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Properties of chirped periodic layered medium with metamaterial layers

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ABSTRACT

Purpose: The purpose of the article was to investigate the absorption and reflectance properties of chirped periodic layered medium with metamaterial layers.

Design/methodology/approach: The use of the algorithm TMM (Transfer Matrix Method) allows to determine the absorption and reflectance for the quasi one-dimensional multilayer structures. Can be analysed structure constructed with RHM (right-handed materials) and LHM (left-handed materials) with layers of any thickness and arranged in any way. It is possible to analyse lossy dispersive materials.

Findings: In all the cases studied linear shift in the peaks with an increase in the k coefficient was observed. In all cases there was a shift to higher wavelengths. Noted an increase in the intensity and broadening half-width of the peaks.

Research limitations/implications: The simulation was carried out only for the binary structure in the visible light range.

Practical implications: Computer simulations allow us to design material with specified properties at a lower cost. The use of chirped periodic layered media allows to shift and broadening of the peak in the required range of work for mirrors or filter.

Originality/value: Absorption and reflectance for chirped periodic layered systems using metamaterials layers have not yet been thoroughly investigated. Research can contribute to the implementation of mirrors with specific nonlinear properties.

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

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PROPERTIES

1. Introduction

The study analysed multilayer photonic materials which are intensively studied group of materials [1-5]. They are used in photonics, optics, solid state physics and optoelectronics. These materials characterized by the appearance of the photonic band gap, that is, the length range of the electromagnetic waves which not propagate in these materials. This property allows for the construction of filters of electromagnetic radiation with specified characteristics [6-32], as well as a mirror for selected wavelength ranges. The production of modern composite materials has created a need to examine the properties of multilayer systems in which one layer is made of metamaterial composite [33-44].

Computer simulations of the properties of multilayer structures allow to design systems with properties adapted to a specific application. Frequently for analysis of the superlattice are used finite-difference time-domain and transfer matrix method algorithm [2,42].

The use of the matrix method allows to determine the transmission parameters, reflectance and absorption for given structures and angles of incidence of the electromagnetic wave.

Electromagnetic wave propagation in a given structure is given by:

$$\begin{bmatrix} E_{in}^{(+)} \\ E_{in}^{(-)} \end{bmatrix} = \Gamma \begin{bmatrix} E_{out}^{(+)} \\ E_{out}^{(-)} \end{bmatrix}, \tag{1}$$

where $E_{in}^{(+)}$ is an electromagnetic wave incident on the structure, $E_{in}^{(-)}$ is an electromagnetic wave reflected, $E_{out}^{(+)}$ is an electromagnetic wave coming out of the multilayer, and $E_{out}^{(-)}$ is always equal zero. Described by equation (2) matrix Γ This characteristic matrix structure determined by the matrix propagation P_j (3) in a given layer and a matrix describing the behaviour of electromagnetic waves at the interlayer interfaces $D_{j,j+1}$ (5).

$$\Gamma = \begin{bmatrix} \Gamma_{11} & \Gamma_{12} \\ \Gamma_{21} & \Gamma_{22} \end{bmatrix} = D_{in,j} \left[\prod_{j=1}^{J} P_j D_{j,j+1} \right]. \tag{2}$$

$$P_j = \begin{bmatrix} e^{i\varphi_j} & 0 \\ 0 & e^{-i\varphi_j} \end{bmatrix}, \tag{3}$$

$$\varphi_j = d_j n_j \frac{2\pi}{\lambda} \cos\Theta_j , \tag{4}$$

$$D_{j,j+1} = \frac{1}{t_{j,j+1}} \begin{bmatrix} 1 & r_{j,j+1} \\ r_{j,j+1} & 1 \end{bmatrix} \tag{5}$$

where: d_j – thickness of the layer j, n_j – refractive index of the layer j, Θ_j – angle of incidence of the electromagnetic wave to the layer j, λ – the wavelength of the incident wave.

