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(54) Matched microwave variable attenuator

(57) The invention discloses a variable attenuator consisting of a dielectric substrate supporting a microstrip layout plus some discrete components mounted on it, comprising: **1)** a first branch connected between the input and output ports of the attenuator including a transmission line with a given characteristic impedance Zo along which two contiguous tracts of λ/4 electrical length at the centre of the operating frequency band is delimited in order to constitute a first line section (LIN1); **2)** a first pin diode connected across the first line section between the two λ/4 tracts; **3)** a second branch connected in parallel to the first one, including a series connection of a second line section (LIN2) having λ/2 electrical length and impedance Z, and two fixed resistors Ro = Zo; **4)** a second pin diode (R2) connected between ground and either the two fixed resistors Ro either one of the ends of the second line section (LIN2) when interposed between the two Ro resistors. The two diodes are serially biased. **5)** pin diode DC-bias control means (A_I) for varying the resistance of the two pin diodes of the same entity. The impedance Z of the second line section (LIN2) can be either equal to, or different from, Zo. In the former case the two microstrips can be either parallel straight-line or semicircular lines forming a ring. In the second case, Z ≠ Zo, the metallic layout is differently shaped (fig.3b and 3c).

STRAIGHT-LINE MICROSTRIPS

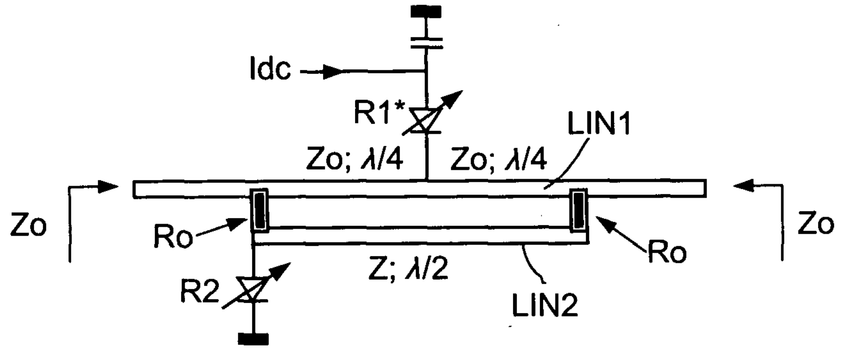

FIG. 3b

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RING MICROSTRIPS

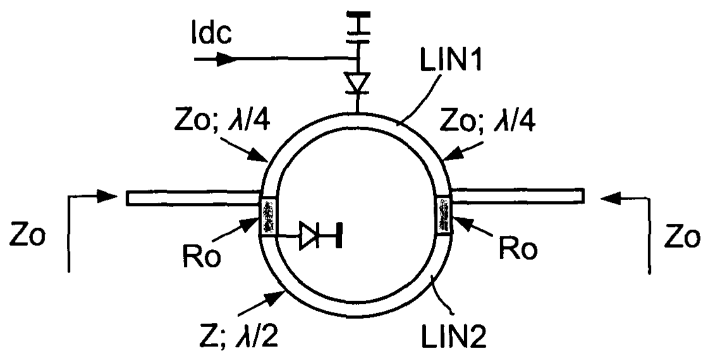

FIG. 3c

Description

FIELD OF THE INVENTION

[0001] The present invention relates to the field of microwave attenuator and more precisely to a matched microwave variable attenuator.

BACKGROUND ART

[0002] Variable microwave attenuators based on pin diodes are well known in the art. These attenuators are derivable from canonical resistive structures such as the one depicted in **Figure 1a**, **1b**, and **1c**, for **T**-cell, π-cell, and T-shunt cell, respectively. Dual-port circuits of **fig.1a** and **1c** can be mathematically described by an impedance matrix of the type:

$$\begin{bmatrix} V_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \qquad (1)$$

where: R_{11} is the resistance seen at the 1-1 port, while R_{21} is the 2→1 transfer resistances. Similar remarks, of course, apply to elements R_{22} and R_{12}.
The dual-port circuit of **fig.1b** is best described by an admittance matrix:

$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix} \qquad (2)$$

For the elements of the admittance matrix dual considerations with respect of the elements of the resistance matrix are valid. Looking at the aforementioned figures it can be seen they are symmetric. The symmetry is reflected on the matrices (1) and (2), so: $R_{12} = R_{21}$ and $G_{12} = G_{21}$. Furthermore matrices (1) and (2) are reciprocal of each other, so the following relation is valid:

$$G = R^{-1}. \qquad (3)$$

Equation (3) is the mathematical tool for shifting from the serial representation of **fig.1a** and **1.c** to the parallel representation of **fig.1.b**, and vice versa. Considering for simplicity the only matricial equation (1), voltages V_1 and V_2 depend on both the characteristics of the generator and the load. Being R_G and R_L the internal resistance of the generator and the load, the maximum transfer of power from the generator to the load, also corresponding to the minimum attenuation, takes place when R_G and R_L are matched to the resistance seen at the respective ports. The matched condition is: $R_G = R_{11}$ and $R_L = R_{22}$. Resistive attenuator starts attenuating as the match condition is left out. The desired attenuation is achieved by opportunely dimensioning the elements of the resistance matrix.

