A Picosecond Optical Shutter for Particle Detection*

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ABSTRACT

Characteristics of an optical shutter utilizing Kerr effect induced by picosecond laser pulses in carbon disulfide are studied experimentally. The shutter has a gate time of 4.5 to 5 ps full width at half-maximum and a transmission of ∿15% at a wavelength 0.53 μm. Such an ultrafast shutter can be used as an optical signal gate in a sampling detection scheme that has picosecond time-resolution. The picosecond optical detection scheme is envisioned to have applications in experimental high-energy physics such as to time-resolve ultrashort Cerenkov or synchrotron radiation emitted by relativistic particles. Methods of synchronizing a laser-activated Kerr shutter with a particle accelerator or synchrotron are discussed.

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I. INTRODUCTION

Detection using a sampling scheme provides a fast yet sensitive method to study the time structure of optical radiation. The sampling detector consists of a signal-gating optical shutter and a conventional photo-electric detector to monitor the gated samples. The envelope of the pulsed radiation is then reconstructed from the samples taken by the sampling detector. The time-resolution of this sampling detection scheme is set by the gating time of the shutter, rather than the speed of the sample-monitoring detector itself which at best has a resolution of few hundred picoseconds. As optical shutters utilizing the Kerr effect induced by picosecond laser pulses have a gate time of only few picoseconds, optical detection can thus be time-resolved on a picosecond scale. Such an ultrafast optical detection scheme has many applications in experimental high-energy physics. For example, using the picosecond optical detector as a timing element in the usual time-of-flight measurement experiment, one can identify particles with high-energy resolution over a moderate flight path length.[1]

II. KERR SHUTTER DRIVEN BY LASER PULSE

The well-known Kerr[2] effect in liquids results from a partial statistical reorientation of anisotropic molecules in an applied electric field that induces birefringence. Because of their anisotropic polarizability, the molecules tend to align themselves with their axis of largest polarizability along the direction of the applied field. Thus, the anisotropic optical properties of individual molecules no longer average out completely, producing a field-dependent birefringence. In dipolar liquids, the Kerr effect may also arise from interaction of the permanent electric dipole moment with the applied field. In liquids consisting of isotropic molecules, birefringence results only from electronic polarization and is extremely small. In amorphous solids the phenomenon is more complicated.

The field-induced birefringence, in conjunction with a pair of crossed polarizers, can be used to construct an optical shutter driven by an electrical pulse. Figure 1 illustrates a typical arrangement of an electro-optical Kerr shutter. A cuvette containing a Kerr substance, usually nitrobenzene, is placed between a polarizer and an analyzer. The electric field required to induce the birefringence is obtained by applying a voltage potential across the two plane-parallel electrodes in the cell. The transmission of the shutter is determined by the state of the birefringence induced by the applied electric field. The shortest opening time of this type of electro-optical shutter that can be achieved is about of few hundred picoseconds. The gate time of the shutter is limited by the availability of high-amplitude, short-duration electrical pulses, rather than by the relaxation time of the Kerr medium used in the shutter.

It is experimentally shown[3] that intense optical pulses, such as those generated by high-power lasers, can be used in place of electrical pulses to induce optical birefringence in a Kerr substance. As intense, picosecond optical pulses are readily generated by lasers, a laser-driven ultrafast Kerr shutter can be constructed.[4] Carbon disulfide with its relaxation time of 2 ps is a liquid commonly used for shutters. The carbon disulfide shutters have an opening time of few picoseconds, and this is limited by the relaxation time of the Kerr medium and the duration of the driving laser pulse. The possibility of using material with a faster relaxation time is the subject of recent theoretical and experimental studies.[5,6]

In liquids the Kerr effect at optical frequencies arises dominantly from molecular reorientation under the influence of an intense electric field of optical radiation.[7] Because the field is of high frequency, the optical Kerr effect depends not on the permanent dipole moment of the molecules, but on their anisotropic polarizability. Optical Kerr effect may also be due to nonlinear electronic polarizability arising from distortion of the electron cloud of the molecules.[8]

