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Investigation of thermal tunable nano metallic photonic crystal filter with mirror symmetry

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Abstract: Using the transfer matrix method, the effect of temperature on the transmission spectra of thermal tunable nano metallic photonic crystal filter has been investigated. Three different materials **H** (high refractive index material), **L** (low refractive index material) and **M** as a metallic layer, have been used to make this structure. **M** layer is considered to be Silver. The complex refractive index of Silver is a function of temperature and wavelength simultaneously so, the structure is tunable with temperature and incident angle. It is found that the transmission peaks shift by changing temperature and incident angle. At a given incident angle, they move toward higher wavelengths by increasing the temperature. The temperature dependence of transmission peaks is linear. At a constant temperature, they move toward the shorter wavelengths by increasing the incident angle. Also by increasing the temperature, due to dissipation the height of transmission peaks gets decreased and this reduction is linear too.

Keywords: Photonic Crystals, Temperature, Filter.

1. INTRODUCTION

Photonic crystals are periodic structures consist of different materials [1-5] such as dielectrics [6], semiconductors [7, 8], left-handed materials [9], superconductors [10, 11], metals [12, 13] and etc. In 1D photonic crystal, the periodicity of refractive index occurs only in one dimension, while in the other two dimensions the structure is uniform [4]. The most important feature of photonic crystal structures is photonic band gap. Photonic band gaps are the frequency range that the electromagnetic waves are not allowed to propagate so the light can be reflected totally with in photonic band gaps [14, 15].
Photonic crystals have too many applications such as optical waveguides [16], optical fibers [3], optical filters [17], optical switches [18] and optical lasers. Optical filters are optical devices that allow the propagation of the specific optical signal while prevents other signals [19, 20].

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In addition, optical filters with nano or micrometers have a very important role in photonic complex circuits, optical communication networks and multiplexing wavelength division systems.
In this work, we propose a thermal tunable 1D photonic crystal filter with mirror symmetry structure. We use three different materials H (high refractive index), L (low refractive index) and Silver (Ag) as a metal layer. Since the permittivity coefficient of metal is simultaneously a function of temperature and wavelength, the photonic band structure, including the temperature dependent metal layer, can be tunable with temperature variation, which is of great importance in optics.
In the photonic band gap area, the transmission peaks will be appeared, which can be considered as a defective mode. The effect of temperature on the defect mode will be investigated by simultaneously considering thermal expansion effect and thermal-optical effect.

2. THEORY

Consider the structure that consists of three materials as H (high refractive index), L (low refractive index) and Silver (Ag) as a metal layer (figure 1). The structure has mirror symmetry as $(MLH)^N(HLM)^N$ where N is the number of periods.

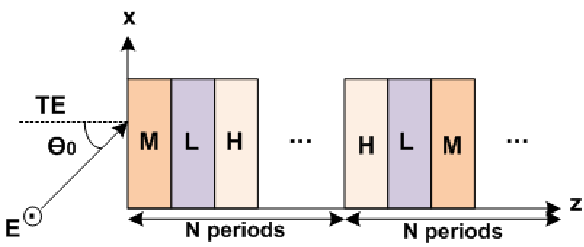


Fig. 1. The structure of photonic crystal with mirror symmetry as $(MLH)^N(HLM)^N$.

The characteristic matrix of each layer is

$$M_l = \begin{bmatrix} \cos\beta_l & \dfrac{-i\sin\beta_l}{p_l} \\ -ip_l\sin\beta_l & \cos\beta_l \end{bmatrix} \quad (l = H, L, M) \tag{1}$$

Here, $\beta_l = 2\pi n_l d_l \cos\theta_l / \lambda$, θ_l is the incident angle in each layer, n_l and d_l are the refractive index and thickness of each layer respectively at room temperature $T = 300K$. p_l is also obtained from $p_l = n_l \cos\theta_l$ for TE mode and $p_l = \cos\theta_l / n_l$ for TM mode. So the characteristic matrix for the whole system is given by [21]

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = (M_M M_L M_H)^N (M_H M_L M_M)^N \tag{2}$$

The dielectric constant in free electron Drude model of the metallic layer is taken from

$$\varepsilon_M(\omega, T) = 1 - \frac{\omega_p{}^2}{\omega(\omega + i\,\omega_c(T))} \tag{3}$$

M stands for metal. ω_p, is the plasma frequency and ω_c is the electron collision frequency. $\omega = 2\pi c/\lambda$, where λ is the wavelength.

