Microwave Switching with Low-Pressure Arc Discharge*

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Summary—**The characteristics of a low-pressure, hot cathode arc discharge have been studied and applied to microwave switching applications. The combination of rapid plasma build-up, low ignition voltage, and fairly rapid plasma decay, offers promise for the development of broad-band, high-power microwave switches which can be closed in tenths of microseconds and opened in a few microseconds or less. Experimental results on some particular switches are reported.**

Introduction

GAS discharge plasmas have long been used to control, attenuate and switch microwave power. TR and ATR tubes use plasmas produced primarily by the microwave power itself. Plasmas produced by hot or cold cathode glow discharges have been used for low power attenuators[1] and switches.[2] RF excited plasmas have been used to develop a phase shifter[3] and Faraday rotator.[4] A magnetically-controlled switch which uses a microwave induced plasma has recently been discussed.[5] The glow discharge control devices tend to be somewhat unstable and are usually restricted to low power applications. Even the ever useful TR can have disadvantages for low power switching or crystal protection, and is always faced with spike leakage problems at high power.

The properties of low pressure arc discharges do not seem to have been exploited for microwave use. A study of some of these properties and their application to switching microwaves will be described.

Propagation in Plasmas

The physical quantity which allows a gas discharge plasma to be used as a microwave switching element is the electron density, or number of electrons, per cubic centimeter. This can be seen from the simplified expression for the microwave index of refraction of a plasma. This is given by

$$N = \sqrt{1 - \left(\frac{f_p}{f}\right)^2},$$

where f_p is the plasma frequency ($f_p \cong 9000 \sqrt{n_e}$ sec^{-1}, where n_e is electron density per cubic centimeter), and f is the frequency of the wave being propagated. When the ratio f_p/f is greater than or equal to one, the index of refraction is 0 or imaginary, and propagation in the medium is forbidden. A careful study of microwave propagation in plasmas should include both source and sink terms for the electron density, the effect of electron density gradients, and nonlinear effects. However, a qualitative picture of what can be expected may be obtained by examining the transmission characteristics of an infinite slab of plasma which is of uniform density throughout the slab and has no dc electric field. If we assume that we have a finite slab of thickness d and a loss term which may be expressed by a collision frequency, ν, the expressions for the power transmission and reflection coefficients for normal incidence are given by[6]

$$T = \frac{\text{Power Transmitted}}{\text{Power Incident}} = \left| \left[\frac{4\gamma e^{(i\omega/c)\gamma d}}{(1+\gamma)^2 - (1-\gamma)^2 e^{(i2\omega/c)\gamma d}} \right] \right|^2$$

$$R = \frac{\text{Power Reflected}}{\text{Power Incident}} = \left| \left[\frac{(1+\gamma)(1-\gamma)(1 - e^{(i2\omega/c)\gamma d})}{(1+\gamma)^2 - (1-\gamma)^2 e^{(i2\omega/c)\gamma d}} \right] \right|^2,$$

where $\gamma = \sqrt{1 - \omega_p^2/\omega(\omega + i\nu)}$, and $\omega_p = 2\pi f_p$. Figs. 1 and 2 give numerical results for these coefficients under the assumption that the thickness of the slab is equal to a free-space wavelength. The transmission and reflection coefficients are plotted against the plasma frequency with the ratio of the collision frequency to the radian frequency of the signal as a parameter. Fig. 1 shows that the transmission coefficient falls very rapidly for densities greater than the plasma density when the loss frequency is of the order of 1/10 or less of the radian frequency. Under the same conditions Fig. 2 shows that virtually all of the incident signal is reflected from the plasma slab. These calculations suggest seeking a low pressure source of plasma for switching purposes.

* Received by the PGMTT, June 10, 1960; revised manuscript received, July 18, 1960. This work was performed under Air Force Contract No. AF 30(602)-1886.

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[1] E. M. Bradley and D. H. Pringle, "The theory and design of gas-discharge microwave attenuators," *J. Brit. IRE*, vol. 15, pp. 11–24; January, 1955.

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

[3] 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.

[4] L. Goldstein, M. A. Lampert and J. F. Heney, "Magneto-optics of an electron gas with guided microwaves," *Elec. Commun.*, vol. 28, pp. 233–234; September, 1951.

