Broadband non-polarizing beam splitter based on guided mode resonance effect*

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A broadband non-polarizing beam splitter (NPBS) operating in the telecommunication C+L band is designed by using the guided mode resonance effect of periodic silicon-on-insulator (SOI) elements. It is shown that this double layer SOI structure can provide ∼50/50 beam ratio with the maximum divergences between reflection and transmission being less than 8% over the spectrum of 1.4 μm∼1.7 μm and 1% in the telecommunication band for both TE and TM polarizations. The physical basis of this broadband non-polarizing property is on the simultaneous excitation of the TE and TM strong modulation waveguide modes near the designed spectrum band. Meanwhile, the electric field distributions for both TE and TM polarizations verify the resonant origin of spectrum in the periodic SOI structure. Furthermore, it is demonstrated with our calculations that the beam splitter proposed here is tolerant to the deviations of incident angle and structure parameters, which make it very easy to be fabricated with current IC technology.

Keywords: non-polarizing beam splitter, guided mode resonance, silicon-on-insulator, rigorous coupled-wave analysis

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1. Introduction

It is known that the guided mode resonance (GMR) effect can be exhibited in sub-wavelength periodic elements.[1−6] The reflection or transmission spectra can show different characteristics when the diffracted orders of periodic structures couple with the waveguide or leaky modes supported by the equivalent waveguide structure. Optical elements under leaky or GMR conditions can produce versatile spectra properties. Based on the above physical mechanism, we can apply the sub-wavelength periodic structures to design a variety of elements including bandstop, band pass filters, wideband reflectors, polarizes, polarization dependent and independent elements,[7] which possess numerous applications in the fields of laser mirror, biosensor, tunable filters, security devices, optical communication, display and others.[7−10]

The non-polarizing beam splitter (NPBS), which separates an input beam into two beams traveling in different directions regardless of their polarization, is a very important element in optical communication and photonic systems.[11−13] A traditional NPBS is designed and fabricated at the normal or oblique angle with thin film technology. The common power division fraction is 50 to 50 for both TE and TM polarizations in a relatively wide wavelength range. These devices consist of stacks of homogenous layers deposited with precise thickness and accurate control of refractive indices and absorption of material. In addition, since different material constitutions are involved in the fabrication of such NPBS structures, problems such as cohesion, stability and thermal expansion mismatches are commonly existent.[11] Furthermore, it is not easy to integrate them into an optical communication system because their large structural dimensions. In addition, for common NPBSs made with multilayer thin film stacks, the wavelength range is only about dozens of nanometers. To further enlarge the spectral band, the structure of the element will become very complicated, which greatly hinders the application of such elements.

Based on the GMR effect of a periodic structure, we propose a broadband NPBS operating in the telecommunication band. This sub-wavelength element is composed of a double-layer SOI structure.

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If TE and TM waveguide modes are excited simultaneously around the designed wavelength range, the sideband spectrum between two resonant peaks can be lifted up since strong modulation modes are involved in the process. Through proper design of such structures, a wideband non-polarizing property can be present in the designed wavelength range. Therefore, the simultaneous excitation of strong modulation waveguide modes around the designed wavelength range plays a key role in the design of such wide band non-polarizing elements.

2. Numerical analysis and simulation

The structure, illustrated in Fig. 1, is a typical strongly modulated SOI waveguide grating with a modulation strength (defined by $\Delta\varepsilon = n_{\rm h}^2 - n_{\rm l}^2$) of 11.11. To design this structure, the incident and substrate media are assumed to be air ($n_{\rm inc} = 1$) and silica ($n_{\rm sub} = 1.48$). The refractive index of silicon (Si) is taken to be 3.48. The refractive indices of the grating ridge and the sublayer possess the same amount of silicon. The structure is illuminated from the top side at the normal incident angle. The resonant line-width, mainly determined by fill ratio f and the grating depth d_1, is not a very important aspect to be considered since the sideband between two resonant dips for TE and TM waveguide modes mainly contributes to the design of an NPBS. We can give relatively reasonable values to the above two variables in advance. In addition, the resonant wavelength $\lambda_{\rm re}$ is a key point for element design, which is primarily determined by the grating period T. For TM polarization, a rough relation between $\lambda_{\rm re}$ and T can be given as follows:

$$\lambda_{\rm re} = n_{\rm sub} T. \tag{1}$$

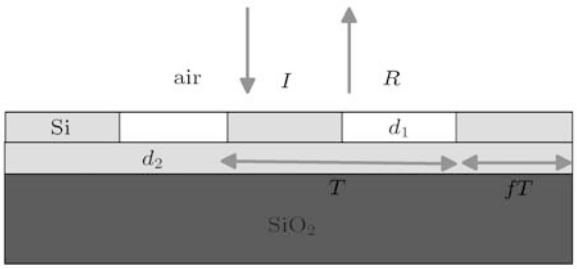


Fig. 1. Schematic diagram of the double-layer silicon-on-insulator structure. T and f are period and fill ratio respectively, d_1 and d_2 represent the grating thickness and depth of waveguide layer, respectively. I and R denote the incidence and reflection, respectively.

For simplifying the analysis process, only TE0 and TM0 modes are considered in our design. If the NPBS is working in the telecommunication band, the position of resonant wavelength for TE0 and TM0 waveguide modes can be designed in or near this designed range. Generally speaking, if the resonant wavelength is longer or shorter than the upper or lower limit of the designed range for TE and TM polarizations, we can obtain a wider bandwidth.

To excite the waveguide modes around this band, we first calculate the logarithmic transmission spectrum versus incident wavelength and waveguide layer thickness, as shown in Figs. 2(a) and 2(b), for TE and TM polarizations, respectively, with RCWA formulation,[14−18] from which we can clearly know the resonant wavelength and its corresponding depth of waveguide layer d_2. Numerous slant shaped low transmission loci reveal the sharp resonant position for each polarization. For convenience, only TE0 and TM0 waveguide modes are considered in our analysis. We may choose a waveguide layer thickness in which the spectrum band between resonant dips for TE and TM leaky modes can just cover or are larger than the designed wavelength range. For example, if the depth of waveguide layer is tuned to about 75 nm, the resonant wavelength for the TM0 waveguide mode can be designed as 1315 nm, thus the corresponding wavelength for the TE0 mode is about 1800 nm. Therefore, under this waveguide thickness, the spectral range between TE0 and TM0 resonant peaks cover the whole designed wavelength band, and the structure has the ability to be designed as a non-polarizing element. In other words, this non-polarizing property is obviously related to the guided mode resonance of each polarization state.

As a rough design, the grating period is specified as $T = 880$ nm by using formula (1), the grating depth and fill ratio can be given relatively reasonable values, $d_1 = 70$ nm, $f = 0.5$. Figure 3(a) illustrates the reflection spectra for both TE and TM polarizations under this waveguide depth. It is clearly seen from this graph that there are two resonant dips in 1800 nm and 1315 nm for TE0 and TM0 waveguide modes, respectively, the sideband spectrum between the above two resonant dips are distinctly lifted up since the strong modulation modes are excited. Therefore, this overlap range can be treated as a nonpolarizing beam split region, which fully covers the telecommunication C+L band (the dark area drawn in the plot). Although the reflections between the above two resonant peaks ob-

scure the target reflections for both TE and TM polarizations, the double-layer SOI structure has possessed the ability to be designed as non-polarizing beam splitter. The reason for the deviation of reflections from the designed values is that the starting values of grating thickness and fill ratio are not optimized and were roughly estimated from our experience.

