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ENHANCED ABSORPTION IN PERIODIC ONE-DIMENSIONAL METALLIC-ORGANIC PERIODIC STRUCTURE

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Abstract—We show theoretically that the absorption of one dimensional metal-organic periodic structure (1D MOPS) can be enhanced due to organic constituents. We have used simple transfer matrix method to calculate the absorption, transmittance and reflectance of the 1D MOPS systems. The absorption, transmittance and reflectance of 1D MOPS containing 3.5 periodic of Ag/N,N′-bis-(1-naphthyl)-N,N′diphenyl-1, 1biphenyl-4, 4diamine (NPB) structure are calculated taking optical constant of NPB [1] and Ag [2]. The enhanced absorption of the considered structure is obtained in the visible and near infrared regions. Besides this, we have also studied the absorption, transmittance and reflectance of the 1D MOPS with air and glass substrates. We find that the absorption is enhanced with variation of thickness of organic layer (NPB). Such absorption enhancement in 1D MOPS could allow many potential applications in photothermal technology, thermo photo-voltaic and blackbody emission.

1. INTRODUCTION

The study of one dimensional metallic photonic crystal has created significant interest due to ease of fabrications, small sizes and lighter weights [3]. The metallic periodic structures with air and MgF_2 are fabricated to be used in the microwave, infrared and visible regions. One dimensional metallic-dielectric photonic crystals (MD PCs) have shown to a new transparent metallic structure within a certain range of electromagnetic wave spectrum due to interference effects. The enhanced non-linear optical response in one dimensional metallic-dielectric photonic crystals has been reported [4, 5]. The study of optical properties suggests that it can be used in photonic and electronic applications [6].

Scalora et al. [7] have shown experimentally that the metallo-dielectric photonic crystals under certain condition transmit light by resonant tunneling, enabling extraordinary transmissions. They have proposed that the metallo-dielectric structures can be made transparent metals and can be used for band pass filters in infrared and visible region. One dimensional metallo-dielectric nano-films have been investigated theoretically and experimentally for the ultra-violet range [8].

Zhang et al. [1] studied the optical properties of a one dimensional metallic organic photonic crystal with periodic Ag/N,N′-bis-(1-naphthyl)-N, N′diphenyl-1, 1′biphenyl-4, 4′diamine (NPB) layers and calculated the field localization within the organic layers at the resonance wavelength. The field localization within the organic layers is strong indication of resonance tunneling. Besides this, they suggested that a broad omni-directional stop band of the metallic organic photonic crystal (MOPC) could be obtained in the visible region by adjusting the thickness of the metal and organic layers. The flexibilities, easier fabrication and lower costs are some advantages of the organic materials compared with other materials [11–14].

In this paper, we report the enhanced absorption of the metallic-organic periodic structure containing 3.5 periodic of Ag/N,N′-bis-(1-naphthyl)-N,N′diphenyl-1, 1′biphenyl-4, 4′diamine (NPB) materials. The sputtered techniques may be fabricated of 3.5 periodic structure of Ag/NPB experimentally. The 1/2 is the organic layer which can be deposited on the top of the multilayer structure. The reflectance, transmittance and absorption of the periodic structure with the air and glass substrates are also calculated with variation of thickness of the organic layer. The optical constants of organic film NPB depends on the wavelength which is taken from [1] which is measured using a variable angle spectroscopic ellipsometer (VASE). The optical constant of the metal (Ag) film also depends on the wavelength which is taken from Palik [2]. The absorption of Ag/N,N′-bis-(1-naphthyl)-N,N′diphenyl-1, 1′biphenyl-4, 4′diamine (NPB) of 3.5 periodic structure is calculated by choosing proper thickness of Ag/PNB layers and with variation of the thickness of the organic layer NPB. The optical properties are calculated using simple transfer matrix method. The study of the absorption of the metallic-organic periodic structure may be used to make many potential applications in thermo photo-voltaic, photo-thermal technology, and black-body emission etc.

