Research on the Wide-angle and Broadband 2D Photonic Crystal Polarization Splitter

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Abstract

Two novel wide-angle and broadband 2D photonic crystal polarization splitters (PCPS) which are the multi-layer wavy films (MWF) structure and arrow-head like structure are designed based on the autocloning method. Plane wave expansion (PWE) method is used to calculate the band structure and explain the reason for the wide-angle and broadband polarization splitting effect. In order to verify the result derived from PWE method, finite-difference time-domain (FDTD) method is employed to test and measure the polarization splitting effect for the MWF structure, finding that it is in the angle range from 25 to 65 degree that the results are perfect. Outside this angle range, the results are unacceptable due to the rapid decay of TM mode power.

Introduction

Photonic crystal (PC) has the optical characteristics of photonic bandgap [1], strong anisotropy and negative refraction [2, 3], so is expected to be useful for novel optical devices [4-6]. However, the severe requirement that the spatial period should be approximately half a wavelength in the medium makes it difficult to find a reproducible and flexible technique to produce high quality multidimensional PCs for the optical wavelength region. A new method named autocloning technique [7] which is based on stacking multilayer wavy films (MWF) onto a substrate with periodically-arrayed holes or grooves by a combined process of sputter deposition and sputter etching overcomes the problem. This technique has been successively applied to fabricate polarization selective grating [8] and polarization splitter [9] for the wavelength of visible region.

Unlike the conventional polarizing beam-splitter which utilizes the Brewster angle, the novel 2D photonic crystal polarization splitter (PCPS) fabricated by the autocloning method has been demonstrated experimentally that it can effectively split TE and TM mode as the field is incident normally, owing to the overlapping of the partial bandgap of TE mode and the passband of TM mode for the wavevector from Γ to X in Brillouin zone (BZ). This is considered as an opening to the wide-angle and broadband 2D PCPS. Wide-angle corresponds to such an band overlapping existing for a continuous range of wavevector direction inside the PC. In this paper, two kinds of wide-angle and broadband 2D PCPS are designed with the materials of SiO$_2$ and a-Si. The first one is MWF structure for the wavelength from 1.48µm to 1.52µm. The second one called arrow-head like structure is the deformation of MWF structure, and designed for the wavelength from 1.28µm to 1.31µm. The theory of plane wave expansion (PWE) method which is useful for band structure analysis is given in Section 1 first.

1. Plane Wave Expansion

Considering electromagnetic wave in materials with source-free space, lossless medium and magnetic uniform, $E$ and $H$ will satisfy the following eigen value equations:

$$\nabla \times \nabla \times \vec{E} (\vec{r}) = \frac{\omega^2}{c^2} \varepsilon (\vec{r}) \vec{E} (\vec{r})$$

$$\nabla \times \frac{1}{\varepsilon (\vec{r})} \nabla \times \vec{H} (\vec{r}) = \frac{\omega^2}{c^2} \vec{H} (\vec{r})$$

For $\varepsilon (\vec{r})$ is a highly discontinuous function, $E$ is also discontinuous consequently. Therefore, the $H$ eigen value equation is chosen to solve the problem. According to Bloch theorem, in periodic structure the complex-valued magnetic field can be expressed as:

$$\vec{H} (\vec{r}) = \exp (i \vec{k} \cdot \vec{r}) h (\vec{r}) \hat{e}_k$$

$$h (\vec{r}) = h (\vec{r} + \vec{R}_j)$$
where $\tilde{R}_l$ is lattice vector, $\hat{e}_k$ is an unit vector perpendicular to the vector $k$ and parallel to the $H$ vector. Any periodic function can be expanded using Fourier series, so is for $\varepsilon \left( \vec{r} \right)$ and $h \left( \vec{r} \right)$:

$$
\varepsilon \left( \vec{r} \right) = \sum_{\vec{G}_j} \varepsilon \left( \vec{G}_j \right) \exp \left( i \vec{G}_j \cdot \vec{r} \right)
$$

$$
h \left( \vec{r} \right) = \sum_{\vec{G}_j} h \left( \vec{G}_j \right) \exp \left( i \vec{G}_j \cdot \vec{r} \right)
$$

