Polarization splitter/combiner in high index contrast Bragg reflector waveguides

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Abstract: Novel designs of polarization devices based on Bragg reflector waveguides in a high index contrast silicon-on-insulator (SOI) platform have been proposed. Brewster angle condition is incorporated in the periodic structures. Numerical simulations with a 3D semivectorial beam propagation method demonstrate the device performance as TE mode polarizer with high TE to TM extinction ratio and TE/TM mode polarization splitter and combiner with high polarization splitting efficiency.

OCIS codes: (230.7370) Waveguides; (230.1480) Bragg reflectors; (230.5440) Polarization-sensitive devices; (130.3120) Integrated optics device; (999.9999) photonic crystals

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1. Introduction

Bragg reflector or photonic crystal waveguides [1,2] and fibers [3,4] as well as Antiresonant Reflecting Optical Waveguides (ARROWs) [5-8] have attractive spectral and polarization properties suitable for photonic devices. These structures typically consist of a low index core with periodically alternating high and low index layers. The light is guided in the low index core through Bragg reflections from the periodic layers, a mechanism different from the total internal reflection. In practice, because of the limited number of periods, these Bragg structures support only leaky modes [2,5]. It was noticed before that thanks to the difference of the Fresnel coefficients for the two polarizations, ARROWs, which are Bragg reflector

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waveguides with very few periods, may be used as polarizers [5]. To further enhance the polarization properties of the Bragg fiber Brewster angle condition was incorporated in the design [4]. On the other hand, wavelength selective coupling between two adjacent ARROWs has been studied [6-8]. The polarization properties of designs based on grazing incidence and Brewster angle condition were studied by the authors [9,10]. A polarization splitter/combiner design based on these properties of Bragg reflector waveguides is proposed here for the first time, to the best of our knowledge.

In this work, we present polarization devices in high index contrast Bragg reflector waveguides based on periodically alternating high and low index layers at both sides of the low index guiding core. The designs incorporate Brewster angle condition and can be implemented as polarizers with a TE to TM extinction ratio of better than 22 dB and polarization splitters and combiners with coupling efficiency of 95% and TE to TM isolation of better than 30 dB within a propagation distance that depends on the design parameters. Simulations with a 3D semivectorial beam propagation method (BPM) of the proposed structures are presented.

The 3D semivectorial BPM method used computes the transmitted power in the guiding core with transparent boundary conditions where the radiation escapes the computational window without reflecting back into the structure. A 3D full vectorial BPM was used on a one-period structure and it was verified that there is negligible coupling between the two polarizations. Thus using the 3D semivectorial BPM saved significant computational time without affecting the accuracy. The fundamental guided mode of the waveguide has been computed using the correlation method which calculates the overlap integral between the launched Gaussian field and the propagating field at each point along the propagation direction. Through a Fourier transform of the correlation function the modal propagation constant is found and the fundamental mode field distribution is obtained through a second propagation with the known constant. A Gaussian of unit power was launched at zero angle centered on the low index core and the overlap integral between the propagated field and the mode field along the propagation direction was calculated. The spectral response was acquired through scanning of the wavelength while maintaining the same launching conditions. The loss due to material absorption was not taken into account.

2. Design of Bragg reflector waveguides

The design of Bragg reflector waveguides incorporates Brewster angle condition at the interface between the high and low index layers. Accounting for Snell's law, the thicknesses d_{high} and d_{low} of n_{high} and n_{low} layers are:

$$d_{high} = (2k+1)\frac{\lambda}{4}\frac{\left(n_{high}^2 + n_{low}^2\right)^{1/2}}{n_{high}^2};\ d_{low} = (2l+1)\frac{\lambda}{4}\frac{\left(n_{high}^2 + n_{low}^2\right)^{1/2}}{n_{low}^2},\ k, l = 0,\ 1,\ 2,\ \ldots, \tag{1}$$

where *k* and *l* can be different, because the layers are considered as independent Fabry - Perot resonators.

