V. Conclusions

In the preceding discussion, a rather specialized application of a printed circuit balun was presented. The use of the balun with a cavity-backed spiral antenna, particularly when the balun is housed within the cavity, places severe limitations on the element size; it is expected that improved performance might be realized if these constraints were relaxed.

Nevertheless, this form factor does have some definite advantages which might not be immediately apparent. For example, by simply joining a second printed line at right angles to the balun (*i.e.*, normal to the printed line), the entire back plate of the cavity is made available for additional circuitry. In this manner, directional couplers, filters, etc., can easily be incorporated directly within the antenna structure with no space and negligible weight penalty.

An alternate configuration which appears to have some merit would involve mounting the balun parallel to the spiral and close to the cavity back plate. For this case, the size constraints can be significantly relaxed and the impedance transformer could now be placed in a printed balanced line connecting the balun output to the spiral input terminals. In other applications, it may be desirable to utilize a shielded configuration. The design described is equally applicable to all of the shielded strip transmission lines in common use.

In conclusion, it should be emphasized that the printed circuit balun is inherently capable of performance comparable to that of other wide-band baluns. With regard to basic design, nothing new is claimed. With regard to physical realization, it is believed that this printed circuit technique offers much in the way of ease of fabrication and miniaturization and, above all, a flexibility found in no other transmission line.

The *P-I-N* Modulator, an Electrically Controlled Attenuator for MM and Sub-MM Waves*

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Summary—**The construction and performance of a millimeter wave modulator are described. The main part of the modulator consists of a *p-i-n* germanium structure inserted into a rectangular waveguide. A modulation depth of 11 db could be obtained at frequencies up to 5 kc, this modulation being caused for the greatest part by attenuation.**

I. Introduction

MICROWAVE modulators are used for various purposes, *e.g.* the formation of sidebands and particularly the increase of the sensitivity of measurements. In view of the great importance of having a modulator available, it is not surprising that various types of modulators are already in use to date.

The one most commonly employed is an absorption type modulator which makes use of a ferrite. Here the losses of the ferrite or the plane of its polarizing action are varied by a magnetic field. The necessity of using a magnetic field limits the modulating frequency to rather low values and the coils required make the device somewhat bulky.

Another type of modulator, also employing a magnetic field, was proposed by Gunn and Hogarth.[1] Here the number of free charge carriers in a semiconductor is varied by driving them either to a surface with a high or to a surface with a low value of the surface recombination velocity.

A modulator in which no use is made of a magnetic field is the so-called transparitor of Arthur, Gibson, and Granville.[2] Here the differential mobility of charge carriers in a semiconductor, and therefore its attenuation, is varied by the application of a strong electric field. An advantage of this arrangement is the possibility of employing very high modulation frequencies, the theoretical response time of the device being of the order of 10^{-12} seconds. A definite disadvantage for use under continuous wave conditions, however, is its great

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[1] J. B. Gunn and C. A. Hogarth, "A novel microwave attenuator using germanium," *J. Appl. Phys.*, vol. 26, p. 353; March, 1955.

[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, p. 145; September, 1956.

power consumption, which gives rise to cooling problems.

Finally, very useful modulators can be made from various types of semiconductor point-contact diodes.[3–5] As in this case the modulation of the microwave signal is caused mainly by changing the reflectivity of the device, this type of modulator has to be used in combination with an isolator or circulator. If such devices are available, point-contact diode modulators show none of the disadvantages mentioned above, as they are small devices with low power consumption allowing very high modulation frequencies.

The *p-i-n* modulator to be described below[6,7] has advantages similar to those of the point-contact diode modulators except that the frequency of modulation is limited to rather low values. On the other hand, it has the advantage that it can be used without an isolator or circulator because its action is based mainly on a varying attenuation rather than on a varying reflection. This implies that it can also be used with advantage as a variable attenuator in control systems. The principle on which the action of *p-i-n* modulator is based is described below.

