Millimeter-Wave Time-Resolved Measurement Near a Discontinuity: Separating Temporally Overlapped Incident and Reflected Signals

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Abstract— **We report a new measurement approach to recover temporally overlapping incident and reflected signals near a discontinuity using time-resolved electrooptic sampling. The technique involves measurement at two closely spaced locations and enables decomposition of the measured waveforms into components propagating toward and away from a discontinuity. We show experimental results for a simple coplanar structure.**

I. INTRODUCTION

ELECTROOPTIC sampling has been used in millimeter-wave time-resolved characterization of passive and active electronic devices [1]–[4], with a demonstrated excitation and measurement bandwidth of 1000 GHz. On-wafer test structures consist of a photoconductive switch signal generator and a transmission line connecting this generator to the device under test (DUT). If the transient voltage is measured at a fixed point on the input transmission line, the waveform will first show the incident signal as it propagates toward the DUT followed by the reflected signal. If the incident signal duration is greater than the round-trip time from the sampling location to the DUT, the incident and reflected signals will temporally overlap and the two will be indistinguishable. This has prevented some previous researchers from determining the reflected signal and forced them to approximate the incident signal [3].

Several approaches have been used to enable independent determination of the incident and reflected signals. The first involves determining the incident signal on a different test fixture by replacing the DUT with a through line or combinations of open, short, and matched load [5]. This approach relies on being able to generate the same input signal reproducibly with two or more generators, which requires careful control of excitation position and focusing, and cannot be verified during the measurement. The second approach relies on having an incident signal duration small enough that the sampling location can be moved sufficiently far from the DUT to prevent temporal overlap. Generation of short incident signals requires reduction of carrier lifetime in the photoconductor by ion-implantation damage or appropriate choice of the photoconductive material, which may be inconvenient or impossible, especially when integrated on-wafer. In addition, the short pulses generated are inconvenient in studies of large-signal switching, where step-like signals are desirable. Furthermore, locating the signal generator far from the DUT limits excitation bandwidth because transmission lines on semiconductor substrates are highly attenuating and dispersive at millimeter-wave frequencies [6]. Finally, it is possible to use an attenuator as a directional device [7]; this approach depends on the quality of the broadband attenuator.

A technique is needed to recover temporally overlapping incident and reflected signals while still allowing their measurement close to the DUT. In this work, we propose and demonstrate a novel approach to accomplish this by making measurements at two closely spaced locations. With suitable processing, the measured waveforms can be decomposed into components propagating toward and away from the DUT.

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II. TECHNIQUE

In order to describe the technique, suppose that $g_A(t)$ is the waveform measured at location A and $g_B(t)$ is the waveform measured at location B, which is closer to the DUT. These signals can be expressed as follows:

$$g_A(t) = f_{inc}(t) + f_{ref}(t) \quad (1)$$

$$g_B(t) = f_{inc}(t-\tau) + f_{ref}(t+\tau) \quad (2)$$

where $\tau = L/\nu$ is the propagation delay from A to B, $f_{inc}(t)$ is the incident signal, and $f_{ref}(t)$ is the reflected signal. The length L is the separation between measurement locations and ν is the propagation velocity on the transmission line. We assume that over the frequency range of the signals the attenuation and dispersion between two measurement locations are negligible, so that the decomposition of measured signals into time-shifted incident and reflected signals and the use of constant propagation velocity are justified.

The reflected signal can be recovered by substituting (1) time-delayed by τ, and (2) into a central difference approximation for the time-derivative, followed by integration:

$$f_{ref}(t) \approx \int_{-\infty}^{t} \frac{g_B(t') - g_A(t' - \tau)}{2\tau} dt'. \quad (3)$$

Similarly, the incident signal can be recovered with

$$f_{inc}(t) \approx \int_{-\infty}^{t} \frac{g_A(t' + \tau) - g_B(t')}{2\tau} dt'. \quad (4)$$

It is easy to show that the finite-difference approximation has a low-pass filtering effect on the recovered signals, with a transfer function of $sinc(\omega\tau)$. Thus, the 3-dB bandwidth of the recovery process is $0.22/\tau$. One can increase the bandwidth by decreasing the distance between measurement locations.

