Mode-Discriminating Electrooptic Sampling for Separating Guided and Unguided Modes on Coplanar Waveguide

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***Abstract*—Mode-discriminating electrooptic sampling (MEOS) of coplanar waveguides was shown to discriminate between the symmetric quasi-TEM guided mode and asymmetric field distributions including unguided electromagnetic radiation. Radiation generated in a photoconductive switch and reflected from the back of the substrate was unambiguously identified. Ultrafast sampling of devices showed features in the transmitted pulse due to multiple substrate reflections. These features are removed using MEOS, leading to increased accuracy in determination of s-parameters.**

I. Introduction

ELECTROOPTIC sampling (EOS) is the highest-bandwidth method for measuring electrical signals propagating in transmission lines [1]. Combined with ultrashort pulse generation in photoconductive switches [2] and coplanar transmission lines with ≈1 THz bandwidth [3], this leads to possibilities for ultrafast time-domain s-parameter measurements. Values of $f_{\max} \approx 100$ GHz have been directly measured in heterojunction transistors using this technique [4].

In coplanar waveguide (CPW), the electrical waveform can propagate in two principal modes: the desired quasi-TEM CPW mode, which is symmetric about the central conductor, and a parasitic slotline mode, which is antisymmetric [Fig. 1(a)]. Since EOS is sensitive to the field rather than to the potential on the central conductor, these modes can be distinguished by probing independently the field in the gap on each side of the line [5], [6], labeled as "same" and "opposite" in Fig. 1(b). We call this technique mode-discriminating electrooptic sampling (MEOS).

In addition to guided modes, EOS can also detect freely propagating electromagnetic radiation that traverses the sampling region [7]. Pulsed illumination of a photoconductive switch generates a photocurrent transient that radiates energy into the substrate. This radiation may be reflected from the back of the substrate and detected by a neighboring photoconductive switch [8] or by EOS. This leads to spurious features in ultrafast sampling measurements of devices. However, the freely propagating radiation is inherently antisymmetric with respect to the CPW and, hence, can be discriminated from the quasi-TEM guided mode using MEOS.

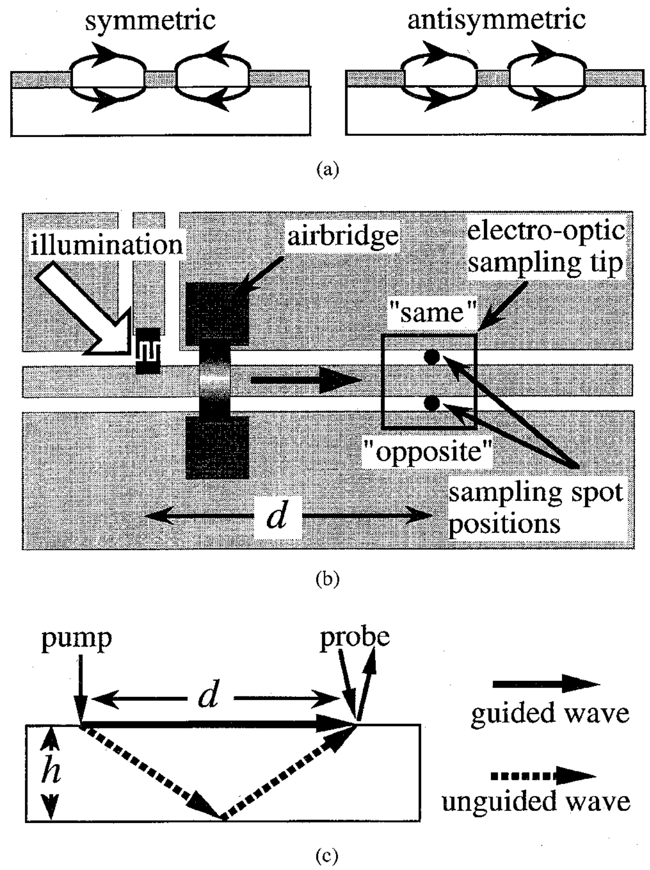

Fig. 1. (a) Symmetric and antisymmetric modes of CPW. (b) Pulse generation by illumination of photoconductive switch, and measurement of propagating modes by EOS on "same" and "opposite" sides of CPW. (c) Propagation paths of guided wave and unguided wave reflected from back surface of substrate.

