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Infrared transmission in aperiodic structures

M. Szota [b], M. Nabiałek [a], S. Garus [a, *], J. Garus [a], K. Błoch [a]
[a] Institute of Physics, Technical University of Częstochowa, ul. Armii Krajowej 19,
42-200 Częstochowa, Poland
[b] Institute of Materials Engineering, Technical University of Częstochowa, ul. Armii Krajowej 19,
42-200 Częstochowa, Poland
Institute of Engineering Materials and Biomaterials, Silesian University of Technology,
* Corresponding e-mail address: gari.sg@gmail.com

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ABSTRACT

Purpose: The analysis of the electromagnetic wave transmission having a wave length near infrared propagating in multilayer structures made of materials GaP and CaF2. Analyzed was the influence of periodicity distribution of layers in the material properties and the presence of photonic forbidden gap for selected wavelengths of the electromagnetic wave.

Design/methodology/approach: Maps transmission, which was performed by the analysis were obtained using a matrix method. Was investigated wave propagation wavelength range of infrared radiation in periodic binary multilayers and aperiodic Severin and Thue-Morse superlattices.

Findings: It has been shown the structure of the transmission band depending on the type of polarization of the multilayer system. Properties of Thue-Morse superlattices were similar to binary superlattices but differed from the behavior of electromagnetic waves in aperiodic Severin superlattices.

Research limitations/implications: The simulation was not considered the impact of losses in the material for propagating electromagnetic wave.

Practical implications: Multilayer materials, which have photonic band gap, can be used as filters for electromagnetic radiation can improve the performance of night vision or electromagnetic waves multiplexers.

Originality/value: Transmission properties of multilayers were examined in visible light but not for infrared light.

Keywords: Transmission; Multilayers; Superlattices; Aperiodic; LHM; RHM

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

Photonic crystals, and in particular their subgroup - quasi one dimensional multilayer structures [1-5] due to their special material properties are of great interest. Using them as filters of electromagnetic radiation is particularly important that certain electromagnetic wavelengths do not propagate in these structures. These structures are usually made of alternating dielectric layers, where the thickness, type of material and the order of applying the layers have a critical role in their filtration properties. Production of the superlattice is designed to permit precise control of the structure [6-32], which allows you to create materials with precisely defined characteristics.

In order to reduce the cost and time needed to perform the actual materials shall be carried out computer simulations of the properties of the superlattice. Most frequently the simulations using the FDTD algorithm or matrix method (transmission maps) are used. Most research has focused on the study of the transmission in the wavelength range of visible light. It seems well founded analysis of the properties of these materials for closer infrared, the more so because for this wavelength range has already been received composite materials called metamaterials having a negative refractive index. The existence of such materials, Veselago predicted in his theoretical work in 1968 [33], but their production came about only in 2000 [34], which in consequence led to considerable interest in the global research centers study the properties of these materials [35-44].

The work we use the analysis of the properties of multilayer structures using the matrix method of the algorithm described in [2].

You can specify the matrix equation (1), in which there is an electromagnetic wave incident on the multilayer structure of the electric field intensity $E_{in}^{(+)}$, a part of it propagates through superlattice $E_{out}^{(+)}$, and part is reflected back $E_{in}^{(-)}$, the coefficient $E_{out}^{(-)}$ is introduced to preserve the dimensions of the matrix, and its value is always zero.

$$\begin{bmatrix} E_{in}^{(+)} \\ E_{in}^{(-)} \end{bmatrix} = F_{in,1} \cdot \left[\prod_{j=1}^{J} \begin{bmatrix} e^{id_j n_j \frac{2\pi}{\lambda} \cos\Theta_j} & 0 \\ 0 & e^{-id_j n_j \frac{2\pi}{\lambda} \cos\Theta_j} \end{bmatrix} \cdot F_{j,j+1} \right] \cdot \begin{bmatrix} E_{out}^{(+)} \\ E_{out}^{(-)} \end{bmatrix} \tag{1}$$

where λ is wavelength of the incident electromagnetic wave, by Θ_j is define, determined from Snell's law, the angle of incidence of the electromagnetic wave to layer j, n_j - refractive index of the layer j, d_j - thickness of the layer j, and $F_{j,i}$ is a matrix that describes the behavior of the electromagnetic wave on the verge of materials.

