CMOS compatible highly efficient grating couplers with a stair-step blaze profile*

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A novel grating coupler with a stair-step blaze profile is proposed. The coupler is a CMOS process compatible device and can be used for light coupling in optical communication. The blaze profile can be optimized to obtain a high efficiency of 66.7% for the out-of-plane coupling at the centre wavelength of 1595 nm with a 1 dB bandwidth of 41 nm. Five key parameters of the stair-step blaze grating and their effects on the coupling are discussed for the application in L band telecommunication.

Keywords: grating coupler, blaze profile, integrated optics, silicon-on-insulator

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1. Introduction

Silicon-on-insulator (SOI) material, which is compatible with CMOS process technology, can be useful for high-density integration of nanoscale waveguides and nanoscale devices in photonics circuits.[1] However, the photonic integration is still not light efficient. One big roadblock is the large mode mismatch between the nanoscale waveguide and the standard optical fiber, which inherently induces the high insertion loss and leads to the low light efficiency in the integrated optical circuits. Recently, an attractive approach to achieve highly efficient coupling is demonstrated by using grating couplers, such as uniform shallow etched teeth,[2,3] gold bottom reflectors[4] and blazed objects.[5−9] Among them, the blazed grating coupler is a good candidate to achieve high diffraction directionality.[5] For the normal blaze profile, the asymmetrical saw teeth were characterized and fabricated in unibond SOI, which were used for coupling light into the substrate.[6] Several procedures were reported to define this kind of saw teeth like grating.[7,8] However these fabrication processes required specially customized dry etching and were not fully compatible with rectangular optical waveguides. In order to fabricate economically in a CMOS foundry, the binary blazed grating coupler with a 53% coupling efficiency was also theoretically proposed.[9] Although the pillars of the binary blazed grating can be made by the CMOS technology, both the lithographically minimum pitch dimension of less than 30 nm and the rather low fabrication tolerance, which is probably several nanometers, limit its application in low cost integrated technology.

Besides these unfeasible blazed gratings, the stair-step blaze profile is an alternative approximation to the asymmetrical saw teeth profile. The stair-step blaze profile can be patterned by multi-step high resolution lithography, such as electron beam lithography (EBL) and ultra-violet lithography, which are compatible with the standard CMOS technology. The grating with stair-step blaze profile also offers more degrees of design freedom, because more widths, depths and their combinations become designing variables.

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In this paper, a novel grating coupler with CMOS compatible stair-step blaze profile is proposed. Considering the EBL fabrication tolerance, 5 and less levels stair-step blazed gratings are discussed, corresponding to the minimum trench width of more than 100 nm. An eigenmode expansion method is employed to analyze different kinds of stair-step gratings. The characteristics of 5-level stair-step blazed grating are analyzed and the related parameters, such as blaze profile direction, number of stairs, etching depth, blaze angle and width profile, are optimized. It is shown that the grating with stair-step structure is more efficient than the uniform grating structure. As high as 66.7% coupling efficiency at wavelength of 1595 nm and 1 dB bandwidth of 41 nm in L band for optical communication are predicted by the simulation.

2. Device structure

The structure is fabricated on an SOI wafer with a top silicon layer ($n = 3.47$) of 340 nm and a buried oxide ($n = 1.44$) layer of 2 μm. The top confinement layer is defined as air ($n = 1$). A side view of the stair-step blazed grating coupler alone with the two dimensional (2D) model is shown in Fig. 1. A transverse electric (TE) polarization light beam is considered to propagate in the nanoscale waveguide, diffracted by the blazed grating coupler and received by a standard optical fiber with a 10 μm diameter optical mode. The fiber is placed at the top of the grating coupler with a certain tilted angle (∼10°) to the normal of the top silicon layer to avoid the second order reflection. This novel blazed grating coupler is simulated with the CAMFR,[10] a two-dimensional fully vectorial solver based on eigenmode expansion method.

According to the Bragg condition, the period Λ of the 1st order diffraction grating should satisfy $\Lambda \cdot (n_{\text{eff}} - n_1 \cdot \sin \Phi) = \lambda_0$, where n_{eff} is the effective index of the fundamental TE mode, n_1 is the media index of the top overlay, Φ is the tilted angle of the fiber (here Φ is 10°) and λ_0 is the free-space wavelength ranged from 1530 nm to 1650 nm. Considering the mentioned SOI wafer structure and the fundamental mode in the grating area, a grating period of 620 nm is chosen. A 5-level stair-step blazed grating, which is a close approximation to the saw teeth like blaze grating, is schematically shown in Fig. 1(b). It can be clearly seen in Fig. 2 that the input light is scattered up efficiently to the fiber, which is tilted 10° with respect to the substrate normal.

