Pulse trapping inside a one-dimensional photonic crystal with relaxing cubic nonlinearity

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We theoretically study the effect of pulse trapping inside one-dimensional photonic crystal with relaxing cubic nonlinearity. We analyze dependence of light localization on pulse intensity and explain its physical mechanism as connected with the formation of a dynamical nonlinear cavity inside the structure. We search for the range of optimal values of parameters (relaxation time and pulse duration) and show that pulse trapping can be observed only for positive nonlinearity coefficients. We suppose that this effect can be useful for realization of optical memory and limiting.

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I. INTRODUCTION

Photonic-band-gap structures are actively studied as promising elements for different devices of nonlinear and quantum optics [1–3]. Study of nonlinear photonic crystals is connected with the possibility of dynamical adjustment of the parameters of the system. Photonic crystals (including two- and three-dimensional) allow one to control dispersion and diffraction properties of light [4,5], obtain pulse reshaping [6], obtain pulsed high-harmonic generation [7], etc. The processes of light self-action in such systems result in localization effects such as gap solitons formation, discrete mode existence, or light energy localization (see, e.g., [8–11]).

The simplest example of a one-dimensional photonic crystal can be represented as a periodic set of alternating dielectric layers with large depth of refractive index modulation. One of the most prominent effects of nonlinear optics of such structures is strong pulse compression in photonic crystals with nonresonant cubic nonlinearity [12,13]. The effect of light pulse localization, or trapping, in one-dimensional photonic crystal with a defect was studied in Ref. [14] and, in more general form, in Refs. [15,16].

In this paper we study pulse propagation in photonic crystal with relaxing cubic nonlinearity. It is obvious that if we reduce incident pulse duration, the inertial properties of medium nonlinearity should be taken into account. Indeed, the lowest values of relaxation time connected with the electronic Kerr mechanism (a few femtoseconds [17]) appear to be comparable with pulse durations obtained at the modern setups. As it was shown in Ref. [18], relaxation of nonlinearity results in vanishing of the effect of femtosecond pulse compression which can be obtained in the relaxation-free case.

In our research we use numerical simulations of the Maxwell wave equation taking into account the process of nonlinearity relaxation. The method used allows one to obtain numerical solutions of the problem without any assumptions about medium parameters modulation or rate of variation of field envelope. We show that, in a certain region of pulse amplitudes, relaxation times and pulse durations, the pulse can be trapped inside a nonlinear cavity dynamically formed by the light. Appearance of the cavity is connected with local change of reflective properties of the photonic structure. In other words, dynamical shift of band spectrum occurs. Trapping pulse inside the photonic crystal is a prospective effect for such possible applications as optical limiters (which transmit light only with proper intensity), optical buffers or memory (which allows one to store light for time, large in comparison with characteristic transmission time). Large advantage of the scheme considered is the absence of necessity to introduce nonuniformity or any imperfections in the structure of nonlinear photonic crystal.

The article is divided into several sections. In Sec. II the main equations are given and the approach for numerical solving of the wave equation is considered. Sec. III is devoted to some phenomenological aspects of the pulse-trapping effect. In Sec. IV the physical mechanism of pulse trapping in photonic crystal with relaxing cubic nonlinearity is discussed. Finally, in Sec. V we consider some conditions for pulse-trapping observation connected with the proper choice of pulse duration and relaxation time.

II. MAIN EQUATIONS AND NUMERICAL METHOD

In this paper we consider ultrashort pulse interaction with one-dimensional photonic crystal made of substance with relaxing cubic (Kerr) nonlinearity. Light propagation along the z axis is governed by the Maxwell wave equation,

$$\frac{\partial^2 E}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 (n^2 E)}{\partial t^2} = 0, \tag{1}$$

where E is electric field strength and n is medium refractive index that depends on light intensity $I = |E|^2$ as

$$n = n_0(z) + \delta n(I,t). \tag{2}$$

Here, $n_0(z)$ is a linear part of refractive index. Time dependence of nonlinear term δn is responsible for the relaxation process and is described by the first-order differential equation due to the Debye model of nonlinearity [17],

$$t_{\rm nl}\frac{d\delta n}{dt} + \delta n = n_2 I, \tag{3}$$

where n_2 is the Kerr nonlinear coefficient and $t_{\rm nl}$ is the characteristic relaxation time. We consider fast relaxing media (electronic Kerr mechanism) with relaxation times as small as a few femtoseconds. Representing field strength as $E = A(t,z)\exp[i(\omega t - kz)]$, where ω is a carrier frequency, $k = \omega/c$ is the wave number, and introducing new, dimensionless

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arguments $\tau = \omega t$ and $\xi = kz$, we come to the wave equation for the pulse amplitude $A(t,z)$,

$$\frac{\partial^2 A}{\partial \xi^2} - \frac{\partial^2 n^2 A}{\partial \tau^2} - 2i\frac{\partial A}{\partial \xi} - 2i\frac{\partial n^2 A}{\partial \tau} + (n^2-1)A = 0. \quad (4)$$

Usually, second-order derivatives are neglected at this point resulting in slowly varying envelope approximation. However, in the case of abrupt changes of refractive index (photonic crystal) it may fail, so that we should solve the full Eq. (4). In addition, this equation allows one to describe the behavior of electric field in the structure without division into forward and backward waves. Equation (4) and the computational scheme considered below are similar to those of Refs. [19,20] where they were implemented to consider light propagation in a dense resonant medium and a photonic crystal containing it.

