New mechanism of self-focusing of light in a gas medium in the presence of absorbing centers

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It is demonstrated that self-focusing of light pulses is possible in media with negative temperature gradient of the refractive index and having discrete absorption centers. The mechanism of the effect consists in an increase of density of the medium in the space between the particles, owing to the averaging of the pressure waves that propagate from the radiation-heated particles.

We describe in this article the effect of nonstationary self-focusing, in a discretely absorbing medium, of light pulses whose duration t_{pul} satisfies the relation

$$(uN^{1/3})^{-1} \lesssim t_{\text{pul}} << (4\chi N^{2/3})^{-1}, \tag{1}$$

where $(4\chi N^{2/3})^{-1}$ and $(uN^{1/3})^{-1}$ are respectively the characteristic times of averaging of the heat and of the travel of the sound in the space between the absorbing centers, whose concentration is N cm^{-3}, χ is the coefficient of the molecular temperature diffusivity, and u is the speed of sound. By way of example, we consider a medium consisting of dust particles in air. The mechanism of the effect is connected with the possible appearance of a positive increment to the refractive index n of the medium in the space between the particles, owing to the hydrodynamic compression of the substance. The hydrodynamic compression is the result of propagation of pressure waves from the regions of local thermal expansion of the medium near the heated particles. If a relation of the type (1) is satisfied, then the regions of local expansion (thermal aureoles) occupy a small volume of the medium, causing a partial aureole scattering of light (see[1–3] and the references therein), and the bulk of the radiation will experience regular refraction as a result of formation in the beam of a statistically averaged profile of "excess" density.

The deviation of the temperature $T(\mathbf{r},t)$ and of the average "excess" density $\tilde{\rho}(\mathbf{r},t)$ from the equilibrium values in a medium with discrete centers of heat release will be described by a system of linearized equations of hydrodynamics in thermal conductivity, which takes, with allowance for (1), the form

$$\frac{\partial T}{\partial t} = \chi \Delta T + 0\left(\frac{u^2}{c_p\rho_0}\frac{\partial\tilde{\rho}}{\partial t}\right); \quad |\mathbf{r}-\mathbf{R}_i| \geqslant a_i; \quad i=1,2,\ldots \tag{2}$$

$$\frac{\partial^2\tilde{\rho}}{\partial t^2} - u^2\Delta_\perp\tilde{\rho} = \frac{\partial}{\partial t}q_\Pi. \tag{3}$$

with boundary conditions $\nabla_\perp\tilde{\rho}(0,t)=\nabla_\perp\partial/\partial t\,\tilde{\rho}(0,t)=\tilde{\rho}(\mathbf{r},0)=0$,

$$T(r,t)\Big|_{|\mathbf{r}-\mathbf{R}_i|=a_i} = \frac{a_i W K_{\text{abs}}(a_i, m_0, \lambda)}{4c_p\rho_0\chi}, \tag{4}$$

where ρ_0 is the equilibrium density of the medium, t is the time, $\mathbf{r}$ and $\mathbf{R}_i$ are the radius vectors of a fixed point of the medium and of the center of the ith particle, c_p is the isobaric specific heat of the air, W is the intensity of the radiation, $K_{\text{abs}}(a_i, m_0, \lambda)$ is the factor of the effectiveness of absorption of light by a particle of radius a_i[5] with complex refractive index m_0, which is assumed to be independent of W, λ is the wavelength, and q_{abs} is a source function defined by the expression

$$q_{\text{abs}} = \beta\rho_0\frac{\partial}{\partial t}\langle T(\mathbf{r},t)\rangle\left[1+0\left(\frac{32}{3}\pi N\chi^{3/2}t^{3/2}\right)\right] = \frac{\alpha_{\text{abs}}\beta W}{c_p}. \tag{5}$$

The angle brackets $\langle\ \rangle$ denote averaging over the spatial realizations. α_{abs} is the volume coefficient of aerosol absorption and β is the coefficient of thermal expansion of the air. Expressions (4) and (5) correspond to the quasistationary regime of overheating of absorbing particles.[3]

An analysis of the change in the effective cross section of the beam

$$\Omega = \pi\iint_{-\infty}^{\infty} R^2 W(x,\mathbf{R},t)d^2R \Big/ \iint_{-\infty}^{\infty} W(x,\mathbf{R},t)d^2R,$$

