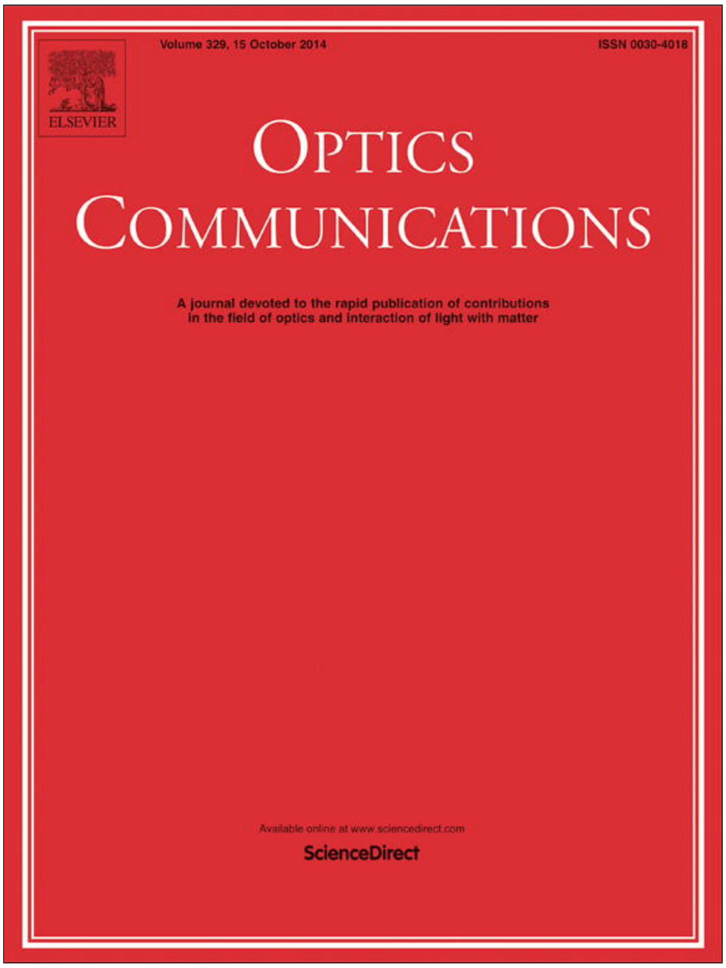

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Experimental demonstration of silicon slot waveguide with low transmission loss at 1064 nm

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A B S T R A C T

Silicon slot waveguides that can operate at the wavelength of high silicon absorption are experimentally demonstrated on SOI wafer. The measured transmission loss coefficient could be as low as 2.28 ± 0.03 dB/mm at the wavelength of 1064 nm (the slot width of 100 nm), which is much lower than the absorption loss of silicon (5 dB/mm at 1064 nm). According to the simulation, such value is dominated by the surface roughness of sidewalls. The transmission loss is potentially to be reduced to < 1 dB/mm if the sidewall roughness could be reduced to ~ 5 nm. We believe that this work could pave the way to achieving all silicon photonic integrated circuits, which are attractive for future optical interconnect and chemical/biological analysis.

1. Introduction

Silicon photonic integrated circuit (S-PIC) has attracted considerable interest due to the possibility of merging electronics and photonics on the same chip for cost-effective mass-production. The silicon detector is readily to be realized through p–n junction, and silicon emitter has come a long way within the wavelength band of 800–1100 nm [1–3]. They provide a great possibility for optical interconnection by achieving all silicon PIC systems with a mature complementary metal–oxide–semiconductor (CMOS) fabrication process today. Furthermore, S-PIC also provides a versatile platform for chemical and biological analyses [4,5]. Specifically, the wavelength window (750 nm to 1200 nm) for optical trapping biological cells and small organisms [6], which is the most essential behavior in the analysis, is fortunately the wavelength band in all silicon PICs. However, if silicon emitter and detector are applied on S-PIC, the transmission waveguide would be a major challenge since the emission from silicon emitter would be highly absorbed by silicon wire waveguide [7]. In our previous work [8], we have proposed and demonstrated that silicon slot waveguide is promising to reduce high material absorption since the light is confined within the slot region [9–11]. Besides, the slot region could also provide a wonderful channel for interaction between filler and light [12] or optical manipulation which is needed in chemical and biological analyses [13].

