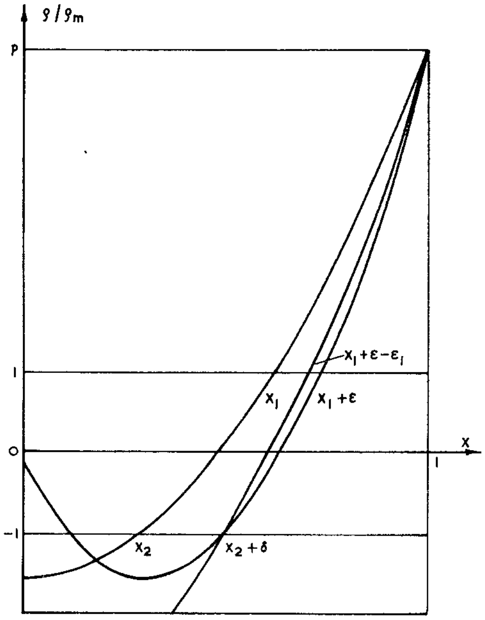

Fig. 8—The normalized reflection coefficient as a function of $x=\cos 2\phi$ for $n=3$ and $n=5$.

line (a step-line consisting of an infinite number of steps) cannot be useful. The application of a continuous taper may be recommended for microwaves if the resulting steps, and the discontinuity capacitances, are large, because the compensation of them will generally result in a narrower bandwidth.

There is always another application where the continuous line is preferable. This is the case when two or more pass bands are required. Because of the periodic structure of the reflection coefficient of step-lines, these requirements may be fulfilled with them only in special cases.

APPENDIX

The parabola for five steps through the points p, $x_1+\epsilon$, $x_2+\delta$ is shown in Fig. 8. The coefficient of the linear term is given by

$$C_1 = \frac{2-(p+1)(x_1+\epsilon)^2+(p-1)(x_2+\delta)^2}{[(x_1+\epsilon)-(x_2+\delta)][1-(x_1+\epsilon)][1-(x_2+\delta)]} \cdot \quad (19)$$

Let us draw now a curve for three steps through the points $x_2+\delta$ and p. This curve cuts the $\rho/\rho_m=1$ line at the point $x_1+\epsilon-\epsilon_1$, where $\epsilon_1>0$[7] and the equation connecting $(x_2+\delta)$ and $x_1+\epsilon-\epsilon_1$ is as follows:

$$2-(p+1)(x_1+\epsilon)^2+(p-1)(x_2+\delta)^2 = -(p+1)\epsilon_1(2x_1+\epsilon-\epsilon_1). \quad (20)$$

We now prove that under the above conditions C_1 is negative. Since the denominator is positive it is sufficient to investigate the sign of the numerator.

Substituting (20) in the numerator of (19) we obtain

$$-(p+1)\epsilon_1[2(x_1+\epsilon)-\epsilon_1] \quad (21)$$

which is negative as far as

$$2(x_1+\epsilon) > \epsilon_1 > 0. \quad (22)$$

Hence C_1 is negative.

ACKNOWLEDGMENT

The author wishes to thank L. Lewin for reading the manuscript, and for a number of interesting and stimulating discussions. Acknowledgment is also made to Standard Telecommunication Laboratories for facilities granted in the preparation of the manuscript and permission to publish the paper.

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[7] ϵ_1 must be positive, because the bandwidth ratio is decreasing as ϕ_2 decreases.

