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FINAL REPORT

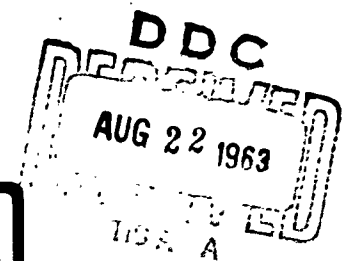
July 1, 1961 to May 31, 1963

HIGH POWER TRANSMISSION LINE
AND
ASSOCIATED MICROWAVE PARTS

Contract No. NObsr 85455

Department of the Navy

MICROWAVE
ASSOCIATES
INC.



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Burlington, Massachusetts

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ABSTRACT

A high power S-band transmission line was designed, constructed and evaluated for operation at 45 kilowatts of average power and 15 megawatts of peak power. The components included straight sections, bends, directional couplers, a window and a gas discharge duplexer. Pressurization and cooling fins were required to meet the power requirements. For super-power transmission lines, it is recommended that the low loss mode in circular waveguide, TE_{01}^0 , be used.

PURPOSE

The purpose of this program is to design, construct and test an optimum high power transmission line for S-band frequencies and to recommend an approach for ultra high power transmission lines. In addition a number of microwave components are to be designed and evaluated for several sets of power levels comparable to that of the transmission line.

INTRODUCTION

The purpose of the program is to help meet the problems arising from the needs for transmitting higher and higher powers at microwave frequencies. Some of the problems have been anticipated and are amenable to theoretical analysis; however, to insure that the power levels under consideration can be safely transmitted, it is necessary to run controlled laboratory experiments. The work in this program was concerned with S-band frequencies, 3 Gc, and was carried out in two phases.

Phase I included the design, construction and testing of an optimum transmission line having a ten percent bandwidth for a peak power up to 15 Mw and an average power of 45 kw. In addition to satisfying these requirements, a study was made leading to recommendations for transmission lines for the following power levels:

<u>Peak Power - Megawatts</u>	<u>Average Power - Kilowatts</u>
20	12
30	20
50	1000

The last set of requirements represents a significant advance in the state-of-the-art and may be termed a super-power level.

Phase II of the program was directed toward the design, construction and testing of the microwave components listed below:

1. duplexer,
2. directional coupler,

3. window,
4. associated microwave parts.

These components should be able to operate at the following power levels:

<u>Peak Power - Megawatts</u>	<u>Average Power - Kilowatts</u>
15	45
20	12
30	20

To meet the requirements of this program enough components were made, including some not specified directly by the program, to assemble a traveling wave resonator for testing the required components at high power levels. Nominally 30 feet of waveguide components were constructed. It was agreed upon with the sponsor that 70 feet of straight waveguide would not be fabricated. The components listed above were successfully evaluated for the power ranges required by the program. As part of the recommendations for the very high power transmission line, 50 megawatts of peak power and 1000 kw of average power, it was pointed out that oversized waveguide carrying the circular TE_{01} waveguide offered the best solution. The supporting reasons are given which include a careful consideration of the various problems which are important for these power levels. As a further part of the recommendations, preliminary design work was done on a compact high-power transducer for the TE_{01}^o waveguide mode.

The contents of this report includes a description of the high power transmission line components and their low level characteristics.

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Next the report discusses the high power tests on these components. Finally, the recommendations for a super-power transmission line at S-band are given.

DETAILED FACTUAL INFORMATION

Description of Transmission Line and Components

The components for the hundred feet of transmission line at S-band are designed to handle peak powers of 15 to 30 megawatts and average powers of 45 kilowatts. The waveguide sections are made from WR 340 aluminum waveguide with five inch square fins spaced one inch apart. Dip-brazing was used in fabrication. For reference, Table I shows the theoretical high power capabilities of several waveguide designs which were considered. The environmental conditions were limited to a temperature rise of 50°F in an ambient of 125°F. For comparison, calculations for liquid cooling are included for the same waveguide sizes and materials. The requirements for flow rate and pressure in cooling with a solution of 60% ethylene glycol and 40% water are not found to be too difficult to achieve for the 45 kilowatts of average power in the waveguide. The peak power capabilities are also indicated in Table I for air at atmospheric pressure.

Although tall waveguide can handle the power requirements of the program, WR 340 waveguide with cooling fins was selected because all components would be of conventional design. The addition of cooling fins and pressurization was considered to be a simpler problem. To support this decision the power dissipation capability of standard waveguide and finned waveguide were verified experimentally with sections of waveguide containing electrical heaters. Although natural cooling is nominally proportional to the total surface area, it was found that the fins tend to interfere with each other so the effective

surface area is generally smaller than the actual surface area¹. According to Table I, where this is taken into account, the dissipated power will be handled adequately by the additional cooling surfaces. Furthermore, the fins themselves strengthen the waveguide so that pressurization will not cause excessive distortion.

The components which have been designed and fabricated are shown in Fig. 1A, a sketch of the complete traveling wave resonant ring which was used for high power testing. Other components which can be inserted are shown and in Fig. 1B there is a list of the components and general specifications. Approximately 85 percent of the ring is made of the required finned WR 340 waveguide and the balance of the ring is made of plain sections of WR 340. Two transitions to WR 284 were required at the input of the ring where the high power S-band transmitter is connected. The input directional coupler, Item 8 in Fig. 1, is so constructed that the coupling into the ring can be varied in discrete steps. Variable coupling was necessary in order to get optimum power gain in the traveling wave ring as different components are inserted. Sections labeled 4 are straight sections of waveguide which will be used for tuning the ring. It has been our experience that adequate tuning can be achieved by judiciously squeezing sections of the straight waveguide, thereby introducing discontinuities which in turn cancel reflections from other components in the ring. Fortunately our high power source is of variable frequency so that as the reflections are tuned out, the frequency of the transmitter can be adjusted slightly to keep the entire ring in resonance. In Fig. 1, in the area above the resonant ring

there are shown a window and a section of dual waveguide that can be inserted into the ring. The dual section of waveguide consists of two 3 db hybrids and a gas discharge switch section. The switch section as an ATR can be tested in the resonant ring just as any other transmission type component. The flanges used in constructing the various components are standard rectangular flanges for WR 340 waveguide and the gaskets are those manufactured by the Parker Seal Company*.

The characteristics of the directional couplers are given in Figs. 2, 3 and 4. The 70 db directional coupler is bi-directional employing an array of coupling holes in the side walls. Its characteristics, Fig. 2 indicate a coupling at the center of the band of 67.5 ± 0.8 db for a 10% bandwidth. To avoid the use of low temperature material in the output arms the waveguide to coaxial transition used a "T" bar configuration. The 3 db hybrid directional couplers that are used for the duplexer are of the transvar type^a; i.e., the coupling at the common narrow wall between the two waveguides consists of a long slot containing an array of bars extending from one broad wall to the other. The characteristics are plotted in Fig. 3. This construction was used to insure the high peak power capability of the component. The directional couplers used at the input to the traveling wave ring were also of the transvar type; however, because the degrees of coupling are smaller, the lengths of the slots are considerably shorter than that for the 3 db hybrid. Three values of coupling are indicated in Fig. 4; they are nominally 12, 15 and 18 db.

*Parker Seal Company, Culver City, California and Cleveland, Ohio

The gas discharge duplexer consists of a balanced ATR switch and a pair of the 3 db hybrids. The ATR switch utilizes two pairs of quartz cylinders as the switching element. The construction of the balanced ATR duplexer is shown in Fig. 5. The individual ATR switches consists of precision-ground quartz cylinder vials which are inserted into precision-bored holes in the mount. Coupling to the main waveguide through the top wall is achieved by slots, whose height and length as well as vial dimensions determine the resonant frequency of the ATR. The use of precision fabricated parts eliminates the need for a dielectric to metal seal, thus permitting a greater degree of latitude in the choice of dielectric and mount materials. The absence of the oxide seals used in conventional windows also leads to extremely low loss values of ATR conductance. Measurements indicate that the conductance of the ATR switches using this design, is sufficiently small to be neglected in determining the theoretical low level response of the balanced duplexer array.

The ability of the duplexer to operate at high power levels is determined by the amount of power absorbed by the switching windows which in turn is directly proportional to the window height. On the other hand the loaded Q is inversely related to the window height. Thus the duplexer design must result in a compromise between high power performance and low level bandwidth, indicating the importance of achieving a duplexer design which uses ATRs of minimum height for a given loss and bandwidth. In the arrangement of Fig. 5 the two ATR switches mounted opposite one another are considered as a single ATR. The use of two

ATR's "zero spaced" has a number of advantages: 1) The effective conductance is one half that of the individual units. 2) The effective Q_L of the two ATR's of window height H is equal to the Q_L of a single ATR with minimum window height $2H$. Thus for the same bandwidth the "zero spaced" arrangement has lowered the power absorbed in each switching element. Since the thermal gradients in the window are also reduced by reducing the height, the net result is to more than double the average power handling capability for the same bandwidth. 3) Measurements made on this configuration indicate that sufficient coupling exists between the two ATR's to make them behave as a single ATR. In theory a slight resonant frequency difference between the two units should result in conjugate matching causing a sharp decrease in loss near the center of the passband. This condition has not been found in practice.

