NONLINEAR COOPERATIVE STEADY STATES OF FRÖHLICH PHONONS IN BIOLOGICAL OBJECTS

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Abstract. *Nonlinear cooperative stationary phenomena are studied at the interaction of Bose-condensed phonons with millimeter electromagnetic radiation in biological media. The real and imaginary parts of dielectric susceptibility and permeability, refraction and reflection indexes determined by Bose-condensed phonons were obtained. The possibility of polariton occurrence in biological objects was predicted.*

Keywords: *millimeter waves, Bose-Einstein phonons, complex dielectric functions.*

I. Introduction

The investigation of the nonlinear cooperative phenomena in complex system is one of the most important and up-to-date problems of the modern science. At present the interest for the investigation of the interaction of the millimeter range coherent electromagnetic radiation with medical-biological objects has increased significantly, due to increasing and effective application of the millimeter waves in applied medicine, biotechnology and agriculture [1-5]. The concept of generation of phonons in alive media was proposed by Fröhlich [6]. He suggested theoretically that biological systems can generate collective vibrational modes (phonons) in the GHz frequency range and these phonons might play a basic role in active biological systems. The basic idea is that if the energy is supplied to the phonon with a rate greater than a certain critical value, then the phenomenon of Bose condensation to the lowest excitation of a single mode can occur. Original idea of the millimeter wave generation in alive systems stimulated further investigations in this domain, aimed first of all at investigation and prediction of essentially new biophysical phenomena and their correct effective usage in biomedicine [7-10]. Although the number of experimental and theoretical papers in that domain continuously grows, nevertheless till now there is no a clear understanding of the mechanism of generation and interaction of the millimeter radiation with biological media, the uniform consistent theory of the low-intensity millimeter wave interaction with biological media was not elaborated, a lot of cooperative nonlinear phenomena is not investigated.

This paper is devoted to the investigation of nonlinear cooperative phenomena at the Bose-condensed phonon interaction with the millimeter electromagnetic radiation that can be generated in a biological object. The collective nonlinear properties of the coherent phonons are obtained, in particular, by the phonon-phonon interaction character, the energetic spectrum of the coherent phonons and their interaction with the non-condensed quasiparticles. Great attention is devoted to the study of the real and imaginary parts of dielectric susceptibility and permeability, refraction and reflection indexes determined by Bose-condensed phonons. The possibility of polariton occurrence is also discussed.

II. Model Hamiltonian and Dielectric Functions

Based on the Fröhlich idea that coherent phonons excited in biological objects turn into coherent internal photons and form the self-correlated interval millimeter electromagnetic field we will describe the mode Hamiltonian and cooperative steady states caused by generated Fröhlich phonons in biological medium. The coherent states of the elementary excitations can appear in the regime of ultrashort pulses and exist during a time period shorter that the relaxation times, as well as in conditions of Bose-Einstein condensation during a time period longer that the relaxation times, but shorter that the quasiparticle life time. The Hamiltonian of the field – phonon system that describes the interaction of Bose-condensed dipole active phonons is given by

$$
\begin{aligned}
H = {} & \sum_{\vec{k}} \hbar\Omega a^{+}_{\vec{k}} a_{\vec{k}} + \frac{1}{8\pi}\sum_{\vec{k}} \int \left(\varepsilon E^{2}_{\vec{k}} + \mu H^{2}_{\vec{k}}\right) dv_{\vec{k}} \\
& + \frac{1}{2V}\sum_{\vec{k}_1,\vec{k}_2,\vec{k}_1',\vec{k}_2'} g\left(\vec{k}_1 - \vec{k}_1'\right)\delta_{kp}\left(\vec{k}_1 + \vec{k}_2, \vec{k}_1' + \vec{k}_2'\right) a^{+}_{\vec{k}_1} a^{+}_{\vec{k}_2} a_{\vec{k}_1'} a_{\vec{k}_2'} - \sum_{\vec{k}} d_{\vec{k}}\left(E^{+}_{\vec{k}} a^{+}_{\vec{k}} + E^{-}_{\vec{k}} a_{\vec{k}}\right),
\end{aligned}
\tag{1}
$$

