

Metamaterial-dielectric photonic crystal waveguide structure

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Abstract: Photonic crystals (PCs) are a revolutionary science that has a great impact on the field of photonics. In purpose of extend the applications of PCs, we introduce a new photonic structure which is composed of alternating lamellae of MTMs and Dielectric. The electromagnetic waves propagating through photonic crystal structures are numerically investigated. Results show improvement in the characteristics of the photonic crystal.

Keywords: Component, Formatting, Style, Styling, Insert

1. Introduction

Understanding of material properties helps to enhance their performance in practical applications. The progresses in metallurgy led to the development of various artificial materials with a fabulous range of mechanical properties. Semiconductors played an important role in modifying the conducting properties of materials, originating the revolution of transistors in electronics. To control optical properties of materials we are free to engineer the structure of materials that respond to light waves over a desired range of frequencies. The periodic microstructure of photonic crystal (PC) is similar to a crystalline lattice solid composed of a collection of atoms arranged in a regular repeated pattern. The periodic potential in the crystal is replaced by periodic dielectric constants in the photonic crystal. Mainly, we can build photonic crystals with photonic band gaps, prohibiting light from propagating in certain directions with specified frequencies [1].

Yablonovitch [2] had created a photonic band gap structure in which spontaneous emission can be severely inhibited in a way similar to the band gaps in semiconductors. The prevention of wave propagation in the forbidden gap has valuable applications as ideal reflective mirrors. Sigalas [3] studied waveguide structures in 3-dimensional metallic photonic band-gap materials, which can be used for the communication of different circuits in printed circuit boards. Similarly, Metamaterials (MTMS) are artificial materials,

which have simultaneous negative permittivity and permeability. These materials are theoretically introduced by Veselago [4]. Later, MTMs are fabricated in the laboratory by Shelby [5] and Pendry [6]. These novel materials have unique properties, which make them valuable in practical applications such as sensors [7,8] and isolators [9].

The goal of this work is to study the application of metamaterials into photonic crystals. We proposed a structure consists of alternating lamellae of MTM and dielectric (SiO₂). Next section is dedicated to the mathematical model. Results and discussion are given in section 3 followed by conclusion.

2. Mathematical Model

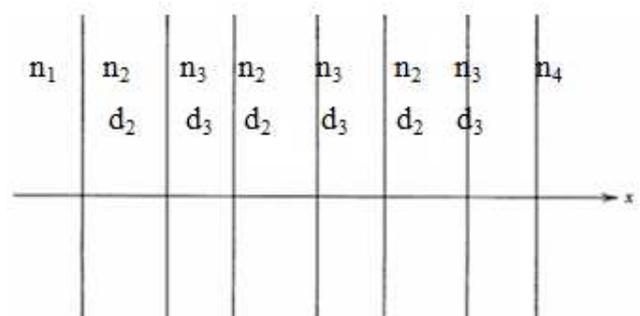


Figure 1. Proposed photonic structure: n_2 and d_2 are the refractive index and the thickness of the MTM, n_3 and d_3 are the refractive index and the thickness of the dielectric.

Fig. 1 displays the proposed photonic crystal lamellar structure, which is constituted of MTM lamella having refractive indices n_2 and thickness d_2 alternating with dielectric lamella having refractive indices n_3 and thickness d_3 . The bounded layers are air having refractive indices n_1 and n_4 .

To determine the propagation of electromagnetic radiation in these media, we use the 2x2 array formulation. The electric field can be written as

$$E = E(x)e^{i(\omega t - \beta z)} \quad (1)$$

where β is the z component of the wave vector. We assume only s wave with $E//y$ (TE) propagating in the xz plane with $E(x)$ can be written as

$$\begin{aligned} M_{11} &= \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) i \sin \phi_2 \right] \cos \phi_1 + \\ & \frac{1}{2} \left[\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) i \sin \phi_2 \right] i \sin \phi_1, \\ 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) i \sin \phi_2 \right] \cos \phi_1 + \\ & \frac{1}{2} \left[\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) i \sin \phi_2 \right] i \sin \phi_1, \\ 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) i \sin \phi_2 \right] \cos \phi_1 - \\ & \frac{1}{2} \left[\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) i \sin \phi_2 \right] i \sin \phi_1, \\ 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) i \sin \phi_2 \right] \cos \phi_1 - \\ & \frac{1}{2} \left[\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) i \sin \phi_2 \right] i \sin \phi_1 \end{aligned}$$

with $k_{\alpha x} = \sqrt{\left(\frac{n_\alpha \omega}{c} \right)^2 - \beta^2}$, $\beta = n_\alpha \frac{\omega}{c} \sin(\theta_\alpha)$, $\alpha=1-4$.

$\phi_1 = \frac{2\pi d_2}{\lambda} n_2 \cos(\theta_2)$, and $\phi_2 = \frac{2\pi d_3}{\lambda} n_3 \cos(\theta_3)$.

