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FR-3223

# MILLIMETER WAVE RESEARCH

## COMPONENTS FOR MILLIMETER WAVELENGTH RANGE

Harold Herman and Robert J. Coates

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Mr. J. P. Hagen, Head, R. F. Research Section  
Dr. John M. Miller, Superintendent, Radio Division I

Problem No. 34R28-06

January 20, 1948



**NAVAL RESEARCH LABORATORY**

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## ABSTRACT

This report describes work conducted to date at the Naval Research Laboratory on the development of components for use in the wavelength range from 3 to 11.5 mm. Wave guide devices such as standing-wave indicators, attenuators, wavemeters, etc., are described.

## PROBLEM STATUS

This is an interim report; work on this problem is continuing.

# MILLIMETER WAVE RESEARCH

## COMPONENTS FOR MILLIMETER WAVELENGTH RANGE

### INTRODUCTION

The program for the measurement of propagation characteristics and properties of materials in the millimeter-wavelength range, looking toward the eventual service use of these frequencies at the Naval Research Laboratory, requires numerous r-f components similar to those in use in the longer wavelength ranges. Since these components are not available, a program has been initiated and many of the necessary components have been developed. It should be emphasized that those described in this report are not necessarily the final models, since some design modifications may be necessary as it becomes possible to test these components over the entire operating range. To date this has not been possible, since power sources giving complete coverage are not as yet available.

### WAVE GUIDES

On 11 June 1946, a conference for the choice of wave guide sizes was held at the Naval Research Laboratory with representatives of the interested laboratories. At this time four sizes of guides were chosen with the following criteria being considered:

- (1) Since it was felt that the greatest interest in this range would lie at or near the maxima and the minima of normal atmospheric absorption, the sizes were tailored to fit experimental data taken at Columbia Radiation Laboratory and theoretical work by Van Vleck of the Radiation Laboratory of the Massachusetts Institute of Technology.
- (2) Further, the sizes were chosen such that at the longest wavelength the ratio  $\lambda_g/\lambda_a$  would not exceed 1.7/1. This establishes the maximum useable wavelength, and an effort was made to keep this ratio as small as possible. The minimum useable wavelength was taken as 92 percent of the cut-off wavelength of the  $TE_{20}$  mode.
- (3) Since breakdown is a major consideration, the height of the guide was chosen as one-half of the wide dimension.
- (4) The indicated dimensional tolerances will restrict the variations in guide wavelength to 1 percent.
- (5) In addition to high power-handling capabilities, the choice of a 2 to 1 height-width ratio allows easy scaling from one guide size to another.

Since this first meeting, considerable interest has been shown by numerous laboratories and by the military services. Hence, on 8 October 1947, the Army-Navy R-F Cable

Coordinating Committee held a meeting to consider standardization of guide sizes. Three sizes were adopted to cover the wavelength range of 4.1 to 11.5 mm, and a fourth size was recommended for the range from 3.3 to 4.5 mm. These sizes are given in Table 1. The

TABLE I  
WAVE GUIDE SIZES

	1	2	3	4
Inside Height (in.)	0.140 (±0.0015)	0.112 (±0.001)	0.074 (±0.001)	0.061 (±0.0005)
Inside Width (in.)	0.280 (±0.0015)	0.224 (±0.001)	0.148 (±0.001)	0.122 (±0.0005)
Frequency Range (KMc)	26-39	39-52	52-74	74-91
Wavelength Range (mm)	11.5-7.7	7.7-5.75	5.75-4.05	4.05-3.3
Mid-Band Guide Wavelength (mm)	13.03	8.36	6.48	4.47
Mid-Band Air Wavelength (mm)	9.60	6.73	4.91	3.62
Theoretical Power Capacity (kw)	110	76	36	23

Wave Guide Wall Thickness——0.040 In.

first and third sizes are those originally chosen; while the second and fourth sizes are slightly different from the original ones. Numerous samples of electroformed wave guides have been made at this Laboratory, and drawn coin silver and silver-lined guides have also been purchased from an outside manufacturer.

