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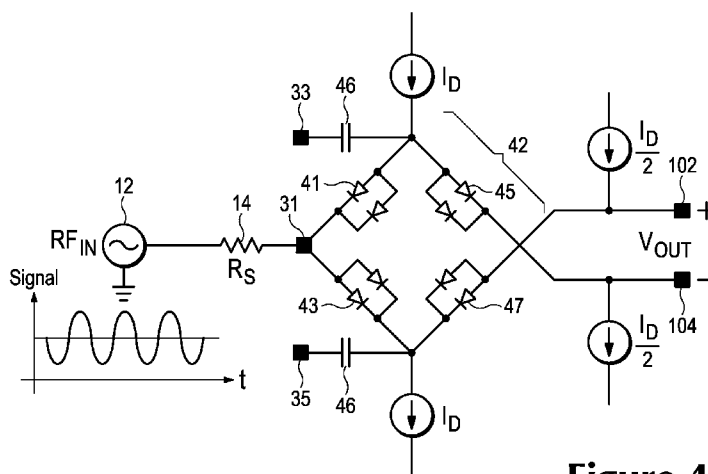
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(54) Title: MICROWAVE VOLTMETER USING FULLY-LINEARIZED DIODE DETECTOR

**Figure 4**

(57) Abstract: A radio frequency diode detector has a set of diodes having a differential voltage output, and a current source electrically coupled to the ring of diodes, the current source coupled to provide a forward bias current. This is followed by nonlinear signal processing to create an overall linear detector suitable for use in microwave power measurement.

MICROWAVE VOLTMETER USING FULLY-LINEARIZED DIODE DETECTOR

RELATED APPLICATION

This application claims priority to and the benefit of U.S. Patent Application No. 14/041,571 filed on September 30, 2013, and is incorporated herein in its entirety.

BACKGROUND

[0001] Many situations require the detection of power in microwave communication links such as point-to-point communication links for high speed data communications. These wide band communication links run at high gigahertz frequencies, typically up to 24 GHz, and incur the need to measure carrier power in both transmitters and receivers over a wide dynamic range. In fact, the determination of power is *indirect*. Practically all integrated circuit (IC) solutions used in power measurement applications actually measure the *voltage* arising across a *known load impedance*, usually, but not necessarily, 50Ω . For example, signal of amplitude 223.6 mVrms develops a power of $P = V^2/R = 0.2236^2/50 = 0.001\text{W}$. RF systems universally express power levels in milliwatts, and use the decibel equivalent expressed in dBm. The power developed by a 223.6 mVrms signal into a 50Ω load is 1 mW, which in decibel form is 0 dBm.

[0002] This power level is roughly at the center of typical ranges which need to be measured, ranging roughly from -30 dBm to +13 dBm. In voltage terms, this requires the determination of voltages spanning the range 7.07 mVrms to 1 Vrms, or about 141:1 in voltage terms and 43 dB in power terms.

[0003] In the past, RF power measurement has often employed logarithmic amplifiers (log amps) to address the dynamic range challenge. However, at microwave frequencies suitable log amps require the use of the fastest available IC processes. They are also relatively

complicated circuits, needing voltage references to establish their scaling rules, slope and intercept, and consume a great deal of supply current, typically of the order of 100mA.

[0004] On the other hand, detectors based on Schottky diodes inherently have a rapid response, and have been used for decades in power measurement applications. They are now available in many IC processes. Their appeal lies in the fact that once the RF amplitude is determined, usually referred to as the ‘envelope response,’ the remaining signal processing can be carried out at relatively low frequencies, and typically at less than 1/100-th the supply current needed for a log amp. Further, the detection response can readily extend to signal frequencies of 100GHz, roughly four times higher than the fastest available log amps.

[0005] Unfortunately, conventional diode detectors have an extremely nonlinear response. This is especially troublesome at small signal amplitudes: their output at low levels follows a roughly square-law characteristic, and consequently they are very insensitive to small signals. As usually implemented they also have inherently poor temperature behavior, which erodes accuracy. These limitations are overcome by the measures described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] Figure 1 shows a prior embodiment of a radio frequency (RF) diode detector.

[0007] Figure 2 shows a graph of a prior art detector response.

[0008] Figure 3 shows a typical embodiment of an RF detection system.

[0009] Figure 4 shows a typical embodiment of an RF diode detector.

[0010] Figure 5 shows an embodiment of a portion of an RF detector.

[0011] Figure 6 shows an embodiment of a nonlinear function circuit.

[0012] Figure 7 shows a more detailed embodiment of a nonlinear function circuit.

[0013] Figure 8 shows an example of the improved detector’s amplitude response.

[0014] Figure 9 shows an embodiment of a converter circuit for an output of a RF diode detector.

DETAILED DESCRIPTION

[0015] Figure 1 shows a prior art embodiment of a radio frequency (RF) power detector. Here, the RF generator 12 generates the signal power whose amplitude the detector must measure; the resistor 14 represents the source resistance of this generator. The diode 16 may consist of a Schottky diode having a metal to semiconductor interface, rather than a semiconductor to semiconductor interface as in traditional diode. A load capacitor 18 and load resistor 19 connect the output of the diode 16 to ground. The polarity direction of the diode is not of operational significance, but we show here the RF signal applied to the anode of the diode, with the output taken from the cathode.

