History of Microwave Passive Components with Particular Attention to Directional Couplers

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Abstract —After Hertz verified Maxwell's electromagnetic wave theory using a spark-gap microwave source, activity in the microwave range was negligible until about 1930, and quite limited until 1939. In that year, an explosion of activity commenced, motivated by military needs for radar and the invention of the high-power pulsed magnetron. Microwave passive component development during World War II (1939–1945) is discussed briefly, and then, because of space limitations, this paper concentrates on the important sub-field of directional couplers. The history of microwave filters is covered by the coauthors in a companion paper, while certain other passive components are touched on in the other historical review papers in this issue.

I. Introduction

THE HISTORY OF MICROWAVES began in 1888 with Heinrich Hertz's experimental verification of Maxwell's theory of electromagnetic waves by means of a spark-gap microwave source. The radiating elements, probes, reflectors, detectors, etc., that he devised for his purpose constituted the first microwave components. They scarcely resemble modern components, however, whose development began roughly in the early 1930's. In the years from Hertz's time until about 1930, the microwave range (roughly 300 MHz to 300 GHz) was dormant, except for occasional physics experiments, while massive research and commercial exploitation occurred at lower frequencies.

In 1932, George C. Southworth began to investigate waveguides at Bell Telephone Laboratories. Because the highest frequency coherent source available to him then was at 200 MHz, he filled his waveguide with distilled water to reduce its electrical cross section. According to Leo Young in an oral paper on microwave history in 1973 [1], Southworth's first transmission of a communication signal through waveguide took place in May of 1933. The first short message stressed a timeless sense of urgency, stating, "Send money!" Also in 1933, transmission of messages took place across the English Channel at 1750 MHz, using parabolic reflectors with 33-dB gain. In the late 1930's, the rigorous theory of waveguide modes in circular, rectangular, and elliptical cross sections was published in various papers by G. C. Southworth and S. A. Shelkunoff working at Bell Telephone Laboratories, and by W. L. Barrow and L. J. Chu at M.I.T. Many laboratory experiments were carried out during the thirties, requiring components such as transitions from coaxial line to waveguide, slotted lines, tuners, etc. The waveguide four-port bridge named the "Magic T" was invented in the late 1930's by W. L. Barrow.

Research and development on radar began independently in the mid 1930's in the United States, England, and a few other countries. All of this early work was done at frequencies of about 100 to 300 MHz using coaxial lines and components. Then, in 1939, the high-power pulsed magnetron was invented in England, and the technology was shared with the United States, thus enabling the development of high-resolution, difficult-to-jam radar in various narrow bands from 1.0 to 35 GHz. During the World War II years of 1939–1945, microwave radar (but not VHF radar) remained a monopoly of the United States and England.

In October 1939, the M.I.T. Radiation Laboratory was organized, reached a peak of 3900 people in 1945, and then was disbanded at the end of 1945 a few months after the war ended. The Radiation Laboratory's principal mission was to develop more and more advanced radar systems for the United States, England, and their allies. Another laboratory was set up at Harvard, the Radio Research Laboratory, with the mission of developing search receivers and jamming transmitters to locate and defeat enemy radar. Also, vast amounts of important work continued in England and in the United States at the Naval Research Laboratory, Bell Telephone Laboratories, Columbia University, Sperry Gyroscope Co., RCA, Philco, Raytheon, Sylvania, etc. As part of this work, new microwave components were devised, developed, and produced at an incredibly rapid rate, often simultaneously at different laboratories, and even in different groups of the same laboratory, so that invention credit often can not be properly ascribed.

After World War II, key personnel at the M.I.T. Radiation Laboratory published a 28-volume Radiation Laboratory Series of books, and the Harvard Radio Research Laboratory published a two-volume series. These describe a very large variety of coaxial and waveguide components, but mainly without giving credit to particular individuals. Almost all passive coaxial and waveguide components in use now, forty years later, are described in at least rudimentary form in these books, and often with their mathe-

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matical theory so completely presented as to be thoroughly modern today.

Several classes of passive components, however, have experienced enormous theoretical and experimental innovation since 1945, and therefore are not adequately covered by modern standards in the flood of books and papers appearing immediately following 1945. One such class is microwave filters, which is treated by the same coauthors in another paper in this issue. Another is directional couplers, which the coauthors have chosen for particular attention in this paper. Directional couplers are by no means ignored in the old literature. For example, Volume 11 of the Radiation Laboratory Series has a 44-page chapter on waveguide and coaxial directional couplers, with principal attention to the waveguide Bethe-hole coupler, branch-guide couplers with two branches, two-hole couplers with holes spaced by $\lambda_{g0}/4$, multiple-hole couplers with binomial distribution, the Schwinger coupler, long-slot couplers, and the loop-probe-resistor coupler.

