The Determination of Diode Resistance from the Transmission Using a Waveguide/Coaxial Line Tee Junction

J. R. G. Twisleton

Abstract—**A method of finding the resistance and conductance of a diode terminating the coaxial arm of a tee junction from the minimum transmission obtained by adjusting the position of the diode, from the effect of an incremental change in this position, or from the frequency bandwidth of the transmission characteristic, is described. The method avoids the direct measurement of high reflection encountered at the extremes of bias with diode terminations. The parameters of the junction needed in the derivation are found experimentally. Allowing for loss in the coaxial line, the resistance of diodes determined at 9.4 GHz was in good agreement with the results of coaxial line measurements at 500 MHz and 3 GHz. The effect of the reactances of the diode capsule, not allowed for in the determination, is considered briefly.**

I. Introduction

FIG. 1 shows a waveguide/coaxial line junction derived from the "door knob" transition [1], which has been widely used as a mount for pin diodes [2]–[4]. The transmission between the waveguide arms depends upon the impedance of the diode as determined by the bias, and the coupling to the coaxial arm, which in this arrangement is modified by the diameter and penetration of a boss into the waveguide. In this paper, a method of finding the resistance or the admittance of the diode at the extremes of bias 1) from the minimum transmission obtained by adjusting the position of the diode, 2) from the change in transmission resulting from an increment in this position, or 3) from the frequency bandwidth of this characteristic above the minimum, is described. Assuming a particular representative circuit, the parameters of the junction needed in the derivation are found experimentally. Allowing for residual loss in the coaxial line, the results of measurements on diodes at 9.4 GHz are given. The resistance with forward bias at a terminal plane in the coaxial line close to the diode is shown to agree well with that determined using a standing wave detector in coaxial line at 500 MHz and 3 GHz. With reverse bias voltage, at 9.4 GHz where the correction for loss was appreciable, the shunt resistance was lower. The effect of the reactances of the diode capsule upon the results is discussed briefly.

II. Theory

From the representative circuit [5] shown in Fig. 2, the voltage transmission coefficient t between the waveguide arms is given by

$$\frac{1}{t} = 1 + \frac{ky_2 + jb_0}{2} \tag{1}$$

where $y_2 = Y_2 Z_c$ is the normalized admittance at a plane in the coaxial line close to the junction, such that for zero loss a short circuit at this plane gives zero transmission. Alternatively, if γ_2 is the voltage reflection coefficient at this plane, then from (1)

$$t = C\frac{1+\gamma_2}{1+A\gamma_2} \tag{2}$$

where

$$A = \frac{2-k+jb_0}{2+k+jb_0} \quad \text{and} \quad C = \frac{2}{2+k+jb_0}.$$

If we now put $\gamma_2 = \Gamma_2 e^{j\phi}$ and consider small changes in t with respect to ϕ about the minimum value of t designated t_m, then as shown in the Appendix,

$$t = t_m - \frac{jd\phi}{k}. \tag{3}$$

At the extremes of bias, the diode will produce almost total reflection. Therefore, putting $\Gamma_2 = 1-\delta$ where δ is a small quantity, in the case of zero susceptance $b_o = 0$, which can be realized in practice, t_m becomes equal to δ/k and (3) simplifies to

$$t = \frac{\delta - jd\phi}{k}, \quad |t| = \frac{1}{k}\sqrt{\delta^2 + (d\phi)^2} \tag{4}$$

as shown in the Appendix.

δ can be expressed in terms of the coaxial line parameters and diode parameters, whilst $d\phi$ can be related to changes in position of the diode δl relative to l at which minimum transmission is obtained, or to changes in frequency δf relative to the frequency f at which minimum transmission is obtained, as follows.

