# AD NUMBER

**AD911339**

## NEW LIMITATION CHANGE

TO

**Approved for public release, distribution unlimited**

FROM

**Distribution authorized to U.S. Gov't. agencies only; Test and Evaluation; JUN 1973. Other requests shall be referred to Air Force Avionics Laboratory, Attn: TEM, Wright-Patterson AFB, OH 45433.**

## AUTHORITY

**AFWAL ltr, 29 Oct 1975**

AFAL-TR-73-204



# MIC TRANSMISSION LINEAR TECHNIQUES

William H. From
RAYTHEON COMPANY

TECHNICAL REPORT AFAL-TR-73-204
JUNE 1973



Distribution limited to U.S. Government agencies only; test and evaluation results reported; (June 1973). Other requests for this document must be referred to AFAL/TEM, Wright-Patterson AFB, OH 45433.

AIR FORCE AVIONICS LABORATORY
AIR FORCE SYSTEMS COMMAND
Wright-Patterson Air Force Base, Ohio

## NOTICE

When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Copies of this report should not be returned unless return is required by security considerations, contractual obligations, or notice on a specific document.

# MIC TRANSMISSION LINEAR TECHNIQUES

**William H. From**
**RAYTHEON COMPANY**



Distribution limited to U.S. Government agencies only; test and evaluation results reported; (June 1973). Other requests for this document must be referred to AFAL TEM, Wright-Patterson AFB, OH 45433.

# FOREWORD

This report was prepared by Raytheon Company, Missile Systems Division, Bedford Laboratories, Bedford Massachusetts under Contract F33615-72-C-1309 for the U.S. Air Force Systems Command, Hq 4950th Test Wing, Wright-Patterson AFB, Ohio. Robert T. Kemerley was the AFAL project engineer. This report describes a one-year program (April 20, 1972 through April 20, 1973).

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

WILLIAM J. EDWARDS
Chief, Radar & Microwave Technology Branch
Electronic Technology Division
Air Force Avionics Laboratory

# ABSTRACT

The significance of this research and development to the Air Force is the demonstration of a new low-cost transmission line technique having properties superior to microstrip; in particular, it provides higher power capability, lower loss and high altitude operation without requiring pressurization.

TABLE OF CONTENTS

## LIST OF ILLUSTRATIONS

# 1. Introduction

PRECEDING PAGE BLANK-NOT FILMED

## 1.1 Objective of Program

The objective of this program was to investigate new methods of microwave transmission that are compatible with or supplemental to microstrip transmission lines. Ease of fabrication and integration of microwave circuits for future military radar, communications & ECM systems was the theme of this effort. The transmission technique should provide significant improvement in performance over microstrip with respect to such parameters as loss, power handling and bandwidth and be a useful technique above 10GHz.

The Ceramic Waveguide technique which is described in this report meets all of the above cirteria. The Ceramic Waveguide technique basically consists of a waveguide transmission line which has the conventional air dielectric replaced by a low-cost "castable" ceramic and the transmission boundary is defined by plating the surfaces of the ceramic.

## 1.2 Scope of Program

This exploratory development program was divided into four technical tasks and a final report as the fifth task. The four technical tasks are:

- Task I — Study ceramic finish & metalization techniques for loss and environmental characteristics.
- Task II — Develop three individual circuits for circuit evaluation of the transmission technique -- included are a circulator, oscillator and a filter.
- Task III — The individual circuits developed in Task II are to be combined by flange techniques and evaluated. An integrated unit containing at least the three circuits of Task II is to be developed and tested using conventional grinding techniques.

Task IV A so-called "green-state" low-cost high production fabrication technique is to be used to produce several of the units defined in Task III. These units are to be processed - i.e. incorporate ferrites, loads, metalization, diodes, magnets, connectors and bias circuits - and be evaluated.

Each of these tasks represents a key advancement to prove the overall objectives of the program.

The metalization studies provide mechanical & electrical data not only for ceramic adhesion and loss, but also for the epoxies required in processing ferrites into the ceramics.

Five circuits were chosen and they represent a set which defines a complete active module. They include a Gunn oscillator, a control or isolation circuit, a filter, load and a waveguide-to-coaxial transition. This selection is a compromise to providing a complete set of circuits from which any integrated active module could be fabricated at X-band. Also, preliminary studies indicate that scaling to other frequencies, in particular, higher frequencies can be realized using lower dielectric constant materials than alumina.

The individual ceramic circuits are combined in Task II as is ordinarily done to complete a sub-system with air waveguide components. This is a critical developmental stage since its success means that individual circuits can be developed and evaluated in buiding block form; they , then, can be combined and tested as an integrated assembly providing a performance check-out prior to the "full-up" integration fabrication step. (The analogy to NASA space flight pre-check-out is a bit lofty, but presents the concept of pre-testing for high confidence of success prior to final launch.) The five circuits are integrated into final ceramic form eliminating all flanges using convenient laboratory grinding techniques.

This is evaluated for mechanical and electrical compatibility with the high production low-cost fabrication technique.

Task IV is the final step to proving the feasibility of this integration approach in terms of electrical, mechanical & cost criteria. As a result of this step in which a minimum number of the same module design are fabricated, in this case 10, the mechanical tolerances as well as electrical performance are compared to prove reproducibility for systems applications.

As a final, but important point, from each of these tasks new ideas, concepts, improvements, etc. will be generated to start a new generation of studies and advancements that will benefit the Air Force in their quest for cost-effective microwave sub-systems.

## 1.3 Program Summary

This USAF funded exploratory program has resulted in the successful demonstration of a microwave transmission line integration technique, referred to as Ceramic Waveguide, which provides significantly improved electrical & mechanical performance over microstrip at X-band. The technique can also be utilized at both higher and lower frequencies.

The ceramic, 99.5% alumina, was chosen for the study for three reasons: Firstly, it is the main medium for microstrip integrated circuits and thus provides direct comparison data, secondly, the sophistication in usage and fabrication techniques are reasonably well known, and thirdly, the size reduction, or scaling at X-band can be considered "optimum" in rectangular waveguide form.

An integrated circuit containing an active device, a circulator, a filter, a termination and a coax-to-waveguide transition has been constructed using the Ceramic Waveguide technique.

Its advantages over microstrip and other existing compact integration techniques are listed below:

1. Circuit performance is predictable.
2. Automatic hermetic seal.
3. Higher power performance - obviously at high altitudes.
4. Circuit isolation is maximized.
5. Higher Q's.

6. Smaller volume & lighter weight.
7. Production costs are significantly lower.
8. Mechanical scaling techniques are applicable.
9. Improved signal control.
10. More natural environment for active devices.
11. Higher reliability - all devices can be pre-tested before integration.

Since this technique utilizes a completely closed structure as with air rectangular, circular, ridge or coaxial lines there is little interference or degradation of circuit performance due to proximity of other circuits as with openline geometries. Temperature studies of filters have shown that the electronic characteristics vary in a predictable manner as a function of the linear and dielectric temperature coefficients. This integration technique offers greater compactness and lighter weight than microstrip techniques.

The advantages of life-cycle costs because of its very low cost in production, reproducibility as shown for 10 units, and its maintainability because of parts replaceability in the field appears clear.

The data contained in this report, therefore, demonstrate that this technique has the above advantages. It also is one of the most promising transmission techniques for the foreseeable future for applications wherein low-cost, small volume, low weight, high reproduceability, high reliability & field-maintainable microwave integrated circuits are required.

## 2.0 Program Results

The objective of this 12 month exploratory development program was to investgate new methods of microwave transmission that were superior, but compatible with microstrip. A clear superiority over microstrip in the categories of ease of integration, cost, performance, power, loss, bandwidth, high frequency applicability, reproducibility and others to be determined was desirable. Future military applications in Radar, Communications and ECM systems demand such an improved transmission technique.

To accomplish this, Raytheon proposed a set of tasks based on earlier research on ceramics which could demonstrate a transmission technique having the desired characteristics. The technique was called Ceramic Waveguide and the tasks were defined in terms of four technical phases representing basic fabrication and design proofs. These tasks are presented:

| | |
|---|---|
| Task I | Demonstrate ceramic and plating process feasibility and technique. |
| Task II | Design and evaluate three circuits using the new transmission medium. |
| Task III | Integrate the three circuits into a module and evaluate performance. |
| Task IV | Demonstrate a low-cost high production fabrication technique of this module and provide test data. |

This report provides the information on each of these tasks in the following sections. Also, the report presents future areas of efforts which should provide the warehouse of techniques and designs for all future microwave integrated modules for Air Force applications.

## 2.1 Ceramic & Metalization Studies

### 2.1.1 Ceramics

The ceramic chosen was 99.5% pure alumina and the frequency was slightly above 10 GHz (X-band). In the course of the program preliminary studies showed that scaling by dielectric constant to higher or lower frequencies was feasible. For example, a design of an oscillator or filter at 10 GHz in alumina could be scaled to circa 16 GHz (same size and dimensions) using quartz.

To achieve broadband circuits, say, octave or higher at X-band ridge guide, multiple-layered waveguide or coax can provide this capability. The preliminary X-band ridge guide designs did, in fact, provide greater than octave bandwidth capabilities, but better performance could be achieved using lower dielectric constant ceramics than alumina.

The ceramic finishes of circa 3 micro-inches and circa 20 micro-inches represented typical polished & un-polished surfaces available from ceramic houses. Studies of loss in scaled rectangular guide were made with alumina having these two approximate finishes.

### 2.1.2 Metalization Techniques

Several techniques for metalizing ceramic waveguide were investigated. Sputtered films of Cr-Cu or Cr-Au followed by plating to final thickness was the technique Raytheon had been using successfully on alumina microstrip substrates. The contention was that other techniques that had been tried earlier and had not proven successful should be reconsidered and any new techniques should be evaluated.

These other and new techniques included (1) sputtering directly with a final high conductive metal and thereby bypassing the step of activating the ceramic surface, usually with sputtered Cr, (2) spraying of copper, gold or aluminum directly on alumina using a flame-spray process, (3) plasma spraying of aluminum or silver on alumina in an ambient environment, & (4) copper electro-chemical and vapor deposition techniques.

Tests of conductive frit made several years ago indicated that requirements of lower purity alumina and relatively rough surface finish as required for this plating technique were not at all compatible with the purposes of this program and therefore was eliminated from the study. The reason for mentioning this is that it has come to our attention, too late for this program, that two companies, Dynasil and Owens-Illinois, have developed such a technique & that it appears worthy of reopening this issue since it should be a relatively low-cost metalization technique. However, it is known that high temperature curing is required which will limit its utility.

A number of companies contributed their talents by virtue of having the special apparatus & capability for various metalization techniques, and they are mentioned below.

| | |
|---|---|
| Sputtering | |
| Cr-Cu & Cr-Au | Raytheon |
| Cr-Au | Electro-Tek |
| Cu | Bendix |
| Vapor Deposition | Raytheon |
| Electrolytic | |
| Copper | Raytheon |
| Silver | American Electroplating |

Plasma Spray

| | |
|---|---|
| Aluminum | Monsanto |

Flame Spray

| | |
|---|---|
| Al & Ag. | Avco Bay State Abrasives |

The parameter of loss, adhesion, solderability and temperature were used to compare these metaization processes. The best all-around performance was achieved with sputtered films. Over 50 pieces of ceramic waveguide in forms as shown in Fig. 1 were used in this metalization study. The requirements for the metalization were the same, to wit: provide completely plated waveguides, including ends, to a minimum plating thickness of .0002". The sputtered and plasma spray processes were the only ones to survive the mechanical evaluations which included evaluations of adhesion, solderability, temperature, porosity & density. Of the two which survived the mechanical tests the sputtering technique provided the best electrical performance.

The flame spraying technique could readily be flaked off the ceramic by tapping with a screw-driver. Electrolytic techniques presented control problems as well as adhesion problems. An adhesion problem also existed for the vapor deposition technique, but this could have been due to poorly cleaned ceramics. A thorough investigation of the conditions for adhesion failure in the latter case was beyond the scope of this program, but this type of failure had been observed frequently on microstrip substrate vapor-deposition platings.

Where the platings appeared satisfactory, i.e. in the cases of sputtered and plasma sprayed platings, a pull test was performed. This test consisted of soldering (150°C indium solder) a thin copper sheet to the plated ceramic waveguide and pulling the sheet. These platings survived even when the copper sheet was pulled free of the guide - the parting took place at the solder joint.

## 2.1.3 Loss Data - Test Methods

The RF loss at 10 GHz was measured for the sputtered and plasma spray metalizations. These metalizations were satisfactory for loss measurements. Various lengths of guide were plated as represented in Figure 1. Two sputtering approaches were studied. In the first, Cr was sputtered to 100 A$^{o}$ thickness followed by Cu sputtered to .2 mil. In the second, Cu was sputtered directly on the ceramic to 1000 A$^{o}$ thickness and this was followed by Cu plating to .2 mil. Two different surface finishes were metalized in the first case - 1 to 2 micro-inches and 18 - 20 micro-inches (rms); and in the second only a 25 micro-inch finish was studied.

The ceramic surfaces which were plasma sprayed were typically smoothed to 1 - 2 micro-inches (rms). This metalization was done in a natural environment rather than a controlled oxygen-free atmosphere. An additional test was performed on one ceramic which was preheated prior to spraying - no loss difference was observed for the two methods.

The results of the loss measurements are presented in Table I.

TABLE I METALIZATION LOSS DATA

| Metalization Process | Surface Finish ( inches) | Loss (dB/inch) |
|---|---|---|
| Sputter: | | |
| (1) Cr 100A$^{o}$ - Cu .2 mil | 1-2 | .045 |
| (2) Cr 100A$^{o}$ - Cu .2 mil | 18-19 | .047 |
| (3) Cu 1000A$^{o}$- Cu .2 mil | 25 | .063 |
| Plasma Spray: | | |
| Al - 5.3 mils | 1-2 | .089 |

Sufficient testing of the sputtered techniques demonstrated that the Cr - Cu approach was as good if not better than the other techniques.

