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Dynamics and Characteristics

of the Self-trapping of Intense Light Beams*

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In an optical medium with non-linear refractive index, an intense light beam may form its own optical waveguide and propagate without diffracting.[(1)(2)] There has already been some experimental evidence for this phenomenon, especially in glasses[(3)] and Raman active liquids.[(4)(5)] This paper reports direct observation of the evolution of beam trapping in CS_2 in the simplest cylindrical mode. The threshold, trapping length, change in index of refraction, and steady-state beam profile have been found to be consistent with theoretical predictions[(1)(6)(7)] calculated from the non-linear refractive index due to the Kerr effect.[(8)] It has been demonstrated that a steady-state condition is asymptotically approached in which the beam collapses to a bright filament as small as 50μ.

A Q-switched (rotating prism) ruby laser beam impinging on a 0.5 mm pinhole produced a diffraction-limited plane wave 10 to 100 kilowatts in power. Changes in beam diameter were obtained by placing various lenses their focal distance after the pinhole. The development of trapping in a cell of CS_2 was studied by immersing microscope slides every two centimeters along the beam in order to reflect a small fraction of it out of the cell. Figure 1 shows the experimental setup and magnified images (8X) of the beam profile as it reflects off the glass plates. Each plate causes two reflections, only one of which is shown here. No changes in properties of self-trapping have been observed to be introduced by the plates, which are very thin

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compared with distances in which the beam is characteristically trapped.

Figure 1b shows the results obtainable with such configuration. It is clear that after a certain distance a steady-state condition is approached consisting of a bright filament, here 100μ in diameter. Simple diffraction would double the size of such a beam in the distance to the next glass plate, proving that we do indeed have beam trapping, i.e. propagation of a beam without spreading by ordinary diffraction. Eventually losses such as two-photon absorption(9) deplete the beam intensity allowing some spreading. Intensity profiles of the beam were measured 50cm. from the entrance to the cell and compared with the theoretical intensity profile.(1) The observed profile (cf. Fig. 2a) was found to consist of a strongly peaked distribution in reasonable agreement with the theoretical curve, super-imposed on a broad background of untrapped radiation. The central peak power was twenty-five times brighter than the background, with roughly half the total radiation in the trapped peak. This peak appeared to be 10 per cent depolarized due to wave guide effects. Stokes radiation was found to be emitted from the 100μ trapped region, in several small filaments the order of 10μ in diameter, with intensity 1% that of the trapped beam.

A threshold was observed in total power, as expected, which remained the same even when the beam diameter was halved. The measured threshold was about 25 ± 5 kilowatts, somewhat higher than the theoretical threshold of 10 kw(10) calculated from the optical Kerr constant $n_2 = 1.8 \times 10^{-11}$ esu(8). This is not unexpected since the incident beam profile is not ideal and only part of the beam traps.

From examination of photographs such as those in Fig. 1b, a characteristic distance for the collapse of the beam into a bright filament can be determined. A theoretical trapping distance has been calculated for Gaussian beams by Kelley, giving $\frac{a}{2}\sqrt{\frac{2n_o}{n_2}}\frac{1}{E_o}$, with $n_2 E_o^{\,2}/2$ the nonlinear contribution to the refractive index, and a the beam radius.[6] For a 90 kilowatt beam 0.5 mm in diameter, the theoretical trapping length of 11 cm, calculated with the optical Kerr coefficient $n_2 = 1.8 \times 10^{-11}$ esu, agrees well with the measured trapping length of 12 cm. At the same power levels halving the beam area roughly halved the trapping length, as expected. Accurate measurements of the trapping length as a function of peak intensity were hampered by a degree of variability in trapping lengths, expecially at smaller beam diameters. Such variability may be caused by unreproducible field gradients such as those introduced by dust particles, or multimoding of the ruby laser. Nevertheless it was observed that the trapping length decreased with increasing power.

A monotonic collapse of the beam into a steady-state condition did not always occur, especially at shorter trapping lengths. Transient phenomena in the form of rings often were present (Fig. 1c). Some of these rings appear to be interference between a spherical wave diffracting from a point in the liquid and the untrapped beam. These phenomena died out in sufficiently long cells leaving only the steady-state profile discussed above. However at higher powers, a persistent ring (Fig. 1d) appeared which may be related to the higher order steady-state modes.[11]

An essential feature of self-trapped optical beams is the increase in refractive index in the trapped region. The resulting slower velocity of the trapped beam causes an accumulation of the phase of a trapped ray relative to those which are untrapped. To detect this phase change, two slits were placed immediately after the cell over the trapped beam profile in the manner shown in Figure 2a. These slits were magnified ten times along their length by a cylindrical lens without altering the two-slit interference pattern. When one of the slits was centered on the intense trapped filament, the resulting interference pattern from a 50 cm cell revealed a phase change greater than 2π. However, when the slit was moved off center, the pattern shown in Figure 2b was obtained, implying a gradual rather than discontinuous phase change across the beam profile. This confirms that not all the beam reached the steady-state waveguide condition in which the entire beam travels with fixed phase. A 10 cm cell yielded 0.6 of a fringe shift (Fig. 2c), which implies $\Delta n = 1.4 \times 10^{-5}$ since the filament was 3 cm long. This is consistent with the optical Kerr effect calculated in the filament which was ten times brighter than the untrapped radiation of 16 Mwatts/cm^2.

Most ruby laser beams have intensities far above threshold for trapping in CS_2 and are sufficiently inhomogeneous to give the complex patterns which have been previously photographed.(4) Figure 1e shows the developments of many filaments from an apparently homogeneous beam about 1 mm in diameter and considerably above threshold power. Each trapped filament was in itself approximately cylindrical and was surrounded by a bright ring in this stage of development.