Matrix $D_{j,j+1}$ from equation (5) is determined by the transmission rate and the Fresnel reflectance determined respectively by the equations (6) and (7) for P-type polarization and (8) and (9) for S-type polarization:

$$t_{j,j+1}^{P} = \frac{2n_j \cos\Theta_j}{n_j \cos\Theta_{j+1} + n_{j+1} \cos\Theta_j} \tag{6}$$

$$r_{j,j+1}^{P} = \frac{n_j \cos\Theta_{j+1} - n_{j+1} \cos\Theta_j}{n_j \cos\Theta_{j+1} + n_{j+1} \cos\Theta_j} \tag{7}$$

$$t_{j,j+1}^{S} = \frac{2n_j \cos\Theta_j}{n_j \cos\Theta_j + n_{j+1} \cos\Theta_{j+1}} \tag{8}$$

$$r_{j,j+1}^{S} = \frac{n_j \cos\Theta_j - n_{j+1} \cos\Theta_{j+1}}{n_j \cos\Theta_j + n_{j+1} \cos\Theta_{j+1}} \tag{9}$$

From the characteristic matrix of the equation (2) it can be directly determine the transmission coefficient T (10), reflectance R (11) and the absorption A (12):

$$T = \frac{n_{out} \cos\Theta_{out}}{n_{in} \cos\Theta_{in}} \left| \frac{1}{\Gamma_{11}} \right|^2 , \tag{10}$$

$$R = \left| \frac{\Gamma_{21}}{\Gamma_{11}} \right|^2 , \tag{11}$$

$$A = 1 - (T + R) \, . \tag{12}$$

The indexes in and out are, respectively, surrounding the layers before and after the structure.

Chirped periodic layered medium are used to build broad-band reflectors. In the periodic superlattices two materials are arranged alternately. The local period is decreasing or increasing function of layers position. It is also possible the construction of chirped layered medium from aperiodic superlattices. The thickness of the layers may vary with position in a linear, exponential, or any other described in a given functional dependency.

2. Research

The study analysed the absorption and reflectance properties of the chirped periodic superlattices. The simulation uses non-dispersive materials. The refractive indices were $n_A = 1.544 - 0.05\,i$ and $n_B = -3.4$. The refractive indices of the environment were $n_{in} = n_{out} = 1$. In these superlattices each subsequent layer increases by a factor k with values from 0 to 6.5, expressed in nanometers. The discretization step value of the k coefficient was $0.1\ nm$. Standard layer thickness was $d = 175\ nm$. The construction of the system is shown in Figure 1. Absorption for $k = 0$ is shown in Fig. 2a (S-type polarization) and 2b (P-type polarization).

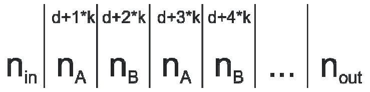

Fig. 1. The design of the analysed superlattice model

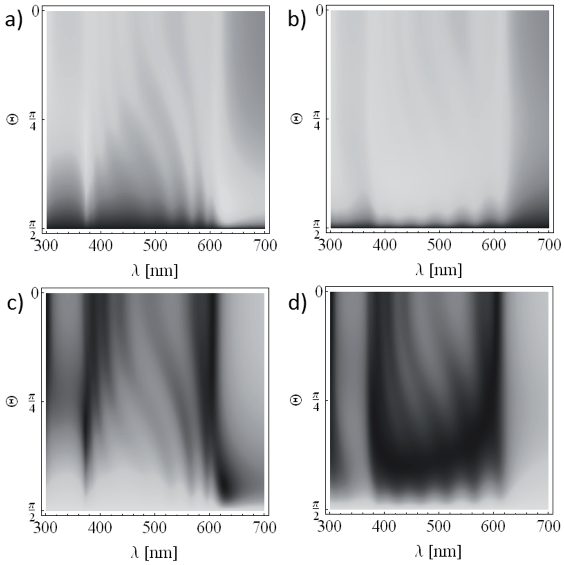

Fig. 2. Absorption maps for polarization type S (a) and P (b) and reflectance maps for polarization type S (c) and P (d)

Figures 3-5 shows the absorption (a, b) and reflectance (c, d) for different values of the k coefficient. Figures presents the data for the two types of polarization: S (a, c) and P (b, d). In each figure, the lowest chart was designated for k coefficient equal to zero. Then values were determined for $k = 0.1\ nm$ and the results also increased by 0.1 which allowed to show changes in the transmission and reflectance depending on the k coefficient. The tests were performed for k coefficient increments of $0.1\ nm$ until the $6.5\ nm$. The calculations were made for angles of incidence Θ equal to 30° (Fig. 3), 45° (Fig. 4) and 60° (Fig. 5).