Equation (4) can be solved numerically by using the finite-difference time-domain (FDTD) approach. The computational scheme is based on calculation of amplitude value at every mesh point $(l\Delta\tau, j\Delta\xi)$ as

$$A_j^{l+1} = \left[-a_1 A_j^{l-1} + b_1 A_{j+1}^l + b_2 A_{j-1}^l + f A_j^l\right]/a_2. \quad (5)$$

Here, the auxiliary values are

$$a_1 = \left(n_j^{l-1}\right)^2(1 - i\Delta\tau), \quad a_2 = \left(n_j^{l+1}\right)^2(1 + i\Delta\tau),$$
$$b_1 = \left(\frac{\Delta\tau}{\Delta\xi}\right)^2(1 - i\Delta\xi), \quad b_2 = \left(\frac{\Delta\tau}{\Delta\xi}\right)^2(1 + i\Delta\xi),$$
$$f = 2\left(n_j^l\right)^2 - 2\left(\frac{\Delta\tau}{\Delta\xi}\right)^2 + \Delta\tau^2\left[\left(n_j^l\right)^2 - 1\right].$$

The values of the refraction index at the mesh points can be obtained in terms of finite-difference representation of Eqs. (2) and (3),

$$n_j^{l+1} = n_{0j} + \delta n_j^{l+1},$$
$$\delta n_j^{l+1} = \frac{\tau_{\rm nl}}{\tau_{\rm nl} + \Delta\tau}\left[\delta n_j^l + \frac{\Delta\tau}{\tau_{\rm nl}} n_{2j}\left|A_j^l\right|^2\right], \quad (6)$$

where $\tau_{\rm nl} = \omega t_{\rm nl}$, and n_{0j} and n_{2j} are the values of the background refraction index and nonlinearity coefficient at $\xi_j = j\Delta\xi$.

To correctly set the boundary conditions we use the total-field–scattered-field (TF-SF) method and the perfectly matched layer (PML) method which allows one to apply the so-called absorbing boundary conditions at the edges of the calculation region [21].

III. PULSE-TRAPPING EFFECT

Let us consider propagation of ultrashort (femtosecond) light pulse in one-dimensional photonic crystal shown in Fig. 1. Spatial periodic modulation of the background refractive index $n_0(z)$ defines the structure of it, so that it can be treated as a set of alternate layers. The parameters used in calculations are as follows: refractive indices of the layers $n_a = 2$, $n_b = 1.5$; their thicknesses $a = 0.4$, $b = 0.24$; number of layers $N = 200$. Nonlinear coefficient of the material is defined as $n_2 I_0 = 0.005$ (i.e., the pulse amplitude is normalized by the value $A_0 = \sqrt{I_0}$). This value of cubic coefficient provides a refraction index change of one-thousandth and one-hundredth of unity and was used in calculations of Ref. [18]. Note that the nonlinear coefficient is positive (focusing nonlinearity), so that the refractive index increases with the intensity. The incident pulse is assumed to have Gauss envelope $A = A_m \exp(-t^2/2t_p^2)$. Here, t_p is a pulse duration which further takes on the value of 30 fs, while the carrier frequency lies on the wavelength $\lambda = 1.064$ μm.

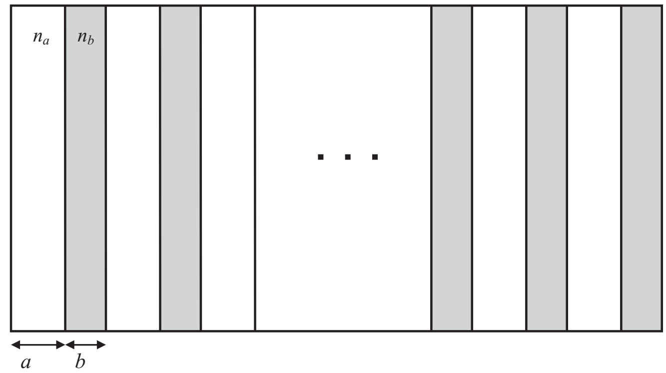

FIG. 1. Scheme of a photonic crystal considered. Parameters: refractive indices $n_a = 2$, $n_b = 1.5$; thicknesses $a = 0.4$, $b = 0.24$; number of layers $N = 200$.

Figure 2 shows the results of calculations of pulse interaction with nonlinear photonic structure with and without relaxation. One can easily see that the effect of pulse compression (obtained at $t_{\rm nl} = 0$) is completely absent when $t_{\rm nl} = 6$ fs. This result is in strict accordance with the conclusions of Ref. [18].

