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Design of a compact polarization beam splitter based on a deformed photonic crystal directional coupler*

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In this paper a compact polarization beam splitter based on a deformed photonic crystal directional coupler is designed and simulated. The transverse-electric (TE) guided mode and transverse-magnetic (TM) guided mode are split due to different guiding mechanisms. The effect of the shape deformation of the air holes on the coupler is studied. It discovered that the coupling strength of the coupled waveguides is strongly enhanced by introducing elliptical airholes, which reduce the device length to less than 18.5μm. A finite-difference time-domain simulation is performed to evaluate the performance of the device, and the extinction ratios for both TE and TM polarized light are higher than 20 dB.

Keywords: photonic crystal, polarization beam splitter, directional coupler
PACC: 4270Q, 4280H, 4280L

1. Introduction

A polarization beam splitter (PBS) is an important functional device for photonic integrated circuits. A conventional PBS is usually realized using a Mach–Zehnder interferometer,[1] an asymmetric Y-branch,[2] or a multimode interference device.[3] These conventional waveguide PBSs require device lengths a few millimetres long, which is a disadvantage in enhancing the density of integration.

Photonic crystals (PCs) are considered as the most promising candidates for achieving high level integration.[4,5] Thus, PBS based on photonic crystal has attracted much attention, and many different kinds of PC-PBSs are studied.[6−10] Among them, a PBS based on an all-PC directional coupler[10] proposed by Liu *et al* shows great advantage of easy integration and good extinction ratio, and, therefore, is more attractive in PC integrated optical circuits. In their work, a short PC-PBS structure is proposed, but the relationship between coupler geometry and device performance is not specifically studied. In this paper, we study the effect of shape change on the coupling strength by introducing deformed airholes in the directional coupler. We then present the design and numerical analysis of a more compact PC-PBS, which separates the different polarizations in a distance less than 18.5μm.

2. Design and analysis

Since two-dimensional PCs could be realized in heterostructure slab waveguides, we use the well-known effective refractive index mechanism[11] to confine light in the vertical direction in our design and finite-difference time-domain (FDTD) simulation.[12] The dielectric material is chosen to be InGaAsP laser-like heterostructure, whose effective refractive index is 3.32 for both transverse-electric (TE) and transverse-magnetic (TM) polarizations.

Figure 1 shows the proposed PC-PBS structure. It is composed of two W1 PC waveguides, and both of them are along the $\Gamma-K$ direction. The lattice period is a=460 nm and the radius of the air holes is $0.36a$, making the bandgap large enough only for TE light. We do not choose a large filling factor to obtain a full band gap for both TE and TM light because large air holes cause severe loss, especially for TM light whose bandgap is relatively narrow.[13] Several groups have found that the polarization mode could be influenced by introducing an anisotropic unitcell structure,[14] or

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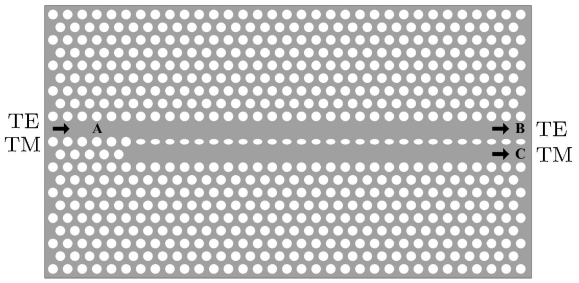


Fig.1. Schematic view of the proposed PC PBS.

breaking the lattice symmetry.[15] Accordingly, the air holes which separate the two waveguides are deformed to elliptic shape. The semi major axis and semi minor axis of the elliptic air holes are $0.34a$ and $0.16a$, respectively. This device structure fulfils the two basic requirements of a compact PBS. First, both TE and TM modes can propagate through the dielectric-core waveguide with low loss, though the mechanisms are different. The TE mode is confined in the waveguide by the photonic band gap (PBG) effect, while the TM mode is confined in the waveguide whose average refractive index in the guiding core region is larger than that of the surrounding area, due to the index-guided effect.[16,17] Second, the different guide mechanisms for TE and TM polarizations lead to strikingly different propagating properties. To illustrate this point, we apply supermode theory to explain the polarization splitting mechanism. In the coupled waveguides, the guided mode propagates in the form of 'supermode'.[18] The supermode is composed of the guided mode of each single waveguide component and defined as even or odd according to different field distribution parity. Because of coupling between the even and odd supermodes, the power of an incident light will shift between the two waveguides in a certain period of length. The minimum required propagating length that power transfers completely from one waveguide to the other and back to itself is defined as the beat length:

$$L_{\mathrm{b}} = \frac{2\pi}{|k_{\mathrm{even}} - k_{\mathrm{odd}}|}. \tag{1}$$

