A Plasma Guide Microwave Selective Coupler*

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Summary—**A new type of microwave coupler has been investigated in the X-band and S-band ranges. In this coupler, a gas discharge tube passes through two rectangular waveguides that are separated by some distance. A metal cylinder surrounds the discharge tube in the separation space. The coupling of microwave power via this plasma guide coupler can be varied electronically over a range greater than 30 db. Pulsed power levels of more than 100 w can be handled. When operated as a switch, a switching time of from 2 to 5 μsec has been observed. This paper describes some of the operating characteristics that have been observed, an approximate theory of operation, and measurements pertinent to a complete description of the coupler.**

I. Introduction

THE use of gas discharges as switching and attenuating elements has been investigated in detail in the development of TR tubes for radar applications.[1] In the main, these devices depend on a gas discharge struck across a waveguide to effectively short it; or if the system is coaxial, a discharge is struck across a gap in the center conductor.[2-4] Another type of device that was investigated earlier depends on the fact that a hollow waveguide containing a plasma has a higher cutoff frequency than in the absence of the plasma; so that the plasma can be used to control the cutoff frequency, and thereby the transmission, of the waveguide.[5,6] Both types of devices are two-port elements, in which the input microwave power is either reflected from or transmitted through the region containing the discharge. The plasma guide coupler described here is different from this class of devices, in that the microwave energy is first coupled out of an input waveguide onto a coupling waveguide containing a plasma column. The energy propagates along the plasma column to a second, output waveguide. Unlike the hollow waveguide, the coupling guide depends on the presence of the plasma column to transmit energy. The wave propagating properties of the plasma column are dependent on the plasma density. Since the plasma density is easily controlled by dc or pulsed circuitry, the amount of power coupled from input to output is readily controlled by external means. Although it is possible to further control the propagating characteristics by a variable magnetic field, this method will not be discussed in this paper. Because input and output waveguides are physically separated, very high isolation between input and output is possible when the plasma guide is in the nonpropagating condition. This paper presents results of an exploratory investigation of plasma guide couplers.

Since the plasma guide coupler employs the unique cutoff properties of the space-charge waves on a plasma column to selectively couple microwave energy, some of the basic properties of the plasma guide modes are described before considering the device itself.

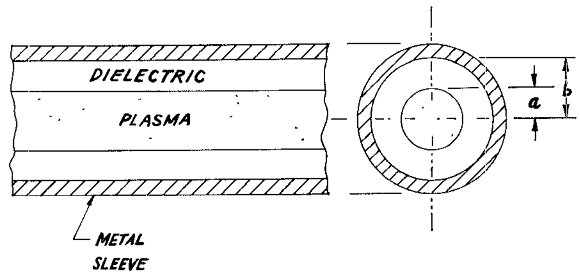

Fig. 1—Plasma guide transmission line.

II. Plasma Guide Modes

The wave-propagating properties of a stationary plasma column have been investigated by Trivelpiece and Gould.[7] They have shown that a plasma column surrounded by concentric dielectric and metal sleeves (as in Fig. 1) can propagate electromagnetic energy provided the plasma density is sufficiently high. The modes of propagation considered are electromechanical in nature and are quite different from the modes of a hollow circular waveguide perturbed by a plasma column. These plasma guide modes are space-charge waves, in which the electron density within the plasma column or on its surface is modulated as the wave passes.

In the absence of any dc magnetic fields, the plasma guide modes are essentially surface waves and can exhibit slow wave properties. In the analysis it is assumed

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[1] For an example, see L. N. Ridenour, "Radar System Engineering," McGraw-Hill Book Co., Inc., New York, N. Y., pp. 407–411; 1947.

[2] L. Goldstein and N. L. Cohen, "Radiofrequency conductivity of gas-discharge plasmas in the microwave region," *Phys. Rev.*, vol. 73, p. 83; January, 1948.

[3] P. Rosen, "The propagation of electromagnetic waves in a tube containing a coaxial d.c. discharge," *J. Appl. Phys.*, vol. 20, pp. 868–877; September, 1949.

[4] D. Kerr, S. C. Brown, and W. P. Kern, "Microwave studies of the dielectric properties of arcs," *Phys. Rev.*, vol. 71, p. 480; April 1, 1947.

[5] L. Goldstein and N. L. Cohen, "Behavior of gas discharge plasmas in high frequency electromagnetic fields," *Elec. Commun.*, vol. 28, pp. 305–321; December, 1951.

[6] D. H. Pringle and E. M. Bradley, "Some new microwave control valves employing the negative glow discharge," *J. Electronics*, vol. 1, pp. 389–404; January, 1956.

