Section 3
ADVANCED TECHNOLOGY DEVELOPMENTS

3.A Propagation of Femtosecond Electrical Pulses on Superconducting Transmission Lines

An electro-optic sampling system has been used at LLE in the past to characterize transistors with rise times as fast as 5 ps at room temperature.[1] With devices operating at these speeds, it now becomes important to consider the details of how these very fast signals propagate. This can be seen in Fig. 28.25, where the impulse response of two types of transistors is shown.[2] Both responses clearly show the effects of the negative input pulse being coupled through to the output. In order to study the propagation of these very fast pulses, the sampling geometry of Fig. 28.26 was used. As shown, the $LiTaO_3$ and GaAs crystals were edge polished separately and then glued together to form a very well-matched interface. After surface polishing, the structure is so uniform that metal electrodes can be evaporated across the interface without discontinuities. This geometry has been used at room temperature to measure an electrical rise time of 460 fs.[3]

Since a superconductor exhibits an absence of dc resistivity, it was expected that a sampling structure with superconducting electrodes would show an increase in speed. In addition to requiring the ambient temperature to be less than the superconducting transition temperature, we also require that the laser pulses propagate undistorted through the experimental apparatus. This is accomplished by the use of superfluid helium, with a temperature of $\approx$ 2°K. When the temperature of liquid helium is reduced below the lambda point, all bubbling is precluded and the liquid becomes completely quiescent. An early version of the sampler, using standard Pb-In-Au alloy electrodes and wire bond

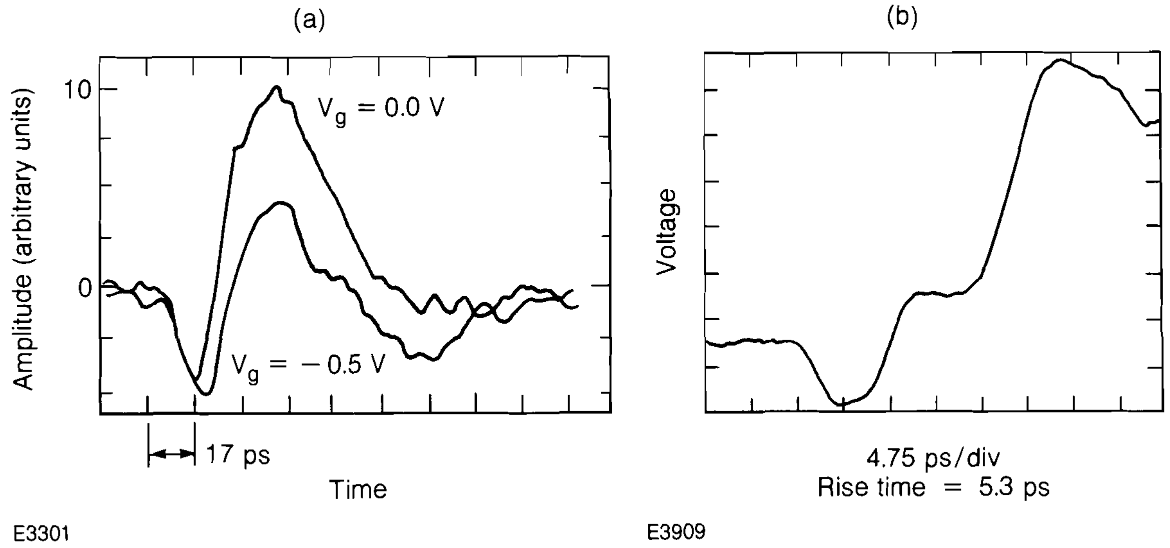

Fig. 28.25
Measured transistor step responses. Both the two-dimensional electron gas FET (a), and the permeable base transistor (b), show the effects of input-pulse coupling through to the output.

connections across the $LiTaO_3$/GaAs interface showed a fivefold increase in performance to 1-ps rise time, when cooled down from room temperature. The temporal response for a sampler with indium electrodes is shown in Fig. 28.27. With a rise time of 360 fs, the propagation characteristics of the coplanar geometry could now be studied.

Pulse distortion can be divided into two separate components caused by frequency-dependent absorption and frequency-dependent propagation velocity, also known as modal dispersion. Frequency-dependent absorption is caused by skin effect losses inside the conductors. As the frequency increases, the skin depth decreases, and so the effective resistance (loss) becomes greater for increasing frequency.

The corresponding mechanism for superconductors is somewhat different. Current is conducted in a superconductor not by electrons, called quasi particles, but by paired electrons called Cooper pairs. It is these Cooper pairs that conduct the zero-voltage current or supercurrent. Cooper pairs constitute a lower energy state than do quasi-particles, but at a high enough frequency these Cooper pairs are broken. This frequency is a material-dependent parameter, related to the energy gap by $E = h\nu$. For indium the energy gap is 1.05 mV, corresponding to a frequency of about 250 GHz. Above this frequency, the current is conducted by quasi-particles, but because of the low ambient temperature, the losses are expected to be much reduced over the room-temperature values.

