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Reshaping of Gaussian light pulses transmitted through one-dimensional photonic crystals with two defect layers

Yu. S. Dadoenkova,[1,2,3,*] N. N. Dadoenkova,[1,3] I. L. Lyubchanskii,[3] and D. I. Sementsov[1]

[1]Ulyanovsk State University, Ulyanovsk 432017, Russian Federation
[2]Institute of Electronic and Information Systems, Novgorod State University, Veliky Novgorod 173003, Russian Federation
[3]Donetsk Physical and Technical Institute of the National Academy of Science of Ukraine, Donetsk 83114, Ukraine
*Corresponding author: yulidad@gmail.com

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We present a theoretical study of the reshaping of subpicosecond optical pulses in the vicinity of double-peaked defect-mode frequencies in the spectrum of a one-dimensional photonic crystal with two defect layers and calculate the time delay of the transmitted pulses. We used the transfer matrix method for the evaluation of the transmittivity spectra, and the Fourier transform technique for the calculation of the transmitted pulse envelopes. The most considerable reshaping of the pulses takes place for pulses with a carrier frequency in the defect-mode center and with a spectrum wider than the half-width of the defect mode. For pulses with the carrier frequency at the low- and high-frequency peaks of the defect mode, reshaping is strong for the twice as wide pulses. The maximal time delay of a spectrally narrow pulse is of the order of the pulse duration and demonstrates extrema at the frequencies of the defect-mode peaks. The time delay of a wide pulse does not depend on the carrier frequency, but is one order of magnitude larger than the pulse duration.

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1. INTRODUCTION

Photonic crystals (PCs), i.e., artificial periodic structures composed of materials with different refractive indices, are of great interest because of their utility for applications in modern photonics, e.g., where the laser radiation should be controlled. During the last decades such structures have been the focus of intense theoretical and experimental investigations. The periodic modulation of the refractive indices ensures the existence of the photonic band gaps (PBGs) in the spectra of the PCs, where the transmittivity is vanishingly small and the incident radiation almost totally reflects [1–5]. Introduction of extra elements into the PC destroys the periodicity and leads to the appearance of the narrow peaks with high transmittivity at a frequency inside the PBG, the so-called defect modes [1,6,7].

Analytical and numerical calculations of the wave packet tunneling through one-dimensional (1D) PCs and structured media, including the pulse reshaping and time delay of the output pulse, have been carried out by many authors [8–17]. Reshaping of the time envelopes (including the asymmetric increase or decay of the pulse front, bifurcation, and shift of the wave packet maximum along the time axis) is typical for transmitting wave packets as a result of differences in the behavior of different spectral components of the pulse [18–20]. The most considerable pulse conversion takes place in the region of high dispersion of the material parameters of the medium [19] as well as when the carrier frequency of the pulse is in the vicinity of the PBG edges [21] or at the incidence angles close to Brewster angles [22].

Investigations of the tunneling of wave packets involve different types of pulses, including linear and frequency-modulated pulses [21,23–31], solitons, and controllable rogue waves [32–34].

Reshaping of ultrashort pulses in the near-infrared regime by using an integrated tunable acousto-optic filter is reported in Ref. [29], where the shape of the optical pulse is controlled by adjusting the different radio-frequency electrical signals driving the acousto-optic filter. Tunneling of femtosecond optical pulses though a 1D PC is studied in Ref. [17]. The measured transit time is found to be independent of the barrier thickness for opaque PCs, and shortening of Fourier-limited wave packets was observed upon transmission. Similarly, ultrashort light pulses can be reshaped to a shorter duration output through self-induced transparency while propagating through a resonant PC [23]. Pulse reshaping in such PCs appeared to be much more powerful than in a bulk atomic medium, leading to both pulse compression and pulse merging when a multipeak input pulse transforms into a single-peak, high-quality transmitted output pulse [23]. Reshaping of the pulses at propagation through an inhomogeneously broadened atomic medium has also been investigated. It was shown that even though the main part of the pulse is unchanged for short propagation distances it is followed by a long weak tail formed by free induction decay from the excited atoms [24].

