CHARACTERISTICS AND SOME APPLICATIONS OF STRIPLINE COMPONENTS

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Abstract

Basic characteristics of Stripline in various frequency bands from 1000 to 16,000 mc are summarized. Various components such as transitions to coaxial line, attenuators, hybrid rings, directional couplers, and filters are shown. Some applications of these components in practical high performance microwave circuits and equipment in the frequency range of 2500-10,000 mc are also described.

Introduction

This paper describes some characteristics and applications of a new type of strip transmission line that offers significant advantages in the fabrication of microwave equipment. This line has losses comparable to those of conventional coaxial transmission lines and waveguide but has the additional features of being small, light, and inexpensive to fabricate. It has been especially useful in complex microwave circuits where numerous components must be built into a small space. In such applications the Stripline circuit is effectively reduced to a two-dimensional structure and all or most of the microwave circuit is etched or printed in one operation. This means that the fabrication costs, at least as far as the Stripline and its circuit elements are concerned, is the same whether the circuit be complex or simple. This is an advantage that the ordinary transmission lines cannot duplicate.

In considering a new type of transmission line the first question must concern the electrical characteristics of the line, in particular, its losses, but also its adaptability to microwave circuits, its power handling capability, etc. The strip line described in this paper is a low-loss line without significant dielectric or radiation losses. As a consequence it may be used for resonators, filter elements and other high-Q microwave components. It is readily adapted to the fabrication of all forms of microwave circuits because components are easily built-in or attached, and the whole circuit etched or printed in one operation in a similar manner to the mechanical fabrication of low frequency circuits. The power handling capability of the line is comparable to that of equivalent size coaxial line but is less than that of equivalent size waveguide.

Characteristics of Stripline

The basic characteristics of Stripline as determined experimentally have been given in detail[1] but are summarized briefly here for convenience. Some new results also are given.

Basic Configurations

Low-loss strip line described in this paper may take one of three forms shown in Fig. 1. All of these three forms utilize two metal ground planes with a strip conductor centrally located between the ground planes. The line at Fig.1A utilizes a solid metal center conductor supported by thin dielectric beads in a manner similar to that of air coaxial line. The strip may be undercut at the beads for compensation if desired, although this is usually unnecessary if the beads are located properly. The line at Fig.1B utilizes a thin metal strip conductor cemented to a thin dielectric sheet which is supported by metal or dielectric posts placed as shown. This line can be etched from a single metal-clad dielectric sheet which is commercially available. The thickness of the metal is usually of the order of .002" and the thickness of the dielectric sheet is as small as structually feasible and is usually in the order of .010 to .020 inch. The line at Fig. 1C is what our Laboratory has called Stripline. It consists of two thin metal strip conductors, one mounted on each side of a thin dielectric support of the type used in the previous line. This line is made by etching both sides of a double metal-clad dielectric sheet which is commercially available. To etch Stripline it is necessary to properly register both sides of the sheet.

The bead-supported line of Fig. 1A has very low losses because the copper losses are small and the dielectric bead losses are small if the dielectric material is low loss. Teflon and polystyrene are generally used. The single metal clad line of Fig. 1B has dielectric losses in the dielectric sheet support but these are small because the dielectric sheet is thin. Also a low-loss dielectric sheet is generally used, the most common for microwave applications being Teflon-glass. This material has a dielectric constant of 2.6 and dissipation factor of .0007 (at 1 mc). However, most of the dielectric between the strip conductor and ground planes is air. The double metal clad line, or Stripline of Fig. 1C has even lower losses because if the two strips are connected in parallel at the input and output of the circuit, the electric fields exist from each strip conductor to its corresponding ground plane and only fringing fields exist in the dielectric sheet. However, in a resonant structure, strong fields exist at voltage maxima, especially in coupling regions, and it is our practice to remove the dielectric from these regions. The losses of the bead line and Stripline are then comparable and very low, and the losses of the single metal-clad line somewhat greater but still low. In the discussion that follows the characteristics of Stripline as given will apply to both the bead line and the double metal clad line (with dielectric removed at voltage maxima) unless otherwise stated.