The TE and TM light have remarkably different beat lengths at certain frequency on the dispersion curve. The photonic band structure of the device in Fig.1 for TE and TM polarizations, calculated by the plane wave expansion method, is shown in Figs.2 and 3, respectively. We only show the modes within the bandgap of TE light (the TE is $0.228< a/\lambda <0.347$). In Fig.2, the even and odd TE supermodes cross at normalized frequency a/λ=0.299, which makes $\Delta k=|k_{\mathrm{even}} - k_{\mathrm{odd}}| \approx 0$. The beat length for the TE mode will be close to infinite, implying that the TE mode is decoupled at this frequency. In Fig.3, however, the even and odd TM modes do not cross at the same frequency and the beat length $L_{\mathrm{b}} = a/|0.0578 - 0.0452| = a/0.0126 \approx 80a$. So the coupler length is designed to be $40a$, or the half beat length of the TM mode. The TE and TM polarized lights enter the coupler via port A. The TE mode at the decoupling frequency propagates through the upper waveguide and exits directly via port B, while the TM mode beats one time into the lower waveguide and exits via port C. Thus, the polarization splitting is realized.

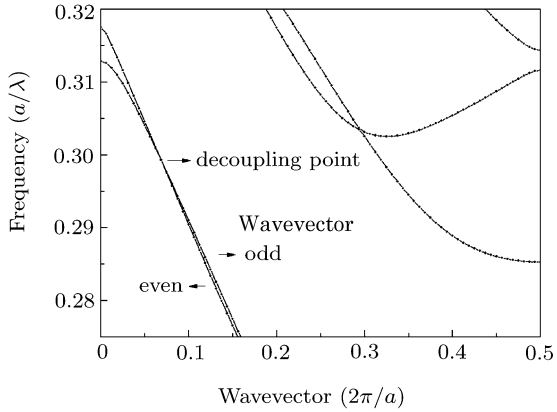


Fig.2. Photonic band within the band gap of the structure in Fig.1 for TE light. (The photonic band gap is $0.228< a/\lambda <0.347$.) Note that the even and odd supermode is decoupled at frequency a/λ=0.299.

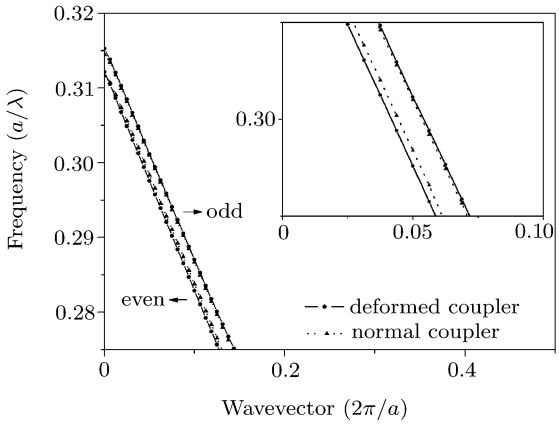


Fig.3. Photonic band within the TE band gap of the structure in Fig.1 for TM light. (The photonic band gap is $0.228< a/\lambda <0.347$.) The solid line with circular symbols and the dotted line with triangular symbols are the guided modes for the deformed coupler and the normal coupler, respectively. The inset shows the distance broadening of the even and odd supermodes of the deformed coupler compared to that of the normal coupler.

In order to analyse how the shape change of the coupler affects the coupling strength, we also calculated the band structure of the normal coupler whose airholes between the coupled waveguides are the same as other PC air holes. For TE mode, the decoupling point of the normal coupler moves to a slightly lower frequency a/λ=0.29 (not shown here), which only causes a small lattice period change for a certain wavelength (1.55 μm for instance). For TM mode, however, the coupling is strongly influenced by the introduction of deformed airholes, as shown in the inset of Fig.3. The dotted lines with triangular symbols are the even and odd supermodes of the normal coupler, and the solid lines with circular symbols are the even and odd supermodes of the deformed coupler. The distance between even and odd supermodes is remarkably broader for the deformed coupler, making Δk Larger, and thus shortening the beat length. In our case, the beat length is $122a$ for the normal coupler, and shortens to $80a$ for the deformed coupler, a reduction in device length of more than 30%.

Coupling strength is enhanced due to the design of the size and shape of the elliptical air holes between the coupled waveguides, which plays a significant role in power coupling. First, the semi major axis of the elliptic airholes should be along the direction of the waveguide. Second, the area of the elliptical air holes is designed to be smaller than that of other circular airholes. These design features make the two waveguides closer in the real space, which contributes to the broadening of the distance of the dispersion curves in the reciprocal space. Thus, the coupling strength is enhanced and the length of the device is reduced.