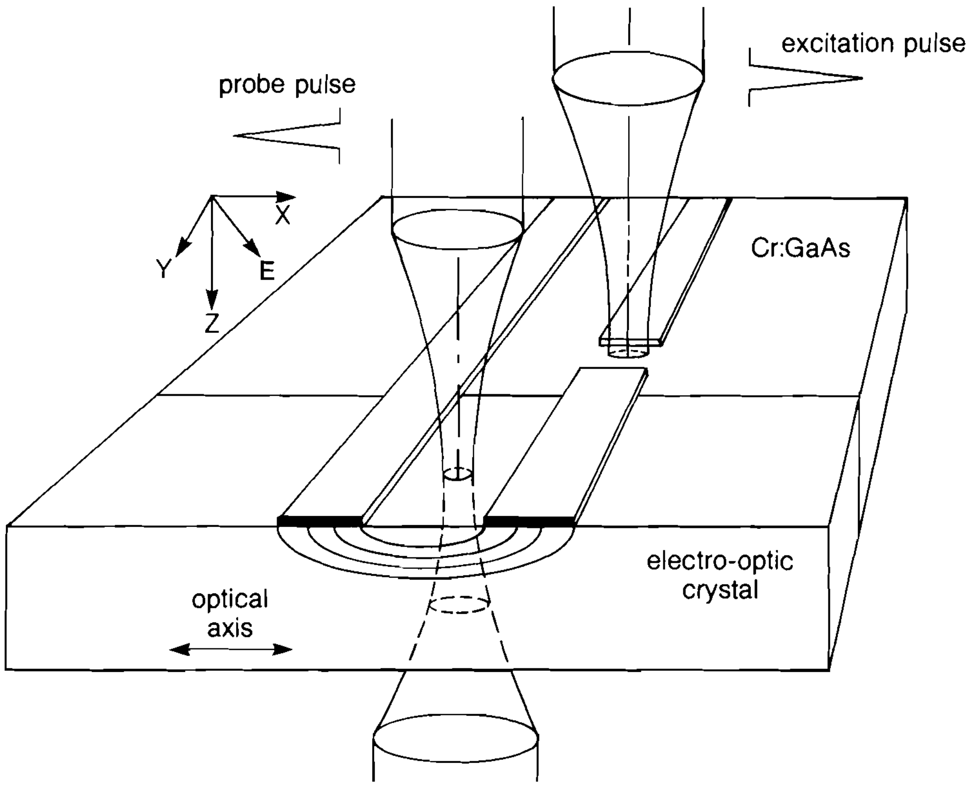

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Fig. 28.26
Sampling geometry. In practice the entire structure is immersed in a superfluid helium bath. This allows undistorted laser-beam propagation into and out of the experimental dewar.

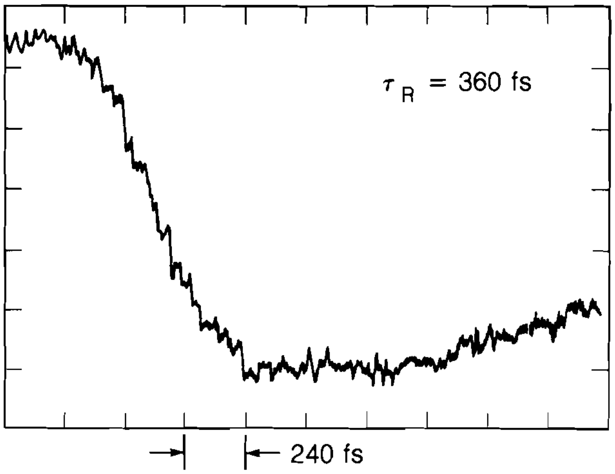

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Fig. 28.27
Rise time of the indium electrode sampler.

Modal dispersion, on the other hand, is not a mechanism based on the materials used, but rather on transmission-line geometry. This effect can be minimized by using transmission lines of small cross-sectional dimension. Consider again the coplanar transmission-line geometry. The electric field propagates above and below the $LiTaO_3$/superfluid helium interface. Since the relative dielectric constants are vastly different ($\approx$ 35 versus 1.08 for the helium), the velocity of propagation will be different above and below the interface. This result can be seen for the superconducting system in Fig. 28.28. The classic features are exhibited by the fall time becoming shorter than the rise time, and by the development of the small post pulses. All of these features have been observed previously at room temperature.[4]

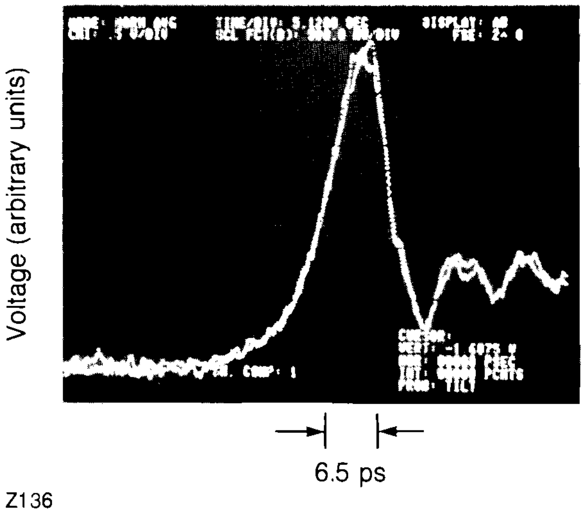

Fig. 28.28
Purely radiational electromagnetic signal demonstrating the classic signs of dispersion: rise time slower than fall time; small post pulses.

