3. In an inhomogeneous plasma in the presence of phase coherence of the particles and resonant radiation conditions, there can appear qualitatively new types of nonlinear regeneration of the waves, for example echo at the summary frequency in an isotropic plasma. Let us consider an inhomogeneous isotropic one-dimensional plasma contained by a monotonically-varying effective potential $\Phi(x)$. The external source is given by

$$I_{ext} = \sum_{n=1}^{2} I_n \delta(x - a_n) \cos \omega_n t .$$

After reflection of the particles from the potential $\Phi(x)$, the phase of the second-approximation distribution function takes the form $[v(x, \mathcal{E}) = \sqrt{2(\mathcal{E} - \Phi)}]$

$$\theta(\mathcal{E}, x) = \omega_1 \left(\int_{a_1}^{x_\mathcal{E}} \frac{dx'}{v} + \int_{x}^{x_\mathcal{E}} \frac{dx'}{v} \right) + \omega_2 \left(\int_{a_2}^{x_\mathcal{E}} \frac{dx'}{v} + \int_{x}^{x_\mathcal{E}} \frac{dx'}{v} \right) \quad (\Phi(x_\mathcal{E}) = \mathcal{E}).$$

Under phase-coherence conditions we have $\partial\theta(\mathcal{E}, x_c)/\partial\mathcal{E} = 0$ in the vicinity of x_c, and a macroscopic current of plasma particles is produced and excites natural oscillations if the resonance point $x_s[k(\omega_1 + \omega_2, x_s) = (\omega_1 + \omega_2)/v(x_s, \mathcal{E})]$ is located near the point x_c.

By way of an example we present a calculation of the echo at the frequency 2ω from one external source, with $\omega < \omega_p(x) < 2\omega$. The field of the echo itself is given by

$$|E_2| = (2\pi)^{5/2} \frac{e\omega_p^2 I^2}{m\omega k_2^3(x_c)} \left| \Pi(x)\, \Pi(x_c) \frac{d^2F_0(\mathcal{E})}{d\mathcal{E}^2} \right| .$$

Here $\Pi(x) = [\partial\varepsilon_2/\partial k_2(x)]^{-1/2}$ and ε_2 is the dielectric constant at the frequency 2ω. The effect under consideration is one of the methods of generating harmonics in an inhomogeneous plasma.

The authors are grateful to Ya.B. Fainberg for valuable advice, and also to V.N. Oraevskii, E.Ya. Kogan and V.A. Lisichenko for useful exchange of information on problems of echos in an inhomogeneous plasma.

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POSSIBILITY OF DIRECT AMPLIFICATION AND GENERATION OF ELECTRIC WAVES IN SEMICONDUCTORS

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Submitted 17 October 1970
ZhETF Pis. Red. 12, No. 11, 532 - 536 (5 December 1970)

It is well known that in semiconducting crystals acoustic waves can experience Cerenkov amplification under conditions when the carrier drift velocity exceeds the phase velocity of the sound [1]. At the aame time, amplification of the electric signal in the system as a whole (i.e., realization of an amplifier based on this principle) is possible only in exceptional cases (see, e.g., [2]). The main difficulty lies in converting the electric signal into an acoustic one and vice-versa even with a relatively large gain of the acoustic wave in the crystal itself.

We shall show in this paper that at certain frequencies, when the so-called coupled acousto-plasma waves exist, these difficulties do not arise. This is due to the fact that in a coupled acousto-plasma wave the energy density accompanying this electric-field wave becomes equalized with the density of the elastic energy, and therefore the amplification, naturally, does not require that the electric signal be transformed into an acoustic one and vice-versa. Moreover, a concrete calculation shows that Cerenkov amplification of a coupled acousto-plasma wave (e.g., in a piezoelectric semiconductor) can greatly exceed the amplification of the ordinary acoustic wave.