#### CONNECTORS

Consideration has been given to the design of choke-flange-type connectors, but the difficulties involved in machining the narrow choke section and the inherent narrow-bandwidth of this type of connector has led to the adoption of a butt-type connector which is shown in Figure 1. The NRL drawing number is RA 49F 253. The blank flange (1-d) is soldered on the end of the wave guide and a few thousandths of an inch machined off the boss to insure a perfectly flat surface to butt against the other connector (1-c). The holes for the aligning pins and screw holes are located and drilled with the help of a drilling jig (1-b). This insures good alignment, since the holes are located relative to the inside of the wave guide. Pins are pressed in diagonally opposite holes and the other two holes reamed slightly with a taper reamer to receive the pins of the opposite connector. The screw holes are tapped and counterbored. The finished connectors (1-a) are normally held together by Allenhead screws, but a cover-type screw coupling (Figure 2) has been designed to slip over the universal connector. The NRL drawing number for this coupling is RA 10F 657.

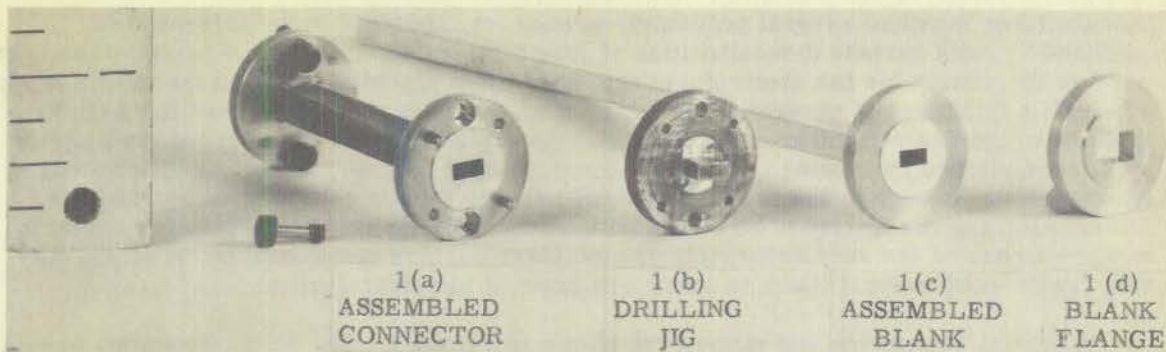


Fig. 1 - Couplings for Millimeter Wave Guide

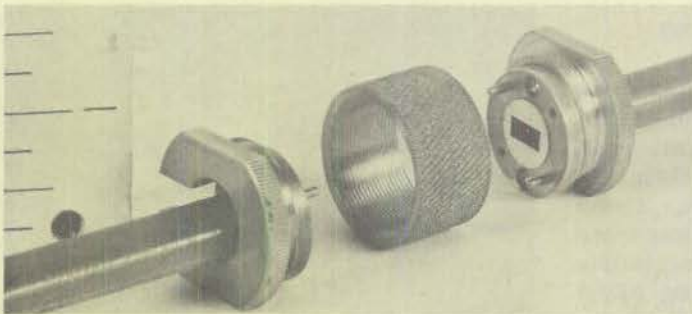


Fig. 2 - Screw Coupling

At the 11 December 1947 meeting of the Army-Navy R-F Cable Coordinating Committee, the subject of connectors was discussed, and it was felt that better pressurization could be obtained by the use of an "O" ring of rubber rather than by the flat washer used with the connector previously described. Further, it was proposed to use four screws instead of two as in the present NRL connector. The method of locating the pin holes relative to the inside of the

guide will be retained. The connector adopted by the Committee is shown in U. S. Army Air Forces Material Command drawing 47D 56922.

#### STANDING-WAVE INDICATORS

Standing wave indicators using micrometer drive of the traveling probe have been developed for each of the first three wave guide sizes. These devices have a wave guide output from the probe, and either crystal- or bolometer-type detectors may be used. The probe penetration into the wave guide can be set very accurately with a calibrated micrometer adjustment. The Naval Research Laboratory drawing numbers for these SWR indicators are: RA 74F 368 (0.140" x 0.280" guide), RA 74F 374 (0.112" x 0.224"), and RA 74F 375 (0.074" x 0.148"). A typical unit for the 0.140" x 0.280" wave guide is shown in Figure 3.