Microwave Semiconductor Switching Techniques*

R. V. GARVER†, E. G. SPENCER‡, AND M. A. HARPER†

***Summary*—This paper describes new microwave techniques employing the properties of *N*-type germanium diode switches. For applications requiring very high isolations, multiple switches are added in tandem. With proper spacing, they form antiresonant cavity circuits. In this case the isolations and insertion losses in db are directly additive. A switch is described which is normally ON and is pulsed OFF. Finally, details are given of a switch in a hybrid-tee configuration in which switching isolations of 50 db are obtained with an insertion loss of 0.7 db.**

INTRODUCTION

IN a previous publication,[1] a description is given of the low-power microwave semiconductor switch using *N*-type germanium. The switch consists of a germanium, point contact, diode placed across a section of standard *X*-band waveguide. Isolations of 25 to 35 db, with insertion losses of 1 db, are obtained over a 1000-mc bandwidth. The switching characteristics are

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[1] M. A. Armistead, E. G. Spencer, and R. D. Hatcher, "Microwave semiconductor switch," PROC. IRE, vol. 44, p. 1875; December, 1956.

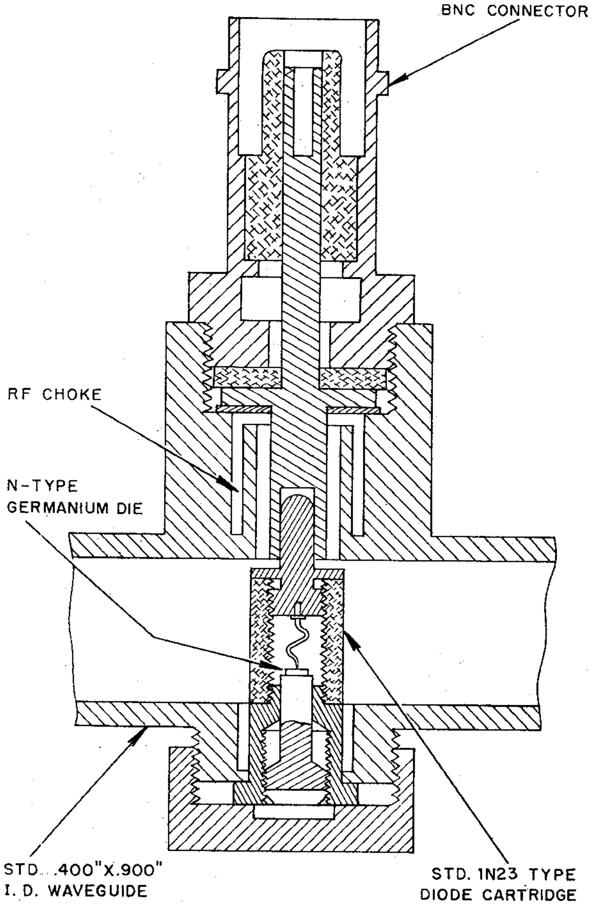

Fig. 1—Microwave semiconductor switch with germanium diode mounted in ceramic cartridge.

deteriorated but little by temperatures of 150°C. Another paper[2] presents data on the switching speeds. Rise times and decay times as fast as 3 millimicroseconds (mμsec) are obtained and there is no measurable dead time between switching events. Further data are given to demonstrate the increase in microwave power-handling capabilities obtained by reducing the number of impurity donors. One watt of RF power has been successfully switched without deterioration of the semiconductor contact.

The purpose of this paper is to describe some new microwave techniques employing the particular properties of the semiconductor switches.

Normal Switch

Fig. 1 shows a diagram of the X-band semiconductor diode with the mounted germanium wafer and the point contact. The diode is shown mounted as a switch in standard X-band waveguide. A photograph of the complete switch showing its small size is seen in Fig. 2. The isolation as a function of applied voltage is given in Fig. 3. The 1N263 curve is characteristic of N-type germanium microwave diodes while the 1N23-B curve

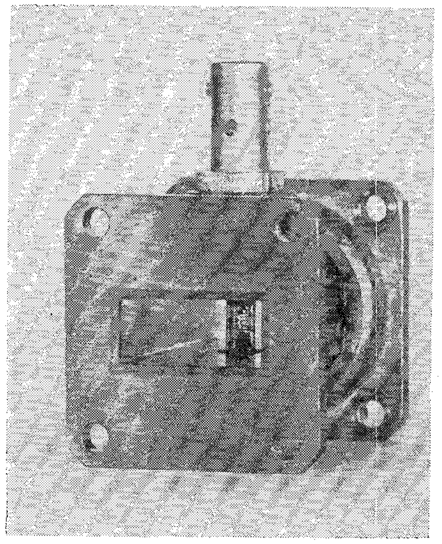

Fig. 2—External view of microwave semiconductor switch employing 1N263 germanium diode showing its small size. The switch can be made as thin as the RF choke permits.

