Gratings are an efficient means of coupling light between optical fibers and high-index-contrast waveguides, such as silicon-on-insulator (SOI) [1,2]. SOI is an interesting material for high-density photonic integrated circuits, which can be fabricated by standard complementary metal-oxide semiconductor (CMOS) technology. One of the challenges is coupling light between optical fibers and SOI waveguides due to a huge mismatch between the waveguide mode and a single-mode fiber mode. To obtain high coupling efficiency, different strategies can be followed. For example, high coupling efficiency can be obtained by using a bottom mirror or Bragg reflector layer [3,4]. In addition, the second-order Bragg reflection can be avoided by slightly tilting the optical fiber with respect to the vertical axis [5,6]. However, it is complicated in the packaging of the photonic integrated circuit.

An alternative method is to etch a deep slit in front of the fiber, which acts together with the grating as a Fabry–Perot cavity [7]. By chirping the grating, backreflections [8] and losses due to mode mismatch [9] can be minimized. Most of these methods are either based on amorphous silicon, which limits the thermal budget, or require a lot of postprocessing. In [10], a shallow-etched diffractive waveguide grating coupler was proposed that consists of two sections, i.e., a variable grating and a uniform grating. This device layout varies the grating coupling strength by designing the grating fill factor to range from 0.08 to 0.4 along the z axis. Another strategy is to use a silicon overlay to enhance the directionality and improve coupling efficiency [11]. Thus, on top of the silicon waveguide layer, a 160 nm thick amorphous silicon layer was deposited, which was then formed into silicon overlay mesas by dry etching. More recently, other strategies have also been considered to settle these problems [12,13]. In general, although high efficiencies can be obtained, these technologies required for fabrication are not CMOS compatible or are very complex, making fabrication and integration with other elements difficult.

In this Letter, we present a new design (a binary blazed grating structure that includes two subgratings with different widths and fill factors, but an identical etching height) that reshapes the grating structure and changes its diffraction properties to improve the fiber coupling efficiency. It promises a coupling efficiency of about 69% over a 1 dB wavelength bandwidth of 80 nm for TE polarization.

A binary-level periodic grating can be fabricated with sufficiently high spatial frequency that only the zero transmitted order is nonevanescent. Furthermore, by varying the fill factor of this high-spatial-frequency grating, one can generate an artificial distributed-index medium [14,15]. Thus, in our previous works [16–18], we proposed and designed a novel binary blazed grating with localized subwavelength, submicrometer features for beam coupling, and splitting functions at telecommunications wavelengths.

Figure 1 is the schematic diagram of the binary blazed grating coupler designed here. Obviously, the incident beam is vertical to the surface of grating, and then is coupled into the Si waveguide. The grating period is T, including two subgratings, such as Δ1 and Δ2, with the same etching depth d, but with different widths and fill factors. The thicknesses of the waveguide and

![Fig. 1. (Color online) Structure of binary blazed grating coupler.](image_url)
the oxide layer are \( h \) and \( w \), respectively. \( L \) is the length of device.

According to planar waveguide theory, the effective refractive indices (ERIs, \( N_{\text{eff}} \)) of the TE mode as a function of wavelength and the thickness of the waveguide satisfy the following equations:

\[
\frac{n_w^2 - N_{\text{eff}}^2}{N_{\text{eff}}^2} 
= m \pi + \tan^{-1} \left[ C_1 \cdot \left( \frac{N_{\text{eff}}^2 - n_s^2}{n_w^2 - N_{\text{eff}}^2} \right)^{1/2} \right] 
+ \tan^{-1} \left[ C_2 \cdot \left( \frac{N_{\text{eff}}^2 - n_s^2}{n_w^2 - N_{\text{eff}}^2} \right)^{1/2} \right],
\]

where \( h \) is the thickness of waveguide. \( n_w \) and \( n_s \) denote the refractive indices at two sides of the waveguide (i.e., up-cladding layer and oxide layer), respectively. \( n_w \) is the refractive index of the waveguide. Thus, for an SOI planar waveguide structure, \( n_w = 3.5 \) (Si), \( n_c = 1 \) (air), and \( n_s = 1.45 \) (SiO\(_2\)), we can obtain the ERI of the TE mode when the thickness of the waveguide is equal to 220 nm and \( \lambda = 1550 \) nm. Next, according to the phase match condition between the gratings and the waveguide mode, the grating period, denoted \( T \), should be

\[
T \times (N_{\text{eff}} - n_1 \cdot \sin \theta) = m \lambda \quad (m = 0, \pm 1, \pm 2, \ldots). \quad (2)
\]

