MEASUREMENT OF PICOSECOND PULSE SHAPE AND BACKGROUND LEVEL

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susceptible to disturbances since the energy barrier to the collapse of the bubble is smaller.

Table I summarizes the comparison of various energy terms for different values of wall thickness l_w. Note that the magnetostatic energy is negative, resulting in a radial force component to expand the bubble, whereas the applied-field, the exchange, and the anisotropy energies all are positive, resulting in a force to collapse the bubble. Also note that in all cases, the bubble energy (i.e., total energy) is small compared to any of the individual energy terms. The bubble energy is around $M_s^2 h^3$ (e.g., 10^{-5} erg for orthoferrites). Besides, bubbles with thicker walls always have less bubble energy, but the discrepancy in the individual energy term is small.

The fact that the bubble energy is small compared to any of the individual energy terms accounts for the negligible dependence of bubble size (d/h) on wall thickness (l_w/h). In fact, we have found that Thiele's model of assuming zero wall thickness is fairly accurate in predicting the relationship between bubble size (d/h), material parameter (l/h), and bias field. Bubbles with thicker walls do result in lower bubble energy and in larger wall mobility (thus higher data rate), though there is very little influence on bubble size (or packing density). These findings are the major conclusions of this work. Note that this method is sufficiently general to consider Neel-type walls and also can be extended to a two-dimensional case.

Helpful discussions with Dr. R.W. Keyes are acknowledged.

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MEASUREMENT OF PICOSECOND PULSE SHAPE AND BACKGROUND LEVEL

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The approximate shape and the background level of picosecond pulses from an Nd:glass laser have been determined by the measurement of a correlation function which is sensitive to pulse shape and asymmetry. A combination of second harmonic generation and a phase-matched four-photon parametric interaction was used to obtain the correlation function. The pulses were found to be symmetric with a mean width of 12 psec and have an average background level of 10^{-4}.

We report the measurement of the approximate shape and the background level of the pulses from a mode-locked Nd:glass laser. This information was obtained by generating a fifth-order correlation of the pulses using a combination of second harmonic generation and phase-matched four-photon parametric mixing. The correlation function measured by the experiment was

$$G_5(\tau)=\int_{-\infty}^{+\infty} I^4(t)I(t-\tau)\,dt \Big/ \int_{-\infty}^{+\infty} I^5(t)\,dt.$$

Although no correlation function of a single delay can provide a unique picture of the pulse shape,[1] correlation functions having integrands of the form $I^N(t)I(t-\tau)$, where $N \gg 1$, are capable of producing a good approximation to $I(t)$. The reason is that for most pulse shapes having a well-defined maximum $I^N(t)$ acts like a sampling function, its width being greatly reduced by raising it to a large exponent. Two examples will illustrate this point.

$$I(t)=e^{-t^2/\tau_p^2};\quad G_5(\tau)=d^{-t^2/\tau_p'^2};\quad \tau_p'=1.12\tau_p \qquad (1)$$

$$I(t)=\begin{cases} e^{-|t/\tau_p|}, & t\geq 0 \\ 0, & t<0 \end{cases};\quad G_5(\tau)=\begin{cases} e^{-|t/\tau_p|}, & t\geq 0 \\ e^{-|4t/\tau_p|}, & t\leq 0. \end{cases} \qquad (2)$$

For the case of the Gaussian pulse, (1), $G_5(\tau)$ is also a Gaussian whose width is only 12% greater. In the case of the exponential with zero rise time and finite decay time, $G_5(\tau)$ produces a pulse with the same decay time, but has a finite rise time equal to only 1/4 of the decay time. Clearly $G_5(\tau)$ provides a much more accurate picture of the pulse shape than do the symmetric second- and third-order correlation functions measured by second[2] and third[3] harmonic generation and two-[4] and three-photon[5] fluorescence. In particular we see from example (2) that $G_5(\tau)$ is sensitive to asymmetries in the pulse shape. It is a reasonably good approximation to assume that $G_5(\tau)$ represents an approximation to the true pulse shape with a resolution of approximately one-quarter the pulse width. (We can always conceive of pathological pulse shapes which $G_5(\tau)$ will not handle well, such as a rectangular pulse, however it appears unlikely that these will occur in practice.)

A sketch of the experiment used to measure $G_5(\tau)$ is shown in Fig. 1. Picosecond pulses were generated in a mode-locked Nd:glass laser. The laser rod measured $\frac{3}{8}$ in. $\times 4\frac{1}{2}$ in. and was posi-

tioned at Brewster's angle between two mirrors spaced by 90 cm having reflectivities of 55 and 100% and radii of curvature of 5 m and ∞, respectively. Mode locking was produced with a 3-mm dye cell containing a solution of Eastman 9860 in contact with the high-reflectivity mirror. The concentration of the dye was chosen to produce a linear transmission coefficient of 65%.

