PHOTOCONDUCTOR-BASED 10-110-GHZ ON-CHIP DEVICE CHARACTERIZATION TECHNIQUE

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Abstract - Integration of reflectometer circuitry and device under test on the same semiconductor chip provides an attractive means for measuring scattering parameters at very high frequencies and over wide, uninterrupted frequency ranges. The investigated approach utilizes high-speed photoconductive circuit elements to perform sampling and incident pulse generation functions, assisted by special pulse shaping and compensation networks. Five test structures, implemented in monolithic format on a GaAs chip, experimentally demonstrate the practicability of the approach for frequencies up through W-band.

INTRODUCTION

The difficulties associated with the acquisition of accurate device scattering parameters at very high frequencies constitute a serious impediment in the development of solid-state circuits for millimeter-wave operation. The issue is of particular concern when frequencies and bandwidths are involved that exceed the limits of available automated vector measurement equipment. Even in situations that fall within those limits, discontinuities at the interfaces between the measurement system and the device under test often introduce troublesome parasitic effects which can be very hard to correct for and can lead to unacceptably poor measurement accuracy. The monolithic integration of the device under test with the high-frequency portion of the measurement system presents itself as a logical solution to the discontinuity problem. And, with the help of optical means, this can be quite readily achieved, permitting compact on-chip realization of critical signal generation and signal detection functions. Emphasis in the following is on demonstrating the practicability of a photoconductor-based concept proposed earlier [1], employing experimental GaAs monolithic circuitry that covers a full 100-GHz frequency interval.

CONCEPT AND IMPLEMENTATION

The approach pursued here is to equip each port of a device under test with its own self-contained miniature reflectometer circuit. Of special interest is the accommodation of wide, simultaneous bandwidths that encompass several octaves, while duly observing the need to conserve semiconductor wafer area. Both optoelectronic and electro-optic techniques are, in principle, well suited for this purpose. This stems from the fact that the high-frequency test signals required to perform the scattering parameter measurements actually originate off-chip from a pulsed or CW-modulated laser system. The on-chip circuitry merely serves as transducer for the optically transmitted high-frequency signals, allowing simple and space-conserving implementations. As illustrated schematically in Fig. 1 for the two-port case, each individual reflectometer circuit comprises an incident signal generator G, a partitioned uniform transmission line connecting the generator to the device under test D, and an array of discrete sensors S strategically placed along the line. What mainly distinguishes the present approach from other recent techniques [2], is the use of multiple sensors and the use of special compensation networks. These networks, which are incorporated into the signal generator and sensor subcircuits, serve to counteract parasitic circuit effects that otherwise would restrict measurement accuracy at the high end of the frequency range. The use of multiple sensors is instrumental in permitting discrimination between signals traveling in opposite directions on the transmission line. In many a practical situation, two sensors, spaced a quarter of a wavelength or so apart at midband, will suffice.

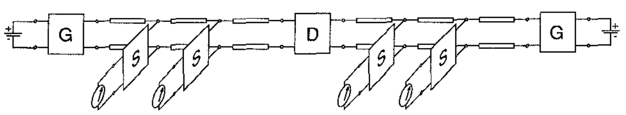

Fig. 1. Schematic block diagram of an on-chip reflectometer system, with signal generators G, signal sensors S, and device under test D.

The applicability of the concept is not restricted to a specific optical technique. But, physical realizations based on the use of photoconductive circuit elements (PCEs) are particularly attractive due to their high-frequency capabilities and their well-defined characteristics. The present example employs PCEs as fast switches to perform both on-chip signal generation as well as on-chip sensing. The generated incident signals encompass trains of pulses with subpicosecond leading edges and more gradual decays. The fast rise times are made possible by the intrinsic speed with which carrier pairs can be produced in semiconductor materials and through the use of a femtosecond CPM laser system to induce the pairs. Photoconductive decay time constants, on the other hand, are governed by the relatively slow process of carrier recombination. Pulse widths can be significantly reduced through radiation damage appropriately applied to the semiconductor material [3]. When represented in the frequency domain, the PCE-generated incident signals comprise dense populations of spectral components at harmonics of the laser pulse repetition frequency. For a typical uncompensated

PCE with a quasi-exponential pulse decay response, the envelopes of the component amplitudes tend to roll off at approximately 6 dB per octave above a critical frequency determined by the decay parameters. In order to improve high-frequency coverage beyond what is currently feasible through radiation damage alone, the present approach employs special pulse shaping networks in conjunction with the pulse generator PCEs. The pulse shaping networks represent a simple and effective circuit means to significantly extend incident signal bandwidth by mimicking much faster, but unrealizable PCEs. The networks also serve to match the high-impedance PCEs to the main reflectometer transmission lines, thereby helping to absorb signals reflected back toward the pulse generators from the devices under test. This, in turn, minimizes the time interval over which signals on the lines need to be accounted for to sustain reliable measurement results.

