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.

Acknowledgment

It is a pleasure to acknowledge helpful discussions with Dr. R. F. Wuerker, Dr. W. D. Hershberger, Dr. R. W. Gould, C. Leiby, and Dr. R. W. Fredricks. The assistance of R. P. Kemp in the laboratory is also very much appreciated.

High-Power Duplexers*

C. E. MUEHE, Jr.†

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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* Received by the PGMTT, May 12, 1961; revised manuscript received, September 5, 1961.

† Lincoln Lab., Massachusetts Institute of Technology (with support from the U. S. Army, Navy and Air Force), Lexington, Mass.

[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.

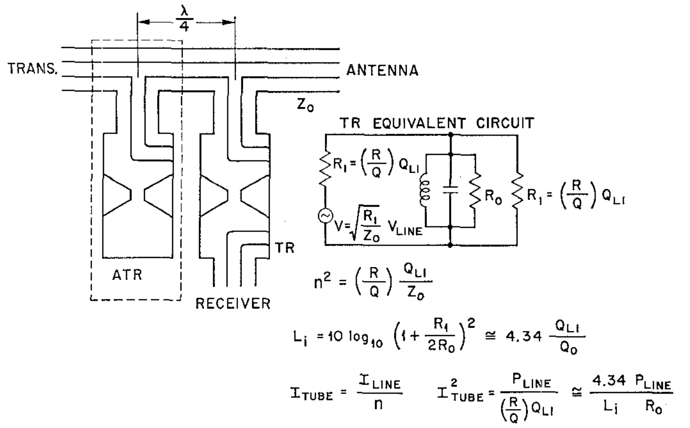

Fig. 1—Typical branched duplexer.

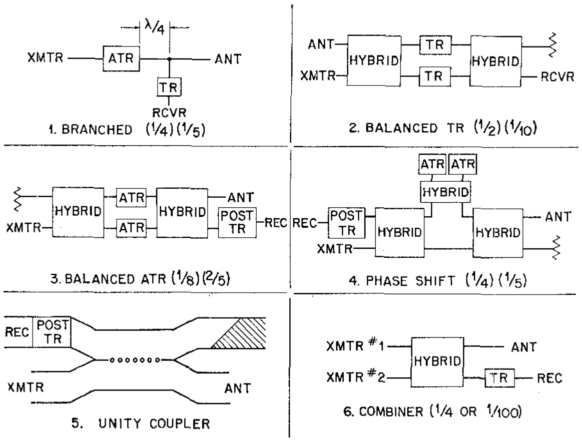

Fig. 2—Circuit arrangements for most duplexers in use at the present time.

to the center of the cavity. When the discharge forms, represented by shorting the capacitor, a current I_{tube} flows through the discharge. The square of the tube current is inversely proportional to the (R/Q) value and the loaded Q_{L1} of the cavity. This fact emphasizes the first principle of high-power duplexer design: to reduce TR-tube current, with its consequent heating, place the discharge in as high Q structure as other system requirements will allow.

The square of the tube current may also be written (Fig. 1) as being inversely proportional to the allowable insertion loss on receive L_i and to the cavity-shunt-loss resistance R_0. Therefore, for a narrow-band system, narrower than the bandwidth of the single cavities used, a compromise may be made between insertion loss on receive and tube dissipation on transmit.

On receive, the return signals pass from the antenna through the TR cavity into the receiver. The purpose of the ATR is to reflect any return signal that goes down the transmitter line. The quarter-wavelength spacing shown is necessary so that an open circuit will be presented by the transmitter line at the junction of the TR cavity and the main line. It can easily be verified that four times as much of the received energy incident on the ATR will be lost in the ATR cavity as compared to an identical TR cavity. However, since in this arrangement only one-fourth of the return signal is incident on the ATR, equal losses will be sustained in both TR and ATR cavity. (The foregoing statements assume that the transmitter presents a match or an open circuit at the junction of the ATR cavity and the main line.)

