High Power, Magnetic Field Controlled Microwave Gas Discharge Switches*

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Summary—**A new type of gas discharge switch is described. It is electronically controllable, broadband, and capable of rapidly switching high power pulsed microwaves from either of two waveguide input ports to a single waveguide output port, or from one waveguide input port to either of two waveguide output ports. The electronic control is achieved by turning on or off a magnetic field set for cyclotron resonance. An approximate analysis is given of the operation of the active element of the switch and the results are compared with experiment. An analysis of the effects of frequency scaling indicates that, with the exception of the magnetic flux density which increases with increasing frequency, the switch parameters either improve or remain unchanged in going to higher frequencies. Two different switch configurations are investigated, one a *Y*-junction switch for operation at *S* band and the other a balanced top-wall hybrid coupler switch for operation at K_u band. Their electrical characteristics are described.**

Introduction

There are many applications in which it is desirable to be able to switch microwave power from one or more waveguide input ports to one or more waveguide output ports in a controlled manner. This investigation has been specifically concerned with switching the output from either of two transmitters to a common antenna.

The controlled switching of pulsed microwave power can be accomplished in a number of different ways. Mechanical waveguide switches are commonly used, but are relatively slow acting, requiring of the order of 100 milliseconds to operate. A voltage pulsed germanium crystal diode can provide microwave switching[1] but is limited to very low powers. The nonreciprocal properties of ferrites in magnetic fields can also be used for switching applications.[2] The temperature dependence of ferrites limits their high power capabilities. The isolation of ferrite switches is also considerably less than that of mechanical switches and gas switches.

Gas discharges are particularly suitable for the rapid switching of high powers. In a TR tube a microwave gas discharge acts as the switching element. The incident high power transmitted signal causes the gas in the tube to break down, thus effectively isolating a receiver. The low power received signal cannot break down the gas and proceeds with low loss to the receiver. Such a power-actuated device has little possibility of providing electronically controlled switching.

Direct current or low-frequency gas discharges can be used to switch microwave power by controlling either the attenuation or phase shift of a switch tube.[3,4] Switching is accomplished by voltage pulsing of the gas tube. Such devices have power limits of a few hundred watts. At higher microwave inputs, the discharge is captured by the microwave power so that the tube fires whether or not the voltage pulse is applied to it, and switching action is lost.

The gas discharge devices mentioned above operate with no applied magnetic field. The presence of a dc magnetic field profoundly changes the characteristics of the discharge,[5,6] and offers the possibility of obtaining controlled high power switching by varying the magnetic field applied to the gas.

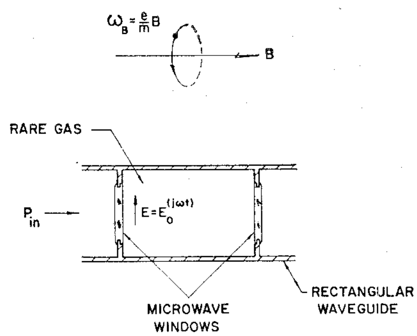

Fig. 1—Schematic of switch tube.

General Description of Switching Element

The active element of the switches to be described below is a tube shown schematically in Fig. 1. It consists of a section of rectangular waveguide sealed off at both ends with vacuum windows and containing a rare gas or mixture of rare gases at a pressure of the order of tenths

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of millimeters of Hg. A dc magnetic field is applied perpendicular to the microwave electric field in the tube. Either a longitudinal magnetic field as shown or a transverse field parallel to the broad face of the waveguide may be used.

The tube is fired by the incident high level microwave power, in a time of the order of one hundredth of a microsecond, when the applied magnetic field is near electron cyclotron resonance. A cyclotron resonant magnetic field is one for which ω_B, the angular frequency of an electron's spiral motion about the flux lines, is equal to ω, the angular frequency of the microwaves. Denoting the charge and mass of the electron by e and m, respectively, $\omega_B = eB/m$ in mks units. The cyclotron resonant magnetic field is denoted by B_c and has a value of around 1200 gauss at S band. Near cyclotron resonance, there is a large transfer of energy from the microwave electric field to the electrons and a strong discharge occurs. The resultant high electron density of the plasma acts like a short circuit at the inside surface of the input window. When the applied magnetic field is zero or sufficiently far from cyclotron resonance, the tube is unfired in the presence of the incident microwaves, and acts like a low-loss section of waveguide. Thus, the on-off action of the switching element can be controlled by varying the magnitude of the applied magnetic field.

Theory

The high level characteristics of the switch tube depend upon certain fundamental microwave gas discharge parameters such as breakdown field, arc loss, and recovery time. The breakdown field is determined by the properties of the plasma during its breakdown period, the arc loss depends upon the plasma's steady state properties, and the recovery time is a function of the properties of the plasma's afterglow period. A complete theoretical analysis of the behavior of the plasma would be very difficult, but one can obtain qualitative information on the switch tube parameters from an approximate analysis. The principal assumptions are as follow.

1) An average electron interacts with a low pressure rare gas.
2) The magnetic field, electric field, collision frequency, diffusion coefficient, etc., are uniform over the gas volume.
3) The only collision processes are elastic collisions and inelastic ionizing collisions between electrons and atoms.
4) The only electron production mechanism is ionization and the only electron loss mechanism is diffusion (free diffusion in breakdown period and ambipolar diffusion during steady state and afterglow periods).

Additional assumptions are mentioned when pertinent.

The continuity equation for electrons can be written as

$$\frac{dn}{dt} = n(\nu_i - \nu_d) \tag{1}$$

where n is the electron number density, ν_i is the ionization rate per electron, or the number of electrons per electron produced per second by ionization, and ν_d is the number of electrons per electron lost per second by diffusion to the walls of the tube.

