

Box-like filtering spectrum response analysis on the cascading race-track silicon microring resonators

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The optical filter which has the box-like filtering spectrum response is one of the most important key optical switching components in the dense wavelength division multiplexing (DWDM) system and the intelligent optical network. The integrated high-order silicon microring resonators (MRRs) are one of the best candidates to achieve the box-like filtering optical spectrum response. In general, all the waveguide-resonator couplers are optimized in those MRRs based schemes, resulting in a high process requirement in fabrication. In this paper, a box-like filtering spectrum response based on the cascading high-order MRRs with uniform couplers is presented and demonstrated, which cascading 6 and 15 coupled race-track MRRs in series. Using the 15 coupled race-track MRRs with 10 μm radius, the 3 dB flat-top pass band of 2 nm, the out-of-band rejection ratio of 30 dB and the rising and falling edges of 49 dB/nm are realized successfully, which achieve the box-like filtering spectrum response.

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1. Introduction

In the lightwave and fiber communication systems, the technique of dense wavelength division multiplexing (DWDM) is widely used to improve the communication capacity, owing to its ability to transmit the single independent signal utilizing different multiple wavelengths as channels [1-3]. The tight channel spacing in DWDM systems require the box-like spectrum response optical filters, which can avoid the channel crosstalk and ensuring the signal fidelity. The integrated high-order silicon microring resonators (MRRs) are one of the best candidates to achieve the box-like filtering optical spectrum response by cascading the MRRs parallel [10-12] or in series [4-9]. Especially, the race-track MRRs in series are one of the most popular choices due to its high coupling degree [4, 6, 8]. Using the cascading high-order MRRs to achieve the box-like filtering spectrum response, the waveguide-resonator coupling coefficient of each coupler should be optimized by varying the coupling region length or the inter-waveguide gap [5]. This will increase the high requirement on process tolerance which is introduced for the fabrication of the couplers. Hence, the integrated high-order MRRs with uniform couplers are more attractive.

In this paper, the box-like spectrum response filters based on high-order race-track MRRs in series with uniform couplers are presented. The integrated MRRs with race-track configuration are fabricated on the silicon-on-insulator (SOI) platform. By cascading different numbers of race-track MRRs in series (6 coupled and 15 coupled MRRs), the optical filters approaching the box-like spectrum response profiles are demonstrated. For the fabricated 6 coupled race-track MRRs in series, the

bandwidth at -3 dB is 2.3 nm, the out-of-band rejection ratio is 30 dB, and the rising and falling edges of the filtering response achieve 38 dB/nm. However, the ripple in the passband is more than 7 dB, which do not have the actual filtering capability in the C-band. For the fabricated 15 coupled race-track MRRs in series, the bandwidth at -3 dB is 2 nm, the out-of-band rejection ratio is 32 dB, the rising and falling edges of the filtering response achieve 49 dB/nm, and the ripple in passband is less than 2.5 dB, which show the good box-like filtering spectrum response characteristics. Furthermore, the complementary metal-oxide-semiconductor (CMOS) compatibility in material system leads to possible applications in integrated silicon photonic-electronic circuits for future on-chip optical interconnects.

2. Theory and device structure

The transfer matrix method is usually used to analyze the multiple MRRs which is shown in the Fig. 1.

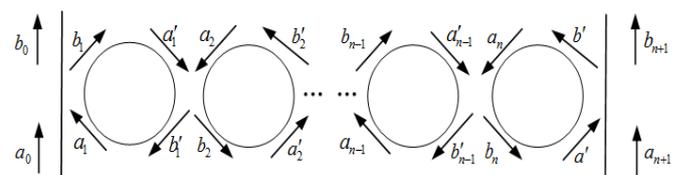


Fig. 1. Cascading MRRs

Assuming the coupling among the ring waveguides and the straight waveguide are lossless and directional, the

electric field quantities (a_i, b_i, a'_i, b'_i) of the coupling part in the resonator i can be expressed as follows [13]:

$$\begin{bmatrix} b'_i \\ b_{i+1} \end{bmatrix} = \begin{bmatrix} \tau_i & \kappa_i \\ -\kappa_i^* & \tau_i^* \end{bmatrix} \begin{bmatrix} a'_i \\ a_{i+1} \end{bmatrix} \quad (1)$$

where the τ_i and κ_i are the transmission coefficient and coupling coefficient of the resonator i , and $|\tau|^2 + |\kappa|^2 = 1$.