Fig. 2 shows most of the circuits used in present-day duplexers. The boxes labeled TR represent band-pass filters, which usually consist of one or more resonant elements in cascade either directly coupled or quarter-wave coupled. In the transmit condition these TR structures break down at their high-voltage points and the band-pass filter turns into a good reflecting structure. The boxes labeled ATR consist of a number of resonant cavities coupled to the transmission line at regular intervals. The ATR structures act as good reflectors on receive and as good transmission structures on transmit. The boxes marked "hybrid" are 3-db directional couplers.

The branched duplexer with single-cavity ATR and TR structures is illustrated in Fig. 1. Notice that on transmit, when the gap is discharged only one-fourth of the line power is incident on each cavity, since the wave incident on each cavity plus its reflection must add to the total line voltage at the junction on the main transmission line. The first bracketed term (one-fourth) states the portion of the line-power incident on the cavities making up the TR or ATR structure.

In the balanced TR[3] duplexer the high power from the transmitter, after being divided in two by the first hybrid, is reflected directly off the TR cavities so that the first bracketed term is (one-half). For the balanced ATR[4] case the transmitter power is first divided in two by a hybrid, then by one-fourth at the junction of the cavities with the main line, giving a first bracketed term of (one-eighth).

The unity coupler duplexer,[5] constructed by putting TR tubes in the coupling aperture of a unity coupler, requires that the TR tubes carry the full current in the guide walls. It will not be compared with the other forms of duplexers.

Sometimes two transmitters are combined,[6] as shown in the last duplexer circuit of Fig. 2. If the transmitters are well balanced in phase and amplitude, somewhat less than 1/100 of the line power will be incident upon the TR. However, in the event of failure of one of the transmitter tubes, the TR will have to handle one-fourth the line power, so it should be designed to stand this

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[3] L. D. Smullin and C. G. Montgomery, "Microwave Duplexers," M.I.T. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 14; 1948.

[4] C. W. Jones, "Broad-band balanced duplexers," IRE TRANS. ON MICROWAVE THEORY AND TECHNIQUES, vol. MTT-5, pp. 4–12; January, 1957.

[5] L. Milosevic, "High-power duplexers," *Le Vide*, vol. 12, pp. 109–116; January/February, 1957.

[6] K. Eakin and R. Rapuano, "A hybrid duplexer," *Microwave J.*, vol. 4, pp. 47–49; January, 1961.

power for at least a short length of time until the situation can be corrected.

COMPARISON FOR NARROW-BAND SYSTEM

The second bracketed term in each figure gives the fractional loss of the receive signal for each structure, assuming that all TR and ATR structures consist of single identical cavities with the same loaded and unloaded Q's and that each TR cavity loses one-tenth of the signal passing through it. Thus, in the case of the balanced TR duplexer, the return signal splits in two in the hybrid and a tenth of each half is lost in each TR cavity, so that the total loss is one-tenth of the incoming signal. The interesting result is that the product of the incident power (first bracketed fraction) times the insertion loss on receive (second bracketed term) is the same for the first four duplexers. But, if we assume that the power-handling capacity and the insertion loss vary directly with the loaded Q of the cavities, so that if we readjust the Q's of the various circuits to give equal insertion losses, then the power-handling capacity of all the structures will be the same. The assumption that power-handling capacity and insertion loss vary directly with the loaded Q is rigorously true for high Q cavities and approximately true for resonant windows.

This analysis is perhaps an oversimplification because it assumes single-cavity TR and ATR structures. With the ATR structures, however, it is possible to put two identical cavities a half-wavelength apart. Their conductances (resistances in series on the main line if they are series mounted) are thus in parallel on the main line so that the insertion loss on receive is halved. The total heat generated on transmit is doubled, of course, but it is distributed over twice the area.