[0016] In a simple analysis, it is stated that when the load capacitor 18 becomes fully charged, no current flows in the diode and the circuit therefore becomes a 'peak detector.' In practice this state of affairs is substantially altered by the presence of the load resistor 19, which discharges the capacitor between the peak instants of the signal, to a greater or lesser degree. There is a finite average current in the diode, causing the output voltage to be less than the peak voltage of the RF input. Because of the diode's voltage/current behavior, even small amounts of average current introduce a very significant voltage drop. This reduction in response becomes very pronounced at even moderate signal levels, and profound so at millivolt-level RF inputs.

[0017] This simple type of detector suffers from other problems in measurement applications, one of which is its extreme variation in scaling accuracy over its operating temperature range. Figure 2 shows an example of the amplitude response for this type of detector, demonstrating the loss of sensitivity at lower powers. The response curve 22 demonstrates the response at

moderate temperatures. At low temperatures, the response would follow the curve 24, while at higher temperatures, it would appear more like curve 26.

[0018] This variation across the operating temperature range raises a serious problem with this simple detector embodiment. A further problem arises because the input impedance of such a detector is also nonlinear, and is prone to generating even-order harmonic signals which are reflected back into the source. A practical transmitter or receiver channel is very susceptible to such distortion components. It should be noted here that modern systems have to meet extremely stringent specifications in this regard, and therefore it is evident that a detector that does not generate such distortion would be valuable.

[0019] Figure 3 shows an embodiment of an RF detection system. The detector 40 provides input to a nonlinear function circuit 60. The elaborated system may optionally include a post-detection RMS (root mean square) module 80 and a logarithmic amplifier (log amp) 100. The RMS module converts a fluctuating output of the detector to a steady state signal more closely representing the signal power, and the optional log amp module may then convert this to a decibel representation. These modules may be used or not depending on the overall requirements of the measurement system.

[0020] Figure 4 shows an embodiment of an improved diode detector having a high dynamic range and stable operation over temperature. The RF source 12 and its source resistance 14 are connected to a set of diodes 42, which, even in the absence of an applied signal, are held in conduction by the small bias current I_D . In this way, the diodes are already operating in forward bias when the applied RF voltage is small, avoiding the insensitivity at the lower levels. The current flows through diode 41 to diode 43, and simultaneously through diode 45 and 47. Two charge-holding load capacitors 46 and 47 are now used, one following positive

signal excursions and the other following negative signal excursions. These connect to circuit nodes 33 or 35, physically placed close to the input node 31 making a very short RF path.

[0021] Due to the use of equal bias currents, there is no net DC voltage developed across the source resistance at the input node, which is at ground or zero potential. Also, in the absence of an RF input, the output of diode 41 is likewise returned the ground potential, due to the matching of the equally sized diodes, having the same saturation current, herein denoted by I_S , as is familiar in semiconductor device theory. With the application of an RF signal, the voltage on the load node 33 increases in a positive direction with increases in the signal amplitude, and the voltage on the output node 102 follows this increase, starting from a zero-input baseline of zero. Similarly, with the application of an RF signal, the voltage on the load node 35 increases in a negative direction with increases in the signal amplitude, and the voltage on the output node 104 follows this voltage, again starting from a zero-input baseline of zero.

[0022] This circuit develops two voltage outputs, which, for large signal inputs essentially follow the positive and negative peaks of the applied RF signal. This provides a voltage-doubling response, without the voltage-drops normally encountered in a simple diode detector.

[0023] Further, due to the symmetry of the Figure 4 circuit, the input impedance is much more linear than in prior art embodiments. In the prior art embodiments, when current flows only during on signal polarity, even-order distortion components are reflected back into the source. In this embodiment, only weak odd-order reflections occurs. Typically the source would consist of power amplifier whose output drives an antenna, but a small sample of which is delivered to the detector by the directional coupler. With the asymmetric half-wave rectifier of the prior art, even-order distortion components may couple back to the antenna

and negatively impact the transmitted signal. Similar problems arise in a receiver channel.

Odd-order distortion is generally more tolerable in this context.

[0024] In a practical embodiment, the diodes are ‘doubled-up’, using eight equally-sized devices, as shown. This is a layout measure taken to mitigate the offset-inducing effects of various chip gradients, such as temperature, strain, etc., and merely one embodiment, which may not be necessary or desirable, depending on the practical circumstances.

[0025] The circuit topology of Figure 4, with the pre-biasing currents I_D to improve the detector response in the several ways just described. But the detector still responds in an essentially square-law manner to small signal amplitudes, becoming progressively more linear at higher input levels. Referring back to Figure 3, the nonlinear function circuit 50 may allow the response to be linearized.

[0026] Figure 5 shows a portion of the system of Figure 3, focusing on the relationship between the detector and the nonlinear function circuit 60. An appropriate example of a nonlinear function circuit would be a ‘square rooting’ circuit that produces an output that is the square root of the input. In Figure 5, the outputs of the detector from Figure 4 are first buffered. The output voltages of the detector are very small at the low end of the input amplitude range. For example, at an input of -35 dBm re. 50Ω, the signal amplitude for a sine wave input is only 4 mV, and the corresponding output voltage of the detector cell will be in the microvolt range.