The temperature dependence of plasma frequency is very small due to volume expansion, and consequently, ω_p can be approximately a constant. So, the Silver dielectric function can be approximately modeled using $\omega_p = 8.28 eV$ and $\omega_c(T) = (0.048/300^{1.3})T^{1.3}$ where, $\omega_c(T = 300) = 0.048 eV$ [22, 23]. The refractive index of the silver is given by $n = (\varepsilon\mu)^{1/2}$ where ε is the relative dielectric permittivity and μ is the relative permeability of the material. For Silver μ is equal to one. Consequently, we have

$$n_M(\omega, T) = (\varepsilon_M(\omega, T))^{1/2} \tag{4}$$

The refractive index of Silicon is also a function of wavelength. It is given by Sellmeier relation as [24]

$$n^2(\lambda) = A + \frac{B\lambda^2}{\lambda^2 - C} + \frac{D\lambda^2}{\lambda^2 - E} \tag{5}$$

Here $A = 4.92719645, B = 7.27691471, C = 11.5786091\times10^2, D = 42.7173925$ and $E = 100$ are Sellmeier coefficients in visible light. The change in temperature causes the thickness of each layer to change with the temperature due to the thermal expansion effect as

$$d(T) = d_0[1 + \alpha(T - 300)] \tag{6}$$

Here d_0 is the thickness of each layer at room temperature and α is the thermal expansion coefficient. The change in the refractive index of ***H*** and ***L*** due to the thermo-optic effect is also expressed as follows

$$n(T) = n_0[1+\beta(T-300)] \tag{7}$$

Where, n_0 is the refractive index of each dielectric layer at room temperature and β is the thermo-optic coefficient of the medium [25].
The transmission coefficient of the spectrum is taken from

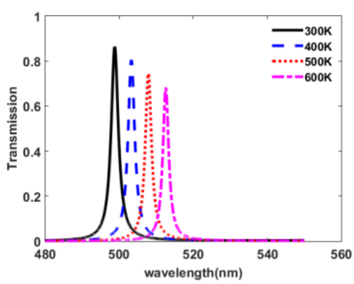
$$t = \frac{2p_0}{(m_{11}+m_{12}p_0)+(m_{21}+m_{22}p_0)} \tag{8}$$

Where, $p_0 = n_0\cos(\theta_0)$. The transmittance can be calculated as

$$\Gamma = |t|^2 \tag{9}$$

3. NUMERICAL RESULTS AND DISCUSSION

In all calculations, H is taken to be Si with refractive index is given by equation (5), thickness of 50nm, and L is SiO_2 with refractive index 1.45, thickness of 90nm at room temperature. The layer M is considered as Ag which its refractive index and thickness are given by equation (4) and 10nm respectively. The thermo- optic coefficients of H and L are 0.5×10^{-6} and 5.5×10^{-7} respectively [6, 26]. The thermal expansion coefficients of H, L and M are also given by 1.86×10^{-4}, 1×10^{-5} and 19.2×10^{-6} [27] respectively. We plot the transmission spectra of this structure in different temperatures and angles of incidence for both TE and TM polarizations in figure 2. For $\theta_0 = 0$ the transmission spectra of both polarizations match each other.



