tangular waveguide to the image line. Their small size and simplicity may offset the greater efficiency that can be obtained with large and lengthy horns. Alternately, greater efficiencies with the monopoles or rings may be obtained by exciting several of them spaced at half-wavelength intervals along the rod.

Both the monopole and ring maintain good efficiency over a wide frequency range. In this respect they are superior to the horizontal slot.

ACKNOWLEDGMENT

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Microwave Switching by Crystal Diodes*

MURRAY R. MILLET†

Summary—**This paper gives the results of an investigation of the use of a microwave crystal as an RF switching element. Variation of a dc bias applied to the crystal will change its impedance, thereby providing an electronic control of microwave power. Empirical data are correlated with the physical structure of the crystal and its equivalent circuit to establish the frequency and power limitations of the switch. A comparison is also made of the switching properties of germanium and silicon crystals. Curves are given for predicting the switching capacity of any diode once its impedance has been normalized with respect to the characteristic impedance of the waveguide. Some methods are suggested for improving the bandwidth and power capacity of the crystal switch.**

INTRODUCTION

IN MANY applications the need arises for a fast acting waveguide switch to serve as either an on-off device or RF modulator. The conventional mechanical switch, either rotor or vane type, switches in milliseconds and also has the disadvantage of large size when physical volume is considered. The electronic switch of the ferrite type is smaller in size and has a switching time measured in microseconds. However, large peak powers are required to drive the solenoid, and the problem of holding a large coil current for the duration of a long pulse with fast rise and fall times introduces complexities. This paper describes an RF switch comprised of a crystal rectifier as the switching element. Because of the small time constant of the crystal and its low impedance there is evolved an electronic switch capable of switching in a fraction of a microsecond and requiring low driving power. The crystal switch may also serve as an RF modulator or variable attenuator.

The common use for crystal rectifiers at microwave frequencies is as a mixer or frequency converter in a heterodyne system.[1] When used as such, the local oscil-

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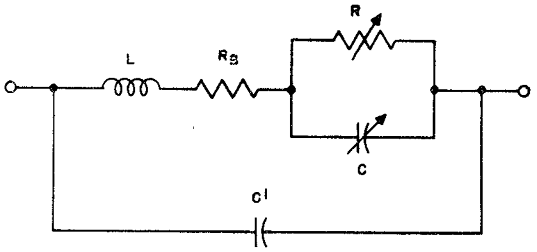

Fig. 1—Equivalent circuit of a crystal rectifier.

lator and signal are both applied to the crystal where, because of the nonlinear element, the two signals are mixed. The result is the generation of new frequencies equal to the sum and difference, and their harmonics, of the original frequencies. In this application the mixing element is localized to the point contact of the crystal where rectification occurs between the semiconductor and the whisker wire. In some cases a bias is applied to the crystal for matching purposes or noise figure improvement.

In addition to use as a mixer, the crystal may serve as a switching device.[2–4] This is accomplished by exploiting the extreme variation of the nonlinear impedance of the crystal with bias. The network representation of the crystal is a resonant circuit composed of nonlinear elements, and thus by changing the bias from a high forward current to a small back current, both the resistive and reactive components of the circuit are radically changed. A large forward bias will decrease the nonlinear resistance and result in a high effective crystal impedance which will absorb little power. On the other hand, a large back bias will result in a low impedance which both absorbs power and causes high reflection. It is this change of impedance which can be used to control power propagated in a transmission line or waveguide.

EQUIVALENT CIRCUIT OF THE CRYSTAL

For analysis as a switching device, a detailed equivalent circuit is necessary. The complete crystal may be represented as shown in Fig. 1. The whisker presents an inductance, L, which is independent of the applied bias. Considering the whisker as a straight wire, the length of which is small compared to λ, the inductance is calculated by

$$L = 0.002l\left(\ln\frac{4l}{d} - \frac{3}{4} + \frac{d}{2l}\right)$$

where L = inductance in microhenries, l = length in cm, and d = diameter in cm. The permeability is assumed equal to one. In the case of the 1N263 crystal the wire is straight except for very small kinks whose mutual inductance may be neglected. The inductance is calculated to be 3.17 millimicrohenries, resulting in an inductive reactance of 180 ohms at 9.0 kmc.