#### WAVEMETERS

The search-type wavemeters for covering the range of each of the wave guide sizes are circular resonant-cavity types employing the  $TE_{11}$  mode. To date, all of these have been of the transmission type with small coupling holes on opposite sides of the cavity for coupling the input and output wave guides to the cavity. Preliminary machined models had a loaded Q of approximately 1000 and an insertion loss of about 20 db. Precision cavities for these wavemeters have been made successfully by electroforming. An outside

manufacturer supplied several accurately ground molybdenum rods (tolerance of  $\pm 0.000025$ " with surface discontinuities of less than  $10^{-6}$  inches) in the cavity sizes to be used as the matrix for the electroforming. Silver was plated directly on the molybdenum rod until a thickness of several thousandths of an inch was obtained. Then the wall was built up to the desired thickness in an acid copper plating bath. Removal of the matrix was accomplished by heating to a temperature of about  $260^{\circ}$  F., where the differential expansion was enough to break the poor bond between the molybdenum matrix and the silver, allowing the matrix to be easily withdrawn. The inside of the resulting cavity is a reproduction of the very accurately ground outer surface of the matrix. A single matrix can be used several times to make a number of identical cavities.

A typical wavemeter and matrix are shown in Figure 4. The Naval Research Laboratory drawing numbers for the units in the first three wave guide sizes are: (1) RA 74F 385, (2) RA 74F 377, and (3) RA 74F 378.

#### GRATINGS AND INTERFEROMETERS

A reflecting echelette grating has been designed and built, incorporating the principle of a changing groove form.\* This grating is composed of 75 reflecting "lines" or elements mounted in a rigid rectangular frame. These elements, semicircular in cross section, were made by grinding away half of a stainless steel rod. This gave a flat reflecting plane having a width of the rod diameter (1 centimeter) and which passes through the axis of the rod. The rods are held at each end by small, precision ballbearing races, the centers of which lie at intervals of one centimeter along a straight line on the top and bottom of the grating frame. The elements

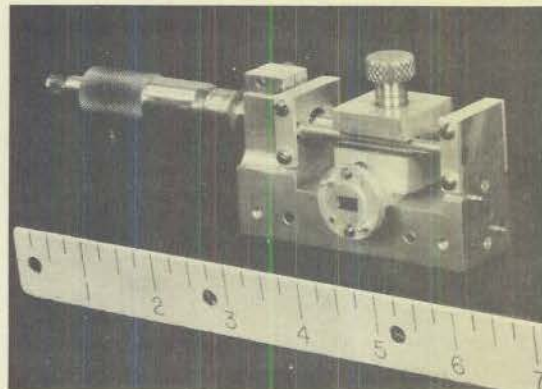


Fig. 3 - Travelling-Probe Standing-Wave Machine  
0.140" x 0.280" Guide

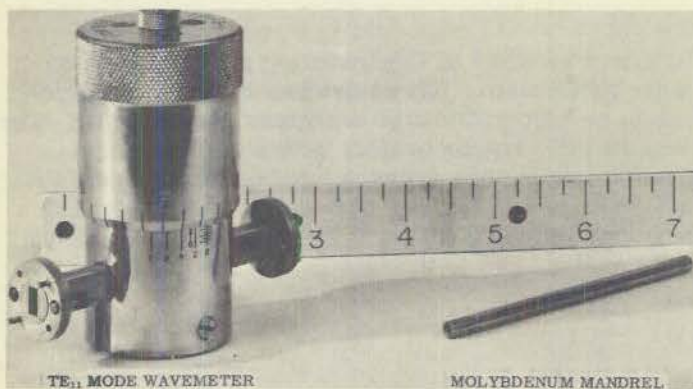


Fig. 4 - Cavity Wavemeter

are interconnected with a parallelogram linkage system which makes the groove form change as the grating is rotated. Because of this linkage method the normal distance between adjacent elements can be set at any value from zero to one centimeter, and any backlash error is reduced by a factor of 25. This grating is shown in Figure 5. The NRL number for its drawing is RA 10F 538B. The measured intensity curves for the different orders agree very well with theory, as shown in Figure 6.

\* Cleeton, C. E., "Grating Theory and Study of the Magnetostatic Oscillator Frequency," *Physics*, 6; 207-9, June 1935

The relation between wavelength and the grating angle of an intensity peak is  $\lambda = \frac{2}{n} \cos \psi$  where  $n$  is the order of the spectrum and  $\psi$  is the grating angle. The grating angles can be measured within  $\pm 0.4$  percent in measurements of wavelengths of about 6 mm.