During the high power pulse, an electron gains energy from the microwave field until it ionizes a gas atom or diffuses out to the walls. Gas breakdown is initiated and the electron density builds up when the number of electrons produced by ionization just exceeds the number lost by diffusion. The electron density increases exponentially from its initial value of around 10^3/cc to approximately 10^8/cc, at which time the much slower process of ambipolar diffusion sets in and the electron density increases at a much faster rate than before. This electron density buildup continues until a condition of "magneto-plasma resonance"[6] is attained, at which time the plasma acts like a short circuit reflecting most of the incident power except for the small amount absorbed to maintain the discharge. Between pulses the discharge decays. If the incident power is much greater than the power required for breakdown, as is usually true in these tubes, $\nu_i \gg \nu_d$ and the diffusion losses can be neglected in determining the breakdown parameters. Breakdown then is determined solely by the power transfer from the microwave field to the electrons, maximum power transfer and hence maximum rate of ionization, corresponding to minimum breakdown power. For sufficiently low pressures and magnetic fields, however, diffusion losses must be taken into account. Now

$$\nu_i = \frac{\nu}{n_i} = \frac{\nu u_c}{u_i} = \frac{P}{e u_i} \tag{2}$$

where ν is the momentum transfer collision frequency or the number of elastic collisions per second between an electron and a neutral atom, n_i is the average number of collisions for an electron starting from rest to reach ionization potential, u_i is the ionization potential in electron volts, u_c is the average energy gain by an electron between collisions in ev, and P is the power transfer per electron or the power absorbed by an electron. P has been derived by Lax *et al.*[5] and is given by

$$P = \frac{e^2 E_0^2}{4m}\left[\frac{\nu}{(\omega + \omega_B)^2 + \nu^2} + \frac{\nu}{(\omega - \omega_B)^2 + \nu^2}\right]. \tag{3}$$

E_0 is the amplitude of an average electric field over the switch tube during the breakdown period and is assumed uniform. The collision frequency ν is directly proportional to the pressure and can be expressed as

$$\nu = 5.9 \times 10^7 u^{1/2} p P_m \tag{4}$$

where $u = mv^2/2e$ is the electron energy in ev, P_m is the so-called "probability of collision" and is a function of the type of gas and the electron's energy, and p is the

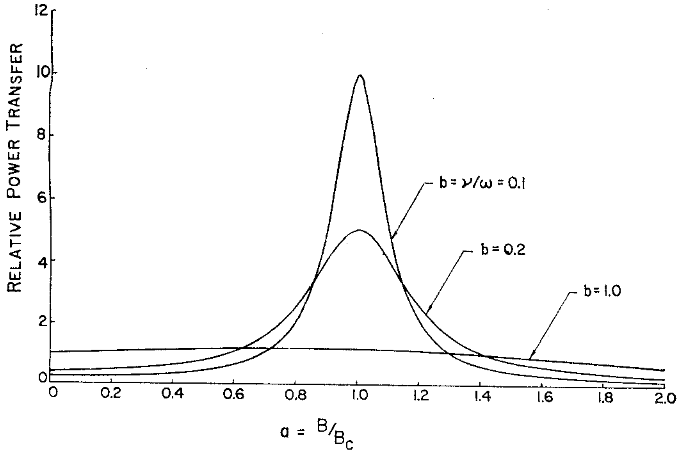

Fig. 2—Power transfer vs magnetic field.

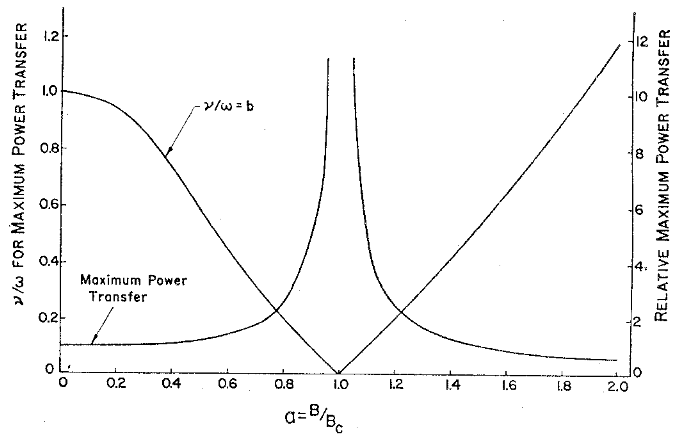

Fig. 3—Maximum power transfer and corresponding ν/ω vs magnetic field.

pressure in mm of Hg. The electronic mean free path is the reciprocal of the quantity pP_m.

The second term of (3) is the resonance term and predominates at low pressures and in the vicinity of cyclotron resonance. Setting $P' = (4m\omega/e^2E_0^2)P$, $a = \omega_B/\omega = B/B_c$ and $b = \nu/\omega$, Eq. (3) is normalized to

$$P' = \frac{b}{(1+a)^2 + b^2} + \frac{b}{(1-a)^2 + b^2} \cdot \qquad (5)$$

P' is the relative power transfer, a is proportional to the applied magnetic field and is called the relative magnetic field parameter, and b is the relative pressure parameter.

Eq. (5) is plotted in Fig. 2, which shows the relative power transfer vs magnetic field for a number of different pressures. The curve has a maximum close to $a = 1$ or cyclotron resonance. The lower the pressure, the nearer the maximum is to $a = 1$, occurring within 1 per cent of this point for $b < 0.4$. The half width of the resonance (between half-power points) decreases with decreasing pressure, and for low pressures it is equal to b. The power transfer at cyclotron resonance increases with decreasing pressure and the power transfer outside the half-power points increases with increasing pressure.