The spreading resistance of the semiconductor is represented by R_s, a resistance of fixed value, which accounts for the compression of current flow paths at the point of contact. This resistance is a function of the conductivity of the semiconductor and the contact area. If σ denotes the conductivity and r is the radius of an assumed circular area of contact,

$$R_s = \frac{1}{4\sigma r}\cdot$$

Alternatively, the spreading resistance may be taken as the slope of the static I-E curve of the crystal in the region of high forward current. For the average 1N263 the spreading resistance is found to be in the neighborhood of 10 to 20 ohms, while a 1N23C crystal has a spreading resistance of 30 ohms because of the lower conductivity of the silicon. The resistance of the wire is considered negligible.

The resistance R represents the nonlinear resistance of the point contact and semiconductor, or barrier resistance, which varies with the amplitude and polarity of bias. As the current increases in the forward direction, R becomes increasingly small until, in the region of constant slope of the I-E curve, its value is small compared to R_s. In the back bias condition R increases with current, attaining values such that R_s is negligible. This latter value of R may be taken from the I-E curve where the slope is constant in the negative current direction.

The barrier capacitance C is also a function of bias, and accounts for the storage of charge in the boundary layer of the semiconductor. For mixer considerations little error is introduced by assuming C constant.[1] Measured values of the barrier capacitance lie between 0.02 and 1 $\mu\mu$f, which at low frequencies presents a low susceptance in parallel with $1/R$ in the back bias condition. However, at microwave frequencies the susceptance of the barrier capacitance may become large compared to $1/R$ and cause considerable shunting action.

The term C' in the above equivalent circuit includes the parasitic capacitances of the internal studs which support the whisker and semiconductor, and the crystal cartridge itself. There may also be included in this term the reactance contributed by the crystal mount. The capacitance of C' can be easily compensated for by tuning and will henceforth be neglected in the analysis.

EQUIVALENT CIRCUIT AS A SWITCH

When used as an RF switch, the crystal is centered on the waveguide axis in a conventional mount whose backplate has been removed to permit the transmission of power. For switching operation the crystal presents one of two different impedances which are determined by the amplitude and polarity of the applied dc bias. In

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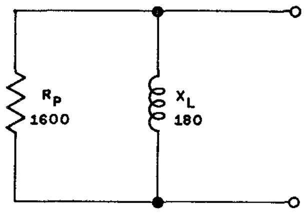

Fig. 2—Equivalent circuit of a crystal under forward bias.

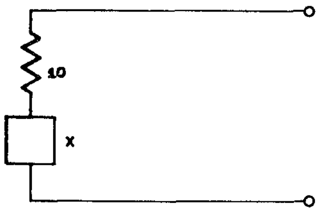

Fig. 3—Circuit of a back-biased crystal in waveguide.

the passing, or ON condition, a positive bias is applied which results in the nonlinear resistance being small compared to the barrier capacitance, thereby shunting it. The result is a series *R-L* circuit shunted across the waveguide. In the stop, or OFF condition, a back bias is applied which causes the nonlinear resistance to attain high values, and thus be shunted by the barrier capacitance. The crystal is now represented by a series *R-L-C* circuit across the guide. At some frequency the series *L* and *C* will resonate, leaving a very small resistance, the spreading resistance, shunted across the waveguide. It is this change of circuit that achieves the switching action.

Consider the crystal with a high forward bias applied. In this case the value of the nonlinear resistance is approaching that of R_s, assumed to be 10 ohms, and is shunting the barrier capacitance C. The resultant circuit is the spreading resistance R_s and a small nonlinear resistance R, a total of 20 ohms, in series with the whisker inductive reactance. At 9.0 kmc the circuit is a series *R-L* circuit with a Q of 9, and is transformed into the parallel *R-L* circuit of Fig. 2 by

$$R_p = R_s(Q^2 + 1),$$

$$Q = \frac{R_p}{\omega L}\cdot$$

The crystal is in the ON condition, and is now considered in shunt with 0.400×0.900 (RG-52/U) waveguide terminated in a matched load, assumed here to be 400 ohms. When plotted on a Smith chart the admittance of the circuit, normalized with respect to the waveguide, is seen to be 0.25-*j*2. Discounting the reflection loss, under these conditions the power absorbed by the load will be reduced by 20 per cent, or approximately 1 db.