[5] S. J. Tetenbaum and R. M. Hill, "High power, magnetic field controlled microwave gas discharge switches," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-7, pp. 73–83; January, 1959.

[6] E. Barrett, private communication.

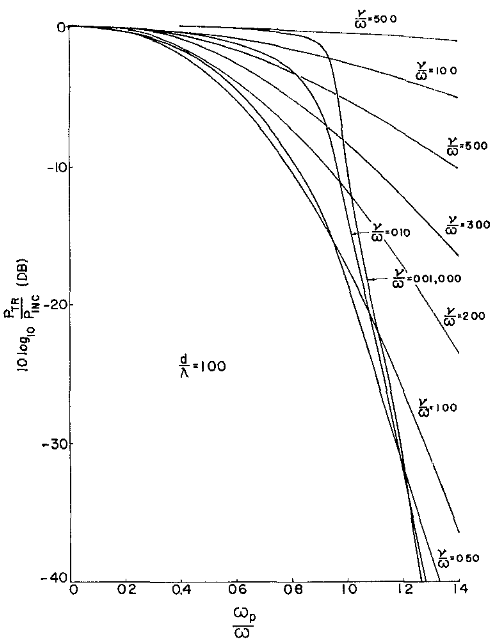

Fig. 1—Layer attenuation vs electron density.

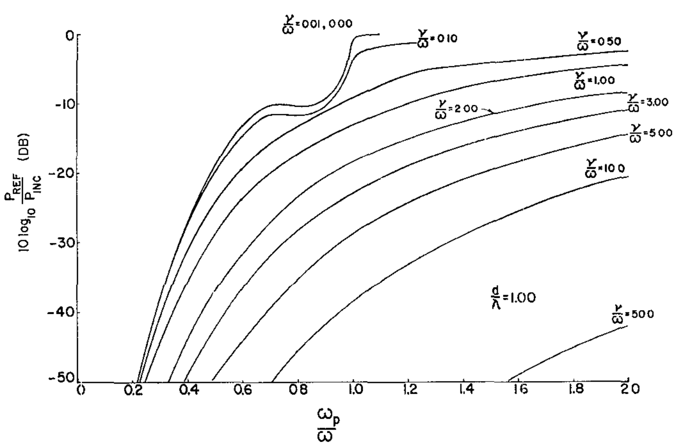

Fig. 2—Layer reflected power vs electron density.

In order to use a gaseous microwave switch with relatively high powers, the question of microwave breakdown of the gas in the switch needs consideration. Brown has shown that,[7] as a function of pressure, there is a minimum in the power required for microwave breakdown which is approximately at the point where the ratio of $\nu/\omega=1$ (ν, the collision frequency, is directly proportional to pressure). Since the above considerations of reflection and transmission require ν/ω to be less than one, it is evident that the pressure should be kept as low as is practical for high-power applications.

Low-Pressure Arc Discharge

The arc discharge is characterized by high current, primarily of electrons, and relatively low voltage drop across the discharge, particularly if a hot cathode is used. This general type of discharge is used in fluorescent lighting fixtures and also in thyratrons. Typical densities in the positive column of the discharge are of the order of 10^{12}–10^{13} electrons and ions per cubic centimeter, which should be sufficient for microwave switching up to frequencies of 30 kMc. Peak discharge currents of one to hundreds of amperes can be carried by such discharges.

Careful study of the mechanisms operating in hydrogen thyratrons[8] of the type used for magnetron modulators has clarified many features of this discharge and make it a very attractive possibility for use as a microwave switch. The ignition of the discharge, or the build-up of electron density, can take place in a triode structure with a grid providing the trigger for the ignition. Build-up of electron density to its equilibrium value is very rapid, being accomplished in ten to a hundred millimicroseconds. This time is primarily a function of the pressure of the gas and of the applied grid and anode voltages.

The grid, of course, loses any control of the discharge after the initial breakdown, and only after the density has again fallen below some fairly low value can the grid again exert any influence on the tube. The decay of the electron density after removal of the anode voltage is influenced by two things. Firstly, if the anode is allowed to reverse itself for a small period of time, much of the density will be removed from the tube by this sweeping voltage. The remainder decays in a time determined by the geometry of the tube and the ambipolar diffusion coefficient, which is for practical purposes equivalent to twice the positive ion diffusion coefficient. Typical decay or recovery times are of the order of one to tens of microseconds. It would appear, therefore, because of the rapid ignition, high equilibrium density and fairly rapid decay of this density, that the low pressure, grid initiated, arc discharge could be applied to microwave switching problems.

