United States Patent [19]

De Brecht et al.

[11] **3,835,421**

[45] **Sept. 10, 1974**

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[54] **MICROWAVE TRANSMISSION LINE AND DEVICES USING MULTIPLE COPLANAR CONDUCTORS**

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[73] Assignee: **RCA Corporation,** New York, N.Y.

[22] Filed: **Sept. 27, 1973**

[21] Appl. No.: **401,554**

Related U.S. Application Data

[62] Division of Ser. No. 315,087, Dec. 14, 1972.

[52] **U.S. Cl.** .... **333/26,** 333/84 M
[51] **Int. Cl.** **H01p 5/10,** H03h 7/42
[58] **Field of Search** .... 333/26, 84 M

[56] **References Cited**

OTHER PUBLICATIONS

Nishide et al., Balance-to-Unbalance Transformers, Monogr. Res. Inst. Appl. Elec. (Japan), No. 18, (1970), pp. 69–73 relied on.

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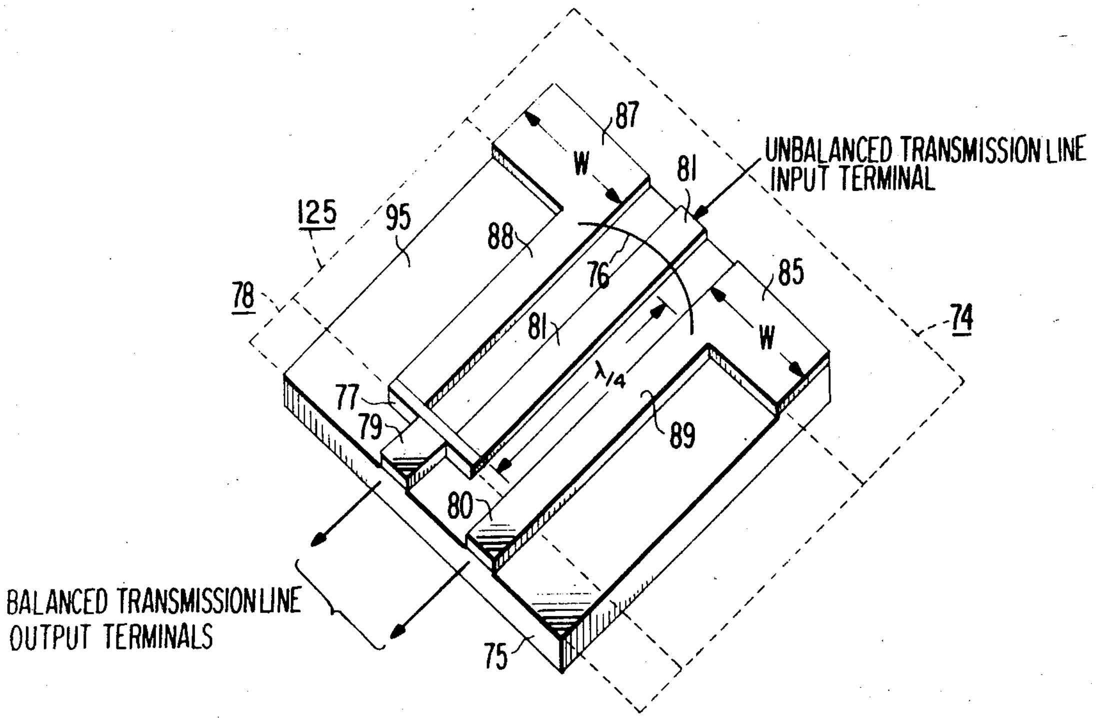
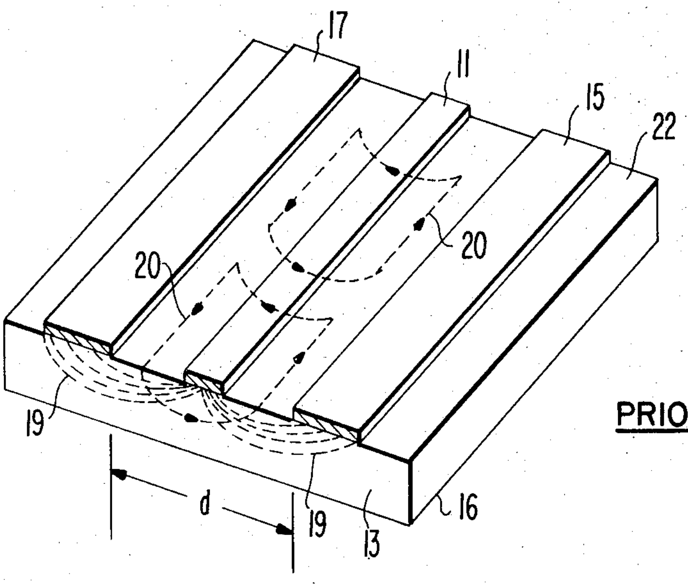
Attorney, Agent, or Firm—Edward J. Norton; Joseph D. Lazar; Donald E. Mahoney

[57] **ABSTRACT**

Three coplanar conductive surfaces on the top surface of a dielectric substrate form a microwave transmission line having first and second transmission modes used in the construction and operation of various microwave devices, such as amplifiers unbalanced-to balanced transmission line transformers and directional couplers.