[7] A. W. Trivelpiece and R. W. Gould, "Space charge waves in cylindrical plasma columns," *J. Appl. Phys.*, vol. 30, pp. 1784–1793; November, 1959.

that the collision frequency ν_c is zero. The modes exist therefore only when the operating frequency $\omega \gg \nu_c$. Because propagation is at a phase velocity less than the velocity of light, the fields inside the plasma are described by modified Bessel functions of the first kind:[8]

$$E, H \propto I_n(\gamma r)\epsilon^{jn\phi}\epsilon^{j(\omega t-\beta z)}. \quad (1)$$

In the dielectric region, the fields are given by a sum of modified Bessel functions of the first and second kinds:

$$E, H \propto [AI_n(\gamma_0 r) + BK_n(\gamma_0 r)]\epsilon^{jn\phi}\epsilon^{j(\omega t-\beta z)}. \quad (2)$$

Here,

$$\gamma_0^2 = \beta^2 - \omega^2\mu_0\epsilon_0 K_e$$
$$\gamma^2 = \beta^2 - \omega^2\mu_0\epsilon_0 + \omega_p^2\mu_0\epsilon_0; \quad (3)$$

μ_0, ϵ_0 = constants of free space,
ω_p = plasma angular frequency—$\omega_p = 5.6 \times 10^4 \times$ (number of electrons/cc)$^{1/2}$,
K_e = dielectric constant of the dielectric sleeve,
A, B = constants determined from the characteristic equation, and
ω = operating frequency.

Propagation can take place in both symmetric modes and in modes with angular variation. Trivelpiece and Gould have computed the frequency-phase ($\omega-\beta$) characteristics of the E-mode solution for circularly symmetric waves. To demonstrate the property of density-controlled propagation characteristics, the $\omega-\beta$ plot of Fig. 2 has been repeated from their paper. Fig. 2 corresponds to the axially symmetric E-mode solution for a plasma column of radius a in an infinite vacuum dielectric; c is the velocity of light. It is seen that a cutoff frequency, at which βa approaches infinity, exists for each value of the plasma frequency ω_p. Above this frequency, no wave propagation in the manner of the plasma guide can take place. Conversely, in order to achieve propagation at a particular frequency ω, it is necessary to raise the plasma frequency (by increasing the plasma density) above a cutoff level. As the plasma density is raised to extremely high values, propagation occurs at the velocity of light; so that the plasma guide behaves as an unloaded coaxial line.

In addition to the axially symmetric mode, it is possible to achieve propagation in modes with angular variation. It is, indeed, the mode of one angular variation which chiefly concerns us in this paper. Here, as in most dielectrically-loaded structures, the nonsymmetric modes are hybrid, *i.e.*, both E_z and H_z are required to satisfy the boundary conditions. Because of this property, the propagation constant and the field distribution become difficult to evaluate and no numerical computations have been done.

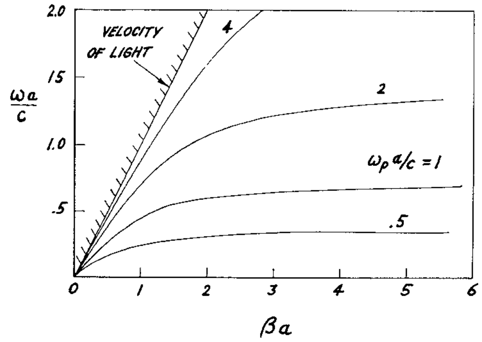

Fig. 2—Phase characteristics for axially symmetric mode; $b/a = \infty$ (after Trivelpiece and Gould).

By using the large argument approximations for the Bessel functions, Trivelpiece has shown that this cutoff plasma frequency for both the symmetric and nonsymmetric modes is given by[9]

$$\omega_p = \omega[1 + K_e]^{1/2}. \quad (4)$$

The space-charge waves can propagate for densities greater than the above; for lower densities the modes are cut off. In practice, the plasma guide transmission line need not have the dielectric tube completely filling the metal sleeve, but an air region can exist between dielectric and metal cylinders. The cutoff plasma frequency for this configuration is also given by (4), since for very large values of βa the field exists chiefly in the vicinity of the plasma-dielectric interface.

In the above discussion of the loss-free plasma, we have seen the possibility of either propagation or reactive attenuation. We are also interested in resistive attenuation. This is due to loss of the coherent energy imparted to the plasma electrons by collisions with other particles and with the walls.

This attenuation is of greatest importance in the propagating region near cutoff. For a general transmission system, the attenuation constant is given by

$$\alpha = \frac{W_L}{2Uv_g}, \quad (5)$$

where

W_L = average power lost per unit length,
U = energy stored per unit length, and
v_g = group velocity.

Since W_L and U both vary approximately as the square of the field intensity, α varies inversely with group velocity. Thus, since the group velocity is very small near cutoff, and since it can be varied by change of the ratio ω/ω_p, the plasma coupler can be used as a variable attenuator.

In summary, therefore, we can state that the cutoff frequency of a given plasma guide is affected by the

[8] S. Ramo and J. R. Whinnery, "Fields and Waves in Modern Radio," John Wiley and Sons, Inc., New York, N. Y., 2nd ed., pp. 412–413; 1953.

[9] A. W. Trivelpiece, "Slow Wave Propagation in Plasma Waveguides," California Inst. of Tech., Pasadena, Nonr 220(13) Tech. Rept. No. 7; May, 1958.

plasma density in the plasma column. Since this plasma density can be changed by external electronic methods, the plasma guide has the property of possessing a cutoff frequency controllable by external electronic apparatus. It is this property that is employed in the plasma guide coupler to make an electronically-controlled microwave variable attenuator or switch.

