the conversion loss when a perfectly symmetrical PDB diode is evaluated. This decrease is shown to be in the order of 5 dB. In this subharmonic mixer configuration, a single PDB diode replaces two well-matched Schottky-barrier diodes in conventional balanced mixers, and the designable barrier height reduces the local oscillator power. These results are presently being applied in the design of very high frequency millimeter-wave subharmonic mixers.

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References

[1] M. V. Schneider and W. W. Snell, Jr., "Harmonically pumped stripline down-converter," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 271, 1975.
[2] R. J. Malik, R. T. AuCoin, R. L. Ross, K. Board, C. E. C. Wood, and L. F. Eastman, "Planar doped barriers in GaAs by molecular beam epitaxy," *Electron. Lett.*, vol. 16, p. 836, 1980.
[3] R. J. Malik, K. Board, L. F. Eastman, C. E. C. Wood, T. R. AuCoin, and R. L. Ross, "Rectifying variable planar-doped-barrier structures in GaAs," in *Inst. Phys. Conf. Ser.*, vol. 45, 1981, p. 697.
[4] M. V. Schneider, "Electrical characteristics of metal-semiconductor junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, p. 1169, 1980.
[5] A. A. M. Saleh, *Theory of Resistive Mixers*, (*Res. Monograph 64*). Cambridge MA: M.I.T. Press, 1971.

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Diode Detector Characteristics for a 94-GHz Six-Port Application

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Abstract—**The suitability of commercially available diodes as power detectors in a 94-GHz six-port is examined. Square law response, noise, variation of reflection coefficient with power, and temperature effects are studied. The results show that silicon Schottky diodes are the best available.**

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I. Introduction

ALONG WITH THE renewed interest in 94-GHz radar systems, there is a need for fast and accurate testing at these frequencies. One very promising approach is the six-port automatic network analyzer which has undergone considerable development at microwave frequen-

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cies [1]–[3], with some work at millimeter-wave frequencies [4], [5]. Critical components in this method are the power detectors at the four output ports of the six-port junction. The purpose of this investigation was to determine the feasibility of using diodes as power detectors in a 94-GHz six-port network analyzer.

Engen and Hoer [1] have shown that using thermistor detectors, the six-port technique can give very accurate measurements in the microwave range. A diode detector system described by Cronson and Susman [2] provided good measurements from 2 to 7 GHz, but was subject to more errors at higher microwave frequencies. At W-band (75 to 110 GHz), true square law detectors exist in the form of bolometers. However, in the six-port configuration, a large amount of input power (~ 200 mW) is required for thermistors to operate in their optimum range. At present, this power must be supplied by expensive klystrons and other devices. On the other hand, diode detectors are very nearly square law at power levels which can be easily obtained by common Gunn and IMPATT sources. Therefore, it would be highly desirable to use diode detectors on the six-port output ports.

There has been much work on general diode detector properties in the microwave region [6]–[8] and some earlier work in the millimeter-wave region [9], [10]. However, none has specifically applied to diodes as power detectors at 94 GHz. Furthermore, new diodes and mounts are being introduced which require evaluation.

This paper presents experimental results on square law behavior, noise, reflection, coefficient, and stability for four types of millimeter-wave diodes. In addition, a computer simulation was performed to determine the effects of nonideal diodes on measurement accuracy. The merits of dc and ac amplification techniques were also compared.

II. Diode Experiments

Four types of diodes with mounts were tested: four 1N53 point contact (Baytron 1R-20 mount with 1R-2/X cartridge), eight silicon Schottky (Hughes 47316–1100), one gallium arsenide Schottky wafer-mounted (TRG W965D), and one gallium arsenide beam lead (TRG W925D). In the first phase of the work, only the point contact and silicon Schottky were tested. Here the silicon Schottky diodes proved superior because their signal-to-noise ratio was 6.25 times higher and their millimeter-wave bandwidth much wider. When the two GaAs diodes later became available, they were compared only to the better silicon Schottky diode. A summary of the results is contained in Table I.