[0027] It is important that the bias currents I_D be very well matched. It will further be apparent that the loading of the outputs of this detector may be only very lightly loaded. This is the function of the buffer amplifier stages 51 and 53 in Figure 5. These need not be unity-gain buffers, although, in view of the typically small supply voltage of a practical IC and the voltage doubling property of the detector, this may be the preferred choice.

[0028] The buffered outputs are applied to the nonlinear function circuit 60, which is arranged to have the inverse amplitude response of the detector at low signal levels, which as we have seen is square-law. The appropriate nonlinear function is the square-root function. In theory, this function has infinite incremental gain at zero input. In practice, its implementation requires the provision of very high increment gain for small inputs.

[0029] It has been explained that while diode detectors exhibit a very weak response to small input signals, this becomes asymptotic to a peak-detection, linear, function at high input levels. One of the requirements of a fully-linearized RF voltmeter, which is a more accurate description of the function of integrated-circuit “power” detectors, is that the square-root function must be gradually “softened” or weakened at high signal levels. A practical implementation requires very careful characterization of the basic detector cell of Figure 4 to ensure an accurate overall fit to a fully-linear response. Further, the scaling of the square-rooting cell must be arranged to have the necessary temperature behavior.

[0030] The signal out from the detector, shown in Figure 4 as V_{OUT} becomes V_{IN} to the nonlinear function circuit 60. This signal is also fed forward to the linear amplifier 55. The nonlinear function circuit 60 injects a current I_{OUT} into the path of the linear amplifier at the node where it connects to the input of the linear amplifier. Because there is a finite resistance at that node, the injected current causes the single-line output to be positive, where the output value can be viewed as flowing in the direction shown. Because the output current is the square root of the input voltage, eventually the nonlinear function circuit will ‘turn off’ or have no further effect on the output signal. The end result is that the output of the linear amplifier results from the nonlinear function circuit at low signal levels, and results from the detector response at the higher signal levels where the detector response becomes linear.

[0031] Figure 6 shows one embodiment of the nonlinear function circuit 60, in this instance a square root circuit. The current I_1 is connected to the transistor 54, Q2. The reference current I_R is connected to the transistor 52, Q1. The unknown current value I_Z is the one of interest and is connected to transistor 56, Q3, and through it to the transistor 58, Q4. The relationships are as follows:

$$V_{BE1} + V_{BER} \equiv V_{BEZ} + V_{BEZ},$$

this leads to:

$$V_K \text{Log} (I_1/I_S) + V_K \text{Log} (I_R/I_S) \equiv V_K \text{Log} (I_Z/I_S) + V_K \text{Log} (I_Z/I_S);$$

where V_K is the thermal voltage of the transistors.

The thermal voltages cancel as do the source currents I_S . Using the rules of logarithms, the sum of $\text{Log } I_1$ and $\text{Log } I_R$ results in $\text{Log } I_1 I_R$ being equivalent to $\text{Log } I_Z I_Z$. The logs cancel and the result is that I_Z equals the square root of $I_1 I_R$. This principle is what produces the inverse function of the detector. One should note that an emitter follower 63 connects to transistor 65 in a ‘tail chaser’ configuration for stability.

[0032] Figure 7 shows a more detailed embodiment of a nonlinear function circuit 60. The current upon which the nonlinear function circuit acts is a current proportional to the V_{IN} of Figure 5. This current is I_{IN} for purposes of this discussion, but was earlier referred to as I_{OUT} IN Figure 5. The reference current I_R scales the whole function. The reference current comes from a reference generator that can be set with the desired scale factor. The amplifier 62 ensures that the voltage of the transistor 64 is sufficient to absorb the current I_{IN} , and controls the reference point of the collector of the transistor 64. Similarly, the amplifier 66 controls the reference point of the collector of the transistor 68.

[0033] The summing node (NODE) of the output amplifier of Figure 5 has a voltage that is lower in voltage than the collector of transistor 70 can tolerate. One embodiment to rectify

this situation replicates the current in transistor 72 to transistor 74. Transistor 74 has a load resistor that takes the output (OUTPUT) almost to ground, and the NODE is set to a fixed voltage. One should note that the ground lines from resistor 78, the transistor 64 and transistor 72 are typically tied together. This avoids any variation on the ground lines, in which even a millivolt variation can have negative effects on the operation of the circuit. The resistor causes the output to behave in a 'translinear' way, in which it functions as a square root or other nonlinear function until the output of the linear path dominates the output of the circuit.

[0034] A translinear circuit is a circuit that functions under the translinear principle. The translinear principle states that in a closed loop containing an even number of translinear elements with an equal number of them arranged clockwise and counter-clockwise, the product of the currents through the clockwise elements equals the product of the currents through the counter-clockwise elements. In Figure 7, the translinear loop is formed within the transistors 68, 74, 72, and 65. Under the translinear principle, similar to the discussion of Figure 6, the product of the currents $I_W I_W$ in the clockwise loop equals the products of $I_{IN} I_R$. The result is that I_W equals the square root of $I_{IN} I_R$. I_W as the output current is then equal to $(A_1/A_2) I_W$.

