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Modeling of thermal tunable multichannel filter using defective metallic photonic crystals

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The transmission spectra of one dimensional metallic photonic crystal containing defects are studied using a transfer matrix method. We consider silver as a defect layer with a refractive index dependent on wavelength and temperature simultaneously. Since the loss factor of silver is the function of temperature, we should find a structure that has sharp transmission peaks to model a filter. We present the structure with a coupled defect. It is found that the number of transmission resonant peaks is equal to the number of coupled defects and they are tunable with temperature and incident angle.

Keywords: photonic crystals, temperature dependent refractive index, multichannel filter, defective mode.

1. Introduction

Photonic crystals are periodic structures which control the propagation of light [1–3]. They can provide various applications such as optical waveguides [4], cavities [5], optical fibers [6], optical switches [7], optical filters [8], optical crystal lasers [9], *etc.* Optical filters are devices which allow the propagation of light with specific frequency, while blocking the others. One of the applications of photonic crystals is using them to design multilayer transmission filters [10, 11]. In general, these filters have structure as $(AB)^N C(AB)^N$. Here A, B and C are dielectric layers and C is a defect. This structure has a channel that permits propagation of only a single optical frequency. The presence of only a single transmission peak cannot be optimal because a wide area of band gaps remains useless. To increase the efficiency, we need to have a multichannel transmission filter with multitransmission resonant peaks. The permittivity or permeability of one of the constituent materials of photonic crystals can be dependent on some external parameters such as temperature [12, 13], voltage [14], external magnetic field [15, 16], *etc.*

In this paper, we use silver (Ag) as a defect layer. The refractive index of Ag is the function of temperature and wavelength simultaneously. So, we need a structure which has transmission spectra with sharp resonant peaks. We present a structure with coupled defects air/$(ABAC)^N$ABA/air [17], as a multichannel filter that is obtained from basic photonic crystal $(AB)^N A$. Here A and B are dielectric layers and C is a metallic defect layer. Our optical filter is tunable with temperature and incident angle in both polarizations TE and TM. It will be noted that the number of filtering channels N is equal to the number of coupled defects. We use a transfer matrix method to calculate the transmission [18].

2. Theory

In order to model a thermal tunable multichannel optical filter, we need to study the transmission spectra. We consider the structure as air/$(ABAC)^N$ABA/air. Using a transfer matrix method, we can obtain the characteristic matrix of this structure as

$$M = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} = (M_\mathrm{A}\, M_\mathrm{B}\, M_\mathrm{A}\, M_\mathrm{C})^N (M_\mathrm{A}\, M_\mathrm{B}\, M_\mathrm{A}) \tag{1}$$

Here, M_l is the characteristic matrix of each layer (l = A, B, C), and

$$M_l = \begin{bmatrix} \cos(\beta_l) & \dfrac{-i\sin(\beta_l)}{p_l} \\ -ip_l\sin(\beta_l) & \cos(\beta_l) \end{bmatrix} \tag{2}$$

where $\beta_l = 2\pi n_l d_l \cos(\theta_l)/\lambda$, and θ_l is the incident angle in each layer, n_l and d_l are refractive index and thickness of layers, respectively, p_l is also given by $p_l = n_l\cos(\theta_l)$ for TE mode and $p_l = \cos(\theta_l)/n_l$ for TM mode.

The metal permittivity in Drude model is taken from [19]

$$\varepsilon_\mathrm{metal}(\omega, T) = 1 - \frac{\omega_\mathrm{p}^2}{\omega(\omega + i\omega_\mathrm{c}(T))} \tag{3}$$

where ω_p and ω_c are plasma and electron collision frequency, respectively, and $\omega = 2\pi c/\lambda$. Temperature dependence of plasma frequency is very small because of volume expansion, so we can take it to be constant. We consider ω_p = 8.24 eV and $\omega_\mathrm{c}(T) = (0.048/300^{1.3})T^{1.3}$ [19, 20], and consequently, we have

$$n_\mathrm{metal}(\omega, T) = \sqrt{\varepsilon_\mathrm{metal}(\omega, T)\mu} \tag{4}$$

where ε and μ are relative dielectric permittivity and relative magnetic permeability, respectively. For our metal μ is equal to 1.