Matrix $F_{j,i}$ for the polarization P is defined as:

$$F_{j,i}^{P} = b1 \cdot \begin{bmatrix} 1 & a1 \\ a1 & 1 \end{bmatrix} \tag{2}$$

where:

$$a1 = \frac{n_j \cos\Theta_j - n_i \cos\Theta_i}{n_j \cos\Theta_j + n_i \cos\Theta_i} \tag{3}$$

and:

$$b1 = \frac{n_j \cos\Theta_j + n_i \cos\Theta_i}{2n_j \cos\Theta_j} \tag{4}$$

The S-type polarization matrix $F_{j,i}$ is defined as:

$$F_{j,i}^{S} = b2 \cdot \begin{bmatrix} 1 & a2 \\ a2 & 1 \end{bmatrix}, \tag{5}$$

where a_2 is defined as:

$$a2 = \frac{n_j \cos\Theta_i - n_i \cos\Theta_j}{n_j \cos\Theta_i + n_i \cos\Theta_j}, \tag{6}$$

and b_2 as:

$$b2 = \frac{n_j \cos\Theta_i + n_i \cos\Theta_j}{2n_j \cos\Theta_j} \tag{7}$$

From equation (1) can be determined the material properties of the matrix describing the structure.

$$\Psi = F_{in,1} \cdot \left[\prod_{j=1}^{J} \begin{bmatrix} e^{id_j n_j \frac{2\pi}{\lambda} \cos\Theta_j} & 0 \\ 0 & e^{-id_j n_j \frac{2\pi}{\lambda} \cos\Theta_j} \end{bmatrix} \cdot F_{j,j+1} \right] \tag{8}$$

The matrix (8) allows for determination of the coefficient of transmission for a specific environment (n_{in} and n_{out}) and the wave propagation direction (Θ_{in}, Θ_{out} - is determined using Snell law for the structure) by the equation:

$$T = \frac{n_{out} \cos\Theta_{out}}{n_{in} \cos\Theta_{in}} \cdot Abs\left(\Psi_{11}^{-1}\right)^2 . \tag{9}$$

The results are shown in the form of a transmission maps $T(\lambda, \Theta)$, where $T = 1$ (white color) means full transmission and $T = 0$ (black) its absence. The vertical axis determines the angle of incidence of the electromagnetic wave relative to the normal to the surface of quasi-structure, and the horizontal axis the wavelength of the incident electromagnetic wave.

Calculations were performed for binary superlattice structure as the reference with the $L = 8$ generation number defined by:

$$\mathrm{X}_8^B = \mathrm{ABABABABABABABAB} . \tag{10}$$

Then analysed aperiodic Severin superlattice [45] with $L = 4$ and structure.

$$\mathrm{X}_4^S = \mathrm{BBABBBABABABBBAB}, \tag{11}$$

Thue-Morse superlattice [46-52] with $L = 4$ and structure

$$\mathrm{X}_4^{TM} = \mathrm{ABBABAABBAABABBA} . \tag{12}$$

The results are shown in Figures 1-8 and Figures 11-14.