Experimental Results

Construction and Operation

Several tubes have been constructed in which the positive column of a low pressure arc discharge is contained in a section of X-band waveguide. These were designed for switching pulsed signals and are fired only during the time that the signal to be switched is present. Tubes to switch CW power could be designed but an average discharge power of 40 to 100 watts would have to be dissipated in the tube. Also, CW switching is restricted to relatively low microwave power levels, probably in the tens of watts region, because the power required to maintain an existing discharge is considerably less than that required for the initial breakdown. The rate of electron loss which governs the power required for break-

[7] S. C. Brown, "Handbuch de Physik," Julian Springer, Berlin, Ger., vol. 22; 1955.

[8] Edgerton-Germeshausen and Greer, Inc., "Research Study on Hydrogen Thyratrons," Final Rept. Contract DA 36-039-sc-15372; 1953.

down is the diffusion rate of free electrons. For existing plasmas, the space-charge forces between electrons and ions give rise to the much slower ambipolar diffusion rate; *i.e.*, equal currents of ions and electrons leave the plasma, governed primarily by the rate of ion motion.

Fig. 3 is a drawing of a typical tube. The waveguide section itself is used as the grid and the narrow walls are covered with a wire mesh which serves both as a grid and as a waveguide wall. The cathode and anode are mounted on opposite sides of the waveguide in separate housings, and waveguide pressure windows seal off the waveguide portion of the tube. The tube can also be constructed such that the anode and cathode are mounted on the broad wall of the waveguide, or on opposite sides of a coaxial line. The tube parts were constructed of copper, and a simple oxide-coated tungsten coil was used as a cathode. A pulse-forming network provided the pulse energy for the tube. The circuit was fed by 0–1000-volt, 0–50-ma power supply. The trigger voltage necessary to fire the tube varied between 10 and 100 volts, depending upon the gas pressure. The trigger rise time should be of the order of 10^{-8} seconds and should last for about 3/10 microsecond. The type of pulse-forming network depends on the length of the signal to be switched. It is also clear that if low to medium power CW signals are to be switched, a pulse-forming network is unnecessary.

Insertion Loss

The tube can be constructed to have essentially wave guide bandwidth in the unfired state. Fig. 4 is a plot of typical VSWR presented by the tube. The unfired insertion loss can be of the order of 1/10 db or less throughout the band. The insertion loss of the fired tube was tested against a calibrated waveguide attenuator. Fig. 5 shows typical traces of the transmitted signal, both fired and unfired, indicating an insertion loss in excess of 67 db. The tube was fired approximately 0.5 microsecond before the beginning of the magnetron pulse. The complete absence of any spike leakage should be noted. This occurs because the electron density is already high enough to produce a very small transmission coefficient by the time the magnetron power is applied. As expected, the gas pressure has a fairly profound effect on the transmitted energy, although over the range of 0.1 to nearly 1 mm of Hg the transmission coefficient is essentially constant. Below these points spike leakage energy appears, and at greatly different pressures the insertion loss deteriorates markedly. At pressures in excess of a few mm of Hg, high-voltage breakdown takes place and results in a continuous glow discharge through the tube. Most of the measurements were made with neon since it has both a relatively low ionization potential, which should keep the power required to run the discharge low, and a low collision frequency, so that the microwave power dissipated in the discharge is low.

