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**PICOSECOND IMAGE CONVERTER STREAK CAMERAS
FOR LASER DIAGNOSTICS**

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PICOSECOND IMAGE CONVERTER STREAK CAMERAS FOR LASER DIAGNOSTICS*

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Abstract

The requirements and techniques for time resolved (< 1 nsec) diagnostics of laser pulses are reviewed. The advantages and limitations of applying gated image converter streak cameras to the problem of laser pulse diagnostics are discussed. The design and operation of a unique 10-psec time resolution streak camera is described. The compact size of the camera results primarily from the use of a micro-channel tube for image intensification. Optically triggered avalanche transistor circuits provide reliable, low jitter electronic operation of the streak tube. The S-1 photocathode response allows direct measurement of neodymium laser pulses. Examples of the uses of streak cameras for laser diagnostics and the data obtained are presented. Comments on additional applications and the development of streak cameras with extended capabilities are included.

Introduction

The development of mode-locked solid-state lasers provided a short, intense packet of coherent optical energy that might lead to new understanding of basic physical processes and perhaps reveal new and unsuspected phenomena. This same development presented experimenters with an intriguing new problem: how to detect and measure the detailed characteristics of these subnanosecond, even picosecond duration pulses of light. The first part of this paper briefly reviews some classes of techniques that are used for this diagnostics problem and points out their strengths and limitations. This quick survey leads into the subject of ultrafast electrooptic streak cameras. The problem being addressed is that of

subnanosecond time-resolved diagnostics. Even more stringently, the application is to time-resolved diagnostics of events (laser pulses, laser-induced phenomena) that are not necessarily repetitive or reproducible, so that single-shot, non-sampling techniques that provide maximum information from a single event are required.

Diagnostics Techniques

One of the most commonly used detectors for laser light is a photodiode. Photodiodes are available in a variety of styles, shapes (solid state, vacuum), and spectral sensitivities. They generally have the attributes of small size, ease of alignment and use, linear response, and sensitivity. The basic problem arises with the time response. Although diodes with 100-psec responses are available, a practical detection-recording system based on a photodiode will have a response, at best, in the 300 to 500-psec range. This can have important consequences. So, while photodiodes play a useful and essential role in the overall diagnostics problem for lasers, other ways must be sought for better time resolution.

A technique known as two-photon fluorescence (TPF) (Ref. 1) has been developed for time-resolved laser pulse diagnostics. A laser pulse is split into two equally intense parts that are directed against each other in a cell filled with a suitable dye. The simultaneous absorption of two photons will excite the dye to an energy state from which it will fluoresce. The excitation energy gap is sufficiently great that a single photon of the laser frequency will not excite the dye. When the two pulses overlap in the center of the cell, the "concentration" of photons is highest and so the probability of two-photon excitation of the dye is

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highest. What one observes then, is a flash of fluorescent light with a spatial extent determined by the duration of overlap, hence the length of the laser pulse. By photographing the flash with an open-shutter camera (sometimes an image intensifier is used), the width of the flash can be measured and, hence, the length of the laser pulse estimated. The advantages of this technique are that picosecond or subpicosecond time scale resolution is possible (e.g. at 2×10^{10} cm/sec for $n = 3/2$, $1 \text{ mm} = 5 \text{ psec}$), and it is fairly convenient to set-up and use. On the other hand, TPF is a nonlinear effect and is fairly insensitive. Normally, tens of millijoules are required in the laser input. This means that small satellite pulses or low-level background energy around a pulse are not detected by this technique. The presence and character of this additional energy is important for the design and performance of a laser system as well as for the interpretation of the interaction of the pulse with a target. Since the response is a convolution of the pulse with itself, a further serious limitation is that the shape of the pulse cannot be obtained from a TPF or other autocorrelation record. (Ref. 2) In spite of these problems, the ease of using the TPF technique makes it useful for estimating laser pulse durations.

Extensions of this type of autocorrelation technique to three-photon fluorescence and examples of other techniques dependent on generating a higher frequency harmonic of the laser pulse and measuring the correlation function with the fundamental have been reported. (Refs. 3 and 4) Detection schemes based on the nonlinear photoelectric effect have been reported. (Ref. 5) We will not go into any further detail of these techniques, but simply comment that the complexity and delicacy of the optical setup required, compared to the detail of information they provide, do not make them serious candidates for the single-shot fast diagnostics techniques needed.

