# Symmetrical fully-etched and chirped beam splitter based on a subwavelength binary blazed grating*

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A novel symmetrical chirped beam splitter based on a binary blazed grating is proposed, which adopts the fully-etched grating structure compatible with the current fabrication facilities for CMOS technology and convenient for integration and manufacture process. This structure can realize nearly equal-power splitting operation under the condition of TE polarization incidence. When the absolutely normal incidence occurs at the wavelength of 1580 nm, the coupling efficiencies of the left and the right branches are 43.627% and 43.753%, respectively. Moreover, this structure has the tolerances of 20 nm in etched depth and 3° in incident angle, which is rather convenient to manufacture facility.
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Beam splitters can split an incident light beam into two or more beams[1-4]. With the development of the theory of silicon photonics and the technology of micro and micro-nano fabrication, more and more attention is paid to the subwavelength microstructure gratings. In particular, the subwavelength binary blazed grating attracts more interests than the common grating due to its high diffraction efficiency in a specified order. For instance, Feng et al[4] demonstrated a polarization beam splitter using a binary blazed grating coupler with high coupling efficiency and good extinction ratio. Yang et al[5] proposed a subwavelength binary blazed grating coupler with coupling efficiency exceeding 65% at the wavelength of 1.55 μm with a 1 dB wavelength bandwidth of 80 nm. Meanwhile, Chen et al[6] proposed a 1 × 2 waveguide splitter/combiner which is based on an etched chirped grating on the waveguide. However, all the mentioned studies concentrated on the etching of shallow and slanted slots into the waveguide or cladding, which have the problem of the etch-stop layer. In the manufacture process, it's difficult to control the etch-stop layer. Therefore, more and more attention is transferred to the fully-etched grating structure without etch-stop layer, which can be fabricated in only one lithography step. Bernd Schmid et al[7] proposed a grating coupler with fully-etched slots, and obtained theoretical maximal coupling efficiency of 49% with a 3 dB bandwidth of 35 nm. Due to the strongly periodic perturbation of the index contrast in the fully-etched slots, it is difficult to couple the light into the grating from the slab waveguides, which results in the low efficiency of the fully-etched grating device.

In this paper, we propose a novel symmetrical chirped grating beam splitter with fully-etched slots, which has the advantages of fully-etched process, high diffractive efficiency of binary grating and easy integration of vertical coupling structure compatible with the current fabrication facilities for CMOS technology. A combination of effective-medium theory and rigorous coupled-wave theory is applied to the design and analysis of this beam splitter. The simulation results are obtained by the finite-difference time domain (FDTD) method, which indicate that the structure can realize the beam's symmetric splitting and has a rather large fabrication tolerance. Moreover, the influence of design parameters on the coupling efficiency is also discussed in detail.

The proposed symmetrical chirped grating beam splitter is depicted in Fig.1. Based on silicon-on-insulator (SOI) waveguide structure, it consists of a fully-etched grating on the top of the silicon waveguide layer, a buried oxide layer and a silicon substrate layer. The core of the beam splitter is the grating structure which consists of two symmetrical chirped subwavelength binary blazed gratings. The chirped grating is the grating with variable density of grating grooves[8]. In our beam splitter, $H$ and $L$ are the height of the fully-etched grating (thickness of the waveguide layer) and the thickness of the buried oxide ($SiO_2$), respectively. $T$ denotes the period of the grating, which is divided into $M$ subperiods with the widths of

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$w_i$ ($i$=1, 2, 3, 4). $W$ is the length of device. The chirped grating beam splitter is essentially composed of two mirror-symmetric binary blazed grating couplers which have the same parameters. The symmetric structure can realize the symmetric splitting of the beam, because part of the incident light is coupled into the right side by the right side of the grating region, and other part of the incident light is coupled into the left side by the left side of the grating region. Thus, the basic theory is analyzed on the basis of the binary blazed grating coupler which is shown in Fig.1(b).

