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3.B Subpicosecond Electrical Sampling

The availability of picosecond and subpicosecond laser pulses has made possible the investigation of material processes in the subpicosecond time range. For the most part, to date, these studies have been of an optical nature. With the advent of picosecond photodetectors,[1-7] photoconductor switches,[8-10] and other ultrafast electrical devices, the need has arisen for a system of measurement capable of characterizing electrical signals with picosecond resolution. In the past, such electrical measurements have relied on sampling oscilloscopes whose temporal resolution is limited to approximately 25 ps. In 1980, Auston et al.[11] demonstrated a sampling technique in amorphous semiconductors that has recently achieved a temporal resolution of less than 3 ps,[18] limited by the carrier lifetime in the material. The use of the electro-optic effect for electrical signal characterization has for the most part been neglected because of the high voltages normally required to observe the Pockels effect.[12,13] Recently, we reported a new approach[14] to the characterization of electrical transients that exploits the speed of the electro-optic effect using sampling techniques[15] and a high-repetition-rate subpicosecond laser. That system used a lithium niobate traveling-wave Pockels cell as an ultrafast intensity modulator and achieved a temporal resolution of approximately 4 ps with a voltage sensitivity near 50 μV. We have since constructed several new modulators using lithium tantalate as the electro-optic medium. This crystal, superior to lithium niobate in several respects, has now enabled us to achieve subpicosecond temporal resolution with similar voltage sensitivity.

The Pockels effect lends itself to the characterization of electrical signals in many respects. First, and foremost, the mechanism respon-

sible for the Pockels effect, i.e., the polarizability to the electric field, has a temporal response in the femtosecond range and hence is not a limiting factor in picosecond operation. Second, the ability to use optical pulses directly to sample voltage levels allows the technique to benefit from the availability of ultrashort laser pulses. This optical arrangement also permits the effective use of velocity-matching techniques to enhance temporal resolution and sensitivity. This is described in more detail below. A third advantage of this approach is that the optical pulse probes the induced electric field without altering the circuit characteristics in any way, an important consideration when dealing with frequencies in the range of hundreds of gigahertz. Other advantages of electro-optic sampling are the large dynamic range of signals that can be measured (up to a few hundred volts), the wide spectral response of the Pockels cell, and the optical isolation of the detection electronics from the signal under investigation.

The system is depicted in Fig. 18 and utilizes a lithium tantalate traveling-wave Pockels cell between crossed polarizers as an ultrafast intensity modulator. A colliding-pulse mode-locked (CPM) laser[13] generating 120 fs pulses at 100 MHz is used to trigger the electrical signal source and synchronously sample the electric field induced by the unknown voltage as it propagates across the crystal. Two detectors are employed to measure the intensities of the transmitted and rejected beams at the analyzer. These signals are then processed by a differential amplifier,

