Designing silicon slot waveguide structure for confinement of light at wavelength range of 1 ~ 2 μm

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The confinement of light in silicon slot waveguide operating at the wavelength range of 1 μm ~ 2 μm is investigated. With the proper structure designing, the optimal confinement of light in slot region for slot waveguide could be realized. This value is 0.59, 0.56, and 0.52 for the wavelength of 1 μm, 1.5 μm, and 2 μm, respectively. Furthermore, the transmission loss and the confinement of light are both calculated and discussed when silicon slot waveguide operates at the material high absorption wavelength.

1. Introduction

Because of the possibility of merging electronics and photonics and the cost-effective mass-production, silicon photonics have attracted much interest in recent decades [1-3]. Silicon optical waveguide is a major workhorse in silicon photonics [4-6]. Silicon slot waveguide is a special silicon waveguide, consisting of two strips with higher refractive index and one slot with lower refractive index [7, 8]. Due to the special structure, the light is confined in the slot region, which is the most key character for silicon slot waveguide [9-11]. That provides many applications for slot waveguide, including chemical and biological analysis [12, 13], optical manipulation [14, 15], high speed signal processing [16, 17], high absorption light transmission [18, 19], quantum information [20, 21], and so on. Almost all applications of slot waveguide benefit by its high confinement of light in slot. The operating wavelength of silicon slot waveguide is usually within the range of 1 μm ~ 2 μm [12-21].

In this paper, the confinement of light in silicon slot waveguide operating at the wavelength range of 1 μm ~ 2 μm is investigated by the finite element method (FEM). The confinement of light is characterized by the ratio between the power in the slot region and that in the total slot mode (P_s / P_t). The structure of silicon slot waveguide is decided by two structural parameters of the waveguide width w_{wg} and the duty cycle factor η. There is always an optimal value for η with a certain w_{wg} considering the confinement of light when the wavelength is $\lambda = 1$ μm, 1.5 μm, and 2 μm. At $\lambda = 1.5$ μm, the optimal η is $\eta_o = 20\%$, 30%, 32%, 33.3%, and 48.6% for $w_{wg} = 300$ nm, 400 nm, 500 nm, 600 nm, and 700 nm, then the corresponding

maximum confinement P_s / P_t is 0.37, 0.50, 0.54, 0.54, and 0.56, respectively. At $\lambda = 2$ μm, $\eta_o = 24\%$, 26.7%, 28.6%, 30%, and 37.8% for $w_{wg} = 500$ nm, 600 nm, 700 nm, 800 nm, and 900 nm, and the corresponding P_s / P_t is 0.42, 0.47, 0.52, 0.52, and 0.52, respectively. Because of the silicon material absorption, for $\lambda = 1$ μm the transmission loss of the slot waveguide must be considered. When the value of η is maximum, that is $\eta_m = 47.0\%$, 61.3%, 69.0%, and 74.1% for $w_{wg} = 200$ nm, 300nm, 400 nm, and 500 nm, the transmission loss rate is lowest, the corresponding value is 0.26 dB/mm, 0.22 dB/mm, 0.21 dB/mm, and 0.21 dB/mm, respectively. However, $\eta_o = 30\%$, 40%, 50%, and 60% for $w_{wg} = 200$ nm, 300 nm, 400 nm, and 500 nm, and the corresponding optimal P_s / P_t is 0.43, 0.59, 0.57, and 0.55, respectively, at $\lambda = 1$ μm. The minimum transmission loss and the optimal confinement can not be realized together by designing the structure of slot waveguide.

This work provides the principle to select the proper structure of silicon slot waveguide for the confinement of light in slot, which is important in many applications of slot waveguide. In addition, to design the structure of silicon slot waveguide operating at the material high absorption wavelength, the transmission loss and the confinement of light should be both considered for some applications.

