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Swanekamp et al.

[11] **3,737,686**

[45] **June 5, 1973**

[54] **SHIELDED BALANCED MICROWAVE ANALOG MULTIPLIER**

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[73] Assignee: **The United States of America as represented by the Secretary of the Navy,** Washington, D.C.

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[21] Appl. No.: **265,933**

[52] **U.S. Cl.**.....**235/194,** 235/181, 235/18 C, 325/446, 333/10

[51] **Int. Cl.** **G06g 7/16,** G06g 7/22

[58] **Field of Search**.....235/194, 186, 181; 307/229; 328/160, 144; 324/77; 343/100 CL; 333/10, 11; 332/40, 43; 325/445, 446, 449, 22–24; 321/60, 69 R, 69 W

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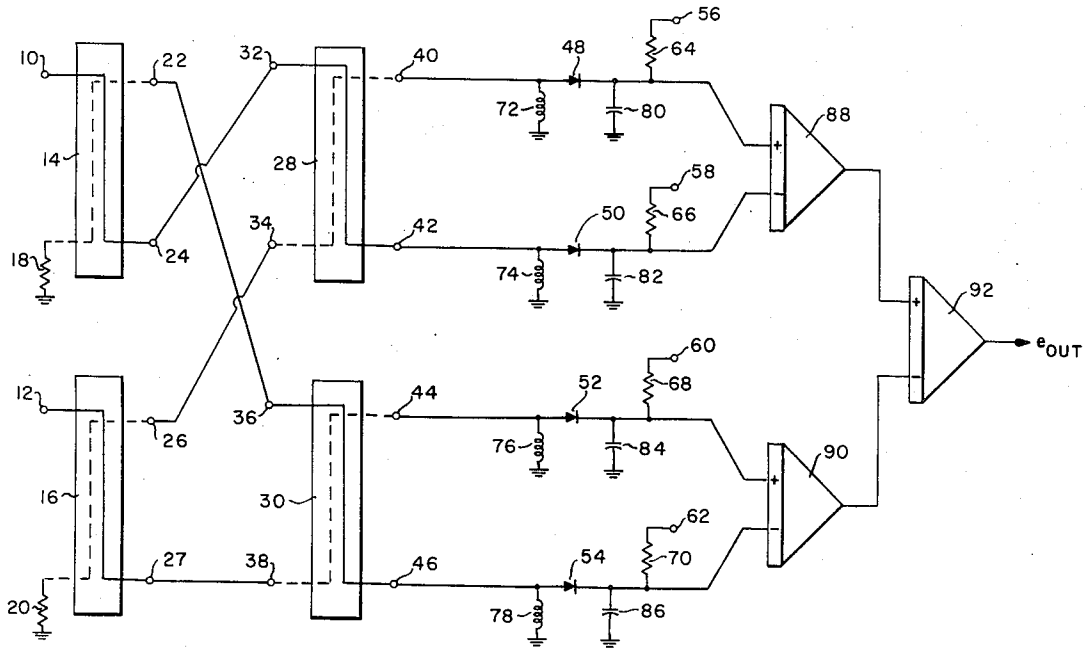
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Primary Examiner—Joseph F. Ruggiero
Attorney—R. S. Sciascia

[57] **ABSTRACT**

A passive, four quadrant, balanced analogue multiplier for use in the microwave and RF region, including four backward-wave, 3 db quadrature couplers. The couplers are interconnected whereby four output signals are supplied to four respective diodes of the mulitplier from the two input signals to be multiplied for parallel signal processing.

