MINIATURE STRIP TRANSMISSION LINE FOR MICROWAVE APPLICATIONS

Eugene N. Torgow and John W. E. Griemsmann
Microwave Research Institute
Polytechnic Institute of Brooklyn

Abstract

The construction of a strip line whose physical size is kept as small as possible consistent with reasonable electrical performance is presented. This line is fabricated by relatively simple techniques and can be shaped to fit line components into relatively confined spaces. The line has good power handling capacity and moderately low attenuation. Various components have been developed in this line including a broadband 3/8" coaxial line to strip line adapter, a broadband matched load, attenuators, and high and low pass filters.

Introduction

The line to be described in this paper was developed at the Microwave Research Institute under a program sponsored by the Rome Air Development Center, Griffiss Air Force Base, Rome, N.Y.[1] The initial purpose of this program was to determine the practicality of using strip transmission line in applications where, in addition to the usual advantages of strip line, it was desirable to keep the size of the line at a minimum and, if possible, to construct a line which could be shaped to fit in confined spaces. The objectives of this program can be summarized as follows:

1. Size: The physical size of the line shall be as small as possible, consistent with the requirements for reasonably low attenuation, reasonable dimensional tolerances and low radiation and stray field effects.

2. Fabrication: The line shall be constructed by simple fabrication techniques. The line is to be relatively flexible in order to permit shaping of the line into confined spaces, for example, by forming the line to fit the contour of a box or by winding a length of line into a coil. In addition, the line shall be durable.

3. Electrical Requirements: The line shall have a characteristic impedance of 50 ohms and shall operate over a frequency band extending from 100 Mc/sec to 12,000 Mc/sec.

Fabrication of the Line

Dielectrics, Adhesives, and Conductors

Three dielectrics initially considered for use in the construction of miniature strip line were polyethylene, polystyrene, and Teflon. All of these materials have relatively low dielectric constants and very low loss tangents. As, it can be shown, the copper wall losses account for the greatest contribution to the attenuation of miniature strip line, it was felt that the surface roughness inherent in the mechanical bonding techniques used in commercially available copper-clad dielectrics would result in excessively high attenuation constants for the line. Consequently initial consideration was given to dielectrics which could be fastened to metals and to each other with low loss, dielectric type adhesives.

At the beginning of this development, no adhesives were found which provided a good bond between teflon and metals. Consequently, the original choice of dielectric for miniature strip line appeared to be between polyethylene and polystyrene. Polystyrene was considered primarily because of the ease with which it could be bonded to itself and to metals. However polystyrene is a rigid material that can be formed or shaped only when heated. Therefore it did not meet the requirements for flexibility or formability. Furthermore, thin sheets of the sizes required for use in miniature lines were not commercially available with the necessary tolerances on thickness. Polyethylene, on the other hand, was commercially available in sheets of suitable thickness and the thicknesses were maintained to close tolerances. Furthermore polyethylene was both flexible and durable. Because, in addition to these factors, suitable adhesives were readily available to bond polyethylene to itself and to metals, all lines constructed under this program have used polyethylene dielectrics.

Recently, several new adhesives have become available commercially that provide good bonds to teflon as well as to polyethylene, so that either material can now be used. The ground plane conductors are copper strips which can be either cut to the desired width from thin sheets, or purchased in spools of the desired width and thickness. (In all the work on the miniature line, an attempt was made to choose the line dimensions in such a manner that stock sizes of commercially available materials could be used.) Both copper and silver center conductors have been used. The copper center conductors were obtained by running small copper wire through a rolling mill until the desired width was obtained (for example, a No.32 B and S guage copper wire, rolled to a thickness of 0.0016", has a resulting width of .033±.001"). Silver wire can be rolled in much the same manner. However, silver ribbons of the desired width are also available commercially.

Determination of Line Dimensions

Using the usual approximations of infinite width of dielectric and zero thickness of center conductor, the characteristic impedance equation

$$Z_0 = \frac{60\pi}{\sqrt{\varepsilon_r}} \frac{K(k)}{K(k')}; \quad k = e^{-\frac{\pi b}{h}}, \quad k' = \sqrt{1-k^2} \qquad (1)$$

was obtained, where

ε_r = relative dilectric constant of the line

$K(k)$ = complete elliptic integral of the first kind

b = width of center conductor

h = distance between ground planes.

For a characteristic impedance of 50 ohms, the ratio of b to h was found to be of the order of 0.82 for a polyethylene dielectric. It was further determined that a change in characteristic impedance of approximately 2% amounted to a change in the b/h ratio of 3%. As 3% of 0.040" amounts to 0.0012", it appeared that a line height of 0.040" was the minimum size that could be used in view of the normal tolerances inherent in commercially available polyethylene. The choice of a line height of 0.040" permitted the use of commercially available polyethylene sheets of 0.020" thickness. Furthermore, this led to a center conductor width of 0.0325" which was readily available in silver ribbon 0.001" thick.