The sensing of signals traveling up and down the reflectometer transmission lines is accomplished with PCEs that operate as high-speed samplers and are otherwise identical to the ones used for incident signal generation. They are excited by femtosecond laser pulses that originate from the common laser source and are subjected to variable time delay with the help of an optical translation stage. The sampler PCEs are embedded in matching and compensation circuitry to insure resonance-free operation throughout the measurement bandwidth and to minimize loading of the transmission line. Each of the reflectometers employed in the present example utilizes three unequally spaced sampler circuits, rather than the minimal number of two required, thereby permitting three different two-sampler combinations that assume optimum quarter-wavelength separations at 25, 50, and 75 GHz, respectively.

The experimental chip used to verify the technique is depicted in Fig. 2. It was fabricated by a commercial foundry (Adams Russell) and contains five monolithic circuits implemented in microstrip format on a 100-μm-thick GaAs substrate. Each individual circuit comprises a one-port load to be characterized and a reflectometer structure complete with incident signal generator and three sampler circuits. One of the loads is a microstrip RF short circuit, encompassing a small segment of 50-ohm transmission line, a 6-pF blocking capacitor, and two parallel-connected via holes to ground. In three of the loads, the segment of 50-ohm transmission line is replaced by a resistor with a nominal value of 25, 50, or 100 ohms, respectively. The fifth case involves a simple microstrip open circuit. As for the reflectometer circuits, they constitute monolithic-circuit interpretations of the arrangement described in detail earlier [1]. The PCEs consist of 10-μm-by-10-μm gaps in the metallic circuit patterns and are equipped with ohmic contacts. The picosecond speed of the photoconductors has been achieved through bombardment of the GaAs substrate with 200-keV protons. This procedure, which comprised the final step in the circuit fabrication process, was performed at the Los Alamos National Laboratory in accordance with their proven recipe [3].

EXPERIMENTAL RESULTS

After dc-probing a number of structures to confirm adequate uniformity of circuit element values across the wafer, two chips were selected to be characterized with the help of the automated high-speed CPM laser set-up at the Los Alamos National Laboratory [4]. Sampler-derived time-domain responses for a complete set of five monolithic test structures are reproduced in Fig. 3. They were all recorded sequentially, due to availability of only one laser beam for sampling purposes. To establish the correct timing among responses derived from the same reflectometer, the well-defined initial positive-going peaks were used as references and staggered in accordance with pertinent propagation delays along the reflectometer transmission line. The delays were calculated with the help of a model based on independent pulse delay and network analyzer measurements. The calibration of signal strengths was accomplished in a similar manner, namely by measuring the attenuation properties of the main transmission line, describing these properties with an empirical model, and then adjusting the incident pulse correlation peaks accordingly. The traces depicted in Fig. 3 were all calibrated in this fashion, with the positive-going correlation peak of each number-one sampler normalized to unity.

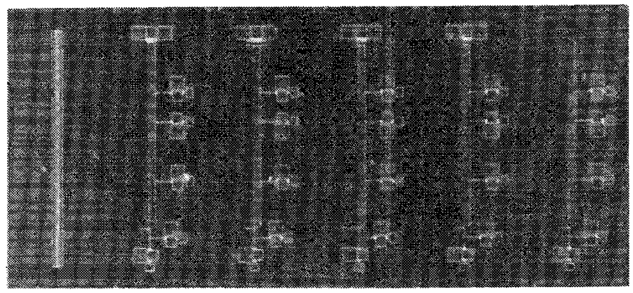

Fig. 2. Experimental GaAs chip containing five one-port test circuits with associated reflectometer structures.

To characterize a given device under test with full measurement accuracy, the time-domain traces need to be accounted for over the entire pulse repetition interval. This interval spans 8 ns in the present situation, corresponding to a laser-determined pulse repetition frequency of 125 MHz. The traces in Fig. 3, however, only contain relevant information over an interval of 200 ps or so, permitting measurements to be conveniently confined to time spans considerably smaller than the pulse repetition interval. The feature that makes this possible is a return loss of around 10 dB designed into the pulse shaping network of each incident signal generator. With the help of these networks, for most practical purposes, signals traveling back and forth between generator and device under test subside after three pulse round trips or less. This holds true also in the case of a totally reactive device, as confirmed by the measurements on the microstrip open and short circuits.

