shire for two months, followed by four months of other assignments. With American forces, except for a few weeks engaged in installing radio links in the Vosges mountains of Alsace, all of the time was spent on operational radar, including the Microwave Early Warning (MEW) radar. At the University of Illinois he received the M.S. and Ph.D. degrees in 1947 and 1949, respectively. He worked for six years at I.T.T. Labs in New Jersey in development of traveling-wave tubes. From 1955 to 1962, he was with the Bendix Research Labs in Michigan working on microwave components and missile guidance systems. In March 1962, he was co-Founder of Omni Spectra, Inc., and served as President and Chief Executive Officer, but managed to spend a great deal of his time on products and their applications. He is now an electronics and business management consultant and consultant to Omni Spectra, subsidiary of MA/COM, Inc.

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Microwave Printed Circuits—The Early Years

ROBERT M. BARRETT

I. Introduction

AN IMPORTANT MILESTONE in microwave technology was the development of the "microwave printed circuit" (MPC), or flat-strip microwave components, fabricated by conventional printed-circuit techniques. This development freed the microwave designer from the constraints, and often prohibitive costs, encountered when designing complex circuitry either in waveguides, coaxial lines, or two-wire transmission systems. The costs and complexities of fabrication often discouraged the development of innovative and complex circuits using these traditional wave guiding or transmission structures.

The purpose of this paper is to present an outline of the concept of "microwave printed circuits" as it was originally conceived, and to add a few brief historical comments on the facts surrounding its conception and initial reduction to practice. Available space precludes a treatment of the current state of the art. This treatment is, therefore, limited to the beginnings and the early trends and applications of MPC.

The microwave printed circuit as described herein is an extension of the well-known techniques which were of such importance in the lower frequency regions where lumped circuit elements are practical—actually it is a marriage of this low-frequency printed-circuit technology and the powerful technology of the coaxial and waveguide microwave systems, where distributed circuit elements have replaced lumped circuits. The new circuit configurations possessed many of the attributes of conventional printed circuits, such as light weight, low cost, ease of manufacture, miniaturization, ease of design, etc., along with their ability to be used at frequencies exceeding 10 000 MHz. The basis of the new technique was the planar coaxial transmission system that was developed during World War II. This development remained unpublished, was relatively unknown in the post-war period, and was not supported by adequate theoretical analysis.

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II. A Little History

A flat-strip coaxial transmission line was first used, insofar as this author was able to determine, by V. H. Rumsey and H. W. Jamieson and was applied to a production antenna system and power division network during World War II. A similar application to an experimental electromechanical scanning radar power distribution system was developed by Mr. John Ruze, an associate of this author, at the Cambridge Field Station of the United States Air Force. A commercial application of a planar coaxial system was the development of a "slotted line" by the Hewlett-Packard Co. Although the basic concept of a transmission system using a line—or strip—between two flat plates was thus in existence, it was thought of in massive terms of large plates or slabs, solid, flat, or cylindrical rods as the center elements, and was essentially to be used only as a special-case power transmission element.

The technique remained dormant until early in 1949 when, while trying to devise a new method of feeding a microwave "Wullenweber" antenna, it occurred to this author that not only could flat-strip coaxial lines, in a flat plate form, 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 since the thickness of the center conductor was relatively unimportant, entire circuits could be "punched out" on a punch press, silk screened using silver "ink," or 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 art of printed circuits has resulted in the "microwave printed circuit" (MPC), which immediately challenged the coaxial line and the waveguide in their application to microwave systems.

This work was initially reported at an IRE meeting in 1951 and in subsequent articles [1]–[4]. After the realization of the potential of the technique, it was decided to expand the R&D base in the field, and contracts were let to explore its potentialities, provide a sound theoretical base for design [5]–[9], and to develop standard techniques and structures, i.e., develop a printed-circuit *Waveguide Handbook* [16]. Among those contractors that worked on this program were Tufts University, the Airborne Instruments Laboratory (Strip Line®), the Polytechnic Institute of Brooklyn, and Sanders Associates (Tri-Plate®).

A short time after the release of the author's work on MPC, a group of engineers from the Federal Communications Research Laboratories announced another form of printed line (December 1952) now known as Micro-strip® which was the adaption of planar geometry of the "two-wire line" in the same way that MPC is an adaption of the coaxial line [10]–[13]. The merits of these two systems are essentially the merits of their respective antecedents. Later, Professor D. D. King of Johns Hopkins University announced the third basic type of planar transmission system, the "dielectric image line," which is the adaptation of the dielectric waveguide to planar geometry. For more details on this line, see [14].

Immediately after the realization of the potential of the MPC concept, the author was anxious to test and exploit the idea to see how useful it really was. With the help of a few colleagues, he quickly engaged in a series of exploratory experiments to establish the validity of a number of the original concepts. These experiments resulted in filters, power distribution networks, directional couplers, matched loads, etc., all of which were tested at 440 MC's. Conceptually, they had considered shielded systems and unshielded systems, and decided to concentrate on a fully shielded technology. It was also decided that for initial work they would not use air-supported center guides but would use guides sandwiched between dielectric slabs. Initial design parameters were based upon experimental measurements of guide characteristics rather than theoretical analysis. Center conductors were fabricated by use of silver paint or by cutting them with scissors from thin aluminum foil. The power of the technique quickly became apparent when it was found that they could design a circuit, quickly cut it from aluminum foil, slap it between plates, and test it all in a matter of a couple of hours. At that period of time, a similar application in coaxial line or waveguide would have been in the machine shop for weeks.

