

# Polarization-independent grating coupler based on silicon-on-insulator

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A novel and simple polarization independent grating couplers is designed and analyzed here, in which the TE polarization and the TM polarization light can be simultaneously coupled into a silicon waveguide along the same direction with high coupling efficiency. For the polarization-insensitive grating coupler, the coupling efficiencies of two orthogonal polarizations light are more than 60% at 1550 nm wavelength based on our optimized design parameters including grating period, etching height, filling factor, and so on. For TE mode the maximum efficiency is ~72% with more than 30 nm 1 dB bandwidth, simultaneously, for TM mode the maximum efficiency is 75.15% with 40 nm 1 dB bandwidth. Their corresponding wavelength difference between two polarizations' coupling peaks is demonstrated to be 35 nm. Polarization independent grating coupler designed here can be widely used in optical communication and optical information processing.

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In optical circuit, high efficiency compact couplers are in great demand due to the significant challenge of low power loss and high integration density. A conventional coupling method such as prism is difficult to alignment. Silicon-on-insulator (SOI) is an attractive photonic platform due to its high refraction-index contrast as well as intrinsic compatibility with the complementary metal-oxide semiconductor (COMS) and their integration potential<sup>[1]</sup>. Various kinds of devices on SOI wafers have been demonstrated in recent years using nanophotonics wire waveguides which have cross-sectional dimensions of only a few hundred nanometers. For example, Nitride grating coupler<sup>[2]</sup>, a peak coupling efficiency of  $-5.1$  dB and 60 nm 1 dB bandwidth is reported. A binary blazed grating coupler<sup>[3]</sup> with coupling efficiency of as high as 69% at a wavelength of 1.52  $\mu\text{m}$  and 65% at a wavelength of 1.55  $\mu\text{m}$  is calculated by using a formula method to design and optimize their corresponding parameters. A high efficiency grating coupler between single-mode fiber and SOI waveguide<sup>[4]</sup> can obtain over 78.5% coupling efficiency ( $\geq 1.05$  dB) with 3 dB bandwidth about 50 nm in experiment. In order to solve the problem of waveguide and fiber model mismatch and the poor directionality (defined as the portion of the light power coupled upwards normalized with respect to the total out-couple optical power)<sup>[5]</sup>, more and more methods are put forward, for example a distributed Bragg reflector<sup>[6]</sup>, a metal layer as a perfect mirror<sup>[7]</sup>, and end fiber coupling techniques with adiabatic tapers<sup>[8]</sup>, and so on. Depend on these design methods, some structures provide a directionality upward exceeding 95% and

coupling efficiency of  $\sim -1.05$  dB with a 1 dB bandwidth of 30 nm and minimum feature size of 100 nm<sup>[8]</sup>.

However, it is well known that photonic integrated devices based on SOI nanowires are usually severely polarization-sensitive due to the large refraction index contrast (the huge structural birefringence), although it is often possible to diminish the polarization independence for some components by using approaches that usually require a critical control for the waveguide dimension. This is especially relevant for grating couplers, where the radiation angle and coupling efficiency strongly depend on the polarization. For that reason grating couplers are usually optimized for TE or TM polarizations. Thus, all of the above designs focus a single polarization because of different boundary conditions for TE. For distinguish effective refractive index, coupling light into the same waveguide for individual polarization at the same time is difficult. Thus polarization sensitive grating limits many applications in practice. The polarization beam splitter (PBS) appears to solve the problem of both polarizations coupling simultaneously. A 1D grating serving both as a PBS and a vertical coupler for silicon photonic circuits is designed, fabricated, and characterized provide over 50% efficiency for both polarizations in experiment<sup>[9]</sup>. Using polarization diffraction gratings as PBSs can separate the output into two non-orthonormal polarization states<sup>[10]</sup>. All of these structures are dependent on grating polarization sensibility, which would limit many practical applications of silicon. Using multilevel grating structure<sup>[11]</sup> can realize coupling when the beams with

