60-nm-thick basic photonic components and Bragg gratings on the silicon-on-insulator platform

Zhi Zou,1 Linjie Zhou,1,* Xinwan Li,1,2 and Jianping Chen1

1State Key Laboratory of Advanced Optical Communication Systems and Networks, Department of Electronic Engineering, Shanghai Jiao Tong University, Shanghai, 200240, China
2University of Michigan and Shanghai Jiao Tong University Joint Institute, Shanghai, 200240, China

*ljzhou@sjtu.edu.cn

Abstract: We demonstrate integrated basic photonic components and Bragg gratings using 60-nm-thick silicon-on-insulator strip waveguides. The ultra-thin waveguides exhibit a propagation loss of 0.61 dB/cm and a bending loss of approximately 0.015 dB/180° with a 30 μm bending radius (including two straight-bend waveguide junctions). Basic structures based on the ultra-thin waveguides, including micro-ring resonators, 1 × 2 MMI couplers, and Mach-Zehnder interferometers are realized. Upon thinning-down, the waveguide effective refractive index is reduced, making the fabrication of Bragg gratings possible using the standard 248-nm deep ultra-violet (DUV) photolithography process. The Bragg grating exhibits a stopband width of 1 nm and an extinction ratio of 35 dB, which is practically applicable as an optical filter or a delay line. The transmission spectrum can be thermally tuned via an integrated resistive micro-heater formed by a heavily doped silicon slab beside the waveguide.

©2015 Optical Society of America

OCIS codes: (130.3120) Integrated optics devices; (130.7408) Wavelength filtering devices; (230.7370) Waveguides; (350.2770) Gratings.

References and links

1. G. Li, J. Yao, H. Thacker, A. Mekis, X. Zheng, I. Shubin, Y. Luo, J.-H. Lee, K. Raj, J. E. Cunningham, and A. V. Krishnamoorthy, “Ultralow-loss, high-density SOI optical waveguide routing for macrochip interconnects,” Opt. Express 20(11), 12035–12039 (2012).

2. J. Cardenas, C. B. Poitras, J. T. Robinson, K. Preston, L. Chen, and M. Lipson, “Low loss etchless silicon photonic waveguides,” Opt. Express 17(6), 4752–4757 (2009).

3. M. Gould, A. Pomerene, C. Hill, S. Ocheltree, Y. Zhang, T. Baehr-Jones, and M. Hochberg, “Ultra-thin silicon-on-insulator strip waveguides and mode couplers,” Appl. Phys. Lett. 101(22), 221106 (2012).

4. L. He, Y. He, A. Pomerene, C. Hill, S. Ocheltree, T. Baehr-Jones, and M. Hochberg, “Ultra-thin silicon-on-insulator grating couplers,” IEEE Photonics Technol. Lett. 24(24), 2247–2249 (2012).

5. S. T. Fard, V. Donzella, S. A. Schmidt, J. Flueckiger, S. M. Grist, P. Talebi Fard, Y. Wu, R. J. Bojko, E. Kwock, N. A. Jaeger, D. M. Ratner, and L. Chrostowski, “Performance of ultra-thin SOI-based resonators for sensing applications,” Opt. Express 22(12), 14166–14179 (2014).

6. S. Yang, Y. Zhang, D. W. Grund, G. A. Ejzak, Y. Liu, A. Novack, D. Prattier, A. E.-J. Lim, G.-Q. Lo, T. Baehr-Jones, and M. Hochberg, “A single adiabatic microring-based laser in 220 nm silicon-on-insulator,” Opt. Express 22(1), 1172–1180 (2014).

7. Y. J. Rao, “In-fibre Bragg grating sensors,” Meas. Sci. Technol. 8(4), 355 (1997).

8. A. Othonos and K. Kalli, Fiber Bragg Gratings: Fundamentals and Applications in Telecommunications and Sensing (Artech House, 1999).

9. J. R. Grenier, L. A. Fernandes, J. S. Aitchison, P. V. S. Marques, and P. R. Herman, “Femtosecond laser fabrication of phase-shifted Bragg grating waveguides in fused silica,” Opt. Lett. 37(12), 2289–2291 (2012).