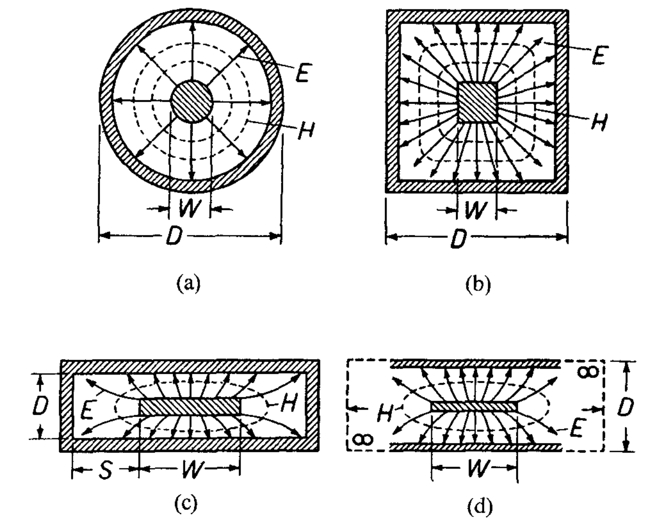


Fig. 1. Evolution of a flat-strip transmission line. (a) Coaxial line. (b) Square line. (c) Rectangular line. (d) Flat stripline.

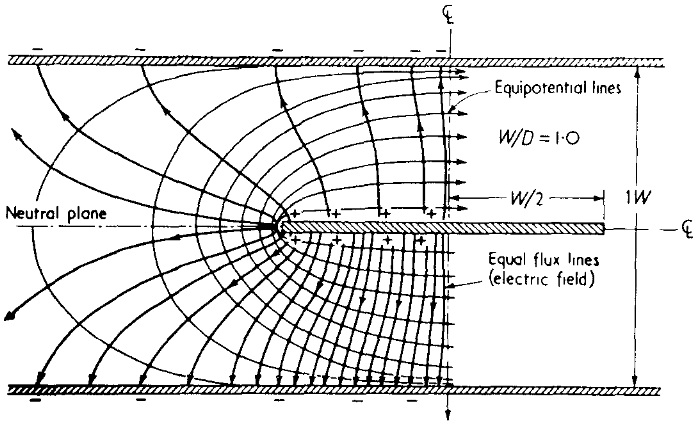


Fig. 2. Flux plot of a flat-strip transmission system.

III. Planar or "Flat-Strip" Transmission Systems

The planar transmission systems upon which the microwave printed-circuit technique is based can be conceived as a progressive evolution of the coaxial and parallel-line transmission system. This evolution can be seen in Figs. 1 and 3.

If the coaxial line is deformed (Fig. 1) in such a manner that both the center and outer conductors are square or rectangular in cross section, and then if the side walls of the rectangular coaxial system are extended to infinity, the resultant "flat-strip" transmission system, while possessing 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 plots in Fig. 2. The flux plots, which were obtained experimentally utilizing resistive paper flux-plotting techniques, indicate the basic field structure of this type of transmission system. These field lines are entirely in the transverse plane and are bounded by the flat outer conducting planes. Almost all of the field is concentrated in the region of the center strip and is relatively uniform within the space directly between the center strip and outer

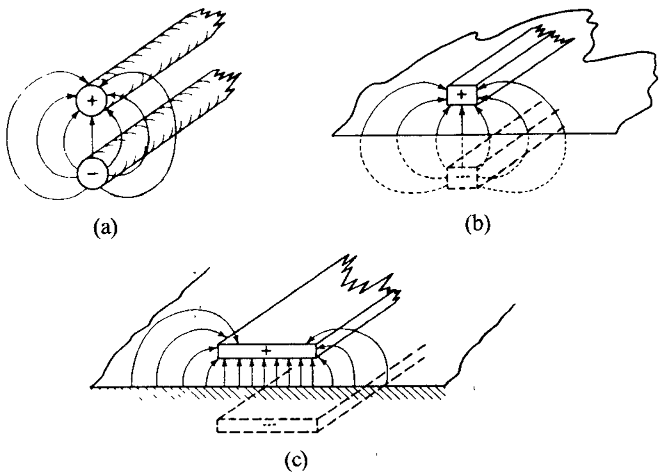


Fig. 3. Evolution of "micro-strip" transmission line. (a) Two-wire line. (b) Single-wire above ground (with image). (c) Microstrip.

