A compact double-layer subwavelength binary blazed grating 1×4 splitter based on silicon-on-insulator

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Abstract: We describe a compact double-layer diffractive waveguide grating splitter which not only achieves efficient coupling between single mode fiber and a silicon-on-insulator optical waveguide, but also realizes effective splitting. By appropriate choice of waveguide/grating parameters including thicknesses, periods, height, and fill factor, to optimize the mode matching, and improve coupling efficiency and decrease the value of power difference of each output ports, a relative high coupling efficiency was obtained for each fiber/silicon waveguide interface. Simultaneously, the values of power difference of all outputs are significantly suppressed by optimizing design parameters and adopting double-layer architecture, leading to further enhancement of the coupling efficiency and splitting performance, which the maximum of power difference between four output ports is about 6.2%, however, the minimum value is only 0.6% or so. Moreover, the average power difference of four output ports is lower than 10% for TE polarization light over the 10 nm wavelength bandwidth centered at 1.54μm. In addition, the splitter structure designed here has the best tolerance for grating fabrication with deviations of grating depth 90nm.

1. Instruction

Silicon-on-insulator (SOI) waveguide shows great potential for high-density integrated circuits due to relatively low losses and high refractive index contrast, which has many promising applications [1-4]. SOI is also suitable to fabricate optical components and circuits using standard complementary metal-oxide-semiconductor (CMOS) technology. However, due to the high refractive-index contrast, there is a huge mismatch between the fundamental mode of SOI waveguide and the mode of optical fiber. This makes an effective optical coupling in and out of silicon photonic circuits is still a big challenge. That is to say, grating couplers, performing as an attractive vertical coupling scheme for the silicon waveguide, have been widely demonstrated. The advantages like the capability of on-wafer testing, potential implementation of low-cost packaging [5], and the versatility as a duplexer [6], a polarization beam splitter [7,8], or a power splitter [9] make the grating coupler an important component for the photonic integrated circuits.

A beam splitter is a key element in the fiber-optic components industry, especially in devices such as switches, routers, and isolators [10-12]. These applications require that a splitter provide low power-difference ratios, tolerate a wide angular bandwidth, have a broad wavelength range of incident waves, and be compact for efficient packaging. Conventional beam splitters are based on the use of the natural birefringence of some crystals or on the polarization properties of multilayer dielectric coatings [13,14]. However, these crystals require a large thickness to generate enough walk-off distance between the two orthogonal polarizations owing to intrinsically small birefringence of the naturally anisotropic materials. Simultaneously, the fabrication of such a multilayer slab structure is a tedious and long process.

With the development of microfabrication technologies, subwavelength gratings (SWGs) have attracted more and more attention. SWGs are expected to realize special optical functions based on their form-birefringence effect. Moreover, their compact size and light weight are advantageous to the miniaturization and integration of optical systems. Consequently, the beam splitter based on SWGs, which may be an alternative design, have been recently developed and researched due to their cost is low, and they are compact and suitable for mass reproduction.

In this Letter we propose a novel compact 1×4 beam splitter with a high performance based on the form birefringence of a SWG. A combination of effective-medium theory (EMT) and rigorous coupled-wave theory (RCWT), is applied to the design and analysis of this beam splitter. Finally, the simulation results are obtained by finite difference time domain (FDTD) method.

2. Single-layer 1×2 splitter

In many applications, the signal beams needs to be coupled into waveguides first for further processes so additional couplers are needed. Thus, we discuss firstly a special SWG device which simultaneously acts as coupler and splitter. In general, a conventional binary blazed grating is often to be used a directional coupler, which can not only couple signal beam into waveguide, but also modulate and control beam transmitting through waveguide along a particular direction [15-17]. However, we optimize firstly the design parameters, and a single-layer SWG coupler and 1×2 splitter can be obtained as shown in Fig.1. A signal beam from fiber is vertically coupled into Si waveguide and effectively split to the right and the left two beams. Obviously, a binary blazed architecture is adopted and explored here, which has an identical etching depth and a period consists of four sub-gratings with different fill factor and ridge width [15,18-19]. In other words, the number of sub-grating *N* is equal 4.