In this work, we experimentally investigate the transmission loss of slot waveguide on silicon-on-insulator (SOI) wafer. Three groups of samples with slot width of 100 nm, 75 nm and 50 nm are fabricated and measured. The measured transmission loss coefficient could be as low as 2.28 ± 0.03 dB/mm at the wavelength of 1064 nm (the slot width of 100 nm). Such value is much lower than the absorption loss of silicon (5 dB/mm at 1064 nm). Furthermore, we analyze and estimate the scattering loss of the fabricated slot waveguide, and it is found that the measured transmission loss is mainly due to scattering caused by the surface irregularities. It can be estimated that the transmission loss is potentially to be reduced to less than 1 dB/mm if the sidewall roughness is improved to ~ 5 nm with better fabrication technologies. To our knowledge, till now there is no report about fabrication and measurement of slot waveguide operated within the high silicon absorption band, *i.e.*, 800–1100 nm.

2. Measurements and results

Fig. 1(a) depicts the schematic of a silicon slot waveguide, which consists of two silicon strips filled with and surrounded by silica. The width of the total waveguide w_{total} can be determined by $w_{total} = w_{slot} + 2 \times w$, where w_{slot} and w represent the width of the slot region and silicon strip, respectively. The height of the silicon strip h is determined by the thickness of top silicon layer on SOI substrate.

In our previous work [8], the transmission loss of silicon slot waveguide has been systematically investigated within the wavelength band of high silicon absorption (800–1100 nm). In this work,

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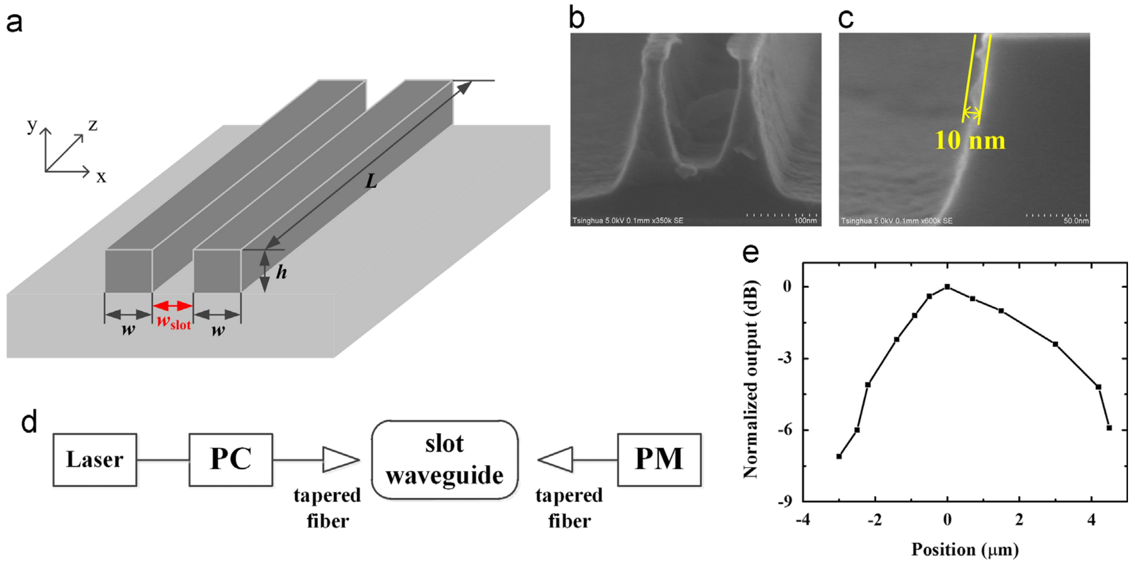

