Electromagnetic Propagation Characteristics in One Dimensional Photonic Crystal

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1. Introduction

Photonic crystals (PCs) are structures with periodically modulated dielectric constants whose distribution follows a periodicity of the order of a fraction of the optical wavelength. Since the first pioneering work in this field, many new interesting ideas have been developed dealing with one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) PCs. Researchers have proposed many new and unique applications of photonic devices which may revolutionize the field of photonics in much the same way as semiconductors revolutionized electronics. They can generate spectral regions named photonic band gaps (PBGs) where light cannot propagate in a manner analogous to the formation of electronic band gaps in semiconductors [1,2]. There are several studies of metallic [3-7] and superconducting photonic crystals [7,8] which are mostly concentrated at microwave, millimeterwave, and far-infrared frequencies. In those frequencies, metals act like nearly perfect reflectors with no significant absorption problems.

Yablonovitch [1] main motivation was to engineer the photonic density of states in order to control the spontaneous emission of materials embedded with photonic crystal while John's idea was to use photonic crystals to affect the localization and control of light. However due to the difficulty of actually fabricating the structures at optical scales early studies were either theoretical or in the microwave regime where photonic crystals can be built on the far more reading accessible centimeter scale. This fact is due to the property of the electromagnetic fields known as scale invariance in essence, the electromagnetic fields as the solutions to Maxwell's equations has no natural length scale and so solutions for centimeter scale structure at microwave frequencies as the same for nanometer scale structures at optical frequencies.

The optical analogue of light is the photonic crystals in which atoms or molecules are replaced by macroscopic media with different dielectric constants and the periodic potential is replaced by a periodic dielectric function. if the dielectric constants of the materials is sufficiently different and also if the absorption of light by the material is minimal then the refractions and reflections of light from all various interfaces can produce many of the same phenomena for photons like that the atomic potential produced for electrons[9].

The previous details can guide us to the meaning of photonic crystals that can control the propagation of light since it can simply defined as a dielectric media with a periodic modulation of refractive index in which the dielectric constant varies periodically in a

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specific directions. Also it can be constructed at least from two component materials with different refractive index due to the dielectric contrast between the component materials of the crystal .it's characterized by the existence of photonic band gap (PBG) in which the electromagnetic radiation is forbidden from the propagation through it.

One of the most important properties of photonic crystal is controlling propagation of light in small submicron scale volumes. We will try to mention another example that may develop our sense about photonic crystals. Metallic wave guides and cavities are related to photonic crystals. They are widely used to control microwave propagation. The metallic cavity prohibits the propagation of electromagnetic waves with frequency below the threshold frequency while the metallic waveguides allow propagation only along its axis [9]. Today a huge number of researchers go ahead to enhance and widen the circle of applications through photonic crystals by using a composite structure which is composed of (metal / dielectric) structure instead of (dielectric / dielectric) structure. Since the metallic – dielectric photonic crystals (MDPCs) can be useful for a large number of applications and also will open the door to new discoveries that depend mainly on the optical properties of the metal. MDPCs have many advantages over dielectric based photonic crystals since:

1. Metal components can be used for wiring of future optoelectronic merger circuits this is due to that, nanowire materials are characterized by the existence of surface plasmon polaritons (spp) and also possess negative refractive index then it can act as left-handed materials[6,7].
2. Metals have stronger non linearity than other optical materials due to that most of metals possess negative refractive indices.
3. The photonic band gap (PBG) of the metallic dielectric photonic crystals (MDPCs) can be more robust against structural disorders.
4. High temperature operating may be possible.
5. Excitation of surface plasmon polaritons (spp) is also possible.

There are certain advantages to introducing 1D MDPCs. These include reduced size and weight, easier fabrication methods, and lower costs. Here, we use the transfer matrix method to study the effect of absorption of metal at the near-infrared and visible frequencies. In particular, we study a simple-one dimensional metallic-dielectric structure. Silver, Gold, Copper, Lithium and Aluminum have been used in order to study the effect of different metals on optical properties.

