A Sampled-Line Reflectometer for Submillimeter-Wave Measurements

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

Abstract— **A reflectometer designed for operation at submillimeter wavelengths and based on the sampled-transmission line architecture is described. The reflectometer is a relatively simple implementation of the six-port network analyzer introduced by Engen and consists of a section of rectangular waveguide and an ensemble of Schottky diode power detectors. Design considerations for the instrument are described and measurements in the 270 GHz to 285 GHz range are presented and discussed.**

Keywords— **Six-port network analyzers, submillimeter-wave systems, reflectometers, Schottky diodes.**

I. Introduction

THE TEST AND measurement infrastructure that has played such a pivotal role in the development of microwave and millimeter-wave systems is either scarce, expensive and complex, or does not exist for much of the submillimeter-wave region. This is unfortunate because the submillimeter-wave spectrum has long been recognized as a fruitful region for fundamental research, particularly in radio astronomy [1], atmospheric remote sensing [2] and molecular spectroscopy. More recently, scientists and engineers have begun to recognize the potential of submillimeter systems in applications ranging from scaled radar range measurements to the detection and monitoring of chemical and biological warfare agents [3]. Because of the importance of these and other applications, a significant effort has been focused on developing electronics capable of operating at submillimeter wavelengths. Still, the limited availability of diagnostic instrumentation remains a major obstacle limiting full use and exploration of the submillimeter portion of the electromagnetic spectrum.

The lack of instrumentation for measuring scattering-parameters in the submillimeter region has prompted a number of investigators to explore methods for extending traditional four-port analyzers to higher frequencies [4,5] as well as finding alternative network analyzer architectures [6,7]. An attractive technique for realizing a submillimeter-wave *s*-parameter measurement system is based on the six-port reflectometer proposed and developed by Engen [8,9]. In this paper, we present a submillimeter-wave implementation of the six-port reflectometer based on a sampled-transmission line structure. Design considerations and calibration of the instrument are discussed and measurements over the 270–285 GHz band are presented.

The authors are with the School of Engineering and Applied Science, University of Virginia, 351 McCormick Road, Charlottesville, VA 22904-4743, U.S.A. R. Weikle is currently visiting at the Department of Microelectronics, Chalmers University of Technology, S-412 96 Göteborg, Sweden.

This work was supported by the U.S. Army Research Office under grant DAAD19-00-1-0404 and the Multi-disciplinary University Research Initiative (MURI) Program. Funding was also provided by the Virginia Center for Innovative Technology.

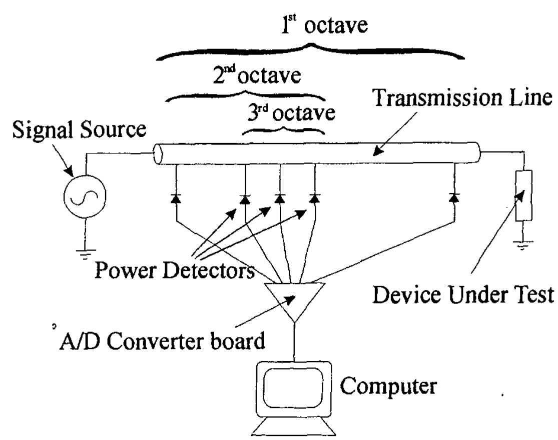

Fig. 1. Basic architecture of the sampled-transmission line six-port reflectometer (based on the work of Williams [10]). A set of power detectors samples the standing wave on the section of transmission line.

II. Background

The sampled-line analyzer was introduced by Williams [10] and is a relatively simple version of the six-port reflectometer. The basic instrument, shown in figure 1, consists of a single section of transmission line and an ensemble of power detectors. The detectors sample the standing wave at discrete points along the transmission line and the error-corrected reflection coefficient is computed from power measurements through a bilinear transformation.

It has been shown that only three power detectors are required if the load being measured is known to be passive [8,10]. Effectively, this apriori knowledge (which is nearly always valid at submillimeter wavelengths) reduces the six-port analyzer to a five-port reflectometer. To eliminate aliasing, the standing wave along the transmission line is sampled at intervals not exceeding a half-wavelength. Consequently, a triplet of detectors spaced by $\lambda_g/6$ (where λ_g is the guide wavelength) will permit reflection coefficient measurements of passive loads over an octave bandwidth. The operating range of the instrument can be extended to several octaves by adding extra power detectors as shown in figure 1.