By considering the thermal expansion effect, the thickness of each dielectric layer is given by

$$d_\mathrm{dielectric}(T) = d_0\Big[1 + \alpha(T - 300)\Big] \tag{5}$$

Here d_0 is the thickness of layer at room temperature ($T = 300$ K), and α is the thermal expansion coefficient. The temperature dependence of the refractive index of each dielectric layer due to the thermo-optic effect is to be taken as

$$n_{\text{dielectric}}(T) = n_0\left[1 + \gamma(T - 300)\right] \tag{6}$$

where n_0 is the refractive index of dielectric layers at room temperature, and γ is thermo -optic coefficient [20–25]. The transmission coefficient of the structure is given by

$$t = \frac{2p_0}{(m_{11} + m_{12}p_0) + (m_{21} + m_{22}p_0)} \tag{7}$$

where $p_0 = n_0\cos(\theta_0)$. So, the transmittance can be calculated as

$$\Gamma = |t|^2 \tag{8}$$

3. Numerical results and discussions

We consider the structure as air/(ABAC)^{N}ABA/air. Here A and B are dielectric layers with high and low refractive index, respectively. Layer A is taken to be Si with $n_A = 3.3$ and $d_A = 117$ nm, and layer B is SiO_2 with $n_B = 1.45$ and $d_B = 140$ nm at room temperature. The defect layer is Ag with the refractive index as the Eq. (4) by thickness 10 nm. The thermo-optic coefficients of A and B are 0.5×10^{-6} K^{-1} and 5.5×10^{-6} K^{-1}, respectively [26]. The thermal expansion coefficients of A, B and C are also given by 1.86×10^{-4} K^{-1}, 1×10^{-5} K^{-1} [26] and 19.2×10^{-6} [27], respectively.

We plot the real and imaginary parts of the refractive index of Ag (Eq. (4)) as a function of temperature and wavelength in (see Fig. 1).

As it can be seen, the refractive index of Ag layers increases with temperature, so the transmission peaks can be shifted as a function of temperature. As a result, we can use this structure to design a thermal tunable filter.

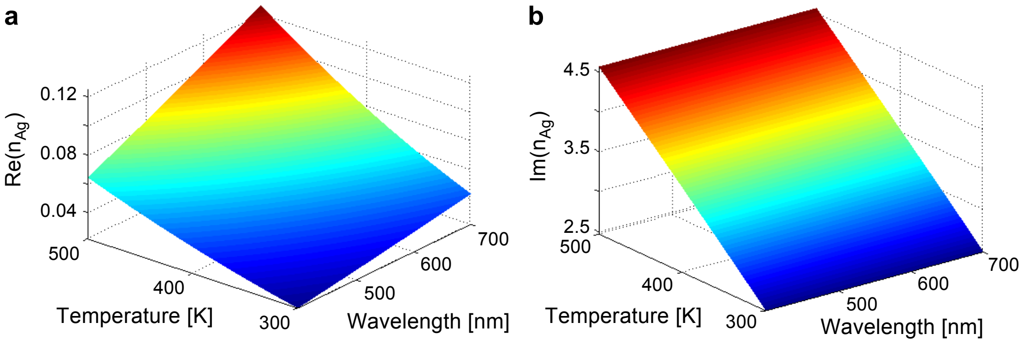

Fig. 1. The variation of real (**a**) and imaginary (**b**) part of refractive index of Ag with wavelength and temperature.

Then we plot the transmission spectra in normal incident room temperature for different magnitudes of *N* (see Fig. 2).

As it can be seen in Fig. 2 the number of transmission resonant peaks is equal to the number of coupled defects *N*.