The loss measurements were based on the cavity resonance method[1] which is quite accurate for low loss measurements. The loaded Q for three different lengths of shorted transmission line are measured and a plot of $(Q_o)^{-1}$ vs $(\text{length})^{-1}$ is constructed. From the intercept value of the plot, the attenuation constant is calculated. A plot for one such sample is shown in Figure 2.

The results obtained by the resonancé technique were verified by insertion loss measurements. In this technique, the specimen is inserted between two 6 dB well-matched attenuators. The results of the two methods differed only in the third decimal place. Figure 3 illustrates the test components used for the insertion loss measurements. The attenuators were fabricated by grinding a slot into the broad surface of the ceramic guide and filling the slot with MF-114 (Emerson and Cuming) load material and metalizing the structure.

2.2 Module Components

The choice of components to be developed for the integration demonstration represents a compromise. It was decided to choose at least a number of circuits representative of those utilized in an active module. An oscillator or an amplifier, an isolation circuit, a filter, an attenuator or termination and an output connector are typical components contained in such modules.

(1) Ginzton, Microwave Measurements, McGraw Hill, pp. 469-471.

A Gunn oscillator, an H-plane circulator, a matched termination, a four pole filter and a coax-to-waveguide transition were selected. In the following paragraphs each of these circuits is described and the performance data tabulated. The order of presentation is (1) Filter (2) Circulator (3) Gunn Oscillator, (4) Termination and (5) Transition.

2.2.1 Filters

Filters are the backbone of all electronic circuits and systems. Microwave or distributed circuit filters often provide more interesting, but often not more desirable, characteristics than lumped circuit types on which nearly all filter theory is based. These filters have responses or passbands harmonically and/or otherwise related to the fundamental mode and frequency. Independent of dielectric medium, the actual performance characteristic of any microwave filter can only be confirmed after extensive adjustment and testing. And, the greater the loss of a filter and the greater the number of elements the greater the disparity between theory and design practice. Because of these facts, filters in ceramic waveguide required major program emphasis.

The main objectives of the filter studies were:

1. To determine the applicability of existing theories and approaches.
2. To determine the applicability of existing air waveguide susceptance charts to scaled ceramic waveguide.
3. To determine design procedures and fabrication techniques necessary for successful filter design.
4. To determine the effects of temperature.

Some clarifying comments are presented with regard to these studies. Detailed data follows these clarifications.

Since Ceramic Waveguide is a compact scaled version of its air counterpart (see Figure 4), the engineer's first consideration is to prove or disprove the scaling concept for filters. The designer is concerned with whether the microwave modes in this high dielectric medium can be reasonably pure TE or TM modes. If so, then most of the direct coupled, quarter wave coupled, Tschebychev, maximally flat, etc., concepts will apply almost as readily as for air guide.

Just as in air guide designs, the designer must have a "feeling" for the degree of departure from the theoretical and he should also be able to use any new degrees of freedom the ceramic technology offers to solve his design problems. For example, the filter study was designed for scaling from .4" X .9" guide according to the square root of dielectric constant and since the operating frequencies were to be above 10 GHz, moding problems and anomalous responses should be expected at least on the high side of the passband. Fortunately, the ceramic waveguide filter designer has that degree of freedom to make the guide dimensions any size he chooses-no traditional or economic barriers exist. Therefore, he can choose these to advantage, to wit; reduce the cross sectional dimensions of the filter section and thereby "adjust" the spurious responses to more desirable spectrum locations. The measured results do indicate that the modes are relatively "good" TE and TM modes for "well-plated" ceramics.

Two courses of action were followed to determine the applicability of air guide filter design techniques to Ceramic Waveguide. The first was to use susceptance sharts for normal "air guide" and scale down the resulting filter design by the square root of the dielectric constant - again this assumes that scaling theories hold. This practice would greatly facilitate ceramic filter designs.

The second action was to measure susceptances of single posts and doublet posts (in the same transverse plane) having various diameters and distances from the waveguide walls. Conventional filter design approaches could then be followed.

Both courses of action corroborated the views that scaling is valid and that post susceptance data in ceramic guide are sufficiently similar to airguide data to be considered identical. Some of the practical aspects of these details are given in appropriate sections to follow.

Ordinarily, waveguide filters are designed using posts, septums or irises as Q's demand. The ordering according to cost-effective design, since much filtering is of the 10% bandwidth variety, is also in the order given. Posts provide the optimum obstacle in terms of cost and performance for 10% or greater bandwidth filters. Although, no irises were studied experimentally as in the case of the other two, irises could be built if very narrow band high-Q filters were desired. One fabrication approach is to make the filter section separately, the filter would be plated and the iris hole provided, the iris plane would be machined smoothly, and then this would be soldered to a mating waveguide section of any ceramic sub-system. Fabrication procedures for the other two susceptance techniques have been developed and will be described in the appropriate section.

Finally, temperature studies were made on these filters. This information is important for three reasons:

1. The electrical designer learns to what extent he must compensate his filter designs to perform over a given temperature range, and
2. It represents an excellent check, for total combined length and dielectric variation effects with temperature.
3. It provides a check on metalization adherence.

Details of the above are now presented.

2.2.1.1 Filter Designs and Experimental Data

A typical filter is shown in Figure 5. It is a four section, direct coupled filter and its response is shown in Figure 6. This design is the one utilized in the production module (See Figure 23) and the one on which temperature measurements were made.

In order to achieve the results obtained, a number of experiments on scaled filters and those designed from experimantal data on susceptance posts and septums in alumina ceramic were made.

One of the first filters designed on scaled dimensions is shown in Figure 7. This is a two pole, direct-coupled, .1dB ripple post-susceptance filter. Its response was typical of a two-pole version of the four pole unit shown in Figure 5. The initial scaling was greater than the square root of dielectric constant in both transverse dimensions, the height by 22% and width by 10%, and thus some higher order mode responses seen in direct scaled units were not observed. The unit shown in Figure 5 also had both height and width reduced to control the spurious responses at the high end of the filter passband.

Figure 8 shows a typical passband response of most of the scaled filters. To obtain a flattened response, small holes were drilled into the center of each filter section and a nut and screw tuning arrangement was effected. An overall response curve of such a filter is given in Figure 9.

One concludes that scaling techniques are valid and design problems are similar to those of air-guide.

Data was accumulated on single and double posts in ceramic waveguide as shown in Fig. 10. It should be noted that direct scaling from post data in air filled guide yields susceptance data which are in close agreement with those presented in standard handbooks. Filter designs based on these susceptance data also provided responses similar to those mentioned earlier on filter scaling.

One experiment was dedicated to determining whether a 1% BW filter was feasible using posts. The results of a 3 section loosely coupled filter are shown in Fig. 11. A minimum loaded Q of 900 was estimated for this section.

It can be concluded that filter designs achieved in this medium follow the techniques developed in air guide and thus the warehouse of knowledge already catalogued is available for the ceramic guide designer. And there is the bonus of freedom to choose as one judiciously desires the cross-sectional dimensions of the transmission line and the overall size according to dielectric constant and Q's.

2.2.1.2 Design Problems & Solutions

Spurious responses, location of filter obstacle reference planes and obstacle perturbation effects are some of the electrical problems challenging the engineer's ingenuity. Among the mechanical are plating of small diameter holes, machining tolerances and fix-up techniques.

A generation of study has provided significant sophistication in the design and tailoring of air filters. As already high-lighted, the transfer of this sophistication to ceramic waveguide designs has been realized in the case of spurious responses. Also, the techniques of mode suppression, such as special surface irises are available for unusual situations. Although there are always exceptions to a rule, it can be concluded that, if losses are "reasonable", all air guide filter design concepts, approaches and techniques can be utilized for ceramic waveguide filters.

The theory of microwave equivalent circuits is based on posts and irises having longitudinal thicknesses which are relatively thin compared to waveguide widths. A ratio of 1 to 10 is the border region for acceptable practice. The ceramic waveguide designer learns quickly that a hole plating problem faces him if he uses small diameters. The rule of thumb followed by platers is "the diameter of the hole should be one third the length of the hole". At X-band the first ratio requires a maximum .030" hole diameter and the second places a minimum requirement of .045".

There are a number of approaches that were attempted to solve this problem and others that represent potential solutions.

For small holes, soft copper rods could be injected into the hole after plating and soldered at each end.

Metalized epoxies could also be used. A new high conductivity frit could also provide a solution. The approach chosen however, was to use .050" diameter holes and determine the consequences.

The theory states that a pure susceptance will not be achieved under these circumstances. On the other hand, it is very doubtful that any obstacle in any waveguide can be considered a pure inductance or capacitance - it therefore, is the degree of departure that the engineer is again concerned with.

The degree of departure turned out to be simply resolved by referencing the front edge of the obstacle as opposed to the center as given in tests. This resolution came about as a result of a computer program developed to accept reflection coefficient measurements and transform these appropriately for the actual susceptance data. Smith chart transformations proved very difficult in the region of large susceptances. The program was designed to find a reference plane at which the posts look purely inductive. This was done also to nullify some small measurement errors. The leading edge of the post or posts was shown to be the "proper" reference plane for the .045" to .055" diameter posts.

In the course of the post susceptance studies, it was found possible to build high pass filters with a given low side response according to ordinary microwave filter theory and with a high side of reasonably low loss. This feasibility provides a method, using either ferrites or diodes as tuning elements, to obtain a controlled high pass response filter.

These filter studies highlighted one other interesting fact. Nearly all filters designed using posts or septums produced a response approximately 1% lower than expected. This is attributed to a dielectric constant higher than that quoted in the literature (9.7). Other dielectric constant experiments indicated relative dielectric constants closer to 10.0. Examples of some of the circuits tested are shown in Fig. 12.

Although there are experimental design techniques to develop waveguide filters without using tuning elements - screws or "dent tuning" - such procedures have usually been followed only where very high power requirements demand it. However, most of the ceramic waveguide filters as with their air-counterparts depend on screw tuning to obtain the ultimate passband characteristics and these same procedures have been followed, with success, using ceramics.

Machining tolerances of .003" in ceramic is approximately equivalent to .010" in air waveguide. Thus, our goal in ordinary shop practice has been .002" max. This has been achieved and has provided satisfactory electrical performance.

### 2.2.1.3 Temperature Data

Filters represent an ideal vehicle for temperature studies. Either narrow band or broadband filters can provide information on the total change in dielectric properties as a result of temperature variation. This is obtained by the change of resonance frequency of a filter with temperature.

This frequency variation is due to differential effects as described in the following equation (2)

$$\frac{1}{f}\frac{df}{dT} = -\left(\frac{1}{2}\tau + \sigma\right)$$

For 99.5% pure alumina, $\sigma$, the linear coefficient of expansion is approximately $7 \times 10^{-6}$ per degree centigrade, and $\tau$, the coefficient of dielectric constant change with temperature was originally estimated to be circa $150 \times 10^{-6}$ per $^{\circ}$C.

Measurements of center frequency change with temperature are given on a 10% bandwidth four pole filter. The bandpass characteristics remained the same except that a shift of -.6% was observed over a temperature range of -55$^{\circ}$C to +75$^{\circ}$C. The results obtained were approximately half that predicted. Since quoted linear coefficients have been carefully substantiated, it is obvious that the dielectric coefficient is in error by a factor of two. Ceramic data was re-consulted and more carefully integrated data indicate that 75 - 80 $\times 10^{-6}$ per degree C is more realistic and the measurements confirmed this. The resultant change in frequency over this temperature range was -60 MHz. At room temperature the center frequency was 10.4 GHz.

This smaller change in frequency is a definite advantage in any design. Fortunately, some ceramics - usually compound ceramics - can provide a zero frequency change with temperature. This is important for cavity stabilization applications and reference frequency monitors.

(2) C.P. Harwig, M.P. Lepie, D. Masse, A. Paladino & R. A. Pucel, "Microstrip Technology", Proc. Nat'l Electronics Conf. 24, 314 (1968).

### 2.2.2 Circulator

A photograph of the circulator used in the module is shown in Figure 13. This circulator had been developed on an earlier program and its performance was more than adequate for this program as the loss and isolation indicate in Figures 14 and 15, respectively.

The design is based on Fay & Comstock's analysis[3] and on simplified procedures based on experiment.

The impedance transformer is a simply calculated quarter wave section since the impedance differences in the guide and in the ferrite are quite similar. To obtain the equivalent bandwidth performance in airguide, approximately three steps are required. This is a distinct advantage for ceramic guide designs over their air counterparts. It is because the dielectric constants of the two media, ceramic and ferrite, are very nearly alike. This same point applies for diodes and other solid state devices in ceramic waveguide.

The magnets shown in Figure 13 are samarian cobalt types developed at Raytheon. Raytheon R-151 material was the ferrite used. The ferrite is a cylindrical post extending thru the guide and epoxied in place.

From the data shown in Figures 14 and 15, it is apparent that with improved matching a much larger 20 dB bandwidth could be realized.

Consideration was also given to using a single thin disc on one side or two thin discs on tow sides. Fabrication-wise the ferrite cylinder provides the best compromise. The two-disc approach would be more valid for circulators designed in the other plane.

(3) Fay & Comstock, "Operation of the Ferrite Junction Circulator", MTT-15-27, January 1965.

2.2.3 Gunn Oscillator

Gunn and avalanche oscillators and amplifiers can readily be developed in ceramic waveguide. The output powers and gains approach those achieved in air guide. As a matter of interest the concept of scaling again was proven here. Most of the ceramic designs are based on air guide designs which had been developed at Bedford over the past several years. The important improvement achieved during this program was the development of a compact oscillator design.

Earlier ceramic cavity designs were based on step transitions as shown in Figure 16. Gunn oscillators operate better in a relatively low impedance line. The parameters of the Gunn devices are determined as referenced in a paper by F. Sullivan[3]. Such data provides the basic circuit design requirements. The stepped transition designs were based on a Tschbychev formulation and were then evaluated by fabricating a back-to-back unit containing two such sets of transitions with the small heights contiguous. In this manner the reflection data was obtained. Satisfactory designs were achieved on the first attempt; however, the results of a good design are always clouded by the fact that standard connectors - almost all of them - have very high mismatches at X-band and higher frequencies. Soldered coax lines appear to be a reasonable method to reduce the connector problem for final RF module designs.