Analysis of the field decay in the plane transverse to the line led to a choice of line width of 0.250". Some experimental work has been done with narrower lines with good electrical results, but fabrication of narrower lines leads to additional problems in the mechanical construction of the line. The over-all dimensions of the miniature strip line are shown in Fig. 1.

Line Characteristics

The computation of the dissipative losses in the line, using a parallel plate field distribution as an approximation to the true field in computing conductor wall losses, indicated that the dielectric and the wall losses in this line were of approximately equal magnitude and approach a total attenuation of 0.6 db/foot at 10 Kmc/sec. Computations of the line attenuation based on a more exact analysis of the field distribution yielded about the same value. The measured value of the line attenuation constant is approxomately twice this figure. This difference has not yet been fully accounted for.

Measurements of the characteristic impedance of the miniature strip line verify the computations of line dimension to a high degree of accuracy. Preliminary computations of the power handling capacity of the miniature line indicate that a line with a polyethylene dielectric can withstand peak powers in excess of 1 megawatt and average powers of the order of 100 watts. A teflon dielectric can more than double the average power rating of this line. No experimental verification of the power handling capacity of the line has been made as yet, but it is felt that these ratings are somewhat optimistic due to the assumptions employed in the calculation of the power handling capacity.

Coaxial-to-Strip Line Adapters

In order to utilize standard coaxial line test equipment to measure the electrical characteristics of strip line and strip line components, it was necessary to develop a broadband coaxial line to strip line adapter. For large strip line sizes, an adapter in which the strip line and coaxial line lie along the same axis leads to simple adapters with excellent broadband characteristics. Due to the extremely small dimensions of the miniature strip line, this type of construction proved to be unfeasible. Consequently, a right angle adapter was designed as shown in Fig. 2a. While preliminary models of this adapter did not yield a suitably low VSWR over the entire frequency band, an analysis of the adapter, based in part on the electrical equivalent to the physical structure of the adapter, and in part based on an earlier analysis of a coaxial line right angle bend,[2] led to the equivalent circuit shown in Fig. 2b. Modifications of the adapter design, based on the equivalent circuit analysis of the adapter, led to greatly improved performance. A typical VSWR vs. frequency curve for this adapter is illustrated in Fig. 3. While it was felt that additional modifications could undoubtedly improve the over-all performance of this adapter, the performance was deemed to be adequate for most applications of miniature strip line.

As an illustration of the performance that can be obtained in cases where a coaxial line to strip line adapter can be built along a common axis, Fig. 4 illustrates the measured VSWR characteristics of such an adapter which has been designed for use with a larger size strip line.

Attenuators and Loads

Early in the development of the miniature strip line, it was found to be necessary to have reasonably well matched attenuators and line terminations. A technique which led to very good results was the use of conductors made of nichrome ribbon. Nichrome conductors of the required dimensions were readily available through commercial suppliers, and calculations indicated that such conductors could introduce appreciable dissipative losses while the effect of these losses on the characteristic impedance was negligible. At 9000Mc/sec, for example, lines with nichrome conductors had an attenuation of over 6 db/foot. Furthermore, as the center conductor thickness is comparable to the depth of penetration for this material in the 9000Mc/sec frequency range; and as the major portion of the loss is caused by the center conductor, the total line resistance per unit length remains reasonably constant over a wide frequency range. The change in attenuation with changes in frequency therefore is quite slow.

Matched line terminations were obtained by using long lengths of nichrome line terminated in short or open circuits. A load consisting of a four foot length of nichrome line, for example, has a one way attenuation of 20 db at 9000 Mc/sec. Therefore, even with total reflection from the back end of such a line, the resulting input VSWR is only 1.02. In the utilization of relatively long lengths of line, the formability of the miniature strip line becomes a very useful property. Matched terminations consisting of long lengths of nichrome line can be wound in spiral form to provide compact matched loads such as those illustrated in Fig. 5.

Design of Strip Line Filters

Virtually all the techniques used in designing filters in coaxial line are applicable to the design of strip line filters.[3,4,5] One technique which has led to the design of filters having wide pass bands and wide rejection bands free from spurious responses involves the design of a lumped circuit ladder filter to give the desired frequency response. A distributed microwave circuit, equivalent to this lumped design in the frequency range of interest must then be realized. In order to insure that spurious responses do not occur in the frequency range of interest, it is necessary to keep the physical length of any line section representing a lumped reactive element less than 1/4 wavelength up to the highest operating frequency. Shunt elements can be realized by suitable lengths of transmission line placed at right angles to the main line. Short lengths of open circuited lines represent capacitors and short lengths of short circuited lines represent inductances.

