Six-Port Reflectometers for Waveguide Bands WR-15 and WR-2.8

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***Abstract*—Millimeter-wave six-port reflectometers for scattering parameter measurements in the WR-15 and WR-2.8 frequency bands have been designed and implemented. These reflectometers represent an effort to (1) develop a cost-effective measurement infrastructure that is scalable to terahertz frequencies and (2) to realize *in-situ* measurement instruments for monitoring the performance of millimeter-wave components. Performance of the six-ports has been assessed by applying them to measure the return loss for various components, including calibration standards and other common waveguide components. Measurement results have been found to be in close agreement with those obtained with a commercial HP8510C vector network analyzer. In addition, a WR-15 six-port reflectometer has been demonstrated as an *in-situ* sensor to monitor the mismatch between adjacent stages of a frequency multiplier chain.**

***Index Terms*—Six-port reflectometer, scattering parameters waveguide, return loss, frequency multiplier**

I. INTRODUCTION

SINCE it was demonstrated in 1977 by Engen [1]-[4], the six-port technique has been recognized as an attractive alternative to conventional four-port network analyzers due to its simple structure and requirement for fewer components. Because it is based only on power measurements, no phase-locked sources or wave splitters are necessary. Moreover, the size of the six-port can be compact compared to commercial network analyzers. For this reason, the six-port technique is promising as a technique for embedded sensing to measure mismatch between components internal to an instrument or system.

In this paper, we describe two six-port reflectometer architectures that (1) can be implemented to measure waveguide components at millimeter-wave frequencies and (2) can be applied as an embedded sensor for monitoring of the performance and operation of adjacent stages in a millimeter-wave circuit, such as a frequency multiplier chain.. By directly monitoring the impedance mismatch between adjacent stages using a six-port reflectometer, circuit designers are provided with a diagnostic tool that can be used for studying the behavior of multipliers as well as a guide for adjusting external operating parameters (such as bias conditions and drive power levels) that impact performance of the entire chain. To accomplish this a six-port reflectometer module designed to be inserted directly between adjacent multiplier stages, thus allowing continuous monitoring of the multiplier chain's operation by measurement of the input impedance presented to a source multiplier stage, is described. In the sections below, the design of the six-port modules are detailed as well as measurements used to characterize their performance.

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II. REFLECTOMETER DESIGN

A. WR-15 Reflectometer Design

As a proof-of-concept demonstration, a prototype six-port reflectometer was designed for V-band (50–75 GHz) operation. The six-port module, shown in Fig. 1, consists of a section of WR-15 waveguide and three probe channels that accommodate microstrip waveguide probes with integrated zero-bias Schottky diode detectors. Note that because only three detectors are utilized, the reflectometer is actually a five-port (which can be considered a simplified version of the six-port). Provided the device to be measured is known apriori to be passive, only three detectors are required to uniquely determine its reflection coefficient [5]. The fourth detector may be used to enhance measurement accuracy, but strictly is not required. Bias protection circuits are included in the detector outputs to reduce the likelihood of damage to the zero-bias Schottky diodes through electrostatic discharge. Because the output power for the first multiplier stage (and drive power for the second multiplier stage) is typically large (on the order of several hundred milliwatts), coupling from the waveguide channel to the probes is designed to be small, less than −30 dB. In addition, two additional ports are included in the design to permit the reflectometer to be calibrated through null double injection technique [6]. Coupling between the two calibration injection ports and the waveguide channel is also designed to be small (less than −20 dB). As a consequence, the probe and calibration injection channels have a small loading effect on the reflectometer waveguide, a desirable feature that reduces loading of these channels on the reflectometer as well the performance of the frequency multipliers connected to its input and output ports.

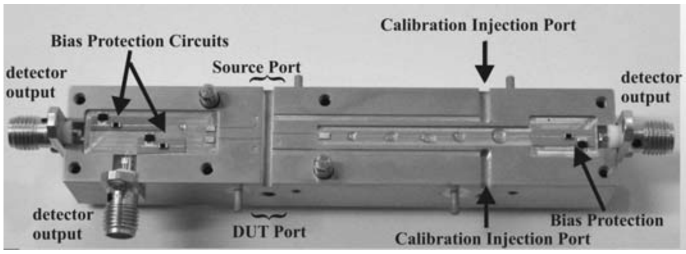


Fig.1. Photograph of the WR-15 six-port module.

