Characteristics of tunable micro-cavity based on one-dimensional photonic crystal doping KTP as defect layer*

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The tunable micro-cavity based on one-dimensional (1D) photonic crystal doped by KTP is designed. The optical transmission properties in the doped one-dimensional defect photonic crystals are analyzed using transfer matrix method (TMM). According to the electro-optic effect, the refractive index ellipsoid equation is established with the applied alternating current at both coordinate axes, and the characteristics of temperature-optics and modulation are studied. Numerical calculations and experimental results show that the tuning range is ~40 nm.

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Photonic crystal (PC) micro-cavities have attracted much attention[1-5]. The continuous wave (CW) PC laser was proposed in 2008 by O'Brien J. D[6], University of Southern California, with high output power of 100 μW. Kim and Sun Woong[7] from University of Kwangwoon proposed a birefringence PC laser with output wavelengths of 611 nm and 618 nm. In 2009, a novel PC diode laser was designed by Morifuji M[8] from Osaka University, employing electric-drive configuration to overcome the trouble of the practical application of PC laser. Additionally, the PC micro-cavity dielectric modulation in term of nonlinearity was utilized by Vignolini Silvia[9] from Florence University in Italy, and the dependence of environmental temperature on dielectric refractive index was studied simultaneously. However, few investigation on tunable PC micro-cavity laser appears.

In this paper, we propose a tunable PC laser micro-cavity, of which the defect layer is the electro-optic crystal KTP, and the transmission characteristic and the tuning range of the micro-cavity are analyzed by the transfer matrix method (TMM).

The one-dimensional PC doping KTP as defect layer is shown in Fig.1. The configuration is $(AB)_5D(BA)_5$ and the black block represents the electro-optic crystal KTP which is around uniform PCs with the same number of periods. A is medium Si with refractive index of n_a=3.42 and B is medium SiC with n_b=2.65. The central wavelength is λ_0=532 nm. The thickness of each layer in Fig.1 can be determined in term of $nd = \lambda_0/4$. The fabrication of PC and micro-cavity are completed utilizing chemical deposition[10], and the cross-section of sample is observed in scanning electron microscope (SEM).

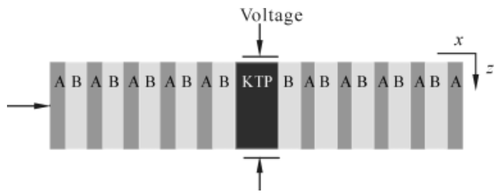

Fig.1 Structure diagram of the photonic crystal doping KTP as defect layer

When the laser beam injects into PC, according to transfer matrix, the eigenmatrix of the *j*th layer can be written as

$$\boldsymbol{M}_j = \begin{pmatrix} \cos\delta_j & -\frac{\mathrm{i}}{p_j}\sin\delta_j \\ -\mathrm{i}\, p_j \sin\delta_j & \cos\delta_j \end{pmatrix}, \qquad (1)$$

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where $\delta_j = \frac{2\pi}{\lambda} n_j d_j \cos\theta_j$, n_j and d_j are the refractive index and the thickness of the jth layer, respectively. θ_j is the angle between transmission direction in jth layer and the normal direction of interface and λ is the wavelength of incident laser beam. p_j is the effective admittance of medium, and taking the polarization of incident beam into account, we have

$$p_j = \begin{cases} n_j / \cos\theta_j & p-\text{polarization} \\ n_j \times \cos\theta_j & s-\text{polarization} \end{cases} . \tag{2}$$