Therefore, when we consider normal incidence and vertical coupling, i.e., \( \theta = 0 \), \( m = 1 \), the grating period \( T \) can also be acquired based on Eqs. (1) and (2). Finally, the ERIs of binary gratings with a localized subwavelength structure (\( N_{\text{eff}} \)) consisting of ridges of material \( n_1 \) with material \( n_2 \) in between can be obtained through [19,20]

\[
n_{\text{eff}} = \sqrt{fn_1^2 + (1 - f)n_2^2}, \quad (3)
\]

where \( f \) is the fill factor, which is defined as the ratio of pillar width to grating subperiod. We can control the width of each pillar to obtain the desired refractive index distribution.

The basic design procedure and discrete processing are shown in Fig. 2. We apply rigorous diffraction analysis to the localized subwavelength features within the grating period and optimize it by the simulated annealing method [16].

Assume that the conventional grating has an index of refraction \( n_1 \) and a height \( H_1 \). The surrounding medium has an index of refraction \( n_2 \). The heights of each of the discrete multilevel grating is \( H_i \) \((i = 1, 2, 3, \ldots, N)\). \( H_3 \) denotes the height of the binary subwavelength blazed grating, and the fill factor of each subperiod is \( f_i \) \((i = 1, 2, 3, \ldots, N)\). Then

\[
h_i = \frac{1}{2} \times \left[ \frac{H_1}{N} \cdot i + \frac{H_1}{N} (i - 1) \right] = \frac{(2i - 1)H_1}{2N}, \quad (i = 1, 2, 3, \ldots, N), \quad (4)
\]

\[
\frac{h_i}{H_3} n_1 + \frac{H_3 - h_i}{H_3} n_2 = n_{\text{eff}}. \quad (5)
\]

According to Eqs. (3)-(5), we have

\[
f_i = \frac{\left[ \frac{2i - 1}{2N} H_1 (n_1 - n_2) + n_2 \right]^2 - n_2^2}{n_1^2 - n_2^2} \quad (i = 1, 2, 3, \ldots, N). \quad (6)
\]

With the assumptions and the calculations given above, finally, all the data required for constructing a ridge-width-modulated grating with localized subwavelength features by straightforward quantization of the conventional grating can be computed.

Consequently, the fill factors can be given as the following equation when \( N = 2 \):

\[
f_1 = \frac{\left[ \frac{5}{8} H_1 + 1 \right]^2 - 1}{11.25}, \quad f_2 = \frac{\left[ \frac{15}{8} H_1 + 1 \right]^2 - 1}{11.25}. \quad (7)
\]

Then

\[
f_1 = \frac{\left[ \frac{5}{8} H_1 + 1 \right]^2 - 1}{11.25}, \quad f_2 = \frac{\left[ \frac{15}{8} H_1 + 1 \right]^2 - 1}{11.25}.
\]

According to the definition of fill factor, \( f_2 \) must satisfy that

\[
f_2 \leq \frac{\left[ \frac{15}{8} H_1 + 1 \right]^2 - 1}{11.25} \leq 1, \quad \text{thus} \quad \frac{H_1}{H_3} \leq \frac{4}{3} \approx 1.3.
\]

![Fig. 2. Design principle of binary blazed grating coupler.](image)

**Table 1. Design Parameters of Binary Blazed Grating Coupler (Unit: Micrometers)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( T )</th>
<th>( h )</th>
<th>( d )</th>
<th>( w )</th>
<th>( \Delta_1 )</th>
<th>( \Delta_2 )</th>
<th>( L )</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>0.6</td>
<td>0.22</td>
<td>0.12</td>
<td>0.9</td>
<td>0.05</td>
<td>0.224</td>
<td>16</td>
<td>1.55</td>
</tr>
</tbody>
</table>
In our design, $H_1/H_3 = 1.1$ and $H_3 = 0.12 \mu m$. That is to say, the etching depth $d$ is equal to 0.12 $\mu m$. Finally, the ridge width of each grating can be obtained. The relative parameters of the binary blazed grating coupler are given in Table 1.

Simultaneously, the finite-difference time-domain method, a powerful and accurate method for a finite-size structure, is chosen to simulate and design this device.

