Invited Paper

SOI Based Waveguide Devices

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ABSTRACT

SOI based waveguide devices are becoming more and more active. The main results of the devices investigated in our team are presented in the paper. Photonic crystal with sharp bends was made and its excess loss is 1.1±0.4dB per mirror. Two kinds of couplers, slot coupler and grating coupler, were successfully fabricated. Coupling loss of the slot coupler is < 3dB between sub-micron optical waveguides and micron-scale optical fibers. A coupling efficiency of 40.7% and 3-dB bandwidth of > 40nm of the grating coupler are obtained. Microring and microdisk resonators were simulated and optimized. Their Q factors and extinction ratios are 5.3×104, 14dB, and 2.8×105, 10dB, respectively. SOI PIN diode electro-optical switches with microring, microdisk and MZI were developed. Rise and fall time is 0.37 ns and 2.57 ns, respectively, for a microdisk optical switch.

Keywords: silicon photonics, waveguide devices, photonic crystal, slot coupler, grating coupler, microring and microdisk resonators, electro-optical switches

1. INTRODUCTION

Silicon-on-insulator (SOI) is one of the most famous materials for photonic integration. SOI wafers are commercially available, SOI devices, including electrical devices and optical devices, can be easily fabricated by CMOS processes. The large refractive index contrast of SOI can provide a perfect platform for sub-micron optical waveguides and photonic components. In the future, SOI sub-micron waveguide devices can be integrated with the electronic circuits on a same chip due to its perfect compatibility on the electrical performances of these circuits. Besides that, its good thermal stability and high thermal conductivity make the SOI substrate a native heat sink for the device on it, which will lead to simple packaging and cost-effectiveness.

In exploring the potentials of SOI, we have successfully fabricated sub-micron optical waveguides [1], photonic crystals (PCs), and other passive and active devices based on these waveguides, such as sharp bends [2], end couplers [3], vertical couplers [4], racetrack resonators [5] and electro-optical switches [6] on SOI. By using the variable free carrier concentration induced refractive index change in silicon, we can realize ultra-high speed optical devices. The response speed of such devices can be further reduced to the order of sub-nanosecond, which implies that SOI has the great potential for fabricating sub-micro and nanometer devices and for the integration of electrical and optical devices with high speed. Also, it has the great potential for optical bio-sensing on a silicon chip.

2. SOI SUBMICRON OPTICAL WAVEDUIDES [1]

For the large scale integration, SOI sub-micron optical waveguides and passive components are essential in building photonic devices and circuits on chip. Silicon based optical rib waveguides are designed, fabricated and characterized, by using a commercial simulation tool FimmWAVE [7] and technologies including electron-beam lithography (EBL) and inductively coupled plasma (ICP) dry etching.

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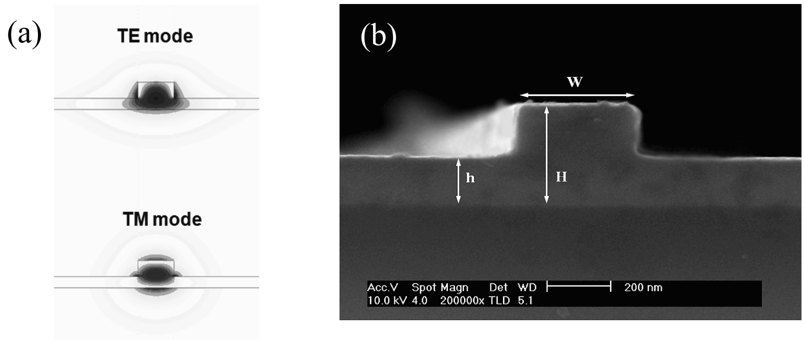

Fig. 1 (a) The fundamental TE and TM mode profiles of a SOI-based rib waveguide, and (b) the SEM graph of the rib waveguides.

The SOI wafers used in our researches were provided by SOITEC [8]. With the help of FimmWAVE, the single-mode condition of sub-micron rib waveguides was simulated [9]. The thicknesses of the top silicon layer and the buried oxide (BOX) layer are 340 nm and 1μm respectively. The waveguide width is 400 ~ 450 nm and the thickness of slab layer is 140 nm. The simulated result of its fundamental mode profile is shown in Fig. 1 (a). The SEM graph of this rib waveguide was shown in Fig. 1 (b). The Fabry-Perot resonance method showed that its propagation loss is about 1.59 dB/mm.