II. Early History of Directional Couplers

The earliest directional coupler is generally credited to H. A. Affel of A.T.T., Co., whose U.S. Patent 1 615 896 was filed in 1922 and granted in 1927. He shows a quarter-wave two-wire line with a resistor at one end and a detector at the other, which is placed parallel to a long two-wire transmission line. He refers to it as a loop antenna, the name "directional coupler" not having been invented yet, but clearly it can be designed to perform as a directional coupler.

In a bibliography on directional couplers published by R. F. Schwartz [2] in 1954, his earliest of about 90 references is U.S. Patent 1 999 250 issued in 1935 to A. Mollath and H. O. Roosenstein, entitled "Power Factor Meter for High-Frequency Measurement." Other early references are by A. Alford [3], published in February 1941, and by Pistolkors and Neumann [4], published in April 1941.

One would expect that other implementations of directional couplers for balanced wire line and coaxial line must have been carried out in the 1920's and especially in the 1930's, but considerable research into the older literature would be needed to discover the extent of such work. Even the origin of the name "directional coupler" is a mystery now.

III. Waveguide Directional Couplers

The earliest waveguide directional coupler probably used a pair of capacitive probes spaced $\lambda_{g0}/4$ along the two waveguides. The first use of a coupling aperture was probably the Bethe-hole coupler, which has a single round hole centered in the common broadwall between two waveguides, the axes of which were at an angle such that, at the design frequency, the electric and magnetic couplings to the secondary waveguide cancel in one direction while adding in the other. The use of two or more holes spaced $\lambda_{g0}/4$ apart along two parallel waveguides was invented by W. W. Mumford and covered in his U.S. Patent 2 562 281, filed June 14, 1944, and issued July 31, 1951. His claims apply not only to waveguide, but also to coaxial line, or any other type of line. His paper on the subject was published in 1947 [5]. For more than two holes, he proposed the binomial distribution of hole couplings to improve broad-band directivity.

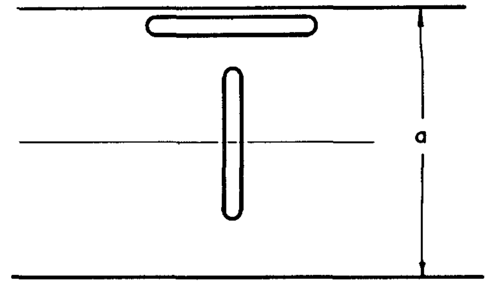

Fig. 1. Riblet and Saad directive slot pair.

H. J. Riblet in 1947 published the correct mathematical theory of n equal coupling devices (which could be holes, probes, branch waveguides, etc., spaced $\lambda_{g0}/4$ apart between two parallel waveguides [6]. He shows that as n is increased, the input power alternates between the primary and secondary waveguide outputs with powers proportional to $\cos^2(nK)$ and $\sin^2(nK)$, and that a 90° phase difference between the outputs is maintained. The 90° property is also evident in the scattering matrix given in Volume 8 of the Radiation Laboratory Series for any fully symmetrical directional coupler, but this phase property is not mentioned specifically in that reference, nor is the potential utility of a quadrature hybrid coupler recognized there.

In 1948, Riblet and Saad published a paper on the use of a pair of slots repeated n times at $\lambda_{g0}/4$ intervals along the common broadwall of parallel waveguides. Each pair of slots is centered in the same cross-sectional plane, with one slot transverse, and the other slot longitudinal and off center, as shown in Fig. 1. This slot pair can be designed to have perfect directivity at a selected frequency f_0, and have flat coupling at this frequency. With additional such pairs spaced $\lambda_{g0}/4$ along the waveguides, the coupling can be increased while, at the same time, the bandwidth for high directivity increases. One of their designs has experimental data showing closely equal power split and high directivity over a 12-percent band. Phase difference was not measured, but 90° is proven in Riblet's previous paper [6] to be inherent. Apparently, this is the first broad-band quadrature hybrid coupler. From the discussion in the paper, however, its enormous potential value as a component was not yet realized.

Riblet's next paper, "The Short-Slot Hybrid Junction," submitted in October 1950 and published in February 1952 [8], is a major advance in microwave technology. For the first time, the true value of a wide-band equal-power-split quadrature hybrid as a basic, versatile component is emphasized. Riblet, however, references a few anticipations for limited applications; namely, in the Radiation Laboratory Series Volumes 14 and 16, in the Riblet and Saad paper [7], and in an unpublished work by N. I. Korman.