Physical Limitations

As would be expected, Stripline has practical limitations on its physical size just as do all microwave lines and components. That is, if only the dominant mode (TEM) is to exist, certain conditions must be met. These apply both to certain dimensions and to the symmetry of the structure. Briefly, these are: (1) the ground plane spacing must be less than half a wavelength, (2) the equivalent electrical width of the strip conductor must be less than half a wavelength, and (3) the center strip conductor must be approximately centered between ground planes and must be approximately parallel to them. The condition of parallelism is especially important for high-Q applications, such as reference resonators, etc., where an extremely small radiation loss in the parallel plate TEM mode or TE modes can have significant effect on the Q.

If the groubd plane spacing equals or exceeds half a wavelength, higher order modes can propagate and radiate to free space or couple to other circuits. This must be avoided. The extension of fields transversely from the strip conductor is a function of the ground plane spacing and frequency, and, if the ground plane spacing is well below half a wavelength, say less than a quarter wavelength, the transverse attenuation of these fields is given by

$$\alpha_t = 27/2b \qquad (1)$$

where α_t = attenuation in db per unit length

$2b$ = ground plane spacing

For example, if 2b is 1/4", the transverse attenuation of the fields is 108 db per inch up to about 10,000 mc. This means that two Stripline circuits between common ground planes need only be separated by approximately the ground plane spacing to achieve negligible coupling.

If the electrical width of the strip exceeds half a wavelength, higher order modes with circumferential variations can exist on the strip in a manner similar to those of a large coaxial line. The electrical width is greater than the physical width of the strip because of fringing effects at the edges. The corrections required to determine the cut-off wavelength for the first higher order mode are given in Fig. 2 for various ground plane spacings in terms of wavelengths.

The tolerance on centering a strip conductor between ground planes may be quite loose without deleterious effects. However, the tilt of the center conductor is very critical in high-Q applications. In order to loosen tolerances on tilt, metal posts or barriers can be used to prevent propagation between ground planes of higher order TE and parallel plane TEM modes. This is generally unnecessary in low-Q or matched applications.

Attenuation

Typical unloaded Q and attenuation characteristics of Stripline are shown in Fig. 3. In this figure the computed attenuation of silver-plated 77-ohm (optimum for Q) 1/4" and 1/2" air coaxial line is shown as well as the measured attenuation for silver-plated Stripline with 1/4" and 1/2" ground plane spacings. The attenuation of Stripline compares favorably with that of equivalent size coaxial air line. Also shown in the figure is the computed attenuation for silver-plated standard size waveguide for X-band. Notice that the left-hand scale in the figure is unloaded Q and the right-hand scale for attenuation in db per wavelength. These are related by the expression

$$\alpha = 27/Q_u \qquad (2)$$

where Q_u is the unloaded Q of a resonator.

We have also measured the unloaded Q of a Stripline resonator with 3/16" ground plane spacing at about 16,000 mc. This Q was over 2100. Measurement difficulties prevented a more precise determination.

Fig. 3 indicates that Stripline is basically a very high-Q line and may be used for all of the usual high-Q applications. The limitations on physical size that have been discussed also limit the Q that may be obtained if it is desired to avoid the possibility of higher modes. In general, the unloaded Q of Stripline rises as either the ground plane spacing or the width of the strip is increased. If even higher Q's are desired than those achieved within the limitations on physical size that have been given, it is possible to increase the width of the strip beyond an electrical half wavelength. We have measured Q's at least 50 percent higher by this technique. However, dimensions must be chosen so that transverse resonances of higher modes in the strip are avoided. It is quite possible to do this, and the technique of using an extra wide strip should not be overlooked if maximum Q is desired.

Power

The theoretical power limitation of Stripline of arbitrary dimensions has not been derived. We have made tests at S-band with 1/4" ground spacing and found the power handling capacity of 50-ohm bead-supported strip line to be at least 100 kw peak. At L-band we have found that the power handling capacity with 3/8" ground plane spacing is at least 150 kw peak. Actually, the components under test had not broken down at these power levels.

Environmental Effects

Humidity and temperature tests on Stripline (double metal clad with Teflon-glass dielectric) high-Q resonators at S-band have also been made and indicate that the effect on Q is small Typical results are given in Table I.

TABLE I.

ENVIRONMENTAL TEST RESULTS OF
STRIPLINE RESONATOR AT S-BAND

Temperature	Humidity	Unloaded Q
-55°C	very low	2760
+25°C	35%	2420
+70°C	98%	1850

Applications of Stripline

Coaxial Line to Stripline Transition

Because of its importance in practical applications a coaxial line to Stripline transition that has been used over a wide frequency range successfully is shown in Fig. 4. The VSWR of a transition of this type with W = .625" and the ground plane spacing = .50" was measured over the 1500-7000 mc frequency range and found to be less than 1.05.