2. Modeling and theory

The silicon slot waveguide consists of two silicon strips and one slot, as shown in Fig. 1(a). Here, the two silicon strips are assumed to be surrounded by silica (SiO₂). The parameter w_{slot} and w_{strip} represent the widths of the

slot between two strips and each strip, respectively. Then, the total width of slot waveguide is $w_{wg} = w_{slot} + 2\,w_{strip}$. The duty cycle factor of slot region is defined as $\eta = w_{slot} / w_{wg}$. So, the structure of a slot waveguide could be determined by w_{wg} and η. In line with the Silicon-on-Insulator (SOI) wafer, the height of the waveguide is $h = 220$ nm, and the heights of the buried oxide and the cladding oxide are both 2 μm.
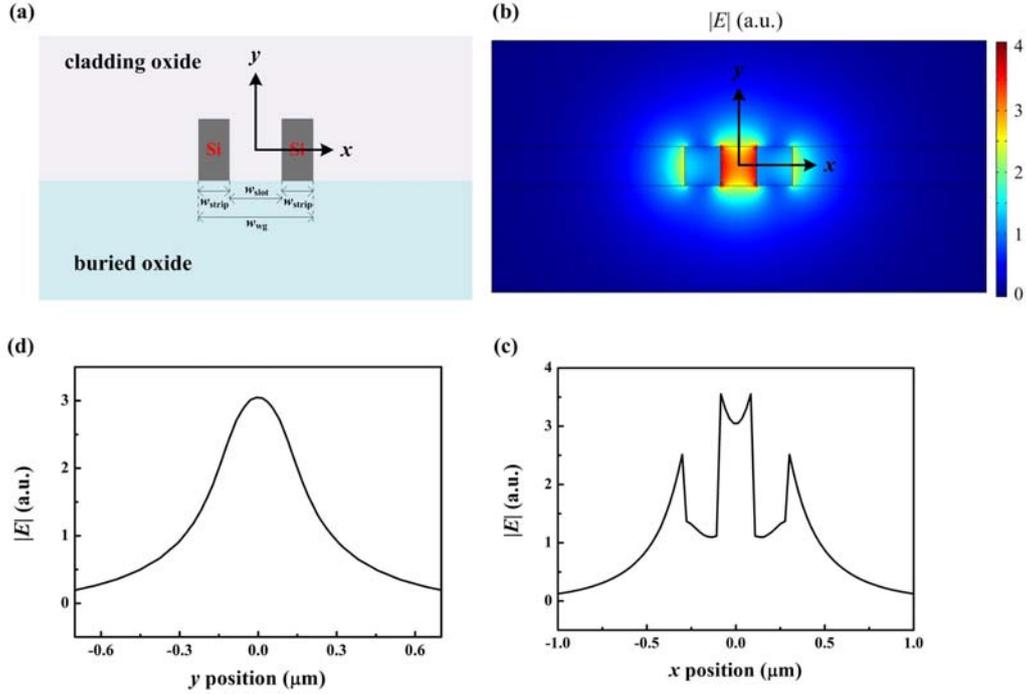
Fig. 1. (a) The schematic diagram of silicon slot waveguide. (b) The mode field of slot waveguide.
(c) The electric field intensity distributing along the x-axis. (d) The electric field intensity distributing along the y-axis.

In slot waveguide, light is mainly confined in the slot region, Fig. 1(b) is a typical mode field of slot waveguide ($\lambda = 1.5$ μm, $w_{slot} = w_{strip} = 200$ nm). The corresponding electric field intensity distributing along the x-axis and y-axis (in Fig. 1(a) and (b)) are shown in Fig. 1(c) and (d), respectively. According to Fig. 1(d), the electric field intensity distributing along the y-axis is similar to that of strip waveguide. However, as shown in Fig. 1(c), the light is confined in the slot region along the x-axis, which is the key characteristic of slot waveguide, leading to many applications of slot waveguide [12-21]. So, in this work, the light power in slot region along the x-axis is used to characterize the confinement of light for slot waveguide. The electric field intensity ($|E|$) distributing along the x-axis is calculated by FEM, as shown in Fig. 1(c). Then, the corresponding power intensity d is proportional to $|E|^2$. Considering that the data calculated by FEM is finite, here the light power P is estimated by the average of power intensity (d_a). In detail,

$$P_s = d_{sa} \times w_{slot} \tag{1}$$

and

$$P_t = d_{ta} \times w_{total} \tag{2}$$

in which, P_s and P_t are the light power along the x-axis in the slot region and the total slot mode, respectively. w_{total} is the total width of the slot mode of slot waveguide. Here, in order to insure the integrity of the slot mode, w_{total} is selected as 4.8 μm. d_{sa} and d_{ta} represent the averages of power intensity in the slot region and the total mode region, respectively. So, the confinement of light for slot waveguide could be characterized by

$$\frac{P_s}{P_t} = \frac{d_{sa}}{d_{ta}} \times \frac{w_{slot}}{w_{total}} \tag{3}$$

which is the relative power in slot region.

