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PHASE CONJUGATION OF ACOUSTIC WAVES IN SEMICONDUCTORS

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Abstract - We discuss a new mechanism of phase conjugation in acoustics based on phonon-plasmon interaction in the conditions when the conduction electrons density is modulated in time. Such modulation can be realized by periodic laser illumination of the sample or due to Zinner’s transitions in the external alternating electric field.

From general point of view the problem of the phase conjugation in acoustics may be formulated as the problem of realization of space-homogeneous parametric interaction in the contrary sound beams system. The using of the interaction between the acoustic oscillations and various types of collective oscillations in solids, which are liable for the external fields, holds great promise in this respect. Altering the parameters of the collective mode with the help of the field, we can reach the necessary coupling of the sound waves.

Here we investigate the possibility of the sound phase conjugation based on the phonon-plasmon interaction in piezoelectric semiconductors in the conditions when the density of conduction electrons is modulated in time. We discuss two mechanisms of such modulation: the direct optical electron transitions under the laser pumping of the sample and Zinner’s electron tunneling in the alternating electric field. We show that the propagation of the acoustic wave in the sample is accompanied by the effective transfer of the energy from the incident beam into the energy of the reflected phase conjugated beam in a definite domain of variations of the parameters of the semiconductor and external pumping.

We consider a semiconducting piezoelectric layer, which has infinite dimensions with respect to the transverse $X$ and $Y$ coordinates and thickness $L$, an external acoustic wave, which is linearly polarized along the $Z$ axis and described by the displacement $U_{\text{inc}}(z,t) = 0.5 \ U^\dagger(z,t) \ e^{i(\omega t-kz)} + \text{c.c.}$, is incident on the layer along $Z$ axis. We shall assume for simplicity and without loss of generality that $Z$ axis coincides with the [011] axis of a crystal of structure class 31, and that the $X$ axis corresponds to the [100] axis. The sample is pumped uniformly by a periodic (with period $T=T_c$) train of laser pulses of intensity $I(t)$, or of electric pulses with field intensity $E_{\text{ext}}(t)$. For the chosen symmetry we obtain a coupled system of equations which describes the variation of the density $N$ of electrons in the conduction band and holes respectively under the action of periodic pumping along with deviation $n, p$ of electron and hole densities and the electron and hole...
velocities $v, v, \text{in}$ connection with the Langmuir plasma oscillations exited by the piezoelectric induction field $E$ accompanying an acoustic wave with displacement $U$ along $x$ axis $/1-4/$:

$$\rho \frac{\partial^2 U}{\partial t^2} = c \frac{\partial^2 U}{\partial z^2} - \bar{e} \frac{\partial E}{\partial z} ; \quad \varepsilon \frac{\partial E}{\partial z} + \bar{e} \frac{\partial^2 U}{\partial z^2} = -4\pi e (n-p) ;$$

$$\frac{\partial \bar{e}}{\partial t} + \nu \bar{e} = -\frac{e}{m} E ; \quad \frac{\partial \bar{p}}{\partial t} + \nu \bar{p} = \frac{e}{m} E ;$$

$$\frac{\partial n}{\partial t} - D \frac{\partial^2 n}{\partial z^2} + N \frac{\partial v}{\partial z} = 0 ; \quad \frac{\partial p}{\partial t} - D_p \frac{\partial^2 p}{\partial z^2} + N \frac{\partial v}{\partial z} = 0 ;$$

$$\frac{\partial N}{\partial t} + \frac{N - N_0}{\tau_{\text{rel}}} = k I(t) ;$$

where $N_0$ is the equilibrium dark density of electrons in the conduction band, $\tau_{\text{rel}}$ is the interband relaxation time of the electrons, $k$ is proportional to the linear light-absorption coefficient, $e$, $m$, $m_p$ are the effective charge and masses of the electron and the hole, $\nu$ is the effective electron scattering frequency, $\rho$ is the density of the crystal, $c$ and $\bar{e}$ are the stiffness constant and piezoelectric stress constant corresponding to the chosen geometry, $\varepsilon$ is the permittivity, and $D$, $D_p$ are the diffusion coefficients for electrons and holes.

For Zinner's mechanism the last equation must be replaced by:

$$\frac{\partial N}{\partial t} + \frac{N - N_{\text{ext}}}{\tau_{\text{rel}}} = 0 ;$$

where $N_{\text{ext}}$ is the equilibrium conduction electron density in the external electric field, $N_{\text{ext}} = N_v p$, $N_v$ is the electron density in the valence band, $P$ is the probability of Zinner's tunneling.

Expanding the function $I(t, E_{\text{ext}}(t)$ in a Fourier series we obtain the corresponding expansion for $N(t)$:

$$N(t) = N_0 + N_1 e^{2i\omega t} + N_{-1} e^{-2i\omega t} + \ldots$$

It is readily shown that the excitation of higher harmonics of $N(t)$, generally speaking, results in the generation of an infinite set of acoustic harmonics during the propagation of the acoustic wave $U_{\text{inc}}$ in the medium, where the frequencies of the harmonics are multiples of $\omega$ and the wave vector $k$ is the same as for the incident wave. However, only the components with the frequency $\omega$ satisfy the dispersion relations for acoustic oscillations in the crystal and thus yield the dominant contribution to the total acoustic field. We therefore retain only written terms in the expansion.

