DYNAMICS AND CHARACTERISTICS OF THE SELF-TRAPPING OF INTENSE LIGHT BEAMS*

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In an optical medium with nonlinear refractive index, an intense light beam may form its own optical wave guide 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 nonlinear 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 50 μ.

A Q-switched (rotating prism) ruby laser beam impinging on a 0.5-mm pinhole produced a diffraction-limited plane wave 10 to 100 kW 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 (8×) 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 compared with distances in which the beam is characteristically trapped.

Figure 1(b) shows the results obtainable with such a configuration. It is clear that after a certain distance a steady-state condition is approached consisting of a bright filament, here 100 μ 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 50 cm from the

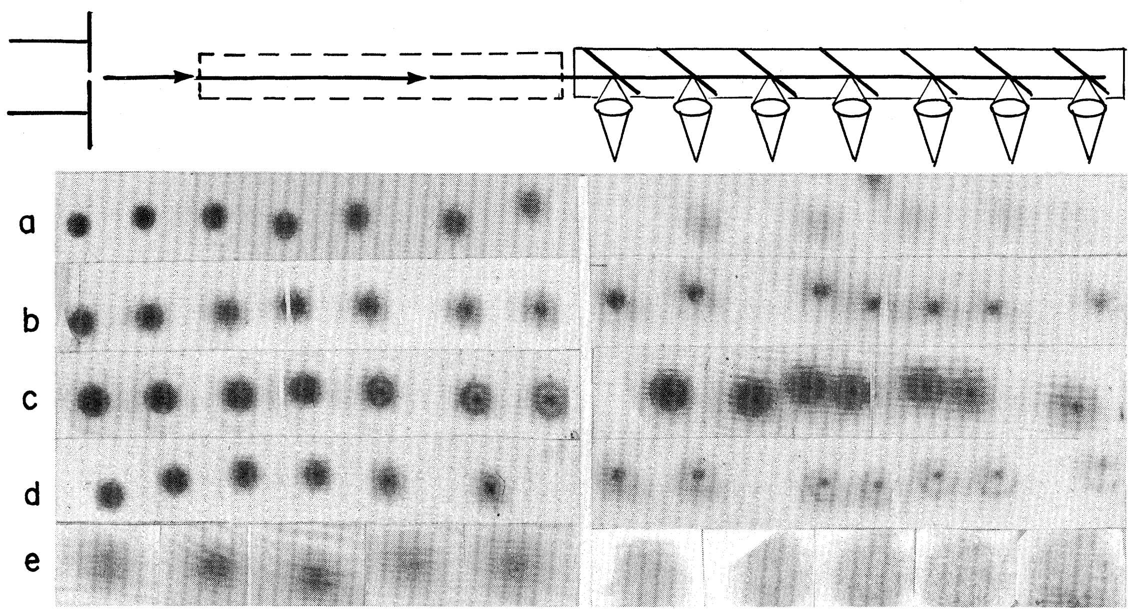

FIG. 1. Evolution of beam trapping in CS_2. Left: without dashed cell; right: dashed cell adds 25 cm path length. (a) Gas laser control; (b), (c), and (d), beam trapping at increasing power; (e) 1-mm pinhole.

entrance to the cell and compared with the theoretical intensity profile.[1] The observed profile [cf. Fig. 2(a)] was found to consist of a strongly peaked distribution in reasonable agreement with the theoretical curve, superimposed on a broad background of untrapped radiation. The central peak power was 25 times brighter than the background, with roughly half the total radiation in the trapped peak. This peak appeared to be 10% depolarized due to wave-guide effects. Stokes radiation was found to be emitted from the 100-μ trapped region, in several small filaments the order of 10 μ in diameter, with intensity 1% that of the trapped laser.