The transmission matrix of the first basic period of defect layer on the left is expressed as

$$\boldsymbol{M}_L = \begin{pmatrix} \cos\delta_1 & -\frac{\mathrm{i}}{p_1}\sin\delta_1 \\ -\mathrm{i}\,p_1\sin\delta_1 & \cos\delta_1 \end{pmatrix} \times \begin{pmatrix} \cos\delta_2 & -\frac{\mathrm{i}}{p_2}\sin\delta_2 \\ -\mathrm{i}\,p_2\sin\delta_2 & \cos\delta_2 \end{pmatrix} , \tag{3}$$

and the right one is

$$\boldsymbol{M}_\mathrm{R} = \begin{pmatrix} \cos\delta_2 & -\frac{\mathrm{i}}{p_2}\sin\delta_2 \\ -\mathrm{i}\,p_2\sin\delta_2 & \cos\delta_2 \end{pmatrix} \times \begin{pmatrix} \cos\delta_1 & -\frac{\mathrm{i}}{p_1}\sin\delta_1 \\ -\mathrm{i}\,p_1\sin\delta_1 & \cos\delta_1 \end{pmatrix} . \tag{4}$$

The transmission matrix of the whole PC with a defect layer in Fig.1 can be expressed as

$$\boldsymbol{M} = (\prod_{N=1}^{5} \boldsymbol{M}_\mathrm{L}) \boldsymbol{M}_\mathrm{D} (\prod_{N=1}^{5} \boldsymbol{M}_\mathrm{R}) = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix}, \tag{5}$$

where $\boldsymbol{M}_\mathrm{D}$ is eigenmatrix of defect layer. The reflective index r and the transmission t of PC are obtained as

$$r = \frac{m_{11} p_\mathrm{L} + m_{12} p_\mathrm{L} p_\mathrm{R} - m_{21} - m_{22} p_\mathrm{R}}{m_{11} p_\mathrm{L} + m_{12} p_\mathrm{L} p_\mathrm{R} + m_{21} + m_{22} p_\mathrm{R}} , \tag{6}$$

$$t = \frac{2 p_\mathrm{L}}{m_{11} p_\mathrm{L} + m_{12} p_\mathrm{L} p_\mathrm{R} + m_{21} + m_{22} p_\mathrm{R}} , \tag{7}$$

where $p_\mathrm{L} = \sqrt{\frac{\varepsilon_\mathrm{L}}{\mu_\mathrm{L}}} \cos\theta_\mathrm{L}$, $p_\mathrm{R} = \sqrt{\frac{\varepsilon_\mathrm{R}}{\mu_\mathrm{R}}} \cos\theta_\mathrm{R}$. ε_L, μ_L, ε_R, μ_R are the dielectric constants and permeabilities of medium at left and right boundaries of PC, respectively. θ_L and θ_R are the angles between the normal direction of medium interface and the incident wave as well as transmission wave direction of PC. The transmissivity of PC is $T = |t|^2$.

Electro-optical effect is the phenomenon that the refractive index changes significantly with direct current field or low frequency electric field[11]. That is to say, the applied electric field can change the optical property of medium. KTP crystal is the orthorhombic crystal system and mm2 point group, and the principal axes of the refractive index ellipsoid are perpendicular to each other. Hence, its electric-optical coefficient matrix is

$$\gamma_{ijk} = \gamma_{ik} = \begin{pmatrix} 0 & 0 & \gamma_{13} \\ 0 & 0 & \gamma_{23} \\ 0 & 0 & \gamma_{33} \\ 0 & \gamma_{42} & 0 \\ \gamma_{51} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} . \tag{8}$$

When E_x or E_y is applied, namely, the electric field is applied on x- or y-axis, refractive index ellipsoid equation is hardly changed, so that the electro-optical effect has no application value. When E_z is applied, the crystal is forced, and the refractive index ellipsoid is written as

$$\left(\frac{1}{n_x^2} + \gamma_{13} E_z\right) x^2 + \left(\frac{1}{n_y^2} + \gamma_{23} E_z\right) y^2 + \left(\frac{1}{n_z^2} + \gamma_{33} E_z\right) z^2 = 1. \tag{9}$$

