A Vector Network Analyzer Integrated into Coplanar-Waveguide Probes

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Abstract

A new type of vector network analyzer integrated with two coplanar-waveguide (CPW) probe tips for making on-wafer measurements is presented. The CPW configuration is capable of large bandwidths and allows measurements to be made directly at the device under test. The analyzer consists of detector diodes spaced logarithmically along two CPW probe tips to sample the signal, and uses six-port theory to calculate s-parameters. A 5–10 GHz proof of concept model was built and used to test a MMIC PIN diode switch.

Introduction

The development of compound semiconductor devices with operating frequencies above 60 GHz has stimulated the demand for accurate instruments that measure scattering parameters at these wavelengths. Measurement systems at lower frequencies typically use coax-to-coplanar probe tips situated between the network analyzer and the device under test. As the frequency of operation is increased into the millimeter-wave range however, the lengths of coaxial line and parasitics introduced by the coax-to-coplanar transition increasingly degrade the performance of the measurement system, and waveguide is required above 60 GHz. These waveguide analyzers are expensive and limit the measurement bandwidth obtainable with a single test set.

As an alternative to existing measurement techniques we propose a new integrated coplanar analyzer. A proof of concept model has been developed at microwave frequencies. The analyzer employs Schottky detector diodes logarithmically spaced along coplanar-waveguide to sample the signal on the line (Fig. 1). The coplanar configuration of the analyzer is broadband and can be integrated directly in the coplanar probe tip, as close to the device under test as possible. The detector measurements are processed using six-port theory [1],[2] to calculate complex scattering parameters. Calibration is performed with a set of coplanar-waveguide offset shorts and a matched load.

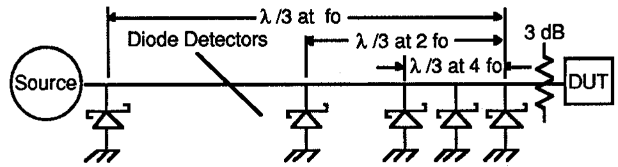

Figure 1. Conceptual diagram of the sampled-line reflectometer used in the coplanar-waveguide analyzer. Readings from the detector triples are used to deterimine the complex reflection coefficient of the DUT over an octave bandwidth. The 3 dB attenuator placed between the sampled-line and the DUT improves numerical stability by preventing deep voltage nulls from occuring on the line when the reflection coefficient of the device under test is near unity.

Principle of Operation

The analyzer is made up of diode detectors placed along a length of 50 Ω coplanar-waveguide in a sampled-line configuration. Based on noise sensitivity analysis and experimentation, it has been shown that octave bandwidth is possible with three diodes spaced $\lambda/6$ apart [1],[3]. To increase the bandwidth of the system, a fourth diode may be placed halfway between a pair of diodes in the original triple (Fig. 1). The second triple has a frequency range that twice the first, and the range of operation can be extended by this method until reaching the maximum frequency range of the detectors. Care must be taken in the design to limit the effect of detector loading on the line.

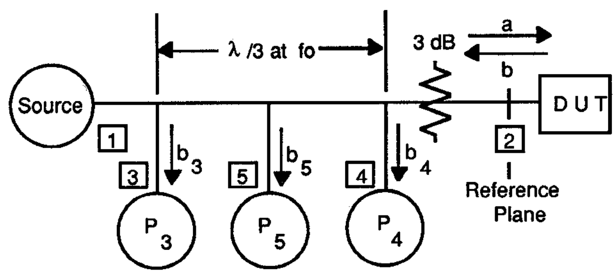

Figure 2. Sampled-line reflectometer for measuring complex reflection coefficients.

The complex reflection coefficient, Γ, of the device under test is calculated from the detector readings using six-port theory. Figure 2 defines the quantities of interest for analy-

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sis. To determine Γ, the objective is to find the ratio b_3/b_4. This ratio is defined as w. Once w is found, it is possible to show that w is related to Γ by a bilinear transform. From six-port theory, the ratio $w \equiv b_3/b_4$ is given by [4]

$$w \equiv \frac{b_3}{b_4} = \frac{C_3}{C_4}\left(\frac{\Gamma + \kappa_3}{\Gamma + \kappa_4}\right)$$

and

$$\frac{b_5}{b_4} = \frac{C_5}{C_4}\left(\frac{\Gamma + \kappa_5}{\Gamma + \kappa_4}\right) \equiv \frac{1}{\sqrt{\zeta}}(w - w_1)$$

where w_1 and ζ are constants that need to be determined. If w can be found from the measured powers then Γ can be calculated. By definition, the readings from the power detectors are

$$P_3 = \alpha_3 |b_3|^2$$
$$P_4 = \alpha_4 |b_4|^2$$
$$P_5 = \alpha_5 |b_5|^2.$$