Filters

Typical filters that have been made in Stripline are shown in Fig. 5. The configurations shown are those of the strip center conductor and are on Stripline etched on Teflon glass dielectric. The filter at Fig. 5A is an S-shaped 600 mc high-Q transmission resonator capacitively-coupled at the ends. The filter at Fig. 5B is a bandpass filter for S-band with a shunt trap added. Filters at Figs. 5C and 5F are low pass filters with m-derived end sections. The filter at Fig. 5D is the same as the one at Fig. 5B without the trap. The filter of Fig. 5E is an X-band transmission resonator.

Typical characteristics for four-section low-pass filters such as those of Figs. 5C and 5F with 1/4" ground plane spacing are shown in Fig. 6. The cut-off frequency for the filter of Fig. 5C is 1500 mc and for the one of Fig. 5F is 3000 mc.

Fig. 7 is a photograph of a high-pass filter in Stripline that we recently developed. This is a six-section filter, four sections of which are the usual constant-K intermediate sections and two sections are constant-K transforming end sections with a cut-off frequency 1/1.3 or .77 that of the intermediate sections. The cut-off frequency of the filter is that of the intermediate sections; that is, 600 mc.

Several of the techniques used in the construction of this filter are of interest. The shunt elements are Stripline grounded at the outside edge. In the pass band these act as inductive elements. The series capacitors in the main line are formed by breaking the top and bottom strips at slightly different points so that one overlaps the other and forms a small 2-plate capacitor with Teflon glass dielectric. The series capacitors required in this filter vary from about 2 to 6 uuf and are easily obtained by the overlap. This permits the filter to be exceedingly compact, the over-all size being about 3½" x 1⅛"; the ground plane spacing is 1/4".

One undesired effect of breaking the top and bottom strip conductors at different points is to unbalance the potentials on each so as to excite the TEM mode in the space between the strips. An interesting initial characteristic of this filter was that it had a point of severe attenuation in the vicinity of 1800 mc. This was due to a TEM resonance in the region between the strips of the shunt inductive elements. This resonance was eliminated by soldering small pins through the Stripline, connecting top and bottom strips together at the critical points of unbalance.

The frequency characteristic of this high pass filter is shown in Fig. 8. The pass band extends from the cut-off frequency of 600 mc to 6000 mc. The insertion loss over the band is generally less than 1 db, although above 3500 mc some small peaks in insertion loss occur These are probably due to the lack of terminating end sections for the high frequency end of the band. Such sections could be added to improve the pass band insertion loss at high end of the band if this becomes necessary.

The equivalent circuits for a single filter section and for the entire filter are also shown in Fig. 8. As a matter of interest, C_1 is 6uuf, C_2 is 2.8 uuf, and C_3 is 2.4 uuf.

Directional Couplers

Although the theory on which to base the construction of directional couplers is well known,[2] we have not had a great deal of success in designing Stripline equivalents of conventional couplers. One exception to this, however, has been in the case of branched line directional couplers, where experimental couplers have matched the theoretical design quite well. In Stripline the branched line directional coupler is a multipath coupler that utilizes high impedance shunt branches as coupling elements between the main and auxiliary lines. This type coupler is characterized in general by extreme frequency insensitivity of coupling and by the fact that close couplings may be obtained without setting up high standing wave ratios in the main line.

Fig. 9 shows center sections of two such couplers for S-band. These are both binomial array type multiple path couplers with a branch spacing of a quarter wavelength. In the two element coupler, the relative amplitude coupling of the two branches is 1:1; in the three element coupler, it is 1:2:1. In both cases the coupling is controlled by the length and impedance of the shunt arms. The directivity is a function of the spacing of the shunt arms. In both couplers, the length and spacing of the arms are about a quarter wavelength.

It may be interesting to note at this point the ease with which Stripline components can be made for experimental purposes. For laboratory work, etching or printing is generally not used because of the time required. The fastest method we have found of fabricating the center sections for Stripline microwave components is to cut the thin metal on the dielectric sheet along a straight edge by means of a razor blade, and then peel off the unwanted metal. Some of our people have become quite proficient in this art. For example, both of the directional coupler center sections in Fig. 9 were made in about 30 minutes each.