[0003] A microwave variable attenuator is obtainable in line of principle by replacing one or more the resistances of the resistive attenuators with pin diodes having a resistance decreasing with the increase of the DC bias current flowing through them. In addition, it can be considered that pin diodes include unwanted reactive elements, such as: junction capacitance, case capacitance, and chip-to-case connection inductance, which limit their performances and call for an optimisation of the design inside the operation band. Two-port network including both dissipative and reactive elements are modelled by an impedance matrix ***Z*** whose elements $[z_{x,y}]$ include both resistance and reactance components, or by an admittance matrix **Y** whose elements $[y_{x,y}]$ include both admittance ad susceptance components. The unwanted reactive elements, namely reactance or susceptance, limit the maximum attenuation (decoupling) on serial branches of the attenuator, whereas they increase the insertion loss on parallel branches.

[0004] Another useful tool for studying microwave attenuators is the so-called scattering matrix **S** having the following representation:

$$\begin{bmatrix} V_1^- \\ V_2^- \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} V_1^+ \\ V_2^+ \end{bmatrix} \tag{4}$$

where apex $^-$ and $^+$ indicate signals outgoing from or incoming to two transmission lines respectively connected to the ports indicated by subscript $_1$ and $_2$. Assuming port 1 as the input port and 2 as the output port, when the output line is terminated in a matched load, it results $V_2^+ = 0$. Stating the above matching condition, S_{11} is the reflection coefficient in the input line, and S_{21} is the transmission coefficient into output line from input line. Similar remarks, of course, apply to elements S_{22} and S_{12}. Different from the only resistive attenuators described by matrix **R**, the microwave attenuators described by matrix **S** other than attenuating by dissipation on the resistive elements, can also attenuate by exploiting the mechanism of reflecting the waves towards the input port due to the various unmatching condition along the propagation path. In the latter case the attenuation can take place without or with partial power dissipation in the load.

[0005] Preferred embodiments of pin diode attenuators are the ones having large attenuations and low insertion losses. The latter being defined as the ratio between the power delivered to the load before and after the insertion of the attenuator driven for null attenuation. The requisite of low insertion loss cannot leave out of consideration the frequency response of the microwave attenuators. In order to reach greater attenuations more attenuation cells can be cascaded to each other.

[0006] The European patent EP 0223289 B1 titled: "Improvements to pin diode attenuators", granted to the same Applicant of the present invention, discloses a pin diode microwave variable attenuator similar to the one reported in **fig.2**. With reference to the figure, the attenuator includes a configuration having two contiguous λ/4 microstrip lines with characteristic impedance of Z_T serially connected at the two ends with two respective microstrips of Z_O, in their turn connected to the input and output ports of the attenuator. The anode of a first pin diode is connected between the λ/4 microstrips while the cathode is grounded. At the input side of the attenuator the cathode of a second pin diode is connected between the two microstrips of different impedance, while the anode is connected to a third λ/4 microstrip whose impedance is less than Z_O. The two diodes are serially biased so that their resistances are the same. The peculiarity of this attenuator is that of using microstrips with two different characteristic impedances, namely the impedance Z_T of the two contiguous λ/4 microstrips is different from the impedance $Z_O = 50\ \Omega$ of the other line sections. Due to the unmatching, the attenuator promotes reflective more than dissipative attenuation. This attenuator, at parity of pin diodes resistance (2 diodes) with respect of the absorptive attenuators of the reference prior art, gives rise to higher attenuation (also termed decoupling or isolation). More precisely, the value of the attenuation increases with the ratio between Z_T and Z_O starting from a minimum attenuation in correspondence of $Z_T = Z_O$. The attenuator of **fig. 2** seems to be inspired to some golden technical rules to achieve good designs with pin diode attenuators, in particular:

- PIN diodes are serially biased by the same current, in such a way they present the same value of resistance.
- The attenuation increases as the bias current increases and the pin diode resistance decreases; if so were not true the pin diodes could be poorly polarized at the highest attenuations giving rise to distortions.
- PIN diodes are not serially connected to the lines for not to increase the insertion losses due to the residual resistance of the diodes.
- The circuit is performed in microstrip without restrictions on the type of substrate.
- The number of pin diodes is minimal.

[0007] In spite of the good design, the major drawback of the attenuator of the cited invention is that to be disadapted (unmatched) both at the input and the output ports, so that two circulators are needed, or equivalent devices, such as hybrids employed with balanced structures. Circulators and hybrids have manufacturing costs comparable if not greater than the cost of the attenuator. Furthermore the area of the complete circuit on the dielectric substrate is noticeable increased to the detriment of miniaturization requirements.

OBJECTS OF THE INVENTION

[0008] Many other types of microwave variable attenuators including pin diodes are known in the art, but the main object of the present invention is that to indicate an alternative structure able to perform prevalently dissipative attenuation keeping the adaptation at both the input and output ports unchanged for all the values of the variable attenuation, without additional circulators, hybrids, or similar devices are needed.