Substituting (3)~(6) into equation (2), the final equation is:

$$
\sum_{\vec{G}_j} \left| \vec{k} + \vec{G} \right| \left| \vec{k} + \vec{G} \right|^{-1} \left( \vec{G} - \vec{G} \right) \left[ \begin{array}{cc}
\hat{e}_2 \hat{e}_2' & -\hat{e}_2 \hat{e}_1' \\
-\hat{e}_1 \hat{e}_2' & \hat{e}_1 \hat{e}_1'
\end{array} \right] \left[ \begin{array}{c}
h_1' \\
h_2'
\end{array} \right] = \frac{w^2}{c^2} \left[ \begin{array}{c}
h_1 \\
h_2
\end{array} \right]
$$

This is a standard eigen value problem which can be implemented by numerical method.

### 2. Band Structure Analysis

#### 2.1 Multilayer Wavy Films

We have made a systematic examination of the band structures as a function of filling ratios for MWF structure. In all the cases, lattice constants $L_x$, $L_z$ and the slope angle $\theta$ were kept constant, the thickness ratio of two materials was varied to change the filling fraction, finding that when the refractive index of SiO$_2$ and a-Si were fixed at 1.5 and 3.5 respectively, the complete band gap of TE mode exists over a wide region of filling ratio. The optimized value of the parameters are:

$$
L_x = 0.56 \mu m, \quad L_z = 0.45 \mu m, \quad T = 0.15 \mu m, \quad \theta = 44^\circ
$$

where $T$ is the thickness of a-Si. $L_x$, $L_z$ and $\theta$ are defined in Fig. 1. The Fourier transformation [10] of $\varepsilon \left( \vec{G} \right)$ which is of great importance to PWE method is given as follows:

$$
\varepsilon \left( \vec{G} \right) = \frac{\left( \varepsilon_1 - \varepsilon_2 \right) \left[ 1 - \exp \left( -iG_z T \right) \right]}{L_x L_z G_z} \left\{ \exp \left[ -i \left( G_x + G_z \tan \theta \right) L_x/2 \right] - 1 \right\} + \frac{\exp \left( -iG_z T \right) - \exp \left[-i \left( G_x + G_z \tan \theta \right) L_x/2 \right]}{G_x - G_z \tan \theta}
$$

$$
\varepsilon \left( \vec{G} \right) = \frac{2 \left( \varepsilon_1 - \varepsilon_2 \right) \left[ \exp \left( -iG_z T \right) - 1 \right] \left[ 1 - \exp \left( -iG_z \tan \theta L_x/2 \right) \right]}{L_x L_z G_z^2 \tan \theta} \quad \text{for} \ G_x = 0, \ G_z \neq 0
$$

$$
\varepsilon \left( \vec{G} \right) = \frac{\left( \varepsilon_1 - \varepsilon_2 \right) \left[ \exp \left( -iG_z T \right) - 1 \right] T i}{L_x L_z G_z} \quad \text{for} \ G_x \neq 0, \ G_z = 0
$$

$$
\varepsilon \left( \vec{G} \right) = \varepsilon_2 + \frac{T}{L_z} \left( \varepsilon_1 - \varepsilon_2 \right) \quad \text{for} \ G_x = G_z = 0
$$

![Figure 1: Geometrical configuration of MWF. (a) The overall structure. (b) The unit cell of MWF.](image)
The complete bandgap of TE mode lies at $L_z/\lambda = 0.295 \sim 0.305$ (see Fig. 2) corresponding to the wavelength from 1.48$\mu$m to 1.52$\mu$m. Focusing on the second band of TM mode, when the wavevector moves along the edge $X - M - X'$ of BZ, the values of this band are all below the complete bandgap, above which the value of $\Gamma$ point lies simultaneously. This situation indicates that for the wavevector of any direction there must be passband of TM mode that traverses through the complete bandgap because of the continuity of band structure. Examples such as passbands in $\Gamma X$, $\Gamma M$ and $\Gamma X'$ directions have been showed in Fig. 2. Since the splitting of TE/TM modes can be achieved inside the PC for all the wavevector directions, the field outside can be omnidirectionally incident. For the configuration described in Fig. 1, omnidirection means the unpolarized field can be incident at an arbitrary angle to the interface in the XZ plane.

