PHOTOETCHED MICROWAVE TRANSMISSION LINES

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Abstract

Microwave transmission line and components of unusual light weight and compact construction can be made employing photoetching techniques to produce strip type transmission line. This report will be a general description of work done at Sanders Associates, Inc., to develop techniques for the design and manufacture of photoetched microwave transmission lines. Discussion will include measurements of attenuation and radiation leakage on parallel plate strip lines, as well as shielded type Tri-plate lines, the problem of mode purity and its relation to electrical parameters, various schemes of making transitions from standard waveguide to photoetched strip line. The basic design and performance of various components, as well as items of test equipment, such as slotted lines, matched loads, fixed attenuators, variable attenuators, directional couplers, crystal holders, phase shifters, hybrid rings, coax to Tri-plate transistors, etc., will also be treated. In addition, data will be presented showing impedance and susceptance values of simple discontinuities and impedance matching transformers. A simple technique for constructing gyrators and resonators will be presented, and the design and fabrication of an S-band signal generator employing photoetched microwave Tri-plate line will be shown, illustrating that practical microwave systems can be constructed far more economically than would be possible utilizing conventional waveguide, techniques.

Microwave transmission lines and components are usually heavy and bulky, and frequently represent a major cost item in the production of radar and communications equipment. It has long been felt that a strip type transmission line consisting of a sandwich of metal foil and dielectric filling could be constructed that would lend itself well to easy fabrication using simple and conventional photoetching techniques.

Over two years ago, Sanders Associates, Inc. started a program to investigate the microwave properties of various types of strip transmission lines. Two types of lines adaptable to photoetching techniques were considered: (1) the conventional parallel plate type Fig. 1(A) and (2) the three-plate modified coaxial type Fig. 1(B). Initial work was done on the former because it would be simpler to manufacture and more readily adaptable to the design of microwave circuits.

It was hoped to minimize radiation leakage in the parallel plate line in three ways: (1) by varying the characteristic impedance, (2) by selecting the optimum ratio of strip width to bottom plate width, and (3) by determining the most satisfactory boundary between air and dielectric.

Radiation Leakage

Since most of our measuring equipment at this time was in waveguide, it was first necessary, in order to experiment with parallel plate transmission lines, to develop transitions from conventional waveguides to parallel plate lines. Figs. 2 and 3 illustrate two transitions from a 220-ohm waveguide to parallel plate transmission line, the impedance of which could be changed simply by altering the width of the metal foil bonded to the surface of the dielectric. While it was felt that radiation leakage would increase with frequency, initial work was begun at X-band because of possible applications to many airborne microwave systems that were currently under development at Sanders Associates, Inc.

Attenuation characteristics of the parallel plate line were determined by insertion loss mechanisms. Radiation characteristics were measured by using a small pick-up horn to sample energy along the axis of the transmission line at a distance of $1\frac{1}{2}$ inches from its center. Results of these measurements are shown in Fig. 4. As is seen from these data, considerable cross-polarized leakage existed. While it could be argued that these were not radiating fields, but merely fringing fields that were not entirely confined within the physical limits of the line, experiments showed that these fields were decaying at a $1/D^2$ rate and not as a true exponential field decay.

Experiments demonstrated that whenever network discontinuities were present, such as crystal holders, matching transformers, etc., the radiation leakage in parallel plate lines greatly increased. It was felt that this radiation leakage would be a serious disadvantage in certain types of radar systems because, for one thing, it would complicate physical structures by necessitating the use of special shielding. Further, it would complicate measurement techniques and procedures. For example, in the construction of a good slotted line the probe is usually decoupled something in the order of 20 db, and if conventional slotted line techniques are to be employed in the measurement of standing wave ratios, the stray radiation leakage must be held well below this level in order to get a smooth reproducible standing wave pattern. Since radiation leakage was attributed to the fringing of the TEM fields (Fig. 5), it was decided at this time to investigate the three-plate transmission line in which, theoretically at least, no electric fringing fields exist normal to the axis (Fig. 6).

Attenuation and leakage measurements were made at X-band using the waveguide to three-plate line transition shown in Fig. 7. The three-plate line used was fabricated by clamping a 3/16" wide copper foil center conductor between two 1/16" polystyrene sheets which were, in turn, clamped between two heavy brass plates that functioned as the two outer conductors. Leakage was found ro be -70 db, and insertion loss was measured as 2 db/meter. The line used in this study had a nominal impedance of 35 ohms.

Mode Purity

Encouraging as these measurements were, however, another problem was encountered. This was severe leakage, of the order of -25 to -30 db, in the region of a discontinuity presented by a component such as a transition or a matching transformer. This leakage was attributed to simultaneous existence in the line of both parallel plate and coaxial transmission modes. The coexistence of these two modes made the tuning of various networks practically impossible, since a good impedance match for one mode would not be satisfactory for the other.

Parallel plate mode, it was reasoned, could be excited in the region of discontinuities by virtue of their unbalance effect on the line, thereby causing a potential difference between the outer plates and, hence, a radiating electric field normal to the axis of the line.

The parallel plate mode was eliminated by positioning the screws which hold the Tri-plate sandwich together (Fig. 8) close enough to the center strip so they function as shorting bars. This forced the two outer plates to remain at equal potential, and, as a result, the line always remained balanced.

For the sake of simplicity, it was decided to investigate the characteristics of Tri-plate transmission line in the region of "C" band. Since the wavelength at this frequency is approximately 2½ times longer than at "X" band, the physical separation between the two outer plates is a less significant fraction of a wavelength. Consequently a negligible voltage gradient exists along the shorting pins, thereby more efficiently forcing the two outer plates to remain at equipotential. Radiation leakage was thus reduced to -50 db or better in the region of even severe discontinuities when measured with the pick-up horn at a distance of 1" from the center of the line. Attenuation was measured as 0.37 db/ft. at 4200 mc.