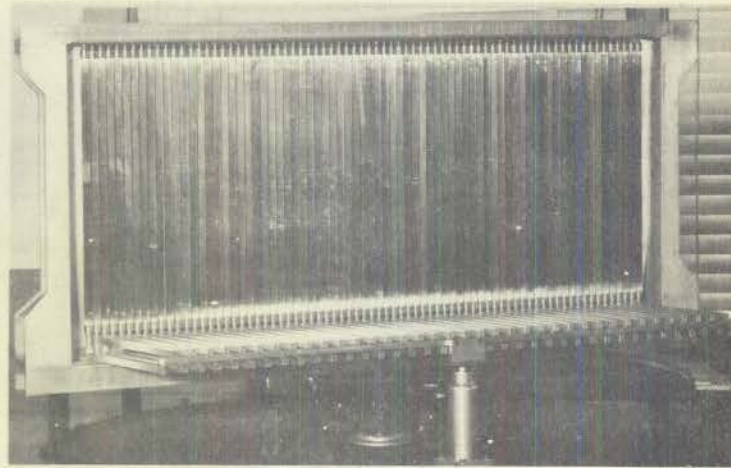


Fig. 5 - 75-Element Echelon Reflecting Grating

A breadboard model of a Michelson interferometer has been tested, and the results indicate that accurate measurements of wavelength are possible with such an instrument. The 50 percent reflecting mirror was made of several long metallic strips, and the other two mirrors were flat aluminum sheets. With a more precise model, which is now being designed, it is expected that wavelength measurements will be accurate within  $\pm 0.001$  percent.

ATTENUATORS

The mechanical design for both variable and fixed attenuators for the first three sizes of wave guide is fairly complete. The variable attenuator employs a cam-controlled, spring-loaded lever-arm system to move a metallized (glass or mica) sheet into or out of the wave guide. This is shown in Figure 7. These units are capable of accurate resetting and direct calibration. The Naval Research Laboratory drawing numbers of the attenuators are (1) RA 63 F 226, (2) RA 63F 228, and (3) RA 63F 229.

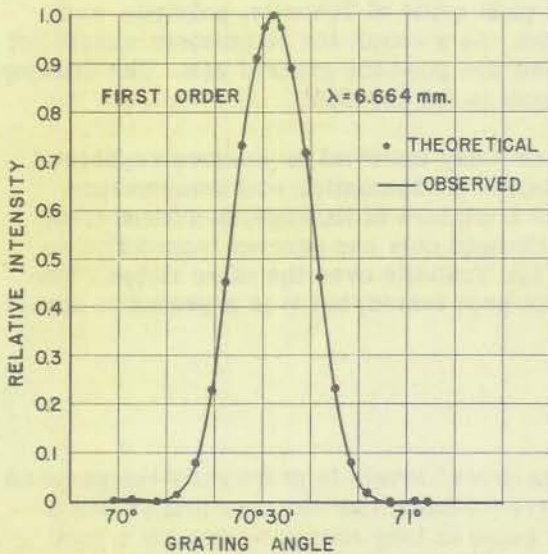


Fig. 6 - Grating Intensity Curve

The fixed attenuator pads that have been developed are of the lossy wave guide type. The first models were made by machining a slot the same size as the inside of ordinary wave guide in a block of Transite. Another piece of Transite was fastened on top of the slot to form the fourth wall of the Transite wave guide. This piece was then pressed into a piece of brass tubing, and the ends were machined until the end of the brass tubing was flush with the end of the Transite wave guide. (See Figure 8.) Connector flanges were soldered on the ends with their rectangular hole lined up with the hole in the Transite. The finished pad is shown in Figure 8. These pads can be used for either high power or low power and introduce negligible mismatch (VSWR less than 1.05). They have an attenuation of about 17 db per inch at a wavelength of 9 mm, but this has been found to vary with the temperature. This variation with