Both the characteristic impedances of these stub lines and their lengths can then be chosen to give the desired reactances, within the limitation that the lengths be less than 1/4 wavelength at the highest frequency of interest. A series inductance can be realized by recognizing that a short length of line of high characteristic impedance is predominantly inductive. As a first order approximation, a short section of such a line can be represented by a lumped π section consisting of two shunt capacitors and a series inductance. It can be readily shown that the inductance and capacitances can be determined from the equations

$$L = \frac{Z\ell}{v} \qquad (2)$$

$$C = \frac{L}{2Z_1^2} \qquad (3)$$

where

ℓ = length of line section in cm.

L = series inductance of line section in henries

C = shunt capacitance at each end of line section in farads

v = velocity of light in the dielectric medium in cm/sec

Z = characteristic impedance of line section

Therefore, for any specified value of series inductance, a length of line is selected, based on the 1/4 wavelength size limitation, and the characteristic impedance of this line section is then determined from Eq. (2). The capacitance determined from Eq. (3) can be taken into account in the design of the shunt capacitances normally used between series inductive elements in filter sections. Series capacitances can be obtained, if the required capacitance is sufficiently small, by a gap in the center conductor of the strip line. However, the values of capacitance normally encountered in filter design work would require gaps that are impractically small. For larger values of capacitance, the structure of a parallel plate capacitor can be physically simulated in series with the line. This is accomplished by overlapping two sections of center conductor, separated by a thin sheet of dielectric (such as mica, or teflon tape). The customary equations for the capacitance of parallel plate capacitors are sufficient to determine the dimensions of such a section.

In cases where the design dimensions prove to be impractical from a structural standpoint, the filter can be designed in a line having either a higher or a lower characteristic impedance than the line in which the filter is to be used. The filter can then be connected to the specified line through the use of tapers or other suitable matching structures. As a case in point, a sequence of filters designed to operate in 50 ohm line over large frequency bands required a series inductive section of such short lengths that the ensuing width of center conductor was 0.003". This led to high insertion losses in the pass band and structural fragility. When the same filters were designed in 25 ohm line and tapered to a 50 ohm line at their terminals, the resulting width of center conductor was increased to 0.012", providing considerably more strength to the line and an appreciable decrease in the pass band insertion loss.

It should be noted that the use of resonant elements such as series or parallel L-C circuits, which can be realized by the use of quarter and half wavelength sections of line, will tend to produce spurious responses at or near harmonics of the design resonant frequencies. Such resonant circuits are frequently encountered in the lumped design of band pass or band elimination filters. A convenient way of eliminating these spurious responses in the design of band pass filters is to design the band pass filter of a tandem arrangement of two successive sections, a wide band low pass filter to provide the high frequency cut-off and a wide band high pass filter to provide the low frequency cut-off.

When shunt resonant structures must be employed, as in the case of the shunt arm of some types of filter terminating sections, it is well to remember that a microwave resonant structure approximates a given lumped resonant circuit only over a relatively narrow frequency range in the vicinity of resonance. Should wide band performance be required, the resonant frequency and the characteristic impedance of the resonant section must be determined empirically.

A number of filters have been designed for particular applications in miniature strip line. Figs. 6 and 7 illustrate the lumped and distributed designs for high and low pass filters respectively. These filters are based on a lumped design encompassing a five section constant-k filter terminated in matching m-derived half sections. The measured insertion loss of several of the low pass filters are shown in Figs. 8, 9, and 10. The measured insertion loss of a high pass filter is shown in Fig. 11.

It will be noted that, while reasonably good results are obtainable from the low pass filter design, the high pass filter insertion loss in the pass band is somewhat higher. While various methods are being employed to reduce the insertion loss in the pass band, other techniques are available to obtain high pass characteristics. This leads to simpler structures with improved characteristics. One technique that has been employed with reasonable success is to utilize the high pass characteristics of cut-off waveguide sections. The construction of a strip line filter utilizing the waveguide cut-off principle is shown in Fig. 12. This filter consists of a strip line whose center conductor tapers out to the full width of the cut-off section. Side walls are placed along this section so that the net effect is of two rectangular cut-off waveguides placed one atop the other. The measured characteristics of a filter of this type are shown in Fig. 13.

Conclusions

The wide variety of uses to which strip line can be applied has been long established. It has been shown that the only limitations to the miniaturization of strip transmission line are the tolerances on the thickness of commercially available materials and the ease with which the line can be fabricated. Photoetching techniques have been successfully applied to the fabrication of miniature strip line filters, in spite of the fact that some of the photoetched line sections were only 0.003" wide. The simplicity of construction and the accuracy to which these components can be reproduced have amply demonstrated the practicality of this line type.

