Terahertz-Bandwidth Pulse Propagation on a Coplanar Stripline Fabricated on a Thin Membrane

H. Cheng, J. F. Whitaker, T. M. Weller, and L. P. B. Katehi

Abstract— **An ultra-broadband coplanar stripline employing a durable 1.4-μm-thick membrane substrate has been devised, fabricated, and tested. Nearly distortionless propagation of terahertz-bandwidth electrical pulses over lengths in excess of 4 mm has been experimentally demonstrated using subpicosecond test signals and a sampling measurement technique based on ultrashort-duration laser pulses. A comparison to pulse propagation data on identical coplanar strips on a GaAs substrate illustrates a dramatic improvement in the radiation attenuation and phase velocity dispersion for the membrane CPS with increasing frequency.**

I. INTRODUCTION

IN ORDER TO EXPLOIT the ultrafast response of high-speed electronic and optoelectronic devices—such as HEMT amplifiers with ultra-high cutoff frequencies, subpicosecond-response MSM photodetectors [1], picosecond digital switching elements, high-frequency Schottky diode mixers, etc.—waveguiding structures with comparable bandwidths must be devised. Unfortunately, when traditional waveguides like microstrip, coplanar stripline (CPS), and coplanar waveguide are fabricated on semiconductor substrates, they can only support signals of limited bandwidth without having excessive dispersion and loss. The main reason for the high-frequency distortion in these transmission lines is the mismatch in permittivity between the substrate and air, which causes, especially in coplanar structures, energy to radiate into the substrate as a shock wave [2]. One way to avoid this radiation loss is to eliminate the inhomogeneous dielectric medium encountered by the electric field. Mechanically or epitaxially capping the transmission-line surface with a material of similar permittivity has been demonstrated to improve the situation somewhat [3], but tiny air gaps or an insufficient thickness of the cap layer have allowed degradation of the propagating short-duration signals. A superior approach appears to be the reduction of the substrate permittivity, as in the guiding structure demonstrated by Keil *et al.* [4], where the substrate material has been mostly etched away, leaving free-standing metal coplanar electrodes.

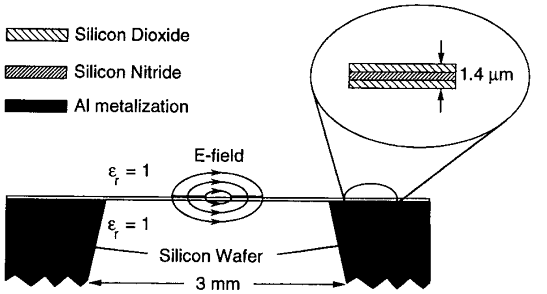


Fig. 1. Cross-sectional view of ultra-low-distortion coplanar stripline employing a 1.4-μm-thick substrate of silicon dioxide and silicon nitride. The transmission line, with strip widths and spacing of 20 μm each, eliminates almost entirely the dielectric mismatch for the electric field.

In this paper, we demonstrate how a CPS fabricated on a durable 1.4-μm-thick membrane can achieve a very low effective permittivity and outstanding propagation characteristics for signal frequencies up to 1 THz. This structure, which has been characterized experimentally in both the time and frequency domains, provides reasonable mechanical support, and is suitable for applications in the submillimeter-wave regime. A comparison has also been made with subpicosecond pulse propagation for a CPS fabricated on a GaAs substrate to highlight the degree to which improvement in pulse transmission is possible using the new CPS.