5 Claims, 2 Drawing Figures



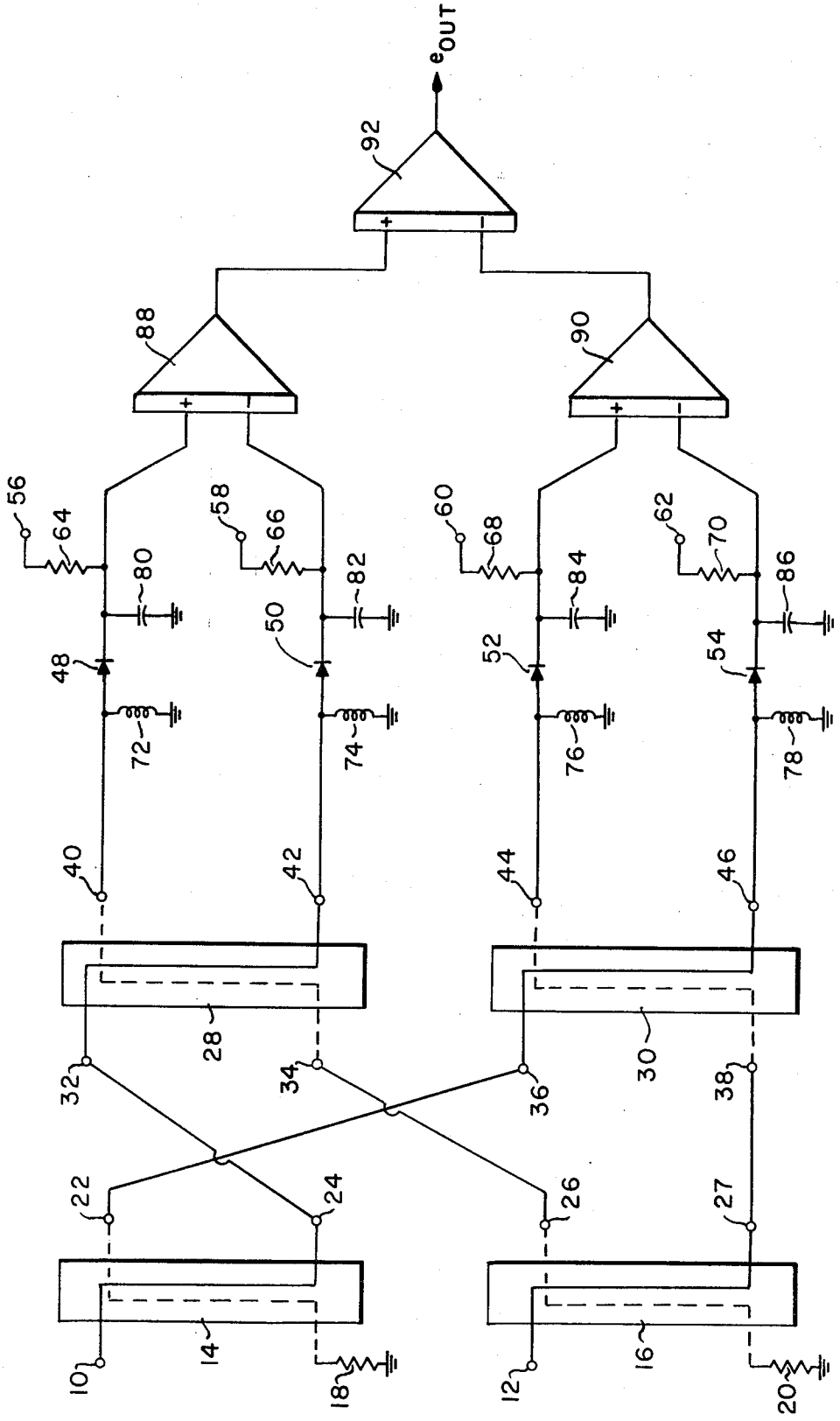

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FIG. 1.

