Flat-top passband filter based on parallel-coupled double microring resonators in silicon

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ABSTRACT

Optical filters with box-like response were designed and realized based on parallel-coupled double microrings in silicon-on-insulator. The properties of this design are simulated, considering the impact of the center-to-center distance of two rings, and coupling efficiency. Flat-top passband in the drop channel of the fabricated device was demonstrated with a 1dB bandwidth of 0.82nm, a 1dB/10dB bandwidth ratio of 0.51, an out of band rejection ratio of 14.6dB, as well as a free spectrum range of 13.6nm.

Key words: optical filter, box-like response, microring resonator, silicon

1. INTRODUCTION

Microring resonators are regarded as building block elements in the integrated photonic circuit. They have many applications in optical devices [1-5] such as add-drop filters, modulators, switches, and sensors. Silicon-on-insulator (SOI) is an attractive material for its low cost and compatibility with the mature complementary metal oxide semiconductor (CMOS) technology. Moreover, the high index contrast of the SOI material allows strong confined optical waveguides, as well as very sharp bends.

The response of a single microring resonator is Lorentzian shape, unsuitable for the practical applications for optical filtering. Hence, multiple-microring resonators [6-9] are always series or parallel coupled to achieve flat-top, fast roll-off, and large out-of-band rejection filtering bands. Recently, a novel design of two parallel-coupled microrings filter was presented [10] to have a flat-top and fast roll-off passband, as well as a uniformly large rejection stop-band in the drop channel. However, no verification in experiment has been reported yet.

In this paper, we have demonstrated a flat-top passband filter based on two parallel-coupled microrings in silicon for the first time, to our knowledge. In section 2, the mechanism and main properties of this device are illustrated and discussed theoretically. Then, in section 3, the experimental results are proposed and analyzed, which are in accord with the simulation.

2. THEORETICAL CALCULATION

The configuration of the parallel-coupled double microrings is sketched in Fig.1. The two microrings are symmetrically coupled to parallel waveguides with a center-to-center distance D. It is assumed that the two microrings are identical, having the same bent-waveguide dimensions, radius (R), internal loss per round (α), and coupling efficiency (k) with the bus waveguides.

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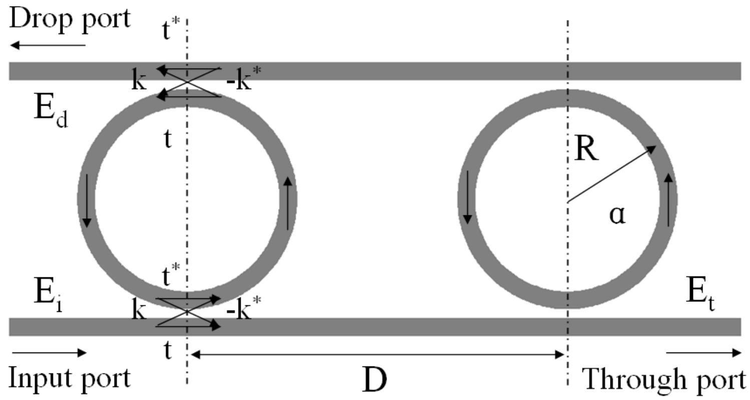

Fig.1. Schematic of the parallel-coupled double microring resonators

Assuming the bus waveguides to be lossless, by means of transfer matrix method, the relationship between the four ports can be determined by the following equation,

$$\begin{bmatrix} E_t \\ E_a \end{bmatrix} = \begin{bmatrix} 1/r & -\tau/r \\ \tau/r & (r^2-\tau^2)/r \end{bmatrix} \begin{bmatrix} \exp(j\theta') & 0 \\ 0 & \exp(-j\theta') \end{bmatrix} \begin{bmatrix} 1/r & -\tau/r \\ \tau/r & (r^2-\tau^2)/r \end{bmatrix} \begin{bmatrix} E_d \\ E_i \end{bmatrix} \tag{1}$$

where the parameters r, τ, θ, and θ' are given by

$$\tau = \frac{\alpha^{1/2} k^* k \ \exp(j\theta/2)}{1-\alpha t^{*2}\exp(j\theta)}$$

$$r = \frac{t-\alpha t^* \exp(j\theta)}{1-\alpha t^{*2}\exp(j\theta)}$$

$$\theta = 4\pi^2 R N_{eff} / \lambda_0 ,$$

$$\theta' = 2\pi D N_{eff} / \lambda_0 \tag{2}$$

where the N_{eff} and λ_0 are the effective index of guided mode and input wavelength, respectively.

