# United States Patent [19]

**Shelton**

[11] **3,737,810**

[45] **June 5, 1973**


[54] **WIDEBAND TEM COMPONENTS**


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[73] Assignee: **Radiation Systems Incorporated,** McLean, Va.



[22] Filed: **May 5, 1969**

[21] Appl. No.: **821,612**

**Related U.S. Application Data**

[63] Continuation-in-part of Ser. No. 485,723, Sept. 8, 1965, abandoned.

[52] **U.S. Cl.**.....**333/10,** 333/11, 333/31 R, 333/84 M

[51] **Int. Cl.**.....**H03h 7/30,** H01p 3/08, H01p 5/14

[58] **Field of Search**.....333/10, 11, 84, 31; 332/29



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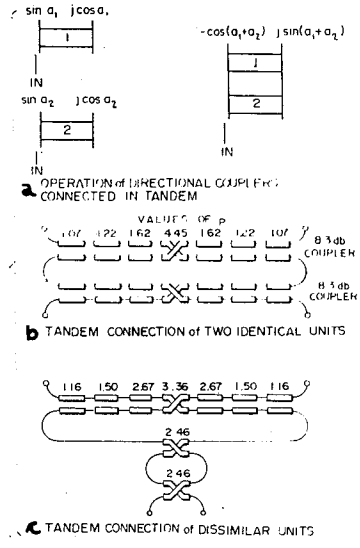
[57] **ABSTRACT**

A prior art microwave component for multi-octave operation includes a plurality of sections of coupled TEM transmission lines interconnected in cascade to form a single composite four-port network in which the coupled sections have progressively tighter coupling coefficients. As the number of sections of the composite network increases, or as the bandwidth requirements of the network increase, the separation between adjacent transmission lines becomes progressively smaller unit a point is attained at which the coupling coefficient cannot be realized using conventional manufacturing processes.

The disclosed invention provides a technique by which coupling coefficients that have heretofore been unrealizable in practice can be achieved for coupled sections requiring such coupling coefficients, by interconnecting one or more additional groups of cascaded coupled sections in tandem with the original cascade configuration.

In a cascade interconnection, the direct and isolated ports of one couple are connected to the input and coupled ports of the next succeeding seciton. In contrast, in the tandem interconnection the direct and coupled ports of one group of cascaded coupled sections are connected to the input and isolated ports of another group of cascaded coupled sections, where a "group" may constitute simply one section, as well as any larger number of sections.

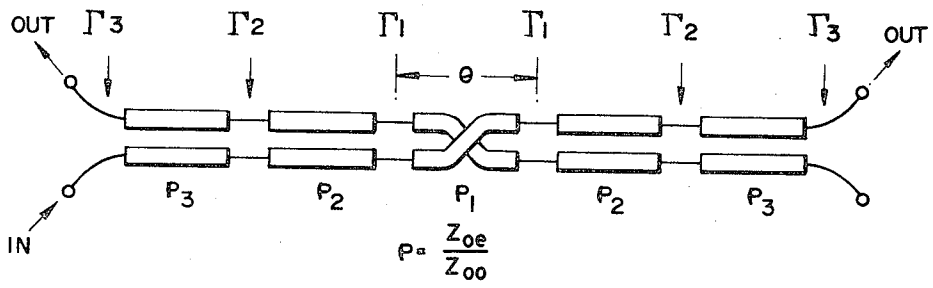

**15 Claims, 23 Drawing Figures**



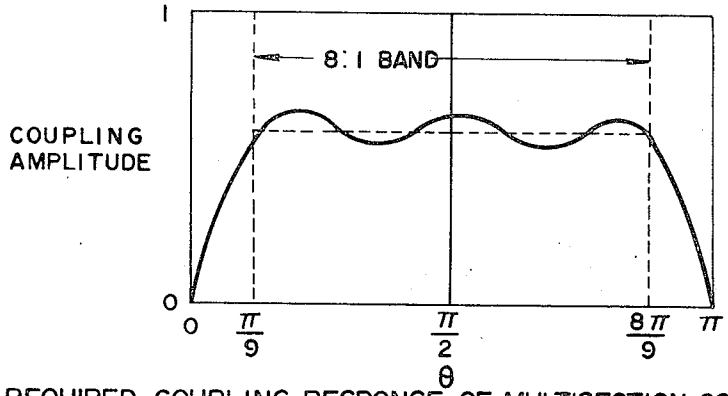
Patented June 5, 1973 3,737,810

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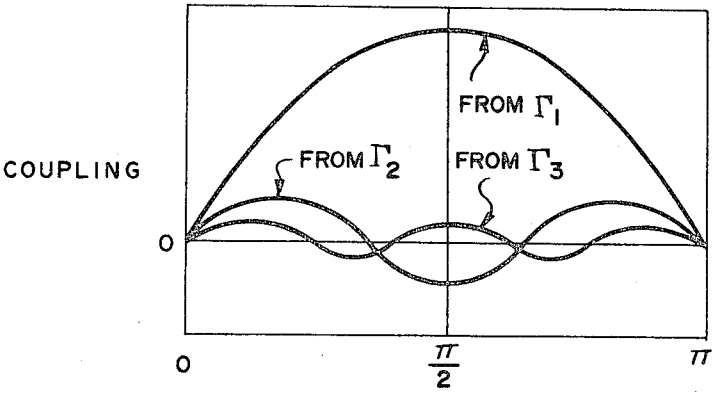
FIG. 1




a CONFIGURATION OF MULTISECTION DIRECTIONAL COUPLER




b REQUIRED COUPLING RESPONSE OF MULTISECTION COUPLER



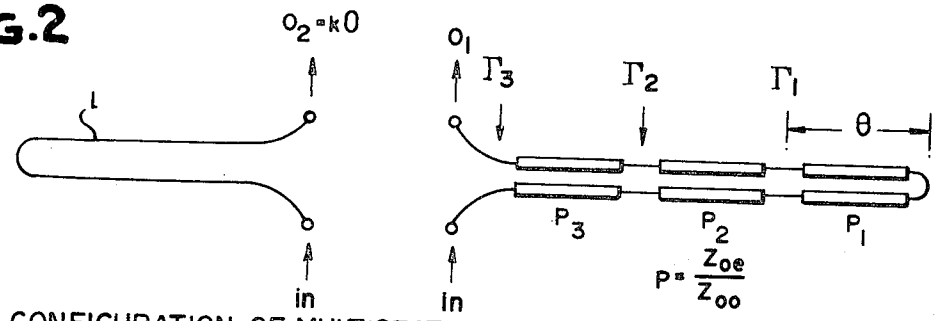

c DECOMPOSITION OF COUPLING RESPONSE

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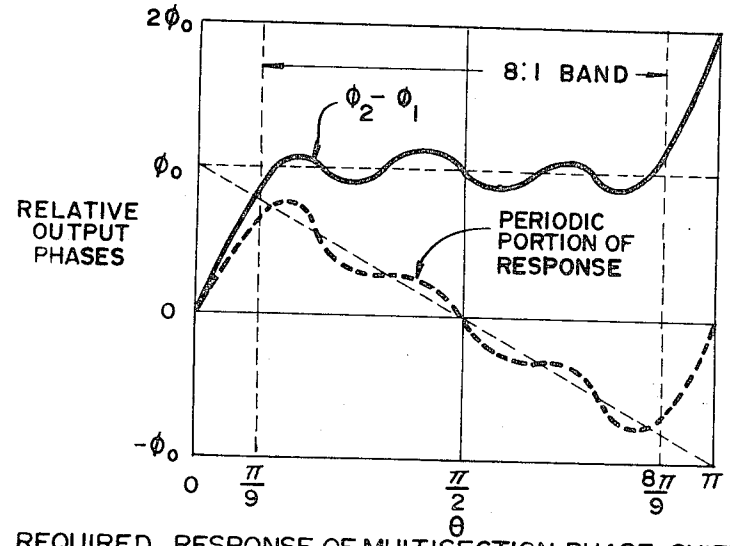
BY Hurwitz & Rose

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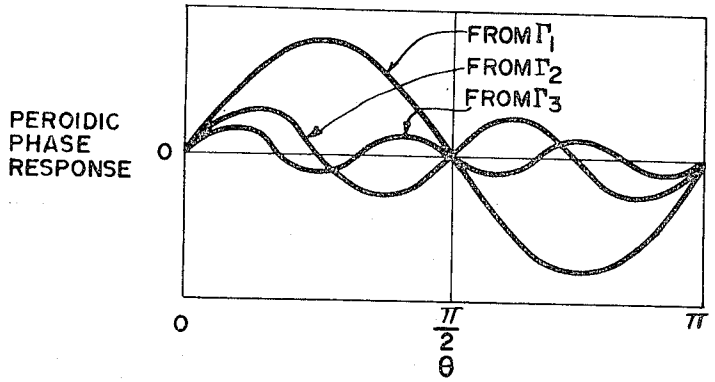
FIG.2




a CONFIGURATION OF MULTISECTION PHASE SHIFTER




b REQUIRED RESPONSE OF MULTISECTION PHASE SHIFTER

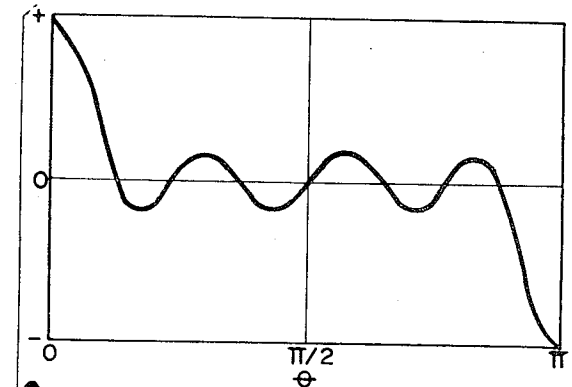



c DECOMPOSITION OF PHASE RESPONSE

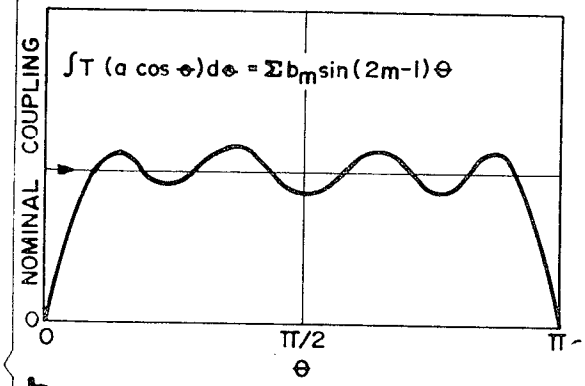
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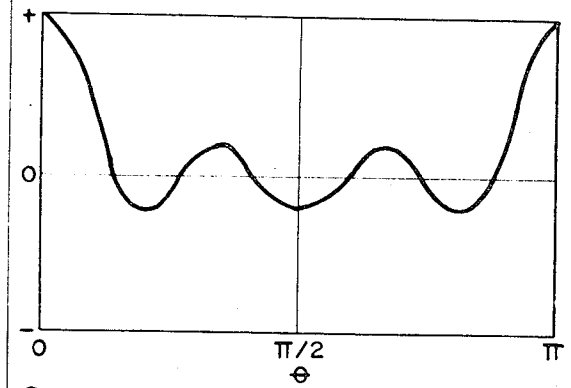
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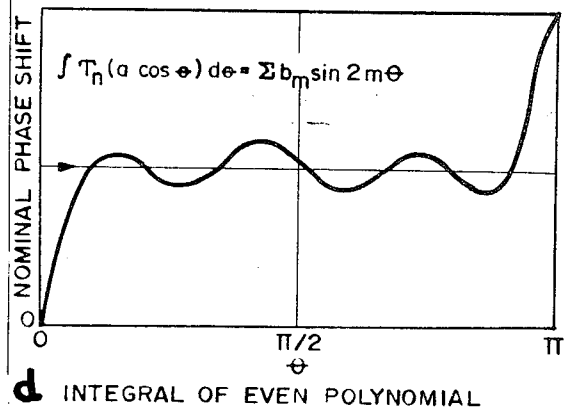