While reducing the dimensions will reduce the area of dielectric mismatch and hence reduce the effect of modal dispersion, the smaller conductor cross section will increase the conductor losses and so increase the frequency-dependent loss. Clearly, in designing a high-speed transmission system these two mechanisms must be balanced.

By measuring the rise time as a function of distance, the severity of the distortion for a particular system can be measured. Propagation measurements that were made on the electro-optic sampling system since 1982 are summarized in Fig. 28.29. The balanced stripline (curve A) shows a nearly vertical dispersion characteristic, resulting in a 9-ps rise time after 3 mm. Curve C shows results from a structure in which the dielectric mismatch between substrate and superstrate was minimized.[5] The increase in rise time per unit length of propagation is relatively low. Finally, the results on the superconducting line show that the signal rise time increased to only 2 ps after 3 mm. The improvement in performance can be seen by comparing the superconducting result to a similar geometry at room temperature (curve B).

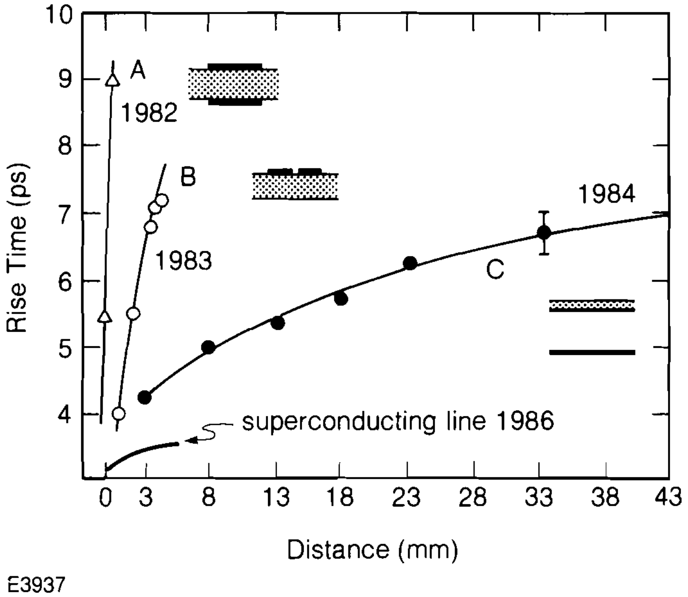

Fig. 28.29
Dispersion measurements made on the electro-optic system since 1982. The transmission-line geometry is shown in cross section, next to each curve.

In order to model these results, a computer program used previously for room-temperature pulse propagation was used.[6] The only change made in the program was to assume that the frequency-dependent losses in the superconductor were negligible. As shown in Fig. 28.30 for a particular data set, the results are very well predicted by the purely geometry-dependent dispersion model.

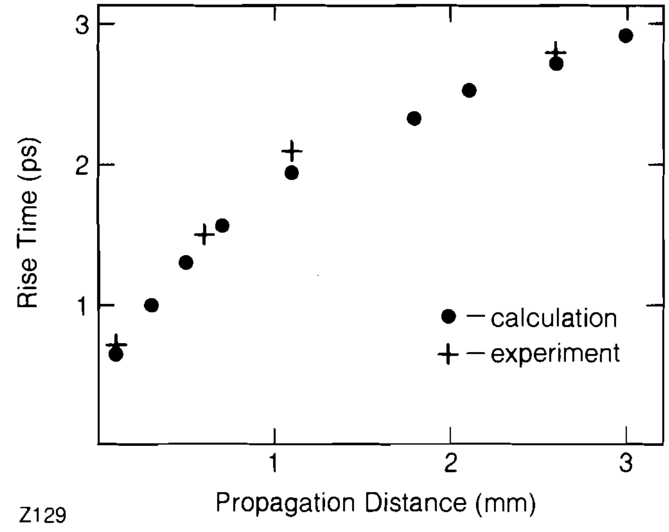

Fig. 28.30
Comparison between superconducting coplanar transmission dispersion data and computer model, using lossless approximation.

In summary, our electro-optic sampling system has been used in the cryogenic regime to characterize electrical waveforms in the THz frequency range. The system has been used to study pulse propagation on superconducting transmission lines where a rise time of 360 fs was measured, dispersing to only 2 ps after 3 mm of propagation. This very significant improvement in dispersion was due to the use of superconducting electrodes, which allowed the effects of modal dispersion to be minimized while still providing for very low-loss signal conduction. Finally, these results were modeled by considering a lossless case for modal dispersion.

ACKNOWLEDGMENT

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