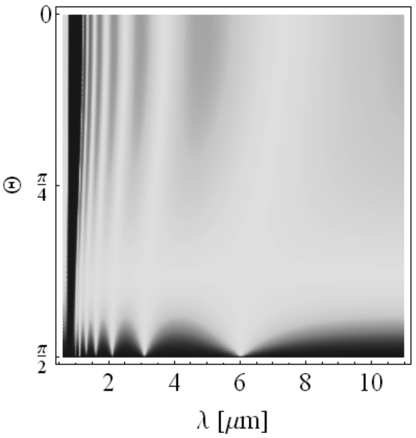

Fig. 1. Binary superlattice transmission map for L = 8 and polarization P

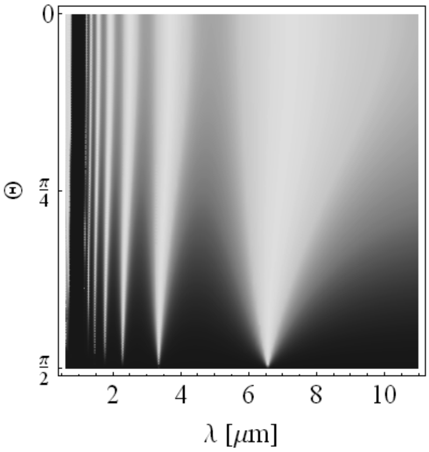

Fig. 2. Binary superlattice transmission map for L = 8 and polarization S

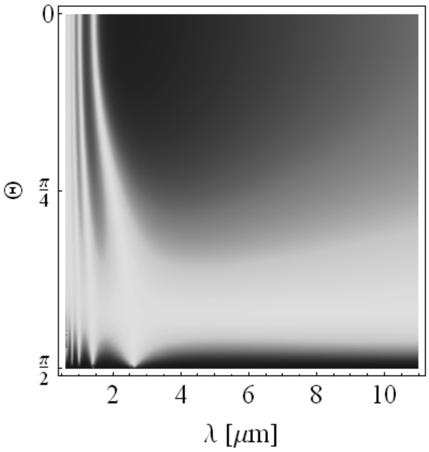

Fig. 3. Binary superlattice transmission map for L = 8, polarization P and metamaterial equivalent of GaP

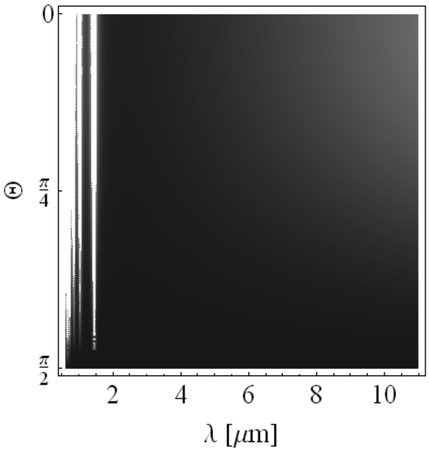

Fig. 4. Binary superlattice transmission map for L = 8, polarization S and metamaterial equivalent of GaP

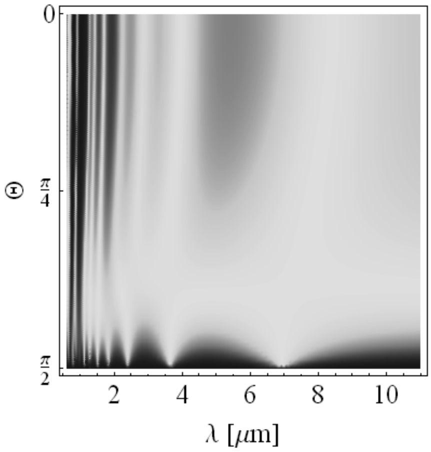

Fig. 5. Severin superlattice transmission map for L = 4 and polarization P

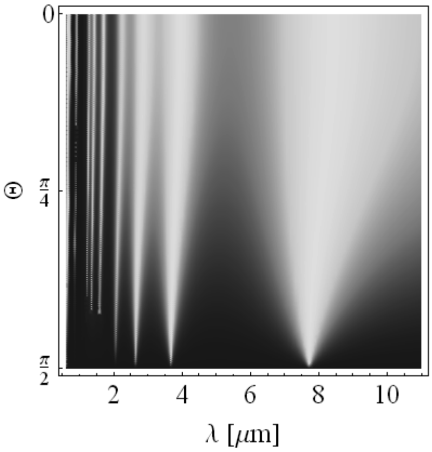

Fig. 6. Severin superlattice transmission map for L = 4 and polarization S

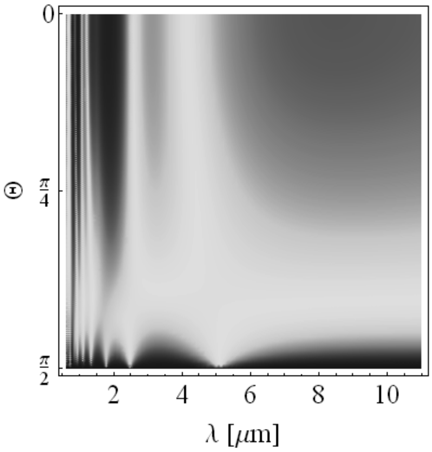

Fig. 7. Severin superlattice transmission map for L = 4, polarization P and metamaterial equivalent of GaP