2. Numerical methods

In order to study the electromagnetic waves propagating through photonic crystal structures and determine the optical properties of these periodic structures. There are six main methods are used to study the propagation of electromagnetic waves through photonic crystals numerically and they called them[10]; the plane wave method(PW), finite time domain method (FDTD), finite element method.(FEM), transfer matrix method (TMM), scattering matrix method (SMM), and study of diffraction gratings (DG). The advantages and defects of these methods were obtained in ref.10. We will now explain in brief a mathematical treatment with a simple one dimensional photonic crystal structure (1DPC) (see fig.1) which is composed of two materials with thicknesses (d_2 and d_3) and refractive indices (n_2 and n_3) respectively. The analysis of the incident electromagnetic radiation on this structure will be performed using the transfer matrix method (TMM).

Fig. 1. Stack of 1 D MDPC ,where n_2 is the refractive index of the metal, d_2 is the thickness of the metal , n_3 is the refractive index of the dielectric material and d_3 is the thickness of the dielectric material.

We also use n_1 to be the refractive index of vacuum while n_4 is that of the substrate material as in fig.1. The electric field that satisfies Maxwell's equations is [11].

$$E(x)=R\exp(-ik_x.x)+L\exp(ik_x.x) = A(x)+\beta(x) \tag{1}$$

Where β the Z-component of the wave is vector and ω is the angular frequency. Also the electric field consists of right and left traveling waves since:-
With $\pm k_x$ are the components of the wave vector and (R, L) being constants in each homogeneous layer.
We will go to mention the mathematical form of the dynamical matrices and for the propagation matrix to obtain an expressions for the reflection and transmission, the dynamical matrices take the form [11]:

$$D_\alpha = \begin{pmatrix} 1 & 1 \\ n_\alpha Cos\theta_\alpha & -n_\alpha Cos\theta_\alpha \end{pmatrix} \text{ for S – wave} \tag{2}$$

$$D_\alpha = \begin{pmatrix} Cos\theta_\alpha & Cos\theta_\alpha \\ n_\alpha & -n_\alpha \end{pmatrix} \text{ for P – wave} \tag{3}$$

with

$$\beta = n_\alpha \frac{\omega}{c} Sin\theta_\alpha \text{ , and } \quad k_{\alpha x} = n_\alpha \frac{\omega}{c} Cos\theta_\alpha$$

while the propagation matrix take the form:

$$P_\eta = \begin{pmatrix} \exp(i\phi_\alpha) & 0 \\ 0 & \exp(-i\phi_\alpha) \end{pmatrix} \tag{4}$$

Since the number of the propagation matrix depend on the number of materials which build our structure [11]. Finally the transfer matrix method can take the form:

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \tag{5}$$

$$P_2 = \begin{pmatrix} Cos\phi_1 + i\,Sin\phi_1 & 0 \\ 0 & Cos\phi_1 - i\,Sin\phi_1 \end{pmatrix}$$

$$P_3 = \begin{pmatrix} Cos\phi_2 + i\,Sin\phi_2 & 0 \\ 0 & Cos\phi_2 - i\,Sin\phi_2 \end{pmatrix}$$

Since;

$$\phi_1 = \frac{2\pi d_2}{\lambda} n_2 Cos\theta_2 , \quad \text{and} \quad \phi_2 = \frac{2\pi d_3}{\lambda} n_3 Cos\theta_3 .$$

The components of the transfer matrix method can be written in a detailed form for an S – wave as:

$$M_{11} = \frac{1}{2}\left[\left(1 + \frac{n_4 Cos\ \theta_4}{n_1 Cos\ \theta_1}\right) Cos\ \varphi_2 + \left(\frac{n_3 Cos\ \theta_3}{n_1 Cos\ \theta_1} + \frac{n_4 Cos\ \theta_4}{n_3 Cos\ \theta_3}\right)\left(i\,Sin\ \phi_2\right)\right] Cos\ \phi_1 +$$
$$\frac{1}{2}\left[\begin{matrix}\left(\frac{n_2 Cos\ \theta_2}{n_1 Cos\ \theta_1} + \frac{n_4 Cos\ \theta_4}{n_2 Cos\ \theta_2}\right) Cos\ \phi_2 + \left(\frac{n_3 Cos\ \theta_3}{n_2 Cos\ \theta_2} + \frac{n_2 n_4 Cos\ \theta_2 Cos\ \theta_4}{n_1 n_3 Cos\ \theta_1 Cos\ \theta_3}\right) \\ \left(i\,Sin\ \phi_2\right)\end{matrix}\right]\left(i\,Sin\ \phi_1\right) \tag{6}$$

$$M_{12} = \frac{1}{2}\left[\left(1 - \frac{n_4 Cos\ \theta_4}{n_1 Cos\ \theta_1}\right) Cos\ \phi_2 + \left(\frac{n_3 Cos\ \theta_3}{n_1 Cos\ \theta_1} - \frac{n_4 Cos\ \theta_4}{n_3 Cos\ \theta_3}\right)\left(i\,Sin\ \phi_2\right)\right] Cos\ \phi_1 +$$
$$\frac{1}{2}\left[\begin{matrix}\left(\frac{n_2 Cos\ \theta_2}{n_1 Cos\ \theta_1} - \frac{n_4 Cos\ \theta_4}{n_2 Cos\ \theta_2}\right) Cos\ \phi_2 + \left(\frac{n_3 Cos\ \theta_3}{n_2 Cos\ \theta_2} - \frac{n_2 n_4 Cos\ \theta_2 Cos\ \theta_4}{n_1 n_3 Cos\ \theta_1 Cos\ \theta_3}\right) \\ \left(i\,Sin\ \phi_2\right)\end{matrix}\right]\left(i\,Sin\ \phi_1\right) \tag{7}$$

$$M_{21} = \frac{1}{2}\left[\left(1 - \frac{n_4 Cos\ \theta_4}{n_1 Cos\ \theta_1}\right) Cos\ \phi_2 - \left(\frac{n_3 Cos\ \theta_3}{n_1 Cos\ \theta_1} - \frac{n_4 Cos\ \theta_4}{n_3 Cos\ \theta_3}\right)\left(i\,Sin\ \phi_2\right)\right] Cos\ \phi_1 -$$
$$\frac{1}{2}\left[\begin{matrix}\left(\frac{n_2 Cos\ \theta_2}{n_1 Cos\ \theta_1} - \frac{n_4 Cos\ \theta_4}{n_2 Cos\ \theta_2}\right) Cos\ \phi_2 - \left(\frac{n_3 Cos\ \theta_3}{n_2 Cos\ \theta_2} - \frac{n_2 n_4 Cos\ \theta_2 Cos\ \theta_4}{n_1 n_3 Cos\ \theta_1 Cos\ \theta_3}\right) \\ \left(i\,Sin\ \phi_2\right)\end{matrix}\right]\left(i\,Sin\ \phi_1\right) \tag{8}$$

$$M_{22} = \frac{1}{2}\left[\left(1 + \frac{n_4 Cos\ \theta_4}{n_1 Cos\ \theta_1}\right) Cos\ \phi_2 - \left(\frac{n_3 Cos\ \theta_3}{n_1 Cos\ \theta_1} + \frac{n_4 Cos\ \theta_4}{n_3 Cos\ \theta_3}\right)\left(i\,Sin\ \phi_2\right)\right] Cos\ \phi_1 -$$
$$\frac{1}{2}\left[\begin{matrix}\left(\frac{n_2 Cos\ \theta_2}{n_1 Cos\ \theta_1} + \frac{n_4 Cos\ \theta_4}{n_2 Cos\ \theta_2}\right) Cos\ \phi_2 - \left(\frac{n_3 Cos\ \theta_3}{n_2 Cos\ \theta_2} + \frac{n_2 n_4 Cos\ \theta_2 Cos\ \theta_4}{n_1 n_3 Cos\ \theta_1 Cos\ \theta_3}\right) \\ \left(i\,Sin\ \phi_2\right)\end{matrix}\right]\left(i\,Sin\ \phi_1\right) \tag{9}$$