As with all six-port reflectometers, calibration of the sampled-line analyzer consists of two steps. In the initial calibration step, the six-port network is converted to an

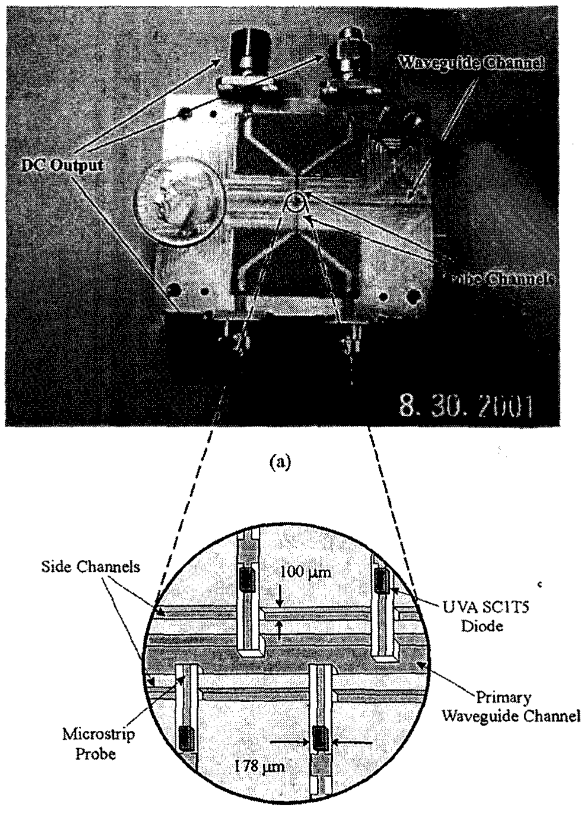

Fig. 2. (a) Photograph of the submillimeter sampled-line reflectometer. (b) Diagram showing details of the microstrip probes and waveguide channels.

equivalent four-port reflectometer. This conversion, which involves finding five calibration constants that are a property of the network architecture, is most easily accomplished using a sliding termination. Details of this procedure are well-documented [11] and will not be repeated here. The second part of the calibration consists of the familiar technique of using three well-characterized standards to determine the error coefficients in the four-port reflectometer model. The extra calibration step required for six-port reflectometers can be inconvenient. However, the vast simplification in circuit hardware that results from the six-port architecture is often worth the inconvenience, particularly at submillimeter wavelengths where complex or intricate circuit designs are difficult to realize.

III. Design

The sampled-line reflectometer investigated in this work consists of a 5 cm section of rectangular waveguide and a set of four Schottky detector diodes. A photograph of the reflectometer is shown in figure 2(a). The waveguide has inner dimensions of 406 μm$\times$787 μm, resulting in single mode propagation over the 190 GHz to 370 GHz band. Shallow (125 μm deep $\times$ 178 μm wide) cross channels are machined

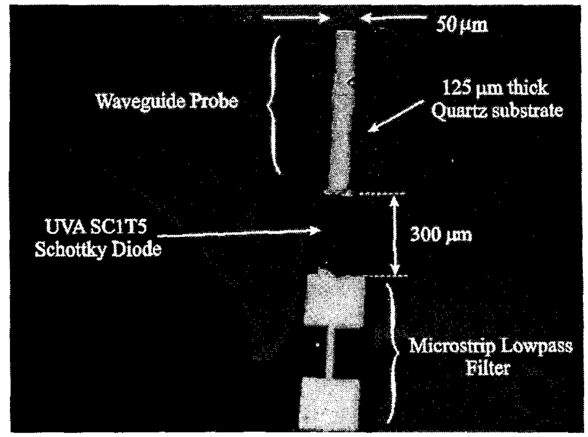

Fig. 3. Photograph of a UVA SC1T5 Schottky diode flip-chip mounted to a microstrip probe. The substrate is 125 μm thick quartz.

in the block to accommodate microstrip probes for sampling the standing wave inside the guide. The probe spacing is 195 μm, corresponding to $\lambda_g/6$ at 320 GHz. In addition, two narrow (100 μm wide) side channels are machined parallel to the primary waveguide channel (see figure 2(b)). These side channels accommodate quarter wave ($\lambda_0/4$) long bond wires that are used as dc returns-to-ground for the Schottky power detectors. The entire waveguide block was fabricated by Custom Microwave, Inc. and was designed with waveguide flanges that mate to standard WR-3 components.