Vanishing of compression effect in Fig. 2 was obtained for pulse peak intensity $I_m = |A_m|^2 = I_0$, where $I_0 = |A_0|^2$ is the value of intensity corresponding to $n_2 I_0 = 0.005$. If we

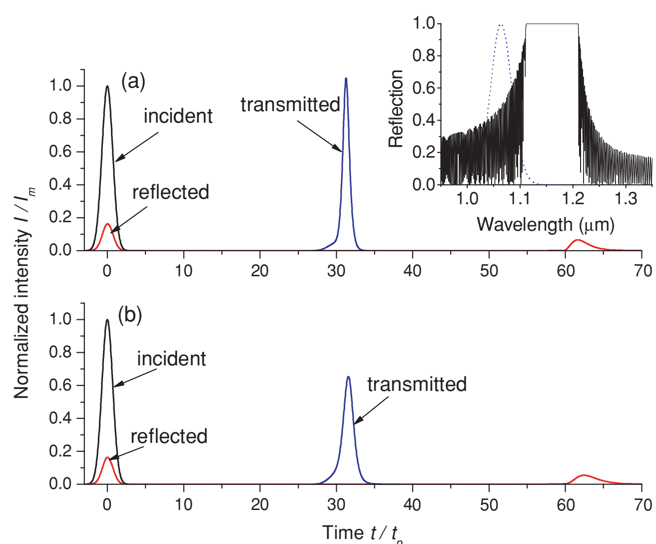

FIG. 2. (Color online) Interaction of ultrashort pulse with the photonic crystal with (a) relaxation-free ($t_{\rm nl} = 0$) and (b) relaxing ($t_{\rm nl} = 6$ fs) cubic nonlinearity. Pulse peak intensity $I_m = I_0$, where I_0 is such that $n_2 I_0 = 0.005$. Other parameters are the same as in the caption of Fig. 1 and in the text of the paper. The inset demonstrates the spectra of the photonic crystal (solid line) and of the pulse (dotted line).

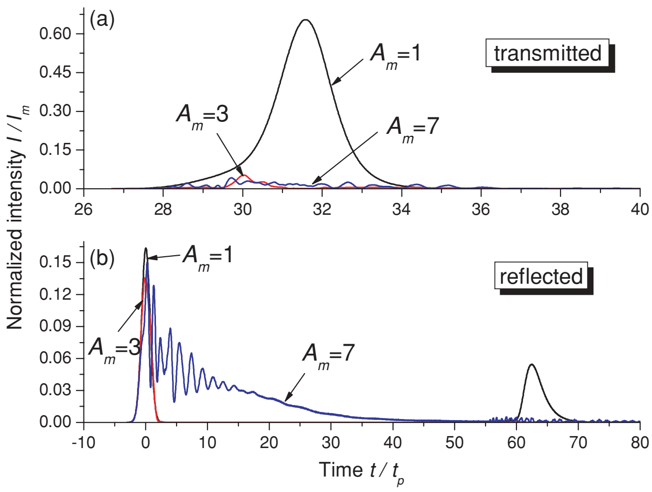

FIG. 3. (Color online) (a) Transmitted and (b) reflected intensity after interaction with nonlinear photonic crystal at different incident pulse peak intensities ($A_m = 1,3,7$ in units of A_0). Relaxation time of nonlinearity $t_{\mathrm{nl}} = 6$ fs. Other parameters are the same as in the caption of Fig. 2.

take greater A_m, the transmitted pulse continues to decrease. As seen in Fig. 3(a), only a small part of incident light can pass through the nonlinear photonic crystal at $A_m = 3A_0$. This situation is observed at $A_m = 7A_0$ as well, though the reflected pulse gets larger in this last case [Fig. 3(b)]. When we integrate intensity of reflected and transmitted light over a certain time interval ($200t_p$ in our calculations, i.e., large enough in comparison with time required for pulse to pass through the photonic crystal which is about $30t_p$; see Fig. 2), we obtain the characteristic energy curves (Fig. 4) that describe the change in behavior of pulses as their peak intensity is increasing. It is seen that, when A_m gets larger than $2A_0$, reflected, transmitted and overall (summarized) energies demonstrate a dramatic decrease. After reaching the minimum (output energy is about 20% of the input one), the curves begin to rise slowly. This slow

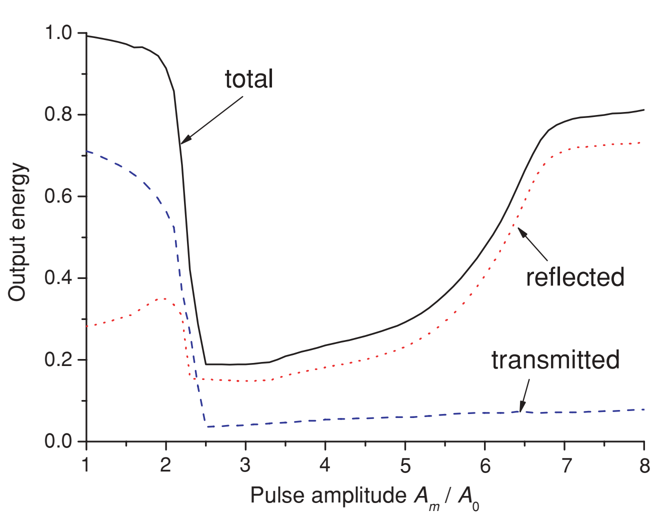

FIG. 4. (Color online) Dependence of transmitted, reflected, and overall output energy (as fraction of input energy) on incident pulse peak amplitude A_m. Relaxation time of nonlinearity $t_{\mathrm{nl}} = 6$ fs. Energy was integrated over the time interval of $200t_p$.

