It can be concluded that the VSWR into any output port is

$$\text{VSWR}_{N} = \frac{1 + |S_{22}|}{1 - |S_{22}|} = 2N - 1; \quad (N \neq 1)$$

the isolation between any two output ports is

$$\text{Isolation}_{(MN)} = 10 \log \frac{1}{|S_{23}|^2} = 20 \log N$$

$$(M \neq 1)$$
$$(N \neq 1)$$
$$(M \neq N)$$

the coupling between the input and any output port is

$$\text{Coupling}_{1N} = 10 \log \frac{1}{|S_{12}|^2} = 10 \log N. \quad (N \neq 1)$$

It can be seen that when multi-outputs are required, say 10 or more, you can obtain some degree of isolation between the output ports. Directional couplers would be required only if there were a necessity for each output port to simulate a matched generator.

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Microwave Absorption Modulation by Electron Mobility Variation in n-Type Germanium*

Microwave-radiation attenuation in a dissipative medium such as germanium in which the conductivity and microwave frequency conditions $\sigma < \omega\epsilon$ and $\omega\tau < 1$ are present has been shown by Gibson[1] to be attributed to the absorption constant relation

$$K = 1635\sigma/n \text{ db/meter}, \tag{1}$$

where τ is the carrier relaxation time, ω the microwave angular frequency, and ϵ the permittivity. In the above equation, σ is the conductivity and n the index of refraction (4.05 in germanium).

Arthur, *et al.*,[2] previously reported that 37.5-kMc radiation absorption in n-type germanium could be modulated by a high external electric field across the crystal. Modulator operation depends on the phenomenon of electron-carrier mobility decreasing as a function of the electric field.[3,4] The semiconductor becomes transparent to the radiation when the carrier slope mobility dv/dE becomes zero in the saturated drift velocity region. Since information is limited on this new type of microwave modulator, a more extensive investigation was made. The present work proposes to investigate the radiation absorption modulation resulting from this effect at a lower frequency and, in addition, to observe the temperature and polarity conditions of the crystal that limit modulator operation.

The experimental arrangement is shown in Fig. 1. Fabrication of the slotted waveguide section through which the sample was inserted consisted of machining a nonradiating slot through each side of the broad section of the rectangular waveguide. The incident 24.2-kMc radiation power was set at 3 mw. An RF substitution method measured the attenuation changes. Measurements of the observed dc signal from a 1N26 crystal detector were made on a Tektronix 545 oscilloscope. The VSWR value with the sample in the microwave field was 1.3, which corresponds to a 0.07-db reflection loss. Polytetrafluoroethylene was placed between the crystal and waveguide section for electrical insulation.

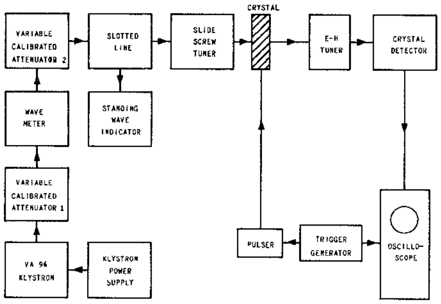

Fig. 1—Block diagram of the experimental apparatus.

Small pieces of 5-ohm-cm n-type germanium were sliced from the bulk single crystal and then lapped to the required thickness. The crystals were highly polished by etching[5] for two minutes in CP4 and rinsed successively in distilled water, ethyl alcohol, and carbon tetrachloride. To reduce hole injection from the positive-going end of each crystal, the wire lead on this end was mounted, using a n-n^+ junction. This junction was made with 95 per cent Sn—5 per cent Sb solder. The solder containing zinc-chloride flux was melted in an argon atmosphere and into this melt, the crystal end was immersed for five minutes at 600°C. This procedure produces alloying of the germanium and the Sn-Sb solder. Ordinary 90 per cent Pb-10 per cent Sn solder was applied for the negative-end connection. The excess flux was removed by placing the crystal in warm distilled water.