a TSCHEBYSHEFF POLYNOMIAL $T_n(a \cos\theta)$--n ODD




b INTEGRAL OF ODD POLYNOMIAL

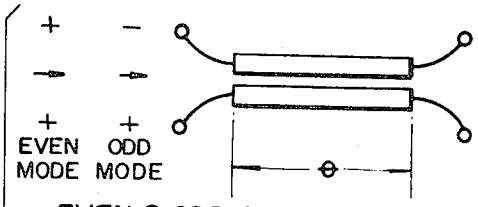



c TSCHEBYSHEFF POLYNOMIAL $T_n(a \cos\theta)$--n EVEN

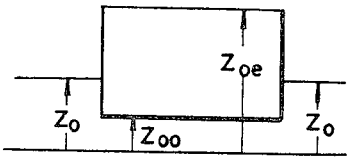



d INTEGRAL OF EVEN POLYNOMIAL

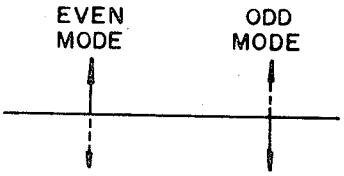
FIG. 3




a EVEN & ODD MODES FOR PARALLEL-COUPLED REGION




b IMPEDANCES FOR EVEN & ODD MODES




c REFLECTION COEFFICIENTS For EVEN & ODD MODES

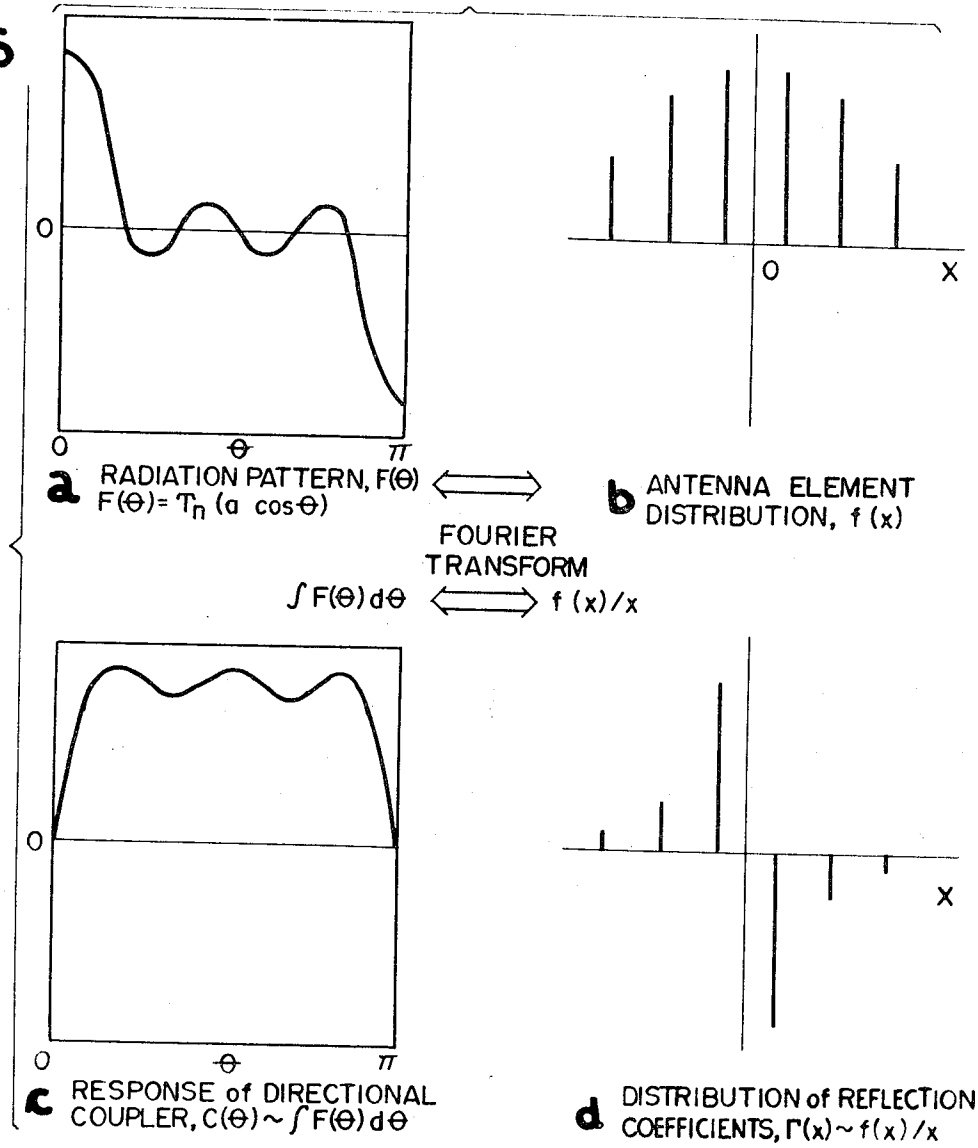
FIG. 4

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ATTORNEY

FIG.5



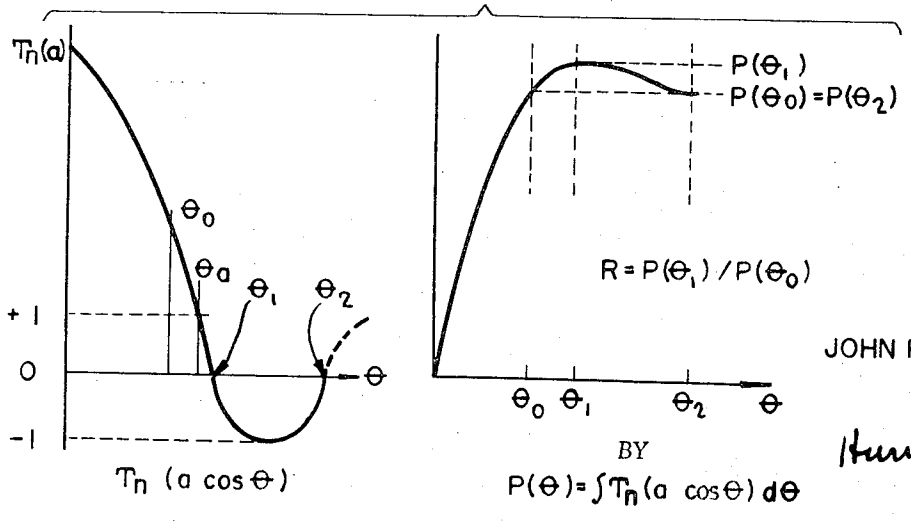




FIG.6

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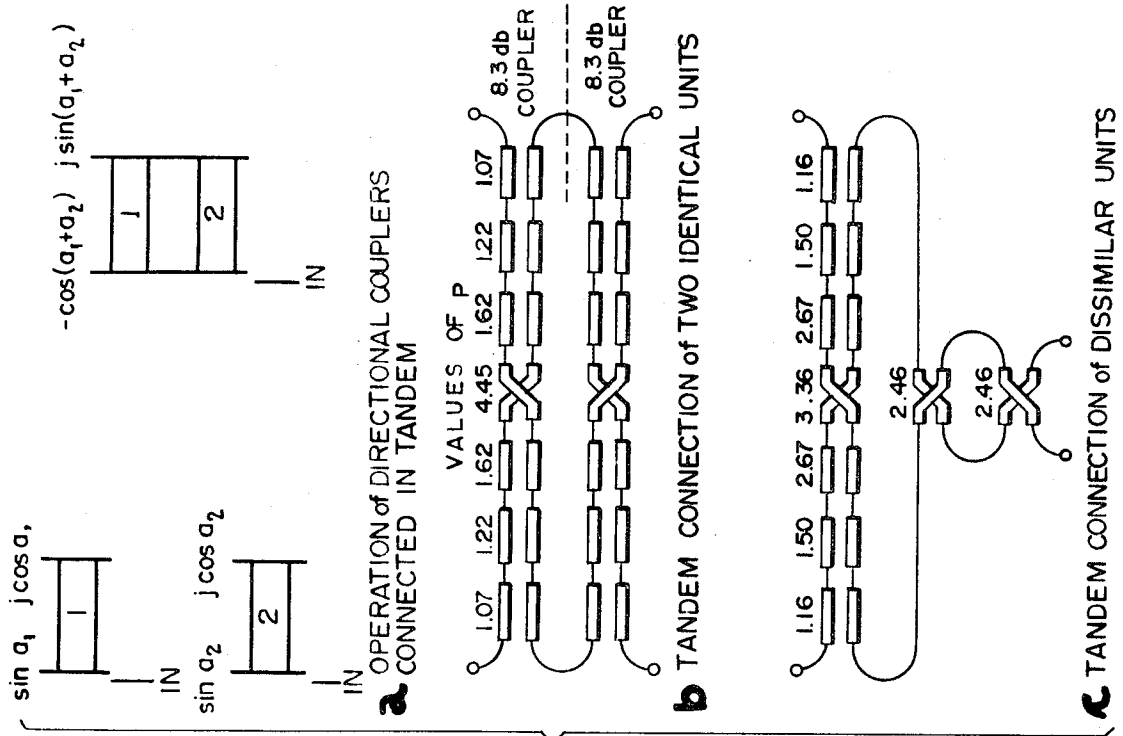