We rewrite the relationship of the four ports as

$$\begin{bmatrix} E_t \\ E_a \end{bmatrix} = \begin{bmatrix} E & F \\ G & H \end{bmatrix} \begin{bmatrix} E_d \\ E_i \end{bmatrix}$$

Then, the transmission in the through and drop channels can be expressed by

$$\frac{E_t}{E_i} = H - \frac{FG}{E}, \text{ and } \frac{E_d}{E_i} = -\frac{F}{E} \tag{3}$$

Fig.2 has shown the transmission of the coupled double microrings having center-to-center distances of $D=\pi R+\lambda_0/(4\cdot N_{eff})$ (labeled as 1#) and $D=\pi R$ (labeled as 2#), respectively. For comparison, the transmission of a single microring is also plotted. It is found that the structure with $D=\pi R+\lambda_0/(4\cdot N_{eff})$ has a steeper bandedge and flatter stopband in the drop channel, while that with $D=\pi R$ has minor advantage, in comparison with the single microring filter.

The impact of coupling efficiency on the device out-of-band rejection, insertion loss, and 3dB bandwidth, as well as 1dB/10dB bandwidth ratio has been evaluated. As seen in Fig.3, the out-of-band rejection and insertion loss both decrease, while the 3dB bandwidth increases with the coupling efficiency, for a fixed power attenuation of 0.98 per round. We also find that the 1dB/10dB bandwidth ratio exceeds 0.50, when the coupling efficiency is larger than 0.15.

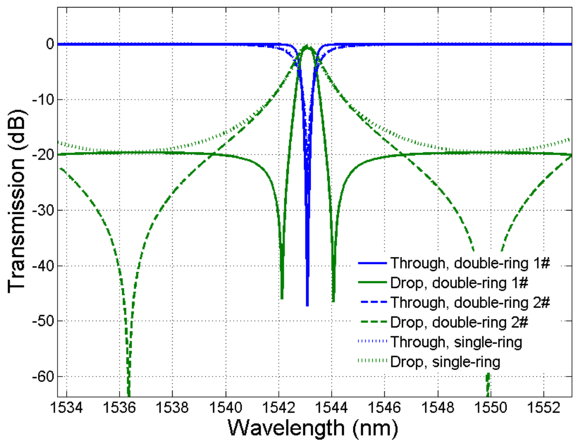

Fig.2. Responses of parallel-coupled microrings with two kinds of center-to-center distances and a single microring with the same other parameters

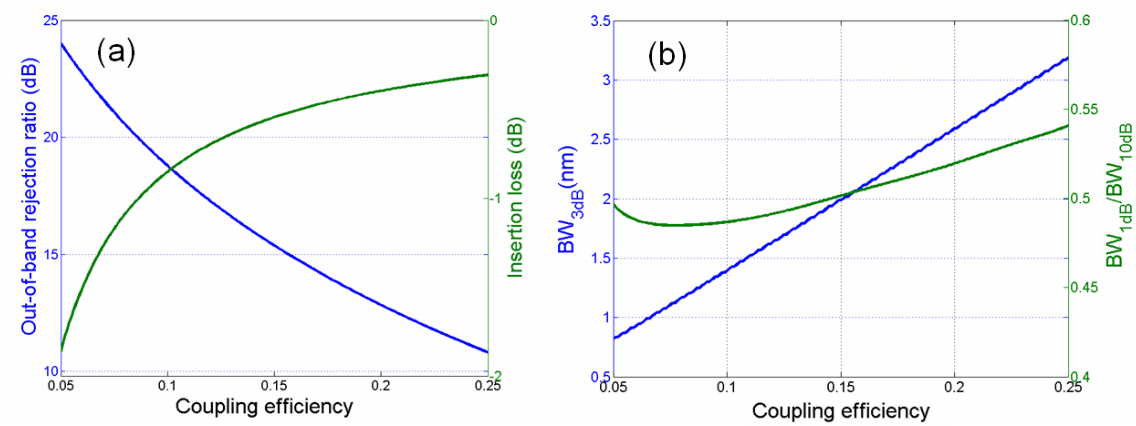

Fig.3. (a) Out-of-band rejection ratio and insertion loss vs. coupling efficiency, (b) 3dB bandwidth and 1dB/10dB bandwidth ratio vs. coupling efficiency, the power attenuation per round in all the microrings is assumed as 0.98

3. EXPERIMENTAL RESULTS

The device was fabricated on a unibond-type SOI wafer, with a 340nm-thick top silicon layer and a 1μm-thick buried silica layer. Electron-beam-lithography (EBL) and inductively-coupled-plasma (ICP) etching processes were employed to fabricate the microring resonators. The fabricated device is shown in

Fig.4. For single mode condition, the waveguides are of rib geometry with rib width of 420nm and slab height of 80nm. The two microrings are identical and symmetrically coupled, having a radius of 6μm, a center–to-center distance of 18.85μm, and spacing between the microring and bus waveguide of 170nm.

