Experimental Characterization of External Electrooptic Probes

Michael Y. Frankel, *Student Member, IEEE,* John F. Whitaker, *Member, IEEE,* Gerard A. Mourou, *Member, IEEE,* and Janis A. Valdmanis

Abstract—**The accuracy and invasiveness of various external $LiTaO_3$ electrooptic probe geometries is investigated experimentally. Such probes are an integral part of external electrooptic sampling systems used for the measurement of high bandwidth electrical signals in microwave integrated circuits. The experimental results indicate that for optimum measurement accuracy and minimum invasiveness of the probe, the electrooptic crystal should be no thicker than the extent of the microwave coplanar transmission line guided mode. Thinned crystals possess additional advantages of reduced thermal drift and reduced stray signal pickup from adjacent signal lines.**

I. Introduction

THE ADVANCEMENT of modern electronics towards higher speeds has necessitated the development of new measurement techniques. To be useful, the techniques must exhibit the following attributes: high bandwidth, accurate signal reproduction capability, minimum invasiveness, and wide applicability.

An excellent candidate that satisfies these requirements is the external electrooptic sampling technique described in detail by Valdmanis, *et al.* [1], [2]. The technique possesses terahertz-electrical-signal measurenent bandwidth and has been applied to a wide array of device and circuit characterization problems that can be subdivided into two broad categories: measurement of ultrafast electrical transients propagating on microwave transmission lines [3]–[6], and measurement at internal nodes of integrated-circuits [7]–[9]. This work is concerned with the former because it has the most stringent requirements in terms of measurement bandwidth, invasiveness, and accuracy. Some preliminary investigations of the probing crystal invasiveness, measurement linearity, and sensitivity have already been carried out [2], [9]. However, no quantitative experimental investigations have been done to optimize the external electrooptic probe (EEP) geometry or to determine the invasiveness and measurement accuracy of the EEP.

We report the experimental results of the characterization of an EEP used for microwave coplanar transmission line measurements. We show that commonly employed EEP geometries can cause substantial inaccuracies in their measurements and that these inaccuracies can be related to specific geometric parameters. An optimized EEP design is suggested, and its superior performance is demonstrated.

II. Experiment

The experimental configuration used to characterize the EEP response consists of a coplanar strip transmission line deposited on a silicon-on-sapphire substrate, as shown from the side in Fig. 1(a) and in cross-section in Fig. 1(b). The substrate was ion-implanted to reduce its carrier lifetime, and consequently its electrical response to a laser stimulus, into the subpicosecond range [10]. A dc-voltage bias was placed across the lines so that when any section of the line was illuminated with a laser pulse, a voltage transient would be launched. A balanced, colliding-pulse, mode-locked dye laser [11] provided 150-fs-duration pulses at a 100-MHz repetition rate for excitation of this photoconductor switch and for sampling of the electrooptic effect that was caused by the fringing electric field of the transient that extended into the EEP. The EEP, as shown in Fig. 1, consisted of a lithium tantalate ($LiTaO_3$) crystal mounted on a fused silica support. It was polished to an inverted, truncated-pyramid shape with an angle of $\sim 25°$. The EEP tip was positioned flat in contact with the substrate surface. The distance from the switching point to the EEP was only 200 μm in order to preserve the electrical-transient bandwidth which degrades with propagation distance due to loss and dispersion.

III. Theory

Considering the experimental configuration described in the preceding section, we expect the measurement system to faithfully reproduce the actual signal within the following constraints. These involve three discontinuities that are within the time window of the measurement.

Referring to Fig. 1(a), the first discontinuity is due to the top $LiTaO_3$ crystal boundary (interface *i*). The signal couples into the EEP, possibly as shock-wave radiation [12], resulting in a detectable reflection from the boundary between the $LiTaO_3$ and the fused silica support. The time delay between the main pulse and the reflection is given as

$$t_{\text{sup}} \approx 2d\frac{\sqrt{\epsilon_{cr}}}{c}, \tag{1}$$

where d is the $LiTaO_3$ crystal thickness and ϵ_{cr} is the $LiTaO_3$ relative permittivity.