A. Square Law

This was considered the most important test because six-port theory assumes a perfect square law response. The square law behavior was measured using two different experiments. The first was designed to cover the −5 to −50-dBm input power range to the diode. This experimental configuration is shown in Fig. 1. A 1-kHz pulse modulates the signal from the 94-GHz Gunn oscillator while the lock-in amplifier and six-digit digital voltmeter (DVM) measures the diode voltage. Input power is measured with an NBS type IV power meter which is always used in the 0 to −10-dBm range.

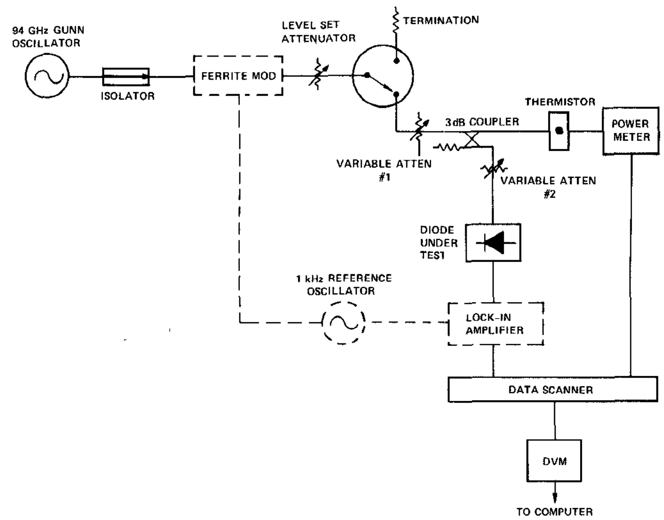

Fig. 1. Experimental configuration for determining diode square law behavior.

TABLE I
Summary of Characteristics for Four Different Diode Types

Diode Characteristic	Silicon Schottky	GaAs(1) Schottky	GaAs(1) Beam Lead	1N53 Point Contact
1. Output voltage at -20 dBm	2.5 mV	3.2 mV	7.9 mV*	0.1 mV
2. Power level below which deviation from square law ≤0.2 dB	-16 dBm	-13 dBm	-32 dBm	-10 dBm*
3. Power level below which deviation from square law ≤0.04	-22 dBm*	No power level (2)	No power level (3)	DNT(4)
4. Frequency of flicker noise corner	50 kHz	2 kHz	2 kHz	1 kHz*
5. Flicker noise at 1 kHz (100 Hz bandwidth)	1 μV	20 μV	4 μV	0.25 μV*
6. White noise (100 Hz bandwidth)	0.1 μV*	5 μV	2 μV	0.2 μV
7. Signal to noise ratio(5)	2500*	160	1975	400
8. Reflection coefficient at -25 dBm	0.2	0.88	0.14*	DNT(4)
9. Power level for 0.02 change in reflection coefficient	-18 dBm	-10 dBm*	-20 dBm	DNT(4)
10. Temperature coefficient	+2.5%/°C	-0.15%/°C*	-0.32%/°C	DNT(4)

****
Notes
* Indicates best response
1. Biased with supplied bias boxes
2. Diode was too noisy
3. Deviation was always ≥0.04 dB
4. Data not taken
5. Row 1 divided by row 5

In the initial experimental procedure, variable attenuator no. 1 is adjusted for minimum attenuation and the power meter is set to 0 dBm using the level set attenuator. Then the thermistor and power meter are placed at the diode under test position and variable attenuator no. 2 adjusted so the power meter reads −5 dBm. This establishes an initial 5-dB difference between the power at the diode and the original thermistor position. The diode and thermistor are then replaced in their original positions, as shown in Fig. 1. Data is obtained by increasing the attenuation in attenuator no. 1, in approximately 2.5-dB steps until the power meter indicates −10 dBm. At this point after the