2. FORMULATION

The Maxwell's equation for homogeneous and isotropic medium is given by [15, 16]:

$$\vec{\nabla}^2\vec{E} - \mu\varepsilon\frac{\partial^2\vec{E}}{\partial t^2} = 0, \tag{1}$$

The solution of the differential Equation (1) is

$$E = E(x/\omega)e^{i(\omega t-\beta y)}, \tag{2}$$

where $E(x/\omega)$ can be taken as the superposition of the incident and reflected wave in each medium, for jth layer can be written in the form

$$E(x/\omega) = A_j e^{ik_{jx}x} + B_j e^{-ik_{jx}x} \tag{3}$$

where $k_{jx} = \frac{\omega}{c}\sqrt{\varepsilon_j}\cos\theta_j$ and ε_j are the wave vector and dielectric constant in the jth layer respectively, and c is the speed of light in vacuum. The coefficients A_j and B_j have to be determined from the boundary condition that both electric field and its first derivative are continuous across an interface. The magnetic field vector along y-axis can be obtained by:

$$\vec{H} = \frac{i}{\omega\mu}\vec{\nabla} \times \vec{E} \tag{4}$$

For convenience, the field is written in the form of a vector as:

$$\vec{E}(x/\omega) = \begin{pmatrix} A_j e^{ik_{jx}x} \\ B_j e^{-ik_{jx}x} \end{pmatrix} \tag{5}$$

It can be shown that the field at x_j in the layer j is related to the field at x_{j-1} in layer $(j-1)$ by 2×2 transfer matrix $\mathbf{M}$ (x_{j-1}, x_j).

$$E(x_j/\omega) = \mathbf{M}(x_{j-1}, x_j)E(x_{j-1}/\omega) \tag{6}$$

where the transfer matrix is given by,

$$\mathbf{M}(x_{j-1}, x_j) = \mathbf{P}_j(\Delta x_j)\mathbf{Q}_{j-1,j}\,\mathbf{P}_{j-1}(\Delta x_{j-1}) \tag{7}$$

Here $\Delta x_j = x_j - d_{j-1,j}$ and $\Delta x_{j-1} = d_{j-1,j} - x_{j-1}$ are the distances from x_j and x_{j-1} to the interface between layers $j-1$ and j located at $x = d_{j-1,j}$, respectively. It is easy to show that the matrices $\mathbf{P}$ and $\mathbf{Q}$ are given by:

$$\mathbf{P}_j(\Delta x) = \begin{pmatrix} e^{ik_j\Delta x} & 0 \\ 0 & e^{-ik_j\Delta x} \end{pmatrix} \tag{8}$$

$$\mathbf{Q}_{j-1,j} = \frac{1}{2}\begin{pmatrix} \left(1+\frac{k_{j-1}}{k_j}\right) & \left(1-\frac{k_{j-1}}{k_j}\right) \\ \left(1-\frac{k_{j-1}}{k_j}\right) & \left(1+\frac{k_{j-1}}{k_j}\right) \end{pmatrix} \tag{9}$$

'**P**' presents field propagation vector; '**Q**' is dynamical part of matrix; it represents the reflectance and transmittance at interfaces of the metal-organic (M-O) periodic lattice with $d = d_1 + d_2$, where d_1 is the thickness of metal, and d_2 is the thickness of organic of refractive index n_2. The band gap structure of M-O periodic layers can be obtained by applying the Bloch theorem:

$$m(0,d)E(x/\omega) = E\left((x+d)/\omega\right) = e^{iK(\omega)d}E(x/\omega) \tag{10}$$

where d and $\vec{K}$ are the period and wave vector of the metal-organic periodic structure respectively. The eigen frequency is then obtained from:

$$\cos(K(\omega)d) = \frac{1}{2}\left[m_{1,1}(0,d) + m_{2,2}(0,d)\right], \tag{11}$$

where $m_{i,j}$ is the element of the 2×2 transfer matrix. The transfer matrix of an M-O periodic structure is given by:

$$m(0,d) = D_{\text{O-M}}\mathbf{P}_{\text{O}}(d_2)D_{\text{ M-O}}\mathbf{P}_{\text{M}}(d_1), \tag{12}$$

For the multilayer metal-dielectric structure, the total transfer matrix is given by:

$$\mathbf{M} = [m(0,d)]^N = \mathbf{Q}_{N,N+1} \prod_{j=N}^{1} \mathbf{P}_j(d_j)\mathbf{Q}_{j-1,j} \tag{13}$$

where N is the number of metal-organic layer, and d_j is width of the jth layer. A standard transfer matrix method is used to study the absorption and transmittance properties of finite one-dimensional metallic organic photonic crystals. The complex transmission and reflection coefficients 't' and 'r' are related to total matrix $\mathbf{M}$ by:

$$\begin{pmatrix} t \\ 0 \end{pmatrix} = \mathbf{M} \begin{pmatrix} 1 \\ r \end{pmatrix} \tag{14}$$

