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SELF-FOCUSING OF A HOMOGENEOUS LIGHT BEAM IN A TRANSPARENT MEDIUM, DUE TO WEAK ABSORPTION

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When a light beam propagates in a medium having a dielectric constant that depends on the electric field of the wave like $\epsilon = \epsilon_0 + \Delta\epsilon$, where $\Delta\epsilon = \epsilon_2 E^2 > 0$, the beam exhibits a tendency to become self-focused [1-3]. A nonlinearity of this type is brought about by the Kerr effect and electrostriction [3], and in many substances the equilibrium value of $\Delta\epsilon_{str}$ is larger (sometimes even much larger) than $\Delta\epsilon_{Kerr}$. An effect which is the inverse of striction gives absorption of light. Even in very weak absorption, the thermal expansion exceeds the striction compression of the substance after a short time. If the field in the beam decreases from the axis towards the periphery, then the thermal increment $\Delta\epsilon_{th}$, which is also proportional to E^2 but is negative, exerts a defocusing action on the beam.

It will be shown below that when a homogeneous light beam is absorbed, nonstationary motion of the substance, due to heat release, leads to such a density distribution that, in contrast with the usual influence of heating, a tendency arises toward self-focusing of the beam.

Assume that a parallel beam of radius R enters the medium at the instant $t = 0$ and the amplitude of the light wave within the limits of the beam is constant along the radius and in time. Let us see how the density ρ of the medium changes in the light channel. In first approximation we shall disregard here the field redistribution connected with the resultant refraction of the rays, and the diffraction spreading of the beam boundaries.

When $E^2(r)$ = const, the radial external force acts only on the surface of the channel and its value (per cm^2) is $p_{str} + p_{th}$, where

$$p_{th} = \Gamma I \kappa_\nu (t - t_z), \quad I = \sqrt{\epsilon_0}\,\frac{cE^2}{4\pi}\ ; \quad p_{str} = -\rho\,\frac{\partial\epsilon}{\partial\rho}\,\frac{E^2}{8\pi}\ . \tag{1}$$

Here p_{th} is the increase in pressure, at the instant of time t, resulting from heat release without a change in density; p_{str} is the striction pressure; I is the radiant energy flux density; κ_ν (cm^{-1}) is the light absorption coefficient; Γ is the Gruneisen coefficient in the case of solid and liquid bodies; for gases $\Gamma = \gamma - 1$, where γ is the adiabatic exponent; $t_z = z/c_1 = z\sqrt{\epsilon_0}/c$ is the instant when the light wave arrives at the cross section z of the channel (the coordinate z is measured along the beam axis from the point of entry into the medium). Compression and rarefaction waves due to the action of p_{str} and p_{th} begin to travel in the section z from the surface inward, at the speed of sound a, starting with the instant t_z. By virtue of the smallness of the effect, superposition of the waves takes place. So long as the perturbation has not yet moved too far from the surface, the motion can be regarded as plane. It is then easy to construct a solution.

Let $x = R - r$. When $|x| > x_s = a(t - t_z)$ the change in density is $\delta\rho = \rho - \rho_0 = 0$. When $|x| \leq x_s$, as shown by calculation,

$$\delta\rho(x,z,t) = \delta\rho_{str} + \rho_{th} = \pm\frac{1}{2a^2}\left\{ |p_{str}| - p_{th}\left[1 - \frac{|x|}{x_s}\right]\right\}, \tag{2}$$

where we choose the upper sign inside the channel ($x > 0$) and the lower side outside ($x < 0$) (see Fig. 1). The partial density jumps on the boundary are equal to their equilibrium values $\Delta\rho_{str(th)} = -p_{str(th)}/a^2$. Inasmuch as $\delta\epsilon = (\partial\epsilon/\partial\rho)\delta\rho$, we obtain for the ratio of the equilibrium values

$$\frac{|\Delta\epsilon_{th}|}{\Delta\epsilon_{str}} = \frac{p_{th}}{|p_{str}|} = \frac{2\Gamma\sqrt{\epsilon_0}}{\rho\partial\epsilon/\partial\rho}\kappa_\nu ct', \quad t' = t - t_z \tag{3}$$

(for a numerical estimate see below).