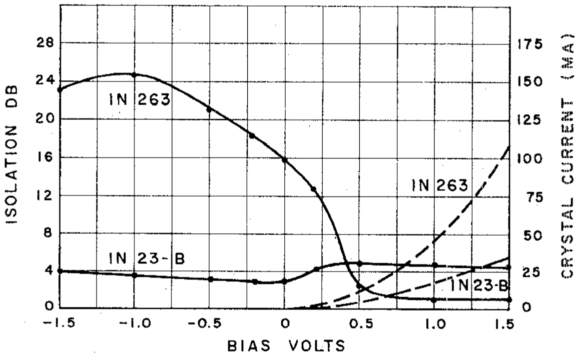

Fig. 3—At a frequency of 9200 mc and incident power of 0.1 milliwatt, the solid lines show switching function of N-type germanium (1N263) and P-type silicon (1N23-B) crystal diodes. Dashed lines show crystal current. The voltage for 1N23-B is shown inverted for purposes of comparison.

is characteristic of P-type silicon microwave diodes. It was found early that the semiconductor material and not the form of the diode cartridge determines the switching action. Therefore, all higher power diode switches were N-type germanium in 1N23-type cartridges, since this cartridge is more easily assembled. The minimum isolation in all cases defines the insertion loss. This curve is necessary for the discussions of this paper. The other data mentioned in the Introduction are not repeated here.

Multiple Switches in Cavity Form

In many applications it is necessary to switch with considerably more isolation than the 25 to 35 db of a single crystal switch.

For example, in the measurement of pulse radar receiver sensitivity, switching of two to three times this value is required. This can be attained by use of a multiple switch arrangement.

In adding switches in tandem, the total isolation depends strongly on the spacing between switching diodes.

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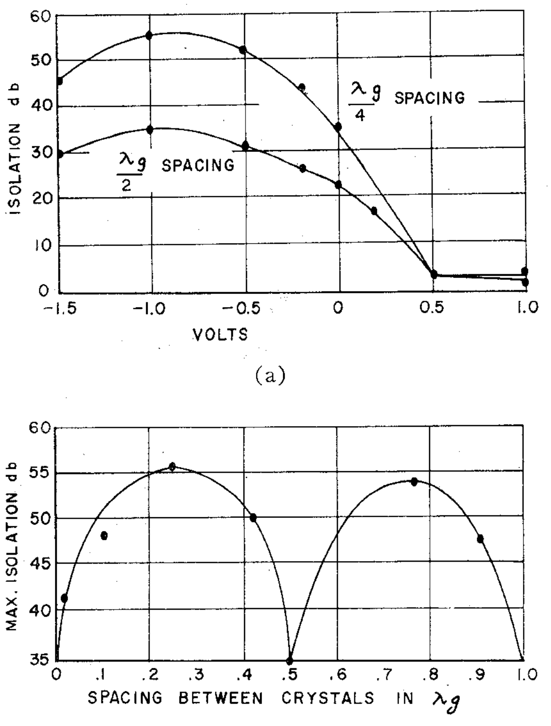
[2] R. V. Garver, E. G. Spencer, and R. C. LeCraw, "High speed microwave switching of semiconductors," *J. Appl. Phys.*, vol. 28, pp. 1336–1338; November, 1957.



(a)

(b)

Fig. 4—(a) Isolation in db for two switches in series spaced $\lambda_g/2$ and $\lambda_g/4$ apart. The individual switches have a maximum isolation of 30 db and an insertion loss of 1 db. In this form the switches in tandem have characteristics of a microwave cavity. (b) Maximum isolation as a function of spacing.

