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Self-induced transparency in graphene

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ABSTRACT

A theory of optical solitons under the condition of nonlinear coherent interaction of surface TM-modes with a two-dimensional layer of semiconductor quantum dots and a graphene monolayer (or graphene-like two-dimensional material) is developed. Explicit analytical expressions for a surface soliton (2π pulse) of self-induced transparency are obtained. It is shown that the optical conductivity of graphene reduces the amplitude of the surface soliton in the process of propagation.

1. Introduction

Surface plasmon-polaritons (SPPs) are evanescent electromagnetic waves which can propagate along the boundary surface of different materials, when the real part of their permittivities has opposite signs, for instance, a metal and a dielectric [1,2]. The electric field of this wave has a maximum at the interface, and its amplitude decays exponentially in the directions perpendicular to the interface. The properties of SPPs are more interesting and manifold when one or more transition layers are present at the interface of the connected media. It is known that a surface transition layer, e.g. a thin film placed between two semi-infinite media, can have an essential influence on the properties of the SPPs if they are in resonance with the electronic excitations of the layer. The properties of SPPs are determined by the dielectric tensors of the surrounding media and by the transition layer(s). SPPs have attracted much interest also in the context of the optics of monolayer graphene which is sandwiched between two media (see, for instance, [3,4] and references therein). Graphene causes considerable attention due to its remarkable electronic and optical properties [5,6]. The optical response of graphene is characterized by its surface conductivity which is closely related to its Fermi energy [7]. Carbon-based materials such as graphene are of recognized importance also for their potential applications [8].

Nonlinear optical effects play an important role in the study of the properties of SPPs. Nonlinear phenomena arise when electronic motion in a strong electromagnetic field cannot be considered harmonic. The nonlinear solitary SPP of invariable profile is one of the brightest demonstrations of nonlinearity in optical many-layered systems. Among nonlinear solitary waves, solitons are very often encountered. In the theory of nonlinear surface waves, the solitons play a fundamental role as harmonic oscillations do in the theory of linear SPPs. The conditions for the existence of nonlinear SPPs are manifold. The determination of the conditions of existence of optical surface solitons and the study of their features are among the principal problems of the theory of SPPs. Depending on the character of the nonlinearity, the nonresonance or the resonance mechanism of the existence of solitons is realized. In the first case of nonresonant nonlinearity, which is expressed by means of the quadratic or cubic nonlinear susceptibilities, its competition with the dispersion (or dissipation) leads to the existence of nonresonance surface solitons. The existence of the transition layer is especially convenient for the investigation of resonance SPPs in the case of resonant nonlinearity (see, for instance [9] and references therein). Resonance nonlinear SPPs can propagate in these systems when the surface modes are in resonance with the optically active impurity atoms or semiconductor quantum dots (SQDs) of the transition layer. The optically resonant solitons of SPP can be excited within the McCall–Hahn mechanism, where a nonlinear coherent interaction SPP takes place via Rabi-oscillations of the carrier density, if the conditions for self-induced transparency (SIT) are fulfilled: $\omega T \gg 1, T \ll T_{1,2}$, where T and ω are the width and the carrier frequency of the pulse, respectively, and T_1 and T_2 are the longitudinal and transverse relaxation times of the atomic systems or SQDs in many-layered systems, respectively. When the area of the pulse of SPP exceeds π, a soliton (2π pulse) is formed [10,11].

A natural extension of the study of the propagation of surface solitons is the investigation of SIT in a graphene monolayer. The ability of tuning the value of the Fermi energy of graphene by an external gate makes it especially interesting, because the properties of nonlinear SPPs can be controlled externally in different

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ways. Usually, the conductivity of graphene has a complex character which can be considered as a sum of intraband and interband processes. But, for simplicity, as a first attempt to study surface solitons of SIT in graphene, we will consider the case where the optical conductivity of graphene has the simplest form and consider its influence on the parameters of the surface soliton. Investigation of SIT in graphene will also open new possibilities for the development of devices for optoelectronic applications.

The main goal of this work is as follows. We investigate the processes of formation of optical solitons of SIT for surface waves propagating along the interface between two infinite media with two transition layers. One of the transition layers is a graphene monolayer and the second one is described using a model of a two-dimensional gas of atoms or SQDs. We determine the profile and explicit analytic expressions for the parameters of the surface soliton.

2. Basic equations

We consider the formation of an optical resonance soliton in graphene for a SPP in the case when an optical pulse of the transverse magnetic polarized mode (TM-mode) with width T and frequency $\omega \gg T^{-1}$ is propagating along positive direction of the z-axis. We consider the structure of four divided media. The graphene monolayer and a thin transition layer with thickness h containing a small concentration of two-level atoms (or SQDs) are sandwiched between two semispaces, medium 1 ($x<0$) and medium 2 ($x>0$) with different permittivities ε_1 and ε_2, respectively. The polarization of the system composed of two-level atoms (or SQDs) has the form $\vec{P}(x,z,t) = \vec{e}_z p(z,t)\delta(x)$, where $\vec{e}_z$ is the polarization unit vector along the z-axis. The electric current density of the graphene monolayer is given by $\vec{J}(x,z,t) = \sigma \vec{E}(z,t)\delta(x)$, where $\sigma(\omega)$ is the electrical conductivity of graphene. For a surface TM-mode, the electric field $\vec{E}(E_x, 0, E_z)$ lies in the xz-plane perpendicular to the boundary of the division between the two connected media. The magnetic field $\vec{H}(0, H_y, 0)$ is directed along the y-axis. We assume translational invariance in the y-direction, so that all field quantities are independent of the coordinate y, i.e. $\partial/\partial y = 0$. The graphical illustration of the model is shown in Fig. 1.

