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Short Communication

2D Few Cycle Optical Pulses in Silicene in the Presence of External Electric Field

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In this paper, we study the influence of external electric field on the propagation characteristics of two-dimensional few cycle optical pulses in silicene. This electric field is perpendicular to the silicene plane. We obtain an effective equation, which has the form of nonlinear wave equation with a saturating nonlinearity. Also, we investigate the dependence of electromagnetic field intensity on the amplitude and on the spatial period of the external electric field.

Keywords: Silicene, Few cycle optical pulses, External field.

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1. INTORDUCTION

In recent years, researchers have increasingly paid more attention and interest to the nonlinear light propagation in the graphene-like structures (graphyne, stanene, germanene, borophene and so on). These structures have unique properties, which can be used in many practical applications [1]. One of such materials is silicene, which consists of a single layer of silicon atoms in a hexagonal lattice [2-3]. Contrary to graphene, silicene is not flat, but has a periodically buckled topology. However, a main feature of silicene is stronger spin-orbit interaction then in graphene (in 1000 times: 10^{-3} meV vs. 3.9 meV) [4].

All of these circumstances and the fact that silicon is still the main element of the modern microelectronic devices makes the problem of its properties investigation more attractive from the point of view of studying the few cycle optical pulses.

In recent works, we studied the problem of the propagation of 1D few cycle optical pulses in silicene waveguides [5]. We observed a signal inversion from a certain time moment. Herewith the amplitude of the inverted signal is almost twice the original amplitude. Thus, we can talk about amplification of the few cycle optical pulses at the change in their shape.

At the same time there are many questions related to the study of the multi-dimensional (2D and 3D) pulses propagation in silicene.

However, the problem of the control pulse parameters within wide ranges (is environment with alternating refractive indices) is not solved. Due to the reflection at the interface and due to the subsequent interference, the velocity of the pulse propagation reduces, and this environment can be used as a delay line.

But, the synthesis of these environments makes it impossible to control the time delay, which has a great influence for applications. In silicene, the silicon atoms do not lie exactly in one plane, and are located above and below it. So, it is possible to control the width of the band gap by applying an electric field in the direction perpendicular to the plane. In this case, since the potential difference between the sublattices of the gap directly depends on the applied constant electric field. Obviously, if we change the value and the intensity of the constant electric field, one can receive the Bragg environment analogue.

2. BASIC EQUATIONS

In the long-wavelength approximation, the Hamiltonian for silicene can be written as [6-7]:

$$H = v\left(\xi k_x\sigma_x + k_y\sigma_y\right) - 0.5\xi\Delta_{SO}\tau_z\sigma_z + 0.5\Delta_z\sigma_z, \quad (1)$$

where $\xi - \pm$ is the valley sign for two Dirac points, υ is the velocity of the Dirac electrons, $\boldsymbol{p} = (k_x, k_y)$ is the electron quasi-momentum, Δ_{SO} is the spin-orbit interaction in silicene, Δ_z is the potential on the one lattice side ($\Delta_z = E_z d$, $E_z = B\cdot sin(\alpha\cdot z)$ is the constant electric field with the spatial period: $2\pi/\alpha$, d is the distance between two sublattice planes, σ_i, τ_i are the Pauli matrices).

We can write the Hamiltonian in the matrix form and we obtain the following eigenvalues:

$$\varepsilon_{\sigma\xi} = \pm\sqrt{\upsilon^2k^2 + \frac{1}{4}\left(\Delta_z - \sigma\xi\Delta_{SO}\right)^2} \quad (2)$$

here σ is the electron spin (spin «up» and «down»).

The Maxwell`s equations with taking into account this calibration: $E = -\partial A/c\partial t$ and the following replacement: $p \to p - eA/c$ (e is the electron charge), can be written in 2D case as:

$$\frac{\partial^2 \mathrm{A}}{\partial x^2} + \frac{\partial^2 \mathrm{A}}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 \mathrm{A}}{\partial t^2} + \frac{4\pi}{c}\mathrm{j} = 0 \quad (4)$$

where vector-potential: $\boldsymbol{A} = (0, A(x,z,t), 0)$, and the density of current: $\boldsymbol{j} = (0, j, 0)$.

Further, we consider the low-temperature case, when the only small area in the momentum space near

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the Fermi level is taking into account. Then the density of electric current can be written as:

$$j = e\int_{-\Delta}^{\Delta}\int_{-\Delta}^{\Delta} dp_z dp_y v_y (p - \frac{e}{c}A(x,z,t)) \qquad (5)$$

The integration region can be defined from the conservation condition for the particle number:

$$\int_{-\Delta}^{\Delta}\int_{-\Delta}^{\Delta} dq_z dq_y = \int_{ZB}\int dq_z dq_y \left\langle a^+_{qz,qy} a_{qzqy} \right\rangle$$

where ZB means the first Brillouin zone.