Early testing of Gunn devices using the circuit presented in Figure 16 provided results approximating those obtained in air guide designs. Efforts were then directed to obtain an optimum size cavity. The approach followed was to combine the

(3) F.J. Sullivan and W.H. From, "Second Harmonic Tuning Effects on Impatt Diode Oscillator Noise Characteristics", GMTT International Microwave Symposium Digest, 1971.

transformation of impedance and the cavity coupling at one transverse plane. Preliminary calculations based on data collected from successful air guide designs provided sufficient information to make a first attempt. Adjustments were then quickly made and a final ceramic breadboard design was developed. This unit is shown in Figure 17.

Several Gunn devices from a variety of vendors were tested in a tapered circuit. The results are presented in Table II.

TABLE II

Gunn Osc. Diode Data

| Type or Lot No. | Mfg. | Osc. Freq. (GHz) | Diode Reson. Freq. (GHz) | Power (mw) | DC Volt (volt) | DC Current (ma) |
|---|---|---|---|---|---|---|
| 9201 EP | VAR. | 10.38 | 11.0 | 40 | 12.0 | 383 |
| 9201 EP | VAR. | 10.40 | 11.0 | 54 | 12.0 | 400 |
| 9201 EN | VAR. | 10.50 | 11.0 | 80 | 12.5 | 394 |
| GD 511 C | N.E.C. | 10.00 | 7-8 | 42 | 13.5 | 600 |
| GD 508 C | N.E.C. | 9.80 | 7-8 | 25 | 14.0 | 540 |
| Y2109 | G.E. | 10.30 | - | 22 | 11.0 | 395 |
| Y2109 | G.E. | 10.20 | - | 30 | 12.0 | 395 |

These are typical results obtained on a number of Gunn diodes. This data shows that the Q's of ceramic waveguide circuits forces the device to operate at or near a prescribed frequency even though the best power performance is achieved when operating near vendor designed resonance frequencies. The module center frequency was designed to operate near 10.4 GHz.

Power levels to 100 milliwatts were achieved as in the air design measurements when the ceramic cavity was adjusted to the vendor recommended frequency. Thus one concludes that oscillators used in this exposition can provide the power performance of air guide designs.

As mentioned in the filter section, higher Q cavities using iris couplings could be used for special applications.

The data in Table II defines another important facet that oscillator and amplifier diodes which are packaged identically and come from the same wafer, etc., usually provide similar performance characteristics. The first two Varian devices in the list come from the same wafer and were packaged similarly but even though not at our specific frequency. Their performances are clearly similar.

2.2.4 Termination

Several design procedures have been followed in designing terminations and attenuators. Some have histories dating to early air guide designs. But the final design used was a double taper. The double taper as well as almost any topological form can be realized in ceramic without incurring a cost penalty. Step, vane, or transverse terminations can be made.

After formulating a reasonable double taper design, experiments using different loss materials was begun. The material used in the module is Emerson and Cuming's CR-114. This is a castable resin which can be used to mold waveguide terminations, attenuators, and loads. When fully cured, the material provides a well defined performance characteristic as described by E & C in their Technical Bulletin 2-13.

It is a two component system that when properly proportioned, cast and cured no further machining is required. Its thermal expansion coefficient is reasonably compatible with the alumina ceramic - thus satisfactory operation can be expected for nearly any environment. The maximum VSWR was less than 1.1:1.0.

To assure good adhesion the cast loads were bonded to the ceramic.

A photograph of a typical termination design is given in Figure 18.

### 2.2.5 Coax-To-Waveguide Transition

The transition used in the module also had been developed earlier and did not require any improvements for the module. An impedance plot taken of this design is shown in Figure 19. A photograph of this transition is shown in Figure 20.

The chart displays a maximum 1.5 VSWR at the outer edge. The module operates in the 10 - 10.5 GHz band and the maximum VSWR from this data is 1.22. This VSWR represents the combined performance of the connector and the probe-ceramic interface. The connector probe is one existing on a standard 3 mm connector.

## 2.3 Fabrication, Processing & Final Module

The individual circuits that were developed by grinding techniques have been described in previous sections. After complete individual R.F. testing they were combined and tested as a module using flange techniques. The resultant module is shown in Fig. 21, and a second view is shown in Fig. 22.

The flange assembly procedure to be described has been successful in every instance. The flanges are machined from 1/8" brass and the rectangular hole for the guide is made undersized and then broached to final dimensions. The flange is attached to the plated ceramic waveguide using Chomerics #584 silver epoxy having .010 -.020 of ceramic protruding from the flange face. This face is then machine lapped with a 500 grit abrasive compound. The completed circuits are then ultrasonically cleaned and are ready for test. Soft soldering of flanges has also been successful.

The module illustrated in Figures 21 and 22 shows the separate components of the module. From left to right on Figure 21 is a coax-to-waveguide transition, a four pole filter, a circulator and a Gunn oscillator (background) and a termination.

The Gunn circuit as noted in Figure 22 is a tapered structure; this structure was the one used to obtain the data given in Table II. A more compact unit was desired and the final design incorporating such improvements gave an ultra-small unit as shown in Figure 17. Tests of this smaller circuit showed that higher Q's were achieved as well as higher output powers, almost 3 dB, for the same devices tested in the tapered design.

The program had thus advanced to the semi-final stage, to wit; to fabricate a complete integrated module sans flanges and compacted. This was completed in early '73 and testing was successful. A photograph of this unit is shown in Figure 23. Various tests on this unit proved that the overall performance was better in the integrated form than with the individually connected components. This result should be anticipated, but it is always necessary to obtain confirmation. The test data is shown on Figure 24 - note the increased power output over that reported in Table II.

The final mechanical dimensions were noted and this data was made available to the vendor, Wesgo, for the 10 production models.

A six week delivery was provided by the vendor. A photograph of one of these ceramic units is shown in Figure 25. Mechanical dimensions were held to an extraordinarily small tolerance as shown in Table III. This data presents average as well as maximum deviations from defined nominal dimensions for the 10 modules. These modules were developed using the "green state" fabrication technique, and this was followed by a final finish grinding operation to eliminate camber.

## TABLE IV

### DIMENSIONAL SUMMARY FOR 10 PIECES OF $AL_2O_3$ MACHINED IN "GREEN" STATE

| PRINT DIMENSION | AVERAGE DEVIATION FROM PRINT DIMENSION | TOTAL DIMENSIONAL DEVIATION FOR 10 PIECES |
|---|---|---|
| .015 | .00097 | .0015 |
| .150 | .00160 | .0015 |
| .196 | .00100 | .0000 |
| .418 | .00170 | .0005 |
| .640 | .00240 | .0010 |
| .836 | .00230 | .0010 |
| .075 | .00002 | .0010 |
| .075 | .00017 | .0010 |
| .103 | .00070 | .0010 |
| .103 | .00050 | .0010 |
| .110 | .00044 | .0012 |
| 1.440 | .00100 | .0022 |
| .125 | .00080 | .0010 |
| .385 | .00030 | .0015 |
| .700 | .00018 | .0009 |
| .015 | .00290 | .0009 |
| .110 | .00120 | .0015 |
| .500 ±.010 | .00900 | .0020 |
| .900 | .00050 | .0012 |
| .129 | .00130 | .0010 |
| .190 | .00090 | .0025 |
| .100 | .00100 | .0006 |
| .060 | .00210 | .0007 |
| .050 | .00050 | .0010 |
| .050 | .00005 | .0005 |
| .050 | .00020 | .0005 |
| .050 | .00014 | .0005 |
| .050 | .00010 | .0005 |
| .050 | .00023 | .0005 |
| .160 | .00034 | .0007 |
| .397 | .00070 | .0015 |
| .080 | .00046 | .0005 |

These results show that even in the case of long dimensions, for example, the 1.440" dimension, the average deviation for ten modules was .001" and the maximum was .0022. This is translated into a tolerance of .0015" per inch, which has proven better than satisfactory for all circuits developed on this program.

2.3.1 Module Assembly

The processing routine which is followed after receiving the ceramic parts from the vendor is now presented.

The terminations and ferrite cylinders are the first parts assembled. The terminations are casted in silicone rubber molds which have been formed from the ceramic mating part. Emerson & Cuming CR 114 is the castable load material. The ferrites are centerless ground to the correct diameter and sliced to provide the proper length cylinder for the ceramic hole. Because of the hole tolerances obtained in producing the ceramic module and that in maching the ferrite, no additional machining for fitting is required prior or after assembly. Both the ferrite and termination are cemented in place using Emerson & Cuming Stycast Hi-K (K=10) adhesive. A photo showing this state of fabrication is given in Figure 26.

Preparation is now made for plating this unit. First, holes that do not receive plating are masked with nylon plugs. After proper cleaning, including back-sputtering, the piece is then D.C. sputtered with 100 $A^{o}$ Cr. and 20 micro inches of Cu and then electroplated with Cu to 300 micro inches. This unit is gold flashed as a final metalization step.

At this phase of fabrication the module is carefully checked for plating weaknesses.

Next the oscillator is mounted into the C.W.G. module and soldered to a heat sink. Gunn devices with 3% efficiencies and 100 milliwatt output powers can be operated in a natural air environment with commercially available vaned heat sinks.

The final assembly operation is to attach the connector and the diode bias circuit. The magnets can be attached using an epoxy but in the module presented the units provide their own force of attachment. The completed module is shown in Fig. 27.

The module is now ready for testing. A typical curve of Gunn power output is displayed in Figure 24.

### 2.3.2 Cost Data

Ceramic Waveguide modules have significant advantages over other integration techniques. All of the electrical performance parameters of these circuits are equal to or better than their counterparts in other transmission media.

Another major purpose of this program was to demonstrate Ceramic Waveguide superiority over other integration techniques in terms of costs and within the scope of the program. Initial cost, production costs and life-cycle costs can at least be surmised from the data already presented and from that which follows.

Initial costs to develop a design in ceramic guide, since scaling applies, depends on the library of information available to the designer-no new theories, no new cute tricks are required. New design ideas and concepts, however, are sure to accrue as this transmission technique is studied further.

Production costs can be appreciated from the data contained in Table V. This pertains to the ceramic part of the module developed on this program and as shown in Figure 25. This data assumes that tooling should last for 10,000 pressings - it is a reasonable assumption according to the vendor.

| No. of Pieces | Unit Cost | Tooling Cost | Total Cost | Total Unit Cost |
|---|---|---|---|---|
| 500 | $.90 | $2270 | $2720 | $5.44 |
| 1,000 | .72 | 2270 | 2990 | 2.99 |
| 10,000 | .53 | 2270 | 7570 | 0.76 |

The unit cost to process 10,000 ferrite cylinders for this module is $0.50; this cost includes $0.30 for material and $.20 for centerless grinding the diameter and slicing. The termination unit cost should be circa $0.30. The connector should be less than $5.00; the Gunn device less than $25.00 in such lots. One vendor has estimated that 100 mw Gunn devices in this quantity should cost less than $10 each.

The assembly of the ferrite and termination would be less than $2.00 per module. Plating for an entire module, including preparation, would be less than $5.00. The heat sink should cost on the order of $2.00. The bias circuit and its fixture for the heat sink should be less than $5.00. The testing time in this particular case should be less than two hours - at $15/hour this would be $30. The total cost of such a module in lots of 10,000 would then be - circa $85. Interestingly, the cost/unit for 1000 units departs little from this cost except for the ceramic cost difference.

Our experience with module designs show that these low production costs cannot be approached using other transmission media. One can obtain a sense of this remark from the photograph in Figure 28. The aluminum box which contains the microstrip circuits in the center is missing. The air guide unit shown at the top is the most expensive and expansive.

Life cycle costs should be lower in CWG since the failures are usually due to active device failures. In ceramic waveguide any active device can be designed to be removed in the field. Although soldering techniques are used here, special mechanically attached thermal heat sinks have been developed so that active devices may be field replaced. Additionally, the ceramic waveguide material completely surrounds the active devices and provides better heat sinking than other transmission media.

## 3.0 Future Application Areas

A viable, low cost high quality microwave integration technique has been exhibited. Five typical module circuits were developed and integrated. Preliminary broadband studies showed that octave and greater bandwidths are achievable using the CWG transmission technique. The CWG technique, therefore, represents a potentially powerful design approach for solid state and gas state module designs of the present and future.

Although representative module circuits have been developed and integrated on this program and these designs have been reduced to the ultimate in reproducibility and scalability - i.e. the electrical design can be checked by determining mechanical tolerances - there are a number of significant circuits that remain to be developed. These circuits will provide all the advantages mentioned for the other circuits but in many cases will provide extra dividends in performance due to the improved symmetry over microstrip and other open transmission lines. Among these circuits are balanced and doubly balanced mixers, switches, push-pull oscillators and amplifiers, phase shifters and tunable filters. The Gunn device represents a potential broadband amplifier while with special packaging to reduce parasitics the transistor and FET can provide reasonable power amplifications and large bandwidths. Active devices generally can be fabricated as chips on a simple heat sink and integrated into the ceramic - thus eliminating the costly packaging and profligate packaging practices of today. Alternatively, standard packages for diodes and three terminal devices could be developed with significant short term and long term cost savings.

An interesting study, beyond the scope of this particular program, would be to develop 50 to 100% bandwidth circulators. Design theory does not preclude this and probably by using combined dielectrics, or ridge guide, such a result could be achieved.

The development of such circuits will provide the building blocks for all future active or passive modules.

The Ceramic Waveguide represents a potentially optimum transmission medium for almost any type of RF module from L-band through K-band and to almost any production level.