A. Forward Bias Condition

If the normalized resistance of the diode $r_f = R_f/Z_c$ is much less than unity, allowing for the attenuation αl in the length of line leading to the diode and the normalized resistance r_o of the non-contacting short behind it, then

$$\delta = 2(\alpha l + r_0 + r_f).$$

Manuscript received December 22, 1993; revised November 17, 1994.
The author is with EEV Co., Lincoln LN1 1SF, UK.
IEEE Log Number 9410708.

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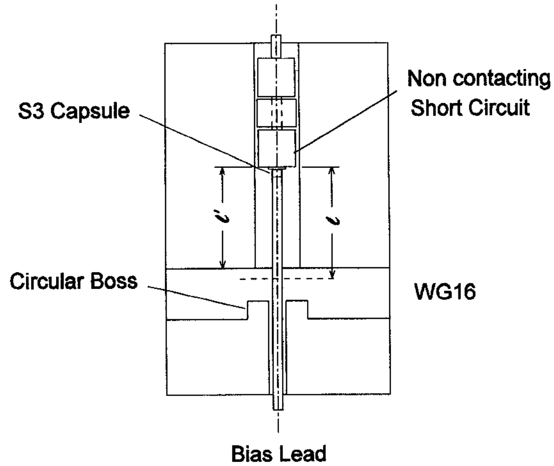

Fig. 1. Diode Mount. Outer dia. of coaxial line = 0.343 in. Inner dia. of coaxial line = 0.093 in. l = distance of short circuit from reference plane. l' = distance of short circuit from face of waveguide.

Differentiating $\phi = \phi_0 - 4\pi l/\lambda$ with respect to l and f we have

$$\delta\phi = \frac{-4\pi l}{\lambda}\left(\frac{\delta l}{l} + \frac{\delta f}{f}\right)$$

and hence from (4)

$$|t| = \frac{2}{k}\sqrt{[\alpha l + r_0 + r_f]^2 + \left[\frac{2\pi l}{\lambda}\left(\frac{\delta l}{l} + \frac{\delta f}{f}\right)\right]^2}. \tag{5}$$

B. Reverse Bias Condition

If the diode is characterized by a conductance $g_r = G_r Z_c$ in parallel with a susceptance b_r, then if g_r is much less than unity

$$\delta = 2\left[\alpha l + r_0 + \frac{g_r}{1 + b_r^2}\right]$$

giving from (4)

$$|t| = \frac{2}{k}\sqrt{\left[\alpha l + r_0 + \frac{g_r}{1 + b_r^2}\right]^2 + \left[\frac{2\pi l}{\lambda}\left(\frac{\delta l}{l} + \frac{\delta f}{f}\right)\right]^2}. \tag{6}$$

Equations (5) and (6) show that for a given k the minimum transmission and the bandwidth of this characteristic, also dependent upon l, is detrmined by the resistance r_f or conductance g_r including the residual $\alpha l + r_0$. Replacing the diode with a short circuit, e.g., a brass diode, the contribution $\alpha l + r_0$ can be determined from the minimum transmission or bandwidth of this characteristic, increasing l in steps of $\lambda/2$ as described in Section III-B.

If the junction susceptance b_0 is zero, minimum transmission occurs when ϕ is an odd multiple of π as stated in the Appendix. Therefore b_r can be found, for $g_r \ll 1$, from

$$b_r = \cot\frac{2\pi l}{\lambda} \tag{7}$$

where l is the distance from any short circuit plane to the reference plane chosen for the diode.

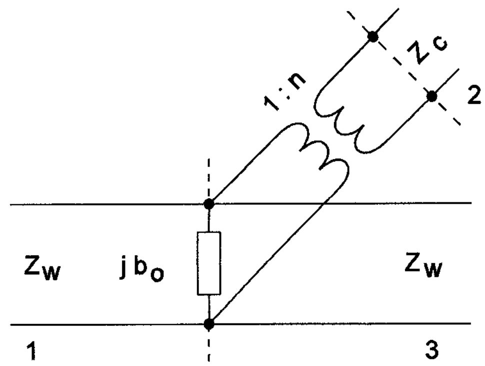

Fig. 2. Representative circuit for tee junction, where $y_1 = 1 + ky_2 + jb_0$, $n^2 = kZ_c/Z_w$.

