EVIDENCE FOR SINUSOIDAL PHASE MODULATION IN SMALL SELF-TRAPPED FILAMENTS

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if indeed a diffusive process is responsible. The capacitance method does not lend itself to such an investigation as the silicon has to be annealed to temperatures beyond this range.

Finally, it is pointed out that the distribution of considerably heavier implants at the same energies as determined by cross-sectioning and staining of various resistivities simultaneously implanted show a sharper concentration fall-off and suggest some difference in distribution with concentration. It has not been possible, however, to measure the same implant by the two techniques as light implants prove to be extremely difficult to stain while if it is attempted to measure heavy concentrations by the capacitance method, avalanche effects are incurred before the profile can be depleted through completely. Some concentration dependence could be expected if channeling is present. Gibbons *et al.*,[7] for example, have noted a concentration-dependent distribution for 40-keV implanted phosphorus in silicon. This they attributed to the initial presence of channeling which was later subdued by interstitial blocking. Due to the symmetry of the measured distribution for the light implants presented, channeling is considered to be negligible in the present case.

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Evidence is presented indicating that, in some cases at least, a sinusoidal phase modulation is responsible for the spectral broadening observed in trapped filaments of laser (and Raman) light. This kind of modulation has been suggested recently by Cheung *et al.*

Several workers have observed spectral broadening of laser light trapped in small-scale filaments.[1-3] These spectra show a series of discrete bright "points," whose frequency separation increases[1,4] as the shift from the laser frequency increases. Two models explaining this broadening phenomenon have been proposed, one involving a propagating pulse, the other a sinusoidal modulation. In this letter we present evidence for the latter model.

Phase-modulation of the waves propagating in a pulse of trapped light (filament) under the influence of an intensity-dependent refractive index has been discussed by Shimizu.[4] Distortion of the pulse due to self-steepening[5] is assumed to be negligible. He shows that, for a pulse long compared with the orientational relaxation time, the instantaneous frequency shift at a given point in the pulse is proportional both to the time rate of change of the intensity envelope and to the distance the pulse has traveled in the liquid. Because there are two points of the intensity profile for any given slope and the frequency components arising from these points may may be mutually in or out of phase, one expects the power spectrum to have interference maxima and minima. Furthermore, the spacing between the maxima increases with the shift from the central frequency. Shimizu's model fits the gross features of the spectra well and in particular suggests that the pulses involved are about 6 psec long (in CS_2).

A somewhat different point of view was Cheung *et al.*[6] who treated the field not in the form of a pulse, but as a strong wave E_0 (at the laser frequency ν_0) modulated by a second weaker wave E_1, shifted from ν_0 by ν_S. For $E_0 \gg E_1$ the power spec-

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trum of the sinusoidally phase-modulated light is given by:

$$S(z=L, \nu=\nu_0 - m\nu_S) \propto \sum_m \delta(\nu_0 - m\nu_S - \nu)\, E_0^2\, J_{m'}^2\,(\alpha),$$

where the Bessel function argument $\alpha = 2k_0 n_2 E_0 E_1 L$, $k_0 = 2\pi/\lambda_0$, n_2 is the coefficient of the nonlinear refractive index. (See Ref. 6.) The spectrum consists of a series of equally spaced lines each of whose intensities is given by the value of the corresponding Bessel function.

We present here the first direct evidence for the existence of the modulation discussed by Cheung *et al.* The experiment was performed by sending the collimated beam of a (pthalocyanine) dye-switched ruby laser into a 10-cm cell containing a self-focusing liquid. The intensity and diameter of the input beam were about 50 MW/cm^2 and 1 mm, respectively. The spectral width of the input beam was less than 0.1 cm^{-1}; thus, there were no pulses (of appreciable energy) shorter than 10^{-10} sec entering the liquid cell. In the liquid, the self-focused beam breaks up into tiny, intense filaments.[7] Images of the emerging filaments, magnified about 10 times, fall on the 20-μ slit of a 3/4-m grating spectrograph.

The resulting spectra occasionally show an equally spaced fine structure with a period ranging from 0.5 to 3 cm^{-1}. (The resolution of the spectrograph is about 0.4 cm^{-1}.) The most striking of these is shown in Fig. 1. This spectrum was produced in bromobenzene; the small interval is 1 cm^{-1} and very regular. The period varies from filament to filament for a given laser shot. For each liquid studied, the range of periods is the same, namely a few wavenumbers, and is consistent with the model of librational motion proposed by Cheung *et al.*[6] as a possible source of the frequency ν_S.[8]

Though it may not be evident in the reproduction, the fine structure becomes diffuse as the frequency shift reaches its maximum value. This may be related to the fact that the number of periods of the modulation that can be sustained is limited by the "lifetime" of the filament.[7] A sinusoid of frequency 1 cm^{-1} has a period of 3×10^{-11} sec and thus the wavetrain in the filament may contain only a few modulation cycles. This has two effects: First, the sharpness of the fine structure is inherently limited, for a finite wavetrain, to roughly $1/2\pi \times$ (the reciprocal of the temporal length of the train). From the 0.5-cm^{-1} width of the individual points in Fig. 1, we conclude that the duration of the wavetrain, and probably of this filament, is no less than 10^{-11} sec. Secondly, it can be shown[9] that the fine structure arising from such a limited wavetrain is expected to become more diffuse at the largest frequency shifts.

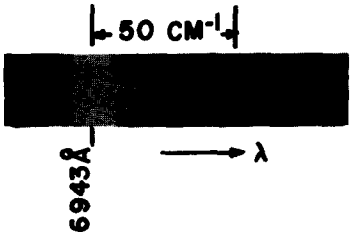

Fig. 1. A spectrum of the trapped light emerging in filaments from a cell of bromobenzene. The longest "track" shows the regularly spaced structure indicative of periodic phase modulation. This particular track showed no upshifted light. The long vertical lines are grating ghosts, spaced 6 cm^{-1} apart.

Because the occurrence of spectra with distinct periodic structure is infrequent, it is unlikely that sinusoidal modulation is generally present in the filaments. It is conceivable that in some cases the period is not resolved. Brewer[2] has reported periodic structure in nitrobenzene spectra in the range of tenths of a wavenumber, also with no apparent relation to any known material resonances. However, if a periodic phenomenon is involved, the spacing between interference maxima close to the laser line should be $2\nu_S$.[6] Thus, it is possible to deduce independently the modulation frequency which would be needed to give rise to our observed spectra. In this way we again find ν_S on the order of a few wavenumbers (for CS_2, bromobenzene, toluene, and nitrobenzene) and hence such spectra should be easily resolved.

Computer-generated spectra[9] for single-pulse and sinusoidal modulation are remarkably similar to each other, with the exception of the underlying fine structure in the latter. Hopefully, with a more general theoretical treatment of phase modulation in filaments, including effects of relaxation,[9] the details of the observed spectra will yield more precise knowledge of the source of modulation causing them.

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