A 1-cm crystal of KDP was used to generate the second harmonic with an efficiency of approximately 8% at the peak of the pulse train. Considerable care was exercised in orienting the crystal to avoid any broadening of the second harmonic pulses due to imperfect phase matching. The fundamental, ω_1, and second harmonic, ω_2, were separated in a calcite polarizing prism, delayed, and then recombined in a 1-mm cell of methanol to generate emission at $\omega_3 = 2\omega_2 - \omega_1 = 3\omega_1$ by phase-matched four-photon parametric mixing.[6] A single 100-cm lens was used to focus both the fundamental and second harmonic beams in the cell. A half-wave plate rotated the fundamental beam to have the same polarization as the second harmonic. The cell thickness was chosen to be only 1 mm to minimize the group delay between ω_1 and ω_2 (approximately 0.7 psec/cm in the methanol) and to prevent any complications arising from stimulated Raman scattering or self-focusing. The phase-matching angle between $\vec{k}_1$ and $\vec{k}_2$ was found to be 188 ± 3 mrad (in the liquid). The emission at ω_3 occurred in the plane of $\vec{k}_1$ and $\vec{k}_2$ at an angle of 65 mrad from $\vec{k}_2$. Corning #7-60, Schott #KG-3 filters and a 100-Å interference filter were used to block the fundamamental ω_1 and second harmonic ω_2 at the photomultiplier tubes. uv blocking filters (not shown in Fig. 1) were used to cut the weak generation at ω_3 due to the KDP and calcite crystals, before interacting in the methanol cell.

Neglecting pump depletion, the intensity of emission at ω_3 is proportional to the product of the square of the intensity at ω_2 and the intensity at ω_1. Also, the second harmonic intensity is proportional to the square of the fundamental intensity (assuming no pump depletion). Hence, the integrated intensity at ω_3 detected by the photomultiplier tube 1 is proportional to $G_5(\tau)$. The conversion efficiency of the combined second harmonic and four-photon mixing was approximately 5×10^{-5}. The signal-to-noise ratio of the detection system was $10^6 : 1$. To check the assumptions of undepleted pumps, the dependence of the emission intensity at ω_3 on the input intensity at ω_1 (input to SHG crystal) was measured at zero delay and found to vary as $I^{\omega 3} \propto (I^{\omega 1})^{4.9 \pm 0.1}$, confirming our assumptions.

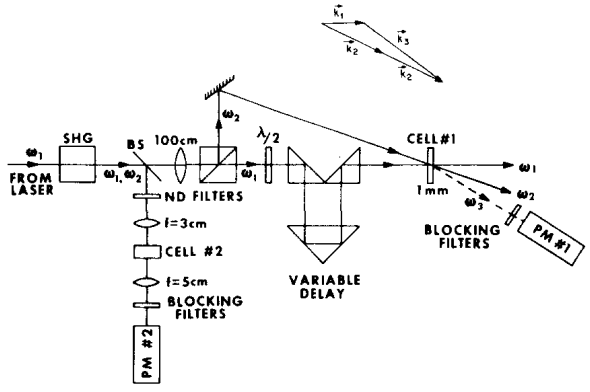

FIG. 1. Schematic diagram of experiment used to measured the fifth-order correlation function $G_5(\tau)$.

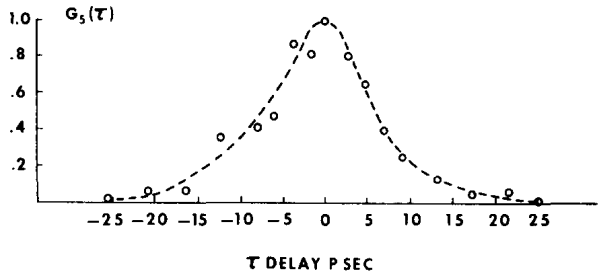

FIG. 2. Fifth-order correlation function $G_5(\tau)$. Leading edge of pulse corresponds to $\tau > 0$. Each point is average of eight shots.

Since $I^{\omega 3}$ is extremely sensitive to fluctuations of $I^{\omega 1}$, a second reference measurement of $G_5(0)$ was conducted simultaneously for each shot. To simplify matters, a collinear geometry was used for this measurement. In this case, the emission at ω_3 occurs in a cone of apex angle.

$$\theta = 2\cos^{-1}[(2k_2 - k_1)/k_3].$$

This interaction is effectively phase matched if the incoming divergence of $\vec{k}_1$ and $\vec{k}_2$ exceeds the cone angle θ. The input intensities to cell 2 were reduced by two orders of magnitude to prevent stimulated Raman scattering and self-focusing. For each shot the signal detected at PM 1 was normalized by the signal at PM 2.

