EXPERIMENTAL INVESTIGATION OF THE EFFECTIVENESS OF SPONTANEOUS WAVEGUIDE CONCENTRATION OF RADIATION PROPAGATING IN A NONLINEAR MEDIUM

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The effectiveness of spontaneous waveguide concentration of radiation propagating in a nonlinear medium is investigated. The conditions under which the concentration effectiveness (the fraction of the energy that had not lost the initial concentration) can be large are determined. It is shown that the multifocus regime of self-focusing for radiation transmission is ineffective.

We describe here the first direct experimental investigation of the effectiveness of spontaneous waveguide propagation of radiation in a nonlinear medium [1 - 4]. No such investigations were performed to date, in spite of the large number of papers devoted to self-focusing, although waveguide focusing and waveguide self-contraction of a beam into a single focus are of greatest practical interest. (We note that the waveguide description of self-focusing is connected with the spatially distributed nature of the focusing action, which is equivalent to the appearance of waveguides that can, as is well known, be of variable cross section, length, and profile.)

The experimental setup for the investigation of waveguide self-focusing is shown in Fig. 1. A Q-switched neodymium laser operating in the longitudinal-mode regime produced a pulse with half-width 20 nsec. The beam passed through a diaphragm D_1 having an opening of diameter $d_1 = 4 \times 10^{-2}$ cm and located several centimeters ahead of the entrance into the nonlinear medium; this ensured a smooth transverse distribution of the beam intensity on entering the medium. The nonlinear medium was nitrobenzene in a cell of length L = 50 cm, in which the linear absorption did not exceed 20%. Located at the output end of the cell was a diaphragm D_2 with an opening of diameter $d_2 = 5 \times 10^{-2}$ cm, which separated the concentrated radiation from the total flux of the transmitted diverging beam, which was measured when the diaphragm D_2 was removed. (The diffraction broadening of the low-intensity beam increased the cross section of the beam several tenfold on leaving the cell.) The incident and transmitted concentrated or fully-transmitted light were measured with two FEK-09 coaxial photocells and registered with two beams of a 6LOR-2-M high-speed oscilloscope.

The linearity of the photocell readings was measured in special experiments. The photocell output pulses, with and without the diaphragm D_2, could correspond to different input flashes, and the input pulses were therefore monitored. The position of the diaphragm D_2 was chosen exactly to intercept the maximum fraction of the incident beam. During the series of flashes, no changes occurred in either the magnitude or the shape of the pulse of light transmitted through the diaphragm D_2 when the incident-light pulses were identical, thus showing good reproducibility of the result, even without special thermostatic control of the liquid.

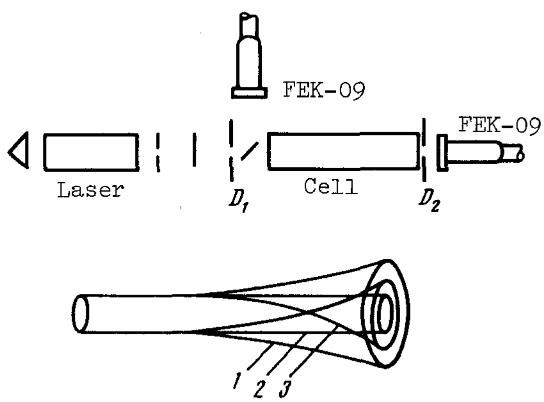

Fig. 1. Diagram of setup. Paths of rays in the cell: 1) $P < P_{thr}$, 2) $P \simeq P_{thr}$, 3) $P > P_{KL}$.

The power of the light past the diaphragm D_1, at the pulse maximum, ranged from 50 to 180 kW, so that the subthreshold, threshold, and above-threshold regimes could be investigated separately (in the latter case, the focal point was located inside the nonlinear medium). The power at which the cell length was equal to the so-called Kelley length was $P_{KL} \simeq 120$ kW, close to the threshold power $P_{thr} \simeq 100$ kW.

In the presence of the diaphragm D_2 the pulses from the photocells characterized the concentrated power P_d entering a diaphragm opening commensurate with the beam dimensions at the entrance into the medium (that part of the power which did not decrease the initial energy concentration), whereas without the diaphragm D_2 we registered the entire power P_{tr} transmitted through the nonlinear medium. Figure 2 shows typical pulses. The second trace of the lower half shows the pulse P of the incident laser beam; its magnitude was the same for both upper pulses with and without the diaphragm D_2. (To be able to compare P_d and P_{tr}, we picked out from the large number of flashes only those pulse pairs for which the initial laser pulses were equal in shape and in magnitude.) Figure 2a shows the result obtained at a power P such that the focus has not yet entered into the medium ($P < P_{KL}$), while Fig. 2b shows the case when the power exceeds the threshold, $P \simeq 1.4P_{KL}$. We see here that the increase of P_d is limited by scattering and absorption of the radiation when the focus enters the nonlinear medium.

