Measuring Beam Leaded Diodes Nondestructively

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Abstract —**A vacuum fixture for the characterization of beam leaded diodes (BLD's) is described along with measurement data showing that nominal 0.020-pF p-i-n diodes can be evaluated with ±0.01 pF and ±0.24 Ω.**

I. Introduction

Beam LEADED diodes (BLD's) enjoy increasingly widespread uses today in microwave hybrid circuits. Because they are so small, 35×12×5 mils as shown in Fig. 1, they have extremely small parasitic reactances when mounted suitably in microstrip, strip line, or coplanar waveguide. A beam leaded p-i-n diode can provide usable switching performance at up to 40 GHz, and they are routinely used in broad-band applications from 1 to 18 GHz [1], [2]. This paper describes results obtained with p-i-n diodes, but similar high-frequency utility exists for Schottky detector and mixer BLD's [3] and the measurement approach is equally applicable.

Microwave BLD's are so small that they easily pass through the holes of a pepper shaker, a disadvantage in the execution of microwave measurements. Most microwave engineers delegate the measurement task to circuit assembly personnel, who routinely bond small components into hybrid circuits using a microscope for visual aid. Although BLD's have been available for ten years, practically no progress has been made in their efficient microwave characterization.

Common measurement practice for p-i-n beam leaded diodes has been to evaluate the capacitance C (Fig. 2) at low frequency, usually 1 MHz, and to calculate the corresponding isolation which would be obtained at microwave frequencies when that diode is mounted in series with a transmission line, the typical switching circuit configuration. Previously, the forward-biased resistance R_F was not measured for all of the diodes; rather, samples would be welded (thermocompression bonded), soldered, or epoxied into a transmission line test fixture, within which both isolation (at reverse bias) and insertion loss (at forward bias) could be measured at microwave frequencies. However, the BLD's fragility precludes removal from such a test cicuit without destroying it. Hence, the customary

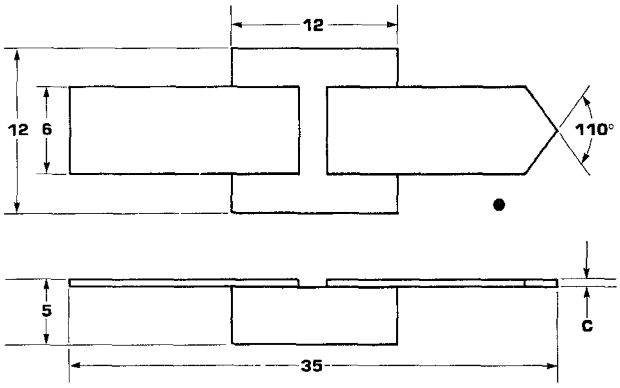

Fig. 1. Outline drawing of the M/A-COM p-i-n beam lead diode.

microwave measurement approach in effect is destructive, and usable only on a sample basis.

Reliance on low-frequency capacitance measurements is not very satisfactory. A typical beam leaded p-i-n has only about 0.020 pF of capacitance. While 1-MHz capacitance bridges can resolve as little as 0.001 pF, the reproducibility of a measurement is usually limited by the fringing capacitance of the test leads, which must be a pair of needle points to measure beam leaded diodes, as well as by the method employed to set the capacitance zero of the measurement set-up with the diode removed. A typical measurement reproducibility variation of ±0.002 pF, and up to ±0.005 pF or more in some cases, can be expected, corresponding to a SPST series switch isolation of 18.1 dB at 10 GHz with ±0.8 dB error typical, ±1.9 dB maximum predicted error. An ancillary problem with 1-MHz measurements is that needle point probes cause diode lead deformation, sometimes even breakage.

Nor do sample-based microwave insertion loss measurements produce results that are relatively any more consistent. Beam leaded p-i-n diodes from a single wafer may have R_F values of 3–8 Ω, corresponding to a microwave insertion loss range of 0.3–0.7 dB in a 50-Ω line. Measurement of reverse-biased resistance R_R, presumed comparable to the magnitude of R_F, is not usually performed, owing to the difficulty of measuring such a high Q and the practical fact that R_R contributes much less dissipative loss than R_F in typical applications.