[0035] Figure 8 shows a curve of a typical detector response. The detector response has a first region 67 often referred to as the 'square law' region, which is exponential in nature. The second region 69 is a linear region. A translinear circuit often operates to linearize the square law region of the response, and then letting the response remain linear in the linear region. The embodiments of the diode RF detector here employ this principle.

[0036] As mentioned previously, the nonlinear function circuit operates on the input current I_{IN} that is proportional to the output voltage of the detector. Figure 9 shows an embodiment

of a circuit that takes the output voltage and generates the proportional current. The circuit in this embodiment consists of a degenerated pair of transistors 82 and 84 having bias currents I_E . They connect to the differential output voltages from the amplifiers 51 and 53 from Figure 5. The voltage swing could have a wide dynamic range from 3.2 V (+15 dBm) to the millivolt range. The pair is connected to a current mirror 90 with some adjustments for offsets at OFFSET, allowing an adjustment at the bottom end of the range to ensure proper function of the circuit at the bottom of the range.

[0037] One should note that the pair of transistors 82 and 84 will more than likely not match perfectly, so they may be connected in a ‘cross-quad’ manner using transistors 86 and 88 to ensure stability of the transistors. Similarly, other transistors in the other figures and embodiments may also have cross-quad transistors, but were not show for simplicity. However, no limitation to using or not using cross-quad transistors is intended nor should any be implied.

[0038] In this manner, an RF power detector using diode detectors is created. It has high dynamic range, even at very high bandwidths in the hundreds of Gigahertz range, good temperature behavior and high sensitivity. Different embodiments and implementations of specific components of the embodiments are shown here and any and all variations of these components and their configurations may be used in any and all of the different embodiments.

[0039] The embodiments described herein can be modified in arrangement and detail without departing from the inventive concepts. For example, some of the principles have been described above in the context of a radio frequency power detector using diodes. Nonetheless, the principles also have utility separately, and in other applications. Many numerical examples have been provided to facilitate explanation of the inventive principles,

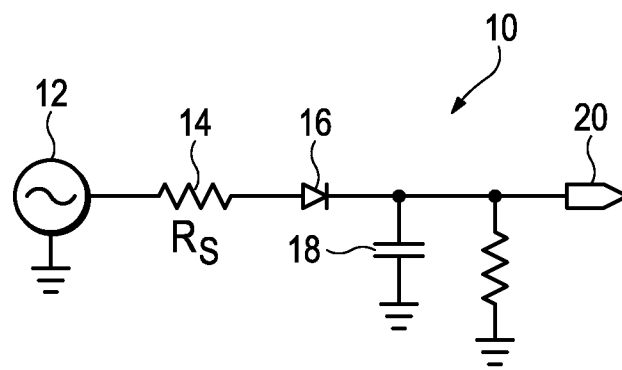
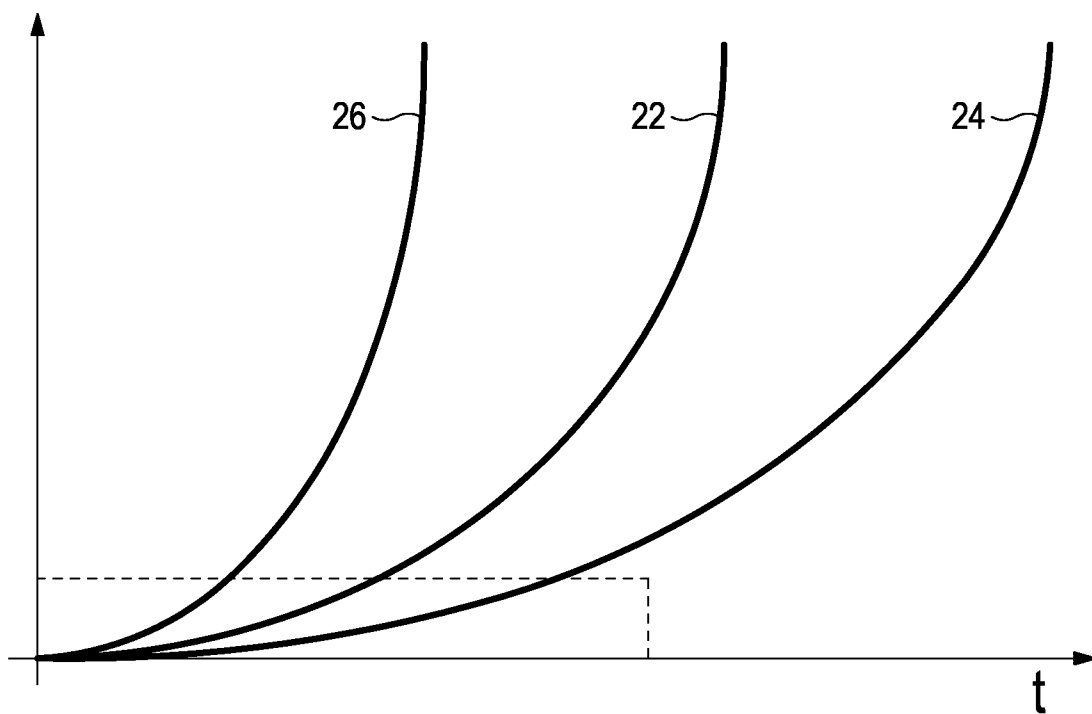
but the inventive principles are not limited to any such specific examples. Accordingly, such changes and modifications are considered to fall within the scope of the following claims.