References

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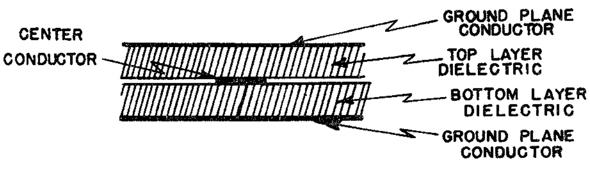
5. "First Quarterly Report on Microwave Strip Line Filter Program," Polytechnic Institute of Brooklyn Report R-365.3-54, PIB-299.3, May, 1954 on Air Force Contract AF-30(602)-980 with the Rome Air Development Center, Rome, N. Y.

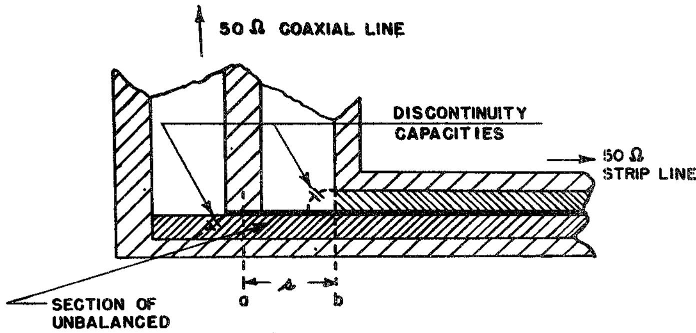
6. "Second Quarterly Report on Microwave Line Filter Program," Polytechnic Institute of Brooklyn Report R-365.6-54, PIB-299.6, July, 1954 on Air Force Contract AF-30(602)-980 with the Rome Air Development Center, Rome, N. Y.



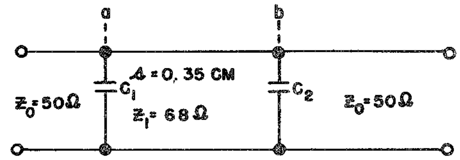
END VIEW OF STRIP LINE

COMPONENT	MATERIAL	WIDTH IN.	THICKNESS IN.
GROUND PLANE CONDUCTORS	COPPER, NICHROME	.25	.001
DIELECTRIC LAYER (EACH)	POLYETHYLENE	.25	.020
CENTER CONDUCTOR	SILVER, NICHROME	.0325	.001

Fig. 1 - Geometry of strip line.



(a) Enlarged sketch of strip line to coaxial line juncture.



(b) Approximate equivalent circuit.

Fig. 2 - Equivalent circuit of strip line to coaxial line adapter.

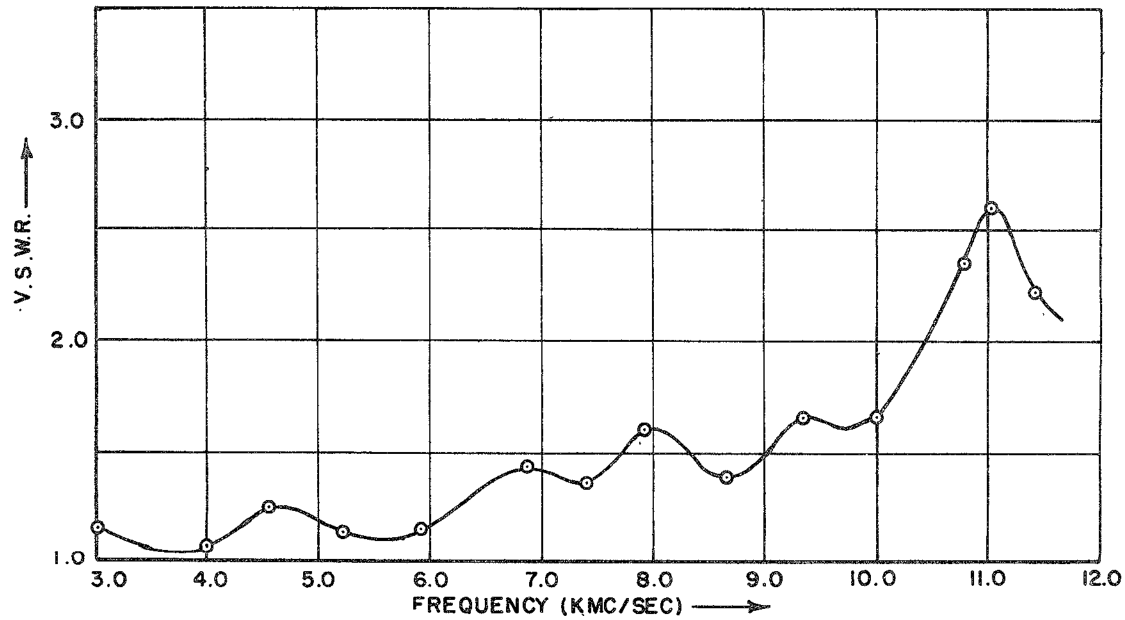


Fig. 3 - VSWR vs frequency of strip line to coaxial line adapter with single tuning adjustment.