3. PHOTONIC CRYSTAL BASED DEVICES [2]

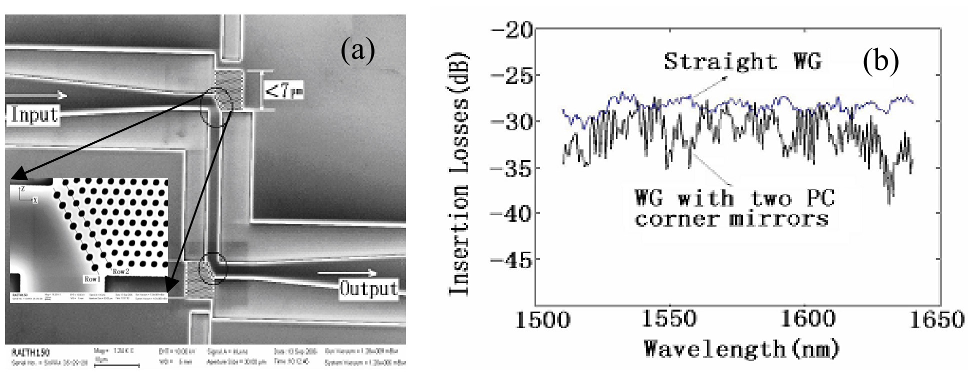

Fig. 2 (a) SEM images of the fabricated sample, (b) measured loss spectrum.

Sharp waveguide bends are really necessary in high density photonic integration, which form a folded optical path. Conventional sharp bends are normally based on optical waveguide corner mirrors by employing total internal reflection (TIR) [10], in which vertically etched faces can be used as mirrors. For example, Liu et al. [11] reported an air trench for a rib waveguide bend with an extra loss of ~ 1.1 dB / bend and a bending area of 30×30 μm2, which was used in a folded optical switch matrix in silicon. However, this dimension is too large for a photonic integrated circuit.

Photonic Crystal (PC) is a good candidate for miniaturizing the optical bends. A simulated air-hole two dimensional PC (2D-PC) is predicted to reduce sizes of waveguide corner mirrors with low excess loss [12]. But this work is only proposed for a 90o bending of a TM mode in a silica waveguide. Here, we show an experimental result of ultra-compact PC-based corner mirror in SOI for TE mode. Fig. 2 (a) shows the top SEM image view of the 2D-PC corner mirror. A hexangular lattice with air hole radius and period of 135 and 450 nm is used for a wider spectrum bandwidth. For a 3 μm wide strip waveguide, the compact dimensions of corner mirrors can be as small as $3\times3\ \mu m^2$. As shown in Fig. 2 (b), the straight waveguides have an averaged insertion loss of 28.3±0.3 dB. With the two PC corner mirrors, the insertion losses increase to 30.5±0.5 dB. Therefore, the measured excess losses of PC based sharp bends are about 1.1±0.4 dB for a wavelength arranging from 1510 nm to 1630 nm.

4. HIGHLY EFFICIENT OPTICAL COUPLERS

Traditionally, light input to and output from a micron or submicron waveguide on a chip require a lensed or high numerical aperture fiber for a low insertion loss by a matched optical mode profile. However, this approach is quite a challenging work for a submicron even less scale waveguide. Several approaches have been followed to tackle the problem.

1) Slot waveguide based couplers [3]

A novel optical fiber-to-waveguide coupler for integrated optical circuits has been proposed. The proper materials and structural parameters of the coupler, which is based on a slot waveguide, are carefully analyzed with a full-vectorial three-dimensional mode solver. As the effective refractive index of the mode in a SOI-based slot waveguide can be designed extremely closing to that of a fiber, a highly efficient fiber-to-waveguide coupling can be realized. For a TE-like mode, the calculated minimum mismatch loss is approximate 1.8 dB at 1550 nm.This proposed coupler can be used in chip-to-chip communication.

