Polarization beam splitter based on dielectric periodic structure with different EFCs for two polarizations

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A dielectric multi-layered structure is studied in this letter. It is found that at some frequency ranges, the equal-frequency contours (EFCs) are almost flat for one polarization but still curve for the other. Based on this property, we propose a novel polarization beam splitter.

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Sub-wavelength structures have attracted many interests in these years. A main kind of them called photonic crystal (PC)[1] which is periodic in one, two, or three dimensions, has been investigated and developed into many applications these years. One of these applications is polarization beam splitter (PBS), which has been studied both in theory and experiments. There are several kinds of PBSs based on different working principles: some are based on the different photonic band gaps for different polarizations[2−5]; some use negative refractive indices[6,7]; and others utilize the different anisotropy for different polarizations[8]. These PBSs are mostly based on two-dimensional (2D) PC. Recently, we have proposed a novel broad-angle PBS based on a one-dimensional (1D) periodic structure[9], which is much simpler and easier for fabrication. In this letter, we will study such a periodic structure further to show its different spatial dispersion for different polarizations, and propose another new way to realize a PBS. The experiment in Ref. [8] reported a 10° separation between the two polarizations beams when they propagated through a 2D PC slab, while for our PBS, we predict a separation angle larger than 25°.

Our 1D dielectric periodic structure (see Fig. 1(a)) has a period of a, with high-index ($n_1 = 3.4$) and low-index ($n_0 = 1$) index materials being arrayed alternatively. And the width of the high-index strip is $w = 0.25a$. The incident and the emergent media are both air. The plane of incidence is x-z plane, and θ is the incident angle. We study the equal-frequency contours (EFCs) of this structure, and show the EFCs for both TE (electric field parallel to y axis) and TM polarization (magnetic field parallel to y axis) for the first band in Figs. 1(b) and (c), respectively. Comparing these two figures, we can see that the EFCs for TE polarization become flat much faster than those for TM polarization as the normalized frequency increases. Thus for certain normalized frequencies (taking $\omega a/(2\pi c) = 0.46$ for example), the EFC for TE polarization has already become flat, while the EFC for TM is still evidently curvature. This difference decides different energy directions for different polarizations, because the propagating direction of the energy will be always along the normal direction of the EFCs. So when a plane wave (with wave vector k) impinges on such a structure with incident angle θ, because of the conservation of the lateral component of the wave vector ($k_x = k \sin\theta$) at the interface, we can find the corresponding energy direction of the refractive wave (see those two arrows in Fig. 1, normal for TE, while oblique for TM). We also find that as the width w increase, the difference between the EFCs of the two polarizations is diminishing, and at the same time the EFCs of the second band will appear to make the EFCs patterns complex, which is bad for design principle of the proposed PBS we discussed above.

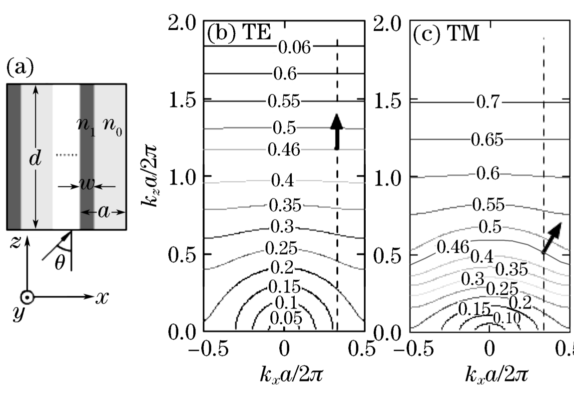

Fig. 1. EFCs of the first band for (a) 1D dielectric periodic for (b) TE and (c) TM polarization.