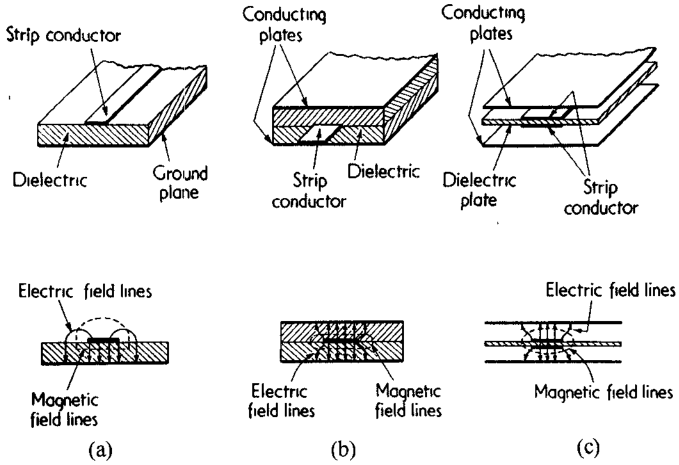


Fig. 4. Typical commercial microwave printed systems. (a) Microstrip® Federal Communication Laboratories. (b) Tri-Plate® Saunders Associates Inc. (c) Stripline® Airborne Instruments Laboratory.

planes. Since no potential difference exists between the outer planes, the plane of the center conductor is an essentially field-free region, except in the area of the center strip. The fringe field (or field external to the space directly between the center strip and ground planes) decays very rapidly. There is no electrical-field component lateral to the center strip; thus, the entire field is confined to a region in the immediate vicinity of the center conductor, and no sidewalls are necessary to confine the field.

As in the coaxial system, if the parallel-wire line is replaced by its equivalent of a single wire (see Fig. 3) and its image in a conducting ground plane, and if this single wire is in turn progressively distorted into a flat strip, the resulting transmission system is again a planar structure. This transmission system, known as Micro-strip, has a field distribution similar to that indicated in Fig. 3(c). The field in this system is again predominantly confined to the area between the strip and the ground plane. It should be pointed out, however, that this is an unshielded system and it is more difficult to confine all of the energy in the vicinity of the strip. In the flat-strip coaxial structure shown in Figs. 1 and 2, it is possible to obtain high Q's because the conductor losses are the only important ones; therefore, this type of line permits the design of high-Q components such as cavities and microwave filters. Due to the losses in the line, particularly due to dielectric loss and radiation, micro-strip in its usual form was not felt to be suited for high-Q applications. However, there are many microwave circuits where high Q is not essential, and it is in these applications where micro-strip is as practical as, or more practical than, cylindrical or flat-strip coaxial structures. References are given to applications of micro-strip [10]–[13], but the balance of this paper will be confined to the coaxial forms of microwave printed circuits, as this is the area in which the author has had experience.

The method of MPC construction, whereby the center conductor is embedded in a uniform dielectric, is not practical in many applications. Three alternative types of lines are illustrated in Fig. 4. 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 bulk of the theoretical and experimental data has been evaluated. This planar system, which is ideally suited for the normal printed-circuit processing and which has been widely used by the author, can be readily constructed by using two sheets of solid dielectric as spacers between the outer conductors, the "patterned" center conductor being supported between these sheets. A commercial form of microwave printed circuit known as Tri-plate® utilizes this technique (see Fig. 4(b)).

The sheet-supported, or the compensated stub-supported, transmission lines are of value when 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. This system, commercially known as Strip-line® (see Fig. 4(c)), has produced circuits with Q's over 4000. Other types of center conductor supports readily suggest themselves for specific applications, but are not of sufficient general interest to be mentioned here.

Since the characteristic impedance of these transmission systems is a function of strip width, they are readily adaptable to circuits requiring impedance changes, such as matching and filter networks.

IV. Design Parameters

A cursory examination of the flat-strip transmission line and its flux plot (Fig. 2) would lead one to believe that the capacitance 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 a characteristic impedance in the order of 150 Ω or greater, the capacity due to the fringing effects at the edge of the center conductor becomes an appreciable portion of the total capacitance and produces a notable effect. As the strip is narrowed for even higher impedances, 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 exact theoretical analysis of the capacitance or impedance of 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 was made by the author in his early work on MPC's [3]. These evaluations checked the later-obtained theoretical values very closely. These measurements were made for convenience at low radio frequencies using simple readily available test equipment. The method of measurement consisted of connecting a Q meter and a precision standard capacitor across the transmission system. While the transmission system was thus connected, the standard capacitor was set at 100 μF and the Q meter was balanced, then the transmission system was disconnected, and the standard capacitor was adjusted to rebalance the Q meter. The difference in readings of the standard capacitance reading was then taken to be the capacitance of the transmission system. From this, the characteristic impedance Z_0 was calculated by the formula

