Study on electro-optic properties of two-dimensional PLZT photonic crystal band structure*

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The band characteristics of two-dimensional (2D) lead lanthanum zirconate titanate (PLZT) photonic crystals are analyzed by finite element method. The electro-optic effect of PLZT can cause the refractive index change when it is imposed by the applied electric field, and the band structure of 2D photonic crystals based on PLZT varies accordingly. The effect of the applied electric field on the structural characteristics of the first and second band gaps in 2D PLZT photonic crystals is analyzed in detail. And the results show that for each band gap, the variations of start wavelength, cut-off wavelength and bandwidth are proportional to quadratic of the electric field.
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Photonic crystal devices have got a lot of applications in optical communications and optical sensing[1-5]. Semiconductor materials, such as Si, AlGaAs, SiO_2, InP, are often chosen as manufacturing materials for photonic crystals because of their features, such as high refractive index and strong light transmittance at communication wavelength[6-8]. However, the band structure of photonic crystals based on the high stability of semiconductor materials is difficult to be modulated in high-speed transmission optical communication system by routine methods. Therefore, the tunability of band structure becomes the bottleneck of wide application in optical communication for photonic crystals.

Lead lanthanum zirconate titanate (PLZT) is an excellent electro-optic material, and it has got a lot of applications in optical devices, such as optical switch, optical waveguide, optical modulator and so on because of its high transparency and good electro-optic properties[9,10]. In particular, $Pb_{0.865}La_{0.09}Zr_{0.65}Ti_{0.35}O_3$ (PLZT(9/65/35)) exhibits excellent quadratic electro-optic effect[11]. The refractive index of PLZT (9/65/35) can be rapidly changed by electro-optic effect, and accordingly the band structure of the photonic crystals has excellent tunability. Thus, the effective extension of applications in optical communication for photonic crystals can be realized.

In this letter, the band structure of PLZT (9/65/35), which is chosen for fabricating two-dimensional photonic crystals is analyzed. In the absence of the applied electric field, as the refractive index of the materials is fixed, the band structure of two-dimensional photonic crystals based on PLZT is not changed. In the presence of the applied electric field, the band structure varies, as the electro-optic effect of PLZT causes change of its refractive index. The band structure of two-dimensional PLZT photonic crystals is computed using the element method. The effect of the electric field change on the band structure, start wavelengths, cut-off wavelengths and bandwidths of the first and second band gaps is analyzed. And the relationship between the band and electric field is given, which lays a theoretical foundation for controlling the optical transmission characteristics of two-dimensional photonic crystals by the applied electric field. Based on this, the corresponding optical devices, such as optical switch, optical filter and wavelength division multiplexer controlled by electric field, can be designed.

PLZT material shows significant quadratic electro-optic effect when an external electric field is applied[12-15], and the ordinary and extraordinary indices of refraction are determined by

$$n_0 = n - \frac{1}{2} n^3 R_0 E^2, n_e = n - \frac{1}{2} n^3 R_e E^2 , \tag{1}$$

where n_0 and n_e are the refractive indices of the ordinary and

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extraordinary light, respectively. R_0 and R_e are the quadratic electro-optic coefficients, n is the refractive index of PLZT, and E is the electric field intensity. The refractive index of the ordinary light is in x-y plane, and that of the extraordinary light is on z-axis. The relationships between them are as follows:

$$n_x = n_y = n_0 \ , \quad n_z = n_e \ , \tag{2}$$

where n_x, n_y and n_z are the refractive indices in the directions of x-axis, y-axis and z-axis, respectively.

In the passive case, the monochromatic wave is considered, so the light propagating in two-dimensional photonic crystals must satisfy the Maxwell's equations in the scalar form as follows:

$$-\nabla \cdot \frac{1}{\varepsilon(\boldsymbol{r})} \nabla \phi = \left(\frac{\omega}{c}\right)^2 \phi \, , \tag{3}$$

$$-\frac{1}{\varepsilon(\boldsymbol{r})} \nabla^2 \phi = \left(\frac{\omega}{c}\right)^2 \phi \ , \tag{4}$$

where $\varepsilon(\boldsymbol{r})$ is the dielectric function, $\boldsymbol{r}$ represents the spatial position, ω is the frequency, c is the speed of light, and ϕ is the scalar field intensity of the transverse electric polarization (TE mode) and that of the transverse magnetic polarization (TM mode), respectively.

