A Millimeter-Wave Six-Port Reflectometer Based on the Sampled-Transmission Line Architecture

Sadik Ülker, *Student Member, IEEE,* and Robert M. Weikle, II, *Member, IEEE*

***Abstract*—This letter presents a proof-of-concept implementation of a millimeter-wave reflectometer for measuring complex reflection coefficients. The reflectometer is based on the six-port architecture and consists of a single section of WR-10 rectangular waveguide and a set of three Schottky power detectors. Design considerations as well as measurements in the 75 to 110 GHz range are described and discussed. Because of its simple architecture, the reflectometer is amenable to scaling for measurements well into the submillimeter-wave region of the spectrum.**

***Index Terms*—Network analyzers, Schottky detectors, six-port reflectometers.**

I. Introduction

SCATTERING parameter measurements based on vector network analysis play a critical role in the design and development of modern microwave components. In fact, scattering parameter measurement techniques are frequently used to study and analyze the properties of dielectrics and other materials [1] as well as quasioptical components such as mesh filters [2]. Unfortunately, the size, cost, and complexity of modern network analyzers often preclude their use in nonlaboratory environments. In addition, commercial network analyzers are typically limited in operation to W-band (75–110 GHz), with extensions to higher frequencies being both expensive and cumbersome [3].

Over the past several years, a number of investigators have explored alternatives to the traditional four-port network analyzer based on the vector voltmeter [2], [4]–[6]. Much of this work has been motivated by the need to characterize new devices and components that are capable of operating far beyond W-band as well as to measure the properties of materials in the submillimeter-wave range. Because of the relative difficulty in implementing complex or intricate circuit designs at millimeter and submillimeter wavelengths, simple architectures tend to be preferred and generally yield superior performance at frequencies exceeding 100 GHz.

In this paper, we present a proof-of-concept six-port reflectometer for millimeter-wave measurements that is based on the sampled transmission-line architecture first proposed and demonstrated by Williams [7]. Because of its simple structure, the sampled-line reflectometer has outstanding potential for being scaled to the submillimeter-wave region of the spectrum.

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The authors are with the School of Engineering and Applied Science, University of Virginia, Charlottesville, VA 22904 USA.

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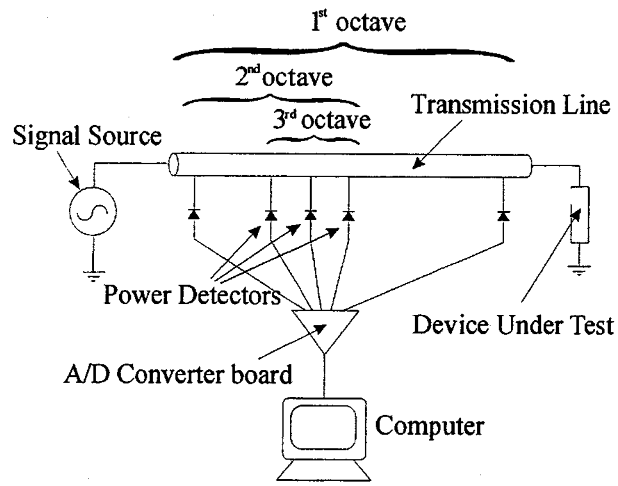


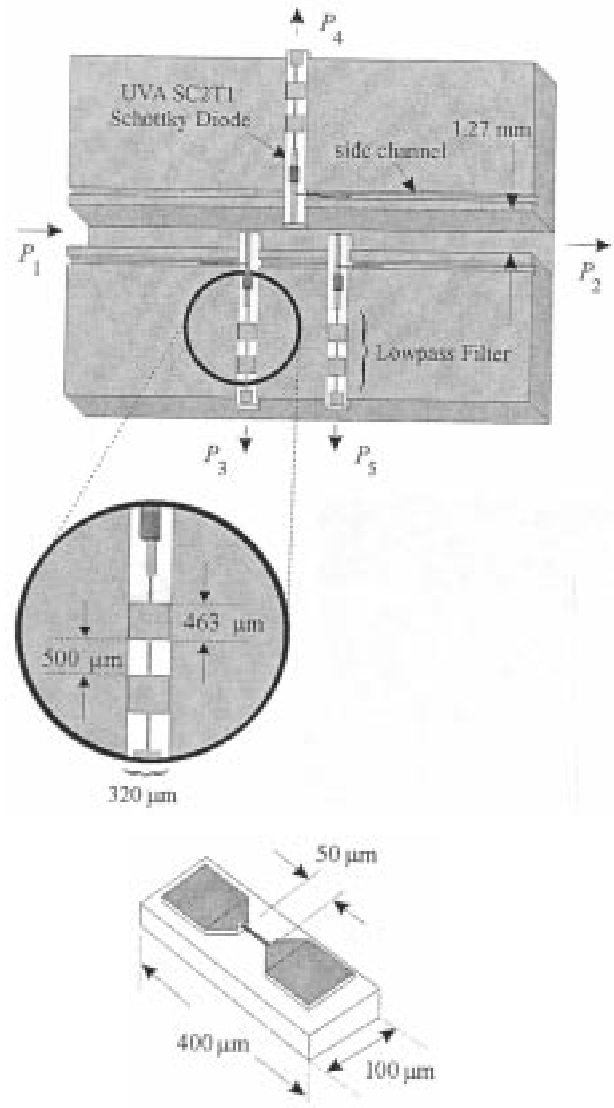
Fig. 1. Basic structure of the sampled-transmission line six-port reflectometer (based on [7]). A set of power detectors samples the voltage standing wave along a section of transmission line.

