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SELF-FOCUSING AND FOCUSING OF ULTRASOUND AND HYPERSOUND IN METALS AND SEMICONDUCTORS

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The propagation of high-intensity ultrasonic and hypersonic waves in metals is considered. The possibility of self-focusing is shown and the conditions of self-focusing are explained. It is noted that for a number of metals of practical interest, the sound velocity decreases upon heating, which guarantees self-focusing and focusing of sound waves because of heating of the medium at the surface by the action producing the intense sound wave (modulated laser or electron beam). The sound velocity may also decrease during absorption of the sound wave itself. Mechanisms of variation of the sound velocity in a semiconductor, due to heating, are analyzed. It is shown that appreciable changes may occur as a result of variation of the carrier concentration. Some practical applications of the effects which influence conditions of destruction of metals are indicated. Some possibilities of explaining the anomalies in the propagation of sound and destruction of the media in the focusing regions are discussed.

NEW means have recently been made available for the creation of powerful beams of ultrasound and hypersound by rapidly-varying heating of the surface of a medium by powerful modulated light or electron beams[1-5]. The concentrated heating of the surface leads to the creation of volume waves because of thermal expansion[2-5] or pressure upon pulsed evaporation[1] in the modulated beam, and the amplitudes of the hypersonic pressures can reach many thousands of atmospheres at the achievable flux densities in the beam. At such pressure amplitudes different significant nonlinear effects should appear. The possibility of self-focusing of ultrasound and hypersound because of heating of matter in the beam was pointed out in[6].

In the present paper, the features of the self-focusing of hypersound inside a metal and a semiconductor are considered and the conditions of concentration of the energy of hypersonic waves, which influence the conditions of destruction of metals, are also considered. The greatest interest attaches to self-focusing of hypersound, focusing of hypersound by local heating of the medium near the surface, and focusing of a curved surface.[3]

An important circumstance for most metals of practical interest is the decrease in the sound velocity with increase in the temperature: $c_S^{-1} dc_S/dT \sim -k \times 10^{-3}\,\mathrm{deg}^{-1} < 0$, where k is a coefficient ranging from several tenths to several units (see, for example,[7]). This fact uncovers a wide range of possibilities for the focusing of hypersound in the heating of a metal by radiation which creates hypersound (focusing), and in the heating by the hypersound itself (self-focusing).

1. The effective change in the index of refraction n_S for sound waves, due to heating, will evidently be

$$\delta n_s = -\delta c_s / c_s \approx k \cdot 10^{-3} \delta T.$$

In the case of focusing upon heating of a medium at the surface the focal length of the "lens" or heated spot is $F \sim R/\delta m_S$, where R is the effective dimension of the heated region. For example, for $F \sim 10R$, it is necessary that $\delta n_S \sim 0.1$, which is made possible by heating by $\delta_T \approx 10^3 \delta n_S/k \approx 100°/k$. Here the time necessary for the formation of the "thermal lens" is $\tau \sim R^2/\chi$; thus, for $\chi \approx 0.1$ cm²/sec and $R \sim 1$ cm, we get $\tau \sim 10$ sec. It is evident that small times of formation of the "thermal lens" are possible only for small R.

The case of the self-focusing of hypersound, when the heating takes place because of the volume absorption and encompasses a large volume in a small time (since the energy is delivered by the sound and not by the thermal conduction), is greatly different. From the condition that the beam be self-guided with a divergence θ, we get the needed jump $\delta n_S \sim \theta^2 \sim k \times 10^{-3} \delta T$, where $\delta T \approx \kappa_S I_S t / C\rho$; κ_S is the sound absorption coefficient and $C\rho$ is the heat capacity of a unit volume of the medium. The value of κ_S depends on the sound frequency and can always be made sufficiently great by choosing the modulation frequency of the radiation heating the surface.

It is easy to obtain the threshold conditions for self-focusing of the hypersound:

$$\theta \sim \theta_D \sim \frac{\lambda_s}{R}, \quad q_{s\,\mathrm{thr}} \approx I_{s\,\mathrm{thr}}\, t \approx \left(\frac{\lambda}{R}\right)^2 C\rho \cdot 10^3/\varkappa_s k,$$

which turn out to be sufficiently low because of the small wavelength of the hypersound. The self-focusing length for subthreshold powers is $L_f \sim R/\theta \approx R/\sqrt{\delta n_S(t)}$ for $L_f \gg 1/\kappa_S$ and $L_f \sim R/\delta n_S$ for $L_f \lesssim 1/\kappa_S$, where $\delta n_S = 10^{-3} k \kappa_S I_S t / C\rho$. Therefore the time necessary for beginning of self-focusing is

