High-efficiency focusing grating coupler with optimized ultra-short taper*

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A novel high-efficiency focusing non-uniform grating coupler is proposed to couple light into or off silicon photonic chips for large-scale silicon photonic integration. This kind of grating coupler decreases the transition length of the linking taper between the grating and the single-mode waveguide by at least 80%. The radian of the grating lines and the size of the taper are optimized to improve the coupling efficiency. An experimental coupling efficiency of ∼ 68% at 1556.24 nm is obtained after optimization and the whole size of the grating is 12 μm × 30 μm, with a very short taper transition of ∼15 μm long.

Keywords: grating coupler, silicon photonics, photonic integrated circuits, silicon-on-insulator

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1. Introduction

As the gateways to communicate with external devices, grating couplers have attracted a lot of attention due to their advantages of on-chip optical integration, such as no need of chip preprocessing, near vertical propagation, and minimal space limitation. The coupling efficiency is an important criterion for evaluating the grating couplers. In order to improve the coupling efficiency, high-directionality grating couplers and high mode-matching grating couplers were investigated. High directionality grating couplers include grating couplers with a bottom mirror,[1,2] grating couplers with an overlay,[3,4] and grating couplers with a large filling factor.[5] The mode matching grating couplers include non-uniform structure[6–10] and double-etched apodized structure[11] couplers, etc. Among these, the non-uniform grating couplers are considered most likely to achieve the highest coupling efficiency in the future. In recent years, non-uniform grating couplers have been developed rapidly because of the improving technology.

At the same time, large-scale integration requires miniaturized devices, including grating couplers. A grating coupler is composed of two parts: the grating structure and the mode-transition structure. The grating structure is about 10 μm to 20 μm long. For a linear grating coupler, the grating structure is adiabatically linked to a single-mode waveguide by a long taper, the length of which is about 150 μm. The length of the taper is determined by the adiabatic transition between the grating and the single-mode waveguide. Focusing grating couplers use the curving line's focusing character to obviate the need for a long adiabatic transition. The decreased taper length results in a higher degree of integration.

In this paper, we propose a focusing non-uniform grating coupler with an optimized short taper, which has a small footprint on silicon-on-insulator (SOI) substrates and a high coupling efficiency.

2. Design and simulation

In order to achieve a high coupling efficiency, every grating unit needs to be designed by setting parameters such as etched depth, period, and filling factor. Under existing process conditions, it is quite difficult to realize grating couplers with variable etch depth. Non-uniform grating couplers with variable period and filling factor are easier to make. So, in our simulation, non-uniform grating couplers with variable period and filling factor were introduced and the etched depth was set to a default value.

For grating couplers, an efficient coupling is expected between an almost vertically positioned single-mode fiber and a horizontal single-mode waveguide. For focusing grating couplers, the wave front is curved cylindrically and focusing occurs in the common focus of the curved grating lines. When the top surface of the waveguide is chosen to be the yz plane of a right handed Cartesian coordinate system, with z along the waveguide axis and the origin at the desired focal point, the grating lines must follow the condition of constructive interference[12]

$$q\lambda_0 = n_{\text{eff}}\sqrt{y^2+z^2} - zn_{\text{t}}\cos\theta_{\text{c}}, \quad q = 1,2,\ldots, \qquad (1)$$

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where q is an integer for each grating line, θ_c is the angle between the fiber and the chip surface, n_t is the refractive index of the environment, λ_0 is the vacuum wavelength, and n_{eff} is the effective index felt by the cylindrical wave in the broad waveguide with the grating. According to the constructive interference, the grating lines can be expressed as

$$\frac{\left(z-\frac{q\lambda_0 n_c\cos\theta_t}{n_{eff}^2-n_c^2\cos^2\theta_t}\right)^2}{\left(\frac{q\lambda_0 n_{eff}}{n_{eff}^2-n_c^2\cos^2\theta_t}\right)^2}+\frac{y^2}{\left[\frac{q\lambda_0}{\left(n_{eff}^2-n_c^2\cos^2\theta_t\right)^{1/2}}\right]^2}=1. \quad (2)$$