The birefringence induced by a plane-polarized uniform optical wave is uniaxial with its optic axis in the direction of the electric field. The difference between refractive indices parallel to and perpendicular to the optic axis, $\delta n = n_{\parallel} - n_{\perp}$, satisfied the following equation:[9]

$$\tau\frac{d}{dt}\delta n(t) + \delta n(t) = \frac{1}{3}K_{\alpha}E^{2}(t) \qquad (1)$$

where K_{α} is the optical Kerr constant of the medium. For polar molecules with large dipole moment, the optical Kerr constant can be much smaller than the static or low-frequency Kerr constant. For nonpolar molecules, Kerr constants at optical and low frequencies are approximately equal. In Eq. (1), the envelope of the electric field of the optical pulse is denoted by $E(t)$ and the intensity of the pulse is[10] $I(t) = (nc/8\pi)E^{2}(t)$ where n is the unperturbed refractive index of the medium and c the light speed. Eq. (1) shows that once the driving field vanishes, the induced birefringence decays with a characteristic time constant τ.

The relaxation time for orientational Kerr effect is typically in the picosecond range. For Kerr effect due to electronic distortion, the relaxation time is about a Bohr orbit period which is of order 10^{-15}s. Table 1 collects Kerr constants and relaxation times of several substances.

Table 1. Kerr constants and relaxation times of several substances.

Substance	K_{α} ($\times 10^{8}$)	τ(ps)
Carbon disulfide	32.6	$2.2^{a,b}$
Nitrobenzene	26.4	45^{c}
Carbon tetrachloride	0.67	$(0.5)^{d}, (20)^{e}$
Schott glass LaSF7	$\sim$0.1	$<5.0^{f}$
β-Carotene	$\sim$19	0.1^{g}

a. Ref. 36.

b. I. L. Fablelinskii, Opt. Spectrosk., 2, 510(1957).

c. C. W. Cho *et al.*, Phys. Rev. Lett., 18, 107(1967).

d. H. S. Gabelnick and H. L. Strauss, J. Chem. Phys., 49, 2334(1968).

e. G. I. Zaitsev and V. S. Starunov, Opt. Spectrosk., 19, 497(1965).

f. M. A. Duguay and J. W. Hansen, National Bureau of Standards Special Publication No. 341 on Damage in Laser Materials (Government Printing Office, Washington, D. C., (1970).

g. Ref. 5.

The induced birefringence has a time-dependence given by integrating Eq. (1):

$$\delta n(t) = (8\pi K_\alpha/3nc\tau)\int_{-\infty}^{t} I(t')\exp[-(t-t')/\tau]dt' \qquad (2)$$

Figure 2 shows various time-dependences of the birefringence induced by Gaussian-shaped pulses of different duration. The Gaussian-shaped pulses describe ultrashort laser pulses well. The time-dependences are obtained numerically integrating Eq. (2) with drive pulses of a constant energy: $I(t) = (1/t_d)\exp[-(t/t_d)^2]$. The quantity displayed in the figure is a quantity proportional to the induced birefringence, $\Delta n(s)/(8\pi K_\alpha/3nc\tau)$, as a function of time, $s = t/\tau$, with pulse duration $s_d = t_d/\tau$ as the varying parameter. It can be seen from Fig. 2 that the induced birefringence, after reaching a maximum, decays exponentially with a time constant τ for pulses with duration $s_d \lesssim 4$. For pulses of longer duration, the induced birefringence follows approximately the temporal variation of the drive pulse.

For a laser-driven Kerr shutter, the optical paths in the Kerr medium for the signal and drive pulses are not necessary collinear as the induced birefringence is uniaxial. If the polarization of the signal light incident on the Kerr medium is at an angle θ with the polarization of the drive pulse, then the intensity transmission of the shutter is

$$T(t) = \sin^2[2\pi(\ell/\lambda)\delta n(t)]\sin(\text{[illegible]}) \qquad (3)$$

where λ is the free-space wavelength of the signal pulse and ℓ is the distance the signal pulse travels in the birefringent medium. For drive and signal pulses of ultrashort duration, the maximum birefringent distance may be limited by the mismatch in the group velocities of the two pulses. In carbon disulfide, the mismatch is about 4.8 ps/cm for pulses of wavelengths at 1.06 μm and 0.53 μm.[11]