The equation of the few cycle pulse propagation has the form:

$$\frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial z^2} - \frac{1}{c^2}\frac{\partial^2 A}{\partial t^2} + \frac{4\pi}{c}\Phi(A) = 0\,, \qquad (6)$$

here $\Phi(A)$ is determined by the integration in Eq. (6).

Equation (6) is solved numerically [8]. The initial condition in two-dimensional case was chosen in the few cycle pulse, consisting one oscillation of the field:

$$A(z,0) = Q\cdot exp\left(-z^2/\gamma_z\right)exp\left(-x^2/\gamma_x\right), \qquad (7)$$

$$\frac{dA(z,0)}{dt} = \frac{2zv_z}{\gamma_z}Qexp\left(-z^2/\gamma_z\right)exp\left(-x^2/\gamma_x\right) \qquad (7')$$

where Q is the pulse amplitude, $v_{z,x}$ are the initial velocity along z and x axis, $\gamma_{z,x}$ are the pulse width along z and x axis. The values of energy parameters are expressed in units of Δ. Time is the evolution coordinate.

3. NUMERICAL MODELING AND RESULTS

The evolution of 2D electromagnetic filed propagating in silicene is presented in Fig. 1.

During propagation, the main pulse form undergoes minor changes, losing in amplitude. It should be noted, that in process of time a "tail" appearing after the main pulse increases. This fact may be associated with the excitation of the nonlinear wave pulses.

Comparison for two cases (with taking into account external electric field and without it) is shown in Fig. 2.

As can be seen in Fig. 2, taking into account the external field of momentum has a great influence on the pulse propagation process. In addition to the "tail" appearance, there is a decrease in the amplitude of the main pulse, caused by an energy transfer to the pulse behind the main pulse. Thus, the introduction of the additional field destroys the balance between the

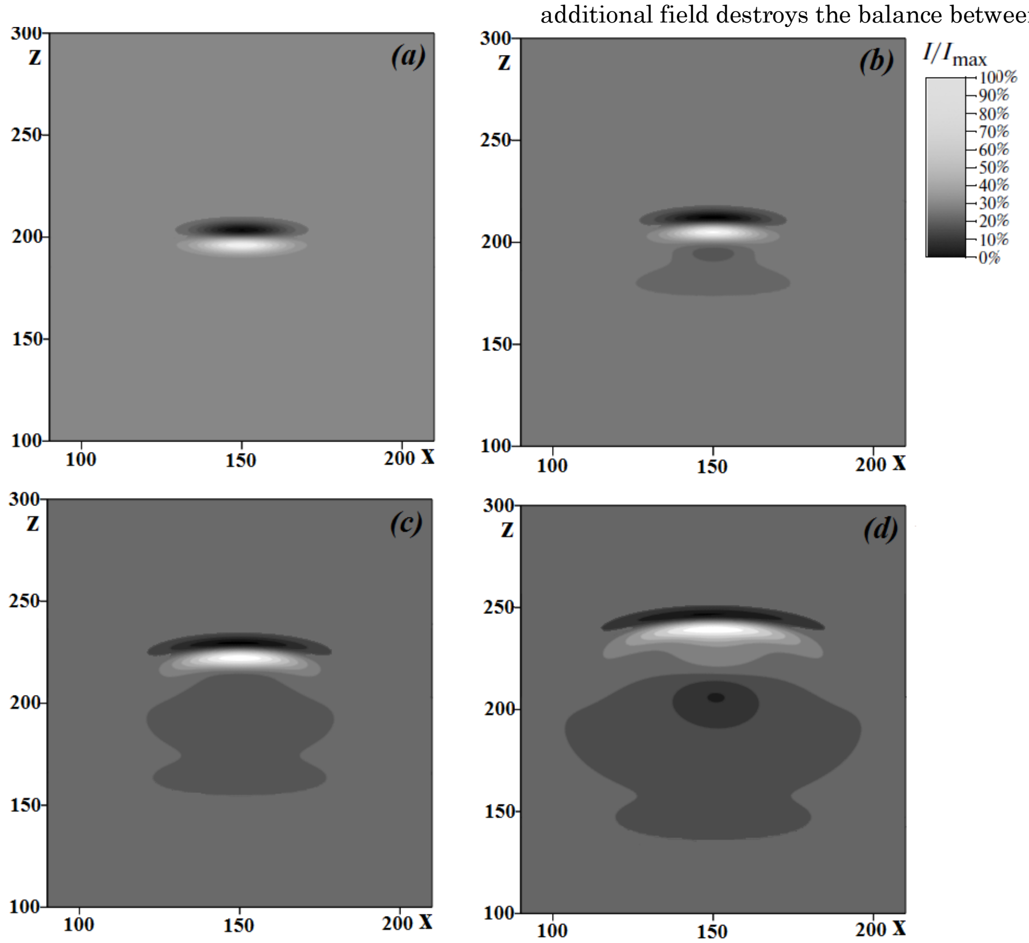

Fig. 1 – The intensity of two-dimensional electromagnetic pulse $I(x,z,t) = E^2(x,z,t)$ in the different time points: a) initial form; b) $t = 1.0\cdot10^{-13}$ s; c) $t = 3.0\cdot10^{-13}$ s; d) $t = 5.0\cdot10^{-13}$ s