CLAIMS

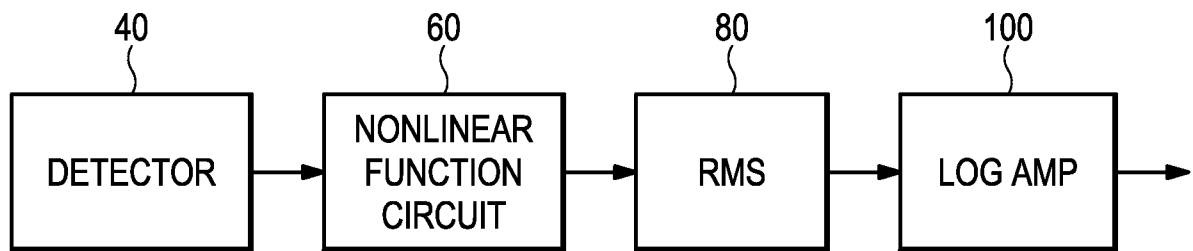
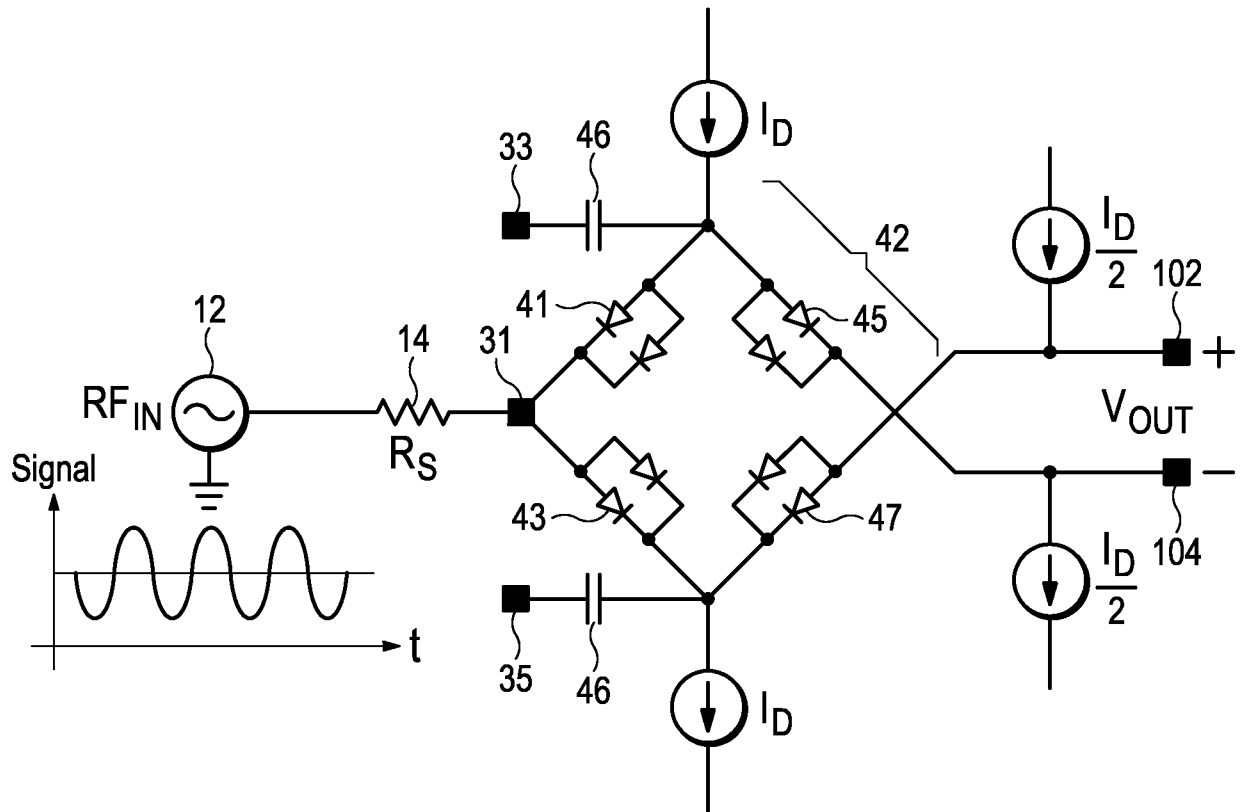
1. A radio frequency diode detector, comprising:
a set of diodes having a differential voltage output; and
a current source electrically coupled to the set of diodes, arranged to provide a forward bias current.
2. The diode detector of claim 1, wherein the set of diodes comprises offset pairs of diodes.
3. The diode detector of claim 1, wherein the diode detector includes a capacitor electrically coupled to the current source.
4. The diode detector of claim 1, wherein the set of diodes comprises a duplicate diode for each diode in the set.
5. The diode detector of claim 1, further comprising a converter circuit connected to the differential output, the converter circuit to convert differential voltage output to a current.
6. The diode detector of claim 1, the diode detector being package into a microwave package.
7. A radio frequency power detection system, comprising:
a radio frequency diode detector comprising a set of diodes having a differential voltage output electrically coupled to an incoming radio frequency signal; and
a nonlinear function circuit electrically coupled to the differential voltage output, the nonlinear function circuit to produce an output signal.
8. The radio frequency power detection system of claim 7, further comprising an RMS (root-mean-square) module electrically coupled to the output of the nonlinear function circuit, the RMS module to produce an RMS output signal.
9. The radio frequency power detection system of claim 8.