Figure 2: Band structure of MWF. Complete bandgap of TE mode is plotted with shadow. The marks 1, 2 and 3 represent the first, second and third band of TM mode.

### 2.2 Arrow-head Like Structure

Based on the MWF structure, arrow-head like 2D PC (see Fig. 3) requires an additional fabrication process called Reactive Ion Etching for the a-Si layer causing it to be discontinuous [11]. The complete bandgap of TE mode appears at $L_z/\lambda = 0.341 \sim 0.354$ (see Fig. 4) corresponding to the wavelength from 1.28$\mu$m to 1.31$\mu$m, if the values of the parameters are set as follows:

$$L_x = 0.72\mu m \quad L_z = 0.45\mu m \quad L = 0.17\mu m \quad T = 0.19\mu m \quad \theta = 50^\circ$$

where $L$ is the lateral extension length of a-Si and $T$ is the central thickness. The other parameters remain the same as MWF. Again, focusing on the second band of TM mode in Fig. 5, along the partial edge $A - M - B$ of BZ, the values of this band are all above the lower bound of the complete bandgap. So is the value of $\Gamma$ point showed in Fig. 4. This time we can’t make sure that there must be passband of TM mode which traverses through the complete bandgap when the direction of wavevector lies in the region painted with gray color in the
inset of Fig. 5. Only for the wavevector direction outside the gray region, can TE and TM modes be splitted as TM mode passes through the PC and the propagation of TE mode is forbidden when the frequency is within the complete bandgap. So, arrow-head like PC can still realize wide-angle polarization splitting.

Figure 4: Band structure of arrow-head like 2D PC. Complete bandgap of TE mode is plotted with shadow.

Figure 5: Enlarged view of the band structure of arrow-head like 2D PC. Wavevector moves along the edge of BZ. Frequency region is selected from 0.22 to 0.47.

3. Numerical Results

The analysis with PWE is just qualitative. In this section, numerical results based on FDTD are presented for MWF structure. We consider a structure of 14 lateral periods located between free space. The grid size used in both directions is 20nm, and the size of the computational domain is 6.74µm by 10.2µm. Periodic boundary conditions are used at the top and bottom boundaries. Absorbing boundary conditions are used for the side boundaries. A time dependence of sinusoidal plane wave source is used to generate the incident field. Fig. 6 shows the electromagnetic wave propagation from the left side of MWF to the right side with oblique incidence angle for TM mode. The gray levels are in one-to-one correspondence with the field amplitudes.

Figure 6: “Snapshot” of field amplitudes within the computational domain.

The wavelength 1.48µm, 1.50µm and 1.52µm are selected to calculate the transmittance against the incidence angle. The results are shown in Fig. 7. For TE mode the transmittance are below 3% except for the angle near 0°, and even below 1% in some angle region. The transmittance of TM mode is not so ideal as expected. It is in the angle range from 25° to 65° that the values are acceptable. Outside this range, the decay of power is so obvious that it is unsatisfactory for practical applications.
Conclusion

We have designed two wide-angle and broadband 2D PCPS which are the MWF structure and arrowhead like structure based on the autocloning method. Particularly, MWF structure has the potential to realize omnidirectional polarization splitting effect. For MWF structure, numerical results calculated with FDTD method are given, which indicates that the characteristic of omnidirection is hardly achieved due to the rapid decay of power for TM mode within some angle range, however the wide-angle polarization splitting effect is still feasible. The device designed in this paper may be useful for optical communication systems in the future.

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