The frequency characteristics of the two-branch coupler are shown in Fig. 10. In this case both the length and spacing of the shunt arms have been adjusted slightly from the theoretical value of a quarter wavelength. The spacing was adjusted to give the best directivity characteristic. This was centered at 3400 mc. The theoretical directivity D is given by[2]

$$D_{db} = 20 \log \sin (\pi/2) \left[(f_o/f) - 1 \right] \qquad (3)$$

where f_o = design frequency
f = actual frequency.

This is plotted in dashed lines in Fig.10.

The measured directivity of the two-branch coupler is greater than 20 db over an 8.5% bandwidth. The coupling is approximately -8 db over this band. Ideally, maximum coupling should occur at the design frequency, in this case 3400mc. Since the measured coupling is peaked at about 3000 mc, the indication is that the length of the branch arms is too long.

The theoretical coupling C over the band is given approximately by[2]

$$C_{db} = -20 \log Z \qquad (4)$$

where Z is the ratio of the branch line impedance to the main line impedance.

Fig. 11 shows the frequency characteristics of the three-branch coupler. In this case the branch length and spacing are each equal to 1.0" which is a quarter wavelength at 2960 mc. The measured directivity indicates that a slight negative correction for the branch spacing is required. For convenience in comparison, the theoretical directivity curve has been centered at approximately the peak of the experimental curve. The frequency shift indicates that the branch spacing should be reduced about 2.5%.

The theoretical directivity[2] of the three-branch coupler is given by[2]

$$D_{db} = 20 \log \sin^2 (\pi/2) \left[(f_o/f) - 1 \right] \qquad (5)$$

The theoretical coupling over the band for this coupler is given by[2]

$$C_{db} = -20 \log Z \qquad (6)$$

where Z is the ratio of center branch line impedance to the main line impedance.

The theoretical directivity and coupling and the experimental coupling are also plotted in Fig. 11. Note that the experimental coupling is peaked at about 2900 mc, indicating that the length of the branch arms is about right.

The measured directivity of the three-branch coupler is greater than 20 db over a 25% bandwidth. The measured coupling is approximately -8.5 db over this band.

Microwave Receivers

We have applied Stripline techniques and components to several experimental and prototype microwave receiver front ends at C- and X-bands. Although in most of these units we have used solid, bead-mounted strip line for convenience in experimentation, we have determined that equivalent performance up to at least X-band is obtainable with Stripline, and at present we are planning a C-band Stripline front end for operational equipment.

Fig. 12 is the top view and Fig. 13 the bottom view of a prototype C-band receiver front end developed for the Raytheon Manufacturing Company under a Bureau of Ships contract. The basic strip line structure is approximately 15" x $6\frac{1}{2}$" x 1". This unit contains two klystron local oscillators, a signal balanced mixer, an AFC balanced mixer, a hybrid ring (multipath) directional coupler, a high-Q sealed strip transmission resonator, and several fixed and variable strip line attenuators. A signal i-f amplifier is shown attached to the microwave chassis. The center strip section (except for the resonator of the microwave unit) has been manufactured as a single unit. This prototype unit meets the Bureau of Ships environmental specifications for electronic equipment. Its average over-all noise figure, including a broadband TR RF loss and a 2 db 30 mc IF amplifier, is about 11.0 db, a figure comparable to waveguide receivers.

We believe the advantages of the high-Q forms of strip line (that is, bead-supported strip and Stripline) over coaxial line and waveguide in complex microwave circuits are well demonstrated in this equipment. Other high-Q elements, such as sharply tuned filters, could have been included in addition to the high-Q resonator shown. The ultimate fabrication costs of complex equipment in strip form in quantity should be relatively low, and this is being confirmed by initial production estimates.

Conclusions

The electrical characteristics of high-Q balanced strip transmission line in the bead-mounted solid metal strip and Stripline forms are in general comparable to those of coaxial air line and waveguide. However, strip transmission line has significant advantages over the conventional transmission lines as far as fabrication costs, space, and weight are concerned, especially in complex microwave circuits.

The use of Stripline in such microwave components as filters, directional couplers, and receiver front ends has demonstrated that it has wide application in high performance low-loss circuits. Significant savings in space and weight are obviously possible, and although no production costs have been given in this paper, it is evident that mechanical fabrication of Stripline is cheaper than the conventional fabrication processes in coaxial line and wavelengths.

