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Few-cycle solitons in the medium with permanent dipole moment under conditions of the induced birefringence

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ABSTRACT

Propagation of electromagnetic pulse in the birefringent medium consisting of symmetric and asymmetrical molecules is investigated. Stationary quantum states of asymmetrical molecules have the permanent dipole moment. Under considered conditions the ordinary pulse component excites quantum transitions between stationary states. The extraordinary component, besides, causes a dynamic chirp of frequencies of these transitions. The new solitonic modes of propagation of the half- and single-period pulses are found. The solitonic mechanism of simultaneous generation of the second and zero harmonics in the modes of "bright" and "dark" solitons is analyzed.

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1. Introduction

To the present time there are many optical solitons capable to be formed in nonlinear media [1]. There are, for example, solitons with accurately expressed carrier frequency and with slowly varying envelope (quasi-monochromatic solitons). These objects were intensively investigated from the 60th to the 90th years of last century. In the mid-eighties in experimental conditions the pulses, which are containing about one period of the oscillations [2,3], were generated. Such pulses are known as "few-cycle pulses" (FCP). These experiments were good incentive for theoretical investigations of interaction of FCP with the matter. Since then the nonlinear optics of FCP gained rapid development. Theoretical studies of propagation of FCP in various media and under various conditions were conducted (see, for example, reviews [4–7] and the works quoted in them). It is clear, that under theoretical investigations, concerning propagation of FCP it is impossible to use standard approximation of slowly varying envelopes.

Recently the investigations of dynamics of optical pulses in systems of asymmetrical molecules gained considerable development [8–10]. Such molecules have the permanent dipole moments (PDM) in stationary quantum states. Quantum dots, quantum rods, etc. can possess such properties. [11–13]. Under such conditions the electric field of the pulse not only excites the quantum transitions between stationary states, but also causes a dynamical chirp of the eigen frequencies of these transitions. Besides, the polarizing response of the medium is characterized by both non-diagonal, and diagonal elements of a density matrix. The scalar (one-component) [9,10,14–16] and vector (two-component) [17–20] models of the pulse electric field were considered. Vector models were used for investigation of propagation of the pulse in the birefringent media. Such vector models in which the ordinary pulse component caused quantum transitions between stationary states were considered. At the same time the extraordinal component only chirped the frequency of these transitions. However, situations when an extraordinary component not only causes chirp of the frequencies of quantum transitions, but also excites these transitions, are possible.

Generally speaking, ordinary and extraordinary components excite different quantum transitions. For this reason it is necessary to refuse two-level model of the medium, which was used in the works noted above. Besides, the one-component model of the medium, generally speaking, does not correspond to a real situation. It is known also that the two-component model of the medium is capable to describe almost adequately a real situation [21–24]. In that case the eigen-frequencies of both atomic component have to differ considerably from each other.

The present work is devoted to investigation of propagation of the vector electromagnetic solitons in the birefringent medium containing symmetrical and asymmetrical molecules. The birefringence is formed by the external electric and magnetic fields. The approaches used here allow to describe the propagation of FCP and quasi-monochromatic pulses.

This article is organized as follows. In Section 2, the two-component model of the nonlinear quantum medium consisting of symmetric and asymmetrical molecules is offered. In Section 3 and in Appendix A the procedures of the excluding of material

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variables are carried out. As a result, the components of a polarizing response of the medium are expressed through the pulse electric field. Here the system of the nonlinear wave equations for ordinary and extraordinary pulse components is obtained. Then this system is reduced to one nonlinear equation of Konno, Kameyama, and Sanuki. Thus, the profiles of ordinary and extraordinary pulse components can be expressed through solutions of this equation. In Section 4, on the basis of soliton and breather solutions is carried out the physical analysis of various modes of the pulse propagation. Simultaneous effective generation of the second and zero harmonics in the modes of “bright” and “dark” solitons is studied (see also Appendix B). Under the considered conditions the second harmonic belongs to visible spectral range. At the same time a zero harmonic is overlapping terahertz spectral range. In Section 5, final remarks to results of work are made.

2. Physical model and main equations

We will consider that the media consists of molecules of two grades. Molecules of a grade 1 are asymmetrical, possessing PDM. Molecules of a grade 2 do not possess PDM. Such situation corresponds, for example, to isotropic dielectric with an inclusion of quantum dots.

Let the electromagnetic pulse propagates along an y-axis, perpendicular to the optical z-axis formed by external permanent electric $\mathbf{E}_{ext}$ and magnetic $\mathbf{H}_{ext}$ fields. Under theese conditions the PDM of asymmetrical molecules are parallel to an optical axis. Thus, the ordinary electric component E_o of the pulse is polarized along an x-axis. At the same time an extraordinary component E_e is parallel to z-axis.

Quantum levels of both types of molecules experience the simultaneous splitting of Zeeman and Stark. The magnetic field removes degeneration with respect to the magnetic quantum number m, and electric field – with respect to the module of magnetic number.