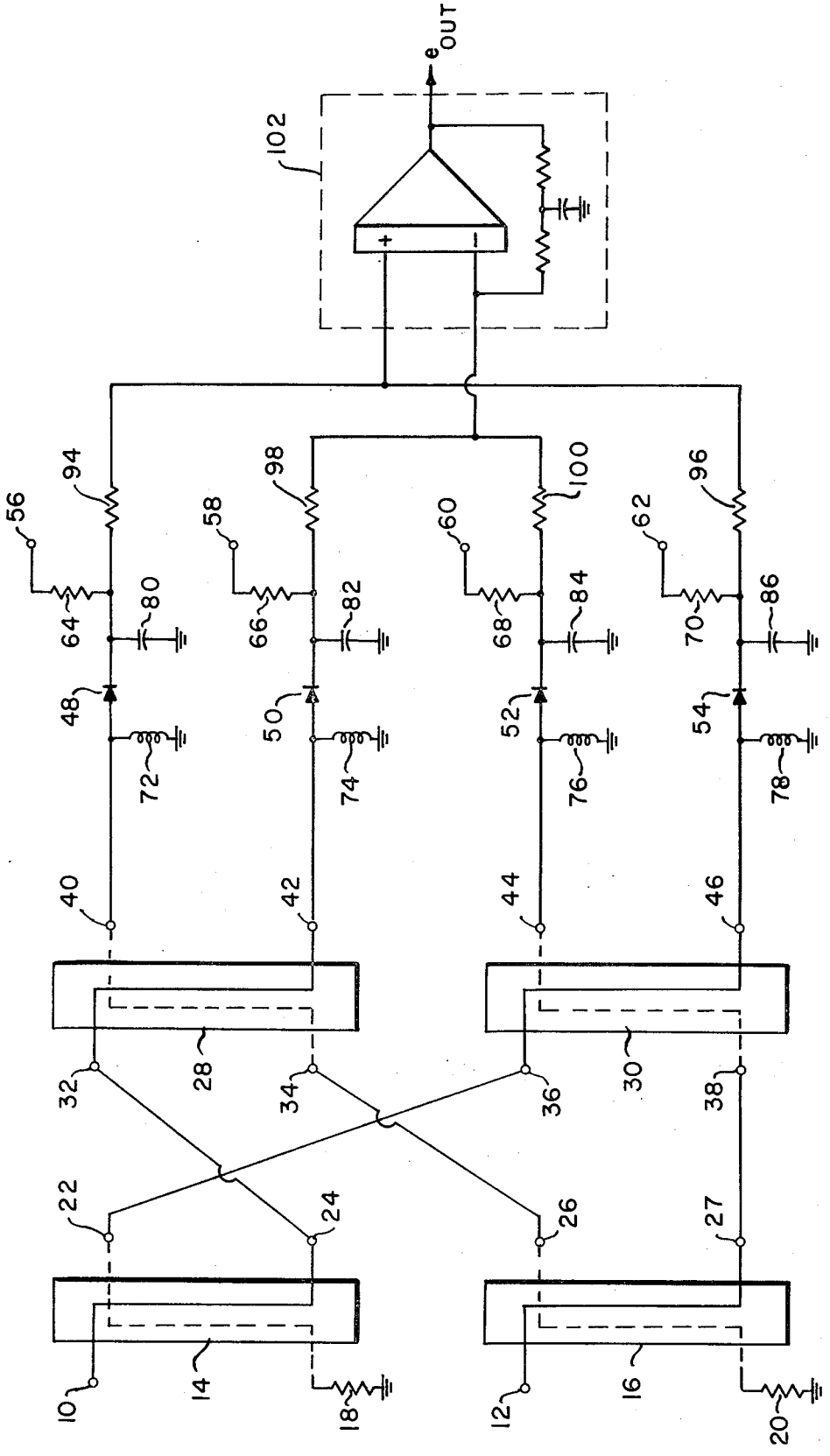

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FIG. 2.

SHIELDED BALANCED MICROWAVE ANALOG MULTIPLIER

BACKGROUND OF THE INVENTION

This invention relates generally to microwave signal processing apparatus and, more particularly, to a shielded, balanced microwave analogue multiplier.