TE polarization and TM polarization are incident at the same time. The coupling efficiencies of the incident TE and TM modes are 49.9% and 49.5% at the wavelength of 1565 nm, and the difference between them is only 0.4%. Nowadays, many grating couplers<sup>[12–15]</sup> that are insensitive to polarizations were introduced. But these structures are difficult to manufacture. Cheng *et al.* present air-cladding apodized focusing subwavelengths grating<sup>[12]</sup> that can effectively couple two polarizations into a single waveguide, but their design performance was complicated and hard to integrate with other photonic devices. The coupling efficiencies for two polarizations are less than 50%. In their previous work<sup>[13]</sup> introduce a novel structure which realized a polarization-independent grating. In the traditional 1D grating, TE effective index is larger than that of TM mode. By allowing effective medium theory (EMT) at the second-order to change the size of 2D grating can made the TE mode effective index equal to that of TM to realize a polarization-insensitive structure. 2D structure is more difficult to realize in existing technology, comparing with 1D structure. Due to technology limit, it is a potential challenge for this 2D structure to realize grating coupler operations and obtain high coupling efficiency. And grating couplers has many others structure and applications<sup>[16–18]</sup>.

In this Letter, we design a novel 1D grating coupler can efficiently and simultaneously couple two polarizations into a single waveguide with more than 60% coupling efficiency at the wavelength of 1560 nm. We apply the different effective refractive index  $N_{\text{eff}}$  and different diffractive order between TE polarization and TM polarization to couple different modes into waveguide simultaneously under some values of the grating.

The polarization-insensitive grating was designed and fabricated on a SOI wafer that has a 460 nm thick top silicon layer ( $H$ ) and 2.0  $\mu\text{m}$  buried oxide (BOX) as shown in Fig. 1. Obviously, polarization independent grating couplers can effectively eliminate the influence of polarization in experiment which results in both of the TE and TM light can be coupled simultaneously into silicon waveguide and transmit along the same directions.

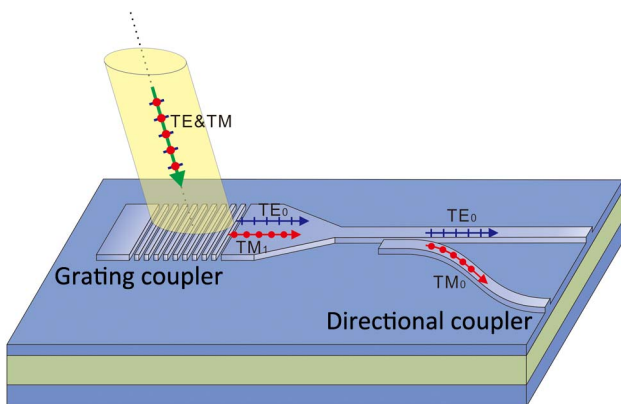


Fig. 1. Polarization-insensitive grating coupler based on SOI.

With the different thickness of SOI waveguide, the effective refractive index's difference for TE mode and TM mode is different as shown in Fig. 2 in which the effective refractive index is as a function of waveguide thickness. Up to date, most papers only consider fundamental mode for coupling, such as double-structure, bidirectional and polarization-independent subwavelength grating beam splitter<sup>[5]</sup>, and so on. However, in practice there are the high order modes transmitting in a SOI waveguides based on the feature size of waveguide including thickness and width. The thickness of waveguide is another factor influence on the number of  $N_{\text{eff}}$ , with

$$\begin{aligned} & (n_w^2 - N_{\text{eff}}^2)^{1/2} \cdot \frac{2\pi}{\lambda} a \\ & = m\pi + \tan^{-1} \left[ C_1 \cdot \left( \frac{N_{\text{eff}}^2 - n_c^2}{n_w^2 - N_{\text{eff}}^2} \right)^{1/2} \right] \\ & \quad + \tan^{-1} \left[ C_2 \cdot \left( \frac{N_{\text{eff}}^2 - n_s^2}{n_w^2 - N_{\text{eff}}^2} \right)^{1/2} \right] \\ & \begin{cases} C_1 = C_2 = 1 & (\text{TE mod } e) \\ C_1 = (n_w/n_c)^2; C_2 = (n_w/n_s)^2 & (\text{TM mod } e) \end{cases}, \quad (1) \end{aligned}$$

where  $n_c$ ,  $n_w$ ,  $n_s$  is the refractive indices of air, Si and SiO<sub>2</sub>. Furthermore, when  $n_c = 1$ ,  $n_w = 3.5$ ,  $n_s = 1.5$ , Fig. 2 reveals the difference of the effective refractive index between TE and TM mode. It is noted that TE<sub>0</sub> and TM<sub>1</sub> is 1.7 when the 460 nm thickness of Si waveguide is selected. Now we consider the coupling of TE<sub>0</sub> and TM<sub>1</sub> mode based on the following designs.