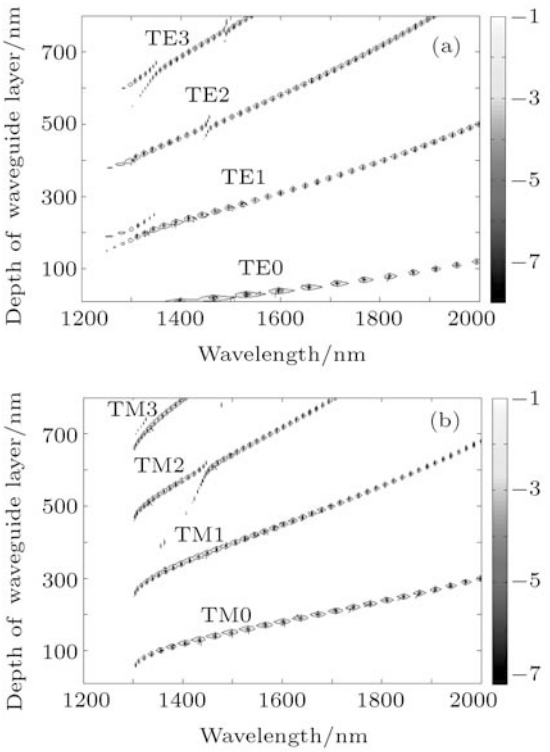


Fig. 2. (a) Logarithmic transmission spectrum of the SOI structure for TE polarizations: parameters are specified as $d_1 = 70$ nm, $T = 880$ nm, $f = 0.5$. (b) Logarithmic transmission spectrum of SOI structure for TM polarizations: parameters are specified as $d_1 = 70$ nm, $T = 880$ nm, $f = 0.5$.

To improve the performance of our NPBS, we calculated the grating parameters by using the optimizing method.[19] The values for grating thickness, waveguide depth and fill ratio are changed to 101 nm, 7 0nm, 0.3 after a minor optimization. The reflection and transmission spectra of TE and TM polarizations across the 1.4 μm∼1.7 μm optical wavelength range are shown in Fig. 3(b). As is seen, this structure can provide about 50∼50 beam ratio with the maximum divergence between reflection and transmission being less than 8% in the whole wavelength range. Moreover, the corresponding spectrum responses in the telecommunication C+L band are also plotted in Fig. 3(c), from which we can obtain an excellent NPBS with the maximum divergences between reflection and transmission being less than 1% for each polarization state. Thus, a high quality NPBS element based on guided mode resonance effect can be designed with a double-layer SOI structure.

