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Weak-Wave Retardation and Phase-Conjugate Self-Defousing in Si

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We describe and measure the effects of self-defocusing on the various coupling effects produced when two coherent, noncollinear, picosecond optical pulses (strong excitation and weak probe) are both spatially and temporally coincident in a thin silicon wafer. Specifically, we observe that the weak probe beam experiences considerably more defocusing than the excitation beam. We believe that this is the first direct confirmation of weak-wave retardation in light-by-light scattering experiments. We also observe the effects of this defocusing on the quality of the forward-traveling conjugate wave.

In our experiments, two 65-psec (FWHM) pulses at 1.06 μm (excitation and probe), separated by an angle $\theta = 1.2°$, were focused to a 600 μm (FWHM) diameter spot on the surface of a thin (~270 μm-thick) Si wafer. The excitation and probe could be delayed by an amount τ with respect to one another by means of an optical delay line. When both excitation and probe are spatially and temporally coincident ($\tau = 0$), the interference between these two parallel-polarized pulses modulates the intensity across the face of the sample. The indirect absorption of the two pulses produces a spatially-modulated optically-created carrier density that results in a spatial modulation of the refractive index.

The coherent interaction between the excitation pulse and the probe can be viewed as the self-diffraction of the excitation pulse from an optically-produced grating. That is, the excitation (E_e) and probe (E_p) pulses interfere to modify spatially the optical properties of the sample, as described above. The excitation pulse (E_e) is then self-diffracted by the grating produced by E_e and E_p to produce two first-order scattered beams. One first-order diffracted excitation beam is collinear with the transmitted probe beam; the other first-order beam E_c travels in the background-free direction $-\theta$. An alternate point of view is to consider the coherent interaction between the two pulses as a transient, degenerate, four-wave mixing process. In this case, the second self-diffracted beam E_c, discussed above, is easily recognized as the forward-traveling phase-conjugate of the probe beam. The self-diffracted excitation pulse that travels in the direction of the probe is responsible for the so-called coherent coupling "artifacts" (e.g., correlation spikes) that are observed in traditional picosecond excitation-and-probe experiments. These interactions have also been called real-time holography (e.g., Ref. 1) and light-by-light scattering (e.g., Ref. 2). Assuming that the sample is optically-thin and that E_c and $E_p \ll E_e$, the general form for the coupled equations for the excitation, probe, and conjugate polarizations in the transient regime are:

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$$P_e(z,t) = -i K E_e(z,t) \int_{-\infty}^{t} |E_e(z,t')|^2 \exp[-(t-t')/\tau_\ell]dt' \qquad (1)$$

$$P_p(z,t) = -i K E_p(z,t) \int_{-\infty}^{t} |E_e(z,t')|^2 \exp[-(t-t')/\tau_\ell]dt' - i K E_e(z,t)$$
$$\times \int_{-\infty}^{t} [E_e^*(z,t')\, E_p(z,t') + E_c^*(z,t')\, E_e(z,t')] \exp[-(t-t')/\tau_G]dt' \qquad (2)$$

$$P_c(z,t) = -i K E_c(z,t) \int_{-\infty}^{t} |E_e(z,t')|^2 \exp[-(t-t')/\tau_\ell]\, dt' - i K E_e(z,t)$$
$$\times \int_{-\infty}^{t} [E_p^*(z,t')E_e(z,t') + E_c(z,t')E_e^*(z,t')] \exp[-(t-t')/\tau_G]dt', \qquad (3)$$

where K is a constant, τ_ℓ is the free-carrier lifetime and τ_G is the grating lifetime, $\tau_G^{-1} = \tau_D^{-1} + \tau_\ell^{-1}$. The grating in the nonlinear refractive index that is introduced by interference between probe and excitation (or conjugate and excitation) decays by recombination τ_ℓ^{-1} or diffusion τ_D^{-1}. For our geometry, the optical pulsewidth (65 psec) is much less than the grating lifetime (~47 nsec).

The various terms in (1) and (2) correspond to changes in the phase of the excitation (strong) and probe (weak) pulses, respectively. Notice that, for picosecond pulses, there is an additional phase delay for the probe wave. This additional increase in refractive index was named weak-wave retardation by Chiao and coworkers [2], who first predicted this effect. These workers later observed light-by-light scattering, but they did not verify weak-wave retardation [3].