10. X. Wang, W. Shi, H. Yun, S. Grist, N. A. F. Jaeger, and L. Chrostowski, “Narrow-band waveguide Bragg gratings on SOI wafers with CMOS-compatible fabrication process,” Opt. Express 20(14), 15547–15558 (2012).

11. D. T. H. Tan, K. Ikeda, and Y. Fainman, “Cladding-modulated Bragg gratings in silicon waveguides,” Opt. Lett. 34(9), 1357–1359 (2009).
1. Introduction

Silicon photonic integration has been developing rapidly in recent years due to its large-scale integration capability and compatibility with complementary metal-oxide-semiconductor (CMOS) technologies. The typical thickness of strip silicon waveguides is around 200-500 nm [1]. Recently, ultra-thin waveguides with thickness <100 nm have also been explored. Silicon waveguides with a core thickness of 70 nm and 90 nm were first demonstrated using an etchless process based on selective thermal oxidation [2]. Low-loss waveguides with a core thickness of 50 nm and mode converters for connection with regular waveguides have been fabricated with CMOS-compatible processes [3]. Grating couplers with a core thickness of 50 nm have been demonstrated with a low insertion loss [4]. When the waveguide height is reduced, the propagating modes are less confined to the silicon core and penetrate deeper into the cladding layer. Hence, the ultra-thin waveguides possess the unique characteristics of strong evanescent field, large mode size, and low effective refractive index. The applications of the ultra-thin waveguides in evanescent field sensing and edge coupling have already been implemented [5, 6].

Bragg gratings have been used as key functional components in optical communications and sensing systems [7, 8]. In principle, the period of Bragg grating is inversely proportional to its effective refractive index. In the material systems with a low refractive index contrast (such as silica and polymer), the period of Bragg gratings is large, making it relatively easy to fabricate [9]. However, it becomes more difficult to realize on the high-index-contrast silicon-on-insulator (SOI) material platform [10–13]. Typically, electron-beam lithography (EBL) is employed for fabrication of silicon Bragg gratings, but it is time consuming and
unsuitable for mass-production. Alternatively, 193-nm deep ultra-violet (DUV) photolithography could be used for its high resolution and mass production capabilities. Compared to the 193 nm DUV photolithography, the 248-nm DUV photolithography is less expensive and more widely adopted in the fabrication of silicon photonic circuits. However, the minimum feature size of the 248 nm DUV lithography is typically 180 nm for many fabrication foundries. The period of Bragg gratings made of regular strip silicon waveguides is less than 320 nm and trench width thus less than 160 nm to satisfy the first-order Bragg condition at the 1.55 μm wavelength. Hence, it is impossible to directly use the 248-nm DUV photolithography to fabricate silicon Bragg gratings with predictable performances. Although double-exposure lithography (DEL) and double-patterning lithography (DPL) techniques could be exploited to achieve a smaller feature size [14, 15], they increase the complexity of fabrication and may also introduce overlap errors. Therefore, it is still very challenging to fabricate Bragg gratings on the SOI platform. Slight fabrication errors might cause significant deterioration in grating performances [16].

In this work, we demonstrate basic photonic components, in particular, Bragg gratings, based on the 60-nm-thick silicon strip waveguides fabricated by standard 248-nm DUV photolithography. With a reduced waveguide height, the period of Bragg gratings is enlarged, making it possible to fabricate using the 248 nm DUV photolithography. Ultra-thin silicon waveguides are less sensitive to waveguide sidewall roughness, a key factor that contributes to the waveguide propagation loss, and therefore, devices based on the ultra-thin waveguides could have a lower loss. Moreover, the lower optical confinement also makes the devices more tolerant to fabrication error-induced dimension variations.