Where the reflectance and transmittance can be written as:

$$R = \left| r^2 \right| = \left| \frac{M_{21}}{M_{11}} \right|^2 \quad (10)$$

$$T = \frac{n_4 \, Cos \, \theta_4}{n_1 \, Cos \, \theta_1} \left| t \right|^2 = \frac{n_4 \, Cos \, \theta_4}{n_1 \, Cos \, \theta_1} \left| \frac{1}{M_{11}} \right|^2 \quad (11)$$

Where r and t is the reflection and transmission and we can also obtain by the same method the components of the transfer matrix method (TMM) for P – wave. Finally the dispersion relation for the metallic –dielectric photonic band gap (MDPBG) which describes the relation between the forbidden band (K) and the frequency (ω) can be written as [11]:

$$Cos \, K\Lambda = Cos \, (k_2 d_2) Cos \, (k_3 d_3) - \frac{1}{2} \left(\frac{n_3}{n_2} + \frac{n_2}{n_3} \right) Sin \, (k_2 d_2) Sin \, (k_3 d_3) \quad (12)$$

with $k_1 = \frac{\omega}{c} n_2 \quad , \quad k_2 = \frac{\omega}{c} n_3 \quad , \quad \Lambda = d_2 + d_3$

Where is Λ the lattice constant and K is the forbidden band.

3. Results and discussions

The periodicity of the permittivity plays the same role for the photons that propagate inside the structure than the atomic potential for the electrons. Leading further this analogy, the thicknesses and the index contrast of the photonic crystal determinate many of its optical properties as it does for conduction properties of semiconductors. Playing on these two parameters, we can obtain frequency ranges for which light propagation is forbidden in the material and others ranges for which light can propagate. These frequency ranges are also scale dependent. Reducing the size of the elementary cell of the periodic lattice shifts the whole frequency range to higher values. The consequence of this property is the possibility

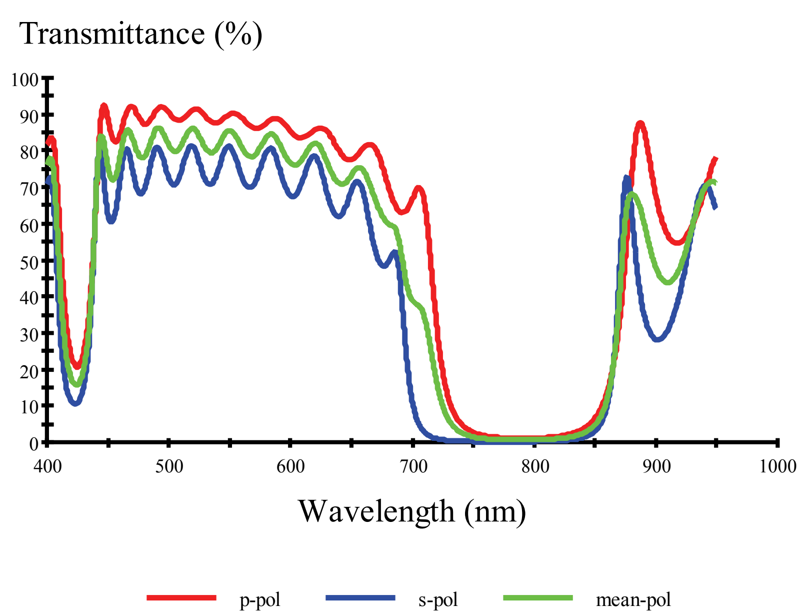

Fig. 2. The transmittance of p-pol, s-pol and the mean pol to Ag-SiO2 structure.