Measurements made of the low level characteristics of the complete duplexer are shown in Fig. 6. The following characteristics were obtained (including high power tests):

Frequency range	2.85 to 3.15 Gc
Loss-low level	0.4 db maximum
Loss-high level (arc loss)	0.1 db maximum
VSWR	1.5 maximum
Isolation to receiver arm	17.5 db minimum

The measured high level loss of .1 db or 2%, we believe, can be made smaller as indicated by more current structures employing more optimum diameter bulbs. A similar unit has been operated for short periods at 20 megawatts of peak power and 100 kilowatts of average power in

WR 284 waveguide. The arc loss of the duplexer was determined calorimetrically by measuring the temperature rise of the cooling water required for safe operation of the duplexer. The resultant temperature rise was 15°C and the flow rate of water was 1300 cubic centimeters per minute. Thus the power dissipation is calculated to be 1400 watts for an input power average power, of 47 kilowatts.

The microwave window which was designed and constructed is sketched in Fig. 7. The window consists of a disc of alumina, mounted in a cylindrical section of kovar. This section is brazed to flanges which mate with standard rectangular flanges for rectangular waveguide, WR 340. Because the diameter of the cylindrical section was held to a reasonable diameter (3 inches) which also reduced the number of ghost mode resonances, it was found necessary to add matching steps at the two flanges. As suggested by the sketch the distance between the steps is nominally equal to the height of WR 284 waveguide. The corners are carefully rounded with a large radius and polished to prevent breakdown under high power conditions. The standing wave characteristics of the window are shown in Fig. 8. The bandwidth is 19% for a maximum value of VSWR of 1.15 which is more than adequate for the requirements of this program. A photograph of the window is shown in Fig. 9. Although several types of construction had been considered in which a metal to ceramic seal would not be necessary, it was felt that the most satisfactory leak proof construction would be that used here: a hard brazed metal to ceramic seal. The cylindrical sleeve was made of kovar which was copper plated to a thickness sufficient to give the low loss characteristic

of copper. The insertion loss was estimated to be .014 db from the calorimetric determinations during the high power evaluation.

High Power Evaluation of Components

The high power tests were carried out in a traveling wave resonant ring. A schematic of the resonant ring with several inserts such as the duplexer and window was shown in Fig. 1. Approximately 85% of the ring components are of the finned construction suitable for the power requirements of the program. The balance of the components were not finned and consequently operated at higher temperatures but this did not effect the evaluation of the finned components. The transmitter provided a 12 microsecond pulse and in the ring the peak power and average power could be raised well above the levels required in this program. A photograph of a resonant ring is shown in Fig. 10. Among the components already discussed there is also shown a plain section of waveguide to which a C-clamp has been applied for tuning the ring to minimize power traveling in the reverse direction. All of the components shown in Fig. 1 can be identified in the photograph. The apparatus in the background consists of the driver and power supplies for the amplitrans which were used to produce the high power.

The evaluation of waveguide temperature rise at 45 kilowatts of average power shows that the fins are effective in maintaining a reasonably low temperature. In an ambient room temperature of 26°C the extremities of the fins were found to be at 37°C while the body of the waveguide near the flange was somewhat hotter, 41°C.* By comparison a section of plain WR 340 waveguide operated at a temperature of 46°C.

*This is a 36°F rise where 50°F is acceptable.

At least an hour was allowed for stabilization of the temperatures. It is interesting to note that at the end of a period of twenty minutes with a peak power of 31.5 megawatts and an average power 180 kilowatts, the fins were operating at 44°C , the waveguide body was at 46°C while the section of waveguide without fins had already risen to a temperature of 62°C .

The complete traveling wave ring was evaluated for peak power capability at various values of pressure with both air and SF_6 . The results plotted in Fig. 11 show that the waveguide system can handle approximately 25 percent of the theoretical value of breakdown power of straight waveguide filled with air. As the pressure was increased the peak power also increased, but not as rapidly as the square of the pressure. The reason for this, after careful consideration, appears to be due to poor joints and small imperfections* as indicated by the characteristic breaks in the curves. The breaks in the curves have been explained in other work²: briefly the effect is due to small discontinuities at which the highly localized ionization can lead to the development of an arc only at high pressures and correspondingly high power levels. Because the evaluation was done with 12 microsecond pulses, this effect is even more pronounced. Since the air filled ring at one atmosphere of pressure began breaking down at 4 megawatts, pressurization to 30 pounds gauge of air was required to handle in excess of the required 15 megawatts. When pressurized with SF_6 , it was found that at essentially atmospheric pressure the system could handle 25 megawatts of peak power. From our observations that arcing occurred more or less at

*Flaws in surface finish were found in the drawn aluminum.

random throughout the ring it is apparent that the balance of the components in the ring such as directional couplers and bends and hybrids are all about equal in their peak power capabilities. Thus pressurization readily provides the peak power capability; the main problem appears to be due to inadvertent factors such as not drawing up the joints tight enough or due to slight irregularities in the waveguide.

Recommendations for a One Megawatt Average Power Transmission Line

The recommendation for a transmission line capable of handling a 1000 kw of average power and 50 megawatts of peak power is to employ circular waveguide propagating the low loss mode, the TE_{01}^0 mode in circular waveguide. In considering this mode of propagation the obvious advantages are that it would be able to handle the average power without additional cooling and handle the peak power without excessive pressurization. Our previous discussions have indicated that both the peak and average powers can be handled in a straight section of circular waveguide approximately eight inches in diameter.* The limiting factors will be the characteristics of the components designed for a complete system.

Careful consideration of the TE_{01}^0 mode in circular waveguide indicates that the following advantages recommend the circular mode for ultra high power transmission lines. The only other mode which warrants attention is the TE_{10} mode in rectangular waveguide; however, once its size is increased to that comparable to circular waveguide then it loses its advantage. The advantages for TE_{01}^0 waveguide are:

*From Reference 3, 100 megawatts at one atmosphere of air and 100°C temperature rise.

1. The circular mode has the advantage of lowest loss when the diameter exceeds two wavelengths.
2. Higher peak powers can be handled in the circular waveguide operating in the low loss mode - a factor of 10 above standard rectangular waveguide.
3. The low loss coupled with the large external surface area provide adequate cooling by radiation and convection.
4. The region of maximum value of electric field does not occur on the walls so wall imperfection cannot greatly influence breakdown.
5. Because only transverse currents exist in the cylindrical waveguide, arcing is minimized at poor joints since the current flows parallel to, rather than across the joint.
6. The disposition of the wall currents allow a simple technique for mode filtering, since all of the other modes except the TE_{0n}^0 modes will have current components which are longitudinal. Any small gaps occurring in a longitudinal direction do not effect the low loss mode, but do effect the other modes.
7. The circular cross-section is relatively free from distortion under conditions of pressurization (on the other hand large rectangular waveguide would be very prone to distortion because the surfaces are so large).
8. The circular waveguide from a practical point of view is easy to machine.

There are disadvantages to using circular waveguide in the TE_{01}^0

mode which are related mainly to the excitation of spurious modes. First, if the power which goes into these modes is simply dissipated in the system, then these losses would wipe out the gains of using the low loss mode in the first place. For example, if the total conversion of power to spurious modes in, say, a hundred feet of transmission line is 20 percent, then it is comparable to the attenuation for a standard waveguide a hundred feet in length and there would be no real advantage with respect to losses. The advantage of handling high peak power levels is not lost however if proper mode filtering is employed. A second disadvantage to be found in the over-sized waveguide is that spurious modes may experience resonances or fall close to cutoff with the result that the field strengths of these modes may become large enough to initiate a discharge and cause a complete failure of the transmission line. Once a discharge has occurred, excessive mode conversion may take place with disastrous results on other components in the transmission line. Finally, a disadvantage may be the large size of the pipe; however, this may only be a laboratory limitation.

In spite of these disadvantages it would seem that every effort should be made to evolve a complete transmission line in the over-sized circular waveguide carrying the TE_{01}^0 mode. In view of the design problems related to spurious modes, the question arises as to whether or not all of the components required for a typical radar transmission line can be realized in circular waveguide or at least in components compatible with circular waveguide. The word compatible is used to indicate that no great lengths of waveguide are required for the

component and also to indicate that no highly involved configurations be required between the component and a straight section of waveguide.

As part of the recommendations several designs were considered for a compact high power mode transducer for the TE_{01}^0 mode in circular waveguide. This component is required because current high power tubes at S-band frequencies launch the TE_{10}^0 mode. Only a preliminary design directed towards achieving a high power and yet a compact structure was initiated and for convenience the design was done in X-band.

The design was based on the folded hybrid tee which when fed from the E-plane arm launches signals in the parallel arm section that are opposite in phase. This orientation is required by the field configuration of the TE_{01}^0 mode as shown in Fig. 12. To complete the transition into the circular waveguide, several quarter wavelength steps were inserted to produce a development into the circular waveguide, Fig. 12. To provide improved matching an adjustable ring, not shown in the figure, was placed in the circular waveguide near the steps. The purpose of this construction was to make the transition region as short as possible since the wavelengths at S-band have become long. The $\lambda/4$ steps in the circular section are in the form of sectors and for this design with two steps, the angle of the sections were varied linearly. A useful aspect of this transducer is that spurious modes with a field configuration such as TE_{11}^0 would be loaded by the H-arm of the hybrid; this is spurious mode resonance suppression which is automatically achieved by this design.