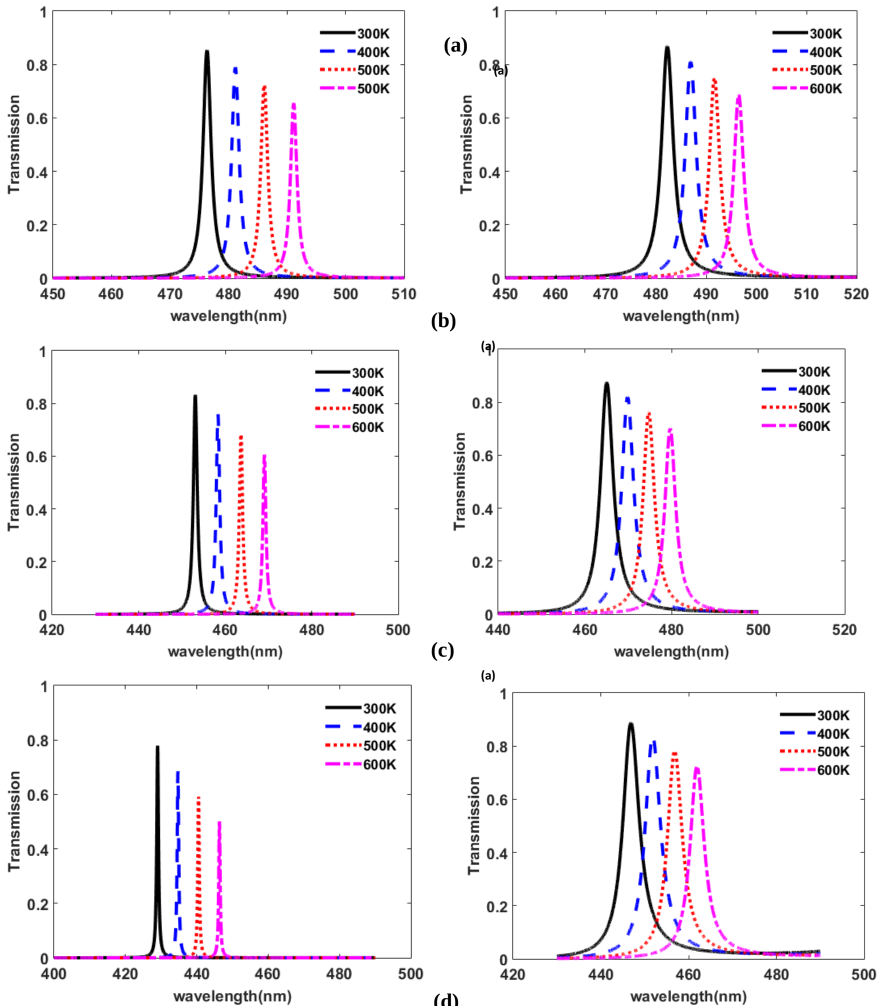


Fig. 2. The transmission spectra of photonic crystal with mirror symmetry as $air/(MLH)^4(HLM)^4/air$ for (a) $\theta_0 = 0$, (b) $\theta_0 = 30$, (c) $\theta_0 = 45$ and (d) $\theta_0 = 60$, in both TE (left) and TM (right) polarizations.

As we have seen from figure 2 the transmission peaks are tunable with temperature. For example for $\theta_0 = 45^\circ$ the position of transmission peaks in 300, 400, 500 and 600K are 453.1, 458.3, 463.6 and 469.1nm respectively for TE mode. So, they move toward the larger wavelength by increasing the temperature. The dependence of the position of transmission peaks to the temperature is linear. This behavior is hold for all incident angles and both polarizations. We can explain it by the condition of the constant phase. The phase of the wave is given by $\beta_l = 2\pi n_l d_l \cos\theta_l / \lambda$. It is clear that at a constant incident angle, the refractive index and thickness of layers are increase by increasing the temperature so, λ should be increased to keep the phase constant.

Since the loss factor of Silver is the function of the temperature the height of the transmission peaks get decreased by increasing temperature. These variations are linear too.

The variations of the position of transmission peaks is presented in figure 3.

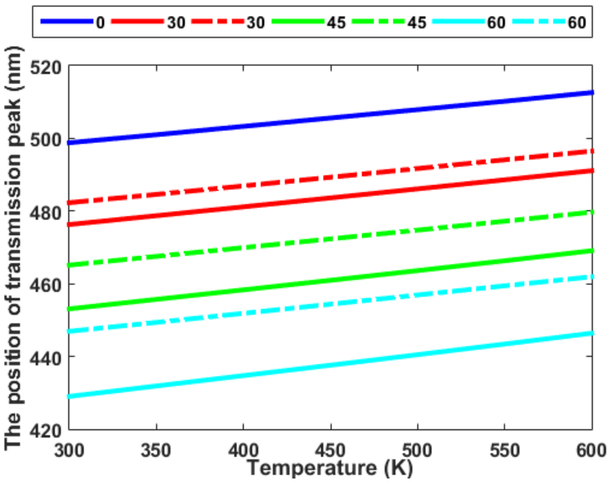


Fig. 3. The wavelengths of defect mode as a function of temperature in $air/(MLH)^4(HLM)^4/air$ at $\theta_0 = 0^\circ, 30^\circ, 45^\circ$ and 60° for both TE (solid line) and TM (dash line) polarizations.