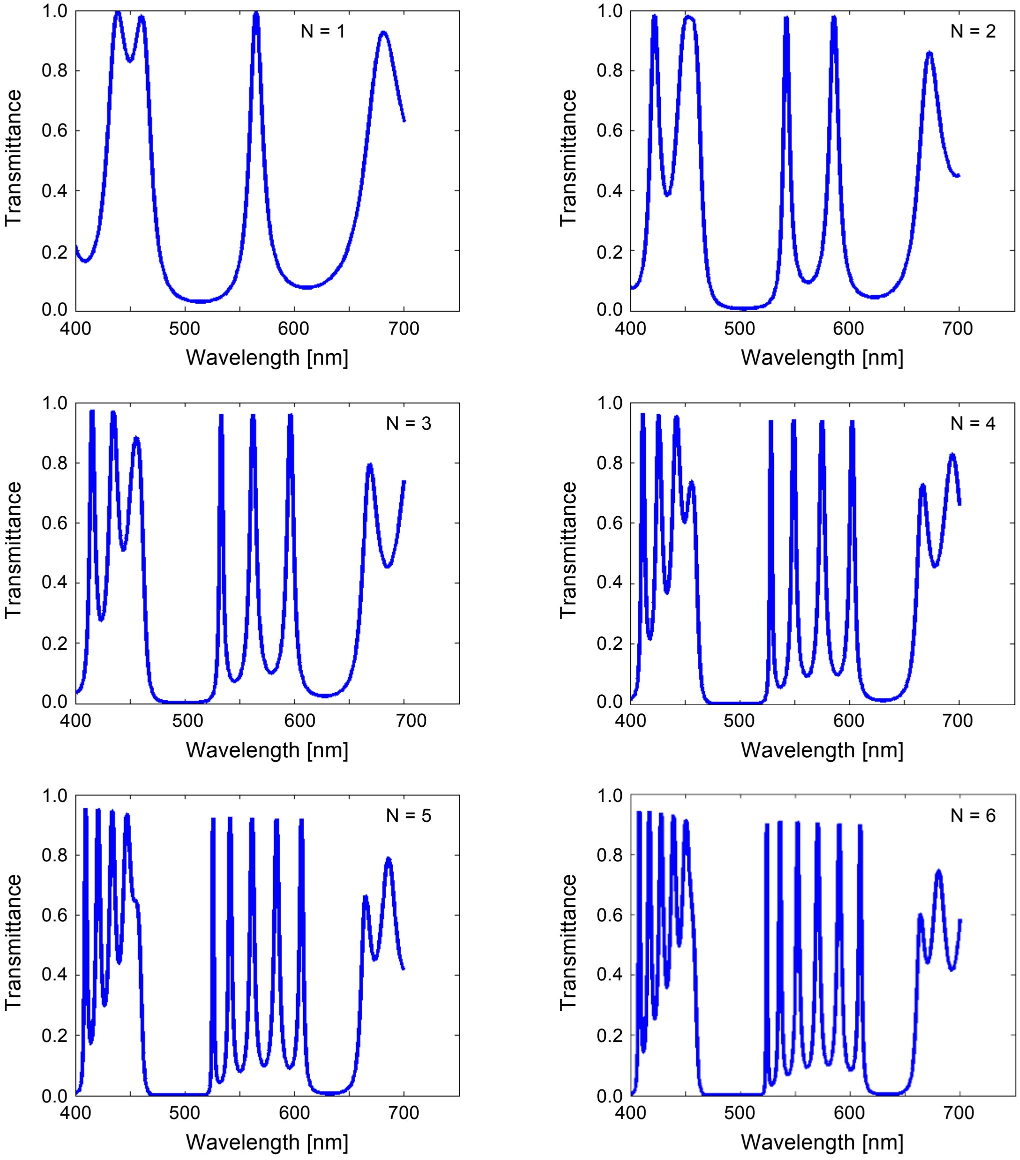

Fig. 2. Transmission spectra of structure air/(ABAC)^{N}ABA/air at normal incidence and different magnitudes of *N* at room temperature.

The transmission spectra as a function of temperature and wavelength at normal incidence are shown in Fig. 3 for different values of *N*.

By increasing the temperature, we can see that the position of resonant transmission peaks is shifted toward the larger wavelengths for all values of *N* and the variations