COMPARISON FOR WIDE-BAND SYSTEMS

The balanced TR, balanced ATR and unity coupler duplexers are recommended for systems requiring wide instantaneous bandwidth. These duplexers take advantage of symmetry to avoid the necessity of using frequency-sensitive line lengths as in the branched and phase-shift duplexers. Since the TR structure is simply a band-pass filter on receive, filter theory may be employed to determine its characteristics. Fig. 3 shows the Q bandwidth products one can achieve. Belevitch[7] assumes a Tchebycheff response function with as many points of perfect match as there are tuned circuits. Fano[8] assumes no matched points in the pass band. The insertion losses are all reactive; any resistive-type insertion loss must be added to them.

The responses of several ATR structures are given by Jones.[4] He considered cavities with typical resistive losses spaced at quarter- and half-wavelength intervals along a waveguide. A simpler analysis has been carried out by the author wherein the equivalent low-frequency, lumped-constant circuits are considered. The analysis thus neglects the effect of the variation of phase angle between the cavities on the resulting insertion loss. It also neglects any resistive losses in the cavities. The results are presented in Fig. 4.

One mode of operation is to place the cavities a half-wavelength apart along the transmission line. The circuit then acts like a number of parallel resonant circuits in series with one another. They must all be tuned synchronously or, according to Foster's reactance theorem, there will appear points of zero impedance between the resonances. The insertion loss is a monotonically increasing function of frequency off resonance.

Alternatively the cavities may be spaced at quarter-wavelength intervals, in which case the equivalent circuit has alternate parallel resonant circuits in series with the line and series resonant circuits in parallel with the line. The best bandwidth is achieved by stagger-tuning the circuits. The power-loss ratio can be set equal to one plus a Tchebycheff function squared. In the two-cavity case, the cavities are tuned to $f_0(1 \pm B/2\sqrt{2})$, where f_0 is the center frequency and B is the fractional bandwidth. In the three-cavity case, the center Q is half the end cavity Q's and is given by the Q_{L1} in Fig. 4. The

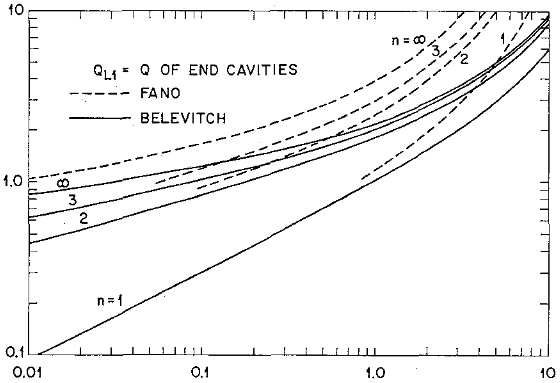

Fig. 3—Q-bandwidth products for TR structures with n-tuned circuits.

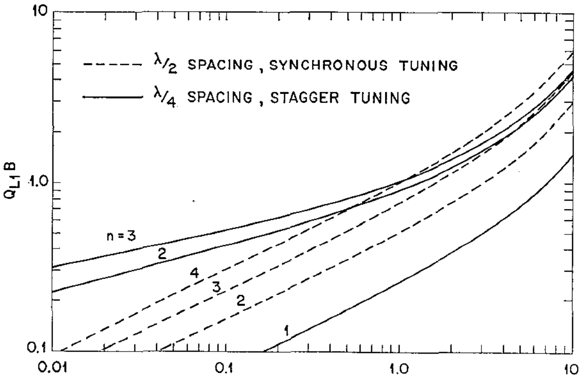

Fig. 4—Q-bandwidth products for ATR structures with n-tuned circuits.

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[7] V. Belevitch, "Tchebychev filters and amplifier networks," *Wireless Engr.*, vol. 29, pp. 106–110; April, 1952.

[8] R. M. Fano, "Theoretical limitations of the broadband matching of arbitrary impedances," *J. Franklin Inst.*, vol. 249, pp. 139–154; January, 1950.

center cavity is tuned to f_0 and the end cavities to $f_0(1 \pm \sqrt{3}/4B)$.