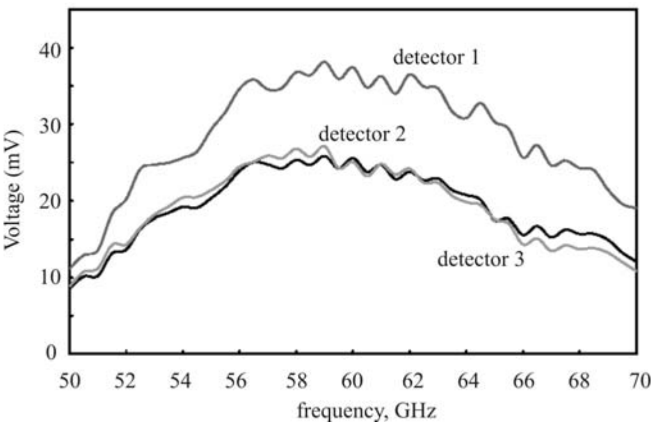


Fig.2. Detected voltages from the reflectometer. The input power is 7 dBm.

Fig. 2 shows the measured voltage response of the various detector diodes in the reflectometer. For this measurement, a source (7 dBm available power) is placed at one waveguide port and a HP W8486A power meter at the other. Detector voltages are monitored with a Keithley digital multimeter controlled by LabView. Initially, a resonance in the response of all the detectors was observed at 56 GHz. This resonance, which was associated with mismatch between the detector and the microstrip probe circuit, was eliminated by integrating a shunt titanium resistor (nominally 130 Ω) in parallel with the detector. This reduces the overall responsivity of the detectors, but also eliminates large variations in detected voltages as well as non-square-law operation of the diodes over the measurement bandwidth. From the measured detector voltages, available power to the waveguide, and waveguide-to-microstrip coupling values (modeled), the responsivity of the detectors is estimated to be 3000 V/W.

Fig. 3 shows the measured detector voltages (at 60 GHz) in response to a waveguide sliding short placed at the DUT measurement port of the reflectometer. Varying the short position allows the standing waves in the waveguide channel to be observed and allows proper operation of the reflectometer to be verified.

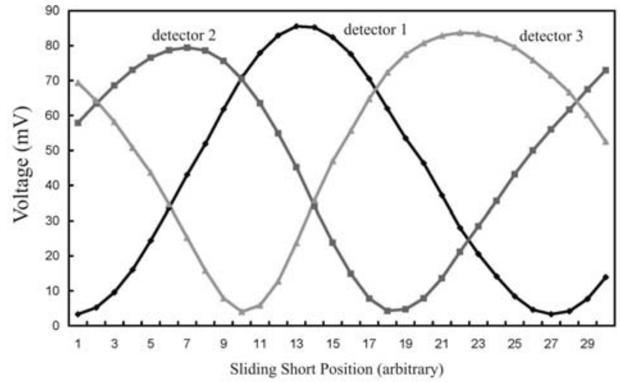


Fig.3. Voltage response of the diode detectors at 60 GHz in response to a waveguide sliding short.

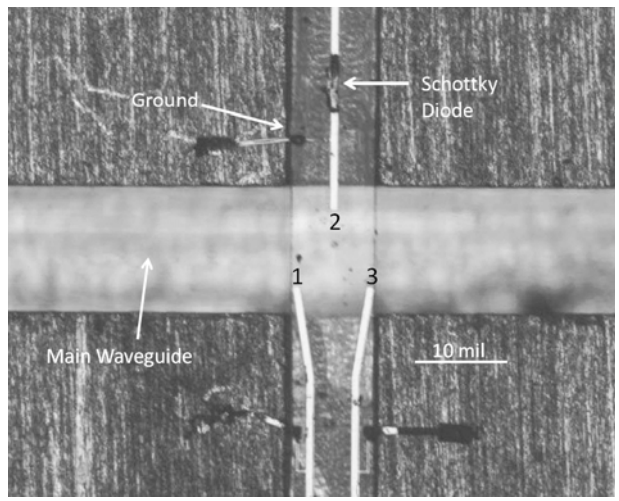


Fig.4. Microscope photo of WR2.8 six-port reflectometer probe structure.

