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Designing low transmission loss silicon slot waveguide at wavelength band of high material absorption

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ABSTRACT

The transmission loss of silicon slot waveguide is investigated by numerical simulation. With the proper designing, the silicon slot waveguide could operate within the wavelength band of high material absorption, *i.e.*, 800–1100 nm. The minimum propagation loss can be as low as 0.05 dB/mm with optimized structural parameters. Furthermore, a linear relation between the slot width and the operating wavelength is found after optimization, which provides a convenient method to design low-loss slot waveguide.

1. Introduction

Photonic integrated circuits on silicon substrate have attracted much interest due to the possibility of merging electronics and photonics on the same chip. In recent years, significant progress has been achieved in developing integrated silicon photonic devices including waveguide, modulator, detector [1,2], as well as silicon light source [3–5]. Especially, one of the major research directions is improving the quantum efficiency (QE) of the emission from silicon material [6,7] and integrating the silicon emitter with other photonic devices so that all silicon photonic integrated circuit could be achieved. There are several approaches that have been demonstrated with low dimensional silicon material including porous silicon, silicon nanocrystals, silicon nanopillars and so on [3]. Meanwhile the Purcell effect is also introduced for enhancing the QE of silicon emitter with photonic crystals or plasmonic nanostructures [6,7]. To apply silicon emitter to photonic integrated circuits, the transmission waveguide is a main challenge since the output of silicon emitter would be highly absorbed by silicon-wire waveguide, which is now widely adopted in photonic integrated circuits. There are two main technical approaches to deal with it. The first one is utilizing other materials, including SiON, SiN_x, and SiO_2 [8,9]. The other one is adopting silicon slot waveguide, in which the light is confined within the slot region [10,11] so that the impact of material absorption is not so significant. The width of slot waveguide could be as small as several tens of nanometers, which is more suitable for highly compact integrated circuit. In addition, highly confined electromagnetic field can be effectively and readily achieved, so that slot waveguide can be used for signal processing [12,13]. In a word, silicon slot waveguide could serve as an infrastructural unit in the optical transmission and signal processing with silicon emitter. For slot waveguide, the transmission loss would be very sensitive to the structural parameters within the material absorption band. However, till now, the investigation about silicon slot waveguide is focused on operating within the telecom band (1.5 μm) [12,13] and there is no report about applying silicon slot waveguide on photonic integrated circuits operating within the high silicon absorption band, *i.e.*, 800–1100 nm.

In this paper, the transmission loss of silicon slot waveguide is investigated by the finite element method (FEM), and a solution to optimize the structure of slot waveguide is proposed. Two structural parameters of the total width w_{total} and the duty cycle factor η, which is defined as the ratio of the slot width over the total width, are concerned and optimized according to the transmission loss while the transmission mode is not converted to radiation mode. Within the wavelength range of 800–1100 nm, the minimum transmission loss of optimized slot waveguide can be as low as 0.05–6.5 dB/mm. Typically, the value is about 3–4 dB/mm at wavelength of 900 nm. As a comparison, the transmission loss for a silicon strip waveguide with the same width would be as high as 500 dB/mm. Obviously, with our proposed optimization procedure, silicon slot waveguide could be properly designed for operating within the wavelength band of high material absorption. We believe that this work is the first step toward the combination of silicon slot waveguide and silicon emitter on photonic integrated circuits in the future. Furthermore, a linear relation between the duty cycle factor and the wavelength is found for

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optimized slot waveguide, which facilitates the design of low-loss slot waveguide.

2. Detailed analysis and results

As shown in Fig. 1, we assume that the slot waveguide is symmetrical, consisting of two identical silicon strips that are filled with and surrounded by silica. The width of the total slot waveguide is denoted as $w_{\text{total}}=w_{\text{slot}}+2w$, where w_{slot} and w represent the width of slot region and silicon strip, respectively. The height of the silicon strip is set as $h=220$ nm, corresponding to the thickness of silicon layer on a Silicon-on-Insulator (SOI) wafer. Both heights of the buried oxide layer and the cladding layer are 2 μm. We define the duty cycle factor η as $w_{\text{slot}}=\eta w_{\text{total}}$. Then with two structural parameters, *i.e.* the total width w_{total} and the duty cycle factor η, a slot waveguide is determined.

