Four-channel reconfigurable optical add-drop multiplexer based on photonic wire waveguide

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Abstract: We designed and fabricated a four-channel reconfigurable optical add-drop multiplexer based on silicon photonic wire waveguide controlled through thermo-optic effect. The effective footprint of the device is about 1000×500 μm². The minimum insertion loss is about 10.7 dB and the tuning bandwidth about 17 nm. The average tuning power efficiency is about 6.187 mW/nm and the tuning speed about 24.4 kHz. The thermo-optic polarization-rotation effect is firstly reported in this paper.

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References and links
1. Introduction

Optical networks are developing towards the direction of high speed, large capacity, intelligentization and remote controllability. Reconfigurable optical add-drop multiplexer (ROADM) is able to provide flexible provisioning and reconfiguration in the dense wavelength-division multiplexing (DWDM) networks. It meets the requirements of the optical networks and is a key component for the automatic switch optical networks. Thus the ROADMs are widely investigated and several schemes based on different technology have been proposed, such as planar lightwave circuits (PLC), fiber arrays, vertically coupled micro-ring resonators (MRR), silicon (Si) photonic wire waveguides (PWW), fiber gratings, micro-electromechanical systems (MEMS), liquid crystals, etc. However, the ROADMs based on PLC [1-5], fiber arrays [6] and fiber gratings [7] are normally several centimeters in length. The tuning bandwidth of the ROADMs based on vertically coupled MRR [8] is 4.18 nm and the average tuning power efficiency about 26.6mW/nm. The radius of the vertically coupled MRR based on Si3N4 is 50 μm [8], which is relatively large and limits the tuning bandwidth of the ROADM. The ROADMs based on Si PWW [9, 10] can only add/drop one channel. The ROADMs based on MEMS [11, 12] and liquid crystals [13, 14] normally use free-space optics technology which makes the alignment and packaging difficult. Thus, the ROADMs are demanded to be more compact, higher-flexibility and lower-power-consumption for building the next-generation optical networks.
The Si PWW fabricated with silicon-on-insulator (SOI) is suitable for the large-scale photonic integrated circuits or the large-scale optoelectronic integrated circuits [15-21] due to its outstanding performance and CMOS-compatible fabrication process. The MRR based on Si PWW is one of the most attractive structures and draws more and more attention from the researchers in the fields of the integrated optics and the integrated optoelectronics for its superior performance in compactness and versatility. The footprint of one MRR based on Si PWW is about $10^{-6}$ cm$^2$ or even less. Various MRR-based optical devices have been demonstrated, such as high-speed modulators [22, 23], add-drop filters [24-29], multiplexers/demultiplexers [30], optical switches [31-33], optical buffers [34], etc. However, to the best of our knowledge, the multi-channel ROADM based on Si PWW MRR has not yet been reported.

This paper is arranged as follows. In section 2, the design and fabrication of the add-drop MRRs and the ROADM are reported. In section 2.1, the definition of the coupling coefficient is given and the calculation method for it is introduced, and the relationship between the performance of the add-drop MRR and its coupling coefficient is analyzed theoretically. In section 2.2, the design and fabrication of the ROADM are described in details. In section 3, the performance of the add-drop MRRs and the ROADM is reported. In section 3.1, the experimental results of the add-drop MRRs are compared with the simulation results. In section 3.2 and 3.3, the static response and the dynamic response of the four-channel ROADM based on Si PWW MRR are characterized respectively. In section 4, the thermo-optic polarization-rotation effect is firstly reported. In section 5, the paper is summarized and the possible optimization method for the ROADM is introduced.

2. Design and fabrication

2.1. Coupling coefficient

Coupling coefficient, which reflects the interactional intensity between the resonant cavity and the external, determines the performance of the MRR [35-39] and is defined as follows. If the amplitude of the input optical field is normalized to 1, the coupling coefficient is the amplitude of the optical field coupled into the MRR in one optical cycle. The coupling coefficient of the structure shown in Fig. 1 is calculated using 3-dimensional (3D) full vector finite-difference time-domain (FDTD) method. The normalized optical field is input into the structure from the input port and passes through the coupling region labeled by the dashed line. There is only half a ring in the simulation, so the optical field coupled into the structure does not interfere with each other and the coupling coefficient is the amplitude of the optical field detected at the output port. The cross-section of the Si core layer of the waveguide is 300×300 nm$^2$. The MRR based on this structure has been demonstrated to be polarization-insensitive in the resonant wavelength [40] and is used here to make the ROADM polarization-insensitive. To make the tuning bandwidth as large as possible, the MRR with the radius of 5 µm, which possibly is the smallest value without significant bending loss [17], is selected and the free spectrum range (FSR) determined by 3D FDTD method is about 17 nm.