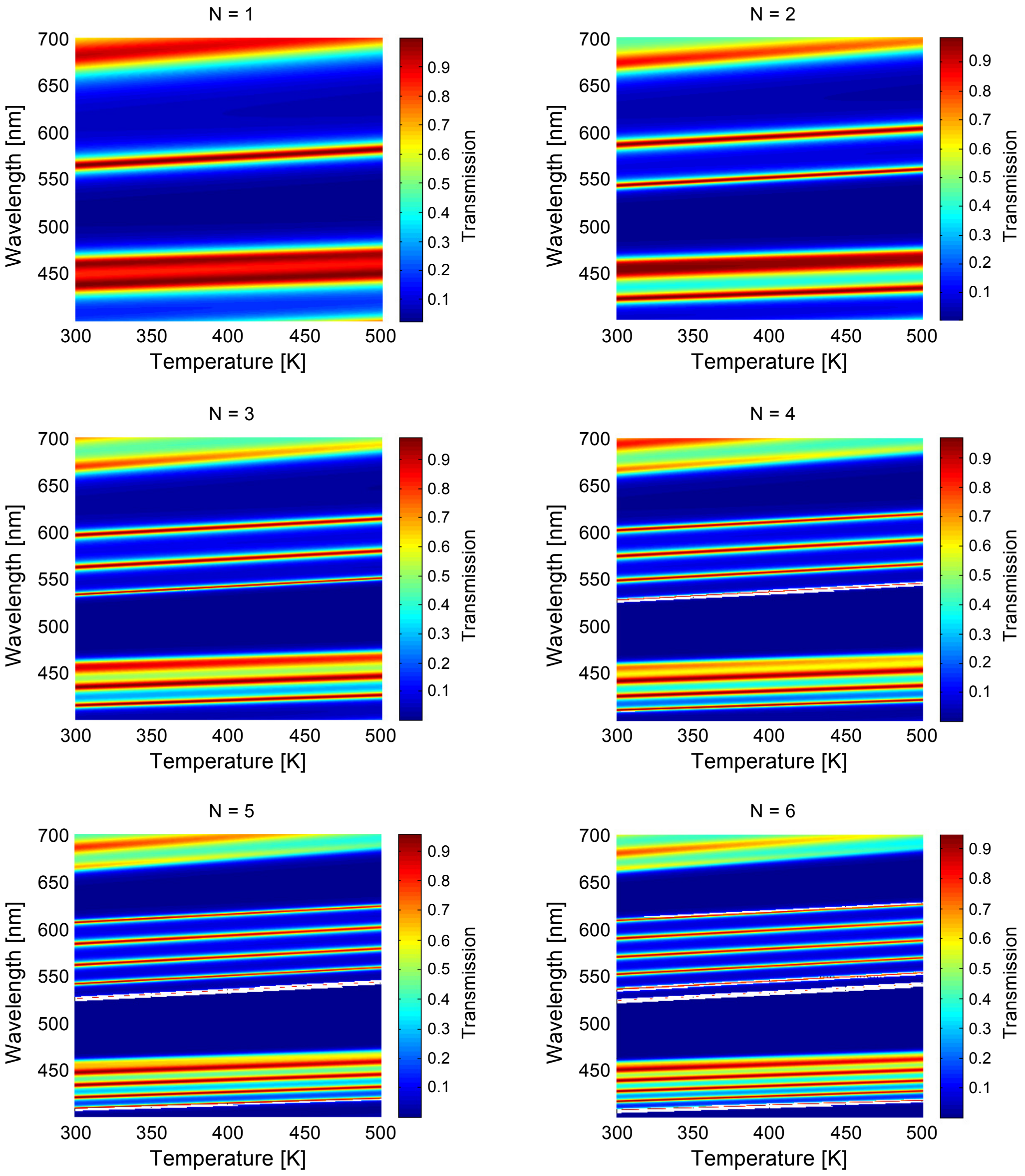

Fig. 3. Transmission as a function of temperature and wavelength at normal incidence for different values of *N*.

are linear. These movements can be justified by using the constant phase condition. Since the phase is obtained from $\beta_l = 2\pi n_l d_l \cos(\theta_l)/\lambda$, and assuming a constant incident angle, the magnitude of $n_l d_l$ increases when the temperature increases so to keep the

