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Transformation of a Gaussian pulse when interacting with a one-dimensional photonic crystal with an inversion defect

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Abstract

A computer analysis of transformation of Gaussian pulse profile after transmission and reflection at a photonic-crystal structure containing an inversion type defect has been performed. The deformation mode depends significantly on duration of the incident pulse and its carrier frequency values. Deformation for short pulses and pulses whose carrier frequency is close to one of the PBG boundaries or coincides with the defective miniband frequency are most significant.

Keywords: Photonic crystals; Photonic bandgap materials; Spectra; Inversion type defect

1. Introduction

Recently, photonic-crystal structures (PCSs) with layer thicknesses on the order of radiation wavelength have been of great interest for researchers [1]. The presence of photonic band gaps (PBGs), frequency bands with no radiation interacting linearly with the medium in the result of a specific dispersion law, is an important feature of PCSs [2–4]. In recent years, active researches of interaction processes of laser radiation with spatially periodic structures have allowed to discover a number of new optical effects (e.g., soliton pulse compression and slow light [5–7]).

Transformation of the envelope shape is a common property of pulses propagating in the medium or reflected ones [8–11]. It is the consequence of differences in the behavior of individual spectral components of the pulse. The pulse envelope transformation mainly includes asymmetric broadening or narrowing of the pulse front, splitting, and shift of the pulse 'centroid' along the time axis [12]. The pulse transformation is most pronounced in the area of strong dispersion of the medium material parameters [13]. If the pulse carrier frequency is close to the PBG border, a significant transformation of its envelope is also manifested [14–16].

Various disorders of PCSs periodicity structure (defects) cause defective minibands in the PBGs which are narrow passbands [17–20]. Classification of the main defects, one of which is the 'inversion', is provided in the paper [21]. Inversion type defects involve changing order of the layers in one or more parts of the structure. From a technological point of view, inversion defects are more preferable than interstitial and substitutional defects, as their creation does not require introduction of an additional material into the layers structure. Changing layers' material parameters in the structure period,

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and creation of an inversion defect within it allows to control its spectral characteristics, and thereby control the incident radiation on the structure and the reflected radiation from it [21,22].

The presence of dispersion in reflective medium or thin film structure greatly complicates the analysis of the reflection and transmission processes of pulsed radiation through the interface due to the difference in the behavior of the individual spectral components. In connection with the complexity of solution of such boundary value problems, the methods of computer simulation have become widely used to assess the nature and degree of deformation of the reflected pulse [23,24]. In this paper, we report the results of studying specific features of the interaction of a Gaussian pulse with a one-dimensional PCS of finite periods and one or two defects of inversion type. The profiles and time shifts of the pulses passed through the structure with their carrier frequency falling into different regions of the PCS spectrum containing defective minibands were numerically analyzed. The results of the analysis may have different applications in numerous problems associated with the interaction of pulsed radiation with the boundaries between media.

2. Transfer matrix

Let us assume the plane waves to be normally incident on a PCS, be reflected, and propagate in it. The structural period contains two layers of different dielectrics, which are assumed to be optically isotropic permittivities $\varepsilon_1 = 2.1025$ and $\varepsilon_2 = 6.1009$ (SiO_2, TiO_2 respectively). Permeabilities of each layer in the optical range are assumed to be scalar and equal to unity. The thicknesses of these layers are L_1 and L_2, structural period is $L = L_1 + L_2$. Refractive indices (RI) of optically transparent dielectric media adjacent to the PCS from the side of the radiation input and output are real values and equal to n_a and n_b. Below, we will consider normal incidence of the pulse on the PCS (along the OZ axis of structure periodicity). In this case, solutions of the Maxwell equations are two orthogonally polarized waves of TEM type with the same propagation constants [25]. Let the origin of coordinates be on the PCS input surface. The dependence of the monochromatic components of the wave field on time and coordinates has the form