From Eqs. (2) and (3), one can see that the state of the induced birefringence, and hence the temporal transmission of the shutter, is affected by the relaxation time of the Kerr medium, particularly when the duration of the drive pulse is shorter than or comparable to the relaxation time. When the duration of the drive pulse is much longer than the relaxation time and the retarded phase of the shutter, $2\pi(\ell/\lambda)\delta n$, is small compared with unity, then the shutter transmission is proportional to the square of the intensity of the drive pulse, $T(t) \propto I^2(t)$. Because Eq. (2) is a convolution integral of material response to an exciting pulse, the *minimum duration* of the induced birefringence, thus the shortest gating time of the shutter, is limited by the relaxation time of the Kerr medium. For a drive pulse that is a Dirac impulse, the shutter opens for a full width at half maximum of $(\tau/2)\ell n2$.

III. OPTICAL DETECTION USING SAMPLING SCHEME

The ultrafast shutter can be used to gate out a portion from an optical signal in a sampling detection scheme. For a signal with intensity $I_s(t)$, the output of the shutter is given by,

$$O(t) = \int_{-\infty}^{\infty} I_s(t')T(t-t')dt' \qquad (4)$$

The optical signal can be either coherent or incoherent. Eq. (4) represents a time convolution of an input signal with the shutter transmission.

If the gating time of the shutter is much shorter than the duration of the signal pulse, the output of the shutter can be considered as a sample of the signal pulse taken at the instant the shutter opens. By taking samples of the signal pulse at regular intervals over its entire duration, the original signal envelope can be reconstructed from these samples. This is conveniently done by successively delaying or advancing the arrival time of the drive pulse relative to that of the signal pulse at the Kerr shutter. In this case, a repetitive signal source synchronized with the shutter is required.

The time-resolution of this optical sampling detection scheme is determined by the gate time of the shutter while the sensitivity is limited, in part, by the maximum transmission of the shutter. Thus using a picosecond optical shutter, time-resolved detection of optical radiation can be achieved on a picosecond scale. It is noted that sensitive but usually slow photo-electric detectors, such as photomultipliers, can be used to register the optical samples. As a maximum transmission of 20% for a laser-driven Kerr shutter can be obtained, one can achieve a high detection sensitivity of as little as five photons. The dynamic range of this sampling scheme, as the optical signal itself is not intense enough to induce nonlinear effects in the Kerr medium of the shutter, is limited by that of the detectors used for registering the samples.

A sampling arrangement is schematically shown in Fig. 3 in which only one signal pulse is needed to obtain its envelope shape. The signal pulse is multiply split into several replicas before being sampled. This is done, for example, with a total reflector and a partial reflector that together serve as a beam-splitter and a step delay line. For the purpose of illustration, only three replicas are produced in Fig. 3. In this example, the partial reflector has a transmission of 1/3, 1/2, and 1 over three different regions, producing three replicas of equal intensity, delayed progressively in time from each other. The time delay between the signal replicas is determined by the spacing between the two reflectors. The signal replicas then pass the Kerr medium of the shutter, each via a different path. If the drive pulse is synchronized with the signal pulse then a portion of each signal replica is gated out by the shutter. The outputs of the shutter are samples of the signal pulse taken at an interval determined by the delay time between the signal replicas. The gated samples, as they are spatially separated, can be monitored conveniently with an array of detectors. The signals from the detector array are then fed into a processing electronics to recover the signal envelope.

The pulse envelope can be graphically displayed, for example, on a cathode-ray tube in an oscilloscope. For this purpose, the electrical outputs from the detectors are delayed progressively in time from each other with a longer time period for easier displaying. This is necessary as the time-resolution of a conventional electronic oscilloscope is of few nanoseconds while the time separation between the optical samples is usually of only few picoseconds. The electrical signals are then combined and the combined signal is fed into an oscilloscope. The oscillogram in display consists of a train of short pulses, whose envelope is the signal pulse shape. The time scale of the displayed signal pulse envelope is expanded and the scale factor is determined mainly by the time delay between the electrical pulses. It is noted that for this application of displaying ultrashort optical pulses, a single photodetector, instead of an array of them, can be used. The outputs of the signal-gating shutter are combined optically before conversion into electrical pulses by a detector. The necessary stretching in time scale is done by letting each output of the shutter pass through an optical fiber of different length.[12]

