A Pre-TR Tube for High Mean Power Duplexing*

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Summary—A gas discharge tube for transmit-receive switching capable of handling average power levels up to at least 25 kw at 3000 Mc is described. The discharge is excited in the annular space between two concentric silica tubes and recovery time is controlled by the dimensions and gas pressure. In this way, a tube with constant characteristics during life has been achieved. The tube is mounted in a thick resonant iris, and sparking is avoided by using accurately ground silica mounted in a precision-bore hole.

The arc loss of the tube in this form of mount is less than 0.1 db at 5 Mw peak 10 kw average, and the recovery time is about 100 μsec to 3 db. The attenuation is about 30 db, and the insertion loss is less than 0.1 db.

Performance of this form of tube is discussed for average power levels of up to 50 kw in a phase-shift duplexer and 25 kw in a balanced duplexer, and the expected performance during life is also considered. Lives in excess of 10,000 hours are deduced from extrapolated data obtained with radioactive krypton in tubes operating at 10 kw average.

Introduction

At power levels below 50-kw peak at 10,000 Mc and 500-kw peak at 3000 Mc, transmit-receive switching can be adequately achieved with conventional narrow-band and broad-band TR cells. Above this level, the complex requirements of the TR cell are difficult to maintain, and Smullin and Montgomery[1] and, more recently, Hawkins[2] have discussed the advantages of performing the switching with a pre-TR cell which is used in conjunction with a TR cell or pulsed attenuator. The first requirement of a pre-TR cell is that it should have a low loss during transmission and reception; that is, its arc loss and insertion loss should be low. Secondly, the recovery time should be adequate. Longer recovery times can be tolerated at very high power levels for long-range radars, since short-range information is normally not required for that application. A recovery time of 100 μsec to 3 db was aimed at in this work. The leakage of the device is less important and an attenuation of 30 db is sufficient.

Several forms of pre-TR cells have been developed. The first, described by Smullin and Montgomery,[1] consisted essentially of a quarter wavelength section of waveguide sealed at the ends with low Q windows and filled with a mixture of argon and water vapor. Detuning of the cell caused by sputtering of metal from the cell body onto the glass window and the rapid clean-up of water vapor were major problems with this type of device. These problems were avoided by Parker,[3] who used a silica tube containing silica wool and filled with rare gas. In this case, recovery time was controlled by diffusion of ions and electrons to the surface of the silica wool where surface recombination takes place. Sparking was avoided by using accurately ground silica so that good contact was ensured between tube and mount. This type of tube has since been developed for handling powers up to 3 Mw peak, 3 kw average at 3000 Mc. Alternate approaches by Dutt[4] and by Gould, Edwards, and Reingold,[5] relied on the same physical processes for achieving rapid de-ionization of the discharge. The main disadvantages of these developments were associated with the complicated structures used to support the discharge tube. Glass-to-metal seals were an integral part of these structures, so that relatively low melting-point glass had to be used.

The high melting point of silica, coupled with its very low loss, make it the most attractive material for use at very high power levels. However, it has been found that sputtering of the silica wool can occur at 4 kw average with the particular tube described by Parker. This results in more rapid gas clean-up and eventual fusing of the silica wool. The properties of silica wool in reducing recovery time can be achieved in a much more controlled manner by confining the discharge to the annular space between two concentric silica tubes. This approach was first applied by Lomer and O'Brien[6] to a microwave pulsed attenuator but is equally applicable to a pre-TR tube. Thus the advantages of controlling recovery time by diffusion and surface recombination are maintained, and very high power operation is possible from this new type of tube.

Description of Pre-TR Mount and Tube

Fig. 1 shows the complete pre-TR unit. The mount, which was first examined by Speake,[7] contains two tubes and is for use with a short slot hybrid. The two waveguide sections are recessed in the mount. In each section there are two thick resonant slots which are perpendicular to the electric field. The iris size is adjusted for resonance at any given frequency, the length of the iris being given for a range of frequencies in Fig. 2,

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[1] L. D. Smullin and C. G. Montgomery, "Microwave Duplexers," Mass. Inst. Tech. Rad. Lab. Ser., McGraw-Hill Book Co., Inc., New York, N. Y., vol. 14; 1948.

[2] P. O. Hawkins, "Active microwave duplexing systems," *Proc. IEE*, vol. 105B, Suppl. No. 10, pp. 505–507; May, 1958.