The coupling coefficient varies with the polarization state (Fig. 2), which makes the MRR polarization-dependent. We also find that the coupling coefficient of the TE mode is larger than that of the TM mode which makes the 3-dB bandwidth for the TE mode larger than that
for the TM mode [41]. It helps us to determine whether the MRR is resonant on TE or TM mode during the measurement.

Scattering-matrix method [41-44] is used to analyze the filtering performance of the add-drop MRR with 3-dB/cm propagation loss in the MRR assumed. Figure 3 (a) shows the schematic structure of the add-drop MRR. The coupling coefficient is denoted by $k_1$ and $k_2$. The performance of the add-drop MRR varies with the change of $k_1$ and $k_2$ (Figs. 3 (b)–(e)).

For a specific $k_1$, there is a minimum through-crosstalk point as well as a minimum drop-loss point (Figs. 3 (c)–(e)). However, the minimum through-crosstalk point is inconsistent with the minimum drop-loss point. Therefore, it is a tradeoff to optimize the through crosstalk.
and the drop loss. The maximum amplitude at the drop port decreases with a decrease of $k_1$. Thus $k_1$ should be as large as possible to make the drop loss small. But larger $k_1$ makes the 3-dB bandwidth larger (Fig. 3 (b)) which induces larger interband crosstalk. Also larger $k_1$ requires the gap (Fig. 1) to be narrower, which makes the fabrication process more difficult. In the layout, a series of add-drop MRRs with various gaps are designed.

2.2. Structural design and fabrication of the ROADM

The schematic structure of the ROADM is shown in Fig. 4, which is composed of four reconfigurable add-drop MRRs (R1–R4). To be applied in the DWDM systems, the 3-dB bandwidth of the add-drop MRR should be less than 0.8 nm, which requires the coupling coefficient of the MRR with symmetric coupling structure less than 0.13 according to the discussion in section 2.1. Comprehensively considering the 3-dB bandwidth, drop loss, through crosstalk and the fabrication process, the coupling coefficient ranging from 0.9 to 0.11 is chosen, which corresponds to the gap ranging from 380 nm to 420 nm. Thus the through crosstalk ranges from 9 dB to 12.5 dB and the drop loss from 1.3 dB to 3 dB. Multi-channel DWDM signals are coupled into the input port and pass through four MRRs. The signals with the wavelengths equal to the resonant wavelengths of R1-R4 are downloaded and exported to D1–D4 ports respectively. The left signals are undisturbedly exported to the output port. Local signals are respectively input into A1–A4 ports, uploaded to the backbone by the corresponding MRRs and exported to the output port.

It is well known that the plasma-dispersion (PS) effect and the thermo-optic (TO) effect can be used to tune the refractive index of Si. The PS effect usually induces extra loss caused by the absorption of the free carriers [45] whereas the TO effect does not induce any extra loss. Although the tuning speed of the TO effect is normally in the order of 0.1 ms, which is much slower than that of the PS effect, it is fast enough for the ROADM. Thus the TO effect is preferred in our device. The insert shows the detailed structure of the reconfigurable add-drop unit. The MRR as well as the buses in the coupling region is covered by the heater to make the coupling in-phase. The reconfiguration of the ROADM is realized through electrically heating the heaters to change the temperature of the MRRs.

The optical field distribution of the waveguide with 300×300-nm$^2$ Si core layer and 500-nm-thick silica cladding for the TM and TE mode, which is calculated by using 3D beam propagation method (BPM), is shown in Fig. 5 (a). There is a large amount of optical field outside the core layer for both polarization states, which is quite different from the conventional waveguide [46]. The imaginary part of the refractive index of metal is quite large at the optical communication wavelength and it can cause large optical loss. Therefore, the thickness of the silica separate layer (SL) between the core layer and the metal must be designed carefully to avoid the unwanted optical absorption of the metal. The effective refractive index (ERI) of the fundamental mode of the waveguide with Si core layer surrounded by the SL and metal is calculated using 3D full vector BPM (Fig. 5 (b)). When the thickness of the SL is less than 1000 nm, the ERI approaches to zero. Figure 5 (c) shows the
optical field distribution of the waveguide with the Si core layer surrounded by 500-nm-thick SL and metal calculated by using 3D BPM for the TM and TE mode. It can be seen that the optical field leaks into the metal totally for the TM mode and most of the optical field leaks into the metal for the TE mode. When the thickness of the SL reaches and exceeds the critical value (about 1000 nm), the ERI jumps to 2.127 and almost keeps constant as the SL further increases. The optical field distribution of the waveguide with the Si core layer surrounded by 1200-nm-thick SL and metal for the TM and TE mode (Fig. 5 (d)) is almost the same as the case in Fig. 5 (a), which means that the optical field is well confined in the core layer of the waveguide. Figure 5 demonstrate that 1200 nm is almost the smallest value for the SL to make the absorption of the metal negligible for any polarization state and simultaneously to ensure as much amount of heat as possible to be generated to incur an index change. Thus 1200-nm-thick SL is chosen.