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 kW, somewhat higher than the theoretical threshold[10] of 10 kW 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. 1(b), 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 $z = (a/2)(2n_0/n_2)^{1/2} \times (1/E_0)$, with $n_2E_0^2/2$ the nonlinear contribution to the refractive index, and a the beam radius.[6] For a 90-kW 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, especially 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. 1(c)]. 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. 1(d)] 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 Fig. 2(a). These slits were magnified 10 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 Fig. 2(b) 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 wave-guide condition in which the entire beam travels with fixed phase. A 10-cm cell yielded 0.6 of a fringe

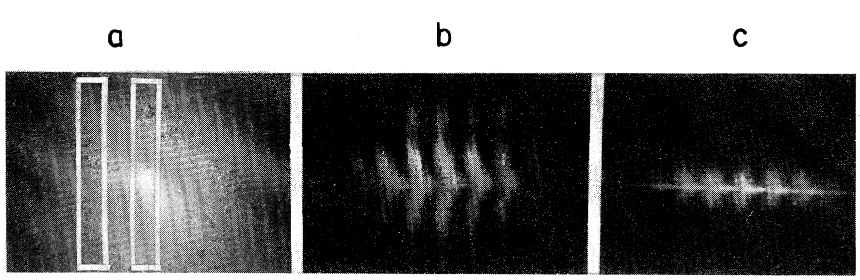

FIG. 2. Two-slit interference experiment. (a) Trapped beam profile showing location of slits. (b) and (c) Interference patterns from 50- and 10-cm cells, respectively.

shift [Fig. 2(c)], which implies $\Delta n = 1.4\times10^{-5}$ since the filament was 3 cm long. This is consistent with the optical Kerr effect calculated in the filament which was 10 times brighter than the untrapped radiation of 16 MW/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 1(e) shows the development 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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[1]R. Y. Chiao, E. Garmire, and C. H. Townes, Phys. Rev. Letters 13, 479 (1964).

[2]V. I. Talanov, Izv. Vysshikh Uchebn. Zavedenii, Radiofiz. 7, 564 (1964).

[3]M. Hercher, J. Opt. Soc. Am. 54, 563 (1964); G. N. Steinberg, J. G. Atwood, and P. H. Lee, to be published.

[4]G. Hauchecorne and G. Mayer, Compt. Rend. 261, 4014 (1965); P. Lallemand and N. Bloembergen, Phys. Rev. Letters 14, 1010 (1965); Y. R. Shen and Y. J. Shaham, Phys. Rev. Letters 14, 1008 (1965).

[5]N. F. Pilipetskii and A. R. Rustamov, Zh. Eksperim. i Teor. Fiz.–Pis'ma Redakt. 2, 88 (1965) [translation: JETP Letters 2, 55 (1965)].

[6]P. L. Kelley, Phys. Rev. Letters 15, 1005 (1965).

[7]V. I. Talanov, Zh. Eksperim. i Teor. Fiz.–Pis'ma Redakt. 2, 218 (1965) [translation: JETP Letters 2, 138 (1965)].

[8]G. Mayer and F. Gires, Compt. Rend. 258, 2039 (1964).

[9]J. A. Giordmaine and J. A. Howe, Phys. Rev. Letters 11, 207 (1963).

[10]The computed power in Ref. 1 should be $P_c = (\frac{1}{2})5.763\lambda^2 c n_{\mathrm{eff}}/8\pi^3 n_2 n_0$, where $n = n_0 + n_2 E_0^{\,2}/2$.

[11]H. Haus, to be published; Z. Jankauskas, to be published.

IMPURITY-INDUCED NEAR-INFRARED SPECTRA AS A SOURCE OF INFORMATION ABOUT THE FREQUENCY DISTRIBUTIONS OF THE ALKALI HALIDES