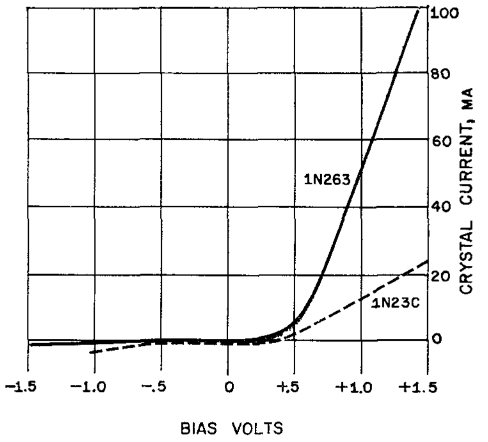

Fig. 4—*I-E* curve of 1N32C and 1N263 crystals.

Now consider the crystal with a high back bias applied, resulting in a small back current. The nonlinear resistance is now very large. The barrier capacitance shunts this large resistance and resonates with the whisker inductance or leaves a small residual reactance because of counteraction with it. The resulting circuit is a small resistance, the spreading resistance, in series with a very small (if any) reactance. This circuit is now considered in shunt with the waveguide, as shown in Fig. 3. The result of placing such a circuit across the waveguide is a standing wave ratio of 40 to 1. The power absorbed by the load will be reduced by 97.5 per cent because of absorption by the crystal, together with considerable reflection.

Essentially the same circuit holds for the 1N23C silicon and 1N263 germanium crystals. The silicon crystal, however, is noted to have a higher spreading resistance, and a lower value of nonlinear resistance when biased in the back direction which is attributed to the lower drift mobility[2] of silicon as compared to germanium. The effect of the decreased R is less shunting by the barrier capacitance under a negative bias, and thus a higher effective resistance of R_s and R placed across the waveguide load, which in turn results in less reflection and more power absorbed by the load. For this reason efforts were centered around the germanium 1N263 as a switching element. However, the silicon diode has been used as a switch but only where the diode is used to shunt a coaxial line.[3] A comparison of average 1N23C and 1N263 *I-E* curves is shown in Fig. 4. A switch using germanium 1N91 diodes to shunt a coaxial line in the 3-kmc range has also been reported.[4]

SWITCH OPERATION

The RF admittance presented by the 1N263 crystal, centered in RG-52/U waveguide, is shown in Fig. 5. The admittances shown, which are referred to the center of the crystal, are those of the mounted crystal only, and exclude the admittance of the waveguide load. In the condition of forward bias the admittance is seen to be less than the admittance of the guide, as was shown in the circuit of Fig. 2. The discrepancy between the calculated and measured imaginary parts of the admittance is attributed to the presence of parasitic reactances not accounted for in the calculations. Reversing the bias is seen to result in a crystal admittance which is much larger than the guide admittance, as explained by Fig.

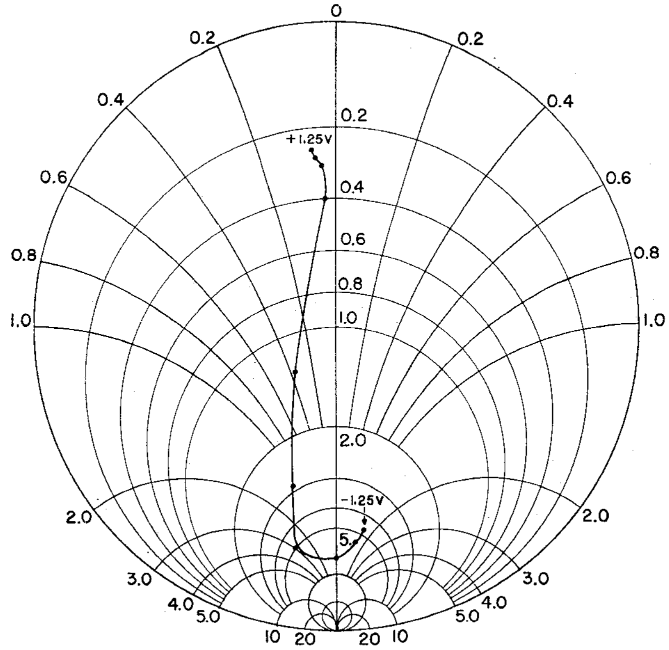

Fig. 5—RF admittance of 1N263 crystal, at 9.2 kmc, 0.5 mw, as a function of bias.