Module designs significant for radar, ECM & Communications applications are:

1. Exciters
2. Fuze systems with integrated antennas
3. Phased array transmit - receive modules
4. ECM broadband video receivers with tunable front ends.
5. Communication systems

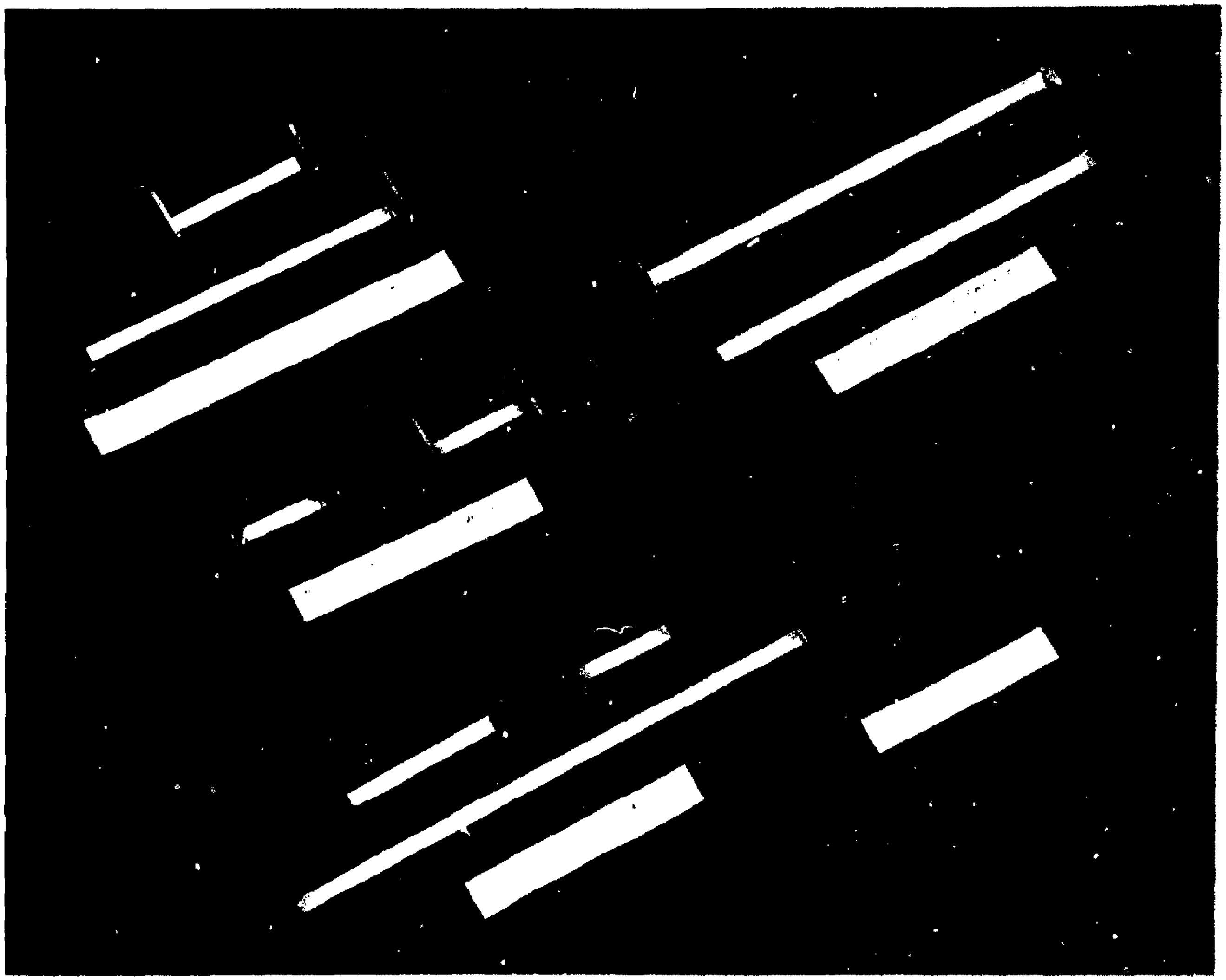


Figure 1 Samples of Ceramic Waveguide Metalizations

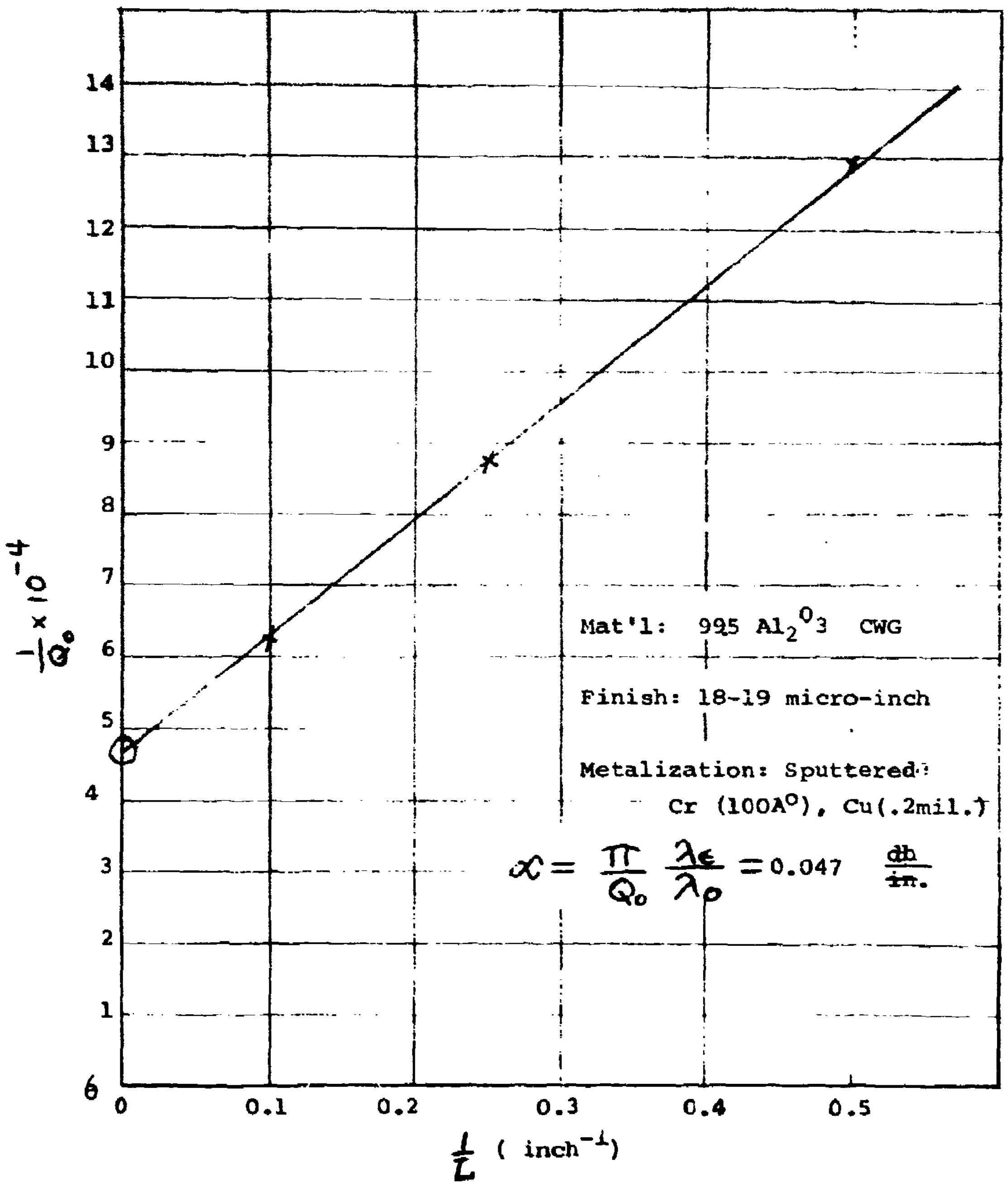



Figure 2. Insertion Loss Data by Cavity Resonance Method.

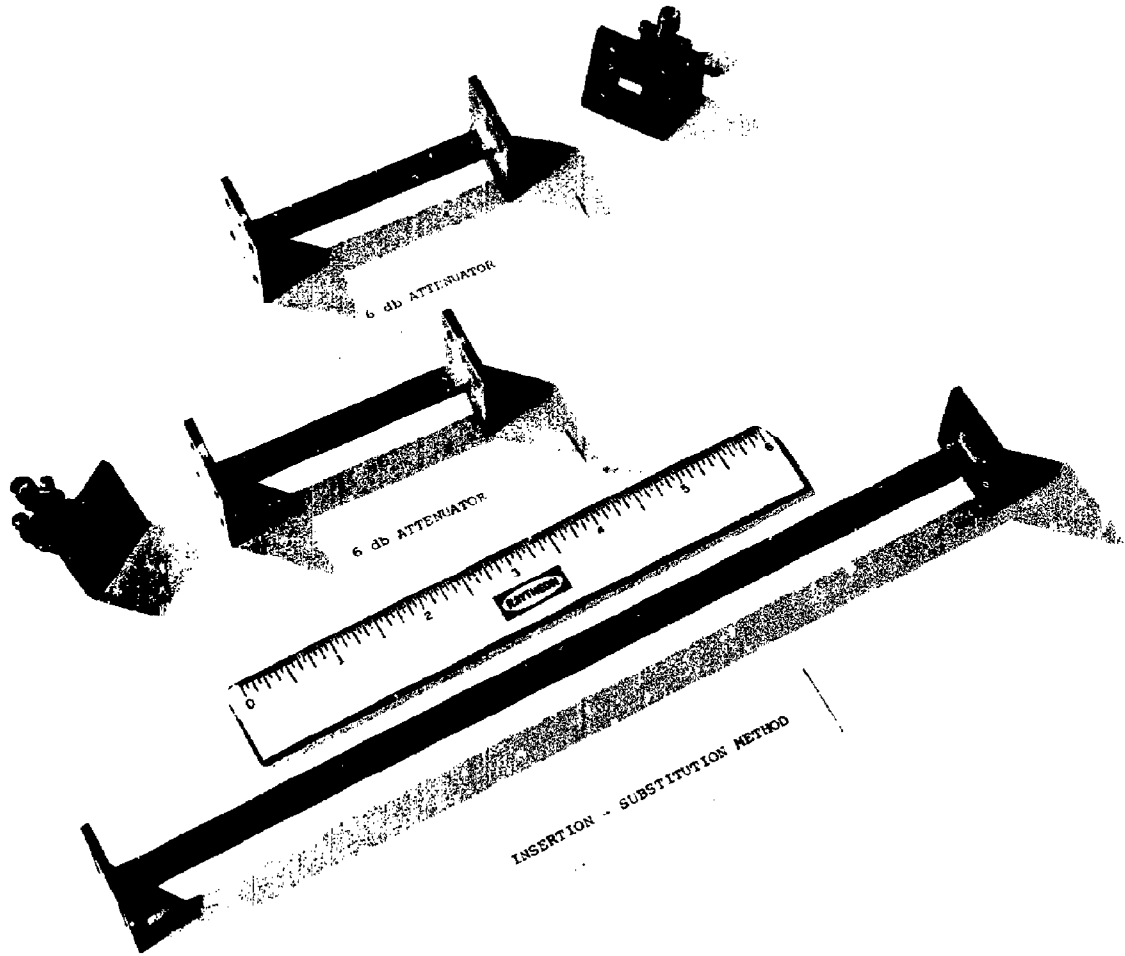



Figure 3. Insertion Loss Test Components

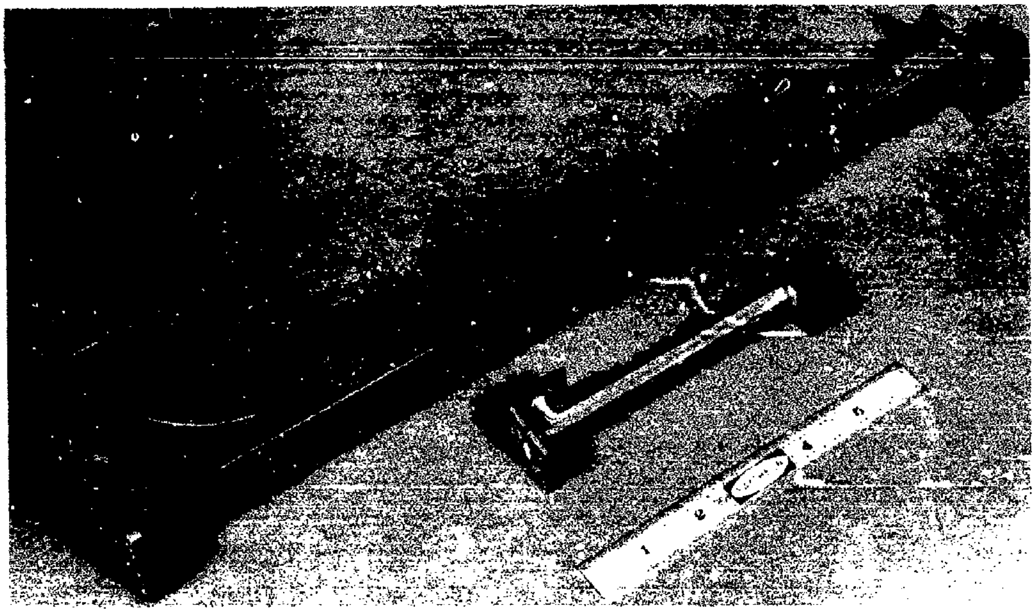


Figure 4. Size Comparison of Air and ceramic waveguides.

