500-GHz Characterization of an Optoelectronic S-parameter Test Structure

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Abstract— **We propose a compact, high-bandwidth optoelectronic S-parameter test structure and characterize its performance via electrooptic sampling over a 500-GHz frequency range. The test structure is shown to be well-behaved over a 300-GHz bandwidth, with further improvement potential. Active devices can be wirebonded into the structure for characterization, or they can be integrated on-wafer for improved performance.**

I. Introduction

HIGH-SPEED active device characterization is placing increasing bandwidth demands on the test instrumentation. All-electronic methods are able to satisfy the lower-speed device test requirements and have recently been extended to over-100-GHz range [1], [2]. However, as device operating frequencies begin to exceed 300 GHz [3], alternative characterization techniques need to be considered. Optoelectronic methods provide an attractive alternative and have demonstrated ~100-GHz bandwidths [4]–[7]. Yet, a bandwidth of 100 GHz is insufficient to make optoelectronics competitive with all-electronic methods: 300-GHz bandwidth is required to justify the increased complexity. The primary bandwidth limitation of optoelectronic methods is the attenuation and dispersion of the transmission lines used for transmitting the signals between critical plane, i.e., the generation plane, the device under test (DUT) plane, and the measurement plane. The discontinuities due to the embedded photoconductor switch (PCS) and test structure terminations need to be spatially separated to permit time-windowing [6]. There are two approaches to overcome this constraint: reduce the attenuation and dispersion and/or reduce the separation distances between the critical planes. Recently, the first approach has been demonstrated on a passive structure [8]. This approach relied on fabricating the transmission lines on a low-permittivity substrate incompatible with semiconductor devices. Although this improves the test structure characteristics, it necessitates wirebonds to the DUT, inherently limiting the true available bandwidth.

A high-bandwidth, compact optoelectronic test structure is needed that would have the potential to be integrated with active devices on wafer eliminating DUT coupling parasitics. In this work, we propose and characterize over a 500-GHz bandwidth a novel optoelectronic test structure that maximizes the bandwidth, can be integrated directly with coplanar devices, and minimizes the wafer real-estate requirements. This is achieved by using high-bandwidth coplanar strip (CPS) transmission lines and by minimizing the PCS discontinuity so that it may be located within the measurement time-window close to the DUT.

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II. Experimental Arrangement

The proposed test structure is shown in Fig. 1. A high-bandwidth CPS line with a quasi-static characteristic impedance Z_0 of ~50Ω was used for signal transmission between the critical planes. A PCS element was embedded into the CPS to decouple the PCS dc bias from the DUT dc bias supplied via the CPS. The PCS element used a side-injection geometry with a coplanar waveguide (CPW) transmission line for biasing. The use of a guiding bias structure insures the generation of clean high-bandwidth pulses. The CPS and the PCS bias lines were sufficiently long to time-window any reflections from their terminations. Furthermore, the CPS was fabricated on a relatively thick (430 μm) Si-on-sapphire substrate without backside metalization to prevent any possible parasitic microstrip modes from being excited.

The PCS was 400 μm away from the ground pad on which the DUT could be mounted and wirebonded to the CPS. In on-wafer implementations, the CPS would be directly matched to the DUT contacts, eliminating parasitics. The PCS was used to generate identical pulses propagating on the CPS in both directions. One of the pulses was directly measured by an electrooptic transducer [9], [10] and was taken as an incident signal. The other pulse reflected off the DUT and propagated through the PCS before being measured; it constitutes a reflected signal. The electrooptic transducer can be also moved to the DUT output to measure the transmitted signal. The 400-μm separation between the PCS and the DUT results in a compact structure and maximizes the bandwidth, yet the generated single-picosecond pulse recovered completely to zero within the DUT reflection round-trip time.

To minimize the degradation of the DUT reflected signal as it propagates through the PCS, the ground conductors were bridged with a short (~100-μm) Au wirebond. Ideally, the wirebond would be replaced with a 30-μm-long airbridge, but this requires additional processing steps that may be detrimental to active devices. We investigate the wirebonded structure, which represents the worst-case scenario.

The 200/2500-Å Ti/Au electrodes were photolithographically defined on an ion-damaged silicon-on-sapphire substrate with a carrier lifetime ≤ 1 ps.