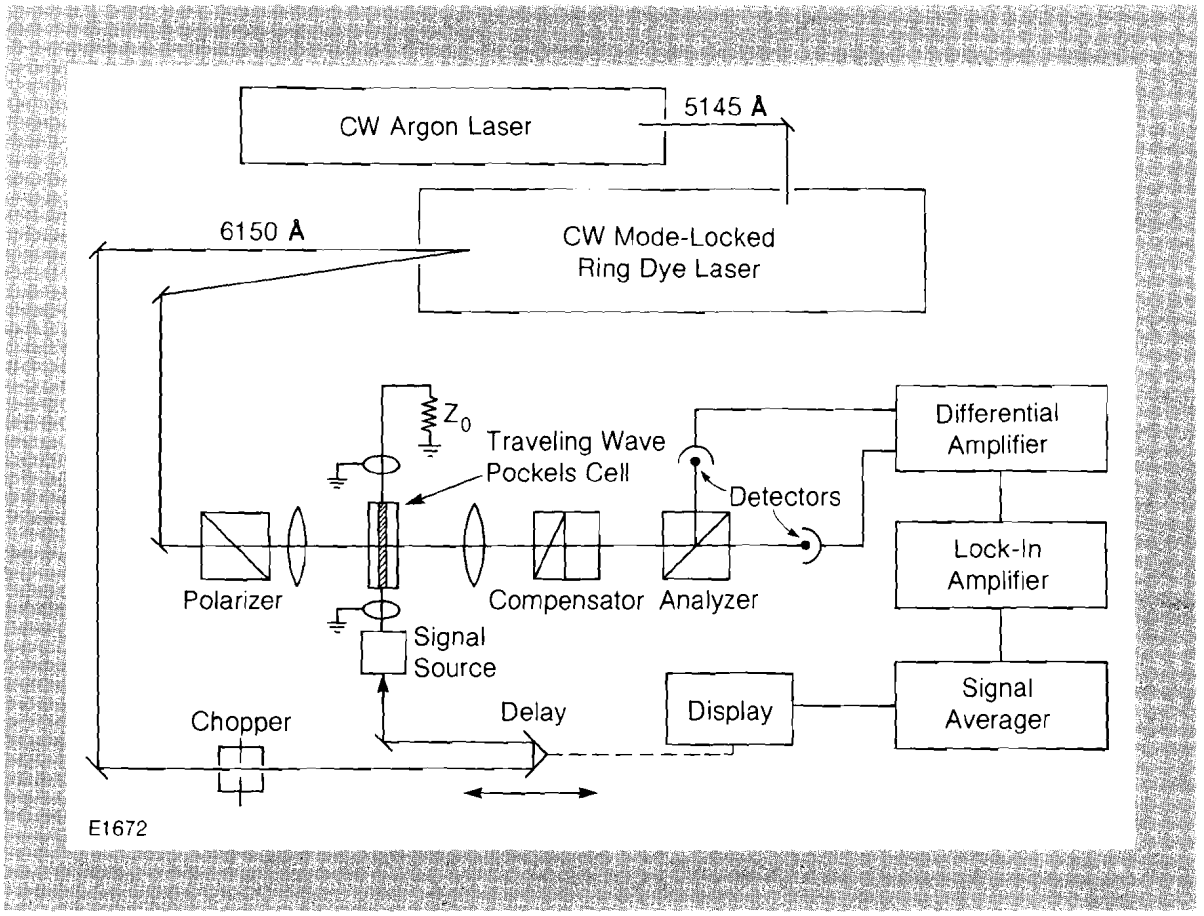

Fig. 18
Picosecond electro-optic sampling system layout.

lock-in amplifier, and signal averager. The differential system provides a means for making the detection system less susceptible to laser fluctuations while increasing the voltage sensitivity twofold. The modulator is optically biased, with a variable compensator at its quarter-wave point in order to achieve linear response as well as maximum voltage sensitivity. An optical delay line permits temporal scanning of the entire electrical profile by the optical probe pulse. The horizontal axis of the display is linearly driven in synchronism with the mechanical displacement of the delay line while the vertical axis is driven by the signal-averager output. This method results in a linear voltage versus equivalent time representation of the unknown electrical signal, requiring no further processing. Relatively slow detectors can be used since their necessary bandwidth is dictated only by the frequency of the light chopper used in conjunction with the lock-in detection system. This frequency is normally about 1 KHz.

The Pockels cell is a lithium tantalate crystal 0.7 mm wide by 0.25 mm thick by 15 mm long. Aluminum strip electrodes 0.3 mm wide are evaporated onto the two largest faces of the crystal, those being normal to the c-axis. This electrode geometry results in a balanced stripline with an impedance of ~45 ohms and a crystal half-wave voltage of nearly 2100 volts. The crystal is mounted between two subminiature coaxial-to-stripline microwave launchers with the optical beam focused through the 0.7 mm dimension. The beam size inside the crystal is optimally less than 20 μm, in order to obtain subpicosecond temporal resolution.

