Section 3
ADVANCED TECHNOLOGY DEVELOPMENTS

3.A Subpicosecond Electro-Optic Sampling Using Coplanar Strip Transmission Lines

The development of new ultrafast electrical devices has stimulated considerable effort to find suitable ways to characterize them. Measurement systems must have both subpicosecond resolution and microvolt sensitivity.

Several systems that meet these requirements have been assembled and tested at LLE. Exploiting the speed of the electro-optic effect and high-repetition-rate subpicosecond laser technology, these systems exhibit response times faster than 1 ps and sensitivities of 50-100 μV. In this section, we describe our newest high-speed electro-optic measurement system. This system avoids certain physical limitations of earlier systems.

Detailed descriptions of our earlier ultrafast electro-optic sampling system have been published.[1,2] In this system the electrical test signal is generated when 100-fs pulses from a colliding-pulse mode-locked laser trigger a Cr:GaAs photoconductive switch. A second beam of pulses is used to probe the birefringence induced by the electrical pulses as they propagate down a transmission line built on $LiTaO_3$. With signal averaging, submillivolt signals are recovered. The temporal response, which was previously limited by the transit time of the optical pulses across the electrode width (i.e., a few ps), was improved by working in a velocity-matching geometry, which is obtained for a particular angle of incidence of the probe beam on the electro-optic crystal. With the proper crystal orientation, a rise time of

500 fs was obtained, limited in part by the transit time of the electrical signal across the beam waist. In this scheme strong dispersion effects occur when the wavelength of the electromagnetic signal is of the order of the cross-sectional dimensions of the transmission line. In order to decrease the amount of dispersion, the transmission-line thickness was decreased to 100 μm. In order to improve the temporal response of the sampler in this configuration, the balanced transmission-line dimensions have to be decreased to the 10-μm range, a severe mechanical constraint.

In order to alleviate the stringent mechanical requirement on substrate thickness, we have used coplanar striplines which do not have the physical limitations of the previous transmission-line geometry.

Coplanar-waveguide (CPW) and coplanar-strip (CPS) transmission lines have been used frequently in microwave integrated-circuit applications.[3] They are generally more easily fabricated than balanced microstrip lines because both the signal and ground lines may be made in the same process step on the same surface of a relatively thick substrate. An even greater advantage, however, is that the electrode dimensions can be reduced to the order of a few microns if the electrodes are fabricated photolithographically. The electrode separation, which is analogous to the substrate thickness in the balanced microstrip geometry, can be made one to two orders of magnitude smaller than is possible for the balanced strip line. This implies that dispersion effects can be reduced even further than was previously possible.

Coplanar geometries have been theoretically characterized to a much lesser extent than have microstrip configurations.[4-7] Calculations available at the present time indicate that coplanar strip transmission lines with dimensions of tens of microns should have frequency cut-offs near 1 THz.[8] Calculations for the frequency dependence of the effective dielectric constant that were originally performed at lower frequencies by Knorr and Kuchler[7] are currently being extended into the terahertz range. These calculations are needed to predict the cut-off frequency for the coplanar strip lines of interest.

Experiment

The experimental arrangement is identical to that of Ref. 1 with the exception of the geometry of the transmission line. A schematic of the coplanar strip transmission line, including the propagating electrical signal and the orientation of the probe laser beam, is shown in Fig. 19.20.

The Cr:GaAs and $LiTaO_3$ crystals were mounted side by side on a glass plate and were subsequently ground and polished together to a thickness of 500 μm in order to present a uniformly flat surface on which to fabricate the electrodes. The electrodes were made by evaporating 0.5 μm of aluminum onto the smooth surface and then using standard photolithographic techniques to define the pattern. For

