MICROWAVE PRINTED CIRCUITS - A HISTORICAL SURVEY

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Introduction

The microwave printed circuit, as described in this paper, is an extension of the well-known technique which is of such importance in the lower frequency regions, where lumped element circuits are practical. This new circuit possesses all of the virtues of other printed circuits, such as light weight, cheapness, ease of manufacture, miniaturization, etc., along with the ability to be used at frequencies as high as 10,000 mc. The basis of the new technique is the planar or "flat strip" coaxial transmission system which was developed during World War II but which has remained unpublished and relatively unknown in the postwar period;[1] and for which an adequate theoretical analysis had not been available.

History

Early in 1949, while the author was trying to devise a new method of feeding a microwave "Wullenweber" antenna, it occurred to him that not only could "flat strip" coaxial lines be employed to carry energy from point to point, but they could also be used to make all types of microwave components, such as filters, directional couplers, hybrids, etc. Furthermore, he realized that the form factor of this type of microwave element was such that the standard methods and techniques used in low frequency "Printed Circuits" could be readily applied to the manufacture of such components. This marriage of the little-known "flat strip" form of the coaxial line to the vigorous art of "printed circuits" has resulted in the so-called "Microwave Printed Circuit" (MPC) or "Strip Line" which is already challenging the waveguide in its application to microwave systems.

In the beginning, the author was engaged in exploiting this technique to see how useful it really was. These experiments resulted in filters, directional couplers, matched loads, hybrids, etc., which were all constructed at 440 mc. This work was reported at the Dayton IRE Meeting in 1951 and in subsequent articles. The body of the present report is essentially this original paper. It is again presented at this time to give an historical backdrop to the more recent advances that will be presented at this conference.

A short time after the release of AFCRC work on MPC, a group of engineers from Federal Telecommunications Research Laboratories announced another form of printed line, now commonly known as "Micro-strip" which was an adaptation to planar geometry of the "two-wire line" in the same way that MPC is an adaptation of the coaxial line. The merits of these two systems are essentially the merits of their respective antecedents.

Very recently, Professor D. D. King of Johns Hopkins University announced the third basic type of line, as yet unnamed, which is an adaptation of the dielectric waveguide to planar geometry. More details of this line will be presented in a later paper.

The Planar or "Flat Strip" Transmission System

The planar transmission system upon which the Microwave Printed Circuit technique is based is, fundamentally, an evolution of the coaxial transmission system. This evolution can be seen from Fig. 1.

If the coaxial line is deformed in such a manner that both the center and outer conductors are square, or rectangular in cross section and then if side walls of the rectangular coaxial system are extended to infinity, the resultant "flat strip" transmission system, while possessing all of the advantages of the coaxial system, now has a form factor which is adaptable to the printed circuit technique. The approximate field distribution in this system can be seen from the flux plot in Fig. 2. This flux

[1] The flat strip coaxial transmission line was first used, insofar as this author has been able to determine, by V. H. Rumsey and H. W. Jamieson, and was applied to a production antenna system during World War II as a power division network. (This work is described in a report by V. H. Rumsey published by the Combined Research Group NRL during the war years, and in a U. S. Navy Antenna instruction book.)

plot, which was obtained experimentally, indicates the basic field structure of this type transmission system. Almost all of the field is concentrated in the region of the strip, and since no potential difference exists between the outer plates, the plane of the center conductor is an essentially field free region.

A cursory examination of the "flat-strip" line would lead one to believe that the capacity of the line, which determines its characteristic impedance, could be readily calculated from the parallel-plate capacitance formula. For wide, low impedance strips this is true, but for strips which have characteristic impedance in the order of 50 ohms the capacity due to the fringing effects at the edge of the center conductor is an appreciable portion of the total capacity and produces a noticeable effect. See Fig. 3. As the strip is narrowed, for even higher impedance, another effect becomes apparent, namely, interaction between the fringing fields at the two edges of the center conductor. This effect which becomes appreciable for very narrow strips must be taken into account in the analysis of high impedance transmission lines.