The second discontinuity in Fig. 1(a), interface *ii*, is the bottom substrate boundary, and has been shown to result in a detectable reflection of switch radiation that couples into the substrate [13]. The time delay between the main pulse and the reflection is given as

$$t_{\text{sub}} = 2\sqrt{\left(\frac{z}{2}\right)^2 + h^2}\,\frac{\sqrt{\epsilon_{\text{sub}}}}{c} - \frac{z}{v}, \tag{2}$$

where z is the distance from the switch to the sampling beam spot within the EEP, ν is the transmission line propagation velocity, h is the substrate thickness, and ϵ_{sub} is the substrate relative permittivity.

The third discontinuity (interface *iii*) is due to the output facet

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The authors are with the Ultrafast Science Laboratory, Department of Electrical Engineering and Computer Science, University of Michigan, 2200 Bonisteel Dr., Ann Arbor, M1 48109-2099.

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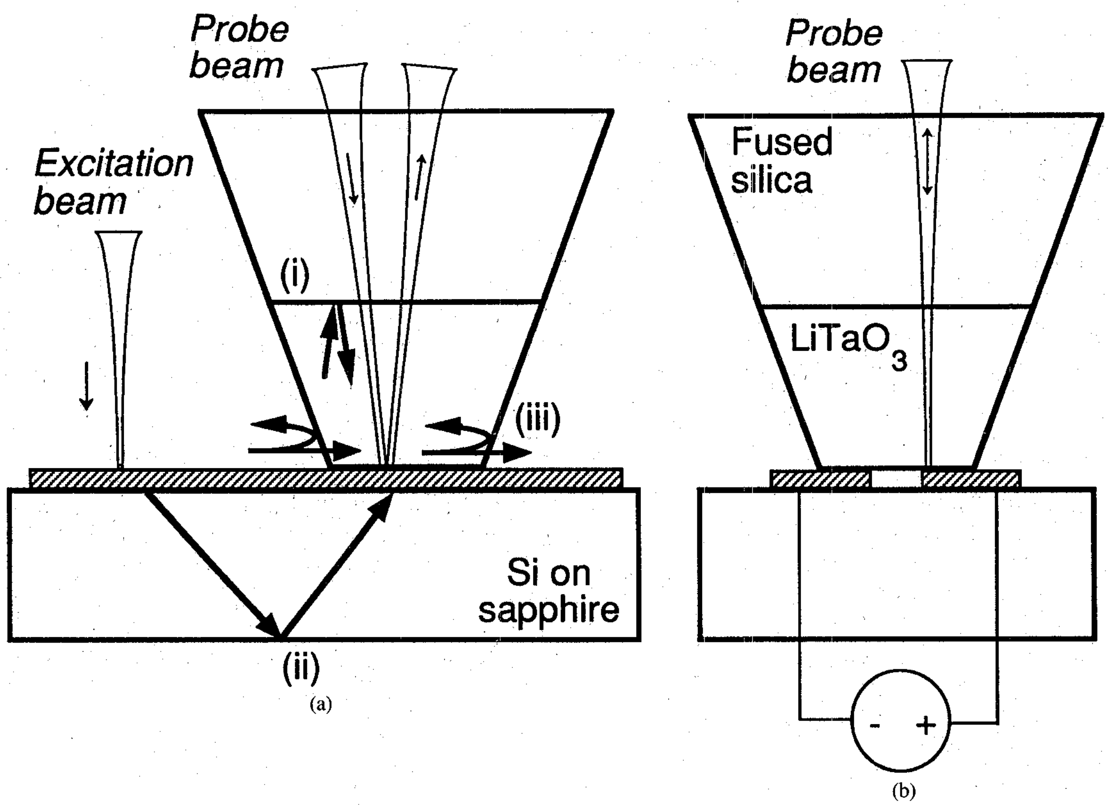

