Research article

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On-chip scalable mode-selective converter based on asymmetrical micro-racetrack resonators

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Abstract: Mode division multiplexing (MDM) technology has been well known to researchers for its ability to increase the link capacity of photonic network. While various mode processing devices were demonstrated in recent years, the reconfigurability of multi-mode processing devices, which is vital for large-scale multi-functional networks, is rarely developed. In this paper, we first propose and experimentally demonstrate a scalable mode-selective converter using asymmetrical micro-racetrack resonators (MRRs) for optical network-on-chip. The proposed device, composed of cascaded MRRs, is able to convert the input monochromatic light to an arbitrary supported mode in the output waveguide as required. Thermo-optical effect of silicon waveguides is adopted to tune the working states of the device. To test the utility, a device for proof-of-concept is fabricated and experimentally demonstrated based on

silicon-on-insulator substrate. The measured spectra of the device show that the extinction ratios of MRRs are larger than 18 dB, and modal crosstalk for selected modes are all less than -16.5 dB. The switching time of the fabricated device is in the level of about 40 μ s. The proposed device is believed to have potential applications in multi-functional and intelligent network-on-chip, especially in reconfigurable MDM networks.

Keywords: integrated optics; mode division multiplexing; optical mode converter; silicon photonics.

1 Introduction

The demand for large capacity of data transmission and information processing has greatly promoted the development of multiplexing technologies. Whereas the wavelength division multiplexing (WDM) technology is being maturely used in daily life, people are still faced with a problem of limited information capacity [1, 2]. The recently developed mode division multiplexing (MDM) technology provides a promising method to meet the ever-growing demands for large channel capacity, and has been demonstrated to further increase the data transmission capacity of photonic network-on-chip (NoC) significantly [3, 4]. In MDM, various devices have been demonstrated to perform fundamental functions, for instance, mode converters [5–9], mode multiplexers [10–17], mode routers [18–20] and mode exchange devices [21–23]. To utilize those optical mode processing devices in multifunctional and intelligent NoC applications, there are still difficulties needed to be solved. Take the mode converter as example, most of the reported mode converters are designed to implement one specific mode conversion, unable to be used for other mode conversions, which limits the device's application in the aspect of constructing multifunctional and reconfigurable NoC. Therefore, it is necessary to develop reconfigurable mode converter. Some reconfigurable mode converters were proposed in recent years, based on LiNbO_3 waveguides [24, 25], two-mode fiber [26], and silicon-on-insulator (SOI) mode switch [27].

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However, the sizes of devices based on LiNbO_3 waveguide and two-mode fibers are too large to achieve large-scale integration, and the tuning voltages are too high when changing the device's working states [24–27]. A mode switch based on SOI Mach-Zehnder Interferometer can be adopted to implement two-mode selective conversion, but its size is still large and is theoretically limited to only two modes [27]. Therefore, it is of necessity and significance to develop an MSC with compact size, low tuning voltages, and more modes for conversion.

Micro-racetrack resonator (MRR) is a promising candidate to form MSC because of its excellent tuning performance for optical switching. Typically, the footprint of an MRR is about several hundred square micrometers, which is small enough for large-scale integration, and the tuning voltage is about several volts, which is very low compared with the voltages applied in LiNbO_3 and two-mode fiber devices [24–27]. In 2014, researchers in Cornell University demonstrated an MRR-based mode division multiplexer [17], which shows that asymmetrical MRR can be adopted to implement mode conversions well. However, that device cannot implement on-chip mode-selective conversion either. Based on the aforementioned examples of the mode conversion devices, there is still no solution for compact, reconfigurable devices for large number of optical modes operation.

