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FEW CYCLE PULSES IN THE BRAGG MEDIUM CONTAINING CARBON NANOTUBES

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The effective equation for few cycle optical pulse dynamics was obtained by virtue of the Boltzmann collision-less equation solution for conduction band electrons of semiconductor carbon nanotubes in the case when medium with carbon nanotubes has spatially-modulated refractive index. The pulse retardation effect, in comparison to an unmodulated medium, was derived. The evaluation was carried out depending on task options.

Keywords: cycle optical pulse, carbon nanotubes, Bragg medium, Boltzmann equation.

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1. Introduction

One of the basic problems of modern optics is medium creation, thanks to which, we can process and control a signal. Among such media, the Bragg media (in which the refractive index is periodically spatially-modulated) is of great interest [1–3]. As much as the medium has a periodically variable refractive index, the light pulse propagates more slowly in it, than in a medium with any fixed refractive index. This makes it possible to construct optical delay lines based on such media, which are useful for femtosecond spectroscopy for example. Such behavior can be understood in essence, providing that the light pulse is reflected and then interferes at the interface of media with different refractive indices. Additional introduction of nonlinearity into that sort of media leads to qualitatively new effects [4–6]. Particularly, Bragg solitons can be formed in such systems. They are revealed as a specified counter assembly of waves, banded in such a manner to move collectively with reduced speed. At the same time, rising interest in carbon nanotube (CNT) physics and particularly heightened attention to the study of CNT nonlinear properties leads to the conclusion that carbon nanotubes, with their characteristic nonlinear optical properties, can be non-conventional material for the nonlinear Bragg media formation [7–9]. Note that carbon nanotube usage perspectives in nonlinear optics in particular for optical bullet formation have been mentioned in some research accounts. All the above-mentioned facts gave impetus for this investigation.

2. Basic equations

Research of carbon nanotube electronic structure is done using the tight-binding approximation within the framework of p electron dynamics. Dispersion expression for zigzag carbon nanotubes $(m, 0)$ has the form [10]:

$$E(\mathbf{p}) = \pm\gamma\sqrt{1 + 4\cos(ap_z)\cos(\pi s/m) + 4\cos^2(\pi s/m)}, \tag{1}$$

where $\gamma = 2.7$ eV, $a = 3b/2\hbar$, $b = 0.152$ nm is a distance between carbon neighbor atoms and quasimomentum $\mathbf{p}$ is defined by (p_z, s), $s = 1, 2 \dots m$.

We will describe the pulse electromagnetic field by virtue of Maxwell equations in Coulomb calibration [11] $\mathbf{E} = -1\partial\mathbf{A}/c\partial t$ while constructing the model of few-cycle optical pulse propagation in the Bragg media with allowance for nanotube system in the case of geometry presented in the Fig. 1. The vector-potential has the form $\mathbf{A} = (0, 0, A_z(x, t))$:

$$\frac{\partial^2 \mathbf{A}}{\partial x^2} - \frac{n^2(x)}{c^2}\frac{\partial^2 \mathbf{A}}{\partial t^2} + \frac{4\pi}{c}\mathbf{j} = 0, \tag{2}$$

where $n(x)$ defines a spatial variation of a refraction index, i.e. the Bragg grating, $\mathbf{j}$ is the current resulting from the electric pulse field exposure on conduction band electrons of carbon nanotubes. Here, we neglect the diffractive blooming of laser beam in directions orthogonal to the distribution axis. The electric field of a template is also disregarded. Within the framework of our model interband transitions are neglected, this fact limits the laser pulse frequency, which belongs to the near-infrared region. Note that since typical CNT dimension and distance between nanotubes much less than the size of typical spatial domain wherein a few cycle pulse is localized, we can use the continuous medium approximation and suppose a current apportioned by volume.

