A Time-Domain Millimeter-Wave Vector Network Analyzer

Ruai Y. Yu, Joe Pusl, Yoshiyuki Konishi, Michael Case, Masayuki Kamegawa, and Mark Rodwell

Abstract—**A millimeter-wave vector network analyzer is implemented with a monolithic GaAs directional time-domain reflectometer integrated circuit mounted directly on a microwave wafer probe. The vector network analyzer performs on-wafer network analysis up to 96 GHz with ±1 dB accuracy.**

As a RESULT of recent advancements in material science and processing technology, 300-GHz transistors [1] and 100-GHz integrated circuits (IC's) [2] have been obtained. On the other hand, the bandwidth of the network analyzers is currently limited to 75 GHz for on-wafer measurements. Recent reports of transistors with $f_{\max}$ in the 300–450-GHz range are generally ≈ 5:1 extrapolations of measurements in the dc-60-GHz range. The limited network analyzer bandwidth is impairing the understanding, characterization, and application of these devices. Nonlinear transmission lines (NLTL's) [3] and NLTL-gated sampling circuits [4]–[6] allow generation and detection of transient signals with ≈ 300-GHz bandwidth. A NLTL-gated directional sampler for network analysis with greater than 10 dB directivity has been demonstrated [5] from 40 to 60 GHz using a microwave frequency sweep source as the stimulus signal. A 2.3-ps time-domain reflectometer (TDR) for millimeter-wave (mm-wave) network analysis has also been fabricated [6]. In this letter, we report fabrication of a time-domain vector network analyzer (VNA) implemented with a monolithic GaAs directional TDR mounted directly on a microwave wafer probe. The resulting VNA is capable of measuring devices up to 96 GHz with ±1-dB accuracy.

A block diagram of the TDR IC used in the VNA is presented in Fig. 1. The VNA differs from the conventional network analyzers in two major aspects. First, instead of using a frequency-swept source as the stimulus signal, it uses a sawtooth time waveform which contains many harmonics. An NLTL generates the stimulus signal, a sawtooth waveform with ≈ 2-ps fall time, corresponding to ≈ 200-GHz bandwidth. A 25-dB attenuator is used to attenuate the stimulus signal to ≈100 mV for small-signal measurements. A second NLTL generates the strobe signal to operate the directional sampler. Secondly, instead of using a directional coupler to independently measure the forward and reverse waves,

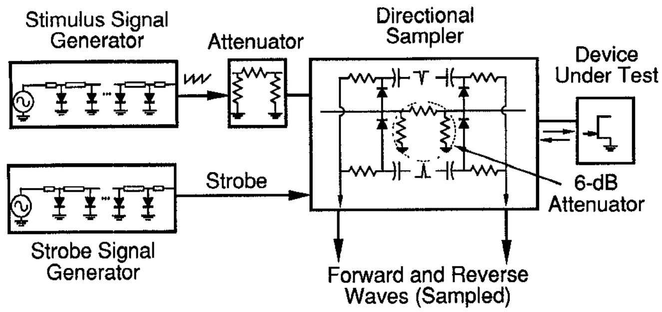

Fig. 1. Directional TDR block diagram.

the VNA uses a 6-dB attenuator as the directional device. A pair of sampling circuits [7] measure the voltage time waveforms at the attenuator ports, and the forward and reverse waveforms are determined by forming linear combinations of these sampling circuit outputs. The amplitudes and phases of the frequency components of the forward and reverse waves are then determined by Fourier transformation, and conventional calibration procedures are performed to obtain the corrected S-parameters of the device under test (DUT).

The details of the operation and fabrication of the directional TDR have been reported earlier [6]. The sawtooth stimulus and strobe signals are generated by NLTL's implemented with coplanar waveguide (CPW) transmission lines periodically loaded with reverse biased diodes. The RF input signal repetition frequency is offset by Δf from the strobe frequency f_0, and the sampled signal (IF) is then mapped out in equivalent time at a repetition frequency of $\Delta f(\approx$ 100 Hz).

One major bandwidth limitation of existing VNA's is that coaxial connectors are currently available only to 65 GHz. To permit > 65-GHz measurements, the directional TDR is mounted directly on a microwave probe (Fig. 2(a)). Ribbon bonds connect the IC to the probe tip. At 100-μm length, the ribbons would have ≈ 60 pH inductance, limiting the connection bandwidth to ≈ 300 GHz. The ≈ 10-GHz NLTL drive signals and ≈ dc-10-kHz IF signals are then routed with patterned gold lines on an alumina substrate to their SMA and SMC connectors, respectively.

The probe tips in conventional microwave probes are implemented with gold plated CPW lines on alumina substrates. Due to the high rigidity of alumina, long probe tips (≈ 1.7 cm) are typically used to provide enough flexibility so that the probe tips do not break when contacting IC's. Long probe tips have high skin and radiation losses, especially at higher frequencies. Instead, we use short (≈ 5 mm) probe tips and mount the probe elastically on the probe arm (Fig. 2(b)).

Manuscript received April 7, 1992. This work was supported by a National Science Foundation PYI award. This work was also supported by Tektronix, Hewlett-Packard Corporation, and Shimadzu Corporation.

R. Y. Yu, J. Pusl, M. Case, and M. Rodwell are with the Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

Y. Konishi and M. Kamegawa are with the Shimadzu Corporation, Kyoto, Japan.

IEEE Log Number 9202007.