Tri-plate lines tested up to this point consisted of copper foil mechanically bolted to polystyrene slabs. A more convenient method of manufacture was found in photoetching. In this process the center conductor of the Tri-plate line was photoetched on one side of each of two identical pieces of copper-clad teflon-glass laminate. The two pieces were then fastened together with rivets, their unetched outside surfaces serving as the two outer conductors of the Tri-plate line. The rivets served the dual purpose of holding the sandwich together and functioning as electrical shorting pins between the two outer conducting surfaces. In the region of discontinuities it was found to be advantageous to use closer spacing between rivets. By etching the center conductor on both dielectric plates instead of only one of them, the line is made insensitive to clamping pressure. In this type of construction, the outer layers may separate as much as 1/8" without any observable change in VSWR and with less than a 15° shift.

Substantially the same transmission characteristics were obtained with the new photoetched lines as with the earlier lines, with one exception: attenuation losses were greater; not sufficiently so, however, to prohibit the use of this cheaper, more convenient method of transmission line fabrication in microwave circuitry. Graphs showing attenuation versus frequency for Tri-plate lines, using both teflon-glass laminate and polystyrene as the dielectric, are shown in Fig. 9.

A final test in this investigation of the characterisitcs of photoetched microwave transmission lines was made to determine the cross coupling which existed between parallel strips of Tri-plate line.

Results are shown in Fig. 10. Lateral attenuation between adjacent lines at 4200 megacycles per second exceeds 70 db per ¼" separation, demonstrating the rapid field decay experienced with this type of transmission line.

Slotted Line

Before components could be readily designed in photoetched Tri-plate transmission line, it was apparent that a reliable slotted line, free from all leakage and modes other than the Tri-plate mode, would have to be designed. Such an equipment was made by constructing a long section of Tri-plate slotted line and etching one of the outer conductors completely away in the central portion, as is shown in Fig. 11(A).

This line was then encased in a machined metal housing with a tapered slot in its surface, the top surface then serving as the missing conductor of the Tri-plate line. This assembly is shown in Fig. 11(B). With the line completely encased in the housing, parallel plate mode is entirely suppressed. The housing, containing the Tri-plate line, is then bolted to a Hewlett Packard type 809B carriage with probe. In use, smooth reliable standing wave patterns were obtained with this slotted line up to frequencies of about 7000 megacycles per second. Above this frequency erratic results were obtained because of the unwelcome introduction of the waveguide $TE_{1,0}$ mode. This problem was solved by removing the side walls of the slotted line casting until they were below cutoff for dielectric filled waveguide propagation at the highest operating frequency desired.

Matched Loads and Attenuators

Matched loads and fixed pad type attenuators were constructed using resistor tape which was conveniently being produced and marketed by Sanders Associates, Inc. To make a load, the tape was cut with a pair of scissors to give the desired taper for a good match and then sandwiched between the dielectric sheets so that its resistive surface was in contact with the center strip of the Tri-plate transmission line. Loads consisting of 3" length of 100 ohm/square tape have been constructed which have a VSWR under 1.05 over a 10% band centered at 4200 megacycles per second. Such a load, assembled and unassembled, is shown in Fig. 12. Note the use of rivets.

Fixed attenuators were made simply by selecting a length of tape with the appropriate resistance value to give the attenuation desired and tapering both of its ends to obtain a good match. Variable attenuators were also constructed using resistive cards cut in the shape of a cam to give the desired attenuation taper. These cards were fastened to a shaft, and as the shaft rotated, a varying amount of the resistive cam was superimposed over the center strip of the Tri-plate line in a slightly hollowed out area in one of the dielectric slabs which form a part of the Tri-plate sandwich. Fig. 13 illustrates a 20 db variable attenuator with its waveguide counterpart. Fig. 14 shows a compact 6 db variable pad.

The resistor tape used for making loads and attenuators in Tri-plate is most convenient for use with strip microwave transmission lines. It can, for example, be cut with scissors, has a thickness of only 4 or 5 mils which makes it convenient for sandwiching between dielectric sheets, and is relatively inexpensive.

Directional Couplers

Directional couplers have been designed to give various coupling values. A typical directional coupler consisting of two stubs spaced $1/4\lambda$ apart, capacitively coupled to the main line and directly coupled to the mixing line, is shown in Fig. 15. This particular coupler has a 20 db coupling and 18 db directivity at 4200 megacycles per second for very small gap spacings, once again illustrating the extremely rapid decay obtained with Tri-plate line.

Impedance Matching Transformer

Fig. 16 illustrates a series stub used as an impedance matching device, and shows the change in Z/Z_0 plotted in VSWR as a/λ is increased from 0 to 0.64 for various values of b/λ. Note that as "a" approaches /2, all of the curves exhibit the properties of a series resonant circuit. This illustrates the compatability of this line's performance with theory, and also demonstrates the capabilities of the slotted line previously discussed.

Measurements taken on an open circuited shunt stub are recorded in Fig. 17. The stub has the same characteristic impedance as the main transmission line. The curves illustrate the change in VSWR as the stub length is varied over 0.7λ. The dotted curve is corrected for line attenuation. Fig. 18 depicts shift variations with changes in the normalized stub length.

A Smith Chart plot of admittance as the stub length increases from 0 to 0.48λ is shown in Fig. 19, and contains a plot of the same data corrected for line attenuation. This plot demonstrates that the open circuited shunt stub is indeed a pure susceptance.

A single shunt stub tuner consisting of an upper plate containing a stationary stub, a spacer, a rotary stub and a lower plate was constructed, and from this evolved the double shunt stub tuner. The double shunt stub is essentially the same as the single unit except that its elements are in duplicate. Fig. 20 is an exploded view of a single shunt stub tuner. Fig. 21 shows both a single and a double shunt stub assembled.

While these stub tuners operate on the principle of a continuous short circuit, it is obvious that the same design can be adapted to an open circuited stub tuner.

Successful phase shifters have also been built utilizing the same operating principles as the single and double shunt stub tuners.