$$\mathbf{F}(t, z) = \mathbf{F_0} \exp(i\omega t - ikz), \tag{1}$$

where $\mathbf{F}$ is a two-component vector whose components are the electric and magnetic field of the wave (E_x, H_y). The relationship between the field amplitudes at both boundaries of one structural period is determined by the transfer matrix $\hat{\mathbf{M}}$, that relates the field amplitudes at the beginning and the end of the period. The matrix elements of this matrix can be written as:

$$\begin{aligned}
M_{11} &= C_1C_2 - \frac{\varepsilon_1 k_2}{\varepsilon_2 k_1} S_1 S_2, \\
M_{12} &= -ik_0 \left(\frac{\varepsilon_2}{k_2} C_1 S_2 + \frac{\varepsilon_1}{k_1} S_1 C_2 \right), \\
M_{21} &= -\frac{i}{k_0} \left(\frac{k_1}{\varepsilon_1} S_1 C_2 + \frac{k_2}{\varepsilon_2} C_1 S_2 \right), \\
M_{22} &= C_1C_2 - \frac{\varepsilon_2 k_1}{\varepsilon_1 k_2} S_1 S_2.
\end{aligned} \tag{2}$$

Here, the wave-vector components in each medium are $k_j = k_0\sqrt{\varepsilon_j}$, $k_0 = \omega/c$, where c is the speed of light in vacuum and the following designations are introduced $C_j = \cos(k_jL_j)$, $S_j = \sin(k_jL_j)$. Note that two different sequence orders of layers in a period are possible: $\hat{\mathbf{M}} = \hat{\mathbf{m}}_1 \cdot \hat{\mathbf{m}}_2$, and the transfer matrix $\hat{\hat{\mathbf{M}}} = \hat{\mathbf{m}}_2 \cdot \hat{\mathbf{m}}_1$, which corresponds to the inverted period, where $\hat{\mathbf{m}}_j$ is the transfer matrix of the relevant layer. The matrix elements of the inverted matrix are associated with the matrix elements of the normal period by ratio $\hat{\hat{\mathbf{M}}}_{\alpha\beta} = \hat{\mathbf{M}}_{3-\beta,3-\alpha}$, $\alpha, \beta = 1, 2$. For a structure including N periods, according to the Abeles theorem [26,25], the transfer matrix has the form $\hat{\mathbf{Q}} = (\hat{\mathbf{M}})^N$, and its matrix elements are determined as follows:

$$\begin{aligned}
Q_{11} &= M_{11} \frac{\sin Nk_{ef}L}{\sin k_{ef}L} - \frac{\sin(N-1)k_{ef}L}{\sin k_{ef}L}, \\
Q_{12} &= M_{12} \frac{\sin Nk_{ef}L}{\sin k_{ef}L}, \\
Q_{21} &= M_{21} \frac{\sin Nk_{ef}L}{\sin k_{ef}L}, \\
Q_{22} &= M_{22} \frac{\sin Nk_{ef}L}{\sin k_{ef}L} - \frac{\sin(N-1)k_{ef}L}{\sin k_{ef}L}
\end{aligned} \tag{3}$$

Here, the Bloch wave number is determined by the expression

$$k_{ef}L = \arccos\left(\frac{M_{11} + M_{22}}{2} \right). \tag{4}$$

For the structure with N periods, the amplitude coefficients of reflection and transmission equal to the ratio of the amplitudes of transmitted and reflected waves to the amplitude of an incident wave can be expressed using matrix elements Q_{ij}:

$$\begin{aligned}
r_N &= \frac{n_bQ_{11} - n_aQ_{22} - Q_{12} + n_an_bQ_{21}}{n_bQ_{11} + n_aQ_{22} - Q_{12} - n_an_bQ_{21}}, \\
t_N &= \frac{2n_b \exp(ik_bNL)}{n_bQ_{11} + n_aQ_{22} - Q_{12} - n_an_bQ_{21}}.
\end{aligned} \tag{5}$$