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ABSTRACT

The intensity-dependent light transmission of nonlinear optical materials can be used to tailor laser pulse shapes for CTR applications. Several interesting systems have been built and shown to be effective pulse shapers. Although pulse shapes matching any particular ideal shape for controlled thermonuclear reactions have not been demonstrated, the potential for producing such pulses is clearly evident. Calculations are presented to show how the optical parameters of the systems can be adjusted to give a wide variety of pulse shapes. These devices have response times in the picosecond range and can, in principle, be modified to operate in any part of the optical spectrum.

I. INTRODUCTION

To achieve laser produced nuclear fusion, it appears necessary to control the rate of delivery of energy to the target.[1-3] Raw laser beams have time evolutions which are far from most theoretical ideal pulse shapes, for example the $\dot{E}(t) = \dot{E}_o(t)/(1-t/t_f)^2$ which has been used in some calculations.[1,2] Figure 1 shows the shape of this theoretical CTR pulse, with a sharp energy cutoff just before time t_f is reached. Geometric schemes[4] and saturable absorbers[5,6] have been used previously for pulse shaping, but they are very limited in adjustability and functional intensity ranges. Neither these methods nor those put forward in this report deal with the sharp energy cutoff after the peak has been reached.

We have found considerable pulse-shaping capability in several devices developed for the purpose of intensity filtration of 1.06-micron light.[7-9] These devices utilize the nonlinear optical responses of saturable dyes and materials like carbon disulfide (CS_2). In one mode of operation, these intensity filters are set to block low-intensity

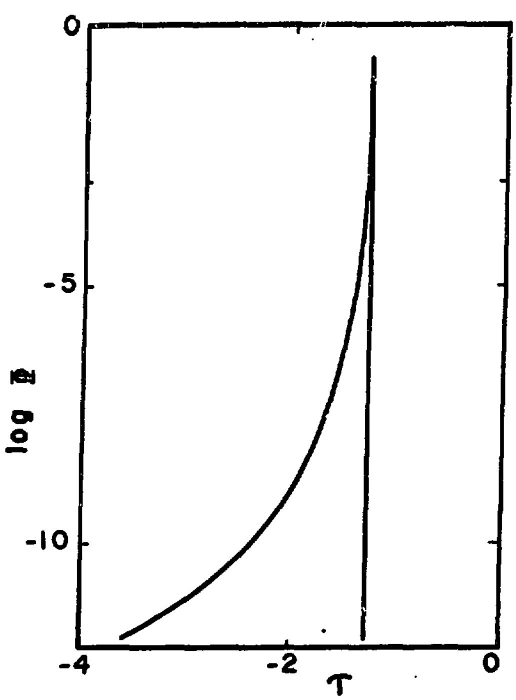

Fig. 1. The theoretical pulse shape required for laser-driven fusion in Ref. 2.

light but transmit high intensities. The response time of the filter is fast enough so that this goal is achieved not only among different pulses but within a given pulse, so that the low-intensity wings of a single pulse are strongly attenuated in both space (perpendicular to the beam axis) and time (along the beam axis). Clearly, this effect allows reshaping of the pulse, and as these filters are highly adjustable, one has a considerable range of shaping available.

It is assumed at this point that the shaping of interest is only narrowing of the raw pulse of light, and that a discussion of the broadening available with a high-intensity rejection mode of operation is not necessary. We shall analyze two filter configurations that show promise for pulse-shaping applications.

II. ROTATION FILTER

The optical system of the rotation[7] filter is shown in Fig. 2. Filtering is achieved by rotation of elliptically polarized high-intensity light as it passes through the CS_2 between crossed linear polarizers. Low-intensity light is not rotated, and therefore is blocked by the final polarizer. The intensity of the light transmitted by this filter is given by[9]

$$I_2 = \frac{1}{2} I_1 \sin^2(kI_1 - \phi) \tag{1}$$

where I_1 and I_2 are the incident and transmitted intensities, k is a constant which depends on the length and nonlinear refractive index of the rotating medium (CS_2, in this case), and ϕ is the angle of displacement of the final polarizer and 1/8 wave retarder from the crossed position.