The proportionality factors, α_j account for detector efficiency and mismatch loss. They cancel from the final result or can be absorbed into other constants, and so are neglected. By taking the squared magnitude, w can be written in terms of the powers measured at the various ports

$$|w|^2 = \frac{P_3}{P_4}$$

$$|w - w_1|^2 = \zeta\frac{P_5}{P_4}.$$

In the complex w-plane these are equations of circles, that intersect at the quantity of interest, $w \equiv b_3/b_4$. Defining the power ratios $r_3 = \sqrt{P_3/P_4}$, $r_5 = \sqrt{\zeta P_5/P_4}$, and using trigonometry gives

$$Re(w) = \frac{w_1}{2} - \frac{r_5^2 - r_3^2}{2w_1}$$

and

$$Im(w) = \sqrt{r_3^2 - x^2}.$$

A calibration procedure is required to calculate the six-port constants w_1 and ζ. The six-port calibration technique applied to the coplanar-waveguide analyzer is based on the assumption that all the standards used in the calibration have values that lie along the $\Gamma = 1$ circle, as described by Engen [5]. This is acheived experimentally using a minimum of 5 offset shorts, or opens, on a coplanar-waveguide calibration wafer, and a least squares fit procedure. After the six-port calibration, the analyzer is essentially reduced to a four-port. The reflection coefficient of the device under test, Γ, is related to w by the transform

$$\Gamma = e_{sf}\frac{(w - e_{rf})}{w - e_{df}}.$$

There are three constants, e_{df}, e_{rf}, and e_{sf}, to be determined. They can be found by measuring three known standards, such as a short, an open, and a matched load [6].

The complex scattering matrix of a two-port device under test can be determined using a pair of reflectometers in a dual six-port configuration [2]. In this case, measurements from the reflectometers are not the reflection coefficients s_{11} and s_{22}, but relate the two waves traveling in opposite directions. By using three different values of incident signals as set by a phase shifter or attenuator, a 6×6 matrix is solved for the s-parameters of the device under test.

Prototype Coplanar-Waveguide Analyzer

The prototype was fabricated using hybrid construction to facilitate quick design revisions. Figure 3 shows the microwave section of the 5–10 GHz reflectometer. The RF signal is coupled through each Schottky detector via a 25 pF chip bypass capacitor. A 1 kΩ resistor is used protect the detector from accidental short circuits or voltage overloads. The 3 dB pad insures numerical stability and improves accuracy of the calculated s-parameters. Airbridges are used to short out the parasitic slotline mode, and the housing

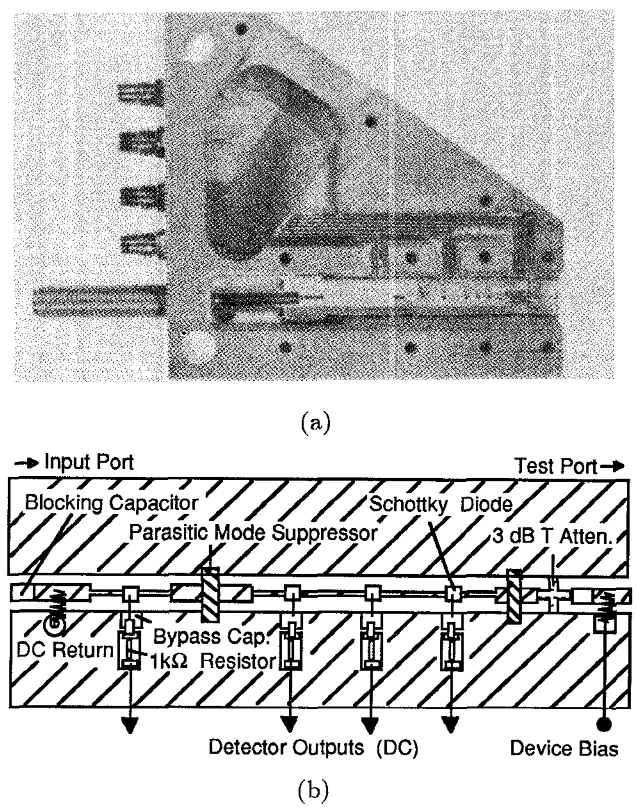
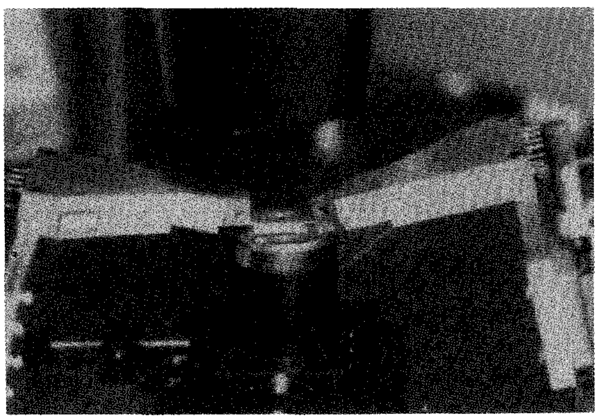