We seek a steady-state solution of Eq. (1) in the form of the sum of the incident wave $U^+$ and a reflected wave $U$:

$$U(z, t) = 0.5 \left[ U^+(z) e^{i(\omega t - k z)} + U^-(z) e^{i(\omega t + k z)} \right] + \text{c.c.}$$

Here $U^+(z)$, $U^-(z)$ are slowly varying amplitudes. The other variables are represented in an analogous form.
Solving (1) we arrive at the final equations for $u^+, u^-$:

$$\frac{du^+}{dz} = -iQ \left[ \frac{\varepsilon v}{\Lambda} + \frac{1}{\Lambda} \left( \frac{\omega^2}{\Omega} + \frac{\omega^2}{\Omega_p} \right) \right] u^+ + \frac{Q}{\Lambda} \left( \frac{\omega^2}{\Omega} + \frac{\omega^2}{\Omega_p} \right) U^-$$

$$\frac{du^-}{dz} = -iQ \left[ \frac{\varepsilon v}{\Lambda} + \frac{1}{\Lambda} \left( \frac{\omega^2}{\Omega} + \frac{\omega^2}{\Omega_p} \right) \right] U^- + \frac{Q}{\Lambda} \left( \frac{\omega^2}{\Omega} + \frac{\omega^2}{\Omega_p} \right) u^+$$

We note that in typical crystals $m_p > m$ and $D_p > D$.

Below we assume for definiteness that the pumping pulses are rectangular. Then, if we neglect the relaxation distortion of the pulse fronts, for small dark density and on condition $\omega T_{rel} << 1$, the function $N(t)$ will reproduce the time profile of the pump: $N(t) = \beta_0 r_{rel} I(t)$, or $N(t) = N_{ext}(t)$.

As it follows from Eq. (2) the picture of waves propagation essentially depends on the relation between the sound frequency $\omega$ and the effective diffusion time in the system. Thus we shall treat two practically important limits.

1. Low frequency: $\omega / D_p k^2 >> 1$. On this condition the phonon-plasmon interaction induces additional attenuation in the system, determined by the invariable component $N_0$. It is clear that the parametric interaction of the waves should be comparable with their attenuation for the efficient conversion of acoustic energy from the incident to the reflected wave. This imposes the following condition on the relation between pumping pulse duration $\tau_{imp}$ and $\omega: \omega \tau_{imp} << 1$. Then for coupling coefficient $A$ we obtain:

$$A = Q \frac{\omega^2}{\varepsilon^2 + \frac{1}{3} (\omega^2 \tau_{imp})^2} \frac{1}{\omega^2_p/\omega^2_p} ; \quad \omega^2_p = \frac{4 \pi e^2 N_0}{m_p} ; \quad M^{-1} = m^{-1} + m^{-1}$$

It follows at once that $A$ increases as the energy of the laser pulse (or $E_{ext}$) is increased up to value $A_{max} = 3^{0.5} Q \nu / 2 \pi \omega \tau_{imp}$, corresponding to $\omega^2_p / 2 \pi \nu / \tau_{imp}$, and then decreases to zero as $\omega_p$ is increased further.

The solution of Eq. (2) with the boundary conditions $U^+(0) = U_0$, $U^-(L) = 0$ gives the following output amplitude of the reflected wave:

$$U^-(0) = -U_0 \frac{l}{l+1} ; \quad l = A \Lambda L$$

We see that the wave front of $U^-$ is reversed relative to the wave front of $U^+(0)$. The amplitude of the phase-conjugated wave increases monotonically with the value of $l$ and at $l = 1$ attains half the amplitude of the incident wave at the input.

2. High frequency: $\omega / D_p k^2 << 1$. Strong diffusion plasmon attenuation decreases sound attenuation. For the efficient conversion now we
demand: $\omega_{\text{imp}} < 2 D_p k^2 / \omega$. The maximum value of coupling coefficient $B$ is

$$B = \frac{Q \nu}{\varepsilon} \frac{\sin \omega_{\text{imp}}}{(\omega_{\text{imp}})^2 + [(\omega_{\text{imp}})^2 - \sin^2 \omega_{\text{imp}}]^{1/2}}$$

For the output amplitude of the phase-conjugated wave we obtain now $U(0) = -iU_0 \cot g \beta L$. Thus this case corresponds to well-known parametric amplification in media with time modulated sound velocity \(^5\). At the length $BL \approx \pi/2$ the layer becomes unstable.

We now make some numerical estimates. We assume that the light-absorption coefficient is about $10^{-7}$ cm\(^{-1}\), $\omega \approx 2 \times 10^8$ rad/s. Then for typical semiconductors 50% conversion is attained for a length $L \approx 0.25$ cm, at the laser pulses intensity $I \approx 10$ W/cm\(^2\). For Zinner's tunneling the same conversion is attained for a length $L \approx 1$ cm at the $E_{\text{ext}} \approx 6 \times 10^4$ V/cm.

The modulation of the density of electrons, which efficiently participate in the Langmuir oscillations, can be realized also due to Hann's transitions in semiconductors with multivalley structure of the conduction band. Under the action of the external variable electric field the transitions of the conduction electrons from the basic energy minimum to the upper-lying minimums will take place. As the effective electron mass in these minimums is much higher than in the basic one, these electrons form the stationary background. The dynamics of the sound propagation in this condition is just the same as for Zinner's mechanism. Still the necessary value $E_{\text{ext}}$ for 50% conversion and the same length $L \approx 1$ cm is now $E_{\text{ext}} \approx 10^3$ V/cm.

In conclusion we note that the contrary acoustic surface-wave generation in multilayer structure LiNbO\(_3\)-GaAs under the action of periodic laser illumination was observed by Nakagawa and Kawanago \(^6\).

REFERENCES

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