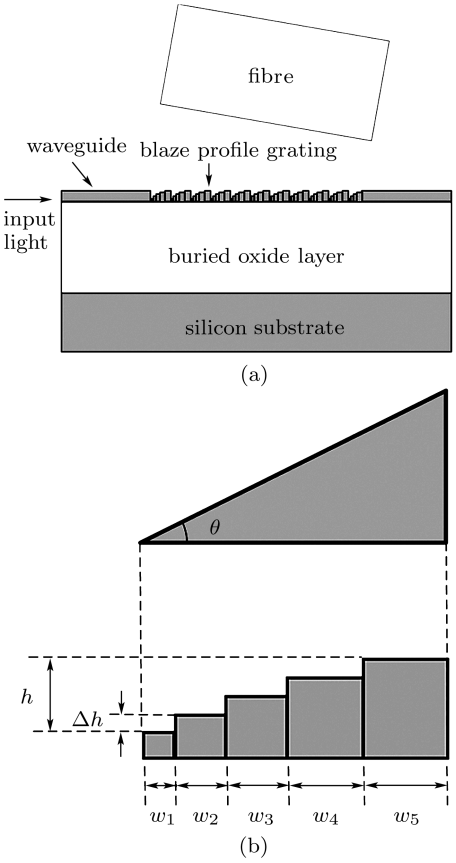


Fig. 1. (a) The schematic diagram of a blazed grating coupler on SOI. (b) The model used for the simulation of the 5-level stair-step blaze grating coupler, whose cross section and effective index profile are similar to the saw teeth like blazed grating coupler. The key parameters are also shown in the plot.

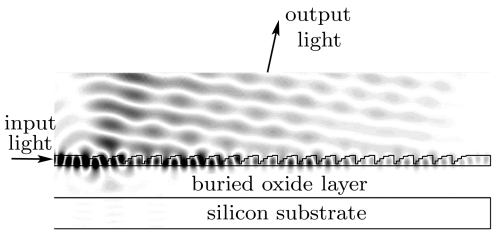


Fig. 2. The electric field plot (the real part of the vertical component of the propagating electric field) of the optimized grating coupler structure reveals that the input light is scattered up efficiently to the fiber, which is tilted 10° with respect to the substrate normal.

3. Simulation and discussion

Since the 5-level blazed grating is more efficient and offers more degrees of design freedom than the

uniform grating for out-of-plane coupling, the coupling efficiency η can be improved by tuning the parameters. The overall coupling efficiency η between a grating coupler and a fiber is mainly determined by three factors as follows:

$$\eta = \eta_1 \cdot \eta_2 \cdot \eta_3. \tag{1}$$

The scattered efficiency η_1, which indicates the ratio of the input optical power in the slab waveguide that is scattered out by the grating and also describes the strength and the scattering ability of the grating, is given by the followed expression:

$$\eta_1 = \frac{P_{\text{scattered}}}{P_{\text{total}}} = 1 - R - T, \tag{2}$$

where $P_{\text{scattered}}$ is the scattered power including the upward and the downward scattering by the grating, P_{total} is the total incident power, R and T are the reflection and the transmission coefficients, respectively.

The η_2 describes the ratio of the upward scattered to the total scattered optical field power by the grating and can be expressed as:

$$\eta_2 = P_{\text{up}}/(P_{\text{up}} + P_{\text{down}}), \tag{3}$$

where P_{up} is the upward scattered power and P_{down} is the downward scattered power. The η_2 is also called the directionality of the grating.

The η_3 represents the overlay efficiency between the upward scatted optical field and the fundamental mode of the fiber, which has been discussed in Ref. [11].

This paper mainly focuses on the optimization of η_1 and η_2. The related parameters, such as the blaze profile direction, the number of stairs, the etching depth, the blaze angle and the width profile of the stair-step grating coupler, are discussed and optimized to achieve high coupling efficiency.