II. SAMPLE STRUCTURE AND PREPARATION

A cross-sectional view of a CPS fabricated on a silicon dioxide/silicon nitride membrane substrate, schematically showing the uniform electric field lines both above and below the membrane plane, is given in Fig. 1. The 1.4 μm-thick insulator is a tri-layer with 7000 Å SiO_2 grown by thermal oxidation on a silicon wafer, followed by 3000 Å Si_3N_4 and 4000 Å SiO_2 formed by chemical vapor deposition. With the tri-layer in place, a section of the silicon substrate 3 mm × 10 mm is removed by chemical etching to isolate the membrane as a free-standing structure [5]. The membrane, despite being very thin, is robust, and subsequent processing (to deposit and pattern metal lines) and electrical measurements are reasonably straightforward. The CPS fabricated on the membrane has a strip width and separation of 20 μm. A CPS with identical dimensions was defined on a semi-insulating GaAs substrate so that the behavior of pulse propagation on the CPS-on-

---

Manuscript received November 22, 1993. This work was supported by the National Science Foundation through the Center for Ultrafast Optical Science under STC PHY 8920108, the Office of Naval Research, the NASA Center for Space Terahertz Technology, and the Jet Propulsion Laboratory.

H. Cheng and J. F. Whitaker are with the Center for Ultrafast Optical Science, University of Michigan, Ann Arbor, MI 48109-2099.

T. M. Weller and L. P. B. Katehi are with the NASA Center for Space Terahertz Technology, Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109-2122.

IEEE Log Number 9216030.

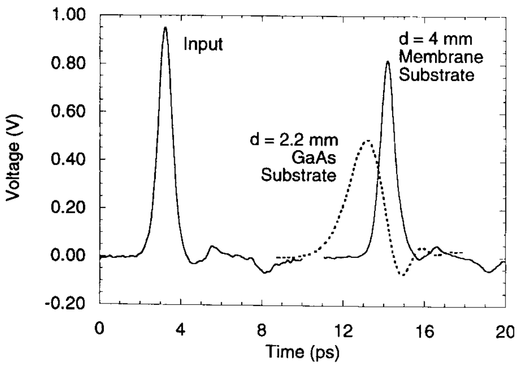


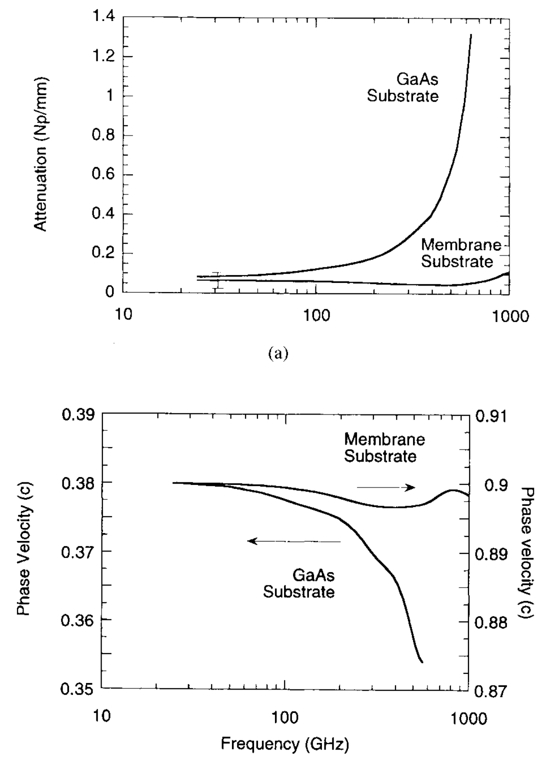
Fig. 2. A 790-fs-duration (FWHM) electrical pulse remains nearly undistorted after propagation along 4 mm of coplanar stripline fabricated on a thin membrane, while it is highly distorted after propagation on only 2.2 mm of an identical line fabricated on GaAs. The propagated-signal delays are the actual delays relative to the input pulse.

membrane could be compared with that of a typical circuit-interconnection reference sample.

A short-duration, broadband electrical pulse was easily generated and launched onto the CPS *in situ* using the optically-excited GaAs substrate of the reference CPS. A 1-μm-thick epitaxial layer of GaAs had been grown on the GaAs substrate at the greatly reduced temperature of 200° C in order to create a semi-insulating material with an ultrafast carrier lifetime [6]. The CPS-on-membrane has no natural provision for the generation of a broadband test signal, so a small patch of the low-temperature-grown thin film of GaAs (LT-GaAs) was removed from its native substrate by chemical etching and then bonded onto the membrane structure to serve as an *in situ* test-signal source. The procedure for this epitaxial liftoff and grafting has been adapted from [7]. With the GaAs film in place on the membrane, it was then possible to generate clean, virtually identical signals for testing the CPS on both substrates.