The properties of lithium tantalate as a traveling-wave modulator are superior to lithium niobate in several respects. The former has a much lower static birefringence, a decreased optical index of refraction, a higher threshold to optical damage, and a slightly enhanced electro-optic coefficient. The static birefringence of lithium tantalate has a value of 0.005, which is a factor of 18 less than its niobate counterpart. Thus, even though 100 fs optical pulses have a bandwidth of 50 Å, there is no need for a static birefringence compensator. The effects of temperature drifting are also minimized. The lower index of refraction ($n = 2.18$) makes it possible to achieve true velocity matching of the electrical and optical wavefronts. This configuration is crucial in obtaining subpicosecond performance.

The temporal resolution of the sampling head is determined by the convolution time of the optical probe pulse and the traveling electrical signal as they both propagate through the crystal. If these two signals travel orthogonally, the temporal resolution, τ_0, is the convolution of the time it takes for the probe pulse to traverse the crystal's electrodes with the transit time of the electrical signal across the probe beam waist. For a waist size of ~20 μm, the latter time is ~0.5 ps. The crystal traversal time is ~7 ps/mm. Thus, for our 0.3 mm electrode, the sampler would have a temporal resolution of 2.2 ps. However, this resolution can be reduced to the beam waist transit time by operating the crystal in the velocity-matching geometry. For this case, the probe beam enters the electro-optic crystal at an angle such that the optical velocity has a component in the same direction as the traveling electric field.

This geometry yields a fundamental resolution, or gating time, governed by the following equation:

$$\tau_0 = (w/c \cos \alpha)(n - \sqrt{\varepsilon} \sin \alpha) \quad (4)$$

where c is the speed of light in vacuum, n is the crystal index of refraction (~2.18), ε is the effective dielectric constant of the crystal, w is the electrode width, and α is the internal angle of incidence. In the present system, we obtain the best performance for $\alpha = 17$ degrees, indicating a fundamental temporal resolution in the order of 0.1 ps. Thus, we see that the beam waist size becomes the dominant factor and limits the expected resolution of this particular arrangement to approximately 0.5 ps.

The optimum temporal response is achieved with the optical probe beam entering the Pockels cell as close to the detector and upper electrode as is possible. This arrangement is necessary to minimize the electrical propagation distance, thereby limiting dispersion and preserving the ultrafast rise time of the detector.

Since this device uses the transverse electro-optic effect, the minimum voltage sensitivity is proportional to the ratio of electrode separation to the effective width seen by the probe beam, w/cos α. The Pockels cell was calibrated by applying a sine wave of known amplitude at the lock-in frequency. The measurement of the resultant intensity modulation yields the sensitivity at that frequency. To a first approximation, using published values of the S and T electro-optic coefficients, this value can be extrapolated to the microwave range. Sensitivity is fundamentally limited by the presence of laser noise at the lock-in frequency and hence is a strong function of the amount of signal averaging that is performed. The integration time necessary to achieve a given signal-to-noise ratio depends on scanning speed, scan length, and the resolution required. Typical times range from 5 seconds to several minutes for high-resolution operation. We have observed a voltage sensitivity of less than 50 μV, which is less than 10^{-7} of the half-wave voltage and corresponds to induced index changes of only 10^{-10}.

In order to verify the temporal performance of the sampling head, a suitably fast test signal is generated by a Cr-doped GaAs photoconductive detector. The detector is placed immediately adjacent to the Pockels cell under a common stripline,[13,14] with the photoconductive gap approximately 100-200 μm from the end of the crystal (see Fig. 19). When the detector is actuated by a 100 fs optical pulse, it generates an electrical pulse with an extremely fast rising edge containing frequencies up to many hundreds of gigahertz. Up to a certain cut-off frequency, determined by the physical parameters of the stripline geometry (in our cases, about 150 GHz), only the fundamental, quasi-TEM mode can propagate. Frequencies above this threshold can be transmitted not only as TEM modes, but also as higher-order TE and TM modes. Such modes, not forced to propagate parallel with the guiding electrodes, can arrive later at the sampling point, thus prolonging the total rise time of the generated signal. We are able to observe this phenomenon experimentally and have found that the relative delay between direct TEM

