Tunable filters based on an SOI nano-wire waveguide micro ring resonator*

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Abstract: Micro ring resonator (MRR) filters based on a silicon on insulator (SOI) nanowire waveguide are fabricated by electron beam photolithography (EBL) and inductive coupled plasma (ICP) etching technology. The cross-section size of the strip waveguides is 450×220 nm^2, and the bending radius of the micro ring is around 5 μm. The test results from the tunable filter based on a single ring show that the free spectral range (FSR) is 16.8 nm and the extinction ratio (ER) around the wavelength 1550 nm is 18.1 dB. After thermal tuning, the filter's tuning bandwidth reaches 4.8 nm with a tuning efficiency of 0.12 nm/℃ Meanwhile, we fabricated and studied multi-channel filters based on a single ring and a double ring. After measurement, we drew the following conclusions: during the signal transmission of multi-channel filters, crosstalk exists mainly among different transmission channels and are fairly distinct when there are signals input to add ports.

Key words: SOI; micro ring resonator; thermo-optic effect; filters; crosstalk

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1. Introduction

With the rapid development of micro/nano technology, micro/nano-optic devices based on silicon on insulator (SOI), and their integration, has become a hot spot of research all over the world[1, 2]. With the high refractive index contrast between Si (Δn = 3.45) and SiO_2 (Δn = 1.45) (Δn = 2), a SOI nano-wire waveguide has the features of strongly confining lights and reducing the bending radius to several micrometers. These features enable optic-devices to be miniaturized and high-density integrated[3, 4]. Tunable filters based on SOI micro ring resonators have been widely researched and demonstrated to have excellent characteristics, such as compact structures and flexible function configuration, which makes it an ideal platform for large-scale-integration optical circuits. There have been many kinds of optic functional devices with this structure, such as high speed electro-optic modulators, filters, wavelength multi-channelers, optic switches, optical add/drop multi-channelers and optical buffers[5−10]. Furthermore, the thermo-optic efficient of Si is fairly high, so it is suitable for thermal tuning[11, 12]. In micro ring resonators that are classified by their numbers of rings, there are resonators based on single rings and multi rings. As for single ring resonators, the fabrication process is simple, but the wavelength spectrum is not ideal, with a Lorentz line type of a sharp top. As for double ring resonators, the wavelength spectrum is improved with a flattened top, in contrast to single ring resonators. However, the size of each multi ring needs to be precisely the same, so it requires high precision in the fabrication process, adding increasing difficulty to the research[13, 14].

Nowadays, the materials mainly used in micro ring resonator filters are Si and photonic crystal. Research based on photonic crystals is still in the theoretical stage, mainly focused on basic analysis and computer simulation[15, 16]. As for research in Si devices, most of the focus has been on demultiplexers based on a single ring resonator without waveguide cross structures[17, 18]. In addition, there are some papers investigating the fabrication and modulation process of the micro ring resonator[19, 20]. However, study on add/drop multiplexers based on a multi ring is still in the start-up stage[21, 22], waiting for more researchers to explore this field. In this paper, using domestic nanowire waveguide process technology, we fabricated a high performance tunable filter based on SOI micro ring resonators. After thermal tuning, we achieved a high-efficiency tunable filtering function in the broadband range. Meanwhile, we fabricated a 5-channel add/drop filter based on a single ring and a 2-channel add/drop filter based on a double ring, and obtain some meaningful testing results from these devices.

2. Device design and fabrication

The devices were fabricated with SOI material, with a top Si (n = 3.47695) layer of 220 nm thickness and an isolation SiO_2 (n = 1.44) layer of 2 μm thickness. We used the micro/nano waveguide process platform at the Institute of Semiconductors, Chinese Academy of Sciences. The process flows are listed as follows: SOI wafer pre-processing, photoresist coating, EBL, photography development, ICP etching of the Si waveguide core area, photoresist stripping, top layer Si growth by plasma-enhanced chemical vapor deposition (PECVD), high-temperature annealing, wafer dicing and end polishing.

The structure of the device is illustrated in Fig. 1. It shows the cross section of the nano-wire waveguide, with a Si core

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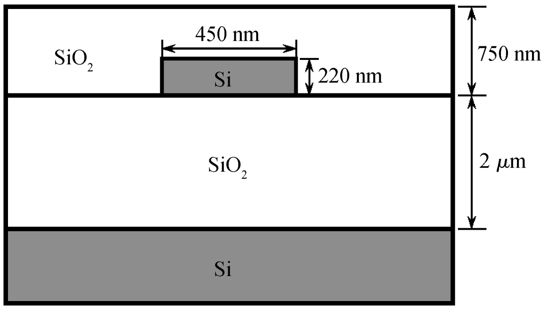

Fig. 1. Cross section of nanowire waveguides.