FIG. 8

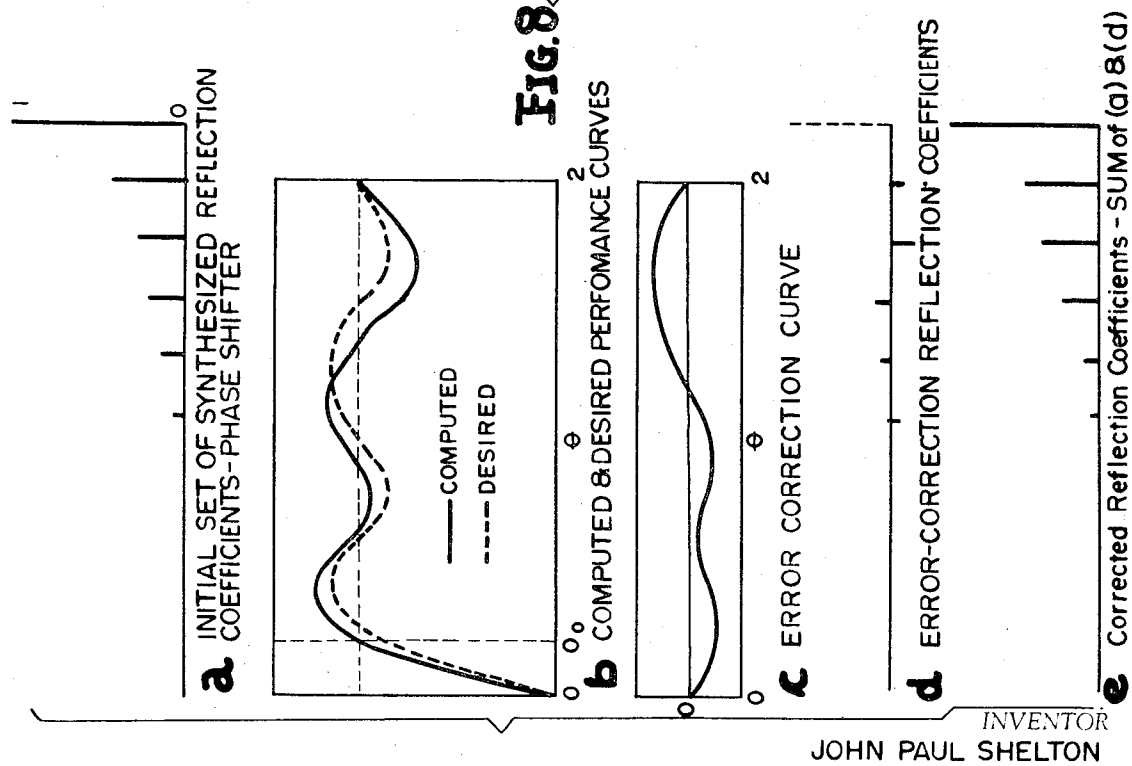


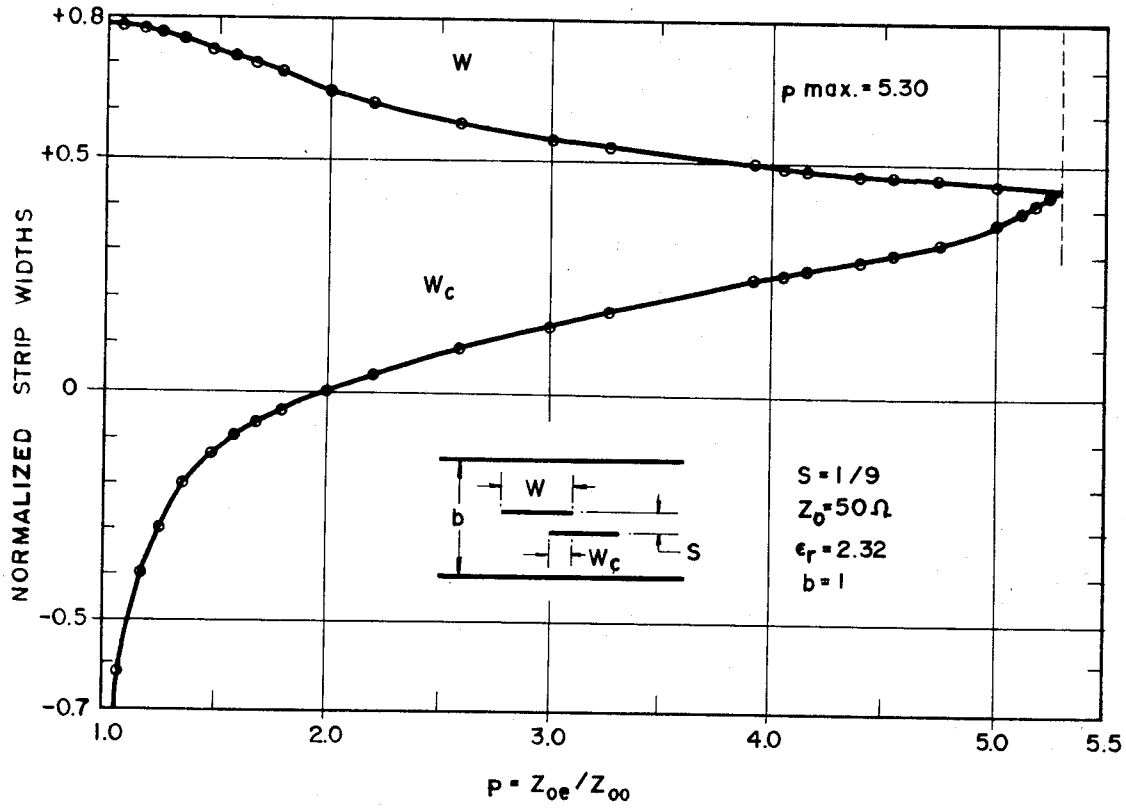

FIG. 7

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FIG. 9



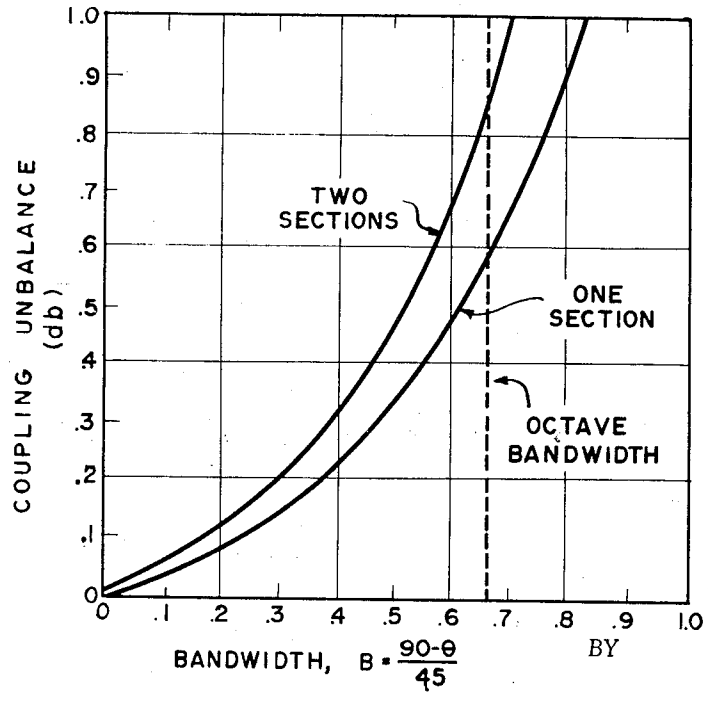




FIG. 10

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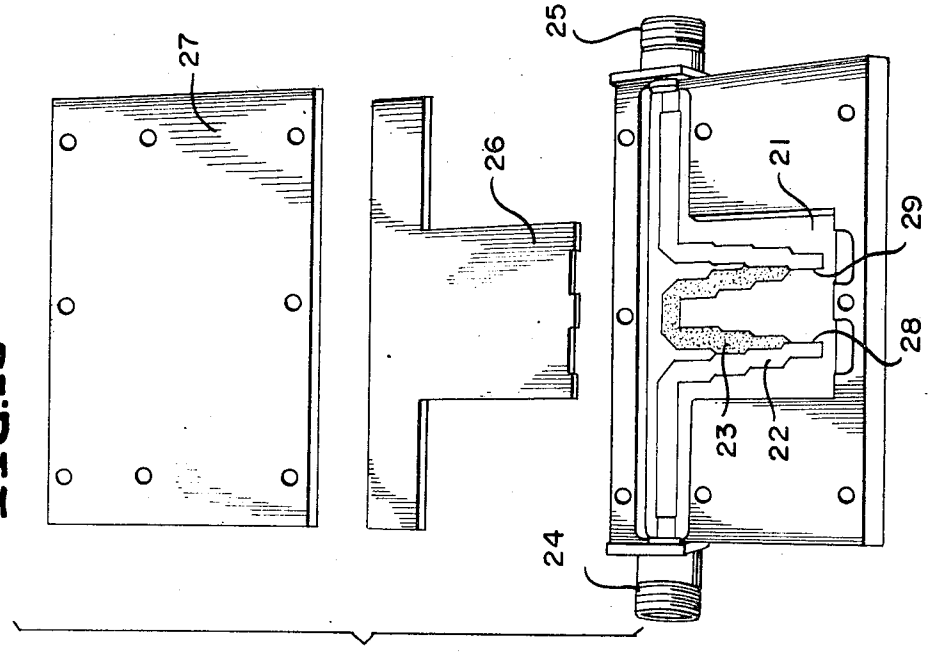



