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Ultra-Small Silicon Photonic Wire Waveguide Devices

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SUMMARY Silicon photonic devices based on silicon photonic wire waveguides are especially attractive devices, since they can be ultra-compact and low-power consumption. In this paper, we demonstrated various devices fabricated on silicon photonic wire waveguides. They included optical directional couplers, reconfigurable optical add/drop multiplexers, 1 × 2, 1 × 4, 1 × 8 and 4 × 4 optical switches, ring resonators. The characteristics of these devices show that silicon photonic wire waveguides offer promising platforms in constructing compact and power-saving photonic devices and systems.

key words: *silicon photonics, photonic wire, optical devices, optical waveguide*

1. Introduction

Silicon photonics is presently one of the most attractive research issues in the field of integrated optics [1]–[5], since it offers a promising platform in constructing compact optical devices and systems. The silicon-based optical devices, which are usually manufactured on silicon-on-insulate (SOI) substrates, are called as silicon photonic devices. Comparing with conventional optical devices made of silica or compound semiconductor (GaAs or InP) materials, silicon photonic devices can be ultra compact [6]–[10], due to their small bends of waveguides with high light confinement, as well as that they can be low-cost, which is benefited from well developed CMOS process technology. Furthermore, the silicon photonic devices that are controlled with thermo-optical effect can be low-power consumption because of the high thermo-optical efficiency of silicon material and the small device footprints [11], [12].

Usually, silicon photonic devices are based on 3 kinds of waveguide structure: photonic crystal (PhC) waveguides, rib/ridge waveguides and photonic wire waveguides. PhC-waveguide devices offer some unique characteristics with their photonic band-gaps. They are expected to be used as optical filters and resonators [13], [14]. However, they are limited in use, due to their polarization dependency, high propagation loss, and the demand of high manufacturing accuracy [15]–[17]. Silicon photonic devices made of rib/ridge waveguides have been widely studied from the beginning of silicon photonics study [18]. Although the rib/ridge waveguides offer low propagation losses [19], [20] and they can be polarization independent [21], they have the mortal wound of that they cannot be very compact due to that the large bend radius of more than several hundred micrometers are needed [20]. Now, the research of rib/ridge waveguide devices are majorly focused on active devices, such as, laser resonators [22], which are controlled through carrier injection effect. Silicon photonic wire waveguides are usually defined as waveguides consists of silicon core of sub-micrometer cross-section size and surrounding air/silica claddings. Many compact silicon photonic wire waveguide devices including active and passive devices have been successfully demonstrated [23]–[27], since silicon photonic wire waveguides can be bent with a radius of several micrometers [27], as well as they offer a low propagation loss of about 1.5 dB/cm [28]. Although silicon photonic wire waveguide devices are also envisaging the problem of polarization dependency, some attempts have been made to solve it using polarization diversity technique [29], [30].

In this paper, we focus on the silicon photonic wire waveguide devices we have developed, including optical direction couplers, reconfigurable optical add/drop multiplexers, optical switches and ring resonators, which are expected to be used in constructing the future photonic network systems.

2. Optical Directional Couplers

Since the light confinement in silicon photonic wire waveguides can be much stronger than those in fibers and waveguides made of silica materials, silicon photonic wire waveguides can be bent with a radius of several micrometers. Using the small bends, we made ultra-compact optical couplers [31], which were one of the most fundamental elements in constructing various photonic devices, such as, power combiner/dividers, wavelength multiplexers and optical switches. The schematic of the optical couplers we fabricated is shown in Fig. 1. The core cross-section size of the waveguides we used was 300 × 300 nm, while the thicknesses of under cladding and upper cladding layers were 1 μm and 0.9 μm, respectively. The propagation losses of the waveguides were 2.56 dB/mm and 1.89 dB/mm for TE-like mode and TM-like mode, respectively. The gap between the two waveguides was 300 nm at the coupling portion. The bend radii of the S-shape waveguides were 10 μm, whose bend losses were both less than 0.1 dB/bend for the TE-like

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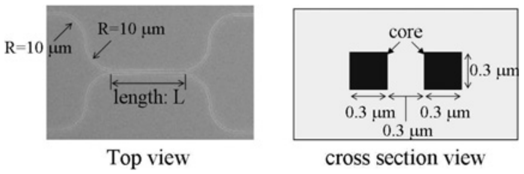

Fig. 1 Optical directional coupler based on photonic wire waveguides.