10. The radio frequency power detection system of claim 8, further comprising a logarithmic amplifier coupled to the RMS module to receive the RMS output signal.
11. The radio frequency power detection system of claim 10.
12. The radio frequency power detection system of claim 6, wherein the radio frequency diode detector comprises a current source electrically coupled to the ring of diodes to pre-bias the ring of diodes.
13. The radio frequency power detection system of claim 6, further comprising a converter circuit electrically coupled between the output of the radio frequency diode detector and the nonlinear function circuit.

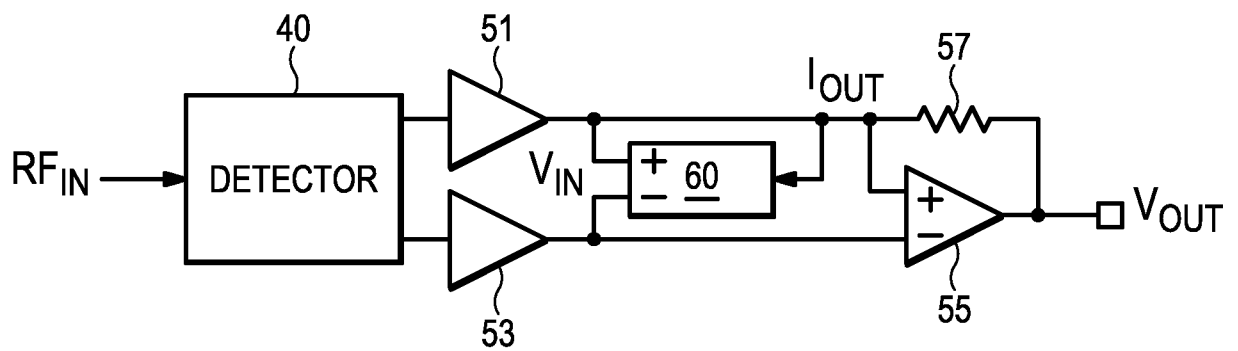
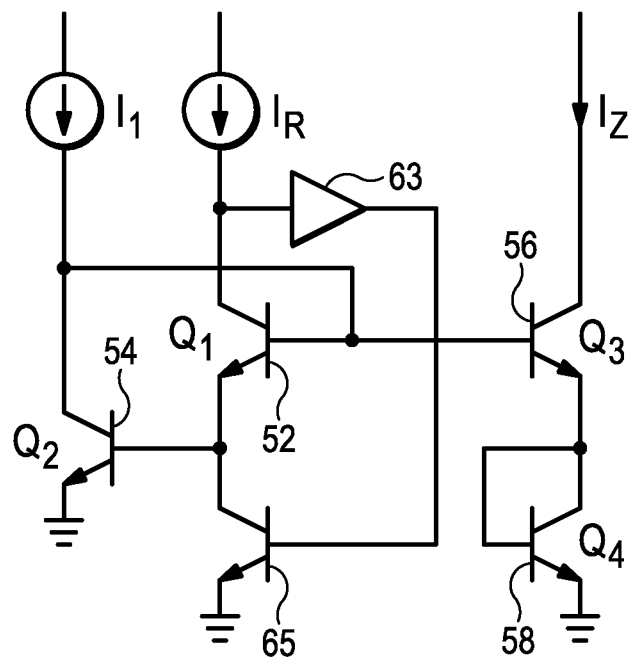
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**Figure 1****Figure 2**