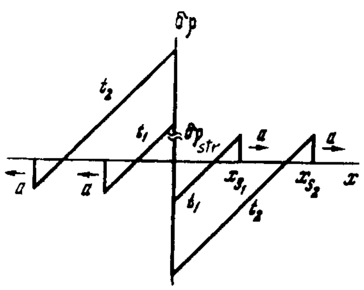

Fig. 1

Let us see how light propagates in a medium with a density distribution (2), neglecting diffraction phenomena (the criterion for the satisfaction of this assumption will be given below). Let $\theta = dx/dz$ be the angle of deflection of the ray trajectory $x(t)$, $z(t)$ from the initial direction parallel to the z axis; $z = c_1(t - t_0)$, where t_0 is the instant of entry of the ray into the medium. For the "material" derivative $(1/c_1)(d\theta/dt) = d\theta/dz$ we have the equation

$$\frac{d\theta}{dz} = \frac{1}{2\epsilon_0}\frac{\partial\epsilon}{\partial x} = \frac{1}{2\epsilon_0}\frac{\partial\epsilon}{\partial\rho}\frac{\partial\rho}{\partial x}. \tag{4}$$

According to (1) and (2), in the region of the light channel which is disturbed by the motion $(0 \leq x \leq x_s = a(t - t_z))$, $d\theta/dz = \text{const} \equiv \beta$, where

$$\beta = \frac{1}{2\epsilon_0}\frac{|\delta\epsilon_{th}(+0,z,t)|}{x_s(t,z)} = \rho\frac{\partial\epsilon}{\partial\rho}\Gamma I\kappa_\nu/4\epsilon_0\rho a^3. \tag{5}$$

Thus, a ray entering the medium with $\theta_0 = 0$ at the point $x_0 < x_s$ is deflected toward the axis, describing a parabolic trajectory $x = x_0 + \beta z^2/2$ (when $x_0 \geq x_s$, the rays are not deflected). The deflected ray enters the front of the perturbation wave at the point $x_k = at_0$, $z_k = [2(at_0 - x_0)/\beta]^{\frac{1}{2}}$ at the instant $t_k = t_0 + z_k/c_1$, at an angle $\theta_k = \beta z_k$ to the surface. It is refracted by the density discontinuity $\delta\rho_{str}$ which is present there (see Fig. 1), and goes out to the unperturbed region with an inclination θ_c, given by the formula

$$\theta_c^2 = \theta_k^2 - \frac{\delta\epsilon_{str}}{\epsilon_0} = \frac{|\delta\epsilon_{th}(+0, z_k, t_k)|}{\epsilon_0}\left(1 - \frac{x_0}{at_0}\right) - \frac{\delta\epsilon_{str}}{\epsilon_0} \sim \frac{|\Delta\epsilon_{th}| - \Delta\epsilon_{str}}{2\epsilon_0} .$$

During the earlier stage, so long as $|\Delta\epsilon_{th}| < \Delta\epsilon_{str}$, total internal reflection by the striction discontinuity takes place (the same pertains also to rays that enter the medium too close to the perturbation boundary). Later, when the growing thermal effect becomes several times larger than the striction effect, the refraction becomes small and $\theta_c \approx \theta_k$. The rays propagate in the unperturbed region along straight lines $x = x_k + \theta_c(z - z_k) \approx at_0 + \theta_k(z - z_k)$. The path of the rays (x-t diagram) is shown in Fig. 2. The distance at which the rays are focused along the beam axis $z_f(x_0, t_0)$ can be estimated by putting $x = R$. This yields

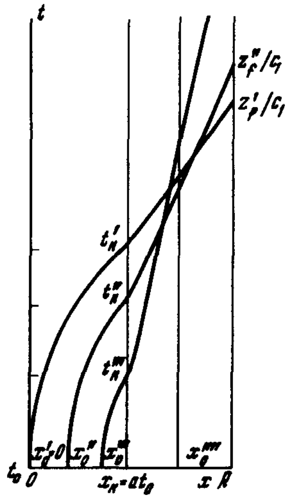

Fig. 2

$$z_f = \frac{(at_0 - x_0) + (R - x_0)}{\theta_k} \approx \frac{R}{\theta_k} = R[2\beta(at_0 - x_0)]^{-\frac{1}{2}} \sim R[|\Delta\epsilon_{th}|2\epsilon_0]^{-\frac{1}{2}} \qquad (6)$$

Formulas (6) and (2) are valid up to $t_0 \lesssim R/a$.