[3] A. B. Parker, "A new form of X-band pre-TR cell," *Proc. IEE*, vol. 105B, Suppl. No. 10, pp. 488–491; May, 1958.

[4] T. L. Dutt, "Plug-in TR tubes for use in S-band duplexers," *Le Vide*, vol. 12, pp. 93–108; January–February, 1957.

[5] 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.

[6] P. D. Lomer and R. M. O'Brien, "A microwave pulsed attenuator using an RF excited discharge," *Proc. IEE*, vol. 105B, Suppl. No. 10, pp. 500–504; May, 1958.

[7] G. D. Speake, unpublished work.

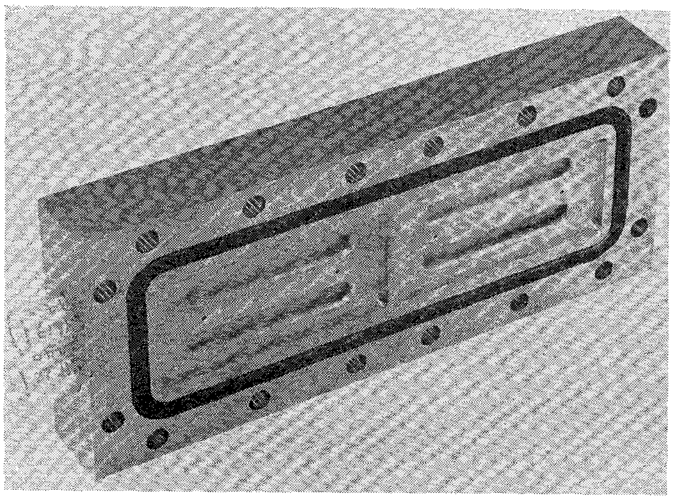

Fig. 1—Pre-TR mount and tubes.

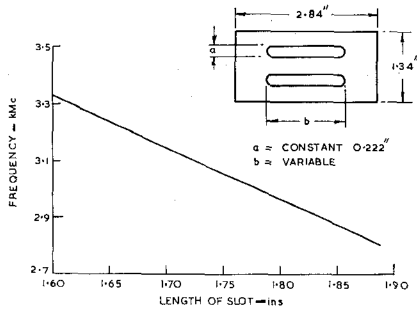

Fig. 2—Resonant frequency as a function of the length of slot.

assuming the height to remain constant. The height of the iris is adjusted to give a large contact area between tube and mount, and this is illustrated in Fig. 3. The loaded Q-factor of both sections of the mount is 2.3.

The discharge tube consists essentially of a silica envelope containing a rare gas. The length of the discharge is accurately defined by the slots in the mount. The discharge does not extend along the tube since it is not coupled to the field. Thus there is little radiation loss from the ends of the tube and negligible coupling between the adjacent waveguides. The discharge acts as a short circuit in reflecting the power, but there is a leakage between discharge and mount. This leakage is about 30 db down on the incident power. The tubes are heated by the discharge, but there is efficient cooling because of the large contact area between tubes and the mount. A further advantage of this type of mount is the relative ease of construction.

The discharge tube which is shown in Fig. 4 consists of two concentric tubes of silica with an annular gap of 0.030 inch between them. Precision-bore silica tubing, ground externally to a fine tolerance, is used so that reproducible resonant frequencies are achieved. A close fit between tube and mount is ensured by accurate control of the outer dimension. The space between the tubes is filled with krypton at a pressure of 60 mm Hg, and about 10 microcuries of tritium is added to ensure

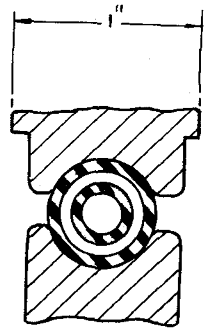

Fig. 3—Cross section of tube in mount.

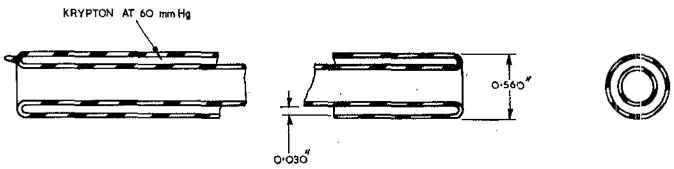

Fig. 4—Pre-TR tube.

immediate ionization on applying the microwave field. Since the inner tube is left open to the atmosphere, the discharge only occurs in the krypton-filled annular space between the outer tube and the insert.