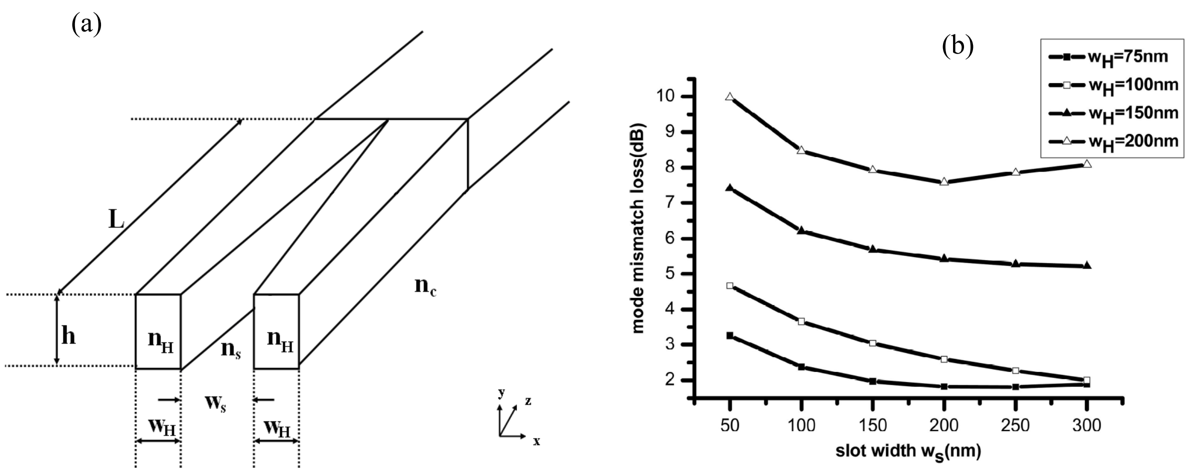

Fig. 3 (a) Schematics of a slot waveguide coupler, (b) simulated mismatch loss of the TE mode depending on slot width.

A SOI optical fiber-to-waveguide inverse nano-taper using Polymethyl Methacrylate (PMMA) is presented for integrated optical circuits. Fig. 3 shows Schematic of a slot waveguide coupler, (b) simulated mismatch loss of TE mode dependent on slot width [3].

A SOI inverse nano-taper overlaid with specially treated silica is investigated for integrated optical circuits. Unlike the conventional process of depositing a layer of silica on silicon waveguides, two layers of silicon dioxide were grown on etched SSC structures by plasma-enhanced chemical vapor deposition (PECVD) successively. Tthe two layers have a index contrast of 0.8 % and supply stronger cladding for incident light beam. Additionally, this process is able to reduce the effective refractive index of the input mode to less than 1.47 (extremely close to that of the fiber), thus substantially weaken the unwanted back reflection. Exploiting this technology, the coupler showed low mode mismatch loss of 1.23 dB for a TE-like mode theoretically, coupling efficiency of 66% was achieved experimentally.

2) Grating couplers for integration [4, 15]

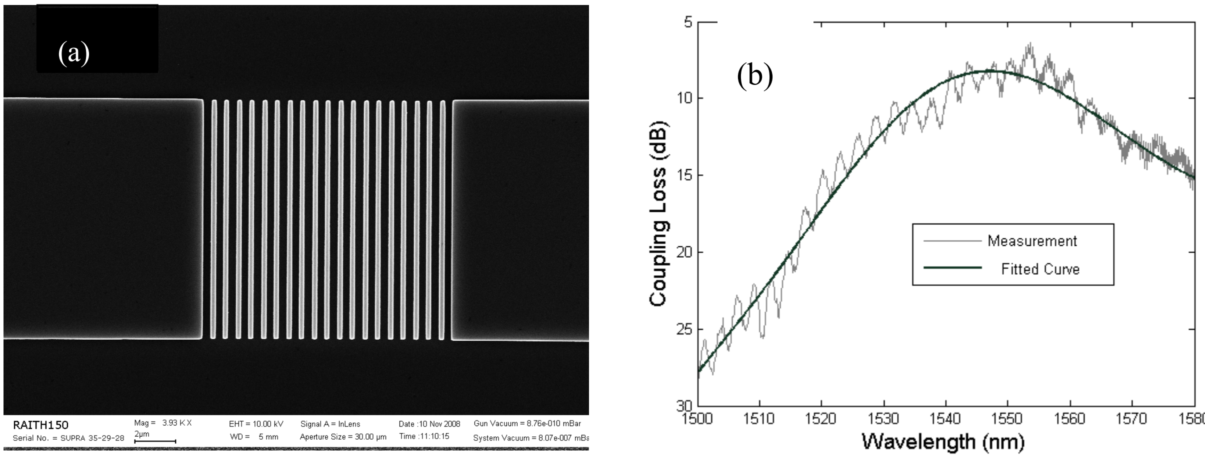

Fig. 4 (a) SEM image of a waveguide grating coupler, (b) measured fiber-to-waveguide coupling spectrum

