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Analysis of Tuning Channel Filter Based on Ternary Lossy Defective Metallo-Dielectric Nano Photonic Crystal

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Abstract—In this paper, we design an optical filter by using one-dimensional (1d) ternary metallo-dielectric photonic crystal (PC). We use a dielectric defect layer between ternary asymmetric cells with this structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ and also increase the number of dielectric defect layers. Then, we plot transmission spectra in terms of wavelength and different angles of incidence in transverse electric (TE) and transverse magnetic (TM) polarizations. We show defect modes and photonic band gap (PBG) on the plane of wavelength and incident angles in both TE and TM polarizations. We also plot transmission in the lossless structure and compared loss and lossless structures. Furthermore, we compare dielectric defect layer with metallic defect layer in both TE and TM polarizations. Moreover, we plot symmetric structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{CBA})^N$ in TE and TM waves. The theoretical analysis shows that there is one defect mode which moves to the shorter wavelength by increasing angles of incidence in asymmetric structure. There are also two defect modes in symmetric structure, and by tuning angle of incidence this structure can be used as single channel filter in asymmetric structure and multichannel filter in symmetric structure.

1. INTRODUCTION

In the last two decades, advances in PC technology have attracted a great deal of attention. Optical filters are devices that selectively transmit light of different wavelengths, while blocking the remainder which is called PBG. PBG is in the ranges of frequency in which light cannot propagate through the PC. If the PBG can reflect electromagnetic waves incident at any angle with any polarization, then an omnidirectional BG can be achieved [1–3]. PBGs have many applications in optical communications, optoelectronics and optical devices. 1d ternary metallo-dielectric PC is a periodic structure consisting of dielectric and metal elements with different refractive indices. There are some advantages to use metals in PCs such as decreased size, simpler fabrication, and lower costs [4]. Because of its easy fabrication, 1d PC has many applications such as multilayer's coatings [5], Bragg reflectors [6], and narrow band filters [7, 8]. There are a lot of researches using dielectric [9, 10] and metals [11–13], in PCs. We use ternary metallo-dielectric PC which has more transmission and wider PBG than binary PC [9, 11]

In this paper, we use transfer matrix method (TMM) [14–16] to calculate PBG width. We apply this method to a 1 dPC consisting of periodically dielectric-metal materials for both TE and TM waves. The structure of metallo-dielectric PC is denoted as $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ where A, B and C are dielectric, metal and dielectric elements, respectively. D is dielectric defect layer, and N and M are the number of periods. This structure is depicted in Figure 1.

We investigate transmission in the lossless structure and compared loss and lossless structures with each other. We also show that the asymmetric structure can be used as a single channel filter, and the symmetric one can be used as a couple channel filter in both TE and TM polarizations. This is because of the enhancement of the number of defect layer (M), and it is investigated in Section 3.

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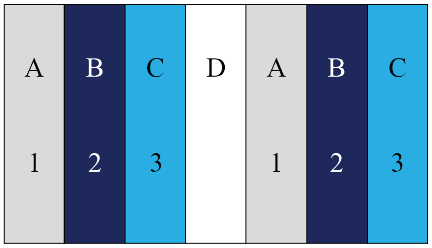


Figure 1. The structure of metallo-dielectric PC with dielectric defect layer.

2. THEORETICAL ANALYSIS

A model structure of optical filter $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ is made of dielectric defect layer with thickness d_d sandwiched by two N-cells in which it puts in air, and each cell makes up with dielectric layers 1, 3 and metallic layer 2. The Drude model [17, 18] is invoked to characterize the wavelength dependence of metallic layer. So metal permittivity in Drude model is

$$\varepsilon_2(\omega) = 1 - \frac{\omega_p^2}{\omega^2 + i\gamma\omega}, \tag{1}$$

where ω_p and γ are the plasma frequency and damping coefficient, respectively. Then metal refractive index is given by $n_2 = \sqrt{\varepsilon_2}$ [19].

