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Two-dimensional Few-circle Optical Pulses in the Inhomogeneous Environment of Carbon Nanotubes

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We consider the task about few-circle optical pulses dynamics (light bullets) in the inhomogeneous environment of carbon nanotubes. Electromagnetic field of pulse describes classically, on basis of Maxwell equation, and carbon nanotubes give dispersion law for electrons, which interacting with pulse. We show that light bullets propagate stably.

Keywords: Few-circle optical pulses, Inhomogeneous environment.

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1. INTORDUCTION

The researching of a few-circle optical pulses dynamics (light bullets) in different environments is very interesting from theoretical view, and has impotent practical applications. [1-3]. Apart from using in the systems of optical calculus, light bullets can use to the spectroscopy marks, because its spectrum extremely wide.

We need to mark, that in vacuum or in linear environments, light bullets don't stable by act of dispersion law, and happens its widening.

For stable existence of light bullets, we need nonlinear environment, where dispersion effects will compensate nonlinear effects [4-6]. Perspective environments are carbon nanotubes, where nonlinearity defines by nonparabolicity of the electrons dispersion law, which interact with light pulse field [7-9]. We know a lot of states devote to nonlinear properties of carbon nanotubes, the impotent of it [9-12]. The critical moment, fundamentally authors had a good look at light bullets propagation in homogeneous environment of carbon nanotubes, it does impossible, for example, to control of light bullets velocity. Recently were suggested models of light bullets propagation in Bragg- environment with carbon nanotubes [13-15], which permit to manage by light bullets velocity in the environment, and, it's very impotent for applications, its cross structure. We mark that, the idea of this states consist in a researching of the environment which contains and carbon nanotubes and space modulate refractive index synchronous. We can have same hardships with experimental getting such environments. More natural, from our point of view, is getting environments, where carbon nanotubes distribute heterogeneous. In this case the space modulation of a refractive index arise (enough to take optical pulse of a small intensity), this fact bring to change of pulse propagation velocity, so gives an abilities to control of a pulse time delay in that environment. All foresaids give us a stimulus to present state.

2. MAIN EQUATION

We suppose that the electric field of the light bullet has a view $E(r) = ezEz(x, y)$. Carbon nanotube will be considered as a single-layer graphen list, coiled in cylinder. We restrict only п-electrons, suppose that their motion can be describe by strong coupling approximation. Also we mark a distortion of the pulse form. The carbon nanotube radius more small than character light bullet size, it's allow to neglect a space heterogeneity of the field in tubes.

In the single-electron approximation the Schrödinger equation accepts next view [16-18]:

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m_0}\Delta\psi + \left[W(r) - e(E\cdot r)\right]\psi \tag{1}$$

The solution of equation (1) can be present:

$$\psi = \sum\nolimits_{l,p} C_l(p)\psi_l(p,r) \tag{2}$$

Where l – quantum number set, which describes π – electrons states with given quasi-momentum. $\mathbf{\Psi}_l(\mathbf{p},\mathbf{r}) = \hbar^{-0.5}\exp(i\mathbf{pr}/\hbar)u_{l,\mathbf{p}}(\mathbf{r})$ – Bloch functions with amplitude $u_{l,\mathbf{p}}$ which which periodical to free vector of lattice $\mathbf{a}$: $u_{l,\mathbf{p}}(\mathbf{r}+\mathbf{a}) = u_{l,\mathbf{p}}(\mathbf{r})$. Here $\mathbf{a} = n_1\mathbf{a}_1 + n_2\mathbf{a}_2$, n_1, n_2 – integer numbers, $\mathbf{a}_1$, $\mathbf{a}_2$ – elementary vectors of hexagonal graphene lattice.

