FULL TWO-PORT ON-WAFER VECTOR NETWORK ANALYSIS TO 120 GHZ USING ACTIVE PROBES

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ABSTRACT

A millimeter-wave full two-port on-wafer vector network analyzer (VNA) is implemented with monolithic GaAs directional time-domain reflectometer integrated circuits mounted directly on low-loss microwave wafer probes. The VNA performs S-parameter measurements to 120 GHz with ± 0.2 dB repeatability using a Line-Reflect-Match calibration method.

INTRODUCTION

Inadequate instrumentation to characterize and measure high f_{max} transistors [1] and 100 GHz MMIC's [2] has impaired the understanding and application of these devices and circuits. Recent reports of high f_{max} (300-450 GHz) transistors are based on 5:1 extrapolations from measurements in the DC-60 GHz range. Such large extrapolations could yield erroneous estimates about device performance at high frequencies. Nonlinear transmission lines (NLTLs) [3] and NLTL-gated sampling circuits [4],[5],[6] allow generation and detection of transient signals with 300 GHz bandwidth. A 1-port vector network analyzer (VNA) incorporating the high speed NLTL-gated directional time-domain reflectometer (TDR) IC [6] was reported earlier [7] as capable of measuring 1-port S-parameters up to 96 GHz. Since then, active probes with improved bandwidth have been fabricated with higher bandwidth directional TDR IC's and lower loss quartz probe tips. Here, we report a 2-port VNA capable of full 2-port measurements to 120 GHz with ± 0.2 dB repeatability using a Line-Reflect-Match (LRM) calibration technique.

METHOD OF OPERATION

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A schematic of the measurement setup and the hybrid assembly of the active probes is shown in Fig. 1. A synthesizer provides the drive signal for the NLTL to generate the stimulus signal on the active probe. The drive signal is switched between the two active probes through a microwave switch to provide the stimulus signal either to port 1 or to port 2. A second synthesizer with the same phase reference provides the drive signals for the sampler strobe NLTLs on the active probes. To eliminate the use of bandwidth limiting cables and connectors, the TDR IC is mounted adjacent to the probe tip and bonded with gold ribbon to provide millimeter-wave frequency paths. Fig. 2 shows a block diagram of the directional TDR IC. The NLTL, a high impedance transmission line periodically loaded with varactor diodes, compresses the falling edge of a sinusoid to picosecond duration. A 25-dB attenuator attenuates the stimulus signal to ≈100 mV for small signal measurements. A 6-dB attenuator is used as a directional device to measure the forward and reverse waves. The directional samplers measure

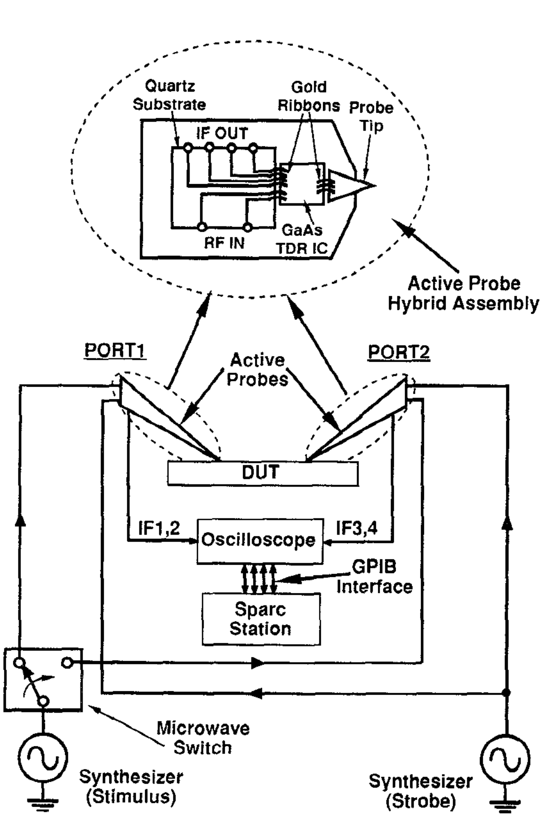

Fig. 1. Schematics of the measurement set-up and the active probe hybrid assembly

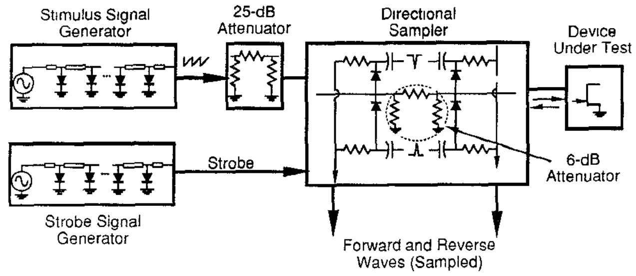

Fig 2 Block diagram of the directional time-domain reflectometer IC.