The transmission wavelength λ is considered within the range of 800–1100 nm, and Fig. 2(a) shows the complex refractive index of silicon within this wavelength band which is expressed as

$$n_{\text{silicon}}=n+ik$$

where n is the refractive index of silicon material and k determines the absorption of silicon material. In Fig. 2(a), the original data shown with scatter symbols are from handbook [14] and others are obtained by spline interpolating the original data. For more clarity, the absorption loss is transformed to the unit of dB/mm and shown in Fig. 2(b). It could be found that the value of absorption loss varies from tens to several hundred within the wavelength range of 800–1100 nm. As an example, absorption loss is as large as 500 dB/mm at wavelength of 900 nm. Obviously, the absorption loss is too large to transmit the electromagnetic wave. One method to reduce the impact of material absorption is confining the electromagnetic field outside the silicon, which could be achieved in silicon slot waveguide.

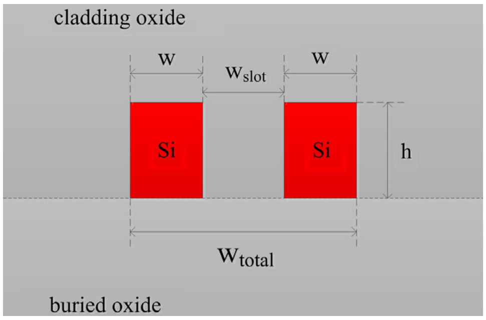

Fig. 1. Schematic diagram of slot waveguide.

In this work, we focus on the transmission loss of silicon slot waveguide (α) within the wavelength range of 800–1100 nm. The two key structural parameters w_{total} and η are optimized to achieve as low transmission loss as possible. For convenience, we first consider the case of $\lambda=900$ nm. It is intuitive that as η increases, silicon region is reduced and the transmission loss of slot waveguide would also decrease since the silica almost does not absorb the electromagnetic wave of $\lambda=900$ nm. At the same time, as η increases, the confinement of electromagnetic field is deteriorated, which could be seen in Fig. 3. In Fig. 3(a), (b) and (c), the mode profiles at $\eta=6.7\%/24.4\%/42.2\%$ with constant total width of $w_{\text{total}}=225$ nm are shown, respectively. And the corresponding electric field intensity distributing along the x-axis is also shown in Fig. 3(d)–(f). Here, the ratio of the maximum electric field intensity in the slot region ($|E|_{\text{ms}}$) over the maximum electric field intensity outside the slot region ($|E|_{\text{mo}}$) is used to characterize the light confinement of slot waveguide, which is denoted as $R=|E|_{\text{ms}}/|E|_{\text{mo}}$. When $R>1$, the light could be considered as mainly confined in the slot region. Otherwise, the slot waveguide would not be used to confine the light wave. In addition, from Fig. 3(a)–(c), it could be found that the mode width of the confined field in slot region is approximately equal to the width of slot region w_{slot}. Thus, slot width w_{slot} is used to denote the mode width in the following session.

With $w_{\text{total}}=150$ nm, 225 nm, 300 nm, the effective index and the transmission loss are calculated with varied duty cycle factor η. Here, utilizing COMSOL Multiphysics the complex effective index of the eigenmode of slot waveguide is calculated as

$$n_{\text{eff}}=n_{\text{reff}}+in_{\text{ieff}}$$

where the real part of the complex effective index n_{reff} makes a contribution to the propagation constant of waveguide, and the transmission loss α can be obtained from the imaginary part of the complex effective index n_{ieff} by

$$\alpha=\frac{40\pi n_{\text{ieff}}\lg e}{\lambda}$$

where e is natural constant. The results are shown in Fig. 4(a), where the effective index and transmission loss are shown as blue solid lines and red short dash lines, respectively. Meanwhile, the refractive index of silica cladding layer is also shown as solid black line. It is clear that as η increases from 6.7% to 44%/59%/67%, the transmission loss would decrease from (186 dB/mm)/(280 dB/mm)/(329 dB/mm) to (4.0 dB/mm)/(3.6 dB/mm)/(3.3 dB/mm) for $w_{\text{total}}=150$ nm, 225 nm and 300 nm, respectively.