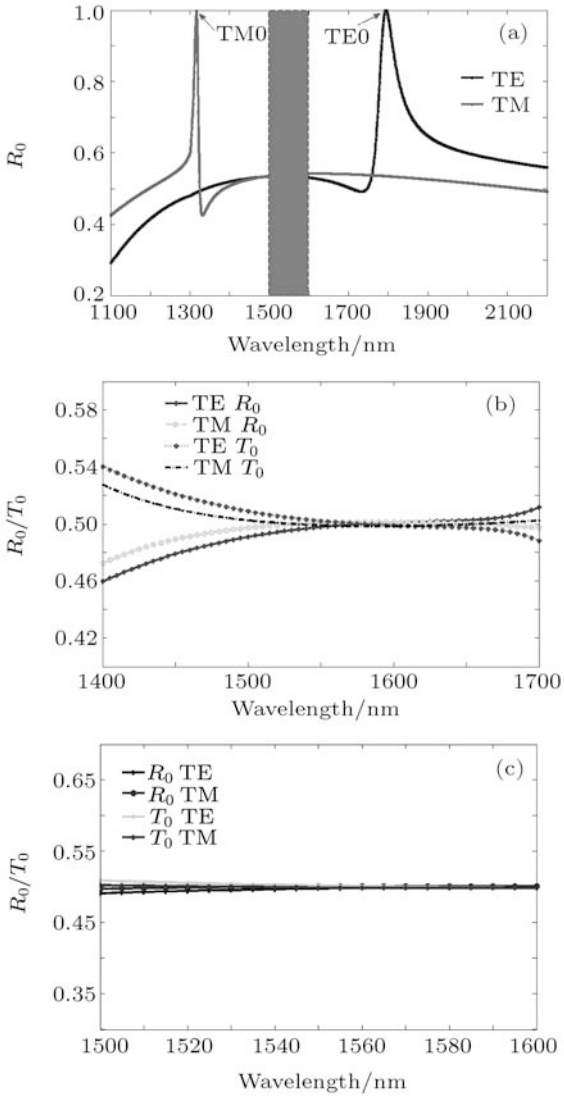


Fig. 3. (a) Reflection spectra for both TE and TM polarizations when the waveguide layer thickness d_2 is specified as 75 nm, other parameters are denoted as $d_1 = 70$ nm, $T = 880$ nm, $f = 0.5$. (b) Reflection and transmission spectra of TE and TM polarizations across the 1400 nm∼1700 nm optical wavelength range, other parameters are specified as $d_1 = 101$ nm, $d_2 = 70$ nm, $f = 0.3$. (c) Reflection and transmission spectra of TE and TM polarizations across the 1500 nm∼1600 nm wavelength range, parameters are the same as those in Fig. 3(b).

Figures 4(a) and 4(b) display the electric field distribution patterns at the resonant wavelengths of 1800 nm and 1280 nm for TE0 and TM0 waveguide modes, respectively. The near field distributions of this structure are obtained using the finite difference time domain (FDTD) for both TE and TM polarizations. The method models exactly the electromagnetic

wave interactions with arbitrary optical structures. It is shown that the guided-mode resonance splitter exhibits electric field enhancement and a laterally standing-wave field inside the waveguide layer at the resonant wavelength. Large modulation strength for SOI structure auguments the loss and hence reduces the order of the electric field of maximum amplitude, which can be controlled by the modulation strength of the dielectric constant of the grating.[20] Therefore, dominant and typical TE0 and TM0 waveguide modes are generated by the first evanescent diffraction order, which verifies that the non-polarizing property is no doubt associated with the leaky mode resonance. It is important to note that the TM0 resonant wavelength has changed from 1315 nm to 1280 nm because the optimizing grating parameters are used in our calculations.

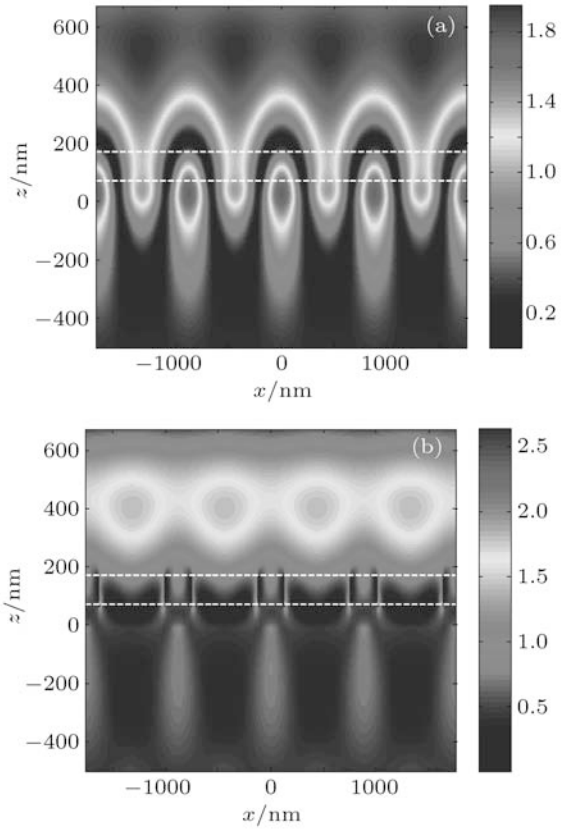


Fig. 4. (a) Amplitude of E_y field distribution, wavelength = 1800 nm, normal incidence, TE wave (the area between the two dashed lines is the waveguide layer with 101-nm thickness). Parameters are the same as those in Fig. 3(b). (b) Amplitude of E_x field distribution, wavelength = 1280 nm, normal incidence, TM wave. Parameters are the same as those in Fig. 3(b).