3. Results and discussions

This work focus on the near-infrared light ($\lambda = 1$ μm ~ 2 μm). For convenience, the case of $\lambda = 1.5$ μm would be first investigated. At 1.5 μm, the refractive index of silicon and silica are $n_{Si} = 3.48$ and $n_{SiO2} = 1.44$, respectively [22]. For slot waveguide, in order to ensure the slot mode, the structure parameters w_{wg} and η are limited. Through FEM, the effective refractive index (n_{eff}) of slot waveguide can

be calculated. Fig. 2 shows n_{eff} of slot waveguide with various duty cycle factor η and waveguide width w_{wg} at λ = 1.5 μm. It can be found that for each w_{wg}, n_{eff} decreases as η increases, which is obvious considering the refractive index of silicon is greater than that of silica. However, according to Ref [23], if η exceeds a certain value, the effective refractive index of slot waveguide would be lower than that of silica. Thus, the mode of slot waveguide would become the radiation mode instead of the transmission mode. So, as n_{eff} = n_{SiO2} (1.44), as shown by the green dashed line in Fig. 2, the value of η is the maximum (η_m). For w_{wg} = 300 nm, 400 nm, 500 nm, 600 nm and 700 nm, η_m = 29.3%, 41.5%, 50.0%, 56.3% and 61.1%, respectively. From these results, it can be seen that η_m increases as w_{wg} increases. According to the previous calculation and analysis, for the slot waveguide with a certain width, the duty cycle factor is limited in a range, that is $\eta < \eta_m$.
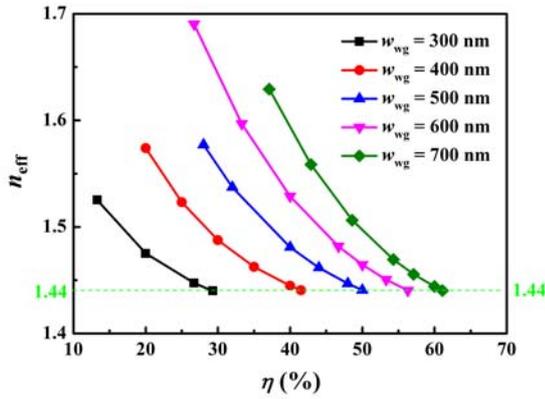
Fig. 2. The effective refractive index (n_{eff}) of silicon slot waveguide with various duty cycle factor (η) under different waveguide width (w_{wg}) at λ = 1.5 μm.
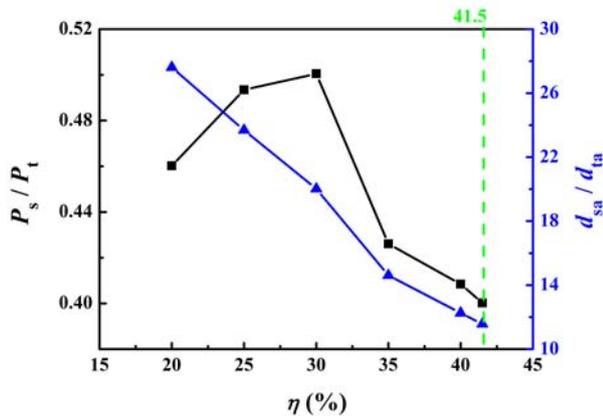
Fig. 3. The results of P_s / P_t (black, square) and d_{sa} / d_{ta} (blue, triangle) under various η with w_{wg} = 400 nm.
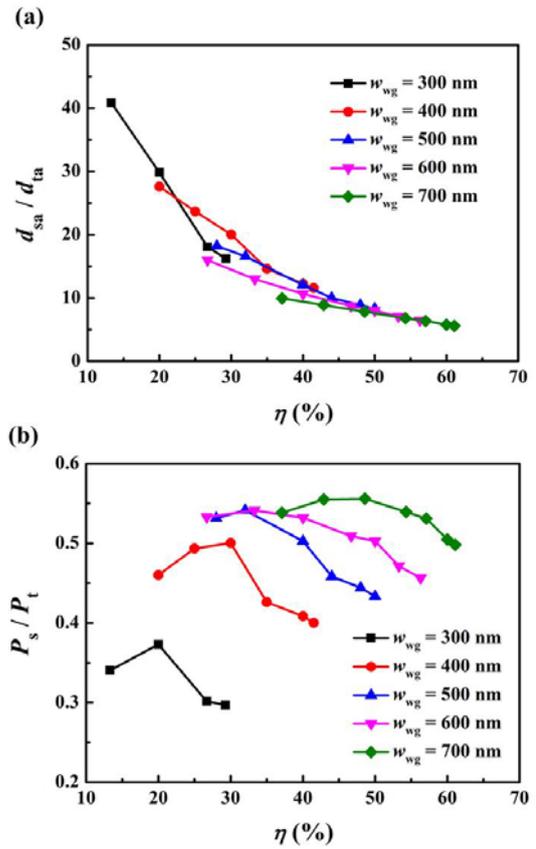
Fig. 4. The results of d_{sa} / d_{ta} (a) and P_s / P_t (b) under various η with different w_{wg} (300 nm ~ 700 nm) at λ = 1.5 μm.