Fig. 1. (a) Side and (b) cross-sectional views of external electrooptic probe and coplanar strip transmission line with 30-μm electrodes and 20-μm gap. Three interfaces create reflection sources that direct part of the electrical signal back to the measurement point: (i) $LiTaO_3$ upper boundary and fused silica support; (ii) substrate bottom; (iii) output facet of $LiTaO_3$ crystal where guided electrical signal reenters open-boundary coplanar stripline.

of the EEP. The boundary between the $LiTaO_3$ and the atmosphere at the point where the guided electrical transient leaves the $LiTaO_3$ causes a reflection in the propagating pulse which influences the measured signal in the crystal. The time delay between the main pulse and such a reflection is given as

$$t_{\mathrm{EEP}} = 2L/\nu_{\mathrm{EEP}}, \tag{3}$$

where

$$\nu_{\mathrm{EEP}} = \frac{c}{\sqrt{\frac{\epsilon_{\mathrm{sub}} + \epsilon_{\mathrm{sup}}}{2}}} \tag{4}$$

is the pulse propagation velocity in the presence of the EEP, L is the distance from the sampling beam position within the EEP to the EEP output facet, and ϵ_{sup} is the superstrate permittivity due to the EEP. The presence of slight air gaps between the substrate and the EEP will make ϵ_{sup} an *effective* superstrate permittivity that is substantially lower than ϵ_{cr}, the $LiTaO_3$ crystal permittivity.

Aside from the measurement-accuracy issues addressed above, the disturbance of a signal caused by the EEP must also be assessed. This invasiveness of the EEP can be determined from its characteristic impedance Z_{EEP} that can be easily computed from the characteristic impedance of the coplanar stripline Z_0 modified by the presence of the superstrate: $Z_{\mathrm{EEP}} = Z_0\sqrt{(\epsilon_{\mathrm{sub}} + 1)/(\epsilon_{\mathrm{sub}} + \epsilon_{\mathrm{sup}})}$.

IV. Results and Discussion

We have made a number of electrooptic measurements on electrical waveforms output from a photoconductor switch to determine the influence on the signal due to the position of the laser probe beam within the EEP. The $LiTaO_3$ crystals tested have not used high reflection or antireflection coating to reflect the probe beam back up through the EEP, thus eliminating the need to analyze any effects due to such a dielectric coating. Rather, the probe beam was reflected off the smooth metal of the transmission line. No substantial differences in the main features of the measured signals were observed at different sampling-beam positions within the crystal, but the sensitivity was best when the beam was reflected off a conductor near its inside edge, as shown in Fig. 1(b).

Of much greater interest was the influence on numerous electrooptic measurements due to the different dimensions of several probe tips that have been investigated. Signals were measured at the air-EEP interface closest to the signal source (input facet) for each of the EEPs which possessed the dimensions specified in Fig. 2. The behavior of photoconductor switches is well known [10], and we expect to measure a single-picosecond-duration electrical pulse. However, as can be seen, there was a long, ringing tail on the top three measured waveforms. The main ringing features correspond to the $LiTaO_3$ crystal thickness and are attributed to electromagnetic radiation coupling into the $LiTaO_3$ crystal and resonating between the top and bottom crystal interfaces. Indeed, (1) predicts an expected delay that matches the measured one: 4.4 ps vs. $\sim$3.5 ps, respectively, for the 100-μm-thick crystal; 13 ps vs. $\sim$13 ps for the 300-μm crystal; and 22 ps vs. $\sim$22 ps for the 500-μm crystal. Thus, we attribute the main measurement error for this type of crystal to bulk resonant effects.