The choice of gas pressure and annular space was based on a series of experiments, the results of which are shown in Figs. 5 through 9. It was apparent from previous work that the recovery time of tubes without inserts decreased with increasing pressure as shown in Fig. 5, so that high pressure of krypton is necessary to achieve short enough recovery times. However, it was found by more detailed examination of these tubes, filled at a pressure of 60 mm Hg, that the recovery time increases alarmingly with the mean power as shown in Fig. 6. This increase in recovery time with mean power indicates that the effective gas density in the discharge region decreases with increasing power level because of the establishment of temperature and hence gas density differentials along the tube. Thus the performance of the tube at high power levels corresponds to a movement along the recovery time/pressure curves to lower pressures.

In tubes with inserts, de-ionization at lower pressures is a function of both recombination and diffusion losses, so that recovery time is fairly constant as a function of pressure. Thus, although the gas density in the working region of the tube decreases as the average power is increased, the recovery time remains fairly constant. In Fig. 7 recovery time at a high average power (10 kw) is given as a function of pressure for tubes containing various sizes of insert. It is apparent that the smallest annular gap should be used, since the recovery time is then least and there is also least variation with pressure. Since recovery time is almost independent of pressure in a tube with a small gap, the choice of pressure must

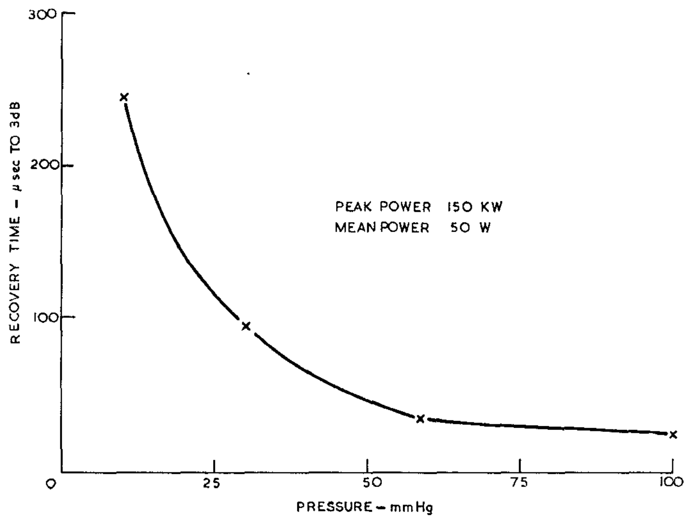

Fig. 5—Recovery time—pressure characteristic for a tube without insert.

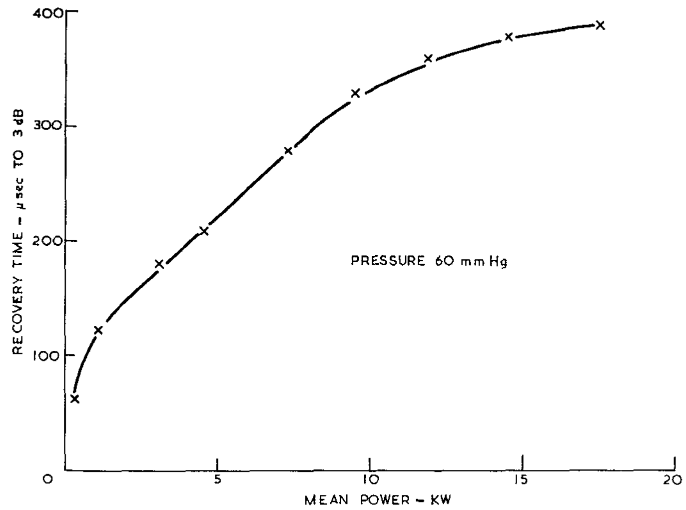

Fig. 6—Recovery time against mean power for a tube without insert.