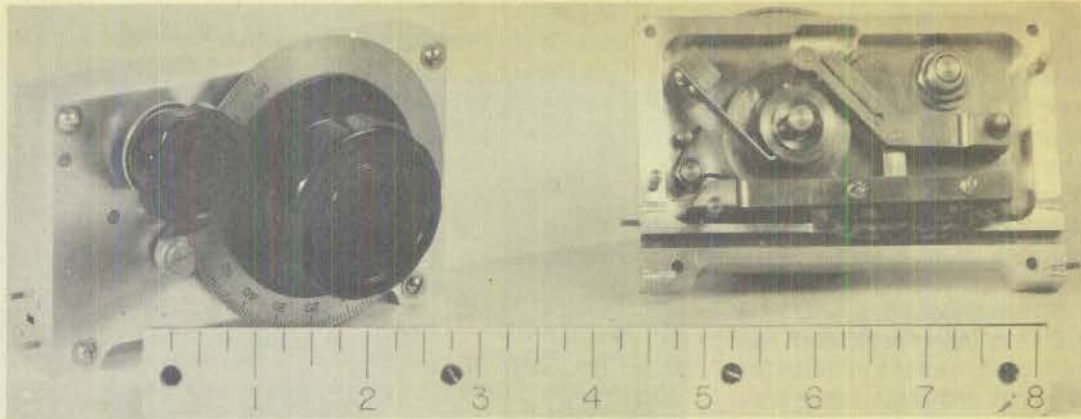


Fig. 7 - Cam-Operated Vane-Type Attenuators  
0.140" x 0.280" Guide - Right; 0.112" x 0.224" Guide - Left

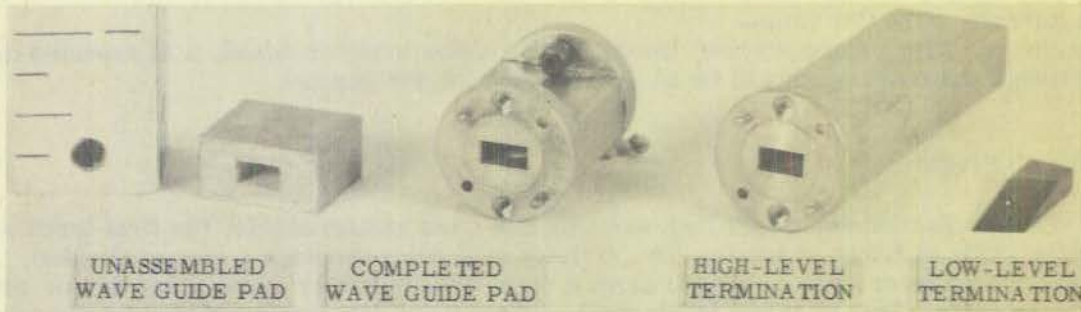


Fig. 8 - Matched Terminations and Attenuating Pads

temperature is an unfortunate characteristic of pads made of Transite, polyiron, and many other lossy materials that have been tested. As a result the attenuators should not be used in applications that require precision, but are good for general use. The drawing number for these pads in all four wave guide sizes is RA 10F 660.

Experiments are now under way to find some lossy material or mixture capable of absorbing high power and having negligible variation of attenuation with temperature change. The most promising material to date is a mixture of litharge, powdered iron, and Transite. The attenuation of this mixture changed only one percent from 25° C to 60° C as compared with a change of 25 percent for Transite over the same range. The power-handling capability of this mixture has not been tested, but it is expected to compare favorably with that of Transite.

#### MATCHED TERMINATIONS

The design of matched terminations for high-power levels is practically the same as for the high-level attenuator pads, the only difference being that the termination has a short instead of a flange on one end. The lossy guide is long enough to present a good match to the wave guide. The Naval Research Laboratory drawing number of these loads for all four wave guide sizes is RA 10F 659.

For low-level use, satisfactory terminations were made with a bakelite molding powder containing graphite (BM-14715, black, Bakelite Corporation). This was molded into the shape of a tapered plug which fits inside the wave guide. These units are about 3/4 inch long, and they have a voltage standing-wave ratio of less than 1.05. The drawing number for the low-level loads is RA 10F 656. Figure 8 shows both the high-level and low-level matched terminations.

## BENDS

E and H plane bends for the first three sizes of wave guide have been made by electroforming copper on a silvered polystyrene mandrel. These bends are the sweeping type, having an approximate radius of 0.75 inches. The polystyrene mandrels were molded under pressure, and dimensions were easily maintained within  $\pm 0.0005$  inches. The cross-sectional dimensions were exactly the inside wave-guide dimensions, the surfaces were free from any scratch marks, and the corners were square. These mandrels were metallized by vacuum-evaporating a thick film of silver on all the surfaces. The silver was then built up to a thickness of 0.002" by plating in a neutral silver-plating bath.