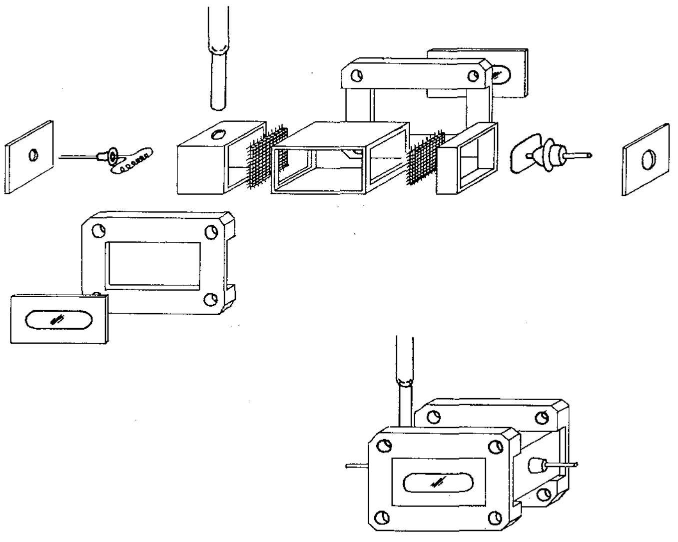

Fig. 3—Pulsed arc discharge switch tube.

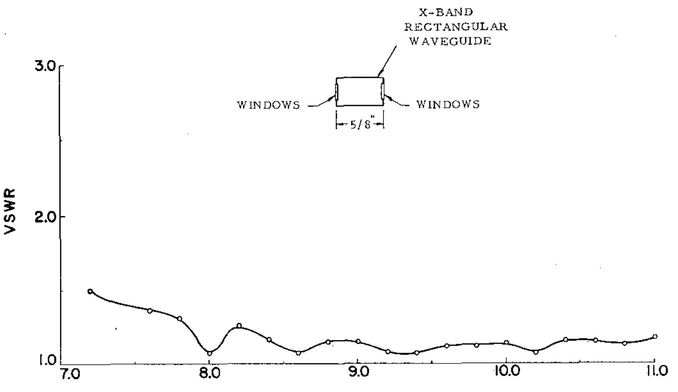

Fig. 4—VSWR of switch tubes.

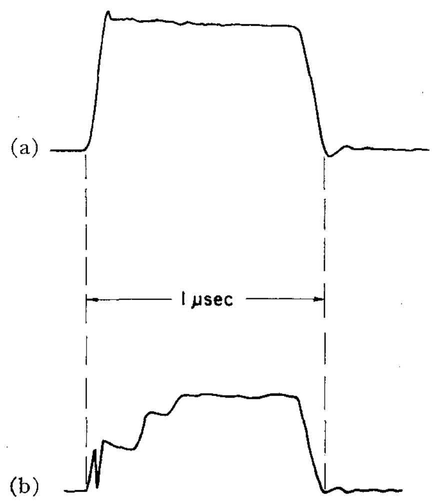

Fig. 5—Typical transmitted waveform. (a) Switch tube fired: no attenuation added at detector. (b) Switch tube unfires: 67-db attenuation added at detector.

Breakdown Power

A discharge can be initiated by the microwave power itself, as in ordinary TR tubes. When this happens, control is lost and the device is no longer switchable. The theory of microwave breakdown in a gas has been treated extensively by Brown.[7] The exact treatment of this problem is fairly complex, but in essence the breakdown power can be expressed as

$$P_{bk} \sim \frac{u_i D_-}{\Lambda^2},$$

where u_i is the ionization potential, Λ is the geometrical diffusion length of the lowest diffusion mode, and D_- is the free electron diffusion coefficient, which is inversely proportional to pressure.

The measurement of breakdown power is quite simple. The power level was slowly increased until the transmitted pulse shape began to change. This took the form of a rapid change of attenuation at the end of the pulse. Fig. 6 shows breakdown data taken for neon and hydrogen plotted against $1/p$. As expected breakdown for hydrogen occurs at higher powers, even though the ionization energy of neon is 21.6 electron volts while hydrogen is 15.7 electron volts. The diffusion coefficient for hydrogen is considerably greater than that for neon. At neon pressures less than 150 microns, the points deviate from this line toward higher breakdown powers. This is expected since the electron mean free path is now of the order of the switch tube dimensions and electron losses increase more rapidly. From these data it appears possible to obtain switches capable of controlling quite high peak pulse powers. Although the choice of gases may be limited, variations of the pressure, p, or the diffusion length, Λ, should allow switching of peak pulse powers in the hundreds of kilowatts range. Since the diffusion length appears squared, minimizing it rather than the pressure may be the most profitable way to insure good high peak power characteristics.

It should be noted here that at high peak powers there is some tendency to clean up even noble gases. One hopes, therefore, to operate with as high a pressure as possible or, perhaps, with a small gas reservoir.