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Figure Captions

Figure 1: Evolution of beam-trapping in CS_2. Left: without dashed cell; right: dashed cell adds 25 cm path length. (a) gas laser control (b, c, d) beam-trapping at increasing power (e) 1 mm pinhole.

Figure 2: Two-slit interference experiment. (a) Trapped beam profile showing location of slits (b, c) interference patterns from 50 and 10 cm cells, respectively.

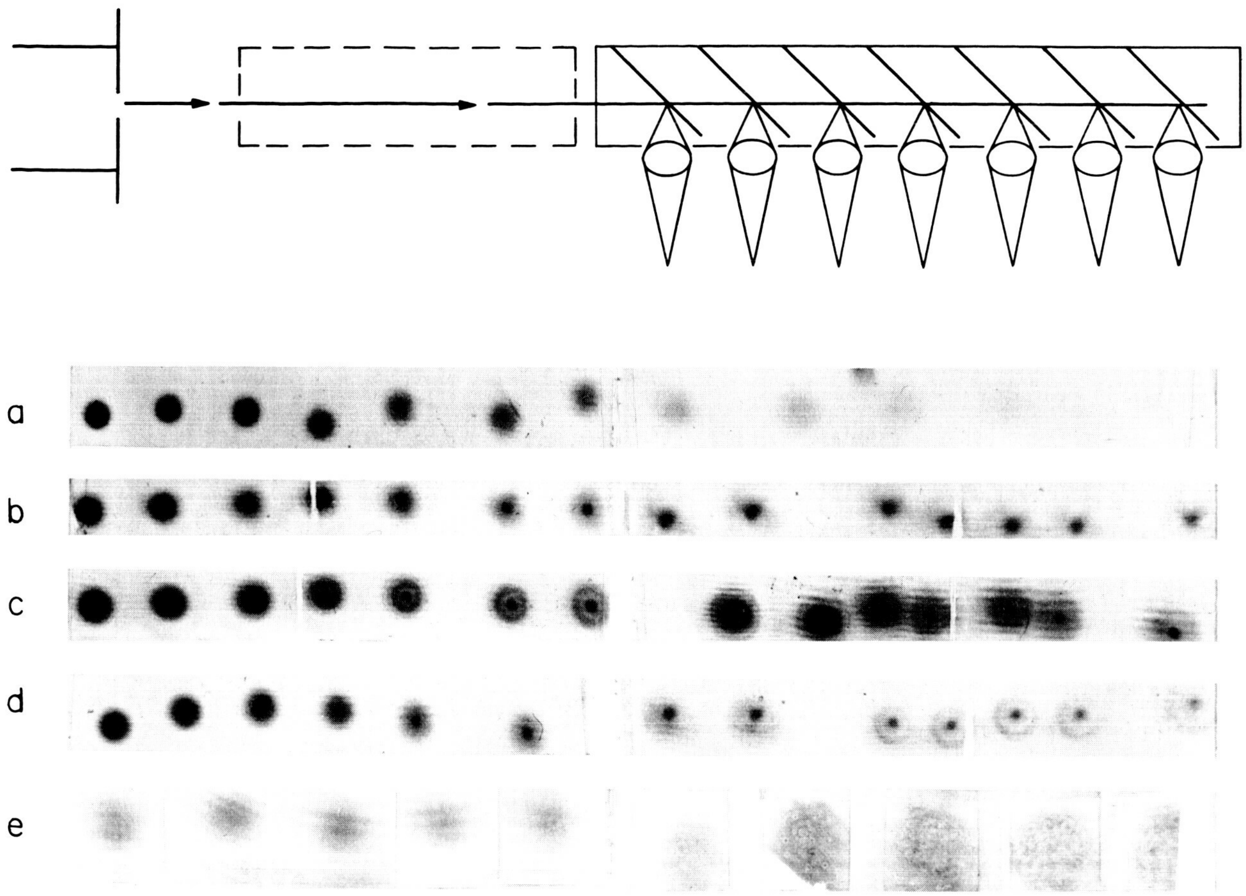

FIG. I

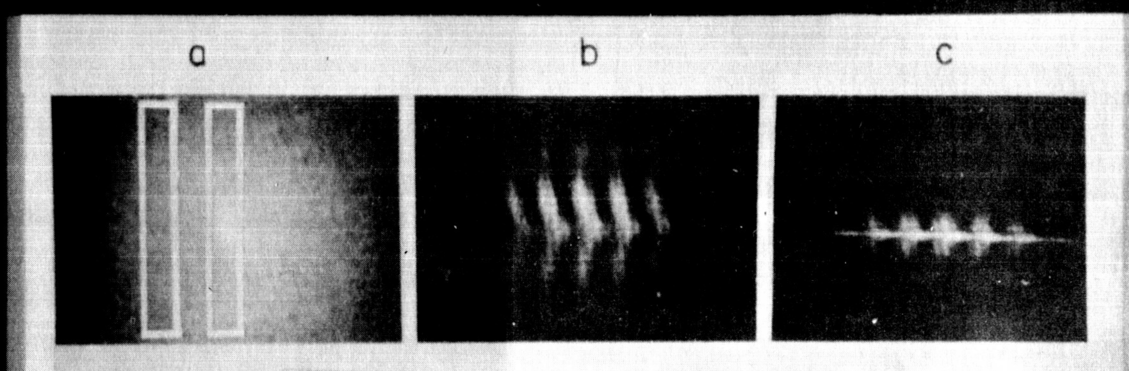

Fig. 2