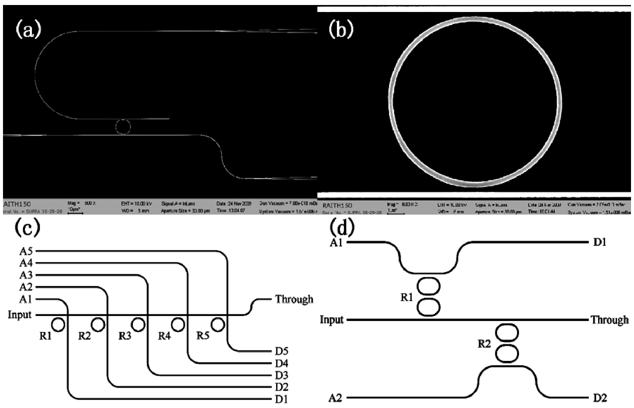

Fig. 2. Structures of filters. (a) SEM of tunable filter. (b) SEM of micro ring resonator. (c) Schematic of a five-channel filter based on single ring. (d) Schematic of a two-channel filter based on double ring.

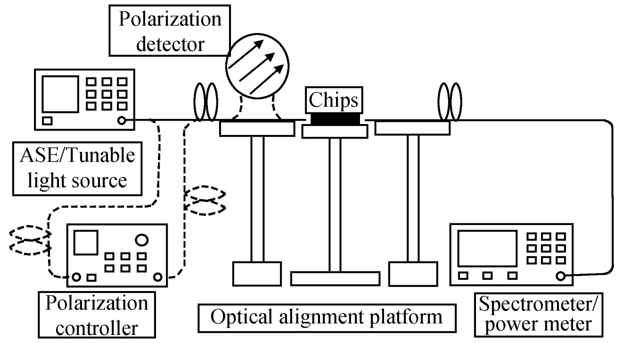

Fig. 3. Schematic diagram of the test system.

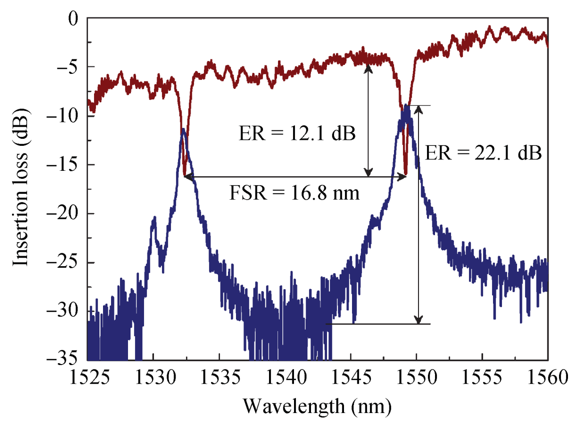

Fig. 4. Wavelength response of MRR filters.

area of 450 nm width and 220 nm height, respectively, and a SiO_2 area of 750 nm cladding layer and a 2 μm isolation layer.

The structure of the filters is illustrated in Fig. 2. Figure 2(a) shows an SEM photograph of the tunable micro ring resonator filter based on a single ring, including the bus line waveguide, drop line waveguide and a micro ring resonator. Figure 2(b) shows an enlarged SEM photograph of a micro ring resonator, from which we can figure out that the radius of the micro ring is about 5 μm and the gap between the micro ring and the straight waveguide is about 350 nm.

In addition, we fabricated multi-channel filters based on a single ring and a double ring. Figure 2(c) shows a five-channel filter based on a single ring and Figure 2(d) shows a two-channel filter based on a double ring.

3. Device measurement and discussion

The device was tested on an Agilent optical platform, assembled by a broadband light resource, polarization controller, tapered fibers, spectrometer and other equipment, as illustrated in Fig. 3. Of this platform, we adopted TE polarization light resource for the measurement.

(1) Tunable filters based on a single ring with a waveguide cross-section size of 450×220 nm^2 and radius of 5 μm.