Another interesting technique was first demonstrated by Duguay and Hansen. (Refs. 6 and 7) Their technique makes use of the optical Kerr effect in CS_2 . The $1.06\text{-}\mu\text{m}$ laser pulse to be measured is sent through a second-harmonic-generation crystal. A dichroic beam splitter separates the original infrared component from the second-harmonic green light ($0.53 \mu\text{m}$) and directs the two pulses along separate paths. The pulse of green light is sent into a cell containing water with a little milk. The milk simply serves to scatter the light. Some of the scattered light is linearly polarized by a polarizer and focused through a cell containing the transparent CS_2 liquid. It is blocked by an analyzing-polarizer so that no

light reaches the photographic film placed behind it. However, CS_2 is a Kerr active material. Under the influence of the electric field in a high-intensity light pulse, the liquid becomes birefringent. The decay time of the birefringence upon removal of the optical pulse or the electric field is 2 psec. (Ref. 7) Now, if the infrared ($1.06 \mu\text{m}$) pulse is timed so that it enters the CS_2 cell at the same time as the green light scattered in the milk cell, the birefringence of the CS_2 under the influence of the intense $1.06\text{-}\mu\text{m}$ pulse will rotate the plane of polarization of the green light and it will be transmitted by the analyzer and expose the film. The CS_2 cell and the $1.06\text{-}\mu\text{m}$ pulse, in effect, form a "fast" shutter that provides a stop-action photograph of the green pulse. The length of the pulse can then be measured and its duration estimated. This technique is also a convolution of the pulse with its harmonic. It provides a graphic display of the pulse, but again detailed interpretation is difficult.

This is sufficient background to have made the point that a different, sensitive, direct, linear, fast detection scheme for the measurement of ultrashort laser pulses is needed. One technique that has proven successful is the use of ultrafast electrooptical streak cameras. They provide picosecond time resolution, linear response, and sensitivity.

Ultrafast Streak Cameras

The development and use of these devices have been pursued in the last few years by groups at the Lebedev Institute (Refs. 8-10), the Kurchatov Institute (Ref. 10), by D. J. Bradley and his co-workers at Queen's University in Belfast (Refs. 11 and 12), by Schelev, Alcock, and Richardson at the National Research Council at Ottawa (Refs. 13 and 14) and by our work at Livermore. (Refs. 15-17).

Figure 1 schematically shows the concept of an ultrafast streak camera. The event to be photographed is incident from the left. Part of the beam is split off to trigger the camera. The main beam (pulse) is suitably attenuated and illuminates a narrow slit that is imaged onto the photocathode of a gated image converter tube that contains a set of deflection plates. The incoming pulse of light is converted to a pulse of electrons that are accelerated, focused, and swept across the phosphor screen. Intensity versus time information in the incident pulse is converted to intensity versus position information of the phosphor screen. To realize the desired time resolution by minimizing effects that will limit the resolution, it is important to operate the image converter tube at as low a level of photocathode illumination as possible. Therefore it is necessary to use a high-gain

image intensifier to amplify the streak tube phosphor image to convenient photographable levels.

As applied to laser diagnostics, there are some additional constraints on the operation of the camera. First, since very high sweep rates are required, it is necessary to have a triggering technique that will provide sufficiently small jitter. Second, the trigger delay must be reasonable, i.e., a 50-nsec trigger delay would be unwieldy as it would require 50-ft optical paths to match the trigger delay. At present, one of the main applications is the diagnostics of neodymium lasers so that photocathodes sensitive at 1.06 μm are required.