Coax to Tri-plate Transition

A Type N coax to Tri-plate adaptor constructed from a standard UG58A/U panel plug is shown in Fig. 22. The mounting flange of the plug is fastened to one of the outer plates of the Tri-plate line by menas of screws which also serve as shorting pins, and its center conductor is soldered to the center strip of the Tri-plate line.

The Smith Chart plot shown in Fig. 23 illustrates both the unmatched impedance of this transition over a 10% band centered at 4300 megacycles per second, and the impedance after it was matched using a series stub matching device such as the one shown earlier in Fig. 17. In this case the stub length equaled 0.12 and the stub width equaled 0.14λ.

Hybrid Ring and Crystal Holder

A balanced mixer consisting of a hybrid ring with crystal holder circuits etched on two of the complementary arms is shown in Fig. 24. The crystals are standard cartridge type 1N23B's. By cutting off the tips of these crystals and placing them in their holders with the disc at the end of the ceramic in contact with the center strip of the Tri-plate line, an appreciable reduction in frequency sensitivity was realized.

Tests using matched crystals and equal dc loads revealed an input VSWR of less than 1.23 for this hybrid ring over the 4100 to 4500 megacycle per second frequency range, and a minimum isolation of 39 db between the out-of-phase arms. VSWR and coupling measurements on a Tri-plate hybrid ring are shown in Fig. 25.

Gyrators and Resonators

It is a simple matter to construct gyrators and resonators in Tri-plate transmission lines. Fig. 26 illustrates a gyrator coupled to a Tri-plate line.

Inside the cylinder shown in the illustration is a central core of ferrite. This is surrounded by polyfoam which is enclosed in a thin dielectric casing. A metal cover encases the entire cylinder. Cylinder diameter is selected so that only $TE_{1,1}$ fields are excited.

The two outside surfaces of the Tri-plate line are shorted to the outside metal cover of the cylinder, while the center strip of the Tri-plate is helically wound through several turns inside the dielectric casing.

With this arrangement, phase shifting can be accomplished through the influence of external magnetic fields.

By removing the ferrite core, cutting the cylinder to the correct length, and capping its ends, the unit can be made to function as a resonator for use with Tri-plate transmission lines.

S-band Generator

The S-band signal generator shown in Fig. 27 demonstrates vividly the practicability of constructing functional microwave test equipments in Tri-plate with an ease and economy which are unattainable when using conventional waveguide techniques.

The equipment illustrated consists of a 726C klystron which series-feeds, through a coax-to-Tri-plate transition in series with a flap attenuator, through a Tri-plate-to-coax transition as a useful output. The output signal is sampled by a 20 db stub type directional coupler which feeds into a matched bolometer.

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Industrial Planning Division

Cambridge Air Force Research Center

National Bureau of Standards

References

1. R. M. Barrett, "Etched Sheets Serve as Microwave Components," Electronics, vol. 25, p. 114-118; June, 1952.
2. Sanders Associates, Inc., report, "Photoetched Microwave Transmission Lines" of June 2, 1954, submitted under Contract CST-1365.
3. Sanders Associates, Inc. monthly progress letters to Cambridge Air Force Research Center under Contract AF19(604) - 1154.

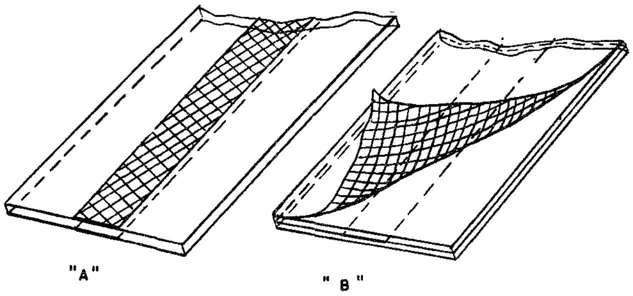


Fig. 1 - Parallel plate line (left) and tri-plate line (right).

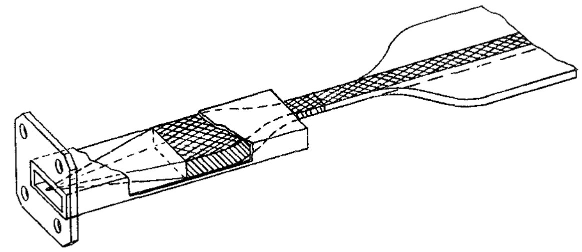


Fig. 2 - Polystyrene transition from waveguide to parallel plate line.

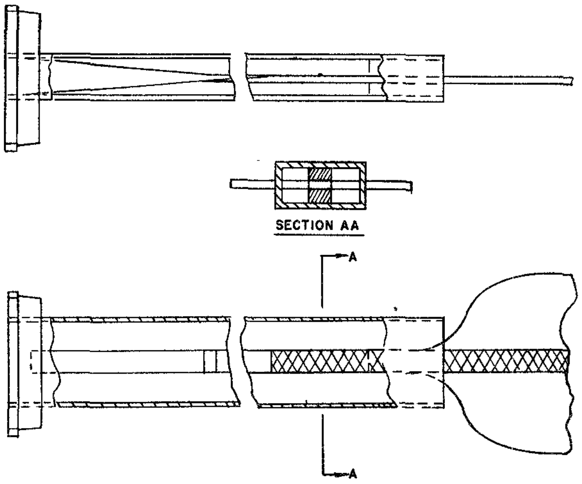


Fig. 3 - Ridge transition from waveguide to parallel plate line.