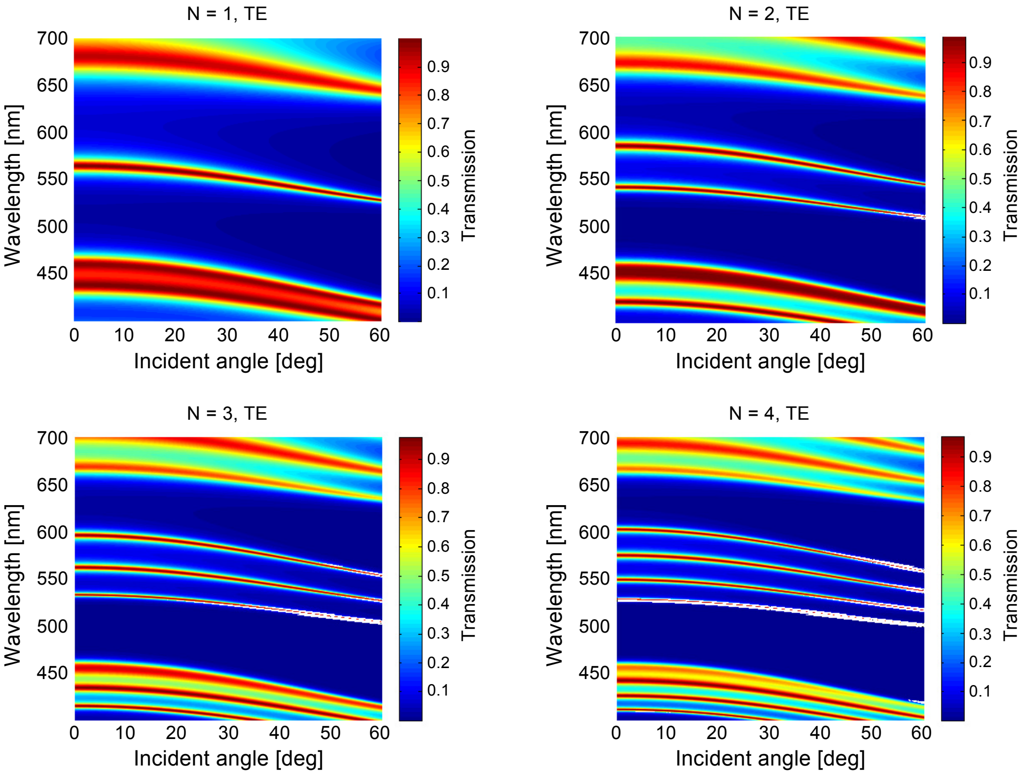

Fig. 4. Transmission as a function of incident angle and wavelength at room temperature in TE mode for different values of *N*.

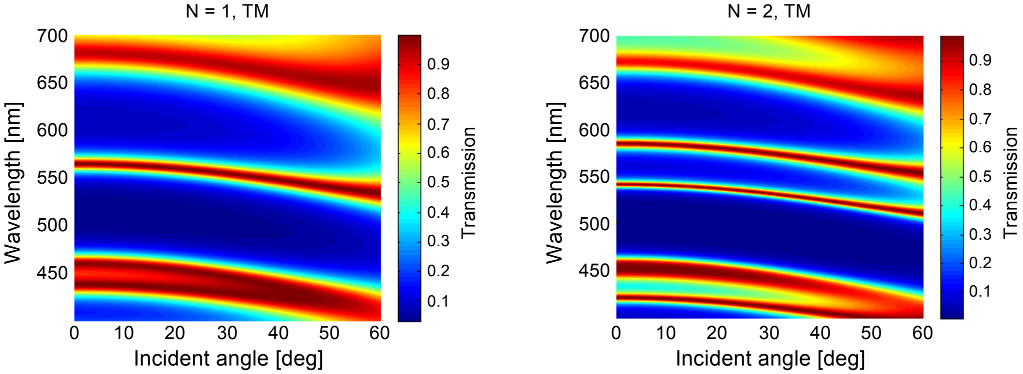

Fig. 5. To be continued on the next page.

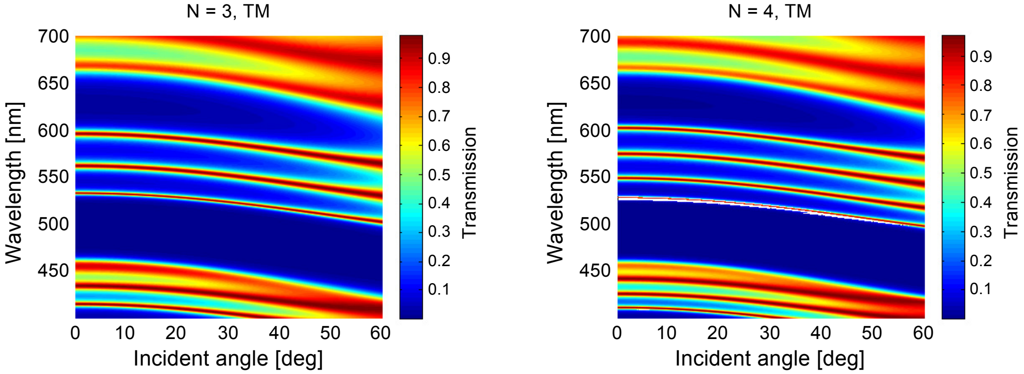

Fig. 5. Transmission as a function of incident angle and wavelength at room temperature in TM mode for different values of *N*.

phase constant, the wavelengths should be increased. Consequently, the movements are toward the larger wavelength.

Next, we study the incident angle dependence of the defect modes. We plot the transmission as a function of an incident angle and wavelength at room temperature for TE and TM polarizations in Figs. 4 and 5.

From Figs. 4 and 5 we find that the transmission peaks are moving towards a shorter wavelength by increasing the incident angle. This movement also can be justified with the constant phase condition. By increasing the incident angle at a constant temperature, refractive index and thickness values remain unchanged while $\cos(\theta)$ is decreased. So, the wavelength should be decreased to maintain the constant phase.

4. Conclusion

By using a transfer matrix method and coupled defects, we can design a multichannel filter in the visible region. As we have seen, this filter is tunable with temperature and the incident angle. We found that the number of resonant transmission peaks is equal to the number of coupled defects. In addition, we demonstrated that the resonant peaks are shifted towards higher wavelengths when the temperature gets increased at normal incidence. Further, as the temperature increases, the peaks become sharper. We also studied the movements of defect modes when the incident angle increases at constant temperature. In this case, the peaks are shifted towards shorter wavelengths.

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