Results are shown in Fig. 4. The upper curves show switching as functions of voltages applied to the switch for $\lambda_g/2$ and $\lambda_g/4$ spacing, where λ_g is the guide wavelength. Results for all other spacings lie between these limits. The lower curve, showing the maximum isolation as a function of spacing, indicates that the two crystal switches form a cavity arrangement. The maximum isolation occurs for antiresonant spacing or odd numbers of quarter wavelengths in the guide. For half-wavelength spacing, the isolation is a minimum, corresponding to insertion losses in a resonant transmission type cavity. The isolations and insertion losses are straightforwardly additive in db for the antiresonant cavity spacing.

Reversed Switch

The microwave semiconductor switch, consisting of a germanium diode placed in the center of a waveguide, is normally OFF for a negative voltage applied to the point contact and normally ON for a positive voltage. There is a current flow for the positive applied voltage (ON) and a negligible amount for the negative applied voltage (OFF). Thus, if it is necessary to hold the switch ON, and pulse OFF, a heat dissipation problem might arise. The heating problem is more serious at the higher switching powers.

This problem has been circumvented by the design of a *reversed* switch, by which is meant that the ON and OFF conditions are reversed. The basic idea behind the reversed switch is as follows. A vertical post is extended down from the top wall of an X-band waveguide and a shorting or switching post is extended horizontally in from the side wall. When the posts are in contact the length of the vertical post is varied to obtain a series resonant structure, and the transmitted microwave power is reduced by 20 db. With the posts almost touching the structure is detuned, and the power reduction is 0.2 db. These values are called the isolation and insertion loss, respectively. The length of the vertical post has to be tuned for maximum isolation and its diameter determines bandwidth and isolation. One is allowed to increase at the expense of the other.

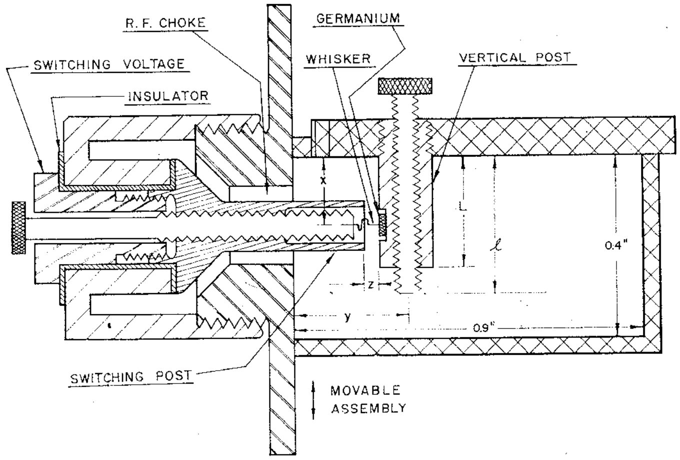


Fig. 5—Semiconductor reversed switch mounted in X-band waveguide. For a negative applied voltage the switch is ON and for a positive voltage the switch is OFF. This function is reversed from that of the switch of Fig. 1.

A schematic drawing of the reversed switch assembly is shown in Fig. 5. The germanium wafer (10^{16} impurity donors per cm^3) is soldered to the vertical post, which is tunable. The contact whisker is 0.003 inch in diameter and is mounted on the switching post, to which the switching voltage pulses are applied. An RF choke also is shown in the mount. The switching post assembly is movable to allow for small adjustments. The diameter of the vertical post is 0.125 inch and the diameter of the switching post is 0.100 inch.

A block diagram of the measurements technique is shown in Fig. 6. A CW klystron furnishes 40 milliwatts at 9300 mc to the semiconductor switch. The switch is biased negatively ON and is pulsed OFF. The resulting pulse is displayed on a high-speed cathode-ray oscilloscope. The insertion loss and isolation are read with the calibrated variable attenuator.