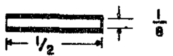
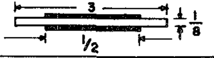
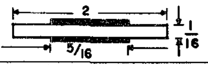
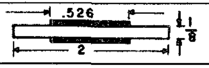
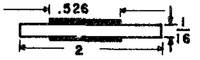
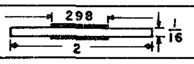
			E PLANE RADIATION		H PLANE RADIATION	
CONFIGURATION	V.S.W.R	ATT. db/METER	NEAR TRANSITION	CENTER OF LINE	NEAR TRANSITION	CENTER OF LINE
	1.53	9.0			-28.52 db	-51db
	1.17	10.5			-21 db	-44 db
	1.38	7.4			-35db	-52db
	1.1	6.9	-40db	50db	-30db	-55 db
	1.1	8.0	-48db	-59db	-36db	-56 db
ALL ABOVE MEASUREMENTS MADE WITH TRANSITION AS SHOWN IN FIG. 2				ALL BELOW MEASUREMENTS MADE WITH TRANSITION AS SHOWN IN FIG. 3		
	1.03	5 2	-32 db	- 42 db	- 37db	- 52 db
SAME AS ABOVE BUT WITH CHOKE AT TRANSITION	1.33	5.1	-35 db	-50db	-53 db	-60 db
SAME AS ABOVE BUT ONE MONTH LATER WHEN SHELLAC ADHESIVE DRIED	1 2	2 1	-35db	-45db	-48db	-55db

Fig. 4 - Attenuation characteristics of parallel plate line.

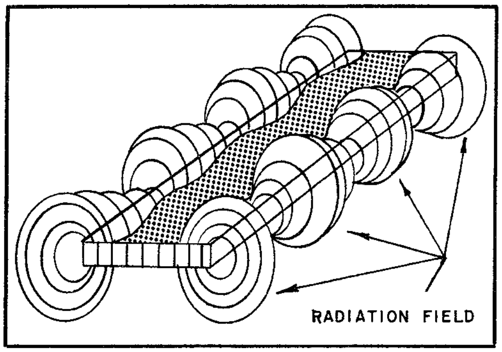


Fig. 5 - Field distribution in parallel plate line.

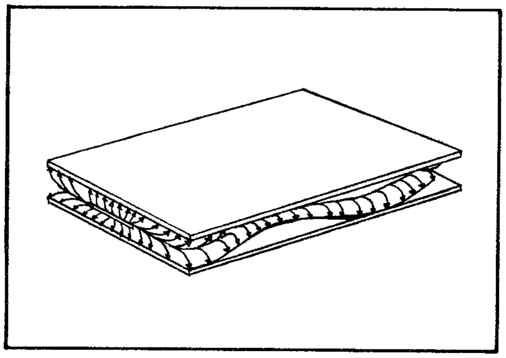


Fig. 6 - Field distribution in tri-plate line.

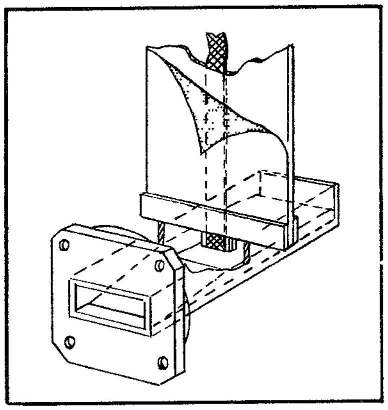


Fig. 7 - Tri-plate transition.

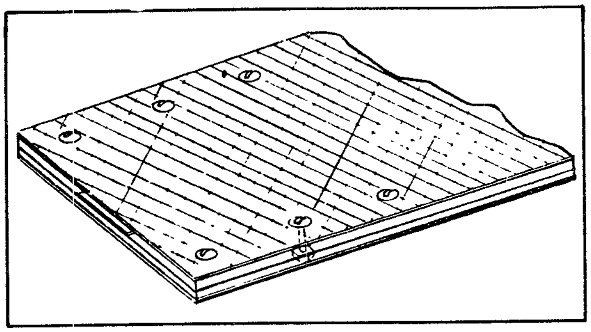


Fig. 8 - Early fabrication of tri-plate line.

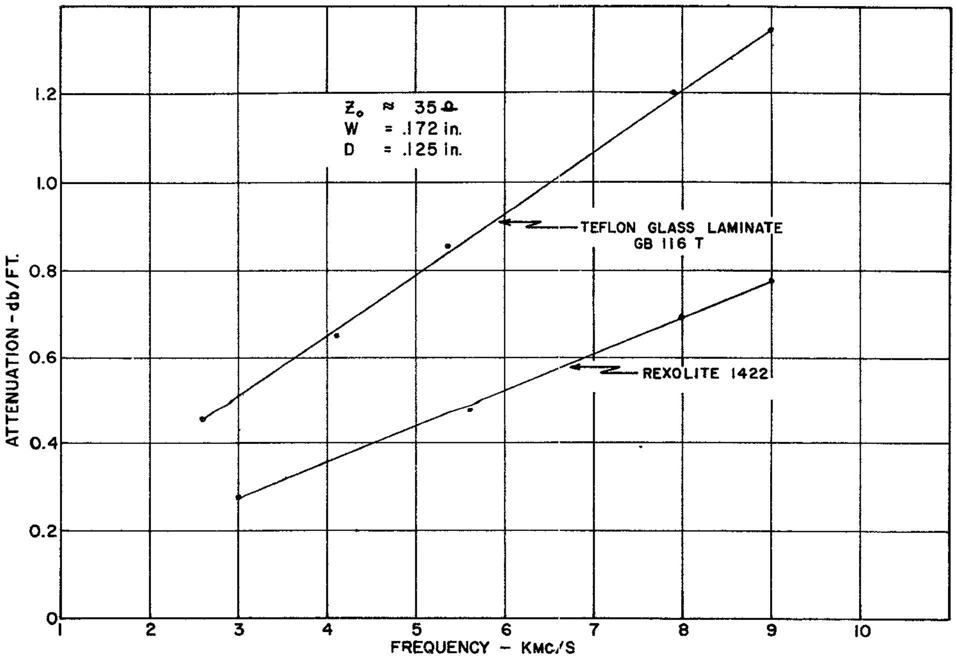


Fig. 9 - Attenuation vs frequency on tri-plate line.