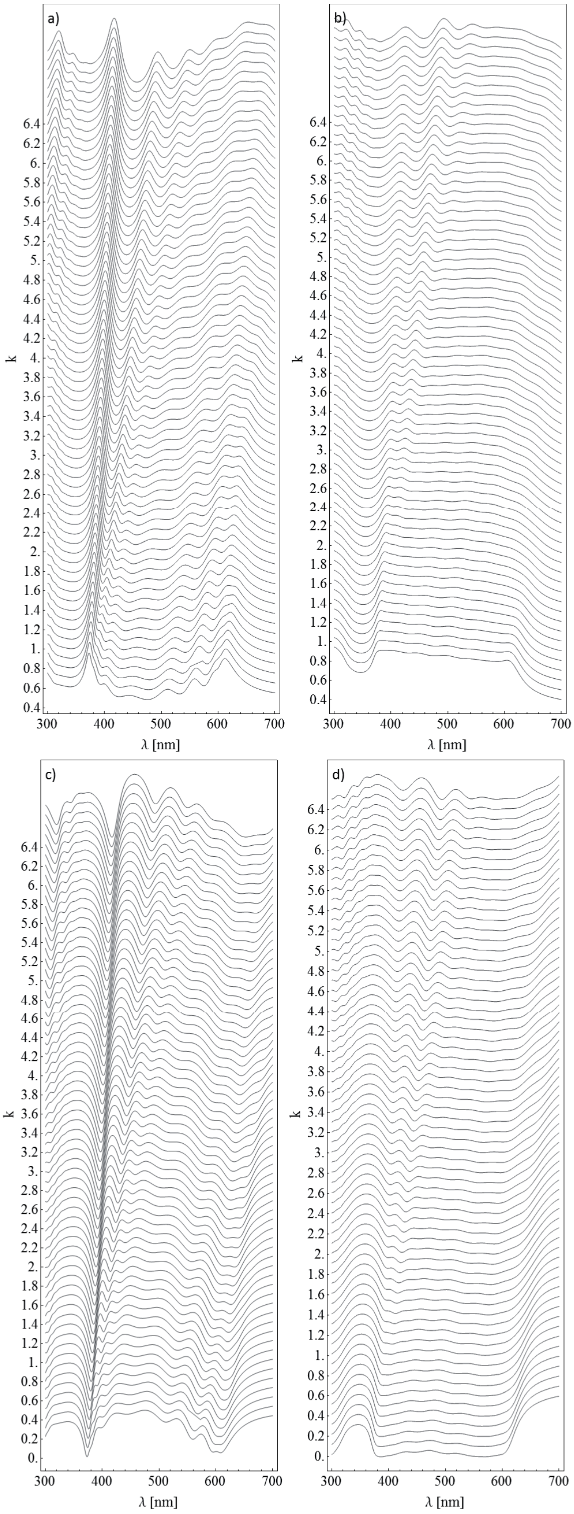

Fig. 3. Absorption (a, b) and reflectance (c, d) for polarization type S (a, c) and P (b, d) depending on the k coefficient for the angle of incidence $\Theta = 30°$