3.1. The blaze profile direction

Comparing with the uniform grating, the stair-step blazed grating is asymmetric in the propagation direction. The grating in one period mainly has two kinds of blaze profile directions. These structures are schematically shown in Fig. 3. For the forward profile, the stair heights increase along the light propagation direction. In the backward profile, the stair heights decrease along the light propagation direction. For more precise comparison, the heights and the widths of the stairs for the gratings are assumed to be the same and then the effective indices of the fundamental modes in the gratings will be the same. It can be seen in Fig. 3 that the coupling efficiency reaches the highest value at the same wavelength, which also supports the former assumption. However the reflection and the transmission features of these gratings are quite different, which may be due to the different Bloch waves propagating in the gratings.[12] The forward profile blazed grating, whose reflection R around the center wavelength is relatively lower, gives higher coupling efficiency. As shown in Fig. 3, another kind of blazed surface profile called combined profile for short is also investigated. The combined profile is a combination of the forward and the backward profiles and shares the same period with the other two. The simulation results show that the combined profile just presents an intermediate state of the forward and the backward profiles and no higher performance is obtained.

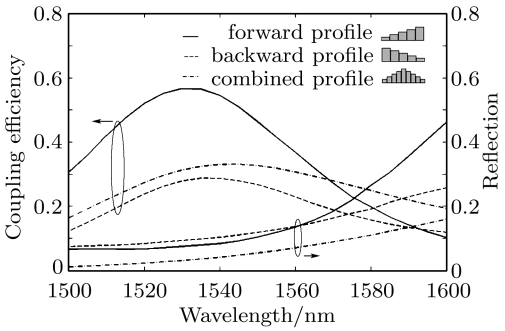


Fig. 3. The coupling efficiency to fiber and the reflection back into the waveguide for different blazed gratings. The schematic blazed grating profiles are shown. The forward profile blazed grating gives higher coupling efficiency, while the combined profile presents an intermediate state of the forward and the backward profiles.

3.2. The number of stairs

As mentioned before, the stair-step blazed grating is a close approximation to the saw teeth like blaze profile and provides a higher coupling efficiency than the uniform grating. Increasing the stair number is the most convenient way to make the approximation more accurate. However, the resolution (∼20 nm) and the tolerance (∼30 nm) of EBL we used limit the stair number of this kind grating to less than five. The 3-level and 5-level stair-step blazed grating couplers (4-level one is not given, whose feature is just between the 3-level and 5-level ones) together with the uniform grating coupler (whose structure is optimized in Ref. [3]) are chosen for comparison. To simplify the simulation, the stairs are defined just by dividing the

height of the top silicon layer and the period of the grating to 3 and 5 parts to form the 3- and the 5-level blazed gratings, respectively. The schematic diagrams and the coupling efficiency curves of the three gratings are shown in Fig. 4. It can be clearly seen that the 5-level stair-step blazed grating is more efficient than the 3-level and the uniform ones. The center wavelength shift between the 3- and the 5-level blazed gratings is induced by their little effective index difference of the fundamental TE mode. The 5-level blazed grating also has more degrees of designing freedom, since more related parameters can be variables. Therefore, later simulations mainly focus on the 5-level stair-step blazed grating coupler.

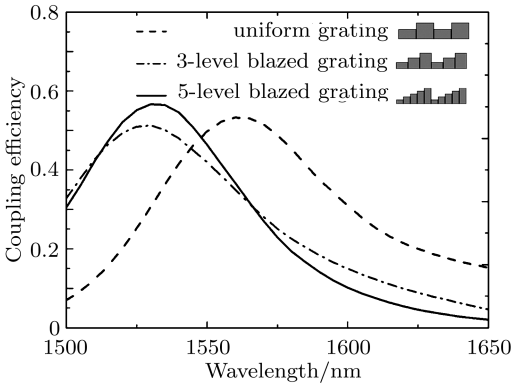


Fig. 4. Comparison of the coupling efficiencies for uniform grating, 3-level stair-step blazed grating (called 3-level blazed grating for short) and 5-level stair-step blazed grating (called 5-level blazed grating for short) couplers. The schematic diagrams of the grating profiles are given. The 5-level stair-step blazed grating is more efficient than the 3-level and the uniform ones.