Next, we assess the angular sensitivity of the designed NPBS if the incident angle deviates slightly from its designed value. Figure 5 illustrates the reflection responses of this structure with respect to 6° deviations in the incident angle. It can be seen that the reflections are kept in the range between 0.49 and 0.52 of the wavelengths from 1.5 μm to 1.6 μm, which make it easily used in practical applications. This remarkably large angular response is mainly due to the co-existence and interaction of leaky modes.[21] To illustrate the effects of deviation from designed parameters on the performance of the element, we have investigated the reflection response of the proposed structure with respect to the depth of waveguide layer and fill ratio of the grating. Figures 6 and 7 represent the reflection spectra of the designed element for TE and TM polarizations, respectively. As can be seen, changes of ±10% in waveguide depth and ±30% in the fill ratio with respect to the designed values modify the reflection spectra slightly in the wavelength range of 1.5 μ ∼1.6 μm, which provides a favorable advantage in the fabrication process.

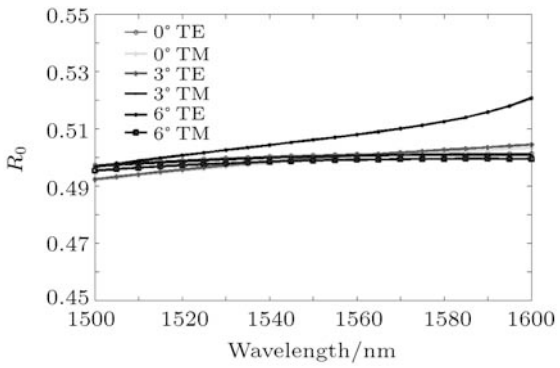


Fig. 5. Reflection responses of the SOI structure with respect to 6° deviations in the incident angle in the wavelength from 1500 nm to 1600 nm. Parameters are the same as those in Fig. 3(b) except for the incident angle.

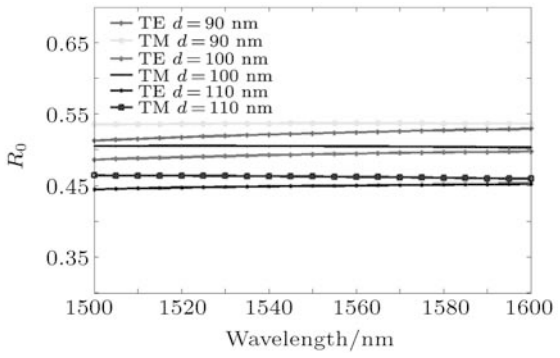


Fig. 6. Reflection responses of the SOI structure with respect to waveguide depth in ±10% change from designed value. Parameters are the same as those in Fig. 3(b) except for the waveguide depth.

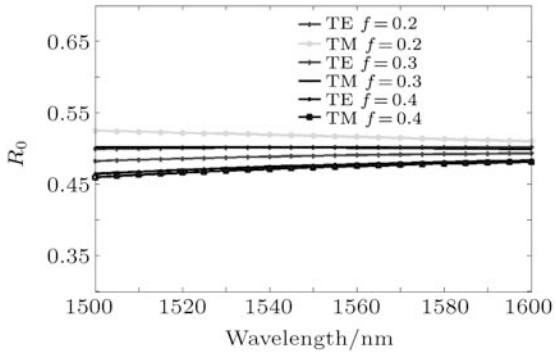


Fig. 7. Reflection responses of the SOI structure with respect to fill ratio of the grating in ±30% deviation from designed value. Parameters are the same as those in Fig. 3(b) except for the fill ratio.

3. Conclusion

In this paper, we introduced a new broadband non-polarizing beam splitter based on the guided mode resonance effect of an SOI structure. Exciting the waveguide modes near the designed wavelength range and optimizing the structure parameters properly, we can obtain a high quality NPBS in the desired wavelength band. Analysis of the proposed element shows that over a broadband spectrum of 1.5 μm∼1.6 μm, it demonstrates a large angular response, an excellent non-polarizing property, as well as remarkable tolerances to fabrication errors. This compact beam splitter is a new element with many potential applications in photonic systems. Current IC technology provides an effective fabrication process for such an SOI-based NPBS.

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