The results of the measurements of $G_5(\tau)$ are plotted in Figs. 2 and 3 on linear and logarithmic scales, respectively. Each point represents an average of eight shots. Shots were fired at equal intervals of 30 sec, and dye was injected into the mode-locking cell every few shots at a rate corresponding to a complete replenishment of the dye every 20 shots. The mean pulse width (FWHM) was found to be about 12 psec. On a linear scale (Fig. 2) no noticeable asymmetry was measured in the mean pulse shape to within an experimental accuracy of approximately ±10%. This result does not agree with the work of Treacy,[7] who measured an asymmetry in the correlation of a compressed pulse with an uncompressed pulse. One difference which may account for this discrepancy is the fact that Treacy used Eastman 9740, whereas we used Eastman 9860 for mode locking.

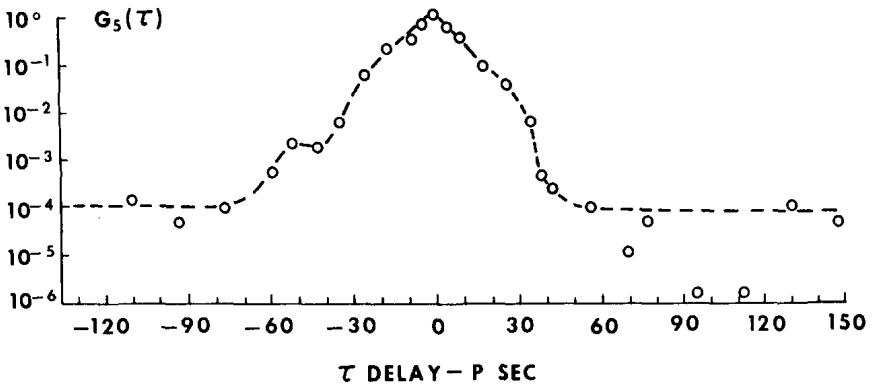

FIG. 3. Fifth-order correlation function $G_5(\tau)$ plotted on logarithmic scale. Leading edge of pulse corresponds to $\tau > 0$. Each point is average of eight shots. Noise level of detection system is at 10^{-6}.

When plotted on a logarithmic scale as in Fig. 3, the measurement of $G_5(\tau)$ shows an exponential decay away from $\tau = 0$ at a rate of approximately 9 psec/Np. Note that for $\tau \gg 0$, $G_5(\tau)$ is very nearly equal to the true relative intensity ratio, $I(t)/I(0)$, averaged over an interval of time equal to the pulse width. In terms of a "best fit", it appears that the pulse shape looks most like a hyperbolic secant. A "spiking" of the pulse at $\tau = 0$ was not observed. Although we might expect a spike[8] due to the possible presence of a subpicosecond structure in the pulse, we would probably not resolve it. The noncollinear geometry of the interaction limited the time resolution to approximately 1 psec. If a structure does exist, our measurements should be interpreted as the envelope of the pulse averaged over the subpicosecond structure.

At a point $\tau = +30$ psec, $G_5(\tau)$ drops rapidly to an average background level of approximately 10^{-4}. The estimated intensity of the pulse inside the laser corresponding to this point is roughly equal to the saturation field intensity of the Eastman 9860 dye. Hence, we might expect a drop in the shape of the pulse at this point, as the intensity goes from a region of nonlinear absorption to linear absorption.

The reason for the lack of a similar "breakpoint" in the pulse on the falling edge, $\tau < 0$, is probably due to small ($\sim 10^{-3}$) secondary pulses generated by multiple reflections in the experiment rather than any lifetime effects in the dye. If we extrapolate the average background level of $\sim 10^{-4}$ throughout the region between pulses (6 nsec), we conclude that approximately 95% of the energy is in the main pulse and only 5% in the background region between pulses. This result contradicts the findings of Wang and Baardson[9] who concluded from measurements of the efficiency of two-photon fluorescence and third harmonic generation that most of the energy was in the background.

The fluctuations of the energy in the background region were very pronounced. All of the energy appeared to be in the form of small randomly occurring pulses. Typically, only noise (10^{-6}) was detected in two out of three shots. There was no measurable uniform background level. Note that a nonmode-locked laser, i.e., random phases, would produce an average background level of 0.2 for $G_5(\tau)$.

From a device point of view, we note that we can view our experiment as an optical sampling device in which the signal beam of interest (ω_1) is sampled by the ω_2 beam, and the result is translated in frequency and direction to produce an output at ω_3. The signal and sampling beams need not be harmonically related, and as long as $\omega_2 > \omega_1$, phase matching can be achieved by adjusting the incoming angle. The time resolution, extinction coefficient, and flexibility and ease of usage compare favorably with other optical sampling devices such as the ac Kerr-effect light gate.[10]

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