The condition for maximum power transfer and hence the approximate minimum breakdown power is obtained from (5) by setting $dP'/db = 0$. The maximum value of P' and the corresponding value of b as functions of magnetic field are plotted in Fig. 3. The maximum power transfer goes through a resonance at $a = 1$ while the value of b for which maximum transfer occurs first decreases and then increases as the magnetic field increases through cyclotron resonance. At zero magnetic field, the maximum value of P' occurs at $b = 1$. Conventional *TR* tubes usually operate near this condition. At cyclotron resonance, the maximum power transfer is infinite and occurs at $b = 0$. It is apparent that in order to take advantage of the large increase in power transfer and hence the large decrease in breakdown power near cyclotron resonance, it is necessary to operate at as low a pressure as possible. In actual practice, as b approaches zero, (3) ceases to be valid so that experimentally there is a low pressure limit below which the breakdown power begins to increase due to the decreased ionization rate and increased diffusion losses. For helium in *S*-band waveguide in a transverse magnetic field, this limit, called the mean free path limit, occurs at a value of b approximately equal to 0.06. The operating pressure which gives optimum breakdown is not necessarily the best pressure as far as the other electrical characteristics of the switch are concerned and it is necessary to compromise on its value. In all cases, however, operation will be in the low pressure region in which $\nu^2 \ll \omega^2$. It therefore is assumed that $b^2 \ll 1$, which is equivalent to the assumption that there are many oscillations per collision. Eq. (5) then reduces to

$$(P')_{a=1} = \frac{1}{b} \quad \text{or} \quad (P_{bk})_{a=1} \sim b. \qquad (6a)$$

$$(P')_{a\neq 1} = \frac{2b(1+a^2)}{(1-a^2)^2} \quad \text{or} \quad (P_{bk})_{a\neq 1} \sim \frac{g(a)}{b}, \qquad (6b)$$

where $g(a) = (1-a^2)^2/1+a^2$.

Eq. (6a) states that the power transfer at cyclotron resonance is inversely proportional to the pressure or that the breakdown power at cyclotron resonance is directly proportional to the pressure. Eq. (6b) implies that beyond the half-power points of the resonance curve, the breakdown power is inversely proportional to the pressure and directly proportional to the magnetic field dependent quantity $g(a)$. The breakdown power dependence given in (6b) would not be valid for pressures and magnetic fields for which the diffusion losses could not be neglected during the breakdown period.

A convenient way to define the breakdown or firing time is to let it represent the time interval between the beginning of the magnetron pulse and the point at which the attenuation of the plasma begins to increase rapidly. This is near the point at which ambipolar diffusion sets in ($n \simeq 10^8$/cc). This point may be identified with the peak of the spike of the transmitted pulse and can be thought of as corresponding to the end of the breakdown period. The small additional time interval required for n to reach magneto-plasma resonance is neglected. Thus, solving (1) for $\nu_d=0$ and using (2) along with the auxiliary conditions, $n=10^2$/cc at $t=0$ and $n=10^8$/cc at $t=t_{bk}$, one obtains

$$t_{bk} = \frac{12 u_i m \omega}{e E_0^2 P'} . \quad (7)$$

Using (6a), (6b), and (4), and assuming that the average energy of the electrons is proportional to the ionization potential and denoting the input power by P_{in},

$$(t_{bk})_{a=1} \sim \frac{u_i^{3/2} p P_m}{P_{in}} . \quad (8a)$$

$$(t_{bk})_{a\neq 1} \sim \frac{u_i^{1/2} g(a)}{P_{in} p P_m} . \quad (8b)$$

One difficulty in attempting to verify (8) experimentally is that t_{bk} is of the same order of magnitude as the rise time of the incident high power pulse and hence, P_{in}, instead of being constant, is itself a function of the breakdown time.

The actual breakdown power, P_{bk}, depends upon the shape of the pulse. However, its qualitative dependence upon the magnetic field, gas, and pressure can be obtained by assuming CW conditions and defining P_{bk} as that input power which breaks down the gas in a given time. Hence, using (8a) and (8b),

$$(P_{bk})_{a=1} \sim u_i^{3/2} p P_m . \quad (9a)$$

$$(P_{bk})_{a\neq 1} \sim \frac{u_i^{1/2} g(a)}{p P_m} . \quad (9b)$$

As expected, (9) is consistent with (6), but also gives the explicit dependence on the fundamental constants of the gas.

The important afterglow parameter is the recovery time, t_r, which may be defined as that time after the end of the high power pulse at which the attenuation of a probing signal transmitted through the switch tube has decreased to 3 db more than its attenuation in the absence of the discharge. It is assumed that the electrons and positive ions are in thermal equilibrium with the gas, that $\nu_i=0$, and that the only decay mechanism is ambipolar diffusion. The loss rate per electron is readily obtainable from the diffusion equation and is given by

$$\nu_d = \frac{D_a}{\Lambda_B^2} \quad (10)$$

where D_a is the ambipolar diffusion coefficient and Λ_B is the effective diffusion length of the gas container. For a rectangular parallelopiped switch tube of dimensions L_x, L_y and L_z, the characteristic diffusion length Λ in the absence of a magnetic field is given by

$$\frac{1}{\Lambda^2} = \frac{1}{\Lambda_x^2} + \frac{1}{\Lambda_y^2} + \frac{1}{\Lambda_z^2} \quad (11)$$

where $\Lambda_x = L_x/\pi$, etc. The effect of the magnetic field is to increase the effective size of the tube in directions perpendicular to the field.[6] Thus, for a magnetic field along the z axis, the effective diffusion length Λ_B is given by

$$\frac{1}{\Lambda_B^2} = \frac{\nu^2}{(\nu^2+\omega_B^2)}\left[\frac{1}{\Lambda_x^2} + \frac{1}{\Lambda_y^2}\right] + \frac{1}{\Lambda_z^2} \simeq \frac{1}{\Lambda_z^2} \cdot \quad (12)$$

The approximation in this equation holds except for sufficiently small applied magnetic fields, or for Λ_x or Λ_y very much less than Λ_z.

Substituting (10) into (1) and solving for n under the assumption that the magnetic field is constant during the afterglow period gives

$$n = n_0 \exp(-D_a t/\Lambda_B^2) \quad (13)$$

where n_0 is the electron density at the beginning of the afterglow. Let n_r be the electron density of the plasma when the 3-db attenuation point is reached. Then $n=n_r$ when $t=t_r$ and

$$t_r = \frac{2.3\Lambda_B^2}{D_a} \log(n_0/n_r). \quad (14)$$

The quantity $(D_a)p$ is a constant for a given gas. The quantity n_0 varies approximately as $(P_{in})^\alpha$ where α is a positive constant. Hence a plot of t_r vs log P_{in} is linear.