B. *WR2.8 Reflectometer Design*

The basic design of WR-2.8 (270 GHz – 390 GHz) six-port is similar that of the WR-15 version, except that three probes were fabricated on a single substrate and placed into one common channel that crosses the primary waveguide. The rationale for using a single chip instead of three separate chips was ease of fabrication, simpler alignment and greater control over the passive circuitry performance. A photograph of the WR-2.8 reflectometer block and probe circuit is shown in Fig. 4. The primary waveguide channel is 28 mils × 14 mils and the widths of the probe circuit channel, quartz substrate, and microstrip lines are 10 mils, 9 mils, and 0.8 mils respectively. The quartz substrate is 1.5 mils thick and the distance between adjacent probes is 4.5 mils, or ~35^o at the center frequency of 330 GHz.

The available power for measurements at WR-2.8 is slightly higher than 0.5 mW over the 275~335 GHz range, a frequency band that overlaps with the V03VNA-T/R Oleson Extension Module. This makes it possible to compare results obtained from the reflectometer with those of the commercial network analyzer.

III. Calibration Procedure

Fig. 5 illustrates the general architecture of the six-port reflectometer, where port 1 is the excitation port, the device under test (DUT) is placed at port 2, and ports 3—6 represent the power detection ports. To obtain the reflection coefficient for various DUT's from the power detection readings, calibration is necessary. A common and straightforward calibration method is Engen's sliding termination method [4]. With this method, the calibration consists of two steps. The first step effectively converts the six-port reflectometer to an equivalent four-port reflectometer and is used to determine the complex ratio b_3/b_4 from the set of power measurements. Once this is accomplished, the reflectometer is effectively a four-port that can be calibrated with one of several standard and familiar techniques.

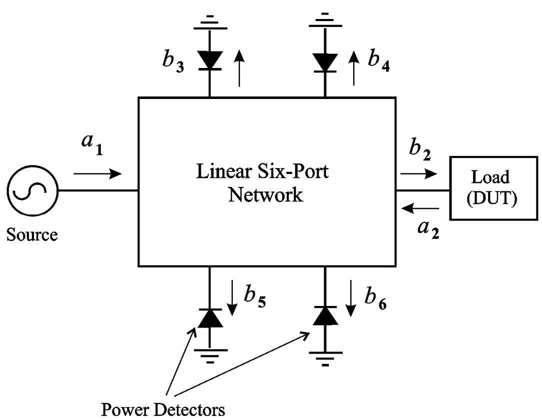


Fig.5. Diagram of a general six-port reflectometer.

For the first calibration step, a sliding termination is utilized so that the reflection magnitude remains unchanged as the position of the load is varied. The complex ratio, b_3/b_4, is obtained from a least-square fitting of data, which ideally forms an ellipse when the power ratios are plotted against one-another.

For the WR-15 six-port reflectometer, a sliding short is used for the first step of calibration. An example of data obtained from this measurement (at 61 GHz) is shown on the P_5/P_4 versus P_3/P_4 plot of Fig. 6. Data from twenty different positions with roughly equal intervals of 220 μm were chosen for this measurement.