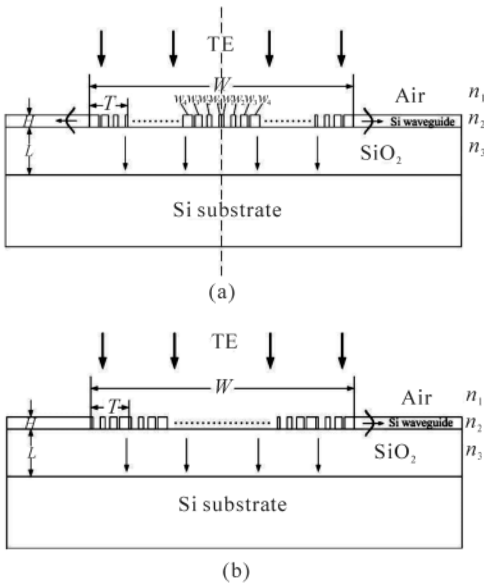


**Fig.1 Schematic diagrams of (a) the beam splitter and (b) the grating coupler**

It is well known that the grating period $T$ can be explained by the phase match condition between the gratings and the waveguide mode (i.e. the Bragg condition)[9]:

$$K_{in} + mK_T = \beta \,, \tag{1}$$

where $K_{in} = |\boldsymbol{K}_{in}| \times \sin\theta = 2\pi n_1 \sin\theta / \lambda$ is the incident wave vector, $n_1$ is the refractive index of air, $K_T = 2\pi/T$ is the reciprocal lattice vector of the grating, $\beta = 2\pi N_{eff}/\lambda$ is the propagation constant of the guided mode in the grating waveguide, $N_{eff}$ is the effective refractive index of the waveguide for the propagating mode, $m$ is the diffraction order which is set to -1, and $\theta$ is the incident angle. The wave-vector diagram which means an intuitive representation of the Bragg condition for the grating coupler is presented in Fig.2[10].

In this paper, the incident wave is designed as normal incidence in which $\theta$ is equal to 0. According to Eq.(1), the grating period $T$ can be rewritten as

$$T = \left| \frac{\lambda}{N_{eff}} \right| , \tag{2}$$

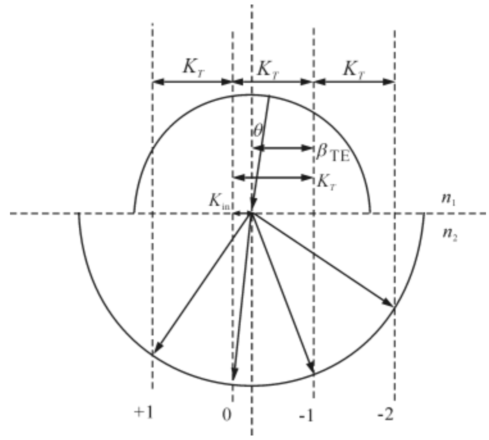


**Fig.2 Wave-vector diagram for the grating coupler**

where $N_{eff}$ can be obtained from the mode dispersion equations of slab waveguide[11]

$$(n_2^2 - N_{eff}^2)^{\frac{1}{2}} \frac{2\pi}{\lambda} H = n\pi + \tan^{-1}\left(\frac{N_{eff}^2 - n_1^2}{n_2^2 - N_{eff}^2}\right)^{\frac{1}{2}} + \tan^{-1}\left(\frac{N_{eff}^2 - n_3^2}{n_2^2 - N_{eff}^2}\right)^{\frac{1}{2}} , \tag{3}$$

where $n_2$ and $n_3$ are the refractive indices of Si and $SiO_2$, respectively. $n$ is the mode ordinal number, which is a non-negative integer. When the incident wavelength is 1.55 μm, the cut-off thickness of the waveguide layer for TE first-order mode is 270 nm[12]. Due to the structure is fully-etched, the thickness of waveguide layer is equal to $H$, i.e., $H$ should be less than 270 nm. The thickness of 210 nm is chosen as a start point of simulation in this paper.

Due to the beam splitter is a mirror-symmetric structure, the incident angle should be 0° so that the output energies at the left end and the right end of waveguide are distributed equally. The grating period can be calculated by Eqs.(2) and (3) with the parameters of $n_1$=1, $n_2$=3.48, $n_3$=1.48, $\lambda$=1.55 μm and $\theta$ = 0°. In order to obtain more ideal results and facilitate the subsequent simulation, the optimum grating period is fixed at 0.7 μm in the simulation.

Another important parameter is the fill factor. Every period of the binary grating is divided equally into $M$ subperiods with the width of $p = T/M$. The fill factor of each subperiod, i. e., $f_i$ ($i$=1, 2, 3,⋯, $M$), is defined as the ratio of the pillar width to the grating subperiod. According to the localized effective refractive indices theory of binary gratings and the discrete processing of signal phase, the fill factors can be computed by[13]

$$n_{eff(i)}^{TE} = \sqrt{f_i n_2^2 + (1 - f_i) n_1^2} \,. \tag{4}$$

In this structure, the number of subperiods in one period is set to 4, and $f_4$ is set to 1, then the rest fill factors can be fixed.