In quarter-wavelength spacing, each cavity is more or less providing the reflection required in any one part of the band so that the resistive loss of one cavity must be added to the insertion losses of Fig. 4. When half-wavelength spacing is used, the resistive loss is that of one cavity divided by the number of cavities used.

A comparison of Figs. 3 and 4 shows that for two- and three-cavity structures, the ATR structure requires half the Q of the TR structure for the same bandwidth and insertion loss. However, since the incident power on the ATR cavities is only one-fourth that incident on the TR cavities, the former will still be able to handle twice the line power. A careful examination shows that the same total power is being dissipated, but it is spread out over more cavities by using the ATR structures.

DETERMINATION OF ARC LOSS

The two most commonly used high-power switch tubes are shown in cross section[1] in Fig. 5. Current is capacitively coupled from the metal frame through the dielectric into the discharge. One reason for this construction is the elimination of all metal from areas adjacent to the discharge. In high-power discharges, metal is sputtered over the inside of the tube and quickly destroys its usefulness. The encapsulated window consists of a glass enclosure for the gas, one side of which is bonded to a kovar frame. In the folded cylinder TR tube the discharge takes place in the annular space between two concentric dielectric cylinders. In both cases the discharge has the electrical conductivity of a poor metal.

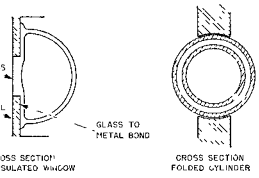

Fig. 5—Encapsulated window and folded cylinder TR tubes shown in cross section.

Arc loss may be measured using the apparatus shown in Fig. 6. The discharge tube is mounted so that the discharge completes the end of a multiple quarter-wavelength stub on a coaxial line. The resonant choke is used to confine the discharge to the desired region. In its absence the discharge would fill the entire TR tube, making computation of the discharge impedance difficult. The slotted line and directional coupler are used to measure the high-power standing-wave ratio and the magnitude of the power incident on the TR tube. Because the geometry of the discharge is well known, these readings are easily converted to the skin resistance and linear current density of the discharge. The component of the electric field in phase with the current is given by the product of skin resistance times linear current density. A typical set of curves taken at 425 Mc is shown in Fig. 7. For low current densities the skin resistance is inversely proportional to linear current density, a fact that indicates a constant sustaining field. At a current density slightly above that at which the skin depth in the plasma equals the spacing in the tube, the skin resistance departs from a straight line. This is caused by the shielding action of the discharge.

The variation of electric field with current density is shown in Fig. 8. For medium current densities there are sufficient electron-electron collisions to insure a Maxwellian velocity distribution among the electrons. The electrons are produced by direct impact of high-energy electrons on gas molecules and are lost by diffusion to the walls. The conductivity of the plasma is directly proportional to the electron density. At higher densities where shielding occurs to give a nonuniform electric field, electron production is higher in regions of high

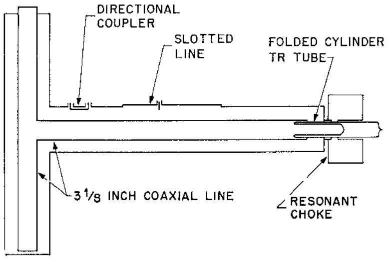

Fig. 6—Apparatus used to measure arc loss.

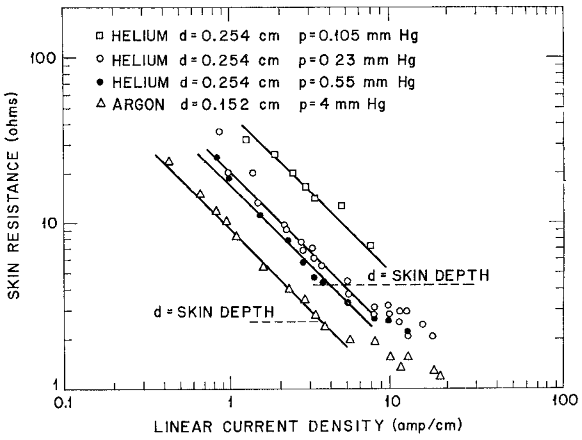

Fig. 7—Measured skin resistance as a function of linear current density for folded cylinders with spacing d and pressure p measured at 425 Mc.