Fig. 3 shows the results of d_{sa} / d_{ta} and P_s / P_t under various η with w_{wg} = 400 nm. According to the previous analysis, the value of η must be smaller than η_m, and η_m = 41.5% for w_{wg} = 400 nm, that is the green dashed line in Fig. 3. As shown by the blue line (triangle) in Fig. 3, the ratio of the average power intensity in the slot region to that in the whole slot mode (d_{sa} / d_{ta}) decreases as η increases, that is obvious. However, based on Equ. (3), the confinement P_s / P_t is decided by not only d_{sa} / d_{ta} but also w_{slot} / w_{total}. The value of w_{slot} / w_{total} increases as η increases. So, the value of P_s / P_t, the black line (square) in Fig. 3, is not monotonic. There is a maximum for P_s / P_t, here that is 0.50 when $\eta = \eta_o$ = 30%. According to the results in Fig. 3, there is an optimal value for η (η_o) with a certain w_{wg} for the confinement of light.

The cases of different w_{wg} are also investigated and the results are shown in Fig. 4. Fig. 4(a) is d_{sa} / d_{ta} under various η with different w_{wg}. It can be found that for each w_{wg} (300 nm ~ 700 nm), as η increases, d_{sa} / d_{ta} decreases. Fig. 4(b) shows the results of P_s / P_t. For each w_{wg}, there is an optimal value of η, that is η_o = 20%, 30%, 32%, 33.3%, and 48.6% for w_{wg} = 300 nm, 400 nm, 500 nm, 600 nm, and 700 nm, respectively. And the corresponding maximum confinement P_s / P_t is 0.37, 0.50, 0.54, 0.54, and 0.56, respectively. It can be seen that in order to realize the high confinement of light the structure of slot waveguide (w_{wg} and η) must be designed properly, and there is an optimal η for a certain w_{wg}.
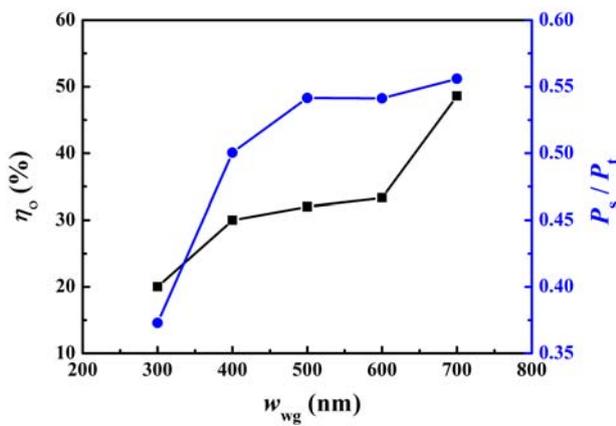
Fig. 5. The η_o (black, square) and the corresponding P_s / P_t (blue, circle) under various w_{wg} at λ = 1.5 μm.

