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TRANSMISSION PROPERTIES OF 1D DEFECT METALLIC-DIELECTRIC PHOTONIC CRYSTALS

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ABSTRACT

In this study, we have theoretically investigated transmission properties of transverse electric fields at visible region frequencies in one dimensional defect Metallic-Dielectric photonic crystals. We examined the effect of photonic crystals thickness, layer numbers, layer refractive indexes and defects on transparency. We use OptiFDTD software for simulations. OptiFDTD software uses finite-different time-domain method.

Keywords: 1D Metallic-Dielectric Photonic Crystal, FDTD Method, Visible Region Wavelength, Transmittance.

1. INTRODUCTION

In photonic crystals (PCs) dielectric constants change periodically [1,2]. Because of this periodic change and layer properties like layer thickness, layer number, and layer material some interesting features occur such as photonic band gaps (PBGs), omnidirectional band gaps (OBG), light flow control, etc [3-4]. PCs can be periodic in one (1D), two (2D) or three dimension (3D) [5]. Because of easily fabricated and simply theoretical investigation 1D PCs attract interest of scientists and many theoretical and experimental studies done. Some important applications of 1D PCs are high-efficiency semiconductor lasers, high-reflection mirrors, light-emitting diodes, waveguides, optical filters, high-Q resonators, antennas, frequency-selective surfaces, amplifiers and antireflection coatings, etc [6-11].

Generally, two different dielectric materials are use in PCs. But the first periodic structures were fabricated from metals rather than from dielectrics. Periodic metallic structures have also interesting properties such as plasmonic lenses, plasmonic waveguides, plasmonic devices, etc. Periodic metallic materials and metallic-dielectric materials named respectively metallic photonic crystals (MPCs) and metallic-dielectric photonic crystals (MDPCs). In MPCs different metallic structures, in MDPCs metallic and dielectric structures periodically lined up. MDPCs show high transmission band in the visible range that we can use them for eye protection device, heat reflecting windows, transparent electrodes and liquid crystal displays. Also we can use MDPCs as high-reflection mirrors, beam splitters, bandpass filters, etc [12-14].

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In this study transmission properties of transverse electric (TE) fields components theoretically investigated in 1D MDPCs for visible region. We examined the effect of photonic crystals thickness, layer numbers, layer refractive indexes and defects over transparency by using OptiFDTD software [15] that use finite-difference time-domain method [16-20].

2. THEORY AND METHODS

Electromagnetic waves propagations and transmissions can be expressed in one dimensional MDPCs by using FDTD method. FDTD method solve the Maxwell equations by separating the time and space expressions. In isotropic and linear media the Maxwell equations are [21]

$$\begin{aligned}\nabla \times \boldsymbol{H} &= \varepsilon \frac{\partial \boldsymbol{E}}{\partial t} + \sigma \boldsymbol{E} \\ \nabla \times \boldsymbol{E} &= -\mu \frac{\partial \boldsymbol{H}}{\partial t} + \sigma_m \boldsymbol{H}\end{aligned} \tag{1}$$

where ε is the dielectric permittivity, σ is the medium conductivity, μ is permeability of medium and σ_m is the magnetic loss of the medium. We assume that TEM wave propagates along z direction then we can write

$$\frac{\partial}{\partial x} = \frac{\partial}{\partial y} = 0$$

and Eq. (1) written as

$$-\frac{\partial H_y}{\partial z} = \varepsilon + \frac{\partial E_x}{\partial t} + \sigma E_x \tag{2}$$

$$\frac{\partial E_x}{\partial z} = \mu + \frac{\partial H_y}{\partial t} + \sigma_m H_y \tag{3}$$

We can write Eq. (2) and (3) according to FDTD method Eq. (4) and (5) occured as

$$E_x^{n+1}(k) = \frac{1 - \frac{\sigma(m)\Delta t}{2\varepsilon(m)}}{1 + \frac{\sigma(m)\Delta t}{2\varepsilon(m)}} \times E_x^n(k) - \frac{\frac{\Delta t}{\varepsilon(m)}}{1 + \frac{\sigma(m)\Delta t}{2\varepsilon(m)}} \times \frac{H_y^{n+1/2}\left(k + \frac{1}{2}\right) - H_y^{n+1/2}\left(k - \frac{1}{2}\right)}{\Delta z} \tag{4}$$

$$H_y^{n+1/2}\left(k + \frac{1}{2}\right) = \frac{1 - \frac{\sigma(m)\Delta t}{2\mu(m)}}{1 + \frac{\sigma(m)\Delta t}{2\mu(m)}} \times H_y^{n-1/2}\left(k + \frac{1}{2}\right) - \frac{\frac{\Delta t}{\mu(m)}}{1 + \frac{\sigma(m)\Delta t}{2\mu(m)}} \times \frac{E_x^n(k+1) - E_x^n(k)}{\Delta z} \tag{5}$$

where k and n are space step integer and time step integer respectively.