III. Plasma Guide Selective Coupler

A. Description

The construction of a typical coupler is shown in Fig. 3. The discharge tube passes through the two narrow walls of each waveguide. The center section, which is the plasma guide, is surrounded by a metal sleeve. Coupling occurs between waveguides when the plasma density in the column exceeds the critical density, given in terms of the plasma frequency approximately by (4).

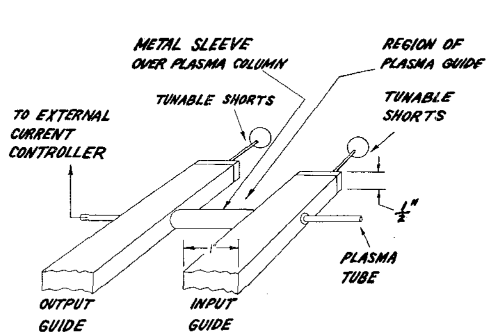

Fig. 3—Plasma guide microwave selective coupler.

In the majority of the experiments, the discharge tube used a mercury pool cathode of the type described by Dattner.[10] In more recent experiments, a thyratron-type hot-cathode tube has given satisfactory results at *S* band. The plasma tube was made of quartz. Tubes of both 8 mm O.D., 6 mm I.D., and 7 mm O.D., 5 mm I.D. were used. The tubes were approximately 250 mm long. The spacing between input and output guides was not critical; distances from 0.7 to 4.5 in were found satisfactory.

As the plasma density gets very large, the properties of the plasma guide approach those of a coaxial line. If efficient high density coupling is to be obtained, the diameter of the metal outer sleeve must therefore be chosen so that the appropriate coaxial mode can propagate. This is true in spite of the fact that cutoff for the plasma guide is given by (4), which contains no dimension.

If the symmetric plasma guide mode is excited, there is no dimensional restriction, just as in TEM mode propagation along a coaxial line. For the couplers described here, however, a mode with one angular variation is excited, and hence the outer dimension must be large enough to allow for the coaxial TE_{11} mode. Furthermore, if no low current coupling is desired, the diameter of the outer sleeve chosen must also be small enough to prevent propagation in the circular waveguide TE_{11} mode.

The pressure of mercury in the discharge tube is controlled by the temperatures of the pool cathode and of the discharge tube. By measurements of these temperatures, this pressure was found to be approximately 0.08 mm Hg during the conditions of coupling reported on here.

B. Coupling

A composite CRO trace of the coupled microwave power vs plasma density, or discharge current, is shown in Fig. 4. The display was obtained by sweeping the plasma tube current with a 60-cycle supply, in series with the dc supply of the tube, from 0.1 to about 2.0 a. The input 8.35-Gc microwave power was square-wave modulated to give the base line trace in each display. The metal sleeve around the discharge tube was made tight fitting, so that no hollow waveguide modes could propagate between the guides at the operating frequency.

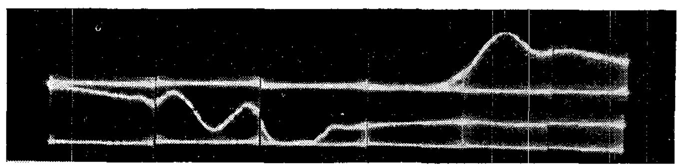

Fig. 4—Display of coupled power (top) and power transmitted past plasma in input guide (bottom) vs plasma current. Minimum current = 0.1 a; maximum current = 2.0 a.

The top of Fig. 4 is a display of the power coupled to the output waveguide. In the transition region, where the plasma guide is beginning to conduct, the device can be used as a variable attenuator with a dynamic range exceeding 30 db by electronically varying the discharge current. By operating at two discrete densities, one above and one below cutoff, the device can be used as a microwave switch.

The bottom trace of Fig. 4 is a display of power transmitted past the plasma tube in the input guide. Here the tunable short of Fig. 3 was replaced by a crystal detector. The resultant spectrum is a display of the Tonks-Dattner dips,[10,11] that are associated with plasma resonance and are discussed below. It is of interest to note that power transmission along the plasma guide occurs only at currents exceeding those at the plasma resonance dips.

A number of workers have observed oscillations in a plasma column, that have characteristic frequencies of 100 kc to 1 Mc. For the currents used in the *X*-band coupler, none of these plasma oscillations were observed. They were, however, evident at lower currents.

The insertion loss of the coupler in the *X*-band range,

[10] A. Dattner, "The plasma resonator," *Ericcson Technics* (*Stockholm*), vol. 13, no. 2, pp. 310–350; 1957.

[11] L. Tonks, "The high frequency behavior of a plasma," *Phys. Rev.*, vol. 37, pp. 1458–1483; June 1, 1931.

when the plasma was in its state of maximum coupling, was on the order of 12 to 15 db when no attempts at impedance matching were made. It appears that this relatively high insertion loss is due to poor coupling of the microwave elements, not to attenuation along the plasma column, since no appreciable attenuation of this type was found in field measurements along the column. The use of matching vanes in the input and output guides reduced the insertion loss to 8.5 db. A further reduction is probably possible with still better impedance matching.