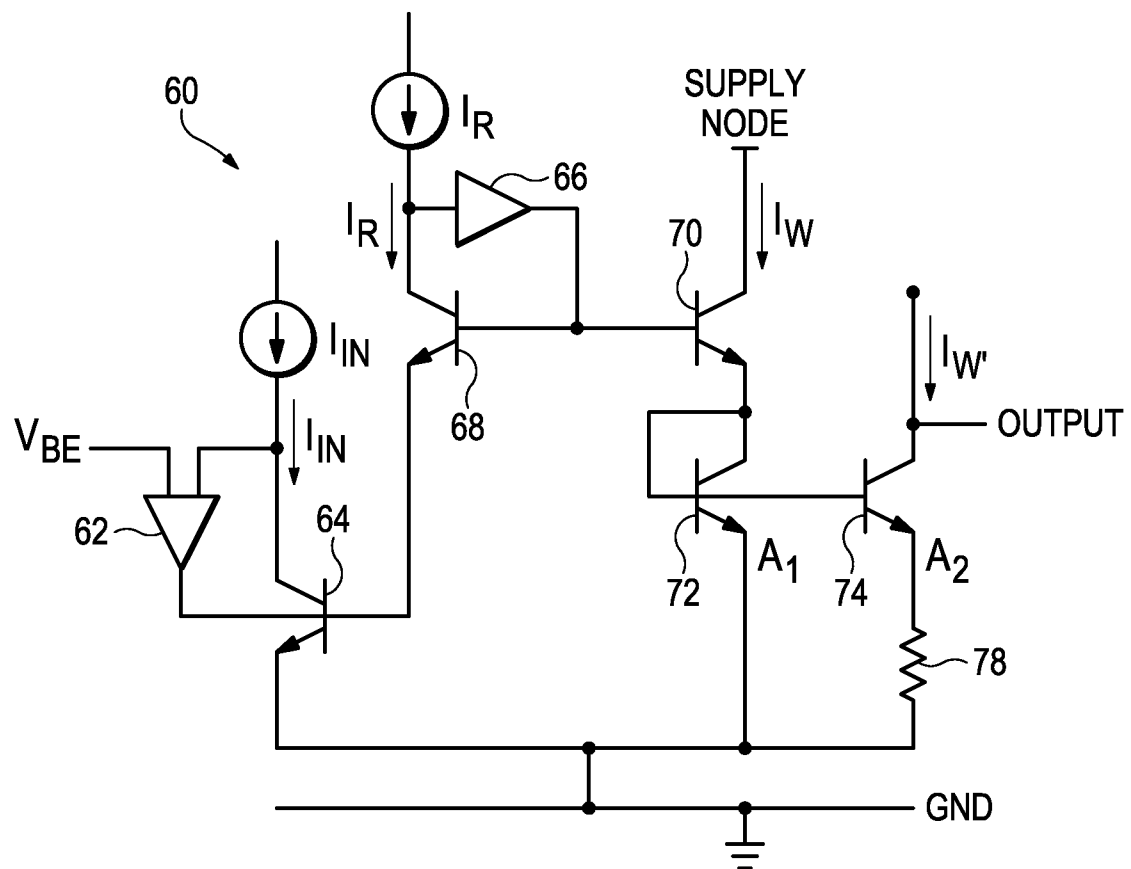
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**Figure 3****Figure 4**