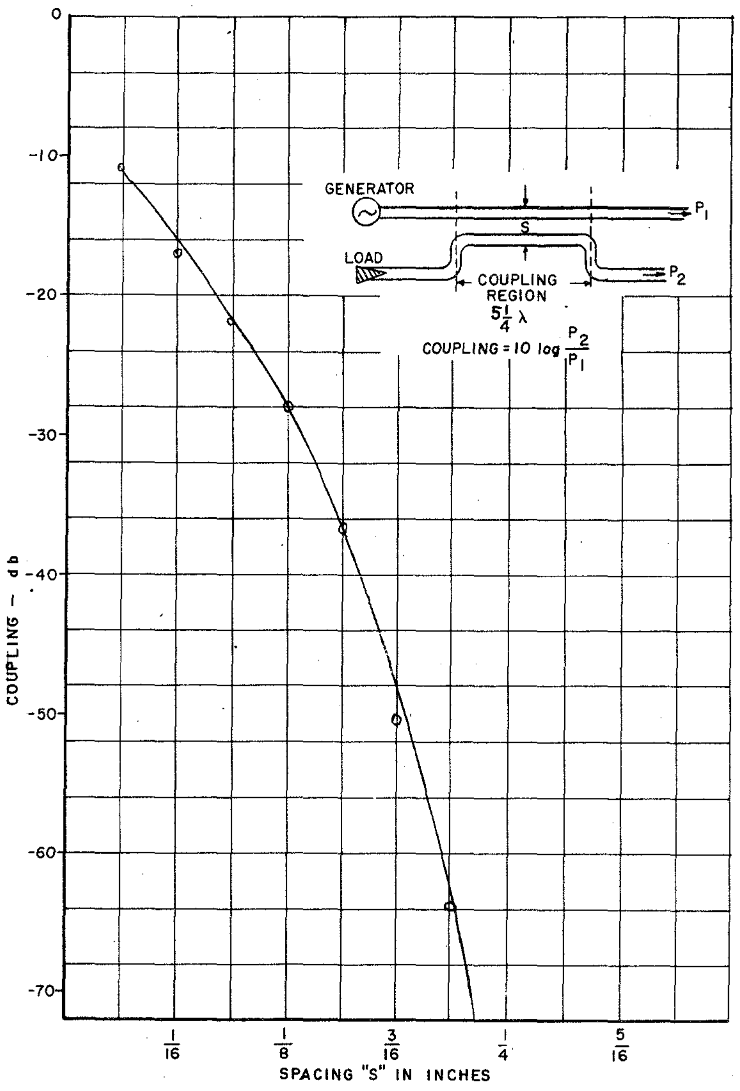


Fig. 10 - Variation of coupling with lateral spacing at 4200 mc/s.

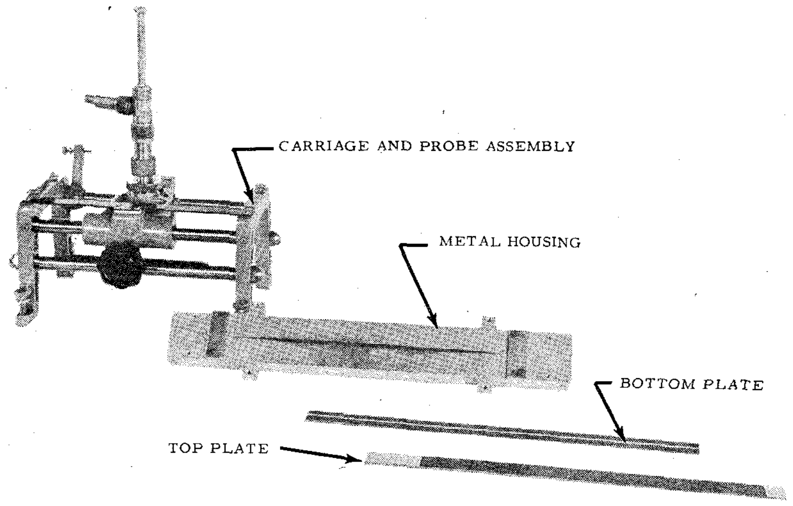


Fig. 11(A) - Tri-plate slotted line, unassembled.

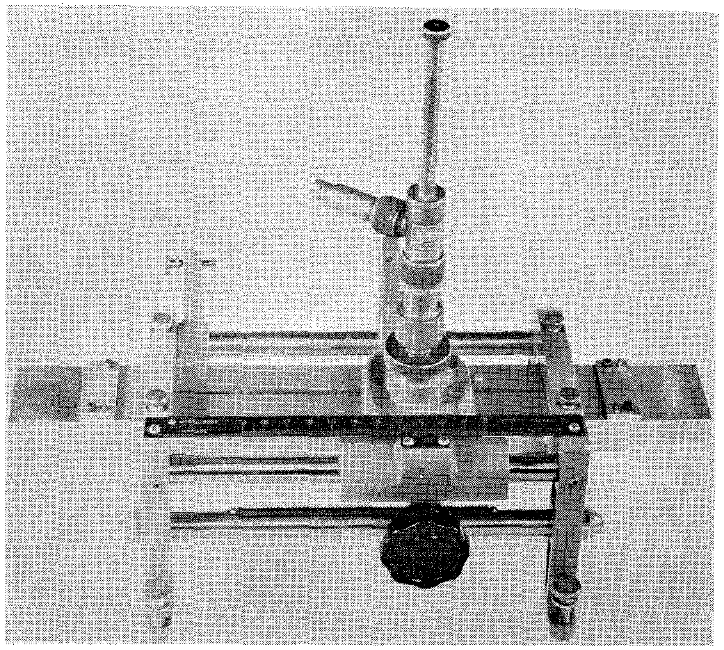


Fig. 11(B) - Tri-plate slotted line, assembled.

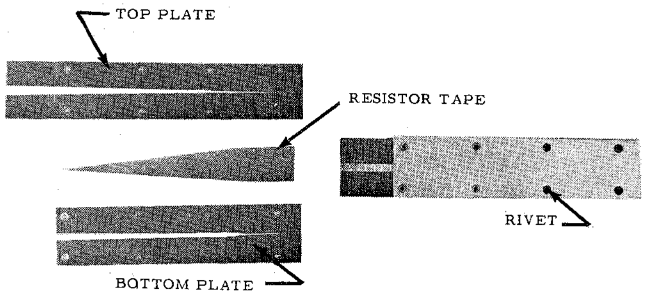


Fig. 12 - Matched load in tri-plate line, assembled and unassembled.