We have used TMM in our calculations [20]. So the characteristics matrix $M(\Lambda)$ for a single period is expressed as [11, 21–23]

$$M(\Lambda) = \begin{bmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{bmatrix} = \prod_{\ell=1}^{3} \begin{bmatrix} \cos\beta_\ell & \frac{1}{ip_\ell}\sin\beta_\ell \\ -ip_\ell \sin\beta_\ell & \cos\beta_\ell \end{bmatrix} \tag{2}$$

where $p_\ell = n_\ell \cos\theta_\ell$, $\beta_\ell = k_0 n_\ell d_\ell \cos\theta_\ell$ with $\ell = 1$, 2, and 3. Then, the total characteristic matrices of the total PC in asymmetric and symmetric structures are given by the following formulas, respectively [15–19],

$$\begin{aligned} M_T &= \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = (M_3M_2M_1)^N M_d^M (M_3M_2M_1)^N, \\ M_T &= \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} = (M_3M_2M_1)^N M_d^M (M_1M_2M_3)^N \end{aligned} \tag{3}$$

So the transmission coefficient t is given by

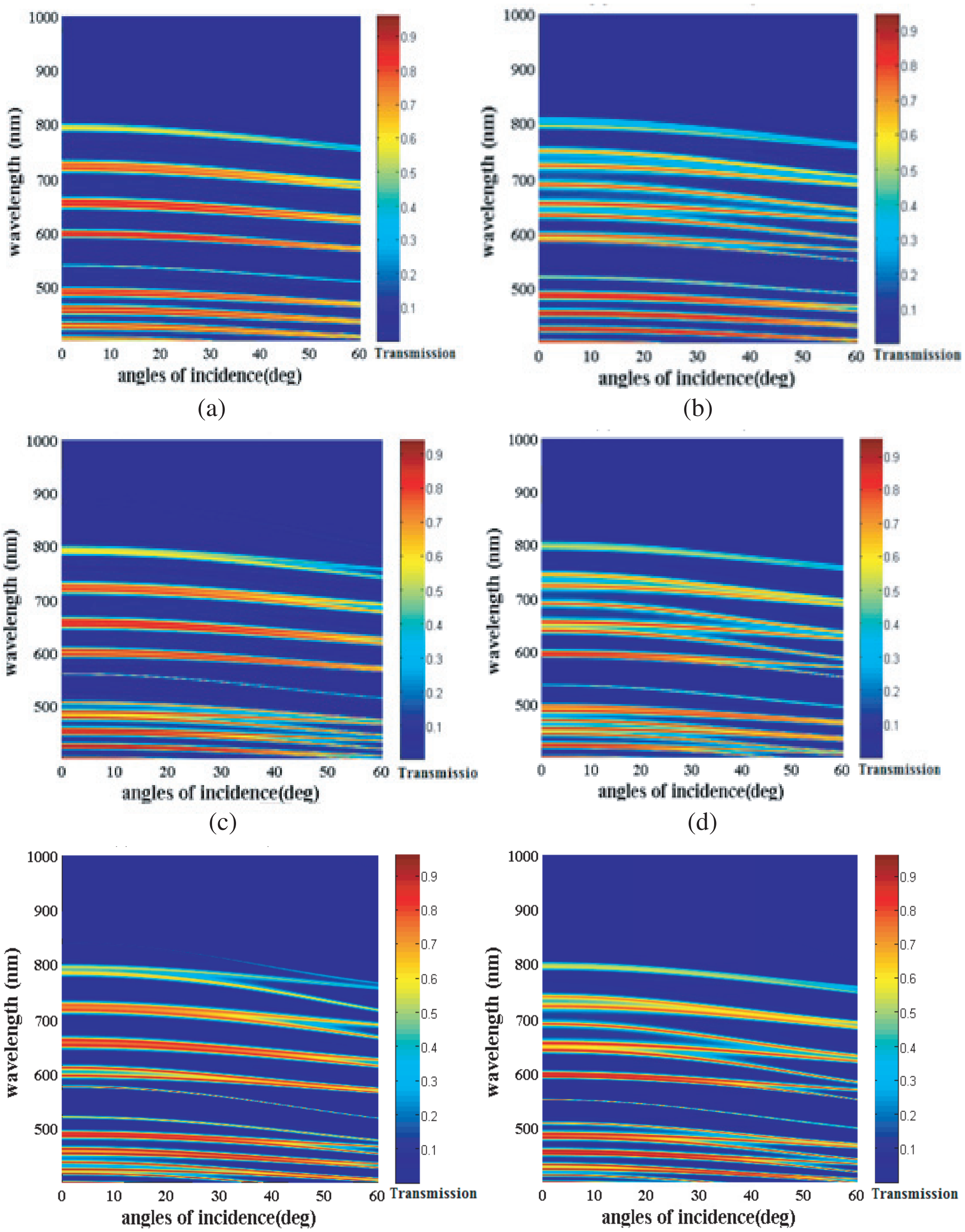
$$t = \frac{2p_0}{(m_{11} + m_{12}p_0)p_0 + (m_{21} + m_{22})p_0} \tag{4}$$