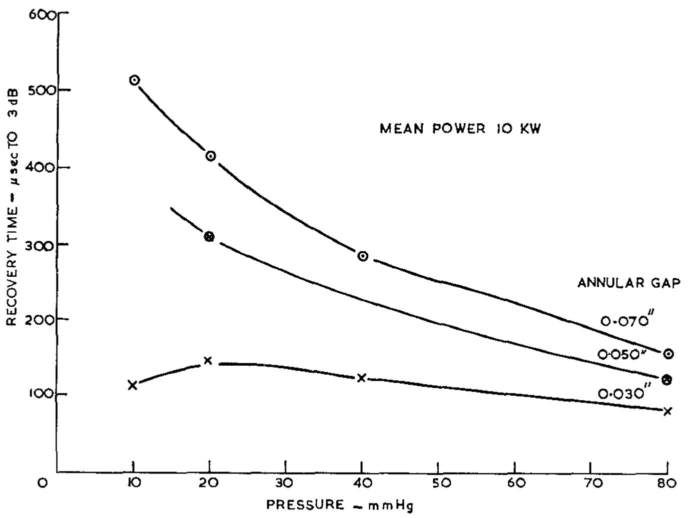

Fig. 7—Recovery time—pressure characteristic for three sizes of annular gap.

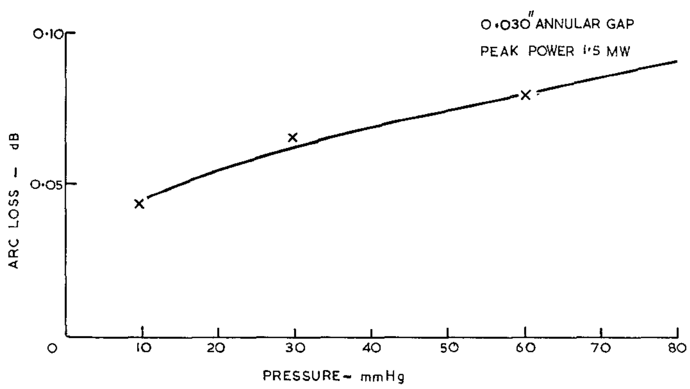

Fig. 8—Arc loss as a function of pressure.

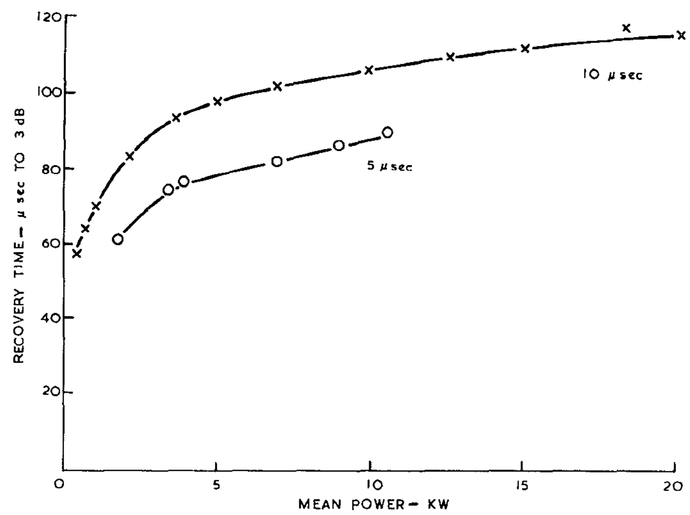

Fig. 9—Recovery time as a function of mean power at two different pulse lengths.

be governed by other factors. Although it is desirable to use as high a pressure as possible, because end of life is determined by clean-up of gas, the arc loss increases with pressure so that a compromise must be made between these considerations. The variation of arc loss with pressure at 1.5 Mw is given in Fig. 8, and it reaches a value of nearly 0.1 db at 60 mm Hg. This will represent a dissipation of nearly 100 w in each tube when working at 10-Mw peak, 20-kw average, so that any increase in pressure above 60 mm Hg is unwarranted. Should life tests prove that the rate of clean-up is small and hence the life very long, it may be desirable to reduce the pressure.

Braden[8] in an independent investigation has achieved much shorter recovery times than those quoted above by reducing the annular gap and also the gas pressure and hence increasing the electron diffusion losses. Braden proposes a tube filled with argon at a pressure of 4 mm Hg. Although the initial performance of such a tube will be good, its life at very high power levels will be very short because of gas clean-up. For example, tubes filled with krypton at a pressure of 10 mm Hg have failed after 400 hours operation at 5 Mw peak, 10 kw average, in a balanced duplexer. This life problem may to some extent be avoided if a gas reservoir can be tolerated.