In an alternate method of coupling between two guides, which has been observed earlier,[12] the plasma column is inserted through the broad walls of the guides. The variation of coupled power with discharge current in this arrangement is essentially the same as Fig. 4. The minimum insertion loss for this type of structure, however, could not be reduced below 15 db, even with the use of ridged waveguides for impedance matching.

The *S*-band coupler exhibited essentially the same coupling variation as the *X*-band device. The maximum coupling observed with no impedance matching vanes was -11 db.

The field measurements indicated that very little attenuation exists along the plasma column when it is in a state of high coupling. It would be of interest to see if this was to be expected from data of collisions in the plasma. Trivelpiece[9] has suggested that the attenuation constant α is given, approximately, by

$$\alpha \simeq \frac{\nu_c}{v_g}, \tag{6}$$

where ν_c is an effective collision frequency, and v_g is the group velocity. This collision frequency is given, approximately, by the sum of collision frequencies of electrons with neutral molecules (ν_{eo}), with ions (ν_{ei}), and with the walls of the container (ν_{ew}).

Based on temperature measurements of mercury pool (76°C) and coupling tube (157°C), the following results were found for an *X*-band coupler while in a state of high coupling:[13]

Gas pressure: 0.08 mm Hg
Electron temperature: 2×10^4 °K
Ion density: $2\times10^{13}/\text{cm}^3$
Neutral molecule density: $2\times10^{15}/\text{cm}^3$
ν_{eo}: 1160 Mc
ν_{ei}: 110 Mc.

The electron wall collision frequency was estimated as the ratio of average electron thermal velocity to discharge tube diameter. This results in

$$\nu_{ew} \simeq 160 \text{ Mc}.$$

It is seen that under these conditions electron-molecule collisions dominate.

Based on these calculations, and from (6), the attenuation constant is 0.4 db/cm, so that the attenuation in a 2-in length coupler should be 2 db. These results indicate that a short coupling tube at high densities should indeed exhibit low attenuation as observed.

C. Cutoff Plasma Density Measurements

Eq. (4) predicts the cutoff plasma frequency, or plasma density for coupling, at a given frequency. To verify that the space-charge modes are the mechanism of coupling, measurements of the cutoff plasma density were made, using the Tonks-Dattner dips mentioned above. Boyd[14] has demonstrated this to be a satisfactory method of measuring the average plasma density, by correlation with other techniques.

The physical arrangement for making these measurements is shown in Fig. 5. The input guide, on the left, was supplied with *X*-band power at the signal frequency. The cylindrical section is the plasma guide and the center waveguide is the output. The probe shown inserted in the cylinder was used for measurements of the angular distribution of the fields as discussed below. The third rectangular waveguide was supplied with power from a second microwave source at the probing frequency. The probing frequency was tuned until the main Tonks-Dattner dip occurred at the same discharge current as the onset of coupling to the output guide at the signal frequency.

The plasma frequency was then calculated from the measured Tonks-Dattner frequency by

$$f_p = [1 + K_{\text{eff}}]^{1/2} f_{T-D}. \tag{7}$$

For the geometry of Fig. 6 a quasi-static analysis yields[15]

$$K_{\text{eff}} = K_e \left\{ \left(\frac{b}{a}\right)^2 \left[K_e + 1 - \left(\frac{b}{d}\right)^2 (K_e - 1) \right] - \left[K_e - 1 - \left(\frac{b}{d}\right)^2 (K_e + 1) \right] \right\} \cdot \left\{ \left(\frac{b}{a}\right)^2 \left[K_e + 1 - \left(\frac{b}{d}\right)^2 (K_e - 1) \right] + \left[K_e - 1 - \left(\frac{b}{d}\right)^2 (K_e + 1) \right] \right\}^{-1}, \tag{8}$$

[12] T. Sekiguchi and R. C. Herndon, "Thermal conductivity of an electron gas in a gaseous plasma," *Phys. Rev.*, vol. 112, pp. 1–10; October 1, 1958.

[13] Collision cross sections were obtained from "The American Institute of Physics Handbook," "Handbuch der Physik," McGraw-Hill Book Co., Inc., New York, N. Y., 1957; and from Band XXII, Springer-Verlag, Berlin, Germany. 1956.

[14] G. D. Boyd, "Experiments on the Interaction of a Modulated Electron Beam with a Plasma," California Inst. of Tech., Pasadena, Nonr 220(13) Tech. Rept. No. 11; May, 1959.

[15] R. W. Gould, private communication.