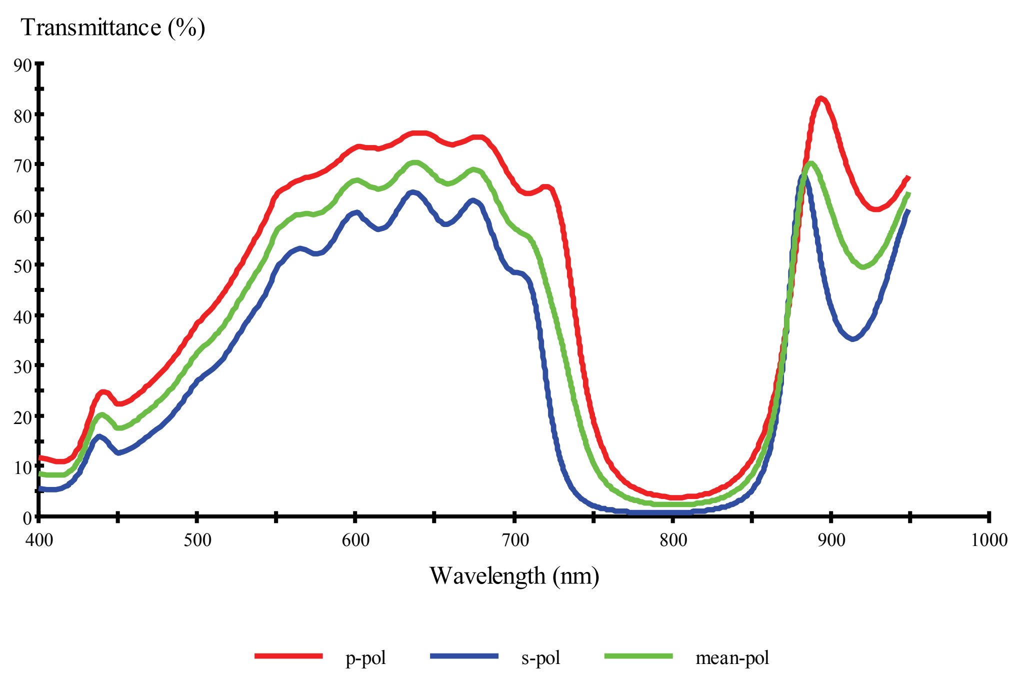

Fig. 3. The transmittance of p-pol, s-pol and the mean pol to Au-SiO2 structure.

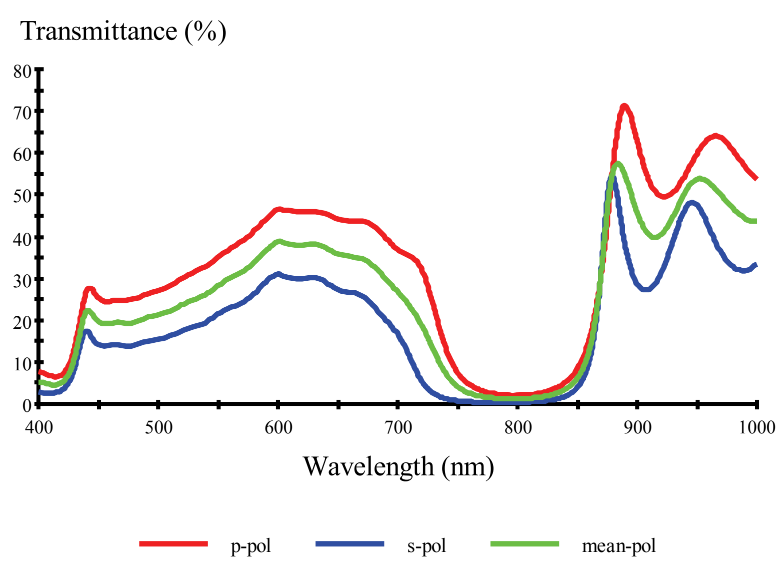

Fig. 4. The transmittance of p-pol, s-pol and the mean pol to Cu-SiO2 structure.

to transpose a photonic crystal design from the microwave domain to infrared or visible range. In our results we have studied one dimensional metallic (different metals) dielectric (SiO2) photonic crystals (MDPC's). In all our figures we have used the thickness of SiO2 layer is 340nm and the thickness layer of metal is 4nm for all results. Also we have used 10 periods and the incidence of angle is 50° for the all our results (Fig's 2-6). In the case of Ag-SiO2 (fig.2) we can see the magnitude of transmittance near the unity with visible light and there is a small photonic band gap (PBG) appeared within the short IR (750-850 nm). The magnitude of transmittance in the case of Au-SiO2 (fig.3) is 10% at 400 nm and increased to ~80 % within 550-700nm with the same PBG range 750-850 nm with s-polarized.