2 Claims, 8 Drawing Figures





PRIOR ART

Fig. 1

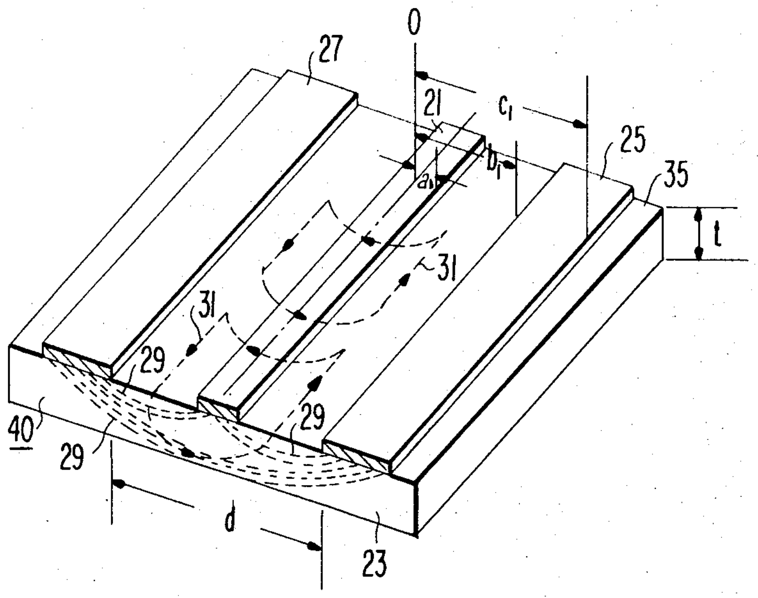


Fig. 2

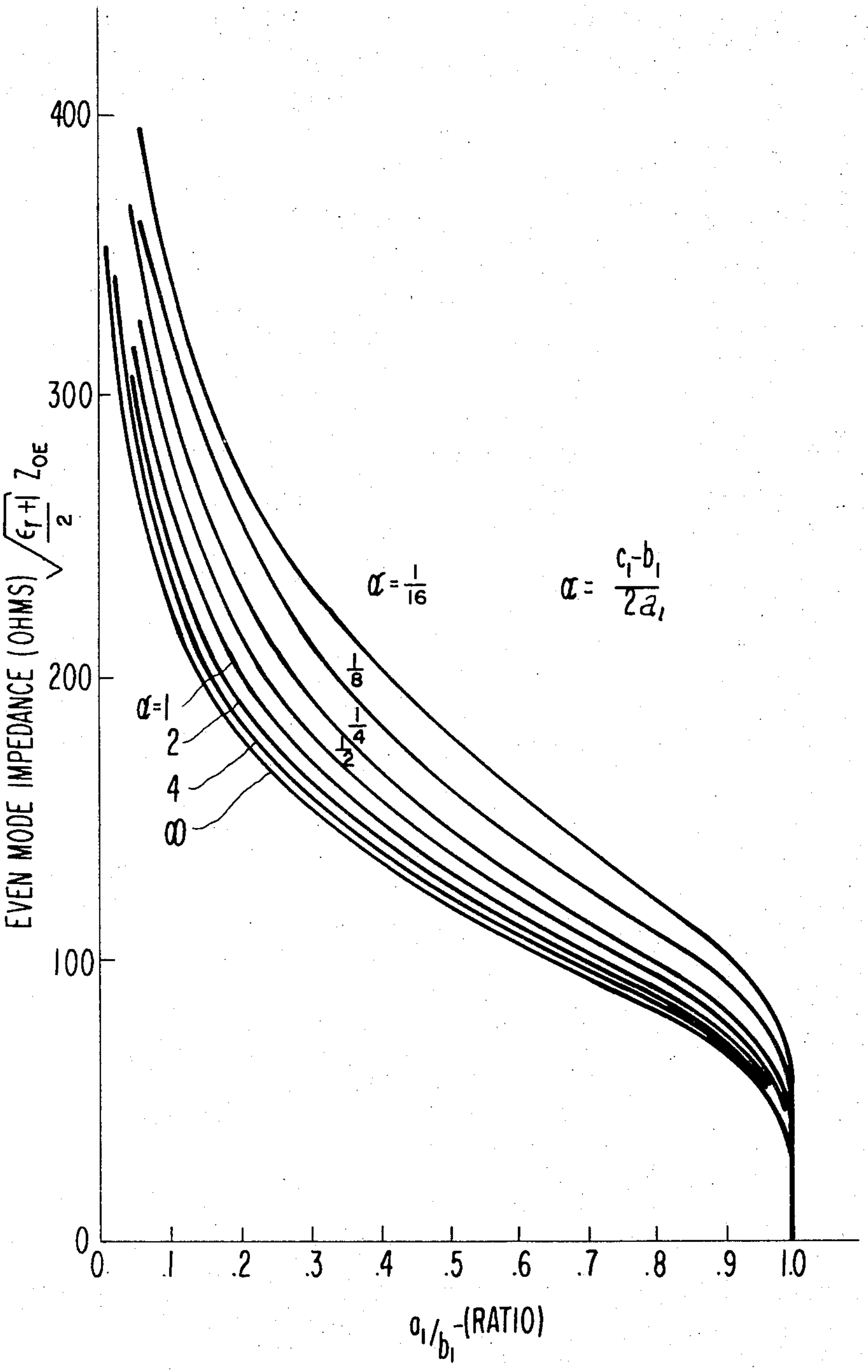

EVEN MODE IMPEDANCE (OHMS) $\sqrt{\frac{\epsilon_r+1}{2}}\,Z_{OE}$
400
300
200
100
0
$\alpha=\frac{1}{16}$
$\alpha=\frac{c_1-b_1}{2a_1}$
$\frac{1}{8}$
$\frac{1}{4}$
$\frac{1}{2}$
$\alpha=1$
2
4
∞
0.
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
a_1/b_1-(RATIO)