The "flat-strip" line, like the coaxial line, operates in the TEM mode. The characteristics of any transmission system, operating in this mode, which are of most importance in the engineering applications are the velocity of propagation v_o and the characteristic impedance Z_o which can be calculated from the known relation.[2]

$$Z_o = \sqrt{\frac{L}{C}} \qquad (1)$$

The velocity of propagation of the principal mode in such a transmission system is given by the relation

$$V = \frac{1}{\sqrt{L\ C}} \qquad (2)$$

and therefore we have

$$Z_o = \frac{1}{VC} \qquad (3)$$

In any two-conductor line the velocity of propagation is the velocity of light in the medium filling the space, thus

$$V = c = \frac{1}{\sqrt{\mu\varepsilon}} \qquad (4)$$

[2] John J. Karakash, "Transmission Lines and Filter Networks," MacMillan Company.

and we have the relation

$$Z_o = \sqrt{\frac{L}{C}} = \frac{1}{VC} = \frac{\sqrt{\mu\varepsilon}}{C} = \frac{\varepsilon}{C}\sqrt{\frac{\mu}{\varepsilon}} \qquad (5)$$

In MKS units these equations are:

$$V_o = \frac{3 \times 10^8}{\sqrt{\mu\varepsilon}}\ \frac{\text{meters}}{\text{sec.}} \qquad (4a)$$

$$Z_o = \frac{\sqrt{\mu\varepsilon}}{3C'10^8}\ \text{ohms} \qquad (5a)$$

where:

L = Inductance per Unit Length - MH/Meter
C = Capacitance per Unit Length -μμf/Meter
Z_o= Characteristic Impedance - Ohms
μ = Magnetic Permeability (Equals 1 for Air and Most Dielectrics)
ε = Dielectric Constant (Equals 1 for Air)
V_o= Velocity of Propagation in Material with Properties μ and ε - Meters/sec.

It is apparent from this formula that the only necessary analysis or calculations required to determine Z_o is that for the capacitance per unit length of the system under study.

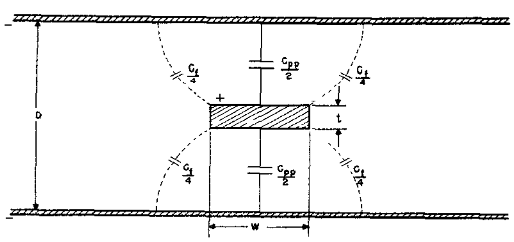
An approximate calculation based upon the well known parallel-plate capacitance formula is instructive and gives some insight into the operation of this type transmission system.

The parallel plate capacitance for the case of three parallel planes is:

$$C_{pp} = 35.4\,\frac{(\frac{W}{D})}{(1 - t/D)}\,\varepsilon\ \mu\mu f/\text{Meter} \qquad (6)$$

where:

W = Center Conductor Strip Width - cm.
D = Plate Spacing - cm.
t = Plate Thickness - cm.
ε = Dielectric Constant - Equals 1 for Air
C_{pp}= Parallel Plate Capacitance - μμf/Meter



The use of the parallel-plate capacitance formula to compute the characteristic impedance is permissible for impedance below 25 ohms. The fringing field capacitance becomes an appreciable portion of the total capacitance for impedances greater than this and must be utilized in the calculations. Under these conditions the total capacitance is

$$C = C_{pp} + C_f \varepsilon \qquad (7)$$

where:

C_f = f(W, t/D) Fringing Field Capacitance per Unit Length - μμf/Meter
C = Capacitance per Unit Length of Line - μμf/Meter

resulting in the formula

$$C = \left[35.4 \frac{\left(\frac{W}{D}\right)}{(1 - t/D)} + C_f \right] \varepsilon, \qquad (8)$$

and the impedance is

$$Z_o = \frac{\sqrt{\mu \varepsilon} \; (1 - t/D)}{3 \times 10^8 \left[35.4 \frac{W}{D} + (1 - t/D) C_f \right] \varepsilon} \qquad (9)$$

Letting the C_f equal a constant (which can readily be determined experimentally) this formula for the characteristic impedance holds, with engineering accuracy, until the impedances reach the order of one hundred ohms at which point the interaction between the fringing fields becomes important; it is then a function of W/D and t/D. In Fig. 3 the parallel plate capacitance, as well as a series of experimental points, are plotted and the experimental curve can be seen to differ from the parallel plate capacitance by a constant fringing capacity except in the region of very low W/D ratios where the fringing capacity becomes a function of W/D. This curve is plotted for a zero thickness center conductor. (Experiments show that $C_f \cong 15$ μμf/meter.)

Mathematical Analysis of Strip Transmission Line

The mathematical analysis of the Flat Strip Transmission line is tedious and involved and would be out of place in an article of this type. The results of such an analysis, however, are of interest and will be presented in other papers during this symposium. Three general methods of analysis for this structure have been employed.[3] They are the boundary value solution of Laplace's Equation, the solution by methods of Conformal Mapping, and the exact computation of Fringing Field Capacitance.

Although the results given by these methods and by other methods do not in general result in exact agreement, they are of sufficient accuracy in the region of interest — in the region of 50 ohms characteristic impedance — and in this region agree with experimental results. Further work is being done to resolve these differences which are mostly in the region of very high characteristic impedances.