Let us consider the simplest case of propagation of an acoustic wave with one type of polarization in a piezoelectric-semiconducting crystal. Then the dispersion equation is [1]:

$$\epsilon_{\parallel}(\omega, q)(\omega^2 - q^2 v_s^2 + i\mu\omega^3) = \eta^2 \epsilon_0 q^2 v_s^2 , \tag{1}$$

where $\varepsilon_{\parallel}(\omega, q)$ is the longitudinal dielectric constant of the plasma medium, μ the viscosity, v_s the speed of sound, η the constant of electromechanical coupling, ε_0 the dielectric constant of the lattice, ω the frequency, and q the wave vector. In the investigations of the character of the amplification of acoustic waves in semiconductors, one is usually interested in the solution of Eq. (1) subject to the condition

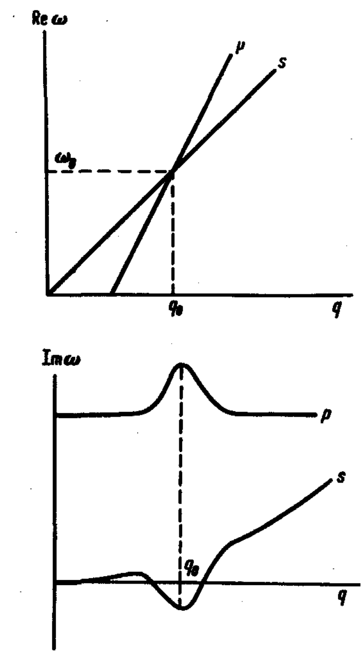
$$\left| \eta^2 \frac{\epsilon_0}{\epsilon_{\parallel}(\omega, q)} \right|_{\omega \approx q v_s} << 1, \tag{2}$$

i.e., when it is possible to confine ourselves to perturbation theory and find the corrections to the wave vector or to the frequency. Near the point of the coupled waves, however, i.e., near the roots of the equation

$$\epsilon_{\parallel}(\omega, q)\Big|_{\omega \approx q v_s} = 0 , \tag{3}$$

such an analysis no longer is valid, and the problem must be solved differently (see [3]). The physical condition (3) means that there exists in the plasma system a longitudinal plasma wave (or waves) having a point of intersection with the acoustic branch of the spectrum. The "turning on" of the interaction between the acoustic and the plasma modes can, generally speaking, lead to a restructuring of the spectrum of the entire system as a whole; this question, however, does not interest us now (see [1, 3]).

It should be noted that the plasma waves corresponding to the roots of Eq. (3) either have no points of intersection with the acoustic branch of the spectrum at all, or have such a large damping increment γ_p that it is meaningless to consider them. It is therefore necessary to indicate immediately the conditions under which the occurrence of coupled acousto-plasma waves is possible. As shown in [4], such coupled waves can arise only in the presence of a sufficiently strong magnetic field, when the cyclotron frequency of the electron in the magnetic field is much larger than the effective collision frequency, and furthermore the wave frequency ω is close to the cyclotron-resonance frequency. In this case for a wave propagating in a direction perpendicular to crossed electric and magnetic fields the longitudinal dielectric



constant of the medium is [3]:

$$\epsilon_{\parallel}(\omega, q) = \epsilon_0 + \frac{\epsilon_0}{q^2 r_0^2}\left\{1 - \frac{\omega - qv_d}{|q|v_T\,\mathrm{tg}\frac{\pi}{\Omega}(\omega - qv_d + i\nu) - i\nu}\right\}, \qquad (4)$$

where $r_0 = (\epsilon_0 T/4\pi e^2 n_0)^{1/2}$ is the Debye radius, $v_T = (2T/\pi m)^{1/2}$ the thermal velocity of the electrons, $\Omega = eB/mc$ the cyclotron frequency of rotation of the electron in the magnetic field, ν the effective collision frequency, and $v_d = c(E_d/B)$ the carrier drift velocity in the crossed fields, with $\Omega \gg \nu$. It follows from (4) that the spectrum of the plasma wave is given by

$$\mathrm{Re}\,\omega = \omega_p = n\Omega\left(1 + \frac{\Omega}{\pi|q|v_T(1 + q^2 r_0^2)}\right) + qv_d, \quad \gamma_p = -\nu, \qquad (5)$$

where account was taken of the fact that near the cyclotron resonance we have $|qv_T/\Omega| \gg 1$. The integer n can assume only such values at which the frequency ω_p remains positive. When $n < 0$ expression (5) describes slow plasma waves that exist only in a medium with a translational motion of the electrons (see the figure). This is precisely the wave which we consider below.