So the width of each pillar can be obtained, and $f_1 = 0.075, f_2 = 0.293, f_3 = 0.601$.

As the $SiO_2$/Si substrate can be treated as a reflector, the coherence stack (interference) can happen between the incident light and the reflected light. When the incident light and the reflected light satisfy the phase match condition (interference condition), the light field can be enhanced strongly, and the coupling efficiency increases. Otherwise, the coupling efficiency decreases when the phase match condition is not satisfied. Therefore, the grating coupling efficiency changes periodically as a function of the $SiO_2$ layer thickness. The optimum thickness of $SiO_2$ layer is fixed at 1.2 μm in the simulation.

The numerical simulation based on the binary blazed grating coupler is done before the analysis of the beam splitter, which is useful to optimize the structure of the beam splitter. Based on the optimized grating period, fill factor, incident angle, grating height and $SiO_2$ layer thickness, the Poynting vector distribution of the coupling case is obtained by FDTD simulations. Obviously, the light propagates along the right direction as shown in Fig.3. In order to realize the symmetric splitting of beam, we choose the symmetrical structure which is shown in Fig.1(a), rather than the structure in Fig.4. Fig.5 shows the Poynting vector distribution of the beam splitter at the wavelength of 1.55 μm calculated by OptiFDTD software.

It is obvious from Eq.(2) that the incident wavelength is one of the core parameter of the phase match condition. The variation of the incident wavelength has great influence on the coupling efficiency. The coupling efficiency decreases due to the incident light can't be coupled into the waveguide very well, when the incident wavelength deviates from the

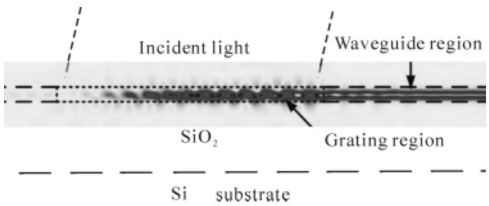


**Fig.3 Poynting vector distribution of the binary blazed grating coupler**

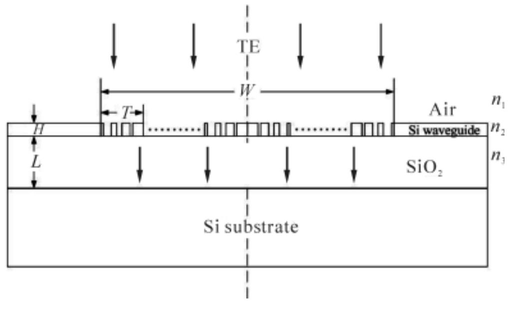


**Fig.4 Schematic diagram of the beam splitter for comparison**

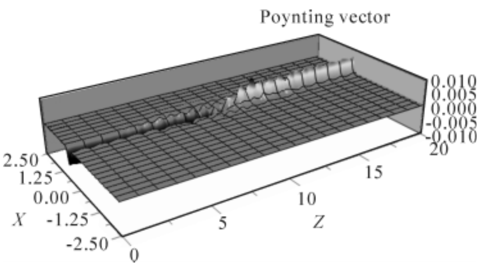


**Fig.5 Field distribution of the beam splitter**

optimum wavelength. The coupling efficiency as a function of incident wavelength is illustrated in Fig.6. As shown in Fig.6, when $\lambda$ is equal to 1580 nm, the coupling efficiencies at the left end and the right end of waveguide get their maximums which are 43.627% and 43.753%, respectively, which means that the difference of the coupling efficiencies between the two output ends is only 0.126%. Thus, the center wavelength of the beam splitter is 1580 nm. It also can be observed from Fig.6 that the maximum difference of the coupling efficiencies is 0.133% and the minimum value is only about 0.046%. It means that the beam splitter can realize the symmetric splitting of beam for the incident light with TE mode. Furthermore, Fig.6 indicates the coupling efficiencies of the two output ends decrease to 80% of the maximum value, when the wavelength changes to 1561 nm or 1592 nm, i.e., the 1 dB bandwidth of the beam splitter is 31 nm, which means the structure can effectively work when the wavelength is in the range of 1561−1592 nm.