In the steady-state discharge condition of the high power switch tubes, the density of the plasma is beyond magneto-plasma resonance and thus shields the interior from the fields outside. This means that the incident power is reflected except for the portion required to maintain the plasma in equilibrium. The power not reflected is absorbed by the discharge, since the power transmitted through the discharge is negligible. The absorbed power is dissipated primarily in the form of heat.

The per cent arc loss of a switch tube can be defined as P_{abs}/P_{in}, where P_{abs} is the power absorbed in the steady-state plasma. P_{abs} may be expressed in terms of σ, the conductivity of the discharge. The presence of the magnetic field gives rise to a tensor conductivity, which can be obtained from the relation $\overleftrightarrow{\sigma} = ne\overleftrightarrow{\mu}$ where the mobility tensor $\overleftrightarrow{\mu}$ is given by Allis.[7] The conductivity tensor, for the magnetic field along the z axis, is

$$\overleftrightarrow{\sigma} = \begin{Vmatrix} \sigma_{11} & \sigma_{12} & 0 \\ -\sigma_{12} & \sigma_{11} & 0 \\ 0 & 0 & \sigma_{33} \end{Vmatrix},$$

$$\sigma_{11} = \frac{e^2 n}{2m}\left[\frac{1}{\nu + j(\omega+\omega_B)} + \frac{1}{\nu + j(\omega-\omega_B)}\right]. \quad (15)$$

[7] W. P. Allis, "Motions of Ions and Electrons" in "Handbuch Der Physik," Springer-Verlag, Berlin, Ger., vol. 21, p. 394; 1956.

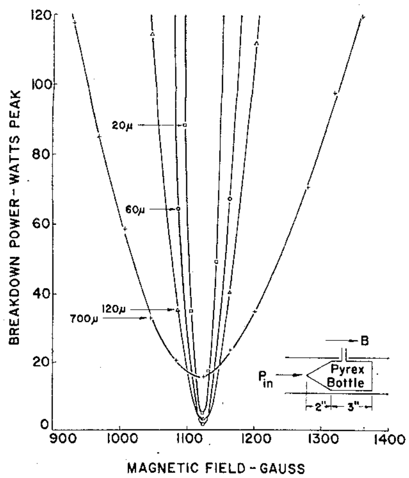

Fig. 4—Breakdown power vs magnetic field in vicinity of cyclotron resonance.

For an incident electric field along the x axis, the electric field E in the plasma will have components essentially along the x and y axes due to the action of the magnetic field. The current density is $\vec{J}=\overleftrightarrow{\sigma}\cdot\vec{E}$ and the absorbed power per unit volume is given by $Re\{\vec{E}\cdot\overleftrightarrow{\sigma}\cdot\vec{E}\}$. Hence using $\vec{E}=\vec{i}E_x+\vec{j}E_y$ and denoting the volume by V,

$$P_{\text{abs}} = VE^2 \text{ Re } \{\sigma_{11}\}. \tag{16}$$

Assuming $\nu^2 \ll \omega^2$, (15) and (16) reduce to

$$(P_{\text{abs}})_{a=1} = \frac{e^2VnE^2}{2m\nu} \cdot \tag{17a}$$

$$(P_{\text{abs}})_{a\neq 1} = \frac{e^2VnE^2\nu}{m\omega^2 g(a)} \cdot \tag{17b}$$

It is not known how E and n in the switch tube vary with the pressure, magnetic field, input power, and type of gas. Experimentally, for peak input powers of around 100 kw, the absorbed power is appreciable, being 10 per cent or more of the incident power. Hence the electric field inside the discharge is determined primarily by the incident electric field rather than the space charge field. Assuming that $E\sim E_{bk}$, or $E^2\sim P_{bk}$ in so far as their variation with the type of gas, pressure, and magnetic field is concerned, (17), (9), and (4) give for all magnetic fields

$$P_{\text{abs}} \sim nu_i. \tag{18}$$

On discharge, the high power switch tube operates beyond magneto-plasma resonance and it is expected that n will not vary much with changes in pressure or magnetic field. If all the input power went into ionization and there were no losses, $n\sim P_{\text{in}}$. Considering losses, one can say very approximately that $n\sim(P_{\text{in}})^\alpha$ where $0<\alpha<1$. Hence, dividing both sides of (18) by P_{in},

$$\text{arc loss} \sim \frac{u_i}{(P_{\text{in}})^\beta}, \qquad 0 < \beta < 1. \tag{19}$$

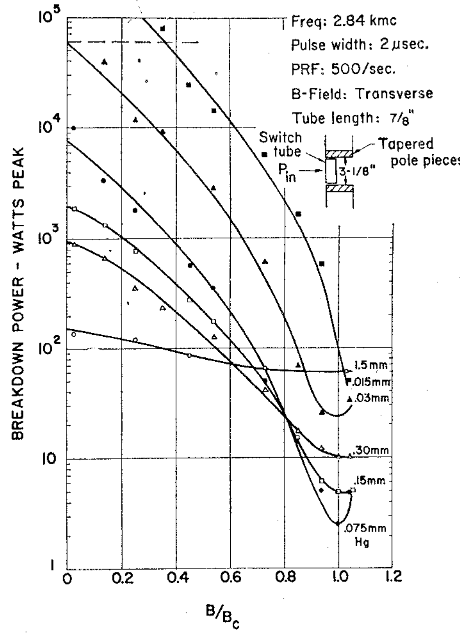

Fig. 5—Breakdown power vs magnetic field in argon.

Comparison of Theory and Experiment

The theoretical curves of Fig. 2 imply that at low pressures, the breakdown power vs magnetic field characteristic should exhibit a minimum at cyclotron resonance, the width of the resonance should decrease with decreasing pressure, the cyclotron resonance breakdown power should decrease with decreasing pressure, and the breakdown power off cyclotron resonance should increase with decreasing pressure.