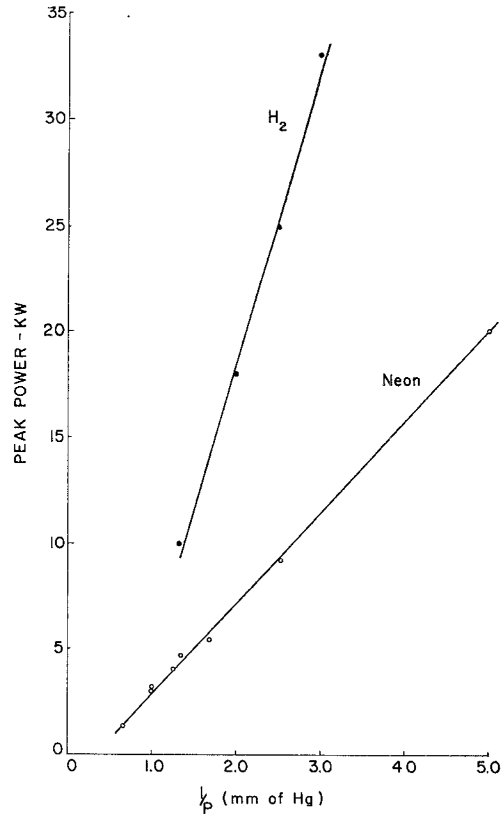

Fig. 6—Breakdown of power vs reciprocal pressure.

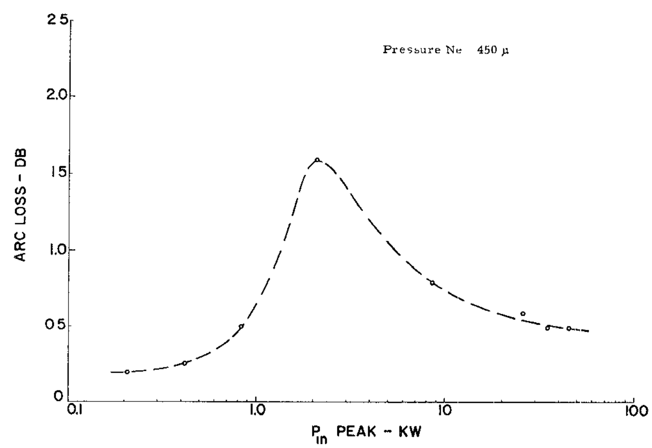

Fig. 7—Arc loss vs input power.

Arc Loss

Figs. 1 and 2 indicate that for plasma densities in the order of 10^{13} or 10^{14} electrons per cc and $\nu/\omega \ll 1$, the expected arc loss should be very small. This is indeed true when the incident power is too low to cause extra ionization in the plasma. Fig. 7 is a plot of arc loss vs power when the arc loss is defined by

$$\text{Arc Loss in db} = 10 \log \frac{P_{\text{Incident}} - P_{\text{Reflected}}}{P_{\text{Incident}}}.$$

The transmitted power is assumed to be negligible. Both the low and high power ends of this curve show that the arc loss is indeed quite low. However, there is a maximum in the medium power range where a larger percentage of the energy of the power is being dissipated by the plasma. The increase in arc loss in the middle power ranges is probably due to increasing the density close to the microwave window. If an attempt is made to run the arc closer to the window, this curve will probably flatten out.

Electron Density

An estimate of the minimum electron density which was achieved during the arc can be obtained by measuring the recovery time of the tube as a function of the frequency of the signal being transmitted. A microwave source at milliwatt power levels in the range of 15 to 21 kMc was used to probe the afterglow of the pulse discharge. If one assumes that recombination and attachment losses are negligible and that diffusion takes place in the lower diffusion mode, which should be true for times later than several microseconds, then the density should decay as a simple exponential with the period of the exponential being determined by the ambipolar diffusion coefficient for the gas used in the tube and the geometry of the structure. A semilog plot, of the recovery time of the tube as a function of frequency, should give a straight line plot, the intercept of which is a measure of the zero time electron density. Fig. 8 shows such a plot. The calculated recovery period for this particular structure was 58 μsec in close agreement with the measured period of 56 μsec and the zero time intercept was approximately 31 kMc. This gives an initial electron density in the lowest diffusion mode of approximately 1×10^{13} electrons per cubic centimeter. It is expected that the actual density during the discharge is somewhat higher, since the density which decays by higher-order diffusion modes could not be measured in this way.