where $p_0 = n_0 \cos\theta_0$. We can calculate the transmittance $T = |t|^2$ [18, 23].

The above calculations can be used for TM wave by substituting $p_\ell = \cos\theta_\ell / n_\ell$ where $\ell = 0$, 1, 2 and 3.

3. NUMERICAL RESULTS

In this work, layers 1 and 3 are Si and ZnSe in which refractive indices and thicknesses are $n_1 = 3.45$, $d_1 = 90\,\mathrm{nm}$ and $n_3 = 2.6, d_3 = 90\,\mathrm{nm}$. The metallic layer is taken to be silver (Ag) with the plasma frequency $\omega_p = 2\pi \times 2.175 \times 10^{15}\,\mathrm{rad/s}$ [24–26] $d_2 = 10\,\mathrm{nm}$ and damping coefficient $\gamma = 2\pi \times 4.35 \times 10^{12}\,\mathrm{rad/s}$. The substrate is assumed to be air with refractive index $n_0 = 1$. The number of unit cells is equal to $N = 5$, and defect layer is taken to be $\mathrm{SiO_2}$ whose index of refraction

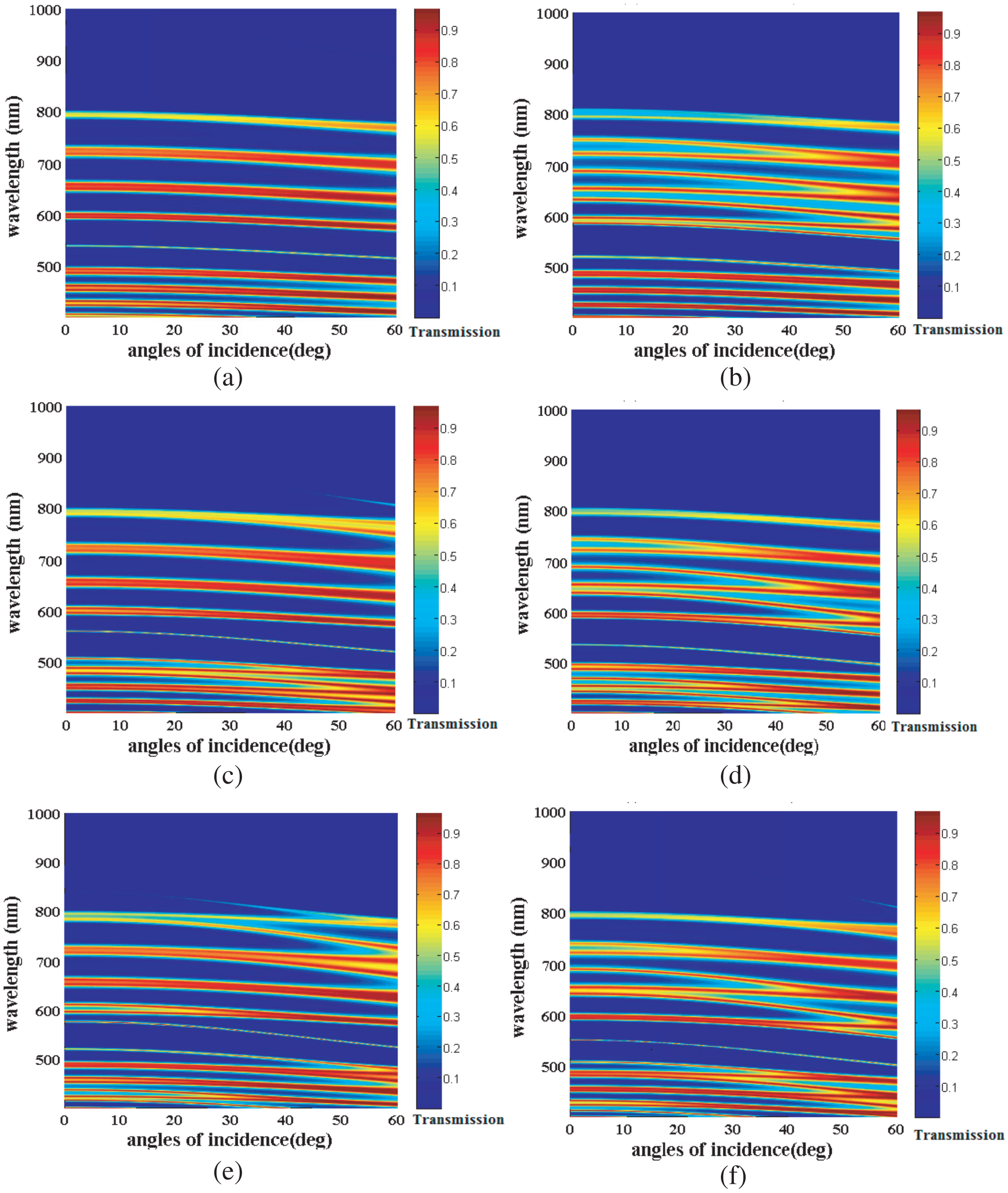


(a) (b) (c) (d) (e) (f)