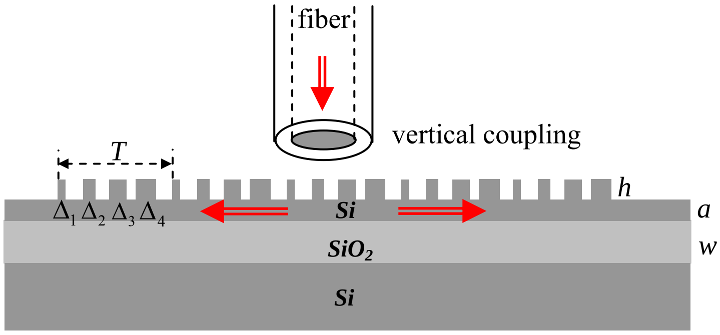


Fig.1 Single-layer 1×2 grating splitter

a and *w* is the thickness of Si waveguide and the buried oxide (SiO_2), respectively. *T* denotes the period of grating. Δ_1, Δ_2, Δ_3 and Δ_4 is the corresponding sub-period, respectively. *h* is the etching depth of grating. According to planar waveguide theory, the effective refractive indices (ERIs, N_{eff}) of TE mode as a function of wavelength and the depth of waveguide satisfy the following equations:

$$(n_w^2 - N_{eff}^2)^{1/2} . \frac{2\pi}{\lambda} a = m\pi + \tan^{-1}[C_1 . (\frac{N_{eff}^2 - n_c^2}{n_w^2 - N_{eff}^2})^{1/2}] + \tan^{-1}[C_2 . (\frac{N_{eff}^2 - n_s^2}{n_w^2 - N_{eff}^2})^{1/2}] \quad (1)$$

$$C_1 = C_2 = 1 \qquad (TE \quad mode)$$

Thus, for SOI planar waveguide structure, n_{Si}=3.5， n_c=1(air)， n_{siO2}=1.45, we can obtain the effective refractive index of TE mode when the depth of waveguide is equal to 300nm, and λ=1550nm. Furthermore, according to the phase match condition between the gratings and the waveguide mode, the grating period, denoted *T*, should be:

$$T \times (N_{eff} - n_1 . \sin\theta) = m\lambda \qquad (m = 0, \pm 1, \pm 2 ...) \quad (2)$$

Therefore, when we consider normal incidence and vertical coupling, i.e. $\theta = 0$， $m = 1$, the grating period T also be acquired based on above equation (1) and (2).

Finally, the fill factor of grating, which is defined as the ratio of pillar width to grating sub-period, is also obtained in terms of the localized effective refractive indices theory of binary gratings and the discrete processing of signal phase [15,18-19].

$$n_{eff} = \sqrt{fn_1^2 + (1-f)n_2^2} \tag{3}$$

wherein f denotes the fill factor of grating. Thus, the ridge of each sub-gratings can also be obtained according to equation (2) and (3).

Furthermore, if the output laser is a Gaussian beam and its beam waist is ω_o, the theoretical optimal grating coupling length L satisfies the following equation

$$\omega_0 = 1.37 L \cos\theta \tag{4}$$

We use optical simulation software based on the finite-difference time domain (FDTD) technique for the grating coupler design. We launch an incident light at 1.55μm for TE polarization (transverse electric field, E-field parallel to the grating grooves) with normalized power one, then detect the amount of light coupled into waveguide, and further calculate the coupling efficiency (η).

According to above theoretical analysis, we take these parameters given in Table 1 as a starting point for simulation.

Table 1 the corresponding parameters to simulation. Unit: μm

	λ	*T*	*h*	*N*	*a*	*w*	*L*	f_i (i =1,2,3,4)			
value	1.55	0.493	0.3	4	0.3	0.9	16	0.018	0.071	0.144	0.239