Following the procedure outlined earlier [1], the measured time-domain data was converted into impedance information in the form of reflection coefficients as functions of frequency. The information thus acquired for each of the five test cases is contained in Fig. 4, with all reflection coefficients referenced to a common plane. As the leading portions of the number-one sampler responses inadvertently got cropped too generously during data acquisition, only the two most closely spaced samplers were subsequently considered when calculating reflection coefficients. The open-circuit case, which exhibited an obviously defective number-two sampler, represents the only exception. Here, the two farthest-apart samplers were employed, confining the upper frequency limit to 50 GHz. In all other cases, an uninterrupted 10-to-110-GHz measurement interval was maintained.

The five measurement-derived responses are compared in Fig. 4 with model-predicted curves. The predictions were based on independent assessments of parasitic circuit elements associ-

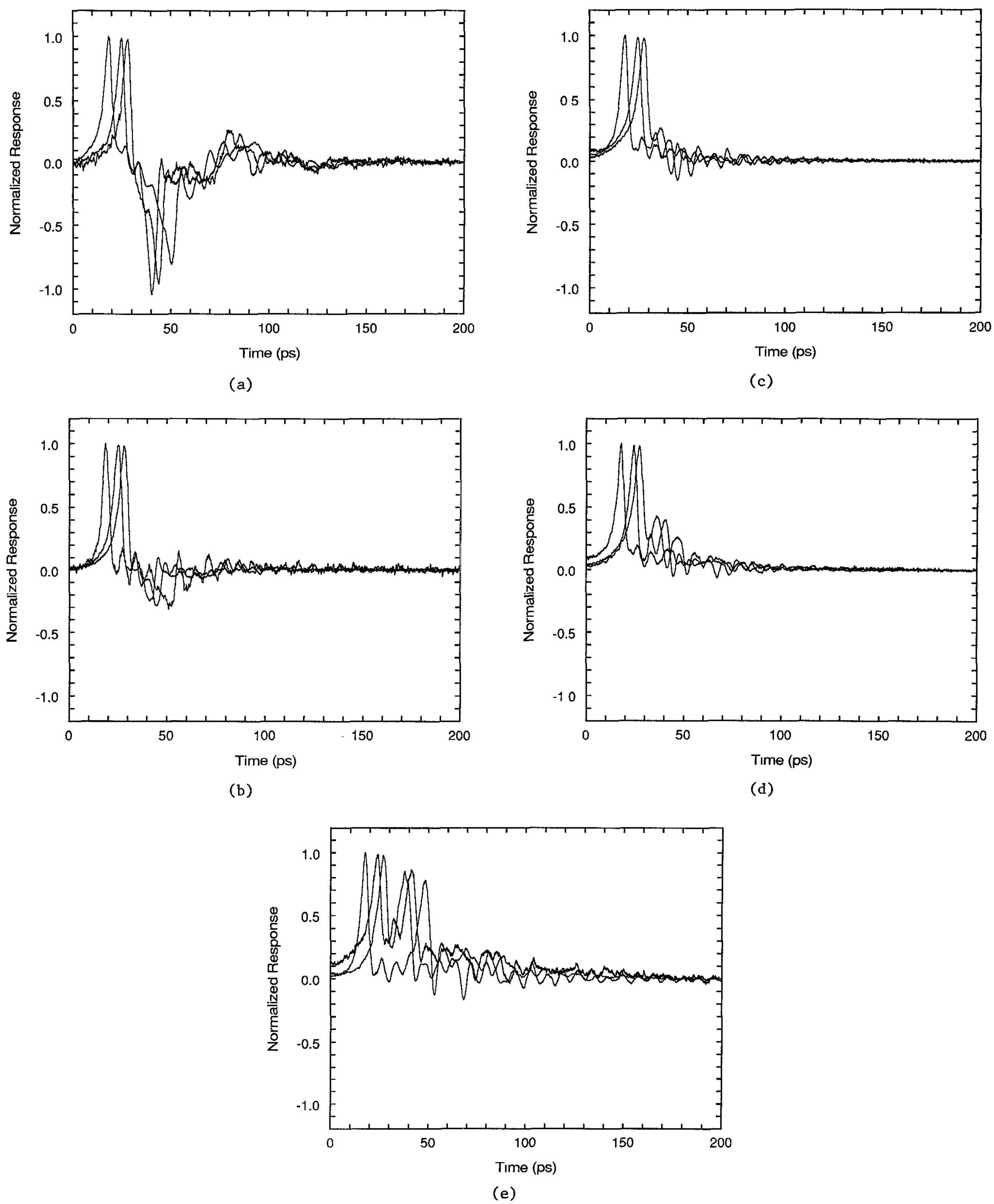

Fig. 3. Measured sampler correlation responses for (a) the short-circuit, (b) the 25-ohm-load, (c) the 50-ohm-load, (d) the 100-ohm-load, and (e) the open-circuit cases, each comprising three traces corresponding to the three sampler outputs of the respective reflectometer.

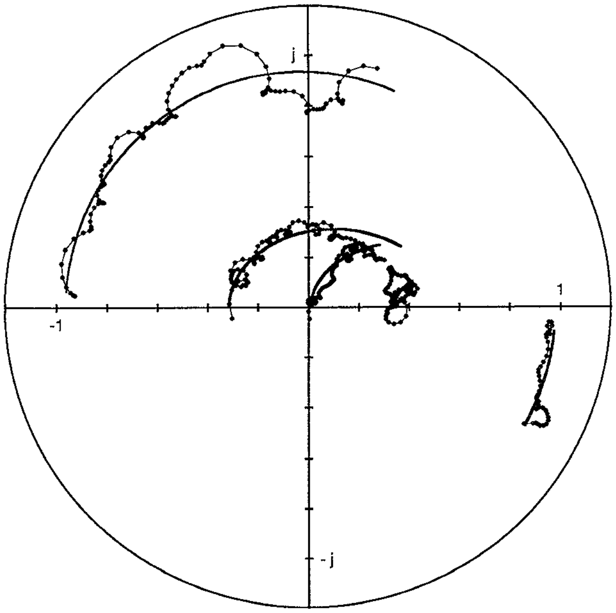

Fig. 4. Measurement-derived reflection coefficient responses (lines with marker dots spaced 1 GHz apart), and model-predicted counterparts (solid lines), covering the frequency span from 10 to 110 GHz, for the short circuit, the 25-ohm-load, the 50-ohm-load, the 100-ohm-load, and the open-circuit cases, respectively.

ated with each load. Care was taken to assure that element values common to individual cases, such as via hole parameters and the like, remained invariant. The achieved measurement accuracy is judged to be very good. Occasional and well-contained discrepancies at frequencies above 70 GHz are attributed to noisy data and variance in sampler characteristics. The noise is due to laser instabilities. The degree of noise contamination, as apparent in Fig. 3, differs from trace to trace, determined by the particular state of the laser when the sequentially acquired sampler responses