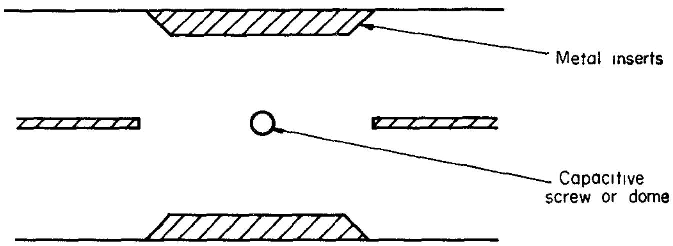

Fig. 2. Narrow-wall short-slot coupler.

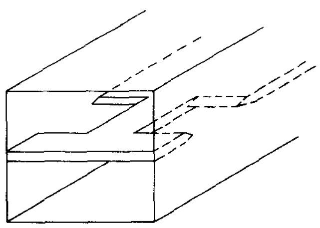

Fig. 3. Broad-wall short-slot coupler.

The main contribution of this paper [8] is the new short-slot side-wall waveguide coupler (Fig. 2), which has closely equal power split, high isolation, low VSWR, and accurate 90° phasing over bandwidths of at least 12 percent. This quadrature hybrid, and a similar top-wall short-slot coupler developed later by Riblet (Fig. 3), was widely adopted by the industry, and is perhaps the most extensively used waveguide component today.

The next major advance in waveguide couplers was the application of the Dolph-Chebyshev antenna-array theory to multi-hole directional couplers, in order to achieve high directivity over broad bands for reflectometer applications. C. L. Dolph published his mathematical method in 1946 in the *Proceedings of the IRE*, and in subsequent years a number of individuals recognized its value for other applications. For example, one of the authors of this paper (SBC) designed a seven-hole side-wall coupler in about 1950 that had over 40-dB measured directivity over a full waveguide bandwidth of 40 percent. This was used at Sperry Gyroscope Co. in an electronically leveled, mechanically swept reflectometer system covering the 4–6-GHz band. However, the most significant advance in reflectometer couplers was made at Hewlett-Packard Co., and described in 1952 by E. F. Barnett and J. K. Hunton [9]. One of their contributions was to place round holes off center on the common broad wall of parallel waveguides on one or both sides of the center line (Fig. 4) such that the coupling of the H_x and H_z field components combine to yield almost flat forward coupling over the full waveguide band. Their second major contribution was to superimpose a number of Dolph-Chebyshev arrays displaced with respect to each other along the direction of the waveguides, such that the sum of the array element values have an almost constant value along most of the total array, with tapering at the ends. Thus, for a given maximum allowable hole diameter, any value of total coupling can be achieved. Designs having couplings of -3.0, -10, and -20 dB were developed for all the common waveguide sizes, yielding

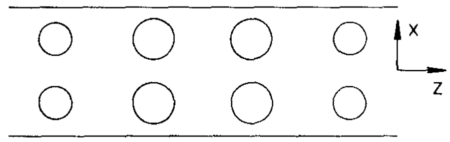

Fig. 4. Multi-aperture broad-wall coupler.

over 40-dB directivity in the full rated waveguide bands. For reflectometer applications, this remains the preferred type of waveguide coupler.

Later improvements in the theory [10], [11] enables multi-aperture couplers to be designed precisely with little or no empirical adjustments. This theory is based on an improved model for the aperture coupling, together with a precise four-port equivalent-circuit representation of the coupler.

IV. Coupled TEM-Line Directional Couplers

The first directional coupler consisted of a two-wire balanced line coupled to a second balanced line along a distance of a quarter wavelength. Later, a pair of rods a quarter wavelength long between ground planes were used by H. A. Wheeler in about 1944. The first exact design theory for TEM couplers that applies rigorously to tight, as well as loose, coupling is in a paper by B. M. Oliver [12] published in 1954. He gives the correct coupling versus frequency for a single-section coupler, and an approximate theory for a coupler having tapered coupling.

At this point, certain fundamental exact properties of parallel-coupled TEM lines will be stated in terms of the even and odd modes of the coupled conductors indicated in Fig. 5. First, the coupling is backward; that is, the coupled wave on the secondary line propagates in the direction opposite to the direction of the wave on the primary line. Second, if $Z_{oe}Z_{oo} = Z_o^2$ at all cross sections along the directional coupler, directivity will be perfect and VSWR unity; therefore, Z_{oe}/Z_o versus the length coordinate completely specifies the design, since $Z_{oo}/Z_o = Z_o/Z_{oe}$. Third, the voltage coupling factor k of the directional coupler is equal to the input reflection coefficient of the even mode when the even-mode circuit is terminated by Z_o; that is

$$k = (\rho_{\text{even}})_{\text{in}} = \frac{(Z_{\text{even}})_{\text{in}} - Z_o}{(Z_{\text{even}})_{\text{in}} + Z_o} = -(\rho_{\text{odd}})_{\text{in}}.$$

The first description of the use of a symmetrical three-section coupler (Fig. 6) to provide a large improvement of bandwidth of almost flat coupling was in 1955 in a paper by E. F. Barnett, P. D. Lacy, and B. M. Oliver [13]. Also in 1955, the idea of connecting TEM couplers in tandem to achieve tighter overall coupling than from either coupler alone was advanced by G. D. Monteath [14]. He also suggested that a wider "flat" coupling bandwidth could be obtained if one coupler were $\lambda_0/4$ long and the other $3\lambda_0/4$ long. The ideas in these two papers were exploited to great advantage from the 1960's to the present time.