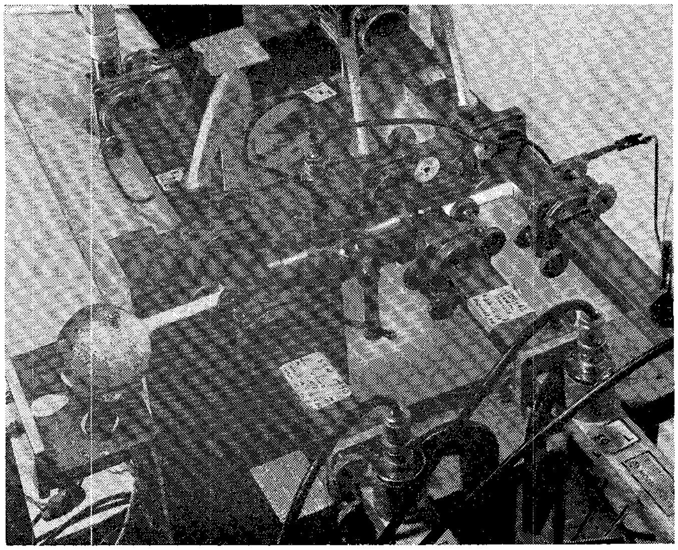

Fig. 5—Plasma coupler, with third waveguide for probing plasma density.

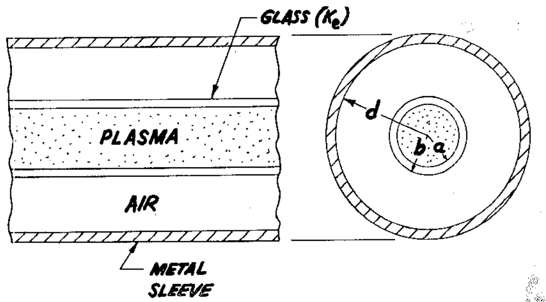

Fig. 6—Three-region cross section.

where

K_e = relative dielectric constant of the discharge tube,
a = plasma radius,
b = plasma tube outer radius, and
d = metal tube inner radius.

The upper and lower waveguide walls will exert nearly the same influence on the resonance as the outer metal cylinder of Fig. 6. In using (7) to determine f_p by the measurement of f_{T-D}, the geometric mean of the values of $[1+K_{\text{eff}}]^{1/2}$ computed from (8) for the two cases of $d=\infty$ and $d=5$ mm was therefore used.

The experimental points are plotted in Fig. 7. They cluster about the dashed straight line that lies considerably below the theoretical line computed from (4). This discrepancy between measured and theoretical plasma frequencies at cutoff has also been observed by Trivelpiece,[9] who explained it on the basis of a radial density variation in the plasma. A density variation introduces an error because the cutoff frequency is determined by the density at the edge of the plasma, while f_{T-D} measurements are of the average plasma density.

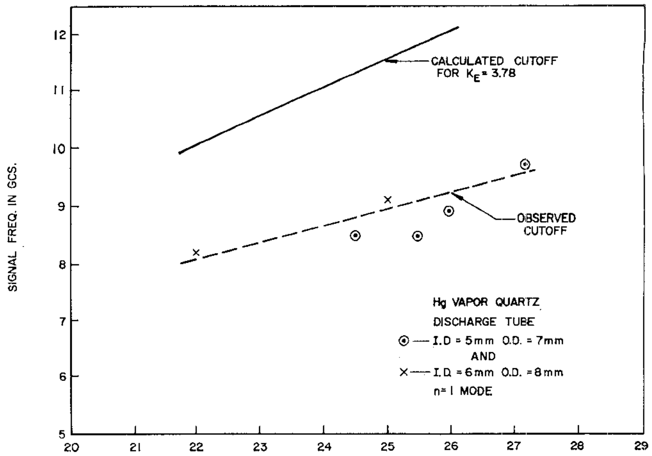

Fig. 7—Cutoff plasma frequency vs signal frequency.

The scatter of points about the dashed line is probably due to the limits on experimental accuracy imposed by the width of the main dip and the temperature fluctuations along the tube.

It should be pointed out that because no attempts were made to accurately control the temperature along the plasma tube, there are definite limitations on the experimental accuracy. The results do, however, correlate with the space-charge wave theory sufficiently to verify the mode of operation of the plasma guide coupler.

D. Wavelength Measurements

Trivelpiece and Gould show that the plasma guide modes have slow wave properties. For plasma densities just above cutoff, the guide wavelength should be very small; at high densities, propagation approaches that in a metal rod coaxial guide. As a further verification of the space-charge wave theory of operation of the coupler, wavelength measurements were made along the plasma at various discharge currents or plasma densities.

For wavelength measurements, the output guide was removed and a movable coaxial metal plunger was inserted in the air region between the quartz tube and the metal outer conductor. A fixed probe was inserted through this outer conductor between input guide and plunger to measure the radial electric field. The readings of the fixed probe plotted against the plunger position give the wavelength at a given discharge current.

Fig. 8 shows the wavelengths as measured on the 5 mm I.D., 7 mm O.D. quartz tube with 25.3 mm I.D. outer conductor. As shown in Section III-E, the mode excited has one angular variation. The data were taken at a fixed signal frequency of 8.50 Gc.