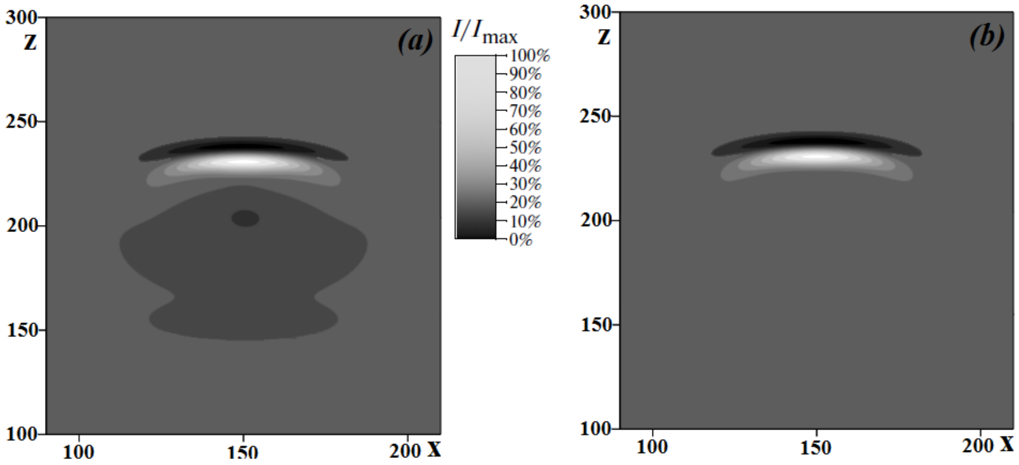

Fig. 2 – The intensity of two-dimensional electromagnetic pulse $I(x,z,t) = E^2(x,z,t)$ at time $t = 4.0 \cdot 10^{-13}$ s: a) $E_z \neq 0$; b) $E_z = 0$

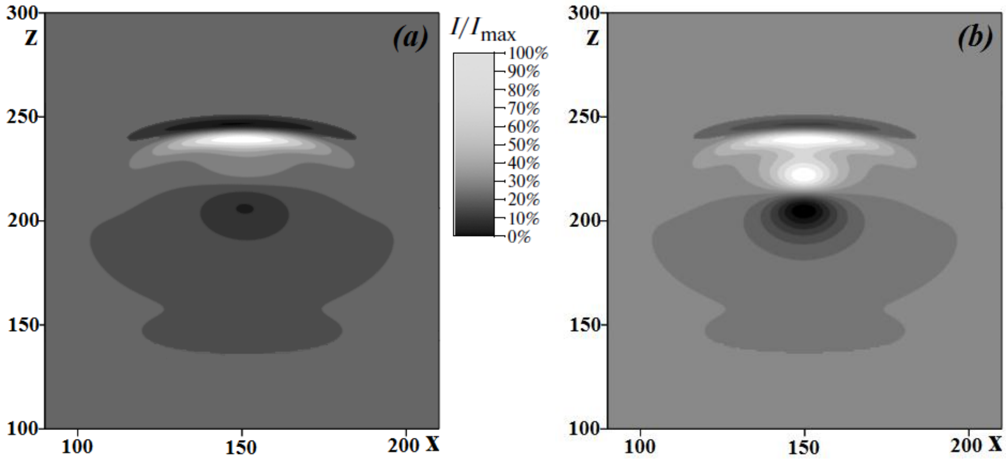

Fig. 3 – The intensity of two-dimensional electromagnetic pulse $I(x,z,t) = E^2(x,z,t)$ at time $t = 5.0 \cdot 10^{-13}$ s: a) $\alpha = 0.05$; b) $\alpha = 0.2$

dispersion and the nonlinearity of the system, which leads to the amplitude damping.

The influence of the spatial period $2\pi/\alpha$ of the alternating momentum field is given in Fig. 3. This figure shows that the wider the pulse of the external alternating momentum field, the smaller the formed "tail". That is changing the spatial period of the field E_z, we can control the form of the few cycle optical pulse.

The numerical results showed that the decrease in the amplitude of the external alternating momentum field is two times reduces the main pulse peak at 1.7%

4. CONCLUSION

1. Consideration of the external alternating momentum field violates the balance between the dispersion and the nonlinearity in the system, causing a reduction in the amplitude of the few cycle optical pulse.

2. Few cycle optical pulse in silicene causes the appearance of the "tail". This fact can be associated with the excitation of nonlinear waves.

3. We can control pulse propagation in silicene by selecting the parameters of the external alternating momentum field E_z (amplitude, and particularly, width).

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