Both pulse broadening and compression have been demonstrated by the propagation of the frequency-modulated subpicosecond optical pulses through waveguides, based on planar PCs [25]. Reshaping of femtosecond pulses through the second-harmonic generation of Gaussian input pulses in nonlinear PCs is studied numerically in Ref. [28]. Shaping of ultrashort optical pulses transmitted through chiral sculptured thin films is calculated in Refs. [15,16] using a finite-difference time-domain algorithm. The circular Bragg phenomenon exhibited by such a chiral system tends to distort the shapes of transmitted pulses with respect to the incident pulses, and such shaping can cause sharp changes in some measures of the average speed with respect to the carrier wavelength.

It has been demonstrated that the PCs with embedded optical nonlinearity provide an opportunity to efficiently compress the laser pulses to a duration of several optical cycles on a submillimeter spatial scale due to the combination of self-phase modulation and controllable dispersion of the PBG, which provides new opportunities for the miniaturization of the femtosecond solid-state laser systems [26,27]. A general approach to the design of PC directional couplers operating with the dispersionless tunneling of slow light was theoretically proposed in Ref. [35] and experimentally confirmed in Ref. [36].

Thus, the optical pulse shaping can be used in the fabrication of integrated wavelength-division-multiplexed devices for the manipulation of coherent, ultrafast time-domain signals [29].

In this paper, we study the theoretical reshaping of subpicosecond optical pulses in the vicinity of the defect-mode frequencies inside a 1D PC, and calculate the time delay of the transmitted pulses. We use the transfer matrix method to calculate the transmittivity spectrum of the PC, and the spectra of the transmitted pulses are calculated with the Fourier transform technique. These methods allow us to solve the boundary conditions problem and Maxwell's differential equations in terms of linear algebra, in contrast to the direct time-domain approach described in [15,16,37]. Changing the parameters of the PC, namely, the thickness of the layers and the number of the periods between the defect layers, allows us to control spectral properties of the defect modes [6,7], thus to tune the characteristics of the transmitted wave packets. This paper is organized as follows. In Section 2, we describe the propagation of electromagnetic waves in a 1D PC with the inversion defects using the transfer matrix method and provide a general description of the wave packet tunneling in the PCs. In Section 3, we show the results of numerical calculations of the time envelopes and time delay of the pulses transmitted through the PC with two defect layers. In Section 4, the conclusions, we summarize the obtained results.

2. GENERAL ANALYSIS

We consider three finite-size two-component dielectric PCs of the structure $(AB)^N$ placed together to form the structure $(AB)^N(BA)^M(AB)^N$ with two defect layers of the inversion type [38], as illustrated in Fig. 1. The period of the structure is $D = d_A + d_B$, where d_A and d_B are the thicknesses of layers A and B, respectively. The layers of the PC are located parallel to the (xy) plane and supposed to be infinite in the x and y directions, and the z axis is normal to the interfaces. We consider the normal incidence of the electromagnetic waves on the left-hand surface of the PC. In general, the PC with two defects would have two defect modes inside the PBGs in the transmittivity spectra of the electromagnetic waves, which could open up possibilities for more pronounced reshaping of the transmitted pulses, on the contrary to the PC with a single defect layer, where interaction of a narrow (in the frequency domain) optical pulse is similar to its interaction with the PBG edge [21]. The further increase of the defect layers number will lead to a set of defect modes, and the analysis of the pulse reshaping in such a multidefect structure will be similar to that of the double-defect PC.

The transmittivity spectrum $T(\omega)$ of the PC under consideration can be calculated by means of the (4×4) transfer matrix method [39]. The transfer matrix $\hat{T}$ for the PC can be presented as follows:

$$\hat{T} = \hat{S}_{0A}\hat{E}_A(\hat{T}_0)^{N-1}\hat{S}_{AB}\hat{E}_B^2\hat{S}_{BA}\hat{E}_A(\hat{T}_0)^{M-2} \times \hat{S}_{AB}\hat{E}_B\hat{S}_{BA}\hat{E}_A^2(\hat{T}_0)^{N-1}\hat{S}_{AB}\hat{E}_B\hat{S}_{B0}, \tag{1}$$