FIG. 12

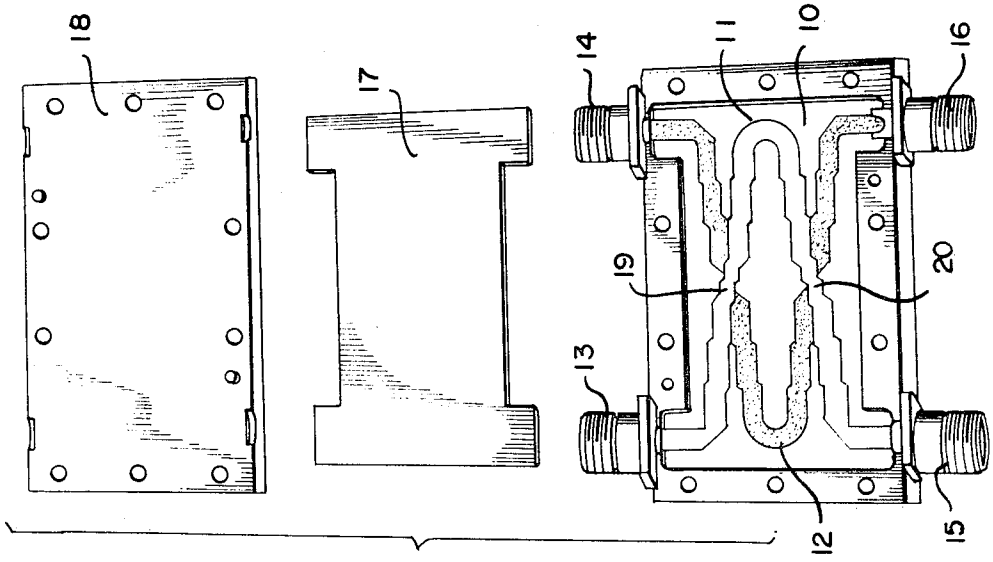


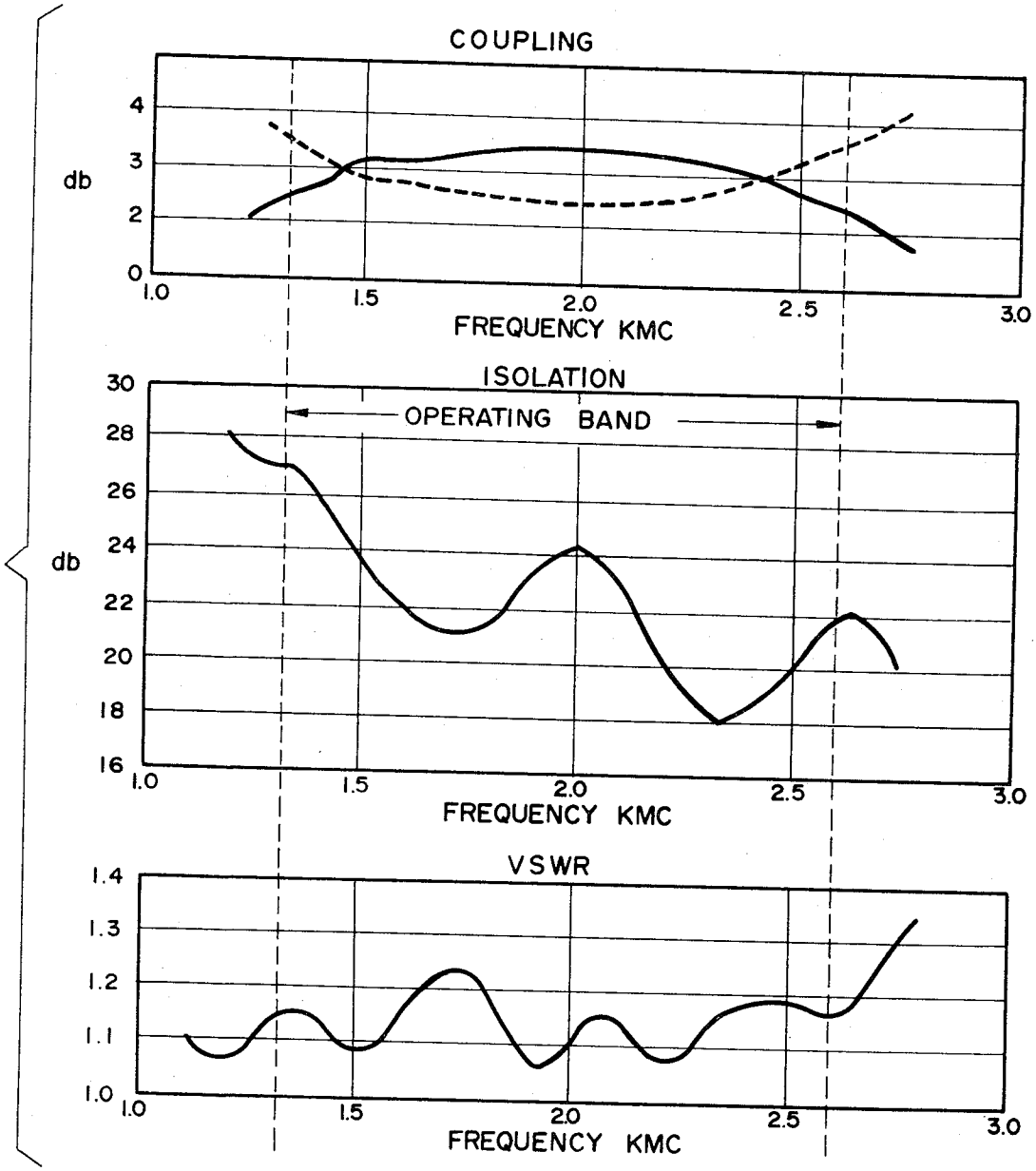

FIG. 11

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FIG. 13




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FIG. 14

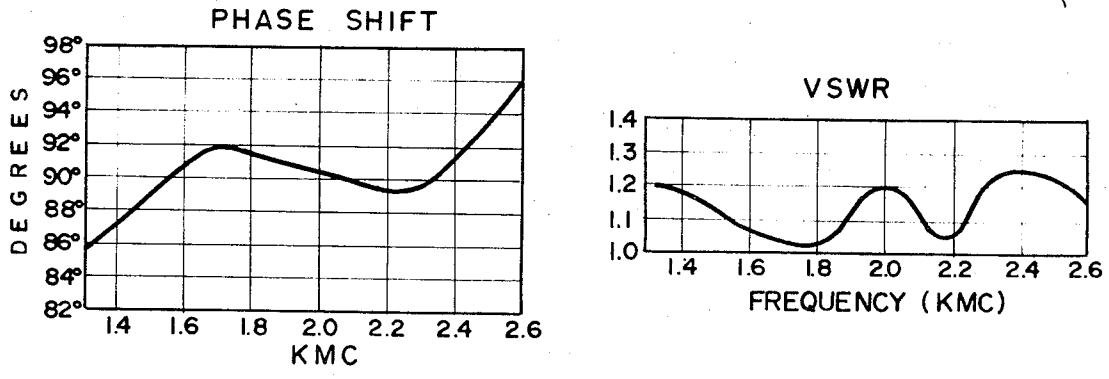
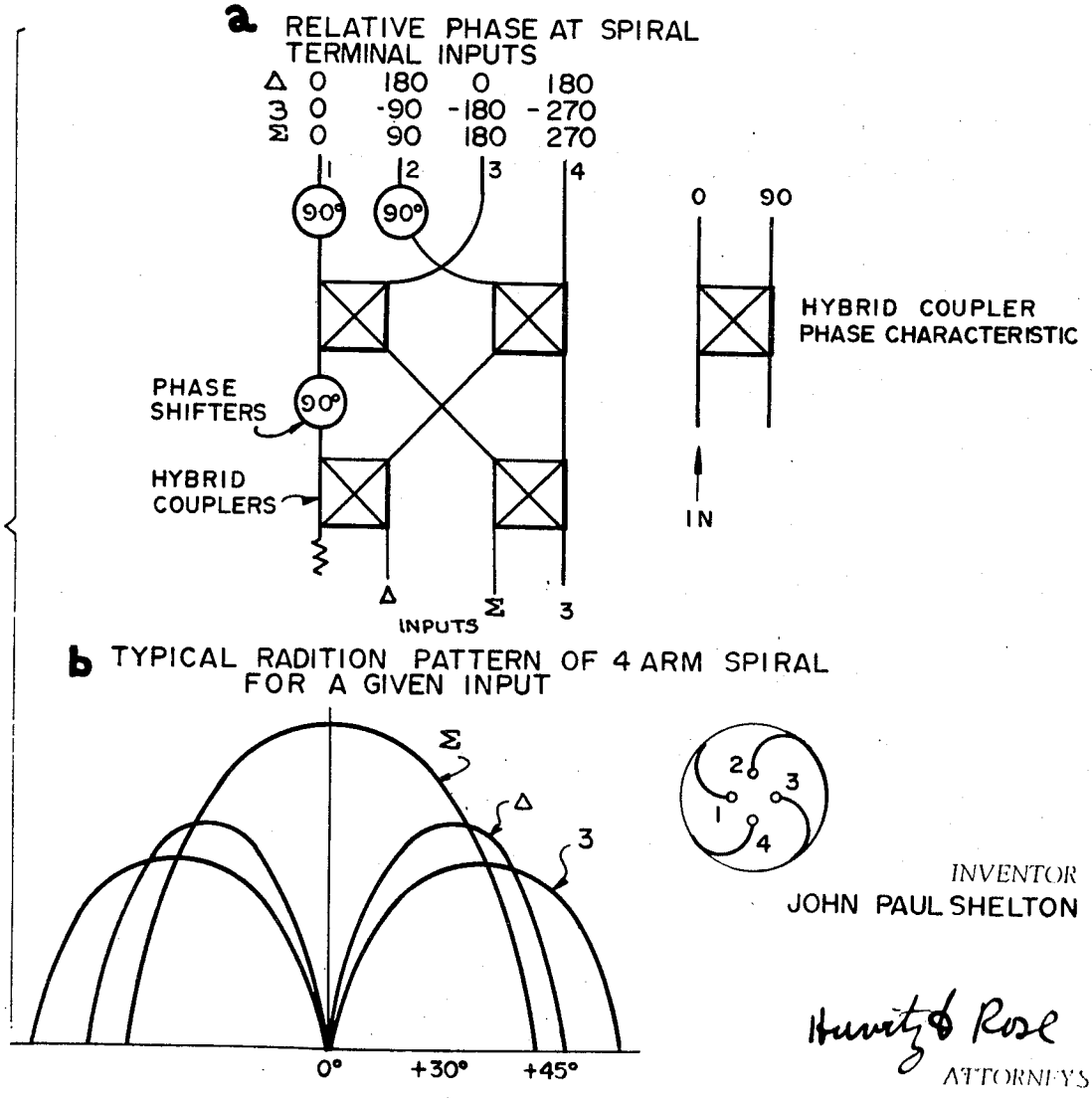



FIG. 15




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Hurwitz & Rose
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FIG. 16

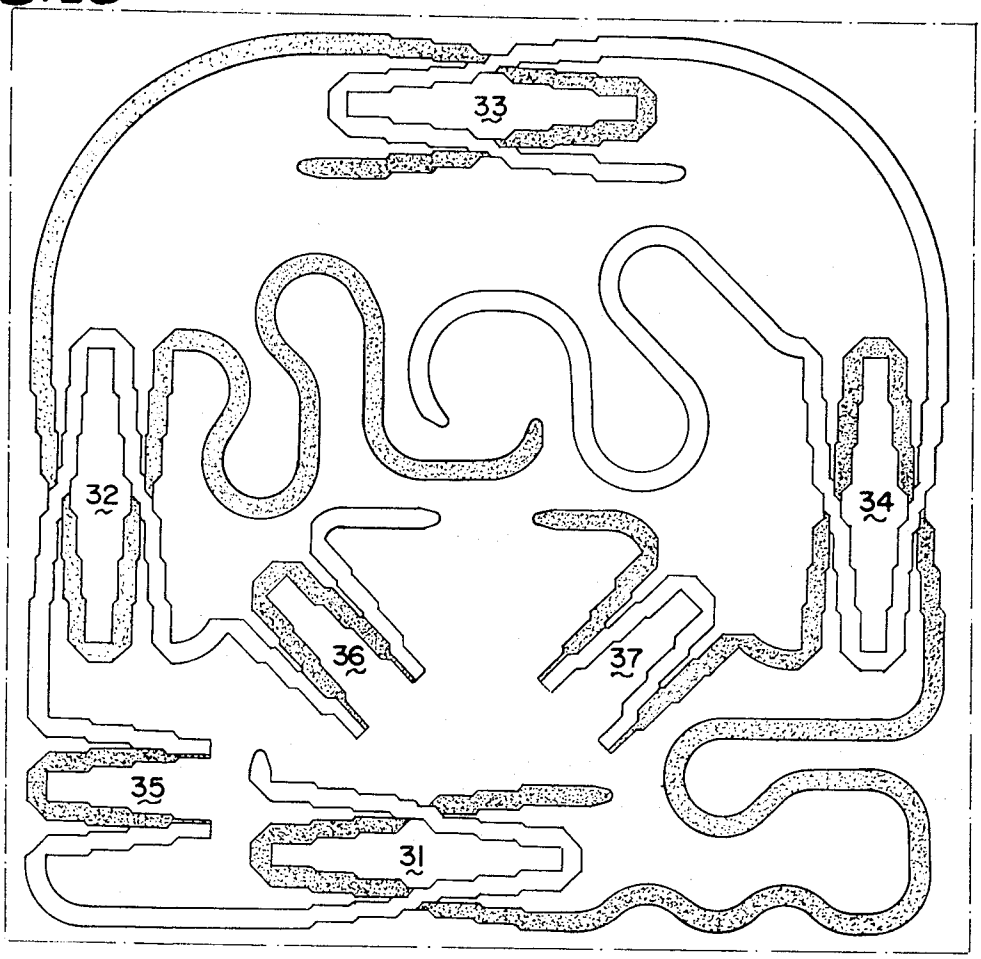



FIG. 17

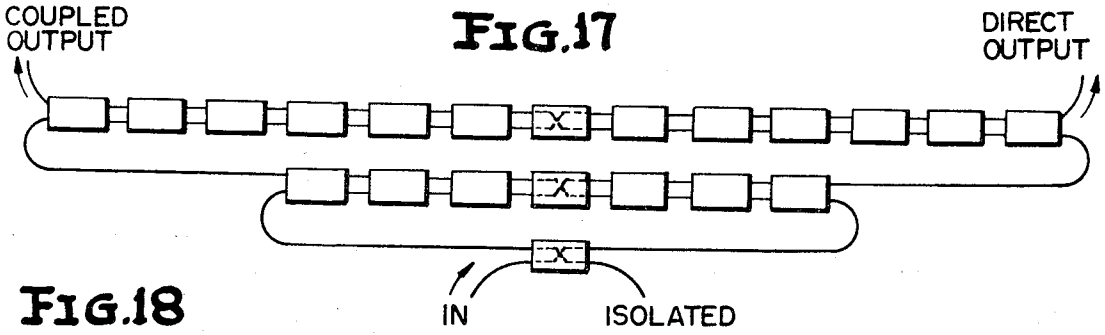
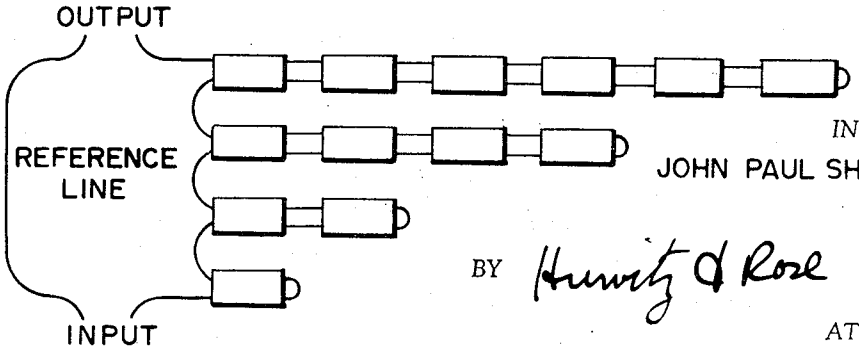



FIG. 18




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FIG. 19a

MULTISECTION DIRECTIONAL COUPLER CONSISTING of FIVE CASCADED SECTIONS of COUPLED TRANSMISSION LINE. (PRIOR ART)