Figure 3 shows the transmission curves of this filter for various values of the adjustable parameters. Rotating the final polarizer and retarder together moves the curve horizontally without distortion (curve B). Rotation of the final polarizer alone will reduce the depth of modulation (curve C) until there is 50% transmission for any intensity at 45° of polarizer rotation. Continuing this rotation, transmission increases, as does modulation, until curve D is obtained. A device with this transmission curve is termed a smoothing filter because it reduces intensity in the hot spots of a laser beam. Curves intermediate to those shown can be obtained with intermediate settings, giving continuous tuning of the filter through this wide range of transmission characteristics.

At this point we must consider the nature of the incident laser pulse. The commonly used TEM_{00} mode has a Gaussian spatial profile which can be described by

$$I_1(t) = I_0 f(t) \exp(-\rho^2) \tag{2}$$

where $f(t)$ is a function describing the time evolution of the pulse, and ρ is the distance from the pulse center measured in units of $1/e$ widths, denoted R. We will assume a spatially Gaussian input pulse for the next calculation.

The quantity of interest in CTR is the radiant flux Φ transmitted by the filter. This can be obtained by integrating over ρ to take into account the variable attenuation of the wings of the Gaussian.

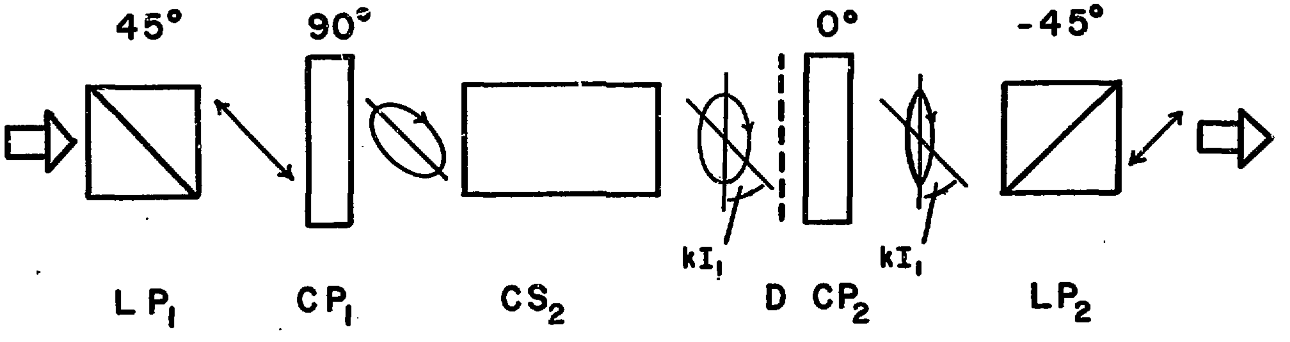

Fig. 2. Optical train of the rotation filter. LP_1 and LP_2 are polarizer (shown crossed), CP_1 and CP_2 are 1/8 wave retardation plates and CS_2 is a carbon disulfide cell. kI_1 is the rotation occurring in the cell. D is the position where a dye cell may be placed to convert to the rotation-dye filter.

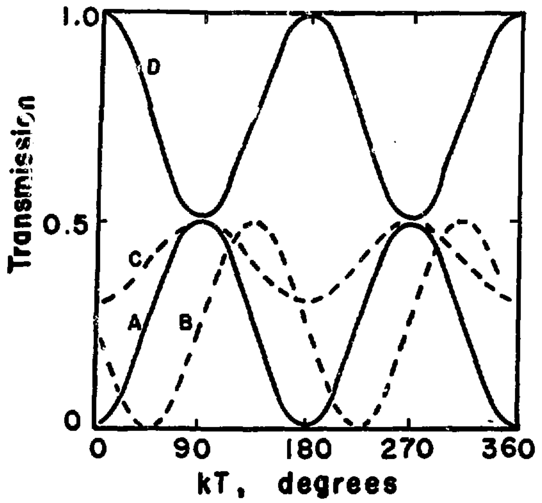

Fig. 3. Calculated transmission of rotation filter for various settings of the optical elements. Curve A, final polarizer and retarder crossed relative to their counterparts. Curve B, polarizer and retarder rotated by 45°. Curve C, polarizer only rotated. Curve D, polarizer only rotated by 90°.