were recorded. As for the sampler characteristics, they proved to be highly reproducible, with exception of the open-circuit case already mentioned. Good reproducibility is important in the current context, as the approach is most easily implemented when identical sampler characteristics may be assumed. Close comparisons among individual correlation responses in Fig. 3 do reveal minor differences in sampler performance, though, judging by the initial ascending portions of the respective correlation curves. Some of these differences appear random in nature and show up in the measurement-derived impedance results. But, to a large extent, the apparent differences among sampler time responses are due to effects of signal dispersion on the line which are fully accounted for in the calculation of equivalent frequency-domain information.

CONCLUSIONS

The motivation to originate a new technique for acquiring device scattering parameters stems from the practical need to improve measurement accuracy at very high frequencies. The particular approach pursued here of employing on-chip photoconductor-based reflectometers is aimed at the critical concern of accuracy degradation due to imperfect interfaces between device under test and measurement system. Among the features distinguishing this approach from others is the introduction of pulse conditioning networks utilized in the on-chip generation of incident signals, and the use of multiple sampling units to fully separate reflected signals from heavily overlapping incident counterparts, as required for reliable scattering parameter measurements. These features permit exceptionally compact physical realizations, as is illustrated by the fact that a GaAs monolithic reflectometer, like the ones implemented, would readily fit in a 0.65-by-0.80-mm area, after allowing for deletion of the redundant extra sampler. A further attractive aspect of the approach, besides the avoidance of all high-frequency waveguide connections to the chip, is its ability to accommodate very broad instantaneous bandwidths. This ability, which applies to one-port and multi-port devices alike, has been demonstrated with the uninterrupted 10- to-110-GHz frequency span covered by the experimental circuitry.

ACKNOWLEDGEMENTS

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