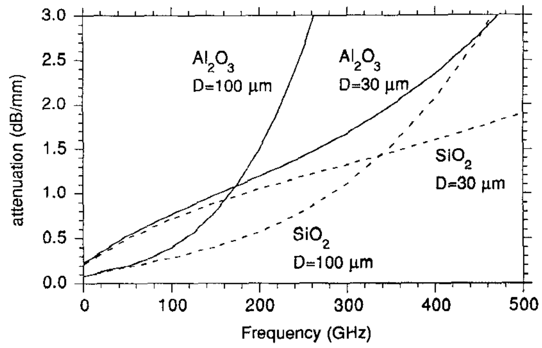

Fig. 3. Computed attenuation-frequency characteristics of different dimentions of CPW on alumina and quartz substrates, where D is the ground-ground spacing of the CPW.

the voltages at the ports of the 6-dB attenuator. These IF signals (IF 1-4 on Fig. 1) of the active probes are digitized with a sampling scope and transferred to a workstation for data processing via a GPIB interface. Raw S-parameters are calculated from these measurements after Fourier transforming the time wave forms to frequency domain. The corrected S-parameters of the device under test (DUT) are obtained from a conventional LRM calibration technique [8] which models everything between the probe tips and the respective 6-dB attenuator ports as 2-ports whose transmission matrices can be determined from measurement of 3 calibration standards.

Earlier we had reported [7] active probes with 50 GHz 3-dB bandwidth (BW) and had also identified ways to improve the active probe BW. One of the BW limitations comes from the probe tip losses. Fig. 3 shows the computed attenuation-frequency characteristics of coplanar wave guides (CPW) with different dimensions on alumina and quartz substrates. For a given line impedance, skin loss (in dB/mm) varies as $\approx \sqrt{\varepsilon_r+1}\sqrt{f}\,/\,D$ while radiation loss varies as $\approx \varepsilon_r^{3/2} f^3 D^2$ [9], where ε_r is the relative dielectric constant of the substrate, f is frequency, and D is the ground-ground spacing of the CPW. As a result, with appropriate scaling of line dimensions, CPW on a quartz substrate (ε_r=3.8) can attain lower attenuation than can be achieved on an alumina substrate (ε_r=9.8). At 200 GHz, D=100 μm results in a minimum attenuation of 0.57 dB/mm on a quartz substrate. Thus, for our 2mm-long quartz probe tips, the calculated round-trip attenuation is 2.3 dB at 200 GHz.

The current active probes use TDR IC's in hybrid assemblies with quartz probe tips. To determine the uncorrected bandwidth of the active probes, we measure the risetime of the reflection from an open circuit load (Fig. 4). The measured 4 ps reflection risetime, corresponding to an active probe 3-dB BW of 90 GHz, includes the convolved contributions of the NLTL pulse generator risetime, the capacitance charging time of the

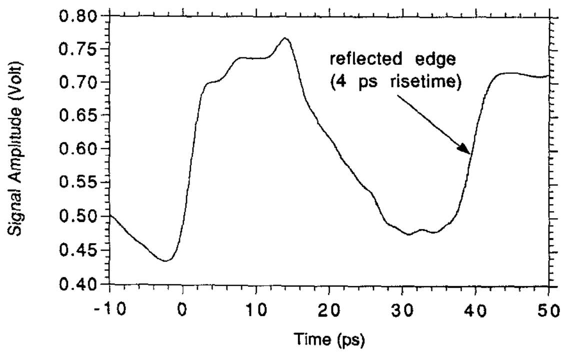

Fig. 4. Step response of the active probe under an open-circuit termination.

two sampling circuits, the probe tip losses, and the inductance of bond wires connecting the probe tip to the TDR IC. As in conventional VNA's, measurements can be obtained significantly beyond the 3-dB BW after calibration.