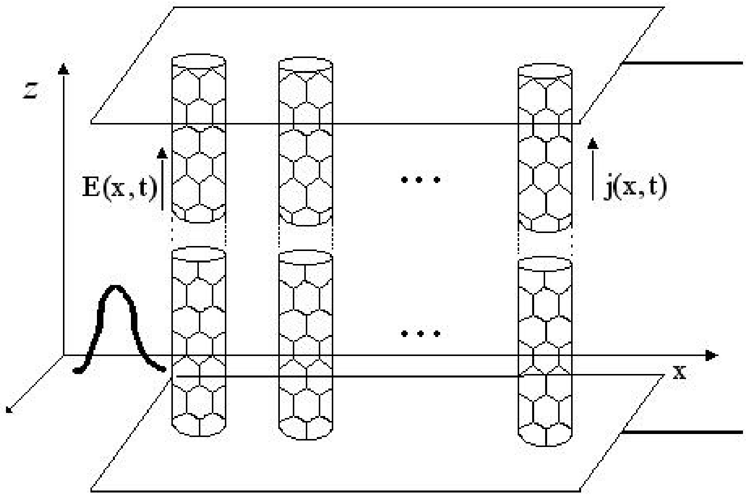

FIG. 1. Theproblem geometry. $j(x, t)$ is the current along the CNT axis, $E(x, t)$ is the pulse electric field

A typical length when the Bragg medium refractive index changes essentially turned out to be greater and dispenses additional constraints.

Since the typical relaxation time for CNT electrons can be estimated by $3 \cdot 10^{-13} A$ [12], then the electron ensemble at a time peculiar to few cycle optical pulse dynamics problems (around 10^{-14} c) can be described by collision less kinetic Boltzmann equation [13]:

$$\frac{\partial f}{\partial t} - \frac{q}{c}\frac{\partial A_z}{\partial t}\frac{\partial f}{\partial p} = 0, \tag{3}$$

where $f = f\,(p_s, s, t)$ is a distribution function, implicitly dependent on coordinate. Moreover, the distribution function f at the initial moment aligns with the equilibrium distribution Fermi function F_0 as follows:

$$F_0 = \frac{1}{1 + \exp\{E(p)/k_b T\}},$$

where T is a temperature, k_b is the Boltzmann constant.

For the current density $\mathbf{j} = (0, 0, j_z)$:

$$j_z = \frac{q}{\pi\hbar}\sum_s \int dp_z v_z f, \tag{4}$$

where $v_z = \partial E(\mathbf{p})/\partial p_z$ is the group velocity. By characteristics method [14] from the equation (3), we can obtain the following:

$$j_z = \frac{q}{\pi\hbar}\sum_s \int_{-q_0}^{q_0} dp_z v_z \left[p - \frac{q}{c}A_z(t)\right] F_0(\mathbf{p}). \tag{5}$$

Integration in (5) is over the first Brillouin zone and $q_0 = 2\pi\hbar/3b$. The group velocity can be expanded to Fourier series, the dispersion law taken into account:

$$v_z(s, x) = \sum_m a_{ms}\sin(mx),$$

where

$$a_{ms} = \frac{1}{\pi}\int_{-\pi}^{\pi} v_z(s, x)\sin(mx)dx$$

are expansion coefficients decreasing with increase in m.

Finally the effective equation can be represented in the form [15]:

$$\frac{\partial^2 A_z}{\partial x^2} - \frac{n^2(x)}{c^2}\frac{\partial^2 A_z}{\partial t^2} + \frac{q}{\pi\hbar}\sum_m c_m \sin\left(\frac{maq}{c}A_z(t)\right) = 0,$$

$$c_m = \sum_m a_{ms}b_{ms}, \quad b_{ms} = \int_{-q_0}^{q_0} dp_z \cos(map_z) F_0(\mathbf{p}). \tag{6}$$

Since the coefficients c_m decrease with increase in m, then in the sum (6) for estimation it is possible to confine to the first two summands and obtain the double equations sin-Gordon [16]. Study of this equation gives us the fact that the character of single pulse break-up depends heavily on its velocity. With an increase in velocity the pulses interact more elastically and minority of their energy goes to vibrational modes [17].