Similarly, the core size incorporating Brewster angle condition for the Bragg reflector can be derived as:

$$d_{core} = m\frac{\lambda}{2}\frac{1}{\left(n_{core}^2 - n_{eff}^2\right)^{1/2}} \quad , \qquad m = 1, 2, \ldots, . \tag{2}$$

From Brewster angle condition, Snell's law and the relationship between incident wave-vector and its transverse component, the effective index of the guided wave and the condition for the core refractive index are [4]:

$$n_{eff} = \frac{n_{high} n_{low}}{\left(n_{high}^2 + n_{low}^2\right)^{1/2}} \qquad \text{and} \qquad n_{eff} \le n_{core} \le n_{low} . \qquad (3)$$

The structure of the Bragg reflector waveguide based on Brewster angle condition design is shown in Fig. 1 with five periods on both sides of the guiding core. The parameters chosen for λ = 1.5 µm using Eqs. (1)-(3) are as follows: $d_{high} = 0.37$ µm; $d_{low} = 1.14$ µm; $d_{core} = 6.1$ µm; $n_{high} = 3.476$; $n_{low} = 1.99$; $n_{core} = 1.8$ for depressed index core and $n_{core} = n_{low}$ for non-depressed index core. The following SOI wafer parameters were used in the 3D BPM simulations: height of the Si substrate layer, $h_{Si} = 1$µm, height of the SiO$_2$ layer $h_{SiO2} = 1$ µm with $n_{SiO2} = 1.5$, height of the region of the photonic crystal structure $h_{core} = 2.2$ µm and $h_{air} = 1.4$ µm air on top.

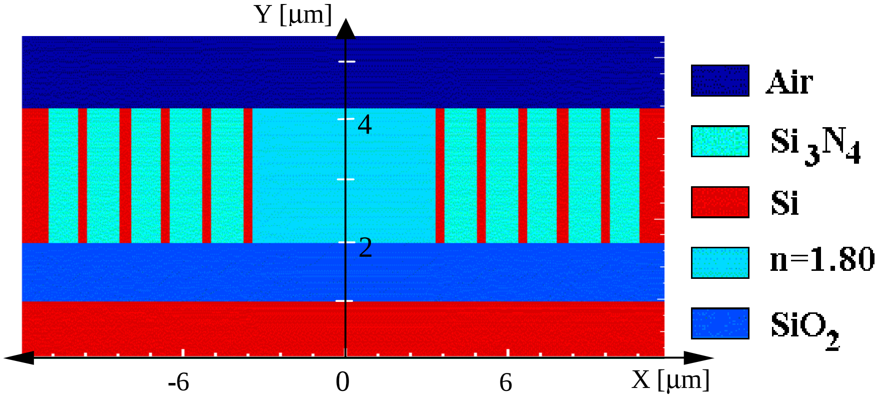

Fig. 1. Design structure of the Bragg reflector waveguide for TE polarizer. Si $n_{high} = 3.476$, Si_3N_4 $n_{low} = 1.99$, SiO_2 $n_{SiO2} = 1.5$, $d_{high} = 0.37$ µm, $d_{low} = 1.14$ µm, $d_{core} = 6.1$ µm, $n_{core} = n_{low} = 1.99$ (non-depressed core) or $n_{core} = 1.8$ (depressed core), height of Si substrate $h_{Si} = 1$µm, SiO$_2$ height $h_{SiO2} = 1$ µm, height of Bragg reflectors region $h_{core} = 2.2$ µm and $h_{air} = 1.4$ µm air.