$$Z_0 = \frac{\sqrt{\mu\epsilon}}{3c} \times 10^8 \ \Omega.$$

These measurements were taken for a series of strips varying over a wide range of widths and thicknesses and between plates whose spacing was also varied. Measurements were made over a range of W/D from 0.001 to 1000. The results of these measurements are plotted in Fig. 5. It can be seen from these curves that the theoretical and experimental results are in close agreement for characteristic impedances below 150 Ω. Since this was the region of primary interest from an applications point of view, the experimental approach was adequate for the majority of practical applications in the early stages of development, until a theoretical basis for these systems was evolved. (As soon as it became apparent that the technology was promising, the author and his laboratory initiated a number of contractural programs to evolve a theoretical basis for the technology, as well as a series of practical design techniques and parameters [5]–[9]. As the applications became more complex, characteristics other than the characteristic impedance became of increasing importance, and much early work was devoted to theoretical and experimental determination of these characteristics. A few more important characteristics that were explored included higher order modes, lateral attenuation or coupling, propagation characteristics, wavelength, attenuation, dimensional limitations, construction tolerances, dependence of impedance on dielectric thickness, and impedance discontinuities. Flat-strip transmission lines differ from coaxial lines in one important aspect. In a coaxial line, an impedance discontinuity acts as a shunt capacitance. In contrast, a discontinuity in a flat strip has a series inductance as its equivalent circuit. These characteristics become important in filter design and other complex circuits. Holes and gaps in center conductor strips also represent discontinuities that can be utilized in many applications to microwave circuitry.

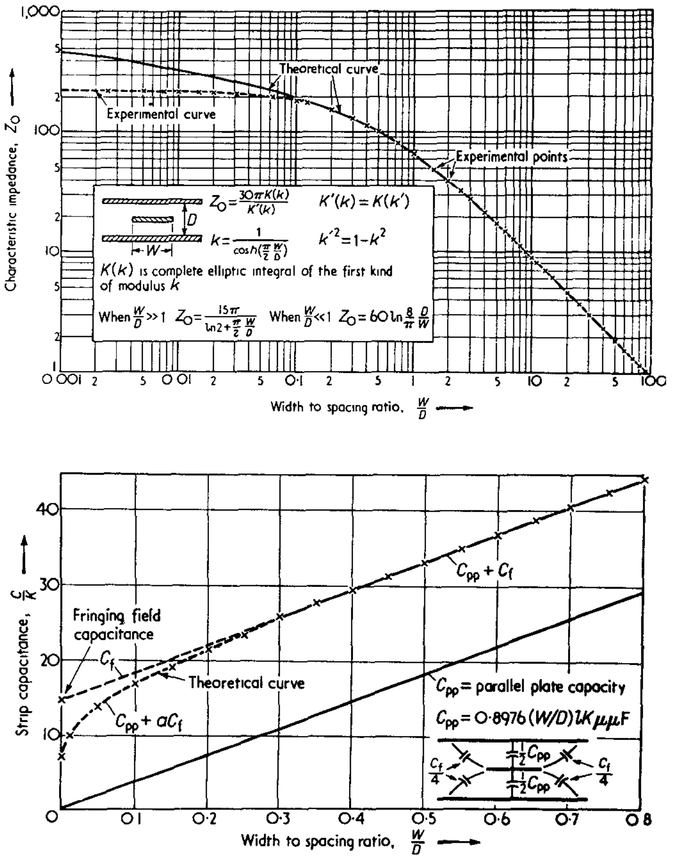


Fig. 5. Capacitance and characteristic impedance data for flat-strip transmission system (zero-thickness case).

V. Application of MPC Techniques to Practical Microwave Structures

With a basic knowledge of the characteristics of flat-strip transmission lines, all of the standard microwave components can be designed. A knowledge of these component designs is likewise required for the development of any complex microwave structures. The purpose of this section is to give examples of some of the components that evolved in the early years of the technology.

A. The Printed-Circuit Power Splitter

The use of the "microwave printed circuit" was first applied, and naturally lends itself, to the problem of power distribution and division. In particular, a power division network, which was used in the author's laboratory, is illustrated in Fig. 6. 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

$$Z_0 = \sqrt{Z_1 Z_2}.$$

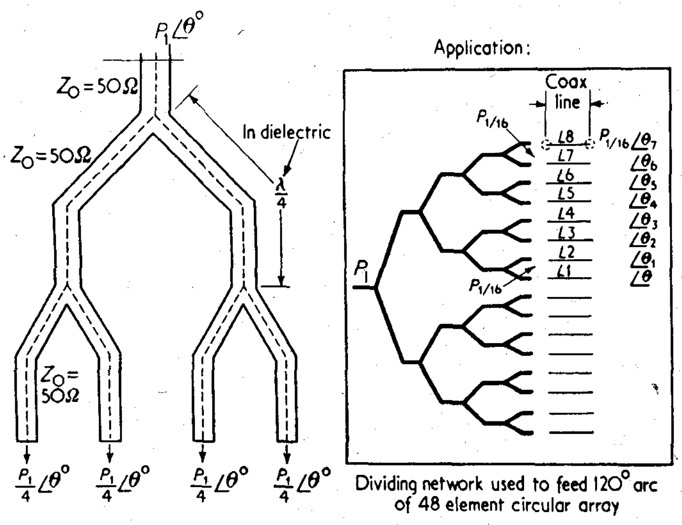


Fig. 6. Printed power divider.