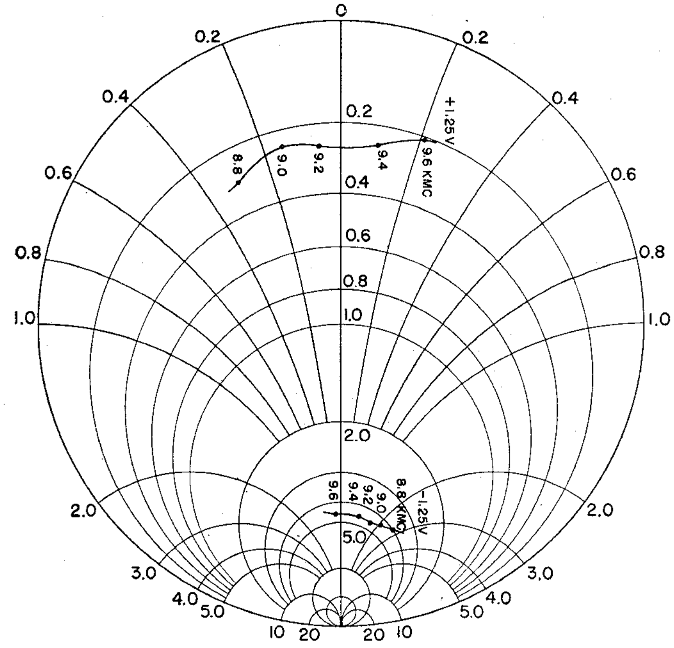

Fig. 6—RF admittance variation with frequency.

3. It is seen that with additional increase of back bias the crystal admittance begins to decrease. This is due to the high back bias reaching the Zener voltage of the semiconductor, at which point the current in the back direction begins to increase.

The frequency sensitivity of the crystal is shown in Fig. 6, where the admittances under two opposite biasing conditions are plotted as functions of frequency. At a little over 9.2 kmc the crystal, mounted in its test holder, is resonant in the forward bias condition and the corresponding admittance is a pure conductance. The

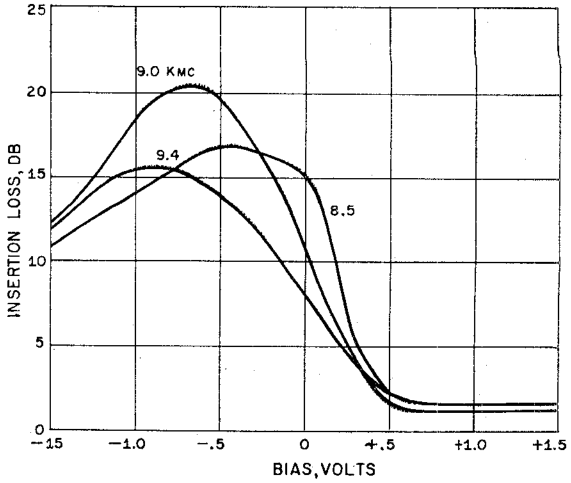

Fig. 7—Insertion loss of crystal switch vs bias.

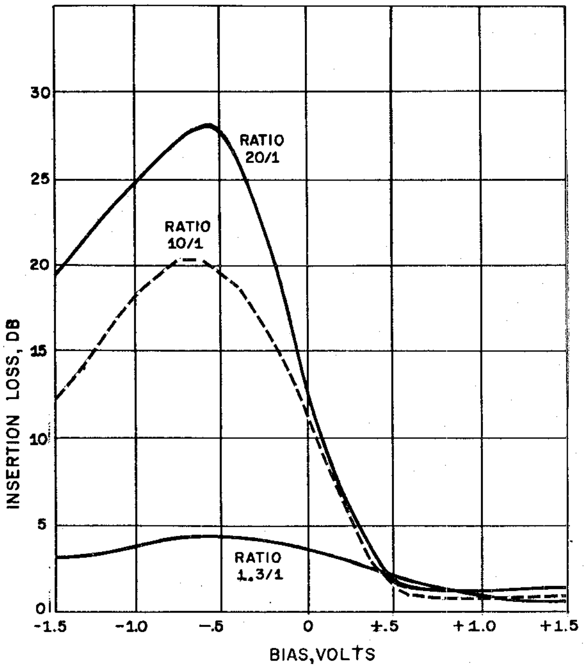

Fig. 8—Variation of switch attenuation with rectifier characteristics.