Figure 3 shows a typical plot of the fraction of the concentrated energy $\alpha = P_d/P_{tr}$ against the ratio of the incident to critical energy P/P_{KL}. We see that at $P > P_{KL}$ (in which case $L_K < L$) the effectiveness of the concentrated-

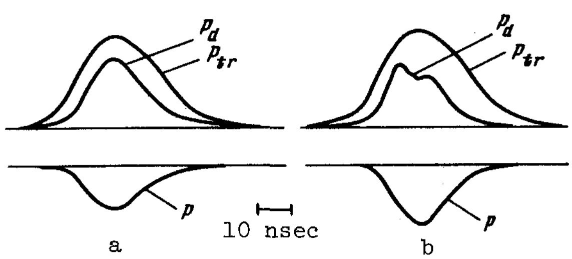

Fig. 2

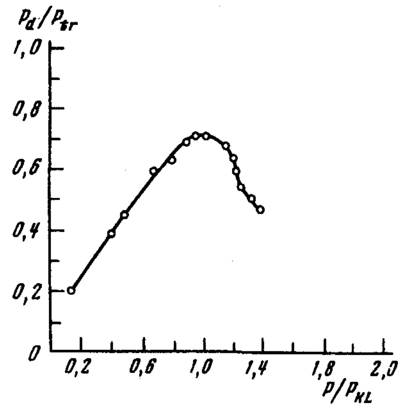

Fig. 3

Fig. 2. Oscillograms of the radiation P(t) incident on a nonlinear medium, of the total radiation P_{tr} transmitted through the medium, and of the transmitted concentration-conserving radiation P_d (which enters the aperture of diaphragm D_2). a) Incident power does not exceed the Kelley power, b) $P > P_{KL}$. The kinks on the oscillogram demonstrate the energy scattering produced when the focus enters into the medium.

Fig. 3. Effectiveness of transmission of concentration-conserving radiation P_d/P_{tr} vs. the excess of power above the Kelley power P/P_{KL}.

radiation transmission decreases sharply. The deviation of α_{max} from unity may be caused by the fact that the initial diffraction profile does not ensure complete gathering of the radiation. The maximum fraction of the concentrated radiation was close to the fraction of the radiation in the principal diffraction maximum, thus demonstrating adequate gathering of the radiation for the employed case of simple initial intensity-distribution profile.

Given the function P(t) of the initial laser pulse, we can estimate the initial flux density $I_{tr}(t) \approx (c/4\pi)E_{tr}^2$ and the power $P_d = \pi r_2^2 I_{tr}$ from the aberration-free formula. The solution of the aberration-free equation for the radius of the beam cross section

$$a''_{zz} = -A(t)/a^3, \quad \text{where } A = n_2 E_0^2(t) a_0^2 - \lambda^2$$

yields at a small initial divergence angle

$$a^2 = a_0^2 - Az^2/a_0^2; \text{i.e.,} L_K = a_0^2/\sqrt{A}; \quad \text{and} \quad \theta_{max} \approx a'_{max} \approx \frac{\sqrt{A}}{a_{min}},$$

i.e., at a distance z = L

$$E_{tr}^2(t) \approx E_0^2(t) a_0^2/a^2 \approx E_0^2(t) \Big/ \left[1 - \frac{L^2}{a_0^2}\left(n_2 E_0^2 - \frac{\lambda^2}{a_0^2}\right)\right] \approx \frac{E_0^2(t)}{1 - L^2/L_K^2(t)};$$

where L_K is a quantity close to the so-called Kelley length [4], coinciding with the latter when $E \gg E_{thr}$.

So long as the radius of the beam spot a(t, L) exceeds the radius r_2 of the diaphragm opening, we have

$$P_d(t) = P_0(t) r_2^2/a_0^2 \left[1 - \frac{L^2}{L_K^2}(t)\right] = P_0(t)(P_{KL} - P_{thr}) r_2^2 / [P_{KL} - P_0(t)] a_0^2$$

at $r_2 < a$, where P_{KL} is the power necessary to make the Kelley lenght $L_K = L$ at a given initial beam radius. At $a < r_2$ we have $P_d(t) \approx P_{tr}(t) \approx P_0(t)$.

It is seen from the foregoing formulas that the power and radiation-energy transfer coefficient increases at $P_{0max} \lesssim P_{KL}$ and decreases at $P_0 \gg P_{KL}$.

Similar conclusions are valid for the multiple waveguide regime of self-focusing [6]. Our results demonstrate also that the transfer becomes extremely ineffective when the focus is inside the medium, owing to the large scattering and absorption of the radiation in the foci [5] that appear ahead of the radiation receiver, which always receives a power close to the threshold value if the transmitted power greatly exceeds the threshold.

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