High efficiency binary blazed grating coupler for perfectly-vertical and near-vertical coupling in chip level optical interconnections

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The high-efficiency binary blazed grating couplers with perfectly vertical and nearly vertical coupling are proposed. The efficiencies of them are much higher than those of other types of grating couplers without bottom mirrors under vertical and oblique incidence respectively. For perfectly vertical coupler with transverse-electric polarized incident light, the coupling efficiency, which is defined as the ratio between the power coupled to the fundamental mode of the chip waveguide and that carried by the fundamental mode of the input optical fiber, is 75%, while the nearly vertical coupler with the incident angle of 10.2° has a coupling efficiency of 84%. Rigorous coupled-wave diffraction analysis and a complete optimization method have been used to make the optimal design valid and unique.

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1. Introduction

Silicon photonics has attracted increasing attention and research effort in recent years because of its potential for low-cost integration using existing complementary metal–oxide–semiconductor (CMOS) technology and the small footprints of silicon photonics compared with external integration using existing complementary metal–oxide–semiconductor (CMOS) technology and the small footprints of silicon chips and external integration using existing complementary metal–oxide–semiconductor (CMOS) technology and the small footprints of silicon chips and external integration using existing complementary metal–oxide–semiconductor (CMOS) technology and the small footprints of silicon chips and external integration using existing complementary metal–oxide–semiconductor (CMOS) technology and the small footprints of silicon chips and external integration using existing complementary metal–oxide–semiconductor (CMOS) technology and the small footprints of silicon chips and external integration. Unfortunately, it suffered from complex fabrication of slits and therefore with little practicality.

Another type of strategy to realize vertical coupling is to use the binary blazed grating (BBG) coupler [15–17]. The BBG coupler is formed with multiple rectangular pillars of a uniform height but different widths, which is realized by using a binary quantified method to approximate a traditional triangular tooth shaped grating, so it can be easily fabricated by only one etching step [18–20]. A BBG can blaze all diffracted light into a single diffraction order and suppress others [15]. As a consequence, the coupling efficiency and directionality of the grating are enhanced. In addition, it is CMOS compatible and is available for mass production.

In this work, we propose a novel high-efficiency perfectly vertical binary blazed grating coupler, which enables a simpler optical alignment process and offers the efficiency as high as 81%. To the best of our knowledge, this is the highest efficiency obtained through a vertical grating coupling method. In order to further study the coupling efficiency of the grating, we also present a novel high-efficiency nearly vertical binary blazed grating coupler which has a little incident angle. Both the new design and the reshaped grating structure contribute to the extremely high coupling efficiency. It promises a coupling efficiency of about 90% over a 1 dB wavelength bandwidth of 42 nm for TE polarization at the incident angle of 10.2°. The simulation results indicate that this structure has a sufficient coupling efficiency and a rather large angle tolerance. In this study, our target of optimization is to realize as high coupling efficiency as possible near the wavelength of 1550 nm. Moreover, the influence of design parameters on the

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coupling efficiency is also discussed. Since the features are smaller than the wavelength of the incident light, the binary blazed grating will be discussed based on rigorous coupled-wave diffraction theory instead of scalar diffraction theory.

2. Vertical coupler design

The schematic diagram of the structure is shown in Fig.1(a). The incident light is the fundamental Gaussian-like mode profile in an optical fiber, the power of which \( P_0 \) is divided into four parts throughout the grating: \( P', P, P_r \) and \( P_t \), \( P' \) and \( P \) are the major and minor parts of input light coupled and transmitted in the waveguide, respectively. The coupling efficiency \( \eta \) in this work is defined as the ratio between the power coupled to the fundamental mode of the access waveguide and that carried by the fundamental mode of the input optical fiber. In the following work, we firstly did the simulation to improve the efficiency defined as \( \eta = \frac{P}{P_0} \), and then we performed an overlap integral between the fundamental mode and the field distribution along a cut in the \( y \) coordinate away from the grating to figure out the proportion of the power coupled to the fundamental mode of the waveguide. In order to achieve high performance, some design parameters should be considered, such as incident wavelength \( \lambda \), grating etching depth \( E \), unetched slab thickness \( D \), grating period \( T \), number of pillars in one period \( M \), fill factor \( f \), grating length \( W \), waveguide thickness \( H \) and \( \text{SiO}_2 \) layer thickness \( L \). \( \theta \) is the angle of incidence and \( \alpha \) is called conical angle. In this paper, \( \alpha \) is set to be 0°, which means the incident wave vector is in the \( yz \) plane.