where $\hbar\Omega$ is the dipole-active phonon energy, $E_{\vec{k}} = E^{+}_{\vec{k}} + E^{-}_{\vec{k}}$, $H_{\vec{k}} = H^{+}_{\vec{k}} + H^{-}_{\vec{k}}$ are the intensities of the electrical and magnetic fields, respectively, $E^{\pm}_{\vec{k}}$ and $H^{\pm}_{\vec{k}}$ are the positive or negative frequency parts of the variable electromagnetic field, $a^{+}_{\vec{k}}(a_{\vec{k}})$ are the operators of creation (annihilation) of the dipole-active phonons that satisfy the commutation relation: $[a_{\vec{k}}, a^{+}_{\vec{k}'}] = \delta_{kk'}$, $[a_{\vec{k}}, a^{+}_{\vec{k}}] = 0$. In the expression (1) the phonon-phonon interaction constant is notated by $g\left(\vec{k}\right)$; $d_{\vec{k}}$ is the dipole momentum of the transition into phonon state and ε, μ are the dielectric and magnetic permeability of the biological medium.

The equation that describes the dynamic evolution of Fröhlich millimeter electromagnetic field and the Bose-condensed phonons is given by the expression

$$
\frac{da_k}{dt} = i\left[\Delta + i\gamma - \frac{g}{\hbar} n\right] a_k + i\frac{d}{\hbar} E\,, \tag{2}
$$

where $\Delta = \omega - \Omega$ is the resonance detuning between the Fröhlich field frequency and the phonon frequency, n represents the concentration of the Bose-condensed phonons. Here, the term $i\gamma a$ takes into account the Bose-condensed phonons leaving from condensed state.

In what follows we consider the steady states i.e. $da_k / dt = 0$. In this case we can obtain the relations for real and imaginary parts of the dielectric susceptibility

$$
\chi' = -\frac{d^2}{V_O\hbar}\frac{\Delta - gn/\hbar}{(\Delta - gn/\hbar)^2 + \gamma^2}\,,\quad \chi'' = \frac{d^2\gamma}{V_O\hbar}\frac{1}{(\Delta - gn/\hbar)^2 + \gamma^2}\,. \tag{3}
$$

We consider that one phonon level is isolated but all the rest energetic levels are supposed to be far on the energetic scale, so the dielectric permeability, that takes into account the phonon level contribution, is described by the expression $\varepsilon = \varepsilon_\infty + 4\pi\chi = \varepsilon' + i\varepsilon''$, where $\varepsilon', \varepsilon''$ are the real and imaginary parts of the dielectric permeability:

$$
\varepsilon' = \varepsilon_\infty - \frac{4\pi d^2}{V_O\hbar}\frac{\Delta - gn/\hbar}{(\Delta - gn/\hbar)^2 + \gamma^2}\,, \varepsilon'' = \frac{4\pi d^2\gamma}{V_O\hbar}\frac{1}{(\Delta - gn/\hbar)^2 + \gamma^2}\,. \tag{4}
$$

Here, ε_∞ is the phonon dielectric permeability that takes into account the dielectric permeability of all excitations besides phonons of the biological media.

For a plane wave, where the surfaces of the field constant values are planes, the dielectric permeability, perpendicular to the spreading direction, is connected with the refraction index $\bar{n}$ and with the absorption index k by the expression: $\varepsilon = \bar{n}^2 - k^2 + 2i\bar{n}k$, where

$$
\bar{n} = \sqrt{\left(\varepsilon' + \sqrt{\varepsilon'^2 + \varepsilon''^2}\right)/2}\,,\ k = \sqrt{\left(-\varepsilon' + \sqrt{\varepsilon'^2 + \varepsilon''^2}\right)/2}\,. \tag{5}
$$

The reflection coefficient R is defined as the ratio of the time average energy flow reflected from surface to the incident flow. At perpendicular flow the reflection coefficient assumes the expression

$$R = \frac{(\bar{n}-1)^2 + k^2}{(\bar{n}+1)^2 + k^2}. \qquad (6)$$

Analogical dependencies are obtained at investigation of the optical bistability phenomena in the excitonic spectrum range in condensed media [11]. Supposing that electromagnetic field is uniformly distributed in the biological media of volume V_O. The equation of the field temporal evolution in the slowly-varying amplitude approximation has the form

$$\frac{dE}{dt} = i\left[\frac{w^2 - c^2k^2}{2w} - \frac{4pd^2}{V_O\mathbf{h}}\right]E + \frac{2pdwi}{V_O}\left[1 - \frac{2}{w}\left(w - \Omega - \frac{g}{\mathbf{h}}n\right) - \frac{2ig}{w}\right]a. \qquad (7)$$

In the stationary case $\partial E / \partial t = 0$ and the dispersion limit, when the attenuation of the dipole-active Bose-condensed phonons can be neglected, from (7) one can obtain

$$\bar{k}^2 = \bar{w}^2\left[1 + \bar{w}_0 / (1 - \bar{w})\right], \qquad (8)$$

where $\bar{k} = k / k_O$, $\bar{w} = w / (ck_O)$, $\bar{w}_O = \Omega_O / (ck_O)$ and $ck_O = \Omega + gn / \mathbf{h}$.