Also during 1955, a group at Stanford Research Institute, including one of the authors (SBC), E. M. T. Jones,

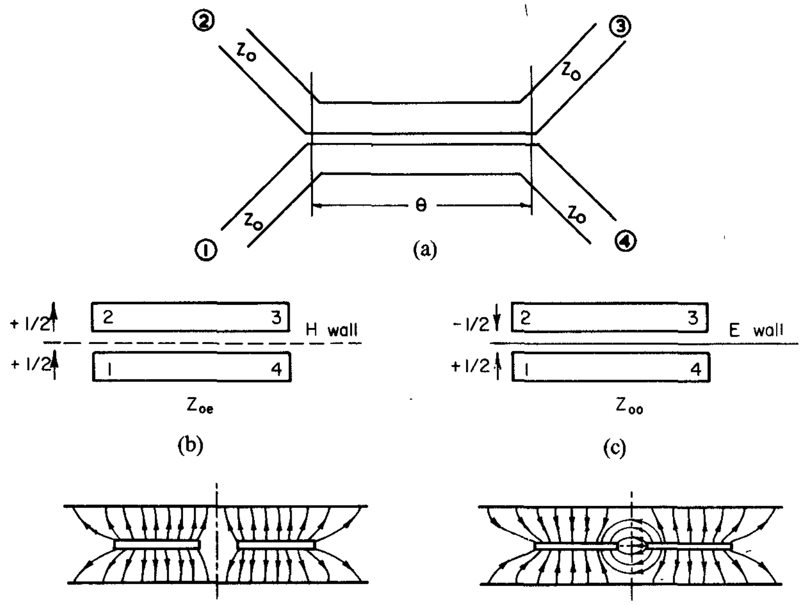

Fig. 5. (a) Single-section TEM-line proximity coupler. (b) Even- and odd-mode circuits and electric-field patterns.

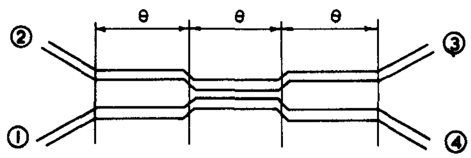

Fig. 6. Three-section symmetrical TEM-line coupler.

J. K. Shimizu, and later W. J. Getsinger, E. G. Cristal, and L. Young, became interested in stripline directional couplers, and published a series of papers on the subject. The first use of flat stripline was probably by H. A. Wheeler in about 1944, using thick strip circuits between parallel ground planes with air dielectric and a minimum of dielectric supports. Another similar World War II application was by V. H. Rumsey and H. W. Jamieson. The idea of using photo-etched strip circuits sandwiched in dielectric sheets was due to R. M. Barrett in 1949. In 1955, one of the authors (SBC) realized that rigorous design of stripline couplers would require quantified knowledge of the orthogonal even and odd TEM modes that can propagate on a pair of coupled strips. He derived exact formulas for the Z_{oe} and Z_{oo} characteristic impedances of these modes for the case of zero-thickness coplanar strips centered between ground planes, and his paper was published in October 1955 [15]. In a later paper, he published formulas for broadside coupled strips arranged both parallel and perpendicular to the ground planes [16]. In another paper, he presented the re-entrant cross section [17], which allowed very tight coupling with acceptable tolerances. The same principle has been used in filter and directional coupler design. Meanwhile, E. M. T. Jones and J. T. Bolljahn [18] derived exact formulas relating coupling to Z_{oe}, Z_{oo}, Z_o, and electrical length, unaware then of B. M. Oliver's prior publication in 1954 [12]. Jones and Bolljahn's paper in 1956 included many other connections of a pair of coupled TEM lines that have proved to be of fundamental importance in the design of filters and equalizers. J. K. Shimizu and E. M. T. Jones [19], [20] extended the idea of symmetrical couplers to any odd number of sections, with approximate formulas for coupling. They also derived an exact coupling formula for the three-section case versus the various parameters, and computed a table of section parameters versus coupling ripple for a mean coupling of -3.01 dB. They also designed one- and three-section couplers that were built and successfully tested. Further important contributions from S.R.I. were W. J. Getsinger's [21] evaluation of the even- and odd-mode impedances of coupled thick strips, E. G. Cristal's [22] evaluation of these parameters for coupled rods between ground planes, and E. G. Cristal and L. Young's [23] precise design theory and tables for symmetrical multiple-section couplers. By coincidence, a similar paper by P. P. Toulios and A. C. Todd [24] arrived at IEEE Headquarters on the same day, November 23, 1964, and the two papers were published in the same issue in September 1965. Cristal and Young's paper has the advantage of much more extensive design tables, covering odd n of 3 to 9, couplings of -3.01, -6.0, -8.34, -10, and -20 dB, each with coupling ripples of $\pm 0.05, 0.1, \cdots$ etc., to ± 1.0 dB.