Recovery Time

The recovery time in this measurement was defined as that time required to reach the 3-db attenuation point after the end of the discharge pulse. The measurement was made during the interpulse recovery time of the switch by monitoring the transmission of a low level signal in the afterglow of the discharge. Fig. 9 shows recovery time data for neon and hydrogen. The neon recovery is considerably faster than that shown in Fig. 8 due to voltage overshoot by the discharge network and consequent cleanup of the plasma during this overshoot period. The recovery time is no longer governed entirely by the geometrical diffusion length Λ, but by a modified diffusion length, Λ_{DC}, due to the presence of an electric field.

For single mode diffusion the electron decay is exponential.

$$N = N_0 e^{-t/\tau},$$

where $\tau = \Lambda^2/D_a$ and Λ^2 is lowest mode diffusion length of the structure. D_a is ambipolar diffusion coefficient of the gas being used and p is the pressure. In the presence of an electric field Λ is modified to Λ_{DC}

$$\frac{1}{\Lambda_{DC}^2} = \frac{1}{\Lambda^2} + \left(\frac{\mu E}{2D_a}\right)^2,$$

where μ is the electron mobility in the gas and E is the electric field strength. For example, if $E = 16$ volts/cm, $\Lambda = \frac{1}{4}$ cm and $D_a/\mu = 0.6$ ev, the decay time τ should be

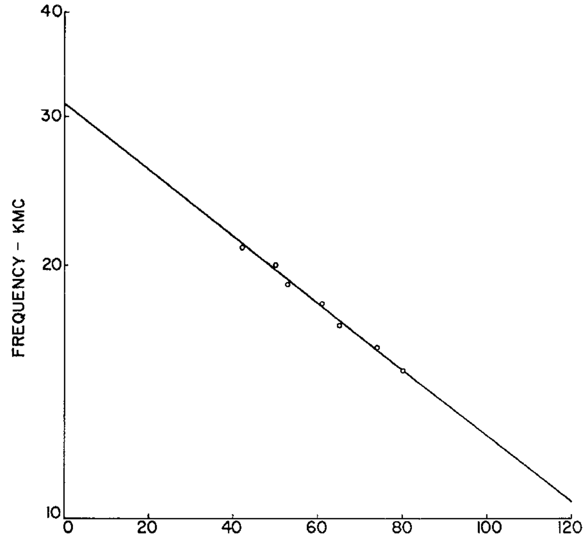

Fig. 8—Recovery time vs frequency (pressure = 0.15 mm Hg of neon).

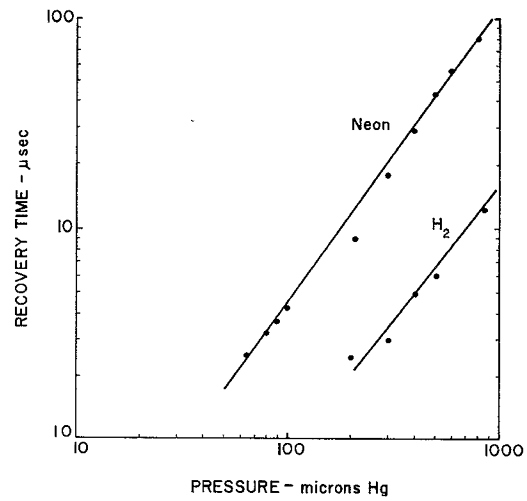

Fig. 9—Recovery time vs gas pressure.

ten times faster than without an electric field. This indicates that a moderate voltage overshoot is a desirable design feature.

Recent data for a hydrogen gas fill show a recovery time less than that for neon. Other data, not shown, indicate that the recovery time can be reduced below 1 μsec.