III. Experimental Verification

The open circuit DUT shown in Fig. 1 was photolithographically defined on a 425- μm-thick semi-insulating GaAs substrate. The coplanar stripline electrode pattern is one that has been used to allow biasing of active devices [3], [4]; it was patterned by lift-off processing of an electron-beam evaporated bilayer of 10 nm of Titanium followed by 200 nm of Gold. Electrooptic measurements were made with 150 fs pulses from a mode-locked Titanium-Sapphire laser, and an external $LiTaO_3$ electrooptic sampling tip with a footprint approximately 220-μm square. While many measurements using external sampling tips have been made with the tip in direct contact with the transmission line, it has recently been shown that the impedance mismatch due to the $LiTaO_3$ tip can cause significant distortions of the measured results [8]–[10]. Therefore, we used the noncontact configuration with an air gap between electrooptic transducer and transmission line of 7 μm for all measurements.

In Fig. 2 we show the data measured for the open-circuit sample described above and the recovered incident and reflected signals. The solid line of Fig. 2(a) shows the signal g_A(t) measured at location A of Fig. 1, located 650 μm from the open circuit DUT. The step-like incident signal f_{inc}(t) starting at about 5 ps is followed by the reflection f_{ref}(t), which starts at approximately 17 ps. The dashed line in Fig. 2(a) shows the signal g_B(t) measured at location B of Fig. 1, which is 50 μm closer to the open circuit DUT than A. As expected, the incident signal is slightly delayed and the reflected signal slightly advanced by the change in location. From the observed propagation delay we expect the 3-dB bandwidth of the recovery process to be 500 GHz, which is much larger than the signal bandwidth of about 100 GHz. The sampling period was chosen to be 150 fs. For numerical processing, the measured waveforms were interpolated by four points between each of the measured data points.

The recovery process for the reflected signal described by (3) requires that the waveform g_A(t) measured at location A be time-delayed to cancel the incident component from the measured signal g_B(t). The time-shift, τ, was chosen to give the best cancellation. The corresponding ν compares well with measurements of the propagation velocity. This was followed by numerical integration to obtain the signal reflected from the device, which is shown in Fig. 2(b) as a dashed line. The incident signal is recovered with a similar procedure, and is shown in Fig. 2(b) as a solid line. As expected, the retrieved incident and reflected signals of Fig. 2(b) show features evident in the measured data of Fig. 2(a) where both signals overlap. The 10–90% rise time of the recovered incident signal is 3.68 ps, which is very close to the 3.77 ps rise time of the incident component from the measured results. In addition, amplitudes of the retrieved signals are very close to the measured results. Finally, we note that the total signal obtained by summing retrieved incident and reflected signals after appropriate time-shifts compares well with the measured total signals at both locations.

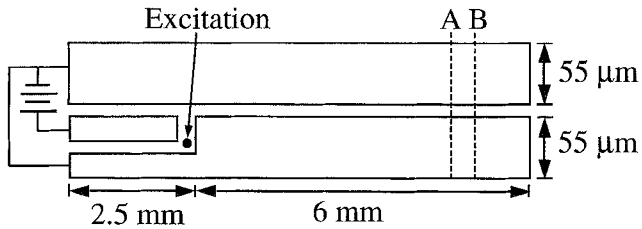

Fig. 1. Layout of coplanar stripline test-structure with open-circuit device, and a photoconductive generator. All gaps are 5 μm.

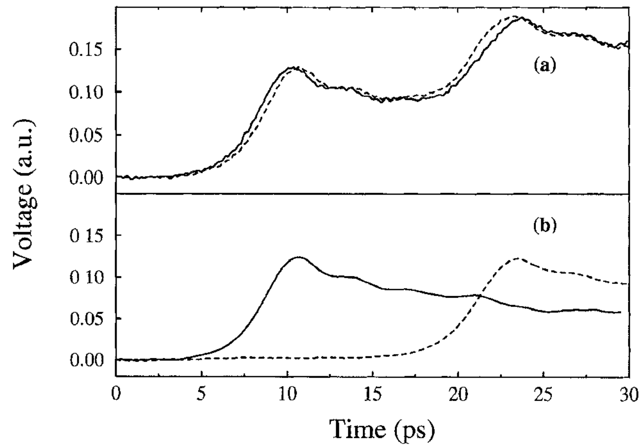

Fig. 2. (a) Waveforms measured at locations A (solid line) and B (dashed line) as shown in Fig. 1. (b) Recovered incident (solid line) and reflected (dashed line) signals.

IV. Summary

We have proposed and demonstrated a new technique, based on electrooptic sampling at two different locations, to resolve superimposed incident and reflected signals propagating in opposite directions. If the two locations are close to one another, the incident and reflected signals can be separated unambiguously. We note that this technique can be applied to any time-resolved sampling technique including photoconductive sampling. In addition, for pulse-like input signals, it can be extended to account for dispersion and attenuation between the sampling locations.

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