For a 1.55 $\mu m$ wavelength, the coupling efficiency is about 65% when we consider the TE mode and normal incidence. The $E_y$ and Poynting vector are given in Fig. 3.

Figure 4 shows the coupling efficiency as a function of wavelength. The coupling efficiency gets its maximum 69% when $\lambda$ is equal to 1.52 $\mu m$. Obviously, the 1 dB wavelength bandwidth is around 80 nm, and the 3 dB bandwidth is about 110 nm.

The relationship between coupling efficiency and incident angle is given in Fig. 5. Since the binary blazed grating structure designed here is applied to couple vertically, the coupling efficiency is decreased with deviation in the tilt angle from 0° to ±5°.

In addition, the fabrication errors, including the etching depth and width of binary grating, are also taken into account, as shown in Figs. 6 and 7. This indicates that the coupling efficiency is larger than 50% when the period changes from 0.588 to 0.618 $\mu m$. Thus, the tolerant error of width is about 30 nm. Simultaneously, it can be seen that the tolerant error of etching depth beyond 30 nm is also obtained since the coupling efficiency is larger than 50% when the etching depth changes from 0.105 to 0.137 $\mu m$. Fortunately, this is enough to control conveniently in practical fabricating process.

In practical applications, part of the light can transmit out to the substrate due to the existence of gratings. One effective way proposed to enhance the coupling efficiency is to deposit a multilayer reflector under the waveguide in the substrate, as shown in Fig. 8. The thickness of each layer $t = \lambda/4n$ must be well controlled to obtain a high reflectivity. $n$ is the refractive index of the layer.

The thicknesses of the Si ($n_{Si} = 3.5$) and SiO$_2$ ($n_{SiO2} = 1.45$) layers are 0.11 and 0.267 $\mu m$, respectively. Our simulation result shows that three or more layers can exhibit very high reflectivity and increase the coupling efficiency significantly, in which case little light can transmit to the substrate. The coupling efficiency can reach up to about 80% with an additional Bragg reflector.

In this Letter, we proposed a subwavelength binary blazed grating coupler for efficient, high performance and vertical coupling. We studied the performance of this grating coupler by simulation and optimum design with coupling efficiencies exceeding 65% at a wavelength of 1.55 $\mu m$ with an 80 nm wavelength bandwidth of 1 dB. The coupling efficiency can reach up to about 80% if the reflector layer is adopted. Because of the mature

**Fig. 3.** (Color online) Distribution of the optical field in the waveguide.

**Fig. 4.** (Color online) Relationship of coupling efficiency and wavelength for $T = 0.6 \mu m$, $h = 0.22 \mu m$, $d = 0.12 \mu m$, and $w = 0.9 \mu m$.

**Fig. 5.** (Color online) Relationship of coupling efficiency and incident angle for $T = 0.6 \mu m$, $h = 0.22 \mu m$, $d = 0.12 \mu m$, $w = 0.9 \mu m$, and $\lambda = 1.55 \mu m$.

**Fig. 6.** (Color online) Relationship of coupling efficiency and period for $h = 0.22 \mu m$, $d = 0.12 \mu m$, $w = 0.9 \mu m$, and $\lambda = 1.55 \mu m$.

**Fig. 7.** (Color online) Relationship of coupling efficiency and etching depth for $T = 0.6 \mu m$, $h = 0.22 \mu m$, $w = 0.9 \mu m$, and $\lambda = 1.55 \mu m$.

**Fig. 8.** (Color online) Multilayer reflector deposited in the substrate to enhance the coupling efficiency.
fabrication process suitable for mass production of the etched silicon grating as a beam coupler, it is easy to realize large-scale integration with other photoelectronic elements due to vertical coupling. This device should have potential applications in the future. Experiments are being carried out and results will be presented soon.

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References
Queries

** Your paper is longer than three pages. You must shorten it by the 50 lines on p. 4. There are no exceptions. Publication will not proceed until a long proof has been shortened.

1. Please check that “vertical coupling” is correct in the title, instead of “vertical couple.”
2. Two things in “However, it is complicated in the packaging of the photonic integrated circuit.” (1) What does “it” refer to? (2) Not sure what “complicated in the packaging of” means. Should “packaging” be “preparation”? or should the phrase be “complicated /by/ the packaging”?
3. What is “Ey”?
4. Is 11 a published proceeding? If so, please provide publisher and page or paper number. If not, please provide paper title and meeting location and dates.
5. Please provide report title at [14].