The optimal duty cycle factor η_o and the confinement of light P_s / P_t when $\eta = \eta_o$ under various w_{wg} are shown in Fig. 5. Because each η is selected as the optimal value η_o, the confinement of light in slot region P_s / P_t is optimal for the corresponding w_{wg}. According to the simulation results in Fig. 5, as slot waveguide width w_{wg} increases, the optimal confinement of light also increases. But, when w_{wg} ≥ 500 nm, the variation of the optimal confinement under different w_{wg} is little. The calculation results provide the principle to select the proper w_{wg} for the confinement of light in slot region on the basis of the practical condition.
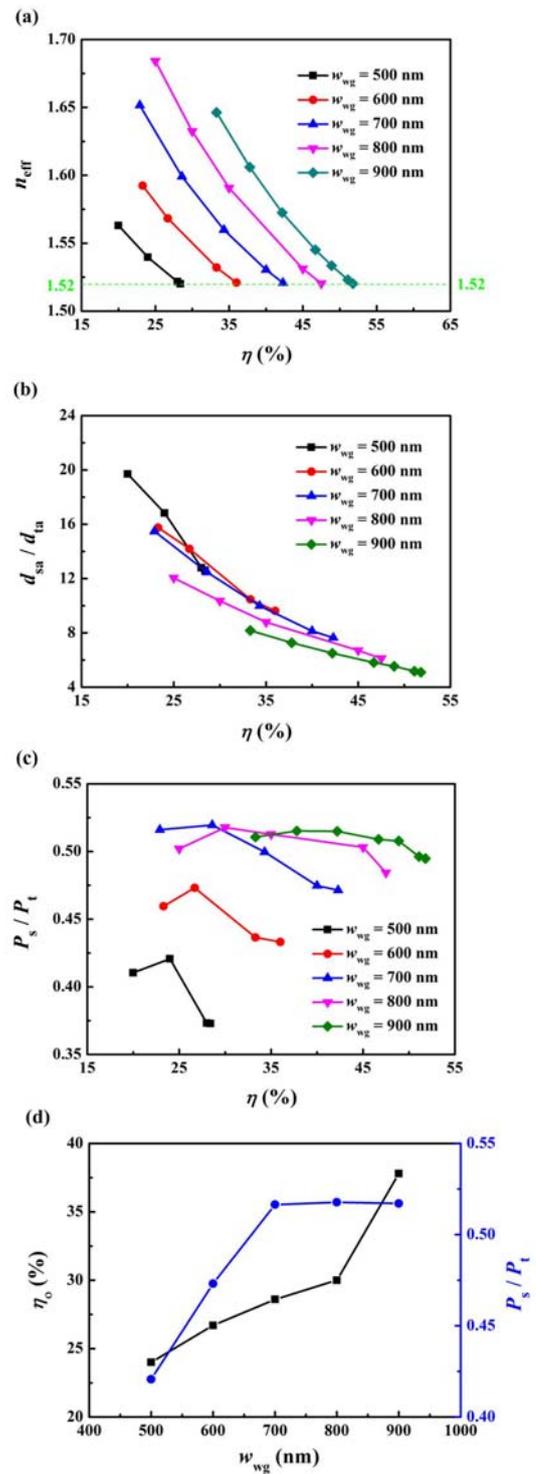
Fig. 6. The n_{eff} (a), d_{sa} / d_{ta} (b) and P_s / P_t (c) under various η with different w_{wg} (500 nm ~ 900 nm) at λ = 2 μm. (d) The η_o (black, square) and the corresponding P_s / P_t (blue, circle) under various w_{wg} at λ = 2 μm.

