SELF-FOCUSING OF INHOMOGENEOUS LASER BEAMS AND ITS EFFECT ON STIMULATED SCATTERING

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Self-focusing of inhomogeneous laser beams in organic liquids is studied. It is found experimentally that for such beams the region of an intense light field (focus) appears at a distance $R_{nl}^{min} = 2\epsilon_0/k\epsilon_2 E_0^2$ which is much less than the self-focusing length for a homogeneous beam $R_{nl} = a\sqrt{\epsilon_0/2\epsilon_2 E_0^2}$. As usual, self-focusing was recorded on the basis of appearance of stimulated scattering. Along with measurement of the self-focusing threshold the stimulated scattering efficiency was measured. By comparing the results for preliminary focused and self-focused beams some conclusions can be drawn regarding the energy efficiency of the process with a self-focused inhomogeneous beam.

INTRODUCTION

IT is quite clear by now that the course of self-focusing of the beam is different in single-mode and multimode lasers. Whereas in the former case the picture has a regular character and consists in the fact that initially the broad beam is compressed as a whole and then breaks up into ultrathin filaments[1-4], the breakdown of the beam in the latter case occurs at the very outset. There are many indications of the foregoing circumstances in the literature[5-7], but no quantitative measurements with inhomogeneous beams have been performed. The theoretical papers dealing with beams having complicated amplitude profiles do not claim to be complete and exhaustive, and therefore an experiment of this type would be of interest.

The purpose of the present work was to study quantitatively the self-focusing of complex beams. By complex beams we mean here beams with a complex amplitude profile. Figure 1 shows a typical photograph of the near field of the radiation of an optical laser operating in the accumulation regime. The inhomogeneities of the distribution of the radiation over the end face are clearly seen. The overall form of the distribution changes from flash to flash. The dimension of each local inhomogeneity is of the order of several hundred microns[8,9].

A parameter of primary interest is the so-called self-focusing length—the length within which a region of strong light field (focus) is produced. For a Gaussian beam, this length is equal to

$$R_{nl} = a\sqrt{\frac{\varepsilon_0}{2\varepsilon_2 E_0^2}}$$

where a is the radius of the beam, ϵ_0 the linear dielectric constant, ϵ_2 the second term of the expansion of the complex dielectric constant in powers of the field, and E_0 the wave amplitude. R_{nl} was determined many times experimentally[1,10]. This can be done by two methods, direct measurements of the beam cross section (as done by Townes and co-workers[1]) and registration of the threshold of the stimulated emission (see[10]). An analysis of[1,10,11] shows that both procedures, at any case for organic liquids with large Kerr constant, lead to practically the same results.

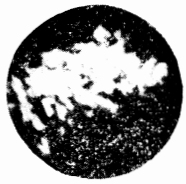

FIG. 1. Typical near-field photograph of initial beam. The inhomogeneities are seen distinctly.

For complex beams, we choose the procedure wherein the stimulated scattering (SS) is recorded. We considered it important to eliminate completely the feedback between the scattering medium and the laser via the stimulated Mandel'shtam-Brillouin scattering (SMBS). This feedback can apparently hinder, in some cases, the interpretation of the experimental data, particularly in cases when no time sweep is used[12].

At the same time, in control experiments, besides registration of the SS threshold, we determined directly the diameters of the "hot" filaments (self-focusing channels). It was also of interest to measure the efficiency of the SS in a self-focusing inhomogeneous beam, and particularly the dependence of the efficiency on the input power.