where the matrix $\hat{S}_{A0}$ describes the electromagnetic wave transition through the boundary "vacuum–medium A" and $\hat{T}_0$ is the transfer matrix for the unit cell of the PC,

$$\hat{T}_0 = \hat{S}_{AB}\hat{E}_B\hat{S}_{BA}\hat{E}_A, \tag{2}$$

defined as a product of the matrices $\hat{S}_{AB}$ and $\hat{S}_{BA}$ [$\hat{S}_{AB} = (\hat{S}_{BA})^{-1}$], connecting the field magnitudes of the electromagnetic wave at the opposite sides of the boundaries "medium A–medium B" and $\hat{S}_{A0} = (\hat{A}_1)^{-1}\hat{A}_0$, with (4×4) matrices $\hat{A}_j (j = 0, A, B)$ written in the quasi-diagonal form

$$\hat{A}_j = \begin{pmatrix} \hat{A}_j^{\mathrm{TE}} & \hat{O} \\ \hat{O} & \hat{A}_j^{\mathrm{TM}} \end{pmatrix}, \tag{3}$$

where $\hat{O}$ denotes the (2×2) zero matrix and $\hat{A}_j^{\mathrm{TE}}$ and $\hat{A}_j^{\mathrm{TM}}$ describe the magnitude coefficients for the TE and TM electromagnetic waves

$$\hat{A}_j^{\mathrm{TE}} = \begin{pmatrix} 1 & 1 \\ -k_j & k_j \end{pmatrix}, \qquad \hat{A}_j^{\mathrm{TM}} = \begin{pmatrix} 1 & 1 \\ -k_j/\varepsilon_j & k_j/\varepsilon_j \end{pmatrix}, \tag{4}$$

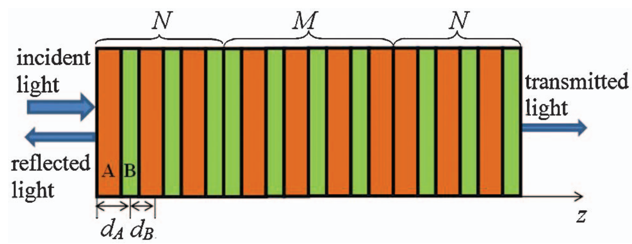

Fig. 1. Schematic of the PC of the structure $(AB)^N(BA)^M(AB)^N$.

with the wave vector's z components as $k_j = n_j\omega/c$ for medium $j(j = A, B)$, where n_j is the refractive index of the corresponding medium. The diagonal matrices $\hat{E}_j$ present the phase incursions as follows:

$$\hat{E}_j = \mathrm{diag}\{e^{ik_jd_j}, \quad e^{-ik_jd_j}, \quad e^{ik_jd_j}, \quad e^{-ik_jd_j}\}. \quad (5)$$

Let us consider the Gaussian pulse of duration τ_0 with the time envelope $E(t)$ propagating with the carrier frequency ω_0 as follows:

$$E(t) = E_0 \exp(-t^2/2\tau_0^2). \quad (6)$$

The time envelope of the transmitted pulse $E_T(t)$ can be expressed using the inverse Fourier transform of the convolution of the Fourier transform of the initial pulse with the complex transmission coefficient $T(\omega)$ as follows:

$$E_T(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \hat{E}_{\mathrm{in}}(\Omega)T(\omega_0+\Omega)\exp(i\Omega t)\mathrm{d}\Omega,$$
$$\hat{E}_{\mathrm{in}}(\Omega) = \int_{-\infty}^{\infty} E(t)\exp(-i\Omega t)\mathrm{d}t, \qquad \Omega = \omega - \omega_0. \quad (7)$$

The tunneling pulse demonstrates a reshaping of its time envelope; thus, the output wave packet, in general, is not a Gaussian one. Further, we investigate the deformation of the transmitted pulse envelope at defect modes of the PC.