Fig. 4 is a plot of the experimental breakdown power in helium plus 1 per cent neon in the vicinity of cyclotron resonance. The data were taken under relatively low input power conditions. The frequency was 3.15 kmc, the PRF was 100 per second and the pulse width was 4.7 μsec. The tube was a tapered pyrex bottle fitting snugly into the S-band rectangular waveguide. A solenoid provided a uniform longitudinal magnetic field. The curves are in qualitative agreement with the theory. One interesting feature is the effect of the mean free path limit. As the pressure decreases, the breakdown power at cyclotron resonance decreases until this limit, which occurs at a pressure near 50 microns of Hg, is reached. Below this limit the breakdown power increases with decreasing pressure.

Fig. 5 shows some experimental data in argon taken over a wide range of input powers. Again, the data are in qualitative agreement with the theory. It can be seen that for sufficiently low pressures, the input power required for breakdown at cyclotron resonance is almost four orders of magnitude less than the breakdown power at zero magnetic field. The dashed line in the figure meets the 30 microns breakdown curve at a point corresponding to 60 kw and zero magnetic field. This means that for the controlled switching of a source power of 60-kw peak, it is necessary to operate at a pressure below 30

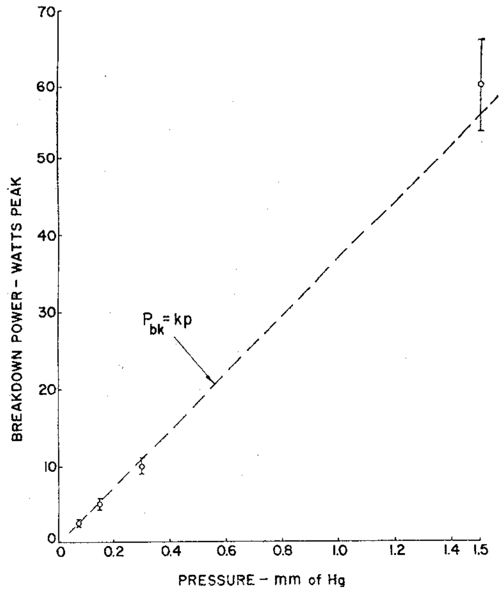

Fig. 6—Breakdown power at cyclotron resonance vs pressure in argon.

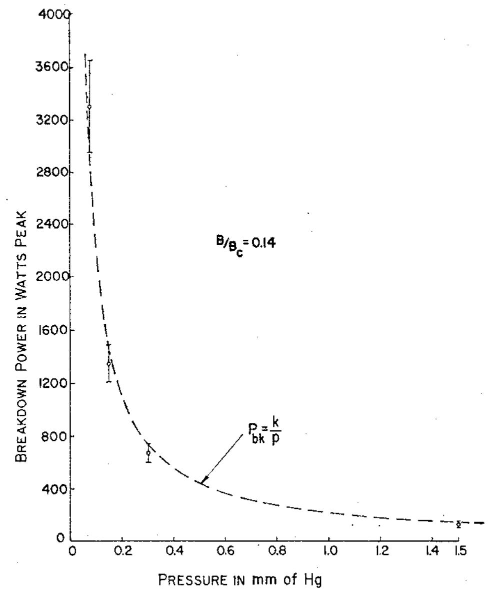

Fig. 7—Breakdown power off cyclotron resonance vs pressure in argon.

microns of Hg. Otherwise, the tube would fire even at zero applied magnetic field and control would be lost. At 30 microns of Hg, less than 25 watts is required for breakdown at cyclotron resonance. At still lower pressures, the breakdown curves are shifted toward higher powers. The power required for cyclotron resonant breakdown also increases, but much more slowly than at zero magnetic field where diffusion losses become important. For example, at pressures below 15 microns, it is possible to hold off approximately 500 kw of pulsed power without breakdown (extrapolated), while at cyclotron resonance the power required for breakdown is still only of the order of 100 watts. The mean free path limit is seen to occur somewhere around 50 microns of Hg and hence, in the particular geometry used, to achieve the wide range of magnetic field control mentioned requires operation below this limit.

The data of Fig. 5 have been replotted for comparison with (6a) and (6b). Fig. 6 shows the breakdown power at cyclotron resonance vs pressure. Only pressures above the mean free path limit were used. The dashed line is the theoretical prediction of (6a), and is in reasonable agreement with the data. Fig. 7 shows the corresponding breakdown characteristic off cyclotron resonance vs pressure. The value of applied field used is sufficient to provide operation beyond the half-power points of the resonance at the highest pressure investigated. The dashed curve is the theoretical prediction of (6b). Fig. 8 shows the breakdown power vs magnetic field in helium in the magnetic field range in which (6b) is applicable. The dashed line is the theoretical prediction of this equation. Breakdown measurements on tubes filled with a number of different gases have given results in qualitative agreement with (9).

The recovery time has been measured in a number of different switch tubes. The results are in qualitative agreement with the predictions of (14).

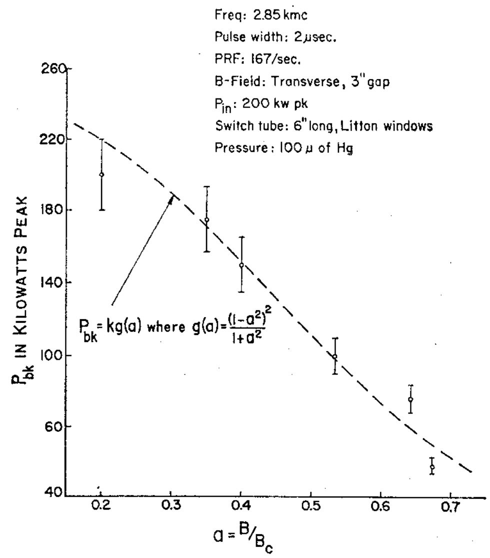

Fig. 8—Breakdown power vs magnetic field in helium.

Experimental arc loss data are in qualitative agreement with (19). In the range of input powers above about 10 kw, the arc loss decreased only slightly with increasing input power; the best experimental fit is for a $\beta \simeq 0.2$. The arc loss is essentially independent of pressure except below the mean free path limit where the excessive diffusion losses cause the arc loss to increase rapidly with decreasing pressure.