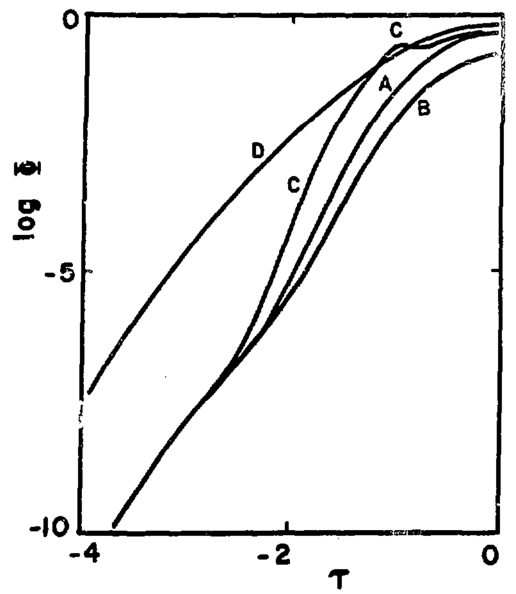

Fig. 4. Radiant flux of a Gaussian pulse transmitted by a rotation filter. Horizontal time axis is marked in units of the Gaussian 1/e width. For these calculated curves $I_o = 1$. Curve A, K = 90°, and $\phi = 0$. Curve B, k = 45°, and $\phi = 0°$. Curve C, k = 360° and $\phi = 0°$. Curve D, k = 90° and $\phi = -30°$.

$$\Phi = \pi\int_0^\infty rI_2\, d\rho = \frac{\pi R^2}{8}\left[I_o f(t) - \frac{\sin(kI_o f(t))\cos(kI_o f(t) - 2\phi)}{k}\right] + LI_o f(t), \qquad (3)$$

where the symbols have been previously defined in this section. The last term has been added to account for leakage of light through the optical system. In our experimental system, L = 0.02, but could have been reduced with higher quality components. It should be pointed out that the product (sin x)(cos x) is very small except near x = (2n+1) π/8 radians. Consequently, this filter does not modify the pulse shape at low intensities unless ϕ is nonzero (initial and final polarizers not crossed). Also note that the peak radiant flux transmission is never more than π/8; about 39%.

Figure 4 shows several graphs of Eq. (3) for various values of k and ϕ, assuming a Gaussian time evolution of the incident light pulse, $f(t) = I_o \exp(-\tau^2)$. I_o and R have each been set equal to 1. It is clear that the pulse shape can be varied over a considerable range.

An experimental demonstration of shaping on a single 20 psec pulse is rather difficult, but the correspondence of theory and experiment may be shown by using the entire train of mode-locked pulses from a Nd:YAG laser. The train consists of 20-psec-long pulses separated in time by 6 nsec, which is far longer than the recovery time of the rotation filter. The envelope of the pulse train is very nearly Gaussian, as shown in the experimental plot of Fig. 5.

With the rotation filter adjusted to k = 45° and $\phi = 0$, the experimental data of Fig. 6 are obtained. Experimental limitations of the detectors prevented taking low-intensity data, but in the accessible range the agreement with the predicted curve is good.

Unfortunately, the rotation filter does not have a dramatic enough response to produce a good match for the leading edge pulse shape shown in Fig. 1. It was suggested that a pulse that was initially Lorentzian in time would result in a sharper output pulse, but as shown in Fig. 7 this does not seem to be true. The only attribute gained in this calculation is the concave upward shape of some of the output curves.

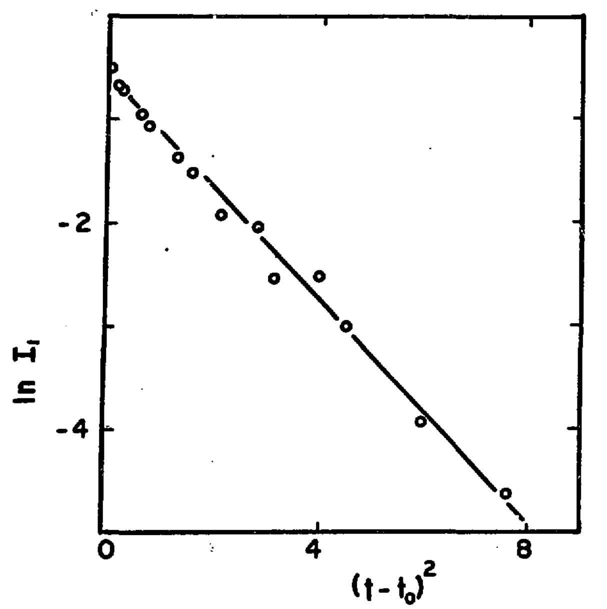

Fig. 5. Gaussian nature of a pulse train envelope; demonstrated by the straight line resulting from a plot of the natural log of experimental pulse intensities plotted against their time of arrival as measured from the center of the envelope.