3. NUMERICAL RESULTS AND DISCUSSION

For the numerical calculations, we consider the PC composed of alternating layers of silicon oxide SiO_2 (layer A) and titanium oxide TiO_2 (layer B), with the refractive indices $n_A = 1.45$ and $n_B = 2.47$ [40]. These dielectric materials are transparent in the optical and near-infrared regimes and, in the first approximation, the damping of the electromagnetic waves can be neglected. The optical thicknesses of the layers are chosen to be equal: $d_A \cdot n_A = d_B \cdot n_B = 2.5$ μm. Varying the number of periods between the defect layers, we fix the total number of the PC's periods $N + M = 16$.

The first PBGs in the transmission spectra of the PC under consideration are shown in Fig. 2(a) for different numbers of PC periods between the defect layers. As one can see, the presence of two defect layers destroying the periodicity of the PC results in the appearance of two defect modes of high transmittivity, which almost merge in the middle of the PBG to form one symmetric double-peak defect mode [5,6]. The more periods M that are placed between the defect layers, the closer to each other the peaks of the defect mode are [compare the transmission spectra of the structures $(AB)^5(BA)^6(AB)^5$ and $(AB)^6(BA)^4(AB)^6$, which are illustrated with green and blue profiles in Fig. 2(a)]. For the PC with $N = 4$, $M = 8$ (red profile) these peaks merge completely into a single-peak defect mode. It should be noted that both silicon and titanium oxides demonstrate low dispersion of their refractive indices in the considered frequency range. Taking the dispersion into account would only result in a slight shift of the PBG spectrum without any significant change in the defect mode intensities and widths [41].

Let us consider tunneling of the Gaussian pulse with the carrier frequency in the frequency range around the defect mode frequencies. We expect that reshaping of such a pulse

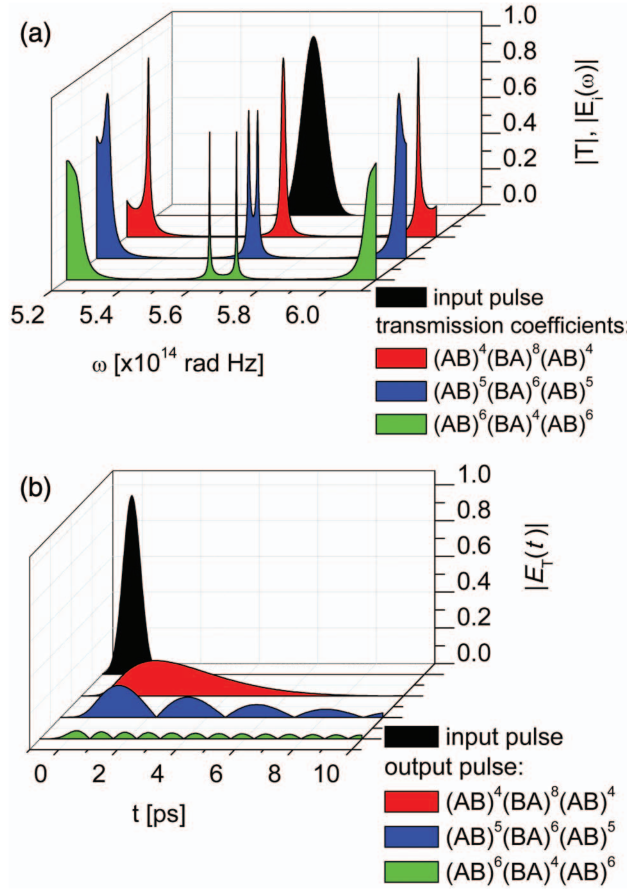

Fig. 2. (a) Photonic bandgaps and defect modes and (b) time envelopes of the transmitted pulse for different numbers of periods between the defect layers: $(AB)^4(BA)^8(AB)^4$, $(AB)^5(BA)^6(AB)^5$, and $(AB)^6(BA)^4(AB)^6$ (red, blue, and green profiles, respectively). The black profiles correspond to the normalized spectrum $|E_{\mathrm{in}}(\omega)|/E_0$ (a) and the time envelope $|E(t)|/E_0$ (b) of the input pulse of duration $\tau_0 = 0.3$ ps and the carrier frequency at the center of the defect mode.