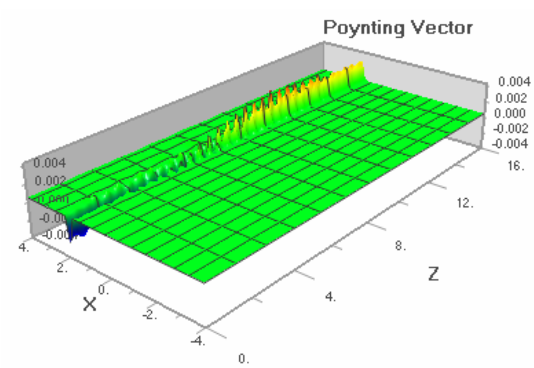
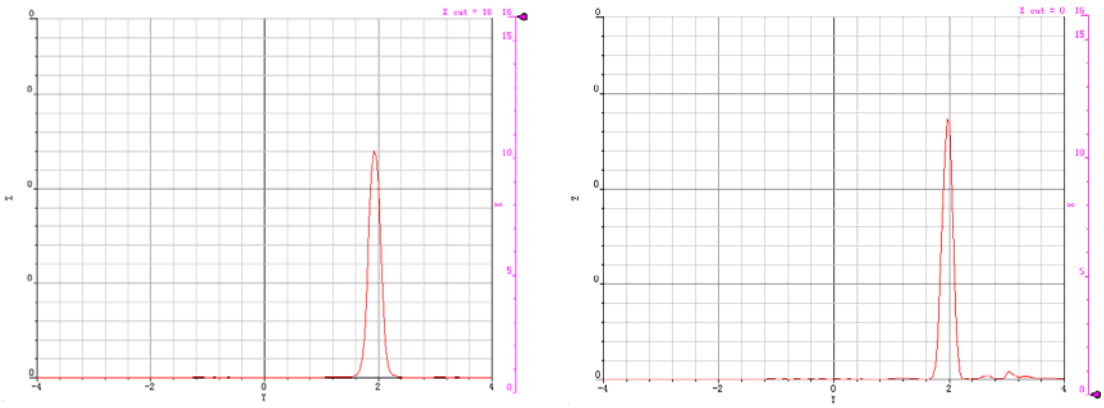


Fig.2 The distribution of poynting vector Sz

For TE polarization, using FDTD to simulate the distribution of poynting vector Sz in Si waveguide, and compute the coupling efficiency. We can obtain the results as shown in Fig.2.

Furthermore, the coupling efficiency of the right and the left branches of waveguide is 27% and 28%, respectively. Obviously, the difference value of coupling power between two branches is only 1%. Their corresponding output wave profile of two branches is given Fig. 3. Consequently, this type of single-layer subwavelength binary blazed grating can realize equal power coupling and splitting operations. That is to say, it is a typical 1×2 splitter.



(a) the right port (b) the left port

Fig.3 compared with output wave profile between two branches

3. Double-layer 1×4 grating splitter

Based on above identical design and principle, double-layer grating structure is proposed firstly, which consists of two same binary blazed grating as shown in Fig. 4.

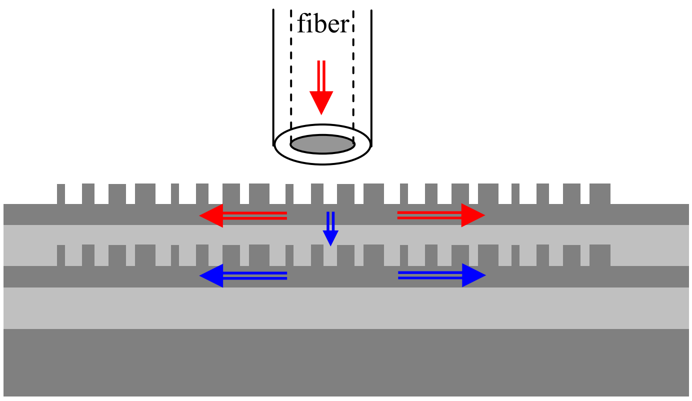


Fig.4 Double-layer binary blazed grating structure

In theory, after part of incident power is coupled into the upper waveguide, the residual part will pass through and flow into the lower grating layer, thus, is coupled into the second layer Si waveguide. The distribution of optical field within double-layer grating also is given in Fig.5.

Obviously, the incident light is split into four beams, which transmit along the right and the left branches of the upper and the lower layer waveguide, respectively.