From the above relation the complex transmission and reflection coefficients can be derived from the elements of the transfer matrix, yielding:

$$t = \mathbf{M}_{1,1} - \frac{\mathbf{M}_{1,2}\mathbf{M}_{2,1}}{\mathbf{M}_{2,2}} \tag{15}$$

$$r = -\frac{\mathbf{M}_{2,1}}{\mathbf{M}_{2,2}} \tag{16}$$

The associated transmittance (T) and reflectance (R) are calculated from $T = |t|^2$ and $R = |r|^2$. Finally the absorption (A) can be obtained:

$$A = 1 - T - R \tag{17}$$

3. RESULTS AND DISCUSSION

The variation of optical constant i.e., refractive indices (real & imaginary) part of N,N′-bis-(1-naphthyl)-N,N′diphenyl-1, 1′biphenyl-4, 4′diamine (NPB) film is taken from [1]. The real and imaginary parts of the refractive indices of the NPB have been measured using VASE [1]. The real part of refractive index of the NPB has larger value than the imaginary one. Fig. 1 shows the optical constant of silver (Ag) versus wavelength taking from Palik [2]. The imaginary part of the refractive index of metal increases linear with increasing wavelength.

Enhanced absorption in metallo-dielectric photonic crystal with large thickness of Ag layer with increasing number of periods has already been shown by Yu et al. [11]. They explained the reason for the absorption enhancement in metallic PCs is due to the existence of photonic band structures. The photonic band gap (PBG) has found no propagating mode. The thickness of the metallic layer in none dimensional metallo-dielectric PCs is taken to equal or smaller than the metal's skin depth. The metallic layer can transmit some portion of electromagnetic waves, and the multiple Bragg scatterings play an important role in the formation of photonic bands in the metallic-dielectric periodic structures. PBGs in infinite PCs is obtained to have considerable transmission for frequencies within photonic bands in finite PCs [11–13]. The main reason of the enhanced absorption in the metallo-dielectric photonic crystal is predicted due to the increase of attenuation of Ag with wavelength as shown in Fig. 1.

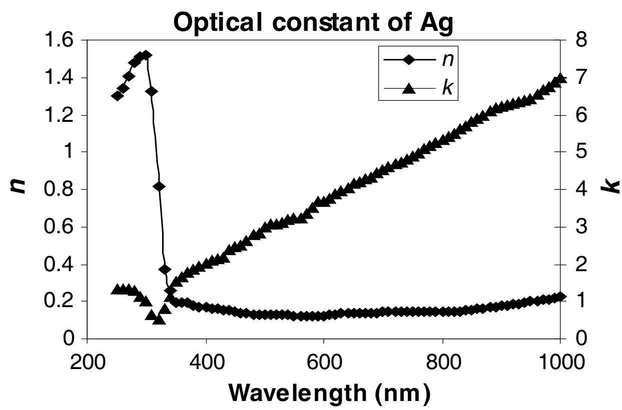

Figure 1. Optical constant of silver (Ag) [2].

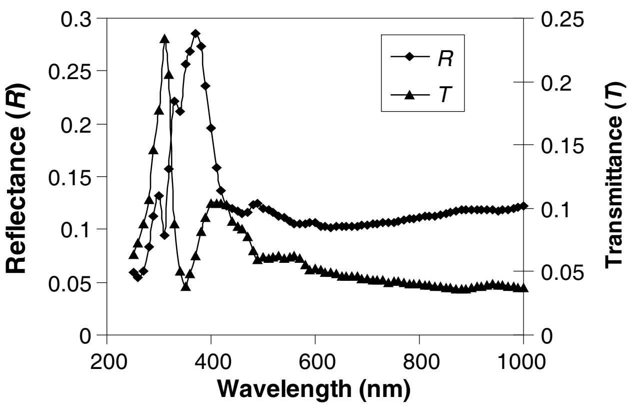

Figure 2. Reflectance and transmittance of 3.5 periods of NPB/Ag materials.