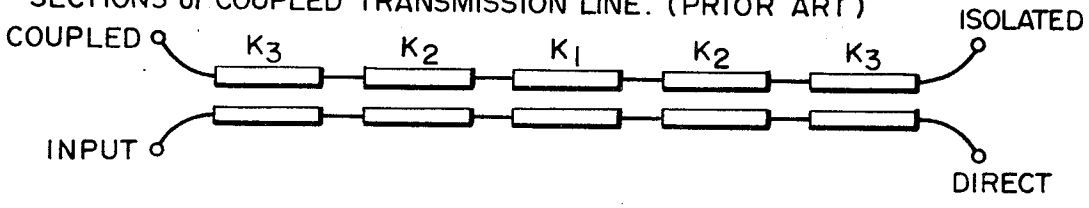



FIG. 19b

MULTISECTION DIRECTIONAL COUPLER with CENTER SECTION CROSS-OVER

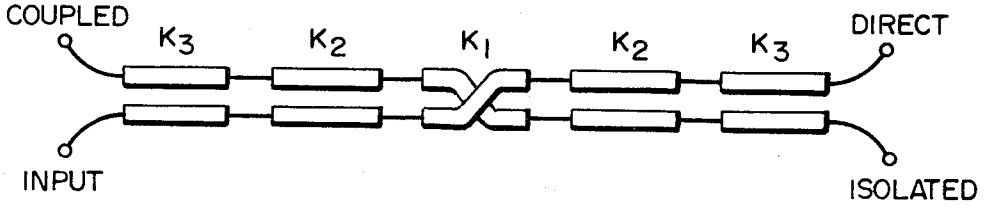
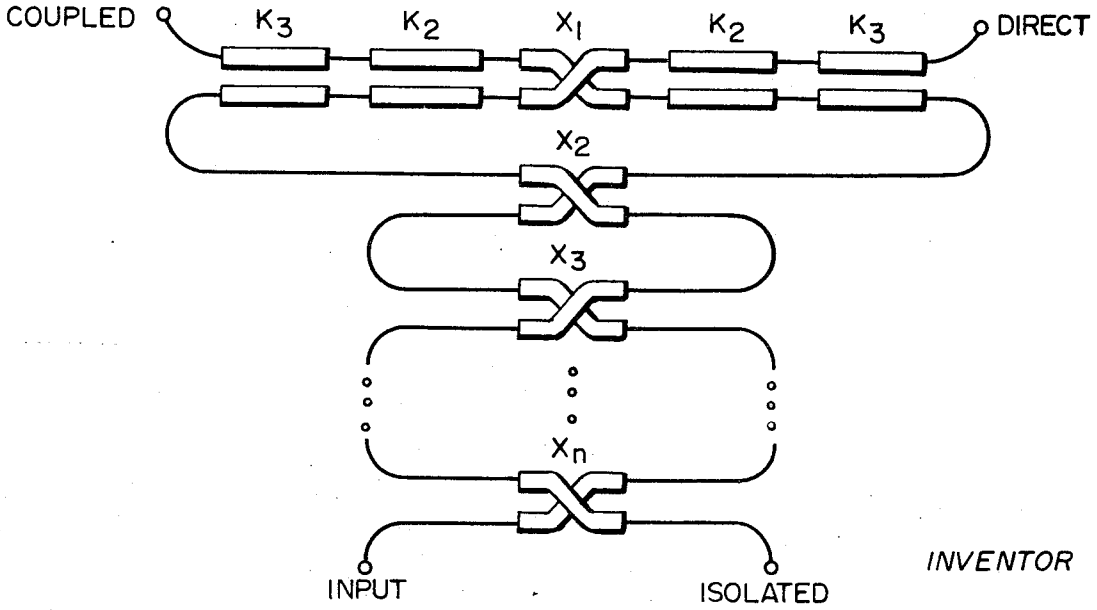



FIG. 19c

TANDEM CONNECTION to REDUCE the MAGNITUDE of COUPLING COEFFICIENT of the CENTER COUPLED SECTION.




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FIG.20a

MULTISECTION PHASE SHIFTER CONSISTING OF A REFERENCE LINE and FIVE CASCADED SECTIONS of COUPLED TRANSMISSION LINE

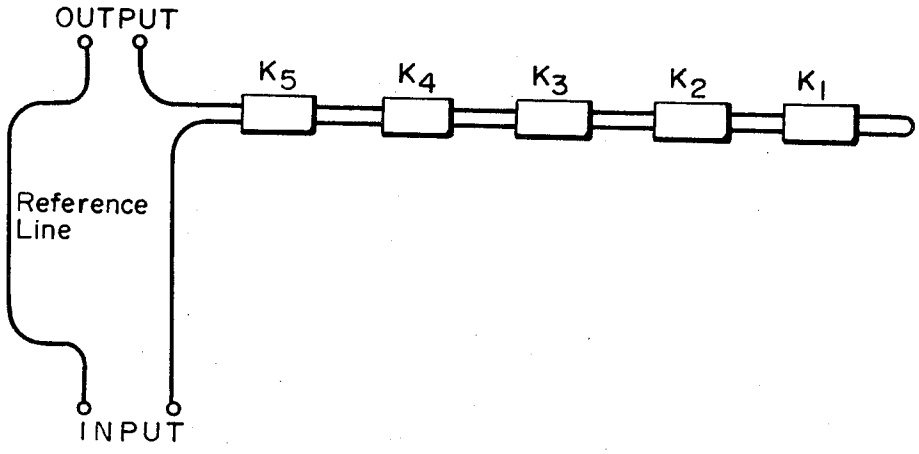
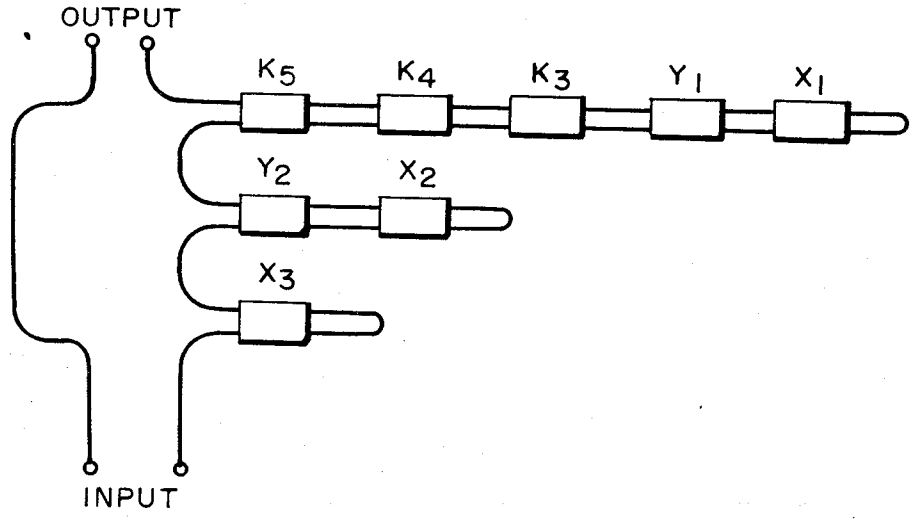



FIG.20b

TANDEM CONNECTION TO REDUCE MAGNITUDE OF COUPLING COEFFICIENTS OF $K_1$ and $K_2$




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# WIDEBAND TEM COMPONENTS

## CROSS-REFERENCE TO RELATED APPLICATION

The present application is a continuation-in-part of my copending application of the same title, Ser. No. 485,723, filed Sept. 8, 1965, now abandoned.

## BACKGROUND OF THE INVENTION

The present invention related generally to transmission line networks capable of operation over multi-octave bandwidths, and more particularly to directional couplers, phase shifters and related components, and to methods of interconnection of corresponding ones of such devices to form single tightly coupled broadband units.

In recent years microwave antennas have been developed that are operable over frequency ranges of 10 or 20 to one. In order to effectively utilize the optimum characteristics of such antennas, it is necessary that related microwave networks be available with similar wideband characteristics. Furthermore, telemetry systems are presently being designed to operate over a band of frequencies ranging from **136** megacycles per second (MGz) to 2,300 MHz and hence a bandwidth of approximately 17:1. Heretofore, however, microwave components have not been available with bandwidths exceeding a ratio of about 5:1.

The physical problems involved in attempts to provide components with multi-octave bandwidths are exemplified by directional couplers and phase shifters of the strip-line type. Theoretically, backward-coupled parallel strip-line couplers can be fabricated with nearly constant coupling over large bandwidths by connecting parallel coupled quarter-wave sections of transmission line in cascade. However, in practice difficulties are encountered in meeting the critically tight manufacturing tolerances that are necessary when one attempts to increase the bandwidth of the parallel strip line coupler. If the bandwidth of this type of coupler, with its parallel coupled sections of progressively decreasing gap widths is to be increased, then the gap between strips must be decreased. For a one octave (2:1) bandwidth symmetrical coupler, for example, the center section gap is in the vicinity of 0.002 inches to 0.003 inches whereas a doubling of that bandwidth to 4:1 requires a gap reduction by an order of magnitude. Obviously, the designer very quickly meets a physical limitation on bandwidth that cannot be overcome using the aforementioned parallel coupling technique.

One of the earliest attempts to solve this dilemma of conflicting requirements in which wider bandwidth is stymied by narrower dimensional tolerances, was the proposal of a reentrant coupler (see e.g., Cohn, "The Re-Entrant Cross Section and Wide-Band 3-db Hybrid Couplers", IEEE, Trans. Vol. MTT-11, No. 4, pp. 254–257, July 1963). The result was tighter coupling with some circumvention of critical tolerances, but further advancement was still necessary to increase coupler bandwidths to 10 or more to 1.

## SUMMARY OF THE INVENTION

Very briefly, I have found that one may avoid the usual compromise between bandwidth and coupling by properly combining two or more relatively loosely coupled components in tandem to theoretically obtain any desired degree of tighter coupling, and hence theoretically unlimited bandwidth. The technique is effective



to provide multi-octave operation for directional couplers, phase shifters and related components with a manyfold relaxation of manufacturing tolerances heretofore not possible using conventional design methods.

In the usual synthesis of multi-octave stripline components, such as couplers and phase shifters, one or more sections of the coupled transmission line making up the directional coupler or phase shifter require coupling coefficients exceeding those physically attainable by reduction of gap width alone, because of the impractical tolerances associated with diminishingly small gap widths. This problem is effectively overcome according to my invention, with negligible compromise of performance, by the addition of one or more coupled sections in tandem with the original coupled sections whose coupling coefficients are to be improved. The added sections may have tolerances which can easily be held and maintained using standard manufacturing techniques.

Assume, for example, that in the synthesis of a particular cascaded five-section strip-line directional coupler, the coupling coefficients of the successive coupled sections are found to be $K_3$, $K_2$, $K_1$, $K_2$ and $K_3$ where the center section is designated by the subscript 1, the next section at either side of the center section is designated by the subscript 2, and each of the outer sections of the five-section cascaded configuration is designated by the subscript 3, and the K's are representative of specific values of coupling coefficient for the respective sections. Assume further, that all values of coupling can easily be realized except $K_1$, in that the value of $K_1$ is such that the gap width of the center coupled section is unattainable in practice using standard manufacturing techniques. According to my invention, the desired coupling coefficient for the center section is achieved by a tandem connection of the original cascaded five-section coupler to one or more additional coupled sections. In general,

$$\sin^{-1}(K_1) = \sum_{i=1}^{n} (\sin^{-1} X_i)$$

where: $n$ = number of coupled sections used to achieve the desired coupling ($n>1$);

$x_i$ = coupling coefficient of $i$th section. In a similar manner, a desired coefficient coupling may be provided for other than the center section by the use of cascaded sections in the tandem connected additional sections.

It is therefore the principal object of the present invention to provide wideband microwave components in which a plurality of electromagnetically coupled sections of transmission line of relatively loose coupling are interconnected in tandem to form a single coupled component of virtually any desired bandwidth.

Another object of the invention is to provide methods of producing wideband microwave components of relatively tight coupling and of virtually unlimited operational bandwidth.

A related object of the invention is to provide wideband microwave components of strip-line configuration commensurate with the preceding objects to permit ease of integration of several such components in a planar (multi-layer) configuration.

Still another object of my invention is the provision of strip-line couplers capable of multi-octave operation

with relatively high coupling coefficients, without need to reduce the spacing between strips to a dimension calling for extremely tight manufacturing tolerances and a dimension that will in any event likely result in dielectric breakdown between the strips.

## BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 schematically illustrates the construction and operation of a multisection directional coupler and further illustrates the crossover of the center section preferred for use with the present invention;

FIG. 2 schematically illustrates the construction and operation of a multisection phase shifter preferred for use with the present invention;

FIG. 3 diagrammatically illustrates the operation of a directional coupler on an even and odd mode basis;

FIGS. 4–7 illustrate the mathematical relationships of the synthesis procedure in accordance with the present invention;

FIG. 8 illustrates the layouts and operation of two embodiments of directional couplers in accordance with the invention;

FIG. 9 is a graphical representation of the relationship of the design parameters in accordance with the invention;

FIG. 10 is a graphical representation of coupling unbalance versus bandwidth for a one-section and two-section coupler;

FIG. 11 illustrates the construction of one embodiment in accordance with the present invention;

FIG. 12 illustrates the construction of another embodiment in accordance with the present invention;

FIGS. 13 and 14 graphically illustrate the performance data for two embodiments in accordance with the principles of the invention;

FIGS. 15 and 16 illustrate a network utilizing components constructed in accordance with the principles of the invention;

FIGS. 17 and 18 schematically illustrate two further embodiments constructed in accordance with the principles of the invention; and

FIGS. 19*a*, 19*b*, 19*c*, 20*a* and 20*b* depict methods of attainment of desired coupling coefficients for various coupled sections of a directional coupler and a phase shifter, respectively.

## DESCRIPTION OF THE PREFERRED EMBODIMENTS

a. Practical Applications

For the moment, attention will be devoted primarily to describing and discussing those Figures of drawing bearing on the practical application of the techniques of the invention to directional couplers and phase shifters; while a discussion of some of the theory involved, including mathematical background and analysis and a representative synthesis procedure, will be deferred to a subsequent portion of this specification.

With reference first to FIG. 19*a*, a prior art five section directional coupler of strip-line configuration is schematically represented as having coupling coefficients of $K_1$ for the center section, $K_2$ for the sections at either side of the center section, and $K_3$ for the outside sections. The coupler has an input port, a direct output port, a coupled output port, and an isolated port. The five sections are cascaded, each section consisting of a pair of parallel-coupled transmission lines, which may be a quarter wavelength long at the center frequency of the band of interest, for a stepped configuration of sections. That is, each section may be composed of spaced transmission lines of progressively diminishing separation relative to the next outer section, so that the least spacing occurs for the transmission lines of the center section and the spacing is increasingly larger, in steps, for each succeeding section outwardly of the center. Rather than the stepped configuration, however, the spaced transmission lines may be continuously tapered toward one another.

If each section of the overall coupler of FIG. 19*a* is considered to be a separate and distinct coupler, then the cascaded interconnection of the separate couplers may be visualized as a configuration in which the direct and isolated ports of the first coupler (section) are connected to the input and coupled ports, respectively, of the next coupler (section), and so forth until all of the individual couplers are connected together to form section of a single overall coupler.

Another form of prior art multi-section directional coupler, shown in FIG. 19*b*, is also of cascaded configuration, but here the lines of the center section cross one another so that the input and isolated ports appear on one side of the coupler while the direct and coupled ports appear on the opposite side of the coupler. The crossover is accomplished by disposing the lines in spaced parallel planes, as by depositing copper striplines on opposite sides of a dielectric layer. Here again, the overall coupler may be of stepped or tapered configuration.

If the desired (computed) value of $K_1$, the coupling coefficient of the center section, is too stringent, i.e., requires a spacing or gap width between striplines of the center section that cannot be achieved in practice, then according to prior art techniques the designer must relax the coupling requirements. Moreover, it has frequently happened that even where the smallest gap width (greatest coupling) in a coupler is realizable in practice, it demands such strict manufacturing tolerances that the fabrication costs are prohibitive.

Referring now to FIG. 19*c*, there is shown a schematic diagram of a directional coupler configuration in accordance with my invention, by which a desired stringent coupling coefficient for the most closely coupled section (usually, but not necessarily, the center section) may be realized without introducing the strict physical tolerances (extremely narrow gap width) that have heretofore been required. Alternatively, one may relax the manufacturing tolerances, even where extremely tight coupling is not required, from those tolerances which had been necessary using prior techniques. In particular, with reference to FIG. 19*c*, one or more additional couplers are connected in tandem with the coupler whose tightest coupling requirement is to be reduced, in the sense that the former physical requirements for the original coupler alone are to be relaxed without comprising the desired level of coupling of a section or sections of the overall unit. As a general proposition, and with the knowledge that the coupling coefficient of any coupler or coupled section can be represented by the sine of an angle (as will be discussed in greater detail in the subsequent portion of the specification devoted to theory), the tandem connection allows one to obtain a desired angle through summation of angles representative of coupling coefficients of the several coupled sections in the tandem configuration. Mathematically,

$$\sin^{-1}(K_1) = \sum_{i=1}^{n} (\sin^{-1} X_i) \quad (1)$$

where the symbols have the definitions stated earlier (in the summary of the invention). Using this approach, one may readily obtain coupler operation over virtually any bandwidth while considerably relaxing the impracticable requirement on tolerance of the gap width for the most closely or tightly coupled section to easily achievable limits. Within a first order approximation, the values of the other coupling coefficients, that is, of sections other than the most tightly coupled (here, the center) section, and the performance characteristics of the overall coupler, are unchanged from what they would have been for the single multi-section cascaded coupler if the tight coupling had been obtainable therein. The tolerances on other coupled sections, such as the coupled sections of FIG. **19***c* possessing coupling coefficient $K_2$, may be reduced in a similar manner.

An arrangement for achieving the same result in multi-section phase shifters may be better understood by reference to FIG. **20**. In FIG. **20***a*, a prior art phase shifter consists of five cascaded coupled sections (or individual couplers) and a reference line. The most closely coupled section has a coefficient designated $K_1$, and the coupling of the remaining sections becomes progressively looser with increasing subscript of coupling coefficient, so that the most loosely coupled section has the coupling coefficient $K_5$. It will be observed that the ports at the right hand end of coupler $K_1$, as viewed in the FIGURE, are short circuited, and that the cascaded interconnection of couplers or coupled sections together with a reference transmission line provides a four port device, with two input ports and two output ports.

A tandem connection of additional couplers to reduce the tolerances associated with the tight coupling coefficients required in the original cascaded section phase shifter is shown in FIG. **20***b* and follows the same principles as were applied in the discussion of directional couplers and as is mathematically expressed in equation (1), above. Here, additional coupled sections are connected in tandem with the original phase shifter, in the sense that the loosely coupled ends of the original coupler are tandem connected to additional coupled sections. For the phase shifter of FIG. **20***a*, the loosely coupled end is that at the free ports of the coupled section with coefficient $K_5$, the coupler at the other end having the most closely coupled lines. For the directional couplers of FIGS. **19***a*, and **19***b*, both end sections are loosely coupled relative to the section of tightest coupling; hence, both ends take part in the tandem connection. In the tandem connected phase shifter of FIG. **20***b*, the individual couplers designated as having coupling coefficients $X_1$, $X_2$ and $X_3$ are utilized to reduce the strict physical requirements imposed on the section having coefficient $K_1$ in FIG. **20***a*, whereas the couplers designated $Y_1$ and $Y_2$ in FIG. **20***b* are used to reduce the requirements on coupler $K_2$ of FIG. **20***a*. It is to be emphasized that the overall phase shifter of FIG. **20***b* may have the same overall characteristics of that of FIG. **20***a*, except that these characteristics are achieved without resort to the impracticable manufacturing limitations imposed on the coupled sections designated $K_1$ and $K_2$. The use of additional couplers or coupled sections is an insignificant penalty to pay for the considerable benefits gained from the tandem configuration.

For a four-port 3-db quadrature direction coupler, a signal applied to one port equally divided to a direct path and a coupled path in one direction of transmission, and no signal energy appears at the fourth port (the isolated port) in the other direction of transmission. The roles of the ports may be interchanged according to which port or ports a signal is applied. Nevertheless, for the sake of convenience, the four-ports of a directional coupler have been and will continue herein to be termed the input port, the isolated port, the direct output port, and the coupled output port. In the tandem connection of directional couplers (or directional coupled sections), the direct output port of one coupler is connected to one of the input port and the isolated port (i.e., to either the input port or the isolated port) of the immediately succeeding coupler (or coupled section), and the coupled output port of the first coupler is connected to the other of the input port and the isolated port (i.e., to the port to which the direct output port was not connected) of the second coupler. The same interconnection scheme is followed for each succeeding coupler with respect to the immediately preceding coupler. Thus, the end result of the tandem interconnection is an overall four-port coupler having input, isolated, direct output, and coupled output ports, and having a considerably tighter coupling coefficient than any of the cascade-type couplers of which it is formed.

A further example of such a configuration is shown in FIG. **8***b* for the tandem connection of a pair of identical couplers. It is desirable that each component coupler have a crossover of the strip lines for that region at or near the center of the region, as was shown in FIG. **19***b*, to facilitate connection between the terminal points of the regions. Thus, the direct and coupled output ports of the lower coupler of FIG. **8***b* emerge on the same side of that coupler region and are directly adjacent the input ports of the next coupled region (upper coupler) to which they are to be connected. This is extremely significant where a large number of strip-line components are to be interconnected (not necessarily entirely in tandem) in a planar or multilayer configuration, such as that shown in FIG. **16**.

As previously observed, the coupling coefficient of each coupled region can be represented by an angle, and the outputs of each coupled region are related to the sine (and cosine) of that angle. The coupling level of an entire unit (coupler or phase shifter) is related to the sum of the individual coupling angles. This is illustrated schematically in FIG. **8***a* for a first (upper, as viewed in the Figure) coupled region having outputs represented by $\sin \alpha_1$ and $j \cos \alpha_1$ and a second (lower) coupled region having outputs represented by $\sin \alpha_2$ and $j \cos \alpha_2$. In the right-hand side of FIG. **8***a*, these two coupled regions are shown connected in tandem with the outputs of the overall coupler represented trigonometrically as shown. Each of the two 8.3 db couplers of FIG. **8***b* has an associated phase angle of 22.5°; i.e., the two outputs of each separate coupler are represented by $\sin 22.5°$ and $j \cos 22.5°$, with an 8.3-db power ratio. The tandem connection of these two 8.3 db couplers produces a single 3-db coupler with an overall coupling coefficient represented by $\alpha_1 + \alpha_2 = 22.5° + 22.5° = 45°$.

The individual coupled regions to be connected in tandem need not be identical or of equal complexity, as has been observed with regard to FIG. 19*c*, for example. The tandem coupler of FIG. 8*c* shows another such arrangement, that is, one in which the separate coupled regions differ from one another in at least one pair of regions. In general, a dissimilar combination is preferred because it requires fewer sections overall and a lower maximum coupling level for a given bandwidth. For example, comparing the tandem configurations of FIGS. 8*b* and 8*c*, both of these have 8:1 bandwidths and 3-db (±0.25 db) coupling. Yet, the overall coupler of FIG. 8*b* has fourteen sections, whereas that of FIG. 8*c* has only nine sections.

The structure of a tandem 3 db coupler generally corresponding to that illustrated schematically in FIG. 8*b* is shown in FIG. 11. The two lines 11 and 12 of copper for example, are disposed on opposite sides of the dielectric 10 (e.g., polyolefin) and are connected to the respective connectors 13, 14, 15, and 16. The crossover sections of the tandem configuration are indicated as 19 and 20, and each quarter wavelength section with its respective spacing in this stepped arrangement, is readily observed. The elements 17 and 18 represent a ground plane and cover member, respectively.

FIG. 12 shows the structure of an octave bandwidth 90 degree phase shifter of tandem configuration using the principles as discussed above with reference to FIG. 20. The materials used are the same as those for the directional coupler of FIG. 11. Copper lines 22 and 23 are disposed on opposite sides of the polyolefin dielectric material 21 and are connected to respective connectors 24 and 25. Elements 26 and 27 represent the ground plane and cover members, respectively.

The components shown in FIGS. 11 and 12 are fabricated by conventional photo-etching techniques, in which the strip outline is transferred from the original drawing to the copper-clad dielectric sheets. Generally, such techniques, well known in the art, utilize a photosensitive polymerizable material which has the negative strip image projected thereon. Thus, the portion of the material corresponding to the strip outline is polymerized, whereas the reaminder is not. The polymerized material then serves as a mask for the etching of the copper clading from the entire surface of the dielectric with the exception of those portions corresponding to the strips.

Thus, a network may be formed on a single unitary dielectric that comprises a number of components in accordance with the invention. The entire network then forms merely a single assembly resembling the type generally referred to as a "printed circuit".