Acknowledgments

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All of the strip line work reported in this paper has been done by members of the Special Devices Section at Airborne Instruments Laboratory. We wish to make special acknowledgment of Mr. H. Keen who did most of the experimental work under Contract AF19(604)-780.

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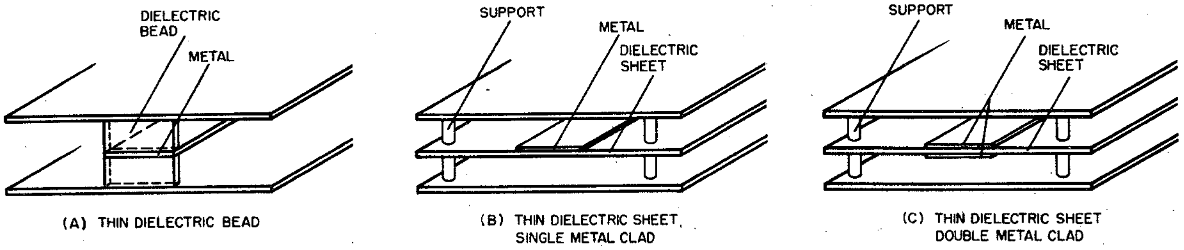
2. R. J. Harrison, "Design Considerations for Directional Couplers," Report 724, Radiation Laboratory, MIT; 1945.

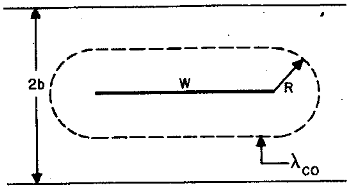


(A) THIN DIELECTRIC BEAD

(B) THIN DIELECTRIC SHEET, SINGLE METAL CLAD

(C) THIN DIELECTRIC SHEET DOUBLE METAL CLAD

Fig. 1 - Three forms of high-Q strip transmission line.



$\frac{2b}{\lambda_{co}}$	R.
0	.281b
.2	.292b
.4	.341b
.5	.503b

Fig. 2 - Cut-off wavelength for first higher order mode with circumferential variations.

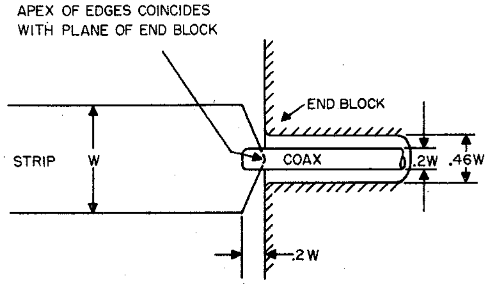


Fig. 4 - 50-ohm coaxial-to-strip transition.

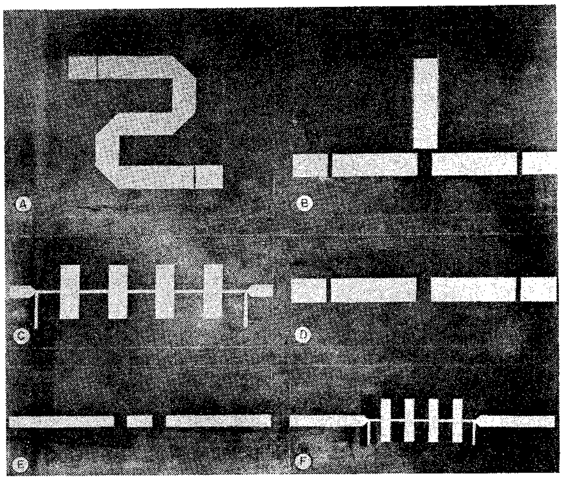


Fig. 5 - Center sections of representative filters.