An efficiency enhanced SOI grating coupler with a refractive index buffer layer above was designed and fabricated for near-vertical off-chip coupling between a silicon photonic nanowire and an optical fiber. By adding an index buffer layer, the diffractive grating becomes more directional and the reflections between the fiber facet and the grating surfaces are reduced.

The refractive index of the index buffer layer is between the fiber and the gratings, it could abbreviate the index difference and thus increase the coupling input-power. The index buffer layer could also act as an anti-reflection coating with a proper layer thickness and refractive index. This can be achieved by choosing the cladding layer with a quarter-wave thickness, or odd multiples, the Fresnel reflections at the two interfaces interferometrically cancel each other. Therefore, the index buffer layer not only reduces the index difference, but also works as an anti-reflection coating to eliminate reflections between the facets; therefore, it enhances the coupling efficiency.

Fig. 4 shows the SEM image of a waveguide grating coupler and its fiber-to-waveguide coupling spectrum. A minimum insertion loss of 7.8 dB at 1547nm and a 3 dB bandwidth of 40 nm (1530-1570 nm) were achieved. Neglecting the propagating loss of the 1000 μm-length waveguide, the coupling loss at each end is 3.9 dB, which means a maximum coupling efficiency of 40.7%. The 3-dB bandwidth of a single grating coupler should be larger than 40 nm.

5. SOI RACETRACK REASONATORS [5]

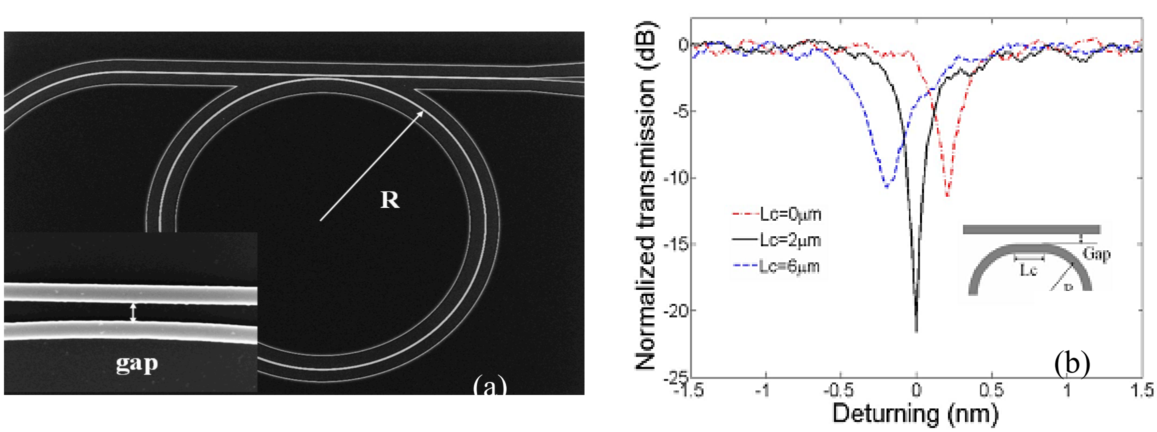

Fig. 5 (a) SEM image of the racetrack resonator, (b) Transmission spectra near 1550 nm wavelength.

Rib waveguides and microring resonators are basic components in SOI photonic devices. The mechanism and properties of microring and microdisk resonators are investigated. Three main factors, including guided mode properties, coupling efficiency and internal loss in resonators are simulated and analyzed. Microring and microdisk resonators with high Q factor and large extinction ratio were fabricated. The Q factor and extinction ratio for the microring resonator and for the microdisk resonator are 5.3×10^4, 14dB, and 2.8×10^5, 10dB, respectively. It is found that TM mode no longer exists, whereas TE mode can be guided for submicron rib waveguides with 'slab thickness-waveguide hight contrast' equals to 0.5. Such a microring resonator functions as a band-stop filter.