The ROADM is fabricated on an eight-inch SOI wafer with 300-nm-thick top Si layer and 2-µm-thick buried dioxide layer. 248-nm deep ultraviolet (UV) photolithography is used to define the device pattern. Inductively coupled plasma etching process is used to etch the top Si layer. Spot size converters (SSCs) are integrated on the input and the output terminals of the waveguide to enhance the coupling efficiency between the PWW and the fibers. The SSC is a 200-µm-long linearly inversed taper with 180-nm-wide tip (Fig. 6 (a)). The fabricated add-drop MRR with the radius of 5 µm is shown in Fig. 6 (c). Direct-crossing structure is used in the ROADM. After the waveguide is etched, a 1200-nm-thick silica layer is deposited on the Si core layer as the SL by plasma enhanced chemical vapor deposition. Then a 200-nm-thick titanium (Ti) is sputtered on the SL and Ti heaters are fabricated by ultraviolet photolithography and dry etching. As shown in Fig. 6 (d), a multi-ring heater [47] is adopted to improve the utilization efficiency of the electrical power consumption. Aluminum (Al) wires and pads are fabricated after the heaters are done. Finally, the end-face of the SSC is exposed by a 110-µm-deep etching process as the world-to-chip interface (Fig. 6 (b)). The micrograph of the ROADM is shown in Fig. 6 (e). It is composed of four reconfigurable add-drop units, each of which is composed of one add-drop MRR, one Ti heater and two Al pads. The total length of the ROADM is about 4 mm whereas the effective length of the device including the SSCs is about 1 mm. Thus the effective area of the device is about 1×0.5 mm², which includes eight Al pads with each size of 100×100 µm².
3. Experimental results

3.1. Response of the add-drop MRRs with different structures

The add-drop MRRs with the radius of 5 µm are fabricated using the same process as the ROADM and their response spectra measured at their drop ports are shown in Fig. 7. The 3-dB bandwidth decreases notably with the increase of the gap from 280 nm to 420 nm while the drop loss increases. Smaller 3-dB bandwidth makes the drop of the stop band sharper, which makes the interband crosstalk smaller. The minimum polarization shift of the resonant wavelength is about 5.5 nm. It means that the device is polarization-sensitive, which is mainly caused by the residual stress in the waveguide.

Figure 8 (a) shows the simulation and experimental results of the 3-dB bandwidth for the TE mode at 1543 nm and 1561 nm, and Fig. 8 (b) shows the simulation and experimental results of the 3-dB bandwidth for the TM mode at 1538 nm and 1555 nm. Both the simulation results and the experimental results have the same trend with an increase in the gap of the add-drop MRR. Especially, the experimental results agree well with the simulation results when the gap of the add-drop MRR is 400 nm, which indicates that the fabrication process is
suitable for the add-drop MRR with 400-nm-wide gap. We can only precisely fabricate one specific line width in one deep UV photolithographic process. The photolithographic error becomes larger as the designed line width departs further from the specific line width of about 400 nm, which makes the experimental and simulation results depart from each other further and further. The fabrication error can be optimized by using electron beam lithography.

3.2. Static response of the ROADM

We use a broadband source to characterize the static response of the fabricated ROADM. The broadband lightwave is coupled into the SSC through a lensed single-mode fiber. An Agilent polarization controller (PC) is used to control the polarization state of the signals. The output signals are collected by another lensed single-mode fiber and are fed into an Agilent optical spectrum analyzer. The use of the single-mode fiber makes the polarization state of the signals impure and a quasi-TE mode is exited in the waveguide. A tunable voltage source is used to provide voltage to the heaters. The ERI of the waveguide is changed through the TO effect of Si to realize the reconfiguration of the ROADM. Response spectra of the ROADM are measured in different configurations, including “input to drops”, “input to output”, “adds to output” and “adds to drops”.