In this paper, we propose and demonstrate a compact and reconfigurable optical mode-selective converter based on asymmetrical micro-racetrack resonators (MRRs). To the best of our knowledge, it is the first demonstration of reconfigurable mode-selective converter based on SOI waveguide. By tuning the resonant states of MRRs, the proposed device can selectively convert the input light to any one of the modes supported in the output waveguide as required. Besides, owing to the wavelength tunability of MRR, the reconfigurable function can also be implemented when several wavelengths are launched simultaneously. A device which can convert the input light to an arbitrary one of the four lowest order modes (TE_0 , TE_1 , TE_2 , TE_3) is fabricated on SOI wafer using the E-beam lithography (EBL) and the reactive-ions-etching (RIE) processes process. The measurement results show that the fabricated device have the extinction ratio (ER) of larger than 18 dB, the modal crosstalk of smaller than -16.5 dB and the switching time of about 40 μs .

2 Device principle and parameters

Figure 1 shows the schematic of the proposed mode selective converter, which is composed of some asymmetrical MRRs. The input waveguide and racetrack waveguide of

each MRR are single-mode waveguides while the output waveguide is either single-mode or multi-mode waveguide to implement mode conversion. The MRRs share the same input single-mode waveguide. The different width output waveguides of MRRs are connected by linear adiabatic tapers to decrease mode transmission crosstalk and form the bus waveguide of the entire device. The widths of input single-mode waveguide and racetrack waveguide are all w_0 . The widths of the output waveguide of MRR_0 , MRR_1 , MRR_2 , and MRR_N are w_0 , w_1 , w_2 , and w_N , respectively. N is a positive integer, and the largest number of N is related to the insertion loss (IL) and modal crosstalk of device. The widths w_0 , w_1 , w_2 , and w_N should satisfy the phase matching condition which corresponds to modes TE_0 , TE_1 , TE_2 , and TE_N in the output waveguide of MRR_0 , MRR_1 , MRR_2 , and MRR_N , respectively [28]. The gap between the input single-mode waveguide and racetrack waveguide for all MRRs are equal to g_0 , while the gap between output bus waveguide and the racetrack waveguide for MRR_0 , MRR_1 , MRR_2 , and MRR_N are g_0 , g_1 , g_2 , and g_N , respectively. Each MRR has a micro-heater on top to tune its resonant state. If a monochromatic light is launched into the MSC, the light can be directed to one MRR by selectively control the resonant states of the MRRs, and then converted to a specific mode to the bus waveguide. For example, as shown in Figure 1, if MRR_2 is tuned on-resonance while other MRRs are off-resonance, the input light will be converted to TE_2 mode and be directed to the output port. Similarly, when only one of the other MRRs is on-resonance, other modes can be obtained. If the input light with several wavelengths λ_0 , λ_1 , λ_2 , ... and λ_N are launched at the input port, for one specific MRR, it can be switched between these wavelengths by controlling its resonant state. By simultaneously controlling all MRRs' resonant states, the input channels of multi-wavelength can also be freely transmitted to the output channels of modes.

Figure 1: Schematic of the salable mode-selective converter, which includes $(N+1)$ asymmetrical micro-racetrack resonators (N is a positive integer).

To determine the waveguide widths of the device for phase matching, we calculated the effective refractive indices of all supported transverse-electric modes in SOI waveguide using finite-element method mode solver [29, 30]. The width varies from zero to 3 μm , and the results are shown in Figure 2(a). From Figure 2(a), we can see that, when the width of single-mode waveguide is 450 nm, its effective refractive index is 2.35. According to coupling mode theory [17, 28], the coupling between two waveguides will be most efficient when propagating constants of the coupled modes are the same. From the calculated results, the widths of TE_1 , TE_2 , and TE_3 waveguides are suggested to be $w_1 = 930$ nm, $w_2 = 1.41$ μm , and $w_3 = 1.93$ μm , respectively, to achieve effective mode coupling. Besides, to decrease the coupling modal crosstalk, the length of coupling region in racetrack waveguide is optimized as 6 μm . For an MRR to achieve high performance (large ER and low insertion loss), the gaps between racetrack waveguide and input/output waveguide are also important. According to the scattering matrix model [31], the ER and IL are related to the gaps of coupling regions.