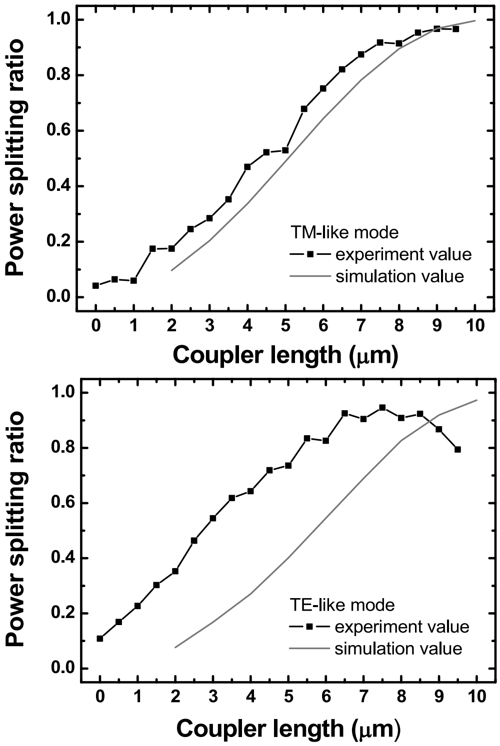

Fig. 2 Power splitting ratio versus coupler length.

and TM-like modes [31]. By fabricating various couplers with different coupling length, we obtained the complete coupling length of 10 μm for TE-like mode and 11 μm for TM-like mode, as shown in Fig. 2, respectively. The results included the coupling influences from the S-shape waveguides, which was estimated to correspond to a coupling length of 2 μm. The experiment results were also in good agreement with the simulation results we estimated with a three-dimensional finite-difference-time-domain (FDTD) method [31], as shown in Fig. 2.

3. Reconfigureable Optical Add/Drop Multiplexers

Optical add/drop multiplexers (OADMs) are essential optical devices in wavelength division multiplexing (WDM) network, in directing light signals with their wavelength. Reconfigurable OADMs (ROADMs) further can tune the wavelength. The OADM we fabricated is shown in Fig. 3. It is a Mach-Zehnder interferometer (MZI) type ROADM, in which Bragg-grating-reflectors are formed on both the MZI branches. The MZI branches were connected with the 3-dB optical couplers described previously. Here, the Bragg-grating-reflectors were selected due to their flap-topped band pass spectra and wide free spectral ranges (FSRs). The Bragg gratings were formed by making small fins at a period of 370-nm on the sidewalls of the 500-μm-long waveguides, whose cross section size were also 300 × 300 nm. The projections of the fins were 30 nm. Upon the Bragg gratings, metal thin-film heaters were formed over the upper cladding layer for thermo-optical tuning of the center wavelength. The device was 700-μm-long, which was more than one order of magnitude smaller than the conventional OADMs made of silica materials [32], [33].

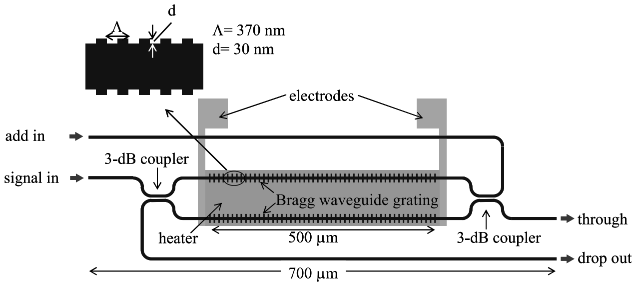

Fig. 3 Schematic of the reconfigurable optical add/drop multiplexer with Bragg-grating-reflectors fabricated on silicon photonic wire waveguides.