SUMMARY AND ADVANTAGES OF THE INVENTION

[0009] The invention achieves said object by providing a variable microwave attenuator, as disclosed in claim 1.

[0010] According to a preferred embodiment of the invention, the variable attenuator consists of a dielectric substrate which supports a microstrip layout plus some discrete components mounted on it, including:

- a first branch connected between the input and output ports of the attenuator including a transmission line with a given characteristic impedance (50 Ω), along which a first line section having λ/2 electrical length at the centre of the operating frequency band is delimited;
- a first pin diode connected across and at the centre of the first line section;
- pin diode DC-bias control means connected to the first branch for varying the resistance of the first pin diode;
- a second branch connected in parallel to the first one, including a series connection of a second line section of λ/2 electrical length and two fixed resistors equal to the given characteristic impedance (50 Ω);
- a second pin diode having a terminal connected to either the two fixed resistors either one of the ends of the second line section when interposed between the two fixed resistors, and the other terminal connected to said DC-bias control means in a way the two pin diodes are serially biased.

[0011] It is useful to remind that the electrical length *l* of a transmission line is:

$$l = \frac{2\pi}{\lambda}\, l_d$$

where l_d is the dimensional length, and λ is the wavelength along the transmission line.

[0012] Different geometries of the microstrip layout in agreement with the above description are possible. For example, according to a first preferred embodiment of the invention the two line sections are parallel straight-lines. A ring configuration of the microstrip layout according to a second preferred embodiment allows to reduce the occupied surface on the substrate and increase the decoupling between the microstrips.

[0013] Similarly to the microwave variable attenuator of **fig.2**, the two pin diodes are serially biased to set equal values of their resistances. Contrarily to this attenuator the one of the invention keeps as far as possible constant the adaptation at the input and output ports during the whole attenuation range. In any case, quite a different structure is disclosed indeed.

BRIEF DESCRIPTION OF THE DRAWINGS

[0014] The features of the present invention which are considered to be novel are set forth with particularity in the appended claims. The invention, together with further objects and advantages thereof, may be understood with reference to the following detailed description of an embodiment thereof taken in conjunction with the accompanying drawings given for purely non-limiting explanatory purposes and wherein:

- **fig.1**, already described, shows canonical resistive attenuator cells;
- **fig.**2, already described, shows a variable pin diode variable attenuator of the prior art;
- **fig.3a** shows the electrical model with bifilar lines of pin diode variable attenuator of the present invention;
- **figures 3b** and **3c** show two microstrip embodiments of the attenuator of the preceding figure;
- **figures 3d** to **3g** show some variants of the microstrip embodiment of **fig.3b**; and
- **fig.4** shows some curves of the attenuation and return loss versus frequency of the attenuator of figures 3b and 3c.

DETAILED DESCRIPTION OF SOME PREFERRED EMBODIMENTS OF THE INVENTION

[0015] With reference to **fig.3a**, an electrical model of the attenuator includes a first bifilar line LIN1 connected between the input and the output ports, and a second bifilar line LIN2 visible under the first one. The input and the output ports are not specifically indicated because the attenuator is symmetric. The two bifilar lines are unbalanced, having a wire connected to the ground. The bifilar line LIN1 is subdivided in two contiguous line sections having an electrical length of λ/4 and a characteristic impedance Z_o = 50 Ω at the central frequency of the band. The second bifilar line LIN2 is λ/2 long and presents a characteristic impedance Z, whose value is indifferent for the aim of the invention. Across the bifilar line LIN1 at the point of contact between the two contiguous λ/4 line sections, the series of a first pin diode with a capacitor is connected. The resistance of the first pin diode into the operating band is indicated with R1*. The anode of the first pin diode is connected to the capacitor while the cathode is connected to the wire of line LIN1 which is not grounded. Two resistors of R_o = 50 Ω are connected between respective ends of the bifilar lines LIN1 and

LIN2. A second pin diode is connected across the second bifilar line LIN2 either at the input or the output of LIN2. The resistance of the second pin diode into the operating band is indicated with R2. The cathode of the second diode is connected to ground, while the anode is connected to the line LIN2, in such a way the second pin diode results biased in series with the first one. The series of the two pin diodes is fed by a current Idc, injected into the anode of the first diode by a current generator A_I. The latter approximates an ideal current generator with in parallel an internal conductance g_{int} very low. Due to the serial connection, the same current Idc flows through the two pin diodes, and a same value of resistance, R1* = R2, depending on the Idc value is set up.

[0016] In **fig.3b** a first microstrip embodiment of the electrical model of the attenuator of the preceding figure is shown. With reference to **fig.3b**, the metallic layout of the upper face of a dielectric alumina substrate is depicted. The bottom face of the substrate includes a metallized ground plane in correspondence of the upper layout for achieving microstrip lines. The metallic layout is lay down by means of well consolidated methods, for example sputtering. The thickness and the width of the lines LIN1 and LIN2 are calculated for obtaining the desired characteristic impedances Z_O and Z, respectively. Connections to the ground plane are performed by metallized through holes. Elements other than microstrips are connected by advantageously employing known tools of the surface mount technology. Alternatively the two resistors R_O can be manufactured by laying down resistive metals. The metallic layout substantially includes: 1) a straight-line microstrip with a characteristic impedance Z_O = 50 Ω connected between the input and the output of the attenuator which includes in a central part the line section LIN1 λ/2 long; 2) the series of the two resistors R_O with the line section LIN2 λ/2 long connected in parallel to the line section LIN1.