$$\text{ER} = 10 \times \log_{10} \frac{(1 + \alpha t_1 t_2)^2}{(1 - \alpha t_1 t_2)^2} \quad (1)$$

$$\text{IL} = 10 \times \log_{10} \frac{(1 - t_1)^2 (1 - t_2)^2 \alpha}{(1 - \alpha t_1 t_2)^2} \quad (2)$$

where α is the amplitude transmission factor of MRR, which specifies the fraction of the amplitude transmitted per pass around the micro-ring waveguide, α is related to the transmission loss of micro-ring waveguide and defined as $\alpha = \exp(-A \cdot L/2)$ where A is the transmission loss of light, and L is the circumference of micro-ring waveguide. t_1 and t_2 are the transmission coefficients of the two coupling

regions of MRR. Here we ignore the coupling loss of each coupling region of MRR, then the transmission coefficients t_1 and t_2 are related to coupling coefficients k_1 and k_2 as $k^2 + t^2 = 1$. The coupling coefficients k_1 and k_2 can be calculated by the model of directional coupler [32].

Figure 2(b) shows the calculated dependence of ER and IL on the coupling gap, from which we can see that the larger the coupling gap is, the larger the ER and IL will be. Therefore, the chosen of gap should compromise between the ER and IL. In our simulation, A is chosen as 10 dB/cm and L is 78.8 μm . Considering the actual application scenario, we choose the gap $g_0 = 240$ nm to implement an ER about 20 dB, of which the coupling coefficient is about 0.42. Meanwhile, to satisfy the critical coupling condition of MRRs and achieve an ER about 20 dB, the gaps g_1 , g_2 , and g_3 are 200 nm, 175 and 150 nm, respectively.

3 Fabrication and experimental characterization

Based on the principle and parameters discussed in Section 2, we fabricated a SOI-based MSC which can convert the input light to any one of the lowest four transverse electric modes (TE_0 , TE_1 , TE_2 and TE_3), for experimental demonstration. A SOI substrate, with 220 nm top silicon layer and 3 μm buried silicon dioxide layer, was utilized to fabricate the device. The waveguides were patterned using Vistec EBPG5000Plus electron beam lithography (EBL) on a 400-nm-thick ZEP520A EBL resist layer spun on the chip. And then the waveguides are fully etched by Oxford PlasmaPro 100 reactive ion etching (RIE) system. A 2 μm thick silicon dioxide layer was then deposited as the cladding layer of

Figure 2: Simulated results of the proposed device. (a) the effective refractive indices of channel SOI waveguide in different waveguide widths, with the height of waveguide of 220 nm, and the wavelength of 1550 nm. (b) the dependence of extinction ratio (ER) and insertion loss (IL) on the coupling gaps.

waveguides by plasma enhanced chemical vapor deposition (PECVD). After that, 100 nm thick and 5 μm wide Titanium (Ti) heaters were fabricated by using e-beam evaporation deposition and lift-off processes. Then, 100 nm Gold (Au) was deposited to realize connection wires and contact pads. Finally, another layer of 500 nm silicon dioxide layer was deposited to protect the device, with via holes to Au pads for electrical access.

The micrograph of the fabricated device which is composed of an MSC and a four-mode demultiplexer is shown in Figure 3. The MRRs are labeled with MRR_0 , MRR_1 , MRR_2 , and MRR_3 , respectively. The radii of the MRRs are designed to be 10 μm for the tradeoff between lowering bending losses and decreasing the device size. Linear adiabatic taper with 150 μm in length was fabricated to connect the output waveguides of MRRs, and thus forming a bus waveguide. The effective footprint of the fabricated MSC is about $40 \times 700 \mu\text{m}$ excluding the electrodes. To characterize the converted mode, an asymmetrical directional coupler-based mode demultiplexer are also fabricated at the Output of the MSC. The additional mode demultiplexer is about $60 \times 400 \mu\text{m}$ in footprint. The input port of the entire device is labeled with I , and the output ports are labeled with O_0 , O_1 , O_2 and O_3 , respectively. To couple light into/out from the device, grating couplers with 70 nm etching depth are fabricated at all the input and output ports of the device. The light output from ports O_0 , O_1 , O_2 and O_3 correspond to TE_0 , TE_1 , TE_2 and TE_3 output

from the MSC. Therefore, if high level of optical power is detected in one of these ports, it means the corresponding mode is obtained in the MSC.