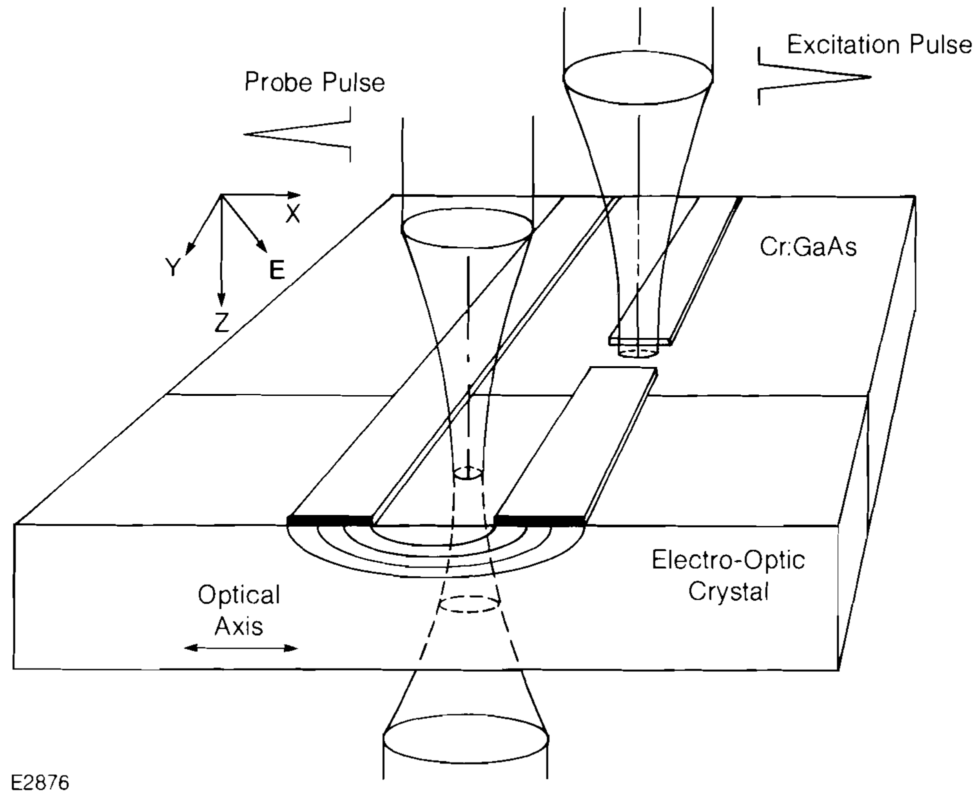

Fig. 19.20
Configuration of the coplanar strip electro-optic sampler. The signal is triggered photoconductively by the excitation pulse at the electrode gap on the Cr:GaAs substrate and probed by the perpendicular probe beam focused a short distance away in the $LiTaO_3$ crystal.

relative ease of fabrication we chose the electrode widths and separation to be 50 μm each. The calculated impedance for the line on the Cr:GaAs is 100 Ω and 56 Ω for the $LiTaO_3$.[4] The electrodes were made long enough (2 cm) to ensure that any reflection from the terminated end of the line arrived at the sampling point long after the initial rise of the electrical signal. The crystal optical axis of the lithium tantalate is parallel to the direction of the electric field between the electrodes, and, contrary to the standard configuration for integrated optical modulators, the probe beam is perpendicular to the electrode plane (see Fig. 19.20).

A typical result is shown in Fig. 19.21. In this case, the 50-μm gap was located 200 μm from the sampling point. The applied dc bias was +50 V. The probe beam was focused to a diameter of 11 μm between the two electrodes and was aligned perpendicular to the substrate. Temporal resolution did not appear to be significantly sensitive to the angle of incidence, which indicates that, as expected, the field depth in the substrate is very small and is of the order of the electrode separation. The resolved rise time (10%-90%), neglecting the foot on the leading edge due to dispersion, is 460 fs. The amplitude of the switched signal is 30 mV. The signal/noise ratio obtained indicates that the sensitivity of the coplanar strip geometry is comparable to that previously demonstrated with the balanced strip line.

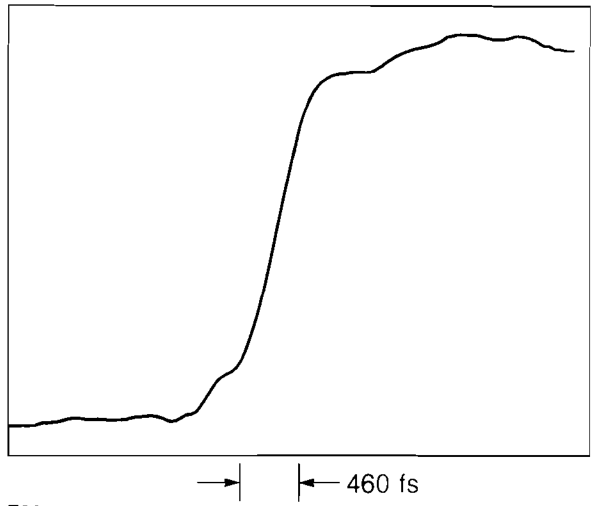

Fig. 19.21
Typical signal obtained with the electro-optic sampler, showing a rise time of 460 fs.

The observed rise time τ_S is the quadrature sum of the electrical pulse rise time τ_E, the transit time of the signal across the optical beam waist τ_W, the transit time τ_o of the optical pulse in the field region, and the laser pulsewidth τ_L:

$$\tau_S = \sqrt{\tau_E^2 + \tau_W^2 + \tau_o^2 + \tau_L^2} .$$

The measured laser-beam waist is 11 μm, so $\tau_W \approx$ 230 fs if we assume $\epsilon_{eff} \approx \epsilon_r = 40$ for very high frequencies and small geometries.[2] The laser pulse width τ_L = 120 fs. If we equate τ_S with our experimental result of 460 fs, then we find $(\tau_E^2 + \tau_o^2)^{1/2} = 380$ fs which implies the limits $0 < \tau_E, \tau_o < 380$ fs. This allows us to place an upper limit of $\sim$ 50 μm on the penetration depth of the electrical field into the substrate, which is in agreement with the strip-line geometrical parameters. The test-pulse rise time is ultimately limited, in the case of a uniformly irradiated gap, by the laser pulse width of 120 fs and by the dielectric relaxation time $\tau = \epsilon/\sigma$. The latter can only be estimated since we are in a regime of transient carrier velocities. In addition, due to the relatively high carrier concentration of 10^{17}-10^{18} cm^{-3}, band filling can occur resulting in an increase in optical penetration. If we assume a peak velocity of 5×10^7 cm/s,[9] an optical penetration depth of 1 μm, and 30 pJ/pulse, we calculate the dielectric time constant to be less than 50 fs.

The temporal resolution of the system may be further improved. The time τ_W may be reduced by reducing the focused diameter of the probe beam. The penetration of the electric field into the dielectric scales down with the separation of the electrodes, and to a lesser extent, with the electrode linewidths.[10] Reducing the dimensions of the strip line will increase the frequency response of the line and reduce the capacitance of the gap. These improvements are presently being incorporated into the experiment.