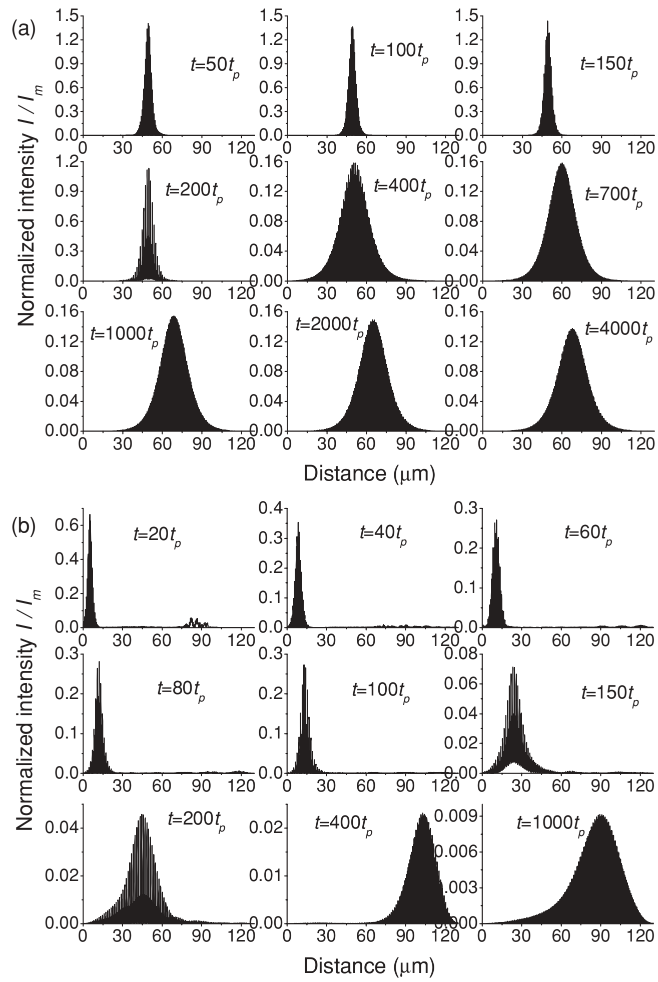

FIG. 5. Distribution of light intensity inside the photonic crystal at different time points. Pulse peak amplitude (a) $A_m = 3A_0$, (b) $A_m = 7A_0$. Relaxation time of nonlinearity $t_{\mathrm{nl}} = 6$ fs.

growing of transmitted energy continues, while, for reflected and total ones, rise becomes more steep (especially, when $A_m > 5A_0$) and, finally, the plateau is observed for $A_m \geqslant 7A_0$. Thus, the input energy almost entirely transforms to reflected light at high intensities of incident pulse.

It is obvious that the energy of pulses with amplitudes between $A_m \approx 2A_0$ and $A_m \approx 6A_0$ is confined inside the photonic crystal. Figure 5(a) demonstrates light intensity distributions along the length of the structure at different instants of time for the pulse peak amplitude $A_m = 3A_0$. At first ($t = 50t_p$), the largest part of the pulse energy is localized in a narrow region of the nonlinear photonic crystal, near the position $L = 50$ μm (the total length of the structure is about 130 μm). As time goes by, energy tends to redistribute more uniformly. Nevertheless, there is still pronounced maximum of intensity distribution, moreover, it is shifted toward larger positions, namely 60–70 μm at $t > 700t_p$. At large time points this distribution stays almost invariant, or stationary. Its maximum only slightly decreases, which seems to be connected with further redistribution rather than with output radiation. Anyway, even at $t = 4000t_p$ approximately 80% of pulse energy is still confined inside the photonic structure, just as at $t = 200t_p$ (see Fig. 4). This time is more than 100 times

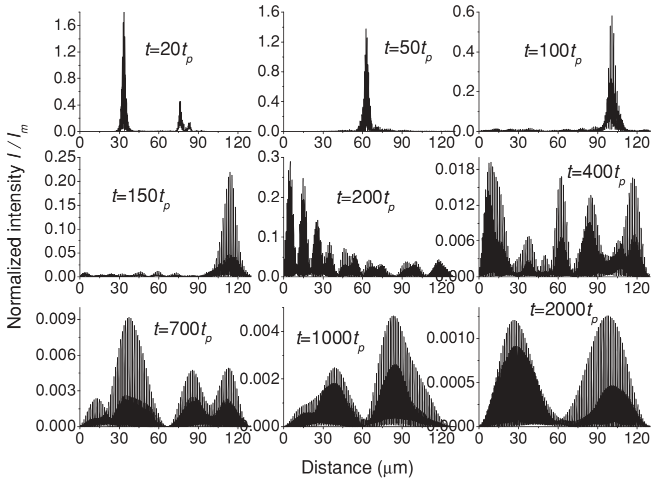

FIG. 6. Distribution of light intensity inside the photonic crystal at different time points. Pulse peak amplitude $A_m = 5A_0$. Relaxation time of nonlinearity $t_{\rm nl} = 0$.