An additional limitation of a sample-testing manufacturing strategy for BLD's is that matched sets of diodes cannot be identified usefully since this requires a

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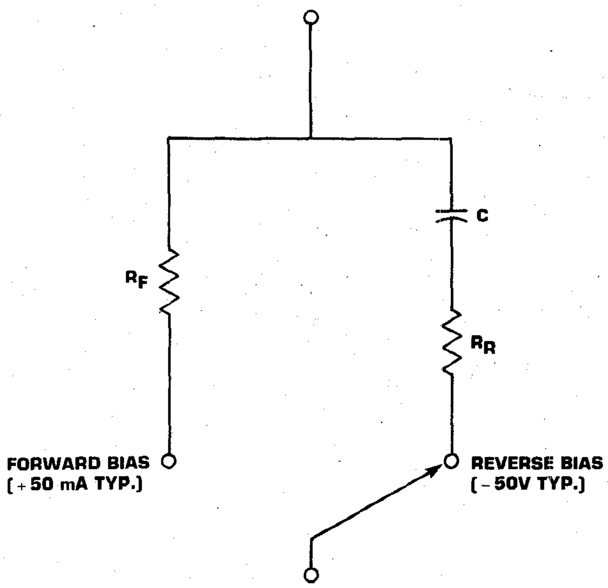

Fig. 2. Beam lead p-i-n diode equivalent circuit.

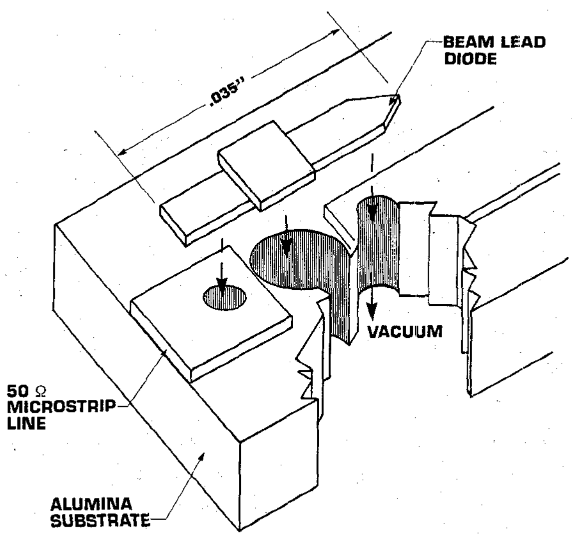

Fig. 3. Beam lead diode and microstrip circuit with vacuum hold-down.

nondestructive individual measurement of all of the candidate specimens.

II. Approach

Our approach is to measure the BLD at microwave frequencies in a microstrip line fixture, replacing the destructive permanent attachment of the diode with a vacuum hold-down method. Fig. 3 is a sketch of the fixture. The diode is positioned above a hole about 7 mils in diameter centered in a gap in the line. Additional 3-mil-diameter holes are located beneath each beam lead. A vacuum supply through these holes of only 1 psi will provide a total of 24 mg of downward force on the diode. The diode weighs only 0.05 mg. Consequently, the most modest laboratory vacuum supply easily provides a hold-down force 100 times greater than the BLD's weight.

Fig. 4 is a photograph of the test fixture. It consists of a 10-mil ground plane spacing, alumina substrate, 50-Ω microstrip line with the three vacuum holes, and the BLD mounting site. The microstrip line has two 90° bends so that both launches to 3-mm coaxial connectors are located on a common edge of the substrate. This permits the substrate to be butted against the connector flanges with no air gap, a serious source of impedance discontinuity.

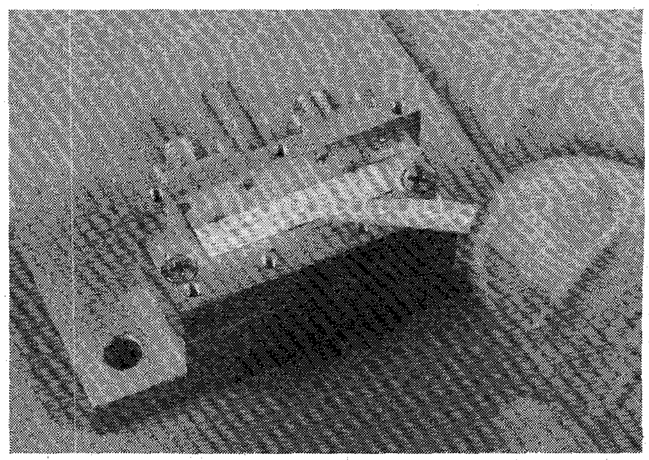

Fig. 4. Overall view of the test fixture. A beam lead p-i-n, wetted with alcohol to the end of a plastic quill, is being conveyed to the gap in the line.