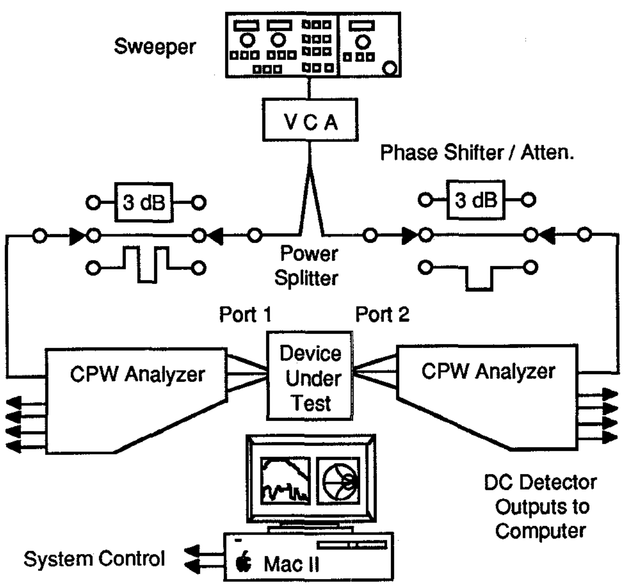
Figure 3. (a) 5–10 GHz coplanar-waveguide reflectometer and (b) circuit layout. Schottky detector diodes are logarithmically spaced along coplanar-waveguide to sample the signal on the line. RF signals incident from the left pass through the analyzer and probe tip (not shown) to the device under test.

is channelized so that the ground plane is located several gaps widths from the center conductor. DC voltages for testing active devices are supplied by a bias structure. A commercially available probe tip is used for the test port. Although microwave hybrid circuit construction was used, the layout is suitable for monolithic integration on a GaAs substrate.

A probe station was built using two coplanar-waveguide reflectometers arranged to form a dual six-port network analyzer [2] at microwave frequencies. Figure 4 shows the probe station and describes the system. A Macintosh II controls the system via an 16 bit interface board, and processes the data. The A/D reads the amplified detector signals, the D/A outputs are used to control the sweeper and voltage controlled attenuator, and the phase shifter/attenuators are set by the parallel port. A control program [7] guides the operator through each stage of calibration and measurement using pull-down menus and dialog boxes. Offset shorts [5] and a matched load are used to calibrate the analyzer. The analyzer's dynamic range is increased by applying the method described in [8] to calibrate for diode detector nonlinearities. Scattering matrices for the device under test are determined by taking data for three independent states of the system set by the phase shifters. As the frequency is swept, the control program calculates the s-parameters and displays them in real time.



(a)



(b)

Figure 4. (a) CPW probe station and (b) system block diagram. The CPW reflectometers, phase shifters and power splitter form a dual six-port network analyzer capable of measuring the complex scattering matrix of a two-port. The voltage controlled attenuator (VCA) and 3 dB attenuators are used for diode linearity calibration.

One of the two phase shifter/ 3 dB attenuator assemblies used in the analyzer is shown in Fig. 5. They contain two SP4T PIN diode switches interconnected with three different lengths of line and a 3 dB chip attenuator. Insertion loss is less than 5 dB and return loss is better then 13 dB over the band of interest. Ideally, the required phase shifts are +90°, 0°, and -90°, but the actual values can deviate considerably without adversely affecting the performance of the system [2]. Various combinations of the two phase shifters can be set to provide the required phase shifts, within a ±30° window, over a 2–18 GHz range. The 3 dB attenuators are switched in and out during the diode linearity calibration.