would be as strong as in the case of the pulse with the carrier frequency near the PBG edge, but more efficiently controlled by the defect-mode tuning. The spectrum of such a pulse of duration $\tau_0 = 0.3$ ps and carrier frequency at the center of the defect mode is shown with the black profile in Fig. 2(a). The time envelopes of this pulse that is transmitted though the corresponding PCs are illustrated in Fig. 2(b). One can see that the time envelopes $|E_T(t)|/E_0$ have a multipeak form when facing the double-peak defect modes, and the less that the periods are placed between the defect layers the less the intensity of the transmitted pulse. For a single-peak defect mode the transmitted pulse does not split but still has a long tail [see the red profiles in Fig. 2]. It should be noted that the overall shape of a Gaussian-like signal seems to be relatively robust even in the presence of dispersion [42]. If such a pulse is tunneling through a dispersive medium, the transmitted signal might be attenuated but still resembles a Gaussian function. This was predicted theoretically [43,44] and verified in many different experiments using media with strong absorption [45] and gain-assisted anomalous dispersion [46].

Further, we investigate pulse reshaping on a double-peak defect mode, focusing on the PC with $N = 5$, $M = 6$. As discussed above, the defect-mode peaks in the PBG of this structure are located close to each other, providing an interaction of both leading and trailing edges of the tunneling pulse with a relatively high output intensity (see the blue profiles in Fig. 2). In this case, the low- and high-frequency maxima of the defect mode correspond to the angular frequencies $\omega_l = 5.642 \times 10^{14}$ rad Hz and $\omega_h = 5.668 \times 10^{14}$ rad Hz, respectively, and the minimum of the defect mode takes place at its center at the angular frequency $\omega_c = 5.655 \times 10^{14}$ rad Hz. The half-width of the defect mode is $\Delta\omega \approx 0.033 \times 10^{14}$ rad Hz. We consider the reshaping of the following two types of pulses tunneling inside the PC: a pulse of spectral width comparable to the defect-mode width (spectrally "narrow" wave packet), and a pulse of width much larger than the width of the defect mode (spectrally "wide" wave packet).

Tunneling of the pulse of duration $\tau_0 = 0.1$ ps (with a spectral width larger than the defect-mode width) is illustrated in Fig. 3. The reduced time envelope $|E_T(t)|/E_0$ of the transmitted pulse as a function of the carrier frequency ω_0 and time t is presented in Fig. 3(a), while Fig. 3(b) shows the time envelopes of the initial pulse (black dotted line) and transmitted pulse (green solid line) for the carrier frequency $\omega_0 = \omega_c$ at the center of the defect-mode position. The transmitted pulse splits into a multipeak pulse while being transmitted though the PC [see Fig. 3(a)]. The spectrum of the transmitted pulse is of the same form as the defect-mode peaks, as one can see from the inset in Fig. 3(b). Note that here the spectrum of the output pulse is normalized to the maximal value of $E_{\text{in}}(\omega)$. It should be noted that the form of the output pulse does not depend on the position of the carrier frequency in the vicinity of the low- and high-frequency peaks of the defect mode because at this frequency range the intensity of the central components of the pulse is high.

The similar case for the "narrow" initial pulse with duration $\tau_0 = 1.0$ ps is presented in Fig. 4. From Fig. 4(a) one can see that, in contrast to the previous case presented in Fig. 3(a), the position of the carrier frequency defines different reshaping types of the transmitted pulse. For the carrier frequency in the center of the defect mode the behavior of the output pulse looks similar to one for the "wide" pulse, but with a more pronounced first maximum of $|E_T(t)|/E_0$ [green solid line in Fig. 4(b)]. The spectrum of the transmitted pulse of $\omega_0 = \omega_c$ is also of the shape of the defect mode, as follows from comparison of the green solid lines on the insets in Figs. 3(b) and 4(b), where the transmitted pulse spectra are normalized to the maximal value of $E_{\text{in}}(\omega)$. For the carrier frequency $\omega_0 = \omega_l$,