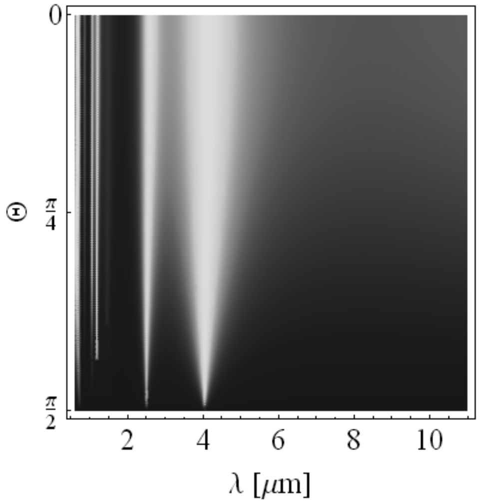

Fig. 8. Severin superlattice transmission map for L = 4, polarization S and metamaterial equivalent of GaP

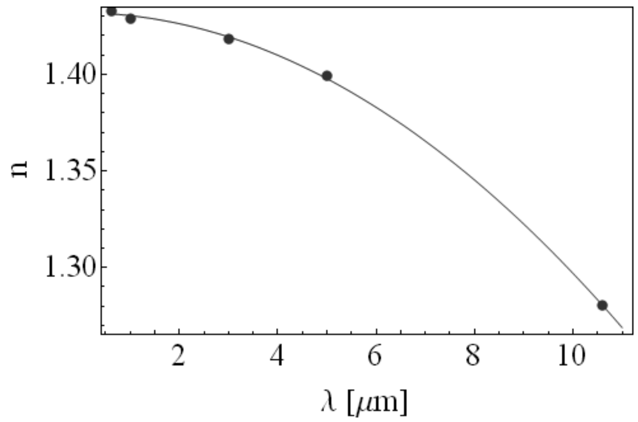

Fig. 9. The dispersion of the refractive index for the CaF_2 [4]

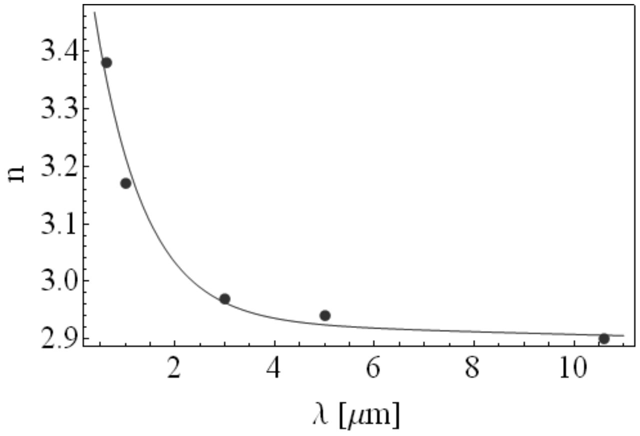

Fig. 10. The dispersion of the refractive index for the GaP [4]