After the desired amount of silver was put on, the piece was put in an acid copper bath, (see Appendix for the composition of this and of the bath previously mentioned) and built up to the desired wall thickness. The mandrel was dissolved out with a solvent such as benzene, leaving the finished bends. The inside surfaces of bends made in this manner are much better than can be obtained by bending a piece of straight wave guide or from fabrication from sheet stock. Measurements on the electroformed bends indicate that they introduce no mismatch. Several typical bends along with the polystyrene mandrels are shown in Figure 9, and the plastic mandrels are shown in the Naval Research Laboratory drawing RA 10F 662.



Fig. 9 - Millimeter-Wave Electroformed Bends and Plastic Mandrels

## TEES

E and H plane tees and hybrid tees have been made by the same electroforming process used for making the bends. Some of these are shown in Figure 10. To date, no measurements have been made on these items, nor has any attempt been made to match them. When these measurements have been done, however, the matching devices will be inserted in the plastic mandrels in the proper place. This method will accurately locate the matching device and eliminate the necessity of any soldering. The Naval Research Laboratory drawing number for the plastic mandrels for tees is RA 10F 662.

## DIRECTIONAL COUPLERS

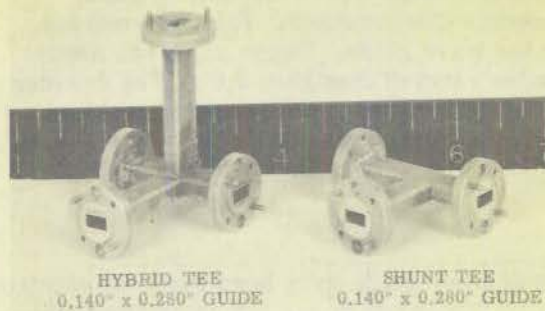


Fig. 10 - Electroformed Tee Sections

given in Figure 11 for a 1.4 to 1 ratio of guide wavelength to air wavelength, which corresponds approximately to the design center wavelength of the guides chosen for millimeter wave use. For other ratios of guide wavelength to air wavelength, this degree of coupling has been found to increase slightly with decreasing wavelength. This condition could be avoided by the use of other types of couplers which are more difficult to fabricate and have a lower directivity. The directivity of the slot-type coupler described here is given by the expression:

$$D_{db} = 20 \log \frac{2\pi l}{\lambda \sin \frac{2\pi l}{\lambda}}$$

where  $l$  is the slot length. This expression holds only in the case where the coupling slot is well centered. The measured directivity of couplers of this type has been found to agree substantially with the calculated values and will be no worse than 30 db.

The method of fabrication of these couplers is as follows: the slot is either punched or engraved in a sheet of silver plated copper of proper thickness. The straight and curved sections are molded of polystyrene, as in the case of the bends and tees. Steel pins are molded in the plastic mandrels to facilitate centering of the copper sheet, which is placed between the two mandrels. The unit is silvered and then plated to the proper wall thickness. Dissolving the mandrels and removing the pins results in a completed unit. A unit of this type is illustrated in Figure 12, and dimensions may be found in NRL drawing RA 50F 352. A coupler made by this method has uniform characteristics and can be readily reproduced. Couplers of other types requiring a thin coupling septum may be similarly made.

An extensive study of long-slot directional couplers at 3 cm has just been completed. Experiments were conducted in 0.45" x 0.90" wave guide so that the results could be scaled to millimeter wavelengths where the guide dimensions have a 2 to 1 ratio. The slot length used was 16 inches — the equivalent of 4.96 inches in the 0.140" x 0.280" guide, and 2.63 inches for the 0.074" x 0.148" guide.

An experimental plot of coupling versus the ratio-of-slot-width-to-guide-width is