3. Simulation results and discussions

Results from the numerical BPM simulations of the above structure with two and five periods are demonstrated in Fig. 2 for the case of depressed index core and Fig. 3 for the case of non-depressed index core, where the power in the TE and TM modes is shown versus propagation distance in the waveguide. A Gaussian beam of size $d_{core}/2$ was launched centered in the low index core at z = 0 for a propagation length of 1000 µm. Here the polarization that behaves accordingly to the Brewster angle condition upon reflection from the lateral layers is referred to as TM mode and the orthogonal one as TE mode. As seen from Fig. 2, the TE mode is well confined and experiences little attenuation with propagation, whereas the TM mode is very lossy; it is extinguished within 800 µm of propagation distance with a TE to TM extinction ratio better than 22 dB. Therefore, this design performs well as a TE mode polarizer. With increasing number of periods, the attenuation of the TE mode decreases, whereas the attenuation of TM mode changes insignificantly. The TE to TM extinction ratio, while linearly increasing with the propagation distance up to 1000 µm and saturating beyond, improves marginally when increasing the number of periods from two to five. For the TE mode, one to two periods result in attenuation close to 1dB/mm, whereas five periods ensure low attenuation in the order of 0.15 dB/mm.

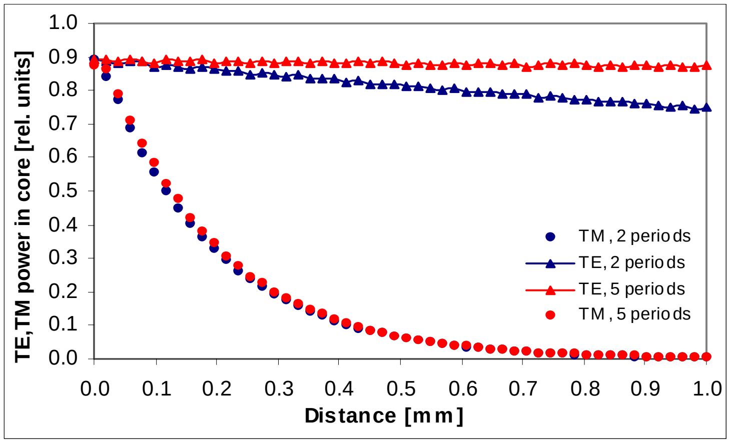

Fig. 2. Power in TE (triangles) and TM (dots) modes versus propagation distance in the Bragg reflector waveguide with depressed index core for two and five periods.

In the case of non-depressed core, as seen from Fig. 3, the waveguide supports both polarization modes. For more than one period, TE and TM modes propagate with a small difference in loss of about 0.5 dB at the end of the waveguide. It can be concluded that Brewster angle condition in the design (see Eq. (2)) is not effective for the TM mode extinction in the case of non-depressed index core and the depressed index core is essential for a TE polarizer with a high extinction ratio.

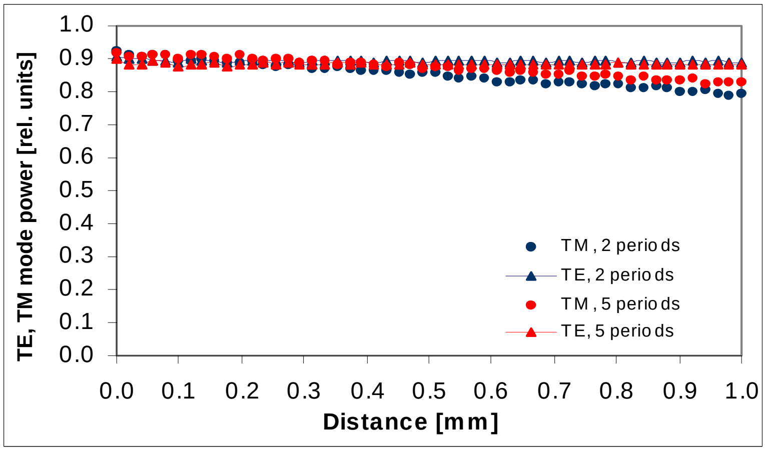

Fig. 3. Power in TE (triangles) and TM (dots) modes versus propagation distance in the Bragg reflector waveguide with non-depressed index core for two and five periods.