II. Identification and Discrimination of Freely Propagating Radiation

EOS measurements of pulses generated and propagated on CPW were performed as shown in Fig. 1(b). An electrical pulse was launched on the CPW by illuminating an interdigitated photoconductor [2], biased from a side arm, with 100 fs pulses from a Ti-sapphire laser. The photoconductor

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consisted of a 1-μm-thick, low-temperature-grown GaAs layer with a response time of $\approx$1 ps, on a 0.6-mm semi-insulating GaAs substrate. The CPW central conductor was 20 μm wide and the gaps were 10 μm. Air-bridges connecting the ground planes of the CPW ensured that the slotline mode was not propagated [9]. The signal was sampled at several propagation distances (d) using a $LiTaO_3$ electrooptic probe tip, and the signals propagating on both "same" and "opposite" sides of the CPW were measured by focusing the probe beam onto the appropriate gap.

Data for $d = 1$ mm is shown in Fig. 2 (the signal propagating on the "same" side of the CPW is shown by the dashed-dotted line). In comparison to the signal sampled at $d = 0.2$ mm, the main pulse is broadened due to dispersion and frequency-dependent radiation losses [3]. An additional small peak can be seen at time delay $\Delta t_{p-r} \approx 10$ ps after the main pulse; a similar feature was previously identified [8] as a freely propagating electromagnetic pulse generated at the photoconductive switch and reflected from the bottom surface of the substrate, as shown in Fig. 1(c). This interpretation is confirmed by the following analysis. For substrate thickness h, the freely propagating radiation travels a distance $\sqrt{d^2 + 4h^2}$ at velocity v_{sub}, whereas the guided wave travels distance d at velocity v_{line}. The difference in arrival time at the measurement point is

$$\Delta t_{p-r} = \frac{1}{v_{\text{sub}}} \sqrt{d^2 + 4h^2} - \frac{d}{v_{\text{line}}}. \quad (1)$$

Fig. 3 shows the experimentally measured time delay Δt_{p-r} as a function of propagation distance d and a fit based on (1). In the fitting v_{sub}, v_{line} and h were allowed to vary freely, resulting in the values $v_{sub} = (0.83 \pm 0.09) \times 10^8$ ms^{-1}, $v_{line} = (1.04 \pm 0.13) \times 10^8$ ms^{-1}, and $h = (0.57 \pm 0.05)$ mm. These may be compared with expected values estimated as follows. The velocity of the electromagnetic wave in the substrate is $v_{sub} \approx c/\sqrt{\varepsilon_r} = 0.83 \times 10^8$ ms^{-1}, where c is the velocity of light in vacuum and $\varepsilon_r = 13.1$ is the dielectric constant of GaAs. For the quasi-TEM guided mode of the CPW, the effective permittivity is approximately the mean of the values in the substrate and in air [10] so that $v_{line} \approx c/\sqrt{[(\varepsilon_r + 1)/2]} = 1.13 \times 10^8$ ms^{-1}. The wafer thickness was measured as 0.59 mm. These values are in agreement with those from the fit and the feature at $\Delta t_{p-r} \approx 10$ ps is therefore confirmed as a reflection of freely propagating radiation from the substrate back surface.

This reflected signal may be attenuated using a microwave-absorbing material on the back of the substrate [8]. Alternatively, as we show in this letter, the signal due only to the guided mode may be extracted by using the sensitivity of EOS to the electric-field vector. Fig. 2 shows the signals sampled on the "same" and "opposite" sides of the CPW. In each case, the EOS signal was calibrated by applying a low-frequency ac electrical signal to the CPW, hence the "same" and "opposite" signals appear with the same polarity. The signals are almost identical, since the antisymmetric slotline mode is eliminated by the air-bridge [9]. However, the unguided radiation lacks the symmetry of the CPW and, hence, is detected in the opposite sense in the two signals.