C. General Case

Alternatively to the use of (5) and (6), for $b_0 = 0$, at $t = t_m$, the admittance y_2 is real at any short circuit plane. Neglecting line loss the normalized impedance $r + jx$, or the admittance $g + jb$ at any other plane at a distance l from a short circuit plane, can be found from the Smith Chart or from the transmission line equations as follows:

$$r + jx = \frac{1 - \Gamma_2^2 - j2\Gamma_2 \sin\phi}{1 + \Gamma_2^2 + 2\Gamma_2 \cos\phi} \tag{8}$$

or

$$g + jb = \frac{1 - \Gamma_2^2 + j2\Gamma_2 \sin\phi}{1 + \Gamma_2^2 - 2\Gamma_2 \cos\phi}$$

where $\arg\gamma_2(l) = \pi + \phi$, $\phi = 4\pi l/\lambda$, and where from (1) the vswr S in the coaxial line, $S = (1 - \Gamma_2)/(1 + \Gamma_2)$ becomes

$$S = \frac{kt_m}{2(1 - t_m)}. \tag{9}$$

Thus a measurement of t_m is equivalent to a measurement of S. If now line attenuation is allowed for, Γ_2 in (8) becomes $\Gamma_2 e^{2\alpha l}$ while S becomes $S - \alpha l$ as in Section IV-A.

III. Determination of Junction Parameters and Residual Loss

A. Junction Parameters

The parameters k and b_0 were found experimentally from the phase of the reflection coefficient γ_1 measured in the waveguide, moving a short circuit in the coaxial line, or from the admittance $y_1 = 1 + k + jb_0$ measured with matched loads, at a reference plane determined using a short circuit in the coaxial line set to give minimum transmission.[1]

For junctions with a boss, k was found to decrease with diameter and height of the boss, with b_0 becoming positive with sufficient penetration, except when the coaxial line was offset laterally. Fig. 3 shows the results obtained for a junction with a 7/16-in.-diameter threaded boss, where for a penetration of 2 3/4 turns, $k = 2.45$ and $b_0 = 0$. Junctions with this size of boss were used for the measurements on diodes, and for the determination of residual loss described as follows.

[1] Alternatively, the parameters might be determined from the field theoretical analyses given in [6] for an unmodified junction, or [7] for a junction with a disc on the coaxial inner conductor.

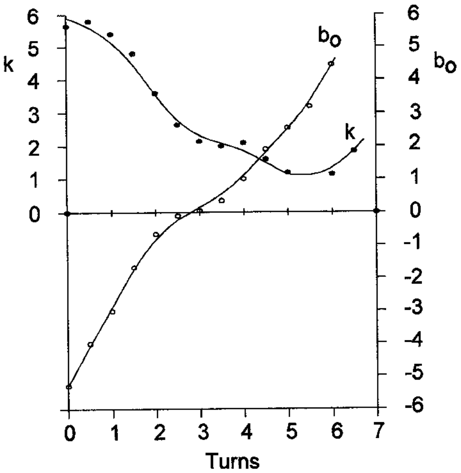

Fig. 3. k and b_0 for mount with boss. Dia. of boss = 7/16 in. threaded 18 turns/in.