[0017] In **fig.3c**, a second microstrip embodiment of the electrical model depicted in **fig.3a** is shown. The second embodiment differs from the preceding one by the only different shape of the metallic layout which is circular instead of rectangular but the electrical behaviour is the same. The ring configuration allows to save space on the upper face of the substrate of alumina.

[0018] The operation of the attenuator of the subjected invention is now described considering the T-shunt attenuator of **fig.1c** as starting point for the design of a variable microwave attenuator. With this assumption the R1 and R2 resistors of the T-shunt attenuator shall be put in correspondence with the R1* and R2 resistors of the two pin diodes. Furthermore, the reasons of the circuital scheme of **fig.3b** (and **3c**) including a mix of distributed and lumped devices shall be explained at the light of the inventive idea. Indicating with Zo the characteristic impedance (resistance) of the external lines connected to the input/output ports of the T-shunt attenuator, and with ATT the logarithmic attenuation in dB, the following equations are valid:

$$R1 = Zo \times (10^{ATT/20}-1) \tag{5}$$

$$R2 = Zo / (10^{ATT/20} - 1) \tag{6}$$

Combining the two equations each other, the following expression is found:

$$R1 \times R2 = Zo^2 \tag{7}$$

that is independent of the attenuation. The inventors have realized that expression (7) is equal to the one used by a quarter wave transformer with characteristic impedance Zo for matching the impedance R1 to R2, or vice versa. Expression (7) is rewritten as:

$$R1 = Zo^2 / R2 \tag{7a}$$

for highlighting the property of an ideal quarter wave transformer to act as impedance inverter. Namely, a given impedance connected to one end is seen as an impedance that has been inverted with respect to the characteristic impedance squared, at the other end. This also means that an impedance inverter with characteristic impedance Zo is able to tie up the variations of R1 with respect to R2 for all the attenuation range. The inventors' intuitions of above have been taken into duly consideration to develop a design for obtaining the circuital structure (unknown) of a variable microwave attenuator. The design consists of handling the T-shunt configuration (known) of **fig.1c** with the constraints of having R1* = R2 so that they can be replaced by two pin diodes controlled by an unique bias current which flows through both of them..As a starting rule, the inventors have decided to act on the serial branch R1 of the T-shunt attenuator, maintaining as far as possible the equivalence of the remaining part. This choice is motivated by the fact of trying to remove the pin diode from the serial branch, according to the arguments raised in the introduction. Because of the symmetry of the T-shunt attenuator, two quarter wave line sections and a resistance Zo^2 / R2 shall be used, as shown in the upper part of **fig.3b**. The effect of this transformation seen at the input/output ports of the attenuator is like a double transformation applied to the resistance R1 of **fig.1c** in order to obtain R1*. Operatively, expression (7a) is applied, at first, to obtain the value Zo^2/R2 for R1 due to the T-shunt configuration; successively expression (7a) is applied again, considering instead of R1 its value Zo^2/R2, to account for impedance inversion, obtaining the impedance R1* of the pin diode attenuators:

$$R1^* = Zo^2 / (Zo^2 / R2) = R2 \tag{7b}$$

which validates the condition on the equal resistances of the two pin diodes arising from their unique bias current. Equality (7b) is valid on condition that the electrical equivalence during the passage from the purely resistive T-shunt of **fig.1c** to the microwave attenuator of **fig.3b** is kept unchanged. During this passage the effect of the phase offset of the signal across the various branches must be taken into account. The RF signal coming to the attenuator is split in two signals, a first one travels along the two contiguous λ/4 tracts undergoing a λ/2 phase offset at the output of the attenuator, the second one crosses the two resistors and leaves the attenuator with a phase offset which depends on the electrical length of the connection. Most critic conditions occur in case the two diodes are interrupted and R1*, R2 tend to ∞. In order to obtain the same phase offset across the two branches crossed by the signal, a line section having an electrical length of λ/2 shall be inserted in series with the two resistances Ro. This prevents the two resistors Ro being crossed by a current when the two diodes are interrupted, or a very low attenuation is set. In fact, phase offset across two whatever paths departing from the input and joining at the output of the attenuator is the same, in this circumstance the two ends of each resistor Ro are equipotential and the current is null. Furthermore, the insertion of the λ/2 line section does not compromise the behaviour of the network. As known, a λ/2 transmission line has the property of reporting the impedance present at one end to the other end unchanged, independently of its characteristic impedance. The property is made immediately perceptible on the Smith's chart, where a λ/2 impedance transformation corresponds to a complete turn terminating in the starting point.