3. Results of numerical modelling

Equation (6) was solved numerically by applying the explicit finite-difference leap-frog scheme [18].The time and coordinate steps are chosen according to standard stability criterion, and then were reduced until the solution changed in the eighth significant character. The initial conditions for vector potential were chosen in the form:

$$A_{t=0} = A_0 \exp\left\{-\frac{x^2}{\gamma^2}\right\}, \quad \left.\frac{dA}{dt}\right|_{t=0} = \frac{2vx}{\gamma^2}A_0 \exp\left\{-\frac{(x - vt)^2}{\gamma^2}\right\}. \tag{7}$$

The refractive index of medium in process was simulated as

$$n(x) = n_0(1 + \alpha\cos(2\pi x/\chi)).$$

The first outcome, depicted in Fig. 2, relates to the fact that in presence of the Bragg grating few cycle pulse propagates steadily and, as it follows from the linear analysis, more slowly than in the case of no grating.

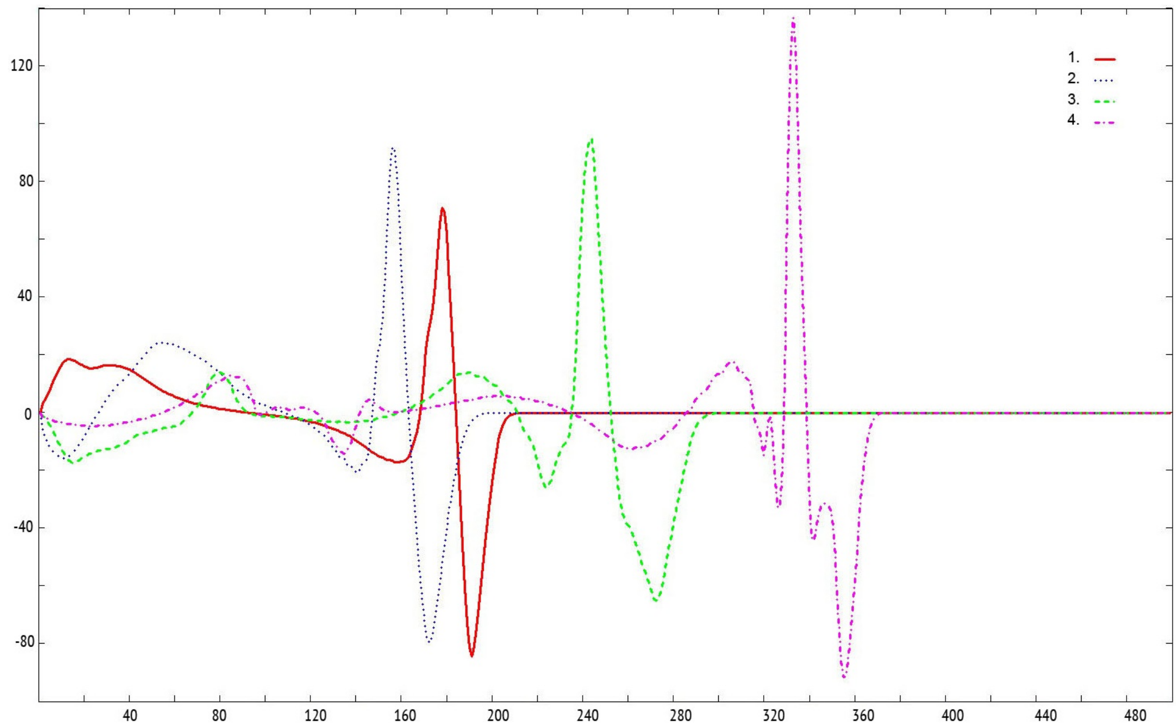

FIG. 2. Few cycle optical pulse evolution at the fixed moment of time T without Bragg grating (3); with Bragg grating present (2); and at the moment of time $2T$ (1) and $3T$ (4) with Bragg grating present. The dimensionless time is along the x-axis, the dimensionless amplitude is along the y-axis

Note that the presence of a lattice predictably leads to pulse shape deformation due to the interference of waves which have a partial reflection. The running pulse delay is correlated with the same interference.