II. Design Considerations

If the intrinsic region of a semiconductor *p-i-n* structure is placed into a waveguide while care is taken that the heavily doped *p* and *n* regions are well outside the guide, the microwave field undergoes only the influence of a nearly insulating dielectric. By applying a forward voltage to contacts on the *n* and *p* regions, electrons and holes are injected into the intrinsic (or at least practically intrinsic) region and microwave power is absorbed by the mobile charge carriers thus introduced into the intrinsic part. The mechanism of transport of charge carriers into this region is governed by diffusion and recombination. Theory shows that the excess-hole and electron concentrations are almost homogeneous if the distance between the *p* and *n* regions is not larger than $L=\sqrt{D\tau}$, the diffusion-recombination length. Here D is the ambipolar diffusion constant and τ the average life time of electron-hole pairs. The time necessary to establish a certain concentration pattern is also of the order of τ. Hence τ determines the maximum modulation-frequency obtainable. From these considerations conclusions can be drawn regarding the width of the *i* region which is to be used in the modulator structure. In fact, as it is desirable to get an appreciable variation of the charge carrier density over all the material within the waveguide, the width of the intrinsic region between the *p* and *n* regions should not be much larger than the recombination-diffusion length L.

Using for germanium the values $D=60$ cm^2/sec and $\tau \approx 5$ μsec we find $L\approx 0.2$ mm. This small diffusion length implies that the distance of the broad faces of the waveguide should be of the same order of magnitude, from which it is clear that the most obvious application of this type of modulator is in the millimeter and submillimeter wave range.

III. Construction of a *P-I-N* Modulator for Use at 4 mm

Into a wafer of germanium, a gold and an aluminum wire are alloyed parallel to each other as shown in Fig. 1. The germanium, which has an impurity content of about 10^{12} cm^{-3}, is intrinsic at room temperature and has a resistivity of about 50 ohm-cm. The gold wire contains a small amount of arsenic and, as arsenic is a donor and aluminum an acceptor in germanium, the recrystallized material underneath the alloyed wires provides heavily doped *n*- and *p*-type regions.

Following the alloy process the wafer is etched in a conventional manner. After washing and drying, nickel wires of 50-μ diameter are attached to the gold and aluminum contacts. Finally the wafer is imbedded in a mylar foil in order to facilitate the mounting of the *p-i-n* structure.

The modulator is inserted into the 4-mm waveguide through slots in the broad faces in such a way that only the intrinsic region is inside the waveguide (see Fig. 2). Because this region is rather small the waveguide has been tapered. Use can be made also of tapered ridged waveguides or striplines. In order to adjust the intrinsic region just inside the waveguide, a simple construction was made to move the *p-i-n* structure up and down.

IV. Performance

An absorption variation of about 11 db was obtained with a dc current variation of about 15 ma and a maximum power consumption of about 10 mw. The insertion losses were a few decibels, due to the rather low resistivity (50 ohm-cm) of intrinsic germanium.

As can be seen from Fig. 3, at modulation frequencies up to about 5 kc the response is practically independent of frequency while the modulation depth has decreased by 3 db at 50 kc. From this the life time τ may be estimated to be of the order of 3 μsec.

Since the length of the active region in the waveguide, 2.5 mm, was about half a wavelength and, at the cost of higher insertion losses, can be made even longer, the response of the modulator covers the whole fre-

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

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

[5] K. J. S. Cave, W. Neu, and A. C. Sim, "A diode modulator for mm-waves," *Proc. IEE*, vol. 106, 1959. (Communication given at the International Convention on Transistors and Associated Semiconductor Devices, London, Eng.; May 21–27, 1959.)

[6] Dutch patent application no. 229531, 11.7.1958.

[7] A. Uhlir, Jr., "The potential of semiconductor diodes in high-frequency communications," Proc. IRE, vol. 46, pp. 1099–1115; June, 1958.