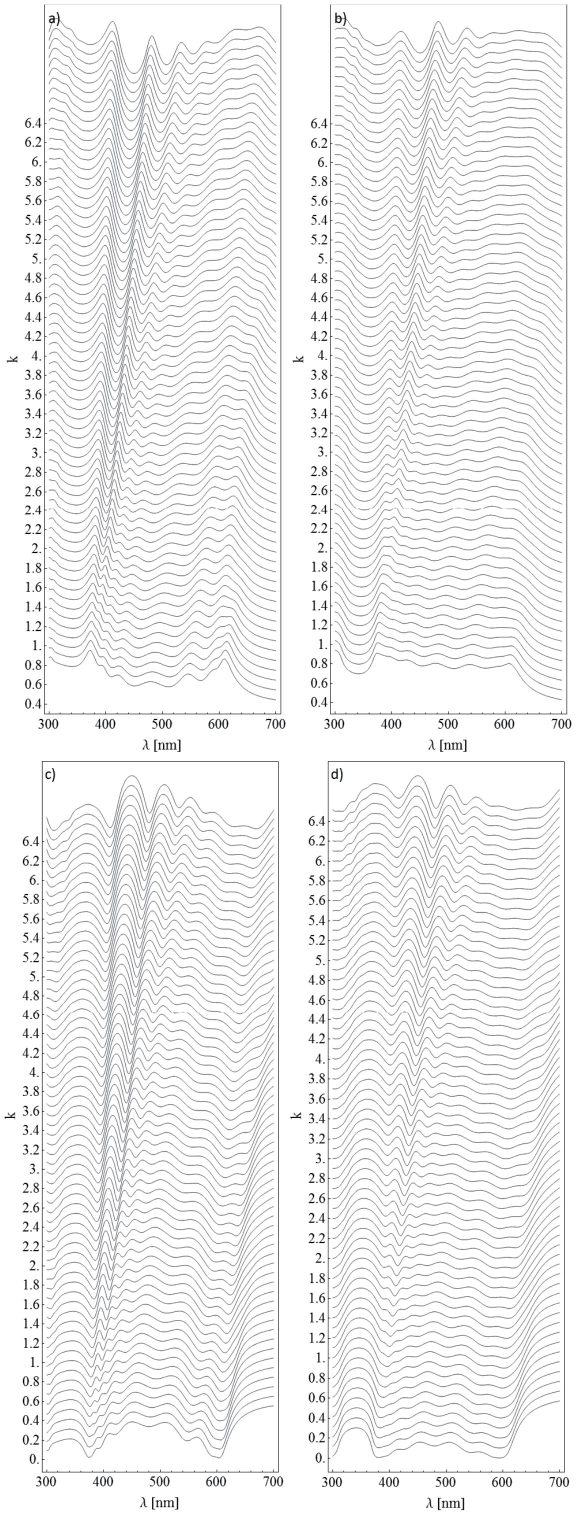

Fig. 4. Absorption (a, b) and reflectance (c, d) for polarization type S (a, c) and P (b, d) depending on the *k* coefficient for the angle of incidence *Θ = 45°*

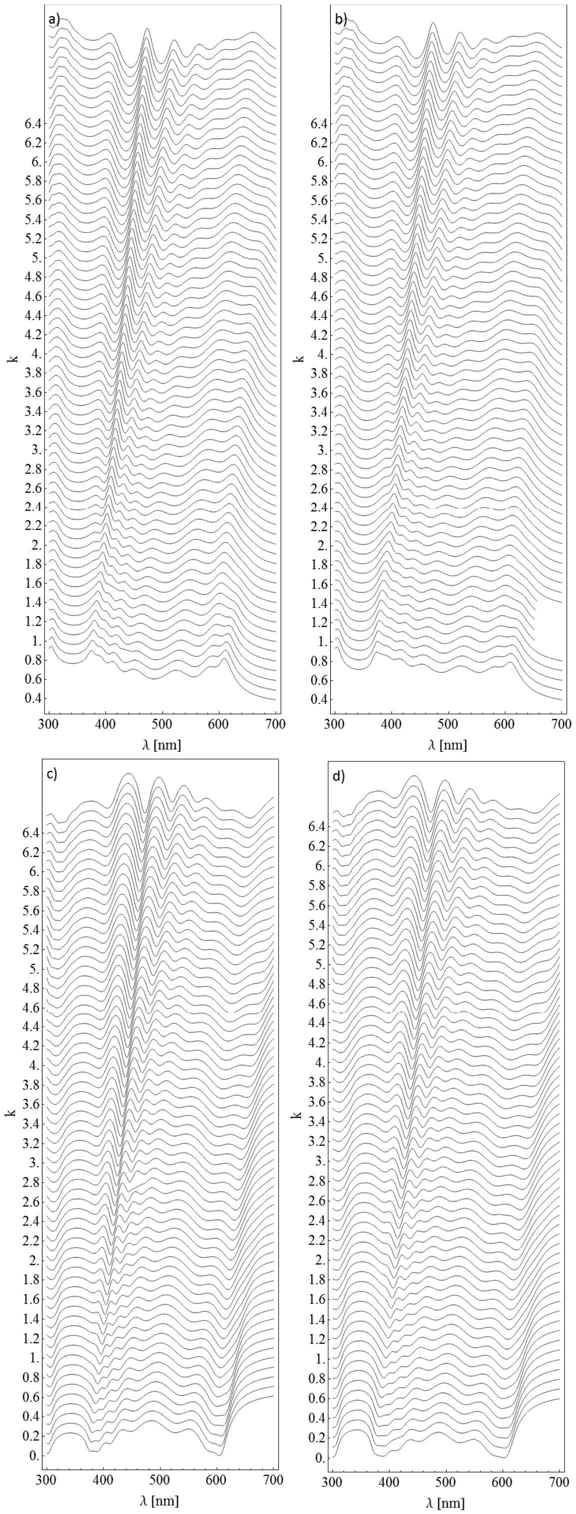

Fig. 5. Absorption (a, b) and reflectance (c, d) for polarization type S (a, c) and P (b, d) depending on the *k* coefficient for the angle of incidence *Θ = 60°*