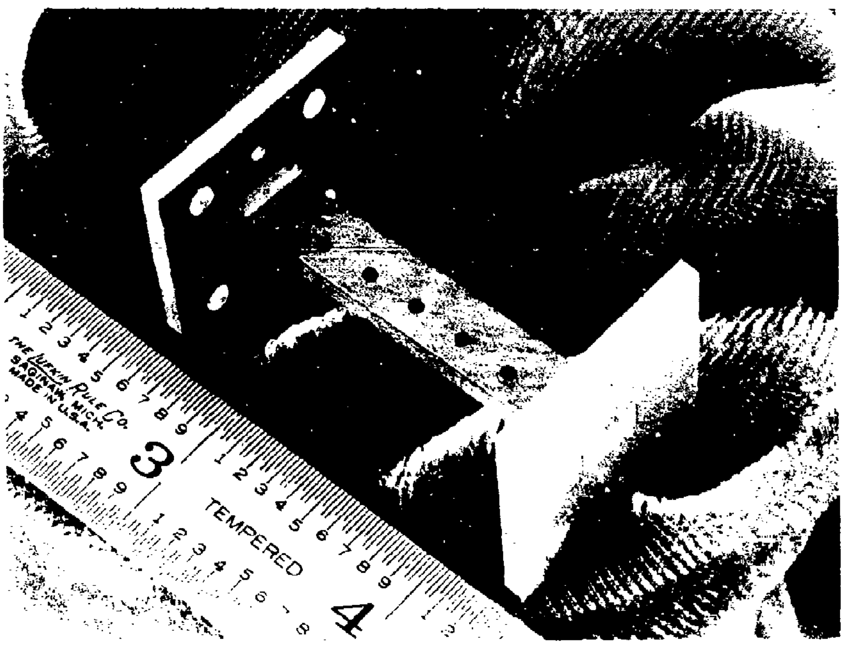



Figure 5. Typical Post Filter Design

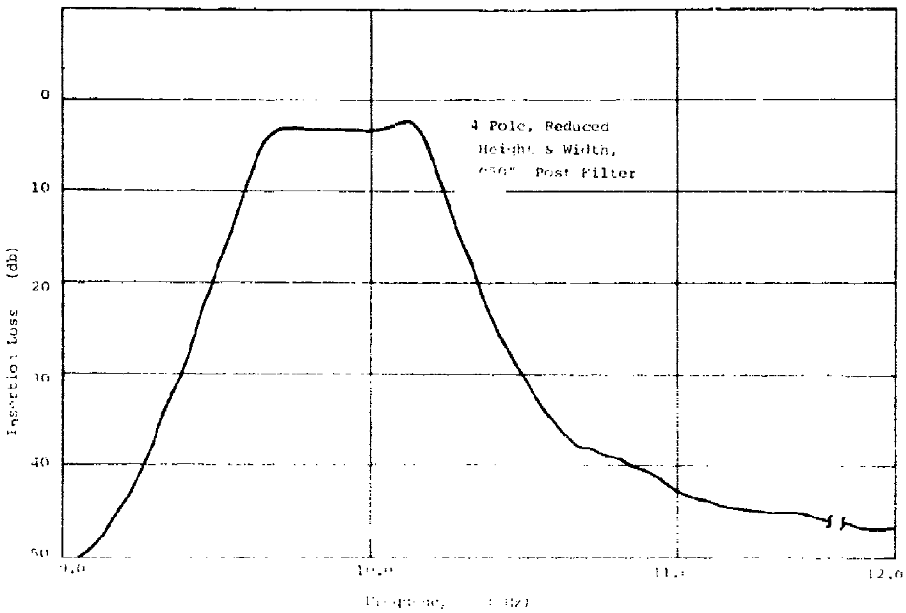



Figure 6. Insertion Loss Characteristic of Filter in Figure 5.

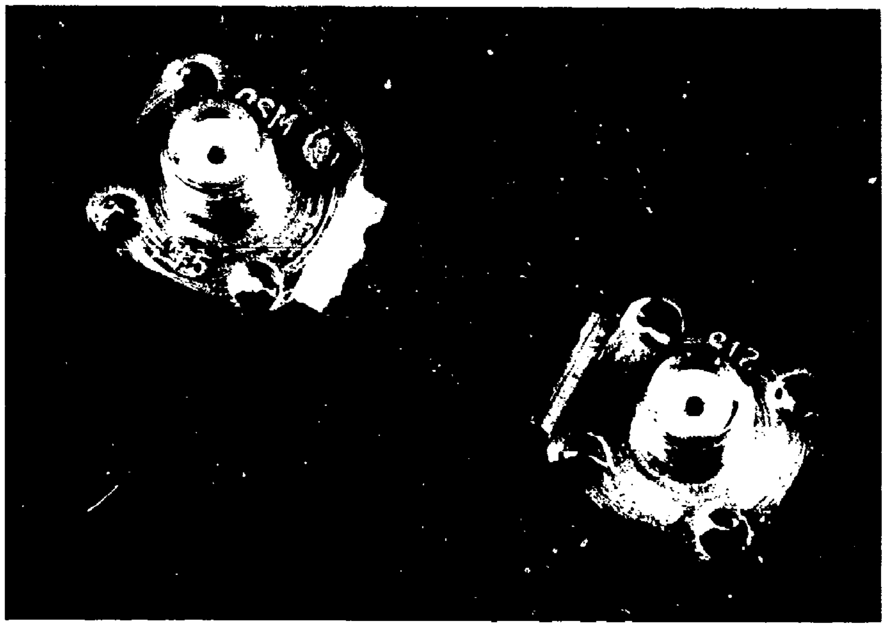


Figure 7. Simple Two Pole Filter

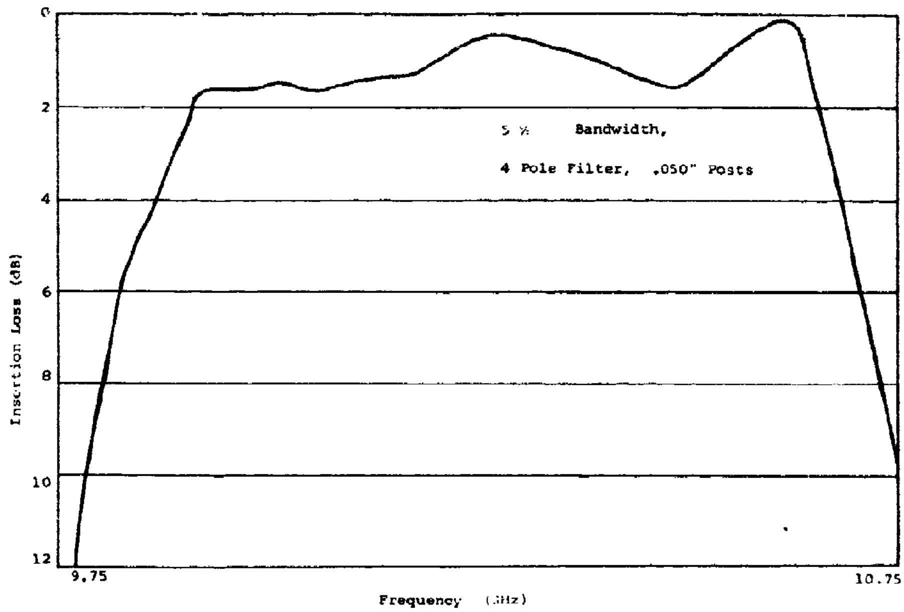



Figure 8. Typical Detailed Passband Response of Post Filters

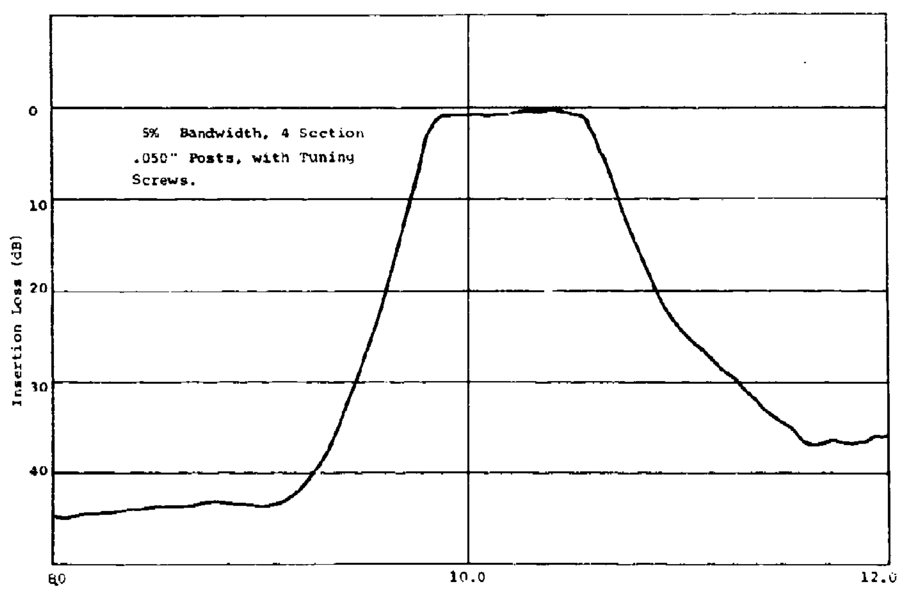



Figure 9. Improved Filter Response by Use of Capacitive Screws.

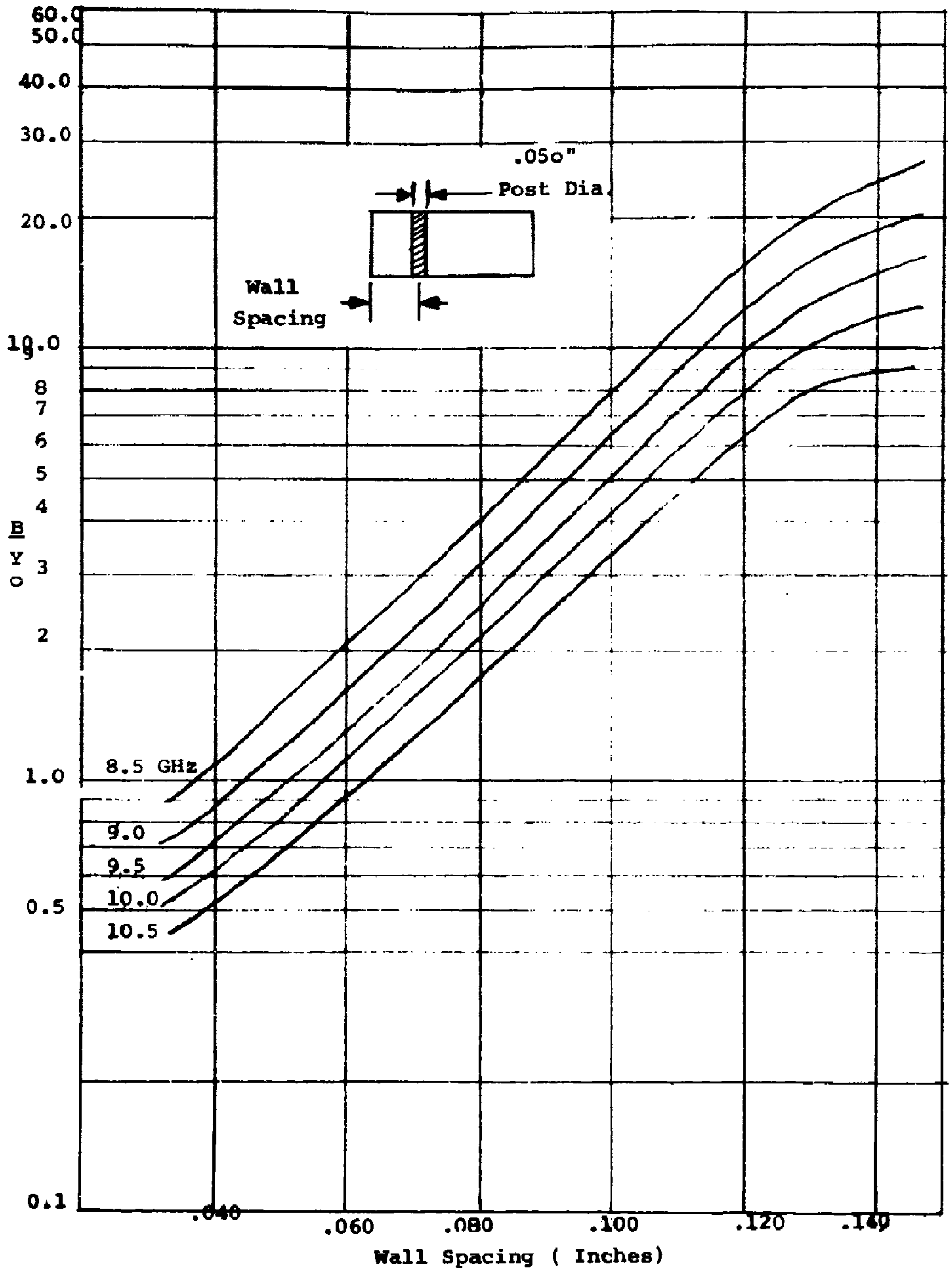



Figure 10. Single Post Susceptance Data

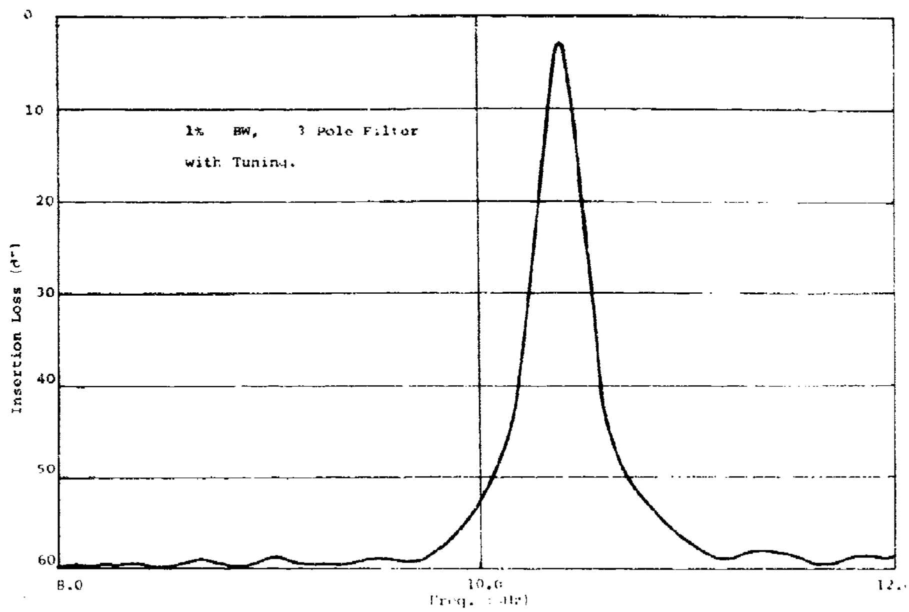



Figure 11. Narrow Band Post Filter

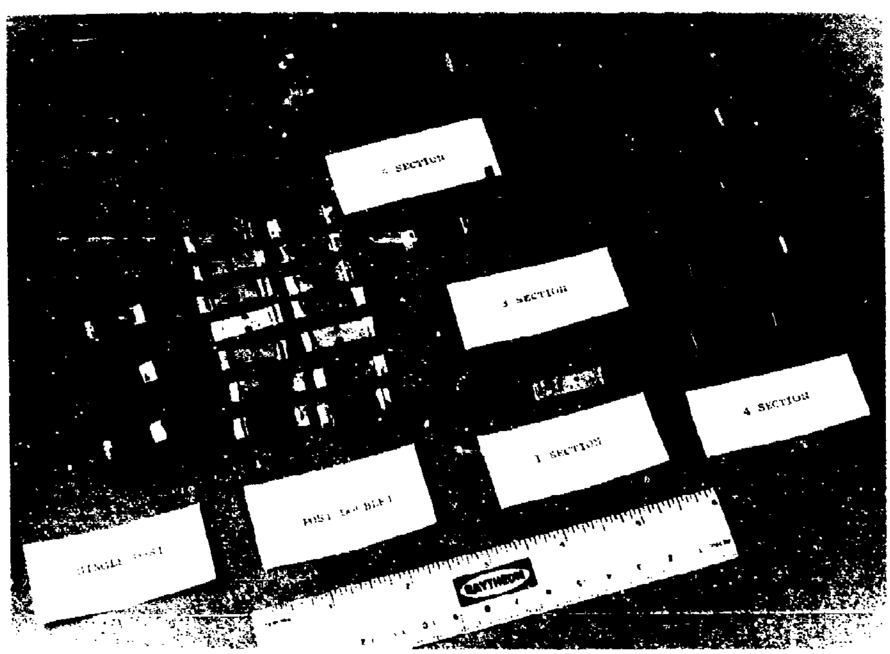



Figure 12. Typical Filter Post & Filter Circuits Evaluated.