The transmittance (T) is given by

$$T = |t|^2 = \frac{n_4 \cos(\theta_4)}{n_1 \cos(\theta_1)} \left| \frac{1}{M_{11}} \right|^2 \quad (4)$$

The dispersion relation between the frequency ω and the forbidden band K for the special case $\beta=0$ (i.e. normal

$$E(x) = E_R e^{ik_x x} + E_L e^{-ik_x x} \quad (2)$$

where E_R and E_L are constants, and $\pm k_x$ are the wave vector x components for the waves travelling in the right and left directions.

The transfer matrix has the form [10]

$$M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \quad (3)$$

where

incidence) can be expressed by the following relation,

$$\cos(K\Lambda) = \cos(k_2 d_2) \cos(k_3 d_3) - \frac{1}{2} \left(\frac{n_3}{n_2} + \frac{n_2}{n_3} \right) \sin(k_2 d_2) \sin(k_3 d_3) \quad (5)$$

where K is the forbidden band, $k_2 = (\omega/c)n_2$, $k_3 = (\omega/c)n_3$, and Λ is the lattice constant, $\Lambda = d_2 + d_3$.

3. Results and Discussions

The dispersion relation (equation 10) is solved numerically. The transmittance (9) is then solved for different values of MTMs refractive index, n_2 . In all calculations, we have used

the thickness of SiO₂ layer is 340nm and the thickness layer of MTM is 4nm. The selected dielectric material refractive index $n_3=1.54427$.

Figs. 2-8 illustrate the transmittance of s-waves as a function of the MTMs refractive index, n_2 . It can be seen from these figures that the transmittance occurs in the range of visible light between 450nm and 750nm depending on the values of n_2 . Moreover, we noticed that transmittance might occur near the short IR for all case except at $n_2=-5$ and -8 .

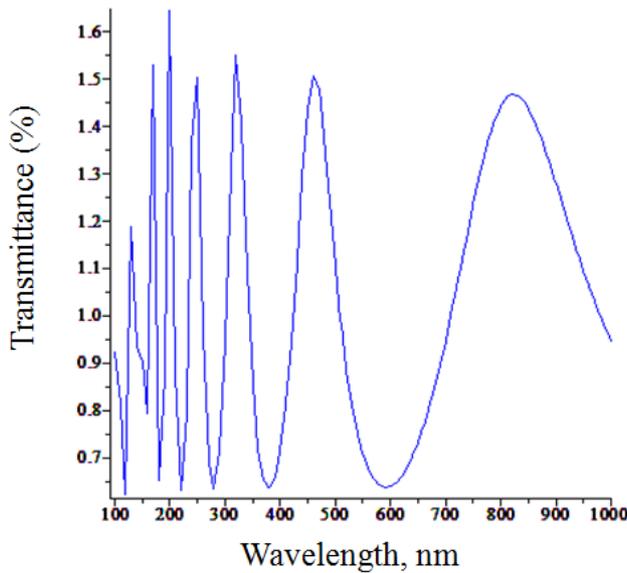


Figure 2. The transmittance of s-wave, $n_2=-1$. The waves propagate in the visible range around 470nm and 800nm and near the IR.

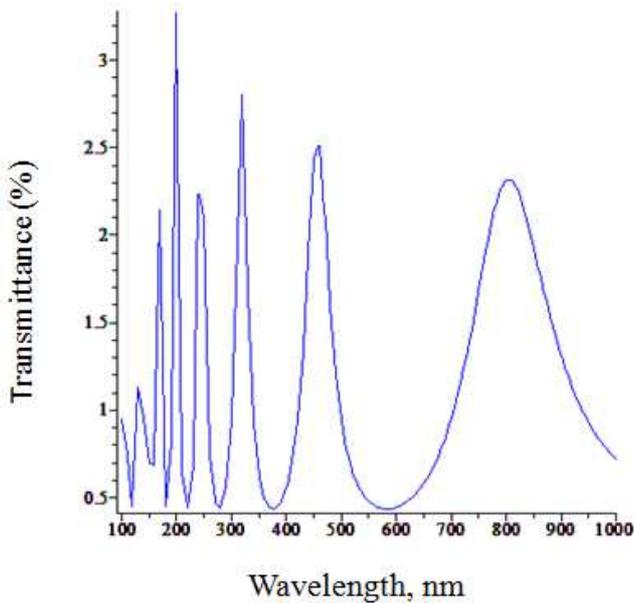


Figure 3. The transmittance of s-wave, $n_2=-2$. The waves propagate in the visible range around 470nm and 800nm and near the IR.

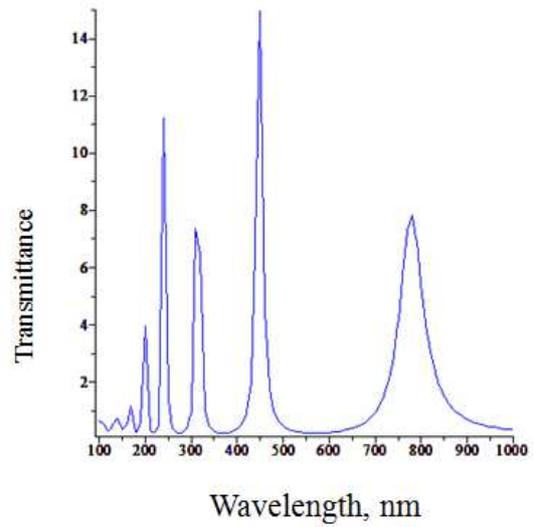


Figure 4. The transmittance of s-wave, $n_2=-4$. The waves propagate in the visible range around 440nm and 800nm and near the IR.