The paper is organized as follows. We first characterize the 60-nm thick silicon waveguides to show that it has a propagation loss of 0.61 dB/cm at 1.55 μm, which is 5 times less than that of a regular 220-nm thick waveguide fabricated using the same process. We then present the basic integrated photonic components, building blocks for more complex structures and circuits, based on the ultra-thin waveguides. We next demonstrate the silicon Bragg gratings which exhibit a stopband width of 1 nm and an extinction ratio of 35 dB. Its spectrum is tunable via a laterally integrated resistive micro-heater formed by a heavily doped silicon slab. The Bragg grating could be used as an optical filter or a delay line.

2. Ultra-thin waveguide structure and fabrication

Figure 1(a) shows the cross section of the ultra-thin silicon waveguide. The waveguide height is 60 nm. A wider silicon core is necessary to guide the propagating mode. The single mode condition for waveguides with a 60-nm-thick silicon core is maintained with a waveguide width up to 1150 nm. The width of waveguide is chosen to be 950 nm in our design. Simulation using Lumerical MODE Solutions shows that the waveguide has an effective index of $n_{eff} = 1.69$ at 1.55 μm, much lower than the effective index of 2.45 of a regular 500 nm (width) × 220 nm (height) silicon strip waveguide. Figure 1(b) illustrates the electric field x-component distribution of the fundamental transverse electric (TE)-mode. The mode size, measured when field decays to 1/e of the maximum, is $\sim 1$ μm (width) × 0.6 μm (height). In contrast, the mode size for a regular waveguide is $\sim 0.35$ μm (width) × 0.25 μm (height). The mode conversion between the 60-nm-thick strip and the regular 220-nm-thick ridge waveguides can be achieved by a double-layer taper, as shown in Fig. 1(c). The optical power in the ridge waveguide is gradually pushed into the thin slab when light propagates along the taper to the nano-tip. To thermally tune the thin waveguide, we integrate a resistive microheater made of a highly-doped silicon slab beside the waveguide as will be shown in Section 3.5.
Fig. 1. (a) Schematic of the ultra-thin waveguide cross section. (b) Simulated electric field x-component distribution for the fundamental TE-mode. (c) Schematic of the double-layer taper for mode conversion between the 60-nm-thick and the regular 220-nm-thick waveguides.

The 60-nm-thick strip waveguide devices were fabricated together with other regular 220-nm-thick ridge waveguide devices. The fabrication was done in the Institute of Microelectronics (IME), Singapore. The SOI wafer has a top silicon layer thickness of 220 nm and a buried oxide (BOX) layer thickness of 2 μm. The device patterns were defined by 248-nm DUV photolithography, followed by anisotropic dry etch of silicon. Three masks were used to pattern the silicon layer. The first mask defines the grating couplers with an etched depth of 70 nm for the 220-nm-thick devices. The second mask defines silicon waveguides with an etched depth of 160 nm. The third mask defines the remained slab region where the 60 nm silicon slab is etched down to the BOX layer. Hence, our ultra-thin waveguide devices were patterned by the third mask on the slab layer. Phosphorus ion implantation was performed to form the highly-doped slab with a concentration of ~10^{20} cm^{-3} to make a silicon resistive micro-heater. Then, a 2.3 μm thick silicon dioxide layer was deposited using plasma-enhanced chemical vapor deposition (PECVD) as the device upper-cladding. Finally, contact holes were etched and aluminum was deposited to form metal connection.

3. Basic photonic components

3.1 Straight waveguides

To evaluate the propagation loss of the ultra-thin silicon waveguides, we measured the insertion losses of a series of waveguides with an incremental length. We used the Agilent loss and dispersion analyzer (86038B) to characterize the device transmission performance. A polarization controller was placed in front of the device to set the TE polarization. A pair of on-chip grating couplers couple light into and out of the device from optical fibers, which will be presented in the following sub-section. Figure 2 shows the experimental data from three chips fit by a straight line. The average propagation loss of the waveguides is 0.61 ± 0.08 dB/cm deduced from the linear fitting. This waveguide loss is 5 time smaller than that of a regular 500 nm × 220 nm waveguide using the same fabrication process as reported in our previous work [17]. The low overlap and interaction between the waveguide mode and the sidewall roughness in the ultra-thin waveguides greatly reduce the scattering loss, leading to the much lower waveguide propagation loss.
Fig. 2. Waveguide propagation loss characterization. Each marker denotes a measured loss for a certain waveguide length. The solid line is linear fitting to the experimental data.