However, it could also be found that the effective refractive index of slot waveguide will be lower than that of silica when η exceeds a certain value, which is 44%/59%/67% for the case of $w_{\text{total}}=150$ nm/225 nm/300 nm, respectively, as shown in Fig. 4(a). With higher η, the transmission mode will convert into radiation mode so that the slot waveguide cannot guide the optical wave. Meanwhile, the light

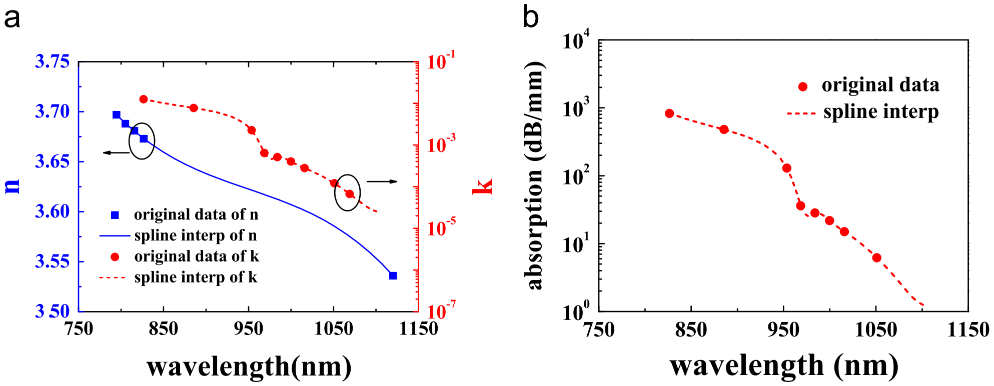

Fig. 2. (a) The complex refractive index and (b) absorption loss of silicon material with wavelength of 800–1100 nm. The discrete dots are original data from handbook while the curves are obtained with spline interpretation.

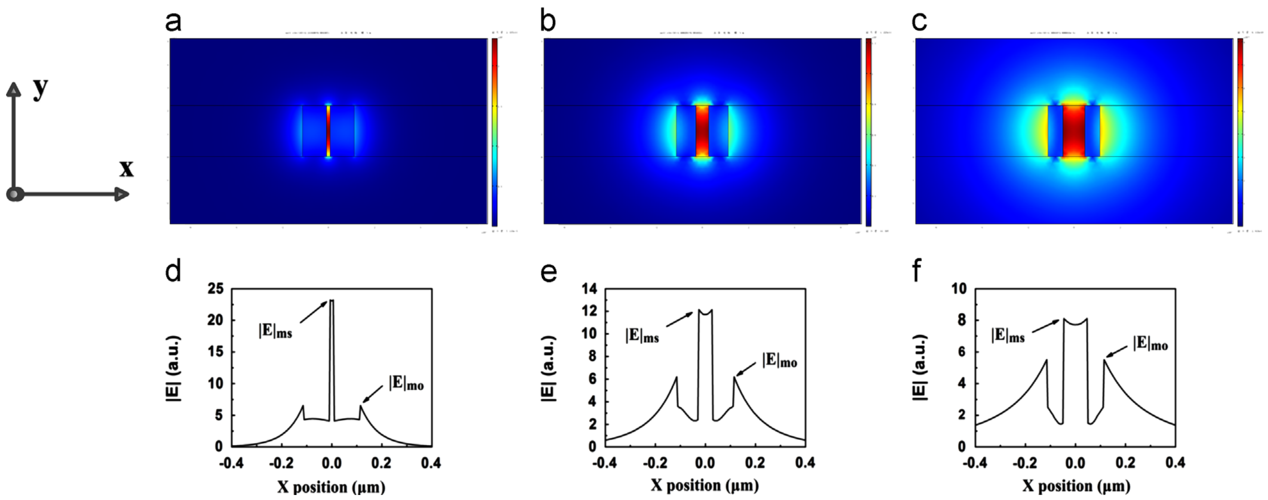

Fig. 3. The mode field and electric field intensity along the x-axis with different η at $w_{total}=225$ nm and $\lambda=900$ nm. $|E|_{ms}$ and $|E|_{mo}$ represent the maximum of the electric field intensity within and outside the slot region, respectively: (a) η=6.7%, (b) η=24.4% and (c) η=42.2%.

