A third-order silicon microring add-drop filter with high extinction ratios

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ABSTRACT

We experimentally demonstrate a compact third-order silicon microring add-drop filter with high extinction ratios. Perimeter compensation method was applied to solve the coupling induced frequency shift (CIFS) problem. After carefully design and accurate fabrication, extinction ratio up to 30dB and 40dB are measured at through and drop port, respectively.

Keywords: silicon photonics, third-order microring, microring filter, high extinction ratio, silicon-on-insulator

1. INTRODUCTION

Extinction ratio (ER) is a very important parameter for optical filters, modulators, switches and sensors. High extinction ratio can depress the crosstalk of the optical switches, reduce the power penalty of the modulators, improve the sensitivity of the resonator-based sensors, and also has many particular characteristics in optical signal processing. Due to the advantages of low-loss and compactness, microrings are considered to be one of the building blocks in future chip-scale optical interconnects and very large scale photonic integrated circuits. Recently, a lot of researches have been done on multistage micro-resonators for various of applications, such as flat-top filters [1], slow light devices [2], and optical switches[3]. However, these particular functions are difficult to realize, as the resonances of each resonators have to be matched, and the power coupling efficiencies between waveguide-resonator and resonator-resonator should be carefully designed.

In this paper, we demonstrate a third-order silicon-on-insulator (SOI) microring filter, with high extinction ratio at both through-port and drop-port. Frequency-matching was realized by slightly changing the perimeter of the middle ring. By careful design and accurate fabrication, extinction ratio up to 30dB and 40dB are measured at through and drop port, respectively.

2. THEORY

Transfer matrix formalism can be used to analyse and design the multistage microring filters, which are also named microring coupled-resonator optical waveguides (CROWs) [4]. We use transfer matrices to theoretically analyse the spectrum responses of a third-order CROW.

The transfer matrix formalism of a third-order CROW can be expressed as:

$$\begin{bmatrix} E_a \\ E_d \end{bmatrix} = P_1 \cdot Q \cdot P_2 \cdot Q \cdot P_2 \cdot Q \cdot P_1 \cdot \begin{bmatrix} E_i \\ E_t \end{bmatrix} = \begin{bmatrix} A & C \\ B & D \end{bmatrix} \begin{bmatrix} E_i \\ E_t \end{bmatrix} \tag{1}$$

where

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$$P_{1,2} = \begin{bmatrix} -\dfrac{t_{1,2}}{ik_{1,2}} & \dfrac{1}{ik_{1,2}} \\ -\dfrac{1}{ik_{1,2}} & \dfrac{t_{1,2}}{ik_{1,2}} \end{bmatrix} \tag{2}$$

$$Q = \begin{bmatrix} 0 & e^{-\gamma/2+j\beta\cdot\pi R} \\ e^{-(-\gamma/2+j\beta\cdot\pi R)} & 0 \end{bmatrix} \tag{3}$$

and

t_{in}, k_{in} are respectively self- and cross-coupling coefficients of microring-to-microring, which describe the interaction intensity in the coupling region;

t_{out}, k_{out} are self- and cross-coupling coefficients of bus-to-microring, respectively;

β is the propagation constant;

R is the radius of the ring resonator;

$e^{-\gamma}$ is the optical amplitude attenuation factor per-round in the ring, see Fig. 1.

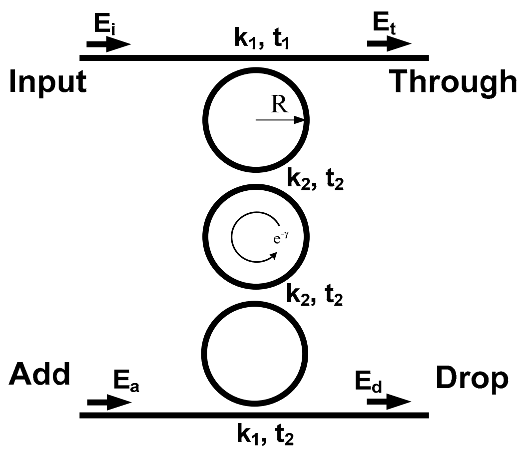

Fig. 1 The schematic structure of a third-order microring filter.

Using Eq. 1 to 3, we have the through-port and drop-port optical transmission of the third-order CROW:

$$T_{thr} = \left|\frac{E_t}{E_i}\right|^2 = \left|-\frac{A}{B}\right|^2 \tag{4}$$

$$T_{drop} = \left|\frac{E_d}{E_i}\right|^2 = \left|C - \frac{AD}{B}\right|^2 \tag{5}$$

As shown in Fig. 2, when k_1^2 is stable, the through-port extinction ratio changes dramatically as k_2^2 changes. So a rather high extinction ratio can be achieved if the power coupling between the inner-ring and out-rings are carefully designed, as well as accurately fabricated.