The importance of having a depressed core to favor the Brewster angle condition was previously mentioned without being elaborated on [4]. In fact, the depressed core leads to a Brewster angle at the core/high index layer interface that is different from the Brewster angle at the high/low index layers interface thus allowing more freedom in controlling how close the angle of beam propagation is to either of the Brewster angles and thus improving the TE to TM mode extinction ratio. In our case, changing the core refractive index n_{core} from 1.99 to 1.8 doesn't change significantly the relatively high Fresnel reflection coefficients for TE and TM polarizations at the core/high index layer interface, while the reflection becomes 0.3 and

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$3 \cdot 10^{-3}$ for TE and TM modes, respectively, at the high index/low index layer interface since there the beam propagates at an angle close to the Brewster one. As a result, for the depressed core the high index layer still acts as a Fabry-Perot reflection enhancing cavity for the TE mode but ceases to act as such one for the TM mode.

Strictly speaking, the depressed index core for the design based on Brewster angle condition requires matching of the longitudinal component of the propagation wave vector in the core with the corresponding component of the wave vector calculated for non-depressed core case assuming Brewster angle condition in the Bragg reflector (n_{eff} in Eq. (3). Effectively, the mode propagation angle in the core, given approximately by $\sin\theta \approx \lambda/2n_{core}d_{core}$ [5] after refraction becomes a Brewster angle in the periodic structure. In our case, matching n_{eff} to Brewster angle condition requires a core size of 1.5 μm, which results in high fiber to waveguide coupling loss and is not practical. Fresnel reflection coefficient for the TM polarization, however, has a slowly varying angular dependence near Brewster angle, i. e. the TM mode has a low reflection for a relatively wide-angle range. Thus TM mode leaks out efficiently even when the structure does not exactly satisfy Brewster angle condition thus relaxing the requirement on matching n_{eff} and on the core size.

The spectral response of the Bragg reflector waveguides was calculated as a function of the free-space wavelength from 1.4 to 1.6 μm and only a negligible wavelength dependency was observed. This is explained by the fact that the antiresonant reflection of the Bragg layers has very broad bandwidth [2,5].

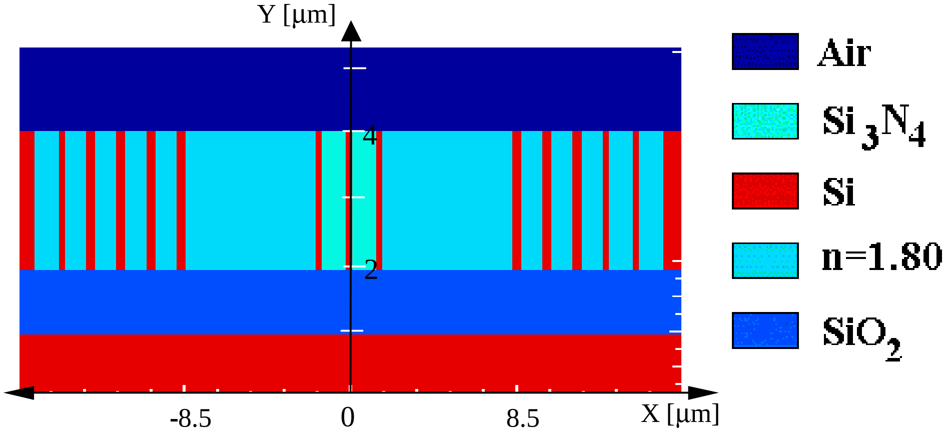

Fig. 4. Asymmetric structure of coupled Bragg reflector waveguides for polarization splitting/combining. Parameters are the same as given in Fig. 1.

The difference in polarization properties of the Bragg reflector waveguides with depressed and non-depressed index core shown in Figs. 2 and 3 suggests that an asymmetric design where the core index is non-depressed relative to the Bragg reflector on one side and depressed relative to the Bragg reflector on the other side will allow good TE mode confinement and asymmetric leakage of the TM mode towards one side. Thus a directional coupler for polarization splitting/combining is designed that consists of two guiding cores with non-depressed index relative to the outer Bragg reflectors and depressed index relative to the inner Bragg reflector coupling region. This coupler provides guiding of the TE mode as well as asymmetric leakage of the TM mode towards the adjacent waveguide core within a certain coupling distance. Such a structure is shown in Fig. 4 where the coupling Bragg reflector region consists of 3.5 periods and the outer Bragg reflectors have five periods each.