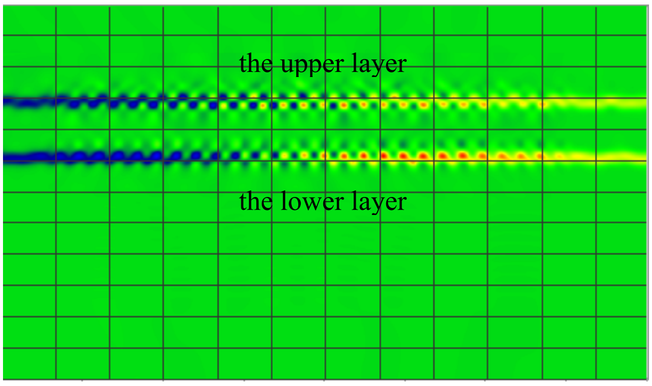
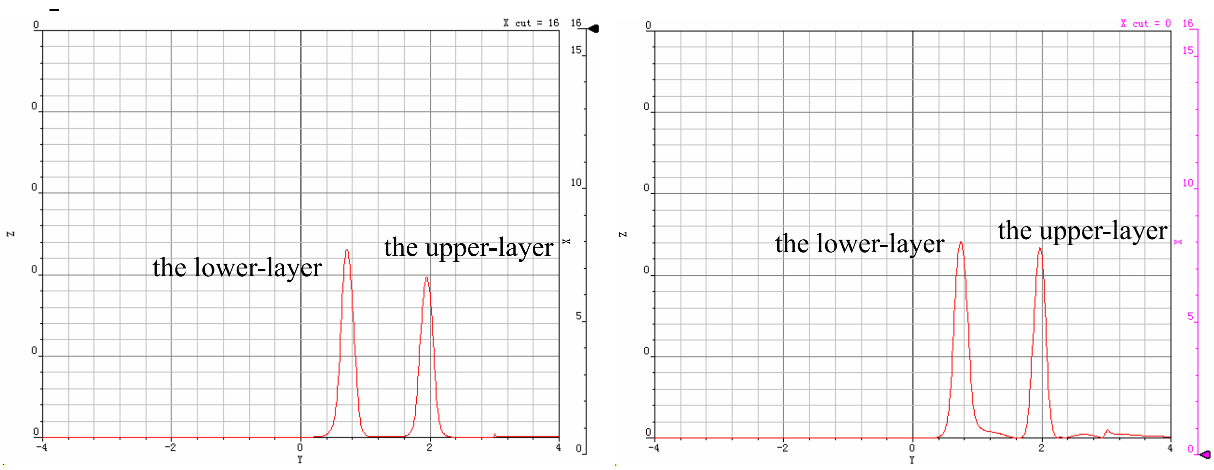


Fig.5 The distribution of optical field within double-layer grating

In order to explore the properties and performances of splitter designed here, it needs to compare with the wave profile and the distribution of power between four output ports. Thus, the wave profiles of the right and the left branches are given in Fig. 6, respectively.



(a) the right port

(b) the left port

Fig. 6 the wave profiles of the right and the left branches

Note that the total power coupled in waveguide was normalized to be 1, then, the coupling power of each port is given in Table 2, respectively. ∇_{port} denotes that the power difference of the identical-side's output port, however, ∇_{layer} indicates the power difference of the identical-layer's output port. Obviously, the power difference between the right and the left output ports of the upper layer and the lower layer (∇_{layer}) both are only around 2.8%. Simultaneously, the power difference between the upper and the lower layer of the right and the left output port (∇_{port}) both are only about 3.4%. Furthermore, the maximum of power difference between four output ports is clearly about 6.2%, however, the minimum value is only 0.6% or so. Consequently, this double-layer subwavelength binary blazed grating well functions as a 1×4 beam splitter according to above discussions because it is nearly satisfied with equal-power output. It is compact in structure capable of integration with other photonic devices; moreover its corresponding energy loss and crosstalk are relatively low. Thus, its corresponding available number of channels is high.

Table 2 normalized power value of each port

	the right port	the left port	∇_{layer}
the upper layer	0.219	0.247	0.028
the lower layer	0.253	0.281	0.028
∇_{port}	0.034	0.034	

4. Discussions

(1) the relationship between normalized power and wavelength

The relationship of normalized power as a function of wavelength is shown in Fig. 7.