The results behave in the manner predicted by the space-charge wave theory. At high currents the wavelength approaches that for the TE_{11} mode on a coaxial line as expected. At lower densities the wavelength de-

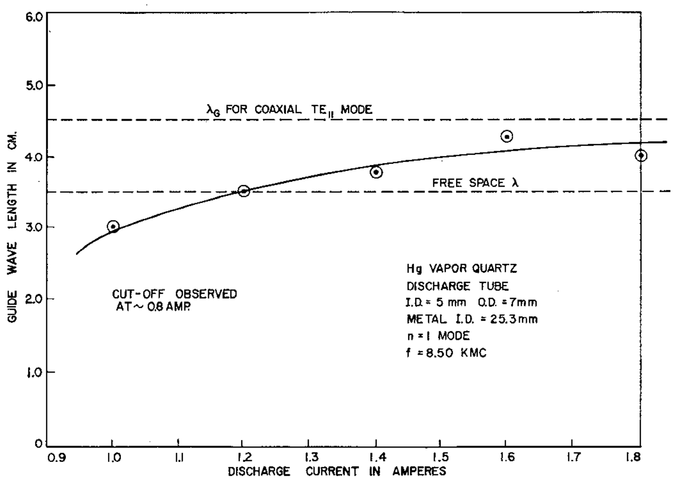

Fig. 8—Measured wavelengths along the plasma column as a function of the discharge current.

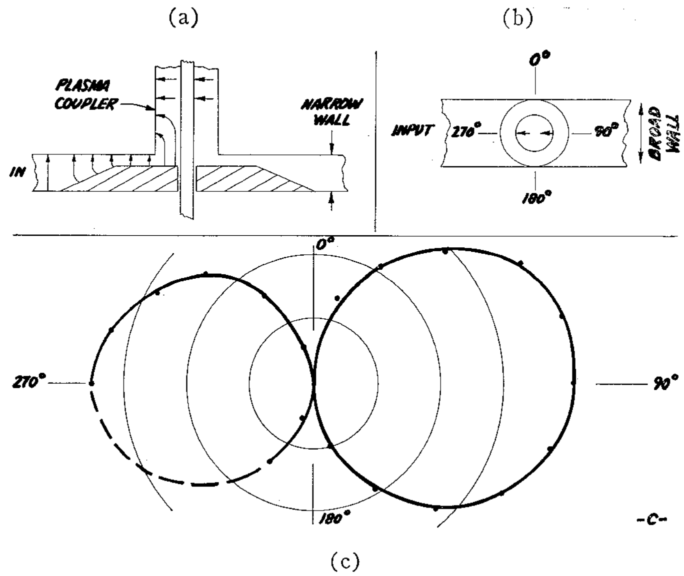

Fig. 9—Angular field distribution for coupling through broad wall. (a) Origin of fields in coupler. (b) Orientation. (c) Field pattern.

creases, showing the slow wave properties near cutoff. Unfortunately, it was not possible to obtain wavelength measurements any nearer to cutoff because of the high attenuation along the plasma guide in this region.

E. Angular Distribution

From the field pattern of the rectangular waveguide, it is to be expected that when the plasma tube is inserted through the narrow walls, the principal mode excited on the plasma coupler should have one angular variation. This was indeed found to be the case. Measurements were made at X band with the probe shown in Fig. 5 as the metal sleeve into which it was inserted was rotated.

Contrary to expectations, a mode with one angular variation was also excited when the plasma column was passed through the broad walls of the rectangular guide. This is apparently because negligible power passes beyond the plasma tube in the exciting guide during conditions of strong coupling. The method of excitation is then shown in Fig. 9(a), so that the plane of maximum transverse E field should be as shown in Fig. 9(b). Results of the probe measurements, in Fig. 9(c), show this to be the case. The slight asymmetry in the field pattern is perhaps due to imperfect alignment, or to the presence of other modes that were also excited.

F. Operation as Microwave Circuit Element

1) *Pulsed Operation:* The coupler was operated as a microwave switch by holding the discharge current at a quiescent value below cutoff. A pulse of voltage was then applied to the discharge tube to increase the plasma density and turn the switch on. Fig. 10 shows the results of applying a 2-μsec, 44-v pulse to the anode of the X-band coupler. Here the top trace is the voltage supplied by the pulser, the center trace the discharge pulse current (2 a), and the bottom trace the microwave power in the output guide. The switching time is about 5 μsec. A switching time of 2 μsec was observed in the

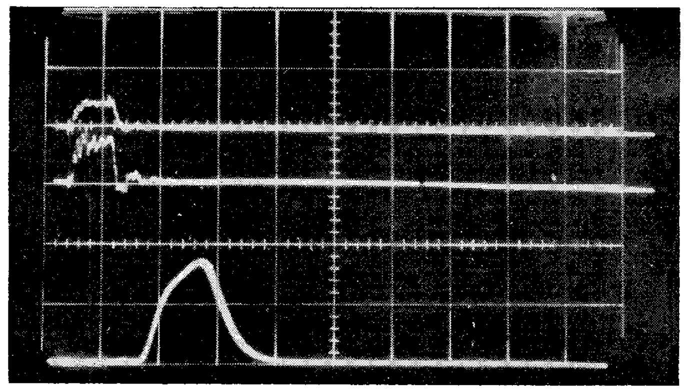

Fig. 10—Response of plasma coupler to 2-μsec voltage pulse. Top trace: voltage pulse (44 v), center: current pulse (2 a), bottom: detected microwave pulse in output guide, frequency, 8.2 Gc; quiescent discharge current, 0.31 a; time scale, 2 μsec/div.