For the WR2.8 six-port reflectometer, a different calibration termination is chosen because commercial sliding shorts are not readily available in this frequency band. Instead, seven fixed offset shorts with different delays were used for the first-step calibration. These seven offset shorts were designed to provide delays up to one wavelength over the entire waveguide band. The performance of the offset shorts has the same effect as a sliding short, except that only seven data points are available for fitting the ellipse. Fig. 7 shows the calibration ellipse plot for the WR-2.8 six-port reflectometer

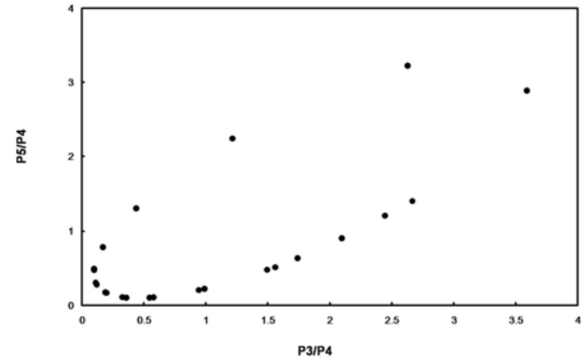


Fig.6. Ellipse curve from the first step calibration for WR15 six-port reflectometer at 61 GHz as an example.

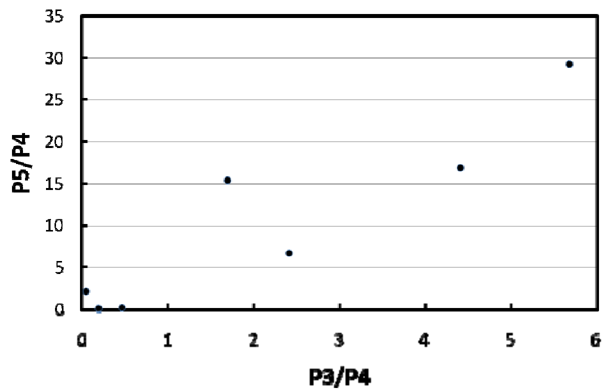


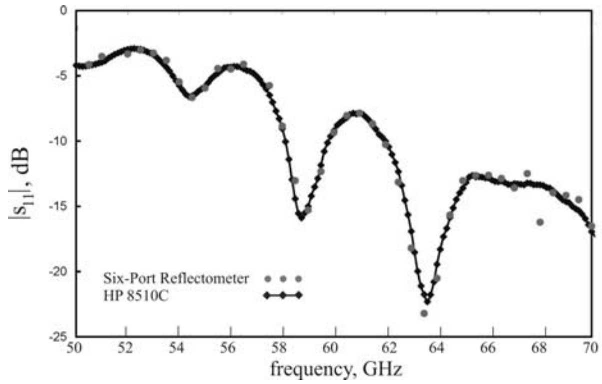
Fig.7. Ellipse curve from the first step calibration for WR2.8 six-port reflectometer at 290 GHz as an example.

from the seven offset shorts.

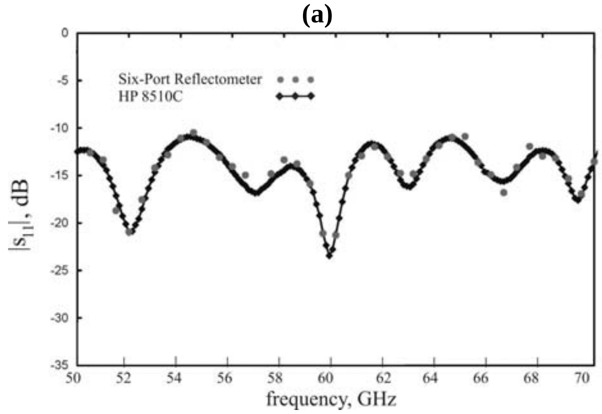
For the second-step of the calibration, the WR-15 and the WR-2.8 six-port reflectometers also employ different calibration standards. For the WR-15 reflectometer, a flush short, two sliding short positions (treated as delay shorts), and a matched load are used. For the WR-2.8 reflectometer, a flush short, two fixed offset shorts, and an open-ended waveguide are used. The open-ended waveguide was chosen for WR-2.8 six-port because its return loss is relatively well-understood and this standard is not subject to misalignment of the waveguide flange connection [7], which is a significant issue at frequencies higher than 100 GHz.