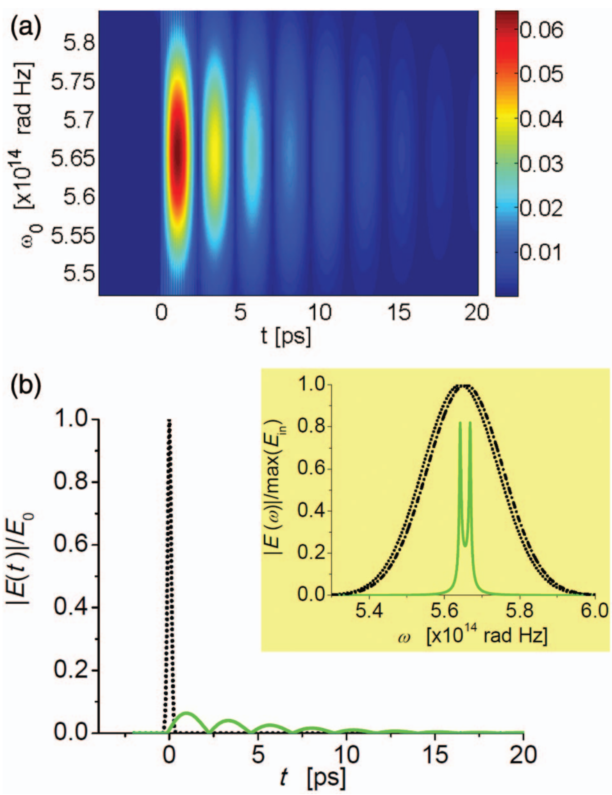

Fig. 3. (a) Reduced time envelope $|E_T(t)|/E_0$ of the transmitted pulse as a function of the carrier frequency ω_0 and time t for the duration of the input pulse $\tau_0 = 0.1$ ps. The color depicts the value of $|E_T(t)|/E_0$. (b) Cross sections of (a) at $\omega_0 = \omega_c$ (green solid line) and the time envelope of the input pulse (black dotted line). The inset shows the spectra of the input (black dotted line for $\omega_0 = \omega_l$ and black dash-dotted line for $\omega_0 = \omega_c$) and transmitted pulses (green solid line for both carrier frequencies).

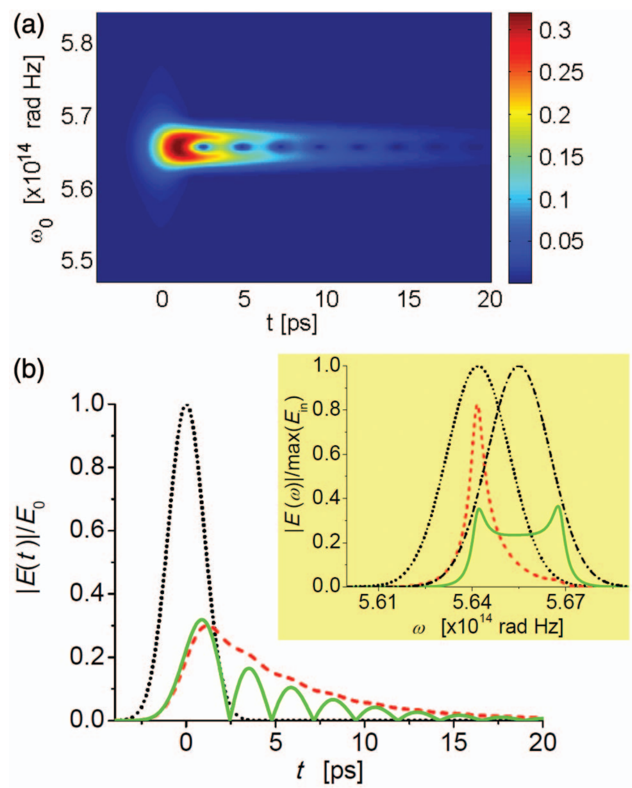

Fig. 4. (a) Reduced time envelope $|E_T(t)|/E_0$ of the transmitted pulse as a function of the carrier frequency ω_0 and time t for the duration of the input pulse $\tau_0 = 1.0$ ps. The color depicts the value of $|E_T(t)|/E_0$. (b) Cross sections of (a) at $\omega_0 = \omega_c$ (solid line), $\omega_0 = \omega_l$ (dashed line), and the time envelope of the input pulse (dotted line). The inset shows the spectra of the corresponding input (dotted line for $\omega_0 = \omega_l$, and dash-dotted line for $\omega_0 = \omega_c$) and transmitted pulses.