In signal correlation systems, it is generally necessary to multiply two or more input signals to form an analogue signal representative of the product of the instantaneous amplitudes of the respective signals. When the input signals are in the microwave frequency range, special problems are posed and conventional audio frequency circuits are not operative.

Prior art attempts to provide signal multiplication at microwave frequencies include systems for heterodyning the signals down to a low frequency range and using a conventional ring modulator as a multiplier bridge. Heterodyning suffers from the disadvantage of not operating at the original microwave frequencies and, thus, requiring an excessive number of components, several of them active.

A passive multiplier, operating at the original microwave frequencies, is inherently unbalanced because the coaxial inputs short out one of the four diodes in the ring modulator, causing an undesirable d.c. bias in the output. In addition, the device is not RF shielded beyond the coaxial inputs, thereby making possible pick-up of undesired signals and causing deterioration of the signal-to-noise ratio. Also, this type of device does not provide for biasing the diodes to provide a balance adjustment and to insure operation in the desired square-law region of the diodes, which is required if the output is to be representative of the product of the instantaneous amplitudes of the applied microwave signals. Still furthermore, this type of device is not adaptable to planar design, that is, it has crossovers, thereby precluding certain construction techniques such as stripline, integrated RF circuitry, or the like.

Another prior art device is disclosed in U.S. Pat. No. 3,160,882 to John H. Malloy. This device utilized four diodes in a ring arrangement driven by a hybrid ring into which the two signals to be multiplied were connected as inputs. The series signal processing in the diodes led to diode bias circuitry which was difficult to adjust for balanced operation. In addition, the use of the hybrid ring drive limited the frequency range over which a single correlator could be used to about 35 10 percent.

SUMMARY OF THE INVENTION

Accordingly, one object of the invention is to provide an improved, passive, analogue multiplier particularly suitable for operation in the microwave frequency range.

Another object of the present invention is to provide a balanced, microwave, analogue signal multiplier.

A still further object of the present invention is to provide an analogue multiplier operable in the microwave frequency range having an improved signal-to-noise ratio.

Yet another object of the instant invention is to provide a microwave signal multiplier with total electromagnetic shielding.

Still another object of the present invention is to provide an analogue signal multiplier adaptable to miniature microwave planar construction.

A still further object of the present invention is to provide an analogue multiplier having a large usable frequency range.

Yet another object of the present invention is to provide a simpler diode biasing arrangement and better isolation in an analogue signal multiplier.

Briefly, in accordance with one embodiment of the invention, these and other objects are attained by providing a shielded, balanced, analogue signal multiplier operable at the microwave frequency range utilizing four backward-wave, 3 db, quadrature couplers connected in such a way as to take two input signals and provide four output signals. These four output signals from the coupler drive network are applied to four parallel diodes of the multiplier, each separately driven into their square law regions. Their output is then processed through integrating amplifiers and a differential amplifier whose output represents the product of the instantaneous amplitudes of the original input signals.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention, and many of the attendant advantages thereof, will be readily appreciated as the same becomes better understood by reference to the following description, when considered in connection with the accompanying drawings wherein:

FIG. 1 is a schematic view of one embodiment of the analogue multiplier according to the present invention, and

FIG. 2 is a schematic view of an alternative embodiment of the analogue multiplier according to the present invention.

DESCRIPTION OF THE PREFFERED EMBODIMENT

The operation of correlation is multiplication followed by time averaging. The correlation function is an even function with respect to the relative time delay between the two input signals to be correlated, with a maximum value at zero relative delay between two input signals, i.e., the correlator, when operating on two signal phasors, must perform the scalar, or "dot" product of the two input voltage phasors. Thus, with two sinusoidal input signals of the form $E_1 \cos \omega_1 t$ and $E_2 \cos \omega_1 (t+\tau)$, the correct correlation multiplication must produce the product of the two signal magnitudes times the cosine of the phase angle between the two input signals, i.e., $E_1 E_2 \cos \omega_1 \tau$.