The results of matching the transition using the adjustable ring

are shown in Fig. 13. The bandwidth achieved was 8 percent for a VSWR below 1.3. This does not represent the best characteristics that can be obtained. With further effort it should be possible to obtain a bandwidth equivalent to the hybrid used at the input.

The simple form of the mode transducer using only two launching ports was not expected to give optimum results in terms of mode purity. The object was to evaluate the launching scheme. The measurements of mode purity bore this out and showed that a large percentage of the power was in the TE_{21}^0 mode. This was further verified by measuring the insertion loss through the transducer and a second TE_{01}^0 mode transducer between which was placed a mode filter for the spurious modes. The large attenuation measured with the mode filter in place indicated that a relatively small amount of power was launched in the TE_{01}^0 mode.

Since in the preliminary design the first object was to verify that the folded hybrid would be suitable for coupling into the circular waveguide, the poor mode purity at this stage of development is not serious. The next step is to employ a further power division so that the circular waveguide can be fed from four input ports. This next step in the design of the transducer is sketched in Fig. 14. The four ports are shown and the power division into the four ports is also indicated schematically. The first power division is by folded hybrid and the next by bifurcated waveguide sections. Following this, 45° waveguide twists are used to align the waveguide sections for launching the circular mode.

REFERENCES

1. M. Gilden, "High Power Transmission Line and Associated Microwave Parts", First Quarterly Report, NObsr 85455, Microwave Associates, September 30, 1961.
2. K. Tomiyasu and S. B. Cohn, "The Transvar Directional Coupler", Proc. IRE 41, p. 922, July 1953.
3. M. Gilden, "High Power Capabilities of Waveguide Systems", Final Report, NObsr 85190, Microwave Associates, May 1963.
4. M. Gilden, "Ultra High Power Transmission Line Techniques", Final Technical Note AF30(602)2545, Microwave Associates, March 1963.

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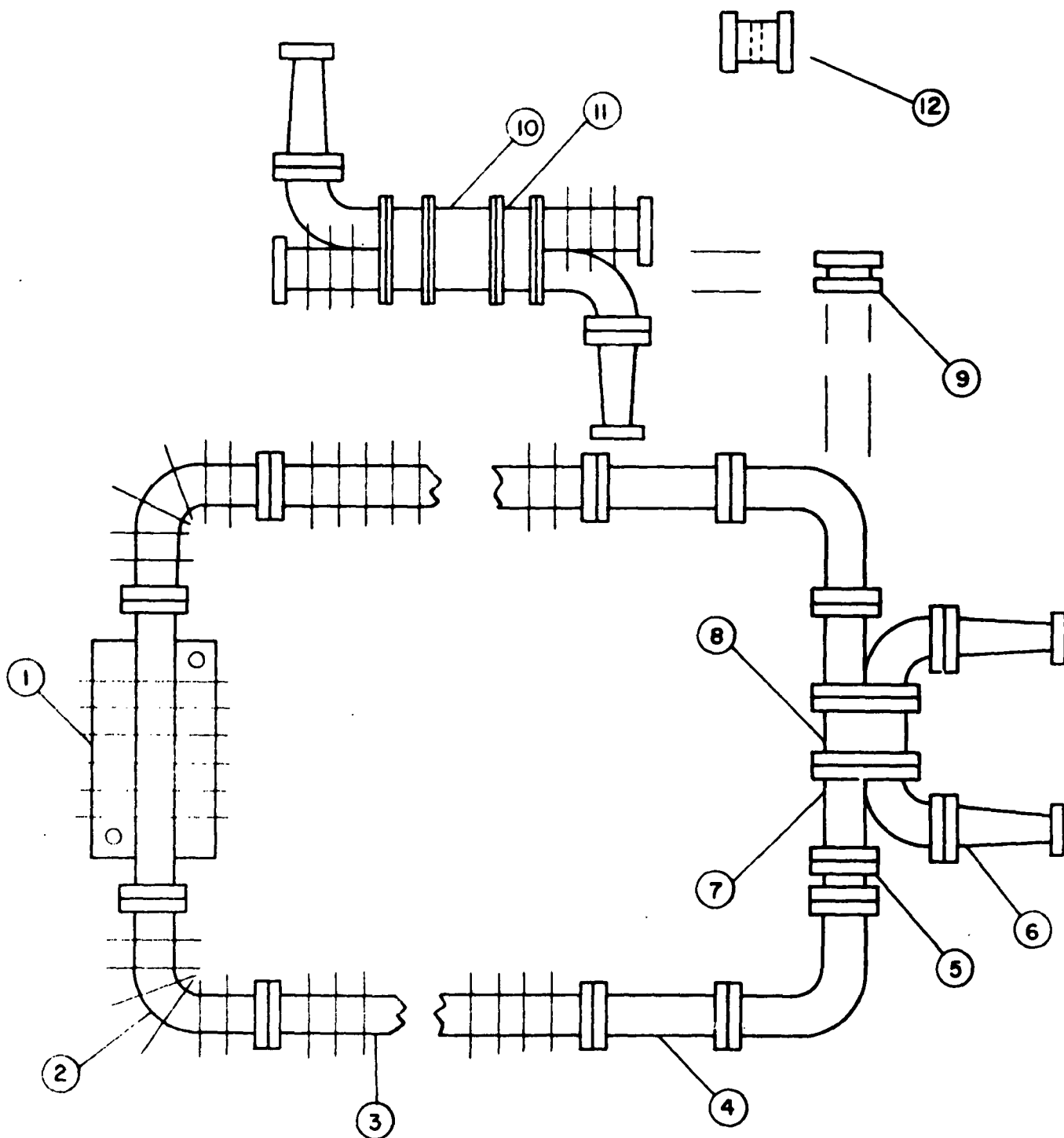


FIGURE 1A
WR340 TRAVELING WAVE RESONANT RING
USING FINNED WAVEGUIDE

GENERAL SPECIFICATIONS

1. FREQUENCY	28 - 3200 MC
2. PRESSURIZATION	30 psig
3. MATERIAL	ALUMINUM
4. FINISH	ACID ETCH
5. FLANGE TYPE	RECTANGULAR COVER EXCEPT FOR CIRC. WR284
6. AVERAGE POWER	45 kw, 80 max.
7. PEAK POWER	15 MEGAWATTS, 30 max.
8. MIN. BEND RADIUS	8 INCHES

ITEM	NO. REQD.	TITLE
1	1	BIDIRECTIONAL COUPLER - 70 DB*
2	4	H-PLANE BENDS*
	4	E-PLANE BENDS*
3	2	FINNED WAVEGUIDE SECTIONS*
4	2	WAVEGUIDE TUNING SECTIONS
5	1	COUPLER RING ADAPTOR
6	4	WR340 - WR284 TRANSITION
7	4	H AND STRAIGHT ADAPTORS*
8	1	RING INPUT COUPLER
9	1	DUPLEXER RING ADAPTOR
10	1	DUPLEXER BODY*
11	2	3 DB HYBRID SECTIONS*
12	1	WINDOW*