By applying Floquet-Bloch theory, the eigenmodes of two-dimensional photonic crystals take the form:

$$\phi = \mathrm{e}^{\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}} \, \psi(\boldsymbol{r}) \, , \tag{5}$$

where $\boldsymbol{k}$ is the Bloch-quasimomentum vector and $\psi(\boldsymbol{r})$ is the value of eigenfunction at spatial position $\boldsymbol{r}$. Then Eqs.(3) and (4) can be rewritten as

$$-(\nabla + \mathrm{i}\,\boldsymbol{k}) \cdot \left[\frac{1}{\varepsilon(\boldsymbol{r})} (\nabla + \mathrm{i}\,\boldsymbol{k}) \psi\right] = \left(\frac{\omega}{c}\right)^2 \psi \ , \tag{6}$$

$$-\frac{1}{\varepsilon(\boldsymbol{r})} (\nabla + \mathrm{i}\,\boldsymbol{k})^2 \psi = \left(\frac{\omega}{c}\right)^2 \psi \ , \tag{7}$$

respectively, and Eqs.(6) and (7) are transformed into the finite element form and then are solved. For this, the two-dimensional domain to be studied is discretized using the linear triangular element. Then, there is an interpolation for element. The scalar field inside the linear triangular element can be expanded as:

$$\psi^{e}(x, y) = \sum_{j=1}^{3} N_j^{e}(x, y) \psi_j^{e} \ , \tag{8}$$

where $N_j^e(x, y)$ is the shape function, and ψ_j^e represents the value of the electric or magnetic field along the jth edge of the e th element.

Based on the variational principle of electromagnetics, in terms of periodic boundary conditions, the functions of two-dimensional photonic crystals can be given by:

$$F(\psi) = \sum_{e=1}^{M} F^{e}(\psi^{e}) =$$
$$\sum_{e=1}^{M} \frac{1}{2} \iint_{\Omega^e} \Bigg\{ \frac{1}{\varepsilon(\boldsymbol{r})} \left[\left(\frac{\partial \psi^{e}}{\partial x} \right)^2 + \left(\frac{\partial \psi^{e}}{\partial y} \right)^2 \right] +$$
$$\left[\boldsymbol{k}^2 \cdot \frac{1}{\varepsilon(\boldsymbol{r})} - \mathrm{i}\,\boldsymbol{k} \nabla \frac{1}{\varepsilon(\boldsymbol{r})} - \left(\frac{\omega}{c} \right)^2 \right] (\psi^{e})^2 -$$
$$2\,\mathrm{i}\,\boldsymbol{k} \frac{1}{\varepsilon(\boldsymbol{r})} \left(\frac{\partial \psi^{e}}{\partial x} + \frac{\partial \psi^{e}}{\partial y} \right) \psi^{e} \Bigg\} \mathrm{d}\,\Omega^{e},$$
$$(\text{for TE mode}) \ , \tag{9}$$

$$F(\psi) = \sum_{e=1}^{M} F^{e}(\psi^{e}) =$$
$$\sum_{e=1}^{M} \frac{1}{2} \iint_{\Omega^e} \Bigg\{ \frac{1}{\varepsilon(\boldsymbol{r})} \left[\left(\frac{\partial \psi^{e}}{\partial x} \right)^2 + \left(\frac{\partial \psi^{e}}{\partial y} \right)^2 \right] +$$
$$\left[\boldsymbol{k}^2 \cdot \frac{1}{\varepsilon(\boldsymbol{r})} - \left(\frac{\omega}{c} \right)^2 \right] (\psi^{e})^2 -$$
$$2\,\mathrm{i}\,\boldsymbol{k} \frac{1}{\varepsilon(\boldsymbol{r})} \left(\frac{\partial \psi^{e}}{\partial x} + \frac{\partial \psi^{e}}{\partial y} \right) \psi^{e} \Bigg\} \mathrm{d}\,\Omega^{e} \ ,$$
$$(\text{for TM mode}) \ . \tag{10}$$