The laser used in these experiments was a balanced colliding-pulse mode-locked dye laser producing ~150 fs full-width at half-maximum (FWHM) pulses at 620 nm with

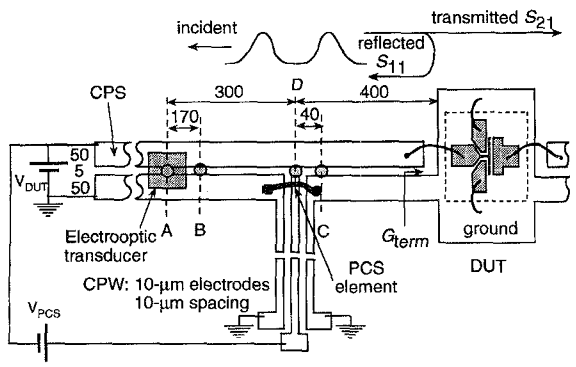

Fig. 1. S-parameter test structure geometry with all marked dimensions in microns. A representative DUT coupling is illustrated, but no DUT was used in these experiments.

a 100-MHz repetition rate. The average optical power in the pump beam was 2.6 mW.

III. Results and Discussion

The PCS characteristics play a central role in the test structure performance. There are three essential requirements on the PCS: minimum reflection and maximum transmission at the PCS element for the pulse propagating along the CPS and ability to generate high-bandwidth pulses with no persistent artifacts.

We investigated the mismatch presented by the PCS structure inside the CPS assuming that the PCS transmission and reflection coefficients are independent of the direction of incidence. The electrooptic transducer was positioned at plane A (see Fig. 1). A sliding-contact photoconductor switch was formed by focusing the pump beam between the dc-biased CPS electrodes at plane B. This switch generated identical pulses propagating in both directions. A single measured waveform contained the incident pulse arriving directly from the sliding-contact switch, a time-delayed reflection from the PCS, and reflections from CPS terminations at much longer delays. Fig. 2 shows the reflection S_{11} parameter of the PCS as computed from the Fourier transforms of the measured reflected and incident signals with additional CPS loss and dispersion contributions removed via known formulas [11]. The PCS return loss is greater than 16 dB over the whole range of 500 GHz, indicating a small impedance discontinuity presented by the PCS.

To measure the transmission parameter S_{21} of the PCS, the transducer was kept at the same position, but the pump was focused between CPS electrodes at plane C (see Fig. 1). The measured pulse was taken as transmitted signal, and the incident pulse was assumed to be identical to one measured previously. The ratio of the Fourier transforms of the transmitted and incident signals, with additional removal of the CPS contributions, gives the PCS structure S_{21} parameter shown in Fig. 2. The structure becomes increasingly lossy with frequency, with a maximum loss of 6 dB at 500 GHz. We attribute this loss to the radiation from the discontinuities in the PCS, and we expect it to be substantially reduced with an improved airbridge design.

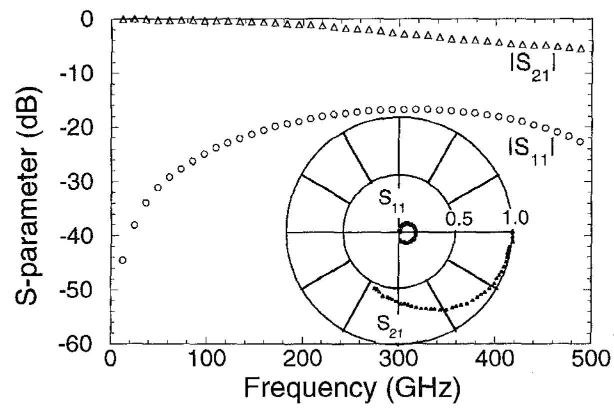

Fig. 2. PCS structure transmission and reflection S-parameters (inset shows the same S-parameters in polar format).

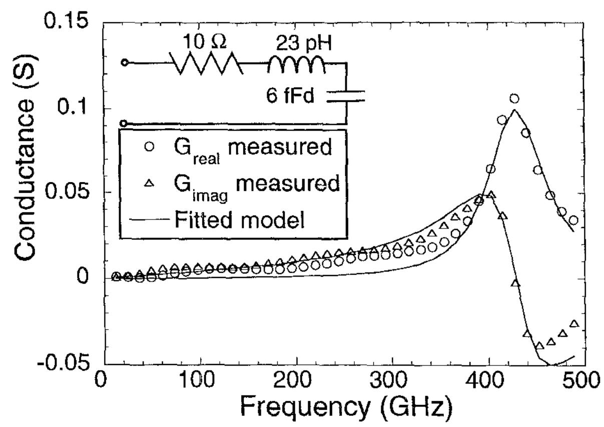

Fig. 3. S-parameter test structure termination admittance (inset shows the termination model with fitted values).

The main function of the PCS is to generate high-bandwidth, time-limited electrical pulses. To verify this function, the center conductor of the CPW forming the PCS was dc-biased and the pump beam was focused onto the gap at plane D (see Fig. 1). The generated pulse had the desired ~1-ps FWHM duration and recovered to zero completely before arrival of the DUT reflection. It is the reflected signal that contains the information about the DUT reflection coefficient.

