Quasisurface nonlinear nonsymmetric waves in symmetric three–layer structure with left-handed film

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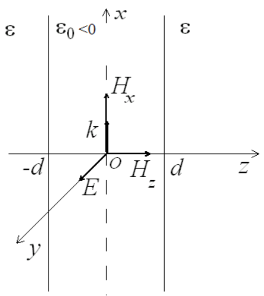
Abstract: We study the theory of nonsymmetric nonlinear s–polarized quasisurface waves, propagating along the plane interface of symmetric three–layer structure with linear left-handed film. The behavior of dispersion laws depends on the core thickness.

Key words: quasisurface waves, left-handed film.

I. Introduction

In recent years due to the rapid development in the field of fiber optics the interest in the producing of new types of waveguides increased very much. It stems from the increased necessity in the rising of the efficiency of the fiber optical communication systems. Fabrication of the multilayer waveguides with the broad transmission bands, hollow fibers, photon-crystallized structures and others gives possibilities to decrease essentially the optical losses. In some studies, nonlinear phenomena in media with the negative refraction of electromagnetic radiation are investigated [1, 2]. The authors of [3] analyzed the propagation of electromagnetic waves in dispersing media and phenomena appearing at the interface with a gyrotropic medium were investigated. The authors of [4] showed the possibility of occurrence of polariton waves with a negative group velocity at optical frequencies. Along with this, the possibility to fabricate waveguides using metamaterials as a core or coverings is actively studied [5–7]. The authors of [8, 9] investigated the properties of TE-polarized and TM-polarized nonlinear surface waves at the interface between the Kerr nonlinear medium and metamaterial medium. The occurrence of the waves with different polarization at interfaces between the Kerr nonlinear media and metamaterials is shown in [10–12]. The authors of [13] investigated the properties of nonlinear TE-polarized surface and waveguide modes in asymmetric three-layered structure with linear coverings and core with the Kerr nonlinearity and negative linear background components of the dielectric and magnetic susceptibility. The occurrence of a slit soliton in the antidirected coupler is predicted and soliton properties of the quadratically and cubically nonlinear media with the negative refraction at a frequency of the fundamental wave are described [14–17]. Therefore, the investigation into the features of propagation of the laser radiation in metamaterials is undoubtedly interesting.

We will study the propagation of the nonlinear TE-polarized nonlinear nonsymmetric quasisurface waves in the symmetric three-layer structure (fig 1).



We suppose that the waveguide consist of the linear slab with the thickness $2d\left(-d \le z \le +d\right)$, which is characterized by the constant dielectric susceptibility $\varepsilon_0 < 0$ and magnetic permeability $\mu_0 < 0$ and of two semi-infinite nonlinear semiconductor claddings, in which the propagating wave excites the excitons from the ground state of the crystal and simultaneously converts them into biexcitons due to the process of optical exciton-biexciton conversion. We use the expression for the dielectric function ε of the nonlinear medium depending on the frequency ω and the amplitude E of the electromagnetic wave obtained in [18-23]:

$$\varepsilon = \varepsilon_\infty \left(1 - \frac{\omega_{LT}}{\Delta} \frac{E_s^4}{\left(E_s^2 - E^2\right)^2}\right), \quad (1)$$

where $E_s^2 = 2\Delta^2/\sigma^2$, $\Delta = \omega - \omega_0$ – in the resonance detuning, $\omega_{LT} = 4\pi\hbar g^2/\varepsilon_\infty$ – is the longitudinal-transversal splitting of the exciton, ε_∞ – is the baclground dielectric, σ – is the constant of optical exciton-boexciton conversion ahd g – constant of the exciton-photon interaction. We will investigate the peculiarities of the steady-state propagation of the TE-polarized nonlinear nonsymmetric quasisurface waves in the geometry of fig.1. We suppose that the electromagnetic wave propagates along the x-axis with the wave vector k. The field TE-polarized wave consists of the transverse electric E (parallel to axis y) and magnetic H_z component, as well as the longitudinal component H_x of the magnetic field. For the Maxwell equation we obtain the following wave equations, which describe the spatial profiles of the electric field E of the electromagnetic wave:

$$\frac{d^2E}{dz^2}=\frac{\omega^2}{c^2}\left(n^2-\varepsilon_\infty\left(1-\frac{\omega_{LT}}{\Delta}\frac{E_s^4}{\left(E_s^2-E^2\right)^2}\right)\right)E \quad , |z|\geq d \quad (2)$$

$$\frac{d^2E}{dz^2}=\frac{\omega^2}{c^2}\left(n^2+\varepsilon_0\right)E, \quad |z|\leq d, \quad (3)$$

where $n=ck/\omega$ is the effective index of medium, c is the speed of light. We look for the spatially confined quasisurface waves, the energy of which is localized near the interface at $|z|=d$. That is why we use the following conditions:

$$\lim_{z\to\pm\infty} E\to 0; \quad \lim_{z\to\pm\infty} dE/dz\to 0. \quad (4)$$