EXPERIMENTAL SETUP. MEASUREMENT PROCEDURE

The experimental setup is shown in Fig. 2. The beam from laser 1 with maximum power density 120 MW/cm^2 (a value averaged over the entire end face, i.e., without allowance for the inhomogeneities) passed through a Faraday cell 2, in which the polarization plane was rotated 45° following a single passage[13]. As is well known, the magnetic rotation of the plane of polarization differs from the natural rotation in that the direction of rotation does not depend on whether the light goes from the northern end to the southern end or vice versa. Therefore the rotation doubles when the light passes through the rotating medium (in this case, type TF-5 glass with Verdet constant V = 0.06 min/Oe-cm) in both directions. The fields required to produce a rotation through $\theta = 45°$ are of the order of

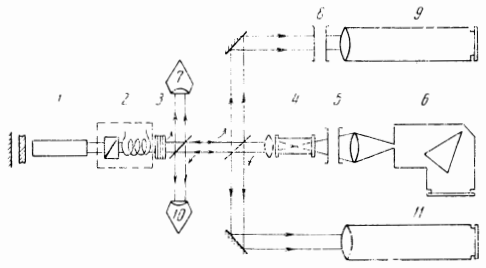

FIG. 2. Block diagram of setup.

$H \sim 10^4$ Oe. In particular, over a glass length $l = 3$ cm, $H = 1.5 \times 10^4$ Oe. The required magnetic field was obtained with a solenoid capable of producing fields on the order of 10^5 Oe. Thus, there was an appreciable margin with respect to the field, making it possible to operate at low supply voltages, and furthermore it was possible to use relatively short samples of glass, placed in the center of the solenoid where the field was not uniform. The solenoid was 70 mm long, the magnetic field pulse was reduced to 1.5–2.5 msec, and by the same token the question of synchronizing the laser radiation and the operation of the Faraday cell was very simple to solve. The same triggering pulse ignited the pump lamps and started the magnet. The radiation loss in the polarizer-solenoid system did not exceed 15–20%.

Thus, the SMBS components were crossed with the polarizer after passing through the glass in a magnetic field, i.e., the feedback loop for the SMBS and the possibility of amplification of these components in the active element of the resonator (excited ruby) were eliminated. This made it possible to investigate the dependence of the SMBS intensity on the intensity of the exciting radiation.

A stack of glass plates, 3, was located behind the Faraday cell to vary the intensity of the laser beam. The beam then entered a cell 4 with the investigated liquid. The energy of the exciting radiation was determined with calorimeter 7, and the SMBS energy with the aid of calorimeter 10. The system 8–9 (Fabry-Perot interferometer with long-focus camera) was used to monitor the monochromaticity of the laser emission (the spectral line width did not exceed 0.02 cm^{-1}) and the absence of feedback for the SMBS components. The Fabry-Perot interferometer 5, crossed with a type ISP-51 spectrograph 6, made it possible to investigate the spectral structure of the radiation passing through the cell. We note that, unlike other investigations where non-decoupled generators were used, in our experiments only 1 SMBS component was always observed, at an angle 180°, in a broad range up to powers exceeding threshold by dozens of times. This apparently gives ground for assuming that, at any rate in liquids, observation of a large number of components is connected with the penetration of the Mandel'shtam-Brillouin components with the generator and their subsequent amplification there.

With the aid of camera 11 (f = 800 mm) we determined the divergence of the SMBS at 180° angle. From the divergence of the SMBS we were able to determine the diameter of the self-focusing channel, since on leaving the liquid the SMBS beam has a diffraction divergence $d/f = 1.22\lambda/n_0 D$, where d is the dimension of the spot in the focal plane of camera 11, determined at half-height of the intensity-distribution curve, f is the focal length of the camera, and D is the diameter of the self-focusing channel.

Thus, the setup made it possible to obtain the energy conversion coefficient (efficiency), the SMBS threshold, and the dimensions of the self-focusing channel. In turn, from the SMBS threshold it was possible to determine the effective self-focusing length R_{nl} [11]. The measurements were performed as follows. The SMBS was registered at the output of a cell of fixed length. By varying the power of the incident radiation with the aid of an attenuator and by recording photographically the threshold of the SMBS, it was possible to assume that at the threshold the length of the cell is equal to the self-focusing length (see also[10]). Once the SMBS was fully developed, it was possible to register the energy relatively simply with the aid of a calorimeter.