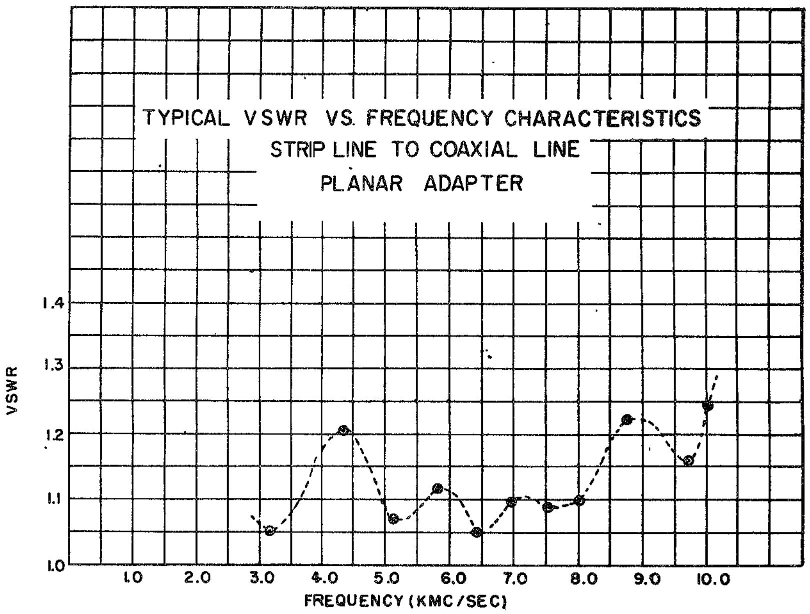


Fig. 4

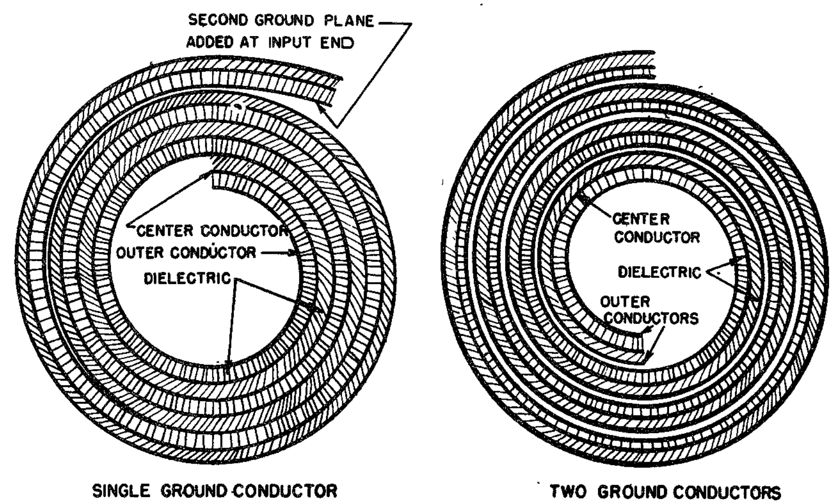


Fig. 5 - Spiral strip line.

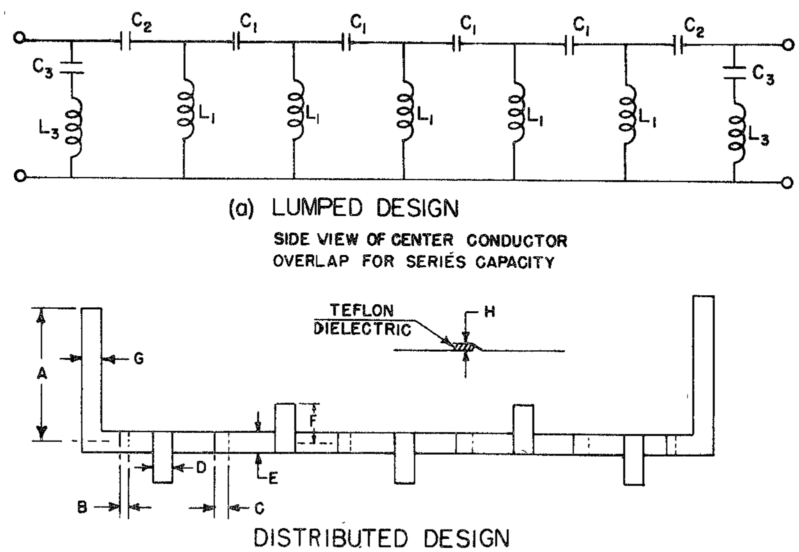


Fig. 6 - 5-section constant K high pass filters with M-derived half section terminations.