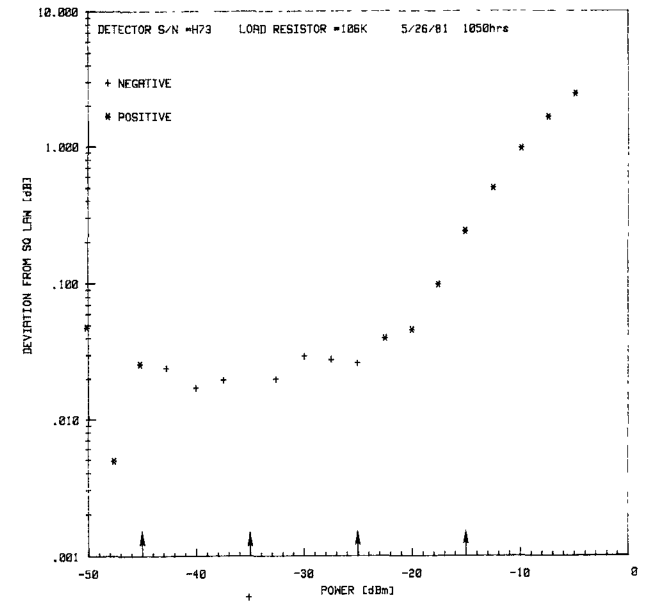

Fig. 2 Deviation from square law versus power for a typical silicon Schottky diode.

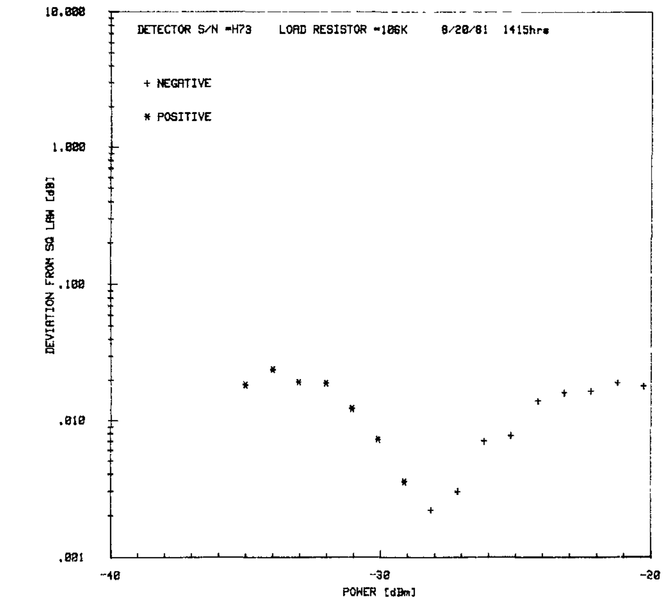

Fig. 3. Deviation from square law versus power for the silicon Schottky diode.

diode voltage v_1 is noted, attenuator no. 1 is returned to its minimum attenuation setting and the attenuation of attenuator no. 2 is increased to return the diode voltage to v_1. Now, with a 15-dB difference between the power at the diode and thermistor, the attenuation of attenuator no. 1 is again increased in approximately 2.5-dB steps. This process is repeated until the power at the diode is about -50 dBm. This resetting of attenuator no. 2 is the largest source of experimental error. It should be noted that prior to the above procedure, an abbreviated test is performed to determine the diode load resistor with the largest square law range. Then, the complete test is done with that load resistor.

Data taken using this arangement is shown in Fig. 2 for a silicon Schottky diode. Note that the deviation from square law remains under 0.05 dB below -20-dBm power levels and reaches a 0.2-dB deviation at -16 dBm. With reference to Table I, the GaAs Schottky and 1N53 were better than this, and the GaAs beam lead was so poor that it is not suitable for six-port applications. Both GaAs diodes were biased with the manufacturer's bias boxes. A close examination of Fig. 2 shows slight jumps in the data where the attenuators are reset at 10-dB intervals. These transition points are indicated by the arrows on the horizontal axis.

To eliminate this error, a second experiment was designed with a reduced power range of -20 to -35 dBm. However, this reduced range still covers the full dynamic range expected at the six-port detector ports. The experimental arrangement is similar to Fig. 1 with several changes. The components indicated by the dash lines—the ferrite modulator, reference oscillator, and lock-in amplifier—are removed. The lock-in amplifier is replaced by a chopper stabilized dc amplifier. This substitution is made to avoid lock-in amplifier scale changes and because of a suspicion that discharges from the blocking capacitor in the lock-in amplifier were damaging the diodes. In addition, the 3-dB coupler is replaced by a 20-dB coupler.