II. Reflectometer Design

The sampled-line analyzer (shown in Fig. 1) is a relatively simple version of the six-port reflectometer introduced by Engen [8], [9]. The six-port architecture removes the requirement for a vector voltmeter and the magnitude and phase of an unknown reflection coefficient are determined from an ensemble of four power measurements. In the sampled-line implementation of the six-port reflectometer, the power detectors are diodes that sample the voltage standing wave at discrete points along a section of transmission line. As a result, the sampled-line reflectometer is reminiscent of the standard slotted line used to measure standing waves in waveguide.

It has been shown that only three power detectors are required for the sampled-line architecture if the load being measured is known to be passive [7], [8]. Effectively, this reduces the sampled-line analyzer to a five-port reflectometer. To eliminate aliasing, the standing-wave voltages along the transmission line are sampled at intervals not exceeding a half-wavelength. Consequently, a triplet of diode detectors spaced by $\lambda/6$ will allow the reflection coefficient to be measured over an octave of bandwidth (see Fig. 1).

A diagram of the millimeter-wave reflectometer investigated in this work is shown in Fig. 2(a). The circuit consists of a 5 cm long section of WR-10 waveguide (with inner dimensions of 2.54 mm $\times$ 1.27 mm) and three microstrip-to-waveguide probes spaced 700 μm ($\lambda_g/6$ at 92.5 GHz) apart. The waveguide probes are fabricated on 125 μm thick quartz substrates and lie



(a) (b) (c)

Fig. 2. (a) Diagram of the W-band sampled-line reflectometer. Shallow side channels parallel to the waveguide accommodate wirebond connections for dc return-to-ground; (b) close-up view of the quartz microstrip probe and low-pass filter section; (c) diagram of the UVA SC2T1 planar Schottky diode chip.

in shallow cross channels as shown in Fig. 2. UVA SC2T1 planar Schottky diodes fabricated at the University of Virginia, shown in Fig. 2(c), are flip-chip mounted across 250 μm wide gaps in the microstrip circuits. These diodes, which are typically used for mixer applications at submillimeter wavelengths, are used as square-law detectors that sample the magnitude of the electric field at three points along the waveguide. $\lambda_0/4$-long bond wires shorted to the waveguide housing provide dc return and the detector outputs are measured with a set of Keithley-2000 6 1/2-digit multimeters. Five-section stepped-impedance microstrip low-pass filters (with high impedance sections of 145 Ω and low impedance sections of 48 Ω) block the millimeter-wave signal from propagating to the detection circuitry.

III. Calibration Procedure

As with all six-port reflectometers, calibration of the sampled-line reflectometer consists of two steps. In the initial step, the six-port network is converted to an equivalent four-port reflectometer. The details of this procedure are well-documented and will not be repeated here [8], [10]. The six-port to four-port conversion involves finding five calibration constants that are a property of the network architecture [8]. This calibration step is most easily accomplished using a sliding termination. With P_3, P_4, and P_5 denoting the measured outputs of the three power detectors (see Fig. 2), Engen has shown that the sliding termination traces out an ellipse in the P_5/P_4–P_3/P_4 plane [10]. A least-squares fit to the data allows the five calibration constants to be determined.

A plot of the calibration ellipses at 75 and 105 GHz for the W-band sampled-line reflectometer is shown in Fig. 3. For measurements throughout the 75–110 GHz range, sliding short measurements were taken using a noncontacting WR-10 tunable backshort (Millitech TSC-10-R000) and the calibration constants were determined for each frequency point of interest by least-squares fitting to the measured data.

The second step of the calibration procedure consists of the familiar technique of using three well-characterized standard loads to determine the error coefficients in the four-port reflectometer model. In this work, WR-10 calibration standards (a matched termination, a short, and an offset short) from the HP W11644A calibration kit were used for this step.

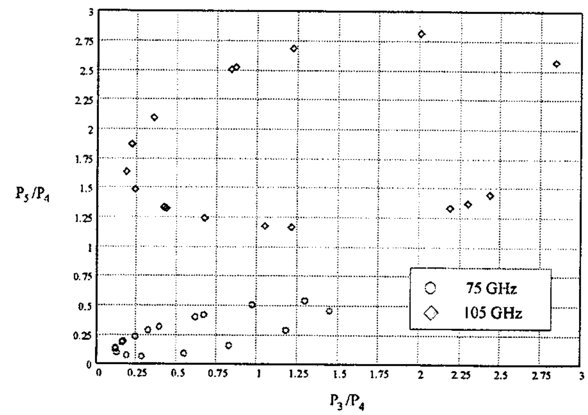


Fig. 3. Plot of the detected power ratios P_5/P_4 vs. P_3/P_4 for the sampled-line reflectometer at various sliding backshort positions. Data is shown for both 75 GHz and 105 GHz. A least-squares fit to the ellipses provides the calibration constants for the six-port to four-port conversion.