Substituting Eq.(8) into Eqs.(9) and (10), the derivate of F^e with respect to ψ_i^e is obtained and re-arranged as follows:

$$\left\{ \frac{\partial F}{\partial \psi} \right\} = \sum_{e=1}^{M} \left\{ \overline{\frac{\partial F^{e}}{\partial \psi^{e}}} \right\} =$$
$$\sum_{e=1}^{M} \left\{ \left(\left[\overline{K^{e}} \right] + \left[\overline{M^{e}} \right] + \left[\overline{\Psi^{e}} \right] \right) \left\{ \overline{\psi^{e}} \right\} - \left\{ \overline{P^{e}} \right\} \right\} = \{0\} \ , \tag{11}$$

where $\{\overline{P^e}\}$ is a vector related to the periodic boundary terms. Then the finite element model of two-dimensional photonic crystals is given by:

$$([K] + [M] + [\Psi])\{\psi\} - \{P\} = \{0\} \ , \tag{12}$$

where ω can be solved as a function of $\boldsymbol{k}$, and for each $\boldsymbol{k}$, there is a set of ω correspondingly. Then, by solving $\omega(\boldsymbol{k})$, the band diagrams of TE and TM modes can be obtained, respectively.

The section of two-dimensional PLZT photonic crystal with hexagonal lattice of air-cylinder is shown in Fig.1(a). And the section of two-dimensional Brillouin zone corresponding to hexagonal lattice is shown in Fig.1(b). R is the air-cylinder radius, and a is the periodicity of the lattice.

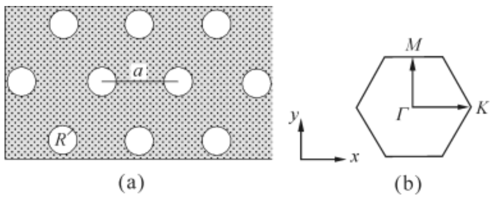


Fig.1(a) Section of 2D PLZT photonic crystal with hexagonal lattice of air-cylinder; (b) Section of 2D Brillouin zone corresponding to hexagonal lattice

The dielectric function of two-dimensional photonic crystals is given by

$$\varepsilon(\boldsymbol{r}) = \varepsilon_B+(\varepsilon_A - \varepsilon_B)\, s(\boldsymbol{r}) \ , \tag{13}$$

where $s(\boldsymbol{r}) = 1(\boldsymbol{r} \quad s_R)$, $s(\boldsymbol{r}) = 0(\boldsymbol{r} \ / \ s_R)$, and s_R is the region in x-y plane defined by the cross section of the inner cylinder. $\varepsilon_A = n_A^2$, $\varepsilon_B = n_B^2$, and n_A and n_B are the refractive indices of the dielectric cylinder (air) and background (PLZT), respectively. Here, the lattice constant and air-cylinder radius are given as a= 600 nm and R = 215 nm, respectively. And the lattice region to be studied is chosen as $18a \quad 18a$. The quadratic electro-optic coefficient of the PLZT is $R_0 = 6 \quad 10^{-16}$ m^2/V^2, and the refractive index is $n_B = 2.5$.

In the absence of the applied electric field, i.e., E = 0 kV/cm, the band diagrams for TE mode and TM mode of two-dimensional PLZT photonic crystals are shown in Fig.2 (solid line). When an applied electric field is imposed, i.e., E=100 kV/cm, the electro-optic effect of PLZT material causes change of its refractive index, and accordingly the band structure varies. The band diagrams for TE mode and TM mode are shown in Fig.2 (dashed line).

The relationships between start wavelength, cut-off wavelength, bandwidth of band gap and the electric field for TE mode and TM mode of two-dimensional PLZT photonic crystals are shown in Fig.3-Fig.5.