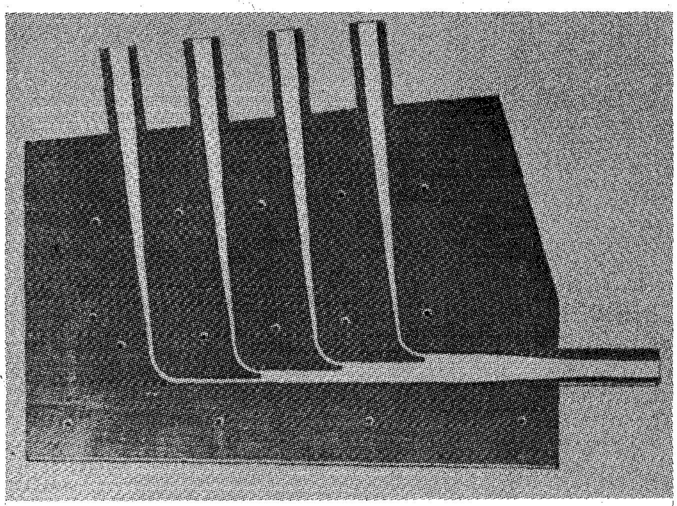


Fig. 7. Series of three unequal power divisions designed to obtain equal power on each of four parallel arms.

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

Now if we take two 50-Ω lines from the output junctions and combine them at their junction, the resultant parallel impedance will be 25 Ω. The quarter-wave line transforms this impedance to 100 Ω at the next junction, where the parallel impedance of the two 100-Ω ends of the quarter-wave transformer is 50 Ω, which is then connected to the input terminal with a 50-Ω line. A 16-element power divider utilizing these four-to-one dividing networks was constructed and used successfully in exciting an experimental antenna array.

A later power-splitter junction in Tri-plate line is shown in Fig. 7. This junction is characterized by the variation of the characteristic impedance of the lines. Contrast this with the power divider of Fig. 6, which maintains a constant impedance line.

B. Printed-Circuit Filters

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

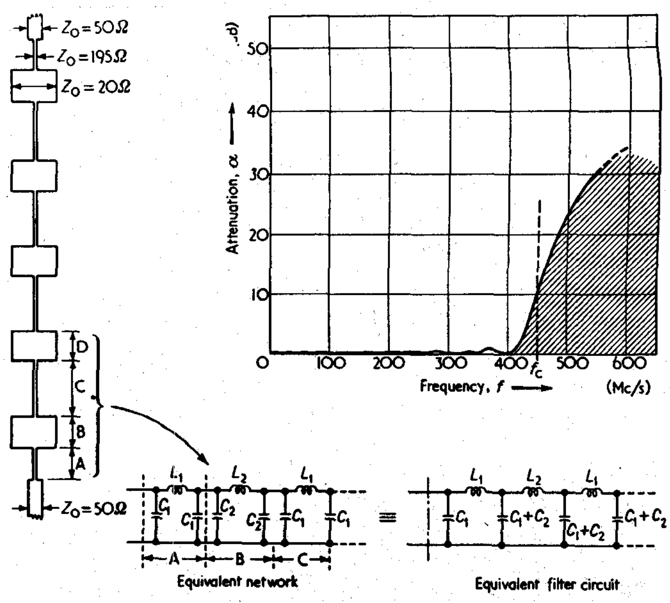


Fig. 8. Printed-circuit low-pass filter.

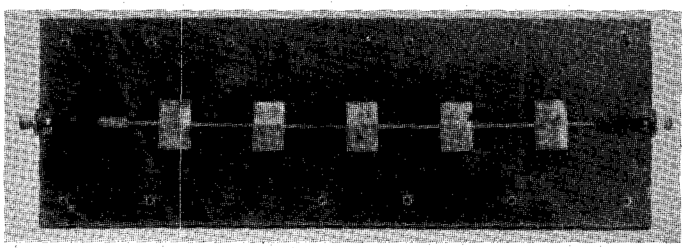


Fig. 9. Experimental low-pass filter of Fig. 8.

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. By varying the strip width, that is, the 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 half a day, thus illustrating the flexibility and speed of the method. This filter, which is shown in Figs. 8 and 9, had a reasonably good low-pass characteristic and a rate of attenuation in the attenuation band which exceeded 0.30 dB per 100 MHz. For precise filter design, it is of course necessary that the discontinuity impedances caused by changes in characteristic impedance be allowed for in the design. (In this regard, it should be noted that the equivalent circuit of such an impedance discontinuity is a series inductance.) More recent filters, such as the ones illustrated in Figs. 10 and 11, have characteristics as shown in Fig. 12.

C. Antennas

Techniques of MPC have been applied to a wide variety of printed microwave antennas [15]. Fig. 13 shows a Tri-plate slotted array at *X*-band. This example is illustrative

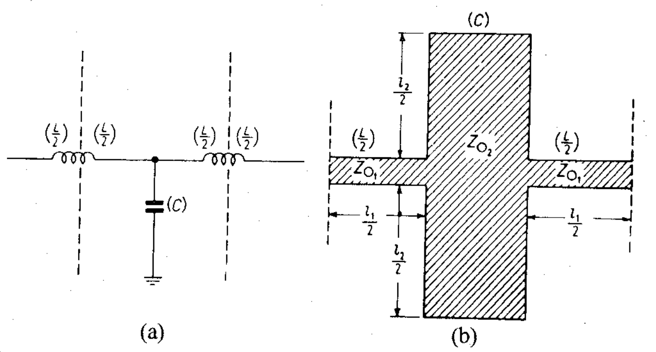


Fig. 10. Comparison of a typical low-frequency ladder network for a low-pass filter with the equivalent center-conductor in Tri-plate line. (a) Equivalent circuit, and (b) center conduction configuration.