The previous simulation and discussion focus mainly $\lambda = 1.5$ μm. Next, the case of $\lambda = 2$ μm would be investigated, where $n_{Si} = 3.45$ and $n_{SiO2} = 1.52$ [22]. Fig. 6(a) is the effective refractive index (n_{eff}) of slot waveguide under various η and w_{wg}. The maximum η is $\eta_m = 28.4\%$, 36.0%, 42.3%, 47.5%, and 51.8% for $w_{wg} = 500$ nm, 600nm, 700 nm, 800 nm, and 900 nm, respectively. Fig. 6(b) and (c) are the d_{sa} / d_{ta} and P_s / P_t under various η with different w_{wg} at $\lambda = 2$ μm, respectively. Similar to the previous results, as η increases, d_{sa} / d_{ta} decreases. There is an optimal value of η to realize the greatest confinement of light for each w_{wg}, and this value is $\eta_o = 24\%$, 26.7%, 28.6%, 30%, and 37.8% for $w_{wg} = 500$ nm, 600 nm, 700 nm, 800 nm, and 900 nm, respectively. And the corresponding maximum value of P_s / P_t is 0.42, 0.47, 0.52, 0.52, and 0.52, respectively. Fig. 6(d) shows η_o and the corresponding optimal P_s / P_t under various w_{wg}. As w_{wg} increases, the optimal P_s / P_t increases, and when $w_{wg} \geq 700$ nm, the optimal confinement varies little, which is similar to the case of $\lambda = 1.5$ μm.
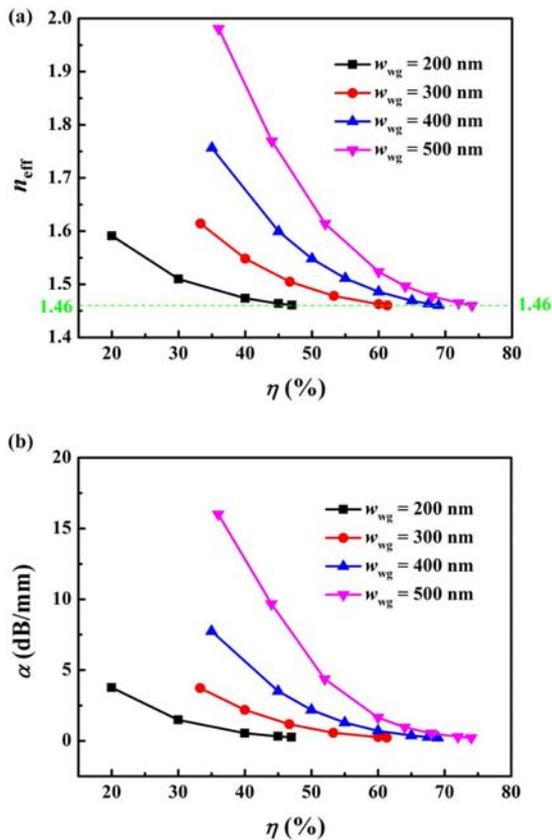
Then, the case of $\lambda = 1$ μm is investigated. At $\lambda = 1$ μm, $n_{SiO2} = 1.46$ [22]. It must be noted that $n_{Si} = 3.60 + 0.0004i$, that is the refractive index of silicon is complex [22]. The real part represents the refractive index of silicon material and the imaginary part decides the absorption of silicon material. This is different with the cases of $\lambda = 1.5$ μm and 2 μm, where the absorption of silicon material can be ignored. The absorption loss rate of silicon material can be calculated by

$$\alpha_{silicon} = \frac{40\pi k \lg e}{\lambda} \qquad (4)$$

in which, e is natural constant and k is the imaginary part of the complex refractive index of silicon. Here, $\lambda = 1$ μm, $\alpha_{silicon} = 22$ dB/mm and this loss is too high for the application of transmission. However, according to Ref [23], slot waveguide could transmit the light within the high absorption wavelength range. Similarly, the complex effective refractive index of slot waveguide calculated by FEM is $n_{slot} = n_{eff} + k_{slot}*i$, in which n_{eff} is the effective refractive index and k_{slot} decides the transmission loss rate of slot waveguide. The transmission loss rate α can be expressed as

$$\alpha = \frac{40\pi k_{slot} \lg e}{\lambda} \qquad (5)$$

Fig. 7(a) and (b) show the effective refractive index (n_{eff}) and the transmission loss rate (α) of slot waveguide, respectively. The maximum value of η is $\eta_m = 47.0\%$, 61.3%, 69.0%, and 74.1% for $w_{wg} = 200$ nm, 300nm, 400 nm, and 500 nm, respectively. As shown in Fig. 7(b), as η increases, α decreases, and the minimum value of α is 0.26 dB/mm, 0.22 dB/mm, 0.21 dB/mm, and 0.21 dB/mm.