design frequency of the 1N263, however, is 9.375 kmc. The deviation here from the design resonance is attributed to the fact that the crystal was tested in a mount differing from the one used in the crystal design, and also the differences in measurement technique and production tolerances. Allowing for these external differences the admittances follow closely the equivalent circuits of Figs. 2 and 3. The effect of the back bias circuit being off resonance is illustrated in Fig. 7. These curves were plotted from averaged data taken from randomly selected crystals.

The effect of variation of the rectifier characteristics, or the *I-E* curve, of the crystal is shown in Fig. 8, where a comparison is made between crystals of different front-to-back ratios, all measured at the same frequency. The ratio 10:1 represents the lower limit of the ratios

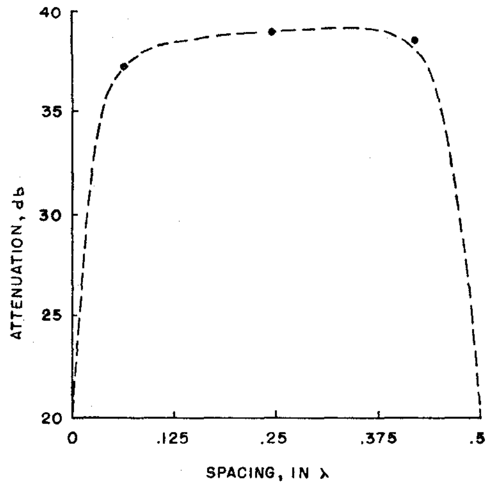

Fig. 9—Insertion loss of two crystal switches vs element spacing.

expected in a production run of crystals. To obtain ratios higher than 15:1 requires hand selection, as was done for the crystal with the 20:1 ratio. The 1.3:1 ratio crystal had been submitted to many previous tests and severely overdriven, both by RF power and direct current.

Limit of Switching

As shown above, the passing and stopping of RF power by the crystal is accomplished by the nonlinear resistance causing either a near match or large mismatch in the guide. The limit of the ratio of passed to stopped power therefore rests entirely in the crystal itself, independent of crystal holder or waveguide tuning. As shown for a 1N263 crystal the pass to stop ratio lies between 25 and 30 db. If, by known means, the stopping limit or isolation of these crystals is to be increased, it appears that this will be only at the expense of correspondingly increased insertion loss in the passing condition.

One method of achieving this is to enclose the crystal in a cavity whose transformer action will increase the impedance of the waveguide as seen by the crystal, and thereby cause a greater mismatch in the stop condition when the crystal impedance is small. However, in the passing condition the impedance is likewise increased by transformer action and will therefore raise the insertion loss. One such model has been built in which the isolation was 40 db, but this was at the expense of the necessary increase of insertion loss to 4.5 db. An alternative method is to increase the guide impedance by narrowing the waveguide in the region of the crystal.

If the length of the over-all switch is no limitation, the crystals may be cascaded, with a spacing between the elements of one-quarter wavelength. The over-all switching attenuation will then be the sum of the individual losses, both in the passing and stopping condition. Fig. 9 shows the isolation vs spacing for two crystals, each of which individually gave 20 db isolation.

Fig. 10 shows the variation of insertion loss as the crystal impedance, which is normalized to the waveguide impedance, is varied. The curve is normalized so that the insertion loss may be predicted for any crystal, once its front-to-back ratio is known and defined in terms of waveguide impedance. The curve also serves in the reverse case where, with a specified insertion loss, the correct crystal and bias limits may be determined and, if necessary, to what extent the waveguide impedance must be increased.