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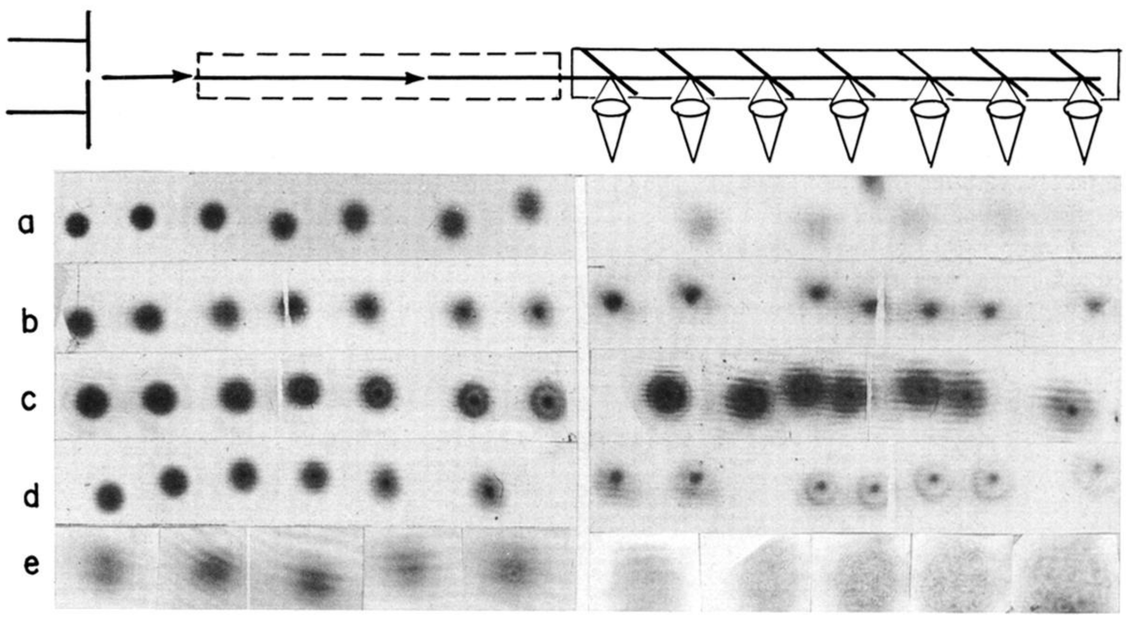
It has been recognized for some time now that bandwidths and band structures in the infrared spectrum of complex ions in the crystalline state cannot satisfactorily be explained by using the rules of factor-group analysis, nor by allowing for combinations with librational modes or optically active lattice fundamentals.[1,2] In general, all normal vibrations and not just the $K = 0$ modes may take part in combination modes. Hence the envelope shape of the band and its combinations depend on the shape of dispersion and frequency distribution curves. Selection rules may still favor some combinations and, therefore, the band shape does not have to resemble the distribution curve in all cases.

Complete experimental dispersion relations, however, are rarely available, which makes a comparison with the distribution function and a determination of the effect of selection rules unattainable.

With respect to the determination and calculation of the dispersion and frequency distribution curves, the alkali halides are among the most favorable cases. The lack of complex ions with readily observable vibrations in these crystals can be overcome by substitution of complex ions as impurities at lattice sites. Such ions may serve as detectors for the lattice modes of the alkali halide by giving combination bands of the internal vibration of the complex ion with the lattice modes of the host crystal.

The influence of the substitute on the lattice frequencies, if present in low concentrations, is negligible for nearly all phonons,[3] so that the band structure due to these combinations will be related to the frequency distribution of the pure alkali halide lattice. The observed band structure may now be compared with the calculated distribution function of the crystal, However, a small number of phonon levels,



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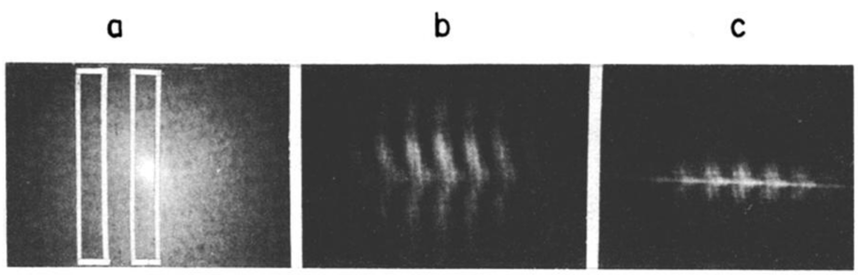

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