The germanium specimens had the form of a rectangular bar whose dimensions were 393 mils long, 125 mils wide, and 5 mils thick. When the crystal was inserted through the waveguide and no voltage pulse was applied, the power attenuated 4.5 db. The crystal was oriented so that the pulsed electric field would be parallel to the RF electric field vector. During operation the crystal was subjected to 0.5-μsec voltage pulses at a repetition rate of 40 pps and fan-cooled. An increase in RF power was detected as the voltage pulse was raised. The change in attenuation as the pulsed electric field across the crystal was increased is shown in Fig. 2. This curve indicates that

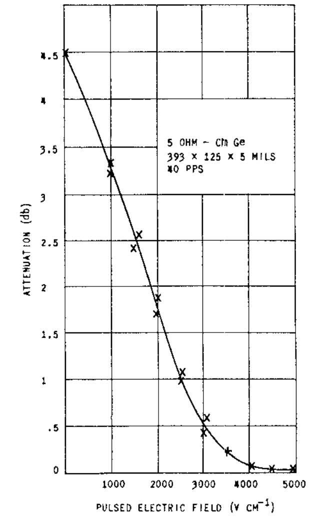

Fig. 2—Absorption variation vs electric field.

practically complete reduction of the 4.5-db attenuation occurs when the electric field across the sample was 4000 v/cm. This field strength represents the onset of the majority-carrier velocity saturation, which is in close agreement with observations made by Arthur.[2] The increase in the RF power when the pulsed electric field across the sample was 4000 v/cm is indicated by the pulse pattern shown in Fig. 3. The amplitude of the RF modulation pulse pattern remained the same when the electric field was increased from 4000 to 5000 v/cm. If the crystal was permitted to operate at a field strength of 3000 v/cm without being cooled, or if the pulse repetition rate was increased to 200 pps and cooling applied, the modulated RF power amplitude was quickly reduced. This microwave absorption effect could be caused by an increase in the carrier density due to thermal ionization. The occurrence, however, was nondestructive. The crystal returned to normal operation when cooling was restored or when the pulse rate of 40 pps was again applied. Fig. 4 indicates the results obtained when the n-n^+ junction was connected initially to the positive-voltage lead and then to the negative-voltage lead when the field strength was 2000 v/cm. From the oscillogram pattern, it is seen that hole injection will limit modulator operation if the n-n^+ junction is not connected to the crystal's positive-going end. It is further seen in Fig. 5 that some crystals with normal operating conditions (cooled and operated at 40 pps) exhibited two regions where RF power modulation changes occurred. These variations occurred

* Received by the PGMTT, October 28, 1960; revised manuscript received, December 23, 1960.

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[2] J. B. Arthur, A. F. Gibson, and J. W. Granville, "The effect of high electric fields on the absorption of germanium at microwave frequencies," *J. Electronics*, vol. 2, pp. 145–153; September, 1956.

[3] E. J. Ryder, "Mobility of holes and electrons in high electric fields," *Phys. Rev.*, vol. 90, pp. 766–769; June, 1953.

[4] J. B. Gunn, "The field-dependence of electron mobility in germanium," *J. Electronics*, vol. 2, pp. 87–94; July, 1956.

[5] J. N. Shive, "Intermediate surface treatment," in 'Transistor Technology," Bell Telephone Labs., Inc., vol. 1, pp. 393–406; September, 1952.

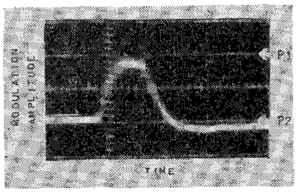
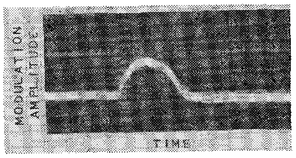
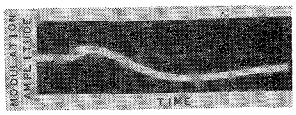


Fig. 3—Microwave absorption modulation pattern. P_1 and P_2 are the initial and absorption power levels respectively. Time scale=0.25 μsec/division (E=4000 v/cm, 40 pps).



(a)



(b)

Fig. 4—Modulator operation dependence on junction polarity. Time scale=0.5 μsecond/division (E=2000 v/cm, 40 pps). (a) N-N^+ junction connected to positive-voltage lead. (b) N-N^+ junction connected to negative-voltage lead.

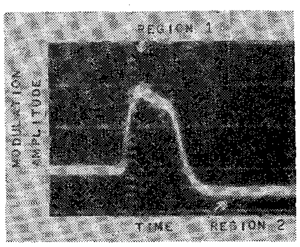


Fig. 5—Modulation changes due to minority carriers. Time scale=0.5 μsec/division (E=4000 v/cm, 40 pps).

both during and following the 0.5-μsec voltage-pulse application. This may be attributed to hole injection or to an ionization effect in these crystals. The region following the high-voltage pulse was of very long duration.