Experimental Evaluations

As was stated in the foregoing section, an exact theoretical analysis of the capacity or impedance of these "flat strip" transmission lines is somewhat difficult and tedious. An experimental evaluation of the "flat strip" transmission system is relatively easy, however, and such an evaluation made by the author checks the theoretical values very closely. These measurements, which were made for convenience at low radio frequencies, utilize simple, readily available test equipment.

The method of measurement consisted of connecting a Q-meter and a precision standard capacitor across the transmission system. See Fig. 4. While the transmission system was thus connected, the standard capacitor was set at 100 mfd and the Q-meter was balanced. Then the transmission system was disconnected and the standard capacitor adjusted to rebalance the Q-meter. The difference in standard capacitor readings was then taken to be the capacity of the transmission system. From this, Z_o, the characteristic impedance, was calculated by the formula:

$$Z_o = \frac{\sqrt{\mu \varepsilon}}{3C'} \times 10^{-8} \text{ ohms} \qquad (10)$$

These measurements were taken for a series of strips varying over a wide range of widths and thickness and between plates the spacing of which was also varied. It was possible with these various strip widths and plate spacings to make a series of measurements over a range of W/D from .001 to 1000. The measurements of the low W/D ratios are of doubtful accuracy, however, because of the difficulty in eliminating the stray-end capacities in these particular cases. The results of

[3] The original analysis on this type of transmission system was accomplished by Dr. Nicholas Begovitch of the Hughes Aircraft Company ("Theoretical and Experimental Studies of a Strip Transmission Line," 12 May 1950 - N. A. Begovitch and A. R. Margolin - Internal Technical Memo No. 234 - Hughes Aircraft Co.)

these measurements are plotted in Figs. 3 and 6. It can be seen from these curves that the experimental and theoretical results are in close agreement for all characteristic impedances below 100 ohms. Since this is the region of primary interest, from an applications point of view, it is apparent that both the theoretical and experimental approaches are adequate for the majority of practical applications.

To gain a more adequate picture of the behavior of the fields in the vicinity of the center conductor, a series of field plots were made by the use of standard flux plotting methods. One of these plots is shown in Fig. 2. The neutral plane, which is not crossed by any electric flux lines, as well as the concentration of field in the region of the strip, are readily apparent in this figure. It is apparent from these plots that as the strip width increases, the fringing field becomes a smaller portion of the total field and its effect upon the impedance is thereby reduced.

Although the theoretical and experimental data presented, to this point, is for the center conductor imbedded in a uniform dielectric, this method of construction is not practical in many of the applications. Three alternate types of lines are illustrated in Fig. 7.

The dielectric sandwich transmission line—when limited to a very thin center conductor, such as a metal foil or a printed conductor, has the same characteristics as the case for which the theoretical and experimental data was evaluated. This system is ideally suited for the printed circuit technique and has been widely used by the author. The sheet-supported or the compensated stub-supported transmission lines are of value when the losses due to a continuous dielectric sheet cannot be tolerated, when the weight of the structure is of paramount importance when thick center strips are to be used, or when high power is to be carried by the system. Other types of center conductor supports readily suggest themselves for specific applications, but are not of sufficient general interest to be mentioned here.

Applications to Printed Circuits

The planar transmission system can be readily adapted to printed circuit techniques by using two sheets of solid dielectric as spacers between the outer conductors, the center conductor being supported between these sheets. This center conductor can be printed on one of the dielectric sheets, with a conducting paint, by the standard silk screen printing process. Experimental work can also be readily accomplished by using thin metal foil center conductors which can be cut with a pair of scissors and glued to one of the sheets. All of the circuits described in the remainder of this paper were fabricated in one of these ways. A method more adaptable to production would be the use of copper coated dielectrics, the unwanted copper being removed by standard "printed circuit" photo etching methods.

Since the characteristic impedance of the system is a function of strip width, it is readily adaptable to circuits requiring impedance changes.

In most practical applications care must be taken in effecting a transition from regular coaxial transmission line to the flat strip transmission line in order that higher modes shall not be excited. A TEM mode, which will propagate between the plates, can be excited by a non-symmetrical junction. This and other modes can be eliminated by placing shorting pins between the outer conductors in the region of the junctions, thus insuring that the outer conductors are at the same potential. A very practical junction which is well matched and excites no higher order modes consists of a regular type "N" connector which is inserted between the edges of the planar line, this line consisting of two 1/4-inch polystyrene sheets between metal conductors. This junction is matched to a 50-ohm center conductor over a wide band of frequencies. See Figs. 8 and 14.

Since the lateral attenuation in the printed circuit structure is high—in the order of 75 db per one-quarter of an inch for one of the circuits tested by the author—it is possible to have several circuits close together without annoying coupling or cross-talk.