Integrating of the equations (2)-(3) and using new spatial variable $\bar{z}=\frac{\omega}{c}z$, we obtain the following integrals of motion:

$$\left(\frac{dE}{d\bar{z}}\right)^2+W(E)=0, \quad (5)$$

$$W(E)=-E^2\left(n^2-\varepsilon_\infty+\varepsilon_\infty\frac{\omega_{LT}}{\Delta}\frac{E_s^2}{E_s^2-E^2}\right), \quad |z|\geq d \quad (6)$$

$$W(E)=-E^2\left(n^2+\varepsilon_0\right), \quad |z|\leq d. \quad (7)$$

Hear $W(E)$ plays the role of the potential energy of the nonlinear oscillator, the evolution of which is described be the equation (5). We represent the expression (6) in the form $W(E)=-E^2\left(n^2-\varepsilon^*\right)$, where in accordance with (6) we obtain the next expression for the effective dielectric function ε^* of the medium:

$$\varepsilon^*=\varepsilon_\infty\left(1-\frac{\omega_{LT}}{\Delta}\frac{E_s^2}{E_s^2-E^2}\right), \quad (8)$$

The analyses of the equation (5) shows that the solutions in the form of the nonlinear nonsymmetric quasisurface modes exist for those values of the field amplitudes $E(x)$, for which the inequality $W(E)\leq 0$ is fulfilled. This means that the solutions exist at $\Delta>0$, $n^2\geq\varepsilon_0$, and $n^2>\varepsilon_{ex}=\varepsilon_\infty\left(1-\frac{\omega_{LT}}{\Delta}\right),\varepsilon^*$. Hence we come to conclusion that the nonlinear nonsymmetric quasisurface waves can exist only in the short-wave region of the exciton self frequency.

The solutions of the equation (3) for the even and odd nonlinear nonsymmetric quasisurface waves have the form

$$E=\frac{C}{q_0}ch\left(q_0\bar{z}+\varphi\right), \quad (9)$$

$$E=\frac{C}{q_0}sh\left(q_0\bar{z}+\varphi\right), \quad (10)$$

where $q_0=\sqrt{n^2+\varepsilon_0}$, φ – phase and C is the integration constant. Now the can satisfy the conditions of the conservation of the tangential components of the electric and magnetic fields at the interface $\bar{z}=D$. Using (9)-(10) and (5) we obtain

$$q_0 th\left(2q_0D+arch\left(\frac{q_0E_b}{C}\right)\right)==\sqrt{n^2-\varepsilon_\infty+\varepsilon_\infty\frac{\omega_{LT}}{\Delta}\frac{E_s^2}{E_s^2-E_0^2}}, \quad (11)$$

$$q_0 cth\left(2q_0D-arsh\left(\frac{q_0E_b}{C}\right)\right)==\sqrt{n^2-\varepsilon_\infty+\varepsilon_\infty\frac{\omega_{LT}}{\Delta}\frac{E_s^2}{E_s^2-E_0^2}}. \quad (12)$$

The expressions (11)-(12) are the dispersion lows, which determine the effective index n of medium depending on the resonance detuning Δ for fixed values of the slab thickness D.

II. Discussion of results

We consider now the peculiarities of the behavior of the energy flow and dispersion low of the nonlinear quasisurface waves. Further we will use the normalized resonance detuning and Raby frequency: $\delta=\Delta/\omega_{LT}$, $f_0=\sigma E_0/\omega_{LT}$. We will investigate the peculiarities of the dispersion curves

$n(\delta, f_0)$ of the even nonlinear nonsymmetric quasisurface wave. From (5) it follows that $n^2 > \varepsilon_0, \varepsilon^*, \varepsilon_{ex}$, where $\varepsilon^* = \varepsilon_\infty\left(1+|\delta|/\left(\delta^2 - f_0^2/2\right)\right)$. Therefore these waves exist only in the spectral range $\delta > 0$.

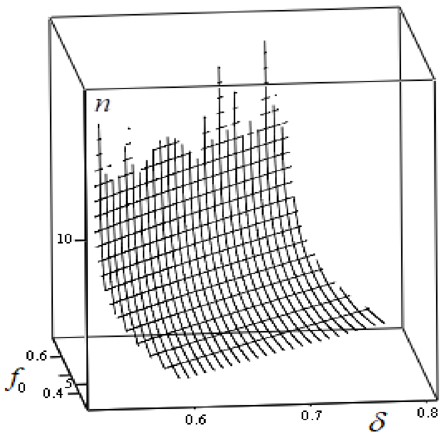


Fig.2 Dependence of the effective refractive index n on the resonance detuning δ for different values of field amplitude f_0 for $\varepsilon_0 = 7$, $\varepsilon_\infty = 5$ and $D = 0.1$.

III. CONCLUSIONS

In conclusion we point out that the obtained results for the s- polarized nonlinear nonsymmetric quasisurface mode propagating in a three layer structure with the metamaterial core and nonlinear claddings, nonlinearity of which is due to the interaction of the exitons and biexitons with the light, essentially differ from the results of the over investigations of the surface waves in the structures on the interfaces between the metamaterial and Kerr media. Obtained dispersion lows are determined by the carried flux and by the thickness of the linear slab.

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