To characterize the fabricated device, an experimental system is established, which is shown in Figure 4(a), including an amplified spontaneous emission adopted to generate broadband light, two single-mode fibers used to direct the light into/out from the device, an optical spectrum analyzer for static response spectra observation, two dual-channel tunable voltage sources utilized to apply voltages on the micro-heaters through micro-probes contacted with the pads. Owing to the limited fabrication accuracy, small differences exist in the four MRRs, which lead to different initial resonant wavelengths. To compensate these differences, $\lambda_1 = 1,550.3 \text{ nm}$ is chosen as the working wavelength of the device. The voltages for MRR_0 , MRR_1 , MRR_2 , and MRR_3 to be resonant at λ_1 are $V_0 = 2.2 \text{ V}$ (33.4 mW), $V_1 = 1.7 \text{ V}$ (18.5 mW), $V_2 = 2.4 \text{ V}$ (36.5 mW), and $V_3 = 1.8 \text{ V}$ (20.0 mW), respectively, while 0.00 V for off-resonance. The measured results are shown in Figure 5. Figure 5(a) shows that when only MRR_0 is on-resonance while MRR_1 , MRR_2 , and MRR_3 are all off-resonance at λ_1 , only the received power of λ_1 at port O_0 is in high level, other ports O_1 , O_2 and O_3 are all in low levels, which means TE_0 is obtained in the MSC. The modal crosstalk (CT) between TE_0 and other modes are all less than -16.5 dB . Similarly, when only MRR_1 is on-resonance while other MRRs are off-resonance, TE_1 is obtained in port O_1 , and the

Figure 3: Micrograph of the fabricated device which contains a mode selective converter and a mode demultiplexer.

Figure 4: The schematic of experimental setups adopted to test the fabricated device. (a) is the setup used to measure transmission spectra of the device, (b) is the setup utilized to measure the device's switching time. (ASE: amplified spontaneous emission; DUT: device under test; TVS: tunable voltage source; OSA: optical spectra analyzer; TL: tunable laser; PC: polarization controller).

Figure 5: Measured static response spectra of the fabricated device. (a) is the measured spectra at four output ports when only MRR_0 is on-resonance, (b) is the measured spectra at four output ports when only MRR_1 is on-resonance, (c) is the measured spectra at four output ports when only MRR_2 is on-resonance, (d) is the measured spectra at four output ports when only MRR_3 is on-resonance, respectively. (CT: crosstalk).

modal crosstalk between TE_1 and other modes are all less than -18.9 dB [Figure 5(b)]. When only MRR_2 is on-resonance while other MRRs are off-resonance, TE_2 is obtained in port O_2 , and the modal crosstalk between TE_2 and other modes are all less than -21.4 dB [Figure 5(c)]. When only MRR_3 is on-resonance while other MRRs are off-resonance, TE_3 is obtained in port O_3 , and the modal crosstalk between TE_3 and other modes are all less than -23.0 dB [Figure 5(d)]. The ILs for selected modes are about 2.0 dB for TE_0 , 2.6 dB for TE_1 , 2.4 dB for TE_2 and 2.6 dB for TE_3 at λ_1 . These losses include two parts, one part is the conversion loss from the MSC, the other one is the transmission and coupling loss in the fabricated mode demultiplexer (De-MUX). The losses of De-MUX are estimated about 0.4 dB for TE_0 , 1.3 dB for TE_1 , 1.5 dB for TE_2 , and 1.3 dB for TE_3 mode by the measured results of fabricated MUX and De-MUX on the same chip. Then we can estimate the losses for MRR_0 , MRR_1 , MRR_2 and MRR_3 to perform different mode conversions are about 1.2 dB, 1.3 dB, 0.9 dB, and 1.2 dB. Further optimizing the device parameters and adopting higher accuracy fabrication process could help to mitigate those on-chip losses of the device. From Figure 5, we can also calculate that, the quality factors of the four MRRs are about 5200, 6400, 7500 and 7500, respectively. Note that all the spectra in Figure 5