Numerical modeling results, in terms of the lattice constant χ, are represented in Fig. 3. As expected, a few cycle pulse propagates faster with an increase in the lattice constant. It is evident that the pulse will propagate at full throttle under the infinite lattice constant, due to lack of interference processes. This was confirmed as a consequence of numeric computation. Note also that the pulse shape has significant disturbance.

The following result relates to dependence of both form and few cycle pulse velocity on modulation depth of the refraction index α, which is depicted in Fig. 4

Conspicuously, an increase in the modulation depth α leads to both a pulse delay (by the reasons mentioned above) and a change in its shape due to strong interference. Particularly, the most significant change is at the pulse front and its asymptotic form, in our opinion, this is due to reflection at lattice process and further interference. The obtained results may be also useful for predictions of pulse spread value under pulse delay by means of the Bragg grating in a carbon nanotube medium.

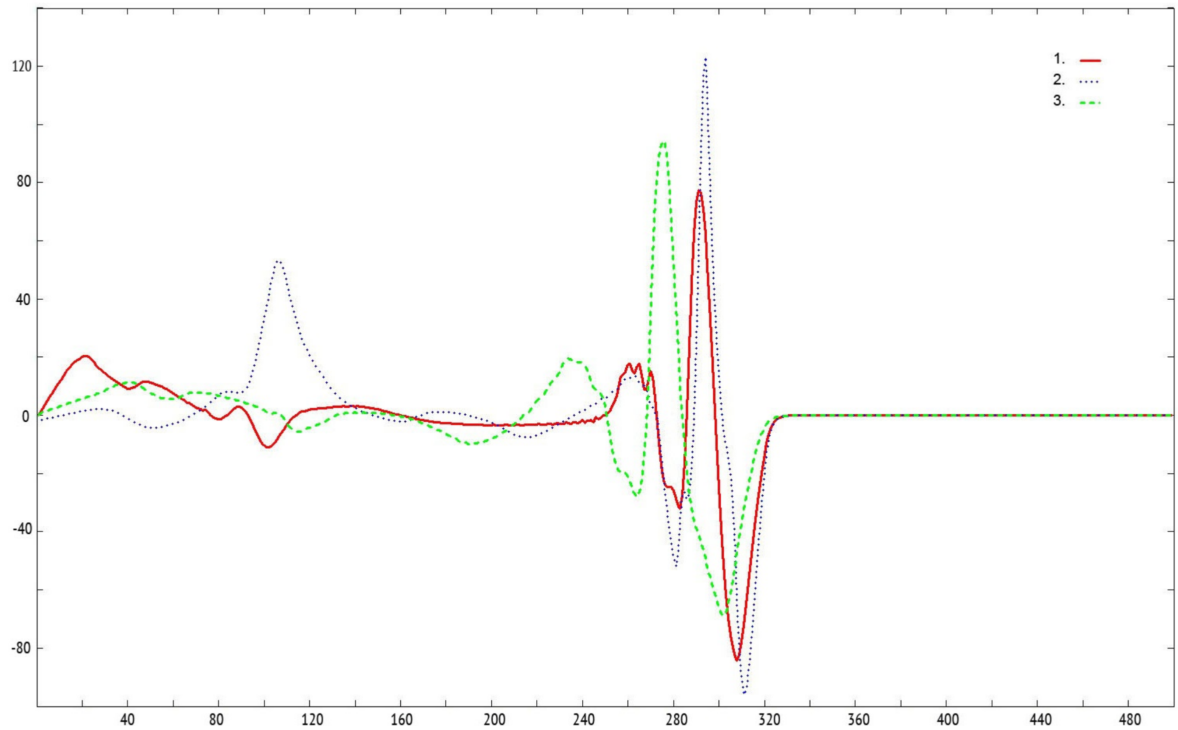

FIG. 3. The pulse shape evolution with various period χ (1), 2χ (2), 3χ (3) at the fixed moment of time under propagation in CNT system. The dimensionless time is along the x-axis, the dimensionless amplitude is along the y-axis