Fig. 1. (a) The schematic of silicon slot waveguide without silica cladding layer. (b) SEM image of the etched slot waveguide with $w_{slot}=75$ nm. (c) Enlarged image of the etched sidewall. The amplitude of the surface roughness is about 10 nm. (d) Experimental setup. (e) Normalized output at different positions along the lateral direction (x axis in (a)) at output end.

the proposed slot waveguide structures are fabricated and tested. Limited by the experimental conditions, the transmission loss is only measured at the wavelength of $\lambda=1064$ nm where the material absorption of bulk silicon is as high as about 5 dB/mm [7]. Here, the width of silicon strips w is selected as 50 nm while the slot width w_{slot} is 100, 75, 50 nm. All waveguides are fabricated on SOI wafer with a 220 nm thick top silicon layer and a 3 μm thick buried oxide layer. The pattern is defined with electron beam lithography (EBL). All the waveguides are etched with inductively coupled plasma reactive ion etch (ICP-RIE), and then covered by a silica cladding layer with the thickness of 600 nm through plasma enhanced chemical vapor deposition (PECVD). The scanning electron microscopy (SEM) is performed to characterize the surface morphology of the fabricated waveguide samples. Fig. 1(b) displays the SEM images of the etched waveguide structure with $w_{slot}=75$ nm and Fig. 1(c) shows the enlarged image of the sidewall. It could be shown that the surface roughness of the etched sidewall is about 10 nm.

The prepared waveguides are characterized with a common system as shown in Fig. 1(d), including a 1064 nm laser, a polarization controller (PC, Agilent 11896A) and a power meter (PM, Agilent 81624A). Two single-mode lensed optical fibers, mounted on a computer-controlled alignment stage, are used to couple light in and out of the waveguides. The output power of the laser is set as a constant value of 1 mW (0 dB m). Since the loss of TM mode is much higher than that of TE mode (the detailed discussion is in the section of simulation), only the transmission loss of TE mode is measured. In order to confirm that the light is transmitted through slot waveguide rather than substrate, the power distribution at output end is measured. Fig. 1(e) shows the normalized output along the lateral direction (x axis in Fig. 1(a)) and the position of 0 μm is the position that the maximum output is achieved. Fig. 1(e) indicates that the waveguide mode is measured. By subtracting the output power of the system from the laser output, the transmission loss of the entire system is obtained. Obviously, the measured result is the sum of the insertion loss of PC, the coupling loss between the tapered fiber and waveguide and the transmission loss of slot waveguide. In order to extract the transmission loss of slot waveguide, samples with varied length for each slot width (w_{slot}) are needed. All samples are uniformly fabricated on a single wafer so that the surface roughness of all the waveguides is supposed to be similar.

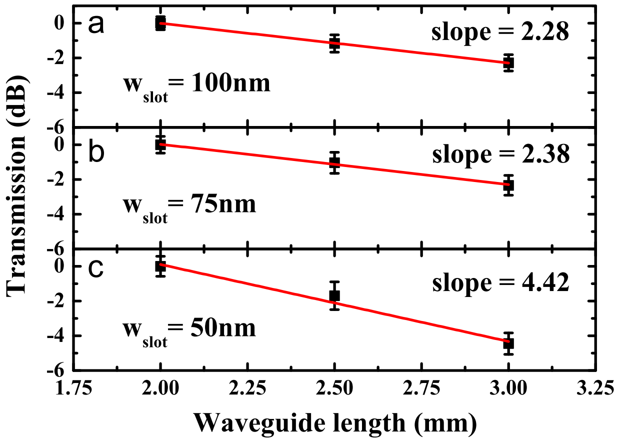

Fig. 2. Measured results of slot waveguides for three cases of $w_{slot}=100$, 75 and 50 nm, respectively.

