An alternative description which allows for the effects of intermolecular interactions in inhibiting alignment would be that of collective phonon-like modes, which take up energy from the field and hence affect the optical response.

While it is clear that the filament lifetime is too short to allow macroscopic motions within the liquid to importantly reduce stresses, there may be sufficient time for an individual molecule to move perpendicularly to its axis of alignment a small amount and thus relieve these stresses. The completeness of such relief is not clear and undoubtedly depends on details of the individual molecular surroundings. The study of transverse acoustic waves in liquids[4] and molecular librations[5] indicates relaxation times in the range 10^{-10}–10^{-12} s for such motions. Consequently, a substantial fraction of the stress produced by sudden molecular alignment must remain during the lifetime of a filament and thus affect its behavior.

[4] G. I. A. Stegeman and B. P. Stoicheff, *Phys. Rev. Lett.*, vol. 21, p. 212, 1968; B. S. Starunov, E. V. Tiganov, and I. L. Fabelinskii, *Pis'ma Zh. Eksp. Theor. Fiz.*, vol. 5, p. 318, 1967 (transl. in *JETP Lett.*, vol. 5, p. 260, 1967).
[5] R. Polloni, C. A. Sacchi, and O. Svelto, *Phys. Rev. Lett.*, vol. 23, p. 690, 1969.

O.6 TE and TM Modes at Optical Frequencies: Generation and Self-Focusing, D. Pohl, *IBM Zurich Research Laboratory, Rüschlikon, Switzerland.*

The self-focusing of TE_{01} and TM_{01} light beams generated by an appropriately constructed ruby laser was investigated. Longitudinal fields and induced birefringence in the focal zone cause characteristic differences in critical power.

O.7 Steady-State Formation of Filaments in Self-Focusing, E. Courtens, *IBM Zurich Research Laboratory, Rüschlikon, Switzerland.*

The possibility of self-trapping an optical beam in a nonlinear index medium was noted soon after the discovery of the laser. The lens-like effect of these media, leading to the self-focusing of beams, was also recognized very early. But in spite of continued activity in these fields, the question of whether the self-focusing of optical beams can lead to the self-trapped solution of Chiao *et al.* (CGT)[1] has never been answered satisfactorily. We analyzed theoretically the conditions under which a steady-state filament could be formed by self-focusing. We also attempted to observe these filaments experimentally using a well-controlled stable single-mode Q-switched ruby laser. The results are the following.

1) Theoretically, using the simplest lowest order nonlinearity in the parabolic wave equation, one finds that the self-focusing of a TEM_{00} Gaussian beam leads to a CGT filament for a distance of the order of the linear beam parameter, provided 1) the power is within a narrow range (~10 percent) just below the critical power, and 2) the beam is initially convergent onto the entrance face of the nonlinear medium.

2) Experimentally, under precisely these conditions, we find that 1) no filament is observed in the forward direction (at the cell exit window), and 2) stimulated scattering is seen in the backward direction, either Brillouin or Raman depending on the Kerr liquid used.

In view of our analysis and in view of experimental and theoretical results obtained here by Pohl,[2] it appears that our theoretical description should have been adequate, except for the neglect of stimulated scattering. We therefore conclude that stimulated scattering is the next nonlinearity to be included in the description of steady-state trapping.

The steady-state filaments should be distinguished from those usually obtained under multimode or mode-locked excitation of the usual Kerr liquids. In such cases the filament duration is of the order of the orientational relaxation time, and a dynamical description is required. The stabilizing influence of the orientational relaxation time can be extremely important, as shown by Shimizu.[3]

[1] R. Chiao, E. Garmire, and C. Townes, *Phys. Rev. Lett.*, vol. 13, p. 479, 1964.

[2] D. Pohl, to be published.
[3] F. Shimizu, to be published.