The equation (8) determines the dispersion law of the nonlinear polaritons, i.e. the energy values of the elementary excitations in biological medium at the Fröhlich radiation interaction with dipole-active Bose-condensed phonons at the same value of the wave vector. The polariton appearance is caused by the intersection of the coherent photon dispersion curves with Bose-condensed phonon ones at small wave vectors.

II. Numerical results and discussions

The expression (8) coincides with the dispersion law of the polariton at the investigation of the soliton appearance in the excitonic spectrum range for the case when the solution temporal width tends to the infinity. At not enough large field intensities, the bond between the phonon concentration and the field one is linear. While excitation increases, the phonon-phonon interaction processes play an important role. It is easy to observe that the relation between N and f is linear for $d < 3$ (see Fig.1a).

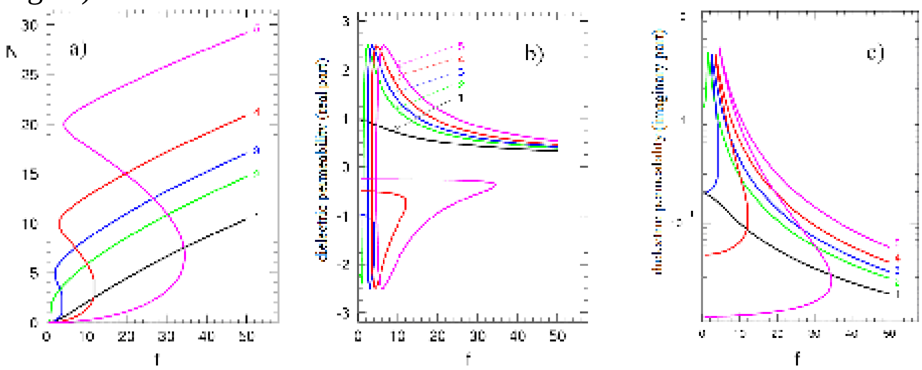

Fig.1 The phonon concentration and the real and imaginary parts of the dielectric permeability dependencies on the field intensity for different values of the resonance detuning: 1. d =-5.0, 2. d =1.7, 3. d =5.0, 4. d =10.0 и 5. d =20.0

When $d > \sqrt{3}$, the dependency $N(f)$ is characterized by three-valued regions i.e. three values of the dipole-active Bose-condensed phonon density correspond to one values of the Fröhlich field intensity. In Fig.1 the phonon concentration dependence on field intensity is represented at various resonance detuning values d. As it is shown in the figure, the field intensity grow leads to the jump increase of the Bose-condensed phonon density at $d > \sqrt{3}$. While field decreases along the upper curve, a jump fall of phonon density occurs at $d > \sqrt{3}$. Thus, the forward and backward alteration of the Fröhlich field intensity leads to the jump changes of the phonon density and to formation of the amplitude hysteresis loop in the $N(f)$ dependence when the resonance detuning value is larger than the critical $d_c = \sqrt{3}$. The frequency hysteresis can be shown to occur also when one resonance detuning value correspond to three values of the phonon density, one of which is unstable, at values larger than the critical field intensity value $f_c = (4/3)^{3/4}$. We mention that we observed also the nonlinear hysteresis dependency in the real and imaginary parts of the dielectric susceptibility and permeability.

III. Conclusion

In this paper we developed a model to describe the interaction of Bose-condensed phonons with millimeter electromagnetic radiation in biological media. The real and imaginary parts of dielectric susceptibility and permeability, refraction and reflection indexes determined by Bose-condensed phonons were obtained. We show that for values larger than the critical field intensity value f_c, the hysteresis appears in the system and three values of the phonon density are observed. The position and the form of the polariton branches depend not only on the parameters of the phonons and of the electrical field but also on the stationary concentration of the Bose-condensed phonons.

IV. References

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