The Printed Circuit Power Splitter

The use of the "microwave printed circuit" naturally lends itself to the problem of power distribution and division. In particular, a power division network which has been used at

AFCRC,[4] is illustrated in Figs. 8 and 9. This power divider is based upon the action of the quarter-wave transformer. If a transmission line is cut to a quarter-wavelength, it possesses the property that any impedance placed at one end of the line will "look like" another impedance from the other end of the line. These impedances are related by the formula:

$$Z_o = \sqrt{Z_1 Z_2} \qquad (11)$$

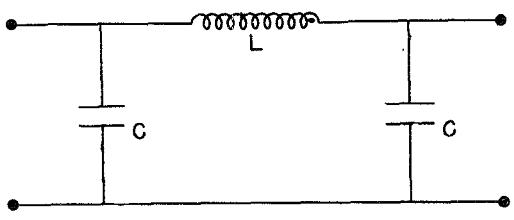
that is, the characteristic impedance is the geometric mean of the end impedances.

Now if we take two 50-ohm lines from the output junctions and combine them at point (A), the resultant parallel impedance will be 25 ohms. The quarter-wave line transforms this impedance to 100 ohms at junction (B) where the parallel impedance of the two 100-ohm ends of the quarter-wave transformer is 50 ohms which is then connected to the input terminal with a 50-ohm line. Thus power entering the circuit at the input terminal will be divided into four equal components at the output terminals and the 50-ohm characteristic impedance is maintained throughout the division. A sixteen-element power divider utilizing these four-to-one dividing networks has been constructed and used successfully in exciting an experimental antenna array.

Printed Circuit Filters

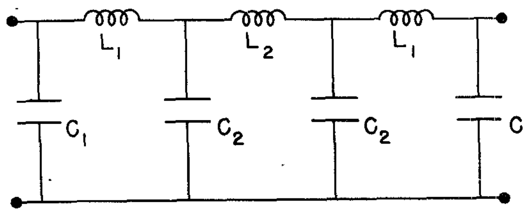
Another application to which this technique is ideally suited is the construction of microwave filters.

A short section of uniform transmission line can be represented by a Pi type equivalent circuit of the type below:



[4]R. M. Barrett and M. H. Barnes, "Microwave Printed Circuits," National Conference on Airborne Electronics, IRE, Dayton, Ohio, May 23-25, 1951.

Inasmuch as a circuit of the low pass filter is a ladder network of the type



It is apparent that, by a judicious choice of short sections of transmission line connected in series, it is possible to construct a low pass filter. In Figs. 10 and 11 the design of a filter of this type is illustrated. By varying the strip width, or characteristic impedance, the ratio between capacitance and inductance of the individual sections may be changed. When these sections are arranged in series they have an equivalent network which can be shown to be essentially the equivalent circuit of a low pass filter. An experimental model of this filter was designed, constructed, and tested in a half-day -- an illustration of the flexibility and speed of this method. This filter, which is shown in Fig. 11, has a reasonably good low pass characteristic and has a rate of attenuation in the attenuation band which exceeds 30 db per 100 mc.

Attenuators or Matched Loads

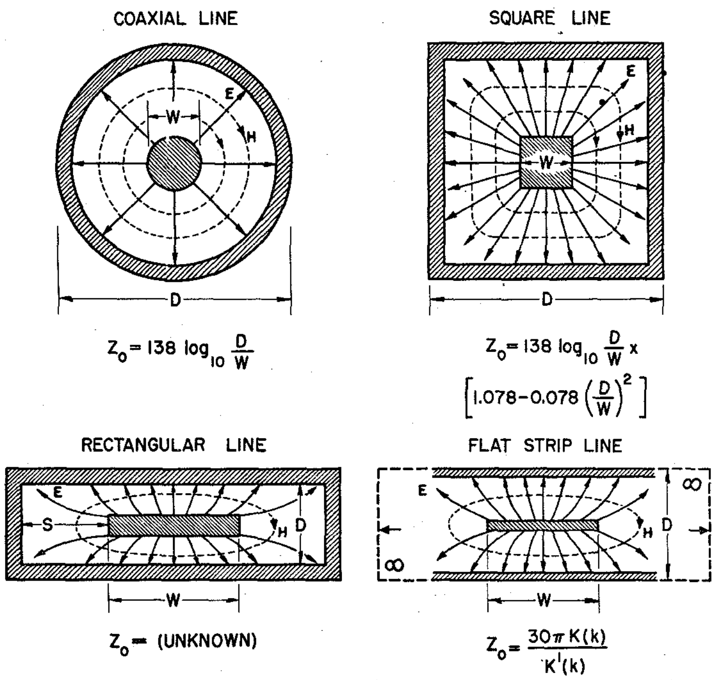
By printing resistive paint on the dielectric sheets prior to printing the conductors, it is possible to construct attenuators, matched loads, etc. An attenuator and a matched load are illustrated in Figs. 12 and 13. The resistive elements were painted on the dielectric spacers with type R-21 resistive paint. The center conductor, which was cut from a thin strip of copper foil was then placed between the sheets. The matched load was tested over a considerable frequency range and proved to have a reasonably good match over this range.