Referring to Fig. 5, the design parameters are the vertical post length L, the tuning length l, the distance between the top waveguide wall and the point contact X, the distance between the side waveguide wall and the center of the vertical post y, and the length of projection of the diode whisker z. Many variations of these parameters were tried but no simple relation was found between these and the switching characteristics. Several regions of good switching were found and the best one

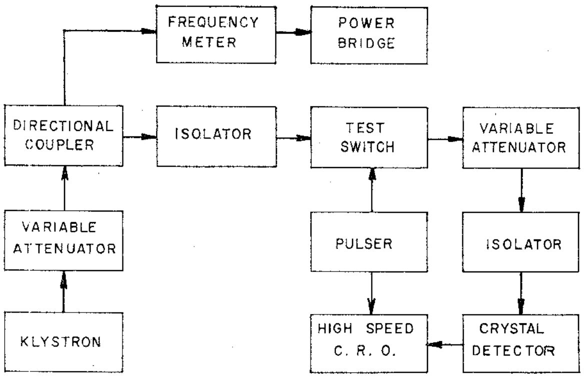


Fig. 6—Microwave equipment used in measurements of the reverse switch.

is shown in Fig. 7. It is felt that a more detailed study of these parameters could lead to much better switching characteristics.

The frequency response of the normal semiconductor switch is more than 1000 mc at X band and is limited largely by the bandwidth of the rectangular waveguide. Since the reversed switch is a resonant microwave structure, the frequency response might be expected to be somewhat less. However, by proper design an optimum in bandwidth is achieved. Measured data of frequency response are given in Fig. 7. This shows that better than 12-db isolation with less than 1.1-db insertion loss is obtained over a frequency range of 200 mc.

To summarize, the reversed semiconductor switch is a small microwave unit in which the ON and OFF functions are reversed. It has low insertion loss and good isolation. Several may be added in tandem for higher switching values. It has the properties of the normal switch such as fast pulse rise times and decay times, and power-handling capabilities depending on the number of donor impurities in the germanium.

HYBRID TEE SEMICONDUCTOR SWITCH

The properties of a balanced hybrid-tee modulator are described in the literature.[3] Silicon diodes are placed in two appropriate arms of a hybrid tee and are backed by tunable waveguide shorts. An RF signal is applied to the two diodes and thus modulates a microwave signal passing through the hybrid tee. By proper adjustment of the diode position and the phase of the modulating voltage, the phase or amplitude of the modulated microwave signals is controlled. Carrier suppression of 40 db can be obtained over a narrow frequency band.

By applying either dc or pulse voltages to two germanium diodes in a similar arrangement, an interesting form of *reversed* switch is obtained. A drawing of the assembly is seen in Fig. 8 with dimensions indicated for an operating frequency of 9375 mc. Standard JAN-1N263 diodes are used.

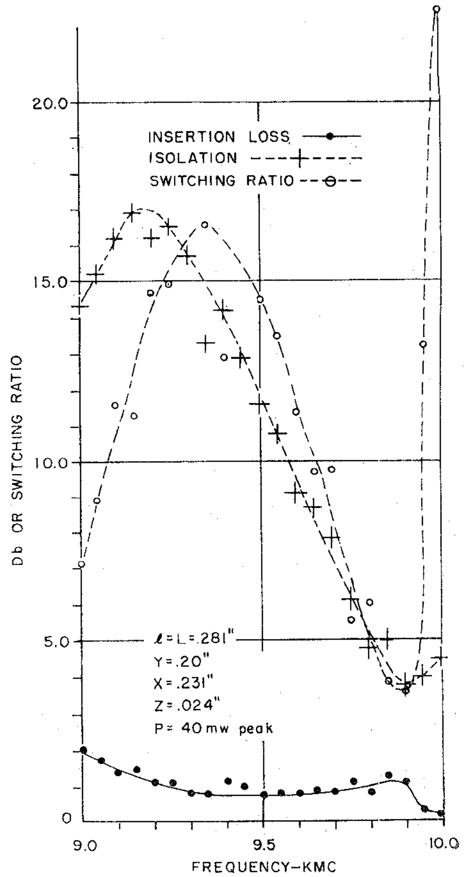


Fig. 7—Frequency dependence of the reverse switch.