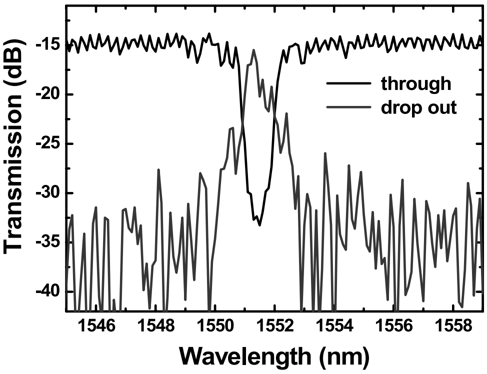

Fig. 4 Transmission loss spectra of optical add/drop multiplexer.

The transmission loss spectra for through and drop-out ports of the ROADM were first measured for TM-like mode, when no heating current was applied. The results are shown in Fig. 4. The dropping center wavelength was 1551.4 nm. The channel dropping bandwidth was about 1.6 nm, which is corresponded to 200-GHz dense wavelength division multiplexing (D-WDM). The device insertion losses were about 15 dB, including the lensed-fiber-to-device coupling losses of about 6 dB/port.

Next, we measured the wavelength tuning characteristics of the ROADM at various heating currents, as shown in Fig. 5. The dropping wavelength shifted to longer wavelength as the heating current was increased, while the transmission spectra retained their shape without conspicuous deformation. The tuning efficiency was 8.05 nm/W. The average tuning speed of the device was about 200 μsec [34].

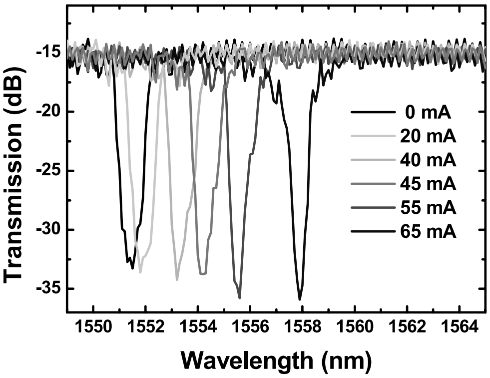

Fig. 5 Heating current dependence of drop-out spectra.

4. Optical Switches

Optical switches are indispensable devices in constructing photonic network systems. Although many studies have been devoted to silicon waveguide optical switches [12], [35], the devices they demonstrated are still insufficient for the real applications on the aspects of extinction ratios, device size or switching power. In this section, we describe some ultra compact MZI-type optical switches based on silicon photonic wire waveguides, which have the same core cross-section size as those introduced in Sects. 2 and 3.

First, we fabricated a 1 × 2 MZI-type optical switch composed of a Y-splitter and a 3-dB directional coupler, as shown in Fig. 6. The Y-splitter was only 7-μm long since a large splitting angle ($> 4.8°$) is possible for the silicon photonic wire waveguides. The radii of the bends in our switches are either 5 or 10 μm. The bending losses were less than 0.1 dB. These small bends are the primary reason for the reduction in device size. The MZI branches were 40-μm long. Thus, the device was very compact with a footprint of $85 \times 30\,\mu$m. The switches were controlled with thin-film heaters formed over the MZI branches.

In characterization, we measured the transmissions on heating power at the wavelength of 1550 nm for TM-like mode, as shown in Fig. 7. From Fig. 7, we found the light outputs of the 1×2 switch were alternately changed between port 1 and 2 at a switching power of 90 mW [11]. In later experiments, the switching power has been presently improved to 25 mW, by optimizing the heater designing, i.e. reducing the heater width to 4 μm from the previous value of 12 μm. The maximum extinction ratio was more than 30 dB. The switching response time was around 100 μsec.

With the 1 × 2 switches, we fabricated a 1 × 4 and a 1 × 8 optical switches. The microscope view of the 1 × 4 switch is shown in Fig. 8. The 1 × 4 switch had a footprint of $190 \times 75\,\mu$m, which was believed to be the smallest one in the world. The 1×8 switch was similar to the 1×4 switch [36]. The operations of the 1 × 4 and 1 × 8 switches were both confirmed [36].