As discussed earlier, symmetrical couplers have quadrature output phasing independent of frequency. This property is essential when a -3.0-dB coupler is used as a hybrid junction, but is usually not needed in weaker couplers used for signal sampling and leveling. S. D. Casper and J. E. McFarland [25] of Narda Microwave Corporation showed in a patent filed in 1960 that the sections from one end to, but not including, the middle section could be omitted, and then after a redesign, the remaining part of the coupler would yield the desired coupling with the same number of ripples as the original symmetrical coupler. They used an approximate design theory with experimental

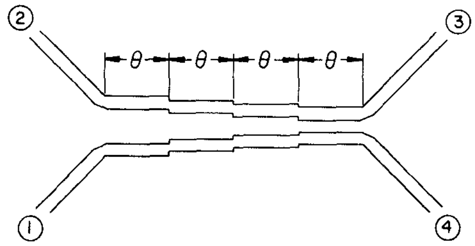

Fig. 7. Asymmetric stepped TEM-line directional coupler.

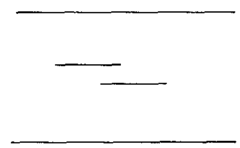

Fig. 8. Offset coupled strips.

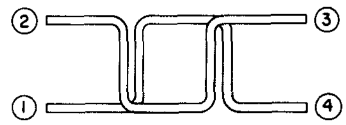

Fig. 9. Tandem-connection of directional couplers.

refinement. Thus, if n (= odd) sections are needed in a symmetrical coupler, only $(n+1)/2$ sections are needed in the corresponding asymmetrical coupler (Fig. 7). This modification abandons the property of quadrature phase independent of frequency, but provides the advantage of a length reduction by almost half.

Also at about this time, one of the authors of this paper (RL) realized the theoretical feasibility of an asymmetric coupler and its length advantage. He attacked the design problem as part of his Ph.D. thesis work, and arrived at a rigorous set of design formulas in closed form, which he published in July 1963 [26]. Later, he programmed his exact synthesis technique and published extensive design tables for 2 to 6 asymmetric sections, couplings of -3.0, -6.0, -10, -15, and -20 dB, bandwidths up to 18.0 to 1, and many different ripple values [27]. This computer program gives designs of up to 60 sections, and by smoothing-out the steps has been used to design continuously tapered couplers.

V. Offset Coupled Strips for Broad-Band Applications

Broad-band 3-dB hybrid couplers and associated components are widely used in present-day photo-etched stripline circuits. The cross sections referred to above are not convenient for this purpose, however. The only cross section permitting easily connected crossovers to allow outputs on the same side of the coupler rather than diagonally opposite is broadside-coupled strips parallel to the ground planes. In this case, the proportional thicknesses of the three-layer dielectric sheets is uniquely determined for a -3.0-dB coupler by the condition $Z_{oe}Z_{oo} = Z_o^2$ and the dielectric-constant value. Therefore, only single-section couplers are practical with this cross section, thus ruling out bandwidths of more than about one octave. The problem was seen clearly by J. Paul Shelton, Jr. in the mid-1960's, and his solution, published in January 1966, was to generalize the fully broadside placement of strips by allowing the strips to be offset from each other in the cross-section plane (Fig. 8), thus allowing weakening of coupling continuously from its full-broadside value to essentially no coupling [28]. Another important contribution was his understanding that the unsymmetrical fringing fields of offset strips would not cause coupling to any undesired modes, but only to the desired even and odd modes, even though four conductors (two strips and two conducting planes) were present. He completed his contribution by deriving a set of design formulas yielding dimensions versus desired Z_{oe}, Z_{oo} pairs. These formulas apply to zero-thickness strips, but corrections adequate for the small thickness of photo-etched strips are easily made. Following the publication of this work, all multi-octave stripline circuits requiring tightly coupled strips have used this offset-coupled three-layer sandwich construction.