*Required components

FIGURE 1B

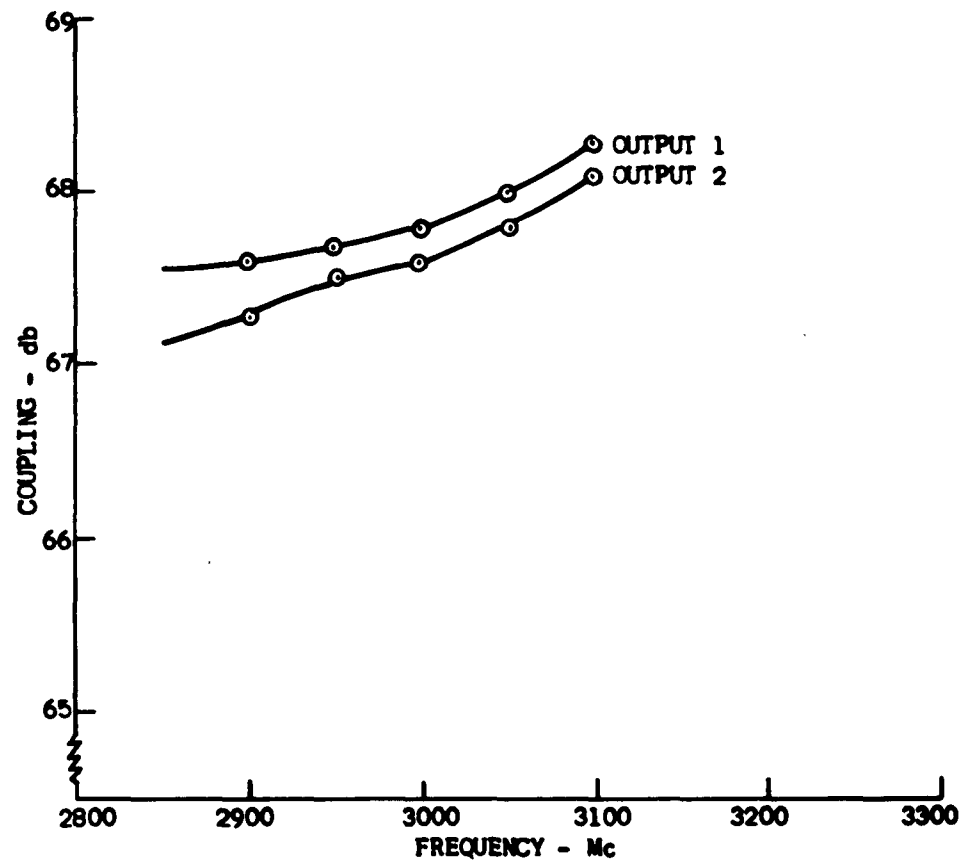


FIGURE 2 CHARACTERISTICS OF 70 db COUPLER -
SIDE WALL COUPLING SLOTS

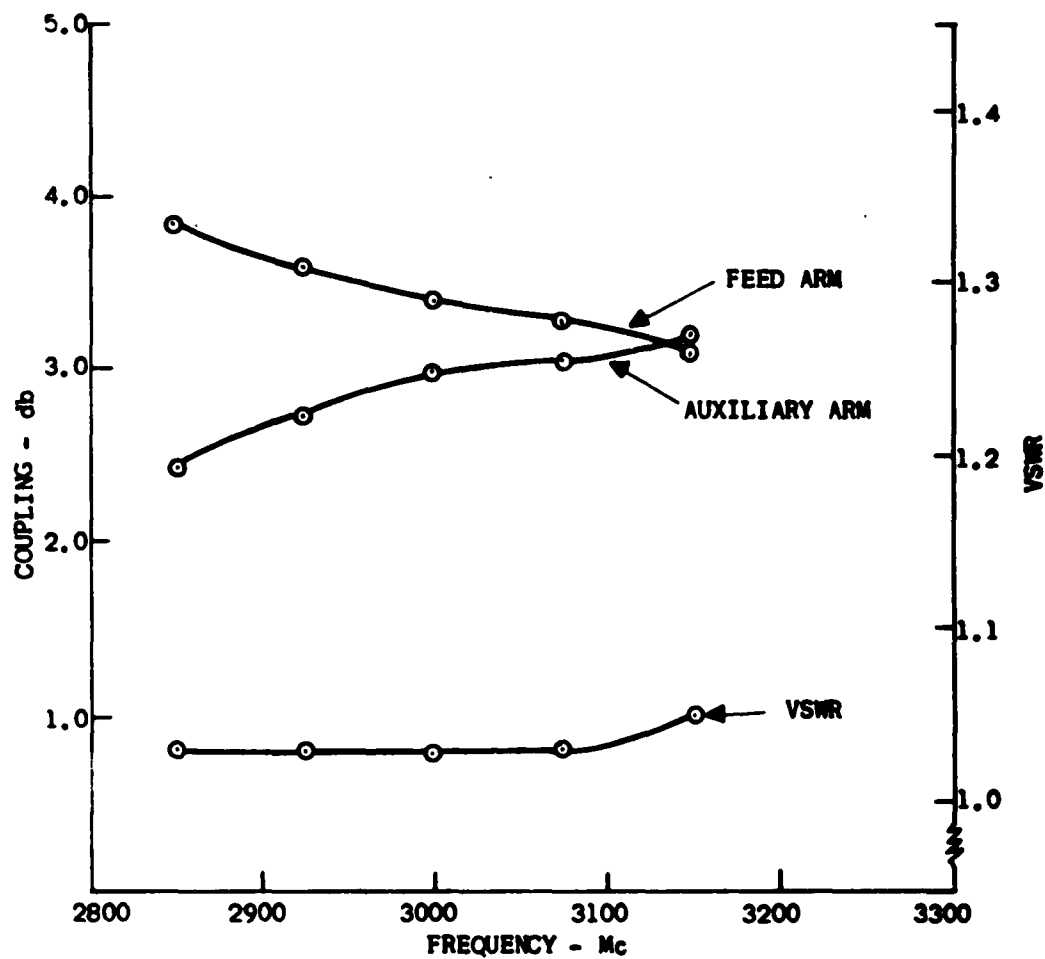


FIGURE 3 CHARACTERISTICS OF 3 db HYBRID - TRANSVAR COUPLING

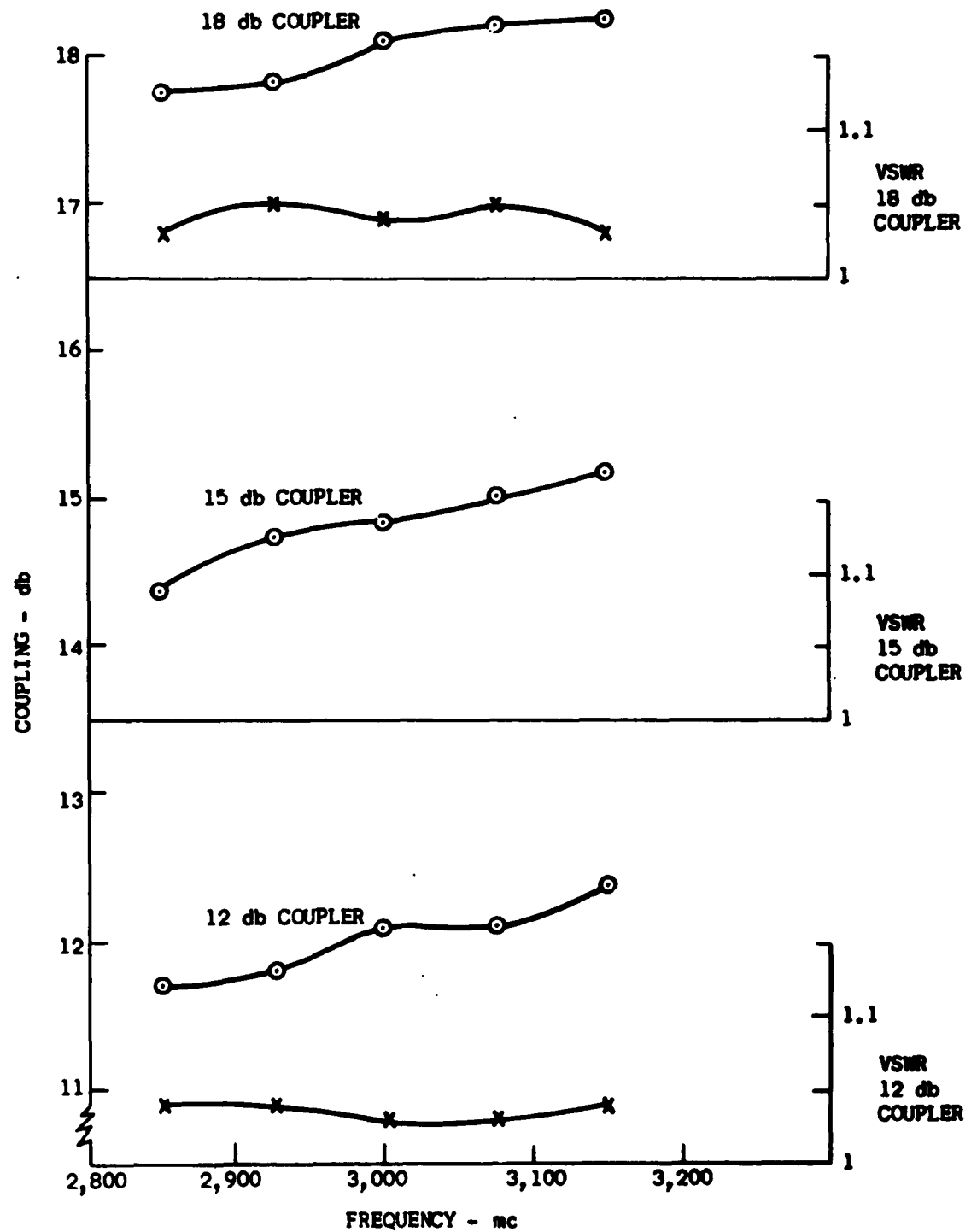


FIGURE 4 CHARACTERISTICS OF THE RING COUPLERS - TRANSVAR COUPLING

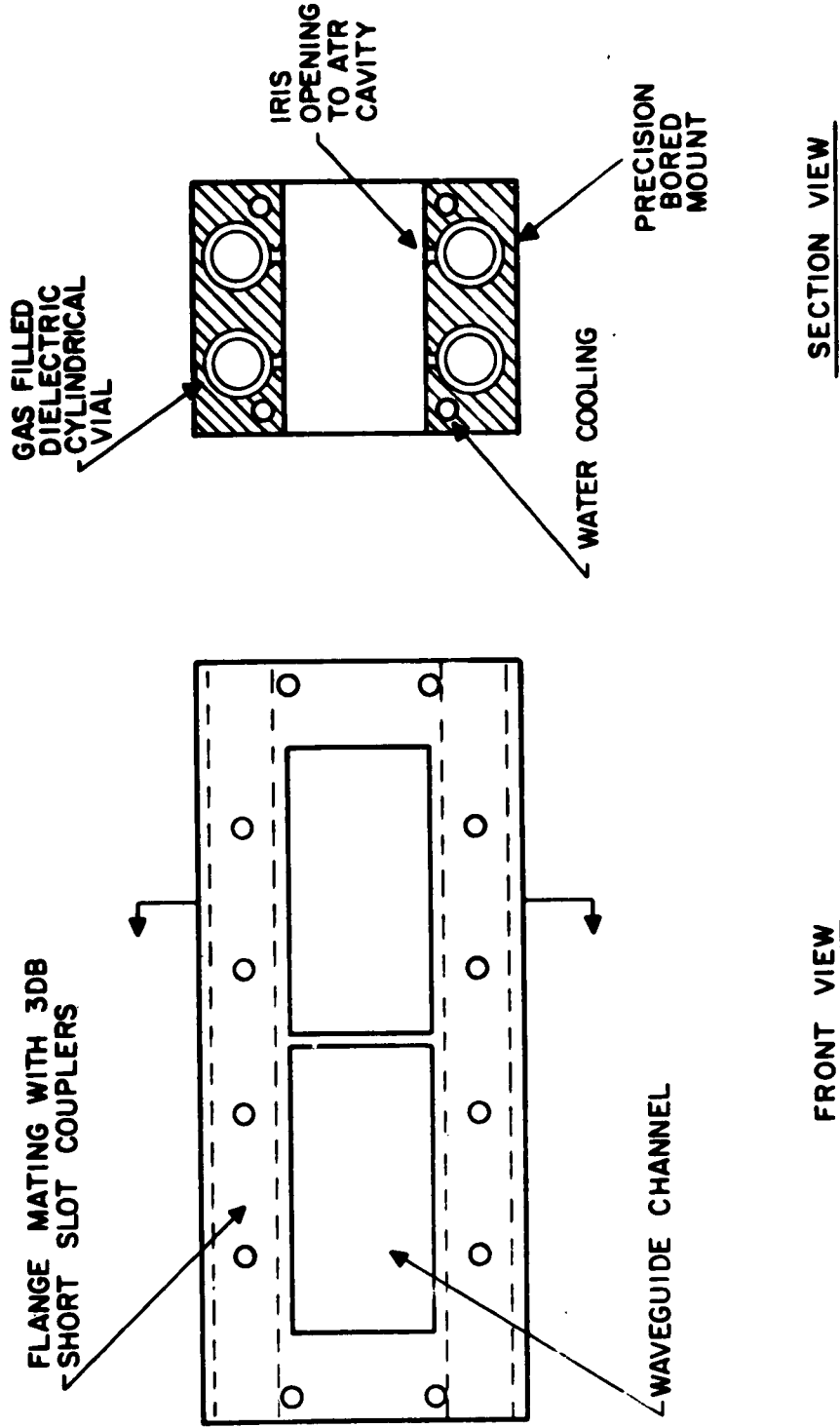


FIGURE 5
BALANCED ATR ARRAY