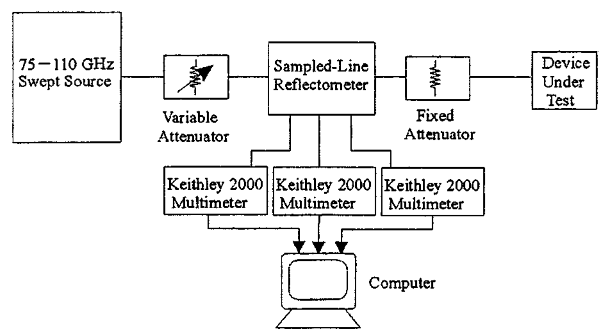
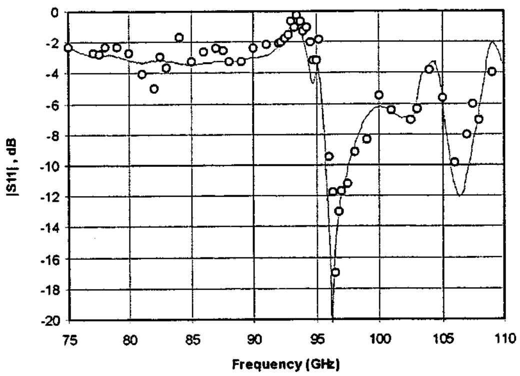
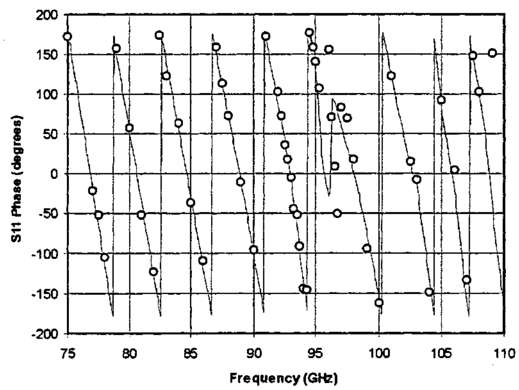


Fig. 4. Measurement setup for the W-band sampled-line reflectometer. The output of an HP8510C millimeter-wave network analyzer is used for the swept source.



(a)



(b)

Fig. 5. (a) Magnitude (in dB) of s_{11} for a waveguide E-plane, H-plane tuner; (b) phase of s_{11} for the E-plane, H-plane tuner. Both plots show data measured using the sampled-line reflectometer (o) and the HP 8510C millimeter-wave network analyzer (—) for comparison.

IV. Measurements

The sampled-line reflectometer illustrated in Fig. 2 was evaluated using a variety of different loads and comparing the measured reflection coefficients with those obtained with an HP 8510C millimeter-wave vector network analyzer. The basic measurement setup is shown in Fig. 4. A variable attenuator placed at the reflectometer input allows the input power to be adjusted appropriately so that the Schottky detectors operate in the square-law region. A second, fixed attenuator (3 dB) is placed between the reflectometer and load being measured. This output attenuator eliminates the deep standing-wave nulls that occur when the reflectometer is connected to a load with reflection coefficient magnitude close to unity. Small errors in measuring the magnitude of these nulls can result in significant uncertainty in the resulting calculated reflection coefficient.

Fig. 5 shows return loss (s_{11}) measurements made for a WR-10 E-plane, H-plane waveguide tuner (Milltech EHT-10-R000). Because of its large variation in return loss magnitude and phase over the 75 GHz to 110 GHz range, the tuner provides a reasonable test on the performance of the sampled-line reflectometer. The input power level used for these measurements was typically less than 300 μW and the detector diodes were forward biased to 0.08 mA. Fig. 5 shows that the return loss measured using the sampled-line reflectometer compares relatively well to that obtained from an HP 8510C network analyzer over the entire WR-10 waveguide band, with the largest discrepancy occurring in the 81–84 GHz range. Over this frequency band, the measured output of the detectors was near the noise floor of our measurement system, resulting in larger errors in the calculated reflection coefficient. This behavior suggests poor RF coupling between the waveguide and diodes in the 81–84 GHz band and is likely due, in part, to misalignments associated with manual assembly of the reflectometer.

V. Summary

This letter has described a proof-of-concept demonstration of a millimeter-wave reflectometer based on the six-port network architecture. The reflectometer design and performance over the 75 to 110 GHz range have been presented and discussed. Because it consists of only a single section of waveguide and a set of Schottky power detectors, the reflectometer is amenable to scaling to much higher frequencies. Future work will focus on extending this technique to the submillimeter range where diagnostic and test instrumentation is both expensive and scarce.

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