the time envelope of the transmitted pulse demonstrates no splitting, as illustrated with the red dashed line in Fig. 4(b), and the intensity of the output pulse decays slowly with time. In contrast to the previous case of a spectrally "wide" pulse, the spectrum of the transmitted "narrow" pulse demonstrates a high-intensity peak at the carrier frequency ω_l and a low-intensity peak at the high-frequency maximum of the defect mode ω_h, as shown with the red dashed line on the inset in Fig. 4(b).

Thus, the most pronounced reshaping of the transmitted wave packet takes place for both the "narrow" and "wide" input pulses as follows: for the former pulse, for the carrier frequency in the center of the defect mode; for the latter one, for all carrier frequencies in the vicinity of the defect-mode frequency, because in these cases the spectra of such pulses contain quite a lot of high-magnitude components at frequencies where the defect-mode intensity is low.

Nevertheless, for both "wide" and "narrow" pulses and any position of their carrier frequency, the maxima of the transmitted pulses are shifted in time in comparison to the position of the initial pulse maximum [compare, for example, the black dotted and green solid lines in Figs. 3(b) and 4(b)], i.e., a time delay of the transmitted pulse takes place, which is illustrated in Fig. 5. The time delay of the first peak of the transmitted "narrow" pulse demonstrates two maxima corresponding to the carrier frequencies at low- and high-frequency peaks of the defect mode, and a minimum at $\omega_0 = \omega_c$, as shown with the blue solid line in Fig. 5. One can see that, for the carrier frequencies far from the defect-mode positions, the time delay of the transmitted pulse is negative. This means that the maximum of the tunneling pulse starts forming before the maximum of the input pulse is reached. In the vicinity of the defect mode, the time delay is comparable to the input pulse duration. The time delay of the "wide" pulse is always positive and almost does not change, with ω_0 being about 0.9 ps, which is almost one order of magnitude larger than the duration of the input pulse, as shown with the red dashed line in Fig. 5.

As follows from the aforementioned discussion, the reshaping of the transmitted pulse on the defect mode of the PC depends on the spectral width of the input pulse, and thus on its duration. In Figs. 6(a) and 6(b) we present the time envelope evolution with the input pulse duration τ_0 and time t for $\omega_0 = \omega_c$ and $\omega_0 = \omega_l$, respectively. Reshaping of the input pulses

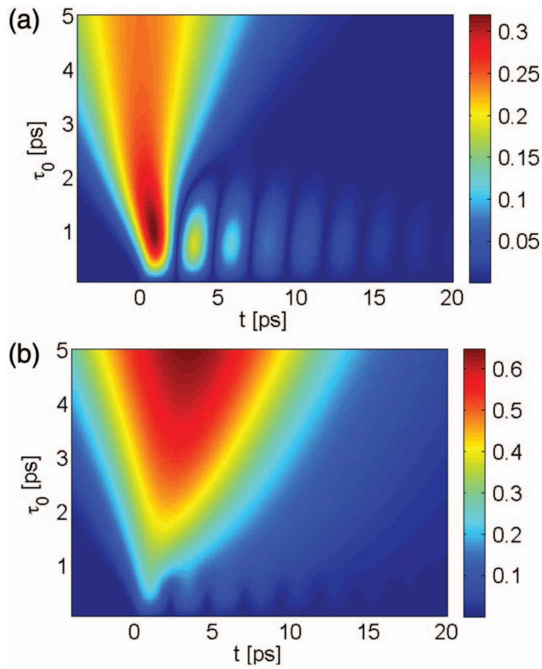

Fig. 6. Time envelope $|E_T(t)|/E_0$ of the transmitted pulse as a function of the input pulse duration τ_0 for carrier frequencies (a) $\omega_0 = \omega_c$, and (b) $\omega_0 = \omega_l$. The color depicts the value of $|E_T(t)|/E_0$.