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Coaxial to Strip Transmission Line Adapter*

Over the past few years, strip transmission line has shown itself capable of being utilized in a large number of microwave configurations which were previously constructed in coaxial line or waveguide. In many cases the components fabricated in strip transmission line are simpler to design and produce particularly where, as in the sandwich type of line, advantage may be taken of photo-etching techniques. This type of construction using copper-foil-clad dielectric material enables the foil to be used for both the center conductor and the ground planes.

However, the use of such thin conducting material with relatively poor adhesion between the metal and dielectric often leads to difficulties where the coaxial line is attached to the strip. The action of soldering the center pin of the coaxial line to the strip tends to destroy the adhesion between the foil and the dielectric. The first time the connection is made the results may be quite satisfactory, but in development work it is often necessary to assemble and dismantle a filter or other device many times to make adjustments and alterations. If a soldered connection is used in such a situation, the end of the strip is soon distorted and loosened to such an extent that measurements made through the junctions are meaningless. To overcome this difficulty, a solderless transition has been devised for use in our laboratory work. An exploded view of this transition showing the important dimensions is given in Fig. 1.

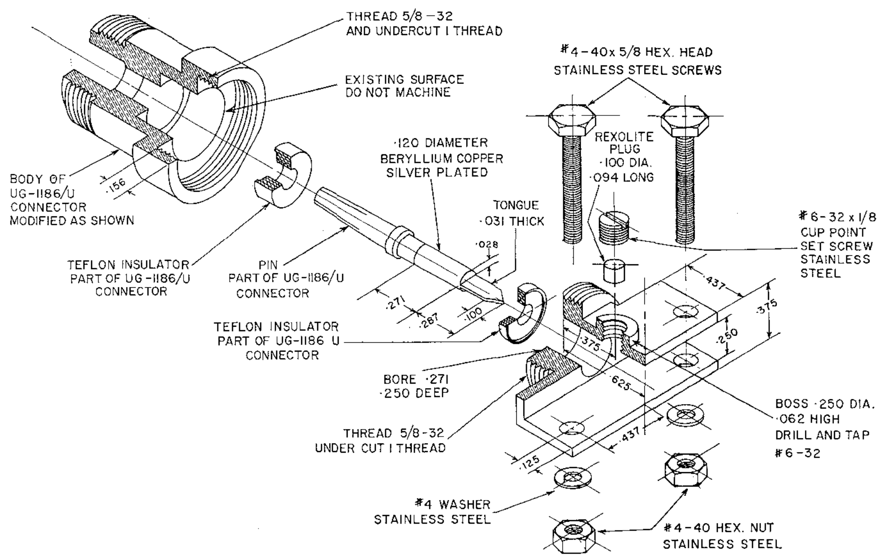

Fig. 1.

The adapter could have been of either the right-angle or in-line type, but the latter was chosen for mechanical strength and convenience, in addition to the fact that a symmetrical transition is less likely to introduce spurious modes. The channelled transition block is fastened to the stripline by two machine screws. This provides the mechanical attachment and the electrical connection to the ground planes. The flattened pin is accommodated in a slot milled in the lower surface of the upper dielectric sheet. The pin is pressed against the etched center conductor by a button of the same material as the dielectric of the line which is a loose fit in a hole in the upper dielectric sheet. A set screw in the threaded boss in the transition block holds the button tightly against the flattened pin, insuring good electrical contact between the pin and the center conductor.

The parts used for the coaxial end of the adapter were originally taken from a standard UG-1186/U connector with the body shortened and threaded as shown. However, after the initial connectors proved successful, a large quantity was made to our design by a manufacturer.

These connectors have been used over the range of frequencies from 300–6000 Mc and have given very satisfactory results. In order to confirm our opinion, measurements were made on a number of these connectors using the method of measuring a junction described by Wentworth and Barthel.[1]

Six adapters, taken at random from stock, were each measured with six different lengths of strip transmission line. This involved 36 assemblies and disassemblies of the transitions, but the uniformity of the results indicated that this had no adverse effect. At any frequency and with one particular length of line, the variation of the position of the voltage minima on the slotted line was less than ±0.2 mm with reference to the mean for the six transitions. This is of the same order as the expected experimental error and represents a spread of less than ±0.005 wavelength at the highest frequency. This close agreement between the measurements on the various adapters enabled the mean VSWR of the junctions to be computed from the average readings (Fig. 2). The true VSWR of a particular junction would not differ from this mean value by more than ±0.03.

* Received by the PGMTT, December 30, 1960.

[1] F. L. Wentworth and D. R. Barthel, "A simplified calibration of two port transmission line devices," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-4, pp. 173–175; July, 1956.