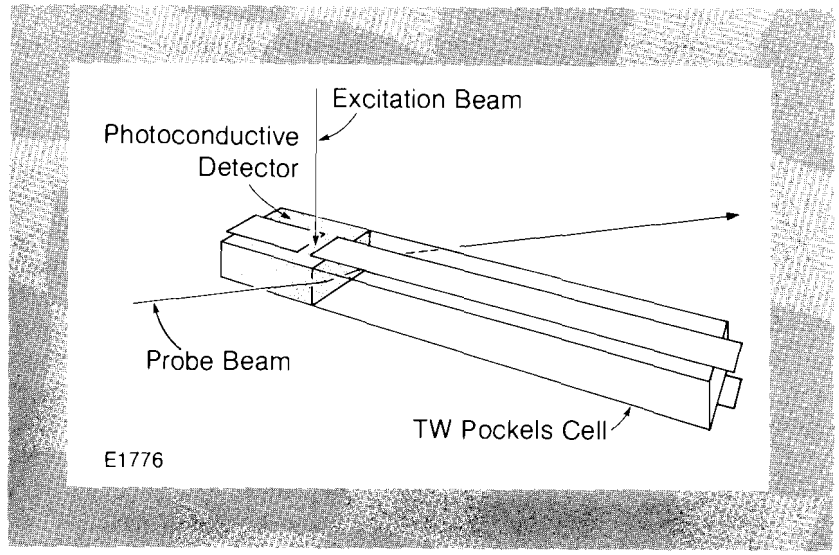

Fig. 19
Electro-optic crystal and detector test arrangement.

modes and indirect higher-order mode scales with sample substrate thickness, thus indicating a wave reflected from the ground plane. In order to avoid propagation of non-TEM, hybrid modes[17] in the range of frequencies up to 500 GHz, substrates and electrode dimensions of less than ~50 μm are required.

We present results that clearly demonstrate the relationship between the various parameters and that show how the resolution of the sampling gate is experimentally determined. Figure 20 shows the signal obtained from a switch built on a 500 μm substrate. An initial rise time of 2.4 ps is observed, followed by a secondary peak ~8 ps later. This delay corresponds very well with that of a wave reflected from the ground plane electrode, and confirms similar effects recently observed by Auston.[18] The ability of the sampling system to generate such a response curve,