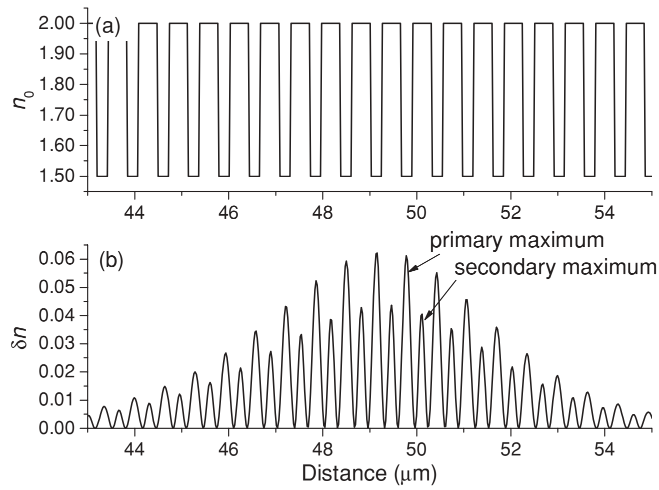

FIG. 7. Spatial variation of (a) the linear part of the refractive index $n_0(z)$, (b) the nonlinear contribution δn. Pulse peak amplitude $A_m = 3A_0$; time point $t = 50t_p$. Relaxation time of nonlinearity $t_{\rm nl} = 6$ fs.

higher than the interval needed for pulse to pass through the system. Recalling that $t_p = 30$ fs, this delay time in absolute units is greater than 100 ps. Therefore, we can say about *pulse trapping* in this case. Only for $t > 4000t_p$ the system starts to slowly emit light so that the sharp distribution shown in Fig. 5(a) becomes violated. More detailed calculations show that even at $t = 10000t_p$ about 50% of the initial energy is still inside the photonic crystal, though it is distributed much more uniformly.

Now let us consider the pulse with $A_m = 7A_0$. The corresponding spatial distributions are shown in Fig. 5(b). It turned out that in this case the pulse is localized near the very beginning of the structure. In this position it rapidly loses energy which is mainly radiated through the front (input) end of the system. So this radiation gives significant contribution to reflection [see Fig. 3(b)]. After light intensity becomes lower than a certain threshold, the pulse starts moving and widening. It moves quite slowly, so that some part (about 20%) of the input energy is confined inside the photonic crystal for a long time, but the peak intensity of the distribution is very low if we compare it with the case of $A_m = 3A_0$.

It is interesting to compare pulse behavior considered with pulse propagation in photonic crystal with relaxation-free nonlinearity (i.e., at $t_{\rm nl} = 0$). Intensity distributions inside the system for this case are demonstrated in Fig. 6. It is seen that any longterm energy localization in nonrelaxing photonic structure is absent. Light exhibits only chaotic "wander" inside it and simultaneous attenuation due to emitting through input and output ends. Finally, almost all energy of the pulse is already radiated by the instant of time $t = 700t_p$. Therefore, we can say that relaxation of nonlinearity is a necessary condition to obtain the effect of pulse trapping inside a photonic crystal.

IV. PHYSICAL MECHANISM OF PULSE TRAPPING

What is the physical reason, or mechanism, of this phenomenon? As pulse propagates inside the photonic crystal possessing cubic nonlinearity, the refractive index of the structure changes dynamically according to light intensity. If nonlinearity is relaxation free, these changes are instantaneous and depend entirely on field distribution at the current instant of time. In the case of relaxing nonlinearity, nonlinear variation of the refractive index (δn in our notation) can form a certain stable structure due to retardation in its change. Appearance of this nonlinear dynamical "cavity" results in pulse trapping: Light tends to change the distribution of δn and leave the cavity, but inertia of nonlinearity stabilizes it so that intensity is transformed to provide steady spatial distribution $\delta n(z)$. The example of this is shown in Fig. 7(b). One can see that maximal values of nonlinear variation of the refractive index δn (so-called primary maxima) are achieved in the layers with low linear refractive index $n_0 = 1.5$ [see Fig. 7(a)]. This is in accordance with the effect of light concentration in low refractive index regions of photonic crystal for radiation tuned to the high-frequency side of the reflection spectrum [2] as it is in the case considered (see the inset in Fig. 2). On the other hand, high refractive index layers of the structure contain minor (secondary) maxima of δn.