We verify the performance of the test structure by extracting its termination complex admittance G_{term} without the DUT from the above measurements and by comparing the measurements to a simple model. The parasitics associated with coupling the signal into the DUT may be partially removed by subtracting this admittance from one measured with the DUT. Furthermore, inherent test structure bandwidth limitations may be revealed more clearly since they are not being obscured by the DUT response. Fig. 3 shows that the imaginary component of the conductance increases linearly with frequency and the real component is relatively small up to 300 GHz. The strong resonance observed near 420 GHz is due to the increasing inductive contribution. The termination characteristics have a transmission-line-like behavior and can be well modeled by a series combination of an inductance and capacitance.

An additional series resistive element is added to model the loss associated with the termination. The agreement between the measured and modeled results is good over the whole frequency range of 500 GHz, and the fitted element values are shown in Fig. 3. The inductance and capacitance values correspond to an equivalent length of $\sim$47-μm of a 62-Ω coplanar line, which may be a reasonable approximation to the open-circuited termination with a nearby ground pad. These results indicate that the optoelectronic test structure has a potential characterization bandwidth of at least 300 GHz.

IV. Summary

We have developed and experimentally characterized over a 500-GHz range a compact, ultrahigh-bandwidth optoelectronic S-parameter test structure. The structure compactness is based on a design that allows the PCS to be located as close to the DUT as permitted by the generated pulse width ($\sim$400 μm). The designed PCS has return loss greater than 16 dB and well-behaved low-loss transmission characteristics for pulses propagating on the CPS. The structure usable bandwidth is at least 300 GHz, limited by the discontinuity at the DUT. Further improvements are possible with improved PCS airbridge designs, and the structure compactness may be enhanced by using lossy transmission lines for selected CPS and CPW segments.

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References

[1] S. M. J. Liu and G. G. Ball, "A new probe for W-band on-wafer measurements,"*1993 IEEE Microwave Theory Tech. Symp. Dig.* , pp. 1335–1338, 1993.

[2] R. Y. Yu, J. Pusl, Y. Konishi, M. Case, M. Kamegawa, and M. Rodwell, "A time-domain millimeter-wave vector network analyzer," *IEEE Microwave and Guided Wave Lett.*, vol. 2, no. 8, pp. 319–321, Aug. 1992.

[3] P. Ho, M. Y. Kao, P. C. Chao, K. H. G. Duh, J. M. Ballingall, S. T. Allen, A. J. Tessmer, and P. M. Smith, "Extremely high gain 0.15-μm gate-length InAlAs/InGaAs/InP HEMTs," *Electron. Lett.*, vol. 27, no. 4, pp. 325–326, Feb. 1991.

[4] C. Rauscher, "Optoelectronic approach to on-chip device and circuit characterization and microwave and millimeter-wave frequencies," *IEEE Trans. Micorwave Theory Tech.*, vol. 39, no. 7, pp. 1179–1193, July 1991.

[5] M. Matloubian, S. E. Rosenbaum, H. R. Fetterman, and P. T. Greiling, "Wide-band millimeter wave characterization of sub-0.2 micrometer gate-length AlInAs/GaInAs HEMT's," *IEEE Microwave and Guided Wave Lett.*, vol. 1, no. 2, pp. 32–34, Feb. 1991.

[6] M. Y. Frankel, J. F. Whitaker, and G. A. Mourou, "Optoelectronic transient characterization of ultrafast devices," *IEEE J. Quantum Electron.*, vol. 28, no. 10, pp. 2313–2324, Oct. 1992.

[7] M. D. Feuer, S. C. Shunk, M. C. Nuss, P. R. Smith, H. H. Law, and C. A. Burrus, "Highly reproducible optoelectronic wafer probes with fiber input," *Proc. on Ultrafast Electronics and Optoelectronics*, 1993, vol. 14, pp. 216–219.

[8] H. Cheng and J. F. Whitaker, "300-GHz-bandwidth network analysis using time-domain electrooptic sampling," *1993 IEEE Microwave Theory Tech. Symp. Dig.*, pp. 1355–1358, 1993.

[9] M. Y. Frankel, J. F. Whitaker, G. A. Mourou, and J. A. Valdmanis, "Experimental characterization of external electro-optic probes," *IEEE Microwave and Guided Wave Lett.*, vol. 1, pp. 60–62, Mar. 1992.

[10] X. Wu, D. Conn, J. Song, and K. Nickerson, "Invasiveness of LiTaO3 and GaAs probes in external e-o sampling," *J. Lightwave Technol.*, vol. 11, no. 3, pp. 448–454, Mar. 1993.

[11] 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, no. 6, pp. 910–916, June 1991.