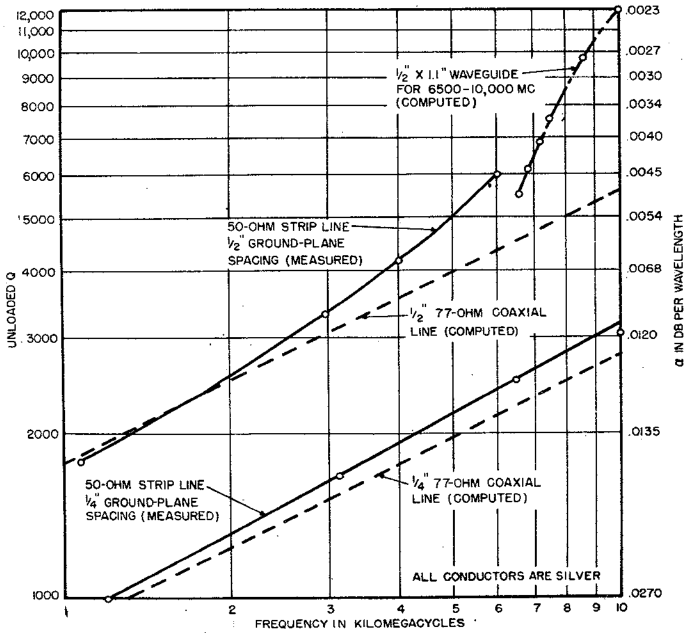
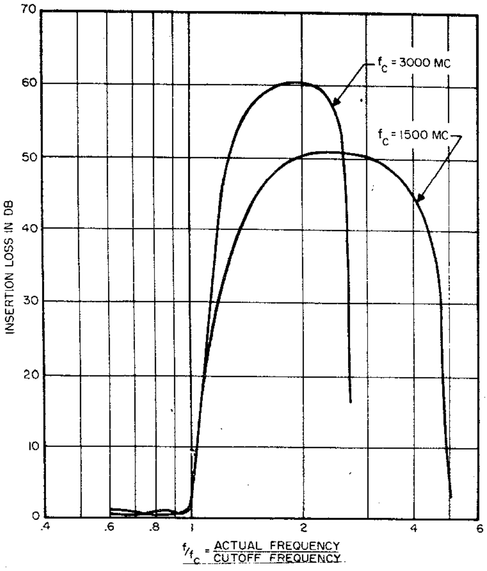


Fig. 3 - Unloaded Q and attenuation of silver-plated stripline, coaxial air line, and waveguide.



CHARACTERISTIC OF FOUR-SECTION LOW-PASS FILTER
(GROUND PLANE SPACING D = ¼ INCH)

Fig. 6 - Characteristics of four-section low-pass filters for 1500 and 3000 mc.

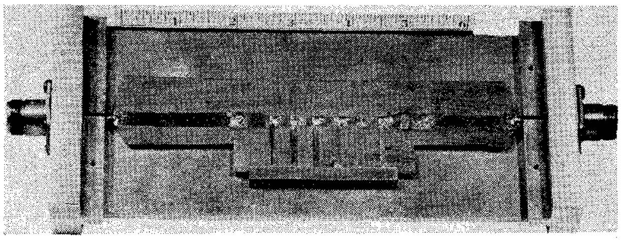


Fig. 7 - High pass filter with 600 mc cut-off.

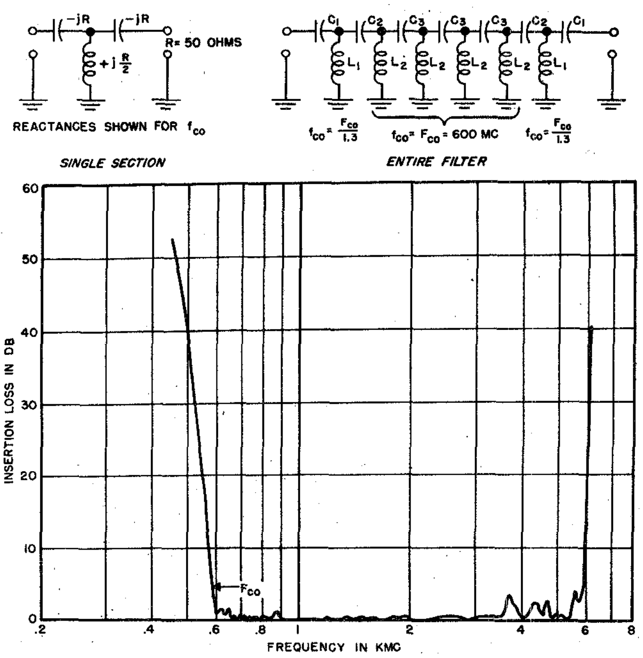


Fig. 8 - Characteristic of 600 mc high pass filter.