In the experimental procedure, the power incident on the diode is changed from -20 dBm to -35 dBm in 1-dB steps using attenuator no. 1. The corresponding change at the power meter is $+5$ to -10 dBm. The largest sources of error are the power meter which has a maximum error of 0.2 percent, and the amplifier which has an estimated error of 0.4 percent at -35 dBm.

An experimental result for the same silicon Schottky diode with this new configuration is shown in Fig. 3. Here, the maximum deviation from square law is always less than 0.025 dB over the -20 to -35 dBm. The change in the sign of the deviation from square law below -29 dBm is caused by errors in the offset subtraction due to noise. In comparing Fig. 2 with Fig. 3 over the same -20 to -35-dBm power level, it is seen that in Fig. 2 the deviation from square law is between 0.02 and 0.04 dB, while in Fig. 3 it is always below 0.025 dB. This maximum deviation of 0.025 dB is considered to be closer to the actual deviation because of the better experimental method. Similar data for the GaAs Schottky diode could not be taken because of large errors due to noise.

B. Noise

The higher the signal-to-noise ratio at the diode output, the lower the value of reflection coefficient that can be measured with the six-port. The diode noise was measured using a Hewlett-Packard 3580A low-frequency spectrum analyzer. The relevant noise properties of flicker and white noise are given in Table I. Note that the noise of the GaAs Schottky is roughly 20 times that of the silicon, and the noise of the GaAs beam lead is roughly 4 to 20 times that of the silicon depending on the frequency of the noise. The higher noise of the GaAs diodes is due partly to the bias requirement of these diodes. Fig. 4 is a spectrum analyzer photograph of the noise spectrum of the silicon Schottky diode. It also shows the increase in the noise when the diode is biased.

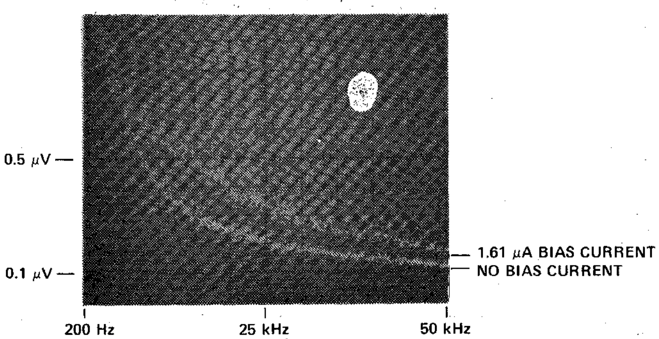

Fig. 4. Spectrum analyzer photograph showing the increase in flicker noise with current for a typical silicon Schottky diode. The diode is biased to 1.61 μA in the top trace, and is unbiased in the lower trace.

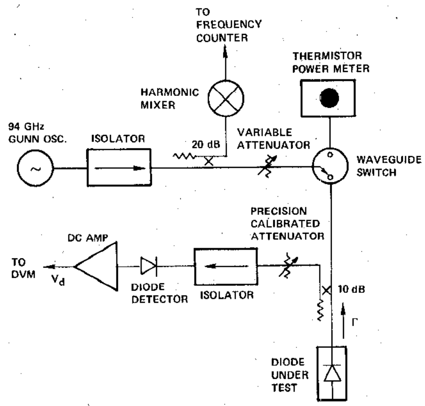

Fig. 5. Experimental setup to measure variation of $|\Gamma|$ with power.

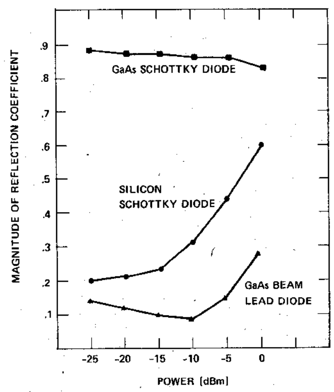

Fig. 6. Variation of the reflection coefficient magnitude versus power for silicon and GaAs diodes.

