Way of designing a periodic grating coupler with fully etched slots

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In order to couple into or out of a silicon photonic waveguide on silicon on insulator (SOI) substrate from optical fibers, we present a simple but practical method to design a grating coupler. The grating is periodic with fully etched slots; strong reflection between the fully etched grating and the waveguide is avoided by adding an antireflection interface. Theoretical coupling efficiency up to 43% is demonstrated. A taper waveguide used to link the grating and waveguide is also designed.

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Silicon photonics hold great promise for the creation of highly integrated photonic circuits. Since silicon is transparent at wavelengths typically used in telecommunications (1 310 and 1 550 nm), the silicon on insulator (SOI) technology is suitable for photonics and compatible to complementary metal oxide semiconductor (CMOS) technology[1,2]. The high refractive index contrast between silicon and silica permits strong confinement of light, thus enabling small bending radii and strong light-matter interaction. Furthermore, this material choice allows optical and electrical components to be fabricated on a single chip. However, the high effective refractive index and small mode dimensions of single mode silicon waveguides make fiber coupling challenging.

A technique widely used is butt coupling; this method is straight forward, where the light beam coming from fiber is focused into the silicon waveguide at the edge of a chip[3]. The high demand on the alignment of the system to focus the beam directly on the facet of such a small waveguide is difficult to fulfill. And the light can only be coupled into the nanostructure at the edges. Another method is the taper coupler[4]. This method is for compact mode conversion. Apart from the fact that coupling is also done into or out of a cleaved edge of a chip, exact cleaving alignment is necessary or additional waveguide deposition is required. Using the prism coupler to couple light into the waveguide is another technique, but this technique is difficult to achieve high accuracy[3].

The grating coupler where periodic perturbations of the waveguide's refractive index leads to couple the propagating light into or out of the waveguide, holds big advantage which is that one is not limited to couple light at the edges. This enables testing devices anywhere on a chip.

A lot of grating couplers with shallow or slanted etched slots into the waveguide or cladding have been proposed[5,6]. Such gratings have the advantage that coupling between the waveguide and the grating occurs with little reflection and the etched slots radiate efficiently. However, a significant drawback, for instance, of such shallow etched gratings is the additional lithography step. There are also many grating couplers with subwavelength microstructure have been proposed[7], but such gratings possess complicated structure which is difficult to design and fabricate.

In this letter, a method of designing a periodic grating-to-fiber coupler with fully etched slots is proposed, thus permitting the fabrication completed in a single lithography step.

Which angle θ should an optical fiber be set to the normal direction of a grating? If θ is too large, on account of the mechanical constraints, the fiber core will be comparatively far away from the grating, thus the beam divergence will limit the coupling efficiency. On the other hand, if θ is too small, the reflection between the fiber and the grating of the beam would be strong. So we chose the incident angle θ equivalent to 10°, which is widely recognized by researchers the relatively optimized angle[8].

In order to couple the beam coming from the titled fiber to the grating on chip surface, one condition must be satisfied; the **k** vector of the beam in the x direction should match the **k** vector of the grating Bloch mode. For specification, because the geometrical structure size of the grating is subwavelength so we consider the grating as one-dimensional (1D) photonic crystal[9].

In the following, we will describe our designing method by introducing specified parameters; it is easy to apply the method to general cases.

In our case, see Fig. 1, the height of the silicon slab waveguide is h=260 nm, on top of it is covered by air, under the bottom of it is a silica BOX layer with thickness d=2 μm. A silicon substrate below the BOX caters for mechanical stability. The refractive index of silicon $n_1 = 3.48$, refractive index of silica $n_2 = 1.45$, refractive index of air $n_3 = 1$. The operating free space wavelength is λ=1 550 nm.