Here, three lengths of $L=2.0$, 2.5 and 3.0 mm are measured. For one pair of slot width (w_{slot}) and waveguide length (L), there are five samples. Thus, the fluctuation of coupling loss could be averaged by measuring of all the five samples. In Fig. 2(a), (b) and (c), the measured loss of waveguides is shown as a function of the length for three cases, $w_{slot}=100$, 75 and 50 nm, respectively. For each curve, the data is normalized to the transmission loss for the 2 mm long waveguide with the corresponding w_{slot}. In Fig. 2, each dot represents the average loss of the five slot waveguides with the same structure and the same length, and the error bar represents the standard deviation of all the five samples. The standard deviation is from 0.38 dB/mm to 0.80 dB/mm, which is mainly caused by different coupling conditions and various surface roughnesses. The red solid lines are the linear fitting results for each structure. Obviously, the slope of fitting curve represents the transmission loss coefficient, which is 2.28 ± 0.03 dB/mm, 2.38 ± 0.13 dB/mm and 4.42 ± 0.49 dB/mm for $w_{slot}=100$ nm,75 nm and 50 nm, respectively. Compared with the absorption loss of silicon (5 dB/mm at 1064 nm), the transmission loss of slot waveguide is much lower. These experimental results indicate that silicon slot waveguide could be applied to transmit light within the high silicon absorption band. As a concrete example, total transmission loss of 5 dB corresponds to the transmission length of 1.1–2.2 mm for our demonstrated slot waveguide (4.4–2.28 dB/mm), which is qualified for short distance transmission and interconnection. If the loss coefficient could achieve our calculated value of 0.3 dB/cm [8], the transmission length would be more than 10 cm.

3. Discussion and analysis

As shown in Fig. 2, the transmission loss of our fabricated slot waveguides is still high. In fact, the transmission loss of slot waveguide covers not only the absorption loss but also the scattering loss. For deep insight of the loss mechanism we have done some numerical simulations and calculations. First, the absorption loss of slot waveguide, which mainly comes from silicon absorption of 1064 nm light while the silicon dioxide is almost no absorption at this wavelength [7], is simulated by FEM, as in our previous work [8]. The calculated absorption losses of slot waveguides with $w=50$ nm and varied w_{slot} are shown in Fig. 3. It could be found that the loss of TE mode is much lower than that of TM mode, which is owing to different mode field distribution. As an example, the electric field distribution of the slot waveguides with $w=50$ nm and $w_{slot}=50$ nm for TE and TM polarization are shown as the left and right insets of Fig. 3 respectively. It is clear that more electric field of TM mode is distributed in both silicon strips and more energy would be absorbed. Here the absorption loss coefficient of TE polarization for $w_{slot}=100$, 75, 50 nm is 0.30, 0.36, and 0.47 dB/cm at 1064 nm, respectively, while that for TM polarization is 10.18, 11.88, and 14.43 dB/cm, respectively.

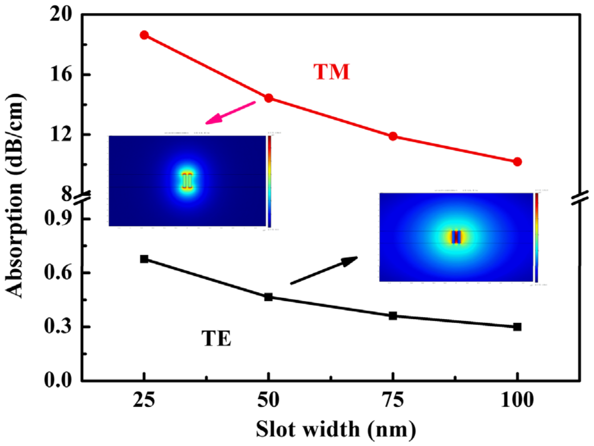

Fig. 3. Absorption loss of TE and TM in slot waveguides with different w_{slot}.