Referring now to FIG. 1, sinusoidal input signal $E_1 \cos \omega_1 t$ is applied to "input" port 10 of backward wave coupler 14 and sinusoidal input signal $E_2 \cos \omega_1 (t+\tau)$ is applied to "input" port 12 of backward wave coupler 16. The "isolated" ports of couplers 14 and 16 are terminated in their characteristic impedances 18 and 20, respectively. The input power is split equally between the two output ports of each coupler whereby a voltage of $E_1/\sqrt{2} (\cos \omega_1 t - 90°)$ appears at "coupled" output port 22 and a voltage of $E_1/\sqrt{2} \cos \omega_1 t$ appears at "transmitted" output port 24 of coupler 12. Similarly, a voltage of $E_2/\sqrt{2} \cos (\omega_1 t + \omega_1 \tau - 90°)$ appears at "coupled" output port 26 and a voltage of $E_2/\sqrt{2} \cos \omega_1 (t+\tau)$ appears at "transmitted" output port 27 of coupler 16. These four output voltages are then coupled to the "input" and "isolated" ports 32, 34, 36, and 38 of couplers 28 and 30 in the following manner: "Coupled" port 22 connected to "input" port 36,

"transmitted" port **24** connected to "input" port **32**, "coupled" port **26** connected to "isolated" port **34**, and "transmitted" port **27** connected to "isolated" port **38**. For voltages connected to the "input" ports **32** and **36**, the output supplied is $1/\sqrt{2}$ times the input voltage with a 0° phase shift at the "transmitted" output port, and a 90° phase shift at the "coupled" port, as was the case with couplers **12** and **16**. With voltages fed into the "isolated" ports **34** and **38**, the 0° phase shift is associated with the output voltage at the "coupled" port and 90° associated with the "transmitted" port. Superposition is then used to sum the voltage at the output ports **40**, **42**, **44** and **46** due to voltage inputs at ports **32**, **34**, **36** and **38**. Thus, the outputs

$v_1 = (E_1/2) \cos(\omega_1 t - 90°) + (E_2/2) \cos(\omega_1 t + \omega_1 \tau - 90°)$

$v_2 = (E_1/2) \cos \omega_1 t + (E_2/2) \cos(\omega_1 t + \omega_1 \tau - 180°)$

$v_3 = (E_1/2) \cos(\omega_1 t - 180°) + (E_2/2) \cos(\omega_1 t + \omega_1 \tau)$

$v_4 = (E_1/2) \cos(\omega_1 t - 90°) + (E_2/2) \cos(\omega_1 t + \omega_1 \tau - 90°)$

appear at output ports **40**, **42**, **44** and **46**, respectively.

While there are 4! (24) distinct possible ways or sets of connecting the four output voltages from ouplers **14** and **16** to the four inputs of couplers **28** and **30**, there are three characteristic classes of eight output voltage sets from couplers **28** and **30**. Only one of these three classes contains the 0° and 180° relative phase relationship between the two input voltage terms appearing in each of the four output voltage v_1, v_2, v_3 and v_4. The interconnection shown in FIG. **1** and described hereinabove is only one of these eight possible combinations and should not be construed to be the only one possible.

Output voltages v_1, v_2, v_3 and v_4 are then processed in hot carrier diodes **48**, **50**, **52** and **54** respectively, each of these diodes operating in its square law ($i = Kv^2$) region, i.e., that the diode bias and its input signal voltage amplitude are such as to assure this operation. The functional relationship of the hot carrier diodes obeys Schottky theory almost exactly and may be expressed as

$$i = I_o (e^{\alpha v} - 1)$$

where i is the current through the diode, v is the voltage across the diode, I_o is the diode saturation current, and α is a diode constant. With the diode forwardly biased at a voltage v_1 and a current I_b, a small a.c. signal voltage v_s applied around this bias point produces an output signal current of

$I_s = (I_b + I_o)(e^{\alpha v} - 1)$ behaving like an ideal square law device.