Sampling probes and microstrip lowpass filters for the reflectometer were designed with the use of Ansoft's *High Frequency Structure Simulator*. To minimize perturbations to the standing wave being sampled, each probe was designed to couple no more than 5% of the energy in the guide to the detectors. The probes and filters were fabricated photolithographically on 125 μm thick quartz substrates. SC1T5 planar Schottky diodes fabricated at the University of Virginia were then flip-chip mounted onto these probes using silver epoxy. These devices are typically used for mixer applications at 600 GHz. A photograph of one of the probe circuits is shown in figure 3.

Commercial calibration standards are not readily available at frequencies significantly higher than 100 GHz. Consequently, a set of custom-designed standards were fabricated along with the reflectometer waveguide housing. These standards consisted of a short-circuit termination or "plug" and two offset shims of lengths 33 mils and 37 mils. The shims, and their combination (70 mils long), are used to realize three offset short-circuits. These loads provide a set of standards that can be used to calibrate the reflectometer over the entire 270 GHz to 360 GHz band.

IV. Measurements

The experimental setup for the sampled-line reflectometer is shown in figure 4. A mechanically tunable 70 GHz to 105 GHz Gunn diode oscillator (Carlstrom H208) with

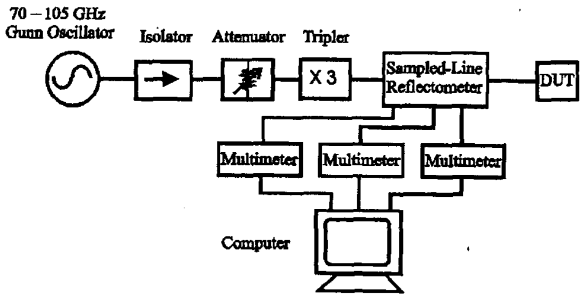

Fig. 4. Experimental setup of the sampled-line reflectometer for measurements in the 270 GHz to 285 GHz range.

output isolator is used as the source. This is followed by a broadband frequency tripler (model WR-3.4-X3-LP) designed by Virginia Diodes, Inc. [12]. An adjustable attenuator placed after the isolator permits control of the input power provided to the tripler and reflectometer. The typical output power of the tripler at 280 GHz is 300 μW. DC bias is supplied to the Schottky detectors with commercial bias supplies (model E3610A by Hewlett Packard) and the output current of the detectors is monitored with a set of Keithley-2000 $6\frac{1}{2}$ digit multimeters.

A. System Calibration

The first step in calibrating the sampled-line reflectometer consists of converting the six-port analyzer to an equivalent four-port by use of a sliding termination. The sliding short used in this work was designed in-house using a commercially available micrometer with a custom-machined fitting. This fitting (shown in figure 5) consists of a cylindrical brass shim of length 1.8 cm and diameter 356 μm. The shim slides into a waveguide adaptor (also shown in figure 5) to act as a sliding load. The complete assembly for the backshort is shown in figure 5.

With P_3, P_4, and P_5 denoting the powers measured at three of the six-port's detectors, Engen has shown that a sliding termination traces out an ellipse in the $P_3/P_5 - P_4/P_5$ plane [11]. Sliding load measurements taken with the sampled-line reflectometer investigated in this work are shown in figure 6. By least-squares fitting an ellipse to the data at each frequency point, the five six-port calibration constants can be determined [11].

The second calibration step for the reflectometer consists of using three well-characterized standards to determine the complex coefficients for the standard one-port error model. In this work, the custom-made short circuit and two offset shorts previously described were used for this calibration step.

B. Waveguide Measurements

Initial measurements performed on the system indicated that above 285 GHz, the output power of the tripler was insufficient to be measured by the Schottky detectors. In addition, above 300 GHz, two of the detectors exhibited very low responsivities, near the noise floor of our measurement system. It is quite possible that this behavior is a result of misalignment and other imperfections resulting from manual assembly of the reflectometer. Consequently, scattering parameter measurements with the instrument were performed in the 270 GHz to 285 GHz range.