The formula (1) can be rewritten as follows:

$$\begin{bmatrix} a_{i+1} \\ b_{i+1} \end{bmatrix} = \frac{1}{\kappa_i} \begin{bmatrix} -\tau_i & 1 \\ -1 & \tau_i^* \end{bmatrix} \begin{bmatrix} a'_i \\ b'_i \end{bmatrix} \quad (2)$$

Assuming the resonator radius is large enough to neglect the bending loss of the ring waveguides and considering the phase change, the transfer matrix can be expressed as follows while the optical signal in the ring waveguide transmits for half a cycle [14].

$$\begin{bmatrix} a'_i \\ b'_i \end{bmatrix} = \begin{bmatrix} 0 & \exp(j\phi) \\ \exp(-j\phi) & 0 \end{bmatrix} \begin{bmatrix} a_i \\ b_i \end{bmatrix} \quad (3)$$

where $\phi = \beta L_i$, $L_i = 2\pi R_i$, $\beta = 2\pi n_{eff} / \lambda$ is the transmitting constant in the waveguide, the wavelength is λ and the effective refractive index is n_{eff} .

According to the recurrence method, the electric field transfer matrix in the N ring resonator can be obtained as follows:

$$\begin{bmatrix} a_n \\ b_n \end{bmatrix} = \begin{bmatrix} t_{11} & t_{12} \\ t_{21} & t_{22} \end{bmatrix} \begin{bmatrix} a_0 \\ b_0 \end{bmatrix} \quad (4)$$

Then the transmissivity can be obtained from the formula (4):

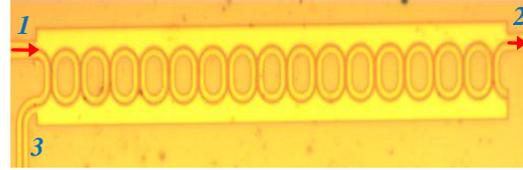
$$T = a_0 / b_{n+1} = t_{21} - t_{22} (t_{11} / t_{12}) \quad (5)$$

The cascading MRRs optical filters coupled with 6 and 15 race-track resonators are fabricated on the SOI platform. The waveguide structure consists of the top silicon, substrate silicon, buried-oxide layer and the upper cladding. In the C-band, the refractive index of silicon and SiO₂ are about 3.46 and 1.45, respectively, and the propagation of the light waves will be limited in the high refractive index of the top silicon. The SOI wafer has a 220 nm top silicon, a 3 μm buried-oxide layer and a 1 μm SiO₂ upper cladding layer. The single-mode silicon waveguides with 600 nm width are designed for transverse

electric (TE) polarization transmission. The race-track MRRs have a radius of 10 μm , the coupling region has the length of 8 μm . All the race-track MRRs are with the identical parameters in order to simplify device design and fabrication. The identical coupling coefficients are formed by unifying the inter-waveguide gap in the couplers, which is 200 nm for the fabricated MRRs. The microscope images of the fabricated cascading MRRs with 6 and 15 coupled race-track resonators are shown in Fig. 2(a)-2(b), where the numbers 1-3 denote the input port, the drop port and the through port of the optical filters, respectively. The input and drop ports for the cascading MRRs optical filter is vertically coupled with the blazed grating couplers.



(a)



(b)

Fig. 2. Microscope images of the optical filters:(a) cascading with 6 resonators;(b) cascading with 15 resonators. (1:input port, 2:drop port, 3:through port)

3. Experiments and analysis

The fabricated race-track high-order MRRs in series are characterized with the experimental setup shown in Fig. 3(a). Using a broad band light source, the race-track MRRs spectrum response is monitored in an optical spectrum analyzer (OSA). The polarization controller (PC) is used to optimize the polarization mode of the input light signal. Both the input port from the light source and the drop port at the OSA are coupled from the chip through a pair of blazed grating couplers. The grating couplers are utilized as the vertical input and output coupling. The period of the grating couplers is 620 nm and its filling factor is 0.5, which microscope image is shown in the Fig. 3(b). The coupling loss for each grating coupler is measured to be less than 3 dB.