RESULTS AND DISCUSSION

The measurements presented here were obtained for a convenient 10 GHz fundamental and its harmonics. Since the active probes can perform correctly over a stimulus drive frequency range of 7-14 GHz, a complete octave in frequency, S-parameter measurements are possible over the whole frequency spectrum from 7-120 GHz. The LRM calibration was performed using the Cascade Microtech calibration standards consisting of a 1ps through line, a 50Ω matched load and a short circuit [10]. Full 2-port measurements are shown for two DUT's. The first DUT is a 3200 μm long transmission line which has a predictable response to mm-wave frequencies. The reproducibility of the data was verified by taking 3 different measurements at 30 minute time intervals. Fig. 5 (a) is a plot of the magnitude of S_{21} in dB. The data taken at the 3 different times are all plotted on the same graph to show that the deviation is less than ±0.2 dB. Fig. 5 (b) shows the phase of S_{21} for the 3 measurements and a comparison to the expected phase assuming a relative dielectric constant of 9.8 for the alumina

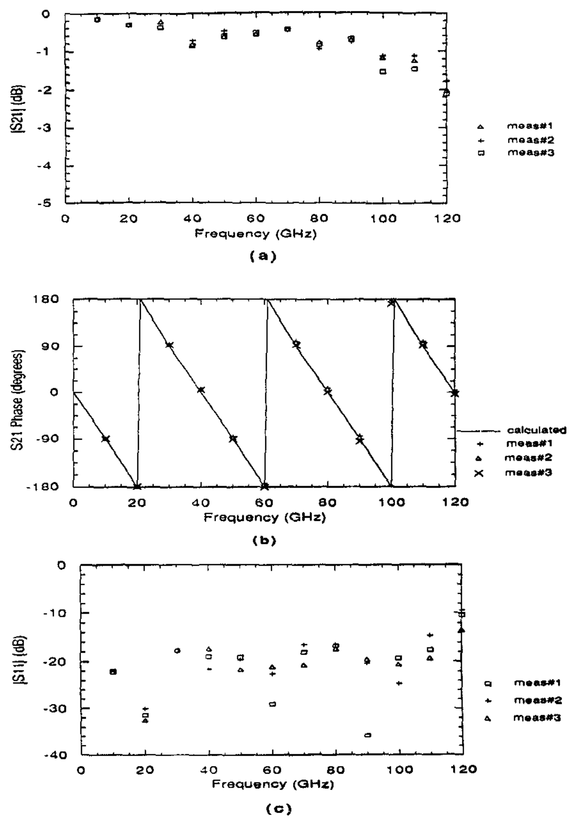

Fig. 5. 2-port S-parameter measurements (taken at three different times with 30 minute time intervals) of a nominal 50 Ω 3200-μm long transmission line : (a) dB plot of the magnitude of S21, (b) calculated and measured phase of S21, and (c) dB plot of the magnitude of S11.

substrate. Fig. 5 (c) shows the magnitude in dB of S_{11}.

For the second DUT, a nominal 6-dB attenuator was measured. Fig. 6 is a plot of the magnitudes of S_{11} and S_{21} of the 6-dB attenuator, which shows good agreement with measurements taken on an HP 8510B VNA to 40 GHz. For these measurements, transmission parameters (S_{21} and S_{12}) of the attenuator agree within ± 0.1 dB and the reflection parameters (S11 and S22) are less than -15 dB to 120 GHz.

The variation in the S-parameters at high frequencies has been attributed to the phase fluctuation between the microwave synthesizers (Fig. 1). In addition, the sampling scope used to measure the IF signals has only 8-bit resolution, putting a severe limit on the dynamic range of the VNA. Improvements to the signal processing and data acquisition electronics are currently

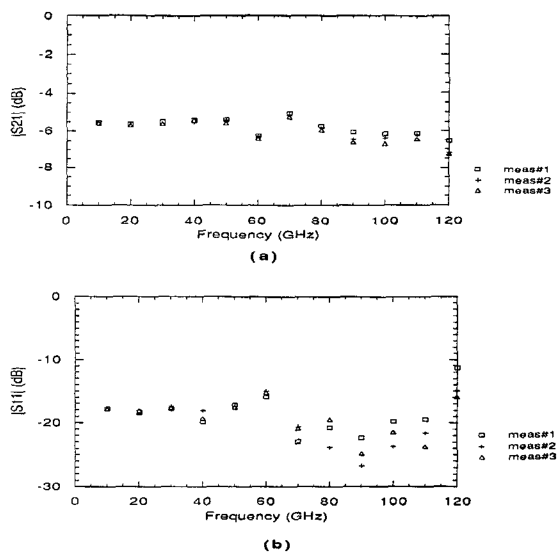

Fig. 6. 2-port S-parameter measurements (taken at three different times with 30 minute time intervals) of a nominal 6-dB attenuator: (a) dB plot of the magnitude of S21, and (b) dB plot of the magnitude of S11.

being pursued to extend the system bandwidth and dynamic range.

SUMMARY

A 2-Port VNA is demonstrated which can measure S-parameters to 120 GHz with ± 0.2 dB repeatability. With an improved data acquisition scheme, 2-port measurements at higher frequencies are expected.

ACKNOWLEDGMENT

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