EXPERIMENTAL DATA: DISCUSSION

As is well known, self-focusing of a homogeneous beam occurs over a length

$$R_{nl} = \frac{a}{2}\sqrt{\frac{n_0}{n_2 E_0^2}} \tag{1}$$

where R_{nl} is the effective self-focusing length, a the radius of the beam, n_0 the static refractive index (which can be taken to be the asymptotic value of n as $E \to 0$), and $n_2 E_0^2$ is the first correction in the expansion of the refractive index in the field. In the case of an inhomogeneous beam containing a sufficiently broad inhomogeneity spectrum, the self-focusing of each inhomogeneous section should occur independently. Then, according to the calculations of[6], the inhomogeneity that becomes self-focused most rapidly has a characteristic transverse dimension

$$a_{opt} = \frac{2}{k}\sqrt{\frac{\varepsilon_0}{\varepsilon_2 E_0^2}}, \tag{2}$$

where k is the wave vector.

It is interesting that the length over which such an inhomogeneous section becomes self-focused is given, in accordance with the calculation, by

$$R_{nl}^{min} = \frac{2}{k}\frac{\varepsilon_0}{\varepsilon_2 E_0^2}, \tag{3}$$

i.e., it is determined only by the wavelength and by the properties of the medium. The results of the calculations are shown schematically in Fig. 3.

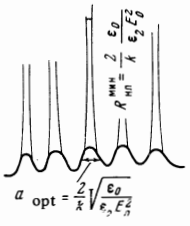

FIG. 3. Schematic diagram explaining the self-focusing of a beam with a complicated amplitude profile.

The experimental data and the result of their comparison with theoretical estimates based on formulas (1) and (3) are summarized in the table for nitrobenzene, benzene, and carbon tetrachloride.

	E_{exp}	E_{theor1}	E_{theor2}	a_{opt} μ
$C_6H_5NO_2$	$(1.58\pm0,23)\cdot10^2$	$2.88\cdot10^4$	$2,48\cdot10^2$	333 ± 48
C_6H_6	$(2,04\pm0,3)\cdot10^2$	$3.05\cdot10^5$	$5,17\cdot10^2$	1081 ± 150
CCl_4	$(1,5\pm0,22)\cdot10^2$	$9,8\cdot10^4$	$8,66\cdot10^2$	1160 ± 160

The values of E are in cgs esu.

The experimentally determined values of the average light field at the input, corresponding to the SMBS threshold, are given by

$$E_{exp} = \sqrt{8\pi\mathscr{E}/\tau_p Sc},$$

where $\mathscr{E}$ is the energy of the laser emission pulse (the energy scatter was determined statistically and did not exceed 15%; this scatter should be ascribed to the change of the distribution of the inhomogeneities from pulse to pulse), τ_p is the pulse duration, S is the cross section of the pulse (inasmuch as we are taking the ratio of the energy to the entire section, without reconstructing the profile of the inhomogeneities, we obtain the average value of the light field), and c is the speed of light.

The calculated values of the threshold field $E_{theor\,1}$ were calculated from formula (1) with R_{n1} assumed equal to the length L of the cell, 20 cm for all the investigated substances except carbon tetrachloride, which was investigated in a cell 60 cm long. The standard tabulated values of n_2 were used for each liquid, and a was set equal to the input aperture of the beam.

The values of the threshold field $E_{theor\,2}$ were calculated in accord with formula (3).

Finally, a_{opt} is the value of the optimal transverse scale.

It is easy to see that for such liquids as nitrobenzene and benzene, there is good agreement between the experimental data and the results of calculations by means of formula (3). Thus, it can be assumed that our data confirm quantitatively the representation developed in[6] for the self-focusing of complex beams. In our opinion, this is all the more interesting if account is taken of the fact, that unlike formula (1) formula (3) has been obtained in a self-focusing theory based on the perturbation method.