One network constructed in accordance with the present invention included four 3 db couplers and three 90° phase shifters. The network is shown schematically in FIG. 15*a* and illustrates a four-part matrix using the eight to one components of the present invention. The network is used in conjunction with a four-arm equiangular conical spiral antenna to afford radiation in the sum ($\Sigma$), difference ($\Delta$) and acquisition (3) modes of operation. The resultant radiation patterns are shown in FIG. 15*b*.

FIG. 16 shows the actual layout of the network of FIG. 15*a*. The 3 db couplers are represented by 31, 32, 33 and 34, while the 90° phase shifters are shown as 35, 36, and 37. Straight sections of transmission line used in conjunction with the coupled regions of the phase shifters are also shown.

FIGS. 17 and 18 schematically show two further embodiments of tandem couplers and phase shifters in accordance with the invention. Such components have been constructed and successfully tested having bandwidths of 2:1, 8:1, and 17:1.

As previously stated, tandem couplers of the present invention have been designed and constructed to operate with relatively high power levels. Three db couplers have been operated at an average power of 7.5 dw. at a frequency of 136 mc. The tolerance is within ±0.1 db., the VSWR is less than 1.1 to 1, and the isolation is greater than 28 db over the 30 per cent band of operation. The coupler is designed in accordance with the principles set forth herein utilizing conventional three-layer strip-transmission line techniques; however, the center conductors are machined from 1/16 inch brass and the dielectric material is machined from solid teflon sheets. The overall package is 1 3/16 inches thick, 17 ⅞ inches long, and 6 ⅛ inches wide.

b. Theory

Referring now to FIG. 3, some helpful mathematical background may be provided by analyzing the operation of a simple conventional parallel-coupled directional coupler, in terms of the even and odd modes of the coupled region. The concept of even and odd modes simplifies analysis from a four-port to a two-port network. (For a description of this analytical technique, see, e.g., Jones et al, "Coupled Strip-Transmission Line Filters and Directional Couplers," IRE Trans., Vol. MTT-4, pp. 75–81, April, 1956, and Cohn "Shielded Coupled-Strip Transmission Line", IRE Trans., Vol. MTT-3, pp. 29–38, October, 1955).

As shown in FIG. 3*b*, the coupled region of FIG. 3*a* represents a low impedance for one mode and a high impedance for the other. Thus, a portion of each mode is reflected by the coupled region, the magnitude of the reflection being a function of the length of the region $\theta$ (the electrical length of a uniform line of length 1 and phase constant $\beta$) and the mode impedance.

If the characteristic impedance of the uncoupled transmission line is $Z_o$, the even-mode impedance of the coupled region is $Z_{oe}$, and the odd-mode impedance of the coupled region is $Z_{oo}$, the reflection coefficients will have the same magnitude if

$$Z_o/Z_{oo} = Z_{oe}/Z_o, \text{ or } Z_o = \sqrt{Z_{oe}Z_{oo}} \qquad (1)$$

where

$Z_{oe}$ is the characteristic impedance of one line to ground when equal in-phase currents flow in both lines; and

$Z_{oo}$ is the characteristic impedance of one line to ground when equal out-of-phase currents flow in both lines.

The satisfaction of equation (1) assures perfect matching and isolation for such a directional coupler.

For the single coupled region shown in FIG. 3, where

$$Z_{oe}/Z_{oo} = \rho \qquad (2)$$

and the length of the region is equal to theta ($\theta$), a transmission-line calculation yields, for the coupled voltage

$$V_c = j k \sin\theta / \sqrt{1-k^2}\cos\theta + j\sin\theta \qquad (3)$$

where

$k = \rho - 1/\rho + 1$ .

For loose coupling, that is for $\rho-1$ small, the coupled voltage $V_c$ is nearly sinusoidal with frequency, i.e., for $\rho \approx 1$, $V_c \approx j\, k \sin \theta$. For tighter coupling, the curve tends to be flatter than a sine curve.

The operation of the component may also be analyzed by considering the reflections from the individual impedance steps. For loose coupling the ssecond-order reflections will be negligible and these reflections can be added separately. Thus, the reflection coefficient for the even mode at the input to the coupled region, for example, is given by

$$\Gamma = \sqrt{\rho} - 1/\sqrt{\rho} - 1 \qquad (4)$$

and the total reflected amplitude from both ends of the coupled region is given by

$V_c = j\, 2\, \Gamma \sin \theta$.

However,

$2(\sqrt{\rho} - 1/\sqrt{\rho} + 1) \approx \rho - 1/\rho + 1 = k$

and therefore,

$$2\, \Gamma = k \qquad (5)$$

Thus, the operation of the coupler, for the case of loose coupling, can be analyzed in terms of the reflection coefficients at the impedance steps.

Referring now to FIG. 1, and specifically to FIG. 1*a*, there is illustrated in schematic form a conventional strip-line directional coupler configuration suitable, and preferred, for use in practicing the present invention. The coupler comprises a pair of strip lines (i.e., long, narrow conductive paths), one of which proceeds from an input port at the extreme left-hand end of the configuration, as viewed in FIG. 1*a*, to an output port at the extreme right-hand end. The second strip line proceeds from the other input port (or isolated port), at the right-hand end of the FIGURE, to the remaining output port. In practice, the coupled lines may be composed of a plurality of parallel-coupled quarter wavelength sections (relative to the wavelength of the center frequency in the band of interest) in which the lines making up each section are laterally offset from one another by progressively decreasing amounts as the central section is approached (see e.g., the coupled regions shown in FIG. 11). This arrangement provides progressively tighter coupling toward the center section. Rather than stepped coupling, however, continuous coupling may be employed in which the separate lines are tapered toward one another. The principles of the present invention are, in fact, applicable to any coupler configuration.

In the stepped coupling region of FIG. 1 *a*, the outer sections are designated as having a coefficient of $\rho_3$, the next inwardly positioned sections having a coefficient of $\rho_2$, and the center section having a coefficient of $\rho_1$. The overall coupled region (or coupler) consisting of the several coupled sections has a mean-coupling coefficient that can be represented by the sine of an angle, $\alpha$. For a symmetric coupler, the direct output is proportional to sin $\alpha$ and the coupled output is proportional to $j \cos \alpha$, i.e., the outputs are displaced in phase by 90° (phase quadrature). The two conductors constituting the strip lines lie in spaced parallel planes and are separated by a dielectric medium. Hence, they may and preferably do cross over each other at or near the center section, or at least enjoy some overlying relation culminating in a crossover, so that the direct arm or port and the coupled arm or port emerge on the same side of the coupled region, albeit they may be spaced from one another on opposite surfaces of a dielectric layer. The reason for this preferred crossover configuration was discussed earlier.

For unlimited bandwidths, the transmission line should be of a type capable of propagating the TEM mode, since such a mode has no cutoff effects at the lower frequencies, and, theoretically, infinite bandwidth propagation. As such, and because other structures would permit the propagation of other modes, not having this characteristic, and for other reasons, stripline construction is often used, and is particularly suited to application of the techniques of my invention.

The synthesis technique developed in accordance with the present invention can be used in the design of directional couplers and fixed phase shifters of arbitrary coupling and phase shift, with which equal-ripple performance is obtained, FIG. 1 *b*.

It has been found that the operation of the multisection coupler, shown in FIG. 1, can be described approximately in terms of harmonics. The innermost impedance steps contribute a term to the coupling coefficient proportional to sin $\theta$, the next steps out contribute a term proportional to sin $3\theta$, and so forth, for as many odd harmonics as required.

The phase shifter configuration shown in FIG. 2 *a* is a prior art extension and improvement of the basic phase shifter components described by Schiffman, ("A New Class of Broad-Band Microwave 90° Phase Shifters", IRE Trans., Vol. MTT–6, pp 232–237, April, 1958). The basic characteristic that is periodic in $\theta$ is the phase dispersion of the multisection coupled region. It has been found that the innermost step provides a term in sin $2\theta$, the next step provides a term in sin $4\theta$, and so on, in even harmonics. For a first-order approximation, the amplitudes of these harmonics for both the couplers and phase shifters are directly proportional to the reflection coefficient at the impedance steps.

Thus, referring back to FIG. 1 *b* and 1 *c*, the coupling response of the multisection coupler is required to have an equal-ripple characteristic which is shown for a coupler having an 8:1 bandwidth. The components of the characteristic can be analyzed by decomposition into the sine terms contributed by each impedance step. As such, it is seen that the impedance steps at $\Gamma_1$ contribute a sin $\theta$ term; the impedance steps at $\Gamma_2$ contribute a sin $3\theta$ term; and the impedance steps at $\Gamma_3$ contribute a sin $5\theta$ term. These three terms are sufficient to provide the approximation of the band characteristics shown in FIG. 1 *b*.

Referring to FIGS. 2 *b* and 2 *c*, the coupling response of the multisection phase shifter is required to have the equal ripple response characteristic shown for the phase shifter having an 8:1 bandwidth. As shown in FIG. 2 *c*, the impedance step at $\Gamma_1$ contributes a sin $2\theta$ term; the impedance at $\Gamma_2$ contributes a sin $4\theta$ term; and the impedance at $\Gamma_3$ contributes a sin $6\theta$ term.

The input to the transmission-line length 1 is shifted in phase an amount $\phi_2$ which is proportional to the electrical angle ($\theta$) of the input signal. The multisection phase shifter provides an output $\phi_2$. The relative output phases $\phi_2 - \phi_1$ are shown in FIG. 2 *b*.

Since $Z_{oe}$ and $Z_{oo}$ are independent quantities, the product $Z_{oe}Z_{oo}$ and the ratio $Z_{oe}/Z_{oo}$ can be independently specified, i.e., $\rho$ and $Z_o$ can be specified from the relationships of equations (1) and (2), since there are two equations in two unknowns. Further, since $\phi_1$ is a

function of $\rho$ and $\theta$, for a given $\phi_1$ , $\rho$ can be determined. For a single section phase shifter the relationship is

$$\phi_1 = (\text{arc cos})\ \rho - \tan^2\theta/\rho + \tan^2\theta \quad (6)$$

and the fixed phase shift is equal to $k\theta - \phi_1$ .

As has been shown, the synthesis for the general case of multisection couplers and phase shifters can be achieved by the summation of the reflection coefficients at each of the impedance steps. The reflection characteristics of the components can be defined by polynomials of the form,

$$\Sigma\ a\ m \sin (2m-1)\ \theta \quad (7)$$

for the odd harmonics, and

$$\Sigma\ a\ m \sin 2m\ \theta \quad (8)$$

for the even harmonics, where $m$ is an integer index.

With respect to the evaluation of the polynomials (7) and (8), they cannot be directly related to Tschebysheff polynomials. However, it has been found that the integrals of the Tschebysheff polynomials are directly applicable to the components of the present invention, both in shape and in mathematical form. FIG. **4** illustrates the effect of integrating Tschebysheff polynomials that have been plotted as antenna patterns, that is with $x = a \cos\theta$. The polynomials of odd degree, as shown in FIGS. **4** *a* and *b*, apply to the couplers, and those of even degree, as shown in FIGS. r *c* and *d*, apply to the phase shifters. The integrated curves are, of course, not equal-ripple because the areas under the ripples of Tschebysheff curves are not equal. However, the curves do represent a good approximation to the desired component characteristics.

The method for obtaining the reflection coefficients at the impedance steps is illustrated in FIG. **5.** In the upper half is shown the relationship between the antenna element amplitude distribution and the array pattern for a conventional Tschebysheff array. The mathematical relationship between the radiation pattern $F(\theta) = T_n(a \cos\theta)$, shown in FIG. **5** *a*, and the antenna element distribution $f(X)$, shown in FIG. **5** *b*, is the Fourier transformation. The information for these arrays ahs been compiled in extensive tables well known in the art. FIG. **5** *c* shows the integral of the Tschebysheff pattern of FIG. **5** *a*, i.e., $C(\theta) \approx \int F(\theta)\, d\theta$. The transform of the distribution $C(\theta)$ is $f(X)/X$ , as shown in FIG. **5** *d*.