Noise

Only a tentative result on the noise measurement will be reported here, since an extensive measurement on the noise output of the switch tube was not undertaken.[9]

A reference noise source of a known output (~16 decibel per megacycle) was used in series with the switch tube. An X-band superheterodyne receiver with a 10-Mc IF bandwidth and a balanced crystal mixer

[9] R. M. Hill and S. K. Ichiki, "Microwave noise from low pressure axes," *J. Appl. Phys.*, vol. 31, p. 735; April, 1960.

was used to detect the noise. Between pulses there was no discernible noise, as expected. Initially, only a very sharp spike of -70 dbm amplitude and a duration of a fraction of a tenth of a microsecond was detected approximately 0.05 μsec after the switch tube was triggered. The sharp spike appeared to be generated by the ionization process of the discharge, and may be due to traveling space potential as described by Westberg.[10]

At first no other noise could be detected, indicating that the switch tube noise was at least 10 db below the noise tube. As the tube aged, noise became discernible in other parts of the pulse and increased monotonically until the cathode ceased functioning. The increased noise generation appears to be due to deposition of cathode material around the tube and on the grid. Secondary electron emission from the grid and other parts of the tube can take place by positive ion bombardment. It may be possible that thermionic emission from the grid may occur. These and the unstable cathode emission probably contributed to the noise output of the tube.

[10] R. G. Westberg, "Nature and role of ionizing potential space waves in glow to arc transitions," *Phys. Rev.*, vol. 114, pp. 1–17; April, 1959.

Conclusion

Low-pressure, hot cathode arc discharges offer considerable promise for the development of rapid, broadband microwave switches and control devices. Plasma densities of the order of 10^{13} per cubic centimeter can be achieved in fractions of a microsecond and dissipated in a few microseconds or less. The power level at which microwave capture of the switch occurs may be adjusted by controlling gas pressure and geometry. Switching action for switching a pulsed source is provided by a low level trigger (10–100 volts) which discharges a storage condenser through the switch tube.

Characteristic Impedances of Broadside-Coupled Strip Transmission Lines*

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Summary—**Formulas are given for the even- and odd-mode characteristic impedances of shielded coupled strip-transmission-line configurations that are especially useful when close coupling is desired. Applications may be made to wideband coupled-strip-line filters, 3-db directional couplers, and many other components. The cross sections considered are thin broadside-coupled strips either parallel or perpendicular to the ground planes. Modification of the formulas for thick strips is discussed. The derivations are outlined, with particular attention given to the underlying assumption that restricts the use of the formulas to cases of close coupling.**

I. Introduction

Coupling effects between parallel transmission lines have applications in the design of many components, such as filters,[1,2] directional couplers,[1,3,4] baluns,[5] and differential-phase-shift networks. Three useful coupled-strip-line configurations are shown in Fig. 1. The coplanar-strip cross section of Fig. 1(a) was analyzed previously and design data are conveniently available,[7] while the broadside-coupled strip-line cross sections of Fig. 1(b) and 1(c) are treated in this paper. In all three cases, the theory applies to strips of zero thickness, which may be approximated by metal-foil conductors sandwiched between dielectric plates filling the cross section. If air dielectric is desired, the strips must be given a moderate thickness to provide

* Received by the PGMTT, June 23, 1960. The work described in this paper was performed at Stanford Res. Inst. with the support of the USASRDL.

† Rantec Corp., Calabasas, Calif. Formerly at Stanford Res. Inst., Menlo Park, Calif.

[1] E. M. T. Jones and J. T. Bolljahn, "Coupled-strip-transmission-line filters and directional couplers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-4, pp. 75–81; April, 1956.

[2] S. B. Cohn, "Parallel-coupled transmission-line-resonator filters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 224–231; April, 1958.

[3] J. K. Shimizu, "Strip-line 3-db directional couplers," 1957 IRE WESCON Convention Record, pt. 1, pp. 4–15.

[4] J. K. Shimizu and E. M. T. Jones, "Coupled-transmission-line directional couplers," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 403–410; October, 1958.

[5] E. M. T. Jones and J. K. Shimizu, "A wide-band strip-line balun," IRE Trans. on Microwave Theory and Techniques, vol. MTT-7, pp. 128–134; January, 1959.

[6] B. M. Schiffman, "A new class of broad-band microwave 90 degree phase shifters," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 232–237; April, 1958.

[7] S. B. Cohn, "Shielded coupled-strip transmission lines," IRE Trans. on Microwave Theory and Techniques, vol. MTT-3, pp. 29–38; October, 1955.