For CCl_4, the threshold field calculated by formula (3) with allowance for only the Kerr effect greatly exceeds the experimental value. The discrepancy between the theoretical and experimental data is much larger here than for the other investigated liquids. Such a large discrepancy cannot be attributed to the experimental error and, in our opinion, is connected with the contribution of electrostriction. It is important to emphasize that the contribution of electrostriction to the behavior of complex beams may be much more appreciable than for a homogeneous beam, inasmuch as in the present case we are dealing with self-focusing of individual thin filaments, whose diameter is small compared with the diameter of the entire beam (in particular, a case is possible when $a/v > \tau_p$, where v is the velocity of the hypersound, and striction does not come into play here). On the other hand, when a/v becomes comparable with the pulse duration, the constriction of the beam is due to electrostriction. For a_{opt}, this ratio becomes of the same order of magnitude as τ_p.

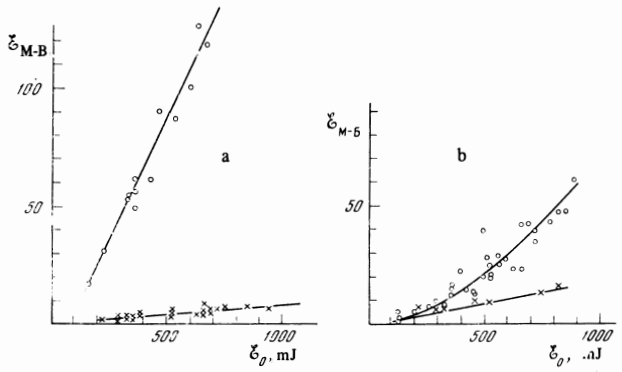

FIG. 4. Energy of stimulated Mandel'shtam-Brillouin scattering $\mathscr{E}_{MB}$ vs. exciting-light energy $\mathscr{E}_0$ (in millijoules) for benzene (a) and carbon tetrachloride (b). Points: O — focused beams, X — self-focusing beams.

Of course, in this case, to make the comparison of theory with experiment more correct, it is necessary to take into account the contribution of the striction and of the Kerr effect simultaneously, but this is difficult and it is therefore necessary to assume in each case that only one of these mechanisms operates.

Besides measurements of the threshold with the SMBS fully developed, we investigated the energy efficiency of the process. Besides measuring the efficiency of the SMBS under conditions when the beam was self-focused, we performed measurements with a short-focusing lens under conditions when the self-focusing could be neglected (short cells were used). A typical result for C_6H_6 and CCl_4 is shown in Fig. 4. Figure 4a shows the plots for benzene. The linear connection between the laser and SMBS powers indicates that the SMBS is fully developed. The great difference between the growth rates for self-focusing and focused beams lies, in our opinion, in the physical representation of the self-focusing of complex beams. Indeed, with increasing input power, we should expect not a concentration of the field in a given filament, but an increase in the number of filaments. Therefore, the power of the MB component increases more slowly than for a focused beam. The same pertains to carbon tetrachloride, although the difference is smaller here.

The most effective conversion occurring during focusing is observed for benzene, which is likewise not surprising, since the threshold field in focusing is determined not by the Kerr or striction nonlinearities, but by the relaxation parameters of the medium[14]:

$$E^2_{foc.\,thr.} \approx \frac{8\pi(\alpha + nk_\omega)^2}{(\rho\,\partial\varepsilon/\partial\rho)^2|q||k|\beta_s},$$

where α is the amplitude coefficient of the sound absorption, nk_ω is the amplitude coefficient of the light absorption, $\rho\partial\epsilon/\partial\rho$ is the fluctuation of the dielectric constant due to the density fluctuation, q is the wave vector of the elastic wave, k is the wave vector of the exciting light, and $\beta_S = -(V^{-1}\partial V/\partial p)_S$ is the adiabatic compressibility. This field turns out to be smaller for benzene than, say, for carbon disulfide.

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