Optics Communications 353 (2015) 56–62

Contents lists available at ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

Disorder-induced light trapping enhanced by pulse collisions in one-dimensional nonlinear photonic crystals

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ARTICLE INFO

Article history:
Received 18 March 2015
Received in revised form
27 April 2015
Accepted 6 May 2015
Available online 8 May 2015

Keywords:
Photonic crystals
Relaxing nonlinearity
Disordered structure
Self-trapping

ABSTRACT

We use numerical simulations to study interaction of co- and counter-propagating pulses in disordered multilayers with noninstantaneous Kerr nonlinearity. We propose a statistical argument for existence of the disorder-induced trapping which implies the dramatic rise of the probability of realization with low output energy in the structure with a certain level of disorder. This effect is much more pronounced in the case of two interacting pulses than in the single-pulse regime and does not occur in the strictly ordered system at the same intensity of the pulses. Therefore it cannot be explained simply as a result of increase in strength of nonlinear light-matter interaction.

1. Introduction

Since Philip W. Anderson's breakthrough paper [1], study of localization and other matter-wave effects in solid-state disordered systems has become a broad and fruitful field of research. Moreover, the notion of Anderson localization stimulated research of wave phenomena in other contexts, including classical wave dynamics in disordered media and the connections with mesoscopic physics [2–5]. In optics, this interest has led to the experimental observation of the Anderson localization of light in 1990s and 2000s [6–8]. Discussion of subsequent progress in disordered optics and photonics can be found in recent reviews [9,10].

In this paper, we deal with some aspects of nonlinear optics of disordered photonic structures. For detailed discussion of short-pulse effects (including tail dynamics [11], localization suppression [12,13], and localized solitons formation [14,15]) in nonlinear disordered systems, see the introduction to my previous paper [16] and references therein. Here we restrict ourselves to referring only to a few recent advances reported in the literature. Among them are the observation of the reciprocity breaking effect in nonlinear random medium [17], the parametric amplification of light localization in the random medium with quadratic nonlinearity [18], self-trapping of light in nonlinear waveguide array with coupling disorder [19], nonreciprocal localization in disordered multilayers with magneto-optical materials [20], wave packet spreading in 1D and 2D photonic lattices [21], control of energy transfer in disordered laser resonators [22], etc.

This paper can be viewed as a continuation of the previous work [16] devoted to propagation and self-trapping of ultrashort pulses in disordered one-dimensional photonic crystals with instantaneous and relaxing nonlinearities. Here we consider the collisions of pulses in such structures and search for the possibility of light trapping which cannot be reached in ordered system with the same parameters. This trapping is fundamentally different from the self-trapping effect in the perfect nonlinear photonic crystals [23] which is destroyed by introduction of disorder. As previously, we consider the regime of strong disorder and strong nonlinearity. We have studied earlier the interaction of co- and counter-propagating pulses in perfect photonic crystals with relaxing nonlinearity [24] and in dense two-level media [25–27]. As far as we know, the influence of disorder on such interaction was not considered in scientific literature yet. The present study makes up for this deficiency.

The paper is structured as follows. In Section 2, we give the main equations and briefly discuss the numerical method and the parameters adopted. Sections 3 and 4 are dedicated to the analysis of results obtained for co- and counter-propagating pulses, respectively. The paper is completed with the short Conclusion.

2. Problem statement

Let us consider the one-dimensional photonic crystal, i.e. a multilayer structure consisting of two different materials –

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http://dx.doi.org/10.1016/j.optcom.2015.05.013
0030-4018/

alternating layers denoted with letters a and b. Light is assumed to propagate along the z-axis which is perpendicular to the layers' interfaces. The results reported here are based on numerical solution of the one-dimensional 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 the electric field strength, n is the medium refractive index which, generally, is a function light intensity $I = |E|^2$,

$$n = n^0(z) + \delta n(I, t, z). \tag{2}$$

Here $n^0(z)$ is a linear part of refractive index changing periodically along the structure. Since we deal with noninstantaneous nonlinearity, the nonlinear contribution δn must take into account the relaxation process which, for definiteness, will be described by the Debye model [28],

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

where n_2 is the cubic (Kerr) nonlinear coefficient, and t_{nl} is the relaxation time. For the disordered periodic structure, we assume the random variations of thicknesses of layers a and b as follows:

$$d_{a,b} = d^0_{a,b} + \Delta d(\xi - 1/2), \tag{4}$$

where $d^0_{a,b}$ are the mean values of thicknesses, Δd is the amplitude of disorder, and ξ is the random quantity uniformly distributed in the range [0, 1].