According to the phase match condition between the gratings and the waveguide mode<sup>[19]</sup>, the grating period, denoted  $T$ , should be

$$T(N_{\text{eff}} + \sin \theta) = m\lambda, \quad m = 0, \pm 1, \pm 2, \dots, \quad (2)$$

where  $\theta$  is the incidence angle,  $m$  is the diffractive order.

Therefore, we consider TE<sub>0</sub> mode and TM<sub>1</sub> mode with normal incidence, and set  $m = 2$  and 1, respectively.

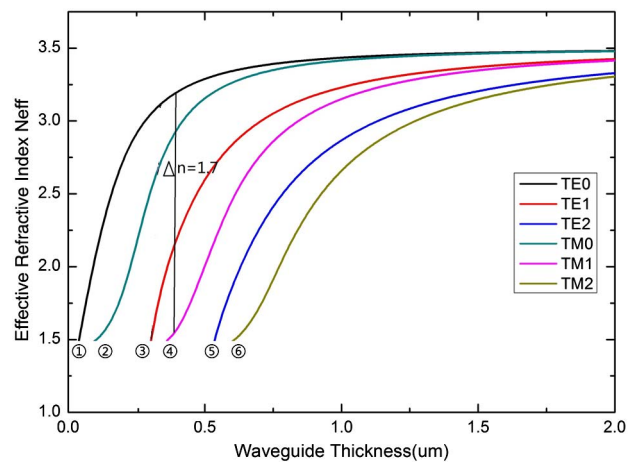


Fig. 2. Effective refractive index as a function of waveguide thickness.

When  $\Delta N_{\text{eff}} = \frac{\lambda}{T} = 1.7$ , the different polarization light can couple into a single waveguide at the same time according to the above phase match equation. As reported in the picture, there are four modes ( $\text{TE}_0$ ,  $\text{TM}_0$ ,  $\text{TE}_1$ ,  $\text{TM}_1$ ) in the waveguide when the waveguide thickness is 460 nm. However only  $\text{TE}_0$  and  $\text{TM}_1$  mode can fulfill with the phase match condition based on the same grating parameters. That is to say, we can design only a grating coupler to realize  $\text{TE}_0$  and  $\text{TM}_1$  mode coupling simultaneously. However, generally it is not desirable to couple power in a first order mode due to large transmission loss. In order to decrease the loss of  $\text{TM}_1$  when the light is coupled from fiber to waveguide, the light for  $\text{TM}_1$  mode can be transferred to the fundamental  $\text{TM}_0$  mode by directional coupler with changing the size of waveguide according to Refs. [20–22]. Moreover, there is almost no influence on the launched  $\text{TE}_0$  mode due to the significant phase mismatching<sup>[19]</sup>. Consequently, by this method we can not only decrease the loss of power, but also improve the coupling efficiency of both orthogonal polarization modes. In other words, polarization independent grating coupler designed here can simultaneously realize high effective coupling and low loss mode changing.

Now, the grating filling factor (filling factor  $f = w/T$ , where  $w$  is the wide of the ridge,  $T$  is the period of grating) can be calculated by using

$$N_{\text{eff}} = \begin{cases} \sqrt{fn_1^2 + (1-f)n_2^2} & (\text{TE mod } e) \\ \sqrt{\frac{1}{\frac{f}{n_1^2} + \frac{(1-f)}{n_2^2}}} & (\text{TM mod } e), \end{cases} \quad (3)$$

$$\sqrt{fn_1^2 + (1-f)n_2^2} - \sqrt{\frac{1}{\frac{f}{n_1^2} + \frac{(1-f)}{n_2^2}}} = \frac{\lambda}{T}, \quad (4)$$

where  $n_1$  and  $n_2$  are refractive indices of Si and air. We set incident wavelength is 1550 nm,  $T = 911$  nm,  $f = 0.67$ , incident angle  $\theta = 11^\circ$  at first calculated by Eqs. (2), (3) and (4). The FDTD method is utilized to simulate and design the grating coupler operated under TE and TM polarization.