[0019] The circular embodiment of **fig.3c** and its design criteria are the same from the electrical point of view as the straight-line embodiment of **fig.3b**. Nevertheless some advantages are recognisable. A first one consists in the smaller area of the layout (even if not apparent from the figure), a second one is lesser constraints for joining the two microstrips interconnecting the resistors Ro.

[0020] In **fig.4** three curves of attenuation versus frequency corresponding to the simulated scattering parameters S(2,1) for three values of pin diode resistance are reported. With reference to **fig.4**, the three curves show a flat behaviour over a wide frequency range. The maximum attenuation of 20 dB is obtained with R1*, R2 = 6.5 Ω. The curves of return loss S(2,2) evaluated in correspondence of 27 Ω has a maximum value (lower than -30 dB) at the centreband frequency of 7.8 GHz. Diode resistances different from 27 Ω give lower reflections. More than 20 dB return loss S(2,2) are obtained in the full band 7.1-8.5 GHz for any attenuation value.

[0021] Though the invention is described for microstrips either including straight-line or circular layouts, it is evident that the skilled in the art can introduce variants without departing from the protections of the following claims. In particular, partial striplines, coplanar lines, or mixed configuration with metallic layers and coaxial cable are possible, although microstrips are preferred. Furthermore, both the embodiments of **figures 3b** and **3c** include microstrips LIN1 and LIN2 equal to each other; that is with the same electrical length and the same dimensional length, in this case the characteristic impedance Z of the microstrip LIN2 is equal to Zo of course. But this is not the rule because embodiments with LIN1 and LIN2 of the same electrical λ/2 length and different dimensional lengths are possible; obviously, different shapes of the layout are resulting. Besides, the position of microstrip LIN2 between the two resistors Ro is not mandatory. The only mandatory thing is the connection of pin diode R2 in series with pin diode R1* as far as the DC current is concerned. **Figures 3d** to **3g** illustrate in self-explicative way some variants on the series connection of the two resistors Ro with the microstrip LIN2.

Claims

1. Microwave variable attenuator having input and output ports including:

- a first line section (LIN1) having an electrical length of λ/2 at the central frequency of the operating band, connected between said input and output ports;
- a first pin diode (R1*) connected across and at the centre of the first line section (LIN1);

- pin diode DC-bias control means (A_I) connected to the first line section (LIN1) for varying the resistance of the pin diode (R1*);

characterised in that further includes:

- a series connection including a second line section (LIN2) having λ/2 electrical length and two fixed resistors (R_o) equal to the characteristic impedance (Z_o) of the first line section (LIN1), said series being connected in parallel to the first line section (LIN1);
- a second pin diode (R2) having a terminal connected to either the two fixed resistors (Ro) either one of the ends of the second line section (LIN2) when interposed between the two fixed resistors (Ro), and the other terminal connected to said DC-bias control means (A_I) in a way the two pin diodes (R1*, R2) are serially biased.

2. The microwave variable attenuator of the preceding claim, **characterised in that** said first line section (LIN1) is connected between the input and output ports of the attenuator by means of continuations at the two ends extending outside the λ/2 electrical length.

3. The microwave variable attenuator of one of the preceding claims, **characterised in that** said second line section (LIN2) has a characteristic impedance (Z) equal to the characteristic impedance (Z_o) of the first line section (LIN1) and is shaped as a straight-line parallel to the first line section (LIN1).

4. The microwave variable attenuator of claim 1 or 2, **characterised in that** said second line section (LIN2) has a characteristic impedance (Z) equal to the characteristic impedance (Z_o) of the first line section (LIN1), and both the first and the second line sections (LIN1, LIN2) are semicircular lines opposite of each other to form a ring shaped layout.

5. The microwave variable attenuator of claim 1 or 2, **characterised in that** said second line section (LIN2) has a characteristic impedance (Z) different from the characteristic impedance (Z_o) of the first line section (LIN1).

6. The microwave variable attenuator of one of the preceding claims, **characterised in that** said first (LIN1) and second (LIN2) line sections are in microstrips.

RESISTIVE VARIABLE ATTENUATOR (KNOWN ART)

T-CELL

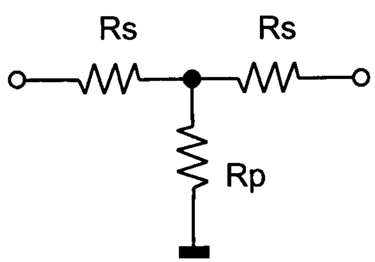

FIG. 1a

π-CELL

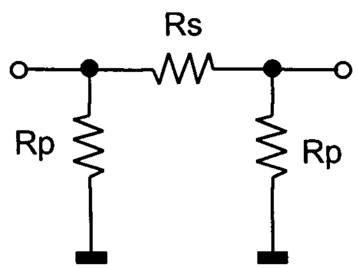

FIG. 1b

T-SHUNT

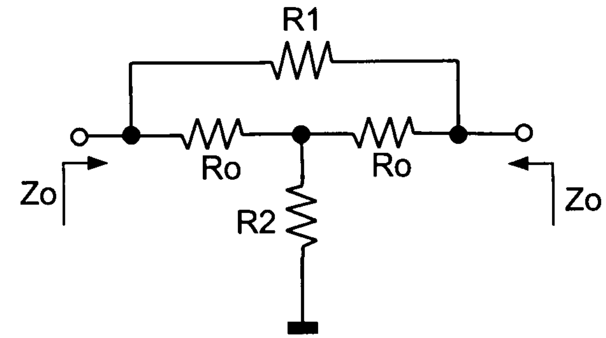

FIG. 1c

MICROWAVE VARIABLE ATTENUATOR (KNOWN ART)