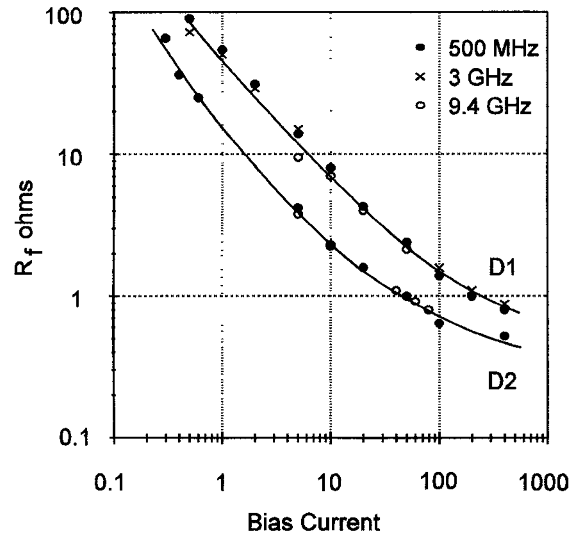

Fig. 4. Resistance R_f versus bias current.

B. Residual Loss

The residual loss in the coaxial line was found using a non-contacting short circuit as shown in Fig. 1. This was set to give minimum transmission at positions corresponding to l = λ/2, λ, and 3 λ/2, where $\lambda = 3.192$ cm. The measured distances $l' = 1.25$, 2.8, and 4.38 cm showed the reference plane closest to the junction to lie 0.34 cm within the waveguide. The quantities

$$\frac{kt_m}{2} = \alpha l + r_0 \quad \text{and} \quad \frac{\pi l}{\lambda} \cdot \frac{\Delta f}{f} = \alpha l + r_0$$

given by (5), where Δf was the bandwidth of the transmission characteristic at 3 db above the minimum were in good agreement at each position of the short circuit. The linear variation of $\alpha l + r_0$ with l gave the attenuation cofficient $\alpha = 0.0012$ Nep/cm from the slope, as compared with $\alpha = 0.00053$ Nep/cm calculated [8], taking the resistivity of the brass inner and outer to be 6.3 10^{-8} Ω meters [9]. For a capsule with internal short circuiting bond wires, the increase in $\alpha l + r_0$ showed a resistance of 0.15 Ω to be introduced, which was small compared with the forward resistance of diodes.

IV. Measurements on Diodes

A. Forward Bias

The resistance $R_f = r_f Z_c$ of pin diodes $D1$ and $D2$ in $S3$ capsules was determined from the minimum transmission t_m where from (1)

$$r_f = \frac{2t_m}{k} - (\alpha l + r_0), \quad \text{for } t_m \ll 1 \tag{10}$$

with k =2.45, l = 1.42 cm, $(\alpha l + r_0) = 5 \cdot 5 \cdot 10^{-3}$, and $Z_c = 78$ Ω. R_f is plotted in Fig. 4 for bias currents up to 60 ma. The resistance was also determined at 500 MHz and 3 GHz with the diodes terminating 50 and 66 Ω coaxial lines, respectively. In this case, $r_f = (S - \alpha l)$ where $S < 1$ was the measured vswr, and αl the correction for line attenuation determined from the slope of standing wave minima, i.e., 2α, with a short circuit termination. As shown in Fig. 4, the resistance at 9.4 Ghz was in good agreement with that at lower frequencies over the range of bias.

B. Reverse Bias

With reverse bias voltage the shunt resistance $R_{sh} = Z_c/g_r$ was determined from t_m and the bandwidth Δf at 3 db above t_m, where from (6) g_r was given by

$$\frac{2t_m}{k} = \frac{\pi l}{\lambda} \cdot \frac{\Delta f}{f} = \alpha l + r_0 + \frac{g_r}{1 + b_r^2}. \tag{11}$$

The difference in l between the forward and reverse states, i.e., δl = 1.66–1.42 cm = 0.24 cm gave b_r = 1.9 at 9.4 GHz. The values of $2t_m/k$ and $\pi l/\lambda \cdot \Delta f/f$, e.g., $7{\cdot}1{\cdot}10^{-3}$ at 120 V, were in good agreement, but the correction for loss $(\alpha l + r_0) = 4{\cdot}8{\cdot}10^{-3}$ was appreciable. The shunt resistance was also found at 500 MHz and 3 GHz, where in this case, the vswr S replaced $2t_m/k$ in (11). R_{sh} is plotted in Fig. 5, where the caption gives the parameters used in the calculations. R_{sh} versus bias voltage is seen to decrease with frequency and at 9.4 GHz, tend to a limiting value with respect to reverse voltage.