C. Variation of Reflection Coefficient Magnitude with Power

One of the assumptions made in six-port theory is that the reflection coefficient of the power detectors does not change with incident power level. Otherwise, the calibration constants would not be valid. To examine how well the diodes satisfied this criterion, their reflection coefficient magnitude $|\Gamma_d|$ was measured using the substitution technique shown in Fig. 5. First, the power into the thermistor power meter is set to the desired level. Then with the diode under test (DUT) attached, and the precision calibrated attenuator set to 0 dB, the diode voltage V_d is recorded. The DUT is then replaced with a short, and the attenuator adjusted to obtain the same diode voltage as before. The difference in the attenuator readings is the return loss L_R, and $|\Gamma_d|$ can be calculated using the formula

$$|\Gamma_d| = \text{antilog}_{10}(-L_R/20).$$

The errors in this measurement are due to: a) the finite directivity of the 10-dB directional coupler; b) resettability of the precision calibrated attenuator; and c) the calibration error of the attenuator. The error caused by the 40-dB directivity of the 10-dB coupler is ± 10 percent when measuring a reflection coefficient of 0.1, and ± 2.5 percent when measuring a reflection coefficient of 0.9. The resettability is determined by the noise of the diode and parallax in reading the attenuator with the former being the dominant error. This diode noise error increases as the power decreases, preventing this test from being performed below -25 dBm into the DUT. The maximum error is ± 2.5 percent which occurs at this power when $|\Gamma_d| \approx 0.1$. The minimum error is ± 0.25 percent and occurs at 0 dBm when $|\Gamma| \approx 0.9$. The calibration error of the precision calibrated attenuator is 0.1 dB. Considering all these factors, the largest error is caused by the directivity and is no greater than ± 10 percent.

The reflection coefficient versus power is shown in Fig. 6 for the three types of diodes. Within the error of the measurement, the reflection coefficient of the GaAs Schottky diode does not change over a power range from 0 to -25 dBm. The silicon Schottky diode has a large change in reflection coefficient over this power range, but within its square law range (< -20 dBm) the two experimental points show no meaningful variation. The GaAs beam-lead diode also has a large variation of the reflection coefficient in the tested power range. However, no conclusions can be drawn about the variation in its square law range which occurs well below -25 dBm. Within the square law range of the silicon and GaAs Schottky diodes, the variation of the reflection coefficient is small and will not impair their use in six-port network analyzers.

D. Stability

Stability of the six-port system is necessary to avoid frequent recalibration. The diodes are the most temperature sensitive components in the system, and to a first approximation their temperature dependence can be calculated from the diode current–voltage equation [6]. Under the square law approximation, this functional dependence is $(1/T)^2$, which results in a temperature coefficient (TC) of the voltage sensitivity of approximately -0.7 percent/°C.

Experiments were performed from 25°C to 35°C to measure the TC of the diodes. The silicon Schottky diode TC was determined to be $+2.5$ percent/°C. This is significantly different from the theoretically predicted value in both magnitude and the sign of the slope. The cause of this large deviation is unknown to the authors. One conjecture is that the impedance match of the diode to the waveguide is itself temperature dependent. The TC of the GaAs Schottky and beam-lead diodes is -0.15 percent/°C and -0.32 percent/°C, respectively. Here the sign of the slope is correct, but the TC is smaller than predicted by the theory.

Although these various temperature dependences are not well understood at this time, the results indicate that

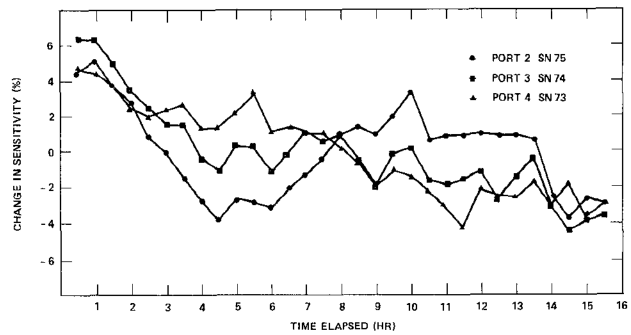

Fig. 7. Long term stability of silicon Schottky diodes.