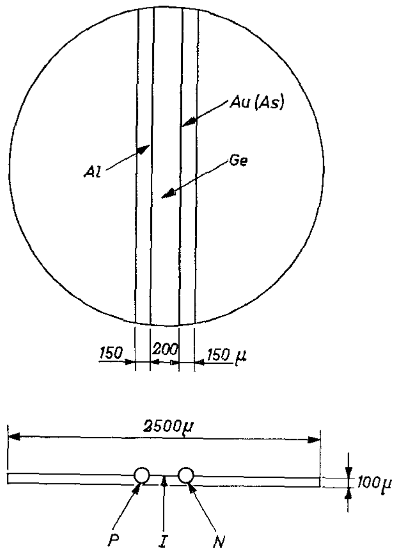

Fig. 1—Geometry of the p-i-n germanium wafer.

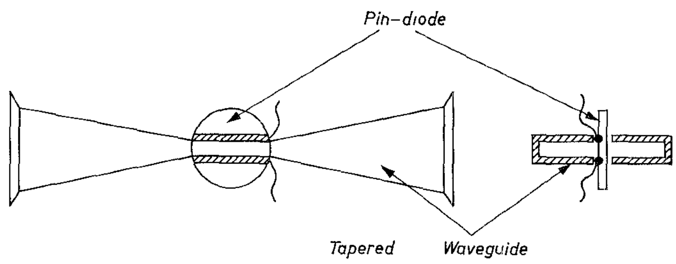

Fig. 2—Position of the modulator in the waveguide.

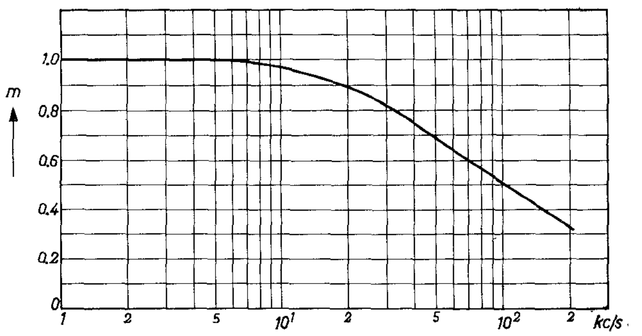

Fig. 3—Modulation depth vs modulation frequency.

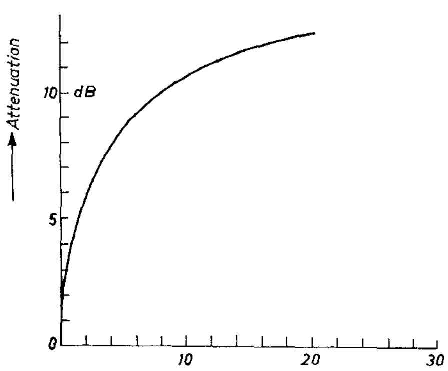

Fig. 4—Attenuation vs modulator current.

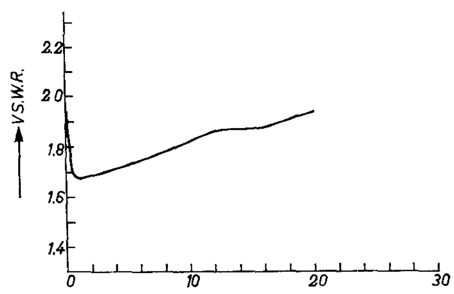

Fig. 5—Voltage standing wave ratio.

quency band of the klystron (67–77 kmc/sec); in fact the device was also successfully used at 120 kmc/sec.

In Fig. 4 the attenuation is given as a function of the current through the modulator. Because the intrinsic region is not tapered there is some reflection. However, as can be seen from Fig. 5, this reflection, measured with the modulator being terminated by a matched load, is nearly independent of the modulator current. A theoretical analysis of the relation between the modulator current and the attenuation was not made because of the considerable amount of numerical calculations involved.

Acknowledgment

We are indebted to D. Ridder for skillfully preparing the p-i-n structures.