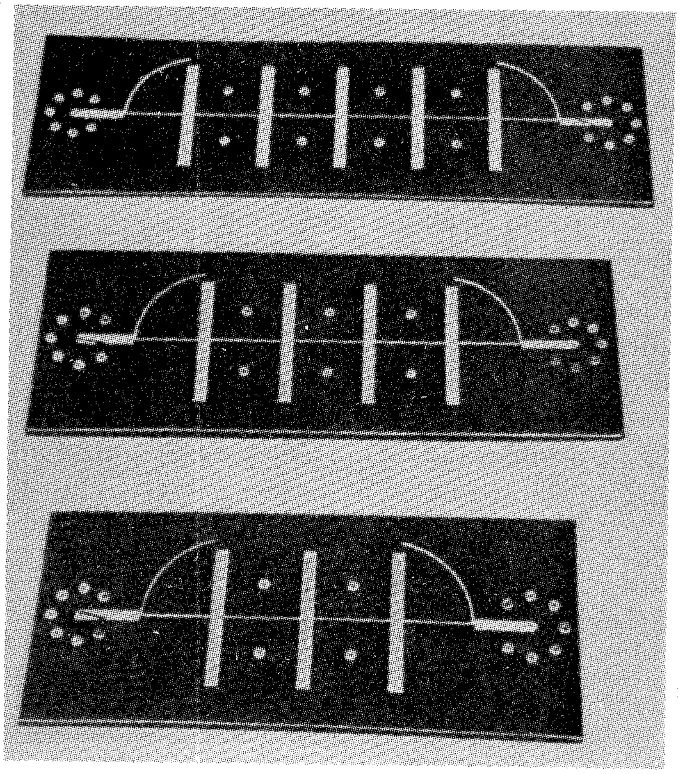


Fig. 11. Center-strip configurations of three low-pass filters designed to cutoff at 1.3 KHz.

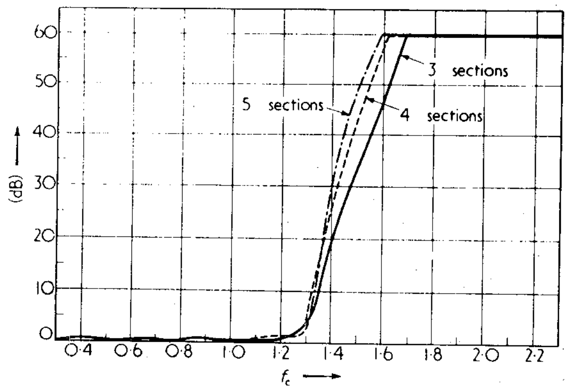


Fig. 12. Attenuation versus frequency for three low-pass filters fabricated in Tri-plate line in three, four, and five intermediate sections (see Fig. 11).

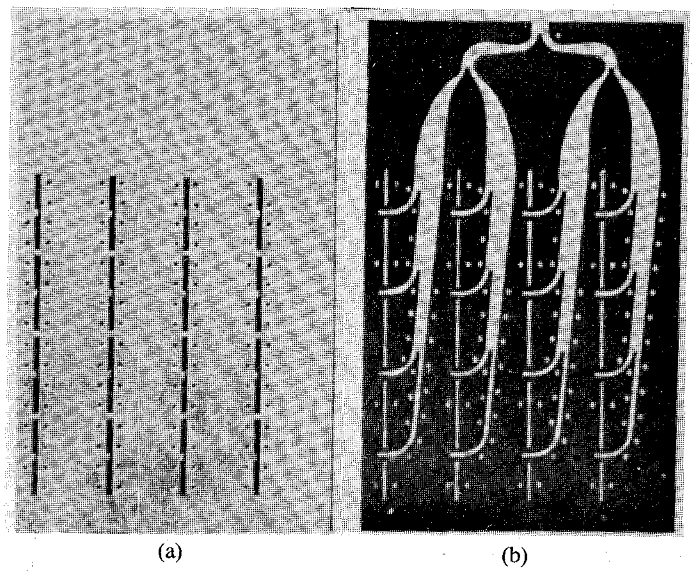


Fig. 13. Composite 4×4 slot arrays. (a) Feed. (b) Slots.

of a wide variety of antenna techniques that have been developed using the MPC concept.

D. Bridge Circuits or 'Hybrid' Junctions

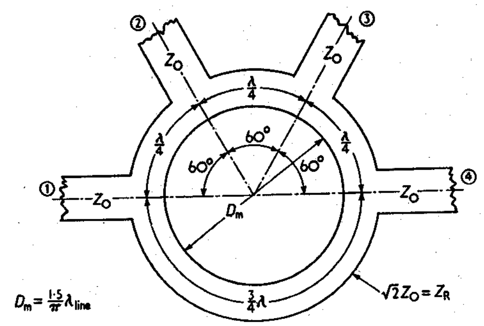
Many microwave applications require use of isolating bridge circuits or "hybrid" junctions; the "Magic T" is a commonly known junction of this type for waveguide structures. The "rat race" or "hybrid ring" is the most suitable configuration for printed-circuit applications as it is a planer network.