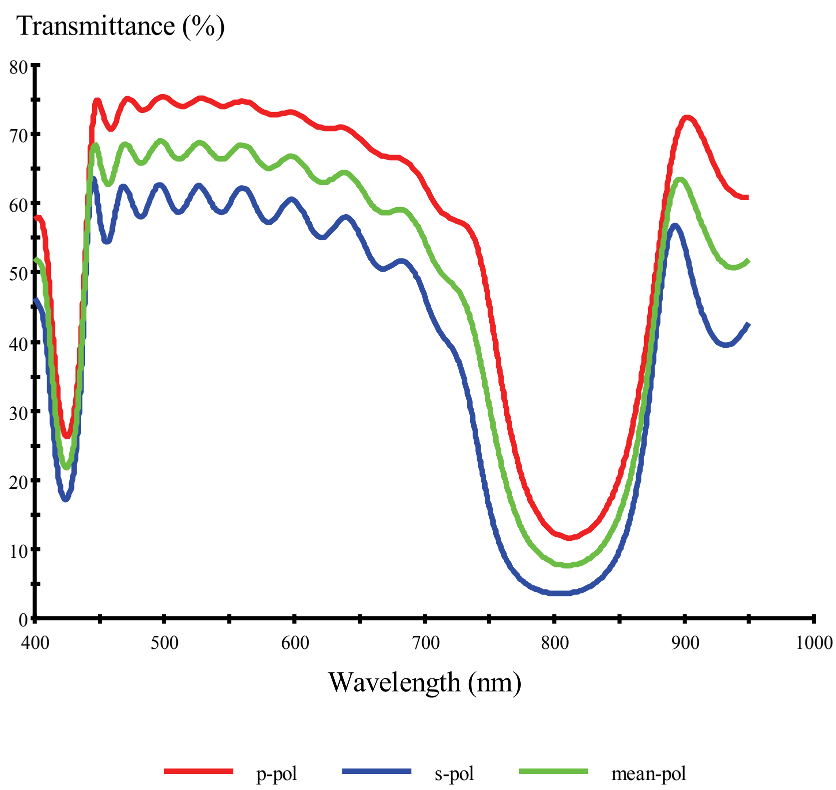

Fig. 5. The transmittance of p-pol, s-pol and the mean pol to Li-SiO2 structure.