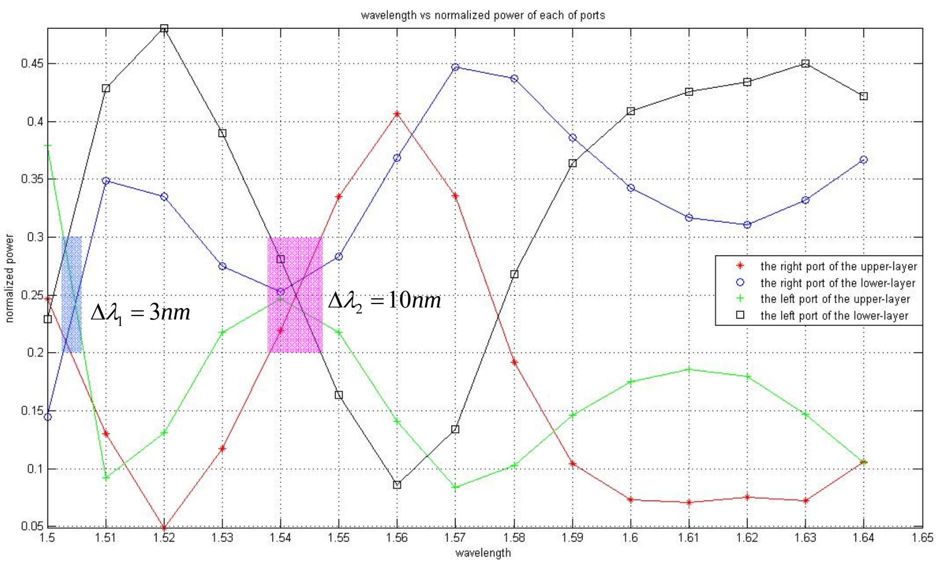


Fig.7 the relationship between normalized power and wavelength

According to simulation and computing results, we know that the power difference of four output ports is less than 10% when the wavelength is in range of $1.502\mu m-1.505\mu m$ and $1.538\mu m-1.548\mu m$. Thus, the wavelength bandwidth is about 3nm and 10nm, respectively.

(2) the depth of grating versus normalized power

The normalized power as a function of the depth of grating is also discussed when $\lambda=1.55\mu m$, the width of Si waveguide is equal to 0.3μm, and the height of SiO_2 layer is 0.9μm. The corresponding relationship curve is given in Fig. 8.

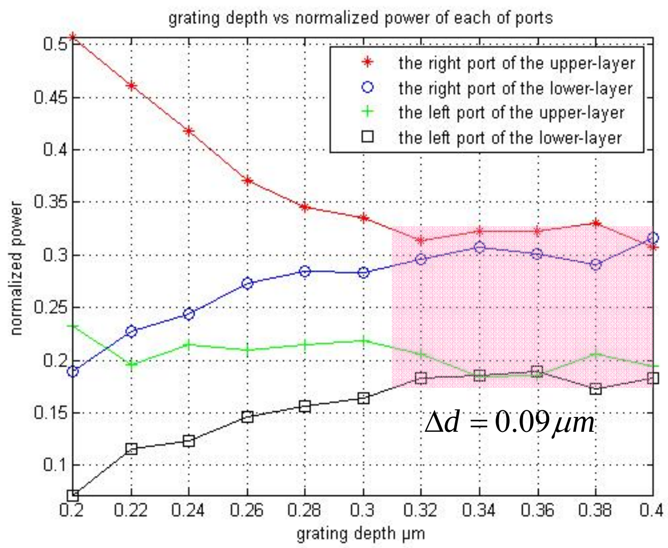


Fig.8 the relationship between normalized power and grating depth

The simulation results show that the power difference of four output ports is less than 15% when the grating depth changes within range of $0.31\mu m-0.40\mu m$. The double-layer binary blazed grating splitter designed here is tolerant of deviations of grating depth ($\Delta d=0.09\mu m$). That is to say, this splitter is broadband and immunity to depth errors.

5. Conclusions

In conclusion, we have proposed and numerically demonstrated a two-layer grating coupler used as a 1×4 beam splitter. It can vertically couple light into two-layer waveguides while splitting them, which is very useful in integrated optical circuits. Very low power difference is achieved by optimizing design parameters, which can nearly realize equal power splitting. Simultaneously, the coupling efficiency can also be further improved by using a distributed Bragg reflector or a subwavelength grating mirror fabricated under the waveguide. In addition, 1×4 beam splitter can be operated with an optical signal of wide etching depth tolerance and relatively broad wavelength range. The most extraordinary and excellent property of this embedded splitter is that it can be combined with other optical elements and can be placed anywhere on a chip because it allows planar coupling, which makes the system design more flexible. These features make this device desirable for use in optical communication as well as other optical information processing applications.

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