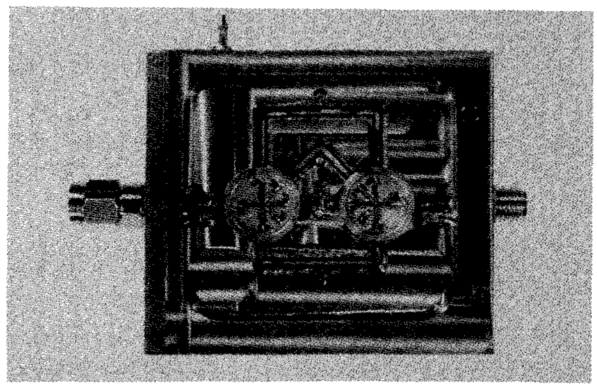


Figure 5. Phase shifter/ 3 dB attenuator assembly.

Experimential Results

The prototype coplanar-waveguide probe station operates over a 5–10 GHz band using three diodes. Magnitude and phase measurements were made with the CPW Analyzer on a high pass filter and a GaAs MMIC PIN diode chip [9]. Figures 6 and 7 compare the results to measurements made with a HP–8510 network analyzer.

Measurements made with the prototype CPW analyzer are in good agreement with HP–8510 data. Variations in measurements between the CPW analyzer and the HP–8510 arise from three major sources. Noise from 60 Hz sources, the detector amplifiers and computer interface contribute to non-systematic errors in the measurements. Modulating the RF signal and using a lock-in amplifier system would improve the repeatability of the measurements [1]. The sec-

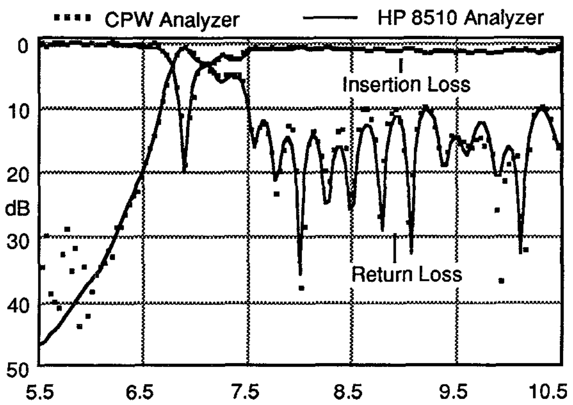


Figure 6. Measurement of a high pass filter made by the CPW analyzer and a HP-8510.

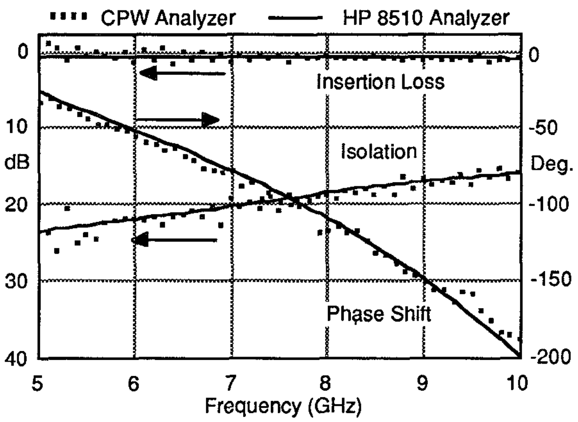


Figure 7. Insertion loss, isolation and phase angle of a MMIC PIN diode in series with the line. Bias is -20 mA in the loss state and 0 V in the isolation state.

ond source of error is attributed to the non-ideal behavior of the calibration standards. The calibration routine assumes that the offset shorts are lossless. Compensation for non-idealities in the calibration standards would require developing a new calibration algorithm to account for losses. A third source of error that has been identified is presence of parasitic slotline and microstrip modes. These modes are suppressed by the grounding straps and the channelized housing.

Conclusions

A new coplanar-waveguide network analyzer has been presented that is designed with the on-wafer characterization of millimeter and microwave devices and circuits in mind. The analyzer has several potential advantages over existing measurement methods at millimeter-wave frequencies. The analyzer is designed to be monolithically integrated into two coplanar-waveguide probe tips, allowing measurements to be made as close to the device under test as possible. Large bandwidths are achievable from the coplanar configuration. The cost of analyzer system is considerably less that other systems that employ vector voltmeters and couplers. A 5–10 GHz model probe station has been demonstrated. Feasibility of the analyzer as a probe station has been established by performing calibration with coplanar-waveguide standards and making measurements on MMIC circuits.

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