This formula is valid with the assumption

$$n_{eff}^{grating}=n_{eff}^{taper}, \quad (3)$$

where $n_{eff}^{grating}$ is the effective index in the grating and n_{eff}^{taper} is the effective index of the taper. In fact, for the grating couplers designed according to formula (2), it is quite hard to fulfill the assumption in formula (3). Especially for the deeply etched gratings, there is a difference in the effective refractive index

$$n_{eff}^{taper}-n_{eff}^{grating}=\Delta n_{eff}. \quad (4)$$

This difference will result in a deviation from the ideal conditions for the grating designed according to formula (2). This deviation will cause coupling loss. An appropriate taper is expected to reduce the deviation. At the same time, there is a mode-mismatch loss between the focusing grating and the taper. In order to reduce the loss caused by the deviation and the mode mismatch, an appropriate taper should be designed and optimized. Two main parameters of the taper were designed and optimized. One was the length of the taper, which was determined by the long axis of the first grating line, and the other was the angle of the taper.

In designing a focusing grating coupler, a constant was set as the default value for the period because of the variable index caused by the variable period and filling factor. According to previous experience, the period was set to 600 nm and the index was calculated from the Prague formula under the condition of wavelength $\lambda = 1550$ nm

$$n_{eff}=n_c\cos\theta_c+m\lambda/\Lambda. \quad (5)$$

Then, the formula of the grating lines could be obtained as

$$\frac{z^2}{(0.6q)^2}+\frac{y^2}{(0.57q)^2}=1. \quad (6)$$

The first line of the grating was set according to the formula. The periods and the filling factors of the grating lines were still consistent with the liner grating in the long and the short axes.

A coupler with a short taper and a high coupling efficiency was desired. In order to reduce the length of the taper, the integer number q should be as small as possible on condition of efficient coupling. When light from the single-mode waveguide was turned to a curved wavefront to couple with the grating, the shape of the wavefront would be influenced by the angle (α) and the length (L) of the taper.

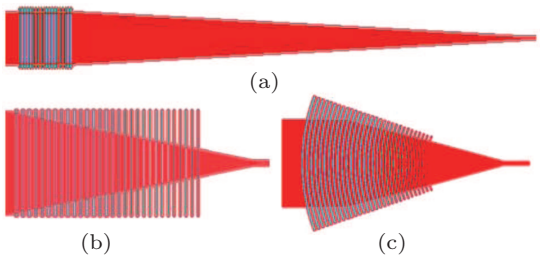


Fig. 1. (color online) (a) Top view of normal grating coupler with a long taper (50 μm); (b) revised grating coupler with curved lines (no taper); and, (c) the novel non-uniform focusing grating in this work.