Referring back to FIG. **1**, an adjustable d.c. bias **56**, **58**, **60** and **62** is provided for each diode **48**, **50**, **52** and **54**, respectively, through resistors **64**, **66**, **68** and **70**, respectively. Reactive impedance elements, such as chokes **72**, **74**, **76** and **78**, provide d.c. return paths for diodes **48**, **50**, **52** and **54**, respectively. The outputs from diodes **48**, **50**, **52** and **54**, operating in their square law regions, are

$e_{on} = k[\alpha v_n + (\alpha^2/2) v_n^2]$, $n = 1, 2, 3, 4$

RF shunt capacitors **80**, **82**, **84** and **86**, at each diode output **48**, **50**, **52** and **54**, respectively, ground the RF signal component centered around frequencies ω_1 and $2\omega_1$, so that e_{on} need include only the d.c. terms and quasi d.c. component centered around $\omega = 0$ (in the case of a dynamic system). As an example, consider the diode voltage v_1 appearing at the input of diode **48** where

$v_1 = (E_1/2) \cos(\omega_1 t - 90°) + (E_2/2) \cos(\omega_1 t + \omega_1 \tau - 90°)$

$v_1 = (E_1/2) \sin \omega_1 t + (E_2/2) \sin(\omega_1 t + \omega_1 \tau)$

Substituting into the equation for e_{on},

$e_{o1} = K\alpha(E_1/2) \sin \omega_1 t + K\alpha(E_2/2) \sin(\omega_1 t + \omega_1 \tau) + K\alpha^2 (E_1^2/8) \sin^2 \omega_1 t + K\alpha^2 (E_2^2/8) \sin^2(\omega_1 t + \omega_1 \tau) + K\alpha^2 (E_1 E_2/4) \sin \omega_1 t \sin(\omega_1 t + \omega_1 \tau)$,

$e_{o1} = K\alpha(E_1/2) \sin \omega_1 t + K\alpha(E_2/2) \sin(\omega_1 t + \omega_1 \tau) + K\alpha^2 (E_1^2/16)[1 - \cos 2\omega_1 t] + K\alpha^2 (E_2^2/16)[1 - \cos(2\omega_1 t + 2\omega_1 \tau)] + K\alpha^2 (E_1 E_2/8)[\cos \omega_1 \tau - \cos(2\omega_1 t + \omega_1 \tau)]$.

After bypassing all $\omega_1 t$ and $2\omega_1 t$ components through shunt capacitor **80**,

$e_{o1} = (K\alpha^2/8)[(E_1^2/2) + (E_2^2/2) + E_1 E_2 \cos \omega_1 \tau]$

Similarly,

$e_{o2} = (K\alpha^2/8)[E_1^2/2) + (E_2^2/2) - E_1 E_2 \cos \omega_1 \tau]$

and

$e_{o3} = e_{o2}$

and

$e_{o4} = e_{o1}$

Thus, e_{o1}, e_{o2}, e_{o3}, and e_{o4} contain only d.c. and quasi d.c. terms remaining for further signal processing. The outputs from diodes **48** and **50**, e_{o1} and e_{o2}, respectively, are supplied to the input of integrating amplifier **88**, and the outputs of diodes **52** and **54**, e_{o3} and e_{o4}, respectively, are supplied to the input of integrating amplifier **90**. The outputs of integrating amplifiers **88** and **90** then form the inputs of differential amplifier **92** whose output is readily seen to be

$$e_{out} = K[(e_{o1} - e_{o2}) - (e_{o3} - e_{o4})]$$

$$e_{out} = K_o E_1 E_2 \cos \omega_1 \tau$$

or

$$e_{out} = K_o R(\tau), \text{ where}$$

$R(\tau) = E_1 E_2 \cos \omega_1 \tau$ the correlation function.