For more details about the normalized frequency range from 0.4 to 0.55, we plot the equal refractive angle contours (all the points on each contour have the same refractive angle) together with the EFCs for TM polarization in Fig. 2. For TE polarization in this range, the EFCs are almost flat, thus the refractive angles for these frequencies are almost all along the z direction independent of the incident angle[9]. From Fig. 2 we can see that, for TM polarization, the refractive angle will rise up as k_x increases to a certain value, and then decrease if k_x keeps increasing (here the increasing k_x means the increase of incident angle). For some cases, refractive angles are more than 25°, which means beams with different polarizations will be apart spatially for a short distance. As an example, we study Gaussian beams with different polarizations incident into this structure. Figures 3(a) and (b) show the results

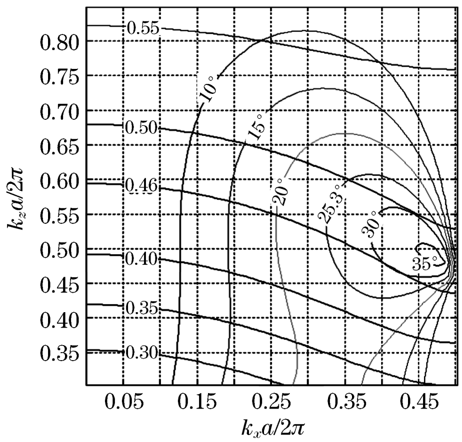

Fig. 2. Equal refractive angle contours (solid curves) plotted together with the EFCs (dotted curves) for TM polarization.

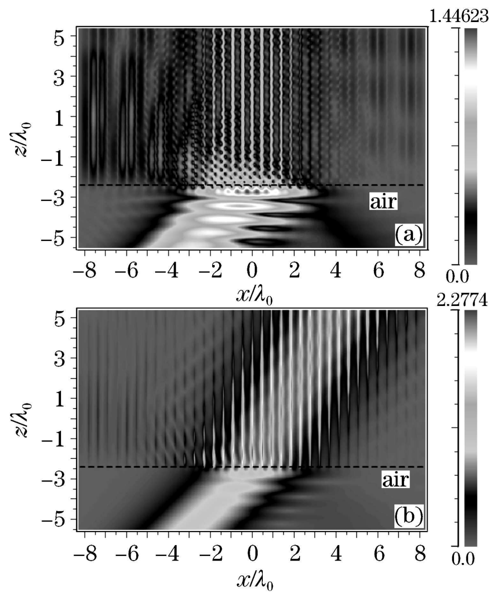

Fig. 3. Time averaged distributions of Gaussian beams with different polarizations incident into the structure. (a) $|E_y|$ distribution for TE polarization; (b) $|H_y|$ distribution for TM polarization.

by finite difference time domain (FDTD) method for TE and TM polarizations, respectively. The normalized frequency is $\omega a/(2\pi c) = 0.46$, and $\theta = 45°$. Figure 3(a) shows that the main energy for the refractive TE Gaussian beam propagates normal to the interface, while Fig. 3(b) shows that for TM beam, there is an evident angle between the main energy direction and the normal. We can estimate the refractive angle is about 25°, which coincides with that predicted by Fig. 2. We can also see that there is a higher reflection for TE polarization (about 23% by the simulation) than TM polarization (less than 1%) at the incident interface. Besides, there is also a little energy escape beside the main beam for both cases because of the effect of high-order photonic band (the second band).