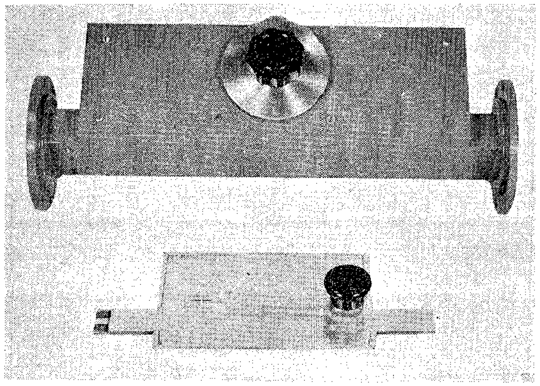


Fig. 13 - 20 db tri-plate variable attenuator with waveguide counterpart.

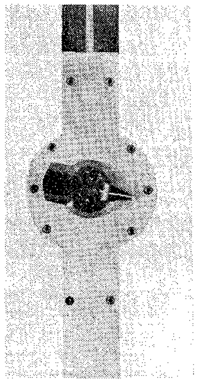


Fig. 14
6 db tri-plate variable attenuator.

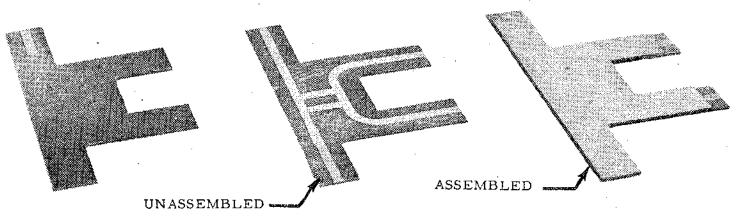


Fig. 15 - Directional coupler on tri-plate line, assembled and unassembled.

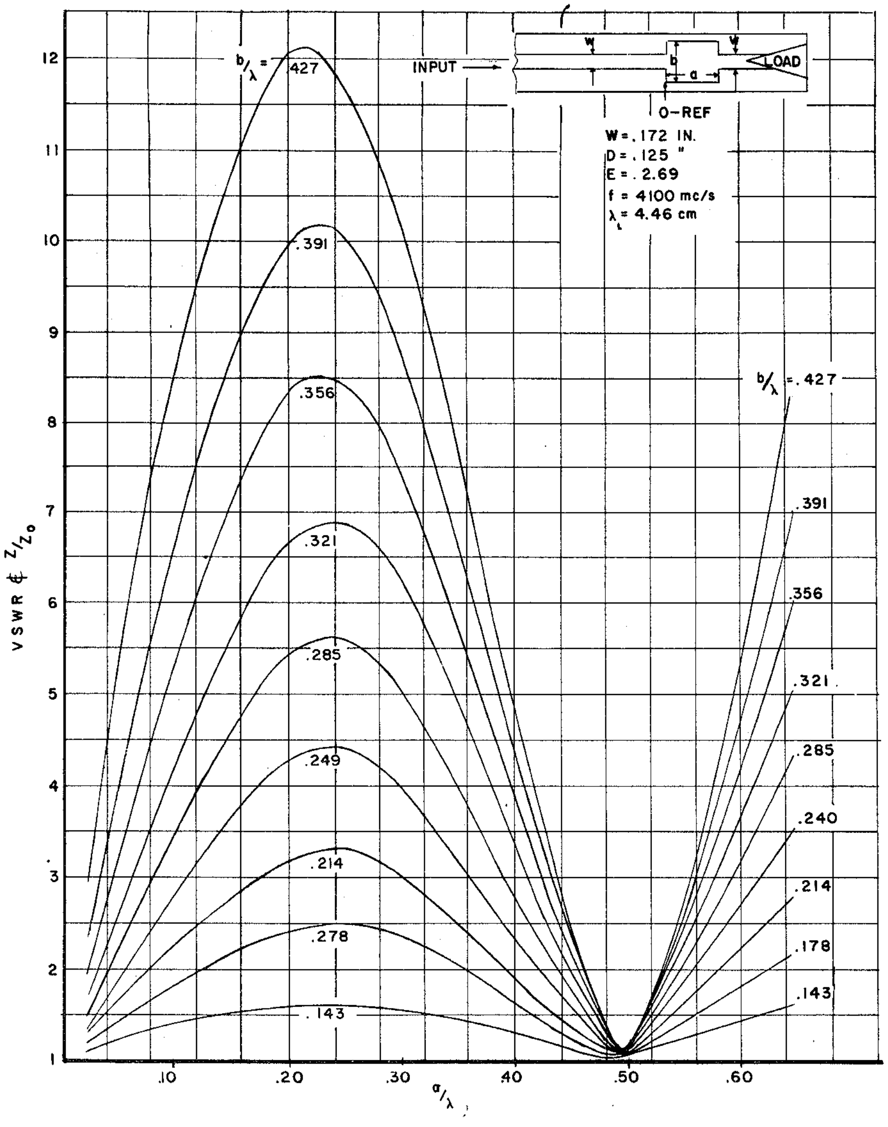
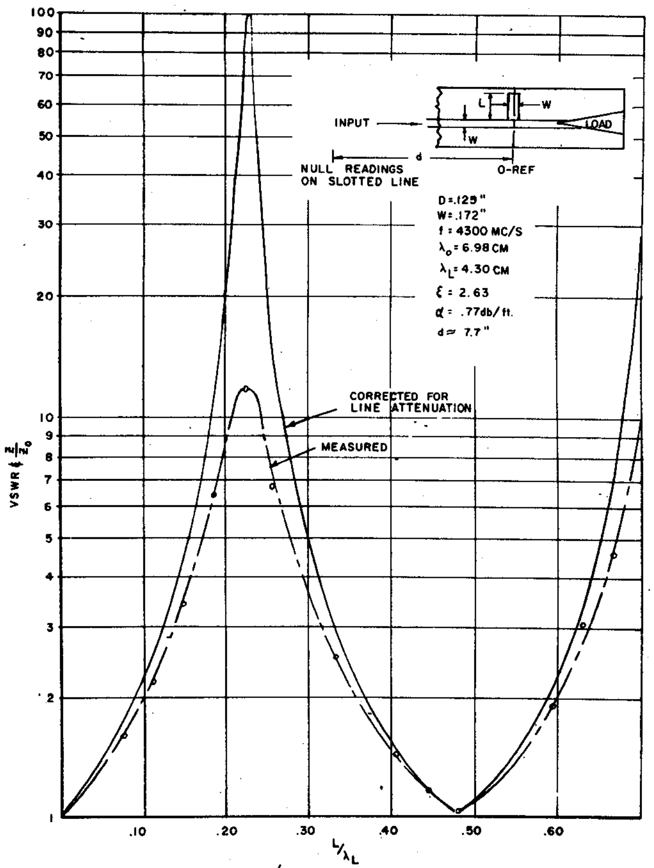