IV. SYNCHRONIZATION WITH A PARTICLE ACCELERATOR

The ultrafast sampling detector can be used to study the time-structure of the Cerenkov or synchrotron radiation emitted by relativistic particles. For this application, synchronization between the laser pulse and the signal pulse is required. The continuous, periodic signal pulses, as the particles are produced at the bunch frequency of an accelerator, facilitates synchronization with a shutter that opens periodically. In this section, several types of lasers that are capable of generating high-power, picosecond optical pulses are reviewed briefly. Then methods of synchronization of a laser-driven shutter with a particle accelerator or synchrotron are discussed.

It is well-known that a train of periodic, short optical pulses can be generated by locking the phase of various oscillating modes of a laser.[13] For a continuously pumped laser, mode-locking can be achieved by modulating the quality factor Q of the laser cavity at the intermode frequency of the cavity or its harmonic. The intermode frequency is a characteristic of the cavity geometry and for a linear cavity of length L, it is given by c/2L where c is the light speed. As the cavity Q is controlled by an external force, usually an electrical signal of radio frequency, the laser is said to be mode-locked actively. The mode-locked laser oscillator generates a continuous train of periodic, short pulses with a period given by the inverse of the intermode frequency. A continuously pumped, actively mode-locked laser can be synchronized with a particle accelerator or a synchrotron as they are operated in a steady state. If the particles are bunched at the intermode frequency of the laser and if the two electrical control signals are phase-locked, the trains of the laser pulses and of the signal pulses generated by particles are then synchronized in time.

Continuously pumped Nd:Yag, Nd:glass, and organic dye lasers have been actively mode-locked.[14-17] The pulses are generally of a duration longer than the inverse of the oscillating bandwidth of the laser gain medium. From an actively mode-locked Nd:Yag laser, a continuous train of pulses of wavelength at 1.06 μm is generated. The pulses have a duration of about 50 ps and a peak power in the kilowatt range. In order to increase the transmission of a Kerr shutter, a pulse power greater than that available from the mode-locked oscillator is necessary. This can be achieved by using a laser amplifier or amplifiers. Simultaneous Q-switching and mode-locking of a laser oscillator also increases peak power 10^3 to 10^4 times.[18]

Trains of short optical pulses, periodic in time, also can be generated by a laser with a saturable absorber. By adjusting the optical density of the nonlinear absorber and the laser pumping condition, the longitudinal modes of the laser is spontaneously or passively locked in phase. The pulse train from a passively mode-locked laser oscillator is either continuous or of finite duration, depending on whether the laser pumping is continuous or pulsed.

A continuously pumped, passively mode-locked laser can be synchronized with a particle accelerator as a reference locking signal for bunching the accelerator can be derived from photo-electric detection of the laser pulse train. From a passively mode-locked dye laser,[18-20] pulses of subpicosecond in duration and tunable over a wide spectral range are generated. Applying cavity-dumping technique, the ultrashort pulses of kilowatts in peak power are obtained at a pulse repetition rate of kilohertz.[21] Using these dye laser pulses to drive a carbon-disulfide shutter, a transmission of a small fraction of a percent and a gate time of 2 ps are achieved.[22]

For a pulsed, passively mode-locked laser, the generation of ultrashort pulses is a transient process.[23,24] Typical train of laser pulses lasts ranging from tens of nanoseconds to few microseconds. As there is no external force to control or means to predict the appearance of the laser pulses, their synchronization with independently occurred events is rather difficult. Using an intracavity optical shutter[25] or double-pulse pumping technique[26] the time jitter for appearance of the pulse train is reduced to a few microseconds. While this jitter is still too large for synchronization on a picosecond scale, these pulsed, passively mode-locked laser oscillators, such as ruby, Nd:glass, Nd:Yag, and dye lasers, are capable of generating picosecond pulses of peak power as high as gigawatts.[27-30] Predictable pulse trains may be obtained from a pulsed, passively mode-locked laser by forced formation of periodic pulses, before the laser threshold is reached.[31] This is done by modulating the cavity Q actively. The pulses are then subsequently amplified by the gain medium and shortened by the saturable absorber.