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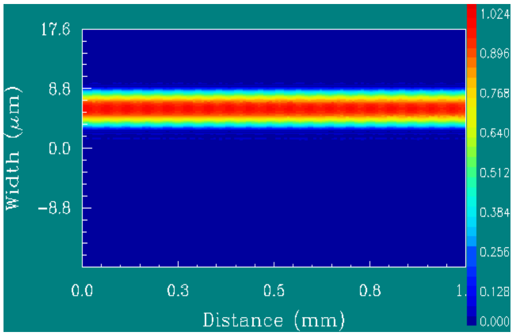

Fig. 5. TE mode distribution versus propagation distance in the waveguides in Fig 4. Light is launched in the upper core.

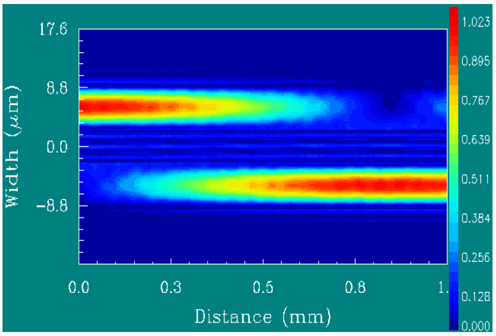

Fig. 6. TM mode distribution versus propagation distance in the waveguides in Fig 4. Light is launched in the upper core.

Figures 5 and 6 demonstrate how the structure operates where the TE and TM mode field distribution, respectively, has been shown in the two coupled waveguides as a function of propagation distance. Figure 7 summarizes the simulation results for the polarization splitter/combiner. The TE mode propagates with small attenuation of 0.2 dB/mm and practically does not couple into the second waveguide. TM mode launched in the same waveguide leaks through the coupling region into the second waveguide within a propagation distance of 800 µm and with a coupling efficiency from one waveguide to another of better than 95%. Such a waveguide performs as a polarization splitter where the TE and TM modes are physically separated with an isolation ratio of better than 30 dB. If TE and TM modes are separately launched into the adjacent waveguides, the TM mode leaks into the waveguide where the TE mode propagates and the two modes combine within the same distance.

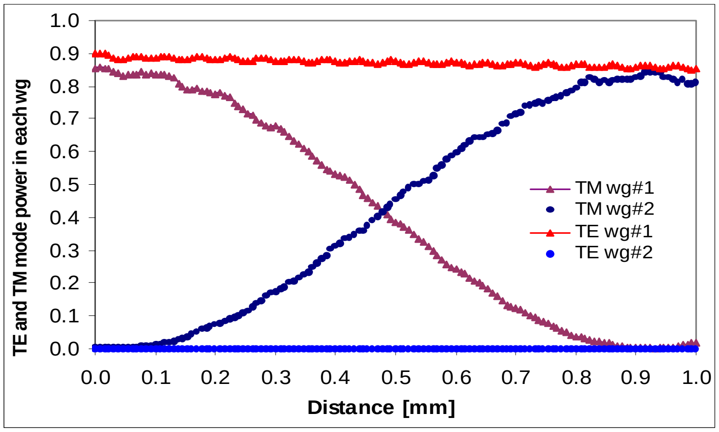

Fig. 7. Power in TE (triangles) and TM (dots) modes from Figs. 5 and 6 versus propagation distance in the coupled waveguides.

4. Conclusions

In this work, we have presented novel designs of polarization devices in high index contrast Bragg reflector waveguides based on the SOI platform. Results from numerical simulations with a 3D semi-vectorial BPM have been presented. The TE mode polarizer has a TE to TM mode extinction ratio of better than 22 dB. The novel polarization splitter/combiner has coupling efficiency of 95% and isolation ratio of better than 30 dB within a short propagation distance in the waveguides.

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