Frequency Scaling

An approximate analysis was made of the way in which the switch parameters change in scaling from one frequency band to another. The principal assumptions were that the input power doesn't change in scaling, that the electric field in the steady-state discharge varies with ω in the same way as the breakdown field, and that the switch operates at the maximum pressure which still allows magnetic field control.

The results of the analysis follow.

1) $p \sim \omega$.
2) $t_{bk} \sim 1/\omega$.
3) P_{bk} is independent of ω.
4) $t_r \sim 1/\omega$.
5) Arc loss is independent of ω.
6) (ΔB) for switching $\sim \omega$.

Although the cyclotron resonant magnetic field varies as ω, the gap spacing of the electromagnet varies approximately as $1/\omega$. Hence, the power rating of the supply for switching the magnetic field remains approximately the same in scaling.

Bandwidth of Switch Tube

The bandwidth of a switch tube depends upon its geometry and upon how the high level switch parameters vary with the frequency for a fixed value of magnetic field. In general, the large energy transfer near cyclotron resonance allows one to use a broadband structure and still achieve a strong discharge.

The low-level bandwidth of a number of S-band tubes was investigated. Two common types of windows used were Sylvania's 1B58 TR tube window and their ATR 345 window (JAN 5792). Fig. 9 illustrates the VSWR of some S-band tubes whose lengths were chosen to optimize the bandwidth. The bandwidth between 1.25:1 VSWR points for the ATR 345 window tube with a window spacing of $\frac{25}{32}$ inch was 37 per cent. The other two ATR 345 window tubes were approximately one halfguide wavelength and one guide wavelength longer than this tube. Although their bandwidth is reduced, the increased length and volume improves both the isolation and tube life.

The cold bandwidth of a number of switch tubes for operation at the upper end of K_u band was also investigated. Bandwidths in excess of 20 per cent were obtained both for tubes using Microwave Associates MA 1341 windows and tubes with ceramic windows in conjunction with a matching section at each end of the tube.

The over-all bandwidth of the switch tubes when in a fired condition could not be measured directly because of the limited frequency range of the high power sources available. However, since the cyclotron resonant magnetic field is directly proportional to the frequency, the frequency variation of the tube parameters at constant magnetic field is approximately equivalent to their magnetic field variation at constant frequency. Experiments were performed to determine how the high level switch tube parameters varied with magnetic field. It was found that the parameters were approximately symmetrical about cyclotron resonance and that they varied only a small amount for variations in the applied magnetic field around cyclotron resonance of ± 20 per cent. For example, for typical operating pressures, the arc loss varied by less than 0.1 db and the isolation decreased by only a few db from its maximum value at cyclotron resonance.

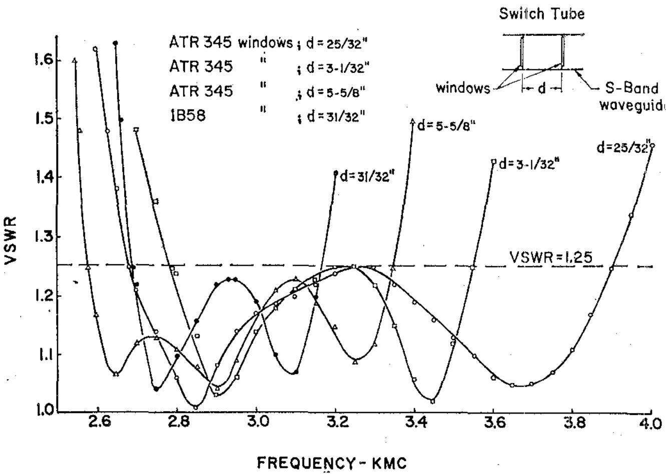

Fig. 9—VSWR of switch tubes.

Design Considerations

The theoretical and experimental switch tube studies have shown that the best over-all operation is obtained by switching between $B=0$ and $B=B_c$ and using the maximum pressure which still allows adequate magnetic field control, *i.e.*, that pressure above which the given incident power would produce breakdown even in the absence of a magnetic field.

The major problem encountered in this investigation was to achieve a satisfactory life. The tubes fail primarily due to excessive gas cleanup. The use of encapsulated windows[8] offers promise of providing increased tube life by eliminating sputtering, which is the major cause of the gas cleanup. Sputtering also reduces life by causing excessive insertion loss. Encapsulated window tubes show a reduced isolation over that of tubes using conventional windows.

The principal gases used in this investigation were argon, helium plus 1 per cent argon, and helium; satisfactory switching was obtained for all three. The lower ionization potential rare gases gave a smaller arc loss and a somewhat larger isolation, but because of the lower pressure required for adequate magnetic field control, the effect of gas cleanup was more pronounced and the life reduced.

The switching time is the time required to go from the condition where the incident power fires the switch tube to the condition where the incident power does not fire the switch tube, or vice versa. It depends upon the recovery time and how fast the magnetic field can be switched; in most cases, the latter is the limiting factor. In this investigation, the tubes were controlled by a manually operated magnetic field but, in principle,

[8] L. Gould, E. V. Edwards, and I. Reingold, "A novel approach to microwave duplexer tube design," IRE Trans. on Electron Devices, vol. ED-4, pp. 300–303; October, 1957.

the tubes can be controlled electronically. Switching times of less than 1 millisecond should be possible. The eddy current losses during the magnetic field switching period are kept small by using a thin-walled tube body.

Switch Applications

Switch tubes can be incorporated into many different kinds of switches depending upon the particular application. Two types of switch configurations were investigated for transferring the output from either of two transmitters to a common antenna and are shown in Fig. 10. The first type is a 120 degree E-plane Y switch and is shown in Fig. 10(a). It consists of two switch tubes located at the junction of a waveguide Y. There are two input ports for connections to the separate transmitters and one output port for connection to the antenna. In one switch state a magnetic field near cyclotron resonance is applied to tube SW1 while a zero or very small magnetic field is applied to SW2. In the other switch state the magnetic fields are interchanged. This type of switch can be used when only one transmitter is active at a time. When transmitter T1 is in operation, the cyclotron resonant field is applied to SW2. The incident power from T1 leaves SW1 unfired but fires SW2, producing an effective short at its input window and thereby connecting T1 to the antenna by means of a 120-degree waveguide bend. When T2 is active, the cyclotron resonant field is applied to SW1 and the antenna is effectively connected to T2.