Based on the discussions above, we design a PBS device. The structure has a finite length d as shown in Fig. 1(a), which should be chosen carefully to reduce the reflection at the interface for TE polarization. The refractive wave of TE polarization mainly goes normally to the interface, and there is evident multi-reflection between the front and the back interfaces of the slab. That means interference will exist inside the structure just like the traditional thin-film theory. Thus if the length d is chosen suitably, the reflection of TE polarization at the input interface will be dramatically decreased. We suppose the parameter d should satisfy $2k_z d = 2M\pi$, where $M = 0, 1, 2, 3, \cdots$, and k_z is the z component of the refractive wave vector for TE polarization. As an example, we let two Gaussian beams ($\omega a/(2\pi c) = 0.46$, $\theta = 45°$) with different polarizations incident into this structure. We note that the length d should be long enough to split these two beams spatially, but we should also consider the computation cost of the FDTD method. Here we choose $M = 60$. In this case, the transmission for TE polarization is more than 87%. The interface reflection for TM polarization is very small and its refractive direction is oblique, thus the length d will not affect the transmission for TM polarization evidently. Figures 4(a) and (b) show the simulation results for TE and TM cases, respectively. We see that the TE Gaussian beam mainly propagates normally to the interface, while the TM beam has a refractive angle about 25.3°. The reflection at the interface for TE beam is reduced dramatically in comparison with that in Fig. 3. The output beam is still 45° oblique because of the conservation of k_x. There is a little diffusion for the output beam because the Gaussian beam does not have a very wide width compared with the wavelength (for saving computation cost). For comparison, the transversal (along x axis) distributions of $|E_y|$ for TE polarization and $|H_y|$ for TM polarization at the location $0.5\lambda_0$ after the output interface are plotted together in Fig. 5. The source field patterns of the two polarizations are same in value thus we use curves to represent the two cases at $0.5\lambda_0$ before the incident interface. We can see that the two beams are separated spatially.

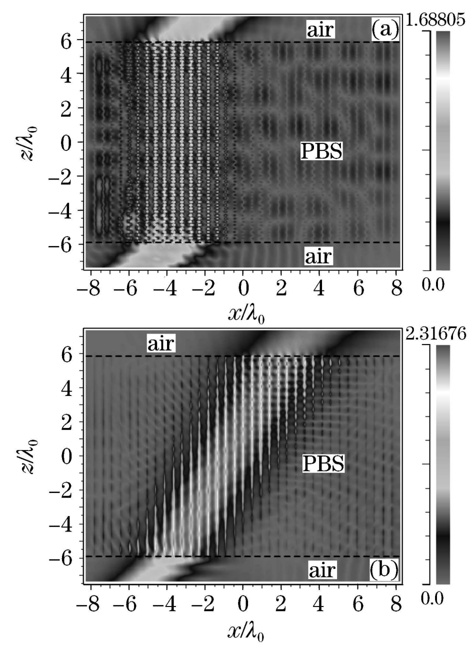

Fig. 4. Time averaged distributions for Gaussian beams propagating through our multi-layered structure with finite length d along z axis. (a) $|E_y|$ distribution for TE polarization; (b) $|H_y|$ distribution for TM polarization.

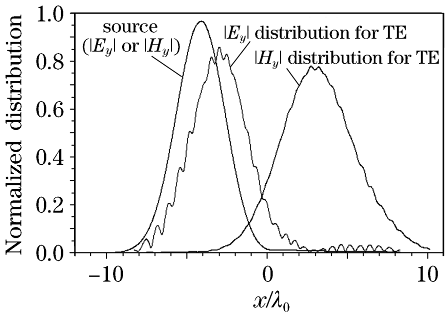

Fig. 5. Transversal (along x axis) field patterns at $0.5\lambda_0$ after the output interface of $|E_y|$ distribution for TE polarization and $|H_y|$ distribution for TM polarization. The source for both TE and TM cases in value at $0.5\lambda_0$ before the incident interface is also given.

In summary, we have studied a 1D dielectric periodic structure and found it shows different spatial dispersion properties for different polarizations. At those frequencies we are interested in, the refractive beam for TE incidence is mainly along z axis, while for TM beams, the refractive angle is large (even more than 25°). Based on this property, we design a PBS with an optimal length d (for decreasing the reflection of TE polarization at the interfaces). Here we mainly discuss the silicon as the high-index medium, so our structure works in infrared. Our structure can be integrated by semiconductor technical as a planar and compact device. Besides, compared with the PBS based on 2D PC, our structure is much simpler and easier for fabrication.

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