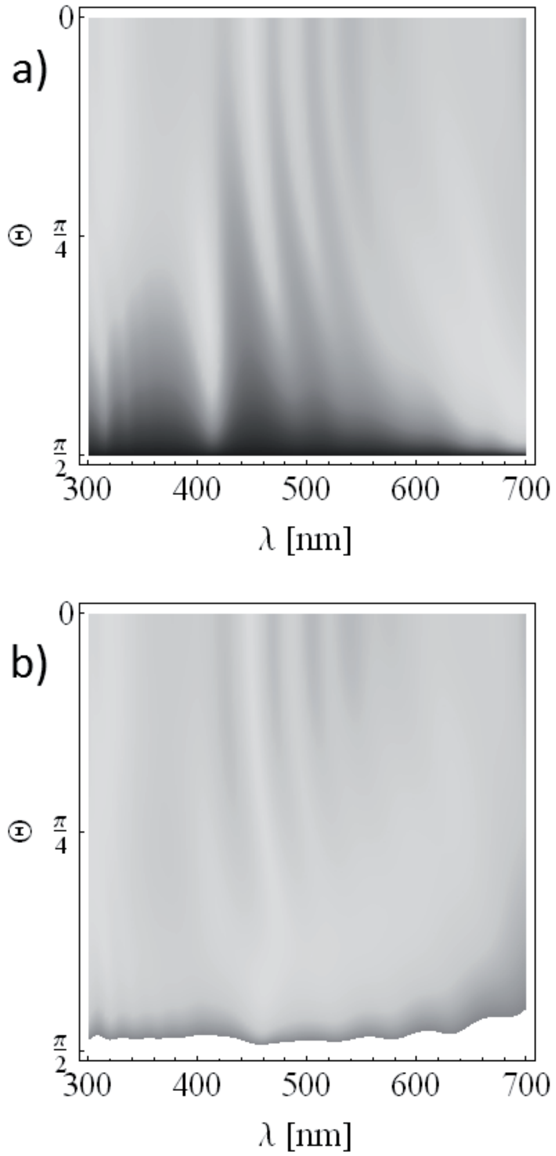

Fig. 6. Absorption maps for polarization type S (a) and P (b) for *k = 5 nm*

Figure 6 shows the absorption map for k = 5 and polarization type P and S, reflectance maps are shown in Figure 7.

3. Conclusions

In all the cases studied linear shift in the peaks with an increase in the *k* coefficient was observed. In all cases there was a shift to higher wavelengths.

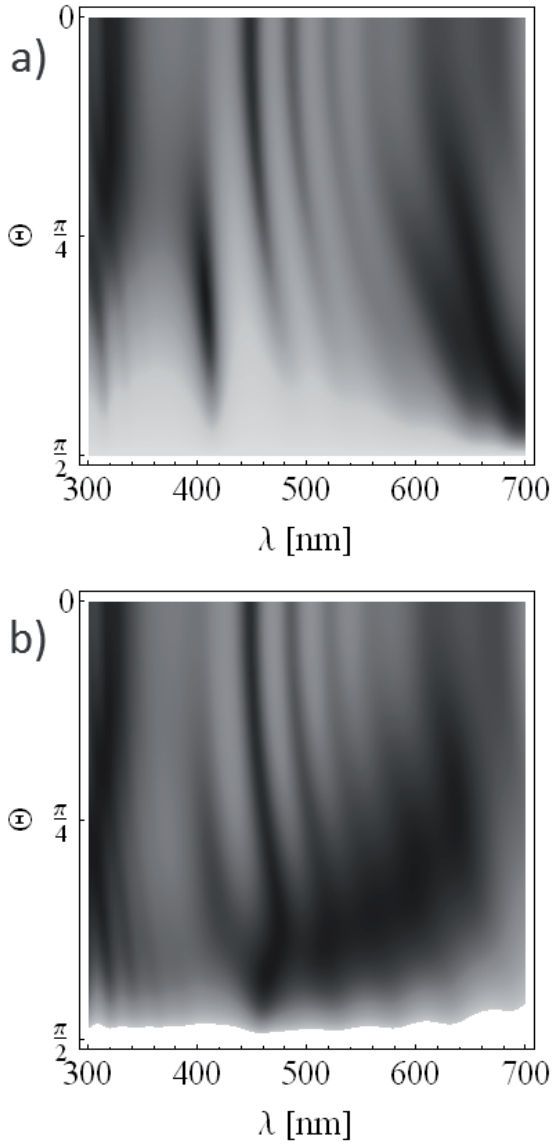

Fig. 7. Reflectance maps for polarization type S (c) and P (d) for *k = 5*

Noted an increase in the intensity and broadening half-width of the peaks.

Noted the presence of absorption and reflectance bands.

Polarization is changing the nature of absorption and reflectance bands.

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