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Letters to the Editor

Interaction of Microwaves Propagated through a Gaseous Discharge Plasma*

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It has been known for some time[1] that when two medium or low frequency radiowaves traverse a common region of the ionosphere, and one of the waves is of sufficient strength, an interaction between the two electromagnetic waves is observed. In particular, there is a measurable transfer of modulation from the stronger wave to the carrier of the weaker. Bailey and Martyn[2] proposed a theory for this phenomenon of "ionospheric cross-modulation." According to this theory, absorption of the interfering waves increases the mean energy of the electrons in the appropriate region in the ionosphere. This increased mean energy of the electrons leads to a change in the collision frequency of the electrons. As the absorption of an electromagnetic wave in a region of the ionosphere is determined by the collision frequency of the electrons in that region, the absorption of the "wanted" wave is modified by the presence of the absorbed "disturbing" wave. Bailey[3] later extended this theory by considering the effect of the earth's magnetic field. According to this more complete theory, an enhancement of transferred modulation was predicted which has since been observed experimentally.[4, 5]

The purpose of this note is to report experimental observations on the interaction of two *microwave* signals which are simultaneously propagated through gaseous discharge plasmas. The frequencies f_1 and f_2 of the electromagnetic waves propagated were chosen for convenience to be 8600 and 9400 Mc/sec, respectively. The plasma, the length of which could be varied from $5\frac{1}{2}$ in. to $8\frac{1}{2}$ in., was produced either by continuous dc or by pulsed dc excitation. Experiments were carried out with helium, neon, argon, krypton, xenon, and hydrogen gases, and over a range of pressures from 0.2- to 20-mm Hg. The power levels of both signals were far below that which is necessary to excite or even to maintain the plasma. For convenience, these waves were propagated in a wave guide containing a gaseous discharge tube. The wave guide was of square cross section in order to permit propagation of the two signals in orthogonal polarizations in the TE_{10} mode. The observations reported here concern the interaction of these electromagnetic waves in the decaying plasma following a 1- or 2-microsecond excitation pulse. Interaction of microwaves has been observed both on the reflected and transmitted waves; however, this note deals with the observations of the transmitted signals.

Measurements were made of the transmitted signals at various times after the cessation of the excitation of the plasma. These time positions were so chosen that the temperature of the electron gas had had time to decay and approach thermal equilibrium with the gas, and so that the electron density and collision frequency had become low enough to permit transmission of f_2 with slight attenuation but high enough to absorb at least a fraction of the lower frequency signal f_1.

In these experiments the disturbing wave ($f_1=8600$ Mc/sec) was pulse modulated. The width of these pulses varied from 2 to 40 microseconds. The wanted continuous wave, transmitted through the decaying plasma and modulated by it, was detected through a highly selective resonant cavity. The amplified envelope was displayed on an oscilloscope. With the application of the disturbing pulsed signal this envelope was modified. The duration of this effect after the removal of the disturbing wave, as is shown in the photographs, varied as a function of the nature of the gas and its pressure, as would be expected on theoretical grounds.

Figure 1 shows the interaction of the two electromagnetic waves in a decaying plasma produced in helium at 12-mm Hg. The upper trace shows a 10-μsec pulse of the disturbing signal introduced 500 μsec after the exciting pulse. The lower trace is double, showing the envelope of the wanted wave with and without the disturbing pulse. The notched trace is the modified envelope. The absorbed peak power during the disturbing pulse is 175 milliwatts. Note that the attenuation of the wanted wave is *increased* as a result of the disturbing pulse.

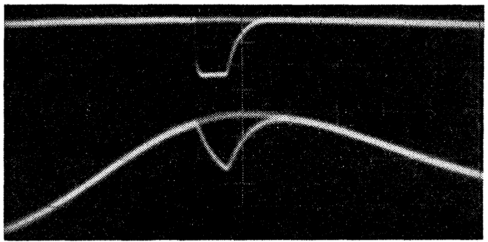

FIG. 1. Transfer of modulation to the wanted wave (lower trace) from the 10-microsecond disturbing wave pulse (upper trace) in the decaying plasma established in helium at 12-mm Hg.

Figure 2 shows the interaction in a decaying plasma excited in argon at 2.7-mm Hg. Trace No. 1 represents a pulse of the disturbing wave which is 35 μsec wide and initiates at 125 μsec after the removal of the discharge excitation pulse. Trace No. 2 is the undisturbed envelope of the wanted wave. Trace No. 3 shows the envelope of the wanted wave when the peak absorbed power from the disturbing signal is 22.5 milliwatts. Trace No. 4 is the envelope of the wanted wave when the peak absorbed power is 450 milliwatts.