It can be found from Fig.3-Fig.5 that in the TE mode, for the first band gap, the relationship between the start wavelength and the electric field is -0.027 nm/(kV/cm)^2, that between the cut-off wavelength and the electric field is -0.056 nm/(kV/cm)^2, and that between the bandwidth and the electric field is -0.029 nm/(kV/cm)^2; for the second band gap, the relationship between the start wavelength and the electric field is -0.018 nm/(kV/cm)^2, that between the cut-off wavelength and the electric field is -0.019 nm/(kV/cm)^2, and that between the bandwidth and the electric field is -0.002 nm/(kV/cm)^2. In the TM mode, for the first band gap, the relationship between the start wavelength and the electric field is -0.054 nm/(kV/cm)^2, that between the cut-off wavelength and the electric field is -0.069 nm/(kV/cm)^2, and that between the bandwidth and the electric field is -0.015 nm/(kV/cm)^2; for the second band gap, the relationship between the start wavelength and the electric field is -0.032 nm/(kV/cm)^2, that between the cut-off wavelength and the electric field is -0.036 nm/(kV/cm)^2, and that between the bandwidth and the electric field is -0.004 nm/(kV/cm)^2.

Therefore, with the field intensity of the applied electric field increasing, for either TE mode or TM mode of two-dimensional PLZT photonic crystals, the start wavelength and cut-off wavelength of band gap both shift towards the anti-wavelength direction. The band gap is gradually decreased. However, for each band gap, the shifting value of

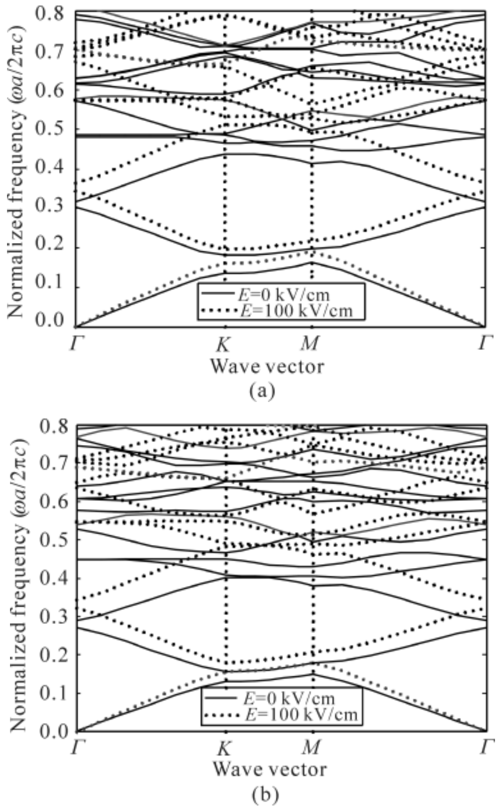
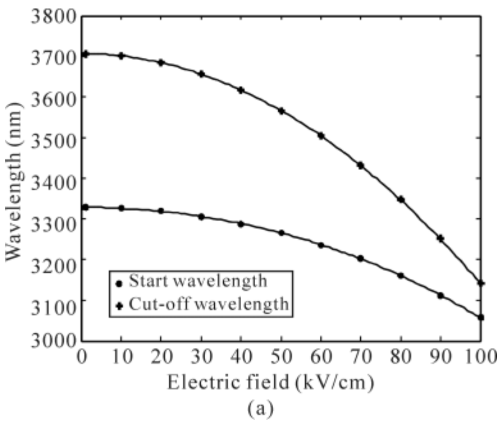


Fig.2 Effect of electric field on 2D PLZT photonic crystal band for (a) TE mode and (b) TM mode



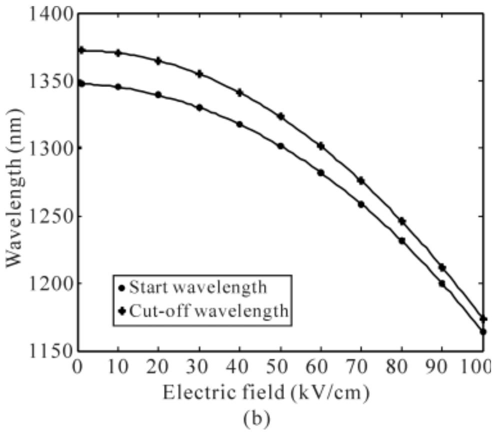


Fig.3 Effect of electric field on start and cut-off wavelengths of (a) the first and (b) the second band gaps for TE mode