Performance of the Pre-TR Tubes and Mount

The performance of the pre-TR tubes containing krypton at a pressure of 60 mm Hg and having an annular gap of 0.030 inch was measured in a mount which was attached to a short-slot hybrid[9] as in a balanced duplexer. Data obtained at 5 Mw, 10 kw is quoted in Table I.

TABLE I

Power Level	5 Mw peak, 10 kw average, 10 μsec pulse
Arc Loss	0.05 db
Recovery Time	95 μsec to 6 db 110 μsec to 3 db 135 μsec to 1 db
Leakage Power	5 kw peak, 10 w average (*i.e.*, 30 db attenuation)
Position of Short	0.06 cm from the face of the tube
Discharge Initiation Power	<10 kw.

The only properties which are influenced appreciably by the power level are arc loss and recovery time. The recovery time, which is shown in Fig. 9, is virtually independent of average power from 5 kw up to 20 kw, as expected from the recovery time/pressure curves, but does change with pulse length. All high power measurements of recovery time were made using a power multiplication circuit.[10] This circuit is a waveguide loop connected to a power source by a directional coupler. The loop acts as a resonator with an amplification dependent on the Q-factor of the circuit. The electrical length of the loop is changed by a high-power phase shifter consisting of a 3-db coupler followed by two waveguide plungers, designed to obviate sparking. Any small mismatches in the circuit are cancelled by the use of four dielectric plungers.

Arc loss measurements at low powers were made by replacing the tubes with metal rods and noting the change in power level. This technique is not of high absolute accuracy, and additional measurements were made using a power multiplication circuit, developed for life-testing four pairs of tubes. The gain of these circuits depends on insertion losses, so that an average value of the arc loss can be obtained with greater accuracy by replacing the tubes with metal rods. These experiments resulted in estimates for the arc loss of one pair of tubes of 0.05 db at 5 Mw peak, 10 kw average.

Performance During Life

The only significant change in the tube anticipated during operation is that of gas pressure. This is expected to decrease steadily as gas is absorbed on the walls of the tube. Some early measurements at $2\frac{1}{2}$ Mw peak, 3 kw average, with tubes containing silica wool and radioactive krypton[11] indicated clean-up at a rate of approximately 10^{-4} cc at STP/hour. This high rate of clean-up was probably due to sputtering of silica from the silica wool and consequent trapping of gas, and indeed further measurements on similar tubes without silica wool yielded clean-up rates of only 10^{-5} cc at STP/hour. More recently, tests on the new tubes described here have been extended to 5 Mw peak, 10 kw average, using the same radioactive techniques for estimating pressure changes and again low clean-up rates of about 2×10^{-5} cc at STP/hour have been recorded despite the increase in average power. These tests have now been extended with eight tubes being simultaneously tested in the power multiplication circuit shown in Fig. 10. Tubes filled at a pressure of 60 mm Hg have been on test at 5 Mw peak, 10 kw average, for 4100 hours with a gas clean-up of about 8 per cent. Hence, a life well in excess of 10,000 hours should be obtained.

There has been little change in performance during life as expected from the small variation of arc loss and recovery time with pressure. Recovery time has slightly increased and arc loss decreased.

[8] R. S. Braden, "A new concept in microwave gas switching elements," IRE Trans. on Electron Devices, vol. ED-7, pp. 54–59; January, 1960.

[9] H. J. Riblet, "The short-slot hybrid junction," Proc. IRE, vol. 40, pp. 180–184; February, 1952.

[10] L. Milosevic and R. Vautey, "The travelling wave resonator and its application to high power microwave testing," *Onde Elect.*, vol. 37, pp. 290–294; March, 1957.

[11] D. W. Downton, "Measurement of clean-up in gas discharge tubes using radioactive krypton," *Proc. IEE*, vol. 105B, Suppl. No. 10, pp. 485–487; May, 1958.

Application to Balanced and Phase-Shift Duplexers

Balanced Duplexer

The performance of the tubes in a balanced duplexer has been examined using a circuit of two short-slot hybrids[9] and the pre-TR mount as illustrated in Fig. 11. The low-level performance is given in Fig. 12, showing that the duplexer has a bandwidth of about 14 per cent. The bandwidth is limited by that of the hybrid junction in this particular duplexer, but the most important limitation is caused by the rather high Q-factor of the mount. Reflections from the mount during reception constitute a loss in power which becomes significant at frequencies more than a few per cent from the center frequency. This is illustrated in Fig. 12; the insertion loss of the duplexer increases rapidly at 2700 Mc and 3100 Mc, and this is entirely caused by reflection losses from the mount.