3.3. The etching depth

The etching depth has an obvious influence on the effective index and on the reflection or the transmission characteristics of the grating, because the etching depth determines the ratio of silicon to air in one period of grating, which corresponds to the ratio of transmission power in the remain silicon layer to the reflection power in the silicon and air interface. The reflection and the transmission of the grating is directly associated with the scattered efficiency η_1. Hence, the 5-level stair-step blazed gratings with different etching depths are theoretically analyzed. The etching depth h corresponds to the deepest etching depth of the 5-level stairs. The influence of the etching depth on $R+T$ and on R is given in Fig. 5. It can be seen that R as well as $R+T$ increases with the etching depth increasing and the rate of change increases suddenly when the etching depths are above 280 nm. It can be explained that when the etching depths are above 280 nm there will be no slab mode existing in the remaining silicon layer and most of the input optical power is reflected with little light transmitted. The lowest $R+T$, which reveals the balance of R and T, is obtained at the etching depth of 260 nm, corresponding to the etching depths of 260, 200, 140, 80 nm for each stairs, respectively.

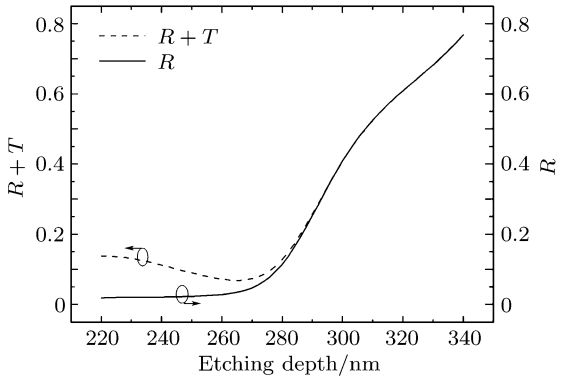


Fig. 5. The influence of etching depth on $R+T$ and on R. The lowest $R+T$, which reveals the balance of R and T, is obtained at the etching depth of 260 nm.

3.4. The blaze angle

As mentioned before, the saw teeth like blaze grating can greatly improve the directionality of the grating coupler in certain diffraction order. For blazed grating, the directionality η_2 is mainly related to the blaze angle θ as defined in Fig. 1(b). Here the 5-level stairs are assumed to have the same width $w_1 = w_2 = w_3 = w_4 = w_5 = 0.2 \times \text{period} = 124$ nm. The stair heights of the 5-level blaze grating increase along the light propagation direction with the same height difference Δh, which has been optimized in previous section. Then θ will be directly related with the value of Δh. The value of blaze angles θ (discrete distribution between 21° and 34°) and the corresponding height difference Δh are given in Table 1. The directionality of the gratings with various blaze angles are investigated. The result is shown in Fig. 6. It can be seen that when the blaze angle θ is around 26° the directionality reaches the highest value of 80.5%. The corresponding height difference Δh is 60 nm.

Table 1. The blaze angles θ and the corresponding height differences Δh.

θ/(°)	21	22	23	24	25	26	27	28	29	30	31	32	33	34
Δh/nm	48	50	53	55	58	60	63	66	69	72	75	77	83	84

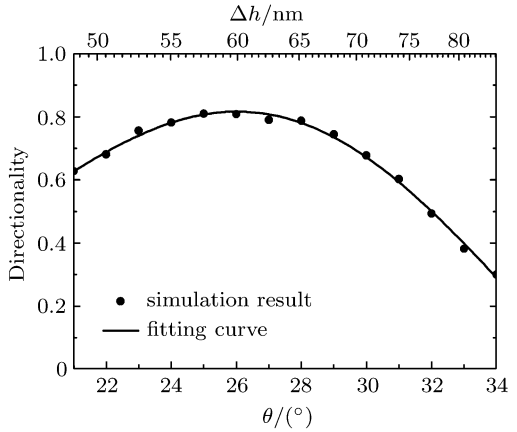


Fig. 6. The influence of blaze angle θ (discrete distribution between 21° and 34°) and the corresponding height difference Δh on the grating coupler directionality. The directionality reaches the highest value of 80.5% at θ around 26°, corresponding to the height difference Δh of 60 nm.

3.5. The width profile

By changing the widths of the stairs (w_1, w_2, w_3, w_4, w_5 as schematically shown in Fig. 1(b)), the effective index profile can be shaped too and then the coupling between the grating and the single mode fiber can be further optimized. Three kinds of stair-step blazed grating couplers with different width profiles are investigated. The width profiles and the result are shown in Fig. 7.