We solve numerically Eqs. (1)–(4) using the method developed in the previous publications [23,16]. As previously, we do not mean any specific materials, since our aim is to study the qualitative and general aspects of light interactions with periodic disordered structures. Therefore, for our calculations, we adopt the parameters of the model from Ref. [16]: $d^0_a = 0.4$ and $d^0_b = 0.24$ μm, $n^0_a = 2$ and $n^0_b = 1.5$. The envelope of the pulse at the input of the photonic structure is supposed to have the Gaussian shape, $A(t) = A_0 \exp(-t^2/2t_p^2)$, where t_p is the pulse duration, and A_0 is the amplitude of the electric field. Further we assume $t_p = 50$ fs and the central wavelength $\lambda_c = 1.064$ μm, so that the carrier frequency lies just outside the band gap of the perfect multilayer [16]. Finally, we restrict ourselves to the structure with nonlinear b layers only. This is justified, because light concentrates in these layers when, as in our case, we deal with the high-frequency edge of the band gap [29]. The strength of nonlinearity ($n_2 I_0 = n_2 |A_0|^2 \sim 0.01$) is taken to be large enough to strongly influence the pulse characteristics. This allows to consider comparatively short systems, namely $N = 50$ periods in our calculations. Construction of such photonic crystals seems to be quite feasible for modern technology. Though we do not mean any specific materials, linear layers may be formed by glass, while for nonlinear layers one can use polymer materials possessing high nonlinearity and fast relaxation [30]. However, as far as we know, such photonic crystals possessing relaxing nonlinearity and disorder simultaneously were not realized experimentally yet. Therefore, our study can be considered as a proposal for building such new optical systems as well.

Thus, we consider the interplay of strong disorder and strong nonlinearity. Generally, this interplay can be studied on the short timescale (pulse shape transformation) and at long times (pulse tail transformation as an evidence for the Anderson localization) as was done in the previous work [16]. In this paper, we deal with the collisions of pulses in the disordered photonic crystals. Since the behavior of the tail and the Anderson localization seem to be insensitive to the number of pulses, we will focus on the shape transformations of the colliding pulses and, in particular, on the possibility to induce light trapping by using the collisions of co- and counter-propagating pulses.

3. Co-propagating pulses

First, let us consider the situation of two co-propagating pulses launched into the structure with some interval one after another. This interval must be not too large for the pulses to interact effectively with each other and not too small so that we can talk about separate pulses. In our calculations, we assume the interval of $10t_p$ between the peaks of the incident pulses. We start with the profiles of the pulses transmitted through the perfect (ordered) photonic crystal (Fig. 1). It is seen that the pulses have different peaks even in the linear case. This means that the interpulse interval is short enough to provide effective energy interchange between them. Perhaps, in the linear case, some residual radiation of the first pulse joins the second one, so that its intensity grows. This simple picture is not applicable for the more complicated nonlinear case. In nonlinear structure, the first pulse is strongly compressed (more intense) than the second one. Fig. 2 shows the changes in the profiles due to disorder with $\Delta d = 0.05$ μm. In the linear case, the averaged transmitted pulses seem to be almost identical, i.e. on average, the distribution of energy between the pulses is uniform. This uniformity is broken as a result of nonlinearity introduction: the first pulse tends to be more powerful than the second one. Now we can add the relaxation of nonlinearity and study its influence on the averaged profiles of the co-propagating pulses (Fig. 3). It is seen that addition of relaxation to the disordered structure results in further decrease of the intensity of transmitted pulses.

What is the reason for this decrease? Does it mean simply strengthening of reflection? The detailed study shows that the answer is “no”. According to the data shown in Table 1, the average transmission $\bar{T}$ (the part of total light energy transmitted through the structure in the time $100t_p$ and averaged over realizations) drops due to the relaxation from 0.514 to 0.419 (remind that we consider the disorder strength $\Delta d = 0.05$ μm). At the same time, the reflection $\bar{R}$ averaged over realizations grows from 0.478 only to 0.509. This means that the total average output $\bar{W}$ (sum of transmission and reflection) decreases from almost unity to 0.928, i.e. *on average* more than 7% of the input energy remains inside the structure due to the relaxation of nonlinearity. We further explored how the average output energy depends on the disorder strength. The resulting curves presented in Fig. 4 show that, as it would be expected of the disordered media, the transmission decreases and reflection increases with the growing Δd. However, these two processes do not compensate each other, so that the dip in the curve for the total output energy appears. The minimum of $\bar{W}$ occurs at $\Delta d = 0.04$ μm and amounts to about 0.92.

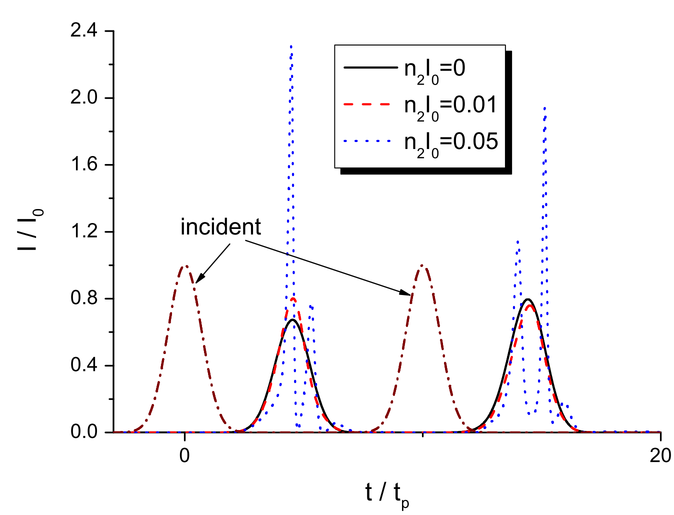

Fig. 1. The profiles of co-propagating pulses transmitted through the perfect (ordered) photonic crystal with and without nonlinearity.