sufficient stability for six-port applications can be achieved with commercially available temperature controllers. For example, commercial proportional controllers are able to control the temperature of the diode to within $\pm 0.07°C$. This should result in a stability of ± 0.2 percent for the silicon diode, ± 0.01 percent for the GaAs Schottky diode, and ± 0.02 percent for the GaAs beam-lead diode. To determine whether these stabilities were achievable, long-term stability tests were performed with the diodes attached to their respective ports on the six-port junction. The temperature of the diodes was kept to within $\pm 0.07°C$ and the Gunn oscillator to within $\pm 0.1°C$. The voltage of the diodes, normalized to the incident power, was recorded every half hour for 15 h. The variation in this ratio is a measure of the stability of the diodes.

The results of the long-term stability test are shown in Fig. 7 where the change in voltage sensitivity of three temperature stabilized silicon diodes is plotted as a function of time. The maximum variation in sensitivity is ± 0.4 percent after discounting the variations in the first two hours due to equipment warm-up. These variations are twice that predicted from the temperature changes along, and may be caused by the diode mount and/or the six-port junction's characteristics changing with temperature.

III. Computer Simulation

A computer simulation of the single six-port measurements of reflection coefficients was performed to determine the effect of nonideal diode characteristics on the accuracy of the six-port measurement. The simulation allows one to separately evaluate the inaccuracy due to different kinds of nonideal behavior and to determine how much deviation can be tolerated for a specified accuracy. In particular, the effect of the diode's noise and deviation from square law was examined.

The ideal six-port is described by the following equations [11]:

$$V_1 = K_1$$
$$V_2 = K_2|\Gamma - q_2|^2$$
$$V_3 = K_3|\Gamma - q_3|^2$$
$$V_4 = K_4|\Gamma - q_4|^2. \quad (1)$$

V_1, V_2, V_3, and V_4 are the voltages of ideal diodes and are proportional to the power at the ports. The K's are multiplying constants used to adjust these voltages to approximately match those in actual measurement, Γ is the reflection coefficient of the device under test, and the q's are the q points of the six-port junction. These ideal voltages are used as "seeds" to model the specific nonideality under study.

The deviation from square law may be modeled by the equation

$$V_n' = V_n \times (1 + D \times V_n) \quad (2)$$

where V_n, $n = 1 \cdots 4$ are the voltages taken from (1), and D determines the deviation from square law at the maximum diode voltage.

The model equation for a noisy diode is taken to be

$$V_n'' = V_n \times (1 + (\mathrm{RND} - 0.5)/N1) + (\mathrm{RND} - 0.5/N2). \quad (3)$$

Again, the V_n are the voltages taken from (1). RND is a random number between 0 and 1 generated by the calculator used in this simulation, while $N1$ and $N2$ are constants that determine the level of the noise. The first term which represents noise that is proportional to the diode voltage, (i.e., power), is predominant at high-voltage levels and is due to the millimeter-wave source noise. The second term which represents additive noise, is predominant at low-voltage levels and is associated with diode noise. In the simulation, these voltages are truncated to six decimal places to approximate the digital voltmeter accuracy. The error is the difference between the reflection coefficient calculated with V_n and with V_n' or V_n''.

The simulation was done on a Hewlett-Packard 9835A desktop calculator using a program taken from the measurement software. The calibration procedure used is the six-port to four-port reduction scheme developed by Engen [12]. It was found that the errors due to deviation from square law are independent of the magnitude of the measured reflection coefficient and are approximately 0.45 percent in magnitude and $\pm 0.5°$ in angle for a square law deviation of ± 0.04 dB; and 0.32 percent in magnitude and $\pm 0.3°$ in angle for a square law deviation of ± 0.02 dB.