IV. Measurements

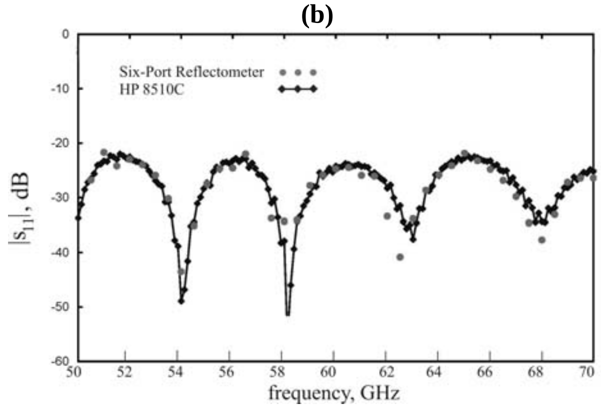
To assess the six-port reflectometer performance, the WR-15 reflectometer was used to measure a variety of WR-15 waveguide components and its performance was compared to scattering parameters obtained from the same components using an HP8510C vector network analyzer. Fig. 8 shows the results of these measurements which are in good agreement. Fig. 8(a) shows the return loss data for a waveguide directional coupler, Fig. 8(b) shows the return loss of a waveguide iris, and Fig. 8(c) the return loss of a horn antenna.



(a)



(b)



(c)

Fig.8. Measurement of return loss performed with the six-port reflectometer compared to data obtained with a HP8510C network analyzer. The devices measured are (a) a WR-15 waveguide coupler, (b) a waveguide iris, and (c) a horn antenna.

The WR15 six-port reflectometer was also implemented as an embedded sensor to monitor the mismatch between two adjacent stages in a frequency multiplier chain. The basic test setup is simple and consists of placing the six-port reflectometer between two adjacent doublers, both of which require a bias voltage. Prior to measuring the multiplier mismatch, a test was done was to examine changes in the multiplier chain performance resulting from introduction of the six-port. Fig. 9 shows the output power of the multiplier chain as a function of frequency for two different bias conditions. This measurement was repeated with WR-15 six-port reflectometer present. As seen from the data, the output power changes slightly, but the reflectometer does not have a drastic effect on the operation of the doubler chain.

Application of a WR-2.8 six-port reflectometer for mis-match measurement of two adjacent stages in corresponding frequency multiplier chains is a subject of ongoing work.

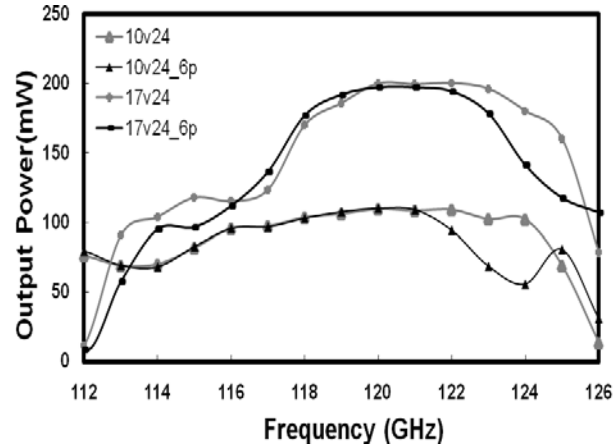


Fig.9. Output frequency dependence of output power at two different voltage bias conditions with and without six-port reflector. The input bias voltage for both bias conditions is 24 Volts, while there are two values for the output bias voltage, 10 Volts and 17 Volts.

V. SUMMARY

Six-port reflectometers at WR-15 and WR-2.8 have been designed and fabricated with initial tests completed. Results show a good agreement between measurements done with the WR-15 six-port and a commercial HP8510C vector network analyzer. As an initial test, the WR-15 six-port reflectometer has been also implemented as an embedded sensor placed between two adjacent stages in a frequency multiplier chain and it was found that the output power did not change dramatically by introduction of the six-port reflectometer. The next stages of this work will include full implementation of WR-2.8 six-port reflectometers studying the mismatch between frequency multipliers as well as full characterization of the performance of these prototype instruments (including dynamic range and measurement uncertainty).

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