If it is required that both transmitters be in operation at the same time, the output of the transmitter not connected to the antenna must be dissipated in a high power load. This Y-junction switch could not be used unless high power isolators were inserted in the input ports. It is possible, however, to use a configuration consisting of three Y junctions and four switch tubes to meet this switch requirement.

The second type is a balanced top-wall hybrid coupler switch and is shown in Fig. 10(b). It consists of two 3-db top-wall couplers with a dual switch tube between them. Top-wall couplers are used rather than side-wall couplers because the gap spacing of the electromagnet supplying the magnetic field in the former case is approximately one half that in the latter case. There are two input ports for connections to the separate transmitters and two output ports for connections to the antenna and a matched termination. In one switch state a magnetic field near cyclotron resonance is applied to both tubes. In the other switch state a zero or very small magnetic field is applied to the tubes. The balanced switch can be used whether one or both of the transmitters are in operation at a time. For the case where both transmitters are active, when a cyclotron resonant magnetic field is applied, the incident microwave power fires both tubes simultaneously. The effective shorts at the ends of the tubes cause the output of T2 to go to the antenna and the output of T1 to go to the high power load. When the applied magnetic field is zero or sufficiently reduced, the tubes are unfired by the incident power and the output of T1 goes to the antenna, while the output of T2 goes to the load. For the case where only one transmitter is active at a time, a cyclotron resonant magnetic field is applied when T2 is active so that its output is reflected out the antenna port, and the magnetic field is reduced to a low value when T1 is active so that its output goes to the antenna. The termination absorbs the small amount of power due to leakage from the couplers.

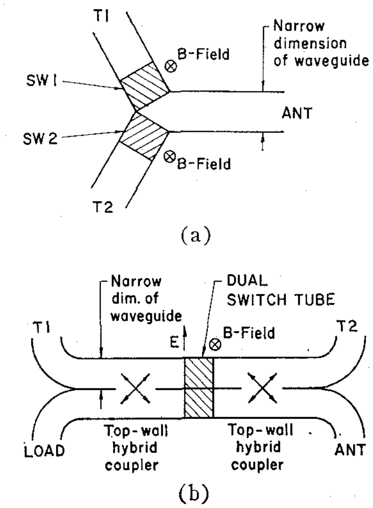

Fig. 10—Switch configurations. (a) 120-degree E-plane Y-junction switch; (b) balanced top-wall hybrid switch.

Each type of switch has certain advantages over the other. The relative advantages of the balanced switch are, first, that only one electromagnet is required instead of two. Second, no flux leakage problems exist in the balanced switch because both tubes are fired or unfired simultaneously. In the Y switch only one switch tube is to be fired at a time, and flux leakage from one electromagnet to the opposite switch tube can result in decreased magnetic field control. Third, matching sections external to the switch tubes can be used to increase the bandwidth of the balanced switch while this cannot readily be done in the Y switch. Fourth, the magnetrons always see a good match in the balanced switch, while in the Y switch, during the approximately 10^{-8} seconds required to fire the proper tube after the initiation of the transmitter pulse, the magnetron sees a mismatch of approximately 2 to 1.

The relative advantages of the Y switch are, first, that the bandwidth of a 120-degree E-plane bend covers the whole waveguide band while the bandwidth of the balanced switch is limited by that of the top-wall couplers. Second, the isolation between transmitters is large in both switch states of the Y switch, while in the balanced switch, in the switch state in which both tubes are unfired, the isolation is only that of the two couplers in series. Third, the peak power handling capacity of the Y switch is greater than that for the balanced switch. Fourth, the insertion losses are less in the Y switch than in the balanced switch.

Experimental *Y*-Junction Switch

A *Y*-junction switch for operation at *S* band was built and tested. Fig. 11 is a photograph of this switch. An individual switch tube is shown on the side. Each switch tube was approximately 1 inch long and had 1B58 TR tube windows at its ends. Measurements were made with a high power microwave source connected to port T1 of Fig. 10(a) and matched loads connected to ports T2 and ANT. A cyclotron resonant field was manually applied to Switch Tube 2 while the magnetic field applied to Switch Tube 1 was essentially zero. The required magnetic field was approximately 1200 gauss across a 3-inch gap.

Typical experimental results achieved for an argon filling at a pressure of 30 microns of Hg were as follows.

Power switched ($f=2.85$ kmc; $PW=2$ μsec)	250-kw peak, 250-watt average.
High level VSWR	1.20:1.
High level insertion loss	0.5 db.
Isolation	50 db.
High level firing time	$<2\times10^{-8}$ seconds.
Recovery time (3 db)	2 milliseconds.

The power switched was the maximum power obtainable from the available test equipment. The high power limit of the switch is determined by gas cleanup and the heat dissipation capabilities of the input window. This window dissipates an appreciable portion of the power absorbed by the discharge. At the 250-watt average power level this dissipation limit had not been reached. The measured recovery time was quite long, although it is sufficient to allow switching times of a few milliseconds provided the magnetic field switching power supply can switch the electromagnet current in this time. Subsequent investigation has indicated that recovery times smaller by at least a factor of ten can be achieved without adversely affecting the other switch parameters.

Only limited attention has been given thus far to the life of the switch. Due to the relatively low operating pressures, gas cleanup can seriously affect the life. Cleanup due to sputtering was observed over a period of only a few hours of operation. Markedly improved life was obtained by using encapsulated windows.

The bandwidth of the *Y*-junction switch is limited primarily by the bandwidth of the switch tube since the effect of the 120-degree *E*-plane bend is small.