C. Effect of Diode Capsule Reactances

At high frequencies, the impedance transformation due to the inductance of bond wires to the diode chip within the capsule, and the capacitance of the alumina sealing ring become important [10], [11]. Assuming the representative circuit for the capsule as shown in Fig. 5(b) of [10], the calculated vswr S, the reflection coefficient Γ, and its phase ϕ at the three frequencies is given in Table I(a) for $R_f = 1\Omega$, $R_{sh} = 5000$ Ω , and $C = 0.4$ pf, (corresponding to $b_r = 1.9$ at 9.4 GHz). Corresponding results are given in Table I(b) for L_1, C_2, etc., zero. The effect of L and C is to retard the phase further than that due to the susceptance $\omega C Z_c$, and to increase Γ as a result of the isolating effect of inductance. As shown in Table I(c) the resistance given by $R_f = S_f Z_c$ as in Section IV-A is overestimated by about 20% at 9.4 GHz, while R_{sh}

TABLE I
C_1 = 0.05 pf, C_2 = 0.212 pf, L_1 = 640 pH, L_2 = 230 pH, Z_c = 78 Ω

(a) Calculated Values for C = 0.4 pf, R_f = 1 Ω, R_r = 5 kΩ							(c) Estimated Values as in Sect. IV-C			
f GHz	S_r	Γ_r	ϕ_r deg.	S_f	Γ_f	ϕ_f deg.	b_r	C pf	R_{sh} kΩ	R_f Ω
0.5	0.0153	0.9698	341.49	0.0128	0.9747	175.98	0.1272	0.5190	5.0002	1.0006
3.0	0.0098	0.9806	262.22	0.0131	0.9741	155.79	0.7477	0.5086	5.1061	1.0214
9.5	0.0026	0.9949	153.45	0.0157	0.9690	99.98	1.9852	0.4264	6.1243	1.2261
(b) Calculated Values for C_1, L_1, C_2, L_2 zero							For C_1, L_1, C_2, L_2 zero			
0.5	0.0154	0.9696	348.80	0.0128	0.9747	180.00	0.0981	0.4003	5.0160	0.9984
3.0	0.0116	0.9771	299.06	0.0128	0.9747	180.01	0.5885	0.4003	4.9940	0.9984
9.5	0.0035	0.9930	236.46	0.0128	0.9747	180.03	1.8638	0.4003	4.9810	0.9984

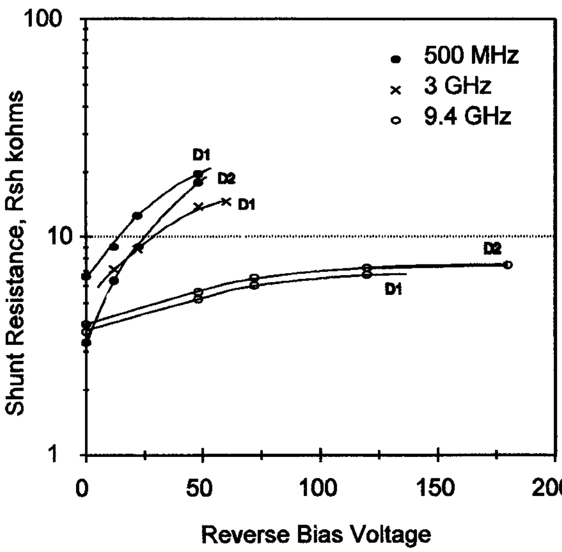

Fig. 5. Shunt resistance R_{sh} versus reverse bias voltage. At 500 MHz, $Z_c = 50\ \Omega$, $b_r = 0.042$. At 3 GHz, $Z_c = 66\ \Omega$, $(\alpha l + r_0) = 6{\cdot}1{\cdot}10^{-3}$, $b_r = 0.67$. At 9.4 GHz, $Z_c = 78\ \Omega$, $(\alpha l + r_0) = 4{\cdot}8{\cdot}10^{-3}$, $b_r = 1.9$.

determined as in Section IV-B where $b_r = \cot(\phi_r/2 - \phi_f/2)$, is also overestimated.