The optical sampling scheme still can be applied even though the train of drive pulses is of finite length and is not synchronized with the signal pulse train. To sample the signal pulse, the bunch frequency of the accelerator is slightly different from the intermode frequency of the laser. Thus, a different portion of each signal pulse in the pulse train is gated out each time the shutter opens. The time between the two successive samplings is given the difference between the periods of the signal pulse train and the drive pulse train. The output of the shutter consists of a train of optical samples whose envelope gives the signal pulse shape if the drive pulse train is sufficiently long. Figure 4 illustrates this particular scheme. The signal pulse train is assumed to consist of triangular pulses and the drive pulse train is of short rectangular pulses. In the figure, the time scale for the output signals from the shutter is greatly reduced for clarity.

Figure 5 shows a schematic arrangement of a pulsed laser system to drive a Kerr shutter. A single pulse is selected from a train generated by a pulsed, passively mode-locked laser oscillator with a conventional electro-optical shutter. The selection is necessary as the pulses from the mode-locked oscillator are generally not of equal intensity and duration. The single pulse then passes through a ring amplifier consisting of an amplifying medium and a saturable absorbing medium. Pulses of shorter duration and higher power can be obtained with this two-component amplifier.[32,33] The output of the amplifier is a train of nearly uniform pulses with a repetition period equal to time required for a round-trip along the ring cavity. The length of the train is determined by the pumping duration of the amplifying medium and it can be several hundred microseconds.

V. AN EXPERIMENTAL CS_2 SHUTTER

Characteristics of an optical shutter using carbon disulfide as a Kerr medium have been experimentally investigated. The shutter is driven by infrared picosecond optical pulses from a repetitively mode-locked Nd:glass laser. The laser consists of an 0.635 mm x 7.60 cm Brewster-angled rod in a near-semiconfocal cavity.[34] Mode-locking is achieved with Eastman Kodak A9740 that is continuously flowing in an 0.3 mm thick cell in contact with the flat output mirror. The laser output is linearly polarized and in a single fundamental transverse mode. This mode structure has a Gaussian radial intensity profile. The mode-locked pulse train consists of about 80 ultrashort pulses with an interpulse separation of 8 ns. The pulses have a duration of about 6 ps as measured with the well-known two-photon fluorescence (TPF) technique.[35] The pulse duration given above is an average over all pulses in the train.

As shown in Fig. 6, the pulse train from the mode-locked laser passes a second-harmonic generating potassium dihydrogenphosphate (KDP) crystal which is purposely mis-aligned in order to have a low harmonic conversion. For parametric generation, as in the present experiment, the green light intensity is proportional to the square of the infrared light intensity. The intense infrared pulses which have a peak power of about 100 MW are used to drive the shutter while the weak green pulses are used to probe the shutter transmission. A dielectric mirror with a high reflectivity at 1.06 μm serves as a dichroic beam-splitter to separate the 1.06-μm radiation from its second harmonic. The drive and the probe pulse trains then travel along two distinct paths that intersect each other at approximately 5° in the Kerr cell. A variable optical delay line in the path for the probe pulse train is used to adjust minute difference in the two path lengths, thereby controlling the arrival times of the two pulses relative to each other at the cell. The diameter of the infrared beam in the cell is about 3 mm at half intensity and this beam diameter defines the aperture of the shutter. The polarizations of the two beams are 45° with each other in the cell.

The probe pulse train is monitored before and after passing through the shutter with two high-speed photodiodes. The signals generated by the detectors are fed into two vertical amplifiers of a Taktronix 7904 oscilloscope. As the probe pulse train incident on the shutter is delayed by 12 ns relative to the probe pulse train transmitted by the shutter, the displayed oscillogram appears as a pulse train interwoven with another of opposite polarity. Fig. 7 reproduces a typical oscillogram. Since the duration of the optical pulses are much shorter than the response time of the detection-recording system, the pulse heights registered on the oscillograms are a measure of relative energy in the optical pulses.