We carry out full wave simulations using COMSOL Multiphysics/RF module based on partial differential equations (PDEs). We select two-dismensional (2D) space dimension, draw one element of the 1D photonic crystal (or grating) as depicting in Fig. 2(a), and select eigenfrequency analysis. The boundaries of left and right are set to be Floquet periodicity, and the **k** vector for Floquet periodicity is set to be $(\sin\theta \cdot 2\pi/\lambda,\ 0)$, where

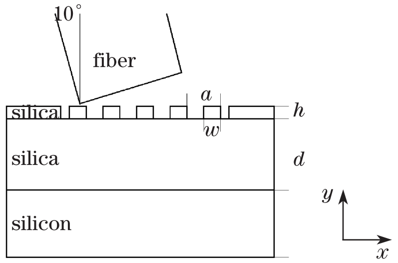
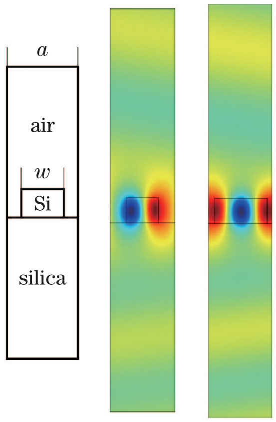


Fig. 1. Schematic representation of the grating coupler. Light is coming from the fiber and coupled into grating then propagates to silicon slab waveguide.



(a) (b) (c)

Fig. 2. (Color online) Representation of searching for a and w. (a) Geometry objects for draw mode, (b) postprocessing mode for a=680 nm, w=334 nm, f=1.937972×10^{14} Hz, (c) postprocessing mode for a=650 nm, w=538 nm, f=1.93565×10^{14} Hz. The predefined quantity presented in (b) and (c) is the z component of electric field. f is the searched eigenvalue, and the desired eigenvalue is f=1.93548×10^{14} Hz.

θ is equivalent to 10°. We should search for eigenvalues around c/λ Hz, where $c = 3 \times 10^8$ m/s is the velocity of light in free space. With all of these preparations, the next procedure is to modulate the period of the grating a and the width of the silicon bar w, until we find the desired eigenvalue. Figures look like Figs. 2(b) and 2(c) are supposed to generate.

According to our experience, the period of the grating a should be set to be around half of the wavelength. For subwavelength grating, there is not diffraction except zero order based on the grating equation $d \sin\theta = n\lambda, n = 0, 1, 2, \cdots$, so that we consider it as photonic crystal[10]. It is proved that the proper period a should be around half of the wavelength, in which case we achieve the highest coupling efficiency[11]. When you work on this subject you can explore several different periods, search for each of them the matched width of the silicon bar w, calculate the coupling efficiency roughly, and then pick out the most appropriate one.

It is worth to mention that when the fill factor (w/a) is around 50% a large proportion of the light coupled into grating will propagate in the opposite direction to the excitation mode (see Fig. 3(a)); while when the fill factor is around 80% the light coupled into grating mostly propagates in accordance with the direction of the excitation mode (see Fig. 3(b))[12]. This phenomenon can be explained reasonably by referring to the band diagram of the photonic crystal, or you can assume that in the first case the effective refractive index of grating is negative yet the latter is positive[9]. Coupling efficiency of each case does not differ much from each other (see Table 2), and you can choose either of the two design proposal based on the fabrication technology you have access to.

In our case, the parameters of the designed grating are given in Table 1

Coupling from a Bloch mode directly into a slab mode, strong reflection will occur on the interface. To overcome this problem we decline the width of the slot between grating and silicon slab waveguide by half compared to the slots inner grating. In this way, reflection on the interface decreases remarkablely. The theoretical explanation is obvious. Narrow slot presents high effective refractive index which is closer to the silicon slab waveguide's, so that reflection turns to be weaker[9]. Figure 3 shows the design of the antireflection layer; it's marked with circles in the figure. Nevertheless, at the other end of the grating, we do not expect to loss optical energy there so we need to gain reflection on that interface, the width of the slot there is relatively larger[9]. Please refer to Fig. 3 for visual image.

Just for the friendly record, to guarantee the accuracy of the simulation results, never forget to add perfect matched layer (PML) condition when you carry out simulation with COMSOL.