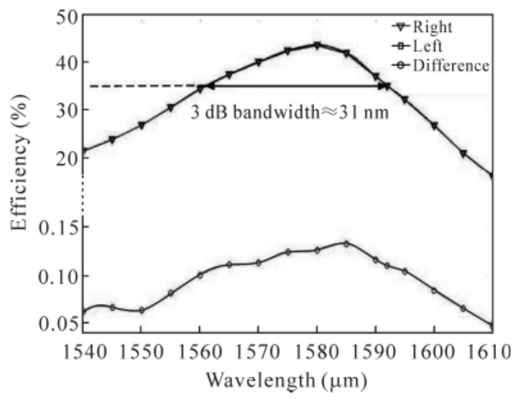


**Fig.6 Coupling efficiency as a function of wavelength**

Due to the small scale trench of the binary grating, the optical field is partly confined in the fully-etched grating slot. Because of the high-index-contrast at air/$SiO_2$ interface, the confined light reflects upwards at the lower interface of the slot. Then there is a strong coherence stack between the incident light and the confined light. As the grating height has significant influence on the distribution of the confined light, it should be carefully selected in order to achieve the best performance of beam splitter. According to Fig.7, the coupling efficiency changes by 20% when the grating height varying by 20 nm, which means that the coupling efficiency of this structure is very sensitive to the change of the grating height in a certain range. The optimal grating height is 210 nm. Fig.7 also indicates the coupling efficiencies of the two output ends decrease to 80% of the maximum value, when the grating height changes to 205 nm or 225 nm, which means this structure has a 1 dB fabrication tolerance of 31 nm in etching depth.

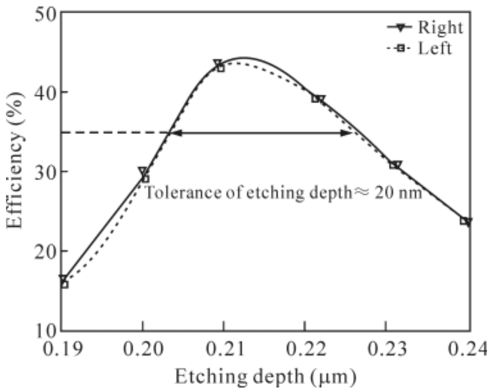


**Fig.7 Coupling efficiency as a function of grating height**

The coupling efficiency as a function of incident angle is illustrated in Fig.8, which indicates that the single side coupling efficiencies at the left end and the right end of waveguide can get their maximums when the incident angles are -4° and 4°, and the symmetric splitting of beam is realized under the condition of absolutely normal incidence. That is because the binary blazed grating coupler shown in Fig.3 realizes the best coupling effect when the incident angle is 4° rather than 0°. Fig.8 also shows that the difference of the coupling efficiencies between the two output ends is less than 10% when the incident angle is in the range from -1.5° to 1.5°, which indicates the tolerance of fabrication error can be up to 3º in incident angle.

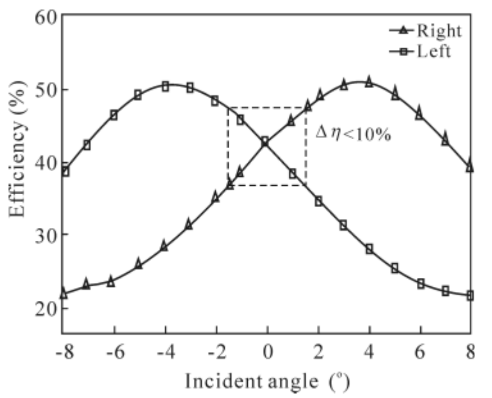


**Fig.8 Coupling efficiency as a function of incident angle**

We design a novel symmetrical chirped grating beam splitter which combines the advantages of fully-etched structure and binary blazed grating. This device is compatible with the current fabrication facilities for CMOS technology, and can be fabricated in only one lithography step. Moreover, the fully-etched structure doesn't need to consider the problem of etch-stop layer, which can significantly reduce the difficulty of fabrication. Besides, this device works particularly under the conditions of TE polarization and absolutely normal incidence which is available in integrated optics applications. The coupling efficiencies at the left end and the right end of waveguide can reach 43.627% and 43.753%, respectively under normal incidence at a wavelength of 1580 nm, and the difference of the coupling efficiencies between the two output ends is only 0.126%. It means that the summation of the energy of the two output ends is equivalent to more than 85% of the incident energy, and the coupling loss is particularly low. Moreover, this structure has tolerances of 20 nm in etched depth and 3º in incident angle, which brings convenience to manufacture facility. The beam splitter has wide prospects in applications, for example, it can be applied in optical interconnection networks and optical calculation.

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