Ideally, in such a junction (at or near the design frequency), a matched load will be presented to any pair of input terminals provided the two adjacent pairs are terminated in matched loads. Power fed on these input terminals will divide equally between the two matched loads, and no power will appear at the fourth or opposite pair of terminals. Fig. 14 gives some data on a "hybrid" ring. The data is typical of the action of these networks. In practical applications, it may be desirable to bring the branch arms into the center of the ring.

E. Directional Couplers

A different form of the hybrid network is the directional coupler. The parallel-line coupler, as shown in Fig. 15, is one of the original structures investigated by the author. This coupler is characterized by its reverse coupling action and its simplicity of design. It does, however, require good matched loads to be most effective. (Data in Fig. 14 was later improved by improving match to loads.) This coupler can provide coupling in the range of 10–40 dB.

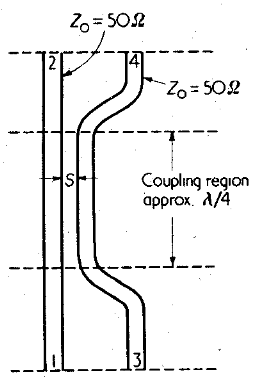
Another successful type of directional coupler is the branch-line coupler shown in Fig. 16. A signal is applied to terminal 1, and the other terminals are terminated in matches, terminals 3 and 4 each have two signal paths from the input. The paths to terminal 4 are of equal length and the signals will, therefore, add in phase. The paths to terminal 3 differ in length by a half wavelength (at the design frequency); the signals are out of phase and, therefore, cancel.



Coupling and input VSWR data for C-band hybrid ring

Frequency (Mc/s)	Input VSWR	Relative power (dB)			
		P_1	P_2	P_3	P_4
4,100	1·19	—	−3·2	−44·0	−3·1
4,300	1·09	—	−3·1	−49·0	−3·1
4,500	1·23	—	−3·1	−39·0	−3·2

Fig. 14. Center conductor configuration of MPC hybrid ring.



S	Power amplitude				Directivity
	1	2 (dB)	3 (dB)	4 (dB)	
1/64	1	−1	−10	−32	3·2
1/16	1	−1	−16	−34	2·1
1/8	1	−1	−21	−40	1·9
1/4	1	−1	−29	−43	1·5
1/2	1	−1	−34	−45	1·3

Frequency = 1,000 Mc/s

Fig. 15. Printed-circuit directional coupler.

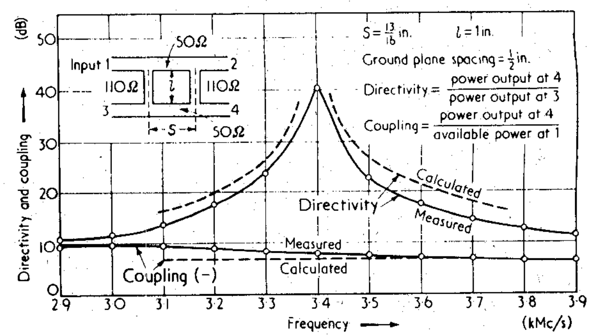


Fig. 16. Two-branch line coupler.

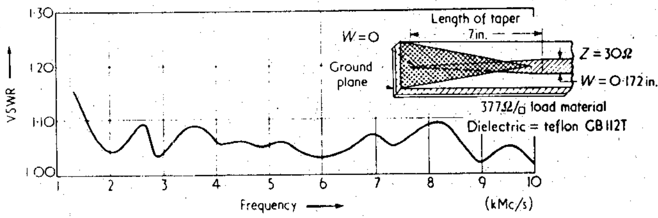


Fig. 17. VSWR of a typical Tri-plate termination.

If each branch of such a coupler is replaced with a complete two-branch coupler, two branches coincide, giving a three-branch coupler. This evolution can continue to higher orders.

F. Terminations and Attenuators

Matched loads and attenuators are often required in applications of microwave printed circuits. The most practical method of causing attenuation is to use a dissipative element such as a carbon-coated material or a thin metallized film as illustrated in Fig. 17. If a good match is required, this dissipative material must intercept fringe energy and intercept it in a gradual manner. Enough area must be in this field to absorb the quantity of energy desired.

Early matched loads and attenuators were made with resistive paint. More recent attenuators have used special metallized films or sheet-coated materials such as an IRC card. It should be noted that less variation of attenuation with frequency occured when thin metallized films were used than when carbon-coated materials were used.

G. Variable Tuners, Junctions, and Transitions

Variable tuners of various types are usable in microwave printed-circuit applications. A very practical Tri-plate double stub tuner is illustrated in Fig. 18. In air-dielectric, forms a MPC various dielectric wedge or screw-type tuners are also very practical.