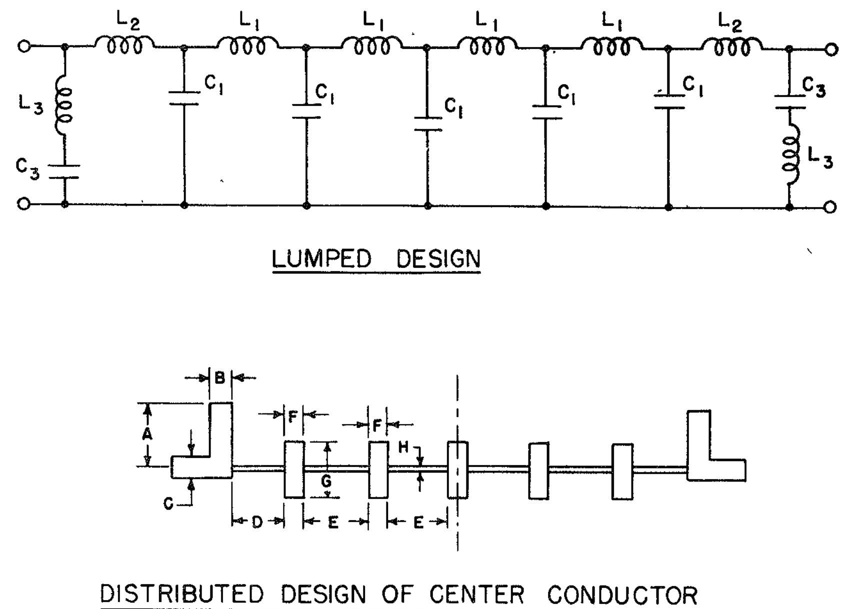


Fig. 7 - 5-section constant K low pass filters with M-derived half section terminations.