Further, we fabricated a 4 × 4 switch with six 2 × 2 optical switches, which was made by replacing the Y-splitter in the 1×2 switch with a 3-dB directional coupler, as shown in Fig. 9. In the 4 × 4 switch, directional couplers in cross state were used as the waveguide cross connections. The output ports of the switch had the same interval as that of the inferred micro-lens-array, which was used for coupling light from optical fiber arrays to the waveguides. The operations of the 4 × 4 switch were also confirmed.

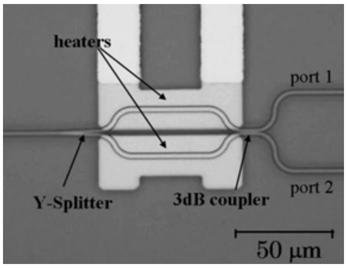

Fig. 6 Ultra-compact 1 × 2 optical switch.

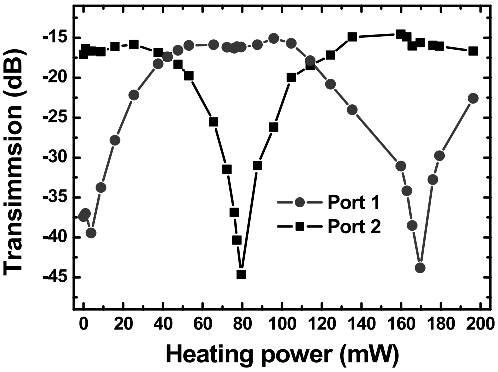

Fig. 7 Switching characteristics of the 1 × 2 optical switch.

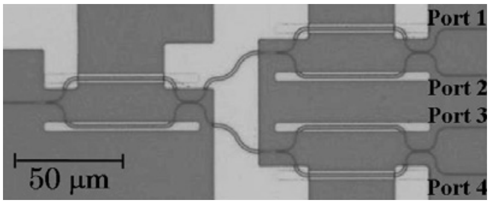

Fig. 8 1 × 4 optical switches fabricated with silicon photonic wire waveguides.

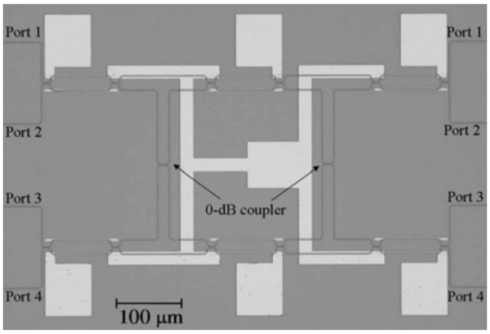

Fig. 9 4 × 4 optical switch.

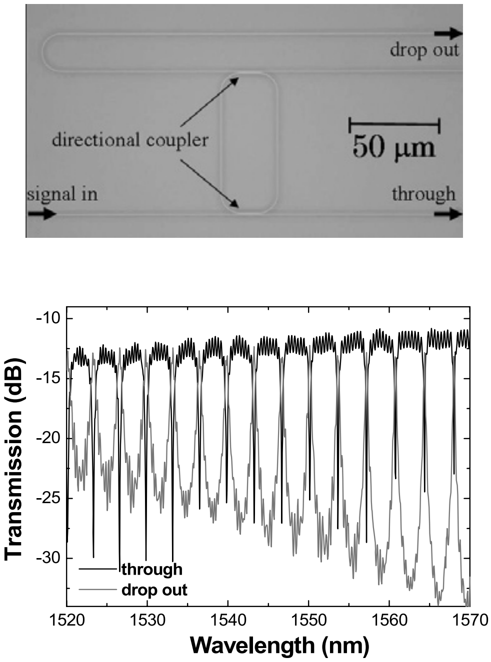

Fig. 10 Single ring resonator and its optical characteristics.