Obviously, low-intensity initial pulses are insufficient to produce high enough nonlinear contribution δn, so that pulse is mainly transmitted and reflected during short time after pulse incidence. For higher intensities [e.g., $A_m = 3A_0$ as in Fig. 5(a)] pulse forms a nonlinear cavity inside the photonic crystal which localizes the most part of pulse energy. Though this cavity slowly tends to uniformity of δn and loses its energy, it allows one to trap pulse light for a relatively large time interval. This behavior is obtained in a wide range of pulse amplitudes, from approximately $2.5A_0$ to $5A_0$. As pulse intensity increases, the cavity formation position moves toward the front end of the photonic structure. Finally, for $A_m \approx 7A_0$ the nonlinear cavity appears so close to the entrance of the system [Fig. 5(b)] that it rapidly emits almost all its energy in the form of reflected light. That is why only intermediate intensities of pulse (not too low and not too high) are suitable to obtain the effect of trapping pulse inside the structure considered.

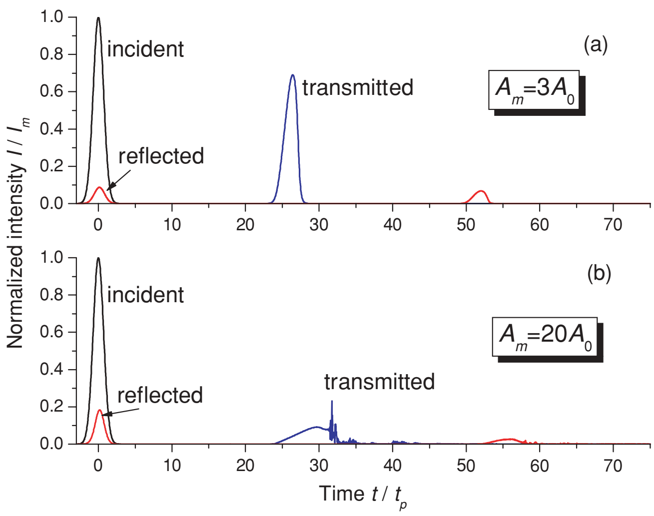

FIG. 8. (Color online) Transmitted and reflected pulses after the interaction with a uniform cubic medium. Pulse peak amplitude (a) $A_m = 3A_0$; (b) $A_m = 20A_0$. Linear part of refractive index $n_0 = 1.8125$. Relaxation time of nonlinearity $t_{\rm nl} = 6$ fs.

Finally, we should explain the role of photonic crystal in this process. Is it necessary to use photonic-band-gap structure or, maybe, the effect of pulse trapping can be observed in a uniform cubic medium? To clarify this question we performed calculations of pulse interaction with the medium possessing relaxing nonlinearity and mean refractive index $n_0(z) = (an_a + bn_b)/(a + b) = 1.8125$. One can see [Fig. 8(a)] that in this case there is not any light localization for pulse amplitude $A_m = 3A_0$. Only much more intensive pulses start to lose considerable part of energy inside the medium. For example, about 40% of pulse energy is found to be trapped for $A_m = 20A_0$ [Fig. 8(b)]. This part of energy stays inside the uniform medium for a long time and is connected with corresponding nonlinear variation of refractive index (see Fig. 9 for the instant of time $t = 1000t_p$). However, the distribution of light intensity in the uniform medium seems to be stochastic and does not resemble pulse envelope as in the case of nonlinear photonic crystal [compare the distributions in Figs. 9(a) and 5(a)]. Therefore, we cannot call light localization in the uniform medium with relaxing nonlinearity by the pulse trapping in the full sense of this term. Moreover, in photonic crystals we need pulse intensities which are less by an order of magnitude than in the case of the uniform medium.

Perhaps, the nonlinear cavity formation is connected with local change of reflective properties of photonic crystal. This results in dynamical shift of the band spectrum of the structure. To examine this situation we consider the refractive properties (for the central wavelength $\lambda = 1.064$ μm) of the structure with refractive index variations shown in Fig. 10(a) [it corresponds to intensity distribution of Fig. 5(a) at $t = 1000t_p$]. We calculate reflectivity of the partial structures, which include the layers from the input to a certain final position (inside the whole photonic crystal), and compare it with the case of linear structure. Difference between reflectivities in these two cases as a function of final position is demonstrated in Fig. 10(b). It is seen that the structure with modified refractive index modulation provides locally large reflectivity deviations