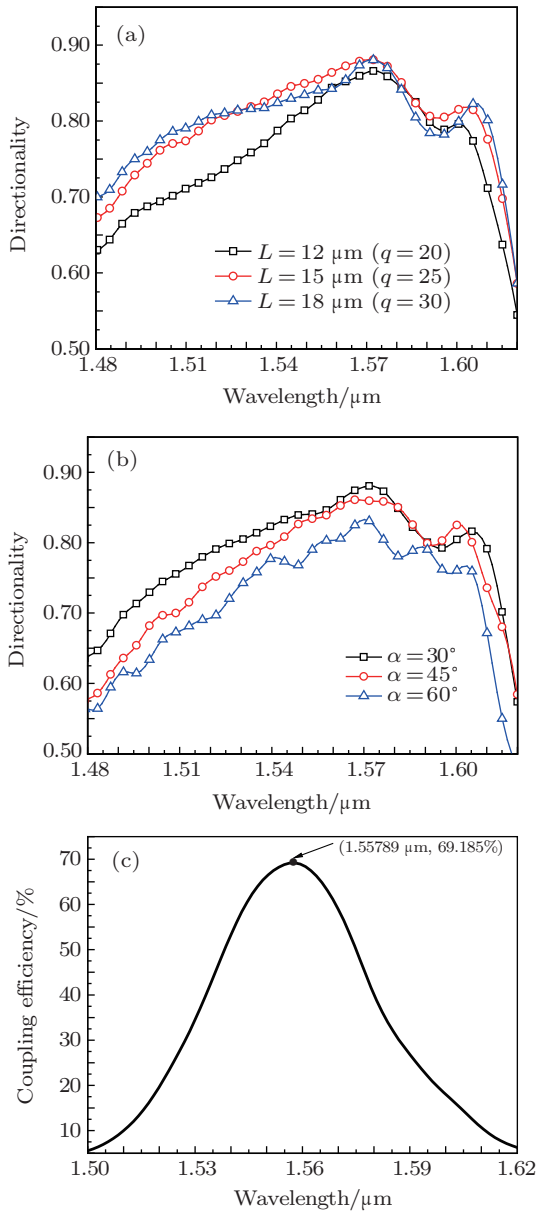


Fig. 2. (color online) (a) Directionality of grating couplers with different taper lengths; (b) directionality of grating couplers with different angles of the taper; and, (c) coupling efficiency of the grating coupler with optimized length and angle in the novel design.

As the integer number q decreased and the grating lines curved, the angle of the taper should be large enough to ensure that all light diffracted from the fiber can be received by the grating. When the length of the taper was decreased from 50 μm to 15 μm ($q = 25$), the directionality of the grating coupler maintained a high value, and it began to fall when the length continued to decrease. Then, the angle of the taper was optimized under the condition $q = 25$. When the angle was 45°, the best directionality was obtained. In the simulation, the largest lateral width of the taper was set to 12 μm, which was wide enough to ensure the directionality and the coupling efficiency. The designed grating coupler is shown in Fig. 1 and the highest coupling efficiency 69% was obtained at a central wavelength of 1559 nm, as shown in Fig. 2.

3. Manufacture and testing

The grating couplers were manufactured with electron beam lithography (EBL) and inductively coupled plasma (ICP) etch. The etch depths of the grating and the taper were designed to be 195 nm. The experimental results are shown in Fig. 3. The highest coupling efficiency was 65% at the wavelength of 1585 nm. From measurement, it was found that the central wavelength shifted from 1559 nm to 1585 nm compared with the simulation results. The liner non-uniform grating coupler on the same chip also had the same shift. This problem resulted from the hysteresis effect in the ICP etch: the narrow slits in the grating were relatively shallow compared to the designed value. For the grating couplers, the coupling mainly occurred in the front half of the grating near the taper, and the latter half was mainly used to reduce the transmission loss. So in order to obtain the desired central wavelength, the etch depth in the ICP etching process was increased to 220 nm. The experimental results showed that the central wavelength shifted to 1556.24 nm and the coupling efficiency was 68%, as shown in Fig. 4, which means that the etch depths of the narrow slits were a little higher than the designed 195 nm.

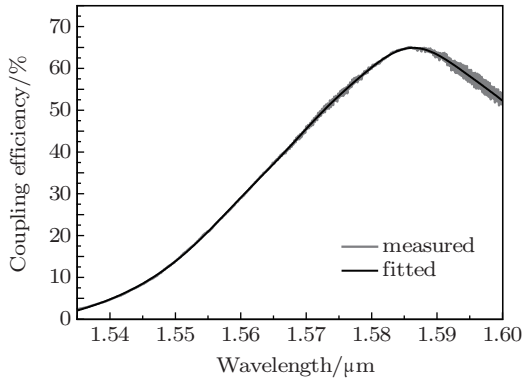


Fig. 3. Experimental result of the grating coupler with etched depth 195 nm and high efficiency of 65% at 1588.06 nm.