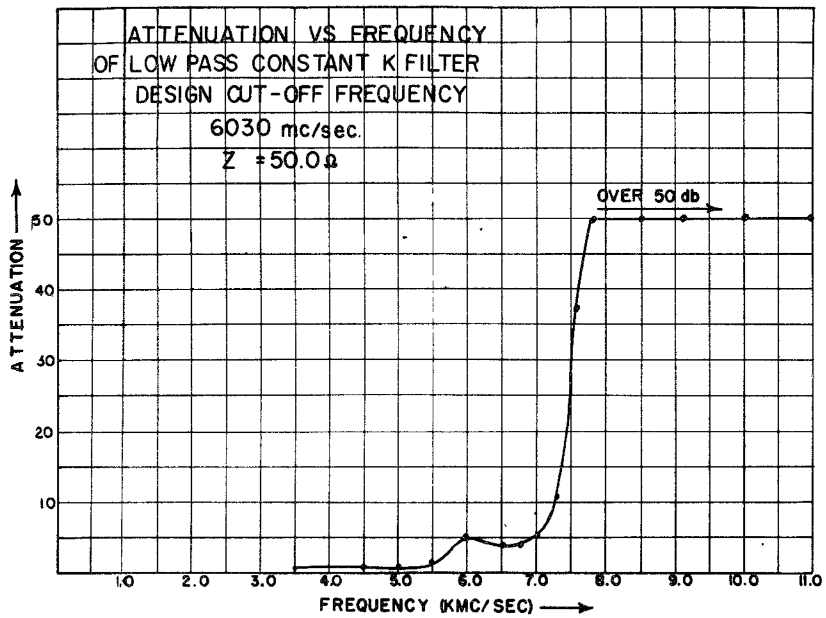


Fig. 8

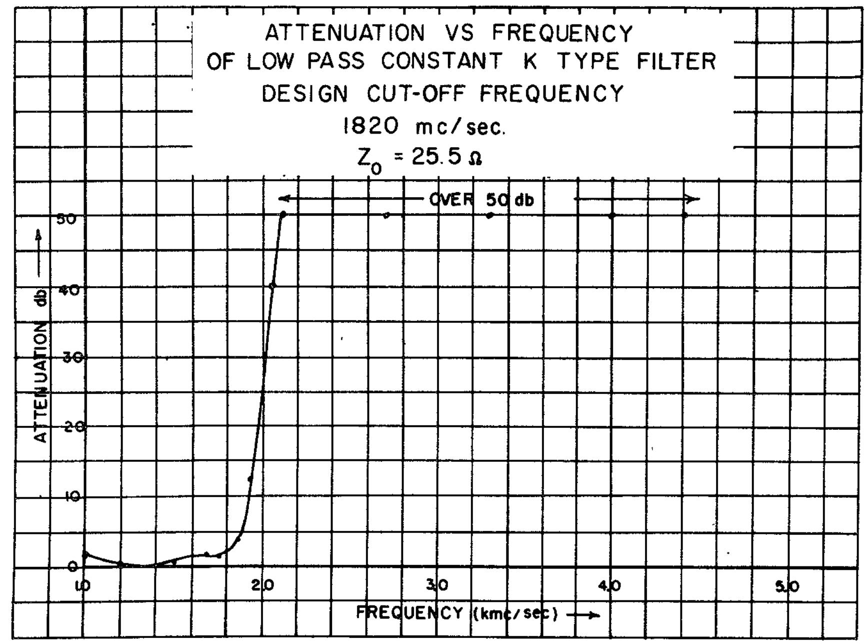


Fig. 9

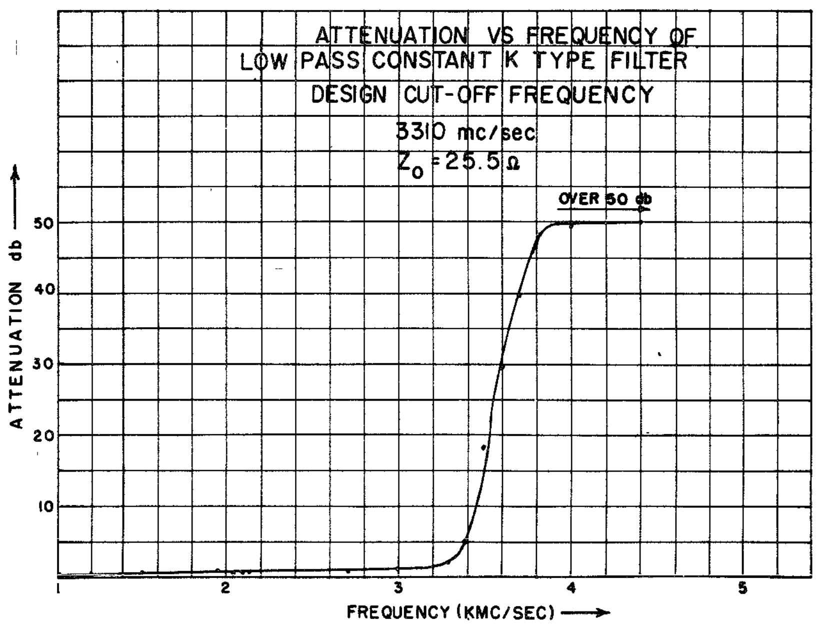


Fig. 10

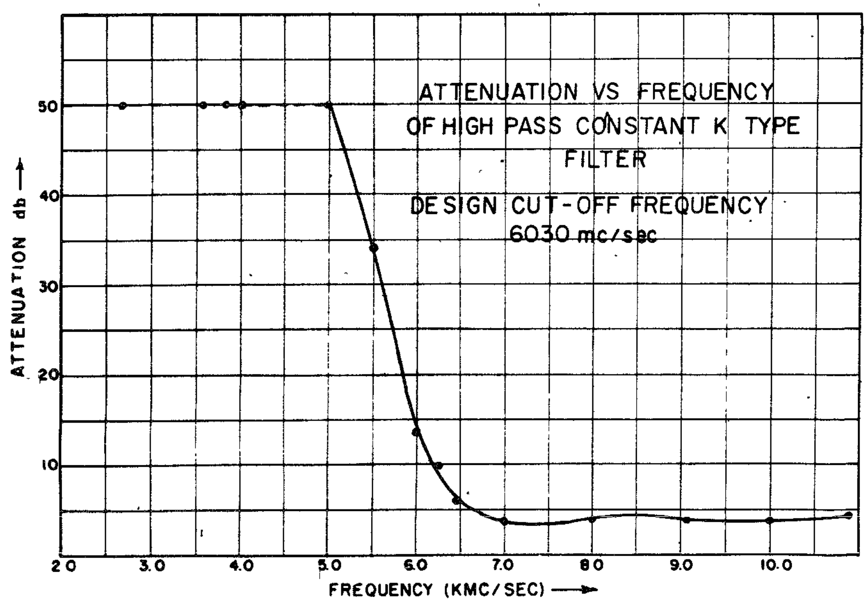
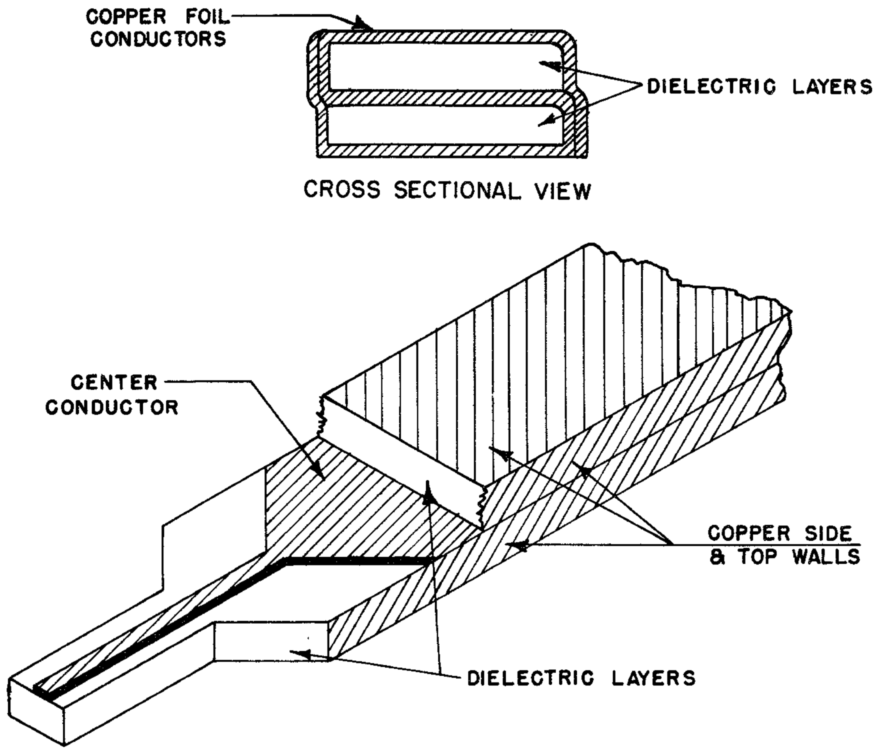