Figure 4 is the normalized wavelength spectrum of the tunable filters. It shows that the two adjacent peak resonant wavelengths are 1532.1 nm and 1548.9 nm, that is, the FSR (free spectral range) reaching 16.8 nm. The ER (extinction ratio) around wavelength 1550 nm (peak wavelength 1548.9 nm) are 12.1 dB and 22.1 dB, respectively.

The high ER results from the thermal annealing process. The process was under 1000 ℃, so it could reduce the waveguide sidewall roughness and internal stress caused by ICP etching.

Recent reports about tunable filters are mainly based on effects such as acoustic-optic tuning, Fabry–Perot interference, fiber Bragg grating and dielectric film interference. However, these are mostly discrete devices and difficult to integrate with others, while tunable filters based on a photonic crystal are still in theoretical stage. In this paper, the tunable filters we fabricated have the advantage of miniaturization and monolithic integration, showing a promising future.

Tunable filters based on a SOI nano-wire waveguide micro ring resonator is small in size, has high integration and various functions, which make it one of the best units to construct vast-large-scale-integration optical circuits. However, the performance of the resonators strictly depends on process precision, and the resonant wavelengths are highly sensitive to waveguide structure and size. Therefore, it needs to tune the devices to obtain the required resonant wavelengths. The thermo-optic effect of silicon is fairly good, with a thermo-optic coefficient of about 1.86×10^{-4} K^{-1}. We adopted a way of entirely heating all of the micro ring resonators to adjust resonant wavelengths. Meanwhile, we wanted to get tunable filtering functions in large range.

During the experiment, we carried out the dynamic tuning tests on micro rings using mini temperature-controlled de-

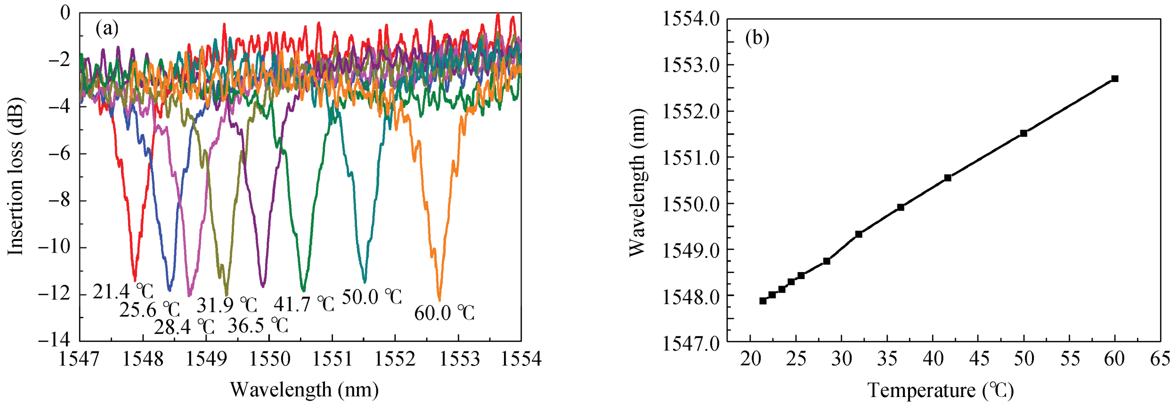

Fig. 5. Thermal character of tunable filters based on single ring. (a) Normalized wavelength response at different temperatures. (b) Relationship between response peak and temperature.