FIG. 3

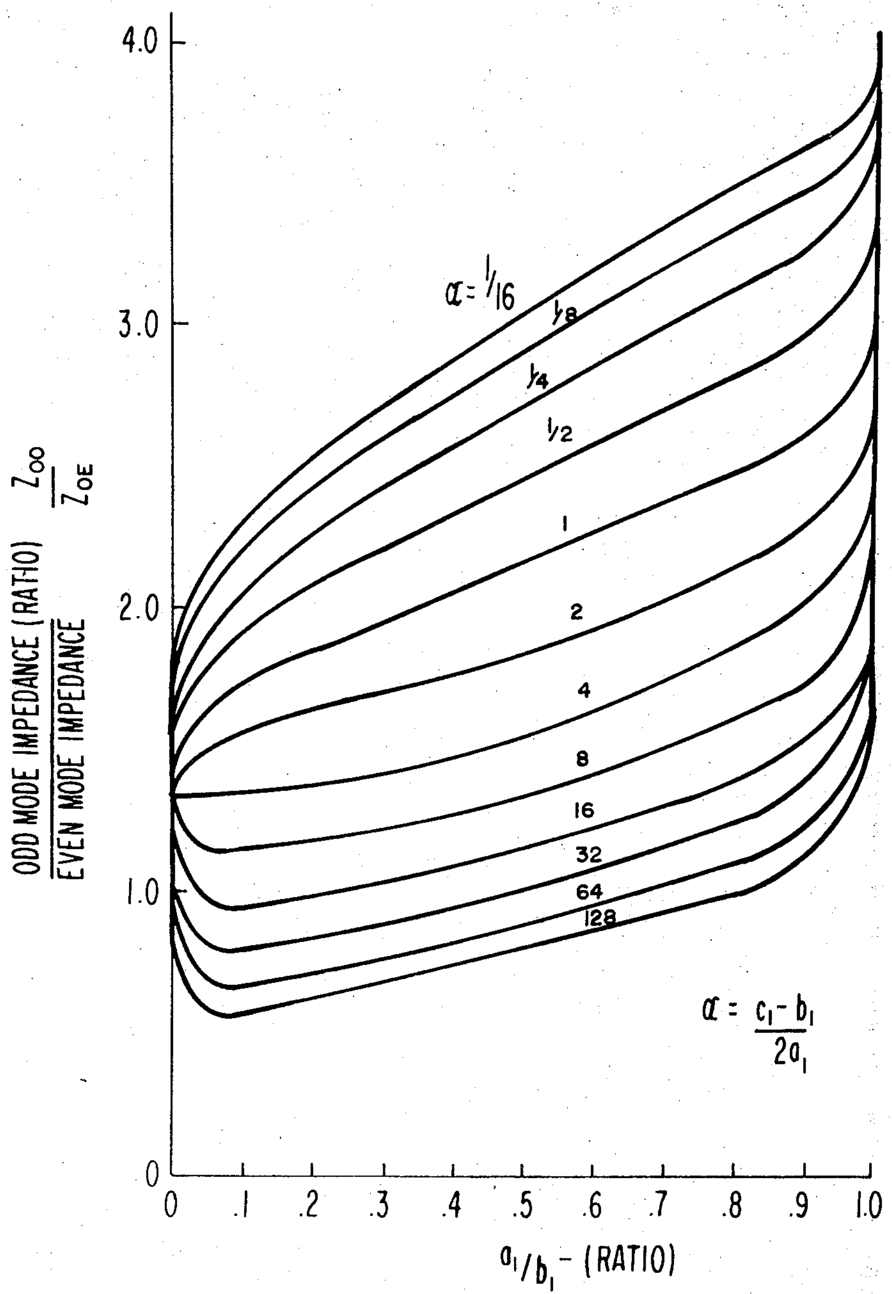

4.0
3.0
2.0
1.0
0
ODD MODE IMPEDANCE (RATIO) / EVEN MODE IMPEDANCE
$\frac{Z_{OO}}{Z_{OE}}$
$\alpha = 1/16$
1/8
1/4
1/2
1
2
4
8
16
32
64
128
$\alpha = \frac{c_1 - b_1}{2a_1}$
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
a_1/b_1 – (RATIO)

FIG. 4

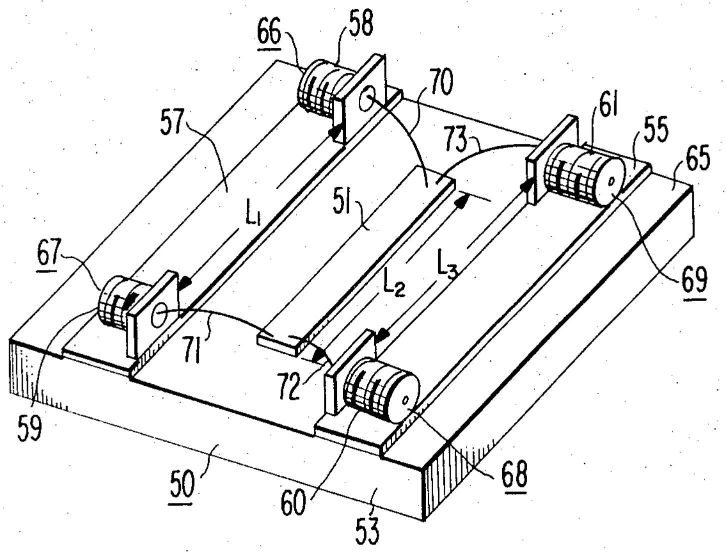

66
58
70
57
73
61
55
65
51
L1
L3
L2
67
69
71
72
59
68
50
60
53

FIG. 5

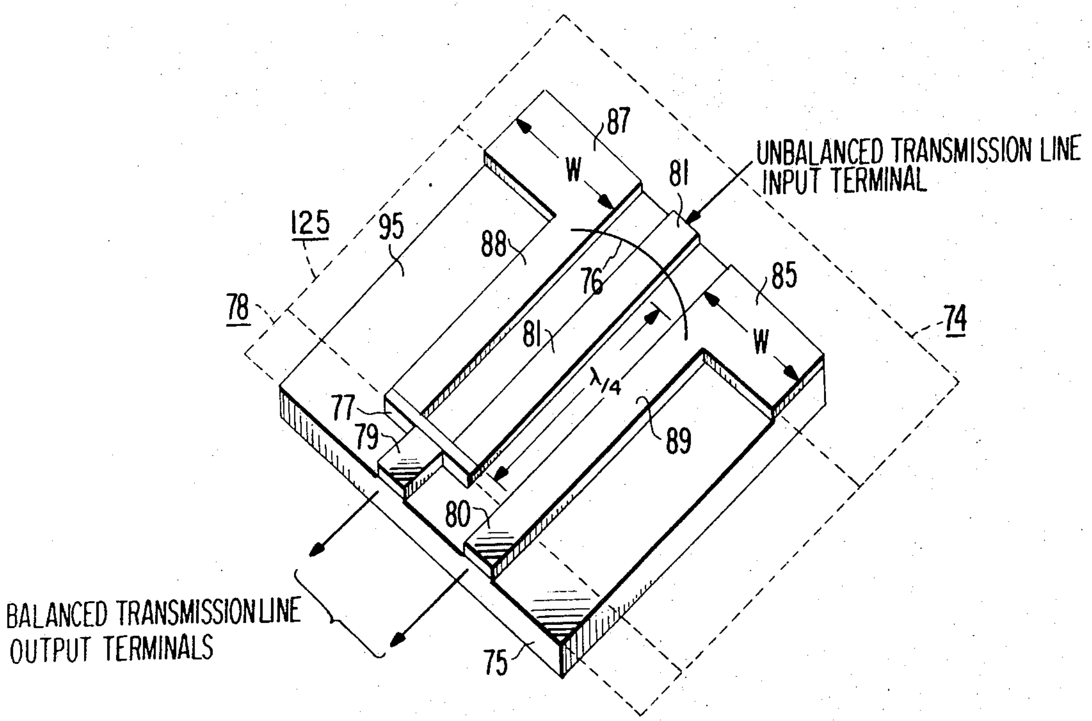

87
W
81
UNBALANCED TRANSMISSION LINE INPUT TERMINAL
125
95
88
76
85
78
81
W
74
$\lambda/4$
77
79
89
80
BALANCED TRANSMISSION LINE OUTPUT TERMINALS
75