When $N1 = 1000$ and $N2 = 5000$, (3) simulates the noise of the silicon Schottky after dc amplification. The standard deviation in the magnitude of the reflection coefficient for this noise level is 0.0002 when $|\Gamma| = 0.1$ and 0.01. It should be noted that when $|\Gamma|$ is low, the source noise predominates over the diode noise. This is because, in this case, the diode voltages are relatively high for any angle of Γ, and are, therefore, operating in the region where the source noise dominates.

IV. Amplification and Detection Techniques

The accuracy of six-port network analyzers depends on the resolution with which the power at its ports can be determined. Since the diode voltage is at most a few millivolts, amplification is required to improve resolution. Therefore, the diode voltage detection or measurement technique has a direct bearing on the accuracy of the six-port measurements. We investigated two possible detection methods: a dc scheme using a cw source with dc amplifiers and a six-digit digital voltmeter (DVM); and an ac scheme using a modulated source with tuned amplifiers followed by a second detector. The second detector is an ac to dc converter which provides a means of accurately measuring the ac voltage. The relevant characteristics of these two techniques which affect six-port accuracy are the gain linearity and the SNR. Here the SNR is defined as the ratio of the average voltage to the standard deviation in a sample of voltages.

A. DC Amplification

The dc detection technique is the simplest, requiring only commercially available chopper stabilized amplifiers and an accurate six-digit voltmeter. These amplifiers have excellent gain linearity but the SNR is limited because of operating in the flicker noise region of the diode. The $1/f$ characteristic of flicker noise has been observed at frequencies as low as cycles per day. Thus, averaging will not increase the SNR since any reasonable averaging time will be short compared to the very low-frequency components of the noise voltage. Using chopper stabilized amplifiers with pre- and post-voltage filtering, we have measured SNR's of the amplified silicon Schottky diode voltage in the 500 to 3000 range in actual six-port measurements. This technique is currently the best scheme for measuring the diode voltages.

B. AC Detection

The ac detection technique has the potential of increasing the SNR by operating outside the flicker noise region of the diode. Therefore, the power must be modulated at a frequency above the flicker noise corner frequency which is 10 kHz to 50 kHz for the silicon Schottky diode. Currently, there are no modulators available with this speed and with attenuation > 20 dB in the off mode. However, at least one manufacturer is developing a p-i-n switch that will meet these specifications.

A potentially serious problem of the ac detection scheme is poor gain linearity because of distortion in the second detector. To evaluate this problem, an ac detection circuit was built using tuned amplifiers and the true RMS detector available as an option with the Fluke model 8502A DVM. The gain nonlinearity was measured to be 0.5 percent at 30 mV and increased linearly as the voltage decreased. This is approximately the same error obtained with dc amplification due to offset subtraction at low-voltage levels. Therefore, this ac technique is no more accurate than the dc technique and has the disadvantage of being more complicated. However, new integrated circuit chips may have better gain linearity at lower voltages.

V. Conclusion

The main conclusion is that the silicon Schottky diode is currently the best commercially available diode for use in millimeter-wave six-port applications. It combines excellent sensitivity and noise characteristics with a modest, but sufficient, square law range to make a fairly accurate power detector. The temperature coefficient of its voltage sensitivity is rather high but it is possible to economically control its temperature with commercially available controllers. However, the potential user should be warned that these diodes are quite susceptible to damage by small static charge and noise spikes. Although considerable care was taken during the experiments, many diode failures occurred.

The next closest contender is the GaAs Schottky diode. Although it has a much larger square law range, this results in very little advantage because of its high noise. It is not passivated and changes in humidity will cause variations in its voltage sensitivity. Another drawback of this diode is that it must be biased, thus adding another source of error. The GaAs beam-lead diode cannot be used in six-port applications because of its poor square law behavior.

A new zero biased silicon Schottky diode has recently been reported [13] which has approximately the same sensitivity as the silicon Schottky diode reported here but much lower video impedance resulting in lower noise. As of this writing this new device has not been available for testing.

The potential advantages of ac detection cannot be realized at this time because of the unavailability of fast millimeter-wave modulators and the poor linearity of second detectors. However, improved devices in both areas may soon be obtainable. Therefore, for the present, the dc detection technique is the best method for amplifying diode voltage in six-port network analyzers.