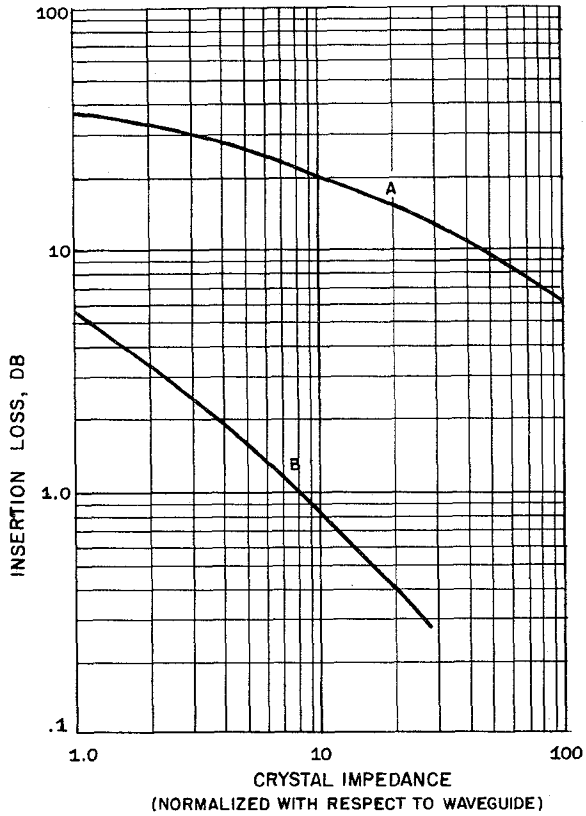

Fig. 10—Insertion loss vs normalized crystal impedance.

Switching Time

Assuming the crystal to be in the back bias condition, the whisker inductance and resistance at switching frequencies are considered negligible and the circuit consists essentially of the low barrier capacitance and high barrier resistance, whose average values may be 0.2 $\mu\mu$f and 5000 ohms, respectively. The time constant is then 100×10^{-12} seconds, a small part of a microsecond. During the rise time of a video biasing pulse the nonlinear resistance decreases while the barrier capacitance increases. Thus, the time constant of the circuit is kept fairly constant by the R and C compensating for each other. The same compensation holds for the decreasing portion of the video pulse. The rise and fall times of the video pulse are shortened by the effective nonlinear curve of bias vs time, where the curve is steepened over the positive bias portion, which suggests one of the basic applications of the crystal switch.

Consider the crystal inserted between a pulsed RF source and load. If the crystal is held in a back bias

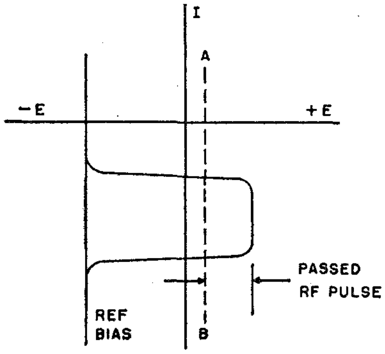

Fig. 11—Pulse shaping by crystal switch.

condition and video pulses of forward bias are applied synchronously with an RF pulse, the transmitted or passed RF pulse will have lower rise and fall times than the incident pulse. Referring to Fig. 11, the passed pulse corresponds to only that portion of the applied video pulse which is to the right of the line *AB* where the slope of the *I-E* curve indicates the nonlinear resistance begins to be small, *i.e.*, a steep slope. Assuming between two and three time constants are needed to arrive at this point from the start of the video pulse, the transmitted RF pulse rise time is only a part of the total rise time, and therefore the passed pulse has a rise time of its own of less than two time constants. Thus it can be seen that RF pulses transmitted through the crystal switch have faster rise and fall times than the original pulse and are also narrower.

Power Limitations

Aside from the power dissipation capacity, the power to be switched is limited by the *I-E* characteristics of the diode. As shown in Fig. 12, the RF signal impinging on the crystal will drive the instantaneous operating point along the curve to voltages corresponding to the peak RF voltage points. In the ON condition the operating point is centered well to the right of the zero bias axis, and must remain on the low resistance portion of the curve for all instantaneous voltages. If the amplitude of the RF signal is such that the operating point is driven into the high resistance portion, the mean impedance of the crystal will increase and thereby increase the insertion loss. Similarly, in the OFF condition the RF signal must be limited to amplitudes such that the operating point is not driven into the low resistance part of the curve, and thereby does not reduce the insertion loss.