FIG. 6

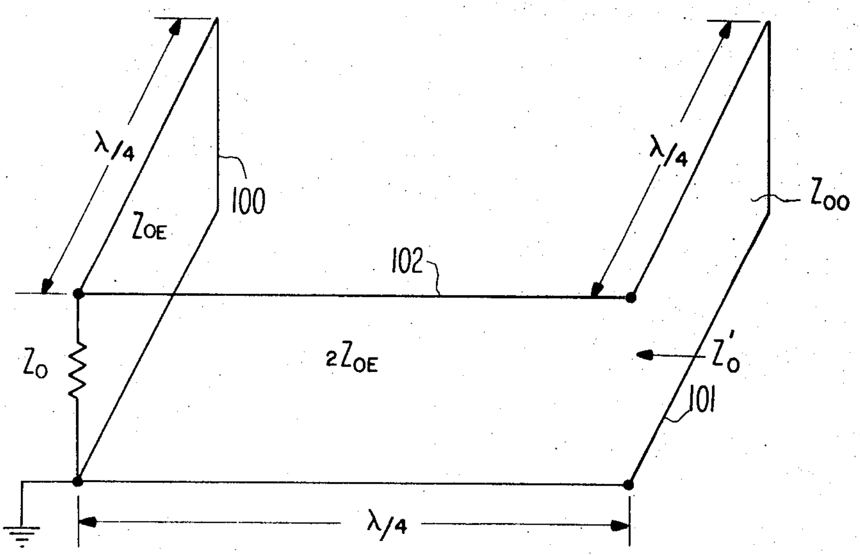

λ/4
100
Z_{OE}
λ/4
Z_{OO}
102
Z_O
$2Z_{OE}$
Z_O'
101
λ/4

FIG. 7

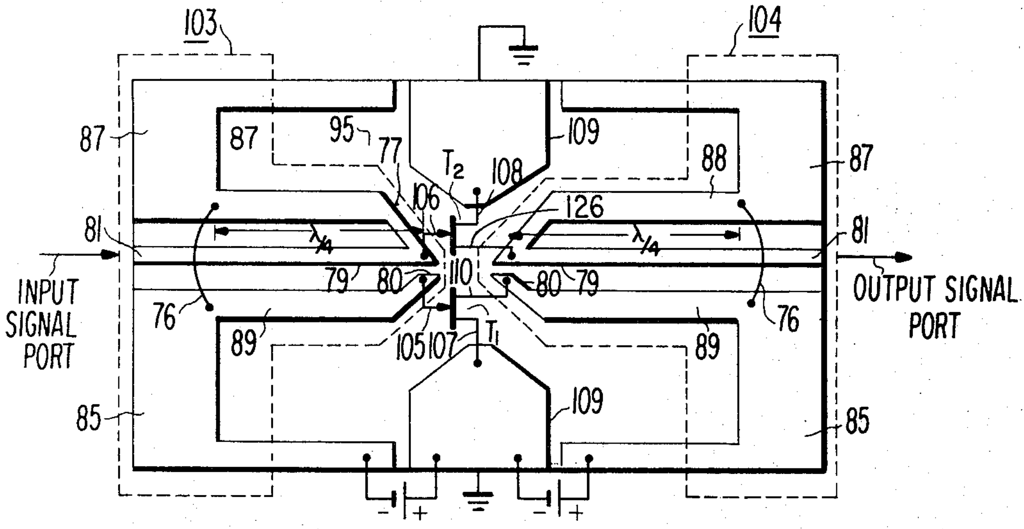

103
104
87
87
95
77
T_2
108
109
88
87
106
126
81
λ/4
λ/4
81
INPUT SIGNAL PORT
79
80
110
80
79
OUTPUT SIGNAL PORT
76
76
89
105
107
T_1
89
109
85
85

FIG. 8

MICROWAVE TRANSMISSION LINE AND DEVICES USING MULTIPLE COPLANAR CONDUCTORS

This is a division of application Ser. No. 315,087, filed Dec. 14, 1972, now U.S. Pat. No. 3,798,575.

DESCRIPTION OF THE PRIOR ART

Existing microwave transmission lines suitable for microwave integrated circuits employ a strip-like conductor on the top surface of a dielectric substrate and a ground planar conductor on the bottom surface of the dielectric substrate. Microwave energy is confined substantially within the dielectric substrate and is transmitted from an input port to an output port in the TEM (transverse electromagnetic) mode. Some microwave integrated circuits employ two adjacent and coplanar strip-like conductors on the top surface of the dielectric substrate. The microwave transmission characteristics of these circuits are dependent on how the electric fields of the microwave energy are distributed between conductive surfaces on both sides of the substrate.

For certain devices, it is inconvenient and impractical to use a transmission line having a ground planar conductor on the bottom surface of a dielectric substrate and one or two coplanar strip-like conductors on the top surface of the dielectric substrate. A prior art transmission line described in U.S. Pat. No. 3,560,893 issued to Cheng Paul Wen on Feb. 2, 1971, describes the use of three coplanar and parallel strip-like conductors on the top surface of a dielectric substrate. Microwave energy is transmitted along the three conductor transmission lines in a first transmission mode that confines the electric field of the applied microwave energy between the center conductor and the two outer ground potential conductors. Certain microwave devices require not only the first transmission mode but a new second transmission mode that confines the field between the two outer conductors for efficient operation.

SUMMARY OF THE INVENTION

According to the present invention a transmission line for electromagnetic energy comprising first, second and third coplanar strip-like conductors having predetermined widths adjacent to one surface of a dielectric substrate confine the electric fields of the electromagnetic energy substantially within the dielectric substrate in first and second transmission modes. The first conductor has a first edge separated from an adjacent edge of the second conductor at a first relative electric potential by a first predetermined gap. The first conductor also has a second edge, opposite the first edge, that is separated from an adjacent edge of the third conductor at a second relative electric potential by a second predetermined gap. The first, second and third conductor widths, the dielectric constant of the dielectric substrate, and the first and second predetermined gaps are arranged to confine the electric fields of the electromagnetic energy substantially within the dielectric substrate between the first and second conductors and between the first and third conductors in a first transmission mode and between the second and third conductors in a second transmission mode.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a perspective view of a prior art electromagnetic energy transmission line.

FIG. **2** is a perspective view of a transmission line in accordance with one embodiment of the present invention.

FIG. **3** is a plot of the even mode impedance of the transmission line shown in FIG. **2** as a function of the ratio of the transmission line dimensions, a_1/b_1, the dielectric constant of the dielectric substrate and the ratio of the transmission line dimensions $c_1 - b_1/2a_1$.

FIG. **4** is a plot of the ratio of odd mode impedance to even mode impedance as a function of the ratio of the transmission line dimensions a_1/b_1, the dielectric constant of the dielectric substrate and the ratio of the transmission line dimensions $c_1 - b_1/2a_1$.

FIG. **5** is a perspective view of a coplanar conductor directional coupler in accordance with another embodiment of the present invention.

FIG. **6** is a perspective view of an unbalanced-to-balanced transmission line transformer in accordance with another embodiment of the present invention.

FIG. **7** is a schematic representation of the unbalanced-to-balanced transmission line transformer illustrated in FIG. **6**.

FIG. **8** is a top view of a microwave transistor push-pull amplifier in accordance with a still further embodiment of the present invention.