3.2 Grating couplers

On-chip grating couplers are critical components for light coupling with an optical fiber. Figure 3(a) shows the scanning electron microscope (SEM) image of the grating coupler. The waveguide is adiabatically tapered to expand the waveguide mode. The grating period is fixed at 1.08 μm, while the trench width linearly increases from 0.34 μm (near the waveguide end) to 0.54 μm with a step of 40 nm in order to generate a longitudinal Gaussian profile of the diffracted field. Figure 3(b) shows the measured output spectrum after light passes through a pair of grating couplers connected by a 1 cm long waveguide. The fiber-to-fiber insertion loss is around 13 dB at the central wavelength of 1565 nm and the 1 dB bandwidth is around 40 nm. The reflectivity of the grating coupler deduced from the 0.4 dB spectral ripples is ~6%.

Fig. 3. (a) SEM image of the grating coupler. (b) Transmission spectrum of a test waveguide with a pair of grating couplers.

3.3 Microring resonators

Silicon microring resonators are promising building blocks for highly compact photonic integrated circuits. We made a symmetrically coupled racetrack ring resonator add-drop filter based on the 60-nm-thick waveguide. Figure 4(a) shows the microscopic image of the fabricated device. The ring resonator has a bending radius of 30 μm and a coupling length of 4 μm with a gap of 300 nm. Figure 4(b) shows the measured through and drop spectra for the add-drop filter. The inset shows the zoom-in view of the resonance spectra around 1547.5 nm. The quality factor (Q-factor) of the resonator is about 17200. The ring intrinsic power loss per round-trip $\kappa_p^2$ (including bending, absorption and surface scattering losses) and waveguide cross-coupling coefficients $\kappa_c^2$ at each resonance wavelength can be calculated from the free spectral range (FSR), the through-port extinction and the drop-port bandwidth obtained from the measured optical responses [18]. Figure 4(c) shows $\kappa_p^2$ has a weak
dependence on wavelength while $\kappa_c^2$ increases with wavelength. The ring intrinsic loss (in unit of dB/round-trip) is related to $\kappa_c^2$ as $-10\log(1-\kappa_c^2)$. At the wavelength of ~1.55 $\mu$m, it is calculated to be 0.030 dB/round-trip. As the straight section is much shorter than the bending part, the ring resonator intrinsic loss is dominated by the straight-bend waveguide junction loss as well as the bending loss. Simulations using Lumerical Mode Solutions show the 0.015 dB loss for a 180° bend mainly comes from the junction loss. The group index $n_g$ of the bend waveguide can also be deduced from the measured resonance FSR [19]. As seen from Fig. 4(d), the deduced $n_g$ linearly decreases from 2.809 to 2.717 as the wavelength increases from 1517 nm to 1593 nm. From the measured group index we can deduce the dispersion parameter $D = (dn_g/d\lambda)/c = -14760$ ps/(nm·km).

![Image](image.png)

Fig. 4. (a) Microscopic image of the fabricated racetrack microring resonator. Inset shows the zoom-in view of the coupling region. (b) Measured transmission spectra at the through and drop ports for the microring resonator. The inset shows the zoom-in view of the resonance spectra around 1547.5 nm. (c) Intrinsic power loss per round-trip $\kappa_p^2$ (black squares) and cross-coupling coefficients $\kappa_c^2$ (blue circles) deduced from the resonator spectra. (d) Group index $n_g$ (black squares) for the 30-μm-radius bend waveguides. The red dashed line is a linear fitting line.