Figure 9 shows the response spectra measured at D1–D4 ports when the broadband lightwave was coupled into the input port and the voltage was applied to the heaters of R1–R4 respectively. In this configuration, the ROADM selects channels to download the signals to the drop ports. The FSR is about 17 nm. The minimum insertion loss is about 10.7 dB, which includes about 1.2-dB transmission loss in the 4-mm-long waveguide, about 2×2.9-dB coupling loss between the lensed fibers and the SSCs and about 3.7-dB drop loss. The insertion loss is different for four different configurations (input-D1, input-D2, input-D3 and input-D4) due to different numbers of the direct-crossing structure with each about 3.5 dB transmission loss. The transmission loss in the crossing can be largely lowered by optimizing the crossing structure [48-50]. The 3-dB bandwidths of D1–D4 ports are 0.402 nm, 0.533 nm, 0.554 nm and 0.555 nm, respectively. As the electrical power consumption increases from 0 to 103.9 mW, the resonant wavelength of the MRR shifts about 17 nm and the reconfiguration of the ROADM is realized. With the heater structure being optimized as reference [47], the average tuning power consumption is about 6.187 mW/nm, which is a little larger than that in reference [47] because different waveguide structure is adopted.

There are small harmonic peaks labeled by pink ellipses in Fig. 9, which are caused by the residual TM mode. The TM resonant peak is small and apart from the TE resonant peak, which means that the resonant wavelength of the MRR is polarization-sensitive due to the residual stress in the waveguide. Polarization sensitivity of the resonant wavelength seriously affects the application of the devices based on Si PWW MRR in the fiber communication systems. To solve this problem, totally polarization-independent scheme [51] and partly
polarization-independent scheme [40] have been proposed. However, the fabrication process should be controlled more precisely for both schemes.

Figure 10 shows the response spectra measured at the output port when the broadband lightwave was coupled into the input port and the voltage was applied to the heater of R1. In this configuration, the ROADM drops channels which are visible as dips in the response spectra measured at the output port. The resonant wavelength of R1 shifts with the increase of the power consumption whereas those of R2–R4 keep constant.

The through crosstalk varies from about -4 dB to about -14 dB due to the different coupling structures of the four add-drop

Fig. 10. Response spectra of “input to output”. Black curve shows the response spectra at the power consumption of 0 mW, red curve at 23.5 mW, green curve at 48.3 mW, blue curve at 74.3 mW and cyan curve at 103.9 mW.

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Fig. 10. Response spectra of “input to output”. Black curve shows the response spectra at the power consumption of 0 mW, red curve at 23.5 mW, green curve at 48.3 mW, blue curve at 74.3 mW and cyan curve at 103.9 mW.
MRRs. The minimum insertion loss is about 21 dB, most of which is caused by the transmission loss in the four direct crossings.

Figure 11 shows the response spectra measured at the output port when the broadband lightwave was coupled into the A1–A4 ports and the voltage was applied to the heaters of R1–R4 respectively. In this configuration, the ROADM uploads the signals to the backbone and exports them to the output port. The 3-dB bandwidths are about 0.453 nm, 0.571 nm, 0.533 nm and 0.593 nm, respectively, which are different from the values measured in the configuration of “input to drops”. The asymmetry in the coupling structures results in the different response bandwidths depending on which waveguide structure is used in the input or output port. The large nonhomogeneity of the insertion loss at different ports is induced by the same reason as the previous configuration. The direct-crossing structure is used in the ROADM. The asymmetric lineshapes in Fig. 11 are caused by the interference between the resonant field which is resonantly coupled to the output port and the coherent background field which is junction scattered to the output port, which can be optimized by using multimode-interference-based waveguide crossings [50].

![Fig. 11. Response spectra of “adds to output”. Black curve shows the response spectra at the power consumption of 0 mW, red curve at 23.5 mW, green curve at 48.3 mW, blue curve at 74.3 mW and cyan curve at 103.9 mW.](image)

Figure 12 shows the response spectra measured at the D1–D4 ports when the broadband lightwave was coupled into the A1–A4 ports and the voltage was applied to the heaters of R1–R4 respectively. The dips in the response spectra correspond to the channels which are uploaded by the ROADM to the backbone. The 3-dB bandwidths are 0.187, 0.295, 0.124 and 0.254, respectively. The 3-dB bandwidths measured in this configuration are the eigenvalues of the MRRs, which are not degenerated by the transmission loss in the MRRs. Thus they are much smaller than those measured in the configuration of “adds to output”.