V. Summary and Conclusion

A method of finding the resistance with forward bias, and admittance with reverse bias, of a diode terminating the coaxial arm of a tee junction has been described. The method is closely related to coaxial line measuring techniques such that a measurement of the minimum transmission t_m and distance l is equivalent to a measurement of vswr and relative position of a voltage standing wave minimum. The resistance or conductance at a plane in the coaxial line is determined from the minimum transmission obtained by adjusting the position of the diode, or from the frequency bandwidth of this characteristic above the minimum, easily determined using swept frequency techniques. In particular, the method avoids the direct measurement of high reflection normally encountered at the extremes of bias. The parameters of the junction needed in the derivation were found experimentally for a waveguide/coaxial line junction with a boss in the waveguide terminating the coaxial inner conductor. The coupling factor k was found to decrease with diameter and height of the boss, whilst for a certain height the susceptance of the junction b_0 was zero. This condition, necessary for the method as described, simplified the determination of diode impedance. Allowing for residual loss, the resistance versus bias current of pin diodes was found at 9.4 GHz to agree with that determined at 500 MHz and 3 GHz using a standing wave detector in coaxial lines with the diodes terminating these lines, but the shunt resistance with reverse bias voltage was lower. Errors could arise from uncertainty in the correction for loss and the sensitivity to errors in phase, i.e., l, in this region of the Smith Chart. Assuming an established LC circuit to represent the packaged diode, R_{sh} and R_f were shown to be probably overestimated. However the limiting of R_{sh} with respect to reverse voltage requires further explanation.

Appendix
Expression for t Near the Minimum Value t_m

Putting $t = t_m + dt$, then from (2) where $\gamma_2 = \Gamma_2 e^{j\phi}$

$$dt = \frac{jC\gamma_2(1-A)\,d\phi}{(1-A\gamma_2)^2}. \tag{12}$$

Substituting $\gamma_2 = (t_m - C)/(C - At_m)$ from (2) in (12) and neglecting terms in t_m^2 then $dt = j(t_m + At_m - C)\,d\phi/(1-A)$, equals $jd\phi(2t_m - 1)/k$ if $b_0 = 0$, giving very nearly

$$t = t_m - j\frac{d\phi}{k}. \tag{13}$$

From (2) the locus of t as ϕ is varied is a circle of radius

$$R_t = \frac{|C|\Gamma_2\sqrt{1 + A\overline{A} - (A + \overline{A})}}{(1 - A\overline{A}\Gamma_2^2)} \tag{14}$$

and position of center

$$C_t = \frac{C(1 - \overline{A}\Gamma_2^2)}{(1 - A\overline{A}\Gamma_2^2)} \tag{15}$$

where $\overline{A}$ is the conjugate of A. At $t = t_m$, the argument of $C_t = \arg t_m$ since $|C_t| > R_t$. Therefore, from (2) and (15) putting $\gamma_2 = \Gamma_2 e^{j\phi}$, the phase $\phi = \pi$ at $t = t_m$ independently of Γ_2 if $b_0 = 0$.

The minimum value of $|t| = |C_t| - R_t$ and hence for $b_0 = 0$, that is A real, putting $\Gamma_2 = 1-\delta$, then $t_m = \delta/k$ for δ small so that

$$t = \frac{\delta - jd\phi}{k} \tag{16}$$

as given in the text.

ACKNOWLEDGMENT

This work was carried out at the former AEI Res. Lab., Rugby, UK. The coaxial line measurements were due to J. G. Gissing.

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