Fig. 16 - VSWR vs length and width of series stub.



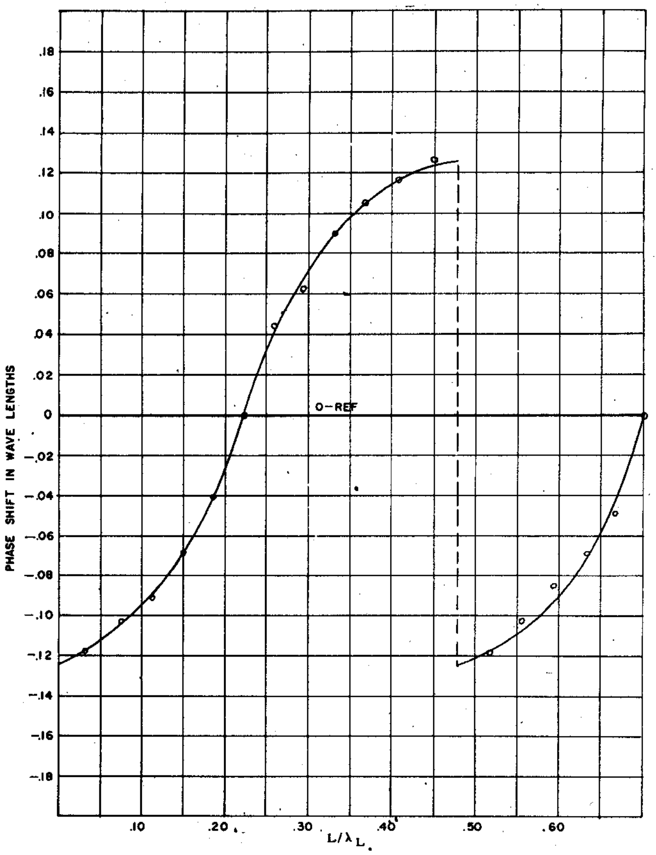


Fig. 17 - VSWR vs L/λ_L for open circuited shunt stub.

Fig. 18 - Phase shift vs L/λ_L for open circuited shunt stub.

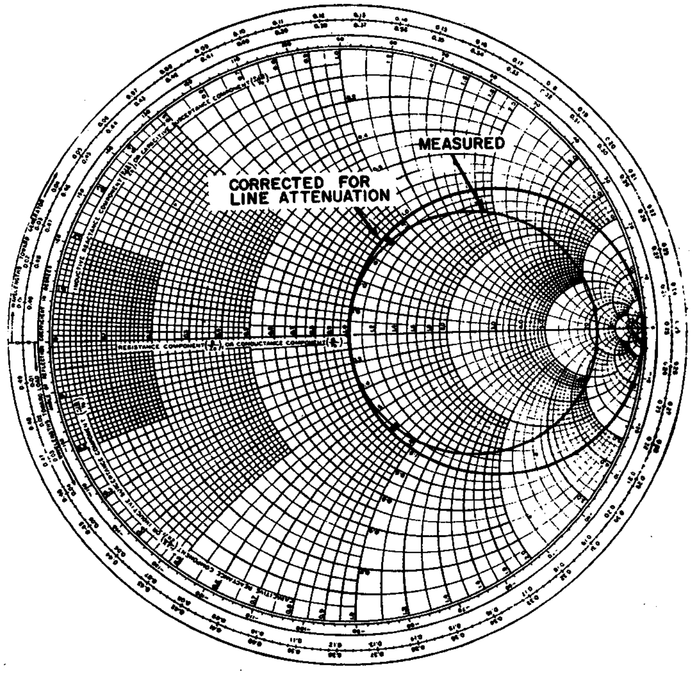


Fig. 19 - Admittance plot of open circuited shunt stub.

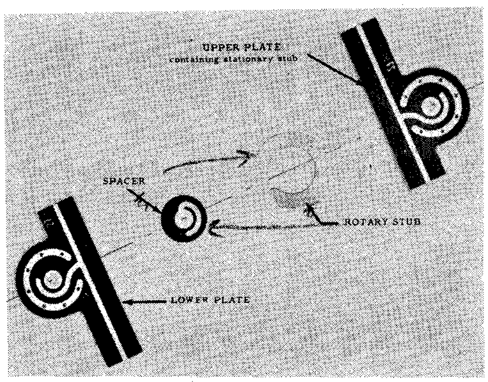


Fig. 20 - Single stub tuner, exploded.

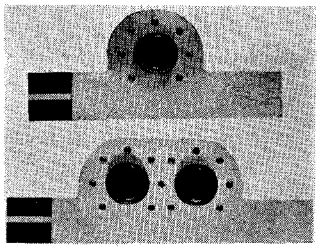


Fig. 21 - Single and double stub tuners, assembled.