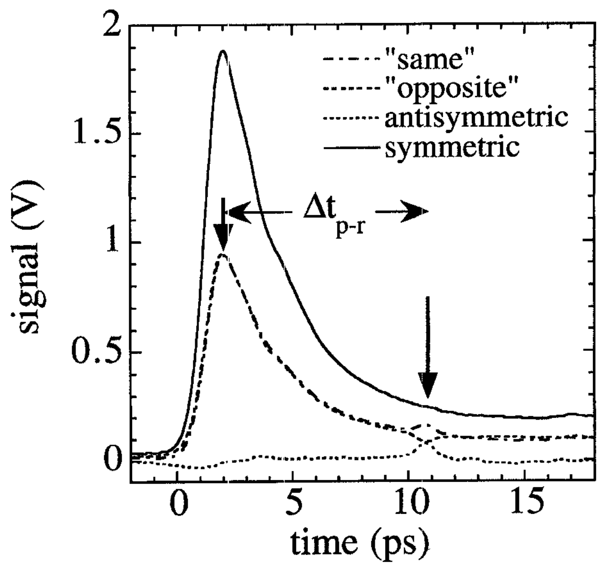

Fig. 2. Signals propagating on CPW at $d = 1.0$ mm, measured by conventional EOS ("same" and "opposite") and by MEOS (symmetric and antisymmetric). Δt_{p-r} is the time delay between the arrival of guided and unguided waves at the sampling point.

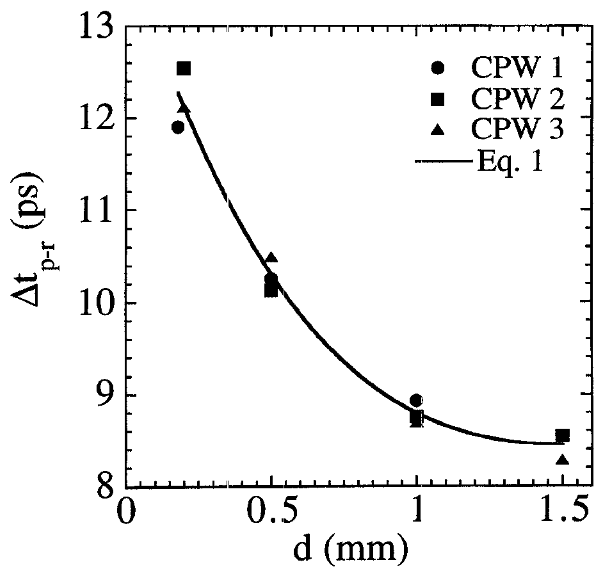

Fig. 3. Difference in arrival time between guided and reflected unguided wave, as function of propagation distance d for three different CPW's. Solid line is a fit to (1).

The symmetric and antisymmetric modes are obtained, respectively, as the sum and difference of the "same" and "opposite" signals (Fig. 2). The reflected freely propagating wave is entirely present in the antisymmetric signal and the guided wave in the symmetric signal, indicating the effectiveness of this discrimination technique.