In the case of the 1N263 crystal, the *I-E* curve limits the RF peak-to-peak voltage to 2 or 3 volts, which is the case for approximately 1 mw. Fig. 13 shows the effect of increasing the applied RF power. The negative bias was increased in an effort to prevent the operating point from moving into the low resistance part of the *I-E* curve with higher RF power applied. The result was a further decrease of insertion loss because of the instantaneous operating point exceeding the Zener voltage, and an increase of current in the negative direction.

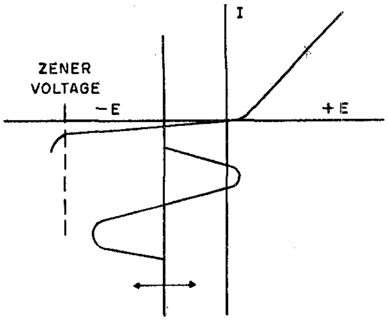

Fig. 12—Operating point on the *I-E* curve due to RF power.

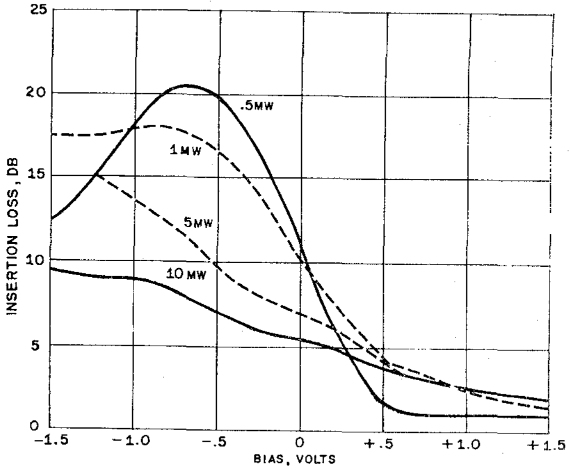

Fig. 13—Insertion loss of 1N263 crystal switch at various power levels.

A method of increasing the power switch capacity of the switch is to cascade the crystals. Though optimum switching is sacrificed in the first crystal, the passed power is sufficiently reduced for optimum operation of the following crystals. What passing insertion loss is tolerable will then determine the number of crystals to be used.

Obviously the switching of higher powers demands a crystal whose *I-E* curve shows a greater Zener voltage and a lower positive slope for the forward bias. By doubling the Zener voltage the RF power to be stopped should more than double, and at the same time the passed power would be increased with higher forward bias. The remaining limitation would be that of heat dissipation.

In an effort to overcome these limitations, existing germanium diodes with higher Zener voltages and higher resistivities than the 1N263 were investigated at *X* band. A 1N34 diode, as packaged by Sylvania, was found to have a Zener voltage indicative of high power switching capacity. The axial leads of the diode were replaced with pins to enable the crystal to be supported in the waveguide mount. The resulting curve of isolation vs bias, at 9.3 kmc, is shown in Fig. 14. The same curve held for all powers up to 15 mw, at which point the excessive current (the sum of the applied dc and rectified RF) caused the point contact to weld into the germanium, after which the diode was no longer a rectifier.

The test was repeated using a Hughes 1N67A. The results showed a limiting power of 5 mw, again only because of the current limitations of the diode. In this case a passing insertion loss of 1 db was attained with a bias of +3 volts and a corresponding current of 300 ma. The maximum insertion loss was 16 db with a negative bias of 125 volts. The 1N67 was supported within a ceramic cartridge for waveguide mounting.

A 1N38 was modified for waveguide mounting in the same fashion as the 1N34. The *I-E* curve and insertion loss vs bias curve at 9.3 kmc are shown in Figs. 15 and 16, respectively. The power switching capacity is seen to follow the prediction of the *I-E* curve. There was no sign of decreased insertion loss at negative biases, or increased insertion loss at positive biases, for all powers up to and including 50 mw. Again the limiting factor was power dissipation.

Conclusions

At present the power limitations of the crystal switch restrict its use to low power applications. However, it has been shown that by utilizing a semiconductor with such characteristics as high Zener voltage and high resistivity, the limit of the power that can be handled can be substantially increased. Experiments are now being conducted toward the development of such semiconductors, and powers of over one watt have been successfully switched.[5] The remaining limitation is that of power dissipation. However, this too can be overcome by proper wafer form factor and semiconductor-to-metal contact area.