Fig. 8(a) and (b) show the d_{sa} / d_{ta} and P_s / P_t under various η with different w_{wg} at $\lambda = 1$ μm, respectively. Also, as η increases, d_{sa} / d_{ta} decreases. For P_s / P_t, there is also an optimal η for each w_{wg}, and this value is $\eta_o = 30\%$, 40%, 50%, and 60% for $w_{wg} = 200$ nm, 300 nm, 400 nm, and 500 nm, respectively. The corresponding optimal value of P_s / P_t is 0.43, 0.59, 0.57, and 0.55, respectively. Fig. 8(c) shows the optimal P_s / P_t and the transmission loss rate of slot waveguide when $\eta = \eta_o$ under various w_{wg}. With $\eta = \eta_o$, $\alpha = 1.48$ dB/mm, 2.19 dB/mm, 2.18 dB/mm, and 1.64 dB/mm for $w_{wg} = 200$ nm, 300 nm, 400 nm, and 500 nm, respectively. It must be noted that when $\eta = \eta_m$, the transmission loss of slot waveguide is minimum, and when $\eta = \eta_o$, the confinement of light is optimal. So, at $\lambda = 1$ μm the minimum α and the optimal P_s / P_t can not be realized together by designing the structure of slot waveguide. In practical application, to design the structure of silicon slot waveguide operating at the material high absorption wavelength, the transmission loss and the confinement of light should be both considered.

Fig. 7. (a) The n_{eff} under various η with different w_{wg} (200 nm ~ 500 nm) at $\lambda = 1$ μm. (b) The transmission loss (α) of slot waveguide under various η with different w_{wg} (200 nm ~ 500 nm) at $\lambda = 1$ μm.
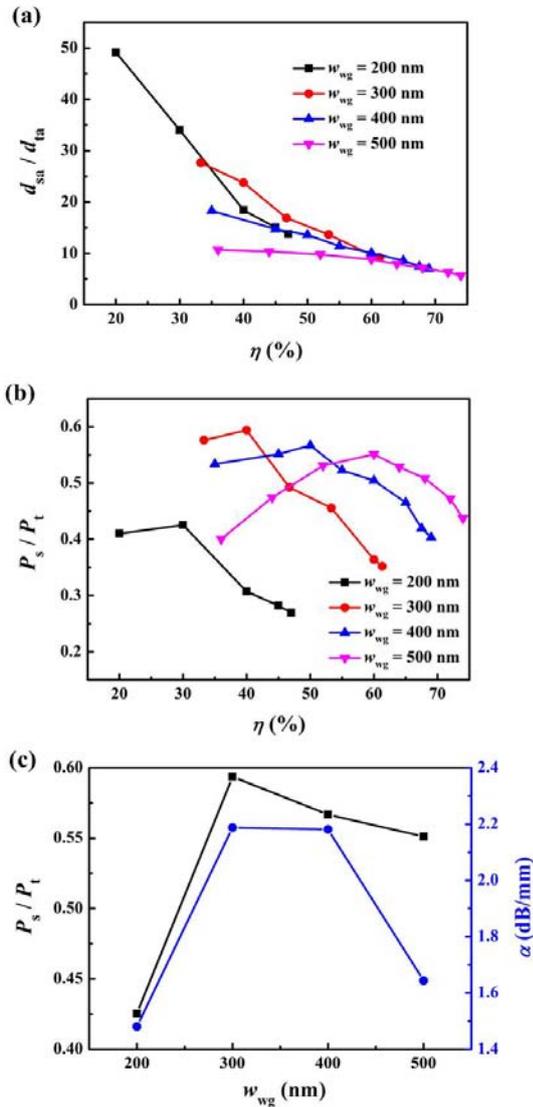
Fig. 8. The d_{sa} / d_{ta} (a) and P_s / P_t (b) under various η with different w_{wg} (200 nm ~ 500 nm) at λ = 1 μm. (c) The P_s / P_t (black, square) and α (blue, circle) when η = $η_o$ under various w_{wg} at λ = 1 μm.

4. Conclusions

The confinement of light in silicon slot waveguide, characterized by P_s / P_t, is investigated within the wavelength range of 1 μm ~ 2 μm. For the confinement of light, there is an optimal value for duty cycle factor with a certain waveguide width. The simulation results and analysis provide the principle to select the proper structure of silicon slot waveguide for the confinement of light in slot region, which is important in many applications. Moreover, the transmission loss and the confinement of light should be both considered, when the structure of silicon slot waveguide operating at the material high absorption wavelength is designed.

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