Figure 3 shows the simulated results to design an appropriate grating coupler with coupling efficiency as a function of filling factor.

The red curve represents the drop of coupling efficiency for TM polarization with the increment of filling factor. In contrast to it, TE mode coupling efficiency rises with the range of 0.6–0.8. Obviously when  $f = 0.75$ , at wavelength of  $\lambda = 1550$  nm, etching height  $H = 160$  nm, incidence angle  $\theta = 11^\circ$ , and grating period  $T = 911$  nm, there are approximated coupling efficiency about 45% for TE and TM mode. Because of different range trend of two polarizations in the picture, we must choice the other point to optimize our design. That is to say, two curves have a cross point as shown in Fig. 3. Furthermore, the grating coupler design here is optimized. When we choose the fill factor  $f = 0.65$  with  $T$  changing from 900 to

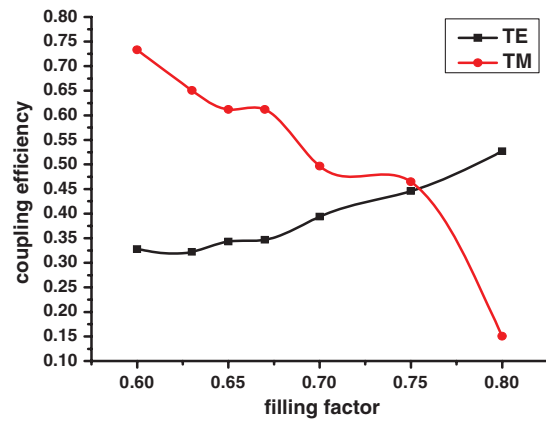


Fig. 3. Coupling efficiency as a function of filling factor.

940 nm, keeping others parameters constant, and we get the relation between coupling efficiency and period as shown in Fig. 4.

As shown in Fig. 4, when  $T = 920$  nm, both the coupling efficiency of TE and TM mode are about 55%. The coupling efficiency of the curve is improved 10%. The dynamic trend of light for different polarization is different with the variation of grating period  $T$ . Obviously, the grating period significantly affect the coupling efficiency for TM and TE polarization because the effective refractive index is sharply varied with the change of period.

The etching height also plays an important role to affect the coupling efficiency of grating. We further discuss the relation between  $H$  and coupling efficiency as shown in the Fig. 5, in which from 120 to 180 nm, the fluctuant value of coupling efficiency for both curve is rather stable, and only 10% ranged from 40% to 50%. Thus  $H = 160$  nm is optimal parameter for this structure, and has  $\pm 20$  nm design tolerance which is convenient to fabricate.

According to the Figs. 4 and 5, to improve the point of intersection of coupling efficiency more high, we choose the period of 930 nm which is not the point of intersection of Fig. 4. When grating period  $T$  is 930 nm, the etching

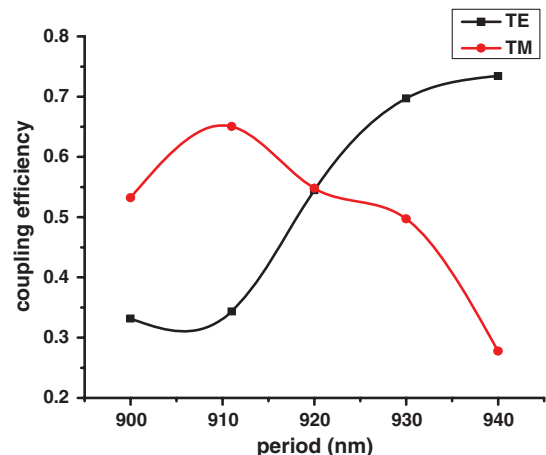


Fig. 4. Coupling efficiency as a function of period.