The enhanced absorption in the 1D MOPS may be attributed to the increase of refractive index of NPB and Ag with increasing wavelength in the visible and infrared regions as shown in Fig. 3. Due to easy fabrication of the one dimensional periodic structure (like 1D MOPS), the 1D MOPS has attracted people to make photonic crystals of metallic-organic periodic structure. Fig. 2 shows the reflectance and transmittance of metallic-organic periodic structure containing 3.5 period of Ag/N,N′-bis-(1-naphthyl)-N,N'diphenyl-1, 1′biphenyl-4, 4′diamine (NPB) with thicknesses of 25 nm Ag and 100 nm of the NPB layers. The reflectance and transmittance of the 1D MOPS have been observed to be 28% and 24% in the visible region, and the absorption in infrared region is found 84% as shown in Fig. 3. It is clearly shown that the absorption value of MOPS is larger than reflectance and transmittance in the visible and infrared regions. Such large absorption property of the metal-organic photonic crystal can be used in many potential applications. In [1] it has already been shown that the attenuation of refractive index is large at 280 nm–320 nm, and it tends to zero at the infrared region. In the metal-organic periodic structure system, large absorption in 500 nm–1000 nm region has been observed, and it presents due to the organic layer. The reason for the absorption enhancement in the 1D MOPS is due to the photonic band structures where no propagating modes are found. These factors can give rise to an absorption enhancement for frequencies within photonic bands.

The reflectance, transmittance and absorption of the 1D MOPSs have been theoretically calculated for variation of the thickness of

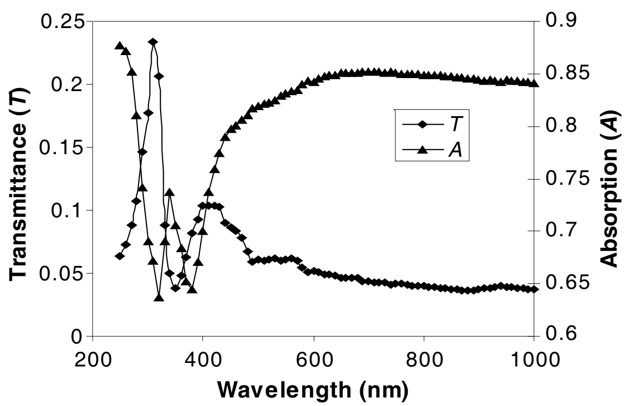

Figure 3. Transmittance and absorption of 3.5 periods of NPB/Ag material.

the organic layer with different incident wavelengths. The refractive indices of metal and organic layers are taken from the experimental data in [1, 2]. The optical constant of the organic NPB layer has high real refractive index and low attenuation of the refractive index in the infrared region as shown in [1]. On the other hand, the optical constant of the Ag has low real refractive index and high attenuation in the infrared wavelength [2]. But in the visible region, the optical constant of organic NPB layer has high n and k in the 350 nm–420 nm wavelength range, and optical constant of silver layer has high n and

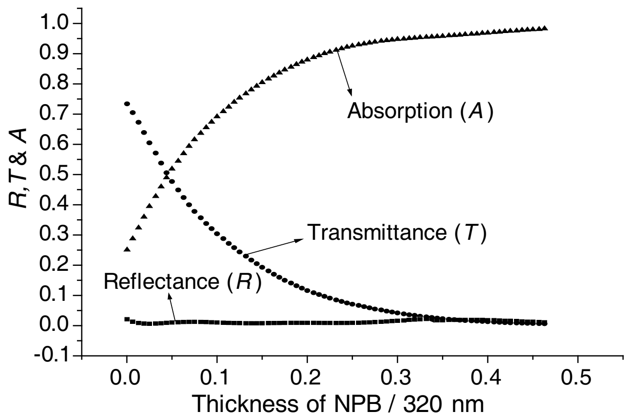

Figure 4. R, $T\&A$ of metal-organic photonic crystals with air-substrate.