The frequency dependence of the dielectric constant of the metals is generally expressed by the Lorentz-Drude model [22]

$$\widehat{\varepsilon_r}(\omega) = \hat{\varepsilon}_r^{(f)}(\omega) + \hat{\varepsilon}_r^{(b)}(\omega) \tag{6}$$

the intraband part $\hat{\varepsilon}_r^{(f)}$ of the dielectric function is described by free electron or Drude model and the interband part $\hat{\varepsilon}_r^{(b)}$of the dielectric function is described by the simple semi quantum model which is similar to Lorentz model. Lorentz-Drude model can be expressed more general equation

$$\hat{\varepsilon_r}(\omega) = 1 - \frac{\Omega_p^2}{j\omega\Gamma_0 - \omega^2} + \sum_{m=1}^{M} \frac{\Omega_p^2}{\omega_m^2 - \omega^2 + j\omega\Gamma_m} \tag{7}$$

For time domain expression in FDTD method the frequency dependence should be transferred into the time domain by Fourier transform [23]. After Fourier transform electric field expression obtain as

$$\boldsymbol{E}^n = \boldsymbol{D}^n - \boldsymbol{S}_1^{n-1} - \boldsymbol{S}_2^{n-1} \tag{8}$$

where

$$\boldsymbol{D}(\omega) = \left[1 + \frac{\frac{\Omega_p^2}{\Gamma_0}}{i\omega} - \frac{\frac{\Omega_p^2}{\Gamma_0}}{\Gamma_0 i\omega} \boldsymbol{E}(\omega) \right] \tag{9}$$

$$\boldsymbol{S}_1^n = (1 + \exp(-\Gamma_0\Delta t))\boldsymbol{S}_1^{n-1} - \exp(-\Gamma_0\Delta t)\, \boldsymbol{S}_1^{n-2} + \frac{\Omega_p^2\Delta t}{\Gamma_0}(1 - \exp(-\Gamma_0\Delta t))\boldsymbol{E}^n \tag{10}$$

$$\boldsymbol{S}_2^n \sum_{j=1}^{k} \Big(2\exp(-\alpha_j\Delta t)\cos(\beta_j\Delta t)\, \boldsymbol{S}_2^{n-2} - \exp(-2-\alpha_j\Delta t)\, \boldsymbol{S}_2^{n-2} + \frac{f_j\omega_p^2}{\beta_j} \times exp(-\alpha_j\Delta t)\sin(\beta_j\Delta t)\Delta t\boldsymbol{E}^n \Big) \tag{11}$$

Transmission of electric field component can be written as

$$R = \left| \frac{E_t(t)}{E_i(t)} \right|^2 \tag{12}$$

3. MODELLING AND SIMULATIONS

We designed a MDPC structure such as $Air/(A)^6(B)^5/Air$. The layout of this structure is shown in Figure 1. The red vertical line represent the input plane and the green point is observation point which observe transmission of transverse electric field component E_y.