The performance at high power levels has already been described in detail. The only feature peculiar to the balanced duplexer is that further receiver isolation is provided by the second hybrid so that a total isolation of 50 db exists between transmitter and receiver. Thus for a duplexer operating at 10 Mw peak, 20 kw average, the power incident on the receiver arm is 100 w peak, 200 mw average. A standard TR cell is needed to protect the mixer crystal from this power level. Alternatively, if a traveling-wave tube is used in the receiver system, it may be necessary to include a simple gas discharge tube for protection.

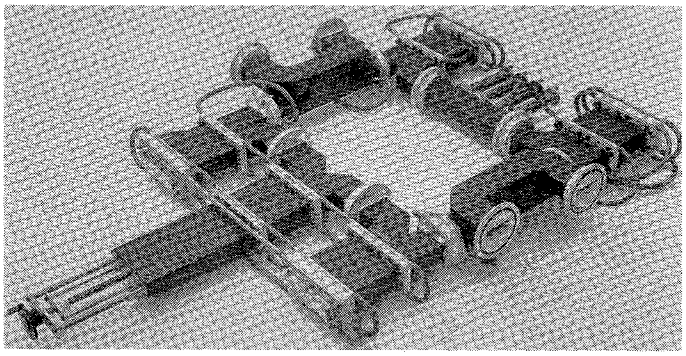

Fig. 10—Power multiplication circuit used for life-testing four pairs of tubes.

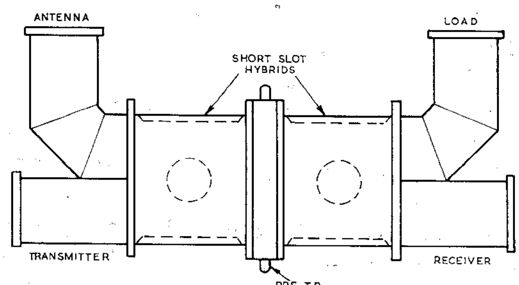

Fig. 11—Balanced duplexer (using short-slot hybrids).

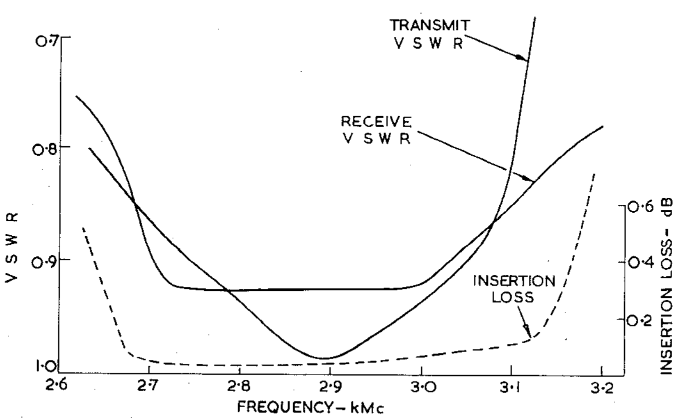

Fig. 12—Balanced duplexer characteristics.