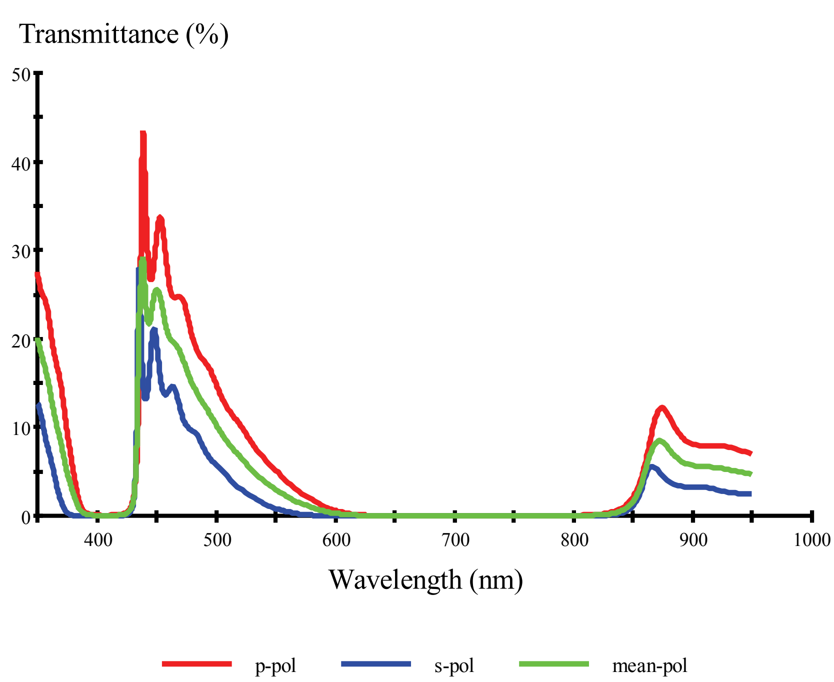

Fig. 6. The transmittance of p-pol, s-pol and the mean pol to Al-SiO2 structure.

In figure (4) the magnitude of transmittance in the case of Cu-SiO2 is go downing under 40% within the range of visible light (400-700) and we got the same PBG between 750-850 nm. But in fig.(5) with Li-SiO2, the magnitude of transmittance going up to around 70% within the visible light and the PBG disappeared.

In the last figure (6) we have examined Al-SiO2 with the same conditions and we found aluminum that gives the lowest possible transmittance within the visible and near IR frequencies.

4. Conclusion

We studied metallic photonic crystals at visible and near-infrared wavelengths with the transfer matrix method. We focused on the transmittance of these structures, thus we studied the simple 1D structure. We expect that our conclusions regarding the transmittance will hold to any other metallic structures. By comparing the results for different metals, we found that copper gives the lowest possible transmittance within the visible frequencies. Silver gives slightly higher transmittance within the visible with small PBG near IR. Gold gives low possible transmittance within short visible and going to near 70% between 550-700nm with small PBG within 750-850nm. Lithium gives higher transmittance. Aluminum is very lossy and is not recommended for optical photonic crystals. Silver, gold and Lithium are acceptable although slightly lower in performance. We also found our results are very sensitive to the thickness of layers as well as PBG is sensitive to the kind of polarizations-pol.

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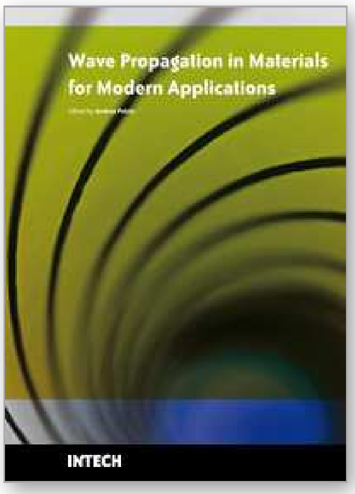

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In the recent decades, there has been a growing interest in micro- and nanotechnology. The advances in nanotechnology give rise to new applications and new types of materials with unique electromagnetic and mechanical properties. This book is devoted to the modern methods in electrodynamics and acoustics, which have been developed to describe wave propagation in these modern materials and nanodevices. The book consists of original works of leading scientists in the field of wave propagation who produced new theoretical and experimental methods in the research field and obtained new and important results. The first part of the book consists of chapters with general mathematical methods and approaches to the problem of wave propagation. A special attention is attracted to the advanced numerical methods fruitfully applied in the field of wave propagation. The second part of the book is devoted to the problems of wave propagation in newly developed metamaterials, micro- and nanostructures and porous media. In this part the interested reader will find important and fundamental results on electromagnetic wave propagation in media with negative refraction index and electromagnetic imaging in devices based on the materials. The third part of the book is devoted to the problems of wave propagation in elastic and piezoelectric media. In the fourth part, the works on the problems of wave propagation in plasma are collected. The fifth, sixth and seventh parts are devoted to the problems of wave propagation in media with chemical reactions, in nonlinear and disperse media, respectively. And finally, in the eighth part of the book some experimental methods in wave propagations are considered. It is necessary to emphasize that this book is not a textbook. It is important that the results combined in it are taken “from the desks of researchers“. Therefore, I am sure that in this book the interested and actively working readers (scientists, engineers and students) will find many interesting results and new ideas.

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