Comparing the calculating absorption loss shown in Fig. 3 with experimental data shown in Fig. 2, it could be found that the transmission loss of our fabricated sample is much higher. It indicates that our experimental result is not dominated by material absorption. As shown in Fig. 1(b), the fabricated slot waveguides is trapezoid rather than ideally rectangular in the previous simulation and there is roughness on the each etched sidewall. First, the isosceles trapezoid shape waveguides are considered according to the fabrication results. Fig. 4 shows the calculated electric field distribution of such two shapes. The detailed geometry parameters of the two shapes are listed in Table 1. The height is considered as 220 nm for all cases. For rectangular waveguide, the width of silicon strip is considered as

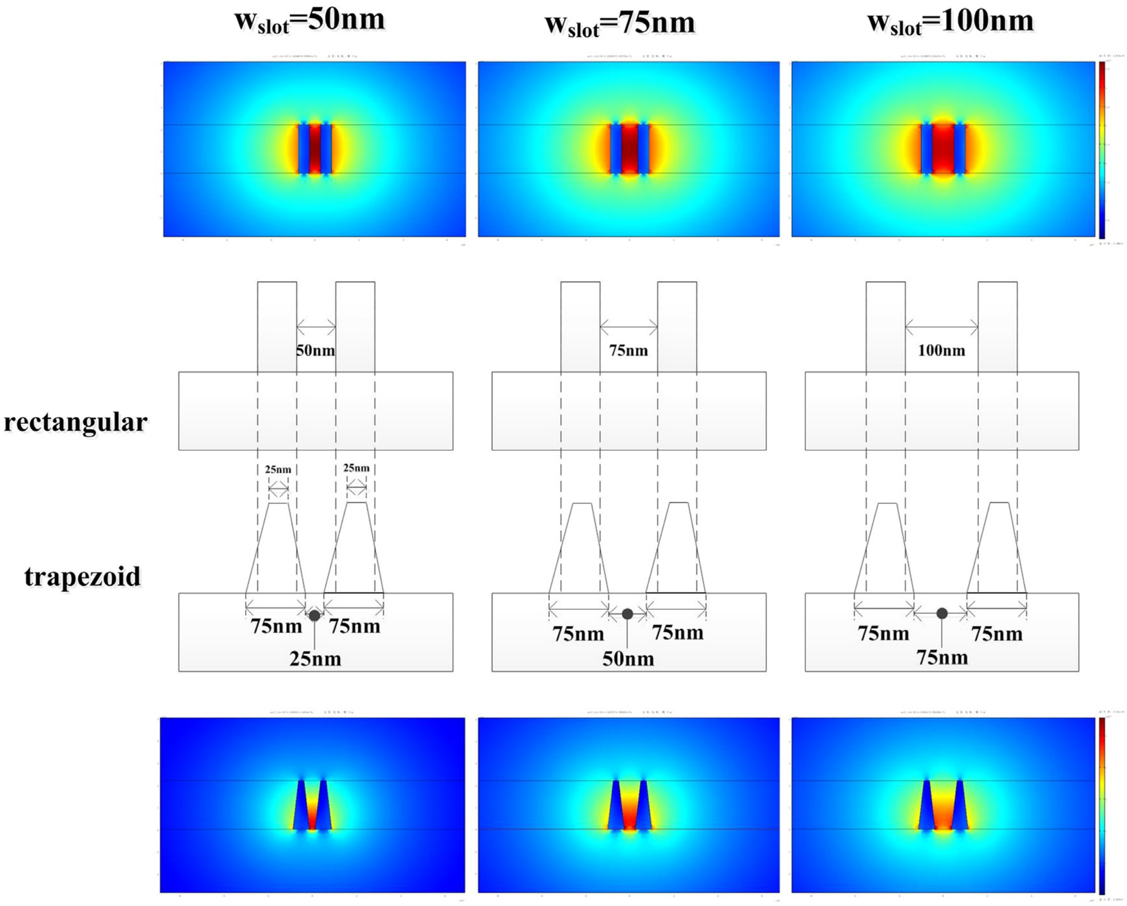

Fig. 4. Schematic and electric field distribution of the rectangular shape and trapezoid shape slot waveguide with $w_{slot}=100$, 75 and 50 nm, respectively.