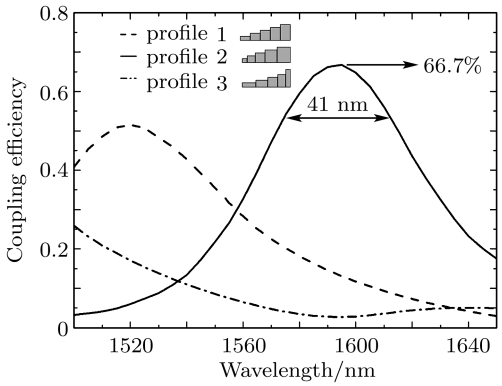


Fig. 7. The coupling spectrum of 5-level stair-step blazed grating couplers for three kinds of width profiles utilizing the previously optimized structure. The different width profiles are also shown in the figure.

These three blazed gratings have utilized the previously optimized structure. In width profile 1, the widths of the stairs are the same, corresponding to values of (0.20, 0.20, 0.20, 0.20, 0.20) × period; in width profile 2, the widths increase along the propagation direction, corresponding to values of (0.10, 0.15, 0.20, 0.25, 0.30) × period; in width profile 3, the widths decrease along the propagation direction, corresponding to values of (0.30, 0.25, 0.20, 0.15, 0.10) × period. The coupling efficiency versus the wavelength is plotted in Fig. 7. It can be concluded that the blaze profile with increasing stair widths along the propagation direction (that is width profile 2) provides a higher coupling efficiency. The variety of the stair widths mainly influences the value and the profile of the effective index of the fundamental TE mode, which will induce the center wavelength shift and the index contrast variety between the grating and the fiber, the latter consequently influence the Gaussian mode overlay between them. Finally, a coupling efficiency of 66.7% at 1595 nm and a 1 dB bandwidth of 41 nm are obtained as shown in Fig. 7.

4. Conclusion

In conclusion, different kinds of stair-step blazed grating couplers can find applications in many fields and the forward profile blazed grating, whose reflection around the center wavelength is relatively low, gives high coupling efficiency. The 5-level stair-step blazed grating can provide high directionality with certain blaze angle. The variation of height and width of the 5-level stairs would influence the refection of the grating and reshape the effective index profile in one period. The coupling efficiency can be optimized. As the simulation indicates, a high coupling efficiency of 66.7% at 1595 nm with a 1 dB bandwidth of 41 nm for L band optical communication can be obtained.

References

[1] Bogaerts W, Baets R, Dumon P, Wiaux V, Beckx S, Taillaert D, Luyssaert B, Van Campenhout J, Bienstman P and Thourhout D V 2005 *J. Lightw. Technol.* **23** 401
[2] Taillaert D, Laere F V, Ayre M, Bogaerts W, Thourhout D V, Bienstman P and Baets R 2006 *Jpn. J. Appl. Phys.* **45** 6071
[3] Zhu Y, Xu X J, Li Z Y, Zhou L, Han W H, Fan Z C, Yu Y D and Yu J Z 2010 *Chin. Phys.* B **19** 014219
[4] Van Laere F, Roelkens G, Ayre M, Schrauwen J, Taillaert D, Thourhout D V, Krauss T F and Baets R 2007 *J. Lightw. Technol.* **25** 151
[5] Masayuki M 1992 *J. Quantum Electron.* **28** 2016
[6] Ang T W, Reed G T, Vonsovici A, Evans A G R, Routley P R and Josey M R 2000 *Appl. Phys. Lett.* **77** 4214
[7] Ang T W, Reed G T, Vonsovici A, Evans A G R, Routley P R and Josey M R 1999 *SPIE* **3896** 360
[8] Wilson D W, Maker P D, Muller R E, Muller R E, Mouroulis P and Backlund J 2003 *Proc. SPIE* **5173** 115
[9] Feng J and Zhou Z 2006 *Proc. SPIE* **6351** 63511H-1-9
[10] Bienstman P 2004 *CAMFR1.2* http://camfr.sourceforge.net
[11] Schmid B, Petrov A and Eich M 2009 *Opt. Express* **17** 11066
[12] Robert M E and Dennis G H 1992 *J. Quantum Electron.* **28** 164