DESCRIPTION OF PREFERRED EMBODIMENTS OF THE INVENTION

Referring to FIG. **1**, there is shown a perspective view of a prior art electromagnetic energy transmission line. The transmission line comprises three coplanar strip-like conductors **11**, **15** and **17** on the top surface **22** of a dielectric substrate **13**. The prior art transmission line, illustrated in FIG. **1**, is described in U.S. Pat. No. 3,560,893 issued to Cheng Paul Wen on Feb. 2, 1971. A single, thin relatively narrow strip-like conductor **11** is separated by predetermined gaps from two relatively wide strip-like conductors **15** and **17** both at the same R.F. and D.C. ground potential. The minimum width of the first relatively wide strip-like ground conductor **15** is more than twice as wide as narrow strip-like conductor **11** and is spaced near to and parallel with coplanar narrow strip-like conductor **11**. The minimum width of the second relatively wide strip-like ground conductor **17** is likewise more than twice as wide as narrow strip-like conductor **11** and is spaced near to and parallel with coplanar narrow strip-like conductor **11** but on the opposite side of narrow strip-like conductor **11** relative to ground conductor **15**. The top surface **22** of dielectric substrate **13** having the three coplanar strip-like conductors **11**, **15** and **17** thereon is open to free space. The bottom surface **16** of dielectric substrate **13** is likewise open to free space.

The distribution of the electric field of electromagnetic energy coupled to the transmission line from a source, not shown, is represented by dashed electric field lines **19**. Electric field lines **19** are distributed only between narrow strip-like conductor **11** and wider strip-like conductors **15** and **17** along their entire lengths. Electric field lines **19** are contained mainly within the dielectric substrate **13** between narrow strip-like conductor **11** and ground conductors **15** and **17**. However, some electric field lines **19**, not shown, are distributed between conductor **11** and conductors **15** and **17** in the free space region. The intensity of the electric field within dielectric substrate **13** is dependent on the magnitude of the dielectric constant of dielectric substrate **13.** A discontinuity in displacement current density at the interface between dielectric substrate **13** and free space is produced by that portion of electric field **19** tangential to the air-dielectric boundary on dielectric surface **22.** The discontinuity in displacement current on dielectric surface **22** produces an axial component of magnetic field, represented by dashed lines **20,** associated with electric field **19.** A portion of the axial component of the magnetic field **20** at the interface between dielectric substrate **13** and free space on surface **22** is in the direction of propagation. The magnetic field **20** extends along both sides of narrow conductor **11** and passes under narrow conductor **11.** The distance, *d*, between conductors **15** and **17** is preferably less than one-half wavelength at the operating frequency in order to prevent the transmission of electromagnetic energy in undesired modes.

In order to distribute the electric field between narrow strip-like conductor **11** and wider strip-like conductors **15** and **17,** a difference in potential must exist between narrow strip-like conductor **11** and wider strip-like conductors **15** and **17.** Since both wider strip-like conductors **15** and **17** are at the same R.F. and D.C. ground potential, the boundary conditions for establishing an electric field between conductors **15** and **17** does not exist. The characteristic impedance of the prior art three coplanar strip-like conductor transmission line is dependent on the establishment of an electric field between only narrow strip-like conductor **11** and wider strip-like conductors **15** and **17.**

Referring to FIG. **2,** there is shown a perspective view of a transmission line **40** comprising three coplanar strip-like conductors **21, 25** and **27** on the top surface **35** of a dielectric substrate **23** in accordance with one embodiment of the present invention. Center strip-like conductor **21** is separated by predetermined gaps from first and second outer strip-like conductors, **25** and **27** having predetermined widths. First outer strip-like conductor **25** is spaced near to and parallel with coplanar center strip-like conductor **21.** Second outer strip-like conductor **27** is spaced near to and parallel with coplanar center strip-like conductor **21** but on the opposite side of center strip-like conductor **21** relative to first outer conductor **25.** The top surface **35** of dielectric substrate **23** having the three coplanar strip-like conductors **21, 25** and **27** thereon as illustrated in FIG. **2** is open to free space. Unlike the prior art transmission line illustrated in FIG. **1,** the minimum width of first and second outer conductors **25** and **27** according to the present invention is not limited to be at least twice as wide as center conductor **27.** Contrary to the prior art arrangements, according to the present invention a difference in R.F. potential is provided between outer conductors **25** and **27** in accordance with several arrangements to be described.

Electromagnetic energy from a source, not shown, is coupled to transmission line **40.** The distribution of the electric field of the electromagnetic energy coupled to transmission line **40** is represented by dashed electric field lines **29.** Electromagnetic energy can be transmitted along transmission line **40** in a first transmission mode that distributes electric field lines **29** between center strip-like conductor **21** and outer strip-like conductors **25** and **27** along their entire lengths since a difference in R.F. potential exists between center strip-like conductor **21** and outer strip-like conductors **25** and **27.** Electromagnetic energy can also be transmitted along transmission line **40** in a second transmission mode that distributes electric field lines **29** between only outer strip-like conductors **25** and **27.** Conditions can be established as will be apparent to those skilled in this art that would allow simultaneous transmission of electromagnetic energy in both the first and second transmission modes. It should be understood that the terms "first" and "second" transmission modes designate for convenience of description and the appended claims both the arrangements and the modes of operation of transmission line **40** according to the present invention.

A portion of electric field **29** is tangential to the air-dielectric boundary on dielectric surface **35** and produces a discontinuity in displacement current density at the interface between dielectric substrate **23** and free space. The discontinuity in displacement current on dielectric surface **35** produces an axial component of magnetic field, represented by dashed lines **31,** associated with electric field **29.** A portion of the axial component of the magnetic field **31** at the interface between dielectric substrate **23** and free space on surface **35** is in the direction of propagation when the distance, d, between outer conductors **25** and **27** is small compared to the electrical distance of one wavelength at the operating frequency. Under these conditions, the magnetic field lines **31** extend along both sides of center conductor **21** and eventually pass under center conductor **21** forming a closed magnetic loop having a portion in the direction of electromagnetic transmission. The magnitude of the magnetic field **31** present at the air-dielectric interface on one side of center conductor **21** is not equal to the magnitude of the magnetic field **31** on the other side of center conductor **31.** If the magnetic field lines **31** were represented by magnetic field vectors, the vectors would appear at the air-dielectric interface on the top surface of dielectric substrate **23** between center conductor **21** and outer conductors **25** and **27.** The vectors would have a magnitude and direction that would define a condition of circular polarization existing on the top surface of dielectric substrate **23** between center conductor **21** and outer conductors **25** and **27.** The sense of circular polarization (clockwise or counterclockwise) would be the same if viewed on opposite sides of center conductor **21.** This polarization condition is significant in the construction of microwave ferrite devices as described by Lax and Button in Chapter 12 of "Microwave Ferrites and Ferrimagnetics," McGraw-Hill publication.