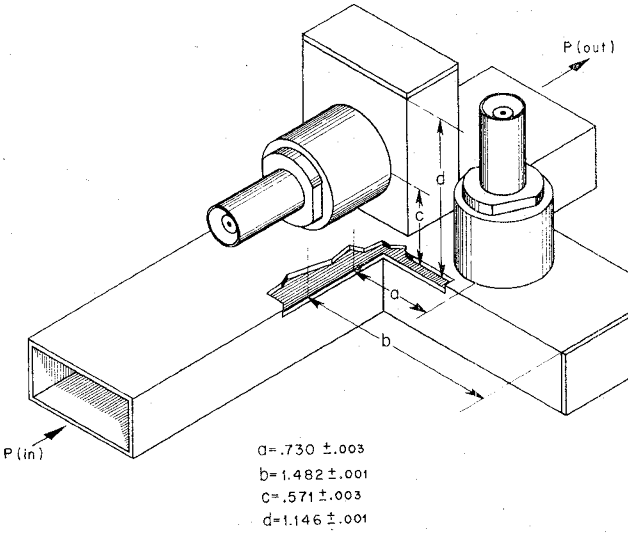


Fig. 8—Design data of hybrid-tee switch for 9375 mc using two 1N263 diodes.

The switching action is shown in Fig. 9. Insertion losses of 0.7 db and isolations of 50 db are obtained at 1 milliwatt incident microwave peak power. It should be noted that since two diodes are used, the characteristics of this switch are to be compared with those of two of the other reversed switches operating in tandem. It might also be noted that if the hybrid tee is replaced by a Riblet hybrid, only the physical form of this switch is altered.

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[3] C. G. Montgomery, "Technique of Microwave Measurements," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 11, p. 331; 1947.

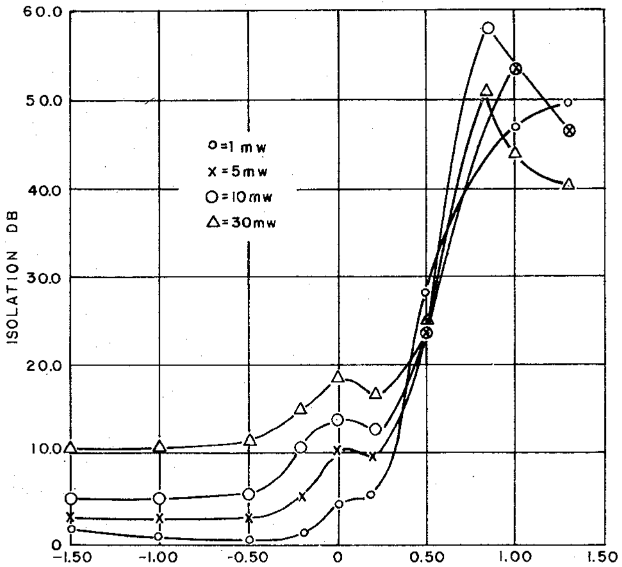

Fig. 9—Switching function of hybrid-tee switch using germanium diodes at different power levels.

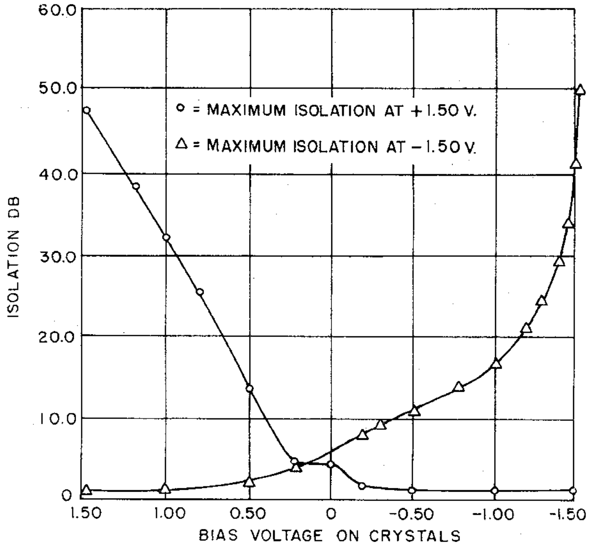

Fig. 10—Switching function of hybrid-tee switch using silicon diodes. Spacing can be optimized to obtain maximum isolation at either plus or minus bias voltage.