the designed value (50 nm). For the trapezoid one, minimum/maximum width of silicon strip is considered as 25/75 nm. Thus the trapezoid strip has the same average width with rectangular one and the shape is close to the SEM image of the fabricated waveguide. The absorption loss coefficient of trapezoid shape slot waveguide for $w_{\text{slot}}=100$, 75, 50 nm is 0.41, 0.52, and 0.73 dB/cm at 1064 nm respectively. These values are higher than that of corresponding rectangular shape slot waveguide. That is because the electric field density in the lower trapezoid slot region is larger, as shown in Fig. 4.

Another factor that should be addressed for the waveguide transmission loss is the scattering loss. For our fabricated slot waveguides, the top and bottom interfaces in SOI wafers are very flat and should have little contribution to the scattering so that the scattering loss is supposed to be caused mainly by the roughness of the etched sidewalls. In Ref. [14], a simple analytical model for scattering loss is proposed as follows:

$$\alpha=\frac{\sigma^2 k_0^2 h}{\beta}\cdot\frac{E_s^2}{\int E^2 dx}\cdot\Delta n^2 \tag{1}$$

where σ is the standard deviation of interface roughness, k_0 is the free space wave number, β is the modal propagation constant, Δn is the difference between the refractive indices of the core and cladding, while h and p are the transverse propagation constants in the core and cladding, respectively. It is shown that the loss is proportional to $E_s^2/\int E^2 dx$, which is the normalized electric field intensity at the interface. For strip waveguide, the electric field intensity and interface roughness of two etched sidewalls are both identical and symmetrical. Thus, Eq. (1) covers the scattering of both the two etched sidewalls, while only one sidewall needs to be considered.

In order to estimate the scattering loss of slot waveguide, we also calculate the TE mode profile and the corresponding electric field intensity distributed along the x-axis of three cases. The results are shown in Fig. 5, in which E_{s1} and E_{s2} are the electric field intensity at the outside and the inside interfaces of slot waveguide, respectively. Similarly, the field is also symmetrical. Different to typical strip waveguide, there are two interfaces in slot waveguide contributing to the scattering, where the electric field intensity (E_{s1} and E_{s2}) has obvious disparities as shown in Fig. 5. Thus, in Eq. (1), the total field intensity is calculated as $E_s^2=E_{s1}^2+E_{s2}^2$. From the electric field intensity distributed along the x-axis shown in Fig. 5, the value of $E_s^2/\int E^2 dx$ could be calculated. In addition, the effective refractive index of the mode, defined as n_{eff}, could be also achieved utilizing FEM, then the modal propagation constant is $\beta=n_{\text{eff}}*k_0$, and the transverse propagation constant is $h=k_0\sqrt{n_{\text{Si}}^2-n_{\text{eff}}^2}$, where n_{Si} is the refractive index of silicon. Based on the previous analysis and results, the scattering loss could be roughly estimated as follows:

Table 1
The detailed geometry parameters of rectangular and trapezoid shapes.

	h (nm)	w_{slot} (nm)	w (nm)
Rectangle	220	50, 75, 100	50
Trapezoid	220	75/25, 100/50, 125/75	25/75

$$\alpha=c_1\cdot\sigma^2 \tag{2}$$

where c_1 is a coefficient related to the mode of slot waveguide. Specifically, $c_1=0.144$, 0.165 and 0.201 dB/mm/nm^2 for $w_{\text{slot}}=100$, 75 and 50 nm, respectively.