If the distance, d, between outer conductors **25** and **27** is larger than the electrical distance of one wavelength at the operating frequency, the axial component of magnetic field lines **31** form a closed loop around center conductor **21.** Under this condition, the closed loop of magnetic field lines **31** around center conductor **21** is then transverse to the direction of electromagnetic transmission.

The term even mode impedance, Z_{OE}, is used to identify the impedance of transmission line **40** when electromagnetic energy is transmitted in the first transmission mode, viz., when electric field lines **29** are distributed between center strip-like conductor **21** and outer strip-like conductors **25** and **27.** The impedance Z_{OE_1}, refers to an even mode impedance having a magnitude dependent on the intensity of the electric field distribution between center conductor **21** and outer conductor **27.** The impedance Z_{OE_2} refers to an even mode impedance having a magnitude dependent on the intensity of the electric field distribution between center conductor **21** and outer conductor **25.**

Referring to FIG. **3,** there is shown a graph of even mode impedance, Z_{OE}, in terms of the relative dielectric constant, ϵ_r, of dielectric substrate **23** versus the ratio of the substrate dimensions, a_1/b_1, shown in FIG. **2.** The dimension a_1 is the distance from the center line of center conductor **21** to the edge of center conductor **21.** The dimension b_1 is the distance from the center line of center conductor **21** to the nearest edge of outer conductor **25.** The dimension c_1 is the distance from the center line of center conductor **21** to the furthest edge of outer conductor **25.** Assuming that the dimensions of strip-like conductors **21, 25** and **27** comprising transmission line **40** and the relative dielectric constant ϵ_r are known, the graph in FIG. 3 is useful for determining even mode impedance Z_{OE} under the condition that transmission line **40** is symmetrical or $Z_{OE_1} = Z_{OE_2}$ and the substrate thickness, t, greater than $4 \times b_1$. In other words, the dimensions b_1 and c_1 determining the width of outer conductor **25** and the gap between center conductor **21** and outer conductor **25** in FIG. **2,** also correspond to the dimensions of the width of outer conductor **27** and the gap between center conductor **21** and outer conductor **27.** The magnitude of the even mode impedance is independent of the thickness, t, of dielectric substrate **23** in FIG. **2** when thickness, t, exceeds $4 \times b_1$.

The term odd mode impedance, Z_{OO}, is used to identify the impedance of transmission line **40** when it is transmitting electromagnetic energy in the second transmission mode, viz., when electric field lines **29** are distributed between only outer conductors **25** and **27.**

Referring to FIG. **4,** there is shown a graph of the ratio of odd mode impedance to even mode impedance, Z_{OO}/Z_{OE}, versus the ratio of the substrate dimensions, a_1/b_1, shown in FIG. 2. The graph in FIG. **4** is useful for determining odd mode impedance, Z_{OO}, knowing Z_{OE} and the dimensions of strip-like conductors **21, 25** and **27** comprising transmission line **40** provided either transmission line **40** is symmetrical or $Z_{OE_1} = Z_{OE_2}$. As explained above, transmission line **40** is symmetrical when the dimensions b_1 and c_1 determining the width of outer conductor **25** and the gap between center conductor **21** and outer conductor **25** in FIG. **2** also correspond to the dimensions of the width of outer conductor **27** and the gap between center conductor **21** and outer conductor **27.** The magnitude of the odd mode impedance is independent of the thickness, t, of the dielectric substrate **23** in FIG. **2** when thickness, t, exceeds $4 \times b_1$.

FIGS. **3** and **4** illustrate that the even mode and odd mode impedances of transmission line **40** in FIG. **2** vary as a function of the a_1/b_1 ratio when transmission line **40** has a predetermined ratio of outer conductor width to center conductor width $(c_1 - b_1/2a_1)$. A transmission line for electromagnetic energy comprising three coplanar strip-like conductors on the top surface of a dielectric substrate permits construction of passive devices requiring a determination of even and odd mode impedances for improved operation. The disclosed transmission line configuration permits easy connection of active devices between center conductor **21** and outer conductors **25** and **27** as well as a similar connection of other passive components.

Referring to FIG. **5,** there is shown a perspective view of a directional coupler, according to this invention, comprising three coplanar strip-like conductors **51, 55** and **57** on the top surface **65** of a dielectric substrate **53.** A directional coupler is a passive microwave device used for dividing microwave energy coupled to an input port between two output ports. The propagation of microwave energy transmitted to each output port is dependent on the desired coupling coefficient. Part of the energy reflected at the two output ports is directed to a fourth port usually terminated in an energy absorbing load. The design of a directional coupler in terms of even mode, Z'_{OE}, and odd mode, Z'_{OO}, impedances is known being described by Matthaei, Young and Jones in Chapter **13** of "Microwave Filters Impedance-Matching Networks, and Coupling Structures." The desired characteristics of a directional coupler (coupling coefficient, bandwidth, etc.) are directional coupler design goals described in Chapter **13** of the above cited text and are used to calculate the magnitude of Z'_{OE} and Z'_{OO}. The magnitude Z_{OE} used in FIGS. **3** and **4** is equivalent to $Z'_{OE}/2$. The magnitude of Z_{OO} used in FIGS. **3** and **4** is equivalent to $2Z'_{OO}$. Thus, FIGS. **3** and **4** can be used to determine the widths of conductors **51, 55** and **57** and the separation between center conductor **51** and outer conductors **55** and **57** that would allow operation of a directional coupler having desired operating characteristics.

FIG. **5** also illustrates a method of coupling microwave energy to and from a transmission line comprising three coplanar strip-like conductors **51, 55** and **57** on the top surface **65** of dielectric substrate **53.** Coaxial outer conductor **58** of coaxial connector **66** is connected to outer strip-like conductor **57.** Coaxial center conductor **70** of connector **66** is connected to the closest end of center strip-like conductor **51.** Coaxial outer conductor **59** of coaxial connector **67** is connected to outer strip-like conductor **57.** Coaxial center conductor **71** of connector **67** is connected to the closest end of center strip-like conductor **51.** A length L_1 of outer strip-like conductor **57** separates coaxial outer conductor **58** of connector **66** from coaxial outer conductor **59** of connector **67.** The length L_1 is equivalent to an electrical length of substantially $\lambda/4$, where λ is the wavelength determined by the equation:

$$\lambda = C/f\sqrt{\epsilon_r + 1/2} \qquad (1)$$

C being the velocity of light in a vacuum, f the mid-band operating frequency and ϵ_r the relative dielectric constant of dielectric substrate **53.**

Coaxial outer conductor **61** of coaxial connector **69** is connected to outer strip-like conductor **55.** Coaxial center conductor **73** of connector **69** is connected to center strip-like conductor **51** at the same end as coaxial center conductor **70** of coaxial connector **66.** Coaxial outer conductor **60** of connector **68** is connected to outer strip-like conductor **55.** Coaxial center conductor **72** of connector **68** is connected to center strip-like conductor **51** at the same end as coaxial center conductor **71** of connector **67.** A length L_3 of outer strip-like conductor **55** separates coaxial outer conductor **61** of connector **69** from coaxial outer conductor **60** of connector **68.** The length L_3 is equivalent to an electrical length of substantially $\lambda/4$, where λ is the wavelength determined by equation (1).