S-band coupler, using a hot cathode tube.

2) *Power-Handling Capability:* The microwave-power-handling capabilities of the variable coupler are limited by the ionization caused by the incident microwave power. If too large an amount of microwave power is fed into the input, it can cause an increase in plasma density sufficient for continuous conduction. The CW operation of the coupler was at the milliwatt level, which caused no problem. In a test of operation as a switch, it was found that 128 w of pulsed X-band power could be handled with 30 db of isolation. The power-handling ability could be increased somewhat by operating at a lower quiescent discharge current, but then more switching power was required.

3) *Bandwidth:* No attempt has yet been made to investigate the bandwidth characteristics of the plasma guide coupler in detail. However, the individual couplers have been operated over a considerable portion of the X- and S-band ranges, although in each case

tuner adjustment was required across the band for maximum output. The final bandwidth of the device will be largely determined by the frequency sensitivity of the impedance match from the rectangular guide to the plasma guide.

IV. ON-OFF-ON Operation

In a second method of operation, the plasma guide coupler can be made to alternately couple, attenuate, and couple power as the discharge current is monotonically increased. In this case, the metal sleeve around the plasma column is made large enough in diameter so that the TE_{11} circular hollow metal waveguide mode can propagate. At very low densities, power is coupled between the input and output guides via this TE_{11} mode. As the density is increased, the cutoff frequency of this mode is increased, similar to that of a plasma-filled rectangular waveguide.[5,6] When this cutoff frequency passes beyond the operating frequency, propagation ceases and the guides are decoupled. In this transition region the plasma coupler again becomes an electronically-controlled attenuator or switch. As the discharge current is increased still further, the plasma column will again start propagating, but now in the space-charge modes described earlier. If the current is increased still further, the guides will continue to be coupled via these plasma guide modes.

This mode of operation was observed at 9.3 Gc when the diameter of the metal sleeve was made 2.16 cm.

V. High-Power Detection of Microwaves

The properties of the plasma guide can be demonstrated further in connection with a nonlinear plasma property. By observing the pulsed voltage across a resistor in series with the plasma tube, the system becomes a high-level detector of pulsed microwaves,[16] the sensitivity of which is related to the plasma guide properties. Detection is due to the increased ionization caused by the microwave power absorbed in the plasma. This extra ionization causes an increase in the discharge current with a resultant voltage pulse on the series resistor.

Fig. 11 shows a series of oscilloscope displays of detected pulses at various quiescent discharge currents for the X-band detector, with constant pulsed 35-w input power of 2-μsec duration. The characteristic 100-kc to 1-Mc plasma oscillations mentioned earlier are evident in the 0.1 to 0.3-a range. The detection sensitivity is summarized in the plot of detected output voltage vs discharge current (Fig. 12). In another test with different levels of power, the minimum detected power was 2 w; the maximum 1.2 kw.

The sensitivity of the detector is a function of the volume of plasma into which the microwave power can penetrate. In the region above plasma guide cutoff, where the energy can propagate along the plasma tube, this volume is determined by the radial penetration of the microwave fields. Fig. 13 shows the radial penetration as calculated from the space charge wave theory for a typical plasma guide. The shape of the curve agrees well with the observed variation in detector sensitivity.

[16] See also, for example, B. J. Udelson, "Effect of microwave signals incident upon different regions of a d.c. hydrogen glow discharge," *J. Appl. Phys.*, vol. 28, pp. 380–381; March, 1957.

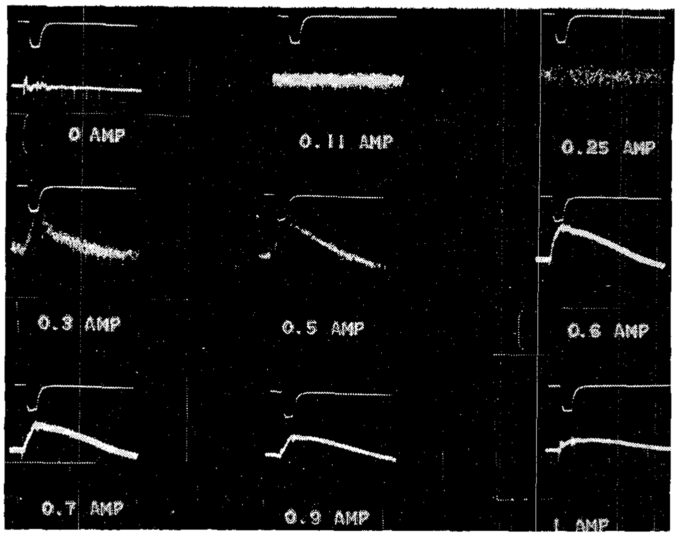

Fig. 11—Input microwave power pulse (top traces) and detected voltage pulse at several values of discharge current.