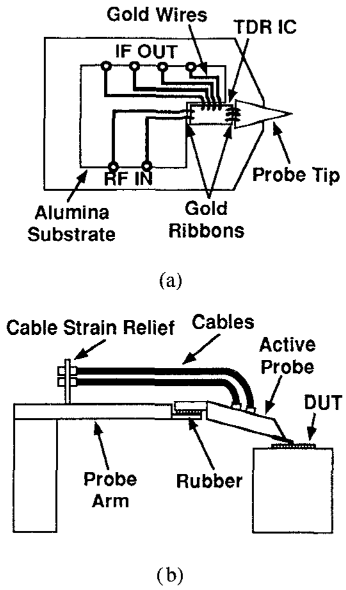

Fig. 2. (a) Hybrid assembly of active probe. (b) Mechanical set-up for network analysis.

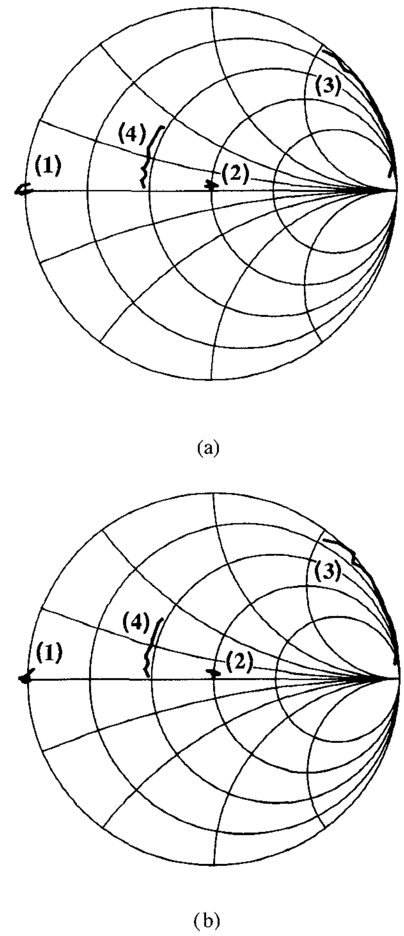

Fig. 3. $S11$ measurements of (1) short, (2) load, (3) open, and (4) 23-Ω resistor from 8–96 GHz. (a) Initial measurements. (b) Measurements performed 30 minutes later.

The necessary mechanical flexure is provided by mounting elastic material (rubber) at the probe/probe arm interface. With elastic mounting, probe planarization is also made less critical. Hundreds of contacts have been made without significant degradation of the probe tips. A strain relief device for the cables is mounted on the probe arm so that accidental pulling of the cables does not displace and break the probe.

The dimensions of the CPW lines on the probe tip are selected so as to minimize the total attenuation. For a given line impedance, skin loss (in dB/mm) varies as $\sqrt{f}/w$ while radiation loss varies as $f^3 \bullet w^2$ [8], where f is frequency and w is the CPW center conductor width. At 150 GHz, $w = 40$-μm results in a minimum loss of 0.5 dB/mm. Thus, for our probe tips, the calculated round-trip attenuation is ≈ 5 dB at 150 GHz. To fabricate the probe tips, CPW lines are patterned with a lift-off of E-beam evaporated 800 Å Ti/800 Å Pt/1.1-μm Au, and 10-μm thick Ni is plated at the contact points.

One-port S-parameter measurements with open-short-load (OSL) calibration procedures were performed from 8 to 96 GHz. The Cascade Microtech 50 Ω, open, and short calibration standards were used, and the open capacitance (Co=-20 fF) and the load inductance (Ll=7.5 pH) suggested by Cascade Microtech [9] were incorporated in the calibration routines. The accuracy of the resulting corrected data depends both upon the probe performance and upon the accuracy of the calibration coefficients over the extended 8–96-GHz frequency range.

Fig. 3(a) shows the initial measurements of the short, open, load, and a 23-Ω resistor that has 30 pH of associated series inductance; Fig. 3(b) shows the measurements of the same impedance standards performed 30 minutes later. The reproducibility in $S11$ is within ±1 dB to 96 GHz.

Several factors limit the bandwidth and accuracy of the VNA. First, the risetime of the reflection from a short circuit is measured to be ≈ 7 ps. Since the falltime of the incident wave is ≈ 3 ps, the deconvolved falltime of the step response of the probe tip and the wire bonds is ≈ 6 ps, corresponding to ≈ 50 GHz -3-dB bandwidth of the probe assembly. As with most commercial network analyzers, calibration permits vector measurements to be made significantly beyond the -3-dB VNA bandwidth. Although the VNA IC and probe tip were designed to connect with $\approx$ 100-μm length ribbon bonds, an error in the VNA IC mask layout forced the use of long 400-μm ribbon bonds from the probe tip to a point 350 μm within the boundary of the VNA IC. The resulting 280 pH bond inductance limits the IC-probe connection to a calculated 55 GHz bandwidth, consistent with our observed 50 GHz. Secondly, the correctness of the calibration standard models are questionable at higher frequencies, which introduces inaccuracy in the corrected $S11$ measurements above 50 GHz. Two-port measurement will give more accurate calibrated measurements because line-reflect-line (LRL) calibration standards can be used in which the exact impedance of the load need not be known [10]. In spite of the 50-GHz -3-dB VNA system bandwidth limitation, measurements were made to 96 GHz, as indicated in Fig. 3.

In conclusion, we have constructed a time-domain VNA capable of performing on-wafer network analysis up to 96 GHz, as limited by probe-IC connection parasitics. With improved bonding and shorter probe tips, and with two-port calibration procedures, much wider bandwidth and higher accuracy can be attained.

ACKNOWLEDGMENT

The authors would like to thank J. Jensen, D. Rensch, and F. Williams of Hughes Aircraft Corporation for their help in probe tip dicing.

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