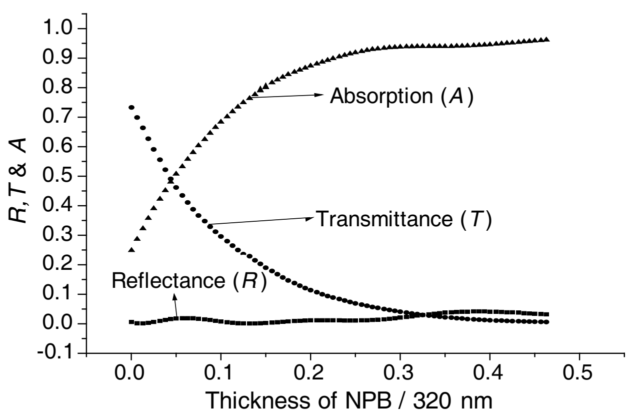

Figure 5. R, $T\&A$ for metal-organic photonic crystals with glass-substrate.

low k in the 250 nm–380 nm wavelength. Fig. 4 and Fig. 5 show the reflectance, transmittance and absorption of the 3.5 period of 1D MOPS with air ($n = 1.0$) and glass ($n = 1.5$) substrates respectively versus the thickness of organic NPB layer at the 320 nm wavelength of the incidence wave.

The optical constants of Ag and NPB are observed $n = 0.815$, $k = 0.526$ and $n = 1.7$, $k = 0.12$ respectively at 320 nm from [1, 2]. Using these data, we have plotted the curves of R, T and A versus

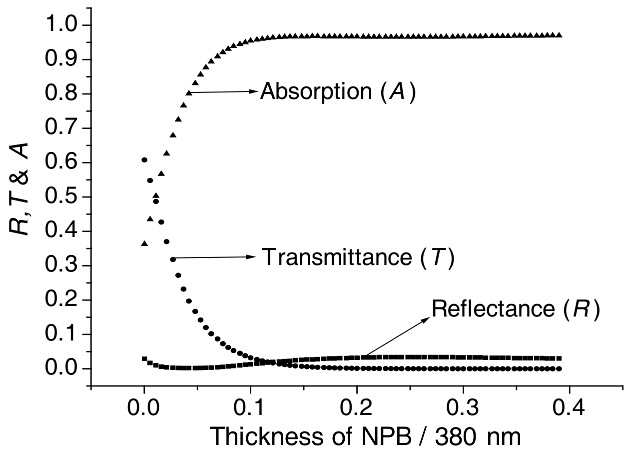

Figure 6. R, T&A for metal-organic photonic crystals with air-substrate.

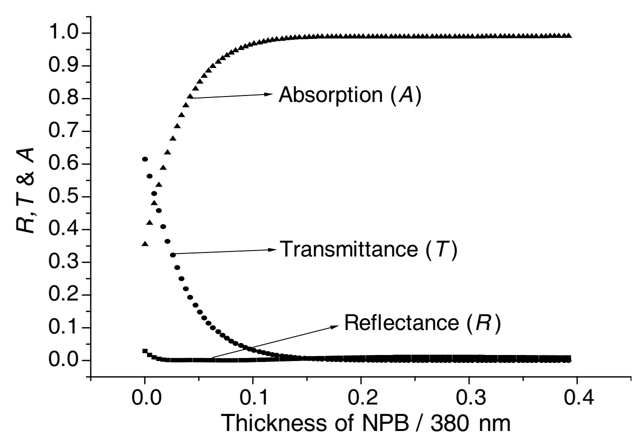

Figure 7. R, T&A for metal-organic photonic crystals with glass-substrate.

thickness of the organic layer with air and glass substrates. From the study we have found that absorption continuously increases and transmission sharply decreases with the increase of the thickness of organic layer. The reflectance is slightly higher for the glass substrate due to the high refractive index of glass compared to air.

Similarly, Fig. 6 and Fig. 7 show the reflectance, transmittance and absorption of the 1D MOPS with air ($n = 1.0$) and glass ($n = 1.5$) substrates respectively versus the thickness of organic NPB layer at the 380 nm wavelength of the incidence wave. Now the optical constants of Ag and NPB are taken $n = 0.178$, $k = 1.86$ and $n = 1.966$, $k = 0.115$ respectively at 380 nm [1, 2]. We have plotted the curves of R, T and A versus thickness of the organic layer with air and glass substrates using these data. We have observed that absorption continuously increases up to thickness of 38 nm (approx.), and beyond this thickness the absorption becomes constant. The transmission sharply decreases with increasing the thickness of organic layer 38 nm thickness, and it approaches zero for a larger one. The reflectance slightly decreases for the glass substrate due to the high attenuation of metal.