Now the principal axis direction cannot be changed but only reshaped. Besides that, the principal refractive index is varied to

$$\begin{aligned} n_x' &= n_x - \frac{1}{2} n_x^3 \gamma_{13} E_z, \\ n_y' &= n_y - \frac{1}{2} n_y^3 \gamma_{23} E_z, \\ n_z' &= n_z - \frac{1}{2} n_z^3 \gamma_{33} E_z. \end{aligned} \tag{10}$$

Here the incident beam into PC is the laser in TE mode, namely, the E-mode polarization is perpendicular to incident plane x-z, and the O-mode polarization corresponds to the relative doping layer. Thus, the refractive index must be applied as the third one of Eq.(10), which can be expressed as

$$n_\mathrm{d} = n_0 - \frac{1}{2} n_0^3 \gamma_{33} E , \tag{11}$$

where n_0 = 1.778, and the thickness of defect layer is $d = \frac{\lambda_0 / 2}{n_0}$ at room temperature. The transmissivity of the light in this composition can be calculated by TMM, so that the curve of wavelength of PC band gap is obtained in Fig.2.

As the KTP is electro-optical material and the wavelength of incident beam is 532 nm, the refractive index of defect layer must be changed when the electric field is applied on KTP along z-axis. In term of Ref.[12], we can modulate the refractive index of defect layer by applying alternating current (AC) field $E = E_0 \sin(\omega t)$, where ω is the frequency of AC field, which is along z-axis to adjust the transmission of the device. Hence, the refractive index of KTP is n_d=1.778 − 0.5×

$1.778^3 \times 9.5 \times 10^{-12} E_0 \sin(\omega t)$(m/V), $E_0 = 10^{10}$ V/m, $\omega = \pi / 50$. In this case, n_d is up to 0.534 as depicted in Fig.3.

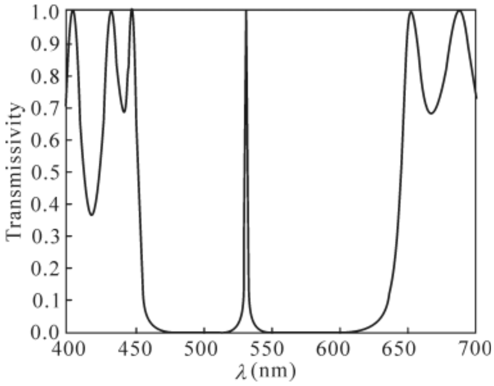

Fig.2 Transmissivity spectrum of doped one-dimensional PC

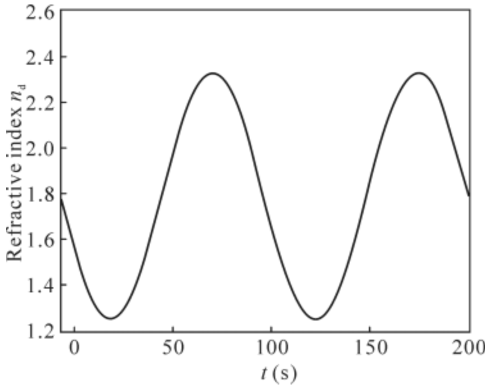

Fig.3 Refractive index curve modulated by AC

The transmission peak wavelength is varied regularly as the electric field applied on PC micro-cavity with KTP defect layer, which is depicted in Fig.4. As the electric field intensities are 1.4×10^{10} V, 0.67×10^{10} V, -0.46×10^{10} V and -0.83×10^{10} V, the peak wavelengths are 507 nm, 517 nm, 540 nm and 546 nm, respectively. Obviously, the tunable range can be ~40 nm by modulating the electric field intensity.