To achieve time resolution in the picosecond range, the contributions to the time resolution of the system must be identified and controlled. The technical resolution τ_t of the camera is determined by the streak speed and the dynamic spatial resolution:

$$\tau_t = \frac{1}{v\delta}$$

where v is the streak speed and δ is the limiting dynamic spatial resolution in lp/mm. The dispersion in electron transit times through the tube is an important factor in the

overall time resolution. The electron transit time dispersion is given by (Ref. 18)

$$\tau_{el} = 2.3 \times 10^{-8} \frac{\sqrt{\Delta\epsilon}}{E},$$

where $\Delta\epsilon$ is the energy spread of the photoelectrons in eV and E is the electric field at the cathode in V/cm. The time resolution of the instrument is given by

$$\tau_{inst}^2 = \tau_t^2 + \tau_{el}^2,$$

assuming Gaussian shape of the response functions. If a pulse of width τ_p is photographed with the camera, then, the "width" of the recorded image, τ , will be

$$\tau = \left(\tau_p^2 + \tau_t^2 + \tau_{el}^2 \right)^{1/2}.$$

To achieve high time resolution, a high streak speed with good spatial resolution is needed and a high accelerating field is required at the photocathode. The field is provided by

Figure 1. Schematic diagram of ultrafast streak camera

operating the streak tube gating grid at sufficiently high voltage relative to the cathode.

Figure 2 is a photograph of a 10-psec resolution streak camera built at Livermore nearly 3 years ago. It represents state-of-the-art techniques employed at that time. The main features are identified in the photograph. This is a lens coupled system approximately 2 m in length. Several of the large power supplies required for its operation are not shown. The system occupies about 3 m³. The size and weight make it difficult and inconvenient to move and adapt to changing or evolving experimental situations.

Laser-triggered spark gaps have been used to generate the operating voltages in some ultrafast streak cameras. (Refs. 11, 19) This technique has a trigger jitter of about 1 nsec. However, for the fast sweep velocities and limited recording length we are considering, this jitter is undesirably long. One of the circuits used to trigger the camera is visible

in Fig. 2. In response to the need for fast low-jitter triggering, we developed optically triggered avalanche transistor circuits. (Ref. 15) A schematic of the circuit used for generating the fast sweep ramp is shown in Fig. 3. One transistor in the string is optically triggered by a portion of the incident laser pulse and the entire string switches. The resulting varying voltage on the deflection plates of the tube sweeps the electron beam along the phosphor screen. This technique provides a trigger jitter of less than 100 psec with a trigger delay of about 2 nsec. Figure 4 is a schematic of a similar circuit used for gating the grid of the image converter tube. These circuits can also be electrically triggered. The option of non-gated operation of the accelerating grid has been provided.

Because of size problems with the original streak camera, we concentrated on the development of a compact 10-psec streak

Figure 2. Original Livermore 10-psec resolution streak camera

Figure 3. Avalanche transistor sweep circuit

camera that can more nearly satisfy our experimental requirements. Figure 5 is a schematic of the compact camera. The overall length is about 29 in, and the unit weighs about 50 lb. The input is at the left where a filter holder and an adjustable slit are adapted to a standard oscilloscope camera. A field-correcting lens is used in front of the photocathode. The streak tube is an RCA C-73435* series with S-1 photocathode and P-11 phosphor fiber-optic output. A principal design feature of the compact camera is the use of a microchannel plate image intensifier tube. Also, the system is fiber-optic coupled; the streak tube and the intensifier are coupled via their fiber-optic faceplates and the photographic film is directly contacted to the output fiber-optic faceplate of the intensifier. Interchangeable camera backs allow the use of either Polaroid or standard film. The proximity coupling

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enhances the light collection by about a factor of 1000 over that of a lens-coupled system. The gain requirement of the image intensifier is correspondingly reduced. This fact makes practical the use of the micro-channel intensifier. Both fiber-optic faceplates of the tubes are operated at ground potential. The tubes have an active diameter of 40 mm, are 25 mm thick, and weigh about 250 g. The measured gain characteristics of the tube are shown in Fig. 6. The various curves are for the different labeled channel plate voltages (tube gain) in the range of interest. The tube can provide a linear dynamic range of 10^2 . The P-11 radiant power gain of the intensifiers has been measured and found to be in the range $2-6 \times 10^4$.

These cameras also use the optically triggered avalanche transistor circuits to provide the electronic gating and sweep functions. The sweep generator is shown on the side of the camera in Fig. 5 and the gate printed circuit board can be seen across the top of the streak tube. The steering optics provided for the trigger beam are also shown.

Figure 7 shows one of the compact cameras with the side access door open to display the sweep generator circuit board. The streak tube is located directly behind it. The optically triggered transistor is in the center of the string of transistors. This camera is completely self-contained; that is, all power supplies and electronic control and operating circuits are contained in the main body of the camera.