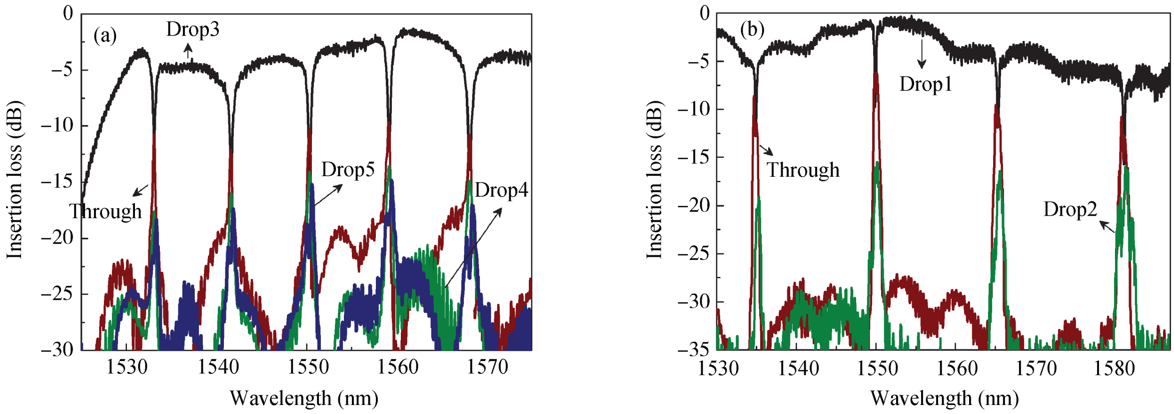

Fig. 6. Crosstalk of multi-channel filters. (a) Normalized wavelength spectrum of five-channel filter based on single ring. (b) Normalized wavelength spectrum of two-channel filter based on double ring.

vices. The wavelength response characteristics are illustrated in Fig. 5.

Figure 5(a) shows the filters' resonant wavelength spectrum around 1550 nm at different temperatures. When the tuning temperatures are 21.4, 22.4, 23.5, 24.5, 25.6, 28.4, 31.9, 36.5, 41.7, 50 and 60 ℃, the corresponding peak resonant wavelengths are 1547.879, 1548.011, 1548.123, 1548.288, 1548.427, 1548.742, 1549.325, 1549.91, 1550.553, 1551.518 and 1552.703 nm, respectively. Obviously, as the temperature rises, the resonant wavelengths present monotonic "red shift". While the temperature rises from 21.4 to 60 ℃, the filters realize 4.8-nm-range-bandwidth wavelengths tunable filtering characteristic.

Figure 5(b) is the curve diagram of corresponding peak resonant wavelength under different temperatures, from which we can see the relationship between resonant wavelength and temperature presents linearity. After calculation, we figure out that when temperature rises by 1 ℃, the resonant wavelength results in 0.12 nm "red shift".

This experimental result is supported by theoretical analysis. We all know that when the wavelength of the optic signals and circumference of the micro ring resonator meet some specific conditions, resonation happens and the signals will be coupled into the micro ring resonator. This condition can be described as

$$m\lambda = n_{\rm eff}L, \tag{1}$$

where λ is the wavelength, m is the stage number of wavelength, $n_{\rm eff}$ and L are effective refractive index and circumference of the micro ring resonator, respectively.

From Eq. (3.1), we can get the relationship between $n_{\rm eff}$ and λ when $n_{\rm eff}$ changes, described as

$$\Delta n_{\rm eff} = n_{\rm eff}\Delta\lambda/\lambda, \tag{2}$$

where Δn and $\Delta\lambda$ are the changes of $n_{\rm eff}$ and λ.

In this paper, $n_{\rm eff} \approx 2.848$, therefore, when the filtering wavelength changes 4.8 nm around 1550 nm, it can be calculated that $\Delta n_{\rm eff} \approx 8.82 \times 10^{-3}$.

As for the thermo-optic coefficient of Si, it varies with temperature following empirical formula (3.3)[23] when the temperature is between 300–600 K.

$$\mathrm{d}n/\mathrm{d}T = 9.45{\times}10^{-3}+3.47{\times}10^{-7}{\times}T-1.49{\times}10^{-10}{\times}T^2+\cdots. \tag{3}$$

When filtering wavelength changes 4.8 nm around 1550 nm, it can be calculated that the temperature variation of the waveguides is about $\Delta T \approx 44.4$ ℃.

From this theoretical result, we can draw this conclusion: when the temperature rises by 1 ℃, the resonant wavelength results in 0.11 nm "red shift". Compared with testing result of 0.12 nm "red shift"/1 ℃, we can see that the experiment coincides fairly well with theoretical calculation.

(2) Multi-channel filters based on single ring/double ring, with different cross-section sizes.

We also fabricated multi-channel filters and did some tests. We studied the filtering characteristic of multi-channel filters and got the wavelength response through experiments, as illustrated in Fig. 6.