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**Figure 5****Figure 6**

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**Figure 7**

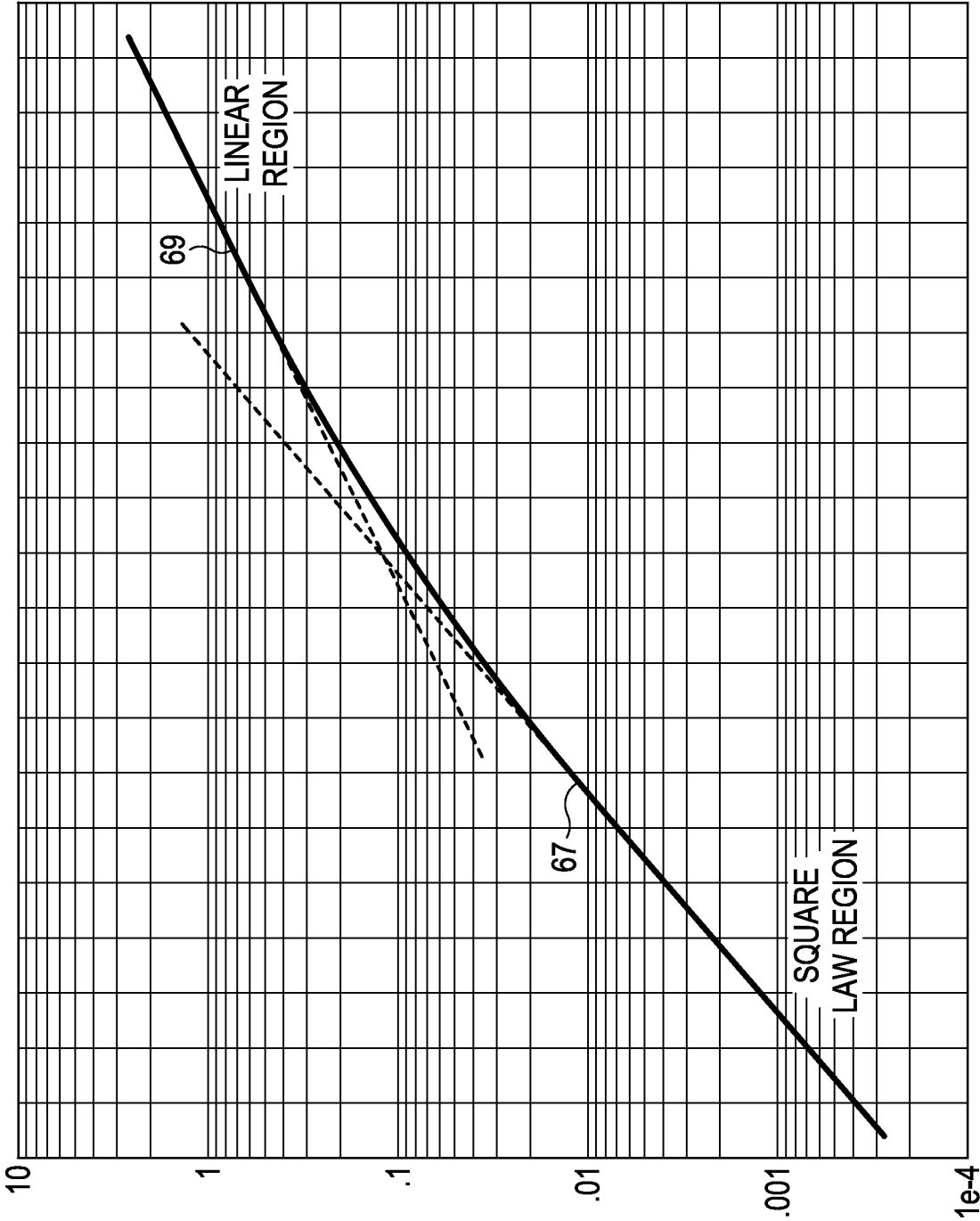
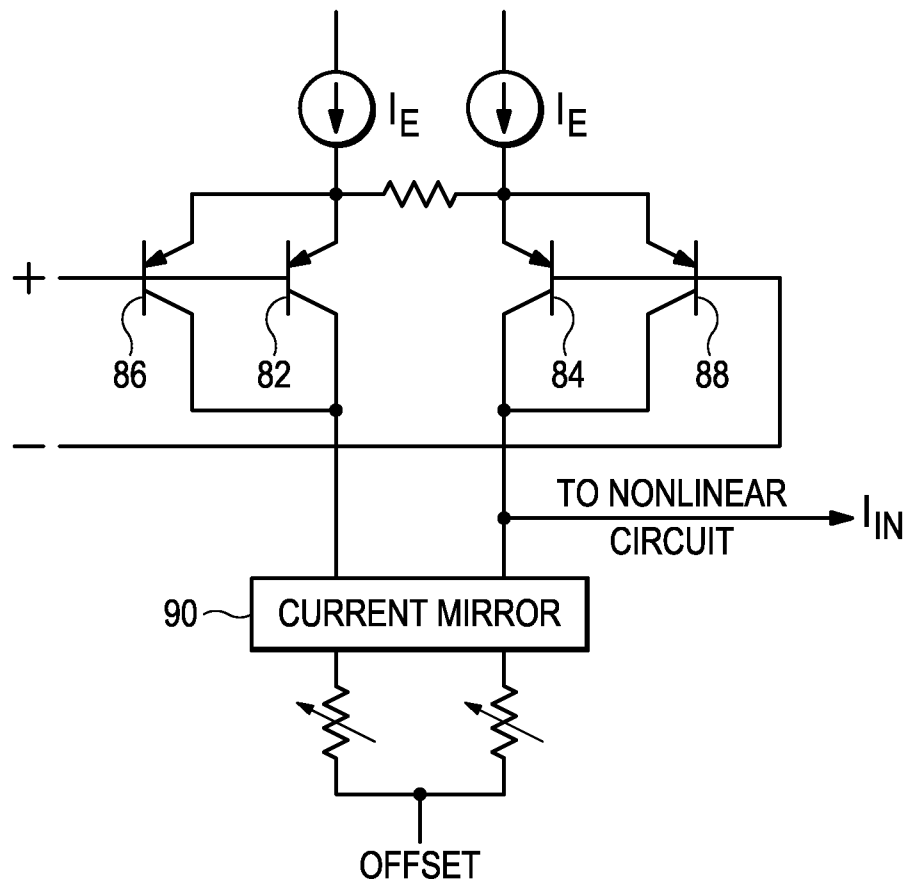


Figure 8

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**Figure 9**

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 14/58046

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - H03D 5/00 (2014.01)

CPC - H03D 5/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8)-H03D 5/00 (2014.01); CPC-H03D 5/00; USPC-329/317Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8)-H03D1/00, H03D3/00 (2014.01); CPC-G01R15/005, G01R29/0871, G01R21/10; USPC-329/328,330,334,347,352,366,370Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Patents/Scholar: terms-RF radio power detector set plurality network group diodes differential output voltage current source forward bias nonlinear function circuit log amplifier

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2004/0217807 A1 (Andle) 04 November 2004 (04.11.2004), Abstract; para [0031]-[0032]; fig. 4.	1-13
A	US 2004/0242170 A1 (Gilbert) 02 December 2004 (02.12.2004), Abstract; para [0045]; fig. 5.	1-13
A	US 2009/0021282 A1 (Matsui) 22 January 2009 (22.01.2009), Abstract; para [0052].	1-13
A	US 2006/0012422 A1 (Saito) 19 January 2006 (19.01.2006), Abstract.	1-13
A	US 6,678,506 B1 (Dolman et al.) 13 January 2004 (13.01.2004), Abstract.	1-13
A	US 2003/0035451 A1 (Ishida et al.) 20 February 2003 (20.02.2003), Abstract.	1-6
A	US 6,429,638 B1 (Wight et al.) 06 August 2002 (06.08.2002), Abstract.	1-13

☐ Further documents are listed in the continuation of Box C.

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"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search

03 December 2014 (03.12.2014).

Date of mailing of the international search report

02 JAN 2015

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