Subject to nanotubes spectrum [19], from equations (1) and (2) follows:

$$\hat{H}_0 = \begin{pmatrix} 0 & H_{12}(p) \\ H_{12}^*(p) & 0 \end{pmatrix} \tag{3}$$

That can rewrite in strong coupling approximation as:

$$H_{12}(p) = -\gamma_0\sum\nolimits_{j=1}^{3}\exp\left(\frac{ip\tau_j}{\hbar}\right) \tag{4}$$

where γ_0 – is an electron jumping integral (2.7 eV), $\boldsymbol{\tau}_j$ – is a vector coupling atom with nearby neighbours.

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Then for a density matrix we get next equations:

$$\frac{\partial\rho}{\partial t}+eE_z\frac{\partial\rho}{\partial p_z}=2\frac{e}{\hbar}E_zR_{ab}\Phi$$

$$\frac{\partial F}{\partial t}+eE_z\frac{\partial F}{\partial p_z}=\omega\Phi \qquad (5)$$

$$\frac{\partial\Phi}{\partial t}+eE_z\frac{\partial\Phi}{\partial p_z}=\frac{e}{\hbar}E_zR_{ab}(2\rho-1)-\omega F$$

For comfort of a numerical integration we need a substitute: $F=\mathrm{Re}(\rho_{cv})$; $\Phi=\mathrm{Im}(\rho_{cv})$; $\rho=\rho_{cc}$, ρ_{cv} – is a density matrix, ω – is a band-to-band transition frequency, e- electric charge,

$$R_{ll',p}=\frac{i\hbar}{2}\int_{\Omega}\left(u^*_{l,p}\frac{\partial u_{l',p}}{\partial p_z}-\frac{\partial u_{l',p}}{\partial p_z}u^*_{l,p}\right)d^2r$$

integration leads by volume Ω two-dimensional elementary cell and Planck's constant equals one.
The initial conditions will be next:

$$\rho_{t=0}=F_0(\varepsilon_c(p_z,s));F\,|_{t=0}=\Phi\,|_{t=0}=0 \qquad (6)$$

It reflect a fact that electrons near indoor temperature distribute in accord equilibrium Fermi distribution with zero chemical potential ($\mu=0$).

The boundary condition reflect a solution periodicity in the quasi-momentum space (similar for F and Φ):

$$\rho\left(t,\frac{\sqrt{3}\pi}{\omega_{cn}a}\right)=\rho\left(t,-\frac{\sqrt{3}\pi}{\omega_{cn}a}\right) \qquad (7)$$

The quantum-mechanical operator of the current density can be written by:

$$\hat{J}_z(r)=-\frac{ie\hbar}{2m_0}\left(\frac{\partial}{\partial z'}\delta(r-r')+\delta(r-r')\frac{\partial}{\partial z'}\right) \qquad (8)$$

We expand general current density to two components: $\overline{j_z}=j_1+j_2$, where for interband transition replay:

$$j_1=\frac{4e}{(2\pi\hbar)^2}\int_{1ZB}\frac{\partial s_c(p)}{\partial p_z}\rho(t,p)d^2p \qquad (9)$$

and band-to-band:

$$j_2=\frac{8e}{(2\pi\hbar)^2\hbar}\int_{1ZB}\varepsilon_c(p)R_{cv}(p_z,s)\Phi(t,p)d^2p \qquad (10)$$

Maxwell equations for non-magnetic dielectric environment bring to view [20]:

$$\frac{\partial^2A}{\partial x^2}+\frac{\partial^2A}{\partial y^2}+\frac{4\pi}{c}c(x,y)\left(j_1+j_2\right)-\frac{1}{c^2}\frac{\partial^2A}{\partial t^2}=0 \qquad (12)$$

Where $\boldsymbol{A}$ – is vector-potential, t – is a time, c – is a velocity of light in vacuum. In (12) we bring in a phenomenological index, which take in to account a carbon nanotubes distribution in the space $c(x, y)$. In further, in numerical calculation this distribution wil be give in a view $c(x, y) = 1 + \alpha\cos(gx)$, where α gives a modulation depth of nonlinearity, and g is a modulation period. We mark that, in this state we take to attention only modulation along direction of light bullet propagation.