Figure 5 shows the measured bending loss (including the loss from two straight-bend waveguide junctions) of a 180° bend versus the bending radius. It can be seen that the bending loss increases exponentially with the reduced bending radius. A low loss bend (< 0.1 dB) can be achieved with a small bending radius of about 15 μm.
3.4 MMI couplers

Optical splitters are frequently used for signal distribution and construction of more complex devices. Compared with directional couplers, multimode interference (MMI) couplers are superior in terms of bandwidth and dimension variation tolerance. Figure 6(a) shows the schematic structure of a 1 × 2 MMI coupler. In order to reduce the insertion loss, the input and output waveguides are linearly tapered to 2.5 μm before connecting to the MMI region. The width of MMI is designed to be 6 μm for a compact size whilst ensuring sufficient separation of the output waveguides to avoid evanescent coupling with each other. The other geometric parameters are optimized by Lumerical FDTD Solutions and labeled in Fig. 6(a).

To determine the excess loss of MMI, we measured the transmission spectra of cascaded MMI couplers as shown in Fig. 6(b). The transmission spectra at different ports are plotted in Fig. 6(c). The ripples in the transmission spectra are caused by reflection from the input and output grating couplers. The excess loss of MMI can be deduced from the insertion loss of various stages of MMIs. Figure 6(d) shows the decrement of transmission at the wavelength of 1560 nm. The MMI excess loss can be extracted from linear fitting and is about 0.035 dB. Here the excess loss is defined as $10 \log \left( \frac{P_2 + P_3}{P_1} \right)$, where $P_1$ is the input power and $P_{2,3}$ is the output power. Figure 6(e) shows the measured excess loss versus wavelength. It can be seen that low excess loss (<0.2 dB) is obtained over a wide wavelength range from 1535 nm to 1587 nm. There are two reasons that may lead to the fluctuation of the excess loss with wavelengths. First, the transmission spectra of MMI exhibit some ripples caused by reflection from input and output grating couplers. Second, the coupling efficiency of grating couplers varies a little bit across the 8 output ports.
3.5 Mach-Zehnder interferometer

A Mach-Zehnder interferometer (MZI) can be built using two $1 \times 2$ MMI couplers. Figure 7(a) shows the microscopic image of an asymmetric MZI with the arm length difference being 100 $\mu$m. To enable thermal tuning of the MZI, two 665 $\mu$m long resistive micro-heaters formed by highly n-type doped ($10^{20}$ cm$^{-3}$) silicon slabs with the same height of 60 nm are positioned along the two arms as depicted schematically in Fig. 7(b). The width of the doping region is 12 $\mu$m and the separation distance from the waveguide edge is 0.9 $\mu$m to avoid perturbation of the waveguide mode as shown in the inset of Fig. 7(b). When current flows through the doped slab, heat will be generated and diffuse to interact with the nearby waveguide, thereby raising its temperature. Due to the thermo-optic effect of silicon, the waveguide effective refractive index changes as a consequence. In order to ensure a low drive voltage, the heater is segmented with a length of 35 $\mu$m by placing interleaved aluminum electrodes along the longitudinal direction of MZI arms. Compared to conventional metallic heaters positioned on top of the silicon waveguide, the fabrication of the implanted Si heater is compatible with that of p-i-n or p-n diodes routinely used for electrical tuning of silicon waveguides, without adding complexity to fabrication process.
Figure 7(c) shows the transmission spectrum of the MZI. The extinction ratio (ER) of the interference pattern is >70 dB. Given the ER, the excess loss of MMI, and the waveguide propagation loss, the splitting power imbalance between the two output ports of MMI is estimated to be <0.002 dB around the 1.55 μm wavelength. The group index $n_g$ of the straight waveguide can also be deduced from the interference fringes. The phase difference $\Delta \phi$ between the two adjacent extremes caused by the phase shift between the MZI arms is derived using the equation [20]

$$\Delta \phi(\lambda) = \arccos \left[ \frac{2I(\lambda) - (I_{\text{max}} + I_{\text{min}})}{I_{\text{max}} - I_{\text{min}}} \right]$$  \hspace{1cm} (1)$$

where $I(\lambda)$ is the wavelength dependent intensity and $I_{\text{max}}$ ($I_{\text{min}}$) is the maximum (minimum) intensity within one half-cycle of fringe. The group index $n_g$ is given by