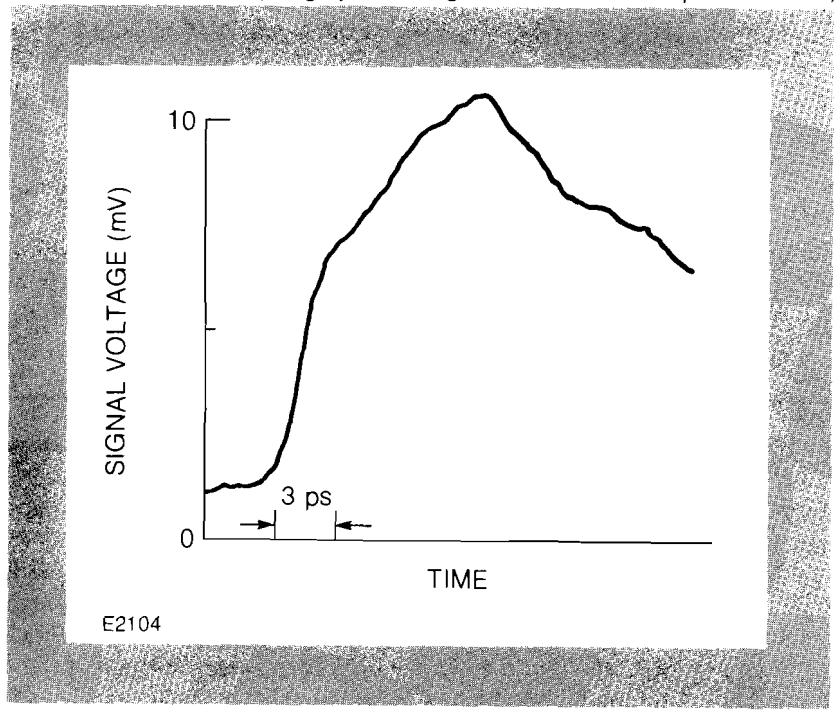

Fig. 20
Response of the Cr-doped GaAs photoconductive detector with 0.5 mm substrate thickness and 50 μm sampling beam diameter.

displaying an initial, steep, continuous rise without the presence of any slow leading edge, or foot, necessitates, from convolution theory, that the sampling gate function as a temporal duration at least as short as the rise time of the initial step. For this sampling head, the 10% to 90% time is ~2.4 ps. By reducing the substrate thickness to 250 μm, we expect the total rise time to be shortened, because the reflected wave incurs a shorter delay time. Figure 21(a) displays this result as a trace with an overall 10%-90% time of 2.3 ps. The direct and indirect waves are no longer resolved. By reducing the spot size of the sampling beam within the crystal (thus increasing the temporal resolution) we see—in Fig. 21(b)—that the two components can be resolved again while retaining the same overall rise time of ~2.3 ps. By reducing the spot size still further, to less than 20 μm, we reduce the electrical transit time across the beam waist to approximately 0.5 ps. Figures 21(c) and 22, respectively, show the rise time and actual trace obtained in this arrangement. The overall rise time is once again the same, as expected, but the direct wave now has a 10%-90% rise time of 850 fs, close to the predicted limit of 500 fs. The ability to resolve a rise time of 850 fs conclusively establishes the maximum possible width of the gating function. Thus, we see how the substrate thickness and beam size play separate roles in determining the overall rise time and resolution, respectively.