were normalized to the transmission spectrum of the reference waveguide fabricated close to the MSC. The peak wavelength of reference waveguide is 1546.9 nm, the loss at the peak wavelength is -11.4 dB, and the full-width-at-half-maximum is 39.7 nm.

The switching time of MRRs are also measured. The measuring setups include a tunable laser to generate monochromatic light, a polarization controller to tune polarization of light in the input fiber, an arbitrary waveform generator to supply dynamical electrical signals, a photodetector to detect output optical power and an oscilloscope to observe the electrical waveform [Figure 4(b)]. The peak-to-peak voltage of the applied electrical signal is 1.0 V. Figure 6 shows measured switching results of four MRRs. The results show that the switching times of MRRs are all about $40\mu\text{s}$ for rise times (RT: 10% $\rightarrow$ 90%) and $14\mu\text{s}$ for fall times (FT: 90% $\rightarrow$ 10%). The values of rise times of MRRs are all larger than the values of fall times, this is mainly attributed to two reasons: (1) the wavelength shifts from initial on-resonance state to off-resonance state of MRRs induced by thermo-optic effect should be smaller than that for the case from off-resonance state to on-resonance state [33]; (2) the heat radiation process is slower compared with heat accumulation process in SOI waveguide.

Figure 6: Dynamical response of the device when the MRRs are switching during time, (a) is the electrical signal applied to the micro-heaters, (b) is the electrical signal obtained from oscilloscope. (RT: rise time, FT: fall time).

In reconfigurable applications which adopting both WDM and MDM technologies, optical mode converters are always faced with multiwavelength signals. To further demonstrate the utility and reconfigurability of the fabricated device, multiwavelength-mode switching results are also measured and shown in Figure 7. Thanks to the good tunability of MRRs, the input wavelength channels can be freely converted to four mode channels by tuning the MRRs simultaneously. In this experiment, we choose four

working wavelengths, $\lambda_1 = 1,550.3 \text{ nm}$, $\lambda_2 = 1,551.9 \text{ nm}$, $\lambda_3 = 1,553.5 \text{ nm}$ and $\lambda_4 = 1,555.1 \text{ nm}$, the MRRs are tuned to resonate at these corresponding wavelengths in different working states. Figure 7(a) shows the result of λ_1 converted to TE₀, λ_2 converted to TE₁, λ_3 converted to TE₂ and λ_4 converted to TE₃, when voltages applied to MRR₀, MRR₁, MRR₂, and MRR₃ are $V_{01} = 2.2 \text{ V}$, $V_{12} = 2.7 \text{ V}$, $V_{23} = 3.6 \text{ V}$, and $V_{34} = 3.8 \text{ V}$, respectively; Figure 7(b) shows the result of λ_1 converted to TE₃, λ_2 converted to TE₂, λ_3 converted to TE₁

Figure 7: Wavelength switching results of the fabricated device. (a) is the result of λ_1 converted to TE_0 , λ_2 converted to TE_1 , λ_3 converted to TE_2 , and λ_4 converted to TE_3 , (b) is the result of λ_1 converted to TE_3 , λ_2 converted to TE_2 , λ_3 converted to TE_1 , and λ_4 converted to TE_0 , (c) is the result of λ_1 converted to TE_2 , λ_2 converted to TE_0 , λ_3 converted to TE_3 , and λ_4 converted to TE_1 , (d) is the result of λ_1 converted to TE_1 , λ_2 converted to TE_3 , λ_3 converted to TE_0 , and λ_4 converted to TE_2 . (FSR: free spectral range).