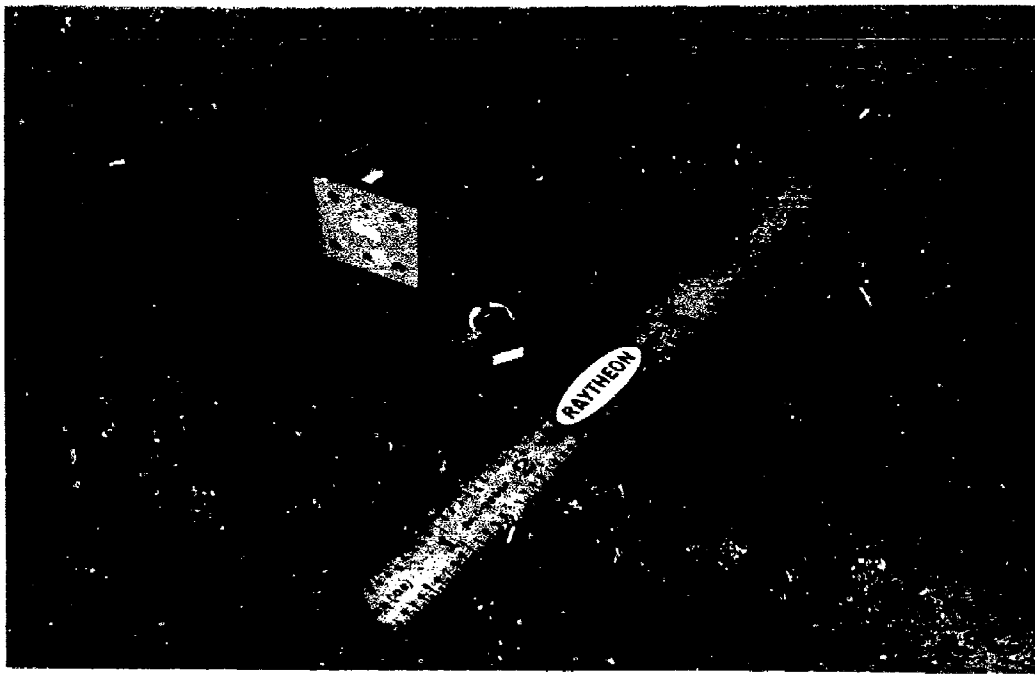



Figure 13. Circulator

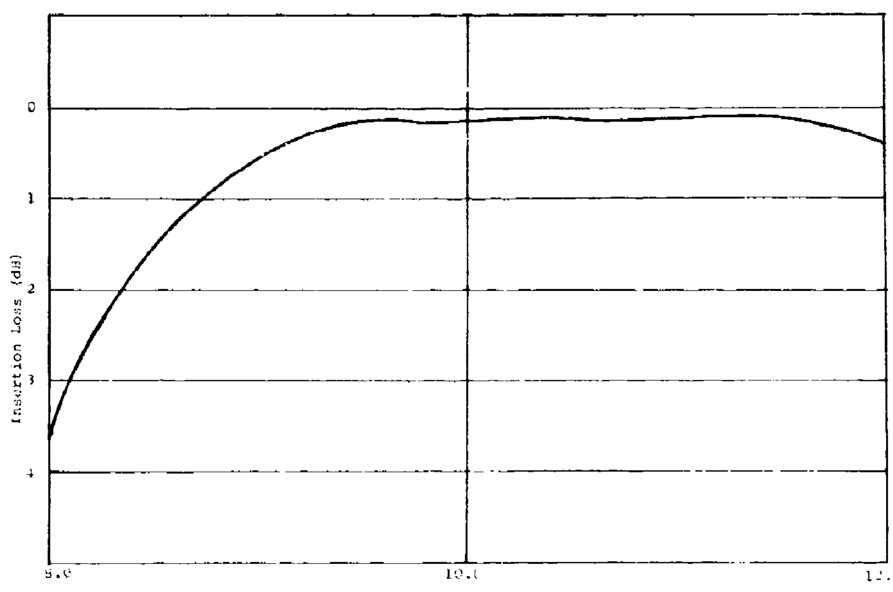



Figure 14. Circulator Insertion Loss

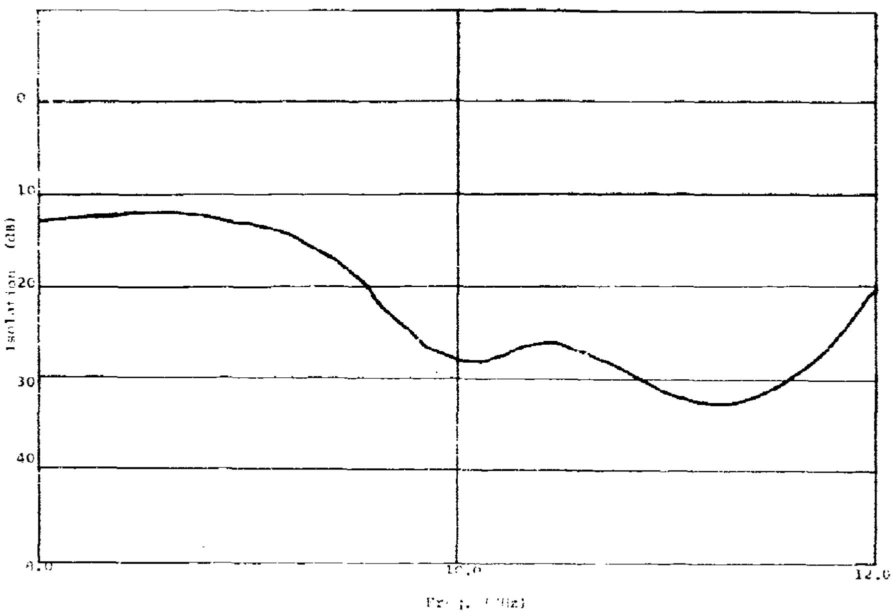



Figure 15. Circulator Isolation

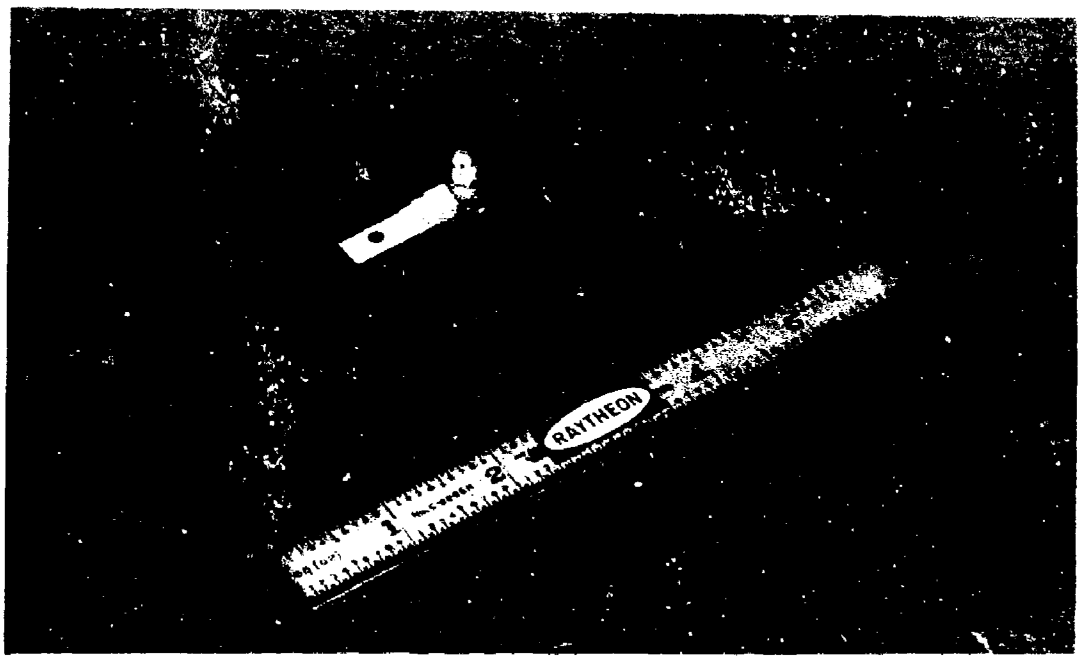



Figure 16 Gunn Oscillator Circuit Using Step Transitions•

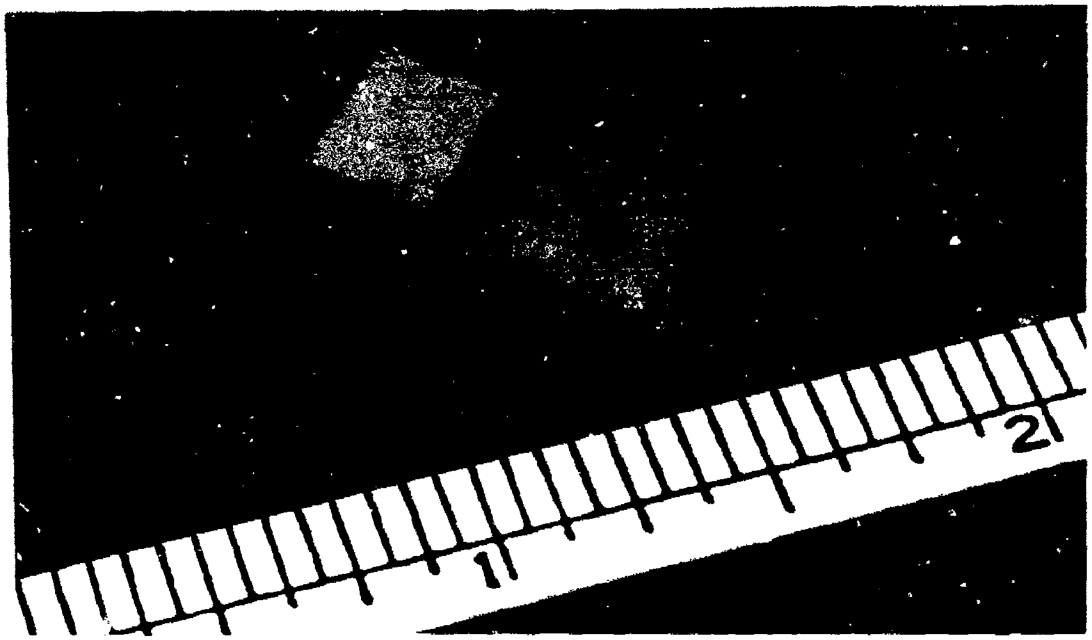


Figure 17. Compact Gunn Oscillator Circuit

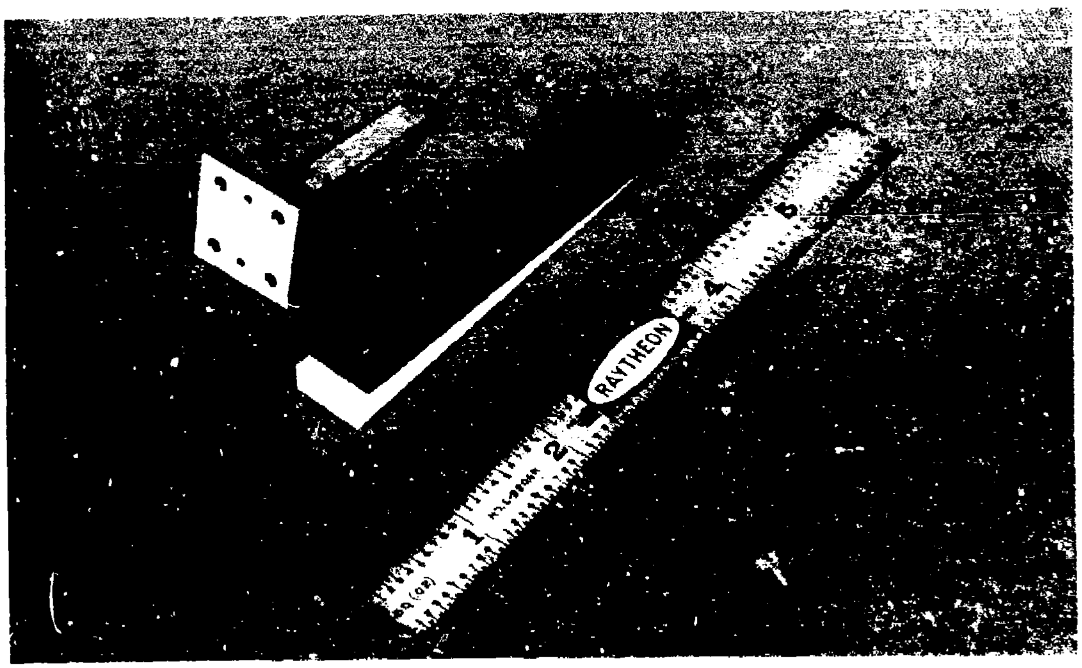
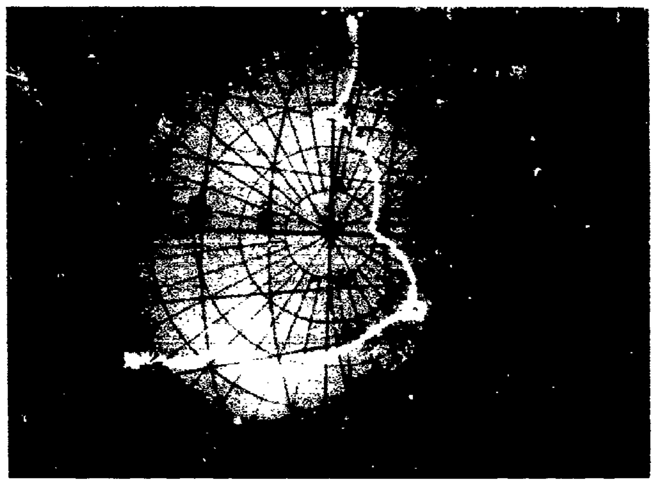



Figure 18. Termination Construction

Transition Ceramic Waveguide To 3mm Coax

Network Analyzer Impedance Plot



1.50 : 1.00 Chart

| f GHZ | VSWR MAX |
|---|---|
| 7.4 - 12.0 | 1.50 |
| 7.5 - 11.5 | 1.33 |
| 7.6 - 10.7 | 1.25 |
| 7.8 - 9.9 | 1.20 |
| 7.9 - 8.6 | 1.17 |

Figure 19. Impedance Characteristics of Coax-to-Waveguide Transitons.