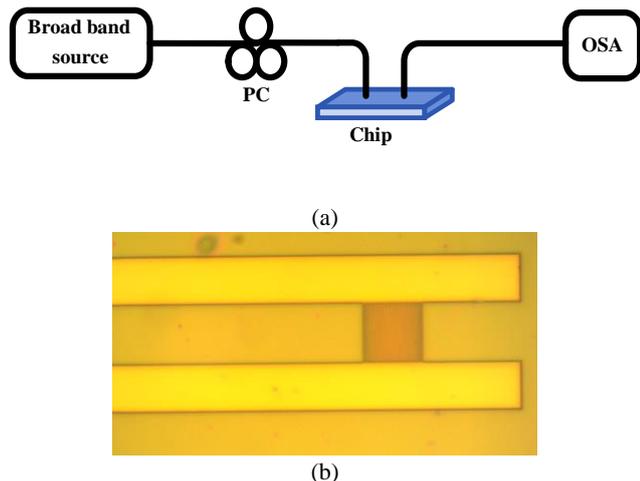


Fig. 3. (a): Experimental setup for device measurements; (b) the grating couplers. (PC: polarization controller, OSA: optical spectrum analyzer)

The measured spectrum response at the drop ports of the race-track MRRs with 6 and 15 coupled resonators are shown in Fig. 4(a)-4(b), respectively. The spectrum response of each coupled MRRs is presented, which the blue and red lines denote the measured and fitting results. The corresponding out-of-band rejection degrees for the 6-resonator and 15-resonator MRRs are measured to be 32 and 30 dB, respectively. The bandwidths at -3 dB for the 6-resonator and 15-resonator MRRs are 2.3 and 2 nm, respectively. The ripple of the 6-resonator and 15-resonator MRRs in the passband are -7 and -2.5 dB, the excess loss of the 6-resonator and 15-resonator MRRs are -4 and -7 dB, and the rising and falling edges from -3 dB to -25 dB of spectrum response for the 6-resonator and 15-resonator MRRs are 38 and 49 dB/nm, respectively. The measurements indicate that although the spectrum response is approaching a box-like profile with the increasement of the cascading resonators, the performance remains the same passband and less ripple with the 15-resonators than that with the 6-resonator. The excess loss will also be increased with more MRRs. To be noted, the results are measured using the broad band light source, and a better performance can be expected if a coherent light source is utilized instead.

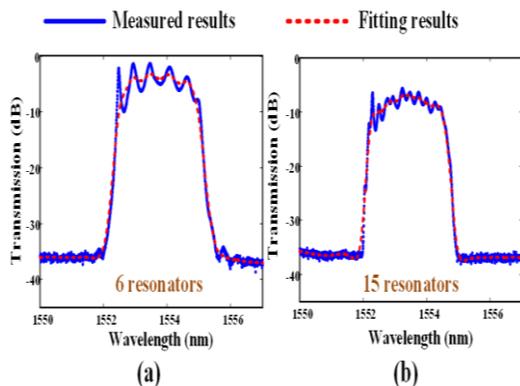


Fig. 4. Measured spectrum response of the cascading MRRs (a): cascading 6 resonators; (b): cascading 15 resonators

Furthermore, the proposed 15 coupled race-track MRRs optical filters work well within the whole C-band. Fig. 5 shows the wide wavelength range transmission measurement through the 15-resonator MRRs stage. From one band to the next, transmission uniformity of each passband is observed over the whole C-band wavelength range which is from 1527 nm to 1565 nm. The free spectral range (FSR), which is determined by the radius of the MRRs, is measured to be 8 nm.

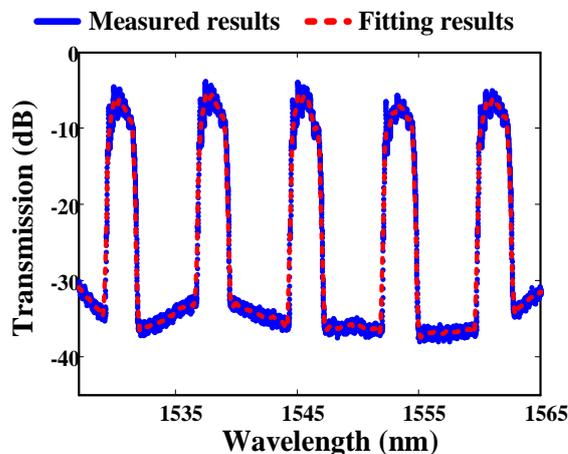


Fig. 5. Transmission spectrum of the cascading with 15-resonator filter in the whole C-band

4. Conclusions

In this paper, the optical filters based on the high-order race-track MRRs which has the box-like spectrum response are presented. In order to simplify the process, all the couplers are uniform with identical gap. For the fabricated 15-microring filter with 10 μm radius, the 3 dB flat-top pass band is 2 nm, the out-of-band rejection ratio is 30 dB, and the rising and falling edges of the filtering response is 49 dB/nm. The CMOS compatibility leads to potential applications in integrated silicon photonic-electronic circuits for future on-chip optical interconnect systems.

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