If beams with Gaussian spatial profiles are used in these self-diffraction experiments, the changes in phase velocities predicted by (1) - (3) should result in differing degrees of self-defocusing for the various transmitted pulses. We measure the degree of self-defocusing by observing the transmitted beam profiles with a vidicon detector. Before summarizing our results, we remark that the self-defocusing of the transmitted probe, excitation and conjugate in Si have been studied recently by Hopf et al. [4] using various nonlinear interferometers. They observed a substantial self-defocusing of all beams, but they were unable to detect weak wave retardation. For their work, the pulsewidth was comparable to the diffusion-dominated grating lifetime. If this were the case, then the second terms in (2) and (3) would be small with respect to the first.

Figure 1 illustrates the distortion of the excitation and probe beam profiles during these self-diffraction studies. The fluence of the excitation pulse was 46 mJ/cm^2, and the fluence of the probe was a factor of 500 smaller. Figure 1a shows scans of the probe profile (in the far field) when the excitation was blocked - the profile is reasonably Gaussian. Figures 1b and 1c show profiles of the transmitted probe and excitation, respectively, when both were simultaneously present. The broadening of the excitation pulse caused by the optically-created free carriers in the Si is evident, and the additional self-defocusing of the probe (weak-wave retardation) is clear. We believe this to be the first direct observation of this effect.

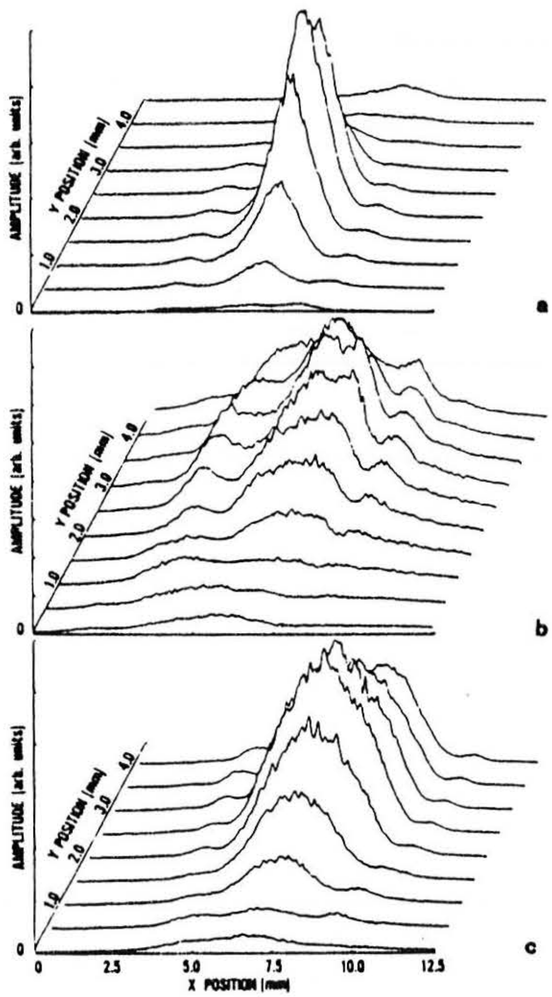

Fig.1 Vidicon scans of the spatial beam profiles of the (a) probe with pump blocked, (b) probe with pump, and (c) pump

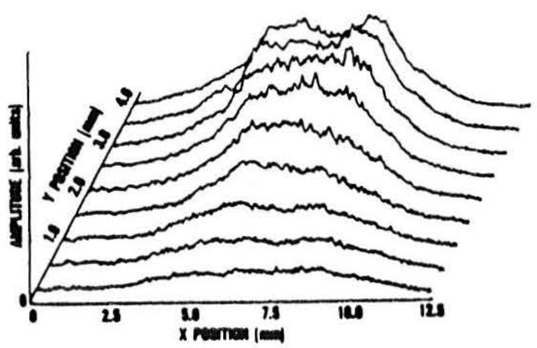

Fig.2 Vidicon scan of the spatial beam profile of the conjugate beam

In addition, we have measured the transmitted beam profile of the forward-traveling conjugate wave under experimental conditions identical to those of Figs.1b and 1c. The observed distortion of the conjugate (Fig.2) is different from the defocusing of either the probe or the excitation, contrary to the disparate conclusions of Refs. 2 and 4.

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