Figures 8 and 9 show the reflectance, transmittance and absorption of the 1D MOPS with air ($n = 1.0$) and glass ($n = 1.5$) substrates respectively versus the thickness of organic NPB layer at the 800 nm wavelength of the incidence wave. Now the optical constants of Ag and NPB are taken $n = 0.144$, $k = 5.33$ and $n = 1.859$, $k = 0.0097$ respectively at 800 nm [1, 2]. We have also plotted the curves of R, T and A versus thickness of the organic layer with air and glass substrates

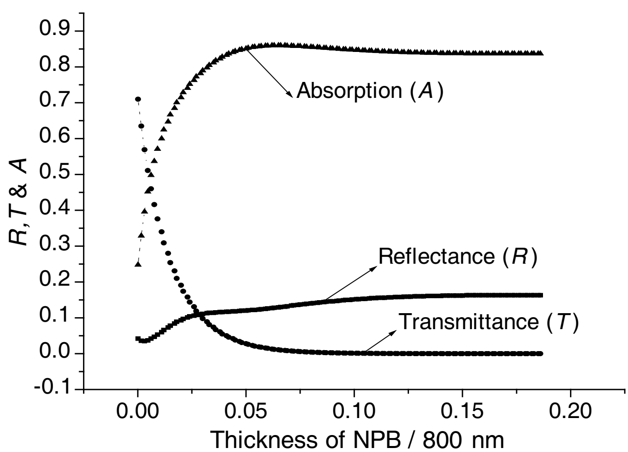

Figure 8. R, T&A for metal-organic photonic crystals with air-substrate.

using these data. The absorption also continuously increases up to the thickness of 38 nm and 40 nm, and above this thickness it is constant. The transmission also decreases sharply with increasing thickness of organic layer and becomes constant above the thickness of 40 nm. The reflectance of the considered structures is not more effective for the larger thickness of NPB of the incidence wavelength 800 nm.

From the study of R, T and A of the structure versus the thickness of the NPB layer at different incident wavelengths, the absorption is enhanced when the attenuation of the metal is low. The reason for the absorption enhancement of the structure had been due to Ag as well as organic NPB. The attenuation of Ag would have been linearly increasing but the NPB shows low attenuation. The other reason for the absorption enhancement in the Ag-NPB periodic system may lie in the peculiar photonic band structures of metalorganic PCs, which has no propagating modes. The periodic structure of Ag-NPB has concentrated more states on the frequency ranges of photonic bands due to the conservation of the total number of states. These factors can give rise to enhanced absorption in the 1D MOPSs compared with the metallo-dielectric photonic crystals for frequencies within photonic bands. Such large absorption property of the metal-organic photonic crystal can also allow many potential applications in photo-thermal technology, thermo photo-voltaic and blackbody emission.

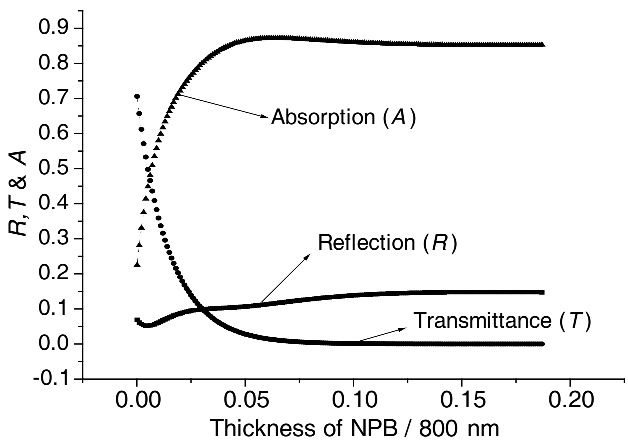

Figure 9. R, T&A for metal-organic photonic crystals with glass-substrate.

4. CONCLUSION

In the metal-organic periodic structure system large absorption in 500 nm–1000 nm region has been observed due to the organic layer. The reason for the absorption enhancement in the 1D MOPS is due to the existence of photonic band gap where no propagating modes are found. Since metal-organic periodic structures have multiple Bragg scatterings which play an important role leading to the formation of photonic band gaps like metallic-dielectric photonic crystals. The attenuation of organic and metallic layers can give rise to an absorption enhancement for frequencies within photonic bands. The study of absorptions of the same structure versus the thickness of the NPB layer at different incidence wavelengths also found the enhanced absorption when the attenuation of the metal is too low. It means that the absorption can be enhanced in periodic structure due to the metal and organic layers, even the attenuation of the metal is too low. The low attenuation at infrared region and large thickness of the organic layers can also enhance absorption in 1D MOPS system.

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