The width of the zone of diffraction spreading of the beam boundary is equal approximately to $x_d = \sqrt{\lambda z/2}$ (λ - wavelength of light in the medium). The beam becomes completely smeared out at a distance $z_d \approx 2R^2/\lambda$. Diffraction can be neglected in the estimate of z_f if $z_f < z_d$, i.e., $\theta_k > \lambda/2R$ (this corresponds to "supercritical" power in the theory of self-focusing). In general the diffraction decreases somewhat the focusing effect of the heating. Absorption of light, in turn, prevents diffraction spreading of the boundary of a homogeneous parallel beam, and also decreases the divergence of a homogeneous fan-like diverging beam.

We present a numerical example. A parallel homogeneous beam can be obtained by placing in the path of a laser beam a screen with small opening in the center.

Let $R = 2 \times 10^{-2}$ cm, I = 100 MW. For a liquid with $\Gamma = 2$, $\sqrt{\epsilon_0} = 1.5$, $\rho(\partial\epsilon/\partial\rho) = 1$, a = 1 km/sec, and $\rho = 1$ g/cm^2 we obtain for $\kappa_\nu = 10^{-2}$ cm^{-1} (it is always possible to increase κ_ν by adding an absorber) $\beta = 2.2 \times 10^{-3}$ cm^{-1}. The thermal effect exceeds the striction effect after $t' \approx 10^{-9}$ sec [1)]. By the instant $t_0 = 3 \times 10^{-8}$ sec we have $at_0 = 0.15R$ and the rays close to the edge converge towards the axis at $z_f = 6$ cm; at the same time $z_d \approx 18$ cm (at ruby frequency). If the giant laser pulse were to last longer, say $t = R/a = 20 \times 10^{-8}$

sec, then the focusing action could encompass the entire beam. Let us note that the condition of "weakness" of absorption, $l_\nu = 1/\kappa_\nu \gg z_f$, is satisfied in this example.

Bespalov and Talanov [4] have shown that at $\epsilon_2 E^2 > 0$ a plane wave with large supercritical power is unstable and breaks up into self-focusing beams. It is easy to see that absorption, to the contrary, stabilizes the wave. After the passage of a time sufficient for $|\delta\epsilon_{th}|$ to increase to $\delta\epsilon_{str}$ and $\Delta\epsilon_{Kerr}$, the thermal effect will suppress the spontaneously arising instability.

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BREAKDOWN AT OPTICAL FREQUENCIES IN THE PRESENCE OF DIFFUSION LOSSES

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The values of the threshold electric field intensity in a light wave, measured in experiments on optical breakdown of gases [1], are in good agreement with the theory of Ya. B. Zel'dovich and Yu. P. Raizer [2], which explains the primary breakdown on the basis of the electron-avalanche concept. No account is taken here of the electron losses during the avalanche development stage, an assumption justified for relatively high gas pressures (1 - 100 atm).

At lower gas pressures, the loss of electrons by diffusion from the focusing volume has an appreciable influence on the time constant of avalanche development, and consequently on the threshold electric field intensity in the light wave.

We present in this communication results of experiments on breakdown in krypton and xenon at optical frequencies and low pressures. In order to clarify the role of diffusion during breakdown, we varied the size of the focusing volume.

We used a ruby laser operating in the single-pulse mode, using a bleaching filter with phthalocyanine solution. The pulse duration was 60 nsec, and the energy of the single pulse of the order of 0.5 J. The beam divergence is estimated at 5'. The foregoing laser parameters were measured directly during the time of the experiment. Lenses corrected for aber-