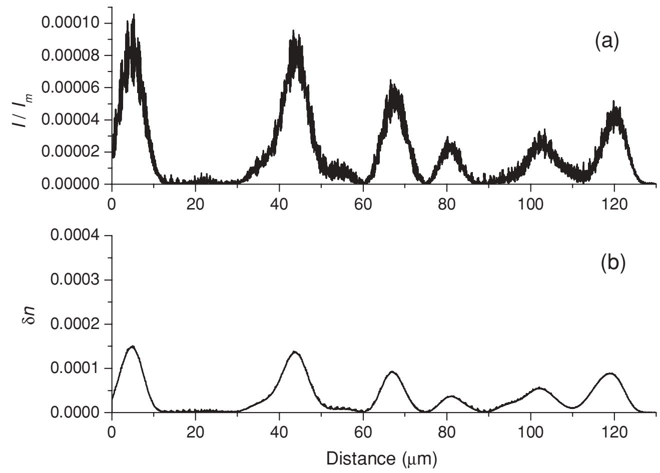

FIG. 9. Spatial variation of (a) intensity, (b) nonlinear variation δn in the case of uniform cubic medium with linear part of refractive index $n_0 = 1.8125$. Pulse peak amplitude $A_m = 20A_0$, time point $t = 1000t_p$. Relaxation time of nonlinearity $t_{\rm nl} = 6$ fs.

from the linear case. These deviations mainly appear at large positions inside the crystal where δn is high enough, so that they can prevent light propagation in forward direction. A similar situation is observed if we consider backward propagation. Hence, it turns out that light is trapped in the central region of the structure. Finally, it is worth noting that this picture of refractive index variations and reflectivity deviations is permanently changing, though it is stabilized by the relaxing properties of nonlinearity.

V. ON OPTIMAL CONDITIONS OF PULSE TRAPPING

In previous sections we considered the effect of pulse trapping in photonic crystal with relaxing cubic nonlinearity only for a single set of time parameters: $t_{\rm nl} = 6$ fs and

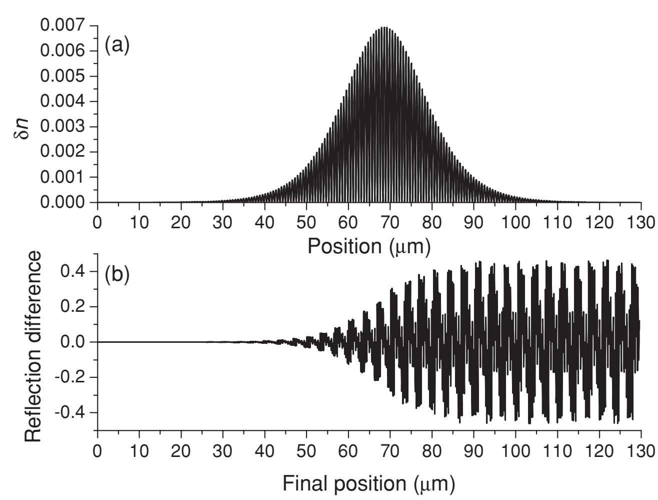

FIG. 10. (a) Distribution of nonlinear refractive index variation δn corresponding to intensity distribution of Fig. 5(a) at $t = 1000t_p$. (b) Difference between reflection coefficients of the partial structures including the layers from the input to a certain final position in the cases of δn given by picture (a) and $\delta n = 0$. Calculations were carried out for the central wavelength $\lambda = 1.064$ μm.

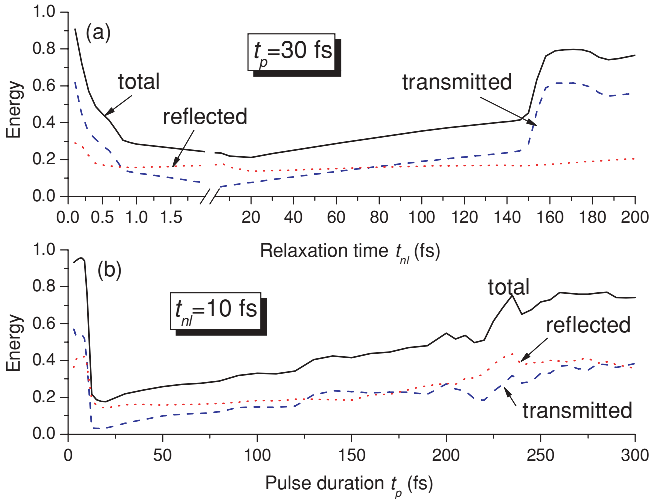

FIG. 11. (Color online) Dependence of transmitted, reflected, and overall output energy (as a fraction of input energy) on (a) relaxation time at $t_p = 30$ fs; (b) pulse duration at $t_{\rm nl} = 10$ fs. Incident pulse peak amplitude $A_m = 4A_0$. Energy was integrated over the time interval of $200 t_{p0}$, where $t_{p0} = 30$ fs.

$t_p = 30$ fs. Figure 11(a) shows the dependence of output energies (reflected, transmitted, and total) on relaxation time at a fixed value of pulse duration $t_p = 30$ fs. The behavior of these dependencies is similar to that of the curves in Fig. 4: abrupt drop in the range of small $t_{\rm nl}$ (less than 1 fs), smooth increasing and, finally, steep rise of the curves for reflected and total energies. The full range of relaxation times where the pulse trapping can be observed is rather wide: from a fraction of a femtosecond (relaxation is so fast that it does not influence the pulse) to about 150 fs that is much greater than t_p (medium reacts so slowly that the nonlinear cavity forms near the very entrance of the system). The optimal value is $t_{\rm nl} \approx 10$ fs.