The transmission of the Kerr shutter is taken as a ratio of the energy in the transmitted probe pulse to that in the corresponding incident pulse. Measurements are taken at various time delays of the probe pulse relative to the drive pulse. To ensure a constant driving condition for transmission calculation, incident probe pulses with a pulse energy uniform within 5% are selected.

Fig. 8 displays the normalized shutter transmission in logarithm as a function of time. The maximum transmission is about 15%, taking account of reflection losses due to various elements of the shutter. Large negative (positive) time indicates that the probe pulse arrive at the cell before (after) the drive pulse. For this particular transmission curve, which is a convolution of the probe pulse with the shutter transmission, the drive pulses are selected from the beginning part of the pulse trains.

It is observed that the transmission of the shutter increases rapidly, and after reaching a maximum, decays exponentially with a time constant of 2.4 ± 0.2 ps. This time constant is the relaxation time of optical Kerr effect and the measured value agrees well with that determined from light scattering experiment.[36] Thus the present experimental result establishes that the molecular reorientation is the dominant mechanism for optical Kerr effect in carbon disulfide.

The transmission curve shown in Fig. 8 has a full width at half maximum (FWHM) of 6.0 ± 0.5 ps. Based on numerical simulation on a digital computer, assuming Gaussian drive pulse and 2.4 ps for Kerr relaxation time, the shutter has a FWHM gate time of 4 to 5 ps and the infrared laser pulse has a duration about 4 ps. It is also observed that the transmission curves corresponding to the drive pulses in the later part of the train broadens, indicating that the pulse in the later part of the train broadens, indicating that the pulse duration increases gradually in time. This observation correlates well with direct fast-streak camera studies of temporal evolution of picosecond pulses in a passively mode-locked Nd:glass laser.[37,38] It should be emphasized that the present measurement of pulse duration, which is an average of single pulses selected from same position in several pulse trains rather than of all pulses in the same pulse train, is more accurate than that previously obtained using the TPF technique.

VI. CONCLUSION

In this paper, theory of a laser-driven Kerr shutter with its application to optical detection is presented. Characteristics of an optical shutter with carbon disulfide as the Kerr medium are experimentally studied. The shutter is activated by pulses from a pulsed, passively mode-locked Nd;glass laser and is found to have an FWHM gate time of 4 to 5 ps. The shutter has a transmission of ∿15% at a wavelength 0.53 μm over an aperture of 3 mm. Both the shutter transmission and aperture can be increased by using laser pulses of higher intensity and of larger beam size, and this can be obtained with a laser amplifier.

Piosecond resolution can be achieved with such ultrafast shutter as a signal gate in a sampling detection scheme. This ultrafast optical detection scheme has unique capability in experimental research in high-energy physics such as studying Cerenkov or synchtron radiation emitted by high-speed particles. Methods of synchronizing a Kerr shutter driven by various types of lasers with a particle accelerator or a synchrotron are discussed.