In order to evaluate the performance of the device, we used the two-dimensional FDTD method with the effective index method to simulate the light propagation in our polarization splitter. Experiments by Notomi *et al* have confirmed that the vertical loss of an 88-period long hexagonal waveguide is only a few dB.[19] So the vertical loss of our 40-period long structure does not need to be considered in our simulation, even when the decoupling point seems to be out of the lightcone. The spatial resolution is 32 grid points per lattice period. The perfectly matched layer boundary condition is added directly to the computation domain to absorb light as it reaches the boundary. At port A, a pulse light source centred at λ=1.55μm with a Gaussian spatial distribution is launched along the $\Gamma - K$ direction as the incident light source for both TE and TM light. Three time monitors, shown as the short line in Fig.1, are located at each port to detect the input and output power. The output power is divided by the input power to calculate the transmission efficiency. The reflected power at port A is excluded from the calculation, so the monitor only measures the power coupled into the coupler.

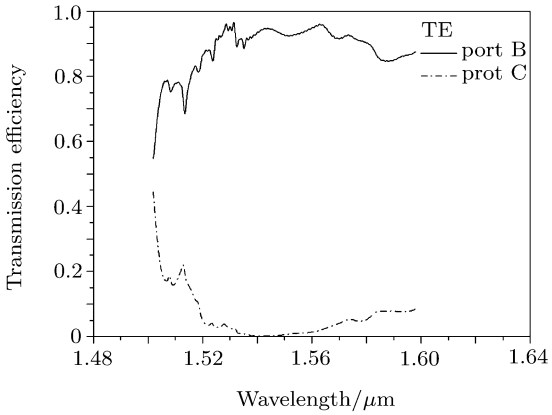


Fig.4. Transmission efficiency of port B for TE light computed by the 2D FDTD method.

The transmission efficiency spectrum of TE and TM light normalized by the input power is calculated by the FDTD method, as shown in Figs.4 and 5, respectively. For TE polarized light, the transmission efficiency is higher than 90% in the wavelength range from 1.53μm to 1.58 μm, which is attributed to the very low loss of the PBG-guided mechanism. For the wavelengths lower than 1.53μm and higher than 1.58μm, the transmission efficiency of port B decreases because the wavelength deviates from the decoupling point, a proportion of TE light power transfers into the lower waveguide, and, thus, the transmission efficiency of port C increases. For TM polarized light, the transmission efficiency is above 80% in the range from 1.53μm to 1.59μm. The transmission efficiency is not as high as for TE light because the TM light is confined in the hexagonal lattice by the index-guided effect. Without a PC band gap, the guided mode tends to couple with adjacent modes scattering into the PC, and it causes propagation loss in the waveguide. In the wavelength range from 1.53μm to 1.57μm, which covers the optical communication wavelength, the extinction ratio of both TE and TM light is higher than 20 dB. At λ=1.545μm, the extinction ratio for TE light and TM light is 27.2 dB and 23.4 dB, respectively. The broad high extinction ratio wavelength range shows great tolerance for fabrication errors in

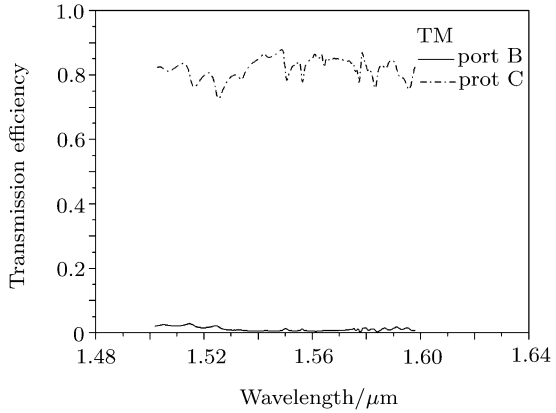


Fig.5. Transmission efficiency of port C for TM light computed by the 2D FDTD method.

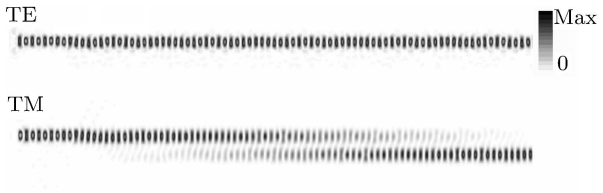


Fig.6. Comparison of Poynting vector distribution along the waveguide direction for TE and TM lights. The wavelength of incident light is λ=1.545μm for both TE and TM polarizations.

the PBS structure. In Fig.6, a CW light wave at λ=1.545μm is launched at the input port for TE and TM polarization, respectively. The simulated Poynting vector distribution along waveguide direction for TE and TM light gives an explicit illustration of the device performance. The polarization splitting is clearly observed.

3. Conclusion

We presented a compact PBS based on a deformed PC directional coupler. Due to different guiding mechanisms, the PBG-guided TE mode is decoupled, while the index-guided TM mode remains closely coupled, which realizes a polarization separation of less than 18.5μm. The effect of deformed airholes on the coupling strength is analysed. In the 40 nm wavelength range around 1.55μm, the extinction ratio of both TE and TM light is above 20 dB. The device could find its application as component of high density integrated photonic circuits in optical communication. Furthermore, this all-PC based PBS is easily integrated with other PC devices.

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