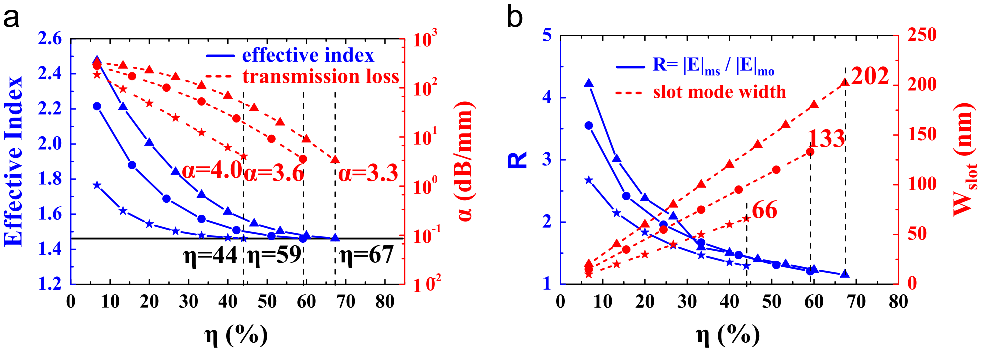

Fig. 4. (a) The effective index (blue) and transmission loss (red) versus varied η. (b) The ratio of electric field intensity (blue) and slot mode width (red) versus varied η. The stars, circles and triangles present the calculation results for total width of $w_{total}=150$ nm and $w_{total}=225$ nm, and $w_{total}=300$ nm, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

confinement would be deteriorated as η increases. The corresponding ratio of electric field intensity R and the mode width w_{slot} are also calculated and shown in Fig. 4(b), as blue and red lines, respectively. It is found that even when the effective refractive index of slot waveguide is close to that of silica cladding layer, R is still more than 1 ($R\approx1.2$). As mentioned above, the light is still confined in the slot region when $R>1$. Thus, the maximum value of η with the lowest transmission loss should be that to make the effective refractive index equal to that of silica. As Fig. 4(a) and (b), the minimum transmission loss α is (4.0 dB/mm)/(3.6 dB/mm)/(3.3 dB/mm) and the corresponding mode width w_{slot} is 66 nm/133 nm/202 nm for the case of $w_{total}=150$ nm/225 nm/300 nm, respectively.

For more clarity, the maximum η and corresponding α with $w_{total}=100$–400 nm and $\lambda=900$ nm are calculated and shown in Fig. 5(a). It could be found that the transmission loss is only 3–4 dB/mm, which is low enough to transmit optical wave in integrated photonic circuits. It is also found that as w_{total} increases, the transmission loss decreases, so lower transmission loss could be achieved for the slot waveguide with a wider total width. In order to further illustrate the advantages of slot waveguide, the optimized slot waveguide and silicon strip waveguide with the same total width w_{total} are compared and shown in Fig. 5(b). For silicon strip waveguide, w_{total} represents the width of silicon strip, and the strip height is also 220 nm. The transmission loss of the optimized slot waveguide is only 3–4 dB/mm, while that of silicon strip waveguide with the same width would be as high as ~400 dB/mm. In the inset of Fig. 5(b), the mode profiles for slot waveguide ($\eta=44\%$, $w_{total}=150$ nm) and silicon strip waveguide ($w_{total}=150$ nm) are also shown. For slot waveguide, the electromagnetic field is mainly confined in the slot region while that of silicon strip waveguide is confined within the strip region. This is the physical origin that the transmission loss of the optimized slot waveguide could be much lower than that of silicon strip waveguide.

Till now, only the case of 900 nm is considered. With the same method, the maximized η and corresponding transmission loss are also calculated with the wavelength range of $\lambda=800$–1100 nm. The results are summarized in Fig. 6. Here, only three representative values of $w_{total}=100$ nm/150 nm/200 nm are shown. In Fig. 6(a), an interesting result is found that the duty cycle factor η is nearly linear to the wavelength and the three curves with different w_{total} show nearly the same slope of about −0.10%/nm. The slope of the curves is nearly independent from the structural parameters of slot waveguide. Although the mechanism is still not clear, we can easily obtain the duty cycle factor η for a slot waveguide with the lowest transmission loss for a given wavelength and total width of waveguide according to such linear relation. Furthermore, in view of the fact that the slope of the curves is determined only by the materials of waveguide, it provides a convenient way to optimize the slot waveguide covered with various kinds of materials, not limited to silica in this paper, which is very important for light transmission in integrated photonic circuits with shorter wavelength and other devices involving slot waveguide. Fig. 6(b) shows the transmission loss of the optimized slot waveguide within the wavelength range of 800–1100 nm, which is as low as 0.05–6.5 dB/mm. It could also be found that as wavelength increases, the

