 1 to Port 3 of the three ZWC-SLR resonator. Clearly, there are four split resonances in each FSR. The structural parameters are \( L_{SLR} = 115 \, \mu\text{m}, L_{1,3} = 115 \, \mu\text{m}, L_{2,4} = 230 \, \mu\text{m}, \) and \( t_s = t_b = 0.88. \) The WSs between the split resonances are \( WS_1 = WS_3 = 100.46 \, \text{GHz} \) and \( WS_2 = 90.37 \, \text{GHz}. \) Figure 8(b) shows a zoom-in view of Fig. 8(a) in the wavelength range of 1548.7 nm – 1550.7 nm.

![Figure 8](image)

Figure 8. (a) Power transmission spectrum of the three ZWC-SLR resonator from Port 1 to Port 3 when \( L_{SLR} = 115 \, \mu\text{m}, L_{1,3} = 115 \, \mu\text{m}, L_{2,4} = 230 \, \mu\text{m}, \) and \( t_s = t_b = 0.88. \) (b) Zoom-in view of (a) in the wavelength range of 1548.7 nm – 1550.7 nm.

The power transmission spectra for different \( t_s \) is shown in Fig. 9(a). The corresponding Q factors (Q1 and Q2) and ERs (ER1 and ER2) for the first two resonances from the left side are shown in Fig. 9(b). In Figs. 9(a) and (b), all the Q factors and ERs decrease with \( t_s \), along with slightly decreased ILs.

![Figure 9](image)

Figure 9. (a) Power transmission spectra of the three ZWC-SLR resonator for various \( t_s \) for input from Port 1 to Port 3 when \( t_b = 0.88, L_{SLR} = 115 \, \mu\text{m}, L_{1,3} = 115 \, \mu\text{m}, \) and \( L_{2,4} = 230 \, \mu\text{m}. \) (b) Calculated Q factors (Q1 and Q2) and ERs (ER1 and ER2) as functions of \( t_s \) for the transmission spectra in (a).

6. CONCLUSIONS

We theoretically investigate advanced multi-functional integrated photonic filters based on ZWC-SLR resonators. Mode interference in the ZWC-SLR resonators is tailored to achieve different filtering functions including compact bandpass filters with improved roll-off, optical analogues of Fano resonances with ultrahigh ERs and SRs, resonance mode splitting with high ERs and low FSRs. This work highlights the ZWC-SLR resonators as a robust and adaptable approach to flexible spectral engineering for a diverse range of applications.
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