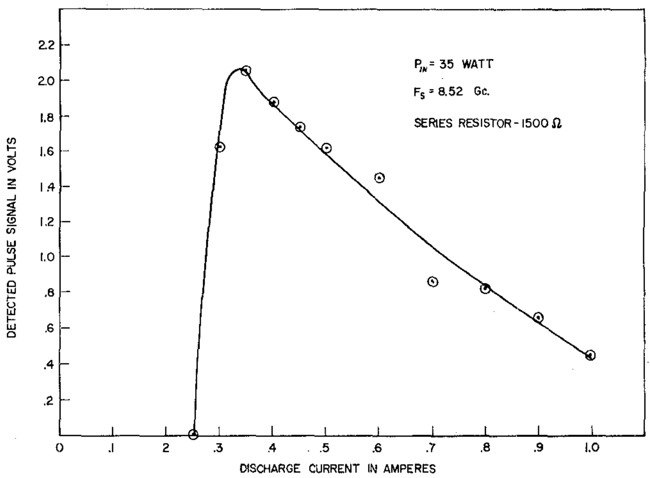

Fig. 12—Detector sensitivity as a function of discharge current.

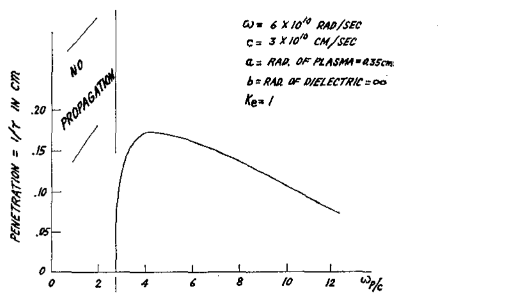

Fig. 13—The variation in radial penetration of the microwave fields into the plasma for a typical plasma guide.

VI. Conclusions

The use of plasma waveguides for coupling microwave energy from one rectangular waveguide to another has been demonstrated. These plasma guides require no dc magnetic field. Since their propagating characteristics may be altered by a change of plasma density, the coupling system becomes an electronically-controllable attenuator or switch. The operation has been demonstrated over a considerable portion of the X- and S-band ranges. The principles of this operation have been verified by measurements of both linear and nonlinear behavior. In operation as a fast microwave switch, switching times of the order of 2 to 5 μsec have been found.

During conditions of no coupling, very high isolation between waveguides exists. Minimum insertion loss during the condition of high coupling found to date has been 8.5 db. Additional work is therefore required on the circuit aspect of effecting broad-band, efficient coupling between rectangular and plasma waveguides. The use of gases with lower collision frequencies than mercury should be considered, to reduce any losses along the plasma guide. Since this coupler operates in the transition region between the slow wave plasma modes and the coaxial metal waveguide, additional theoretical work on the propagating properties of plasma guides in this transition region is also required.

Finally, additional effort should be aimed at the production of plasmas whose densities can be controlled fairly accurately, if this type of coupler or switch is to find wide application. These can be gas discharge plasmas for the lower microwave frequencies and semiconductor plasmas for the higher ranges.

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High-Power Duplexers*

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Summary—**The various circuit arrangements used in duplexers are analyzed in terms of their power-handling ability in two situations: first, where the bandwidth is narrow so that insertion loss determines maximum Q, and second, where large bandwidths are required and the maximum Q is determined by available Q bandwidth products. In both cases the ATR duplexer has an advantage. Arc loss was measured for folded cylinder TR tubes. At medium current densities the results agree well with experimental measurements in dc positive columns. At high current densities a constant conductivity is reached. Graphs of power-handling ability for a unity coupler duplexer using different methods of cooling are presented. It is shown that the requirements for easy firing and long life limit the achievable recovery time.**

Two recent survey articles[1,2] discuss advances in microwave duplexer design that provide circuits with less low-level insertion loss and greater bandwidth and that provide TR tubes with lower-arc loss, less leakage to the receiver, faster recovery and longer life. We will direct our attention to a problem that continues to plague duplexer designers—that of switching higher and higher powers while still meeting the requirements on insertion loss, bandwidth and recovery time. This problem concerns mainly the switching tubes (*i.e.*, the ones nearest the source of high power). It will be assumed that an adequate number of TR gaps or attenuators of one form or another follow the switching tubes in order to lower the leakage to an acceptable level.

We will first discuss the circuits in which the switching tubes are used, then arc-loss measurements and their interpretation, and finally, the effect of gas fill and geometry on gas breakdown and recovery time.

Circuits

Fig. 1 shows a version of the common branched duplexer which consists of two cavities shunt-mounted on a transmission line. On transmit, gas in the gaps becomes ionized, the cavities are detuned and the transmitter power proceeds to the antenna with a small amount leaking through to the receiver. The equivalent circuit (see Fig. 1) shows that the cavity may be adequately represented by a certain (R/Q) value. The resistors R_1 represent the input and output impedances transformed

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[1] A. F. Harvey, "Duplexing systems at microwave frequencies," IRE Trans. on Microwave Theory and Techniques, vol. MTT-8, pp. 415–431; July, 1960.

[2] A. M. Starik, "Principal directions in the development of antenna TR-switches," *Radiotekh. Elektron.*, vol. 5, pp. 1035–1051; July, 1960.