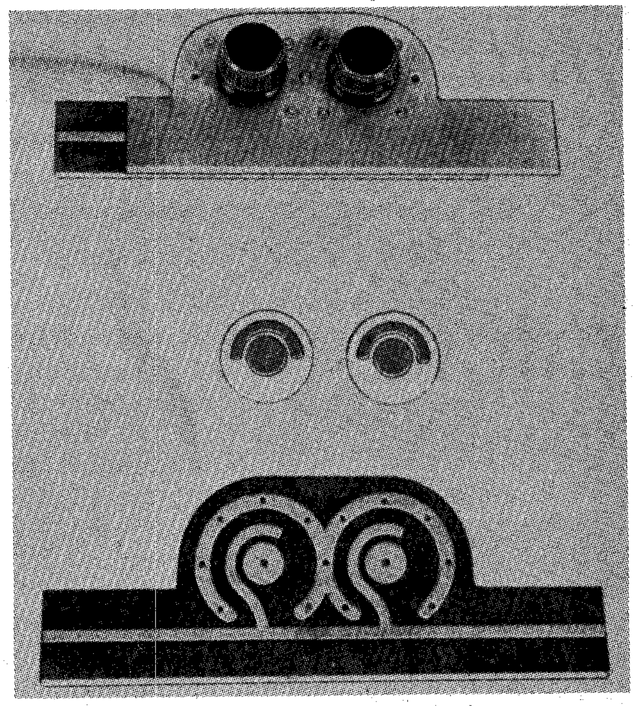


Fig. 18. Tri-plate open-circuited double-shunt stub tuner.

Although complex MPC circuits are usually fabricated all in one piece, for experimental work it is customary to fabricate separate components and join them together to form experimental circuits in much the same manner as in waveguides. These junctions should not only be reflectionless, but should also be mechanically rigid, self-aligning, reversible, easy to use, and have minimum leakage.

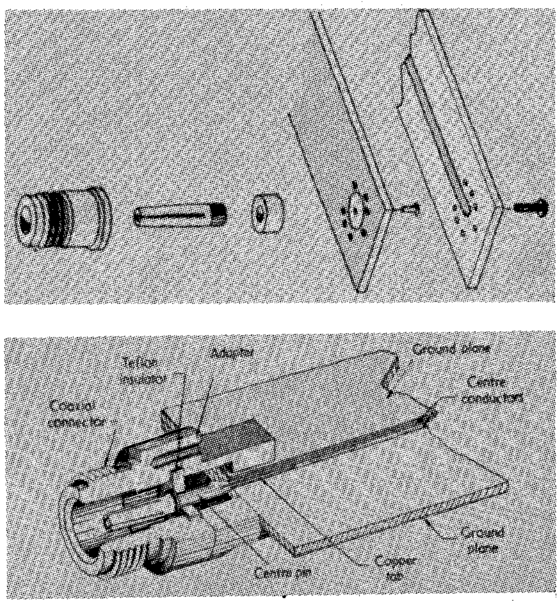


Fig. 19. Transition from coaxial-line to flat-strip transmission system.

Transitions from coaxial to flat-strip lines are often required and can be accomplished in several ways. The Tri-plate transitions illustrated in Fig. 19 are typical of these types of transition. The small pins that surround the junction are for suppressing higher order modes as well as giving mechanical strength.

H. Miscellaneous Structures and Complex Circuits

A wide range of circuits for miscellaneous structures based upon the use of resonant elements can easily be constructed in MPC.

The microwave printed-circuit technique has been applied to the entire RF circuitry of modern microwave receivers at great savings in cost and fabrication time. These circuits lend themselves to the production of "throw-away" systems for use in such expendable weapons as guided missiles, rockets, etc.

VI. Summary

These comments on the concepts and early trends in microwave printed circuits are of necessity very brief. From these early beginnings, the MPC, in its many forms, has become a workhorse of microwave technology and has developed into a sound and pervasive technology. I regret that space has not allowed a treatment of some of the current and existing applications.

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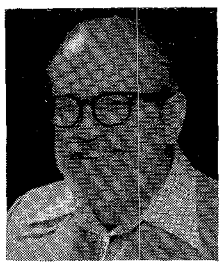

Robert M. Barrett was born in Farmington, UT, on March 3, 1920. He graduated from the University of California, Berkeley, with the B.S. degree in electrical engineering in 1942. He also did graduate work in physics at Boston University and the Massachusetts Institute of Technology.

Subsequent to World War II, during which time he was a Major in the Air Force, he worked at the Air Force Cambridge Research Laboratory in the field of antennas and microwave engineering, and then as the Deputy Director of the Electronics Research Directorate. In mid-career, he changed to the new field of solid-state physics, where, as a research physicist, he became the Director of the Solid State Physics Directorate of the Air Force Cambridge Research Laboratories and later the Rome Air Development Center.

He recently retired from active laboratory work and has established a freelance photographic business under the name of "Barrett Photo Graphics". During his long career as a research scientist, he also pursued photography, partially as a hobby and partially in connection with his work. He is a member of the Photographic Society of America (PSA), and the Societé Internationale de la Photographie.

Mr. Barrett had the first exhibit of his photographic work in Boston during June of 1980. Subsequently, he has exhibited widely. He has had six one-man exhibits of his work.