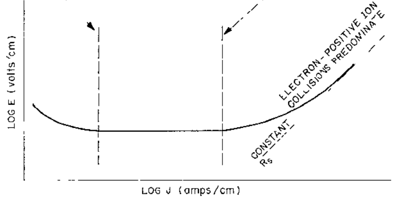

Fig. 8—Variation of the sustaining field with current in a folded cylinder TR tube.

field adjacent to one of the walls of the tube. Electrons are lost more easily by diffusion, which results in a higher sustaining field.

At still higher electron densities, the electron-positive ion collisions determine the conductivity of the plasma. The limiting value of conductivity (approached usually when the fractional ionization is between 10^{-3} and 10^{-2}) is that of a fully ionized gas.[9] The conductivity depends on the ratio of electron charge density to collision frequency. The collision cross section for positive ions is much larger than for gas molecules; moreover, since the number of positive ions equals the number of electrons in the plasma, the ratio of electron charge density to collision frequency at high electron density will be a constant and thus will give a conductivity of about 2000 mho/m. (For comparison, copper has a conductivity of 6×10^7 mho/m.)

Comparison with DC Data for Medium Current Densities

Except for the shielding effect in the RF discharge, the conditions prevailing in the folded cylinder are exactly those existing in the positive column of a dc discharge at low pressure, for which considerable theoretical and experimental[10,11] work has been done. The electric fields derived from the straight-line portions of the curves of Fig. 7 are compared with the measured fields in the dc-positive column in Fig. 9. The agreement is very good. In comparing the data for helium, Klarfeld states that at pressures slightly below the low-pressure end of his curves the sustaining field rises very rapidly, in agreement with the RF data.

Examination of dc data can now be used to determine the dissipation in the discharge when moderate current densities are involved. Notice that no polyatomic gases are shown in Fig. 9 because their sustaining fields are all above those of helium. In fact, it has been observed that even a trace of polyatomic gas in an inert gas discharge will increase the arc loss. One part in 10^3 of oxygen in argon has been found to double the arc loss. The reason for this is that polyatomic molecules have vibrational and rotational energy levels which are excited by electron collision, so that energy dissipation is higher than in the monatomic gases. For inert gases, dc data indicates that the heavier the molecules, the lower the sustaining field, and that some of the metal vapors, particularly mercury, look very promising. This is especially true in the case of tubes using diffusion as a recovery mechanism, since the pressure must be kept low where the problem of gas clean-up in inert-gas tubes is severe. Mercury offers what is an essentially infinite gas reservoir.

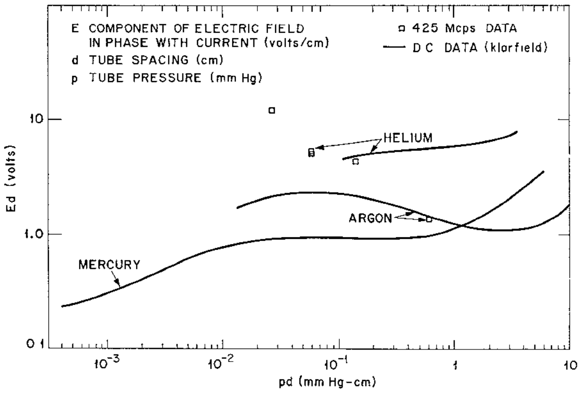

Fig. 9—Comparison between the sustaining field in an RF discharge and that in the positive column of a dc discharge.

