Gratings are an efficient means of coupling light between optical fibers and high-index-contrast waveguides, such as silicon-on-insulator (SOI) [1,2]. 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]. An alternative method is to etch a deep slit in front of the grating, 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. In [10], a shallow-etched diffractive waveguide grating coupler was proposed that 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]. More recently, other strategies have also been considered to settle these problems [12,13]. In general, although high efficiencies can be obtained, these technologies are not complementary metal-oxide semiconductor compatible or are very complex, making fabrication and integration with other elements difficult.

In this Letter, we present a new design 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.

In our previous works [14–16], 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 \( \Delta_1 \) and \( \Delta_2 \), with the same etching depth \( d \), but with different widths and fill factors. The thicknesses of the waveguide and 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:

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

where \( h \) is the thickness of waveguide. \( n_c \) 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

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

![Fig. 1. (Color online) Structure of binary blazed grating coupler.](image-url)
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 [17,18]

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

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 [14].

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 height of each of the discrete multilevel grating is \( h_i \) \((i = 1, 2, 3,...N)\). \( H_3 \) denotes the height of the binary subwavelength blazed grating, and the fill factor of each subperiod is \( f_i \) \((i = 1, 2, 3,...N)\). Then

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

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

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

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

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 \( N = 2 \):

\[
f_i = \frac{\left( \frac{2i - 1}{4} \frac{H_1}{H_3} (3.5 - 1) + 1 \right)^2 - 1}{3.5^2 - 1} = \frac{\left( \frac{5}{8} (2i - 1) \frac{H_1}{H_3} + 1 \right)^2 - 1}{11.25}.
\]

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

\[
f_2 = \frac{\left( \frac{15}{8} H_1 + 1 \right)^2 - 1}{11.25} \leq 1, \quad \text{thus} \quad \frac{H_1}{H_3} \leq \frac{4}{5} \approx 1.3.
\]

In our design, \( H_1/H_3 = 1.1 \) and \( H_2 = 0.12 \mu m \). 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 69% when we consider the TE mode and normal incidence. \( E_y \) and the 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

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

![Fig. 3. (Color online) Distribution of the optical field in the waveguide.](image)

<table>
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<tr>
<th>Parameter</th>
<th>Value</th>
<th>( T )</th>
<th>( h )</th>
<th>( d )</th>
<th>( w )</th>
<th>( \Delta_1 )</th>
<th>( \Delta_2 )</th>
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Table 1. Design Parameters of Binary Blazed Grating Coupler (Unit: Micrometers)
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 \( \mu \text{m} \) to 0.137 \( \mu \text{m} \). 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 (\( n_{\text{Si}} = 3.5 \)) and SiO\(_2\) (\( n_{\text{SiO}_2} = 1.45 \)) layers are 0.11 and 0.267 \( \mu \text{m} \), respectively. 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 with coupling efficiencies exceeding 69% at a wavelength of 1.55 \( \mu \text{m} \) with an 80 nm wavelength bandwidth of 1 dB. The coupling efficiency can reach up to about 80% if the reflector layer is adopted. This device should have potential applications in the future. Experiments are being carried out and results will be presented soon.