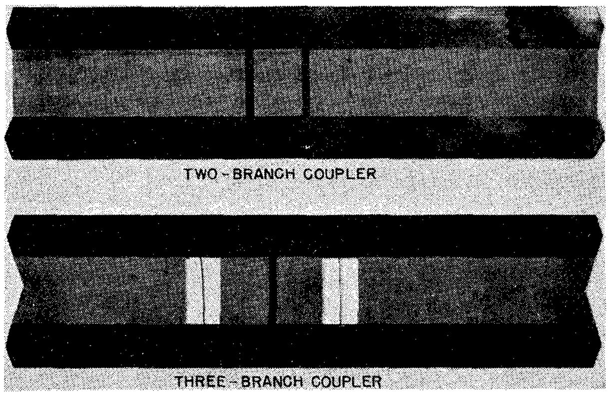


Fig. 9 - Two- and three-branch directional couplers.

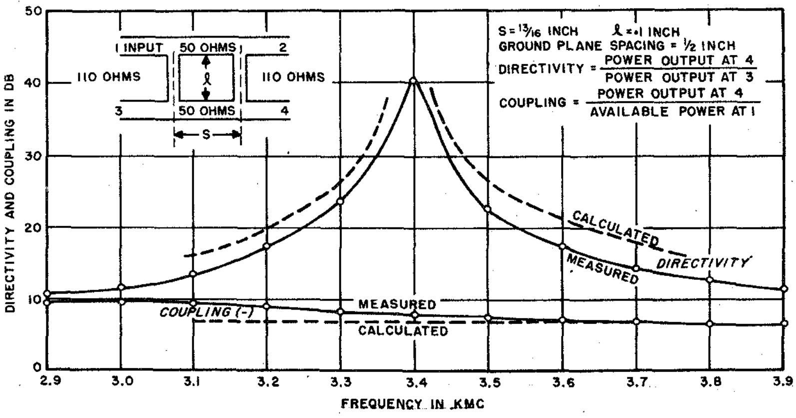


Fig. 10 - Directivity and coupling of two-branch stripline directional coupler.

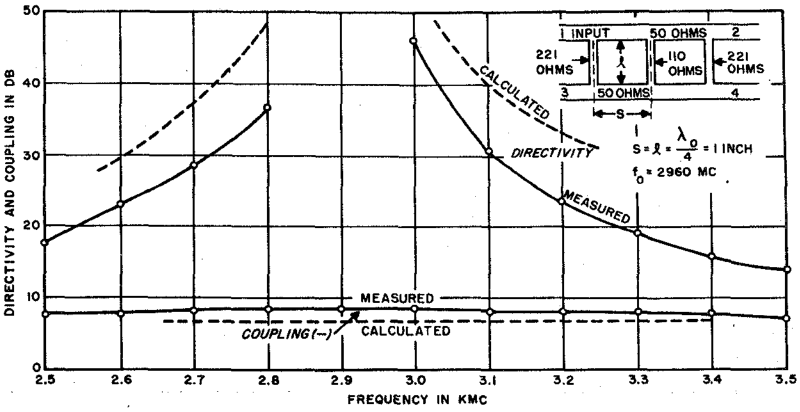


Fig. 11 - Directivity and coupling of three-branch stripline directional coupler.