Power-Handling Ability for High Current Densities

The lowest percentage arc loss occurs at high-power levels where the conductivity approaches a constant value, that of a fully ionized gas. Consider a rectangular waveguide of a 2:1 dimension ratio operating at a frequency where the guide wavelength is twice the width of the guide. A window (Fig. 10) is mounted in a long aperture made by cutting away the side wall of the guide. The window thickness is assumed to be one tenth the height of the guide and to make good thermal contact with the guide at its edges. Behind the window, just outside the guide, is a plasma with the conductivity of a fully ionized gas. The nature of the gas is not important except that lower pressures and gases which have lower sustaining fields will approach the fully ionized conductivity at lower current densities. The currents in the plasma are the same as in the guide wall.

Under these conditions, it is an easy task to calculate the heat dissipated in the plasma for a given power in the main guide. The power-handling capacity of such an arrangement depends on the method of heat transfer out of the discharge and the maximum allowable temperature rise. Results are presented (Fig. 10) for various types of surface cooling (solid lines) and for conduction cooling through the dielectric to the guide (dashed lines). Surface cooling means removal of heat from the surface of the window by forced air, radiation, or a liquid flowing across the surface of the window. Conduction cooling refers to transfer of heat out of the discharge by passage through the dielectric material of the window to the waveguide which is assumed to be held at room temperature. The peak window temperature was assumed to be 400° to 500°C because at these temperatures either the window material fails (glass deforms) or the loss tangent increases rapidly making the insertion loss on receive too large. The high power-handling capacity when aluminum oxide and beryllium oxide dielectrics are used is a reflection of their relatively higher heat conductivities.

It is to be emphasized that this graph applies to very wide-band duplexers operating at high peak power

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[9] L. Spitzer, "Physics of Fully Ionized Gases," Interscience Publishers, Inc., New York, N. Y., p. 81; 1956.

[10] A. von Engel, "Ionized Gases," Oxford University Press, London, Eng., p. 209; 1955.

[11] B. Klarfeld, "The potential gradient in the positive column," *J. Tech. Phys. USSR*, vol. 5, pp. 725–740; September, 1938.

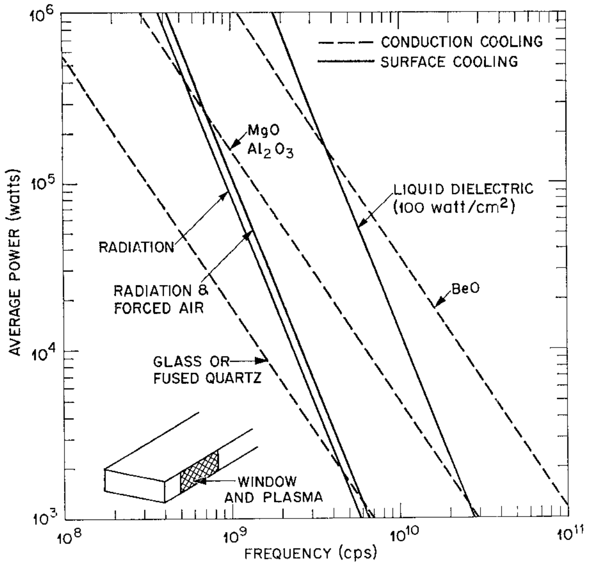

Fig. 10—Calculated power-handling capacity of a full size TR tube mounted in the side of a rectangular waveguide carrying the TE_{01} mode.