It is easy to see that the corrections to the frequency at the point of the coupled waves $\{\omega_0 q_0\}$ will be

$$\Delta\omega_{\pm} = -\frac{i}{2}\left[\nu + \frac{\mu\omega_0^2}{2} \pm \sqrt{|n|G + \left(\nu - \frac{\mu\omega_0^2}{2}\right)^2}\right], \qquad (6)$$

where $G = 2\eta^2 q_0^2 r_0^2 v_s \Omega/\pi v_T(1 + q_0^2 r_0^2)^2$. Negative values of n at the point of the coupled waves are possible only at a drift velocity exceeding the phase velocity of the acoustic waves. It is precisely in this case, as seen from (6), that one of the oscillation modes, which we shall call acoustic, will increase. It is important that when $G \gg (\nu + \mu\omega_0^2/2)^2$ the increment is proportional simply to the modulus of the constant of electromechanical coupling, and not to its square as in the case of amplification of an ordinary acoustic wave far from the coupled-wave point. For a crystal such as InSb, where $\eta = 6 \times 10^{-2}$, $v_s = 2.3 \times 10^5$ cm/sec, $v_T = 2.3 \times 10^7$ cm/sec, and $\Omega = 2.2 \times 10^{13}$ sec^{-1} for the maximum gain increment (i.e., at $q_0 r_0 = 1$), we obtain from formula (6) Im $\Delta q = 8.7 \times 10^4$ cm^{-1}.

The electric field produced in the coupled acousto-plasma wave is best characterized by means of the dimensionless ratio

$$\psi = \left|\frac{\frac{1}{16\pi}\frac{\partial}{\partial\omega}[\mathrm{Re}(\omega\epsilon_{\parallel})|E|^2]}{\frac{1}{2}\rho\omega^2|u|^2}\right|. \qquad (8)$$

Using the connection between the vectors $\vec{E}$ and $\vec{u}$ [1], we can easily show that at the point of the coupled waves we have $\psi = (1/4)[|n|G/(\mathrm{Im}\Delta\omega_- + \nu)^2]$, and for the acoustic mode, at the parameters indicated above, we have $\psi = 2.5 \times 10^{-2}$, which is ten times larger than the ratio of the energies in a piezodielectric.

In addition to amplifying an external electric signal, it is possible also to generate coupled acousto-plasma waves. In a number of experiments, high-frequency generation of electromagnetic oscillations were observed in InSb single crystals in crossed electric and magnetic fields [4]. In our opinion, the reason for the occurrence of such generation is closely connected with the formation of the acousto-plasma wave. Indeed, Cerenkov generation of phonons occurs at an electron drift velocity larger than the speed of sound in a crystal. Most frequently, a broad frequency spectrum is generated, and naturally, the spectrum contains frequencies for which formation of coupled acousto-plasma waves is possible. Since the electric field accompanying this wave is relatively large, it is clear that the electromagnetic radiation received by the receiver from the crystal will have a sharp minimum at the frequency (or frequencies) corresponding to the coupled-wave point. Thus, in spite of the relatively broad spectrum of the generated acoustic phonons, the resonator will receive effectively, in the experiment, only those frequencies that correspond to coupled acousto-plasma waves.

In conclusion, we are sincerely grateful to V.L. Ginzburg and L.V. Keldysh for discussions.

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ERRATUM

In the article by V. A. Margulis, Vol. 12, No. 5, p. 186, the factor h/m* was omitted from formulas (5) and (6). In addition, the factor h was omitted from formula (4) (p. 185) and formula (7). Formula (8) should read

$$\frac{1}{\pi}\,\frac{1/r}{\left[\dfrac{\kappa P_y}{m^*} + \left(\dfrac{\tilde{\omega}^2}{\omega_0^2}\right)^2\left(\dfrac{\hbar k^2}{2m^*} - \tilde{\omega}\right)\right]^2 + \dfrac{1}{r^2}}\,.$$

NOTE

For technical reasons, the balance of the Russian version of Volume 12, Number 11 will be published in Volume 12, Number 12 of the translation.