III. RESULTS

The test input pulses for both the membrane and reference-GaAs CPS had FWHM durations of less than 800 fs (Fig. 2) and were generated when 100-fs laser pulses illuminated the photoconductive switch defined by the epitaxial GaAs between the dc-biased coplanar lines [8]. The fast onset occurs as the energy from the optical pulse is deposited onto the photoconductor, while the rapid fall time results from the ultrafast carrier lifetime of the GaAs, providing us with a test signal having a spectrum with usable frequencies in excess of 1 THz. Subpicosecond-duration voltage signals are readily resolved using an electro-optic sampling probe, consisting of a tiny crystal of $LiTaO_3$ which can be dipped into fringing electric fields such as those above the transmission lines [9]. In this measurement technique, as the 100-fs laser pulses pass through the crystal, their intensity is modulated to a degree which is determined by the amplitude and phase of the microwave electric field present in the crystal during this 100-fs window.



(a)

(b)

Fig. 3. The attenuation (a) and phase velocity (b) extracted from terahertz-bandwidth pulse propagation experiments for identical coplanar striplines fabricated on a thin membrane and GaAs.

Measurements in the time-domain allowed a qualitative comparison of the two different coplanar lines through monitoring of the distortion of subpicosecond pulses as they propagated over various distances. For instance, after 4 mm of travel on the CPS-on-membrane (Fig. 2), the input pulse showed little of the pulse broadening and amplitude degradation normally associated with transmission-line losses, and none of the increase in the rise time or onset of trailing oscillations characteristic of modal dispersion. Only a decrease in amplitude of less than 15%, which likely arose from skin-effect loss, was obvious, although the pulse width did increase slightly from 0.77 to 0.83 ps. However, for propagation on the CPS with the GaAs substrate, it was seen that after only 2.2 mm, all the classic signs of high loss and modal dispersion were present [10], with the amplitude falling about 50% and the pulse width stretching to 1.8 ps.

The time-domain data was also transformed to the frequency domain through the use of a Fast Fourier Transform routine so that a more quantitative analysis could be performed for these structures. By comparing the frequency-domain data for pulses at two different propagation distances for the two transmission lines, the propagation constants were determined for each. In Fig. 3, the attenuation and phase velocity are plotted over a wide range of frequency, extending to 1 THz for the CPS on the membrane. The data for the CPS on the GaAs substrate are limited because of the high loss and poor signal-to-noise ratio above 600 GHz.

Compared to the greatly increasing attenuation (Fig. 3(a)) and large phase velocity dispersion (Fig. 3(b)) for the CPS on the GaAs, the loss and phase velocity for the membrane CPS are virtually flat with frequency. There is effectively none of the radiation loss, dielectric loss, or modal dispersion which would be characteristic of a typical open-boundary transmission line of such dimensions at very high frequency. Furthermore, the propagation velocity is very close to 90% of the speed of light over the entire band, although it would be still higher if the substrate was totally absent, or if the skin-effect loss did not affect the phase factor. On the GaAs CPS, for a broadband signal, the dielectric mismatch leads to devastating radiation loss, the propagation of non-quasi-TEM hybrid modes (leading to the dispersion behavior predicted in [11] and observed in Fig. 3(b) and [12]), and consequently very poor signal transmission in the submillimeter-wave regime.

It should also be noted that uncertainties in the measured amplitudes of the time-domain signals on the membrane CPS lead to a significant error in the attenuation extracted in Fig. 3(a). While the $\sqrt{f}$ -dependence of the resistive loss can thus not be well-resolved here, the trend indicating only a small variation of attenuation with frequency is unmistakable, and the time-domain data verify that nearly undistorted waveform propagation is taking place over a substantial distance.