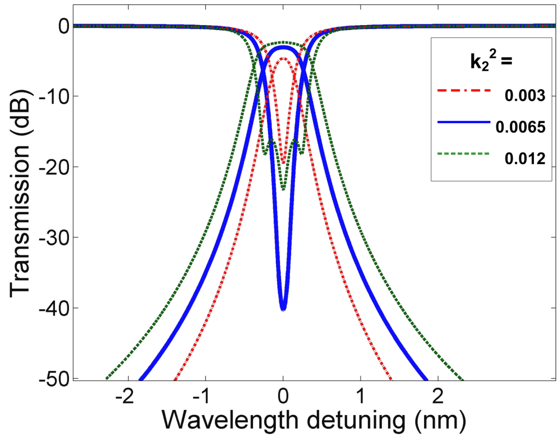

Fig. 2 The spectrum responses of a 10 μm-radii third-order CROW when $k_1^2 = 0.2$ and the round-trip amplitude attenuation in the microring equals to 0.98.

3. DEVICE FABRICATION AND CHARACTERISTICS

The microrings were fabricated on a SOI wafer with a 340 nm top silicon layer and a 2 μm buried oxide layer (see Fig. 3). The device patterns were exposed in a ~ 200 nm-thick PMMA with Raith150 electron-beam lithography (EBL) system. Inductively-coupled-plasma (ICP) reactive-ion-etch was then applied to etch the device patterns to the silicon layer. All the devices are based on rib waveguides, which can further be integrated with microelectronics in future optoelectronic hybrid circuits. Fig. 3 shows the SEM images of the third-order microring filter with a ring radii of 10 μm and slab thickness of ~ 130nm. The bus waveguides are 450 nm wide and the average ring waveguide width is ~ 525 nm. The width of the ring waveguide nearby the bus is a little wider to ~ 550 nm due to the e-beam proximity effects. The gaps between the bus waveguide and outer rings are 140 nm wide and the gaps between the rings are 390 nm wide. The power coupling efficiency k_1^2 and k_2^2 were calculated to be 0.2304 and 0.0102, by 2D-FDTD simulation.

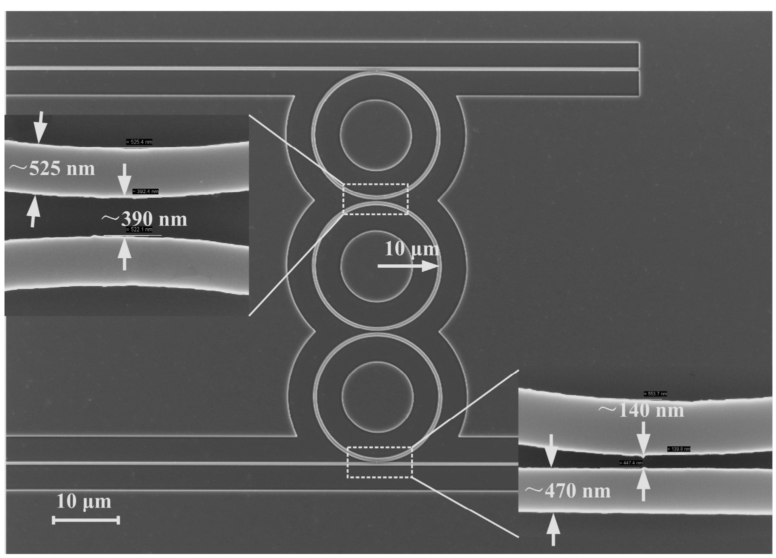

Fig. 3. The SEM images of the fabricated third-order microring filter. The ring radius is 10 μm and slab thickness is ~ 130nm. The ring waveguides and bus waveguides are ~525 nm and ~470 nm wide, respectively. The inner gaps are ~390nm wide and the outer gap are ~140 nm wide.

However, the determination in the value of the power coupling coefficients is not the only difficulty in realizing the high ER third-order CROW. Due to coupling induced frequency shift (CIFS) effect [5], the spectrum responses are badly distorted. Fig. 4 shows the spectrum curves of the third-order CROW with the three rings' dimensions to be the same. As the existence of the CIFS, the resonating wavelengths of the inner ring and out rings deviated each other for over 2 nm. The ER was very low as little light power can simultaneously propagate in the three microrings. For demonstrating a high-ER CROW, the resonating wavelengths of each rings must be the same in order to realize ' sympathetic vibration'. Dose compensation of the middle ring, as was mentioned in previous reports [6,7], is the main method to solve the resonance-mismatch problem. In our case, a slightly increase in the perimeter of the middle ring is applied to compensate the resonance mismatch. This method is independent on the EBL resists, and do not need additional meticulous dose tests. After increasing a length of ~130 nm to the perimeter of the middle ring, the resonating wavelengths of the three rings get matched, see Fig. 5. Rather high extinction ratios of 30 dB and 40 dB are found appearing at through-port and drop-port respectively. The cross-talk between these two output-ports are as low as -24.4 dB. Other measured and calculated data are presented in Tab. 1.