The dispersion law of zig-zag carbon nanotubes further will be select in a view:

$$\varepsilon_s(p)=\pm\gamma\sqrt{1+4\cos(ap\ )\cos(\pi s/m)+4\cos^2(\pi s/m)} \qquad (13)$$

where $s=1,\ 2\ ...\ m$, nanotube has a type $(m,0)$, $\gamma\approx 2.7$ eV, $a=3b/2\hbar$, $b=0.142$ nm – is a distance between neighbouring carbon atoms.

3. NUMERICAL ANALYSIS

The researching equation (12) subject to (11) and (9) was solved by numerically. We mark that a band-to-band j_2 current equals zero. A light bullet spectrum lies higher then apparent part of spectrum and minimal oscillation frequency in bullet spectrum lies in near infrared area.

The initial condition for vector-potential of the light bullet electric field choose in Gaussian form:

$$A(x,y,0)=Q\exp(-\frac{(x-x_0)^2}{\gamma_x})(-\frac{(y-y_0)^2}{\gamma_y})$$

$$\frac{dA(x,y,0)}{dt}=\frac{2Qxv}{\gamma_x}\exp(-\frac{(x-x_0)^2}{\gamma_x})\exp(-\frac{(y-x_0)^2}{\gamma_y})$$

Here Q – is a pulse amplitude; γ_x, γ_y – is a pulse width in xandydirection accordingly, v – is an initial pulse velocity Equation (12) was solved by numerically using a direct finite-difference cross-like scheme [21]. Stride by time and coordinate are determine by standard conditions of stability, even so, strides of finite-difference scheme are halved serially, until the solution didn't change in 8th sign.

As shown results of our numerical calculations, the light bullet propagation is stable and the evolution we can see in Fig. 1.

As we see from such dependences, the solution for two-dimensional light bullet in the inhomogeneous environment stay located, but change, as a result of cross dispersion, its space structure. The combined action of effects of the pulse spreading, as a result of dispersion and nonlinearity leads to formation of complex structure in the of the pulse front, which stays located in limited space area.

The results of our numerical modeling, depends on lattice period, presents in Fig. 2. As follow to wait for, when we increase a lattice period, the few-circle optical pulse propagates more quickly. Obviously, when a lattice period is infinite, as a result of absence of the interference process, the pulse will be propagate with maximal velocity. It was confirmed in our numerical calculations. Also we mark a distortion of the pulse form.