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The main performance of the ROADM in the four configurations mentioned above is listed in Table 1. The interband crosstalk is taken with a 1.6-nm channel interval. The interband crosstalk as well as the through crosstalk can be improved by using the cascade-MRR structure [10, 25, 26]. The transmission loss in the crossing and the nonhomogeneity of the insertion loss can be lowered through optimizing the structure of the crossing [48-50].

### 3.3 Dynamic response of the ROADM

The dynamic response is characterized using an Agilent tunable laser, a functional signal generator, a power detector (PD) and an oscilloscope. A signal of 1545.3 nm is coupled into the input port and the output fiber is connected to D1 port. A square-wave voltage of 10 kHz is applied to the heater of R1. The output optical power is detected by the PD and the time response of the optical current is displayed on the oscilloscope (Fig. 13). The rise and fall time is 21.5 μs and 19.5 μs, respectively. The tuning speed is about 24.4 kHz, which is fast enough for the application of the ROADM in the DWDM systems. The high frequency ringing on the photodiode voltage at the switching junctions is caused by the high frequency noise induced by the electrical circuit. It can be eliminated by adding a lowpass filter.

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**Fig. 12.** Response spectra of “adds to drops”. Black curve shows the response spectra at the power consumption of 0 mW, red curve at 23.5 mW, green curve at 48.3 mW, blue curve at 74.3 mW and cyan curve at 103.9 mW.
Table 1. Main performance of the ROADM in different configurations.

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<th>Input to output and drops</th>
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<th>D2</th>
<th>D3</th>
<th>D4</th>
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Fig. 13. Time response of the ROADM.

4. Thermo-optic polarization-rotation effect

During the measurement, an interesting phenomenon is observed. With an increase in the applied voltage, the polarization state of the signals output by the waveguide is changed whereas the states of other equipments are stable. We call it the thermo-optic polarization-
rotation effect which means that the polarization state of the output signals changes with the temperature of the waveguide.

The polarization state of the signals is controlled by the PC which makes the signals output by the waveguide be quasi-TE mode and the state of the PC is kept unchanged during the experiment. When the voltage is 1.2 V, quasi-TE-mode signals are output. The resonant peak of the TE mode is about 11 dB larger than that of the TM mode. When the voltage increases to 1.6 V and 2.1 V, the resonant peak of the TM mode enhances and its amplitude increases rapidly (Fig. 14).

After elaborate analysis, we believe that the thermo-optic polarization-rotation effect is induced by the asymmetric thermal stress in the waveguide. There is a temperature gradient in the vertical direction of the waveguide, which makes the thermal stress of the waveguide asymmetric. The asymmetric thermal stress changes the orientation of the optical axis of the waveguide material, which results in the rotation of the polarization direction of the signals in the waveguide. The asymmetric thermal stress increases with the increase of the voltage or temperature, which makes the deflection of the optical axis more serious and the polarization-rotation angle larger. If the voltage continues to increase, the polarization state of the signals may be changed totally from quasi-TE mode to quasi-TM mode and a thermo-optic polarization rotator or controller is probably realized. The thermal stress in the waveguide is fabrication-process-dependent. Thus it is difficult to get the accurate initial condition for the finite-element analysis, which makes the finite-element analysis inaccurate. We are doing our best to make a deep research on the thermo-optic polarization-rotation effect, and the results will be published in another paper.

![Insertion loss graph](image_url)

Fig. 14. Phenomena of the thermo-optic polarization-rotation effect. Black curve shows the response spectra at the voltage of 1.2 V, red curve at 1.6 V and green curve at 2.1 V.

5. Conclusions

The fabrication of a four-channel, low-power-consumption, high-flexibility and ultra-compact integrated ROADM based on Si PWW MRR is reported. The effective footprint of the ROADM is about 1x0.5 mm², which can be further reduced by optimizing the layout of the device. The tunable bandwidth covers about 17 nm, which improves the flexibility of the ROADM. The device can add/drop any four optical channels in half C-band with adjacent channel spacing of 1.6 nm and its interband crosstalk is better than -11.5 dB. The interband crosstalk and the through crosstalk can be improved by using cascade-MRR structure [10, 25, 26]. The coupling loss between the fiber and the SSC can be lowered by optimizing the structure of the SSC [52]. The propagation loss of the waveguide can be improved by optimizing the fabrication process, for example, using thermal oxidization process [53, 54]. The transmission loss in the crossing and the nonhomogeneity of the insertion loss can be
largely lowered by optimizing the structure of the crossing [48-50]. A polarization-transparent scheme based on high-confinement waveguide structures has been proposed in reference [51]. It can solve the polarization sensitivity of the devices based on Si PWW and enables their application in the fiber communication systems possible.

Acknowledgments

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