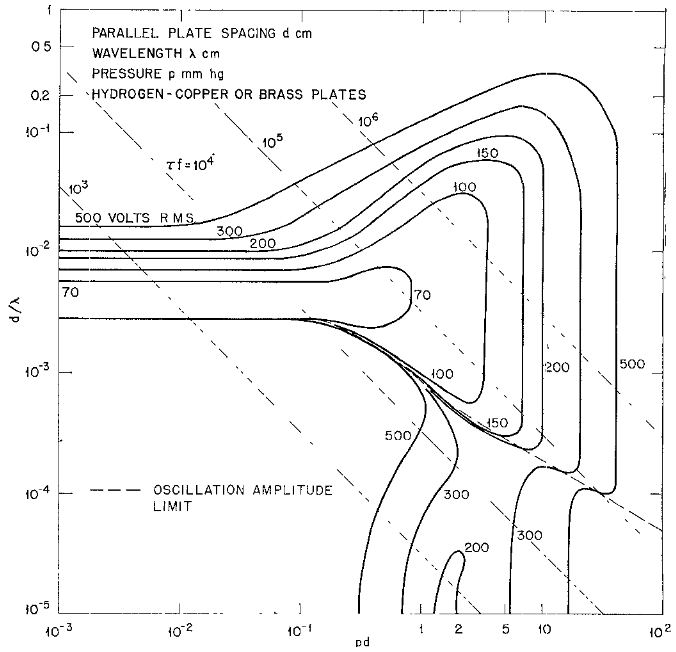

Fig. 11—Contours of constant breakdown voltage with lines of constant frequency recovery time products superimposed.

levels, such as the unity coupler duplexer. The power-handling of existing duplexers of this type agrees quite well with Fig. 10.

Two methods can be used to increase the power-handling capacity over that shown in Fig. 10. The first is to decrease the height of the window and/or increase its thickness but still mount it in the guide wall. This procedure raises the dashed lines of Fig. 10 but at the same time increases the loaded Q. The second method involves placing the window at the center of a cavity. This reduces the current in the tube, but again raises the Q of the circuit. Notice that both methods achieve increased power-handling ability by an increase in Q and thus a decrease in bandwidth of the duplexer.

Other Considerations in Duplexer Design

More often than not, the actual geometry and gas fill of a TR tube are chosen for reasons other than the optimization of its power-handling capacity. The choice is usually made on the basis of easy firing, adequate recovery time and long life. Fig. 11 illustrates the interrelation between breakdown voltage and recovery time for hydrogen gas and parallel-plate geometry. Similar graphs for other geometries and gas fills would have similar contours but would be somewhat different in magnitude and position. The graphs of breakdown voltage show that a very steep gradient exists starting at the left of the graph at d/λ equals 0.0025 and proceeding to lower values of d/λ as the pressure is raised. This gradient occurs because at tube spacings smaller than this value, all of the electrons can be swept out of the discharge space in half a cycle by fields smaller than those required for breakdown.[12]

Modern high-power switching tubes do not use attaching gases (those which cause electron disappearance by the formation of negative ions), because they cause a large increase in arc loss. Recovery is achieved by diffusion (electrons diffuse to the walls where they recombine with positive ions) or volume recombination (usually dissociative recombination). Diffusion-controlled recovery is preferred because the electron density decays with time in an exponential manner instead of inversely with time, as in recombination. This means that the duplexer is fully recovered at about one and one-half 3-db recovery times, whereas recombination-controlled recovery allows a fraction of a decibel loss at several times the 3-db recovery period. For both types of recovery, the recovery time is practically independent of power level and pulse length, but it depends directly on loaded Q for recombination while it is independent of Q for diffusion.

Recovery is controlled by recombination at high pressures and by diffusion in the low-pressure region where the arc loss tends to be least. The product of recovery time τ (sec) for diffusion-controlled recovery multiplied by frequency f (cps) is plotted on Fig. 11.

Examination of this graph shows that a good operating point falls at $d/\lambda = 0.003$ and at as low a pressure as possible to give quick recovery. It is found, however, that when the pressure is reduced too far, the arc loss goes up precipitously as shown in Fig. 9 for helium. Another problem associated with low-pressure operation is that of gas clean-up. It is found that even in the absence of sputtering, gas is lost into the walls by the action of the discharge. Lower pressures may be used when a large reservoir for gas is provided.[13]

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[12] S. C. Brown, "Basic Data of Plasma Physics," John Wiley and Sons, Inc., New York, N. Y., p. 142; 1959.