O.8 Study of Spectral Broadening of Light in a Filament Induced by a Moving Focus,[1] G. K. L. Wong and Y. R. Shen, *Department of Physics, University of California, Berkeley, Calif. 94720, and IMRD, Lawrence Berkeley Laboratory, Berkeley, Calif. 94720.*

Spectral broadening of light in a small-scale filament has long been used as evidence for self-trapping. However, recent theoretical and experimental results have shown conclusively that at least for nanosecond pulse excitation, the observed filaments are the result of moving foci. In particular, we have shown[2] that because of the appreciable Δn induced by the moving focus, the self-focused light traversing the medium can acquire a phase modulation which leads to the broadened spectrum. Broadening of the order of 100 cm^{-1} can be obtained if a 1-ns input pulse with peak power of a few tenths of 1 kW is used in CS_2 of a few tenths of 1 cm long. In order to verify the theory quantitatively, we have performed experiments with a single-mode 1.2-ns ruby laser pulse, which consistently yields a single filament in self-focusing. Such a laser pulse was obtained by switching out a single pulse in a train of weakly mode-locked pulses. The beam diameter was about 300 μm, and the maximum peak power of the pulse was about 40–70 kW.

We have measured the spectral broadening of light from the filament as a function of the peak power and the cell length in CS_2 and toluene. According to the theory,[2] broadening on the Stokes side is given by $\Delta\omega_{max} \cong (\omega/c)(1/c' - 1/v)(\Delta n^*_{max})_l$, where c' is the light velocity in the medium, v is the velocity of the moving focus at the end of the cell, and $(\Delta n^*_{max})_l$ is the maximum effective field-induced refractive index at the end of the cell. Knowing the characteristics of the input pulse, we can calculate v for a given cell length, and hence $\Delta\omega_{max}$ if $(\Delta n^*_{max})_l$ is also known. We can then compare the calculated $\Delta\omega_{max}$ with the measured data. In our case, we choose for each cell length a value of $(\Delta n^*_{max})_l$ which gives the best fit to the experimental data. This value varies between 0.8×10^{-3} and 1.6×10^{-3} for CS_2 and between 2.5×10^{-4} and 4×10^{-4} for toluene and is smaller for longer cell lengths as expected. The calculated $\Delta\omega_{max}$ versus peak power of the input pulse appears to be in fair agreement with the experimental curves for several cell lengths in both CS_2 and toluene. Both theory and experiment show that the broadening increases with the cell length and the peak power in the range of our investigation. The good agreement between theory and experiment in this case is another strong support for the moving focus model.

[1] This work was supported by the U. S. Atomic Energy Commission.
[2] Y. R. Shen and M. M. T. Loy, *Phys. Rev.*, vol. A3, p. 2099, 1971.

O.9 Self-Focusing Threshold of Gaussian-Elliptic Light Beams, C. Giuliano, *Hughes Aircraft Laboratories, Malibu, Calif.*, and A. Yariv, *California Institute of Technology, Pasadena, Calif.*

There is now substantial evidence to indicate that the long damage filaments created by laser beams passing through solid materials are due to self-focusing. In an effort to increase the damage threshold of such materials we considered the problem of self-focusing of Gaussian-elliptic beams of the form

$$E(\mathbf{r}) = \frac{A}{\sqrt{\omega_x(z)\omega_y(z)}} \exp\left[-i(kz - \phi) - x^2\left(\frac{1}{\omega_x^2(z)} + \frac{ik}{2R_x(z)}\right) - y^2\left(\frac{1}{\omega_y^2(z)} + \frac{ik}{2R_y(z)}\right)\right] \quad (1)$$

where the Gaussian parameters ω and R describing the beam evolution in the x–z and y–z planes are, in general, not equal to each other. This leads to equi-intensity contours which are ellipses with

planes normal to the z axis.

We show theoretically that the self-focusing threshold power P_c, defined as the beam power at which the nonlinear focusing gives rise to an increasing intensity on the axis, is a strong function of the beam *initial* aspect ratio v/u. For a circular beam ($v = u$) our result reduces to the well-known result

$$P_c\left(\frac{v}{u} = 1\right) \equiv P_{co} = \frac{\epsilon^2\lambda^2 c}{4\pi\epsilon_2}.$$

In the limit $v \gg u$, $P_c = P_{co}\,(v/u)$ so that large increases ($\sim v/u$) in the threshold power are indicated.