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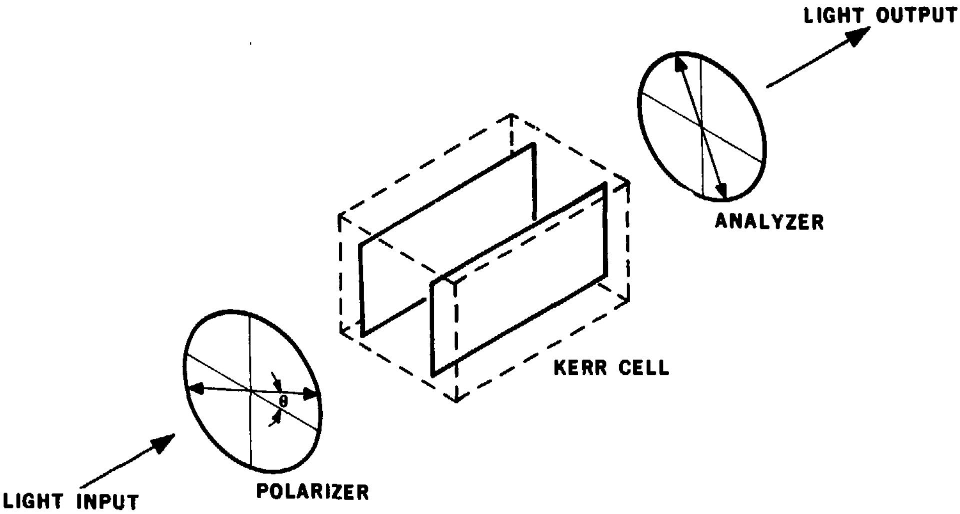
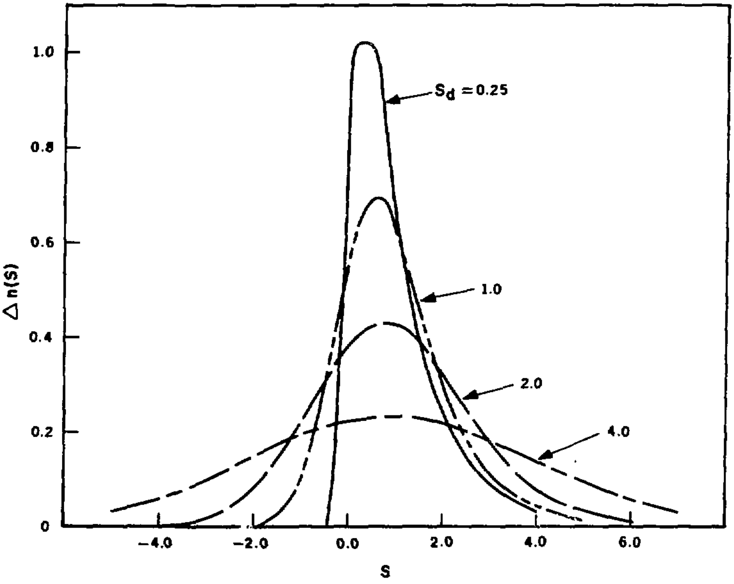


XBL 759-8177

Fig. 1. Typical arrangement of an electro-optical Kerr shutter.



XBL 759-8171

Fig. 2. Temporal changes in the birefringence induced by Gaussian-shaped pulses of different duration.

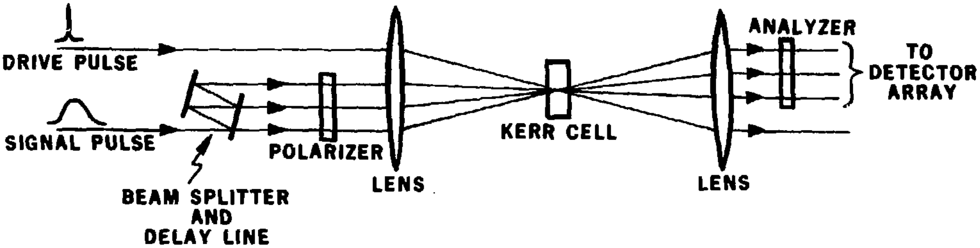


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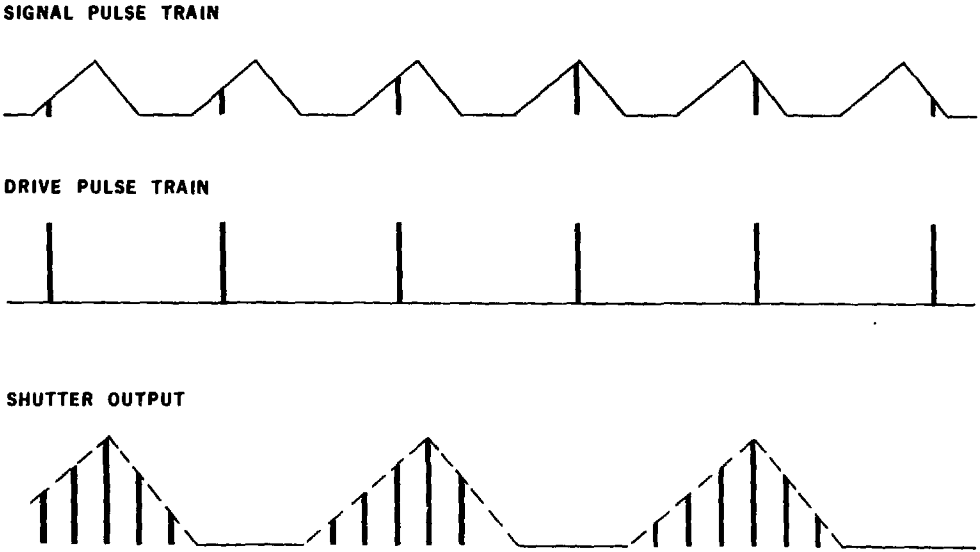
Fig. 3. A sampling arrangement requiring a single signal pulse.