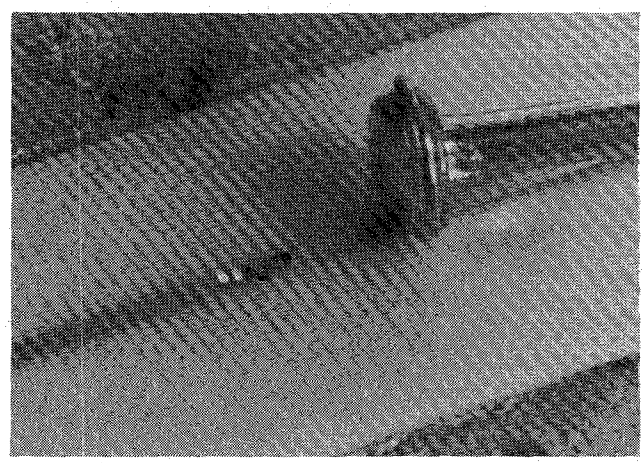

Fig. 5. Close-up of a beam lead diode in the test fixture. A common straight pin rests on the 10-mil-wide center conductor as a size comparison.

An appreciation for the small size of the beam leaded diode fixture can be obtained from Figs. 4 and 5. In Fig. 4 the BLD is being conveyed on the end of a quill to the test site, and it is barely visible as a speck on the quill's point. In Fig. 5 the diode can be seen on the microstrip line. For size comparison a standard straight pin, of the kind one finds in a new shirt, has been laid on the 10-mil-wide microstrip line. The beam lead shows electrode marks from previous 1-MHz measurements.

III. Results

The swept return loss of the fixture, with a 10-mil gold shorting strap at the diode measurement gap, is shown in Fig. 6. The return loss of the fixture, connectors, and network analyzer is below −20 dB over the 2–12-GHz

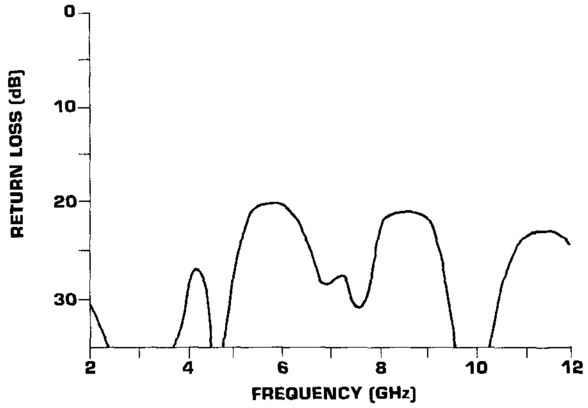

Fig. 6. Swept return loss measurement, 2–12 GHz, of the test fixture with a 10-mil strap bridging the beam lead test gap.

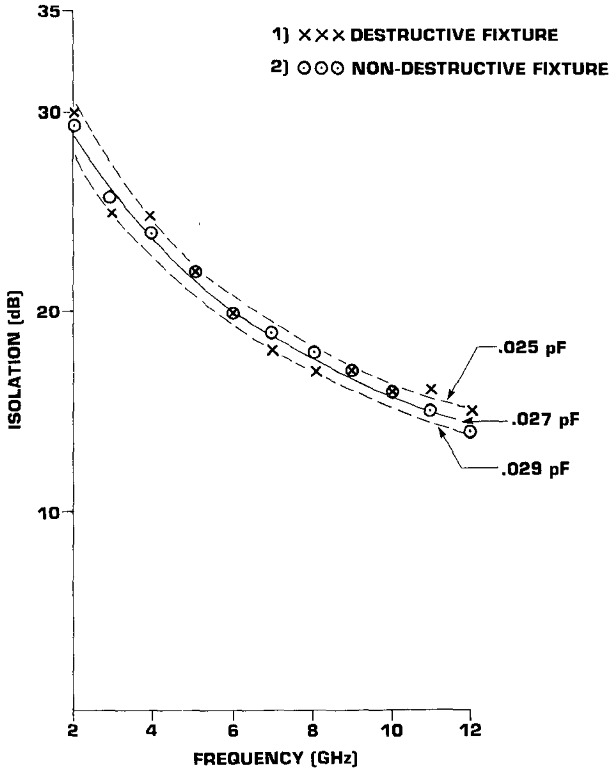

Fig. 7. Isolation versus frequency measurements for a single beam lead in [1] the nondestructive fixture and [2] a destructive fixture.