USING CYLINDER WINDOW ATRs

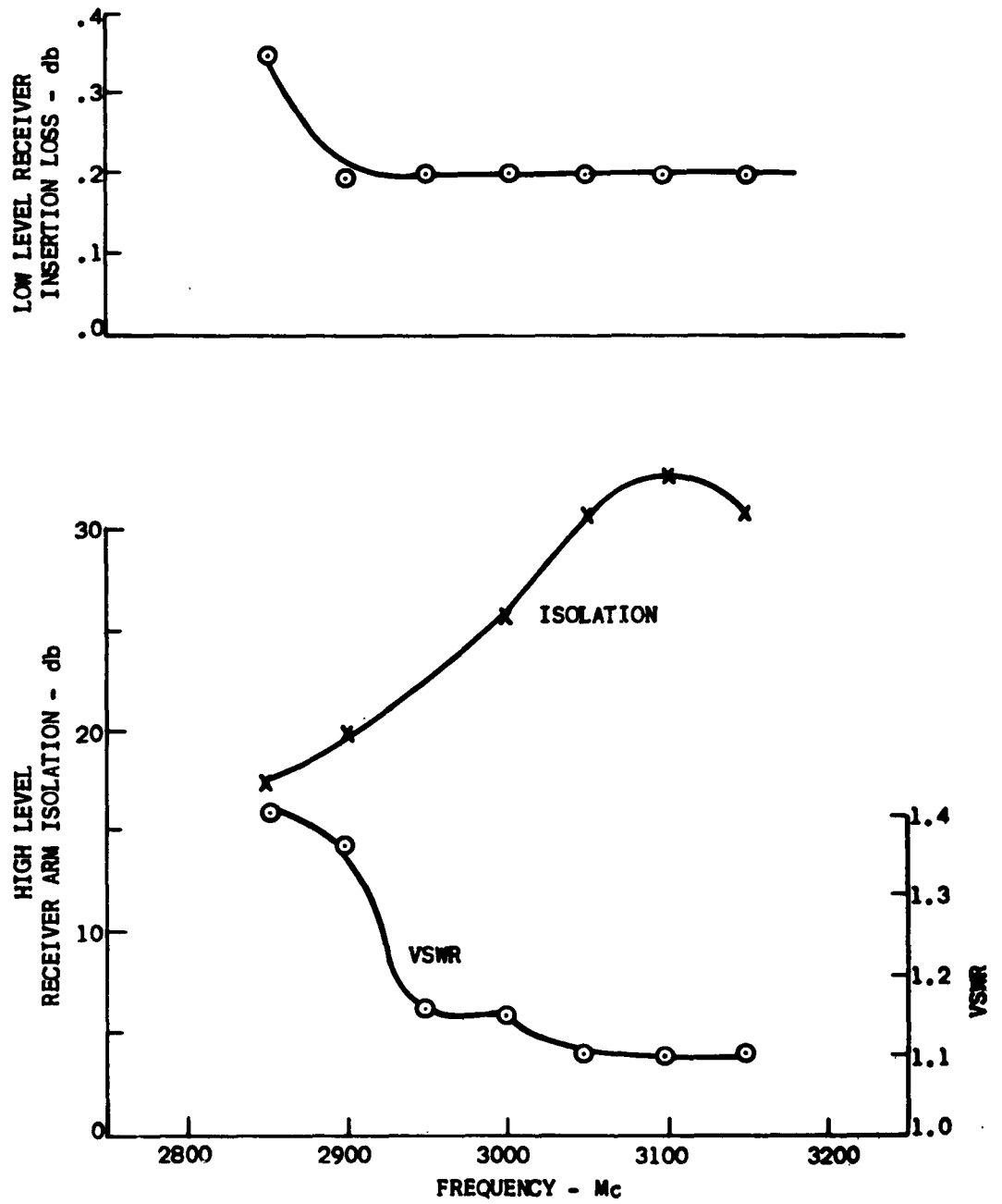


FIGURE 6 BALANCED DUPLEXER CHARACTERISTICS

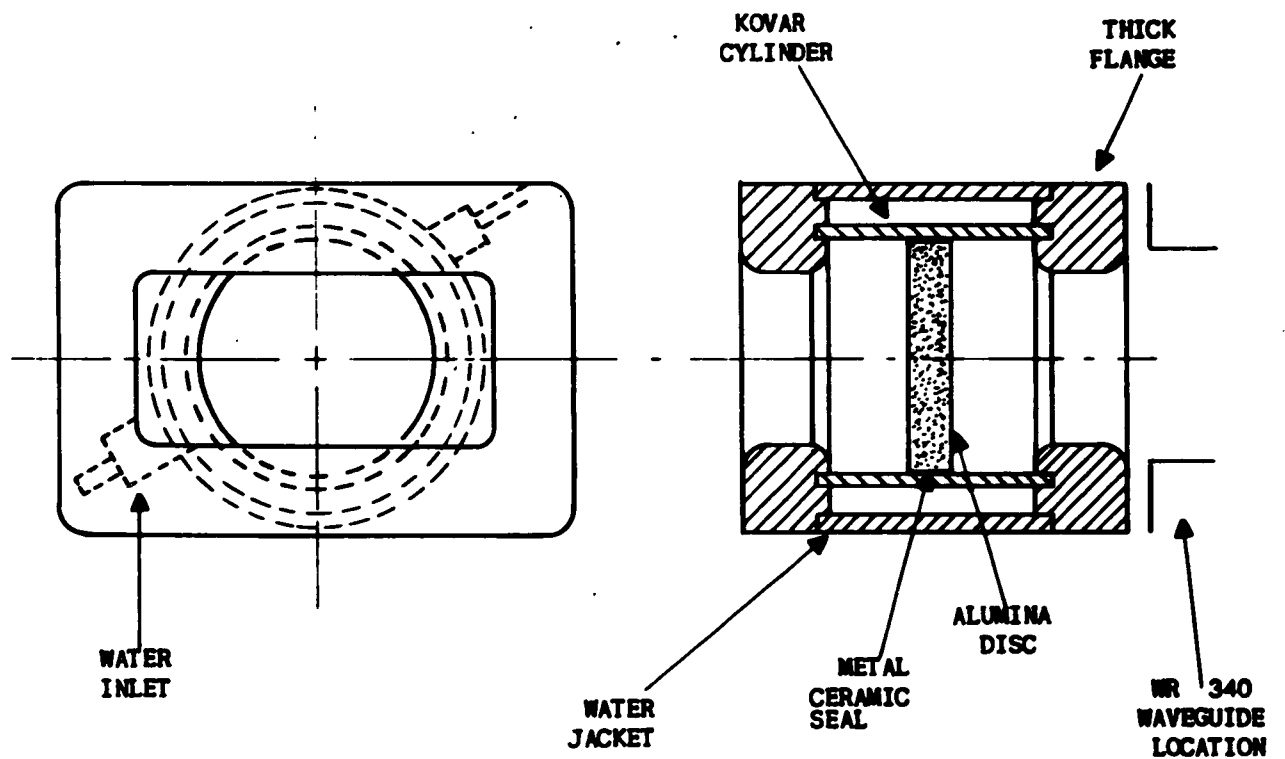


FIGURE 7 MICROWAVE WINDOW

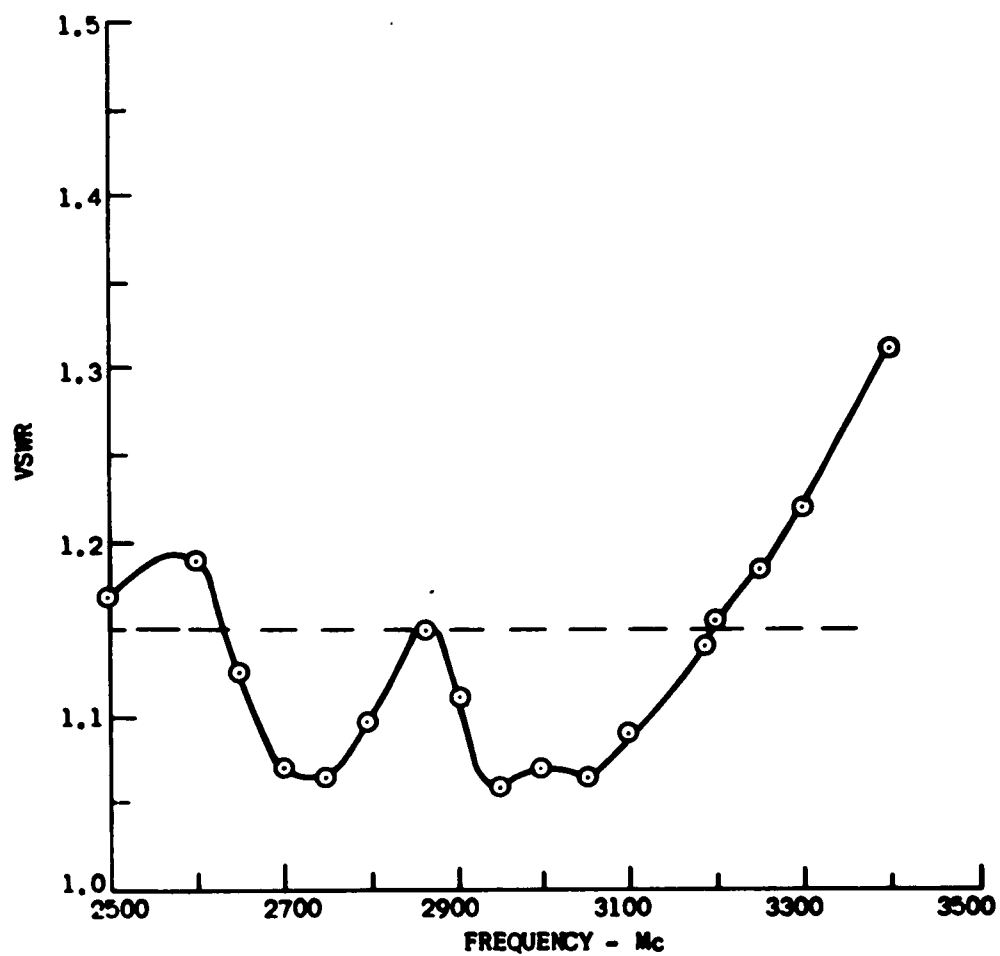


FIGURE 8 MICROWAVE WINDOW CHARACTERISTICS

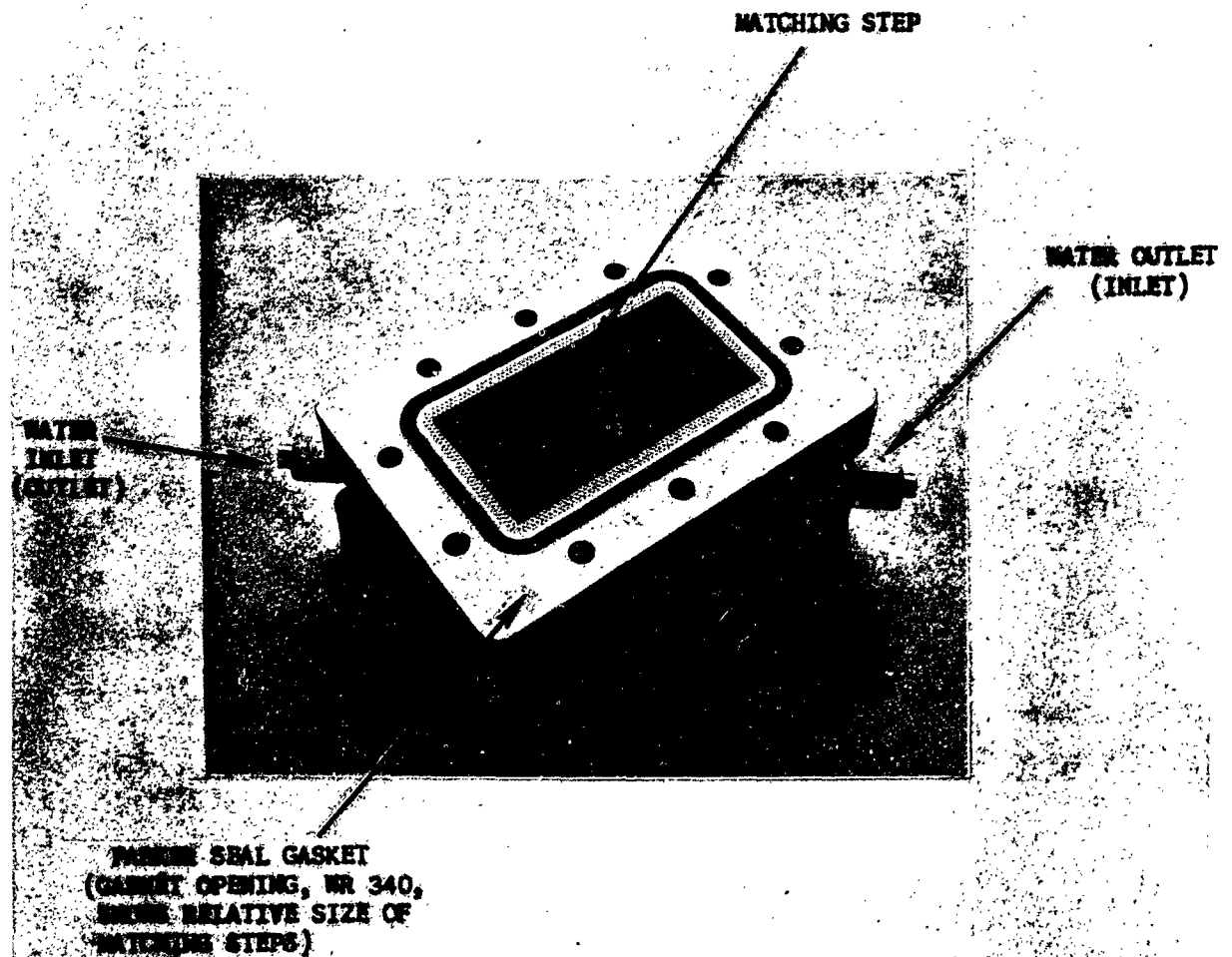


FIGURE 9
HIGH POWER WINDOW

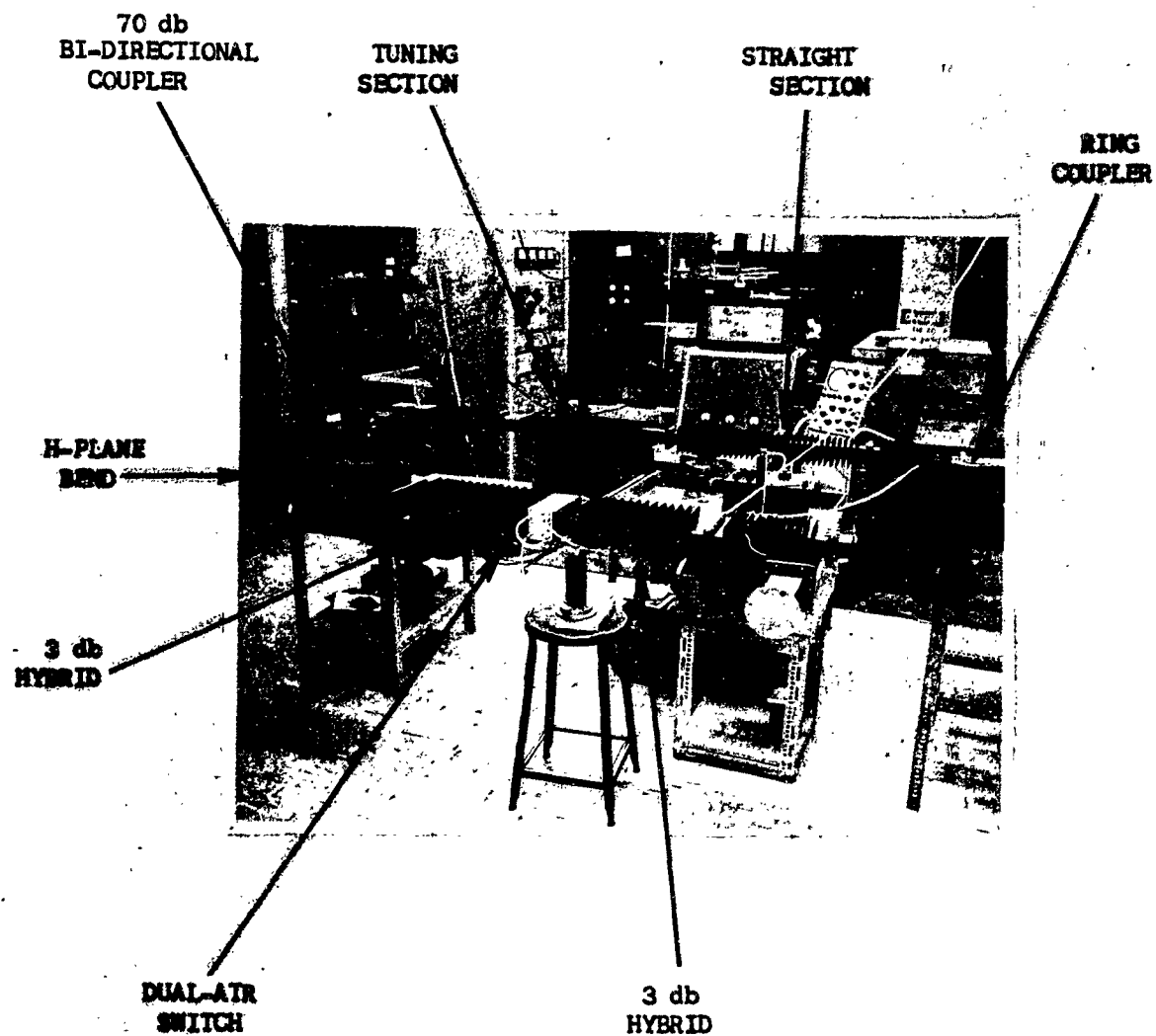


FIGURE 10