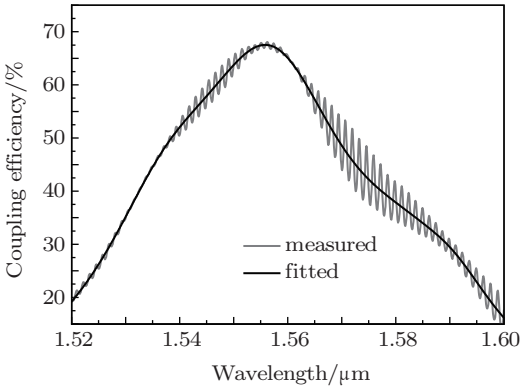


Fig. 4. Experimental result of the optimized focusing non-uniform grating coupler and high efficiency of 68% at 1556.24 nm with the fitting curve under 220 nm etching.

4. Conclusion

In order to focus a laser beam into a small size waveguide, and to increase the coupling efficiency between the single mode fiber and the SOI single mode waveguide, a new kind of grating coupler was designed and made. Our simulation and experimental results can be summarized as follows.

(i) Our simulation of the devices showed that the introduction of the focusing structure to the non-uniform grating coupler could decrease the whole size of the grating coupler efficiently. The experimental results showed that the device can be as small as 30 μm×12 μm.

(ii) Within the wavelength range of 1540–1575 nm, the coupling efficiency between the optical fiber and the SOI waveguide could be larger than 50%, and the highest coupling efficiency was 68%, which appeared at 1556.24 nm.

(iii) By optimizing the structure's parameters, including the period number, distance, etching depth, and filling factor, the highest coupling efficiency could be adjusted to appear in a desired wavelength. The shift of the central wavelength induced by the hysteresis effect was controlled through optimizing the ICP etch depth.

In conclusion, this kind of coupler can reduce device size and provide a high coupling efficiency. Such devices will play an important role in SOI optical integration circuits in the future. Our experimental results show that a grating coupler with a small footprint and a high coupling efficiency can be realized in the established CMOS process.

References

[1] Van Laere F, Roelkens G, Ayre M, Schrauwen J, Taillaert D, Van Thourhout D, Krauss T and Baets R 2007 *IEEE J. Lightwave Technol.* **25** 151

[2] Selvaraja S, Vermeulen D, Schaekers M, Sleeckx E, Bogaerts W, Roelkens G, Dumon P, Van Thourhout D and Baets R 2009 *Conference on Lasers and Electro-Optics*, p. CTuC6

[3] Anastasia N, Xiao X, Yang B, Chu T, Yu J and Yu Y 2012 *Chin. Phys. Lett.* **29** 114213

[4] Lischke S, Wohlfeil B, Knoll D, Zimmermann L, Mai C, Yamamoto Y, Marschmeyer S, Voigt K and Tillack B 2013 *Asia Communications and Photonics Conference (ACP 2013)* **12**

[5] Zhou L, Li Z, Zhu Y, Li Y, Fan Z, Han W, Yu Y and Yu J 2010 *Chin. Phys. B* **19** 124214

[6] Zhang C, Sun J, Xiao X, Sun W, Zhang X, Chu T, Yu J and Yu Y 2013 *Chin. Phys. Lett.* **30** 014207

[7] Yu H and Yu J 2005 *Chin. Phys. Lett.* **22** 2865

[8] Taillaert D, Bienstman P and Baets R 2004 *Opt. Lett.* **29** 2749

[9] Tang Y, Wang Z, Wosinski L, Westergren U and He S 2010 *Opt. Lett.* **35** 1290

[10] Halir R, Cheben P, Schmid J H, Ma R, Bedard D, Janz S, Xu D X, Densmore A, Lapointe J and Molina-Fernandez I 2010 *Opt. Lett.* **35** 3243

[11] Ding Y, Ou H and Peucheret C 2013 *Opt. Lett.* **38** 2732

[12] Waldhäusl R, Schnabel B, Dannberg P, Kley E B, Bräure A and Karthe W 1997 *Appl. Opt.* **36** 9383