Future Applications

A series of other experimental microwave circuits have been successfully fabricated by this technique (See Figs. 14 and 16), and it seems quite conceivable that the entire RF Circuitry of a modern microwave receiver could be successfully constructed by this method. (In fact, certain classified radar receivers are now being constructed using these methods.) This would mean a great reduction in cost and fabrication time and would lend itself to the production of "throw-away" systems for use in such expendable weapons as guided missiles, rockets, radio controlled bombs, VT fuses, etc.

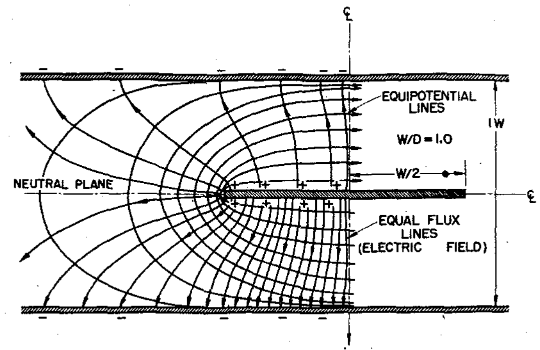
The technique also lends itself to the miniaturization of RF circuits since the dimensions of such circuits built by this method are a function of the dielectric constant of the media upon which the circuit is printed, the reduction in size being approximately the square root of the dielectric constant used. Another technique can be used for circuits which must be long in one dimension, such as a microwave filter. This scheme consists of rolling the circuit up, in a manner similar to the construction of a paper condenser, and enclosing it in a can; see Fig. 15.

All of the possible applications of this technique cannot be foreseen and continuing work is being accomplished along this line.