Now the reflection problem on grating-waveguide interface has been solved, we list the optimized parameters of the designed grating in Table 2.

Compared with some reported figures of merit for fiber to TE mode silicon waveguide grating couplers at 1 550 nm: Ref. [13] needed 4 steps of process, used 70-nm timed etch, and got simulated coupling efficiency of 42%; Ref. [14] needed 4 steps of process, used 70-nm timed etch, and got simulated coupling efficiency of 44%; Ref. [15] needed 8 steps of process, used epitaxial silicon overlay, and got simulated efficiency of 66%. Our work with single lithography step, simple structure of 1D periodic grating and simple and practicable designing method, gets simulated coupling efficiency of 43%.

If the side walls of waveguide are deviated from the straightforward direction, light will be reflected on them. Figure 4 shows the transmission efficiency depending on the slant degree of the side walls of taper waveguide.

Table 1 Grating Parameters for Wavelength of 1.55 μm

Propagation Direction	a (nm)	w (nm)	θ (deg.)
Backward	680	334	10
Forward	650	538	10

Table 2 Optimized Parameters of Grating for Wavelength of 1.55 μm

Propagation Direction	Width of Left End Slot (nm)	Width of Right End Slot (nm)	Coupling Efficiency (%)
Backward	150	340	37
Forward	100	100	43

The coupling efficiency is calculated by the power flow coupled into the slab waveguide divide the incident power flow.

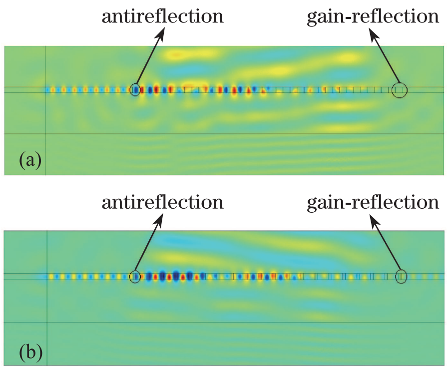


Fig. 3. (Color online) Plots of simulation results for designed grating couplers. (a) Excitation mode and coupled mode goes in opposite directions; (b) Excitation mode and coupled mode goes in the same direction. The predefined quantity presented in plots is z component of electric field.

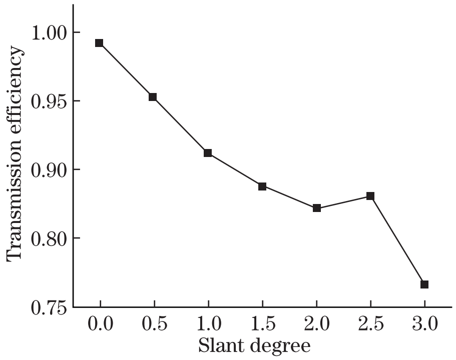


Fig. 4. Transmission efficiency depending on the slant degree of the side walls of taper waveguide.

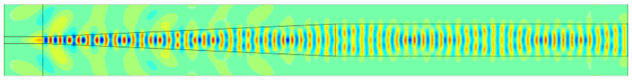


Fig. 5. (Color online) Plot of simulation result for taper waveguide. Slant degree is 2.5°, and length of the taper waveguide is 15 μm. The predefined quantity presented in plots is z component of electric field.

Weighing and considering balance between absorption and reflection loss, we figure out the slant degree would be approximate 2.5°. Figure 5 shows the electric field distribution when electromagnetic wave propagates in taper waveguide.

In conclusion, we present the design of a fiber-to-grating coupler with fully etched slots. The fabrication can be completed in a single lithography step, which is advantageous to shallow etched. By matching the in-plane portion of incident light **k** vector with the **k** vector of Bloch mode, we find the period and fill factor of the grating. An antireflection slot is added on the interface between grating and slab waveguide. Taper waveguide with side walls of suitable slant degree is presented. You can design the fiber-to-grating coupler you needed in a simple way, as well achieving the relatively high coupling efficiency.

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