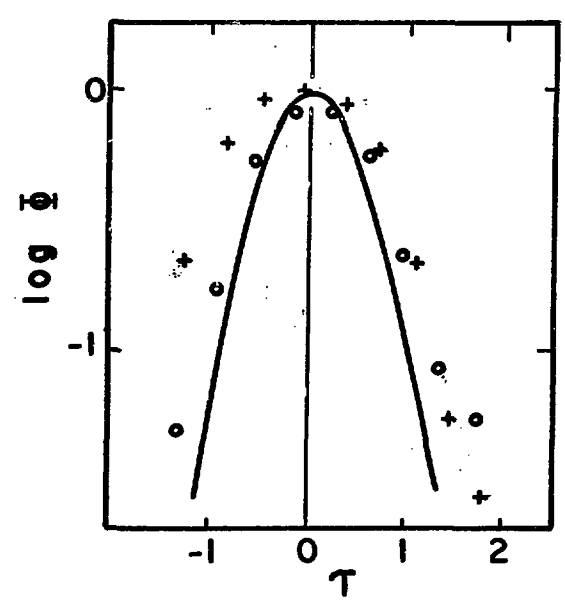

Fig. 6. Radiant flux transmission of rotation filter showing predicted curve (solid line), transmitted pulses (circles), and attenuated incident pulses of two pulse trains (crosses).

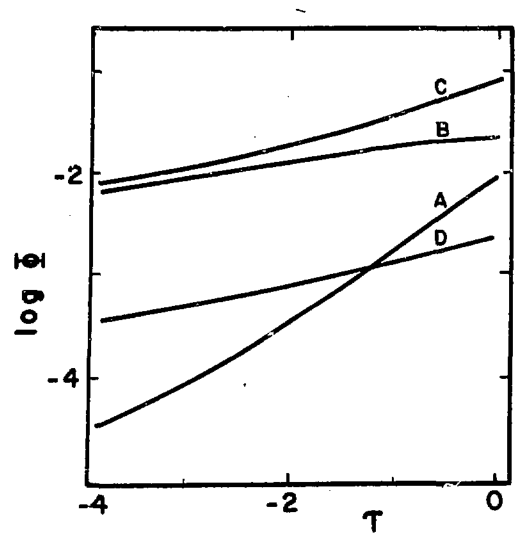

Fig. 7. Calculated radiant flux transmission of a rotation filter with a Lorentzian incident pulse. Curve A, k = 90° and ϕ = 0. Curve B, k = 90° and ϕ = 30°. Curve C, k = 90° and ϕ = -30°. Curve D, no rotation filter, pure Lorentzian times 0.001.

III. ROTATION-DYE FILTER

The increased intensity response required can be obtained by inserting a cell filled with a saturable dye at point D in the optical train of Fig. 1. The intensity-filtering characteristics are greatly improved[9] and pulse shapes appear to approach those theoretically required for CTR. We have termed this device the rotation-dye filter. Mild self-focusing (but not self-trapping) occurs in the CS_2. Intense pulses are brought to a focal point at the dye cell where their bleaching ability (and transmission) is greatly enhanced by the focusing. Low-intensity light is not focused and is severely attenuated by the dye.

Figure 8 shows the radiant flux transmission of this filter. It can be observed that the pulse train envelopes are narrowed considerably and that the slope of the curve has been increased. Again, the limited dynamic range of the detection system precludes measurements over more than two orders of magnitude.

To compensate for the experimental difficulties, one would like to develop the theory of this device to the point where useful predictions of pulse shaping could be made, but the rotation-dye system does not lend itself to simple mathematical modeling. Saturable dyes are normally modeled by a time-