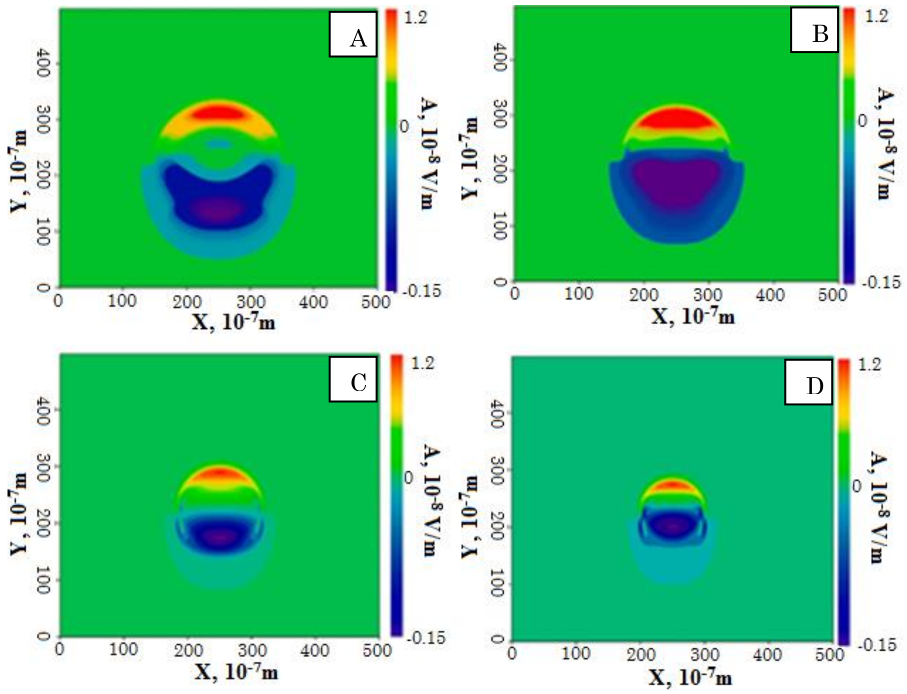

Fig. 1 – The light bullet propagation in inhomogeneous environment with cross modulation (lattice period $\chi = 6$ mkm) with carbon nanotubes in different time moment T A) 10×10^{-12}, B) 8×10^{-12}, C) 6×10^{-12}, D) 5×10^{-12}

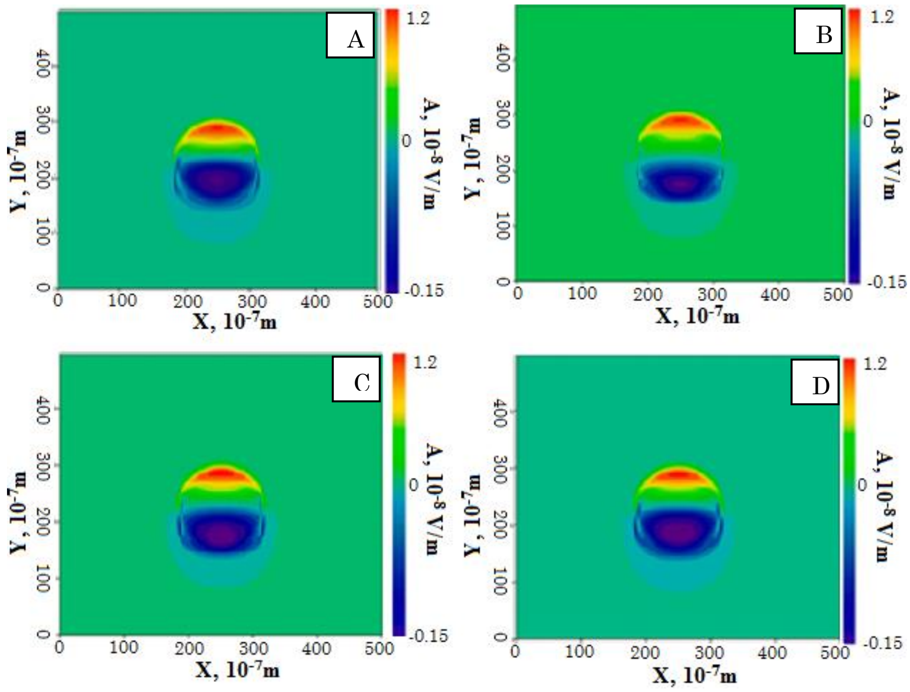

Fig. 2 – The light bullet propagation in inhomogeneous environment with cross modulation with carbon nanotubes in fixed time moment $T = 6$ ps, with different lattices period χ A) 0.125 mkm, B) 0.1 mkm, C) 0.25 mkm, D) 0.05 mkm

4. CONCLUSION

From our research, we can do next resume:

1. The few-circle optical pulses propagation in the inhomogeneous environment of carbon nanotubes is stable. The environment heterogeneity in sizeable degree influences to pulse form, smooth out it.

2. Was fixed that, a heterogeneity period of environment influences to the propagation velocity of the few-circle optical pulse. The period increase leads to same fact that pulse "reflect" from "borders" more rare, and, as a result its velocity increase. When we change a heterogeneity period, we can control the propagation velocity of pulse. It's very impotent for applied tasks of optics.

3. The pulse slowdown, and also change it form happen when we increase a depth modulation of heterogeneity, cause strong interference. Especially strong form changes we can see on the slump of the few-circle optical pulses.

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