We will consider that molecules of both types are characterized by the scheme of the quantum transitions displayed in Fig. 1. Let the characteristic frequencies of molecules of the first ω_1 and second ω_2 types lie in the terahertz and in visible ranges respectively. Assuming in such a way that $\omega_1 \sim 10^{13}\ \mathrm{s}^{-1}$, $\omega_2 \sim 10^{15} - 10^{16}\ \mathrm{s}^{-1}$ and a pulse duration $\tau_p \sim 10^{-14}$ s, we will have inequalities:

$$\mu_1 \equiv \omega_1 \tau_p << 1, \tag{1}$$

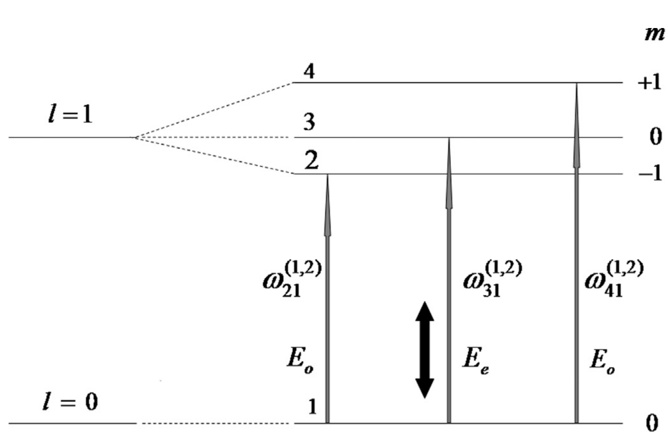

Fig. 1. A scheme of the quantum transitions under conditions of the Zeeman and Stark splitting. A pulse propagates perpendicularly to the optical axis. Numbering of quantum levels corresponds to the increase of energy. The ordinary pulse component excites transitions s and h. The extraordinary component excites g transition. The solid double arrow corresponds to that the extraordinary component causes also the dynamic shift of quantum levels.

$$\mu_2 \equiv (\omega_2 \tau_p)^{-1} << 1. \tag{2}$$

Let us note that the conditions (1) and (2) for an excluding of material variables were for the first time offered in works [25,26]. Later this approach was used in works [21–23,27–30].

The inequality (1) designates, that the spectral width of the pulse considerably exceeds frequencies of the quantum transitions. In this regard it is possible to call it approximation of spectral overlapping. We will notice also that an inequality (1) sometimes is designated as the approximation of sudden excitation [31].

The meaning of a condition (2) consists in rather weak interaction of the pulse with the matter. Therefore, it is possible to call it approximation of optical transparency.

We will pass now to the obtaining of the material equations. The interaction Hamiltonian in electro-dipole approximation we will write down in the form of $\hat{V}_{\mathrm{int}}^{(j)} = -\hat{d}_x^{(j)} E_o - \hat{d}_z^{(j)} E_e$, where $j = 1, 2$, $\hat{d}_x^{(j)}$ and $\hat{d}_z^{(j)}$ are the corresponding Cartesian projections of the operator of the dipole moment. The up index in brackets designate the belonging to first ($j = 1$) or to second ($j = 2$) grade of the molecules.

The eigen functions of the energy operator $\hat{H}_0^{(1)}$ of free molecule with PDM, accounting for its axial symmetry with respect to z-axis, we will write down in the form of $\Phi_{l,m}^{(1)} = f_{l,m}(z, r)\exp(im\varphi)$. Here $f_{l,m}(z, r)$ are the real functions of coordinates z and r of the cylindrical coordinate system, φ is the azimuthal angle, and l is the angular quantum number ($m = -l, \ldots, l$).

Assuming that $x = r\cos\varphi$, we come to a conclusion that nonzero matrix elements of the operator of the dipole moment in representation of the eigen functions of operator $\hat{H}_0^{(1)}$ have an appearance:

$$d_{21} = \left(d_x^{(1)}\right)_{21} = -\pi e \int_0^{\infty} r^2 dr \int_{-\infty}^{+\infty} f_{1,-1} f_{0,0} dz,$$
$$d_{31} = \left(d_z^{(1)}\right)_{31} = -2\pi e \int_0^{\infty} r dr \int_{-\infty}^{+\infty} z f_{1,0} f_{0,0} dz, d_{41} = \left(d_x^{(1)}\right)_{41}$$
$$= -\pi e \int_0^{\infty} r^2 dr \int_{-\infty}^{+\infty} f_{1,+1} f_{0,0} dz,$$
$$D_{11}^{(1)} = \left(d_z^{(1)}\right)_{11} = -2\pi e \int_0^{\infty} r dr \int_{-\infty}^{+\infty} z f_{0,0}^2 dz, D_{22}^{(1)} = \left(d_z^{(1)}\right)_{22}$$
$$= -2\pi e \int_0^{\infty} r dr \int_{-\infty}^{+\infty} z f_{1,-1}^2 dz,$$
$$D_{33}^{(1)} = \left(d_z^{(1)}\right)_{33} = -2\pi e \int_0^{\infty} r dr \int_{-\infty}^{+\infty} z f_{1,0}^2 dz, D_{44}^{(1)} = \left(d_z^{(1)}\right)_{44}$$
$$= -2\pi e \int_0^{\infty} r dr \int_{-\infty}^{+\infty} z f_{1,+1}^2 dz.$$

Here e is the elementary charge; numbering of quantum levels corresponds to increase of values of their energy (see Fig. 1).

Diagonal elements of the operator of the dipole moment are designated by capital letters. It is made to distinguish them from not diagonal elements corresponding to quantum transitions between stationary states.

Thus, in considered geometry the ordinary pulse component causes the sigma-transitions $1 \leftrightarrow 2$ and $1 \leftrightarrow 4$, for which $\Delta m = \pm 1$. The extra-ordinary component causes pi-transition $1 \leftrightarrow 3$ ($\Delta m = 0$). Besides, the extra-ordinary component chirps the eigen frequencies of quantum transitions.

We will take into account that in case of the Zeeman triplet equalities $d_{31}^{(j)} = d_j$ and $d_{21}^{(j)} = d_{41}^{(j)} = d_j/\sqrt{2}$ ($j = 1, 2$) are carried out [32]. Besides, $D_{\mu\mu}^{(j)} = 0$, if $j = 2$.

Taking into account the told we will write down expressions for quantum meanings of the ordinary $P_o^{(j)} = n_j \mathrm{Tr}\left(\hat{\rho}^{(j)} \hat{d}_x^{(j)}\right)$ and extra-

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