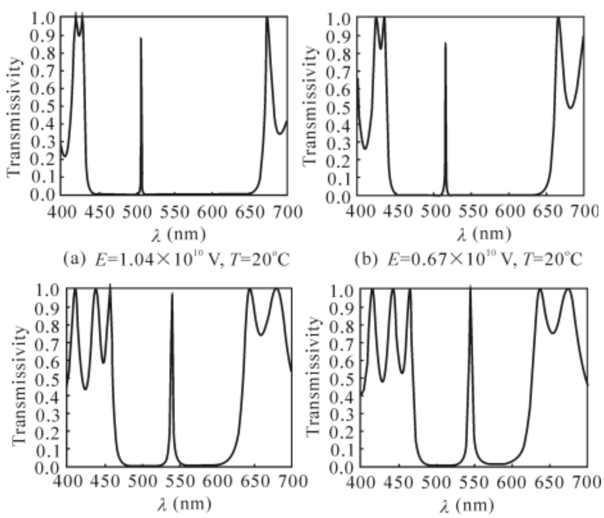

Fig.4 Transmission spectra of one-dimensional photonic crystal micro-cavity with KTP as defect layer under different electric fields

The temperature coefficient of refractive index plays an important role in optical field[12,13]. We can change temperature to achieve the variation of the refractive index. The equation of the temperature coefficient of refractive index is given by

$$\frac{\mathrm{d}n_d}{\mathrm{d}T} = (0.1323\lambda^{-3} - 0.4385\lambda^{-2} + 1.2307\lambda^{-3} + 0.7709) \times 10^{-5}(^\circ\mathrm{C}^{-1}) \ . \tag{12}$$

The refractivity of KTP as a function of temperature is $n_d = 1.778 + 1.1 \times 10^{-5}\ T$ ($^\circ$C^{-1}) when the wavelength is 532 nm and the temperature coefficient of refractive index is 1.1×10^{-5} ($^\circ$C^{-1}). Due to the fusion point of KTP is 1172 °C, the variation of temperature can change the crystal characteristics, especially changing the refractive index. The KTP will be melted partially as the temperature reaches 900 °C. Fig.5 shows the refractive index of KTP as a function of temperature, and it can be demonstrated by the designed PC composition and calculated numerically in this paper, which is shown in Fig.6. As the increasing of temperature, in the range within 900 °C, the refractive index of KTP is enhanced, which can lead to red-shift for defect mode.

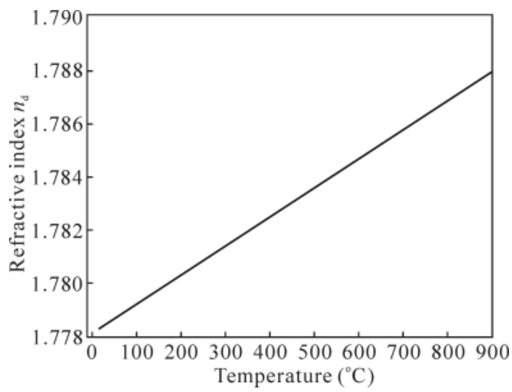

Fig.5 Refractive index with the influence of the temperature

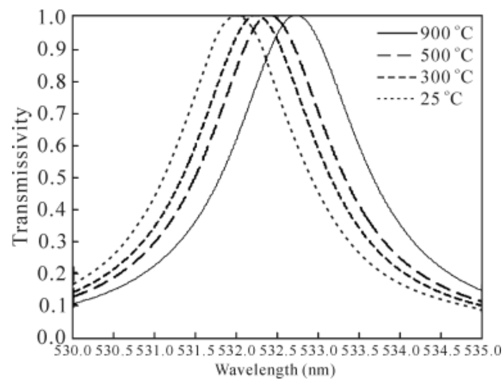

Fig.6 Transmissivity with the influence of the temperature

The laser micro-cavity is formed by KTP-doped one dimensional PC with periodical symmetric composition, employing the electro-optical effect of KTP at room temperature. The output peak wavelength is tunable for obout 40 nm around the central wavelength. The numerical calculation results have the theoretical and application significance for the fabrication of PC laser and positive optical device.

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