Figure 6(a) shows the normalized wavelength spectrum of a five-channel filter based on single ring. In this spectrum, around the wavelength of 1550 nm (1550.3 nm), the ER of the through signals from port Drop3 is 11.5 dB, the ER and 3 dB bandwidth of filtered wavelength peak signals from port Through are 19.1 dB and 0.8 nm. In addition, the ER of the crosstalk signals from port Drop4 and Drop5 are 15.8 dB and 14.7 dB, respectively .The optic signals were input in port Add3. From port Drop3 we got the through signals spectrum with several concaves in specific resonant wavelengths. From port Through we got the spectrum of filtered wavelength peaks, which were the right resonant wavelengths meeting resonant conditions of the third micro ring. From port Add4 we also got spectrum of filtered wavelength peaks, which were the crosstalk, caused by the tiny difference in radius of the micro rings in different channels. According to resonant conditions, the tiny radius difference made the resonant wavelength different with each other channel, so the filtered signals by the third micro ring should go through the fourth micro ring without extra resonance. However, such extra resonances appeared while passing the fourth micro ring, coming into being the crosstalk. From port Drop5 we got spectrum of filtered wavelength peaks, crosstalk too. The cause was the same as that of Drop4. After an extra resonance passing the fourth micro ring, the filtered signals of the third channel, of which there were some specific wavelengths meeting the resonant conditions of the fifth micro ring, inducing another extra resonance, causing the crosstalk.

Figure 6(b) shows the normalized wavelength spectrum of a two-channel filter based on double ring. In this spectrum, around the wavelength of 1550 nm (1549.9 nm), the ER of the through signals from port Drop1 is 9.3 dB, the ER and 3 dB bandwidth of filtered wavelength peak signals from port Through are 25.2 dB and 1.0 nm. In addition, the ER of the crosstalk signals from port Drop2 is 15.8 dB. The optic signals were input in port Add1. From port Drop1 we got the through signals spectrum with several concaves in specific resonant wavelengths. From port Through we got the spectrum of the filtered wavelength peaks, which were the right resonant wavelengths to meet the resonant conditions of the first micro ring. From port Drop2 we got the crosstalk spectrum of the wavelength peaks. The filtered signals of the first micro ring, of which there were some specific wavelengths meeting resonant conditions of the second micro ring, inducing an extra resonance, causing crosstalk.

Considering the factors influencing crosstalk, we drew the following conclusions. In multi-channel filters, the forward direction crosstalk contributes a large portion to the overall crosstalk, while the reverse direction crosstalk is minus and able to be neglected. The crosstalk exits between different transmission channels, when signals input to the add ports of the filters. According to resonant conditions, signals satisfying it would be filtered by the micro ring and coupled into the corresponding bus line waveguide as we designed. In ideal conditions, we could get spectrum of several peaks in some specific centre wavelengths. However, the fact is that these peaks are not ideal peaks and are several nanometers in width. In addition, the radius of different transmission channels we designed is so close to each other, with only several nanometers difference. Therefore, some portion of signals around the centre wavelength, due to satisfying resonant conditions of nearby micro rings, would be output in other channels, causing crosstalk.

During the fabrication of the devices, due to some inaccuracy of processing technology, the actual parameters of the devices we gained were not the same as we designed, which would deteriorate the crosstalk. Consequently, in actual application each micro ring of the different transmission channels should be tuned independently, in an effort to lower crosstalk. For this reason, the design of the tuning structures becomes a key factor in the research of multi-channel filters.

4. Conclusions

We fabricated and tested tunable filters based on a SOI nano-wire waveguide micro ring resonator. This device has the advantages of small size, large FSR (16.8 nm), high ER (22.1 dB), and good linear thermo-optic effect (0.12 nm/℃). It is worth mentioning that the thermo-optic tuning bandwidth reaches 4.83 nm when temperature varies from 21.4 to 60.0 ℃. This kind of micro ring resonator structure can be widely applied to high-performance filters, high-speed modulators, high-precision optical waveguide sensors, multichannel reconfigurable optical add/drop multiplexers (ROADM), etc. In addition, from the testing results of multi-channel filters, we drew some meaningful conclusions on signal crosstalk. Crosstalk mainly exists among different transmission channels, while cross-waveguide induced crosstalk can be modified with an improvement of the waveguide structure. With such structures, the double ring multi-channel filters we proposed could avoid the waveguide-crossing between the bus line waveguide and add ports waveguide, thus improving cross-waveguide-induced crosstalk. When there are signals input to add ports, due to tiny radius differences and the limitations of fabrication technology, crosstalk among different channels becomes deteriorated, which impacts badly on performance. Therefore, the improvement of the fabrication precision is necessary and each channel should be tuned independently in actual application. Multi-channel filters show great prospects in optical communication and are a core device of ROADM. Filters based on multi ring can improve the performance of wavelength spectrum and passband flatness, so it can meet the demands of future optical communication.

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