band, corresponding to an equivalent pair of discontinuities having SWR of about 1.1 each. Return loss increased appreciably above 12 GHz, inhibiting measurements above this frequency. However, as will be seen, the equivalent C and R_F values are essentially constant to 12 GHz, suggesting that isolation and loss calculations to 18 GHz could be made with good approximation. When the shorting strap was removed, the isolation produced by the 10-mil gap in the center conductor was found to be 34 dB at 10 GHz. This corresponds to a fringing capacitance of the test fixture of only 0.003 pF, the low value a result of the small, 10-mil ground plane spacing and the large hole in the substrate at the measurement gap.

A standard 0.02-pF capacitor having the dimensions of a beam lead diode does not exist. Therefore the efficacy of

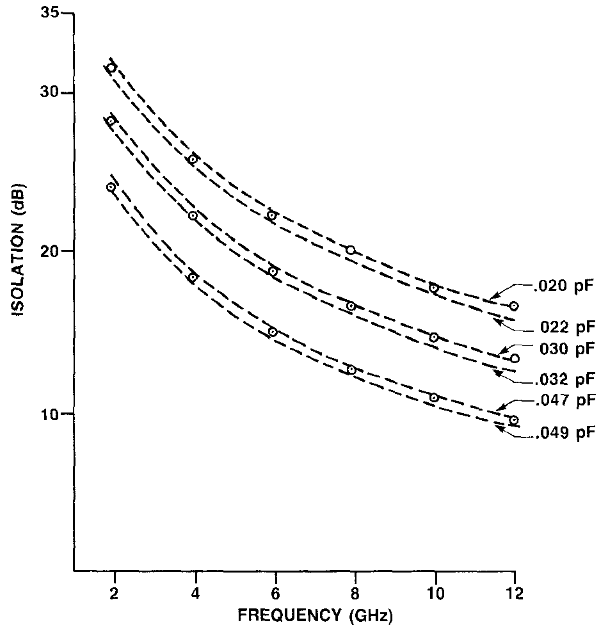

Fig 8. Isolation versus frequency measurements for single beam leads in the nondestructive fixture.

the vacuum jig was tested by a series of comparative measurements.

Fig. 7 shows isolation versus frequency data for a single BLD measured, first, in the vacuum fixture and, second, when thermocompression bonded into a microstrip line in a destructive measurement. The results are similar, with no loss of accuracy resulting from use of the nondestructive fixture.

Fig. 8 shows similar data for three different capacitance diodes. The capacitance curves have been calculated for a series impedance Z at each frequency f using [4, p. 147, eq. (1)]. The results demonstrate that the diode has constant capacitance with a consistency of $\pm .002$ pF over the 2–12-GHz measurement range:

$$\text{Loss/Isolation (dB)} = 20 \text{ Log} |1 + Z/2Z_0| \qquad (1)$$

where

$$Z = R - j/(2\pi f C).$$

Fig. 9 shows the resistance (at +50 mA bias) determined from measured insertion loss for the same three diodes. A consistency of ± 0.4 Ω for 3-Ω nominal resistance diodes is obtained, increasing to ± 0.9 Ω for higher resistance, 9-Ω diodes.

The repeatability of the diode capacitance measured at 1 MHz is shown for two separate groups of ten measurements in Fig. 10, demonstrating a reproducibility of ± 0.003 pF about a center value of 0.032 pF in the first measurement session. A spread in the data of ± 0.0035 pF occurred in a second measurement session except the data were distributed about a center value of 0.030 pF. This shift is commonly experienced and often can be even larger in magnitude. It is likely attributable to a shift in the zero capacitance calibration, a difficult step to perform reproducibly with needle point probes.

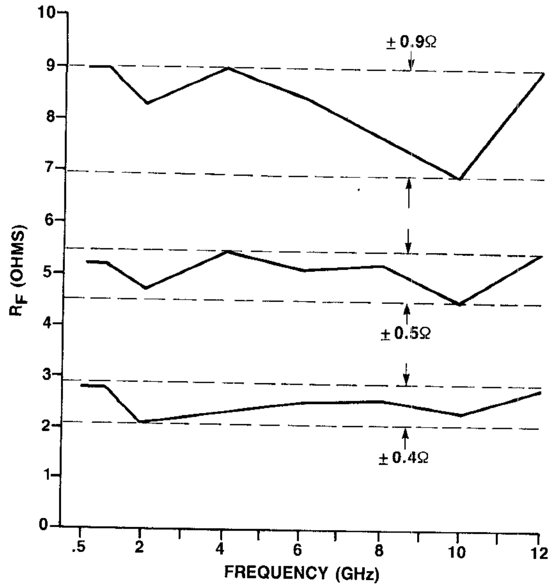

Fig. 9. Resistance determined from insertion loss measurements for three different diodes.