In an alternative embodiment, shown in FIG. **2**, the multiplication process is performed identically with the four 3 db hybrid couplers and the four biased, hot carrier diodes previously illustrated and explained with respect to FIG. **1**. The four output voltages e_{o1}, e_{o2}, e_{o3}, and e_{o4} from diodes **48**, **50**, **52** and **54**, respectively, are the same as before, but rather than supplying them to integrating and differential amplifiers, voltages e_{o1} and e_{o2} are added in resistors **94** and **96**, respectively, and voltages e_{o3} and e_{o4} are added in resistors **98** and **100**, respectively. These two summing voltages are then supplied as the input to summing integrating amplifier **102**, whose output e_{out} is also of the form $K_o E_1 E_2 \cos \omega_1 \tau$.

It is to be particularly noted that the entire device, except for the d.c. bias sources, is totally shielded from external electromagnetic radiation and stray RF signals. The ability of the instant invention to provide a completely shielded system is a distinct advantage over the prior art which, heretofore, has been unable to completely shield the multipliers. Thus, the prior art multiplier had been forced to sacrifice either shielding, which is important at microwave frequencies, or a balanced system, which is advantageous in operation, or both.

The microwave multiplier will provide simple and reliable analogue multiplication at microwave frequqneics. By providing true balance and complete shielding,

a significant increase in signal-to-noise ratio over prior art devices may be obtained.

It is readily apparent that any transmission line made may be utilized to fabricate the multiplier. Thus, coaxial cable, stripline, waveguide and miniature microwave planar fabrication may be utilized. Furthermore, any desired shielding may be used.

The four outputs from the coupler drive network enable the four diodes of the multiplier to be each separately driven, thereby utilizing parallel signal processing which permit better isolation of the diodes and a simple, easily adjustable biasing arrangement. In addition, the use of backward-wave couplers gives the coupler drive network an octave band frequency range capability, i.e., ± 33.3 percent frequency range. This means that less correlators are required to cover a given broad frequency range, or a broader usable frequency range is available from each correlator. A continuously variable delay at one of the inputs can generate a complete correlation function.

Obviously, numerous modifications and variations of the present invention are possible in light of the above teachings. Thus, as an alternative to using backward wave couplers, 3 db line couplers may be used in the coupler drive network. Seven other combinations for interconnecting the couplers to implement the doubly balanced correlator concept will become obvious as other alternatives to the proposed embodiment. It is therefore to be understood that, within the scope of the appended claims, the invention may be practiced otherwise than as specifically described herein.

What is claimed as new and desired to be secured by Letters Patent of the United States is:

1. A shielded, balanced microwave analogue multiplier comprising in combination:

a first set of backward wave couplers having at least two ports for receiving two sinusoidal input signals;

a second set of backward wave couplers connected to the output ports of said first set of couplers, said second set of couplers having four output ports and producing four output signals;

a unilaterally conducting device connected to each of said output ports;

means for biasing said unilaterally conducting devices whereby they operate in their square law region, and

means coupled to said unilaterally conducting device for producing an output signal proportional to the product of the instantaneous amplitudes of said two input signals.

2. A shielded, balanced microwave analogue multiplier according to claim **1** wherein

said unilaterally conducting devices comprise diodes, and wherein said biasing means comprises a d.c. bias course.

3. A shielded balanced microwave analogue multiplier according to claim **2** wherein

each of said set of couplers comprises two backward-wave 3 db quadrature couplers.

4. A shielded balanced microwave analogue multiplier according to claim **3** wherein said producing means comprises:

an integrating amplifier coupled to two of said diodes;

a second integrating amplifier coupled to the other two of said diodes; and

a differential amplifier coupled to the outputs of said integrating amplifiers.

5. A shielded balanced microwave analogue multiplier according to claim **3** wherein said producing means comprises:

summing resistors coupled to each of said diode outputs and a summing integrating amplifier coupled to the other terminal of said summing resistors.

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