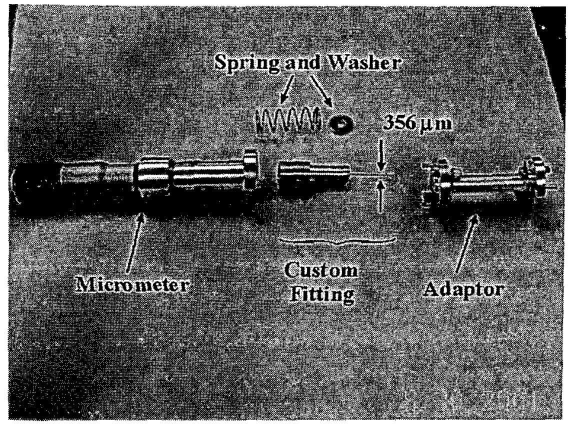

Fig. 5. Photograph of the sliding backshort assembly. This tunable short was used in the six-port calibration procedure.

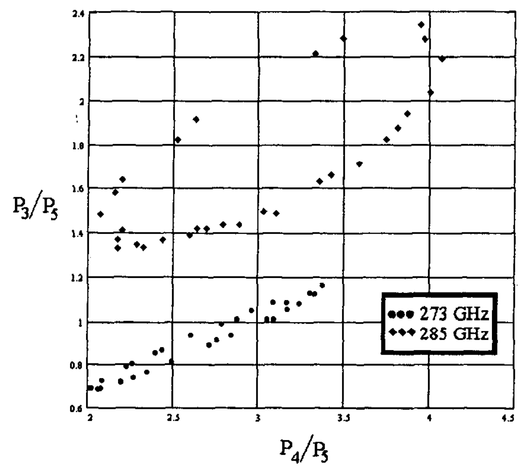

Fig. 6. Measured "calibration ellipses" for the sampled-line reflectometer at 273 GHz (•) and 285 GHz (◇). A least-squares fit to the data provides the calibration coefficients for the six-port to four-port conversion.

Verification standards are unavailable for submillimeter-wave frequencies and, as a result, operation of the reflectometer was evaluated using the offset shorts designed for calibration. Because only two offset shorts (of lengths 33 mils and 37 mils) are used in the calibration procedure for the 270 GHz to 285 GHz range, the third offset (70 mils) can be used as a check to verify the reflectometer is working properly. Remeasurement of the standards used for calibration can provide information regarding the repeatability of measurements.

Figure 7 shows the measured phase of s_{11} for the three

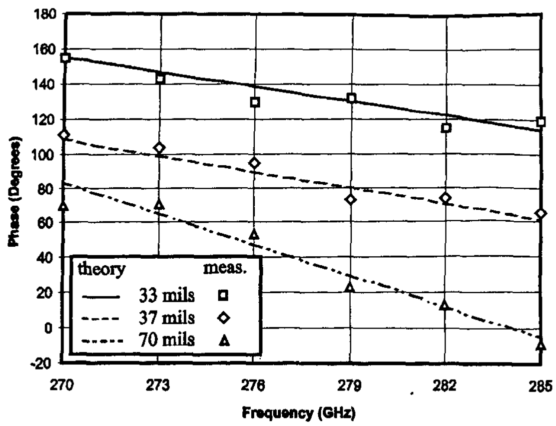

Fig. 7. Measured phase vs. frequency for three offset short circuits.

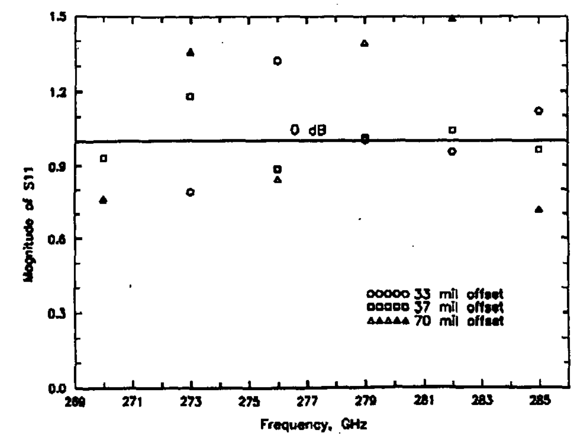

Fig. 8. Measured magnitude vs. frequency for three offset short circuits. Also shown is the 0 dB reference for lossless terminations.

offset shorts over the 270 GHz–285 GHz band. The measured phase is close to that predicted using an ideal, lossless short-circuited waveguide as a model and follows the expected slope as a function of frequency. It should be noted that no waveguide losses are accounted for in either the theoretical curves or circuit models used for the calibration standards. In addition, there is approximately a $\pm 5°$ uncertainty in the phase measurements arising from use of the Gunn diode source. This uncertainty arises from frequency drift of the device as well as small errors in adjusting the micrometers used for frequency tuning.