Outer strip-like conductor **57** may be at the same D.C. potential as outer strip-like conductor **55** if either coaxial outer conductors **58** or **59** is at the same D.C. potential as either of coaxial outer conductors **60** or **61.** However, outer strip-like conductors **55** and **57** are not at the same R.F. potential when coaxial outer conductors **58, 59, 60** and **61** are connected to outer strip-like conductors **55** and **57** as illustrated in FIG. **5.** Thus, by arranging the connections as just described, the previously discussed boundary conditions for exciting the even and odd mode impedances in a transmission line comprising three coplanar strip-like conductors are preserved.

The length L_2 of center strip-like conductor **51** is equivalent to an electrical length of $\lambda/4$, where λ is the wavelength determined by equation (1). Center strip-like conductor **51** is coextensive and parallel with outer strip-like conductor **55** over length L_3 with outer strip-like conductor **57** over length L_1.

It is well known that a microwave signal coupled to an input port connector of a directional coupler may be divided into two output signals that are coupled from two output port connectors that are directly opposite the input port connector. For example, if a microwave signal is coupled to input port connector **66,** part of the microwave signal is transmitted directly to directly opposite output port connector **67** and part of the microwave signal is coupled to directly opposite output port connector **69.** Substantially none of the input microwave signal is coupled to diagonally opposite connector **68.**

Referring to FIG. **6,** there is shown according to this invention a perspective view of an unbalanced-to-balanced transmission line transformer commonly referred to as a balun. The balun provides an impedance transformation from the impedance magnitude of the signal source, not shown, coupled to the unbalanced transmission line input terminal section **74** to the impedance magnitude of a load, not shown, coupled to the balanced transmission line output terminal section **78.** The balanced transmission line output terminal section **78** consists of two coplanar strip-like conductors **79** and **80** on the top surface **95** of dielectric substrate **75.** The balun is designed to transmit energy to a load terminating conductors **79** and **80.** The design of balun section **125** determines the characteristic impedance of balanced transmission line **78** and section **125** also provides a condition that establishes a phase difference of **180** electrical degrees between conductors **79** and **80.**

Unbalanced transmission line input terminal section **74** consists of an arrangement of three coplanar and parallel strip-like conductors **81, 85** and **87** in the top surface **95** of dielectric substrate **75** more fully described in U.S. Pat. No. 3,560,893 issued to C. P. Wen on Feb. 2, 1971. Relatively narrow strip-like center conductor **81** is separated by predetermined gaps from two relatively wide strip-like conductors **85** and **87** both at the same R.F. and D.C. ground potential. One method of establishing the same R.F. and D.C. ground potential at conductors **85** and **87** is to connect the outer conductor of a coaxial connector, not shown, to conductors **85** and **87** and the center conductor of the connector to conductor **81.** The width, W, of outer conductors **85** and **87** is at least twice as wide as the width of center conductor **81.** A length of 10 mil diameter wire **76** is connected from outer conductor **85** to outer conductor **87.** Wire **76** is used to maintain the same R.F. and D.C. ground potential between outer strip-like conductors **85** and **87** at the end of unbalanced transmission line input terminal section **74.**

Balun section **125** consists of three coplanar and parallel strip-like conductors **81, 88** and **89** on the top surface **95** of dielectric substrate **75.** Center strip-like conductor **81** is separated by predetermined gaps from outer strip-like conductors **88** and **89.** One end of outer strip-like conductor **88** is connected to outer strip-like conductor **87** near the connection point of wire **76.** The other end of conductor **88** is connected to one end of strip-like conductor **77.** The electrical length of conductor **88** from the connection point of wire **76** to the connection point of conductor **77** is substantially $\lambda/4$, where λ is the wavelength determined by equation (1). The electrical length of conductor **77** is negligible. One end of center strip-like conductor **81** is connected to the other end of strip-like conductor **77.** One end of outer strip-like conductor **89** is connected to outer strip-like conductor **85** near the connection point of wire **76.**

One end of strip-like conductor **79** of section **78** is connected to conductor **77** anywhere along the length of conductor **77.** One end of strip-like conductor **80** of section **78** is illustrated in FIG. **6** as being an extension of outer strip-like conductor **89.** Such an arrangement is exemplary only of other possible arrangements. The end of strip-like conductor **80** may be connected to conductor **89** anywhere along the end of conductor **89.**

Referring to FIG. **7,** there is shown a schematic equivalent of section **125** of the balun illustrated in FIG. **6.** The impedance Z_O is the load impedance terminating the balanced transmission line output terminal section **78.** The schematic representation of section **125** is useful in explaining the determination of odd mode impedance, Z_{OO}, and even mode impedance, Z_{OE}, necessary for the design of a balun operative over a broad frequency band. Section **125** is schematically illustrated as having a first short circuited transmission line stub section **100,** having a characteristic impedance $2Z_{OE}$, connected in shunt with a transmission line section **102** having a characteristic impedance $2Z_{OE}$. A second short circuited transmission line stub section **101** having a characteristic impedance Z_{OO} is also connected in shunt with transmission line section **102.** The electrical length of transmission line section **102** separating the connection points of sections **100** and **101** to section **102** is substantially $\lambda/4$, where λ is the wavelength defined by equation (1). The electrical length of sections **100** and **101** from their connection to section **102** to their short circuited ends is substantially $\lambda/4$, where λ is the wavelength defined in equation (1).

The characteristic impedance, Z_O', of balanced transmission line section **78** at mid-band frequency, f_o, is

$$Z_O' = (2Z_{OE})^2/Z_O \tag{2}$$

where Z_{OE} is the even mode impedance of section **102** and Z_O is the magnitude of the impedance of the signal source, not shown, coupled to unbalanced transmission line section **74.** At mid-band frequency, f_o, the shunt connected short circuited stub sections **100** and **101** each appear as an open circuit or very high impedance connected in shunt with section **102** and thus do not affect the determination of balanced transmission line characteristic impedance Z_O'.