[13] D. W. Downton, "Measurement of clean-up in gas discharge tubes using radioactive krypton," *Proc. IEE*, vol. 105, pt. B (suppl.), pp. 485–487; November, 1958.

As an example, a folded cylinder for use at L band should have a spacing between cylinders of 0.030 in. At a pressure of 1 mm Hg of argon, the recovery time will be about 60 μsec. This spacing is still about twice the skin depth in a fully ionized plasma.

CONCLUSIONS

There is no reason why gas tube duplexers cannot be designed so as to handle extremely high powers and still meet other system requirements. The power-handling ability of a duplexer may be increased by using pure inert gases, by using tube materials with high heat conductivity, such as beryllium oxide, by narrowing the height of the window, or by putting the TR tube at the center of a high-Q cavity. An ATR duplexer may be used to spread the heat dissipation over a larger area. The actual tube spacing and fill are usually determined by considerations of easy firing, recovery time and tube life.

ACKNOWLEDGMENT

The author wishes to thank C. W. Jones and Dr. R. J. Carbone for many helpful discussions during the preparation of this paper.

Quasi-Optical Surface Waveguide and Other Components for the 100- to 300-Gc Region*

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Summary—**Components and techniques for the generation, transmission, and detection of energy in the 100- to 300-Gc frequency region were investigated theoretically and experimentally. The design and construction of fundamental components, such as harmonic generators and detectors, were necessary since many items are not available commercially. A detailed theoretical analysis was performed for the propagation characteristics of single-conductor transmission lines, and attenuation calculations were made for several dielectric image lines. Experimental measurements were made at 105 and 140 Gc on these two types of surface waveguides. Attenuation of these lines is compared with that of dominant-mode rectangular waveguide. An analysis of phase-correcting Fresnel zone plates was carried out, and several zone plates were designed, constructed and successfully tested at frequencies of 140, 210, and 280 Gc. Zone plates were used at several frequencies to make relatively long path transmission measurements and were also used in a specially designed Michelson interferometer. The frequency stability of the source klystron and the dielectric properties of a number of plastic materials were determined by measurements made with the interferometer. A method of frequency filtering by focal isolation was demonstrated with this equipment.**

I. INTRODUCTION

An investigation is being conducted to develop new components and techniques for use at wavelengths shorter than 3 mm. Much of the work completed to date has dealt with special rectangular waveguide devices, surface waveguides (dielectric image lines and coated or uncoated single-conductor transmission lines), and devices of an optical nature.[1] The basic instrumentation consisted of adaptations of conventional rectangular waveguide components. Signal power was provided by crystal harmonic generators driven with a few tens of milliwatts of power at a fundamental frequency of either 35 or 70 Gc. Experimental measurements were made at 105, 140, 210, and 280 Gc. Video detection with silicon crystals resulted in output signal levels with a dynamic range of about 45 db above noise, except at 280 Gc, where the range was somewhat less. For some sets of measurements at 140 Gc, a range of 55 db was available.

At the time the program was started there was a scarcity of commercial components for frequencies above 100 Gc, and it was therefore necessary to design and construct various waveguide items such as detectors, harmonic generators, horn antennas, and filter sections.[2] Coin-silver waveguide with a cross section of 0.0325- by 0.065-in ID (RG-136/U) was chosen because the guide has a TE_{10}-mode cutoff frequency of 90.8 Gc and propagates only the dominant mode at frequencies below about 180 Gc.[3] (The slightly larger size RG-138/U

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† Res. Div., Electronic Communications, Inc., Timonium, Md.

[1] M. J. King, *et al.*, "Quasi-Optical Components and Surface Waveguides for the 100 to 300 kMc Frequency Range," Electronic Communcations, Inc., Timonium, Md., Rept. No. 2 on AFCRL Contract No. AF 19(604)-5475; November, 1960.

[2] *Ibid.*; design details are given in this report.

[3] The harmonic generators use RG-96/U or RG-98/U waveguide inputs.