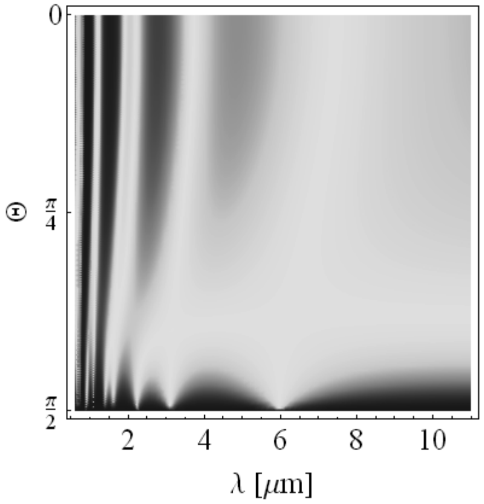

Fig. 11. Thue-Morse superlattice transmission map for L = 4 and polarization P

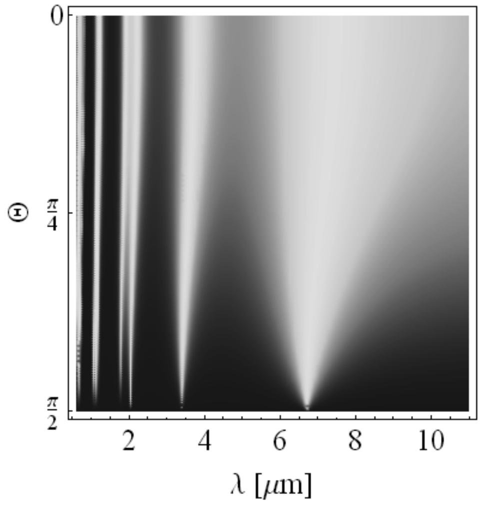

Fig. 12. Thue-Morse superlattice transmission map for L = 4 and polarization S

2. Research

Multilayer structures made of two materials of equal layer thicknesses, respectively $d_A = d_B = 100\ nm$, and the total thickness of each of the structures is $d = 1.6\ \mu m$.

As material A was taken CaF_2 with a refractive index defined by the dispersion shown in Fig. 9 [4]. The material B was GaP, which is described with the refractive index depending on the wavelength shown in Fig. 10 [4]. Figures 3, 4, 7, 8, 13, 14 illustrate the transmission maps specified for material B having a negative refractive index as defined by the $n_{B2}(\lambda) = - n_B(\lambda)$ for different types of polarization. Transmission characteristics were examined at wavelengths $\lambda \epsilon (0.6;\ 11)\ \mu m$ for the near infrared.

The calculations were made for the types of polarization P and S. The analysis was conducted for quasi one-dimensional lossless materials, and the environment material was air.

The simulation was performed for three structures: binary - periodic superlattice (Figs. 1-4) and Severin (Figs. 5-8) and Thue-Morse (Figs. 11-14) aperiodic multilayers.

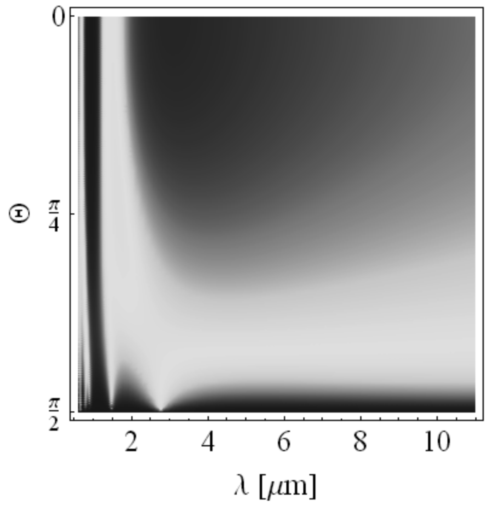

Fig. 13. Thue-Morse superlattice transmission map for L = 4, polarization P and metamaterial equivalent of GaP

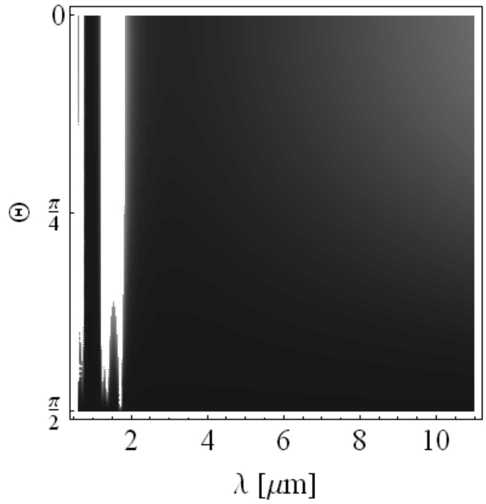

Fig. 14. Thue-Morse superlattice transmission map for L = 4, polarization S and metamaterial equivalent of GaP

3. Conclusions

Designated transmission maps can observe a significant effect on the polarization of the structure filter properties. A change of material B in superlattices on the metamaterial equivalent alters the properties of the filter structure. Transmission of studied multilayers constructed entirely of right-handed materials is similar, there are slight variations in the band structure. It can be seen the presence of photonic band gap which is typical for photonic materials. Transmission of binary superlattices is very similar to that occurring in the Thue-Morse structure. Bandwidths decrease with decreasing length of the incident electromagnetic wave.

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