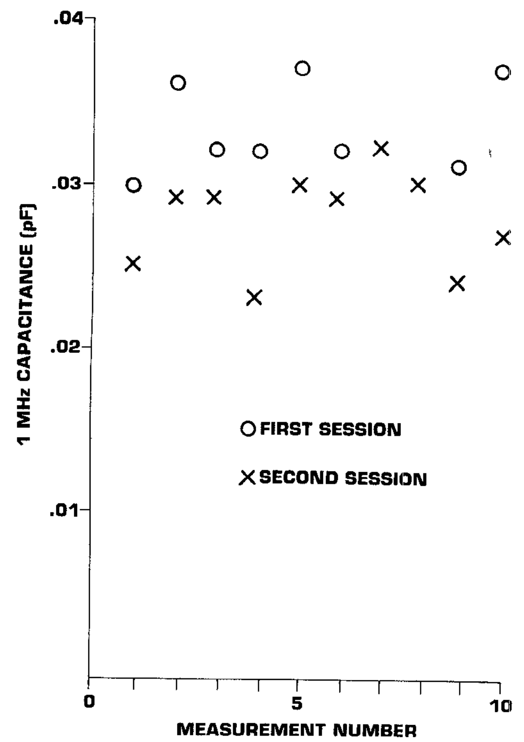

Fig. 10. Reproducibility of 1-MHz capacitance measurement.

By contrast, the data obtained with the vacuum microwave fixture at a single frequency of 10 GHz data realized for the same diode are shown in Fig. 11. The advantages are as follows.

First, both R_F and C are obtained from the same insertion of the diode in the measurement jig. The insertion is the most labor-intensive portion of the BLD's measurement.

Second, the capacitance data spread for all the microwave measured values is smaller, ±0.0015 pF, less than one half the spread obtained in either of the 1-MHz measurement sessions.

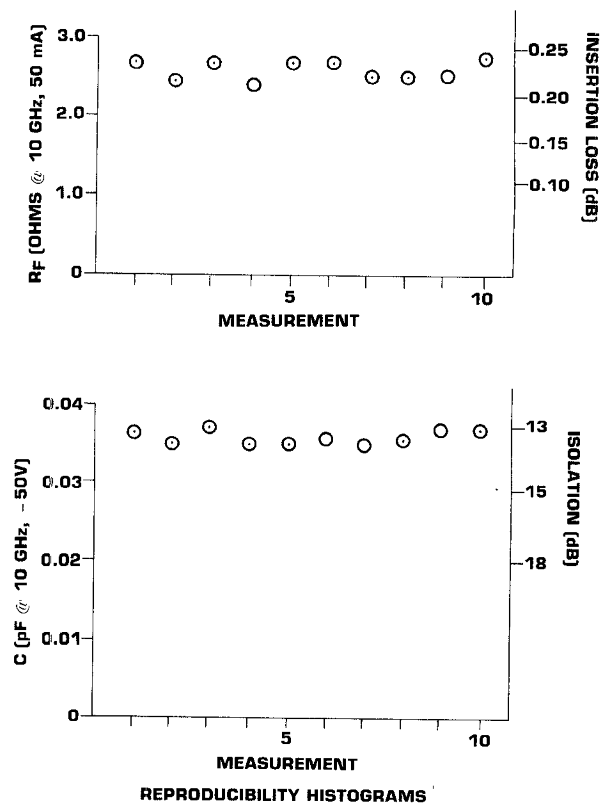

Fig. 11. Reproducibility of 10-GHz measurement using vacuum mount test fixture.

Third, the nominal microwave determined capacitance value, 0.020 pF, is shifted 55 percent from the 0.031-pF average obtained in 1-MHz measurements. As noted, this probably is attributable to the zero reference setting used for the 1-MHz measurement. The 1-MHz bridge was zeroed with the needle probes lifted just off of the diode. Since the BLDC value is usually used to estimate microwave isolation, the 10-GHz isolation derived value of 0.020 pF could be considered the more reliable for microwave applications, an inherent advantage of the 10-GHz nondestructive measurement.