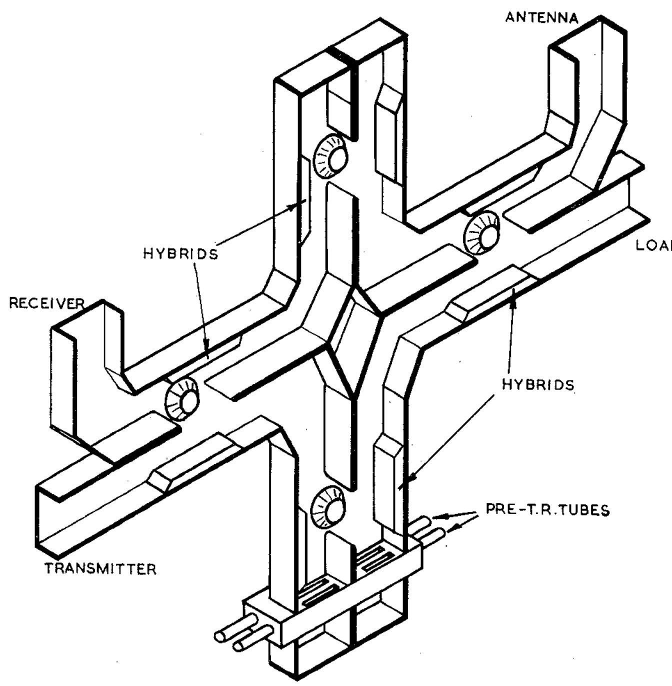

Fig. 13—Phase-shift duplexer (using short-slot hybrids).

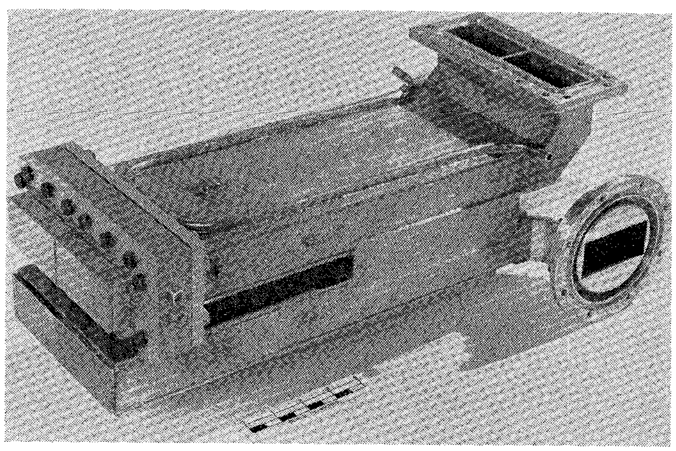

Fig. 14—Phase-shift duplexer using short-slot and binomial-slot hybrids.

Phase-Shift Duplexer

The circuits examined for a phase-shift duplexer have been described by Lomer and O'Brien[12] and are shown in Figs. 13 and 14. The low-level performance of this form of duplexer depends again on the performance of the hybrid junctions and is very similar to that of the balanced duplexer. The insertion loss is about 0.25 db over the frequency band. The high-level performance is favorable since only half the power is incident on the tubes and, in fact, this type of duplexer will handle twice the power of the corresponding balanced duplexer. Since the tubes have been tested in a balanced duplexer at 10 Mw peak, 25 kw average, this corresponds to a phase-shift duplexer operating at 20 Mw peak, 50 kw average.

Power Handling Limitations

The majority of the tests on the tube were made with balanced duplexers operating at 10 Mw peak, 25 kw average, or less. Any extensions of peak power levels require pressurization in excess of 45 pounds per square inch, and would require much stronger waveguide components. On the other hand, extensions of average power with relatively low peak power is feasible, provided water cooling is provided.

No serious extension in average power could be examined in these experiments however, since the source of power was a 3 Mw peak, 3 kw average magnetron operating into a power multiplication circuit in which peak and average power levels are both increased. Thus, a serious study of average power handling above 25 kw requires a source of high average power with low peak power.

There have been no indications of an approaching limit to average power handling. For example, the temperature of the inner wall of the inserts has only reached 280°C at 20 kw average. This temperature could be considerably reduced by air cooling, and undoubtedly the silica tubes could be used at much higher temperatures without affecting the performance. Thus, from this point of view, much higher power levels could be handled.

Conclusions

A pre-TR tube capable of handling up to 10 Mw peak, 25 kw average, in a balanced duplexer, and 20 Mw peak, 50 kw average in a phase-shift duplexer, has been developed for 3000 Mc. The properties of the tube are controlled by its dimensions and do not vary greatly with gas pressure. Thus, the performance of the tubes will not change, appreciably during life. Life tests at 5 Mw peak, 10 kw average, have been in progress for 4100 hours and have provided data from which lives in excess of 10,000 hours are obtained by extrapolation.

Acknowledgment

The tubes were life tested at the Services Valve Test Laboratory under the direction of G. J. Halford, whose constant cooperation is gratefully acknowledged.

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[12] P. D. Lomer and R. M. O'Brien, "A new form of high-power microwave duplexer," IRE Trans. on Microwave Theory and Techniques, vol. MTT-6, pp. 264–267; July, 1958.