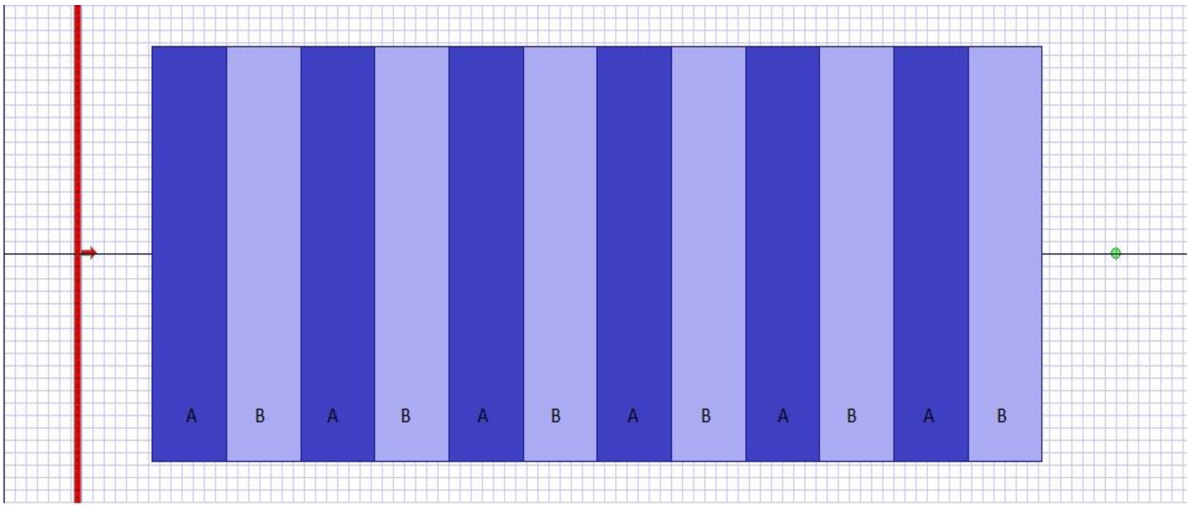

Figure 1. Layout of MDPC.

In MDPC A and B represent SiO_2 (Silicon dioxide) and W (Tungsten) whose refractive indexes are $n_A = 1.54$, $n_B = 3.50$ [24] and thicknesses are $d_A = 50\,nm$, $d_B = 50\,nm$ respectively. The red vertical line represent the input plane which is taken to Gaussian modulated continuous wave whose wavelength is $0.543\,nm$ (He-Ne laser) [25] and propagates along z direction. The green point is observation point which observe transmission of transverse electric field component E_y.

In Figure 2, the transmittance graph of TE_y, between $400\,nm$ and $700\,nm$ is shown.

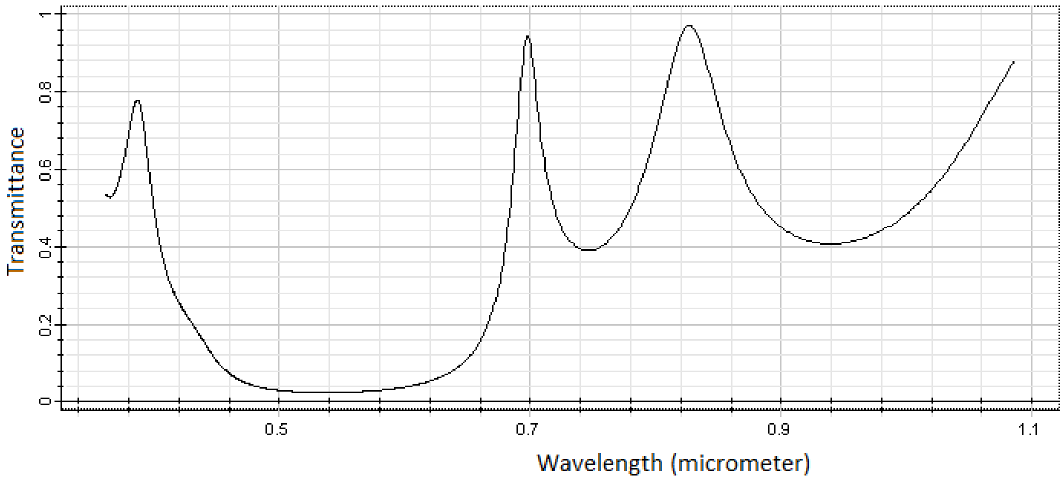

Figure 2. TE_y transmittance of 1D MDPC

Now we investigate the effect of PCs layer thickness, layer numbers, layer refractive indexes and defects over transparency in visible band ($400\,nm - 700\,nm$). The width of the resonance is an important performance factor of the filters because of this we try to obtain the wider transmittance by fixing the layer properties.

3.1. Investigation the Layer Thicknesses Effect Over Electric Field Transparency

When we take the layer thicknesses $50\,nm$, $75\,nm$, $100\,nm$ and $125\,nm$ respectively transmittance graphs of TE_y in visible band, shown in Figure 3.