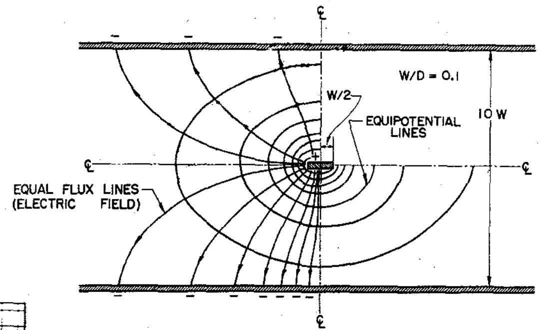
EVOLUTION OF FLAT STRIP TRANSMISSION LINE

Fig. 1



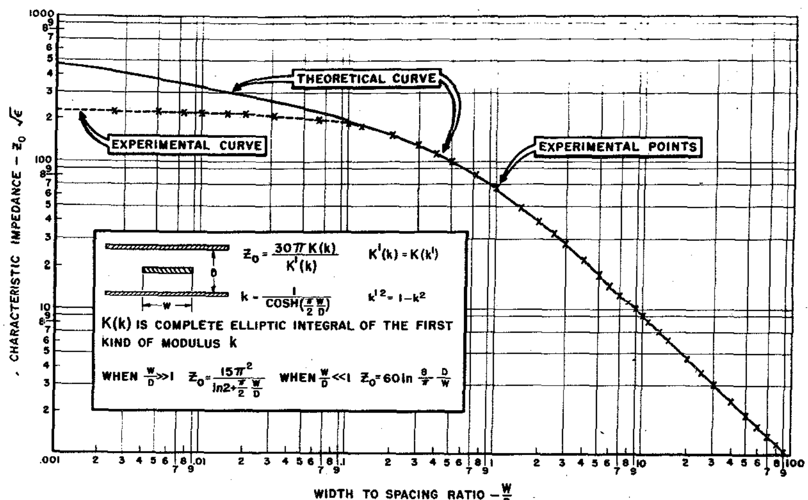
FLUX PLOT OF FLAT STRIP TRANSMISSION SYSTEM

Fig. 2



FLUX PLOT OF FLAT STRIP TRANSMISSION SYSTEM

Fig. 2a



CHARACTERISTIC IMPEDANCE OF FLAT STRIP TRANSMISSION LINE
—ZERO THICKNESS CASE—

Fig. 3

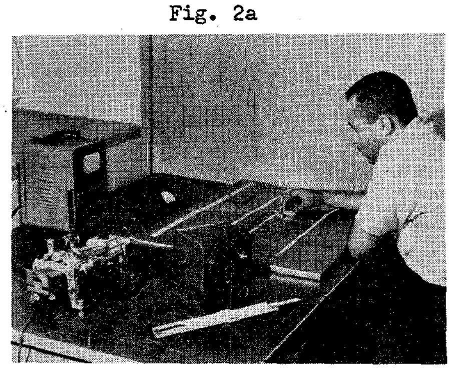
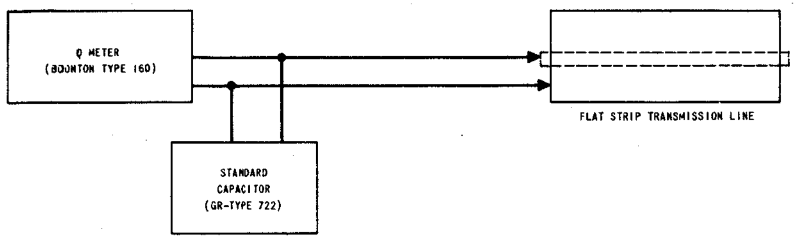


Fig. 2b



1) BALANCE Q METER WITH LINE DISCONNECTED AND STANDARD CAPACITOR SET AT 100 $\mu\mu f$

2) CONNECT LINE AND REBALANCE Q METER BY ADJUSTING STANDARD CAPACITOR

3) CAPACITY OF LINE IS DIFFERENCE IN CAPACITOR READINGS

4) COMPUTE Z_0 FROM FORMULA:

$$Z_0 = \frac{\sqrt{\epsilon}}{3 \times 10^8 \; C} \text{ OHMS}$$

EXPERIMENTAL PROCEDURE

Fig. 4

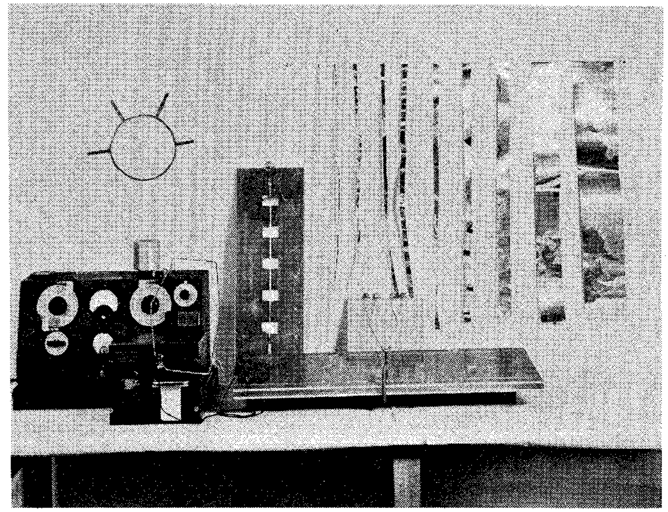
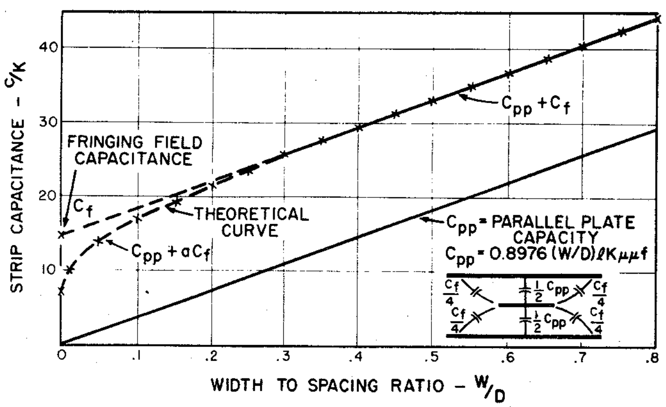
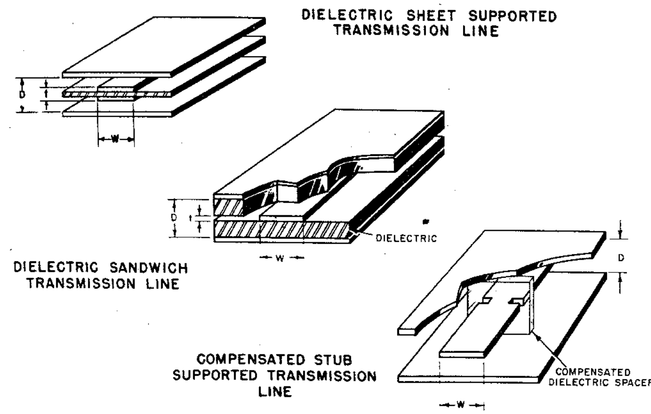