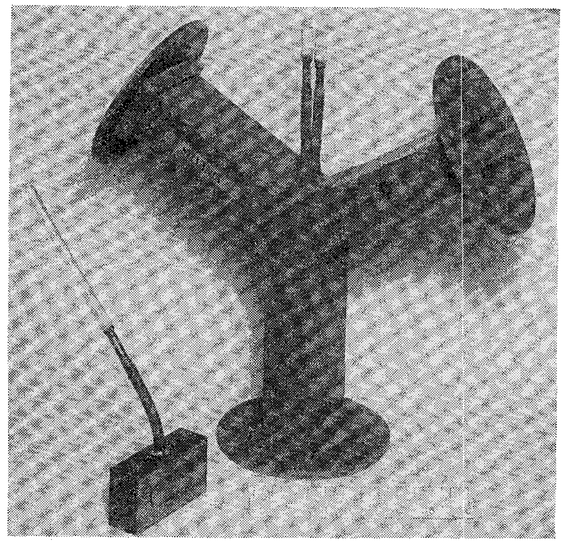

Fig. 11—120-degree *E*-plane *Y*-junction switch for *S* band.

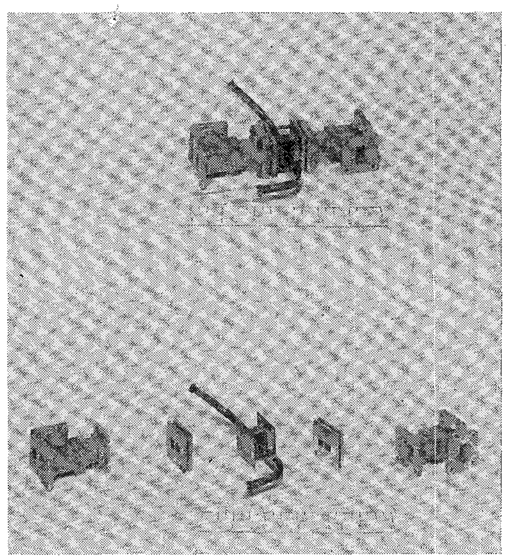

Fig. 12—Balanced top-wall hybrid switch for K_u band.

Experimental Balanced Hybrid Switch

A balanced switch for operation at the high end of K_u band was built and tested. A photograph of this switch is seen in Fig. 12. The separate components of the switch shown assembled at the top are from left to right, a top-wall coupler, a dual matching section, the dual switch tube, a second dual matching section and a second top-wall coupler. The tapered pole pieces of the electromagnet are positioned at the top and bottom of the dual switch tube. The required magnetic field is approximately 5800 gauss across a $\frac{21}{32}$-inch gap. Each switch tube consists of a 0.020-inch wall low-loss ceramic body with 0.020-inch-thick ceramic windows at each end. A $\frac{3}{16}$-inch ID OFHC copper tube is used for evacuation and gas filling. The outside surface of the body of the tube is metallized to provide the conducting sides of the waveguide and to minimize eddy current losses. The matching sections are required to match out the discontinuities due to the ceramic windows.

Fig. 13 shows the VSWR and insertion loss of this switch in its unfired state. The cold bandwidth between 1.25:1 VSWR points is more than 20 per cent. The insertion loss is less than 0.5 db from 15.5 to 17.5 kmc. The increase in insertion loss at each end is due to the fact that the top-wall couplers used were designed for operation only in the 15.5 to 17.5 kmc region. The unfired isolations exceed 20 db over the band.

High power measurements on the balanced switch were made with a microwave source connected to port

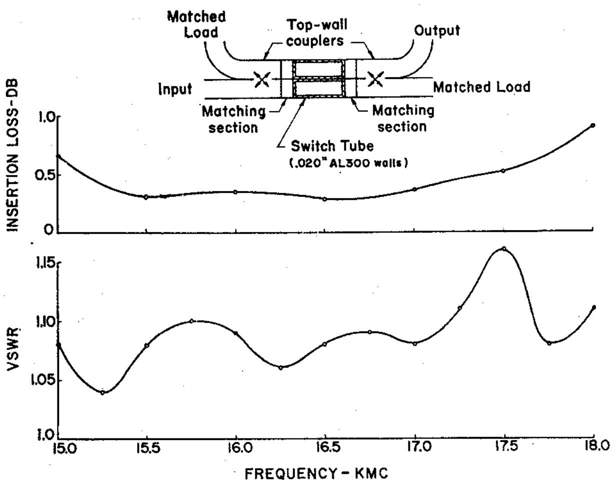

Fig. 13—VSWR and insertion loss of balanced switch in unfired state.

T1 of Fig. 10(b) and matched loads connected to the other three ports. A cyclotron resonant magnetic field was manually applied to the switch tube pair. Typical experimental results achieved for an argon filling at a pressure of 100 microns of Hg were as follows.

Power switched	60-kw peak,
($f=16.0$ kmc; $PW=1$ μsec)	60-watt average.
High level VSWR	1.12:1.
High level insertion loss	1.0 db.
Isolation	50 db.
High level firing time	$<2\times10^{-8}$ seconds.
Recovery time (3 db)	0.60 milliseconds.
Recovery time (0.1 db)	1.0 millisecond.

The power switched was close to the limit of the available sources. The insertion loss measured with a shorting plate simulating the fired tubes was 0.2 db so that the actual arc loss was 0.8 db. In an application in which both transmitters are active simultaneously, the output of the transmitter whose power is to be dissipated in the high power load also contributes to the discharge. Hence less power of the other transmitter is needed to maintain the discharge and the high level insertion loss would be reduced considerably.

The variation in the switch parameters for a ± 20 per cent variation in the magnetic field around cyclotron resonance was relatively small. The principal limitation on the bandwidth of the switch is the limited operating frequency range of the top-wall couplers.

Only preliminary life studies have been performed on this switch so no definite conclusions can be reached.

Conclusion

A new type of waveguide switching element employing a gas-filled tube immersed in a magnetic field was investigated both theoretically and experimentally. The operation of the switching element is based on the phenomenon of cyclotron resonance. The results were sufficiently promising that two different types of switches were constructed for transferring high power pulsed microwaves from either of two transmitters to a common antenna. The switches were broad-band, had high isolation, and can provide switching times considerably less than that of mechanical waveguide switches.

Acknowledgment

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