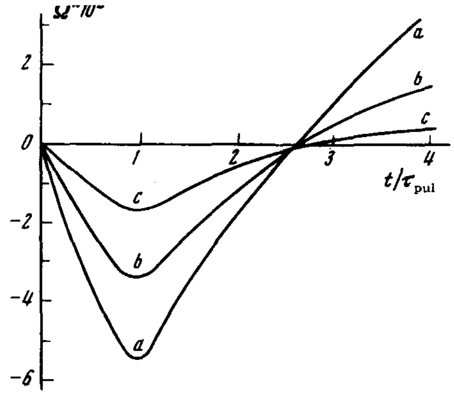
for allowance for the influence of the focusing lens and the nonlinear scattering by the aureoles, can be carried out by using the general form of the solution of the small-angle radiation-transport equation[4] for a Gaussian beam, $W(0,\mathbf{R},t)=W_0\exp(-R^2/R_0^2)$, where W_0 is the intensity on the axis, R_0 is the beam radius, and $\mathbf{R}$ is a radius vector in the cross section of the beam. The nonlinearity of the medium is taken into account in the given-field approximation. As applied to the considered problem, this solution takes the form

$$\Omega = \pi R_0^2[1-(\eta x)^2] + \frac{\pi x^3}{k^2}\left[1-\frac{(\eta x)^2}{3}\right]\left(\frac{\alpha^{(0)}}{a_i^2}+\frac{\alpha^N}{\chi t}\right). \tag{6}$$

The solution is valid in the region $\eta x \ll 1$ and $x \ll ct$, c is the speed of light, η^2 is the coefficient of the quadratic term of the expansion of the solution (3) in powers of R in the region near the beam axis, $\alpha^{(0)}$ is the volume coefficient of light scattering by the unperturbed aerosol,[5] and α^N is the volume coefficient of nonlinear scattering of light by the thermal aureoles, calculated within the framework of the applicability of the Rayleigh-Gans scattering

$$\alpha^N = 2kN\left(\frac{dn}{nT}\right)^2\int_0^{2k} d\kappa\,\kappa F^2(\kappa,t), \quad k=2\pi/\lambda, \tag{7}$$

$$F(\kappa,t) = \frac{\pi a_i^2 K_\Pi W_0}{2c_p\rho_0\chi\kappa^2}[\cos(\kappa a_i) - \exp(-\kappa^2\chi t)]. \tag{8}$$



Dynamics of dimensionless beam cross section in absorbing aerosols for different values of the radiation power density: a-$W_{01}K_{abs} = 8\times10^3$ w/cm^{-2}, b-5.4×10^3 W/cm^{-2}, c-2.7×10^3 W/cm^{-2}.

$F(\kappa, t)$ is the Fourier transform of the temperature field near the absorbing particle with respect to $|\mathbf{r}-\mathbf{R}_i|$ and is determined by the solution of Eq. (2). At $t \ll \tau_{pul} = R_0/u$, the solution of (3) takes the simple form $\tilde{\rho} \approx \int_0^t q_{abs}\,dt_1$. In this case, taking (6)—(8) into account, we can obtain limitations on the beam and medium parameters, at which in self-focusing becomes the predominant effect in comparison with the broadening of the beam as a result of scattering by the thermal aueroles:

$$\frac{t}{W_0 K_\Pi a_i^2 x} \gtrsim \frac{\ln 2\left(\frac{dn}{dT}\right)}{384\pi c_p \rho_0 \chi^2} \qquad (9)$$

An analysis based on the exact solution of (3) for a beam with exponential saturation in time, $W_0 = W_{01}[1 - \exp(-t/\tau_p)]$, where τ_p is the intensity relaxation time and W_{01} is a constant, shows that in the case $\tau_p \gtrsim \tau_{pul}$ the lifetime of the excess density in the beam is proportional to τ_{pul}. At $\tau_p \geq \tau_{pul}$ the excess density is present in the beam during the entire time of the noticeable change of W_0, but its maximum value is smaller by a factor $(\tau_p/\tau_{pul})^2$ than in the first case.

The figure illustrates the results of the calculation of the time dependence of the relative change Ω^N of the effective cross section of the beam at parameter values $R_0 = 2$ cm, $x = 10^3$ cm, $a_i = 3\times10^{-4}$ cm, $N = 2500$ cm^{-3}, $\lambda = 0.69$ μ, and $\tau_p = 0.1$ msec.

We note in conclusion that the considered light self-focusing mechanism can be typical also of other classes of media, solid and liquid, containing centers of elastic perturbations and deformations.

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