These theoretical predictions are verified by a series of experiments in which the damage threshold in sapphire is measured as a function of the ellipticity of the input ruby laser beam. We find that for $v = u$ damage power is typically $\sim$1 MW, while for $v/u = 7$ it rises to 4.5 MW. For $v/u = 85$ no self-focusing is observed up to the maximum available beam power of 17 MW.

The evolution of the beam under a variety of input and power conditions is described using numerical techniques.

O.10 Self-Defocusing of Light by Rubidium Vapor, D. Grischkowsky, *IBM Thomas J. Watson Research Center, Yorktown Heights, N. Y. 10598.*

We report the observation of self-defocusing of light due to a resonant electronic nonlinearity. The narrow-line ($\delta\nu < 0.005$ cm^{-1}) output of a laser-pumped dye laser was strongly self-defocused by passing through a 100-cm rubidium vapor cell in a magnetic field of 4 kG. The 15-ns pulse of the dye laser had a maximum intensity of 25 kW/cm^2 at the input window of the vapor cell. The frequency ν of the dye laser was on the low-frequency side of the Zeeman split $^2P_{1/2}$ resonance line (7948 Å) of rubidium with $(\nu_0 - \nu)/C = 0.6$ cm^{-1} for the σ^- coponent of the line, where ν_0 was the transition frequency, and $(\nu_0 - \nu)/c = 1.1$ cm^{-1} for the σ^+ component. The conditions under which self-defocusing occurred agree with theory. The constitutive relationship between the applied field and the induced polarization is known precisely for the rubidium vapor. For modest intensities the expression for the dielectric constant ϵ of the vapor may be approximated by $\epsilon \approx \epsilon_0 + \epsilon_2 E^2$, where E is the electric field strength. For some of the results reported here $\epsilon_2 = -3.7 \times 10^{-8}$ ESU, which is quite large for a fast response system. For comparison $\epsilon_2 = 4.2 \times 10^{-11}$ ESU for CS_2 the most nonlinear Kerr liquid. The response time of the resonant nonlinearity causing the self-defocusing was roughly equal to the period of the frequency difference, and for $(\nu_0 - \nu)/c = 0.6$ cm^{-1} the response time was approximately 55 ps. There was no evidence of absorption of light by the vapor. An upper limit for the absorption coefficient α for the conditions of the experiment is given by the low-level steady-state result $\alpha = 1.7 \times 10^{-4}$ cm^{-1}.

For each pulse of the dye laser the beam (near field) was photographed at the exit window of the rubidium vapor cell; the far-field was photographed by directing part of the emergent beam through a +203-cm lens with the film plane at the focal distance. An excess of rubidium was distilled into the Pyrex glass cell, which was then sealed under vacuum. Increasing the cell temperature increased the number density $N(N = 7 \times 10^{12}$ at 110°C) of rubidium atoms and consequently increased ϵ_2. A 1-nm aperture was centered on the dye laser beam approximately 12 cm from the input window of the vapor cell. Data were taken as a function of cell temperature and direction of rotation (σ^+ or σ^-) of the input circularly polarized light.

The strength of the observed self-defocusing increased smoothly with cell temperature and input beam intensity. As expected, self-defocusing was much stronger for σ^- light than for σ^+ light, because $\epsilon_2 \sim (\nu_0 - \nu)^{-3}$ and ϵ_2 for σ^- light was approximately six times ϵ_2 for σ^+ light. At 110°C and for σ^- light the magnitude of the self-defocusing was roughly equivalent to an $f = -30$-cm lens; at 110°C for σ^+ light the self-defocusing was roughly equivalent an $f = -100$-cm lens. These results are to be compared with theoretical values of $f = -25$ cm for σ light and $f = -60$ cm for σ^+ light. The theoretical values of f were calculated from the relationship $f = -d/(2|\delta\epsilon|^{1/2})$, where d was the diameter of the input beam and $\delta\epsilon$ was the change in ϵ caused by the beam. Both the near- and far-field photographs of the σ^- beam at 110°C showed ring structure. Whether this structure can be explained by spherical aberration is unclear.