Figure 2. The calculated wavelength and angles of incidence dependent transmittance for the structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ for different M in TE polarization. (a) TE polarization, $M = 1$. (b) TE polarization, $M = 2$. (c) TE polarization, $M = 3$. (d) TE polarization, $M = 4$. (e) TE polarization, $M = 5$. (f) TE polarization, $M = 6$.

and thickness are $n_d = 1.45$ and $d_d = 120\,\mathrm{nm}$, respectively. We consider the loss for metallic layer in this structure.

In Figure 2, we plot the calculated wavelength and angles of incidence dependent transmittance $T(\lambda, \theta)$ for the structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ in TE polarizations and for different M. We see that there is one BG with a defect mode between 500 nm to 600 nm in which by increasing angles of incidence,



(a) (b)

(c) (d)

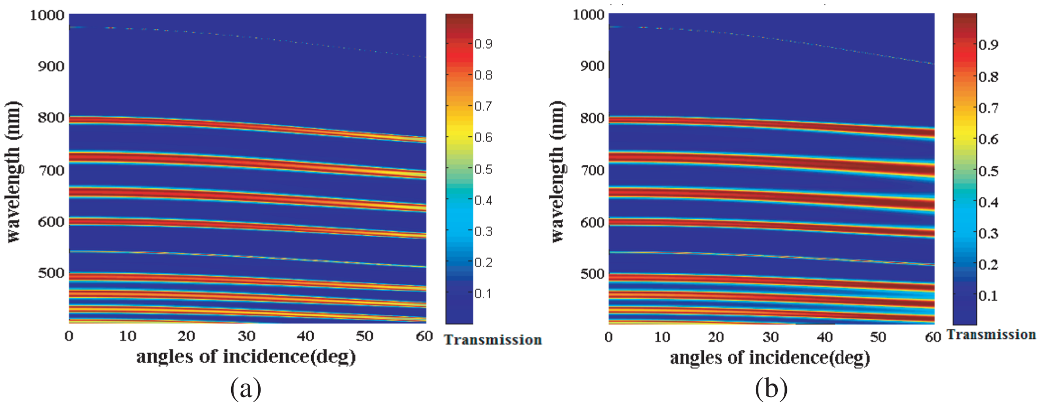
(e) (f)