Fig. 5



CAPACITANCE DATA FOR
FLAT STRIP TRANSMISSION SYSTEM
— ZERO THICKNESS CASE —

Fig. 6



TYPES OF FLAT STRIP TRANSMISSION SYSTEMS

Fig. 7

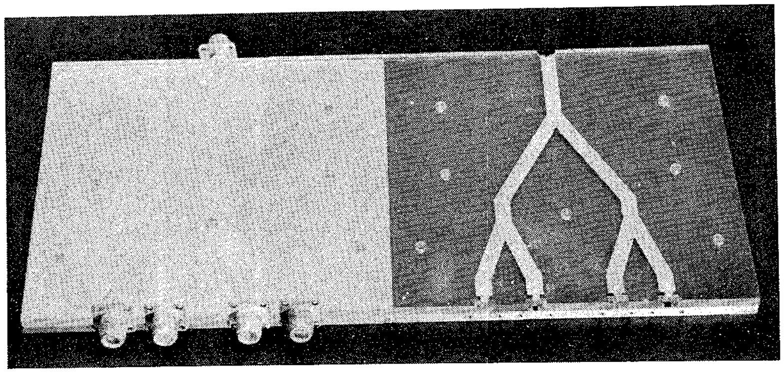
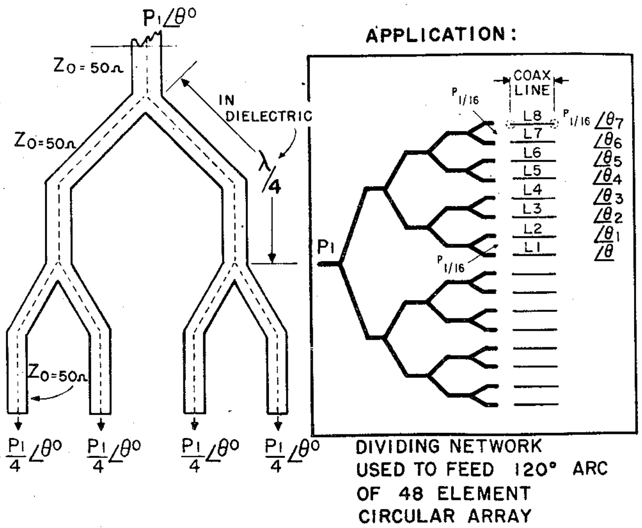
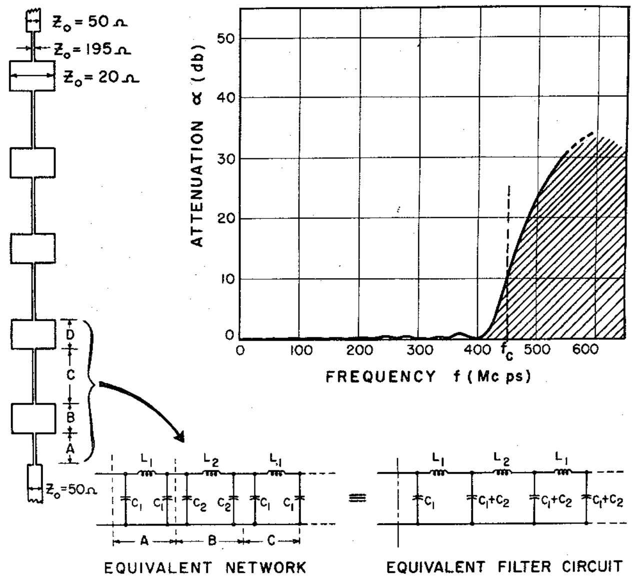


Fig. 8



PRINTED CIRCUIT POWER DIVIDER

Fig. 9



PRINTED CIRCUIT LOW-PASS FILTER

Fig. 10

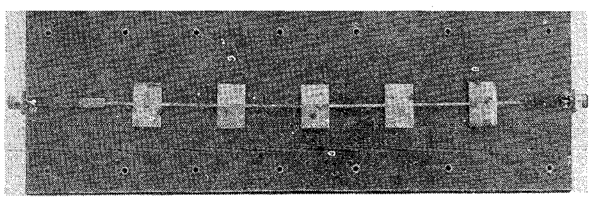
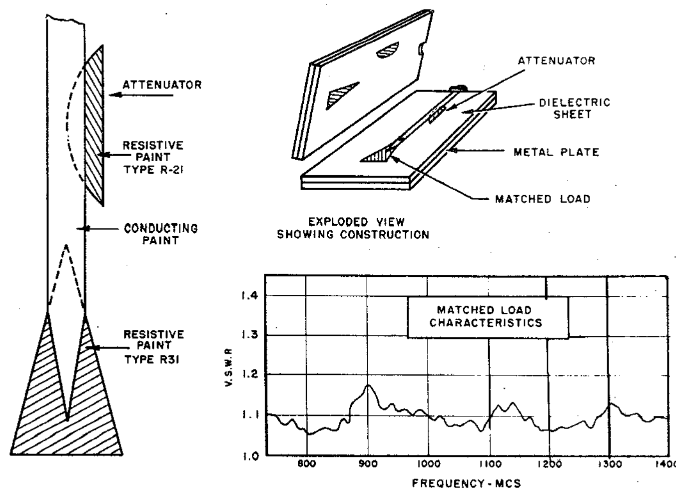