$$n_g(\lambda) = \frac{\lambda_{\text{max}} \cdot \Delta \phi(\lambda)}{2\pi \cdot \Delta \lambda \cdot (\lambda_{\text{max}} - \lambda)}$$ \hspace{1cm} (2)
where $\lambda_{\text{max}}$ is the spectral position of maximum intensity within one half-cycle of fringe and $\Delta L$ is the length difference of the MZI arms. Then, the mean group index $n_{g, \text{mean}}$ in each max-to-min half-cycle of fringe is obtained. This method permits the analysis of not only the fringe maxima and minima but also all intermediate data points, which can minimize the experimental noise-induced error [21]. Figure 7(d) shows the group index $n_g$ deduced from the measured transmission spectrum. The group index decreases from $\sim2.55$ to $\sim2.45$ as the wavelength increases. Note that group index oscillates with wavelength, which probably stems from the superimposed residual Fabry-Perot resonances. The average dispersion $D$ is calculated to be $\sim13200$ ps/(nm·km) by using $D = (dn_g/d\lambda)/c$, where $dn_g/d\lambda$ is obtained by linear fitting. We remark that the dispersion of the straight waveguide is smaller than that of the curved waveguide as measured from the ring resonators.

Figure 7(e) shows the shift of MZI spectrum upon thermal tuning. The spectrum is redshifted with the increased thermal power consumption. The phase shift $\Delta \phi$ can be obtained from the transmission spectra using the Eq. (1), where $\lambda$ is fixed at 1.5446 $\mu$m. The waveguide effective refractive index change is related to $\Delta \phi$ as $\Delta n_{\text{eff}} = \Delta \phi / (2\pi L)$, where $L = 665$ $\mu$m is the active arm length. The deduced waveguide effective refractive index change and phase shift as a function of power consumption are shown in Fig. 7(f). The $\pi$ phase shift is obtained under $\sim302$ mW power consumption. The power consumption is relatively high compared to other thermal tuning structures [22]. The inset in Fig. 7(f) shows the simulated temperature rise at the cross-section of the tuning arm when the waveguide effective refractive index changes $\Delta n_{\text{eff}} = 0.0012$, corresponding to a $\pi$ phase shift. It reveals that the center of micro-heater has the highest temperature rise of 23°C, while the waveguide has a temperature rise of 15°C. The temperature has a fast drop in the buried oxide layer due to the good thermal conductivity of silicon substrate and hence large heat leakage into the silicon substrate. Heat lateral diffusion is low due to the very thin layer of silicon slab as the heating source, which lowers the thermal tuning efficiency. The lower optical confinement also contributes to the low thermal efficiency. The thermo-optic coefficients of silicon and silicon dioxide are about $1.8 \times 10^{-4}$/K and $1.0 \times 10^{-5}$/K, respectively. The thin waveguide with its modal field distributed more in the silicon dioxide cladding and substrate weakens its sensitivity to temperature variation.