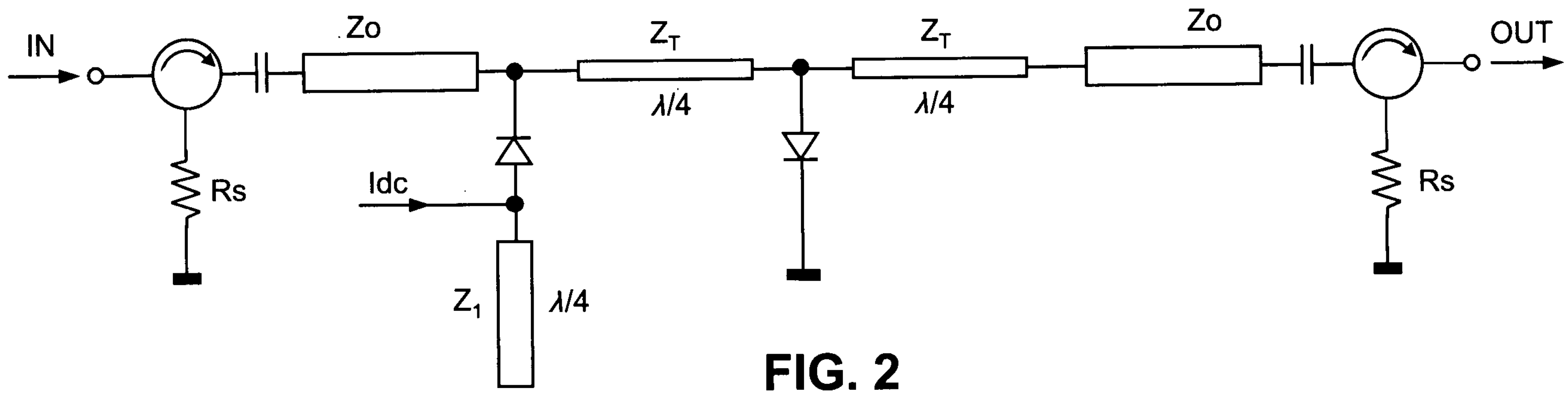

FIG. 2

2-DIODE MICROWAVE VARIABLE ATTENUATOR

ELECTRICAL MODEL WITH BIFILAR LINES

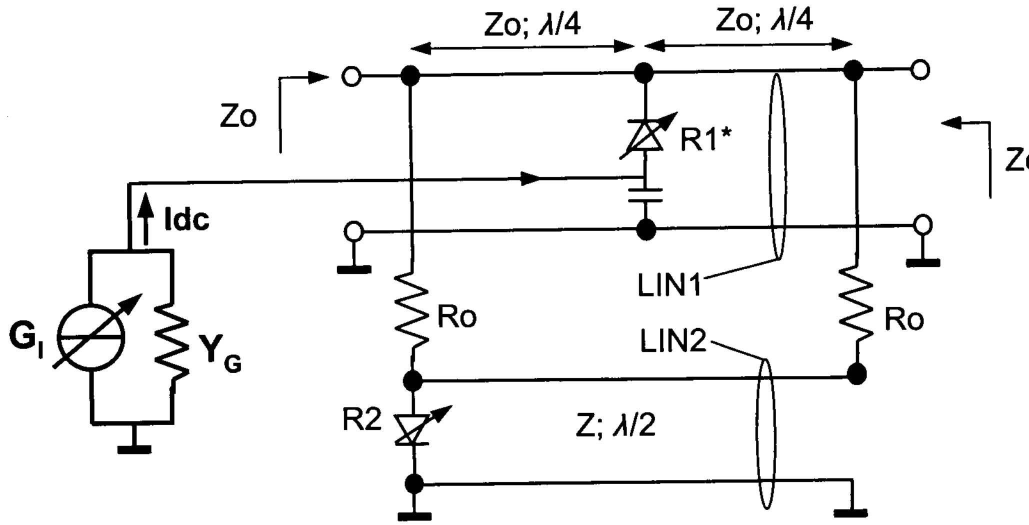

FIG. 3a

STRAIGHT-LINE MICROSTRIPS

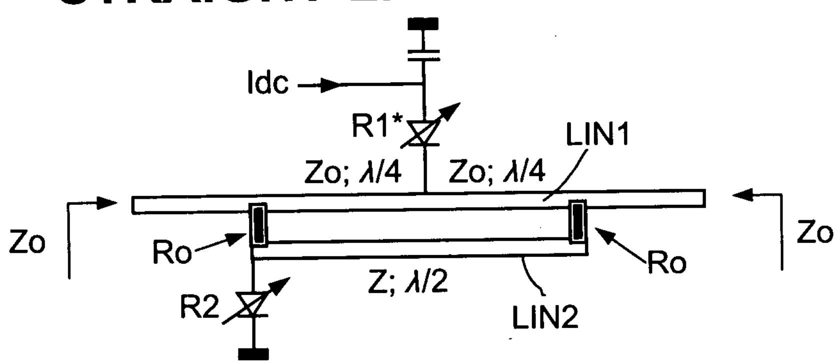

FIG. 3b

RING MICROSTRIPS

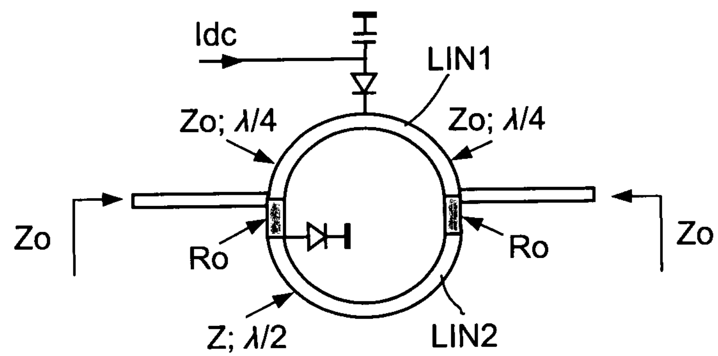

FIG. 3c

VARIANTS ON STRAIGHT-LINE MICROSTRIPS

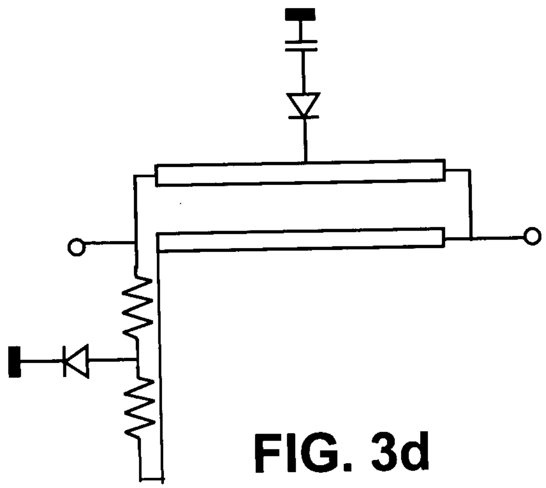

FIG. 3d

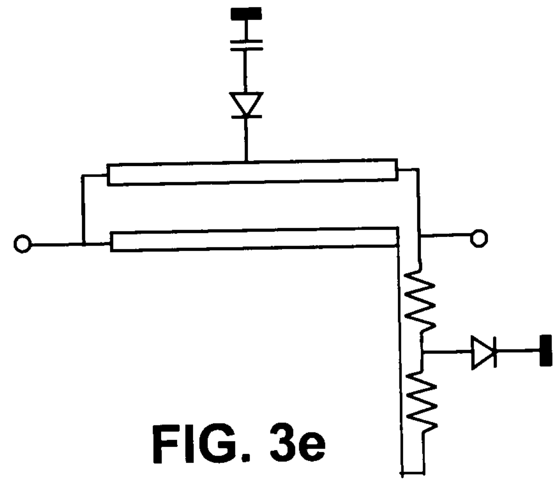

FIG. 3e

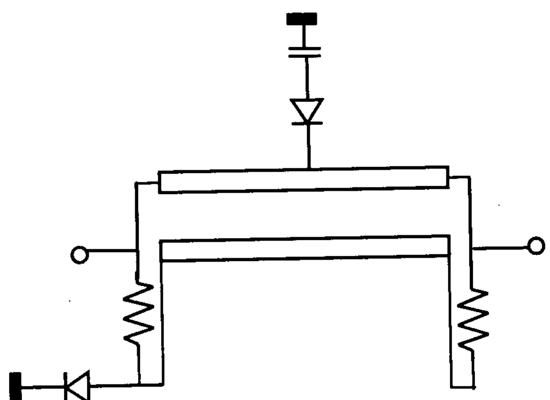

FIG. 3f