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References

[1] G. F. Engen and C A. Hoer, "Performance of a dual six-port automatic network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-27 pp. 993–998, Dec. 1979.

[2] H. M. Cronson and L. Susman, "A dual six-port automatic network analyzer," *IEEE Trans Microwave Theory Tech.*, vol. MTT-29, pp. 372–378, Apr. 1981.

[3] C. A. Hoer, "A high-power dual six-port automatic network analyzer used in determining biological effects of RF and microwave radiation," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, pp. 1356–1364, Dec. 1981.

[4] M. P. Weidman, "A semiautomated six-port for measuring millimeter-wave power and complex reflection coefficient," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1083–1085, Dec. 1977.

[5] H. M. Cronson and R. A. Fong-Tom, "A 94-GHz diode-based single six-port reflectometer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 1260–1264, Aug. 1982.

[6] G. U. Sorger and B. O. Weinschel, "Comparison of deviation from square law for RF crystal diodes and barretters," *IRE Trans. Instrum.*, pp. 103–111, Dec. 1959.

[7] A. M. Cowley and H. O. Sorenson, "Quantitative comparison of solid-state microwave detectors," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-14, pp. 588–602, Dec. 1966.

[8] C A. Hoer, K. Roe, and C. Allred, "Measuring and minimizing diode detector nonlinearity," *IEEE Trans. Instrum. Meas.*, vol. IT-25, no. 4, pp. 324–329, Dec. 1976.

[9] K. Ishii and A. L. Brault, "Noise output and noise figure of biased millimeter-wave detector diodes," *IRE Trans. Microwave Theory Tech.*, pp. 258–262, July 1962.

[10] F. L. Warner, "Detection of millimetre and submillimetre waves," ch. 22, in *Millimetre and Submillimetre Waves*, F. A. Benson, Ed. London: Iliffe, 1969.

[11] G. F. Engen, "The six-port reflectometer: An alternative network analyzer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-25, pp. 1075–1080, Dec. 1977.

[12] 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.
[13] A. R. Kerr and Y. Anand, "Schottky-diode millimeter detectors," *Microwave J.*, vol. 24, no. 12, pp. 67–71, Dec. 1981.

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A Quasi-Optical Polarization-Duplexed Balanced Mixer for Millimeter-Wave Applications

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Abstract —**An integrated planar antenna-mixer structure for use at millimeter-wave frequencies is described. A simple but accurate theory of the slot-ring antenna is applied to several experimental devices. Mixer conversion loss of about 6.5 dB was obtained from an *X*-band model. Measured radiation patterns of structures designed for 65 GHz agree reasonably well with theory.**

I. Introduction

As MILLIMETER-WAVE systems increase in complexity, a strong need arises to simplify each component to the utmost extent. What may be a practical size for a single receiver front end (antenna, mixer, and associated waveguides) becomes highly impractical if one tries to build an array of such receivers. The planar structure described in this paper combines the functions of receiving antenna and balanced mixer in one simple metallized pattern on a dielectric substrate, which indeed can be the semiconductor from which the mixer diodes are formed. A working model tested at *X*-band gave a conversion loss of 6.5 ± 3 dB, and actual devices designed for use above 30 GHz yielded antenna radiation patterns which agree with the theory developed in this paper. Detailed discussion of operation will begin with the antenna structure itself.

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II. Slot-Ring Antenna

The slot-ring antenna is one of a class of radiating structures formed from a gap or hole in an otherwise continuous metallic sheet. The sheet may or may not be backed on one side by a dielectric layer. In this paper, both the conducting sheet and the dielectric are assumed to be lossless. The slot-ring structure is the mechanical dual of the more familiar microstrip-ring resonator (see Fig. 1). The microstrip ring is a segment of microstrip bent into a loop; the slot ring is a segment of slot line bent into a loop. Slot line, first described by Cohn [1], has recently found application in millimeter-wave mixers [2]. The technique of bonding mixer diodes across the slot results in a connection with minimum stray inductance. This advantage is utilized in the mixer to be described.

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