Figure 4. Avalanche transistor gate circuit

Figure 5. Schematic diagram of Livermore compact 10-psec resolution streak camera

Figure 6. Gain characteristics of microchannel image intensifier used in the compact streak camera

To calibrate the streak speed, a short laser pulse is split into a sequence of pulses by a pair of partially transmitting mirrors whose spacing is accurately known. Therefore, the time interval between pulses is known. By measuring the position of the pulses on a streak photograph, the camera

curve can be plotted. The sweep rate determined in this way is 34 psec/mm (3×10^9 cm/sec) and is linear. Total sweep length is 1.3 nsec.

The spatial (or streak limited) resolution is measured by streaking the elements of a resolution chart placed at the camera slit and illuminated with a laser pulse. The limiting resolution is 0.2 mm.

The overall camera resolution can now be summarized. From the data given, the technical resolution is 6.8 psec. The electron transit time dispersion is 7 psec or less, as a result of the 2600 V applied to the gating grid. Quadratic summations of these values yield an instrumental time resolution of 10 psec.

A few examples of data we obtained with the ultrafast streak cameras are given in Figs. 8, 10, and 11. Figure 8 is a streak photograph of the "single" switched out pulse from a mode-locked Nd: glass oscillator. The fast photodiode-oscilloscope trace of this pulse cannot resolve this multiplicity and shows a single spike. Each of the subpulses is about 15 psec long; they are separated by about 20 psec.

Figure 9 is a photodiode oscillogram of the Q-switched laser pulse generated in an early stage of the Livermore Long Path Laser. The pulse width is 2 nsec. Note the smooth

Figure 7. Livermore compact streak camera

Figure 8. Streak photograph of a mode-locked Nd:glass laser pulse

temporal profile here. Figure 10 is a streak photograph (10 psec resolution) of the laser pulse. The 2-nsec envelope contains regular, deep 28-psec modulation and a weaker 300-psec modulation. The source of this

structure was traced to reflecting surfaces in the oscillator cavity producing subcavity modes. This intensity pattern is a result of the mode-beating.

Multiple-exposure streak photographs have been taken to accurately determine the width and shape of a pulse from a laser oscillator (Fig. 11). (Ref. 20) This is the output of a mode-locked Nd-YAG oscillator that has been pulse-stretched by the addition of some inter-cavity optical elements. The multiple-exposure streak record, with a known intensity ratio between exposures is shown in the inset. The film densitometer traces are shown also. The half-width of the pulse is 140 psec and the profile is smooth. The fluctuations apparent on the curves do not reproduce from curve to curve and are caused by intensifier and film noise.

The ultrafast streak cameras have also been used to study the effects of nonlinear optical effects on high-power laser pulse propagation. (Ref. 20) The time-dependent

self-focusing of pulses has been observed directly. More recently a time resolved interferometric technique has been employed to measure the refractive index changes in

Figure 9. Photodiode oscillogram of laser pulse generated in the Livermore Long Path Laser

Figure 11. Detailed laser pulse measurement with ultrafast streak camera

Figure 10. Streak photograph of laser pulse generated in the Livermore Long Path Laser

optical materials induced by the passage of a high power light pulse.

Three areas that will be important in the further development and application of ultrafast streak photography can be identified. First, continued work on linear streak cameras with time resolution in the 1-psec range will be pursued. The best linear streak cameras at present are reported to provide 1 to 5-psec resolution. (Refs. 10,12) The further development of streak tubes with improved capability is needed in this area. Circular sweep systems currently approach or exceed 1-psec resolution. (Ref. 10) A second area will be to extend the wavelength range of these cameras. Present applications are limited to the near infrared, visible, and ultraviolet regions of the spectrum by tube and photocathode technology. The extension to operation at longer ($10.6\ \mu\text{m}$) and shorter (vacuum, ultraviolet, and even x-ray) wavelengths will be important. Third, the design and evolution of the instruments must proceed. The present concept of ultrafast streak camera construction is based on historical precedent and the availability of components. New, integrated approaches to the tube and readout design will surely produce cameras with improved performance, extended capabilities, and much wider usefulness.

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S. W. Thomas and G. R. Tripp of the Lawrence Livermore Laboratory have been principal contributors to the streak camera development described.

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