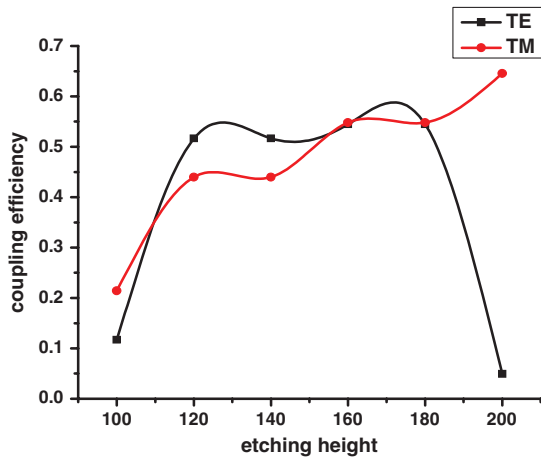


Fig. 5. Coupling efficiency as a function of etching height.

height  $H = 160$  nm, we change incidence angle  $\theta$  from  $7^\circ$  to  $12^\circ$  and wavelength from 1520 to 1610 nm, we plot the following curve which represents coupling efficiency as a function of wavelength and incident angle.

Figure 6 shows that the wavelength difference between coupling peaks of two polarizations is improved with the angle increasing. By contraries coupling efficiency difference for TE and TM mode is decreased. The minimum wavelength difference between coupling peaks of two polarizations is  $\sim 20$  nm for  $7^\circ$  incidence angle. For TE mode maximum efficiency is 43.64%, but maximum efficiency of TM mode is 77.91%. The performance of TE mode is more sensitive to angle than that of TM mode. When the incidence angle is around  $\theta = 11^\circ$ , this offers a nearly equal coupling efficiency as high as 63%. In other words, TE mode and TM mode can achieve common coupling result at the same condition including grating period, etching height, incidence angle, etc. Their corresponding wavelength difference between two polarizations' coupling peaks is demonstrated to be 30 nm as shown in Fig. 7.

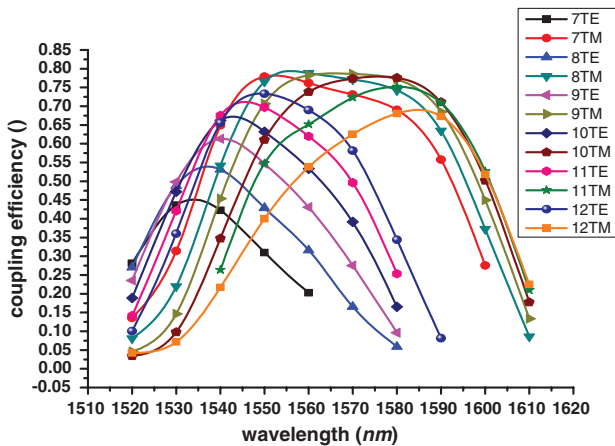


Fig. 6. Coupling efficiency as a function of wavelength and angle.

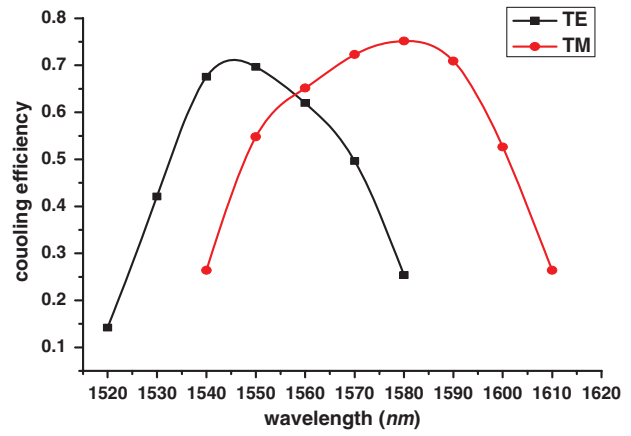


Fig. 7. Compare with coupling efficiency and wavelength for TE and TM mode.