Later in the same year, 1966, J. P. Shelton and J. A. Mosko [29] published a paper on tandem connections of identical and nonidentical multisection, symmetrical couplers (Fig. 9) to achieve 3-dB quadrature broad-band couplers. Tandem connection alleviates the physical problem of tight coupling, since two individual couplers need only -8.34-dB coupling to achieve a -3.0-dB coupler. The strip crossovers needed for tandem connections are easily achieved with the three-layer sandwich, offset-strip cross section. In their paper, they presented an iterative design method by computer for evaluating the Z_{oe}/Z_o values of the various sections to achieve a close approximation to equal-ripple coupling over a specified bandwidth. They treated nonidentical couplers in tandem, as well as identical couplers. Although they originally believed that they had conceived the tandem connection idea, they found and credited Monteath's suggestion for this [14] before publication. Shelton and Mosko included tables of Z_{oe}/Z_o for coupled-line sections of numerous cases. In this same paper, they also treated and tabulated multisection coupled-line phase-difference designs. In their mathematical method, they first compute a crude approximate solution by a simple method, and then improve the parameter values by an iterative process involving a Fourier analysis of the error from equal-ripple coupling response, until the parameters are refined to yield equal-ripple coupling within a tolerance judged sufficiently small.

VI. Tapered TEM Directional Couplers

The symmetric and asymmetric couplers described above consist of discrete equal-length coupling sections, each of which has constant coupling. Abrupt steps of coupling and dimensions occur where these sections join. (There were a few proposals for tapered asymmetric couplings, but, even in these cases, an abrupt step from zero to maximum coupling is required at one end.) Step discontinuities cause coupling error and directivity degradation. Adequate compensation of these discontinuities is possible for $b\sqrt{\epsilon_r}/\lambda$ less than about 0.1, but is difficult in the 0.15 to 0.25 range encountered in designs for use up to about 18 GHz. The offset between the center and adjacent strips of a multisection symmetrical coupler are typically almost equal to the strip width, and hence particularly severe. This problem was dealt with for symmetrical couplers in 1966 by C. P. Tresselt, who replaced the steps between sections by gradual tapers [30]. Simply tapering the steps would cause a droop in coupling toward the high end of the band, but a coupler specifically designed to include tapers can yield broad-band, flat coupling with equal-ripple deviations. Tresselt realized this, and worked out and published a mathematical design method which replaced a prototype discrete-section symmetrical coupler by a continuously tapered coupler. The individual sections are recognizable as approximate flattenings in the continuous curve. Somewhat tighter maximum coupling is required at the center of the coupler compared to the discrete-section prototype, but this penalty is not important in practical work. Tresselt's ingenious mathematical method yields a coupling response that is only approximately equal ripple, and hence is not quite optimum. His experimental model had -8.34-dB coupling, intended for tandem connection to provide an overall -3.01-dB hybrid coupler.

In 1969, D. W. Kammler published an iterative optimization method for tapered couplers that yields true equal-ripple coupling over the design band to as close a tolerance as desired [31]. He attributes the basic mathematical approach to E. Remez, who published his optimization method in France in 1934. (One of the authors, SBC, arrived at this method independently but much later, in 1972, and has used it to design tapered and discrete directional couplers, phase-difference circuits, filters, transformers, etc. A feature that may be new, however, is a mathematical process of locating the maximum and minimum points automatically and precisely during the last few computer iterations, thus reducing the time and labor of a design. This procedure is described in the *MTT Symposium Digest* for 1974 [32].)

The combination of the offset-strip cross section, tandem connection, and tapering has solved the major problems of practical, broad-band TEM quadrature couplers, and has been used extensively from the late 1960's to the present time.

VII. Tapered Asymmetric TEM Couplers

There are actually two distinct kinds of asymmetric couplers that have practical importance. One, solved exactly by one of the authors (RL) for the case of discrete, uniform-length sections [26], [27], is characterized by minimum length and an output phase difference that varies widely over the frequency band. The other, described in the next section, is about twice as long, but has the useful 0°, 180° output phasing characteristic of a T hybrid. Both kinds of asymmetric couplers can be designed with continuous tapers, as well as with discrete uniform sections. In 1970, F. Arndt published tables for designing tapered versions of the short, phase-wandering kind of directional coupler yielding constant ripple deviation form f_1 to ∞ [33]. He represents his tapered coupling function by a sixth-degree polynomial in powers of normalized length z/l, and gives tables of the coefficients a_0 through a_6 for couplings of -3.01, -6.02, -8.34, -10.0, and -20.0 dB for a wide range of ripples. For each case, he gives l/λ_1, which defines the low-frequency edge of the band.