To make the design valid and unique, the rigorous coupled-wave analysis for diffraction [21] and the simulated annealing optimization method [22] have been applied for the design process. The simulation software Opti-FDTD is applied. A 2D simulation is carried and the mesh-resolution is 0.03 μm. Diffraction efficiency will be our main concern in this paper, which is the most important parameter for optical interconnection.

It is well known that the grating period \( T \) can be designed by the phase match condition between the gratings and the waveguide mode. To satisfy the Bragg condition [23]

\[
K_m + m \cdot K_f = \beta,
\]

where \( K_m = 2 \pi n_1 \sin \theta / \lambda \) is the incident wave vector (\( n_1 \) is the refractive index of air), \( K_f = 2 \pi / \Lambda \) is the reciprocal lattice vector of the grating, \( \beta = 2 \pi N_{ef} / \lambda \) is the propagation constant of the guided mode in the grating waveguide. \( (N_{ef} \) is the effective refractive index of the waveguide for the propagating mode), \( m \) is the

Fig. 1. Basic structure for simulation (a) 2D scheme, (b) 3D scheme and (c) (I) common blazed grating. (II) Discrete multilevel grating. (III) Binary blazed grating.
diffraction order which is set to \(-1\), and \(\theta\) is the incident angle, respectively. So Eq. (1) can be written as

\[ T(N_{\text{eff}} - n_{dc} \sin \theta) = m \lambda, \]  

(2)

At the same time, reducing the leakage of substrate should also be taken into consideration to improve coupling efficiency, as shown in this formula:

\[ T(N_{\text{eff}} - n_{dc} \sin \theta) \neq m \lambda, \]  

(3)

where \(n_i\) is the refractive index of the upper cladding and \(n_{dc}\) is the refractive index of the down cladding. In this paper, \(n_i = n_1\), and the incident wave is designed as normal incidence, in which case \(\theta\) is equal to 0. So the grating period \(T\) can be given by \(T = \lambda/N_{\text{eff}}\), where \(N_{\text{eff}}\) can be obtained from the mode dispersion equations of slab waveguide [24]

\[
\left( n_i^2 - N_{\text{eff}}^2 \right)^{\frac{1}{2}} \frac{2 \pi}{\lambda} H = m \pi + \tan^{-1} \left( \frac{N_{\text{eff}}^2 - n_i^2}{n_i^2 - N_{\text{eff}}^2} \right),
\]

(4)

where \(n_i\) and \(n_H\) are the refractive indices of Si and SiO\(_2\), \(H\) is the waveguide thickness and \(m\) is the mode ordinal number, which is a non-negative integer. The grating period \(T\) can be calculated by Eqs. (2)-(4) with the parameters of \(n_1 = 1.48, n_2 = 3.48, \lambda = 1.55 \mu m\) and \(\theta = 0^\circ\).

The BBG is composed of variable sub-wavelength pillars with uniform height and different widths shown in Fig.1(b). In our structure, every period is divided into \(M\) equal sub-periods with the width of \(q = T/M\). The optimum \(M\) is fixed as 4, which is a compromise of considering both the coupling efficiency and the fabrication constraint [18]. Each ridge’s width is modulated to obtain the blaze effect [19]. \(h_1\) is the height of the common blazed grating, \(h_i (i = 1, 2, 3, 4)\) is the height of each discrete multilevel grating. The fill factor of each sub-period \(f_i (i = 1, 2, 3, 4)\) is defined as the ratio of the pillar width to the sub-period width, which can be derived by discretizing the common blazed grating structure. According to the localized effective refractive indices theory of binary gratings and the discrete processing of signal phase, the fill factors can be computed

\[ n_{\text{eff}}^{\text{TE}} = \sqrt{\epsilon_{\text{eff}}} = \sqrt{f_i n_f^2 + (1 - f_i)n_i^2}, \]