If we fix relaxation time $t_{\rm nl} = 10$ fs and vary pulse duration, the behavior of output energies is quite different [Fig. 11(b)]. As in the previous case, it demonstrates abrupt decrease

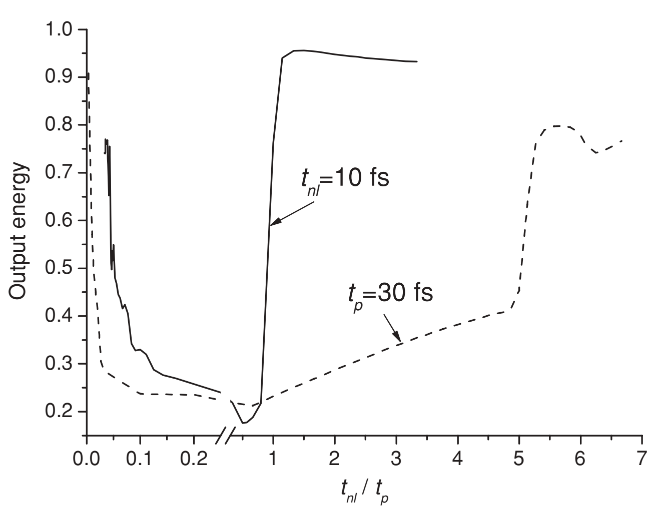

FIG. 12. Dependence of overall output energy on the ratio $t_{\rm nl}/t_p$ plotted according to the data of Fig. 11.

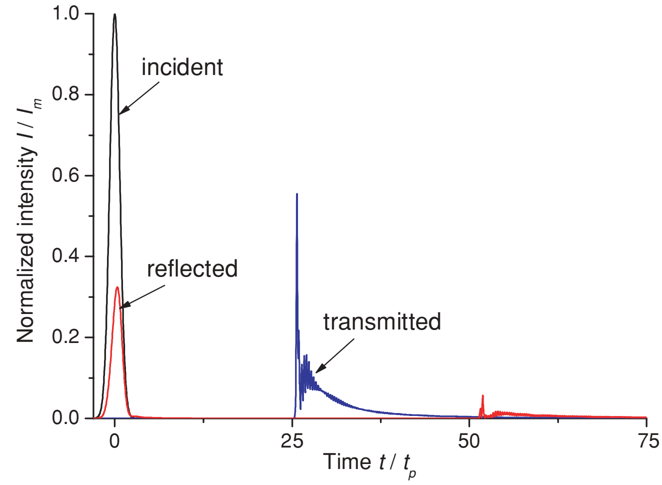

FIG. 13. (Color online) Transmitted and reflected pulses after interaction with a photonic crystal with negative nonlinearity coefficient $n_2 I_0 = -0.005$. Pulse peak amplitude $A_m = 3A_0$. Relaxation time of nonlinearity $t_{\rm nl} = 6$ fs. Other parameters are the same as in the caption of Fig. 1.

for small times, namely, pulse durations $t_p \simeq 10$ fs which correspond to only a few optical cycles. Such very short pulse is not able to create a stable nonlinear cavity. On the other hand, if t_p is increasing, there is only stepless growth of output energies, reflected and transmitted ones being approximately of the same magnitude. The reason is the same: nonlinear cavity is not formed as long as a whole pulse cannot be placed inside the structure. The optimal value of pulse duration is about 20 fs.

Since the limits of the pulse-trapping region are due to different reasons in the cases of fixed t_p and $t_{\rm nl}$, the width of this region will be different, too. In Fig. 12 we plotted the curves of Fig. 11 versus the ratio $t_{\rm nl}/t_p$. This figure shows explicitly that relaxation time can be varied in much more wide range than pulse duration. This also implies that we can use media with relatively slow relaxing nonlinearities to obtain the effect of pulse trapping.

Another question is connected with the role of sign of nonlinearity. So far we considered only the positive nonlinearity coefficient such that $n_2 I_0 = 0.005$. If we take $n_2 I_0 = -0.005$ (defocusing nonlinearity), there are not any symptoms of pulse trapping as one can see in Fig. 13 for the amplitude $A_m = 3A_0$. Though this problem should be studied in detail, the preliminary conclusion is that trapping can be observed only for $n_2 > 0$, at least for comparatively low intensities.

VI. CONCLUSION

To summarize, we have analyzed the possibility of trapping pulse in photonic crystal with relaxing cubic nonlinearity. By using numerical simulations, we showed that this process is due to the balance between light spreading and inertia of nonlinearity which results in steady nonlinear cavity formation and pulse trapping within it. Photonic crystal is a necessary element for this cavity to appear, due to the processes of dynamical local change of reflection and transmission of the nonlinear structure, and, in addition, leads to decreasing of pulse intensity required to observe trapping. We discussed the reasons for pulse trapping disappearance at high and low values of both pulse duration and relaxation time resulting in existence of the range of optimal magnitudes of these parameters.

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