XBL 759-8176

Fig.4. Sampling with an unsynchronized signal gate.

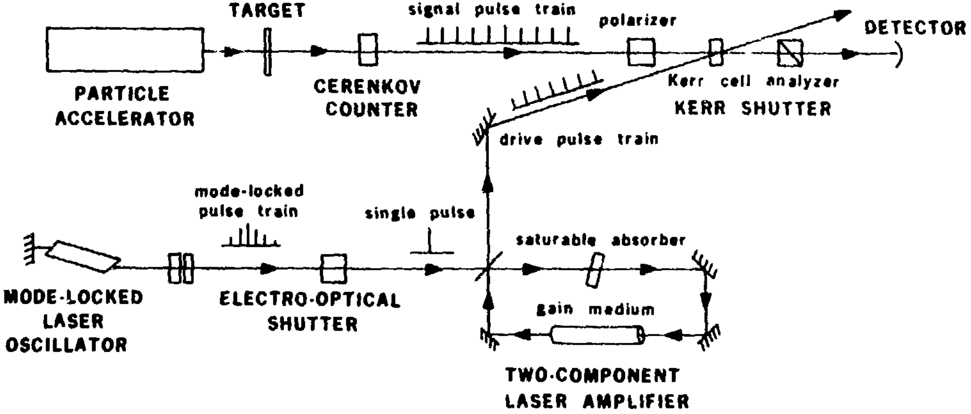


Fig. 5. A pulsed laser system for driving a Kerr shutter.

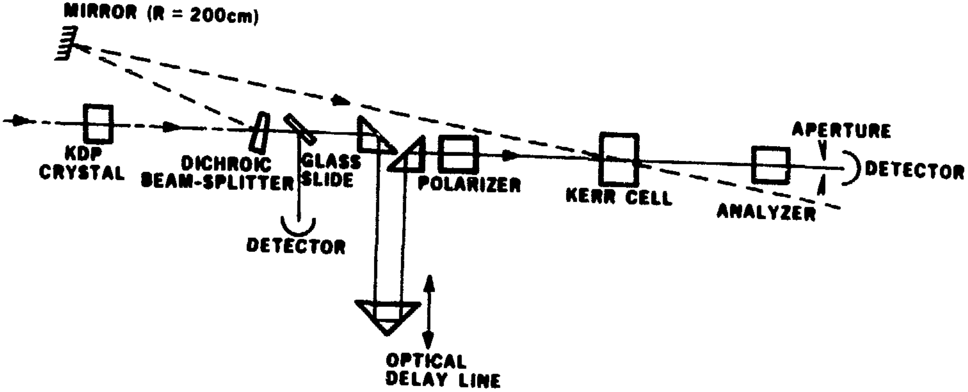


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Fig. 6. Experimental setup for studying an ultrafast CS_2 Kerr shutter.

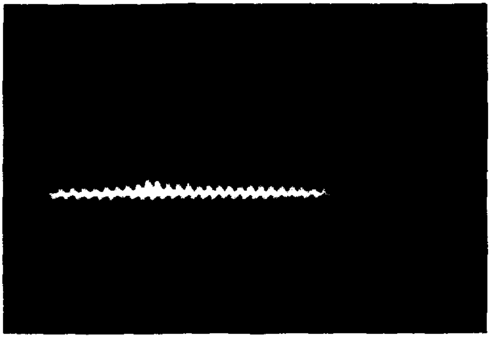

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Fig.7. Oscillogram showing incident and transmitted probe pulse trains of the shutter.