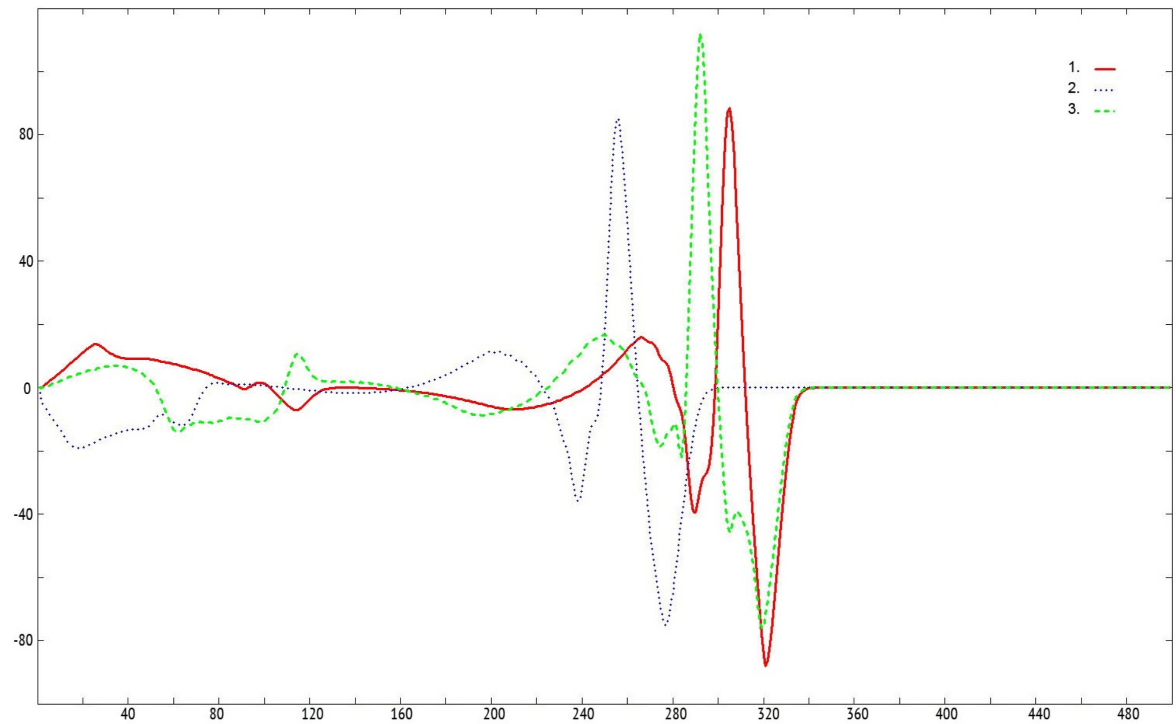

FIG. 4. The pulse shape evolution with various modulation depth α (1), 3α (2), 5α (3) under the propagation in CNT system. The dimensionless time is along the x-axis, the dimensionless amplitude is along the y-axis

4. Summary

This study allows to make the following observations:

1. Few cycle optical pulse propagation in the Bragg medium with carbon nanotubes is steady. As expected, the presence of Bragg grating deforms pulse shape, and also delays its propagation by virtue of counter wave interference.
2. It is stated that the lattice constant affects the velocity of few cycle pulse propagation. The increase in the lattice constant causes the pulse to less reflect from the lattice sites whereupon its velocity increases. Thus, we can manage the pulse propagation velocity by varying the lattice constant, which is important for solution of applied optics problems.
3. Both the pulse delay and its shape change come with the refractive index modulation enhancement by virtue of strong interference. Particularly strong changes in shape can be seen at the front of few cycle optical pulse.

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