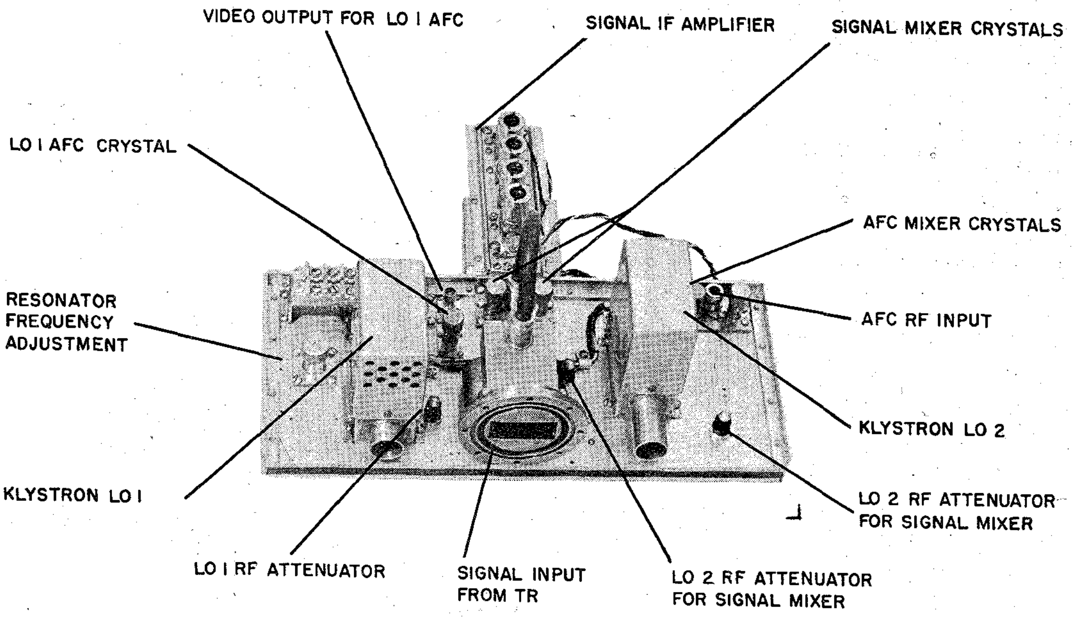


Fig. 12 - Top view of prototype C-band receiver front end.

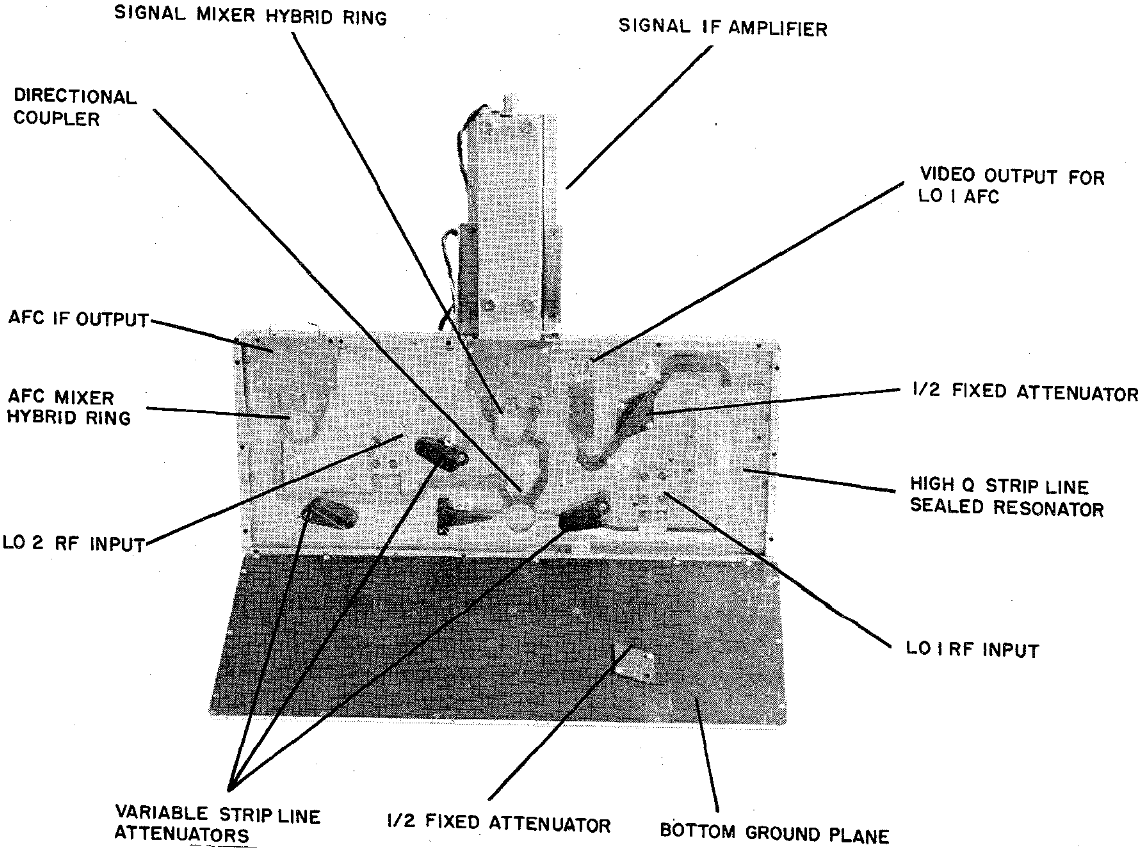


Fig. 13 - Bottom view of prototype C-band receiver front end.