In all of the asymmetric designs mentioned thus far, including Arndt's tapered design, an abrupt step from zero to the tightest coupling is required. This is physically impossible, of course, although it may be approximated by having the connecting strips arrive at the junction point with ninety degrees between them, thus making magnetic coupling negligible, and inserting one or more grounding pins or a blade perpendicular to the ground planes in the arrival region to minimize electric coupling. Inevitably, however, the discontinuity effects and stray coupling at this junction will deteriorate the high-frequency performance. One of the authors (SBC) has alleviated this problem by purposely providing a tapered region in place of the abrupt step. This taper must be considerably steeper than that of the main part of the coupler, but an included angle between the two centerlines of up to about 35° is tolerable. The asymmetric coupler including this initial taper is synthesized as a whole by an iterative process to yield equal-ripple coupling over bandwidths of at least 20 to 1. This work has not been published, but has been used in quite a number of successfully produced designs.

VIII. Asymmetric TEM Hybrid T Couplers

As mentioned above, a symmetric coupler can be designed to provide the 0°, 180° phasing of a hybrid T. To achieve ideal performance, the coupling must be stepped abruptly from zero to maximum coupling, and then decoupled so gradually along its length that reflection of the even and odd modes occurs only at the initial step. For equal power split, the coupler requires $Z_{oe}/Z_o = 5.828$ at the tight end, and a virtually reflectionless impedance transformer between this point and the far uncoupled end where $Z_{oe}/Z_o = 1$. These ideas and their implementation were described by R. H. DuHamel and M. E. Armstrong in a company report in October 1964, and finally published in an accessable reference in 1972 [34]. For the impedance-transformer design, they used a Klopfenstein taper, which yields a small equal-ripple reflection from an initial frequency f_1 to infinity. The normalized length l/λ_1 at f_1 is a function of the reflection ripple, lower ripple requiring longer length. Coupling and phase variations from ideal are caused by this ripple, and hence choice of length is a compromise that fortunately has reasonable bounds. Because $Z_{oe}/Z_o = 5.828$ is impractically high, DuHamel and Armstrong used two -8.343-dB couplers of this type connected in tandem to achieve an equal-power-split broad-band T hybrid. In this case, the maximum Z_{oe}/Z_o is 2.240, an easily achieved value. The DuHamel and Armstrong T hybrid has been, and continues to be, widely used.

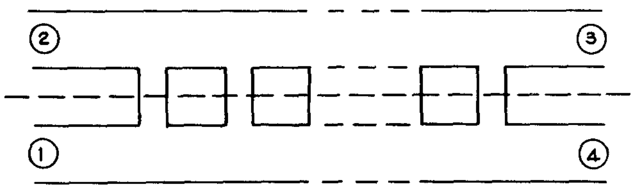

Fig. 10. Branch-line coupler.

IX. Branch-Line Couplers in Waveguide and TEM-Line

A cross section through the E-plane of a typical broad-wall waveguide branch-guide coupler is shown in Fig. 10. This can represent also a planar strip TEM branch-line coupler. The branch lengths and main-line spacings are each one-quarter wavelength at the midband frequency.

The branch-guide coupler was developed in the 1940's, and the design and analysis of a two-branch coupler was described by R. L. Kyhl [35] in Volume 11 of the Radiation Laboratory Series. The early work concentrated on the analysis, and no attempt at synthesis of higher order couplers was described. The 3-dB version of the branch-line coupler was one of the first kinds of 90° hybrids, but was soon outmoded by the short-slot type of coupler [8], so that the branch-line coupler was seldom considered in applications for several years.

The first paper on general multibranch couplers with tapered distributions of the couplings was published in 1957 by Lomer and Crompton [36], using a binomial (maximally flat) distribution. The obvious extension to the Chebyshev case was carried out by one of the authors (RL), and a marked improvement in match and isolation bandwidth resulted [37]. At the same time, the author was discussing the problem with a colleague in London, Guy Patterson, whose alternative theory appeared in the same year [38]. In all cases, extensive use was made of the fundamental even/odd mode analysis of Reed and Wheeler [39].

In most of the multibranch designs described up to 1962, only the branch-line impedances were tapered, the main-line impedance remaining uniform. A major step in the right direction was then taken by Leo Young, who described a design which required the main-line impedances to vary [40]. The design was based on the use of the quarter-wave transformer prototype, relating the steps or junctions of this to the T-junctions of the branch-guide coupler in its even- and odd-mode two-port circuits. The technique suffered from the rather poor approximation that the series stubs which appear in these circuits have frequency-invariant reactances. This causes the bandwidth of the coupler to compress relative to the prototype, although graphical correction factors were presented to alleviate this drawback.