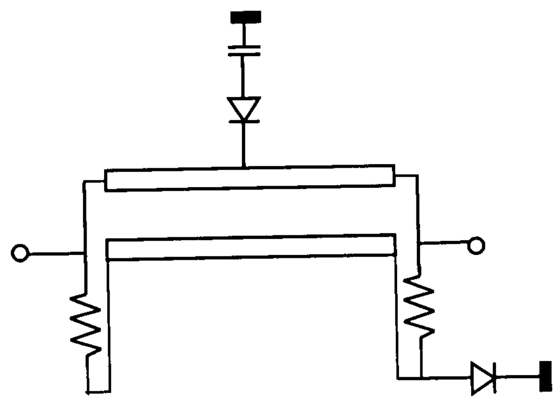

FIG. 3g

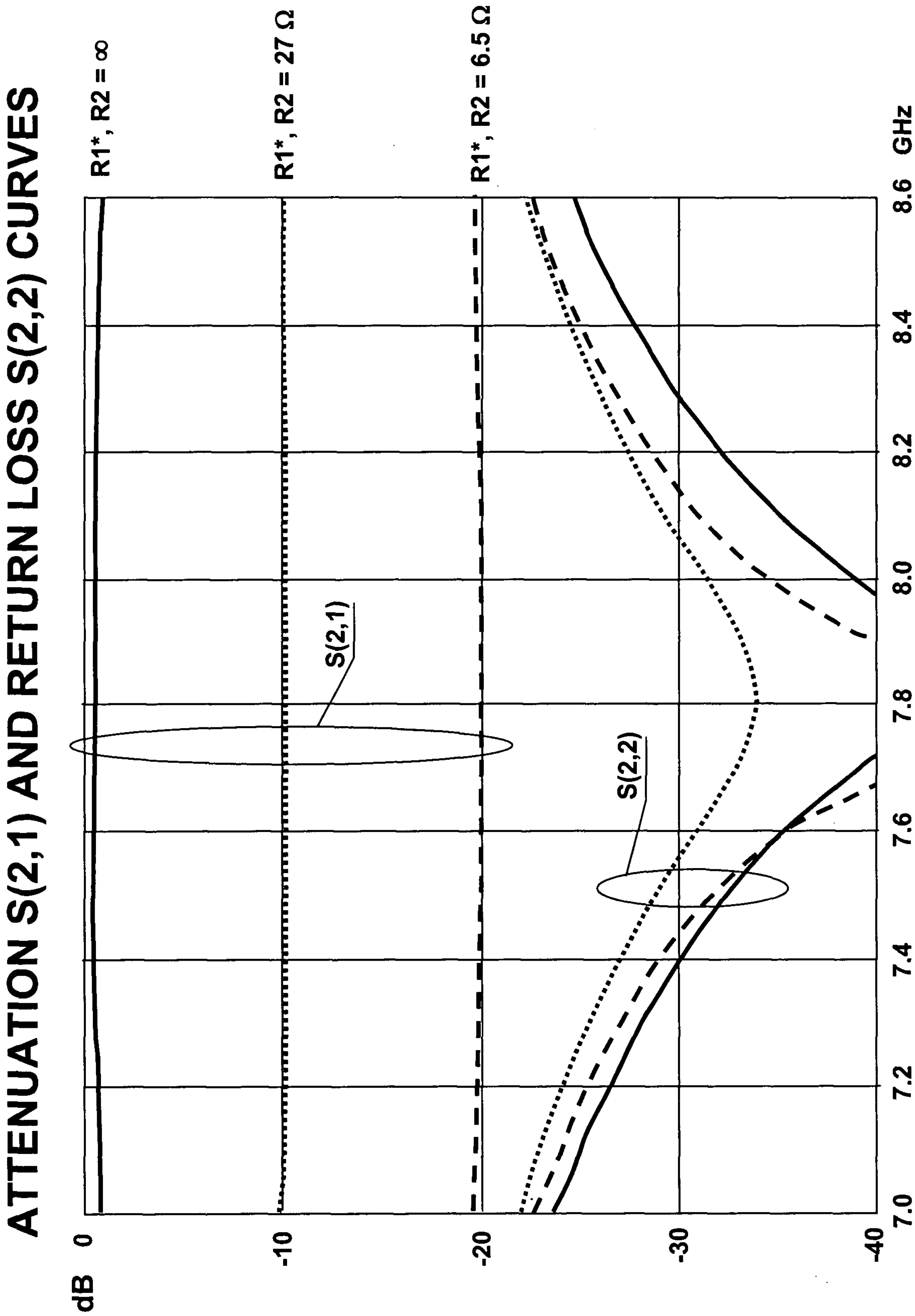
ATTENUATION S(2,1) AND RETURN LOSS S(2,2) CURVES
dB
0
-10
-20
-30
-40
7.0
7.2
7.4
7.6
7.8
8.0
8.2
8.4
8.6
GHz
R1*, R2 = ∞
R1*, R2 = 27 Ω
R1*, R2 = 6.5 Ω
S(2,1)
S(2,2)

FIG. 4

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EUROPEAN SEARCH REPORT

Application Number
EP 03 42 5804

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int.Cl.7)
X	NAVARRO M S ET AL: "Non-reflecting electronically variable attenuator" 9 August 1999 (1999-08-09), , PAGE(S) 541-544 , XP010509842 * page 541, left-hand column, line 12 - line 35; figure 1 * * page 543, right-hand column, line 1 - line 15; figure 4 * -----	1-6	H01P1/22
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TECHNICAL FIELDS SEARCHED (Int.Cl.7)
H01P
H03H

The present search report has been drawn up for all claims

3

Place of search	Date of completion of the search	Examiner
The Hague	22 April 2004	Pastor Jiménez, J-V

CATEGORY OF CITED DOCUMENTS

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