with the carrier frequency at the center of the defect mode into a multipeak transmitted pulse takes place for the short pulses with $\tau_0 < 2$ ps, as shown in Fig. 6(a). This pulse duration interval corresponds to the pulses with a spectrum wider than the defect mode half-width. For the pulses with $\omega_0 = \omega_l$, the corresponding duration is more than twice shorter [see Fig. 6(b)]. The longer pulses (i.e., the spectrally "narrower" ones) are tunneling without any strong reshaping, meaning that the leading and trailing edges of the pulse do not interact with every peak of the defect mode.

However, the time delays of the pulses with carrier frequencies at the low-frequency peak and at the center of the defect mode are characterized by different behaviors, as illustrated in Fig. 7 with the blue and red lines, respectively. The time delay

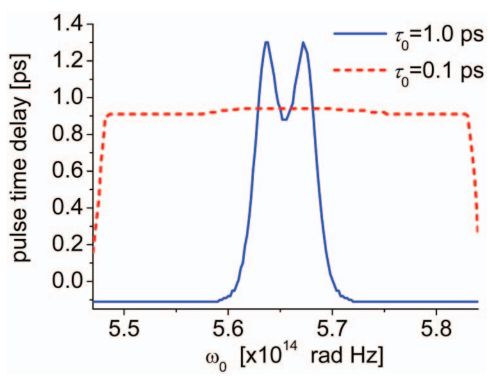

Fig. 5. Time delay of the first maximum of the transmitted pulse as a function of the carrier frequency ω_0 for the duration of the input pulse $\tau_0 = 1.0$ ps (blue solid line) and $\tau_0 = 0.1$ ps (red dashed line).

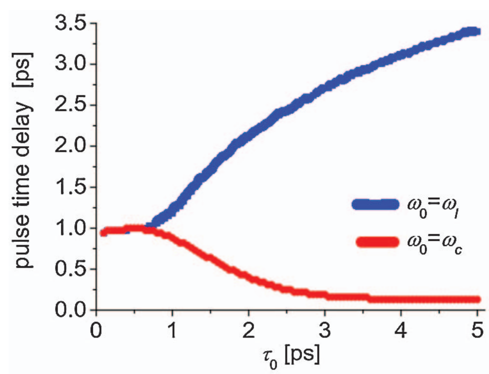

Fig. 7. Time delay of the first maximum of the transmitted pulse as a function of the incident pulse duration $\tau0$ for the carrier frequency at the low-frequency peak of the defect mode $\omega_0 = \omega_l$ (blue line) and at the center of the defect mode $\omega_0 = \omega_c$ (red line).

of the pulse with $\omega_0 = \omega_c$ decays with the growing duration of the input pulse, whereas it increases with τ_0 for the pulse with $\omega_0 = \omega_l$.

4. CONCLUSIONS

We have investigated the reshaping and the time delay of picosecond optical pulses with carrier frequencies in the vicinity of a double-peak defect mode formed by two defect layers of the PC. The parameters of the defect mode inside the photonic bandgap can be varied by changingthe geometric parameters of the PC, which makes it possibile to change the spectral properties of the optical pulses transmitted through the structure. It has been shown that the transmitted pulses demonstrate a strong reshaping of the time envelopes, depending on their duration and carrier frequency. The most considerable pulse reshaping takes place for input wave packets of the carrier frequency in the center of the defect mode and with the spectrum being wider than the half-width of the defect mode. For the wave packets with a carrier frequency at the low- and high-frequency peaks of the defect mode, reshaping is strong for pulses with twice the width, which provides an interaction of the high-intensity spectral components with the defect mode. The maximal time delay of a spectrally narrow pulse is of the order of the pulse duration and demonstrates extrema at the frequencies of the defect-mode extrema, while the time delay of a wide pulse almost does not depend on the carrier frequency, but is one order of magnitude larger than the pulse duration.

Thus, the predicted evolution of wave packets being transmitted through 1D PCs with defects should be taken into account in the design of photonic devices.

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