The spread in R_F values (Fig. 11) measured with the nondestructive jig was ±0.24 Ω about a center value of 4.4 Ω when single-frequency, 10-GHz, measurements were made. This represents an unusually precise microwave measurement, corresponding to a loss measurement variation of only ±0.02 dB. Usually, a wider spread is encountered, unless a power measuring setup is employed which corrects for amplitude level variations in the microwave generator used for the measurements. One such device is the HP438A dual-head power meter. The measurement setup employed for these microwave loss and isolation measurements is diagrammed in Fig. 12.

Finally, the capacitance at −50 V of ten BNLD's was measured at both 1 MHz and 10 GHz in the nondestructive test fixture. The results, shown below in Table I, agree within 0.01 pF, suggesting that it is the microstrip line environment which affords the capacitance measurement reproducibility.

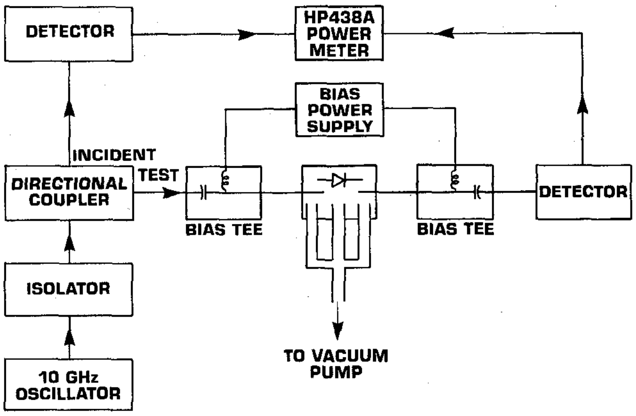

Fig. 12. Beam lead diode transmission measurement test setup.

TABLE I
MEASURED CAPACITANCE AT −50 V

Diode	1 MHz	10 GHz
1.	0.025 pF	0.024 pF
2.	0.029	0.029
3.	0.027	0.027
4.	0.029	0.028
5.	0.026	0.025
6.	0.028	0.028
7.	0.024	0.023
8.	0.026	0.025
9.	0.022	0.022
10.	0.024	0.024

IV. ANALYSIS AND OBSERVATIONS

The most critical parameter to measure for a typical beam leaded p-i-n diode is its effective capacitance at microwave frequencies when embedded in the circuit of use. The common practice of measuring capacitance at 1 MHz using needle point probes is much less accurate than is a measurement in which the BLD is mounted in microstrip. This can be appreciated by noting that the zero capacitance reference can be more reproducibly performed with the microstrip fixture.

The actual fringing capacitance bridging a gap of given width in 50-Ω microstrip line is significantly dependent upon the ground plane spacing of the line and, when employed, the presence and height of a grounded cover for the line.

For example, the vacuum fixture used a 10-mil ground plane spacing with a 10-mil center conductor gap. The capacitance calculated [5] for the 10-mil gap (without the vacuum hole) was 0.0032 pF. This is close to the 0.003-pF value determined from the 10-GHz residual isolation measurement of the test fixture, with the diode removed. However, had a 20-mil ground plane spacing been employed, the calculated capacitance for a 10-mil gap in the correspondingly wider center conductor would have been 0.015 pF.

These calculations demonstrate the sensitivity of the circuit contributions to the effective installed capacitance of a BLD in a microwave transmission line. This suggests the desirability of utilizing not only a microwave circuit characterization of candidate beam leaded diodes but also one which employs as similar a transmission line topology as possible to that of the intended end use.

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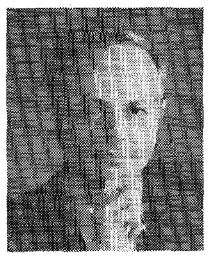

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In addition to numerous IEEE papers for conferences, proceedings, and transactions, Dr White has presented lectures and talks both in the United States and Europe. He is a member of Eta Kappa Nu and Sigma Xia, reviewer for the IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, and author of *Microwave Semiconductor Engineering*, a text on microwave control circuits and semiconductors. He continues, since 1978, as the Consulting Editor for the magazine *Microwave Journal*. The MTT Group awarded Dr. White its Application Award for "The development of practical high-power p-i-n diode phase shifters utilized in various phased array radars."

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