(5)

\[ n_{\text{eff}}^{\text{TE}} = \frac{h_i}{H} n_f + \frac{H - h_i}{H} n_i, \]

(6)

\[ h_i = \left\lfloor \frac{H h_i}{M} + \frac{H (i - 1)}{M} \right\rfloor = \frac{(2i - 1)h_i}{2M}, \]

(7)

According to Eqs. (5)-(7), \(f_i\) should be

\[ f_i = \frac{\left[\frac{(2i - 1)h_i}{2M} \right]}{n_f^2 - n_i^2}, \]

(8)

In this structure, \(f_4\) is set to 1, then the rest fill factors can be optimized as \(f_1 = 0.075, f_2 = 0.293\) and \(f_3 = 0.6\), and the width of each pillar can be obtained by \(w_i = f_i q\). It should be noted that in

Fig. 2. (a) Relationship of \(\eta\) and \(\lambda\) (\(\theta = 0^\circ\), \(L = 2.43 \mu m, W = 9.81 \mu m, E = 350 \text{ nm}\)). (b) Poynting vector distribution of the coupling case at the wavelength of 1.55 \(\mu m\). (c) Relationship of \(\eta\) and \(\theta\) (\(L = 1.55 \mu m, W = 2.43 \mu m, E = 9.81 \mu m, E = 350 \text{ nm}\)). (d) Relationship of \(\eta\) and SiO\(_2\) layer thickness (\(L = 1.55 \mu m, \theta = 0^\circ, L = 2.43 \mu m, W = 9.81 \mu m, E = 350 \text{ nm}\)).
this case, the thinner pillar in the first subperiod is joined with its adjacent period’s last subperiod.

The coupling efficiency as a function of incident wavelength is illustrated in Fig. 2(a). All the important parameters used in the simulation are optimized as follows: the grating etching depth \( E \) is 350 nm, and a 160 nm-thick slab waveguide is left, grating period \( T \) is 545 nm, waveguide height is 220 nm for optical integration with other silicon devices, BOX layer thickness \( L \) is 2.43 μm. The efficiency can reach 81% at the wavelength of 1560 nm with a 1 dB bandwidth of 44 nm. We also get the reflectivity and transmissivity versus wavelength and angle of incidence graphs for clarification. It is clear that the main part of the input light is coupled in and directed forward (in this case, the positive z direction). Fig. 2(b) shows the Poynting vector distribution calculated by Opti-FDTD software. Obviously, the main part of the coupled-in light propagates along the positive z direction. In Fig. 2(c), the tolerance that gives 80% of peak coupling is 8.8°. The structure is carefully optimized to guarantee the high efficiency of 81% under the perfectly normal incidence, i.e. \( \theta = 0^\circ \).

Moreover, considering the mean-field diameter (MFD) of the 1550 nm single-mode fiber, the grating length will be fixed at 9.81 μm (18 \( T \)) in the simulation. As the Si/SiO\(_2\) substrate can be treated as a reflector, the coherence stack will happen between the incident light and the reflected light. Therefore, the grating coupling efficiency varies periodically as a function of the SiO\(_2\) layer thickness, as illustrated in Fig. 2(d). Finally, we numerically analyzed the fabrication tolerance, i.e. all grooves are wider or narrower than expected. The efficiency is higher than 80% of peak efficiency when line-width error varies from \(-25 \text{ nm} \) to \(+25 \text{ nm} \), which shows a tolerance of 50 nm.

The 81% efficiency is quite high compared with other common vertical grating coupler case which is 65% [17]. As a consequence of the waveguide effect of the subwavelength ridges, an intense and coherent wave is able to flow straight through the grating, and a novel high diffraction efficiency is achieved. This property is intrinsic to diffractive elements composed of sub-wavelength features and cannot be achieved with common drafactive elements.

3. Nearly vertical coupler design and optimization

In the above discussion, a substantial part of the light still can transmit out to the substrate and reflect up to the air cladding due to the perfectly vertical incidence. In order to further enhance coupling efficiency, the influence of a tilted incident angle on the coupling efficiency was studied.

According to the phase match condition between the gratings and the waveguide mode, the grating period \( T \) and the incident angle \( \theta \) can be obtained based on Eq. (1), that is, \( T = 580 \text{ nm} \) and \( \theta = 10^\circ \). Then other design parameters were further optimized to enhance the coupling efficiency of the BG.