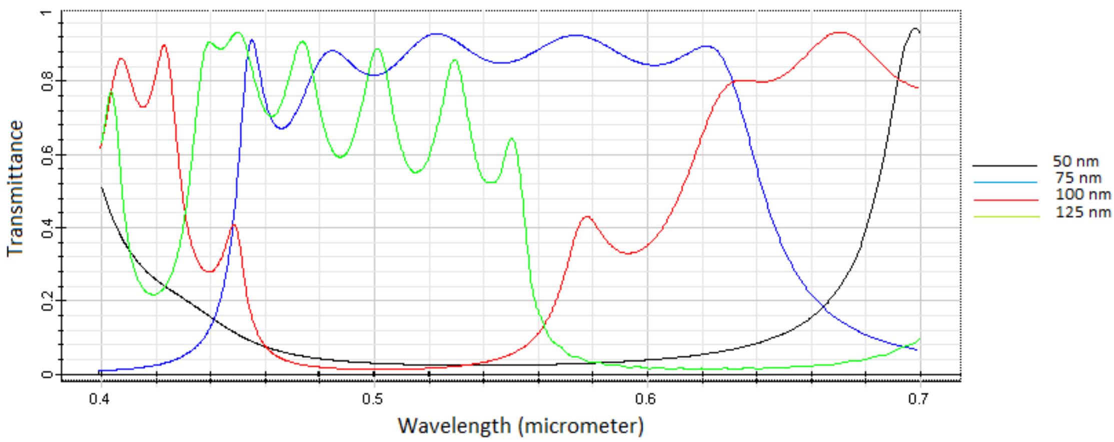

Figure 3. Transmittance of TE_y whith layer thicknesses are $50\,nm$, $75\,nm$, $100\,nm$, $125\,nm$

In Figure 3, PBG do not occur and maximum transmittance width is shown in layer thickness 75 nm. From this result 75 nm is more suitable for wide band filter.

3.2. Investigation the Layer Number Effect Over Electric Field Transparency

For investigate the effect of layer number over E_y transparency in 75 nm thicknesses MDPCs layer number is choosen 12, 22 32 and 42 respectively.

In Figure 4, PBG occurs in layer number 22 at between 400-425 nm, in layer number 32 at 400-429 nm and in layer number 42 at 400-439 nm.

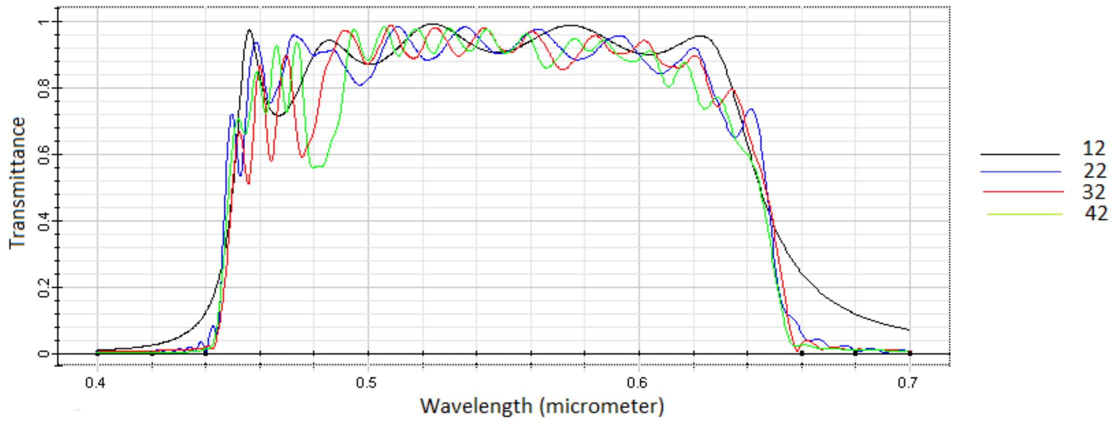

Figure 4. Transmittance graph of TE_y which layer number is 12, 22, 32 and 42

Maximum transmittance width is shown in layer number 12. From this result, layer number 12 is more suitable for wide band filter.

3.3. Investigation the Refractive Indexes Effect Over Electric Field Transparency

To investigate the refractive indexes over E_y transparency, we choose layer thicknesses 75 nm layer number 12 and MDPC composed Tungsten (W) and SiO_2, $LiNbO_3$, TiO_2 whose refractive indexes are 1.54, 2.31 ve 2.97 respectively. The transmittance of TE_y in MDPC shown Figure 5.