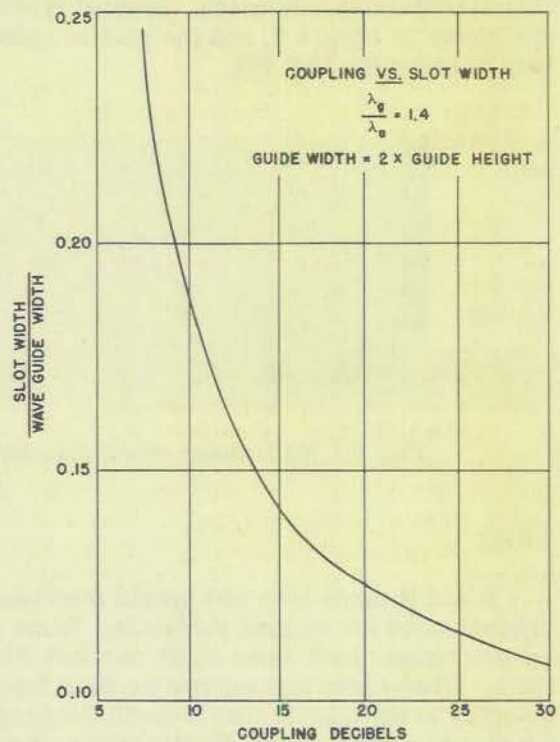


Fig. 11 - Design Curves for Long-Slot Directional Couplers

## HORNS

A series of horns having a theoretical gain of 20 db for the center of each of the wave guide ranges has also been electroformed. In this case, however, a cold-rolled-steel mandrel was employed. This mandrel was ground 0.001" smaller than the desired inside dimensions of the horn and cadmium-plated up to the proper dimensions. The mandrel was then given a flash of copper in a cyanide bath, and the ends were painted with masking lacquer. The copper walls were built up on the mandrel in an acid bath. The mandrel was flashed in a cyanide copper bath to give a protective coating so that the acid copper bath would not attack the steel mandrel. To remove the mandrel, the piece was heated to the melting point of cadmium and the mandrel pulled out. The small amount of cadmium that was left on the inside of the horn was dissolved in cold hydrochloric acid.

It is possible to make horns much more accurately by electroforming than by fabricating them from sheet metal. All horns made to date have proved satisfactory.

A typical horn and its steel mandrel are shown in Figure 13. The Naval Research Laboratory drawing number for the steel mandrels in the four wave guide sizes is RA 10F 658.

## SHORTING PLUNGERS

Choke plungers for each of the wave guide sizes have been developed along with a spring-loaded driving mechanism, free from backlash, which is attached to the wave guide section by means of the regular connector flange. The reason for this is that the millimeter wave guides are so small that it is extremely difficult to hold a driving unit by screws as was done in K- and X-band units. The short introduced by one of these plungers is better than 35 db over the wavelengths of 7.6 to 9.1 millimeters. One of these choke plungers and driving units is shown in Figure 14. The Naval Research Laboratory drawing number for both the drivers and plungers is RA 10F 661.

## GENERATORS

Reflex klystrons of a type similar to the 2K33 tube used at K-band are in the developmental stage at Raytheon under Navy auspices. To date, reasonably satisfactory tubes

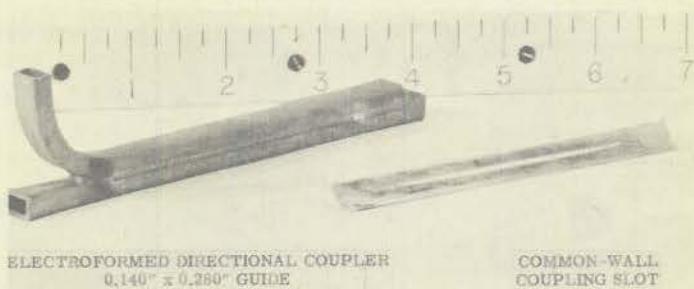


Fig. 12 - Long-Slot Directional Coupler

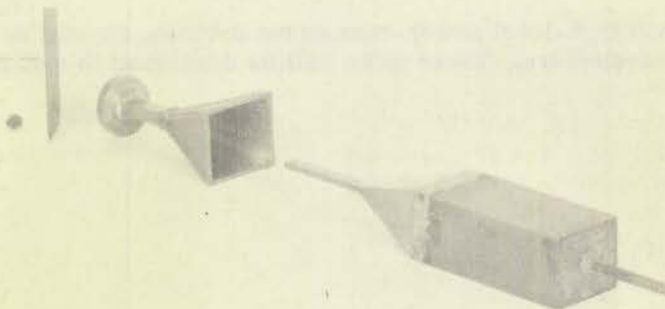


Fig. 13 - 20-db Horn and Mandrel  
0.074" x 0.148" Guide

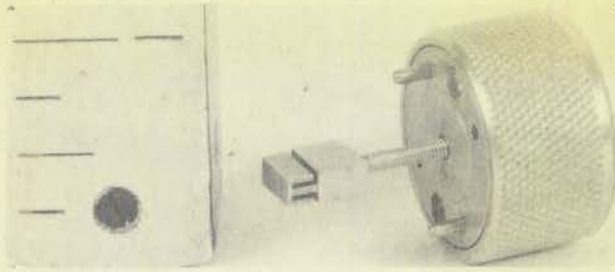


Fig. 14 - Choke Plunger  
0.140" x 0.280" Guide

covering the ranges of 5.75 - 7.5 millimeters and 8.0 - 9.6 millimeters have been received and are in use for the testing of these components.