We consider the optical spectral region $h \ll \lambda$, where λ is the length of the surface optical wave. Therefore, SIT can be modeled as a SPP propagation along the flat border of the division (at $x=0$) between two semispaces with boundary conditions in which we take into account the surface current caused by the presence of a system of two-level atoms (or SQDs) and by the conductivity of the graphene monolayer.

After the integration of the Maxwell equation [12]

$$rot\, \vec{H} = \frac{1}{c}\frac{\partial \vec{D}}{\partial t} + \frac{4\pi}{c}\vec{J},$$

the boundary conditions for SPPs at $x=0$ read

$$H_{2;y} - H_{1;y} = \frac{4\pi}{c}\left(\frac{\partial p}{\partial t} + \sigma E_{1;z}\right), \quad E_{1;z} = E_{2;z}, \quad D_{1;x} = D_{2;x}, \tag{1}$$

where $\vec{D}$ is the electric induction, c is the velocity of light in vacuum.

We will consider a Fourier-decomposition of the fields $H_{2;y}$ and $H_{1;y}$ which are given by

$$H_{1;y}(x,z,t) = \int \mathcal{H}_{1;y}(\Omega, Q) e^{\kappa_1 x} e^{i(Qz - \Omega t)}\, d\Omega\, dQ \quad \text{for } x<0,$$

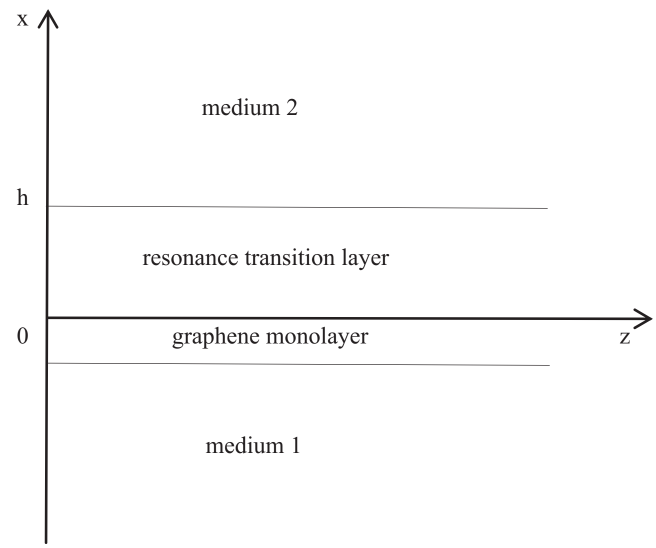

Fig. 1. The direction of propagation of the surface TM-mode is along the z-axis. The vector of the electric field $\vec{E}$ lies in the x–z-plane. The vector of the magnetic field $\vec{H}$ is directed along the y-axis perpendicular to the plane of the figure. The resonance transition layer with thickness h contains two-level atoms (or SQDs).

$$H_{2;y}(x,z,t) = \int \mathcal{H}_{2;y}(\Omega, Q) e^{-\kappa_2 x} e^{i(Qz - \Omega t)}\, d\Omega\, dQ \quad \text{for } x>0, \tag{2}$$

where

$$\kappa_i^2 = Q^2 - \frac{\varepsilon_i}{c^2}\Omega^2, \quad i = 1,2. \tag{3}$$

Analogous expressions exist for the quantities $E_{1,2;x}$ and $E_{1,2;z}$.

Substituting Eqs. (2) and (3) into Eq. (1), we obtain the nonlinear wave equation for the E_z component of the strength of the electrical field at $x=0$, in the following form:

$$\int \mathcal{F}(\Omega, Q) E_z(\Omega, Q) e^{i(Qz - \Omega t)}\, d\Omega\, dQ = -4\pi p(z,t) + 4\pi\sigma \int E_z\, dt, \tag{4}$$

where

$$\mathcal{F}(\Omega, Q) = \frac{\varepsilon_1}{\kappa_1} + \frac{\varepsilon_2}{\kappa_2},$$

$E_{1;z}(\Omega, Q) = E_{2;z}(\Omega, Q) = E_z(\Omega, Q)$. This equation is valid for any dependence of the polarization of two-level atoms (SQDs) $p(z,t)$ on the strength of the electrical field at $x=0$.

In order to determine the dependence of the polarization $p(z,t)$ on the strength of the electrical field at $x=0$, we have to consider the Schrödinger equations for two-level atoms [13,14]:

$$i\hbar \frac{\partial c_1}{\partial t} = -dE_z c_2 e^{-i\omega_0 t},$$

$$i\hbar \frac{\partial c_2}{\partial t} = -dE_z c_1 e^{i\omega_0 t} \tag{5}$$

where c_1 and c_2 are the probability amplitudes, ω_0 is the frequency of excitation of the two-level atom, d is the electric dipole moment for the corresponding transition, assumed to be real, n_0 is the concentration of optically active two-level atoms (SQDs), and $\hbar$ is Planck's constant.

3. Equations for envelopes

Using the method of slowly changing envelopes,

$$E_z = \sum_{l=\pm 1} \hat{E}_l Z_{-l}, \tag{6}$$

where $\hat{E}_l$ is the slowly varying complex envelope of the electric field and $Z_l = e^{il(kz - \omega t)}$ contains the rapidly varying phase of the