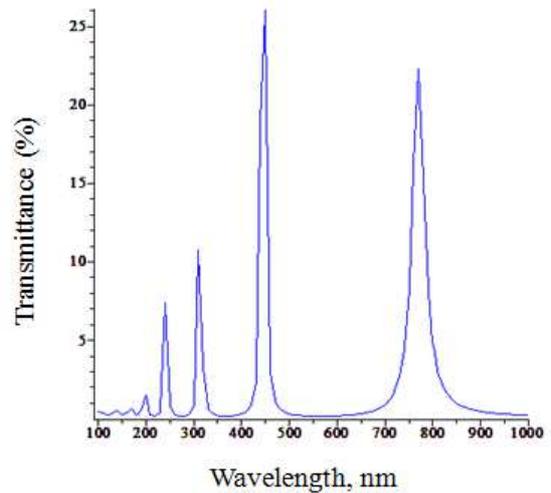


Figure 5. The transmittance of s-wave, $n_2=-5$. The waves propagate in the visible range around 450nm and 780nm.

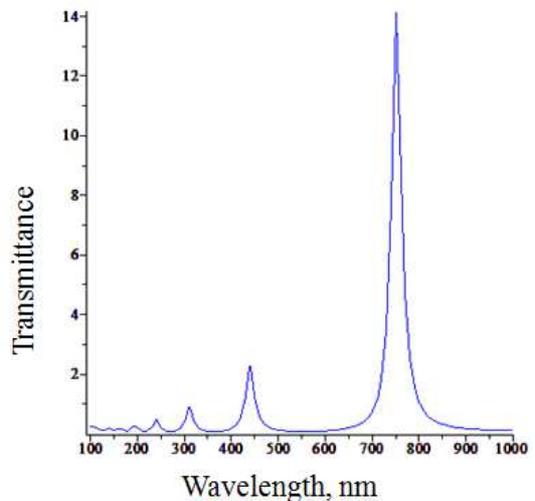


Figure 6. The transmittance of s-wave, $n_2=-8$. The waves propagate in the visible range around 450nm and 750nm.

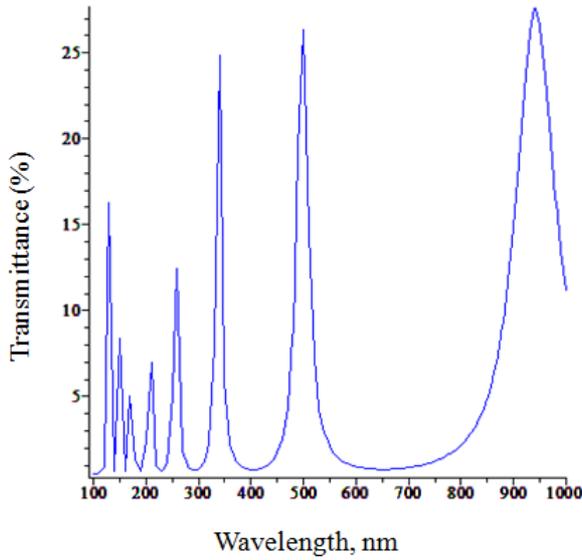


Figure 7. The transmittance of *s*-wave, $n_2 = -1 + i 2$. The waves propagate around 500nm and near the IR.

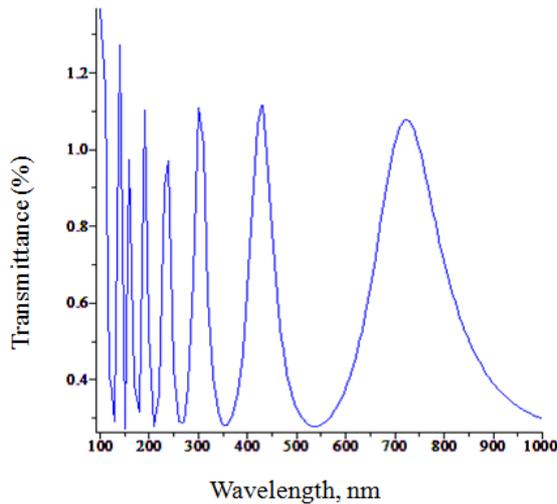


Figure 8. The transmittance of *s*-wave, $n_2 = -1 - i 2$. The waves propagate in the visible around 470nm and 750nm and near the IR.

4. Conclusions

In the present work, we introduced PC consists of MTMs layer interchanged with dielectric layers. The structure works as a waveguide in the visible region near 450nm and 750nm. Moreover, it allows transmission of short IR light.

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