The hybrid junction is a symmetrical four terminal-pair network and may be considered from the viewpoint of the equivalent circuit for such a network. See, for instance, Marcuvitz.[4] By proper choice of terminal planes the equivalent reactances representing the open hybrid tee may be evaluated. It then becomes possible, through the application of network theory, to calculate the reactive loads that must be placed on the shunt and series arms, with a matched resistive load on the fourth arm, to convert the equivalent impedance of the network into a pure reactance. This calculation, however, is extremely tedious and it is convenient to determine the most satisfactory position for the short circuit behind the crystal diode experimentally. This is also true because of the imperfect conductivity of the waveguide walls which introduces an error in computations.

It has been observed experimentally that if a curve is plotted showing the position of one short circuit as a function of the other short circuit as the microwave null is maintained, that the sharpest nulls occur at positions coinciding with the knees of the curve. The use of such a curve therefore permits a quick selection of the waveguide lengths in designing the basic switch structure.

In Fig. 3 (see also Armistead, *et al.*[1]), a comparison is made of the switching properties of P-type silicon and N-type germanium for switching. The germanium diode changes microwave resistance with applied voltage while the silicon diode changes microwave reactance. This reactance change is not effective in a normal waveguide switch. In the hybrid-tee switch, however, the changes in reactances cause microwave phase changes which can cause a switching action. Fig. 10 shows the properties of this switch using standard 1N23-B P-type silicon diodes. An insertion loss of 1.5 db and an isolation of 45 db are obtained.

The effect of increasing microwave power incident to the silicon hybrid tee switch is the same as for germanium which is to increase minimum insertion loss (Fig. 9). Also, either hybrid switch can be made to have maximum isolation for plus or minus applied voltages by changing the dimensions shown in Fig. 8. See Fig. 10.

Isolation decreases rapidly as the frequency is changed from the design value (Fig. 11) on either hybrid switch. Isolation greater than 30 db is available over a 20-mc bandwidth. The insertion loss remains flat.

CONCLUSIONS

The microwave semiconductor switch using germanium diodes may take the form of the *normal* switch, the *reversed* switch, the tandem cavity-type switch, or the hybrid-tee switch. In various forms, it has become an important microwave device in this laboratory. It is being used in radar receiver circuits, in conjunction with precise microwave measurements, and for bench testing of pulse radar systems. In some applications it is used to sample and measure RF signals at accurately specified time intervals.

Because of the similarity of functions, the crystal switch might be compared with ferrite high-speed switches.[5–7] At the present time the semiconductor

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[4] N. Marcuvitz, "Waveguide Handbook," M.I.T. Rad. Lab. Ser. McGraw-Hill Book Co., Inc., New York, N. Y., vol. 10, pp. 117, 386; 1951.

[5] R. C. LeCraw, "High speed pulsing of ferrites," *J. Appl. Phys.*, vol. 25, pp. 678–679; May, 1954.

[6] R. C. LeCraw and H. B. Bruns, "Time delay in high-speed ferrite microwave switches," *J. Appl. Phys.*, vol. 26, p. 124; January, 1955.

[7] R. F. Sullivan and R. C. LeCraw, "New type ferrite microwave switch," *J. Appl. Phys.*, vol. 26, pp. 1282–1283; October, 1955.