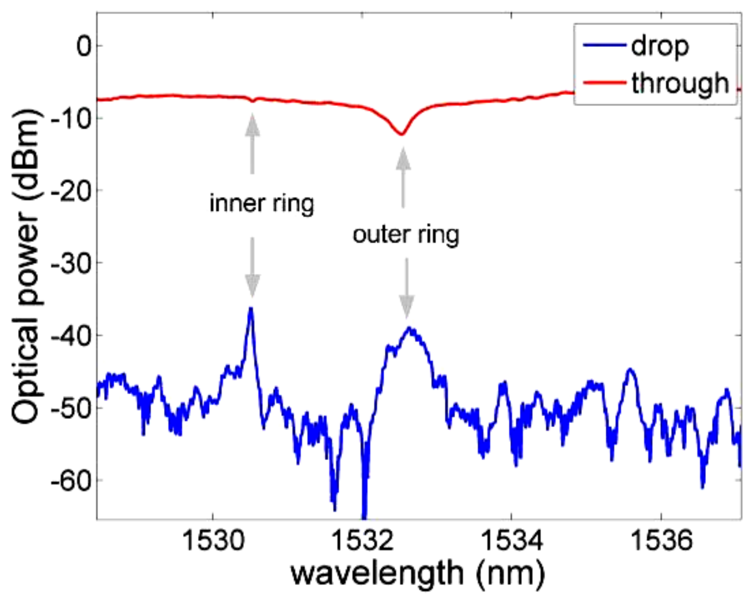

Fig. 4 The drop-port and through-port spectrum curves without perimeter compensation. The inner-ring and outer-ring resonating wavelengths were not at the same location due to the CIFS effect.

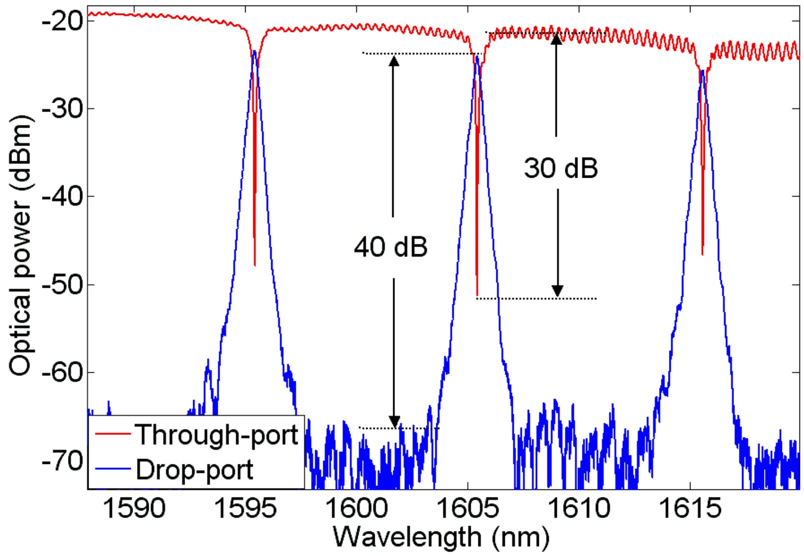

Fig. 5 The drop-port and through-port spectrum curves with ~130 nm perimeter compensation on the inner-ring. The through-port ER is ~30 dB and drop-port ER is ~40 dB. The cross-talk between these two output-ports are as low as -24.4 dB.

TABLE 1. The simulation data of the third-order microring filter

Measured data						
R	W_{ring}	W_{bus}	$gap_{ring-ring}$	$gap_{bus-ring}$	FSR	λ_0
10 μm	~525 nm	~470 nm	~390 nm	~140 nm	10.07 nm	1605.42 nm

Calculated and simulated data				
n_{eff}	n_g	$e^{-\gamma}$	k_1^2	k_2^2
2.8013	4.07	0.980	0.2304	0.0102

4. CONCLUSION

We have demonstrated a high ER third-order microring filter on SOI by careful design on the ring-ring and ring-bus coupling efficiencies. Perimeter compensation method was applied to solve the CIFS problem. Finally, high extinction ratios of 30 dB and 40 dB are measured at through-port and drop-port respectively. The cross-talk between these two output-ports are as low as -24.4 dB.

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