and λ_4 converted to TE_0 , when voltages applied to MRR_0 , MRR_1 , MRR_2 , and MRR_3 are $V_{04} = 3.5$ V, $V_{13} = 3.0$ V, $V_{22} = 2.8$ V, and $V_{31} = 1.8$ V, respectively; Figure 7(c) shows the result of λ_1 converted to TE_2 , λ_2 converted to TE_0 , λ_3 converted to TE_3 and λ_4 converted to TE_1 , when voltages applied to MRR_0 , MRR_1 , MRR_2 , and MRR_3 are $V_{03} = 3.1$ V, $V_{11} = 1.7$ V, $V_{24} = 4.0$ V and $V_{32} = 2.7$ V, respectively; Figure 7(d) shows the result of λ_1 converted to TE_1 , λ_2 converted to TE_3 , λ_3 converted to TE_0 and λ_4 converted to TE_2 , when voltages applied to MRR_0 , MRR_1 , MRR_2 , and MRR_3 are $V_{02} = 2.8$ V, $V_{14} = 3.4$ V, $V_{21} = 2.4$ V, and $V_{33} = 3.6$ V, respectively. The modal crosstalk in the four working states is all less than -14.1 dB. By reducing the bandwidths of MRRs, this crosstalk can be further improved. From Figure 7, we can also calculate that, the ERs of the MRRs' resonant spectra are all larger than 18 dB, and the free spectral ranges are about 7.2 nm.

Comparing with the state-of-art approaches for mode selective converters, illustrated in Table 1, ours has the most compact footprint, more than three times smaller than the report in ref. [27]. For the driven voltage, ours is also very attractive, comparable to the one of ref. [25] and smaller than 50% of the on-chip one in ref. [27]. Most importantly, due to the extendable capability of our devices, we have four available modes to realize the reconfigurable functionality. Since the losses for four MRRs are quite close, and the crosstalk for different mode conversions are all less than -16.5 dB, the modes available to be selectively converted can be extended to more in the future. According to the recently reported optical mode multiplexer [34], the state-of-art number of modes can be converted and multiplexed with acceptable IL and crosstalk is as large as 11. Hopefully, by adopting similar sub-wavelength grating micro-ring waveguide, the integer N of

Table 1: Results compared with similar devices reported by previous works.

Results	Device size	Largest crosstalk	Driven voltage	Modes available	Extensible
Ref. [24]	~8 mm	−18 dB	35 V	2	No
Ref. [25]	~24 mm	−20 dB	0–1.7 V	2	No
Ref. [26]	100 mm	−9 dB	90 V	2	No
Ref. [27]	70 × 1500 μm	−12 dB	5.7 V	2	No
This device	40 × 700 μm	−16.5 dB	0–2.4 V	4	Yes

our proposed device in Figure 1 is supposed to be as large as 10, which will be an interesting topic in future works.

4 Conclusion

In summary, a SOI-based reconfigurable optical mode selective converter has been proposed using asymmetrical MRRs. By controlling the resonant states of MRRs, the input monochromatic light can be selectively converted to any one of the optical modes supported in the Output waveguide. When several wavelengths are input simultaneously, the one-to-one relations between input wavelengths and converted modes can be freely changed. As a proof of concept, an MSC that can convert input light to one of the lowest four transverse electrical modes is fabricated and demonstrated. The measured static response spectra show that the fabricated device have ERs larger than 18 dB. In mode selective conversion, the modal crosstalk is all smaller than −16.5 dB. Finally, dynamical tuning of fabricated device is demonstrated, the switching time for conversion is about 40 μs and the multiwavelength-mode conversion crosstalk is all less than −14.1 dB. Compared with similar devices reported in recent years, our device has much compact size, lower tuning voltages, more modes available, and extensible structure. Therefore, the proposed optical mode selective converter holds great promise for future multi-functional and reconfigurable optical communication networks.

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