PHOTOGRAPH OF TRAVELING WAVE RESONATOR

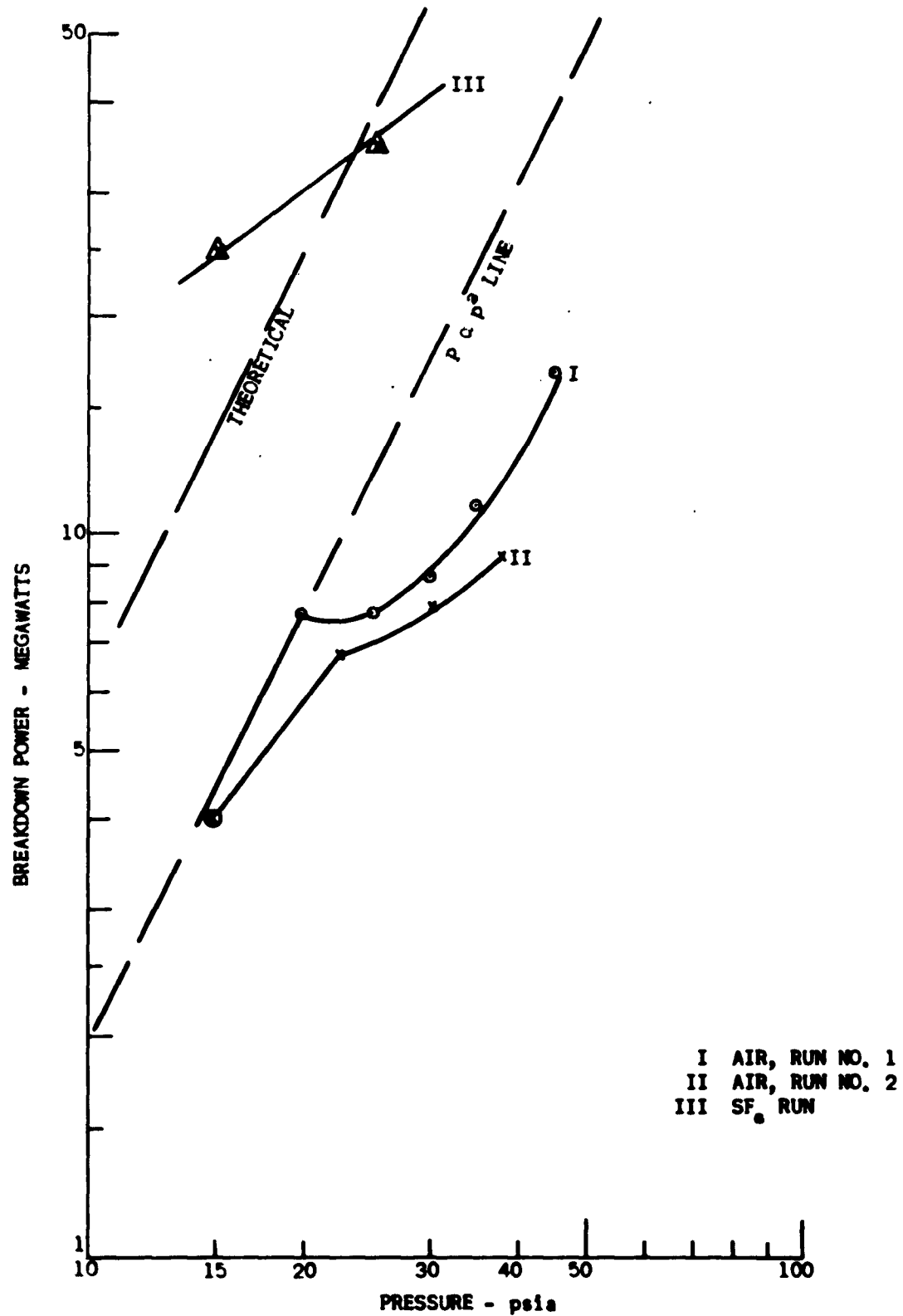


FIGURE 11 BREAKDOWN POWER OF TRANSMISSION LINE

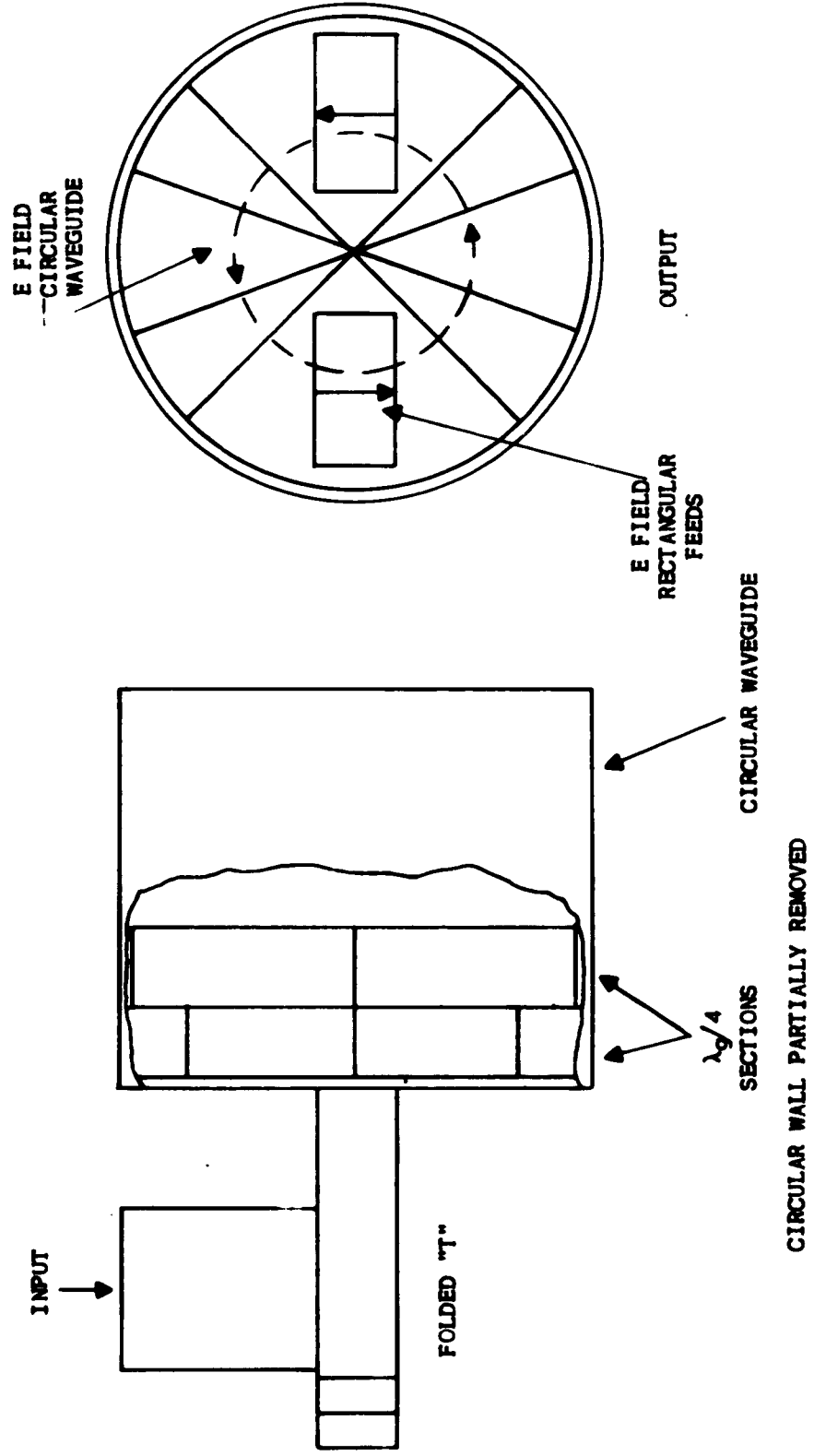
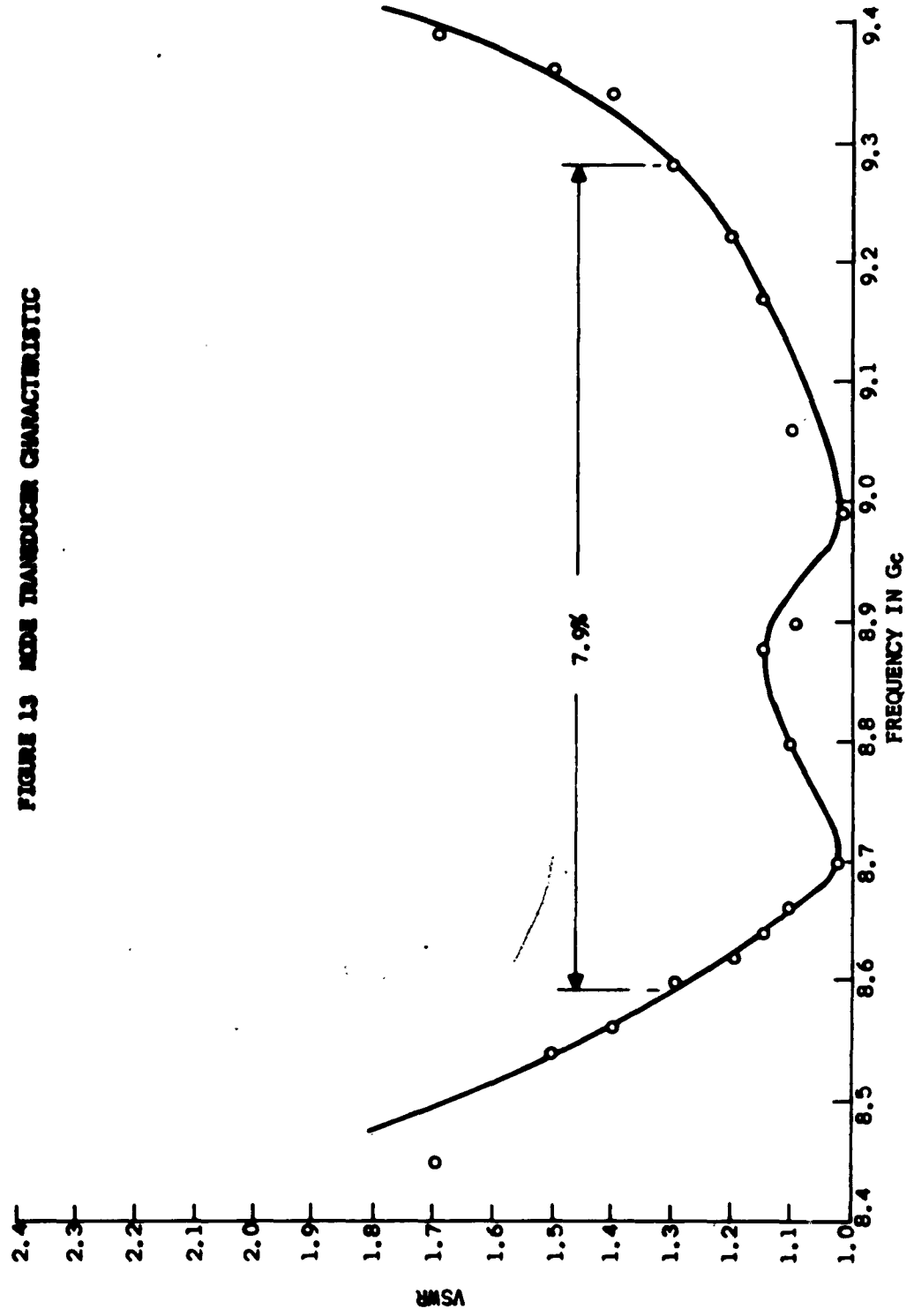


FIGURE 12 INITIAL TE_{10}^D - TE_{01}^D MODE TRANSDUCER



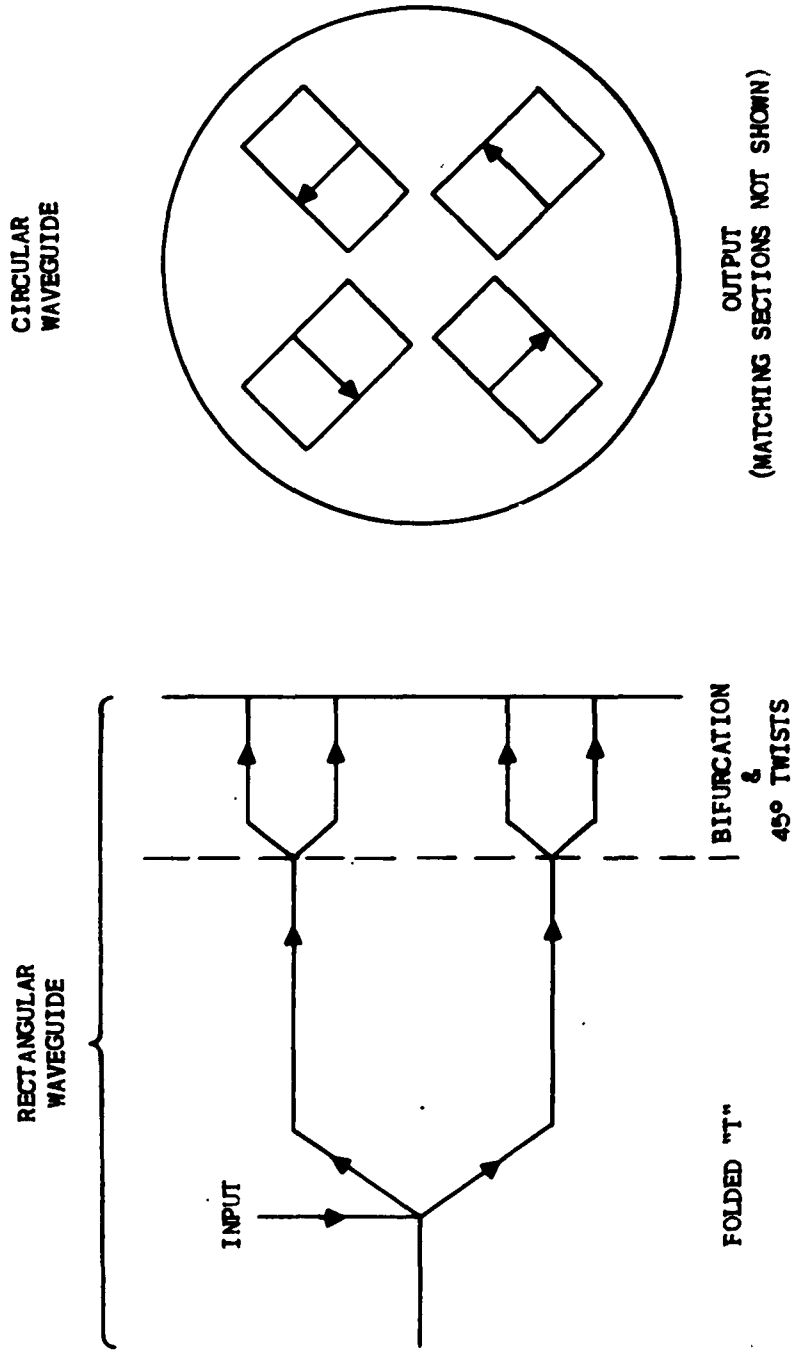


FIGURE 14 $TE_{10}^o - TE_{01}^o$ MODE TRANSDUCER

TABLE I

HIGH POWER CAPABILITY OF SEVERAL WAVEGUIDE DESIGNS

<u>Construction</u>	<u>Waveguide Size</u>		<u>Material</u>
	<u>WR-284</u>	<u>WR-340</u>	<u>Tall*</u>
<u>Average Power</u>			
Natural Cooling - kilowatts			
$T_o = 125^{\circ}\text{F}$, $\Delta T = 50^{\circ}\text{F}$			
Standard	21 15 11	37 27 19	131 96 68
Finned†	56 40 29	100 74 52	354 259 183
Liquid Cooling for 45 kilowatts of Average Power			
Pressure/flow rate - pounds and and gallons/minute (60% ethylene glycol, 40% water)			
100 feet of line	9.2/2.4	1.6/1.6	.62/.75
four 100-foot pipes	33/4.2	17/2.9	2.1/1.4
1/4 x 1/4 inches I.D.	.01/.25	.01/.13	.01/.01
10 feet of line	.01/.48	.01/.32	.01/.25
four 10-foot pipes			
1 x 1 inches I.D.			
<u>Breakdown Power - megawatts</u>			
One Atmosphere, 175°F	7.3	11.5	38

*3.40" x 5.75"

†Total surface area 4.37 greater than
that for plain waveguide.

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