We also calculate the polarization dependent loss (PDL) which is determined by

$$\text{PDL} = 10 \times \log \left| \frac{\varphi_{\text{TE}}}{\varphi_{\text{TM}}} \right|,$$

where  $\varphi_{\text{TE}}$  and  $\varphi_{\text{TM}}$  is coupling efficiency of TE and TM mode. According to Fig. 7, when  $\lambda \approx 1560$  nm,  $\text{PDL} \approx 0$ , our structure is a completely polarization independent grating coupler, which both of TE and TM mode are coupled simultaneously based on the same grating parameters including period, etching depth, incident angle, and filling factor. Table 1 shows the optimized design parameters. As the incident angle varies from  $7^\circ$  to  $12^\circ$ , the maximum coupling efficiency of TE mode is  $\sim 72\%$  at the wavelength of 1550 nm, however  $\sim 78\%$  for TM mode at wavelength of 1550 nm. Thus, besides to design polarization independent grating coupler above discussed, we can also obtain a high performance TE or TM mode grating coupler only to control the incident angle of TE or TM and without changing grating structure.

The Figures 8(a) and 8(b) is TE mode and TM mode optical field distribution at the wavelength of 1.560  $\mu\text{m}$ . Obviously, two polarization incident lights are simultaneously coupled into the same direction based on polarization independent grating coupler.

In conclusion, we demonstrate high-efficiency non-polarization grating couplers on 460 nm top silicon SOI wafer. We use FDTD method to optimize the grating, in which TE polarization and TM polarization incident light can be coupled into a silicon waveguide at the same time. At 1550 nm wavelength, the coupling efficiency of the polarization-insensitive grating is more than 60%.

Table 1. Optimized Design Parameters (Unit:  $\mu\text{m}$ )

Parameters	$\lambda$	$T$	$H$	$f$	$\theta$
Value	1.56	0.93	0.16	0.65	$11^\circ$

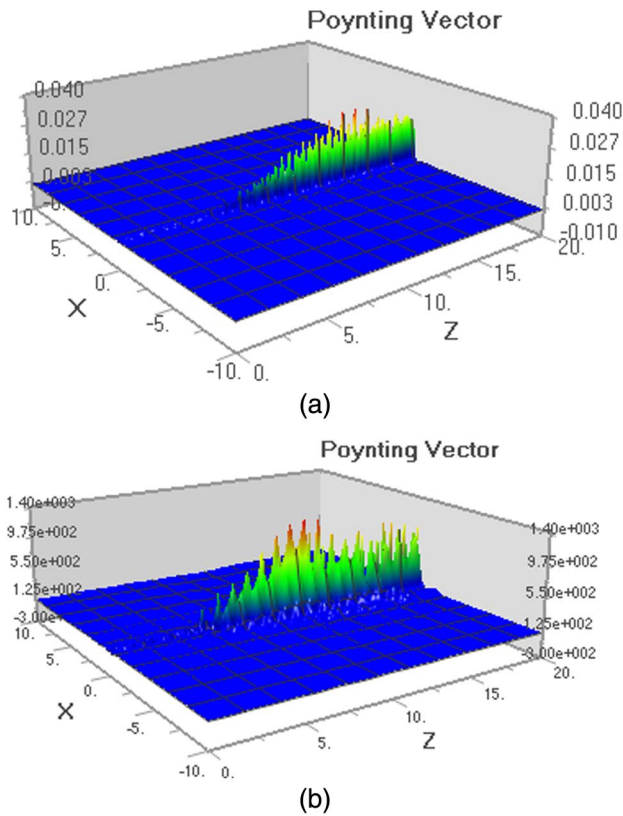


Fig. 8. Optical field distributions at the wavelength of  $1.56 \mu\text{m}$  for (a) TE mode and (b) TM mode.

For TE mode the maximum efficiency is 69.69% with more than 30 nm 1 dB bandwidth, and the maximum efficiency of TM mode is 75.15% with 40 nm 1 dB bandwidth. The wavelength difference between two polarizations' coupling peaks is demonstrated to be 30 nm.

The theoretical results are in good agreement with simulation results. Polarization independent grating coupler is compact in structure, efficient in performance, and insensitive to polarization. Because of the mature fabrication process suitable for mass production of the etched silicon grating as a coupler, it is easy to realize large-scale integration with other photo electronic elements. Further analysis and the relative experimental works will be summarized in our next study.

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