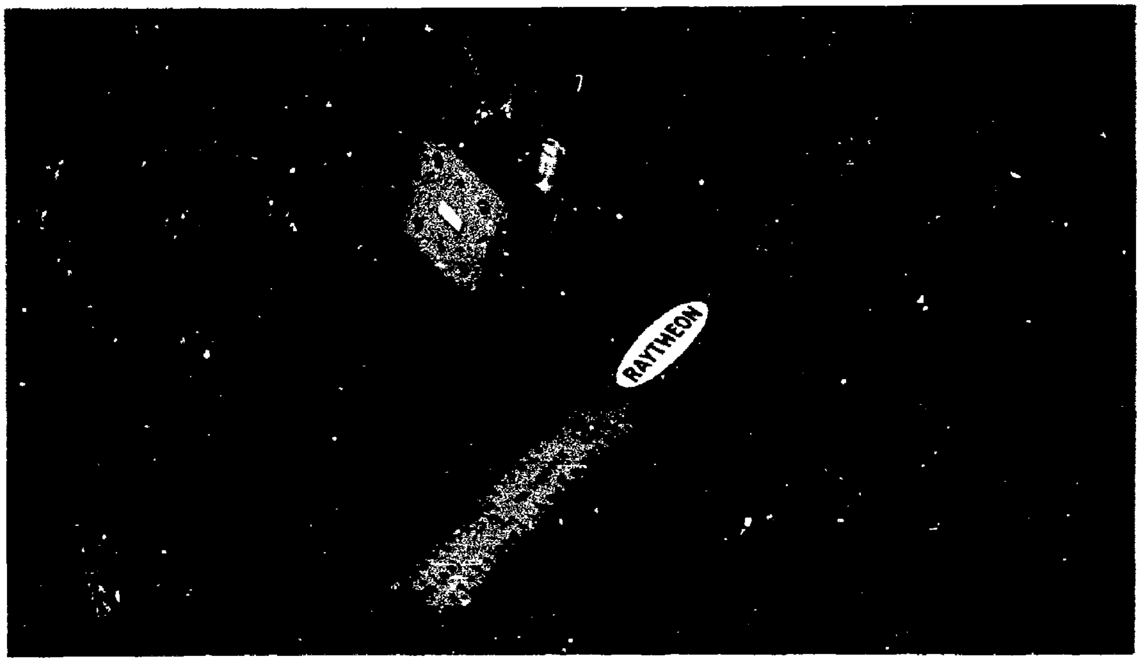


Figure 20. Coax-to-Waveguide Transition Design

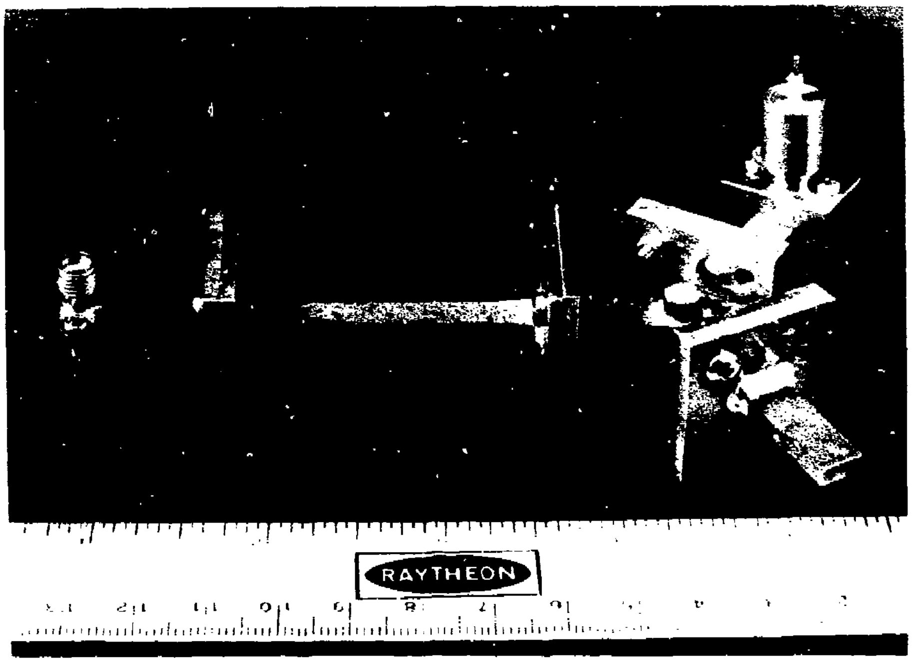


Figure 21. Module with Individual Components

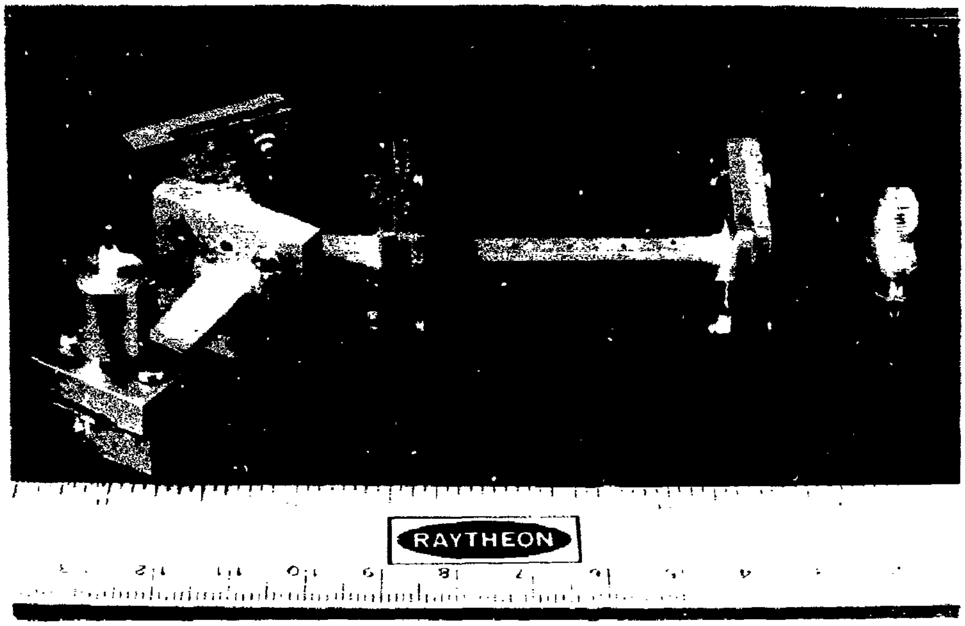



Figure 22. A second view of Module in Figure 21.

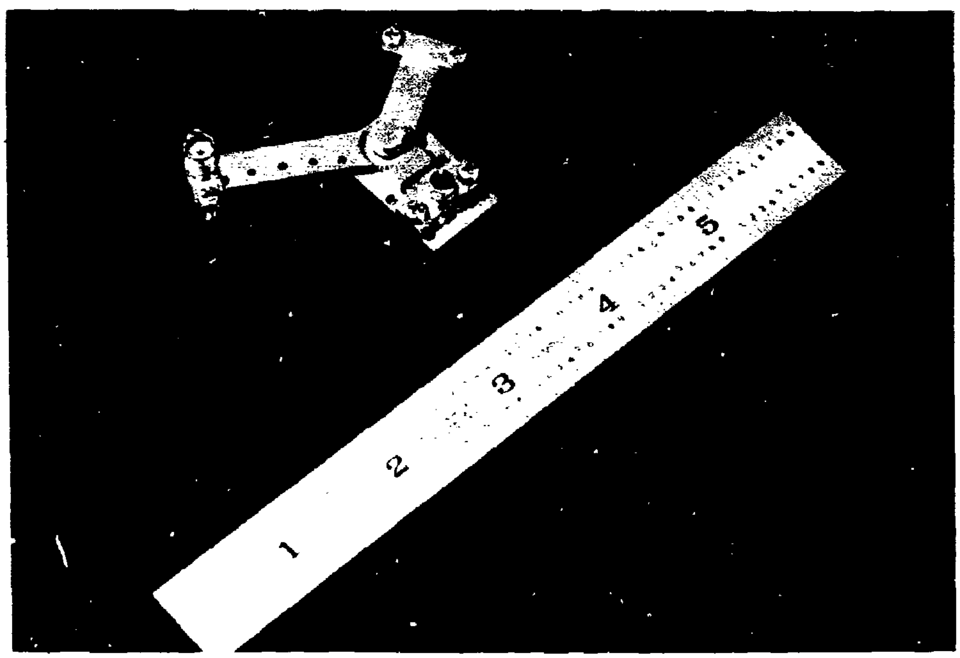
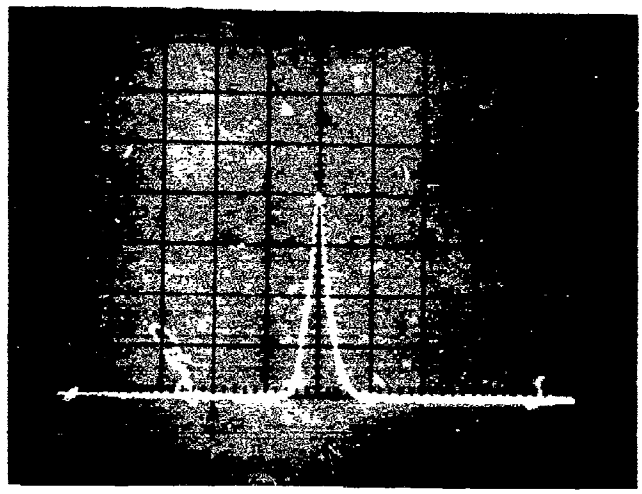



Figure 23. Compact version of Module in Figure 21.

## Microwave Integrated Circuit

## X-Band Ceramic Waveguide SN 001

HORZ
1 MHZ/cm



One piece module containing 1 each.

a. Gunn Oscillator
b. Ferrite Circulator
c. Termination
d. Band pass Filter
e. Transition

| | |
|---|---|
| Power Output | 90 mw |
| Output Frequency | 10.8 GHZ |
| Diode DC Voltage | + 11.0 V |
| Diode DC Current | 410 ma |

Figure 24. Power Output Data of Module in Figure 23.