Fig. 11



PRINTED CIRCUIT MATCHED LOAD AND ATTENUATOR

Fig. 12

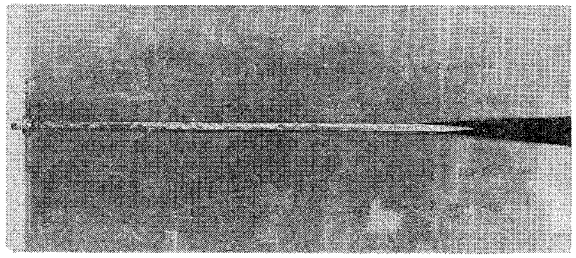


Fig. 13

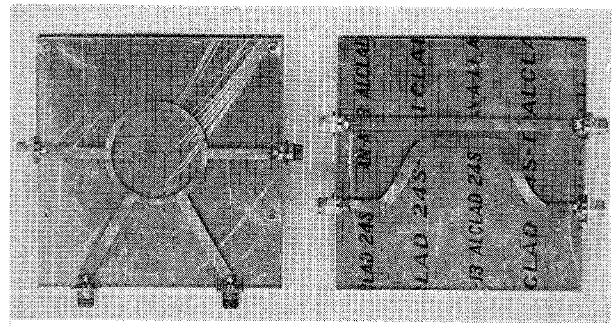


Fig. 14

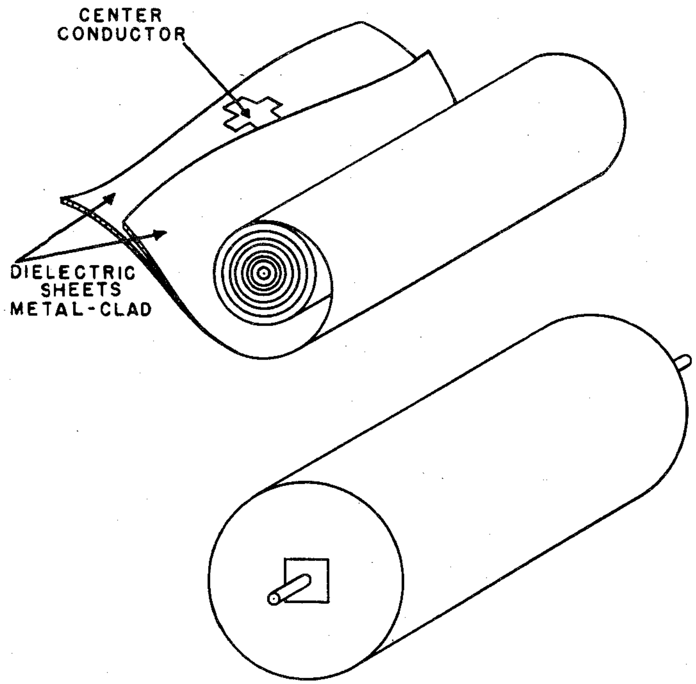
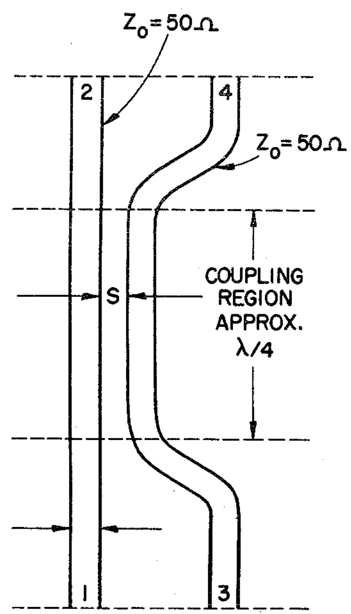


Fig. 15



S	POWER AMPLITUDE 1	2	3	4	DIRECTIVITY
1/64	1	-1 db	-10 db	-32 db	3.2
1/16	1	-1 db	-16 db	-34 db	2.1
1/8	1	-1 db	-21 db	-40 db	1.9
1/4	1	-1 db	-29 db	43 db	1.5
1/2	1	-1 db	-34 db	45 db	1.3

FREQUENCY = 1000 Mcps

PRINTED CIRCUIT DIRECTIONAL COUPLER

Fig. 16