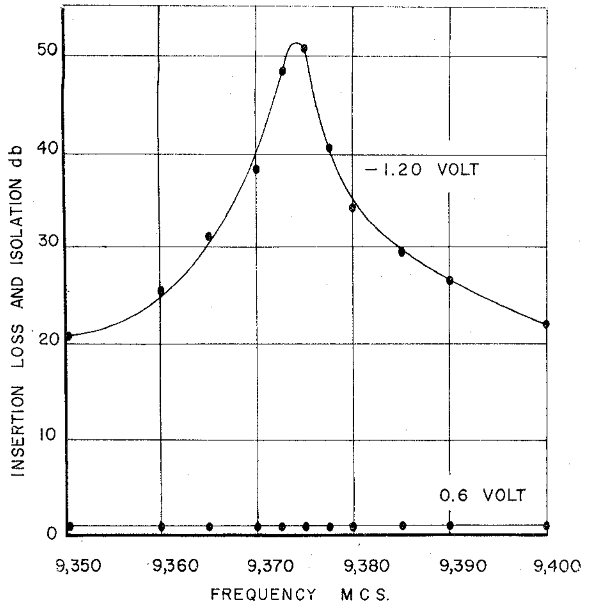

Fig. 11—Frequency dependence of hybrid-tee switch characteristic of both silicon and germanium diodes.

switch has proved to be faster than the ferrite switch. As far as the solid-state material is concerned, both germanium and ferrite have relaxation times less than 1 mμsec. It is considerably more difficult to develop fast rise time magnetic pulses (20 to 30 oersteds) for ferrite switching than it is to develop fast rise time voltage pulses for semiconductor switching. Ferrite switches are indicated for high-power high-speed microwave switching and semiconductor switches are indicated for low-power high-speed microwave switching.[8]

ACKNOWLEDGMENT

The authors thank R. D. Hatcher, R. C. LeCraw, R. F. Sullivan and H. B. Bruns for many helpful discussions and suggestions.

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[8] Since the writing of this article, another microwave diode switch has been proposed by A. Uhlir, Jr., "The potential of semiconductor diodes in high-frequency communications," PROC. IRE, vol. 46, pp. 1099–1115; June, 1958. If his theory results in another practical switch, the techniques reported here should be equally useful with either switch.

Microwave *Q* Measurements in the Presence of Coupling Losses*

E. L. GINZTON†

Summary—**In the use of the impedance (Q-circle) method of measuring the cavity Q values, the presence of losses in the coupling network (between the cavity and the available external terminals) is usually neglected. If appreciable losses are present this simplification is not justified, and its use can lead to significant errors.**

The losses in any coupling network can be described by means of an equivalent canonical circuit containing a series and a shunt resistor. The losses due to the series element are immediately apparent from the character of the impedance locus when plotted on a Smith Chart and can be corrected for an "apparent" Q value. However, unless the shunt loss can be determined by a separate calibration of the coupling network, the apparent Q value will be ambiguous because the shunt losses occurring in the coupling network are not distinguishable from those in the cavity proper.

Methods for using the impedance data for determining the Q values are given on the assumption that the coupling network parameters can be found. It is also pointed out that due to the presence of coupling losses the loaded and external Q values are no longer uniquely defined, but their meaning depends upon the application of interest. Formulas relating these to the coupling network parameters are given.

INTRODUCTION

A COMMON useful method of measuring the Q values of a microwave cavity consists of measuring the self-impedance of the cavity as a function of frequency. The equivalent circuit of the main elements of apparatus needed for this measurement is shown schematically in Fig. 1, where the cavity is shown as if it were a lumped-constant resonant circuit inductively coupled to the uniform transmission line (which contains a slotted section for impedance measurements). This special form of the equivalent circuit has been shown to be sufficiently general and accurate for most practical cases: the resonance phenomenon occurs within the cavity so that the losses within it can be represented by the resistor in series with L_2 and C_2.

The losses in the *coupling network*, *i.e.*, in the elements which transfer energy from the transmission line into the cavity, are generally very small and usually their presence can be neglected. The theory of the experiment required to determine the Q values, details of

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