Figure 3. The transmittance in terms of wavelength and angles of incidence for the structure $(\text{ABC})^N\text{D}^M(\text{ABC})^N$ at different M in TM polarization. (a) TM polarization, $M = 1$. (b) TM polarization, $M = 2$. (c) TM polarization, $M = 3$. (d) TM polarization, $M = 4$. (e) TM polarization, $M = 5$. (f) TM polarization, $M = 6$.

defect modes move to the shorter wavelengths. Also, the number of defect modes does not change by increasing the number of defect layers (M).

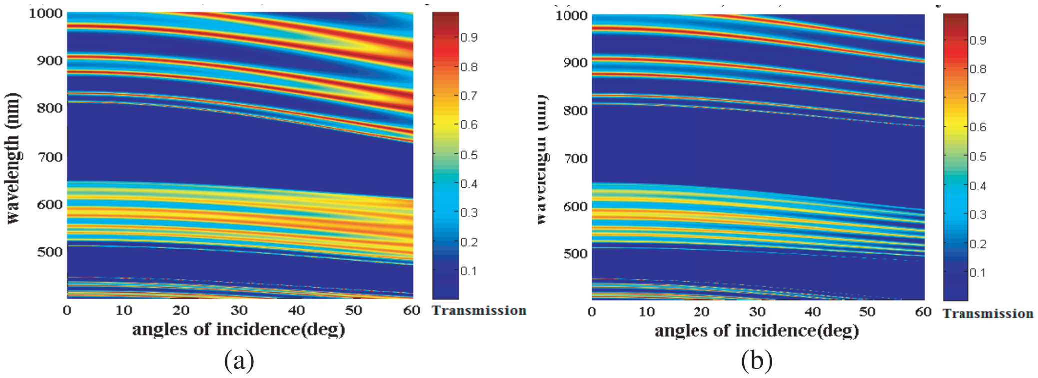
Figure 3 shows transmittance $T(\lambda, \theta)$ in terms of wavelength and angles of incidence for the structure $(\text{ABC})^N\text{D}^M(\text{ABC})^N$ at different M in TM polarization. We see that by increasing angles of incidence, defect modes move to the shorter wavelengths. Also, the number of defect modes does not change by increasing the number of defect layers (M) like TE polarizations.

Figure 4 plots the transmission response for the asymmetric structure $(\text{ABC})^N\text{D}^M(\text{ABC})^N$ at different M in the plane of wavelength and angles of incidence for structure without loss in both TE and TM polarizations. We see that in this structure there are two defect modes, one between 500 nm



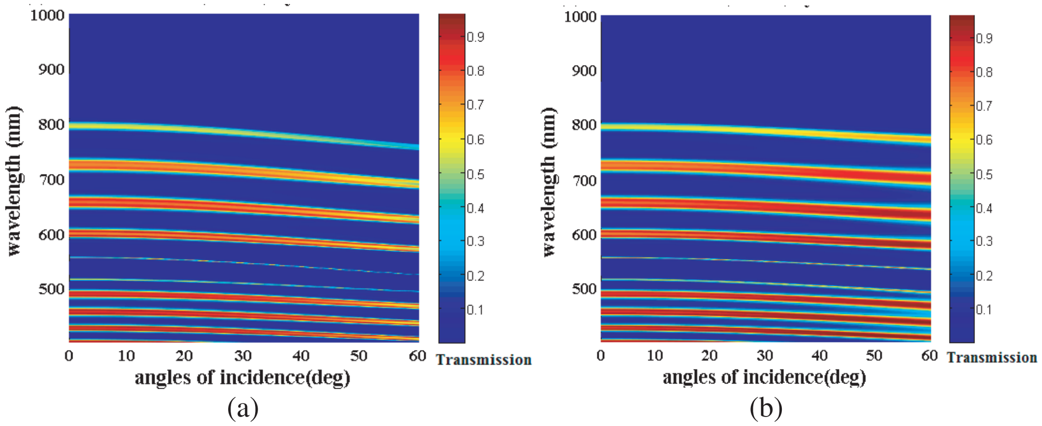
(a) (b)