4. Bragg grating

A Bragg grating is essentially a one-dimensional photonic crystal on which various functions could be realized. Figure 8(a) shows the schematic of a Bragg grating with an inward grating profile apodized by a tanh function. The effect of the inward apodization is to remove the uniform grating ripples at wavelengths below the stopband [23, 24]. The inward apodization profile causes a decrease in the grating effective index as the grating width decreases. This results in a lower Bragg wavelength in the center as compared to the ends. Light with wavelengths below the stopband no longer experiences the abrupt effective index transition as occurs in uniform gratings. Hence, the inward apodization results in smooth transmission and delay spectra at wavelength below the stopband. Still, the ends of the grating form a Fabry-Perot cavity at wavelengths above the stopband, leading to resonant ripples. The Bragg grating has a width $W$ of 900 nm, a grating length $L$ of 5 mm, a side corrugation depth $w$ of 70 nm and a grating period $A$ of 473.4 nm. The full width at half maximum (FWHM) of the employed tanh apodization function of order 12 is 3.9 $\mu$m. Figure 8(b) shows the SEM image of a part of the Bragg grating. The solid lines in Figs. 8(c) and 8(d) show the measured transmission intensity and group delay spectra, respectively. The dotted lines are the simulation spectra with $W$ and $w$ as fitting parameters based on the GratingMOD module from the RSOFT. From fitting, we get $W = 890$ nm, $w = 30$ nm and the height of the waveguide $h = 70$ nm. The grating width is close to the designed value. However, the corrugation depth is much smaller than the designed value. The SEM image in Fig. 8(b)
confirms the grating teeth are significantly smoothed to become sinusoidal corrugation after fabrication. The discrepancy may originate from the proximate effect incurred in photolithography [25]. One solution for this problem is to adopt “mask engineering” or “wavefront engineering” approaches, in which optical proximity correction and phase shift masks could be used to compensate for the loss of diffracted light from masks [26]. The deviation of waveguide height from the designed value is probably caused by the non-uniform silicon layer thickness of SOI wafers as well as the inaccuracy in silicon etch. The variation in waveguide height leads to the shift of Bragg wavelength. Both experimental and simulated spectra exhibit smaller ripples at wavelengths below the stopband than above the stopband, because of the inward apodization of the Bragg gratings. The remained ripples below the stopband may be caused by the fast apodization. The group delay is greatly enhanced near the stopband edges, as shown in Fig. 8(d). The discrepancy between the experimental and simulation results may be due to the variations in waveguide width and height that perturb the modal effective index [16, 27]. The robustness of Bragg gratings to phase noise could be improved by using wider or spiral waveguides [27].

Fig. 8. (a) Schematic structure of the Bragg grating. (b) SEM image of the Bragg grating. (c) Measured and simulated transmission spectra. (d) Measured and simulated group delay spectra.

The transmission intensity and group delay spectra can be thermally tuned using the integrated resistive micro-heater as shown in Figs. 9(a) and 9(c). With the increment of tuning power, the spectra both experience redshift. Figure 9(b) shows the wavelength shifts as a function of tuning power. The tuning efficiency is around 0.95 pm/mW. The group delay decreases with an increasing effective index, provided that the incident wavelength is fixed at the left stopband edge. In particular, the group delay changes from 62 ps to 13 ps with a power consumption of 266 mW at 1618.85 nm, as shown in Fig. 9(d). The thermal tuning efficiency can be improved by using air trenches to isolate the active arms.
5. Conclusions

In conclusion, we have demonstrated basic photonic components and Bragg gratings in 60-nm-thick strip waveguides on the SOI platform. The ultra-thin waveguide exhibits a propagation loss of 0.61 dB/cm, a low bending loss of \(-0.015 \text{ dB/}180^\circ\) for a 30 \(\mu\text{m}\) radius. Based on the ultra-thin waveguides, micro-ring resonators, \(1 \times 2\) MMI couplers and MZIs were implemented. The excess loss of the MMI is \(<0.2 \text{ dB}\) in a 52 nm wavelength range and power imbalance is 0.002 dB. The extinction ratio of the MZI is larger than 70 dB. By reducing the waveguide height, the effective index of the waveguide reduces and in turn enlarges the grating period, making it possible to realize Bragg gratings using the 248-nm DUV photolithography. A tunable Bragg grating has been demonstrated to possess a stopband width of 1 nm and an ER of 35 dB. The central wavelength and the group delay can be actively tuned by the integrated micro-heater. A group delay of 62 ps is obtained at the edge of the stopband. These results indicate that the ultra-thin waveguides could be used to build complex optical devices. Our work demonstrates the possibility of integrating waveguides with different core thicknesses on the same chip. Besides its advantages in edge coupling, sensing and fabrication of Bragg gratings, the low confinement feature of the ultra-thin silicon waveguides could also alleviate the nonlinear effects when a high optical power signal is guided and processed on chip. The long evanescent field outside the silicon core could also provide strong interaction with hybrid upper cladding materials such as III-V gain material or two dimensional membranes like graphene and MoS etc.

Acknowledgment

This work is supported in part by the 973 program (ID2011CB301700), the 863 program (2013AA014402), the National Natural Science Foundation of China (NSFC) (61422508) and SRFDP of MOE (Grant No. 20130073130005). We also acknowledge IME Singapore for device fabrication.