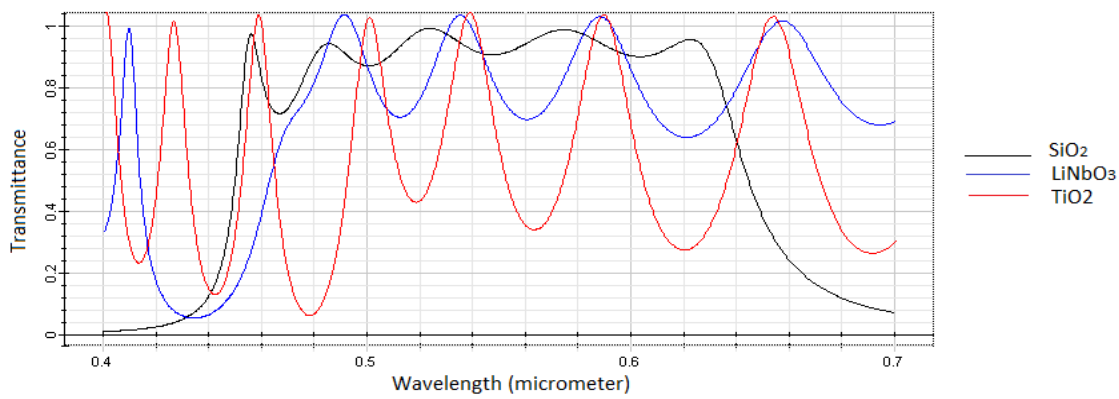

Figure 5. Transmittance graph of TE_y in $SiO_2 - W$, $LiNbO_3 - W$ and $TiO_2 - W$

From Figure 5, we can see that PBG do not occur. The maximum transmittance width is observed at $TiO_2 - W$ MDPC so this PC is more suitable for wide band filter.

3.4. Investigation the Defect Layer Effect Over Electric Field Transparency

For investigate the defect layer effect E_y transparency we create a defect layer made of Tellurium (Te) whose refractive index is 4.6, in the center of $TiO_2 - W$ MDPC. The transparency of TE_y in MDPC is shown Figure 6.

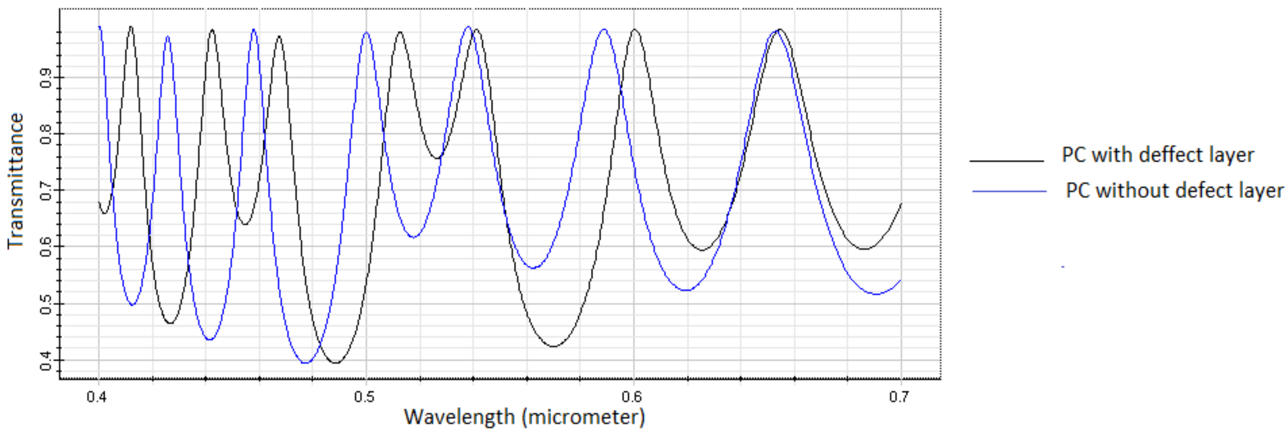

Figure 6. Transmittance graph of TE_y in $Te - W$

In Figure 6, PBG do not occur and maximum transmittance width is observed in MDPC with Tellurium defect which make MDPC more suitable for wide band filter.

4. CONCLUSION

We have presented a theoretical study on the transparency of TE in 1D MDPCs. We investigated the effect of layer thickness, layer numbers, layer refractive indexes and defects over transmittance of *TE*.

It was found that maximum transmittance of TE_y in visible band occur in $500\,nm$ thickness at 12 layer, TiO_2-W MDPC with Tellurium defect. So, MDPC is more suitable for wide band filter.

From our study, we can say that electromagnetic waves can be controlled by changing variables of MDPC. Therefore some applications can be made such as solar cells, laser safety goggles, sun glasses, optical filters, optical sensors, and optoelectronic devices.

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