Since the sampling beam integrates the transverse-electric-field

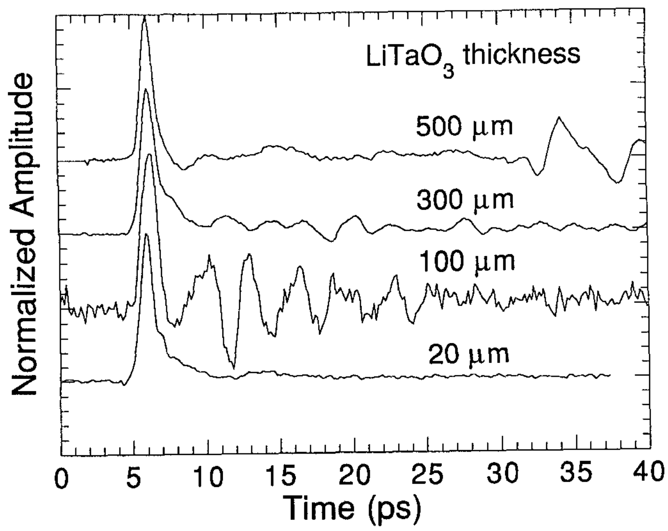

Fig. 2. Photoconductively-switched electrical transient as measured by four different external electrooptic probes: 310-μm × 210-μm footprint × 500-μm-thick probe; 70-μm × 100-μm footprint × 300-μm-thick probe; 100-μm-μm footprint × 100-μm-thick probe; 200-μm × 200-μm footprint × 20-μm-thick probe.

strength along its entire path in the $LiTaO_3$, the whole thickness of the crystal affects the probe beam and the measured output. Thus, in addition to the main ripples, we observe that the signal is generally corrupted throughout the measurement time window.

The best way to eliminate the deleterious effects of the EEP material bulk is to use a thin $LiTaO_3$ crystal that will act as a single lumped-element and eliminate the undesirable bulk resonant effects. the thickness that is expected to be optimal should be similar to the extent of the guided mode confinement near the conductors. A thicker than optimum crystal will exhibit resonance, and a thinner one will have reduced sensitivity due to a reduced signal integration path. For typical microwave coplanar transmission lines with dimensions of 5-50 μm, an optimum crystal thickness is expected to be ~ 20 μm.

The bottom trace of Fig. 2 shows the measured signal at the center of an ~ 20-μm-thick EEP with a 200 × 200-μm-footprint dimension. The long-lived ringing tail disappears, but the sensitivity remains practically unchanged. The small bulge appearing in the signal ~ 7 ps after the main pulse is due to the reflection from the substrate bottom, as given by (2). The time delay between the main pulse and a small shoulder on its falling edge is due to the EEP output facet reflection, as given by (3).

The invasiveness of the EEP is estimated from the time delay between the pulses measured at the input and output facets of the EEP. Using (3), we compute the effective EEP-induced superstrate permittivity to be ~ 5, making the perturbed characteristic impedance lower than that of the open coplanar stripline by $\sim 10\%$. The electrical signal transmission through and the reflection from the EEP interfaces with air will be resonant, but since the ϵ_{sup} is smaller than ϵ_{sub} the overall perturbation is quite low.

In addition to the improvements in measurement accuracy derived from the reduced-thickness EEP's, several other benefits of these tips have also been identified. Thermal drift of the static birefringence of the EEP is reduced proportionately to the reduction in crystal thickness, and a small increase of measurement bandwidth is possible for some circuit geometries, due to a decreased interaction time between the electrical signal and the probing light pulse. Furthermore, if adjacent signal lines are spaced by such a distance that their electric field lines extend far above the surface, an EEP with a thin birefringent crystal will have a reduced sensitivity to these neighboring fields due to the reduced signal integration path. This property is useful in minimizing the integrated circuit measurement crosstalk from conductors that are spaced far apart.

V. Conclusion

We have experimentally investigated the measurement accuracy and invasiveness of a $LiTaO_3$ external electrooptic probe. The experiments conclusively show that the probe geometries used for most experimental measurements introduce significant errors due to the relatively large signal integration path through the crystal. We have demonstrated that a thin crystal results in superior measurement accuracy with little sacrifice in sensitivity.

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