IV. CONCLUSION

A novel coplanar strip transmission line to be used for the propagation of ultrashort-duration pulses with very low distortion, perhaps over a distance of centimeters, has been fabricated and tested. The superior properties of a CPS fabricated on a thin membrane have been demonstrated in the time and frequency domains, with a markedly escalated loss and dispersion found for a CPS on a higher permittivity substrate.

ACKNOWLEDGMENT

The authors wish to thank Frank Smith, Kirby Nichols, and Mike Manfra of MIT Lincoln Laboratory for supplying the LT-GaAs photoconductors used in the generation of test signals.

REFERENCES

[1] Y. Chen, S. Williamson, T. Brock, F. W. Smith, and A. R. Calawa, "375-GHz-bandwidth photoconductive detector," *Appl. Phys. Lett.* vol. 59, pp. 1984–1986, Oct. 1991.

[2] D. Grischkowsky, I. N. Duling, III, J. C. Chen, and C.-C. Chi. "Electromagnetic shock waves from transmission lines," *Phys. Rev. Lett.*, vol. 59, pp. 1663–1666, Oct. 1987.

[3] J. Nees, S. Williamson, and G. Mourou, "100 GHz travelling-wave electro-optic phase modulator," *Appl. Phys. Lett.*, vol. 54, pp. 1962-1964, May 1989.

[4] U. D. Keil, D. R. Dykaar, A. F. J. Levi, R. F. Kopf, L. N. Pfeiffer, S. B. Darack, and K. W. West, "High-speed coplanar transmission lines," *IEEE J. Quantum Electron.*, vol. 28, pp. 2333–2342, Oct. 1992.

[5] N. I. Dib, W. P. Harokopus, L. P. B. Katehi, C. C. Ling, and G. M. Rebeiz, "Study of a novel planar transmission line," presented in the 1991 IEEE MTT-S Int. Microwave Symp., Boston, MA, June 1991.

[6] S. Gupta, M. Y. Frankel, J. A. Valdmanis, J. F. Whitaker, G. A. Mourou, F. W. Smith, and A. R. Calawa, "Subpicosecond carrier lifetime in GaAs grown by molecular beam epitaxy at very low temperatures," *Appl. Phys. Lett.*, vol. 59, pp. 3276–3278, Dec. 1991.

[7] E. Yablonovitch, D. D. Hwang, T. J. Gmitter, L. T. Flores, and J. Harbison, "Van der Waals bonding of GaAs epitaxial liftoff films onto arbitrary substrates," *Appl. Phys. Lett.*, vol. 56, pp. 2419–2421, June 1990.

[8] S. Gupta, J. F. Whitaker, and G. Mourou, "Ultrafast carrier dynamics in III-V semiconductors grown by molecular-beam-epitaxy at very low substrate temperatures," *IEEE J. Quantum Electron.*, vol. 28, pp. 2464–2472, Oct. 1992.

[9] M. Y. Frankel, J. F. Whitaker, G. A. Mourou, and J. A. Valdmanis, "Experimental characterization of external electrooptic probes," *IEEE Microwave and Guided Wave Lett.*, vol. 1, pp. 60–62, Mar. 1991.

[10] S. Gupta, J. F. Whitaker, and G. A. Mourou, "Subpicosecond pulse propagation on coplanar waveguides: experiment and simulation," *IEEE Microwave and Guided Wave Lett.*, vol. 1, pp. 161–163, July 1991.

[11] G. Hasnain, A. Dienes, and J. R. Whinnery, "Dispersion of picosecond pulses in coplanar transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-34, pp. 738–741, June 1986.

[12] M. Y. Frankel, S. Gupta, J. A. Valdmanis, and G. A. Mourou, "Terahertz attenuation and dispersion characteristics of coplanar transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. 39, pp. 910–916, June 1991.