Figure 4. The transmission without loss for the structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ for $M = 1$ in TE and TM polarizations in the plane of wavelength and angles of incidence. (a) TE polarization — $M = 1$, without loss. (b) TM polarization — $M = 1$, without loss.



(a) (b)

Figure 5. The transmission in asymmetric loss structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ with metallic defect layer in both TE and TM polarizations for $M = 1$ in the plane of wavelength and angles of incidence. (a) TE polarization, $M = 1$, metallic defect layer. (b) TM polarization, $M = 1$, metallic defect layer.



(a) (b)

Figure 6. The transmission in symmetric loss structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{CBA})^N$ with dielectric defect layer in both TE and TM polarizations and for $M = 1$ in the plane of wavelength and angles of incidence. (a) TE polarization, $M = 1$, symmetric structure. (b) TM polarization, $M = 1$, symmetric structure.

and 600 nm and the other between 900 nm and 1000 nm for different angles of incidence compared with Figures 2(a) and 3(a). Also, in this structure, defect modes move to the shorter wavelengths when angles of incidence increase.

Figure 5 shows transmission for the structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ with metallic defect layer (Ag). In fact, we substitute layer 2 with defect layer. So now layer 2 is $\mathrm{SiO_2}$ with $n_2 = 1.45$ and $d_2 = 120\,\mathrm{nm}$, and defect layer is Ag with $d_d = 10\,\mathrm{nm}$. As we have shown in this structure, there are two BGs in the range 400 nm to 500 nm and 600 nm to 800 nm approximately. There is just one defect mode in the first BG in both TE and TM polarizations.

In all figures above, we show transmission for the asymmetric structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$. In Figure 6, we use symmetric structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{CBA})^N$ and show that in this case there are two defect modes in the BG with wavelengths 515.4 nm and 555.7 nm for $M = 1$ in both TE and TM polarizations. Also, the defect modes move to the shorter wavelengths by increasing incident angles.

4. CONCLUSION

In this paper, we show that a 1d ternary metallo-dielectric PC with dielectric defect layer based on multilayered structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{ABC})^N$ can act as a channel filter. We show transmission in terms of wavelength and different angles of incidence in both TE and TM polarizations and investigate that by increasing number of defect layers (M), the number of defect modes does not change in loss structure. Also, defect modes move to the shorter wavelengths by increasing angles of incidence. Besides, we compare the systems with loss and without loss and show that in lossless structure there are two defect modes, one between 500 nm and 600 nm and the other between 900 nm and 1000 nm for different angles of incidence. Moreover, we compare dielectric defect layer with metallic defect layer in both TE and TM waves and show that there are two BGs in the range 400 nm to 500 nm and 600 nm to 800 nm approximately in the structure with metallic defect layer. There is just one defect mode in the first BG in both TE and TM polarizations. Furthermore, we plot a symmetric structure $(\mathrm{ABC})^N\mathrm{D}^M(\mathrm{CBA})^N$ and show that in this case there are two defect modes in the BG with wavelengths 515.4 nm and 555.7 nm for $M = 1$ in both TE and TM polarizations. Moreover, by increasing M, the number of defect modes does not change. Our theoretical analysis shows that asymmetric structure can be used as a single channel filter, and the symmetric one can be used as a couple channel filter in both TE and TM polarizations.

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