III. Application to S-Parameter Measurements

Reflected freely propagating radiation presents particular problems for ultrafast time-domain s-parameter measurements of devices, where the propagation distance d may be long (several mm) to allow a sufficient time window free of pulses

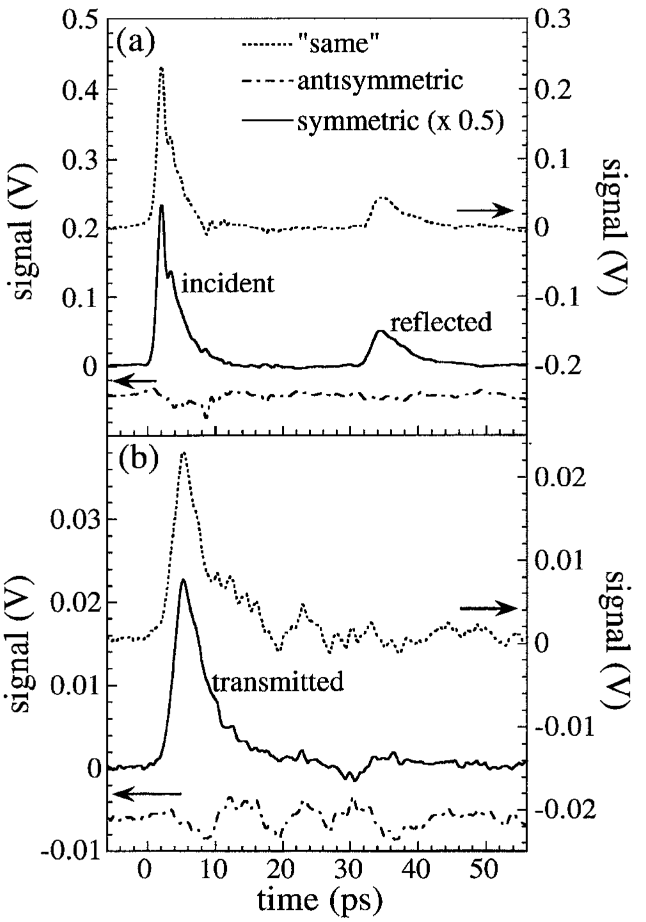

Fig. 4. Time-domain characterization of an FET gate integrated with CPW. (a) Incident and reflected pulses and (b) transmitted pulse (arbitrarily shifted in time). Results of conventional EOS ("same") and MEOS (symmetric and antisymmetric) are shown.

reflected from the ends of the CPW. The minimum value of Δt_{p-r} and the corresponding position may be obtained by differentiating (1), giving $\Delta t_{p-r} = 8.55$ ps at $d = 1.52$ mm with the fitted values of v_{sub}, v_{line}, and h. Hence, the reflection may fall within the desired time window. Multiple reflection from the substrate or lateral boundaries of the CPW groundplane may lead to complex features that are hard to remove by data analysis. Either the reflected or transmitted signal may be small compared to the incident signal, hence the unguided radiation increases in significance.

In a second experiment, MEOS was performed on a narrow wire of dimensions 20 μm × 0.3 μm, forming the gate of an FET that was connected to a CPW at each end. The distance from the photoconductive switch to the gate was 3 mm, and the sampling of the incident and reflected pulses was performed at 1 mm distance from the device in order to separate them in time. The transmitted pulse was measured by sampling the CPW close to the other end of the gate.

Fig. 4 shows the incident, reflected, and transmitted pulses measured by conventional electrooptic sampling and by MEOS. The amplitude of the transmitted pulse is small since most of the energy is reflected by the gate due to the large impedance mismatch. The conventional EOS measurement shows features in the trailing edge of both the incident and transmitted pulses due to reflected radiation. The guided CPW mode and the unguided radiation are discriminated in the MEOS measurement. For the transmitted pulse, the antisymmetric MEOS signal indicates the presence of up to four separate reflections. The transmitted pulse is significantly "cleaner" in the symmetric MEOS measurement, with fewer spurious features on the trailing edge and a well-defined baseline. This allows more reliable time-windowing of incident, reflected, and transmitted pulses for Fourier transformation into the frequency domain, and, hence, more accurate determination of s-parameters.

IV. Conclusion

In conclusion, we have employed the symmetry of CPW and the field sensitivity of electrooptic sampling to discriminate between symmetric guided modes and antisymmetric unguided electromagnetic radiation. This leads to more reliable determination of s-parameters from ultrafast time-domain measurements.

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