

( $c_{ij}$  being the elements of the transfer matrix of a two-arm junction) and

$$P = dd_r.$$

We have pointed out that to have  $D_1$  and  $D_2$  belonging to the same family it is necessary and sufficient that the corresponding matrices  $P$  verify

$$P_2 = q_1 P_1 q_1^{-1}.$$

Therefore, all the elements of the family have the same equation:

$$\det. (\lambda I - P) = \lambda^2 - [ |c_{11}|^2 + |c_{22}|^2 - |c_{12}|^2 - |c_{21}|^2 ] \lambda + 1 = 0,$$

and the expression

$$T = |c_{11}|^2 + |c_{22}|^2 - |c_{12}|^2 - |c_{21}|^2$$

is an invariant in the family.

- 1)  $T > 2$  is the case that Beatty<sup>1</sup> has considered. By the diagonalization of  $P$ , the intrinsic losses are easily set up.
- 2)  $T = 2$  cannot be diagonalized. One can decompose the two-arm junction into a complex admittance preceded and followed by nondissipative two-arm junctions (one of them being a length of lossless waveguide), and if this two-arm junction is symmetric, it can be decomposed into a complex admittance preceded and followed by two equal lengths of lossless waveguide. In this case, we can theoretically reduce the insertion loss to a value as small as we want.

These notions will be generalized to the  $m$ -arm junctions in a later paper.

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## Correction to "Superheterodyne Radiometers for Use at 70 Gc and 140 Gc"<sup>1</sup>

In Appendix II of the above paper, (9) and (10) should read

$$\omega_s = 2\omega_c + \omega_{IF} \quad (9)$$

$$\omega_i = 2\omega_c - \omega_{IF}. \quad (10)$$

Each  $n$  in (15) and (17) should be an  $\eta$ ; and, in the equation immediately above (18), the large curly bracket should be an integral sign.

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<sup>1</sup> R. Meredith and F. L. Warner, "Superheterodyne radiometers for use at 70 Gc and 140 Gc," IEEE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-11, pp. 397-411; September, 1963.

## Measurements of Varactor Diode Impedance

### SUMMARY

Impedance measurements of varactor diodes have been made on a slotted line in the frequency range 2-18 Gc. The experimental technique is described, and a method for deriving a simple lumped equivalent circuit is shown. Typical circuit values are quoted.

### INTRODUCTION

In earlier microwave measurements of varactor diodes, e.g., by Houlding,<sup>1</sup> Harrison,<sup>2</sup> and Mavaddat,<sup>3</sup> the work has been done in such a way that the circuit values derived have been those of the actual semiconductor junction, rather than over-all values for the complete encapsulated diode. In general, the method used involved matching the varactor diode and its mount to the waveguide or line and studying the variations in impedance at a chosen reference plane as the bias was altered. The measurements have usually been made at a single frequency.

This approach to the problem has difficulties; there are, for example, uncertainties due to losses in matching components and in the correct choice of reference planes. It is nevertheless quite helpful to varactor diode manufacturers as the technique gives results which apply to the semiconductor junction alone, regardless of the encapsulation.

The microwave circuit designer has, however, almost the opposite problem. He is particularly concerned with the impedance properties of the encapsulated varactor package for various ranges of frequencies. The method described in this communication was developed with this purpose in mind and the results should be of particular interest to the designers of parametric amplifiers.

A direct microwave measurement technique was employed, using normal methods for measuring high mismatch on a slotted line. The results showed that the varactors could be successfully represented by a simple lumped constant circuit, with circuit values close to those quoted by the manufacturers for the junction.

### MEASUREMENT TECHNIQUE

The physical form of the diodes measured is as shown in Fig. 1(a). In early experiments, the diode was mounted in a simple collet, and measured on a 50-ohm slotted line, with an  $N$ -type connector between the diode and the line. The results of these experiments showed that the connector and the collet caused an appreciable perturbation of the results, and a simpler mounting arrangement was devised. This is shown in Fig. 1(b). The diode was mounted directly at the end of the 50-ohm slotted line, being

held in position by gentle pressure from the inner conductor. In this arrangement the diameter of the inner conductor of the line is the same, or very nearly the same, as the diameter of the end caps of the diodes. This avoids discontinuity capacitances which might be confused with the stray capacity of the diode itself. A reference plane was chosen 0.020 inch inside the diode as shown in Fig. 1(b), and a short circuit could be provided across the line at this plane, which corresponds to the inner edge of the brass cap. When this short circuit was in place, the position of this reference plane, with respect to the scale of the slotted line, could be found by measuring positions of minima.

Having established the reference plane, impedance measurements of the diodes could be made by normal slotted line methods. However, several precautions had to be taken.

First, the input power had to be kept below a certain level, as the impedance of the varactor diode was affected by power level. This upper limit of power was that, giving a voltage of 1 mv across the diode. A convenient way of ensuring that the power was low enough was to use the slotted line method in which source and detector of the slotted line are interchanged.<sup>1</sup> In this method, the load and the detector operate at comparable power levels; in some other methods the power level at the probe is some 20 or 30 db below that at the load and it is more difficult to obtain sufficient sensitivity.

Second, the VSWR of the diodes was very high. Because of this, the double minimum method<sup>4</sup> of impedance measurement was used. In this method, measurement is made of the distance  $\Delta x$  between the two symmetrical carriage positions about a minimum for which the detector reading is twice the minimum reading. For a square-law detector, provided  $S > 10$

$$\text{VSWR} \quad S = \frac{\lambda}{\pi \Delta x}$$

where  $\lambda$  is the wavelength. This method is better for large VSWR values than the conventional one, which would demand calibration of the detector system over a wide dynamic range.

When this method is used with source and detector in the normal positions, the errors due to probe coupling are very low, as the probe is operated in a region of low impedance. Similarly with the probe-feed arrangement, tight probe coupling will introduce little error, as the impedance seen by the probe in the region of the minimum differs little from the probe capacitance only. This gives the constant-current source that this method requires to be accurate. Fig. 2 shows the experimental arrangement. An unmodulated source was used, and the detector output was measured on a valve voltmeter (V.V.M.).

### RESULTS

Fig. 3, page 470, shows some typical results obtained with diode "A." The line is drawn dashed beyond the 12-Gc point since

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<sup>1</sup> N. Houlding, "Measurement of varactor quality," *Microwave J.*, vol. 3, p. 40; 1960.

<sup>2</sup> R. I. Harrison, "Parametric diode Q measurements," *Microwave J.*, vol. 3, p. 43; 1960.

<sup>3</sup> R. Mavaddat, "Diode Q-Factor Measurements," University College of North Wales School of Applied Science; February, 1963.

<sup>4</sup> E. L. Ginzton, "Microwave Measurements," McGraw-Hill Book Company, Inc., New York, N. Y., p. 266; 1957.