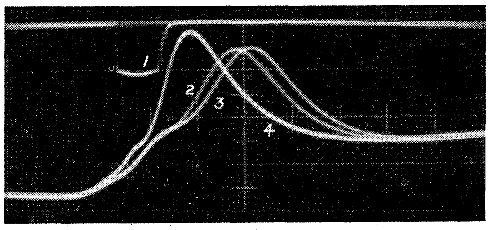

FIG. 2. Effect on the wanted wave (lower traces) in the decaying plasma established in argon at 2.7-mm Hg with the application of a 35-microsecond disturbing wave pulse. Trace 2: the undisturbed envelope of the wanted wave. Trace 3: 22.5 milliwatts absorbed in the plasma. Trace 4: 450 milliwatts absorbed in the plasma.

In contrast to Fig. 1, the result shown by trace 4 is a *decrease* in attenuation of the wanted signal during the disturbing pulse. In addition, a power dependence is observed in the shape of the traces after the disturbing pulse has been removed. For example, trace No. 3 indicates an increase in attenuation of the wanted wave shortly after the disturbing pulse, while trace No. 4 shows a decrease in attenuation of the wanted signal in the same region.

Interaction in the presence of a magnetic field.—When the disturbing wave is absorbed in the plasma at the gyro-resonance intensity of a magnetic field,[6]—here transverse to the electric vector of the disturbing wave—the interaction is observed even for low level signals for which no effect is observed in the absence of the magnetic field. This appears to be consistent with gyro-interaction theory of radiowaves in the ionosphere.[3]

A detailed discussion of the phenomenon of interaction of electromagnetic waves in a gaseous discharge plasma will be published at a later date.

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* Supported by Air Force Cambridge Research Center and Wright Air Development Center.

[1] B. D. H. Tellegen, Nature **131**, 840 (1933).

[2] V. A. Bailey and D. F. Martyn, Phil. Mag. **18**, 369 (1934).

[3] V. A. Bailey, Phil. Mag. **23**, 774 (1937).

[4] M. Cutolo, Nature **166**, 98 (1950).

[5] Bailey, Smith, Landecker, Higgs, and Hibberd, Nature **169**, 911 (1952).

[6] Goldstein, Lampert, and Heney, Phys. Rev. **83**, 1255 (1951).

Ultrasonic Attenuation Measurements in Germanium

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ULTRASONIC attenuation (scattering and absorption) in solid materials has been studied as a function of the ultrasonic frequency and as a function of the state or condition of the material for a number of materials. In particular, it has been found that differences in the state of a semiconductor can be examined by these attenuation measurements.[1] Single crystals of germanium[2] with various histories were examined over a frequency range from 15 to 100 Mc/sec. The attenuation measurements show large differences among the germanium samples; differences caused both by heat treatment and by impurities deliberately introduced.

Figure 1 shows the attenuation as a function of frequency for four samples of germanium in the frequency range from 15 to 45 Mc/sec. The top curve, marked 1, was obtained from measurements on a sample of N type germanium with resistivity $\rho \cong 0.6$ ohm cm. This sample had a lot of N type impurities deliberately introduced. Curve number 2 was obtained from measurements on a sample of P type germanium, in this case with a lot of P type impurities deliberately introduced and again with $\rho \cong 0.6$ ohm cm. Curve number 3 was obtained from a sample of basic germanium with as small an amount of impurities as can readily be obtained. The resistivity was 12.7 ohm cm. The lowest curve, number 4, was obtained from a sample of germanium which was produced from pure germanium with $\rho = 13.2$ ohm cm and then raised in temperature to 915°C for one hour and quenched. The final germanium crystal was P type with $\rho = 0.2$ ohm cm. All of these single crystals were carefully oriented so that the propagation is normal to the 100 planes.

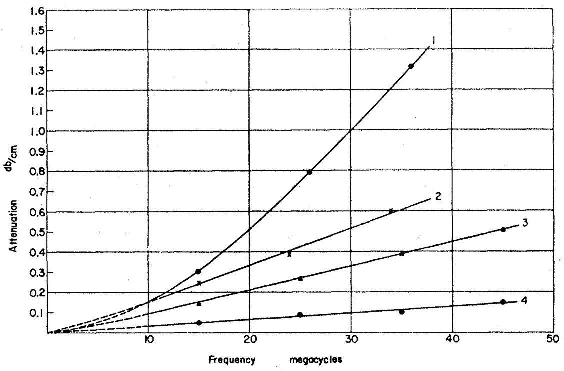

FIG. 1. Ultrasonic attenuation in germanium, as a function of frequency. Propagation normal to 100 planes.