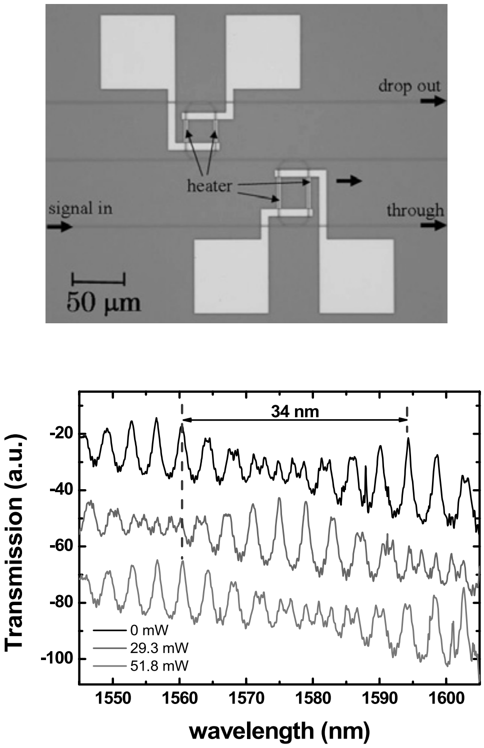

Fig. 11 Double ring resonator and its optical characteristics.

5. Ring Resonator

Ring resonators are one of the most attractive devices based on silicon photonics wire waveguides, since they can have a very wide FSR, due to that their very short cavity lengths with a small radius of several micrometers. The ring resonators are expected to be used in fabricating many novel devices, such as, laser resonator, optical delay/buffer and optical filters for applications in data communication and processing. Many researches have been reported on ring resonators [22]–[24]. However, most of them used carrier injection technique in tuning the resonator frequency. To date, we did not find any report on tuning the ring resonator through thermo-optical effect, which was an easy way in device fabrication and can widely tune the resonance frequency.

Here, we fabricate 2 kinds of ring resonator with silicon photonic wire waveguides: single ring resonators and double ring resonators. The waveguides had a core cross-section size of 450 × 220 nm. The thickness of the under cladding and upper cladding layers are 3 μm and 2 μm, respectively. The propagation losses of the waveguides were 0.8 dB/mm for the TE-like mode and 0.6 dB/mm for the TM-like mode, respectively. In characterizations, TM-like mode only was used. Figure 10 shows the microscope view of the single ring resonator we fabricated and the optical characteristics. The FSR of the single ring resonator was about 380 GHz. The cross talk between the through and drop-out ports was more than 10 dB at the C-band and the L-band in WDM optical communication.

Although it is also possible to obtain a high side-mode suppression ratio for single ring resonators, the resonating wavelength tuning range is still limited due to the small change of effective index [37]. However, the double ring resonator can have a much wide tuning range which is enhanced via Vernier effect [37]. The microscope view of the double ring resonators is shown in Fig. 11. Since the radii of the two rings were designed with slight difference, the FSR of the two rings also differed slightly. Thus, we could get a wavelength range between the two transmission-peaks, which were formed at the points when transmission peaks of the two ring resonators matched to each other [37], [38]. Then, by changing the resonating wavelength through thermo-optical effect, we could change the transmission wavelength of the double ring filter, which was set to the C-band or the L-band in WDM optical communication. Figure 11 also shows the characteristic of the double ring resonator with different heating currents to the small ring. From Fig. 10, we can see that the resonating wavelength shifted to shorter wavelength discretely by a FSR of about 4200 GHz, when heating current increasing. The tuning efficiency was 656 nm/W, which is 10 times higher than that of the silica double ring resonators [38].

6. Conclusions

Silicon photonic devices are highly expected to be used in constructing future optical interconnection systems and photonic network systems. Among them, the devices based on silicon photonic wire waveguides, which are waveguides with core cross-section size of less than 0.5 μm, are especially attractive, since they can be ultra-compact and low-power consumption. In this paper, we demonstrated various devices fabricated on silicon photonic wire waveguides. They included optical directional couplers, reconfigurable optical add/drop multiplexers, 1×2, 1×4, 1×8 and 4×4 optical switches, ring resonators. The characteristics of these devices show that silicon photonic wire waveguides offer promising platforms in constructing various novel photonic devices. Consequently, it is believed that the silicon photonic devices, including those built with photonic crystals, rib/ridge waveguides and photonic wire waveguides, are future key devices in building optical interconnection and telecommunication systems.

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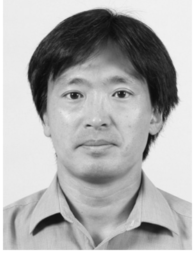

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