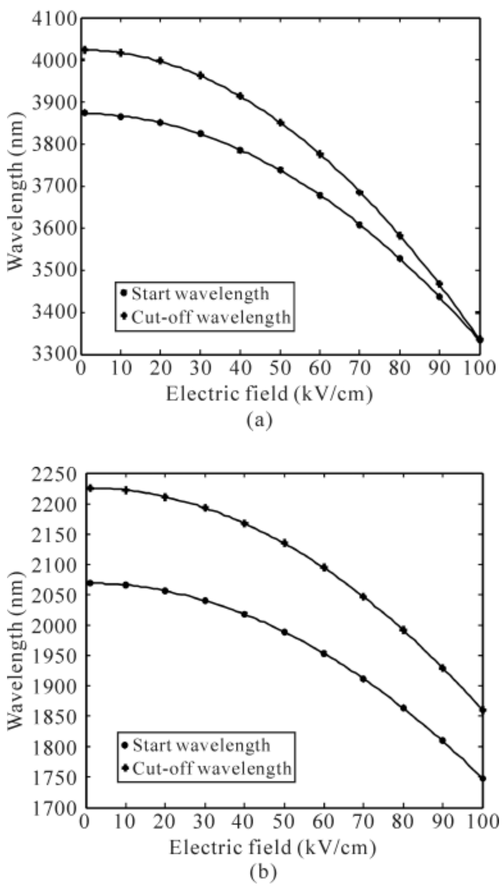


Fig.4 Effect of electric field on start and cut-off wavelengths of (a) the first and (b) the second band gaps for TM mode

start wavelength is different from that of the cut-off wavelength. The variations of different band gaps with the electric field are also different. The influence of the change of the applied electric field on the characteristics of the first band gap is larger than that on the second one. And the variations of start wavelength, cut-off wavelength and bandwidth of each band gap are proportional to quadratic of the electric field.

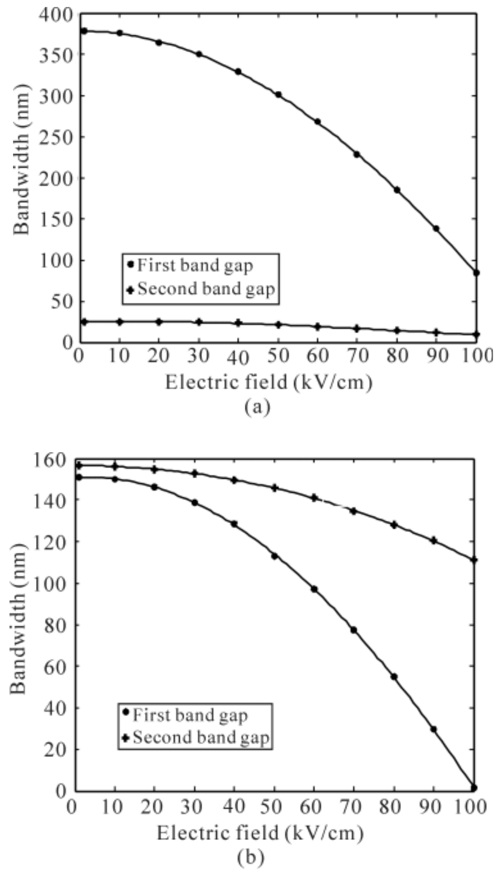


Fig.5 Effect of electric field on band gaps for (a) TE mode and (b) TM mode

The band structure of two-dimensional PLZT photonic crystals is calculated by finite element method. And the relationship between the band structure and the applied electric field based on the electro-optic effect is analyzed. The results show that with the field intensity of the applied electric field increasing, the band structure of two-dimensional PLZT photonic crystals shifts towards the direction of high frequency on the whole, as the electric field change causes the variation of the refractive index of PLZT materials. The shifting value of each band gap is proportional to quadratic of the electric field.

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