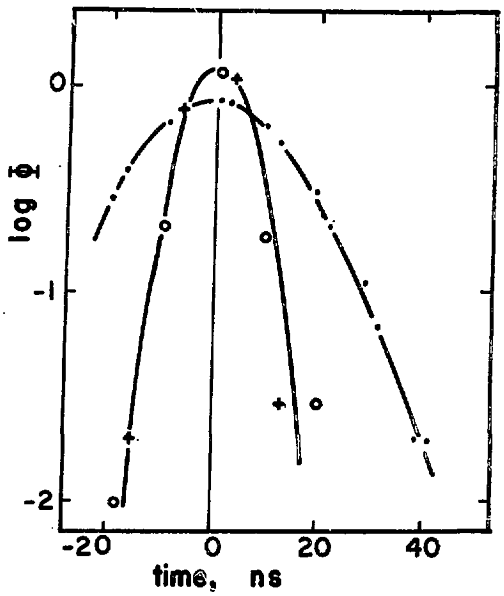

Fig. 8. Radiant flux transmission of a rotation-dye filter. Circles and crosses represent flux transmission of two different pulse trains. Dots represent the attenuated input pulses of the trains, showing the unfiltered envelope width.

consuming, iterative computer code,[6] and this is further complicated by the geometry of self-focusing in the CS_2. However, at low intensities the dye will obey Beer's Law (no intensity dependence) and self-focusing will be negligible. The radiant flux output Φ' of the rotation-dye system will then be given by

$$\Phi' = A\,\Phi \qquad (4)$$

where A is the transmission of the dye at low-light levels, and Φ is given by Eq. (3).

If we assume the high-intensity portion of the laser pulse completely bleaches the dye, then

$$\Phi' = \Phi. \qquad (5)$$

If the dye bleaches smoothly over the intensities between these extremes, we may extrapolate the curve between them.

The resulting curve is shown in Fig. 9. This curve can probably be taken a little more seriously than the crude splicing methods would seem to justify because of the wide range over which the optical parameters of the device can be varied, allowing defects to be corrected. With the dye cell, we now have two additional sensitive parameters, cell position and dye concentration. Positioning changes the

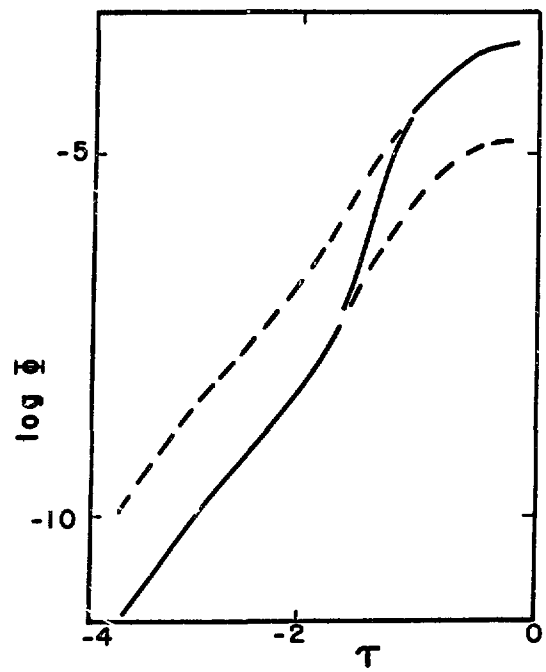

Fig. 9. Estimated transmission of rotation-dye filter over an extended range of intensities (solid line). Bleached dye curve (upper dashed line), and unbleached dye curve (lower dashed line).

range of intensities over which bleaching occurs, and concentration determines the bleaching onset intensity and the low-level light transmission. In addition, the usual adjustment parameters of the simple rotation filter are still all in effect. No prolonged attempt has been made to adjust all of the parameters to achieve the CTR pulse of Fig. 1, but Fig. 9 indicates that the proper slope and curvature can probably be achieved.

IV. CONCLUSIONS

Intensity filters have been shown to have definite pulse shaping capabilities. The rotation-dye filter appears to be capable of shaping Gaussian pulses to match almost any suitable pulse shape for fusion. These filters are adjustable over wide ranges so that pulse shapes can be easily tailored. Continuous adjustability slightly away from the predicted ideal CTR pulse shape may prove important if amplifier saturation and intensity-dependent anomalous absorption must be compensated for in real systems.

In principle, these filters will operate at any wavelength. In practice, suitable polarizers, retarders, and dyes must be found for the desired wavelength. These components are available for the visible, UV, and near IR portions of the spectrum. The filters will operate at any speed down to the response time of the dye (8 psec for Eastman 9740 mode-locking dye for 1.06 μm light). They will probably operate on even shorter time scales, but with reduced efficiency.

It is clear that considerably more experimental and theoretical work needs to be done in this area, but it is hoped that this report points out the potential and versatility of intensity filters used as pulse shapers.

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