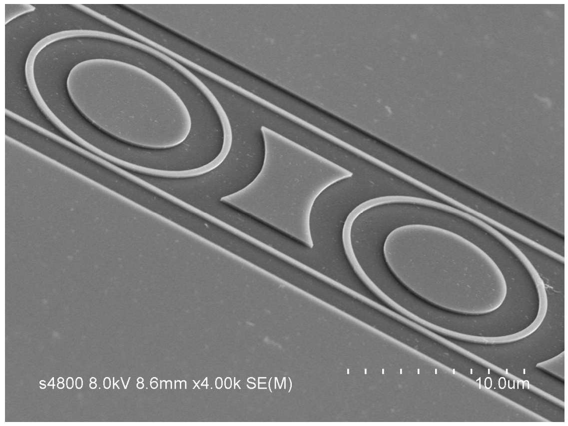

Fig.4. SEM image of the fabricated device

The input light is transverse-magnetic (TM) polarized. By making the light source and spectrum analyzer scanning synchronically, we obtained the transmission spectra of parallel-coupled double microring resonators, as seen in Fig.5. The information at the through and drop channel is presented. The free spectrum range was measured to be 13.6nm. Fig.6 shows the zoom-in of the peak around 1543nm. In the drop channel, the 1dB bandwidth of the passband achieves 0.82nm, and the 1dB/10dB bandwidth ratio is as high as 0.51, showing a steep band edge. The out-of-band rejection is 14.6dB. The insertion loss of the center in passband is about -2.0dB, which can be further reduced by lowering the internal loss in the microrings. From these results, we can infer that the internal power attenuation per round in the ring is 0.92, the coupling efficiency is 0.17, and the group index is 4.67. Due to the fabrication imperfection, the radius variation of the two rings is also considered here. It is observed that the simulation fits the experimental results very well.

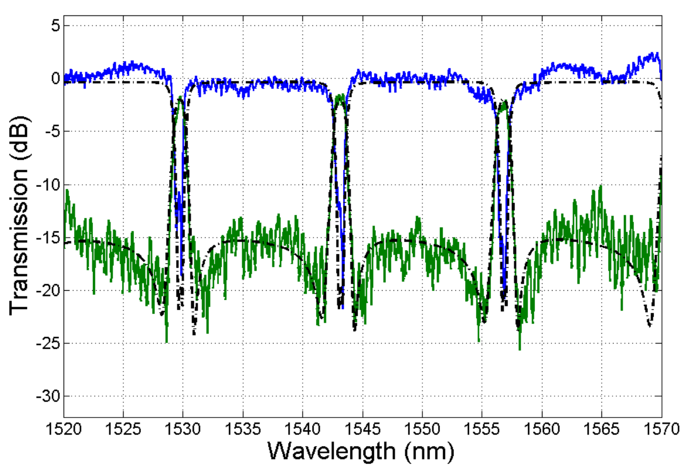

Fig.5. Transmission of the device at both the drop and through channel, the solid lines and dash dot lines represent the experimental results and simulation, respectively

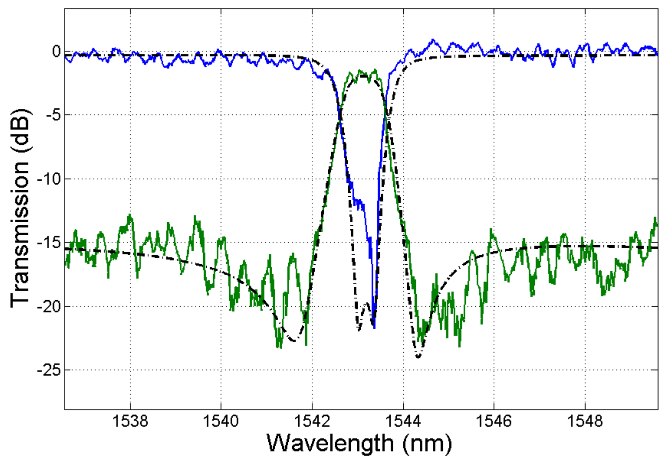

Fig.6. zoom-in of the peak around 1543nm, the solid lines and dash dot lines represent the experimental results and simulation, respectively

4. CONCLUSION

In summary, we have demonstrated a high-performance optical filter based on parallel-coupled double microring resonators in silicon. Flat-top and fast roll-off passband is realized with a 1dB bandwidth of 0.82nm, a 1dB/10dB bandwidth ratio of 0.51, as well as an insertion loss of -2.0dB. The out of band rejection ratio and free spectrum range of device were measured to be 14.6dB and 13.6nm, respectively. Properties of the design are also investigated theoretically, and the simulation fits the experimental results well.

5. ACKNOWLEDGMENTS

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