From figure 3, it is found that the dependence of the transmission peaks on the temperature is linear for all incident angles and both polarizations. At a constant incident angle, the transmission peaks shift toward the larger wavelengths by increasing temperature. At a given temperature, the difference between the wavelengths of transmission peak gets increased by increasing the incident angle.

Now we plot the transmission spectra in terms of wavelength and incident angle in figure 4 due to investigation of the structure tunability to the incident angle for two different temperatures 300 and 600 in both TE and TM polarizations.

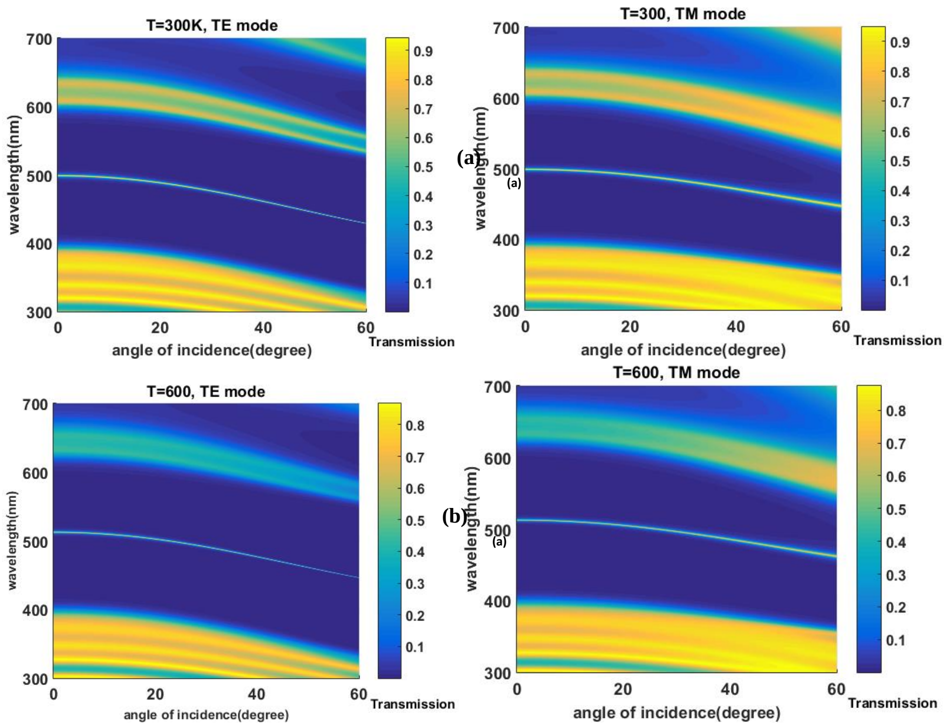


Fig. 4. Transmission as a function of incident angle and wavelength at two different temperatures (a) 300K and (b) 600K in TE (left) and TM (right) polarizations.

As we have seen from figure 4, it is found that at a given temperature the transmission peaks move toward the shorter wavelength. These displacements also can describe by the condition of constant phase. When the temperature is constant the refractive index and thickness of layers are constant too so by increasing the incident angles the wavelength should be decreased to keep the phase constant. The shift of the wavelength of transmission peaks with respect to the incident angle in TE polarization is more tangible than the TM polarization.

4. CONCLUSION

Using the transfer matrix method, we investigated the effect of the temperature on metallic photonic crystal filter with mirror symmetry. We plotted the transmission spectra of the structure in terms of the incident angle and temperature for both polarizations. This structure is tunable with temperature and incident angle. As the temperature increases, the defect modes move toward larger wavelengths. This is a linear shift. Also, because the loss factor of silver is a function of temperature, the height of defect modes decreases linearly with increasing temperature. This decrease is more noticeable in the TE than TM mode. Also, the width of the defect mode in TM mode is larger than TE mode.

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