#### FUTURE DEVELOPMENTS

It is anticipated that, in the future, work will be carried out to evaluate and improve the described components over as wide a wavelength range as possible. Work is now in progress and will continue on the development of low-level

and high-level power-measuring devices, crystal devices, crystal detectors, and high-Q wavemeters. These units will be described in a future report.

\* \* \*

## APPENDIX I - PLATING BATHS

### Neutral Silver Plating Bath

Silver nitrate (tech.)	4 oz/gal
Sodium cyanide (tech.)	4.5 oz/gal
Potassium nitrate (tech.)	16 oz/gal
Current density	3-6 amps/ft <sup>2</sup>
Anodes	Anode-grade silver

It is necessary to use a bath of this composition if silver is to be plated on the evaporated silver mandrel, since the usual cyanide silver bath will strip the silver from the mandrel.

### Silver Cyanide Plating Bath

Silver cyanide	4 oz/gal
Potassium cyanide (free)	5.5 oz/gal
Potassium carbonate	6 oz/gal
Brightener (in a new solution)	1/8 fluid oz/gal
Current density	5-15 amps/ft <sup>2</sup>
Anodes	Pure silver (over 999.5 fine)

### Cadmium Plating Bath

Cadmium oxide	3.5 oz/gal
Sodium cyanide	14.5 oz/gal
Brightener	as required
Current density	5-25 amps/ft <sup>2</sup>
Anodes	cadmium bars

### Cyanide Copper Plating Bath

Copper cyanide	3.0 oz/gal
Sodium cyanide	4.5 oz/gal
Sodium carbonate	2 oz/gal
Current density	2.5-15 amps/ft <sup>2</sup>
Anodes	Rolled annealed copper

### Acid Copper Plating Bath

Copper sulfate (crystals)	27 oz/gal
Sulphuric Acid	6.5 oz/gal
Current density	15-40 amps/ft <sup>2</sup>
Anodes	Rolled annealed copper

For further information on these plating baths, consult some good plating handbook.



## APPENDIX II - DRAWING NUMBERS FOR MILLIMETER COMPONENTS

Wavelength (Millimeters)	11.5 - 7.7	7.7 - 5.75	5.75 - 4.05	4.05 - 3.0
Wave Guide Size (Inches)	0.140 x 0.280 (±.002)	0.112 x 0.224 (±.001)	0.074 x 0.148 (±.001)	0.056 x 0.112 (±.0005)
Standing Wave Indicator	RA 74F 368	RA 74F 374	RA 74F 375	
Wavemeter	RA 74F 385	RA 74F 377	RA 74F 378	
Precision Attenuator	RA 63F 226	RA 63F 228	RA 63F 229	
Low-Level Matched Loads	RA 10F 656	RA 10F 656	RA 10F 656	
High-Level Matched Loads	RA 10F 659	RA 10F 659	RA 10F 659	RA 10F 659
Attenuating Pads	RA 10F 660	RA 10F 660	RA 10F 660	
Water Loads	RA 10F 669			
E & H Plane Bends	RA 10F 662	RA 10F 662	RA 10F 662	
E & H Plane & Hybrid Tees	RA 10F 662	RA 10F 662	RA 10F 662	
Tuning Plungers & Plunger Drivers	RA 10F 661	RA 10F 661	RA 10F 661	
Butt Connectors & Drilling Jigs	RA 49F 253	RA 49F 253 (0.103 by 0.206 Wave Guides)	RA 49F 253	RA 49F 253
Laboratory Couplings	RA 10F 657	RA 10F 657	RA 10F 657	RA 10F 657
Horns (20 db Gain)	RA 10F 658	RA 10F 658	RA 10F 658	
Directional Couplers	RA 50F 352	RA 50F 352	RA 50F 352	