It is clear that above 20 Mc/sec there is a large difference among the samples as far as ultrasonic attenuation measurements are concerned. It seems reasonable that curves 1 and 2 should give rise to higher attenuation than curve 3, since the former samples should have many more defects than the latter sample. It is perhaps surprising that the pure germanium which has been heat treated to P type should have lower attenuation than the original crystal, especially since the heat treatment included quenching. It seems that this heat treatment has removed some of the "defects" from the germanium, but it is difficult to determine the nature of the "defects." It is of interest to note that while for each of the two samples with N and P type impurities the resistivity is 0.6 ohm cm, the attenuation differs by as much as a factor of two at 35 Mc/sec. Between the heat-treated sample and the N type impurity sample the attenuation differs by a factor of about ten to one at 35 Mc/sec.

The data pertaining to curve 4 is not quite as satisfactory as regards accuracy[3] as the other data for the remaining three curves, but the relative position of curve 4 with respect to the other curves is as shown.

It is believed that the attenuation measurements can be used to show relative amounts or numbers of defects present. It is desirable, of course, to separate or sort out the relative amounts of various types of defects. Measurements over a wide range of frequency and over a set of specially prepared samples may permit this separation or sorting of types of defects.

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[1] H. Roderick and R. Truell, J. Appl. Phys. **23**, 267 (1952).

[2] The germanium single crystals used in this experiment were kindly supplied to us by Dr. W. P. Mason of the Bell Telephone Laboratories.

[3] These low attenuation values are at present difficult to measure.

Temporary Traps in Silicon and Germanium

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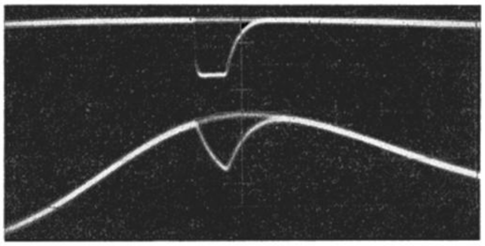
EVIDENCE indicating the existence of trapping centers other than recombination centers for minority carriers in germanium and silicon has been obtained[1] from drift velocity measurements. Specifically, in p-type silicon at room temperature and n-type germanium at -80°C and lower temperatures some of the carriers appeared to suffer an additional time delay in their transit between emitter and collector. This straggle could be eliminated by increasing the ambient light falling on the semiconductor specimens. A qualitative explanation of these observations was made in terms of a simple trap model. For low external illumination some of the carriers are caught in "traps" where they sit for a time and then are ejected back into the conduction stream. High external illumination, however, creates sufficient electron-hole pairs to keep the traps filled, and no straggle is observed. By adjusting the external illumination so that a few of the carriers arriving at the collector are trapped once and the rest are not trapped at all, an estimate of the mean lifetime in a trap, τ_g, can be made.

Photoconductivity and lifetime experiments recently have furnished independent evidence for the existence of traps and have led to a quantitative empirical description of traps in a uniform crystal of 28-ohm-cm p-type silicon.[2] The basic experiment with the silicon crystal is the following. The darkened crystal is first illuminated by a light source; then the source is cut off, and the decay in photoconductivity is measured as a function of time. The decay occurs in three well-defined steps: first comes a rapid decrease in conductivity with a time constant of 20 μsec; there follows a slower decrease in conductivity which asymptotically is exponential with a final time constant of 10^{-2} sec; this is followed by a very slow decrease in conductivity with a final time constant of 260 sec.

The experiment is interpreted as follows. Illumination creates electron-hole pairs at a rate sufficient to fill two sets of volume traps, deep and shallow, and also add electrons to the conduction band. When the illumination is removed, the electrons in the conduction band recombine ($\tau_r = 20$ μsec) before the occupancy



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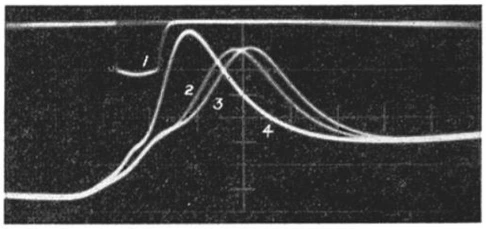

FIG. 2. Effect on the wanted wave (lower traces) in the decaying plasma established in argon at 2.7-mm Hg with the application of a 35-microsecond disturbing wave pulse. Trace 2: the undisturbed envelope of the wanted wave. Trace 3: 22.5 milliwatts absorbed in the plasma. Trace 4: 450 milliwatts absorbed in the plasma.