In addition, observing the curves for isolation vs bias as a function of frequency, it is seen that the crystal switch is not a broadband device but operates optimumly at the resonant frequency of its whisker inductance and barrier capacitance. In the case of the microwave crystals used the optimum operation was at about 9.3 kmc. However, the fabrication of a crystal to operate at a different frequency should present no problem. By correctly selecting the length of the whisker wire the crystal can be made to operate optimumly at any desired frequency. To broaden the bandwidth of the crystal switch the physical configuration of the crystal must be changed, since both the semiconductor and whisker determine the band over which the crystal will satisfactorily operate. Such a change could be the elimination of the whisker inductance, which would eliminate the resonance of the present crystal. Such a crystal has been described,[6] in which the crystal is matched, RF-wise, up to the point of semiconductor-to-metal contact.

The crystal switch may be compared to the fastest ferrite switches. The latter achieve isolations of 20 db in millimicroseconds, and have capacities of many watts, but demand high driving powers. A crystal switch is seen to give comparable isolation, and more if used in multiple, in comparable switching time with the advantage of low driving power.

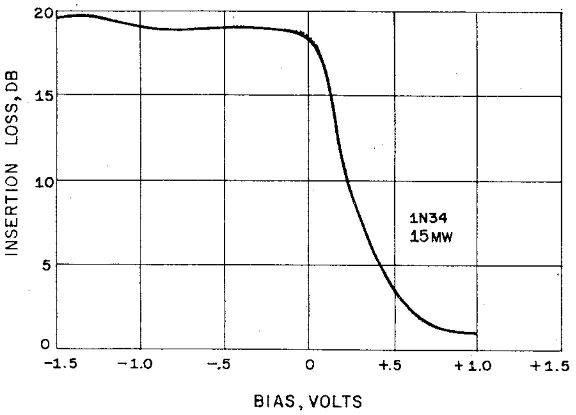

Fig. 14—Insertion loss of a 1N34 germanium diode at 15 mw.

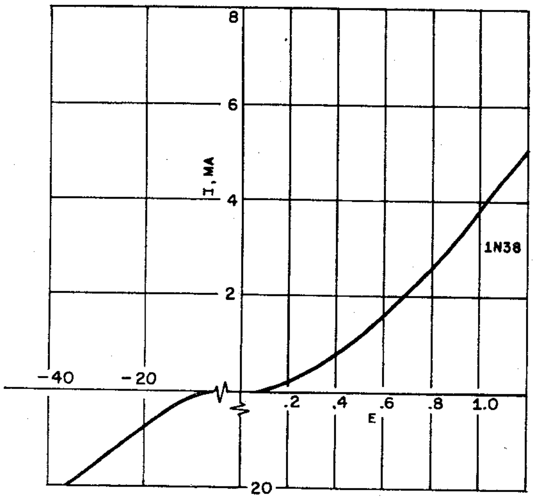

Fig. 15—*I-E* curve of 1N38 diode.

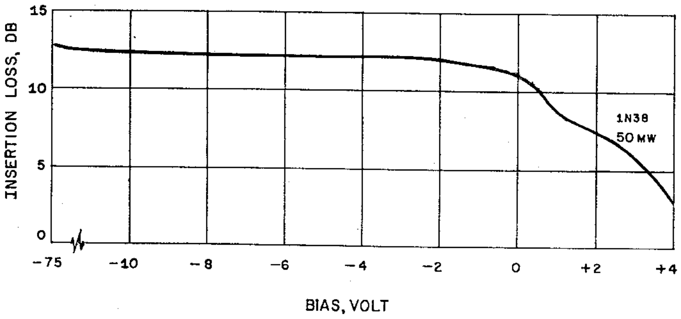

Fig. 16—Insertion loss of a 1N38 diode.

Acknowledgment

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[5] Personal communication with E. G. Spencer, Diamond Ordnance Fuze Labs., Washington, D. C.

[6] Bell Telephone Labs., "Crystal Rectifiers," Signal Corps Contract No. DA-36-039, Second Interim Rep., January, 1955.