Since the etched depth \( E \) and the unetched slab thickness \( D \) have a significant influence on the distribution of the optical field, \( E \) should be carefully selected in order to couple more power into the waveguide. Fig. 3 shows the coupling efficiency as a function of etched depth with different combination values of \( E \) and \( D \). For a fixed sum value of \( E \) and \( D \), the coupling efficiency rises first and then declines as \( E \) increases. Meanwhile, the peak of the coupling efficiency shifts to a larger \( E \) when the sum value of \( E \) and \( D \) is greater. However, the coupling efficiency no longer rises when the sum value exceeds 0.5 μm. Therefore, from Fig.3, the optimal combination of \( E \) and \( D \) is derived, that is, \( E \) equals 0.35 μm and \( D \) equals 0.15 μm. With further optimization using this method, the maximum efficiency we get is 90% under the condition that \( E = 0.35 \mu \text{m} \) and \( D = 0.16 \mu \text{m} \).

The coupling efficiency as a function of incident wavelength is illustrated in Fig. 4(a). The efficiency can reach 90% at the wavelength of 1550 nm with a 1 dB bandwidth of 42 nm, and 3 dB bandwidth of 68 nm. Fig. 4(b) shows the Poynting vector distribution calculated by Opti-FDTD software. The main part of the coupled-in light propagates along the positive z direction, not much different in the field distribution profiles from that in vertical coupling cases. Fig. 4(c) presents the efficiency is higher than 80% of peak efficiency when incident angle varies from 6.3° to 14°, indicating an angle tolerance of 7.7°. The efficiency reaches its peak value of 90% under the condition of 10.2° incidence angle. Fig. 5(a) shows the relationship between coupling efficiency and the grating period \( T \). The coupling efficiency first increases monotonously with the grating period and then decreases when the grating period exceeds a certain length about 0.58 μm. The efficiency is higher than 80% of peak efficiency when \( T \) varies from 564 nm to 591 nm, which shows a tolerance of 27 nm with the grating period. The unetched thickness \( D \) is an important freedom in the optimization procedure, since the reflection and transmission will occur when the unetched slab thickness of grating area is too thick or too thin, which accordingly reduces the coupling efficiency. The relationship between coupling efficiency and the unetched thickness was discussed to study the tolerance about this parameter. As shown in Fig. 5(b), the efficiency can reach 90% at the thickness of 160 nm with the etched depth of 350 nm and the wavelength of 1550 nm. Same as the perfect-vertical coupling case, a tolerance analysis about fabrication errors in near-vertical coupling situation is carried out, which indicates that the degradations of coupling efficiency are less than 20% while the width of each groove deviates \( \pm 20 \text{ nm} \) from the optimized size.

4. Conclusions

We designed and demonstrated high-efficiency binary blazed grating couplers with perfectly vertical and nearly vertical coupling. This perfectly vertical coupler has a 1 dB bandwidth of 44 nm and a high coupling efficiency of 81% at the wavelength of 1560 nm, while the nearly vertical coupler has a 1 dB bandwidth of 42 nm and a high coupling efficiency of 90% at the wavelength of 1550 nm. The efficiency obtained above refers to the power efficiency without mentioning anything about the modes. To figure out the proportion of the power coupled to the fundamental mode of the waveguide, we have performed an overlap integral between the fundamental mode and the field distribution along a cut in the y coordinate away from the grating. Based on the
overlap integral formula, the performed average overlap ratio is about 93%, which means such portion of power $P$ (defined as coupled forward in the waveguide) is coupled to the fundamental mode of the access waveguide. For perfectly vertical coupler, the ratio between the power coupled to the fundamental mode of the chip waveguide and that carried by the fundamental mode of the input optical fiber is 75%, while the nearly vertical coupler has a coupling efficiency of 84%. The efficiencies of the novel perfectly vertical and nearly vertical couplers are higher than those of chirped grating couplers without bottom mirrors under vertical and oblique incidence respectively. This structure has an angle tolerance of 8.8° for perfectly vertical coupler and 7.7° for nearly vertical coupler, which brings much convenience to photonic integration.

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References