Because the loads measured in figure 7 are ideally lossless, the magnitude of the reflection coefficient is expected to be near 0 dB. Magnitude measurements performed on the offset shorts are shown in figure 8. In general, the measurements for each shim average near the expected 0 dB, but some data deviate substantially, showing significant error in the calibration. Sources of this error may include imprecise modeling of the calibration standards, repeatability in connecting the waveguide flanges, and the low power levels used for the measurements. Magnitude measurements, in particular, are relatively sensitive to variations in power level and waveguide losses. The phase response, on the other hand, depends primarily on the delay between the measurement reference plane and the load. This is known with good precision for the offset shorts and probably explains why the phase measurements shown above are relatively close to that expected from theory.

V. Discussion

In this paper we have presented and demonstrated a six-port reflectometer for scattering parameter measurements in the submillimeter region. Because the instrument relies only on fundamental submillimeter components (transmission lines and Schottky detectors) and a simple architecture, it can be scaled in principle to frequencies approaching 1 THz. Future work will focus on improvements in the system calibration, extension of the instrument's frequency range, and incorporation of monolithic processing technologies to produce an integrated instrument. In addition, the reflectometer will benefit from improvements in submillimeter-wave source technology.

Acknowledgments

The authors are grateful to Prof. T. Crowe and Prof. J. Hesler at the University of Virginia for providing diodes and much helpful advice for this project.

References

[1] T.G. Phillips and J. Keene, "Submillimeter astronomy," *Proc. of the IEEE.*, vol. 80, no. 11, pp. 1662–1678, Nov. 1992.

[2] J.W. Waters, "Submillimeter-wavelength heterodyne spectroscopy and remote sensing of the upper atmosphere," *Proc. of the IEEE*, vol. 80, no. 11, pp. 1679–1701, Nov 1992.

[3] N. Gopalsami and A.C. Raptis, "Millimeter-wave radar sensing of airborne chemicals," *IEEE Trans. on Microwave Theory and Tech.*, vol. MTT-49, no. 4, pp. 646–653, April 2001.

[4] P. Goy, M. Gross, and J.-M. Raimond, *15th Int. Conf. on Infrared and Millimeter Waves*, Orlando, FL, SPIE **1576**, 487 (1990).

[5] 355 Woodview Dr., Suite 300, "Using the OML millimeter wave vector network analyzer frequency extension modules with the HP 8510 vector network analyzer," in *OML HP 8510 Millimeter Application Note*, Morgan Hill, CA 95037: Oleson Microwave Laboratories.

[6] Y. Konishi, M. Kamegawa, M. Case, R. Yu, S.T. Allen, and M.J.W. Rodwell, "A broadband free-space millimeter-wave vector transmission measurement system," *IEEE Trans. on Microwave Theory and Tech.*, vol. MTT-42, no. 7, pp. 1131–1139, July 1994.

[7] U. Stumper, "A simple multiport reflectometer using fixed probes and an adjustable attenuator, in *Proc. 11th Eur. Microwave Conf.* , 1981, pp. 622–626.

[8] G.F. Engen, "The six-port reflectometer: an alternative network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, no. 12, pp. 1075–1080, Dec. 1979.

[9] G.F. Engen, "An improved circuit for implementing the six-port technique of microwave measurements," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, no. 12, pp. 1080–1083, Dec. 1979.

[10] W.L. Williams, "Computer-aided measurements of microwave circuits," Ph.D. dissertation, California Inst. of Technol., Pasadena, 1989.

[11] G.F. Engen, "Calibrating the six-port reflectometer by means of sliding terminations," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 951–957, Dec. 1978.

[12] Virginia Diodes, Inc., 321 West Main Steet, Charlottesville, VA 22903, U.S.A. URL: http://www.virginiadiodes.com