At operating frequencies other than the mid-band frequency, f_o, the characteristic impedance Z_{bal} of balanced transmission line section **78** is:

$$1/Z_O = j(1/2Z_{OE}+1/Z_{OO}) \cot \theta + (\sec^2/2Z_{OE}\, Z_O - j2\cot\theta)(1/2Z_{OE}) \tag{3}$$

where Z_{OE} is the even mode impedance of section **102,** Z_{OO} is the odd mode impedance of section **102,** θ is the electrical length of stub sections **100** and **101** at the operating frequency and Z_O is the magnitude of the signal source, not shown, coupled to unbalanced transmission line section **74.** Thus, the desired characteristic impedance Z_O' of balanced output terminal section **78** and its variations over a desired frequency band can be determined from equations (2) and (3). The even mode impedance, Z_{OE}, and the odd mode impedance, Z_{OO}, used in equations (2) and (3) together with the graphs of FIGS. **3** and **4** may be used to determine the width of strip-like conductors **81, 88** and **89** and the spacing between center conductor **81** and outer conductors **88** and **89** of the balun illustrated in FIG. **6.**

Referring to FIG. **8,** there is shown a top view of a microwave transistor push-pull amplifier according to the invention, having all conductive surfaces and transistors on the top surface **95** of a dielectric substrate. The push-pull amplifier uses the balun illustrated in FIG. **6** as push-pull amplifier input transformer **103** and push-pull amplifier output transformer **104.** For convenience, the numbers identifying the conductive surfaces of the balun illustrated in FIG. **6** are used to identify the conductive surfaces of input and output push-pull amplifier transformers **103** and **104.** A detailed explanation of push-pull transformer-coupled power amplifiers is disclosed in Section 4.2 of "Electronic Designers' Handbook" by Landee, Davis and Albrecht.

Gate electrode **105** of transistor T_1 is connected to balanced transmission line terminal **80** of input balun **103** and gate electrode **106** of transistor T_2 is connected to balanced transmission line terminal **79** of input balun **103.** Source electrode **107** of transistor T_1 and source electrode **108** of transistor T_2 are connected to strip-like conductors **109** which are at D.C. ground potential. As previously discussed, in the description of the balun illustrated in FIG. **6,** the widths of strip-like conductors **81, 88** and **89** and the separation between inner conductor **81** and outer conductors **88** and **89** of input balun **103** are determined from FIGS. **3** and **4** when the magnitudes of even mode impedance, Z_{OE}, and odd mode impedance, Z_{OO}, are known. Equations (2) and (3) are used to determine the magnitudes of Z_{OE} and Z_{OO} necessary for the proper impedance transformation from the known impedance of the input signal source, not shown, to the known input impedance magnitude of transistors T_1 and T_2. As an example, the impedance of the input signal source is 50 ohms and the magnitude of the combined input impedance of transistors T_1 and T_2 is substantially 200 ohms. The relative dielectric constant, ϵ_r, of the dielectric substrate is 2.2. The width of center strip-like conductor **81** of balun **103** is 0.020 inches. The widths of outer strip-like conductors **88** and **89** of balun **103** is 0.020 inches. The separation between center strip-like conductor **81** and outer strip-like conductors **88** and **89** of balun **103** is 0.028 inches.

Drain electrode **110** of transistor T_1 is connected to balanced transmission line terminal **80** of output balun **104** and drain electrode **126** of transistor T_2 is connected to balanced transmission line terminal **79** of output balun **104.** The widths of strip-like conductors **81, 88** and **89** and the separation between inner conductor **81** and outer conductors **88** and **89** of output balun **104** are determined from FIGS. **3** and **4** when the magnitudes of even mode impedance, Z_{OE}, and odd mode impedance, Z_{OO}, are known. Equations (2) and (3) are used to determine the magnitudes of Z_{OE} and Z_{OO} necessary for the proper impedance transformation from the output impedance magnitude of transistors T_1 and T_2 to the impedance magnitude of the load, not shown, terminating the output signal port. As an example, the impedance of the terminating output load is 50 ohms and the magnitude of the combined output impedance of transistors T_1 and T_2 is substantially 450 ohms. The width of center strip-like conductor **81** of balun **104** is .016 inches. The widths of outer strip-like conductors **88** and **89** of balun **104** is .016 inches. The separation between center strip-like conductor **81** and outer strip-like conductors **88** and **89** of balun **104** is .035 inches.

A negative D.C. bias voltage of 2 volts is applied to gates **105** and **106** of Gallium Arsenide Schottky-barrier FET (Field Effect Transistor) transistors T_1 and T_2. A positive D.C. bias voltage of 5 volts is applied to drains **110** and **126** of transistors T_1 and T_2. The gain of the push-pull amplifier was 1.5 db over a 1.0 GHz band of frequencies centered at 5.2 GHz. The magnitude of the output power was 20 mw and the efficiency of the amplifier was 13 percent.

What is claimed is:

1. An unbalanced-to-balanced transmission line transformer operative over a desired band of frequencies for transforming a first impedance to a second impedance comprising:

a dielectric substrate having a predetermined dielectric constant;

a transmission line for electromagnetic energy, said transmission line having first, second and third coplanar strip-like conductors each having input and output ends and predetermined widths and lengths adjacent to one surface of said dielectric substrate, said first conductor having one longitudinal edge substantially parallel to and separated from an adjacent longitudinal edge of said second conductor by a first predetermined gap, said first conductor having a second edge opposite and substantially parallel to said one edge, said second edge being substantially parallel to and separated from an adjacent longitudinal edge of said third conductor by a second predetermined gap, said first conductor input end being adjacent to said second and third conductor input ends and said first conductor output end being adjacent to said second and third conductor output ends, said second conductor being arranged to be at a first R.F. potential relative to said first conductor and said third conductor being arranged to be at a second different R.F. potential relative to said first conductor in the presence of said electromagnetic energy intermediate said ends, said first, second and third conductor widths, said dielectric substrate, and said first and second predetermined gaps being arranged to form said transmission line,

means for establishing a predetermined D.C. potential at both said second conductor input end and said third conductor input end, whereby said first, second and third conductor input ends, said dielectric constant and said first and second predetermined gaps form at said first, second and third conductor input ends an unbalanced transmission line input terminal section having said first impedance; and

means for connecting said second conductor output end to said first conductor output end, whereby said first and second conductor output connected ends, said third conductor output end, said dielectric constant and said first and second predetermined gaps form at said first, second and third conductor output ends a balanced transmission line input terminal section having said second impedance.

2. An unbalanced-to-balanced transmission line transformer according to claim **1,** wherein each of said first, second and third conductor predetermined lengths from said input to output ends is substantially λ/4, where λ is the wavelength at the center frequency of said desired frequency band.

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