$$t \sim \left(\frac{R}{L}\right)^m \frac{10^3 C\rho}{k \varkappa_s I_s},$$

where $m = 2$ in the first case (when $L \gg 1/\kappa_S$) and $m = 1$ in the second case (when $L \sim 1/\tau_S$). For example, for $R \sim L \sim 1/\kappa_S$, we get $\tau \approx 3 \times 10^3/kI_S < 0.1$ sec for $I_S > 30k^{-1}$ (kW/cm²) for $C\rho$ of the order of several J/cm², $\kappa \sim 1$ cm⁻¹. This hypersound flux density $I \approx (\delta p_S)^2/\rho c$ corresponds to the pressure amplitude $\delta p_S \leq 300$ atm, which is easily obtainable with the help of modern hypersound sources.

The choice of frequency of modulation, which determines the hypersonic frequency and its absorption coefficient (which depends strongly on the frequency), can be realized not only by special modulation apparatus, but also by a mixture of light waves of neighboring frequencies, beat modes and so forth.

2. We now consider the features of focusing of ultrasound and hypersound in semiconductors. The dependence of the sound velocity on the concentration of the carriers, which is always sensitive to a temperature change, makes these phenomena very sharply delineated.

We consider the case of sound waves in a piezosemiconductor, when the dispersion equation for the propagation of sound waves can be written in the form

$$\omega^2 - q^2 v_s^2 \left\{1 + \eta^2 \frac{\varepsilon_0}{\varepsilon_{\|}(\omega, q)}\right\} = 0,$$

where η^2 is the square of the electromechanical coupling constant, ϵ_0 the dielectric permittivity of the lattice, $\epsilon_{\|}(\omega, q)$ the longitudinal dielectric permittivity with account of the plasma carriers, v_S the sound velocity. Setting $|\eta^2 \epsilon_0/\epsilon_{\|}(\omega, q)| \ll 1$, we obtain the increment

$$\frac{\Delta v_{ph}}{v} = \frac{1}{2}\eta^2 \operatorname{Re} \frac{\varepsilon_0}{\varepsilon_{\|}(\omega, q)}.$$

If we consider the case of low frequencies $ql \ll 1$, where l is the free path length of the electron, then, by using the well-known expression for $\epsilon_{\|}(\omega, q)$, we get

$$\frac{\Delta v_{ph}}{v_s} = \frac{1}{2}\eta^2 \frac{1 + (4\pi\sigma_0/\varepsilon_0\omega)^2 q^2 r_D^2 (1 + q^2 r_D^2)}{1 + (4\pi\sigma/\varepsilon_0\omega)^2 (1 + q^2 r_D^2)^2},$$

where $r_D = (kT\epsilon_0/4\pi e^2 N)^{1/2}$ is the Debye radius, $\sigma_0 = en_0\mu$ the dc conductivity.

It is easy to see that the greatest change in the sound velocity depends on the change in the carrier concentration which, in certain semiconductors, changes sharply even for small temperature changes, (for example, in CdSe crystals, in a temperature change of at most 20–30°, the carrier concentration changes by 2–6 orders of magnitude). Here the sign of the derivative dN/dT can be both positive (for $N(T) \sim N_0 e^{-\epsilon/T}$ — for crystals with acceptor of donor centers) and negative ($N(T) = N_0/(1 + Ae^{-\epsilon/T})$ for crystals with temperature quenching of the conductivity). Change of $\Delta v_{ph}/v_S$ is such that for a concentration change (n) from 0 to ∞, the ratio $\Delta v/v$ changes by an amount $\frac{1}{2}\eta^2$. For example, in CdS, for longitudinal waves, the quantity $\eta^2 \sim 3 \times 10^{-2}$, for transverse waves—$7 \times 10^{-2}$. For Te in transverse waves, $\eta^2 \sim 0.12$.[8,9] Therefore, for a noticeable temperature change, it is easy to obtain $\Delta v/v \sim 10^{-2} - 10^{-1}$. Such a velocity change can change significantly the angle of divergence or slope $\theta \sim \sqrt{\Delta v/v} \sim 0.1$–$0.3$. Thus, the range of change of angle is sufficiently large, so that it can be observed and used in practice. For example, for self-guiding of powerful radiation, $\theta \sim \lambda_S/a \sim 0.1$ is sufficient, or for $\lambda_S \sim 10^{-4}$ cm the self-focusing will take place even for a beam radius $a > 10^{-3}$ cm.

The considered effects show wide possibilities for the observation and utilization of nonlinear effects, leading to a sharp increase in the concentration of the sound rays in a number of media of practical interest, to the explanation of sound propagation anomalies and to destruction of media in the focusing regions.

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