By selecting the appropriate value of $a$, the reflection coefficients can be determined, since

$$\Gamma(X) \approx f(X)/X$$

and $f(X)$ is the Fourier transform of $C(\theta)$, where

$$C(\theta) \approx \int T_n(a \cos\theta)\, d\theta.$$

Two methods are generally available for finding the parameter $a$. One is trial-and-error integration of the original polynomial for various values of $a$. This method is feasible for polynomials of relatively low degree, but for components with ten sections or more, direct integration becomes unwieldy. The alternative is the approximation procedure illustrated in FIG. **6.** The polynomial curve of FIG. **5** *a* is assumed to be sinusoidal between zeros, and the zeros are assumed to be equally spaced. Thus, assuming

$T_n(a \cos\theta)$ is sinusoidal between zeros,

and

$$\theta_2 - \theta_1 = (\pi/2) - \theta_1/[(n-1)/2]\ ,$$

the expressions can be derived from the following design equations: From FIG. **6,**

$$R-1 = (\pi/2) - \theta_1/[(n-1)/2]\ T_n(a)\ \theta_1$$

$$\log [T_n(a) + \sqrt{T_n^2(a)-1}] = n\cosh^{-1} 1/\cos\theta_a$$

This result is approximately equal to

$n\ \theta_a$ for $\theta_a$ small

and

$$\theta_a = \theta_1\ (1 - [2/\pi\ T_n(a)\ ])$$

$$\sin(\pi/2\ \theta_0/\theta_1) = 1/R\ .$$

On this basis, the indicated expressions are derived, and for a given bandwidth and number of sections, the parameter $a$ can be estimated. Then the Tschebysheff antenna tables are used to obtain the reflection coefficients at the impedance steps, since $X = a \cos\theta$.

In order to correct the design characteristic so that true equal-ripple performance will be achieved, the correction procedure outlined in FIG. **7** is used. First, the performance curve of the approximate design is calculated with the aid of a high-speed electronic computer in accordance with the aforementioned method, using, for example, the integral of the even Tschebysheff polynomials. The difference between the actual and desired curves is taken, and a synthesis is made in the form of a Fourier curve-sampling process. The resulting reflection coefficients are added to the original set, and a first correction is obtained. The process is repeated until the computed performance of the component is satisfactory. In practice, it has been found that three or four iterations yield precision that is adequate for engineering purposes. The Tschebysheff antenna tables list distributions of forty elements; therefore, the maximum bandwidths amenable to this technique range from 40–80 to one, depending on the specified tolerance. After the reflection coefficients at the impedance steps are determined, the impedances of the coupled sections can be determined and the value of $\rho$ is given by

$$\rho = [\ \Gamma + 1/\Gamma - 1\ ]^2\ .$$

Given the maximum $\rho$, the characteristic impedance $Z_o$ and the dielectric constant $\epsilon_r$, the relative spacing between the strips $S$ is determined by the derived equation

$$1 - \rho\ \text{max}\ S/\rho\ \text{max} = \sqrt{\epsilon_r}\ Z_o/60\ \pi^2)\ \log 4 \quad (9)$$

The only variables remaining are strip width and strip overlap. These parameters are derived and shown in FIG. **9** as a function of $\rho$. For $\rho$ equal one, the strips are completely separated, and the strip width is that of the uncoupled transmission line. The curves are for $S = 1/9$, where $b = 1$, or layers of relative thickness of 4:1:4, polyolefin dielectric with $\epsilon_r = 2.32$ and $Z_o = 50$ ohms. The equation shown as **9** relates maximum $\rho$, spacing, dielectric constant, and characteristic impedance, and enables the initial design choices to be made once the components are synthesized.

The general case may be referred to as offset parallel-coupled strips between ground planes. In practical applications the ratio of spacing between center conductor planes and ground-plane spacing is kept constant, so that the entire component can be fabricated from the three layers of copper-clad dielectric material. The maximum coupling is achieved when the strips are disposed one above the other and this configuration was analyzed by Cohn, supra. The offset strips, presently described, have been analyzed by standard fringing-capacitance techniques which provide very good results.

The method of synthesis and design here presented can easily be applied for any reasonable bandwidths or coupling level, and is applicable to various forms of TEM components, including directional couplers and fixed phase shifters.

For the arrangement shown in FIG. **8** *b* using two identical 8.3 dm. couplers in tandem, the maximum value of $\rho$, the ration of even mode impedance to odd mode impedance, is 4.45, the minimum value of $\rho$ is 1.07, and the number of sections is **14.** In the arrangement of FIG. **8** *c*, the maximum value of $\rho$ is 3.36, the minimum value of $\rho$ is 1.16, and the number of sections is 9.

The effect of the minimum value of $\rho$ is significant in that generally, the lower the value of $\rho$, the greater the separation between transmission lines, and hence, the greater the difficulty in stepping into more tightly coupled sections.

The advantages of using the arrangement of FIG. **8** *b*, in which the relatively high coupling coefficient associated with a 3 db. coupler was avoided by using the 8.3 db. couplers in tandem, lie in the improvement of the strip-transmission-line mechanical tolerances obtained thereby, which are outlined in Table 1.

Table 1

EFFECTS OF MECHANICAL TOLERANCES IN COUPLING TOLERANCES

| Physical Characteristics | Performance | |
|---|---|---|
| | Present Invention | Prior Art Design |
| Strip Width S | $S = 0.062$ | $S = 0.014$ |
| Groundplane separation *b* | $b = 0.188$ | $b = 0.204$ |
| Strip Width tolerance | 0.027 db change/mil | |
| Material thickness tolerance | | 0.1 db change/mil |
| (Center layer) | 0.140 db change/mil | 0.4 db change/mil |

It has been found that the coupled regions can be constructed conveniently with a three-layer sandwich in which each layer is of equal thickness.

In addition to the improved reproducibility which results from the superior mechanical tolerances, the tandem arrangement, in accordance with the present invention, permits the design of 3 db. couplers at relatively high microwave frequencies without the use of elaborate tuning adjustments as had been required heretofore. For example, a commercially available 3db. coupler designed for operation in the S-band region, contains six tuning screws.

Furthermore, the increased spacing between center conductors according to the present design, enables the use of these components at increased power levels.

In the case of single-section components, the slight degradation of the bandwidth vs. coupling tolerance curve, as shown in FIG. **10,** when the tandem configuration is used, should be more than offset by its advantages. For example, an octave-bandwidth 3 db. coupler has a tolerance of $\pm$ 0.31 db. for a single coupled region, and a tolerance of $\pm$ 0.45 db. for the tandem arrangement.

The general design procedure outlined herein was used to determine the values of $\rho$ and hence, the even and odd mode inpedances of the seven section 8.3db. coupler such as that of FIG. **8** *b*, with tolerance of $\pm$ 0.35 db. The unit was fabricated on copper clad polyolefin base material because of its low insertion loss and negligible dielectric constant variation. The units were designed for a three-layer strip transmission line package with an $S/b$ ratio of 1/9, using $S = 0.031$ and $b = 0.281$. The strip widths and gap spacings of the unit were calculated and determined to be as shown in Table 2.

Table 2

SEVEN SECTION COUPLER

| $\rho$ | Strip Width | Strip Overlap |
|---|---|---|
| 4.4470 | .133 | .085 |
| 1.6256 | .197 | .020 |
| 1.2197 | .215 | − .087 |
| 1.0708 | .219 | − .187 |

The 90° phase shifter of FIG. **12** is formed by the coupling of two four-section 45° phase shifter regions wherein the strip widths and gap spacings were calculated and are given in Table 3.

Table 3

FOUR SECTION PHASE SHIFTER

| $\rho$ | Strip Width | Strip Overlap |
|---|---|---|
| 5.033 | .128 | .106 |
| 2.202 | .171 | .013 |
| 1.462 | .204 | − .037 |
| 1.158 | .218 | − .113 |

The 45° miters provided between the quarter wavelength sections of the components were found to lessen impedance discontinuities caused by the large changes in gap spacings from one section to the next.

The performance curves of the 8:1 bandwidth hybrid coupler is given in FIG. **13,** while that for the 90° phase shifter is given in FIG. **14.** The power division data recorded for the hybrid coupler is very close to the calculated curve; however, the relative phase data recorded for the 90° phase shifter indicates wider phase tolerance than anticipated. Part of this discrepancy, however, is attributable to measurement errors, and part to the imperfect realization of the calculated strip widths and spacings. It has been found that strip width and gap spacing tolerances must be held to within $\pm$ 0.005 inch on the loosely coupled sections and $\pm$ 0.002 inch on the tightly coupled sections. Also, it was found that a slight variation in thickness of the center dielectric layer has appreciable effect on the coupling value of the tightly coupled section.

I claim:

**1.** A directional coupler system, comprising

a first directional coupler having a first direct and a first coupled output port,

a second directional coupler having a second input port and an isolated port,

said second input port and said isolated port constituting signal input ports, and

means directly connecting said signal input ports, respectively, one to each of said first direct and said first coupled output ports.

**2.** The combination according to claim **1,** wherein said first coupled output port is connected to said isolated port and wherein said first direct output port is connected to said second input port.

**3.** The combination according to claim **1,** wherein said first coupled output port is connected to said second input port and said first direct output port is connected to said isolated port.

**4.** The combination according to claim **1,** wherein said first and second directional couplers are identical.

5. The combination according to claim 1, wherein said first and second directional couplers are composed of dissimilar numbers of sections.

6. The combination according to claim 1, wherein one of said directional couplers includes an odd number of cascaded sections, the center section having a crossover.

7. The combination according to claim 1, wherein said second directional coupler is a single quarter wave length coupler.

8. An array of directional couplers, comprising

plural directional couplers, each directional coupler including two coupled transmission lines having a central crossover,

each of said couplers including two input ports and two output ports, and

means directly connecting the output ports of each directional coupler to the input ports of the next succeeding directional couplers of said array,

wherein said directional couplers are quarter wave length couplers and wherein is further provided a multiple cascaded directional coupler having an odd number of quarter wave sections, and having an input and an isolated port, and

means connecting said input and isolated ports, respectively to the output ports of the last quarter wave coupler in said array.

9. A coupled transmission line phase shifter, comprising

a cascade of directional couplers,

each comprising an n quarter wave length two conductor transmission lines, where n is an integer greater than 1,

the first of said couplers in the cascade providing an input port and an output port,

the last of the couplers in the cascade having directly interconnected direct and isolated ports.

10. A coupled transmission line phase shifter, comprising

a first phase shifter including a directional coupler having an input port and a coupled output port and having directly interconnected direct and isolated ports.

11. A coupled transmission line phase shifter, comprising

a first coupled transmission line phase shifter having a first input port and a first coupled output port, and further having direct and isolated ports directly interconnected,

a second coupled transmission line phase shifter having a second input port directly connected to said first output port and having a coupled output port, and having directly interconnected direct and isolated ports.

12. A coupled transmission line phase shifter, comprising

a first coupled transmission line phase shifter having a first input port and a first coupled output port, and further having direct and isolated ports directly interconnected,

a second coupled transmission line phase shifter having a second input port connected to said first output port and having a coupled output port, and having directly connected direct and isolated ports,

wherein the second transmission line phase shifter has closer interline coupling than the first transmission line phase shifter.

13. In a directional coupler system,

a first directional coupler having an input and an isolated port and further having a coupled and a direct output port,

a second directional coupler comprising two coupled transmission lines having proximate ports and remote ports, and

means connecting said coupled and said direct output ports respectively to one of said coupled transmission lines one at a proximate port and the other at a remote port, the remaining ports of said two coupled transmission lines constituting output ports.

14. A directional stripline coupler system, comprising

a first stripline coupler having two first direct and coupled output ports, and

a second stripline coupler having two further output ports and two further ports, constituting respectively a direct and an isolated port, connected respectively to said first output ports.

15. A directional coupler system, comprising

a first directional coupler having a first input port,

a first direct output port,

a first isolated port and a first coupled port,

a second directional coupler having a second input port,

a second direct output port,

a second isolated port and a second coupled port,

a direct connection between said first coupled port and said second input port, and

a direct connection between said first direct port and said second isolated port.

* * * * *