Fig. 11



CUTAWAY VIEW SHOWING TRANSITION BETWEEN STRIP LINE AND FILTER SECTION

Fig. 12 - Construction of stripline high pass cut-off filter.

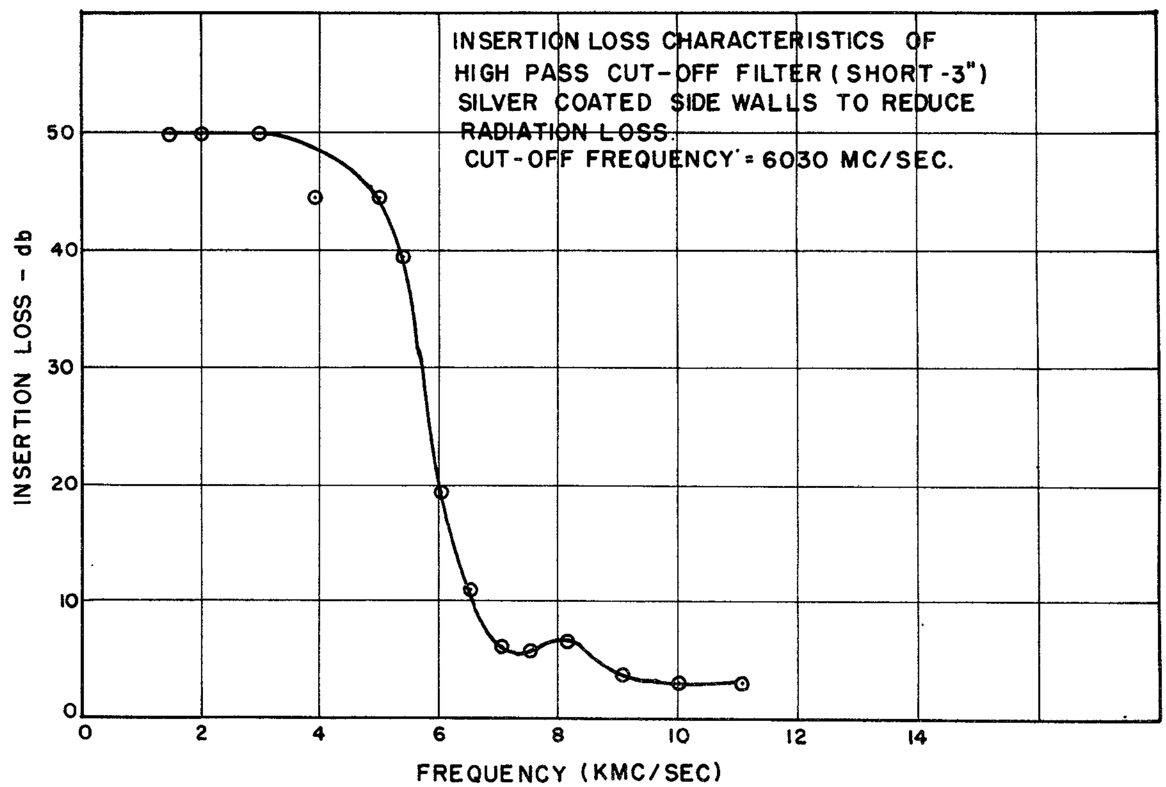


Fig. 13