From the SEM image shown in Fig. 1(c), the amplitude of the surface roughness at etched sidewall of our fabricated slot waveguides is about 10 nm. Following the result shown in [15], the standard deviation of interface roughness is estimated to be $\sigma\approx 4$ nm. Then, with Eq. (2), the scattering loss coefficient is calculated as 2.3, 2.6 and 3.2 dB/mm for the $w_{\text{slot}}=100$, 75 and 50 nm, respectively. The estimated scattering loss is comparable to the experimental result and much higher than the calculated absorption loss. Thus, we believe that the scattering loss caused by the surface roughness of sidewalls is the dominant factor of our fabricated slot waveguides. According to reported silicon strip waveguide [15], the typical standard deviation of interface roughness is ~2 nm (the amplitude of the surface roughness is ~5 nm). If the same roughness could be achieved on our proposed slot waveguide, the scattering loss coefficient would be 0.58, 0.66 and 0.80 dB/mm, and the whole transmission loss coefficient, with the addition of absorption, would be 0.61, 0.70 and 0.85 dB/mm with $w_{\text{slot}}=100$, 75 and 50 nm, respectively. Furthermore, the transmission loss of these slot waveguides could be further reduced by improving the fabrication technologies. We believe that it is possible to make slot waveguide more promising for the PIC.

4. Conclusions

The silicon slot waveguides with three structures are fabricated on SOI wafer, and their transmission losses are experimentally investigated at the wavelength of 1064 nm. The measured transmission loss coefficient for three cases of $w_{\text{slot}}=100$, 75 and 50 nm could be as low as 2.28 ± 0.03 dB/mm, 2.38 ± 0.13 dB/mm and 4.42 ± 0.49 dB/mm, respectively. These values are lower than the material absorption loss of silicon (5 dB/mm at 1064 nm). Furthermore, we calculate the absorption loss of designed slot waveguide and estimate the scattering loss of the corresponding fabricated waveguide. The scattering loss coefficient is estimated at 2.3,

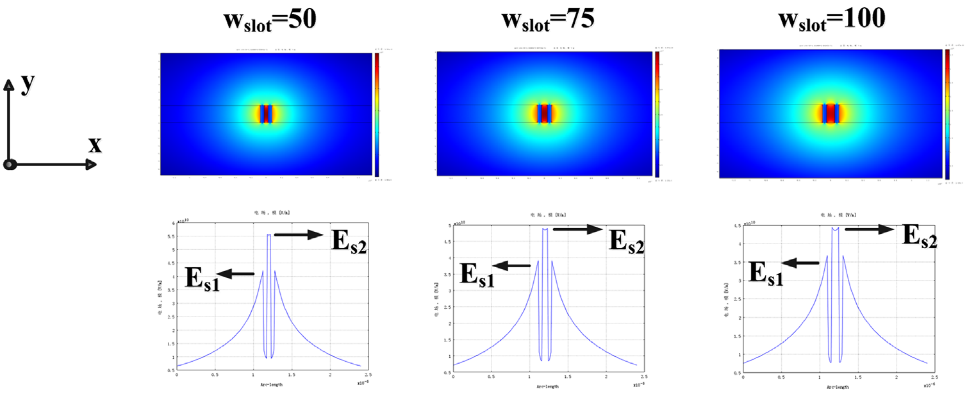

Fig. 5. The profile of TE polarization and corresponding electric field intensity distributing along the x-axis for slot waveguide with $w_{\text{slot}}=100$, 75 and 50 nm, respectively.

2.6 and 3.2 dB/mm for the $w_{slot}=100$, 75 and 50 nm, respectively, with the amplitude of the surface roughness being about 10 nm (standard deviation $\sigma \approx 4$ nm). It indicates that the measured transmission loss is mainly due to scattering by the surface irregularities. The transmission loss could be further reduced with better fabrication technologies. The silicon slot waveguide with low loss provides a direct way to realize all silicon photonic integrated circuit, which would be an attractive solution for optical interconnect and chemical/biological analysis.

Acknowledgments

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