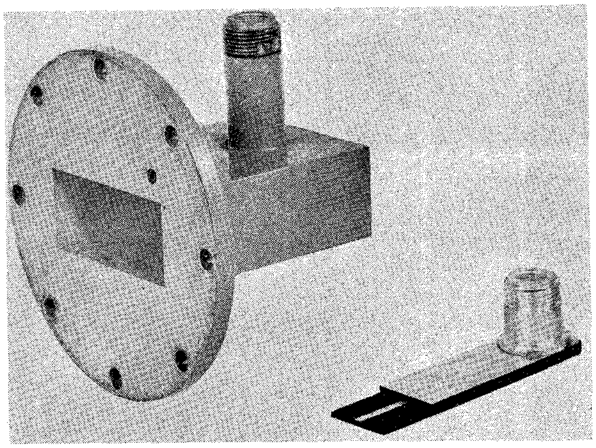


Fig. 22 - Coaxial adaptors: waveguide (left) and tri-plate (right).

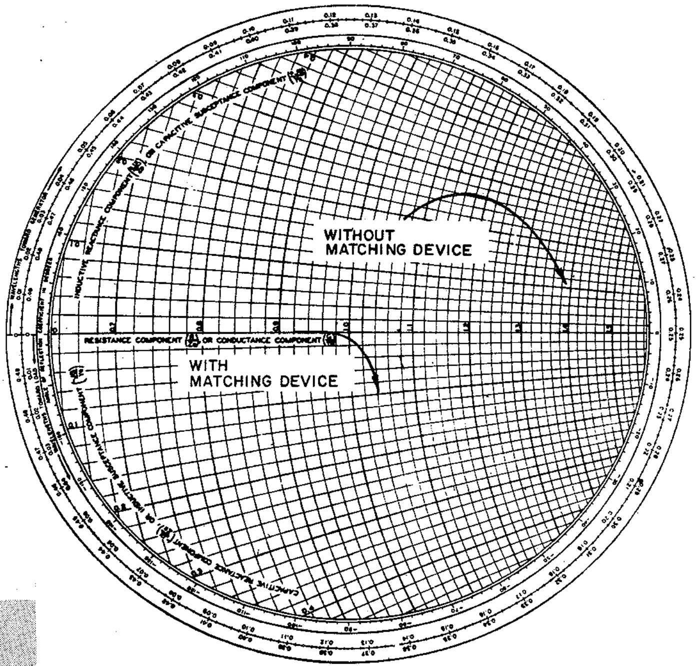


Fig. 23 - Impedance plot of tri-plate to coaxial transition.

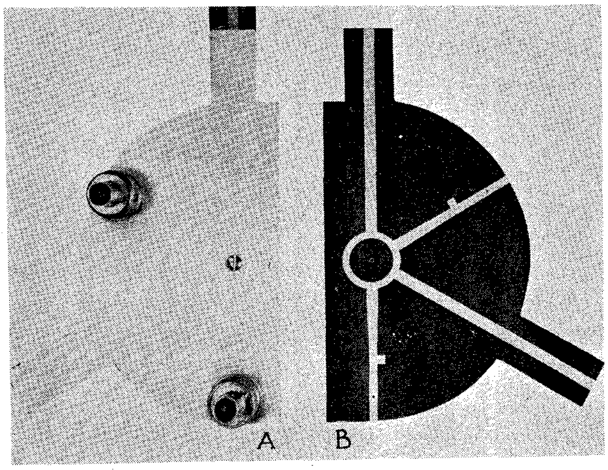
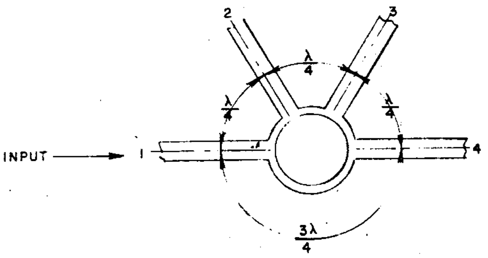


Fig. 24 - Tri-plate hybrid ring with crystal holders (A) assembled (B) internal view.



FREQUENCY MC/S	INPUT VSWR	RELATIVE POWER			
		P_1	P_2	P_3	P_4
4100	1.19	0db	- 3.2db	-44db	- 3.1db
4300	1.09	0db	- 3.1db	-49db	- 3.1db
4500	1.23	0db	- 3.1db	- 39db	- 3.2db

Fig. 25 - VSWR and coupling measurements on tri-plate hybrid ring.

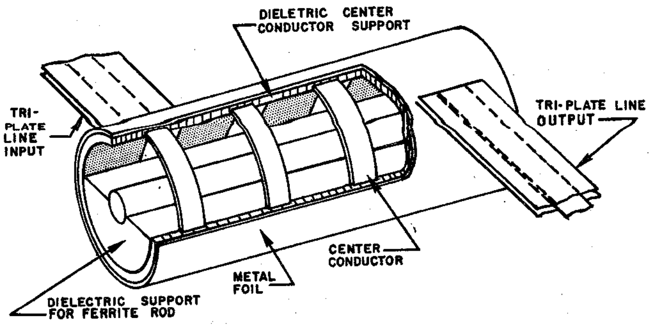


Fig. 26 - Typical method of constructing tri-plate gyrator.

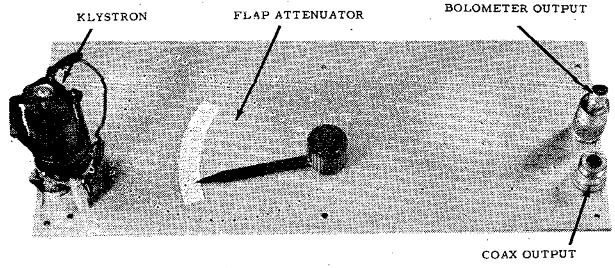


Fig. 27 - S-band signal generator.