Fig. 5 shows (a) the SEM images of the racetrack resonator, (b) transmission spectra ~1550 nm. A novel polarization splitter was demonstrated using a microracetrack resonator. Submicron waveguide is polarization sensitive, and microring resonator is wavelength sensitive, therefore, polarization splitting can be obtained for a resonator in submicron waveguides. By using rib waveguides, the coupling efficiency was enhanced, and the propagation loss was reduced as well, resulting in high-performance operating for both TE and TM polarizations. In experiment, the splitting ratio for TE and TM polarization is 20dB in ~ 1550nm.

Using PIN diodes, high speed silicon electro-optic modulator/switch is realized in a microring or a microdisk resonator. When positive bias voltage was applied, the resonant wavelength was blue shifted notably, indicating that free carrier plasma dispersion effect works. For the optical modulator, the size of microring resonator is 28μm×20μm, the measured modulation depth is 97%, the power consumption is 0.58mW, the switch rise time is 0.37ns, and the switch fall time is 2.57ns. For the optical switch, the radius of microdisk is only 10μm, the cross talk between through port and drop port is as low as -20.2dB, the insertion loss for the drop port is 1.7dB, the power consumption is 0.46mW, the switch time for the through port is 1.31ns, while it is 2.48ns for the drop port.

6. Si PIN-MZI ELECTRO-OPTICA SWITCH

Using PIN diode as the electrical structure, MZI as the optical structure, PIN-MZI electro-optic modulator and optical switch have advantages of high modulation efficiency and low process complexity. We realize a program for simulating electro-optic modulators by combining the electrical and optical simulations together. The static, transient, and ac properties of the PIN-MZI modulators and switches are simulated and analyzed by this program. It is found that the distance between heavily doping region and waveguide boundary, SRH lifetime, and surface recombination velocity of the carriers play key roles in the modulation speed of the devices.

Recently, a novel design of silicon EO modulator was proposed by our team in an IEEE conference in 2008 [6], which is based on interleaved PN junctions under a reversed 3 V driving voltage. This modulator has a bandwidth > 40 GHz and modulation efficiency of $V_\pi \cdot L_\pi \sim 1.5$ V·cm.

PIN-MZI electro-optic modulator and optical switch based on SOI submicron rib waveguides are designed, fabricated and measured. The 1×1 electro-optic modulator has a figure of merit $V_\pi L_\pi$ of 1.14 V·mm, extinction ratio of 17.21 dB, DC power of 5.26 mW, large optical bandwidth of 1500-1600 nm, insertion loss of 21.5 dB, 3-dB bandwidth of 35 MHz, switch time of 3.74ns and 640 ps for the rise and fall edge respectively, and data rate up to 400Mb/s. The 2×2 optical switch has a figure of merit $V_\pi L_\pi$ of 1.25V·mm, extinction ratio of 12.43dB and 18.31dB for the bar and cross port respectively, cross talk of -12.79dB, DC power of 4.89mW, insertion loss of 24.36dB, 3dB bandwidth of 30MHz, switch time of 4.72ns and 2.71ns for the rise and fall edge respectively, data rate up to 300Mb/s. These are the first SOI electro-optic modulator and optical switch with nanosecond switch time in Chinese Mainland to our best knowledge. After comprehensive discussions on the measurement results, some improvement suggestions are proposed for the devices in order to reduce the insertion loss and to achieve modulation speed larger than 1GHz and switch time less than 1ns.

7. CONCLUSIONS

The recent achievements of our team are summarized in the paper. Our interest is focused on SOI sub-micron waveguide devices, which include sub-micron straight rib waveguides, small size sharp bends, compact PC based corner mirrors, slot waveguide based end-couplers, grating based vertical-couplers, high-Q racetrack resonators and fast response optical switches. Coupling loss of slot coupler is < 3dB between sub-micron optical waveguides and micron-sacle optical fibers. A coupling efficiency of 40.7% and 3-dB bandwidth of > 40nm of the grating coupler are obtained. Q factors and extinction ratios for microring and microdisk resonators are 5.3×10^4, 14dB, and 2.8×10^5, 10dB, respectively. Rise and fall time of the SOI PIN electro-optic switche is 0.37ns and 2.57ns, respectively. All these optical sub-micron elements in SOI are reliable blocks for building a photonic system.

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