The problem of the exact synthesis of branch-line couplers remained a puzzle for a number of years. The idealized network shown in Fig. 10 is commensurate, but no theory for *synthesis* of four-ports existed. When the even- and odd-mode circuits are formed, as in Fig. 11, we have

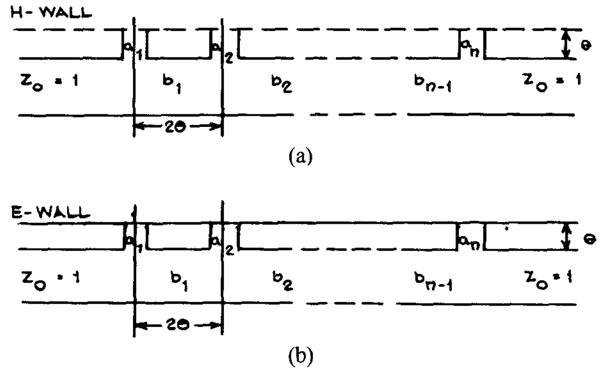

Fig. 11. (a) Even-mode and (b) odd-mode two-port network of a branch-line coupler.

two (apparently) entirely different types of networks, one with open- and one with short-circuited stubs. No method was known which could simultaneously synthesize these networks, maintaining identical impedances in the even- and odd-mode circuits.

The solution to this dilemma occurred to one of the authors (RL) in January 1966. Expressing a double-length unit element in terms of the Richards' variable

$$S = j \tan\theta \tag{1}$$

he saw that it was invariant to the transformation

$$S \to 1/S \tag{2}$$

apart from a 180° phase change. Since the open- and short-circuited stubs are transformed by this same reciprocal relationship, the problem was as good as solved, because it was necessary only to synthesize one circuit (say, the even mode), and the odd-mode circuit would have identical impedance levels and be similarly matched over a coincident band. The details of the synthesis were worked out by his research student L. Lind, and published in 1968 [41].

Branch-line couplers have become economically important for a number of reasons. Short-slot hybrids remain difficult to design, and are suitable only for coupling values of 3.0 dB or 4.77 dB (2:1 coupling). Multi-aperture couplers are lengthy, and have restricted power-handling capability. With highly precise computer-aided design techniques available for branch-line couplers, it is possible to generate any coupling value in the useful 0–15-dB coupling range. Waveguide designs have been used in large complex feeds for phase-array radars, are compact, highly predictable in amplitude and phase characteristics, and handle very high power. In coax, microstrip, or stripline, branch-line couplers are very useful and provide simple planar structures of moderate bandwidth capability, up to about two-thirds of an octave.

The earlier synthesis techniques gave impedance levels which were often difficult or impossible to realize, but later work [42] has enabled this problem to be largely overcome. This statement is true both for waveguide and TEM-line structures, but the mathematical difficulty of generating the Zolotarev designs has inhibited widespread applications. It is hoped that design tables will be generated in the near future to overcome this barrier.

Another technique for broadbanding branch-line couplers involves the use of external matching, proposed originally by A. Podell [43]. A somewhat different approach was taken (without prior knowledge of Podell's work) by G. P. Riblet [44], who used external matching to design a highly practical TEM-line quadrature hybrid having practically perfect 3.01-dB coupling over a 15-percent bandwidth.

X. Microstrip Couplers

Achieving a full range of weak to strong coupling and good directivity in microstrip presents a problem not affecting TEM couplers in homogeneous dielectric. This is inequality of the even- and odd-mode phase velocities, which degrades directivity, especially in the range of weak coupling.

For a -3.0-dB hybrid coupler, two strips on the substrate surface would require an infinitesimal, impractical spacing. This problem was solved by J. Lange [45] with his interdigitated design in which four narrow strips are used with alternate pairs connected in parallel by means of small-diameter gold jumper wires. Thus, there are three gaps instead of one, and, for -3.0 dB-coupling, the gaps are small, but feasible. This design yields acceptable power split and isolation over about a two-to-one band. A few variations of Lange's design have also been published [46]–[48].

In the case of weak coupling, below about -8 dB, directivity is seriously deteriorated by microstrip's unequal mode velocities. A. Podell has shown a method of compensation using a zig-zaggered gap [49] that yields good directivity improved from -8 to at least -27 dB. Compensation has also been obtained by dielectric overlays [50].

XI. Conclusions

Directional couplers are, together with filters, probably the most interesting of passive components, and hence this paper has concentrated on this topic, the companion paper dealing with filters. Further reading on directional couplers will be found in [51]. The reason for the enduring fascination with this general area is due to continual advances in network synthesis techniques, to which the designs are particularly amenable. Most other passive components are comparatively mundane (although requiring much engineering experience and expertise), and present less challenge and opportunity for the inventor or designer. Other topics having considerable interest are constant phase-shift networks (e.g., Schiffman-type phase shifters) and impedance transformers, since these topics are, in fact, amenable to treatment by modern circuit theory.

Commercially important components, such as coax-to-waveguide transitions, rotary joints, etc., are treated in the Radiation Laboratory Series, and their history may be developed from that starting point.

Finally, it is felt that the sentiments expressed in the closing remarks of the companion paper on filters are equally applicable to this paper.

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