The conditions for adiabatic following were satisfied for this experiment. The term adiabatic following indicates that the pseudomoment, associated with the near resonant transition, follows (remains aligned along) the adiabatically changing effective field direction of the applied laser pulse. For adiabatic following and circularly polarized light propagating along the magnetic field, the dielectric constant of the rubidium vapor is

$$\epsilon = 1 - \frac{4\pi N_e {p_{12}}^2}{h(\nu - \nu_0)(1 + 2E^2/{E_s}^2)^{1/2}}.$$

Here N_e is the number density of atoms initially in the $M_J = \pm\frac{1}{2}$ Zeeman state of the $5^2S_{1/2}$ level (N_e is one-half the total atomic number density N); E is the field strength of the input σ light; $p_{12} = 6.16 \times 10^{-18}$ ESU is the absolute value of the matrix element of the electric dipole moment for the $\sigma^\mp$ transition between the $5^2S_{1/2}, M_J = \pm\frac{1}{2} \leftrightarrow 5^2P_{1/2}, M_J = \mp\frac{1}{2}$ Zeeman states; ν is the frequency of the incident light; ν_0 is the frequency corresponding to the energy separation between the $5^2P_{1/2}, M_J = \mp\frac{1}{2}$ and $5^2S_{1/2}, M_J = \pm\frac{1}{2}$ levels; $E_s = |h(\nu - \nu_0)/p_{12}|$. When $E^2 \ll E_s^2$, ϵ can be expanded as $\epsilon = \epsilon_0 + \epsilon_2 E^2$, where $\epsilon_0 = 1 - 4\pi N_e P_{12}^2/[h(\nu - \nu_0)]$ and $\epsilon_2 = 4\pi N_e P_{12}^4/[h(\nu - \nu_0)]^3$.

Experiment and theory will be discussed and compared.

O.11 Explanation of Limiting Diameters of the Self-Focusing of Light, O. Rahn and M. Maier, *Physik Department, Technischen Universität, Munich, Germany.*

There has been extensive experimental and theoretical work on the self-focusing action of intense laser beams. Many questions (e.g., self-focusing length, threshold power, and spatial and temporal development) have been solved. One of the most important questions still open is the origin of the limiting diameters. We have strong experimental and theoretical evidence that for giant laser pluses, stimulated Raman scattering limits the beam diameter.

Investigations of self-focusing were carried out using ruby laser giant pulses with a peak power of 500 kW and a duration of 20 ns. The light beam was collimated by a telescope and traversed a liquid cell with a length of $l = 30$ cm. A microscope produced a magnified image of the exit window on a photographic plate. The beam diameters were obtained from microdensitometer traces of the photographic plates. We have obtained the following experimental results:

1) The beam diameter was measured as a function of laser power in transparent and absorbing CS_2 ($\alpha l = 0$ to 2). First, the beam diameter decreases with increasing laser power. If a definite laser power is exceeded, the diameter remains constant. The corresponding value is the limiting diameter d. It is important to note that whenever the limiting diameter is reached, stimulated Raman scattering (SRS) in the forward and backward direction occurs (followed by stimulated Brillouin scattering).

2) We measured the limiting diameters d as a function of absorption in liquid CS_2. Absorbing CS_2 was used because the limiting diameters can be easily varied over one order of magnitude in this substance. For transparent CS_2 a value of $d = 4\ \mu$, for absorbing CS_2 ($\alpha l = 1.5$) a value of $d = 70\ \mu$ was found for the laser light. In the region $0 < \alpha l < 2$ the limiting diameter increases continuously with absorption. When the limiting diameter is reached, SRS occurs with a diameter somewhat smaller than the diameter of the laser light.

In order to explain the experimental results, solutions of the wave equation were obtained using a computer. We solved the following coupled equations for the laser field E_L and the first Stokes line E_S of SRS including the nonlinear refractive index n_2 which leads to self-focusing action:

$$2ik_L\frac{\partial E_L}{\partial z} + \frac{\partial^2 E_L}{\partial r^2} + \frac{1}{r}\frac{\partial E_L}{\partial r} = -\frac{n_2}{n_0}k_L{}^2(|E_L|^2 + |E_S|^2)E_L - ig_L\frac{cn_0k_L}{8\pi}|E_S|^2 E_L$$