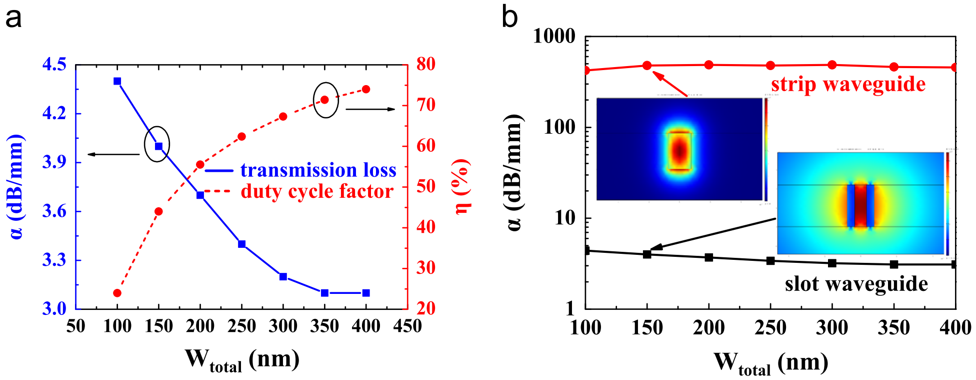

Fig. 5. (a) The optimized η (red circles) and corresponding transmission loss (blue squares) versus total waveguide width. (b) The transmission loss comparison between the optimized slot waveguide and silicon strip waveguide. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

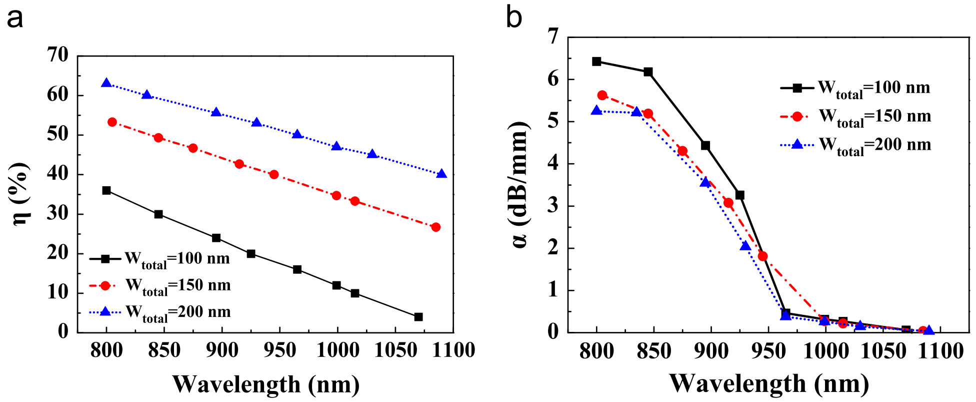

Fig. 6. (a) The optimized η versus wavelength for varied total waveguide width and (b) corresponding spectrum of transmission loss in slot waveguide.

transmission loss of the slot waveguide decreases. Such result could be understood that silicon absorption loss would dramatically decrease within long wavelength range as shown in Fig. 2(b). More in detail, the transmission loss of slot waveguide can be as low as several dB/mm within the range of 800–950 nm while the absorption loss of silicon is several hundred dB/mm. Within 950–1100 nm, the corresponding values are <1 dB/mm versus tens of dB/mm. These results indicate that the impact of silicon absorption could be significantly reduced with slot waveguide.

3. Conclusions

The transmission loss of silicon slot waveguide is investigated by FEM, and a solution to optimize the structure of slot waveguide is proposed. Low-loss silicon slot waveguide is properly designed for operating within the wavelength range of 800–1100 nm, where the absorption loss of silicon is very high. The minimum losses can be as low as 0.05–6.5 dB/mm through optimizing two key structural parameters, w_{total} and η. Furthermore, a linear relation between the duty cycle factor and the wavelength is found for optimized slot waveguides, which is very helpful to design low-loss slot waveguide conveniently.

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