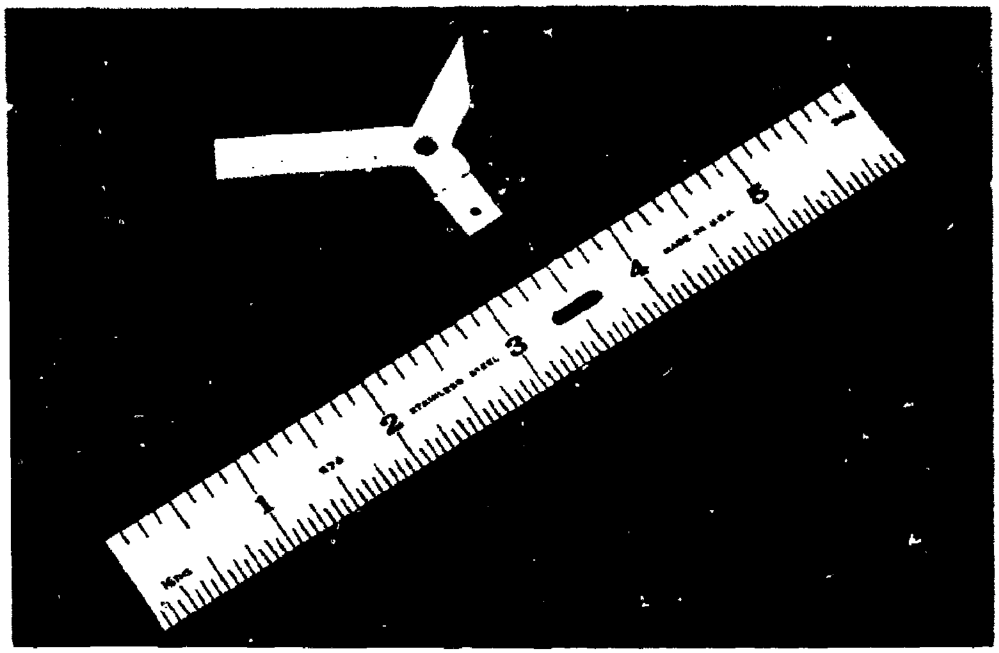


Figure 25. "Green State" Fabricated Module

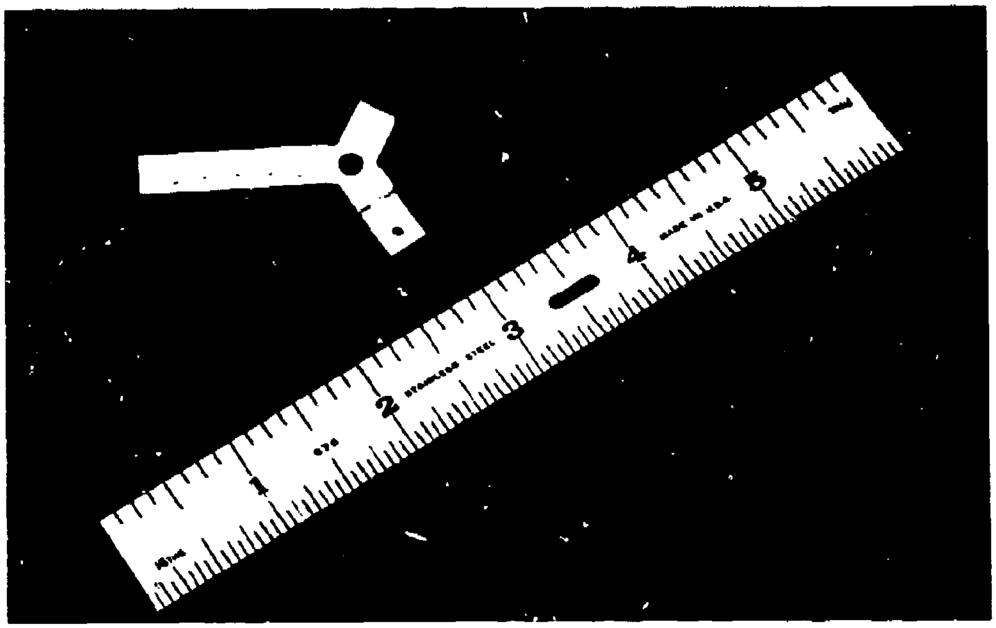


Figure 26. Module Fabrication Prior to Plating

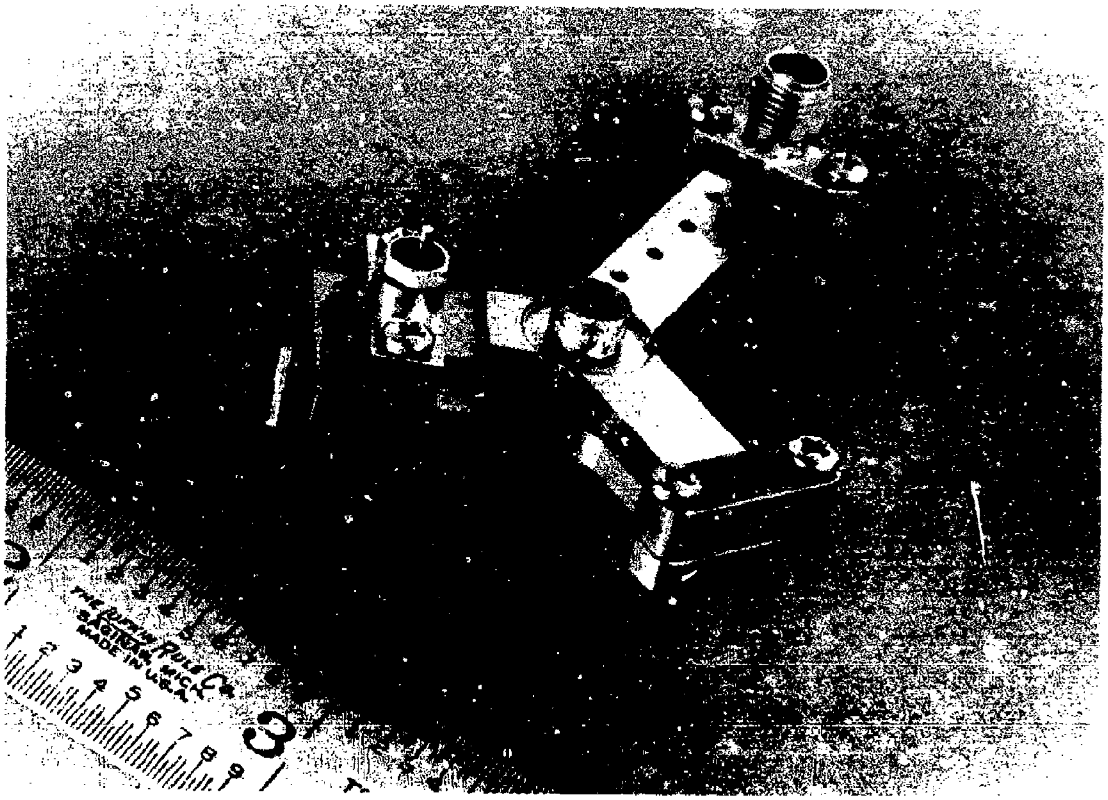


Figure 27. Completed Module.

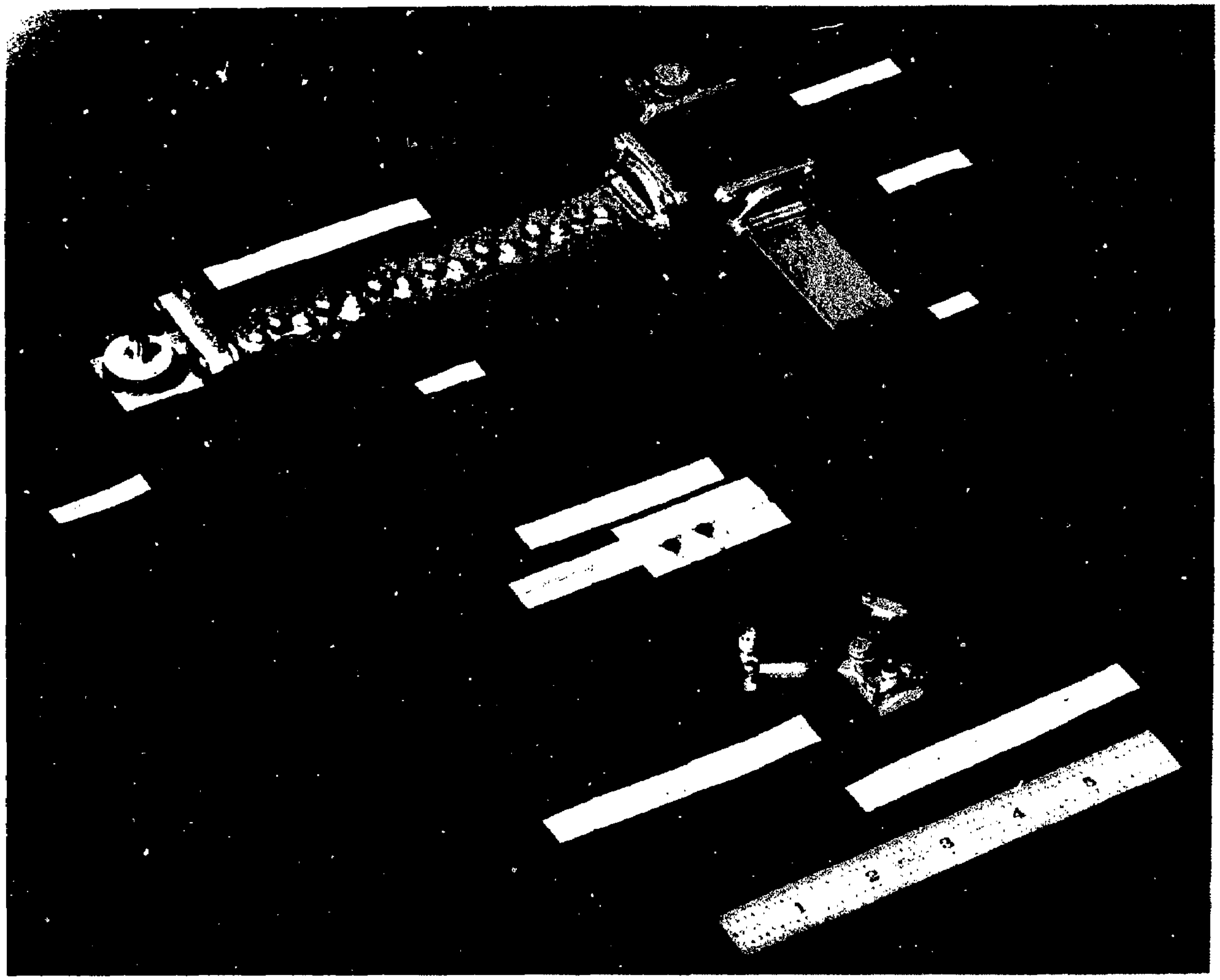


Figure 28. Module Size Comparison,

UNCLASSIFIED
Security Classification

**DOCUMENT CONTROL DATA - R&D**

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author)<br>RAYTHEON CO., M.S.D.<br>HARTWELL RD.<br>BEDFORD, MA | 2a. REPORT SECURITY CLASSIFICATION<br>UNCLASSIFIED<br>2b. GROUP |

3. REPORT TITLE

MIC TRANSMISSION LINEAR TECHNIQUES

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Report; 20 April 1972 through 20 April 1973

5. AUTHOR(S) (Last name, first name, initial)

From, William H.

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| June 1973 | 48 | 4 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO.<br>F 33615-72-C-1309 | 9a. ORIGINATOR'S REPORT NUMBER(S) |
| b. PROJECT NO. | |
| c. | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) |
| d. | |

10. AVAILABILITY/LIMITATION NOTICES

Distribution limited to U.S. Government agencies only; test and evaluation results reported, June 1973. Other requests for this document must be referred to AFAL/TEM, Wright Patterson AFB, OH 45433

| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY |
|---|---|
| | Air Force Avionics Laboratory<br>Air Force Systems Command<br>Wright-Patterson Air Force Base, Ohio |

13. ABSTRACT


The significance of this research and development to the Air Force is the demonstration of a new low-cost transmission line technique having properties superior to microstrip; in particular, it provides higher power capability, lower loss and high altitude operation without requiring pressurization.


DD FORM 1 JAN 64 1473

UNCLASSIFIED
Security Classification

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| X Band | | | | | | |
| Oscillator | | | | | | |

INSTRUCTIONS

1. ORIGINATING ACTIVITY: Enter the name and address of the contractor, subcontractor, grantee, Department of Defense activity or other organization *(corporate author)* issuing the report.

2a. REPORT SECURITY CLASSIFICATION: Enter the overall security classification of the report. Indicate whether "Restricted Data" is included. Marking is to be in accordance with appropriate security regulations.

2b. GROUP: Automatic downgrading is specified in DoD Directive 5200.10 and Armed Forces Industrial Manual. Enter the group number. Also, when applicable, show that optional markings have been used for Group 3 and Group 4 as authorized.

3. REPORT TITLE: Enter the complete report title in all capital letters. Titles in all cases should be unclassified. If a meaningful title cannot be selected without classification, show title classification in all capitals in parenthesis immediately following the title.

4. DESCRIPTIVE NOTES: If appropriate, enter the type of report, e.g., interim, progress, summary, annual, or final. Give the inclusive dates when a specific reporting period is covered.

5. AUTHOR(S): Enter the name(s) of author(s) as shown on or in the report. Enter last name, first name, middle initial. If military, show rank and branch of service. The name of the principal author is an absolute minimum requirement.

6. REPORT DATE: Enter the date of the report as day, month, year; or month, year. If more than one date appears on the report, use date of publication.

7a. TOTAL NUMBER OF PAGES: The total page count should follow normal pagination procedures, i.e., enter the number of pages containing information.

7b. NUMBER OF REFERENCES: Enter the total number of references cited in the report.

8a. CONTRACT OR GRANT NUMBER: If appropriate, enter the applicable number of the contract or grant under which the report was written.

8b, 8c, & 8d. PROJECT NUMBER: Enter the appropriate military department identification, such as project number, subproject number, system numbers, task number, etc.

9a. ORIGINATOR'S REPORT NUMBER(S): Enter the official report number by which the document will be identified and controlled by the originating activity. This number must be unique to this report.

9b. OTHER REPORT NUMBER(S): If the report has been assigned any other report numbers *(either by the originator or by the sponsor)*, also enter this number(s).

10. AVAILABILITY/LIMITATION NOTICES: Enter any limitations on further dissemination of the report, other than those imposed by security classification, using standard statements such as:

(1) "Qualified requesters may obtain copies of this report from DDC."

(2) "Foreign announcement and dissemination of this report by DDC is not authorized."

(3) "U. S. Government agencies may obtain copies of this report directly from DDC. Other qualified DDC users shall request through ________________."

(4) "U. S. military agencies may obtain copies of this report directly from DDC. Other qualified users shall request through ________________."

(5) "All distribution of this report is controlled. Qualified DDC users shall request through ________________."

If the report has been furnished to the Office of Technical Services, Department of Commerce, for sale to the public, indicate this fact and enter the price, if known.

11. SUPPLEMENTARY NOTES: Use for additional explanatory notes.

12. SPONSORING MILITARY ACTIVITY: Enter the name of the departmental project office or laboratory sponsoring *(paying for)* the research and development. Include address.

13. ABSTRACT: Enter an abstract giving a brief and factual summary of the document indicative of the report, even though it may also appear elsewhere in the body of the technical report. If additional space is required, a continuation sheet shall be attached.

It is highly desirable that the abstract of classified reports be unclassified. Each paragraph of the abstract shall end with an indication of the military security classification of the information in the paragraph, represented as *(TS)*, *(S)*, *(C)*, or *(U)*.

There is no limitation on the length of the abstract. However, the suggested length is from 150 to 225 words.

14. KEY WORDS: Key words are technically meaningful terms or short phrases that characterize a report and may be used as index entries for cataloging the report. Key words must be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location, may be used as key words but will be followed by an indication of technical context. The assignment of links, rules, and weights is optional.