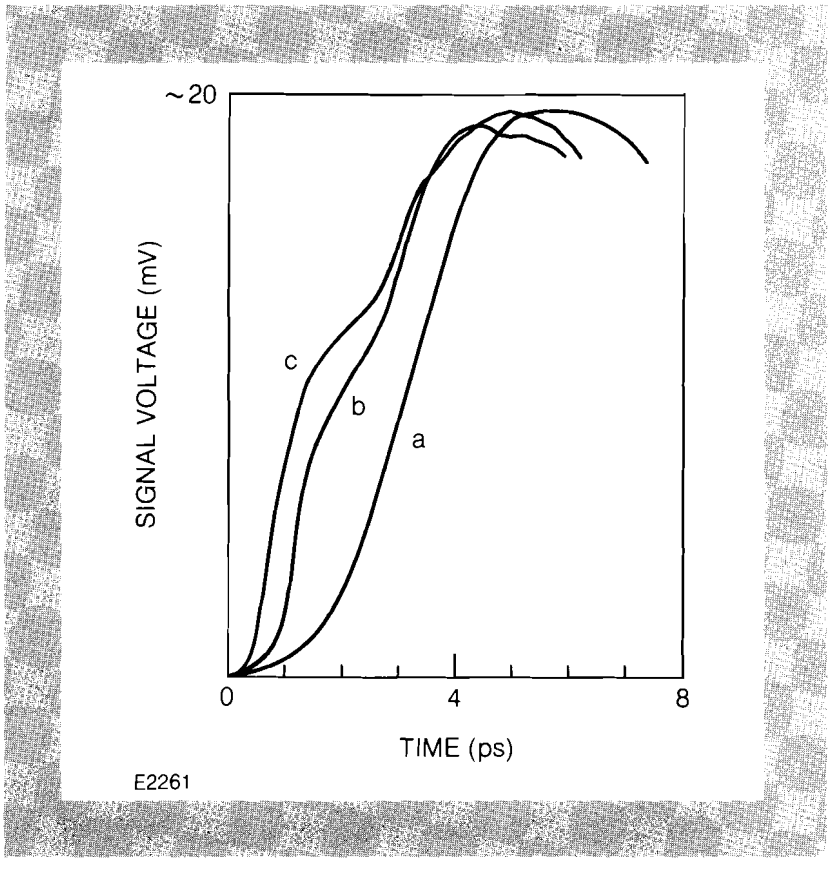

Fig. 21
Initial response of a Cr-doped GaAs photoconductive detector with 30 μm gap fabricated on a 0.25 mm substrate as a function of sampling beam diameter.
a) 50 μm
b) 25 μm
c) less than 20 μm

In short, we have developed an electro-optic sampling gate capable of characterizing electrical transients with subpicosecond resolution. Combining several conventional electronic instruments, we have been able to exploit the ultrafast response of the Pockels effect while retaining a voltage sensitivity of less than 10^{-7} of the crystal half-wave voltage.

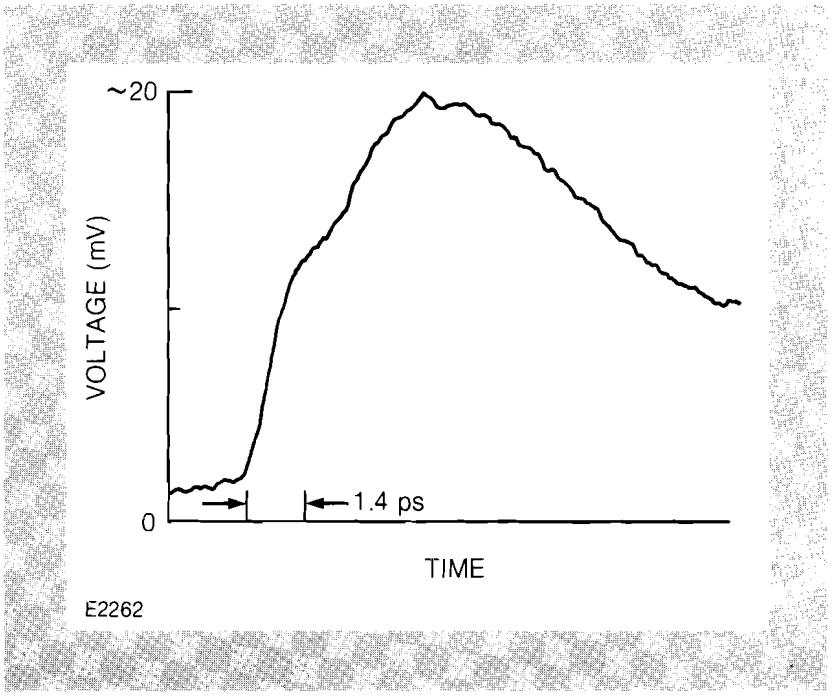

Fig. 22
Photograph of the actual display resulting from sampling the impulse response of a 30 μm gap Cr:GaAs photoconductive detector with a 250 μm substrate thickness. An initial rise time of 850 fs is clearly resolved, indicative of a comparable sampling time.

Also, it is important to emphasize that the temporal resolution of this system is not limited by the inherent response time of the active material but rather by the finite extent of the optical beam waist and the dispersive characteristics of the modulator striplines. Such a system now permits the possibility of analyzing ultrafast electrical processes such as those involved in photoconductive materials, photodetectors, and other picosecond electronic devices with the goal of understanding and improving their operation. Also, by employing high-repetition-rate, ultrafast electrical pulses that can now be well-characterized, it could be possible to reverse the roles of the optical and electrical signals in order to measure the performance of electrically-driven optical modulators[15] with picosecond resolution.

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