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(54) SQUARE LAW EXTENSION TECHNIQUE FOR HIGH SPEED RADIO DETECTION

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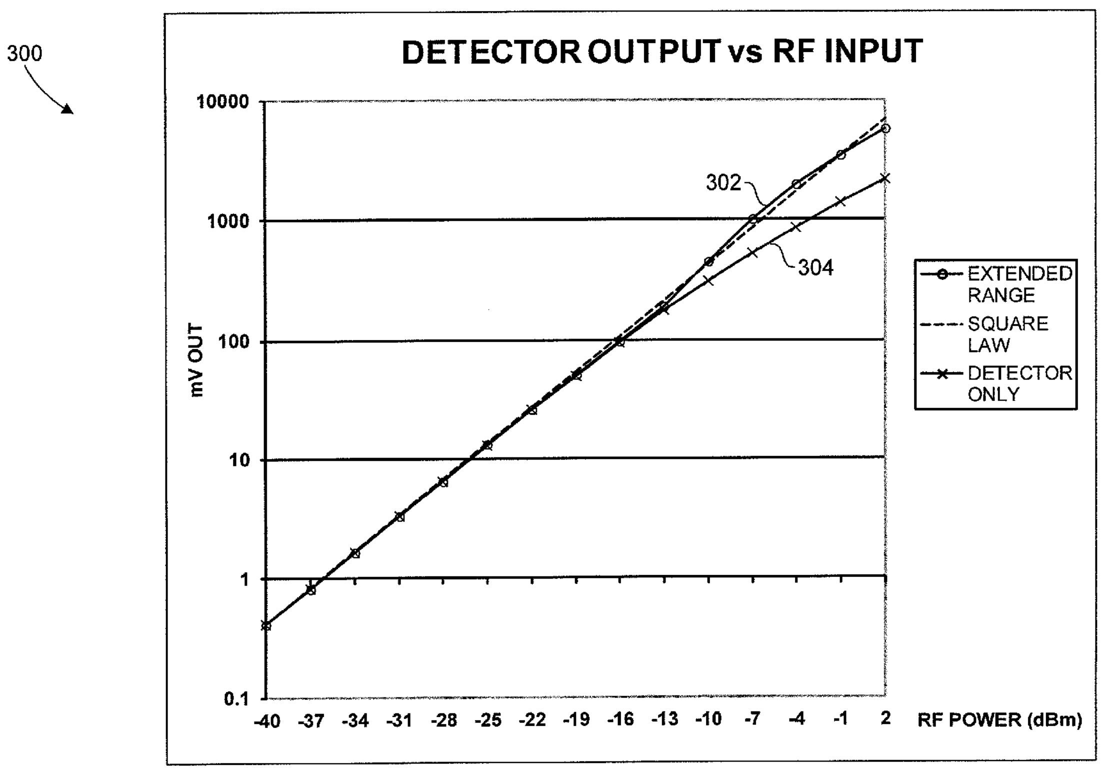
(57) **ABSTRACT**

A square law extension circuit is disclosed that operates over a range of frequencies and power levels. The square law extension circuit includes a detector, an amplifier, and an expander. The detector has an input for receiving radio frequency (RF) signals and providing a detected signal output. The amplifier has an input that receives the detected signal output of the detector and provides an output for an amplified detected signal. The expander has an input that receives the amplified detected signal and is arranged to provide an expanded signal output. The expanded signal output is a signal that increases in a first proportion to the amplified detected signal up to a predetermined threshold and increases at a second proportion to the amplified detected signal that is more than the first proportion when the expanded signal output exceeds the predetermined threshold.



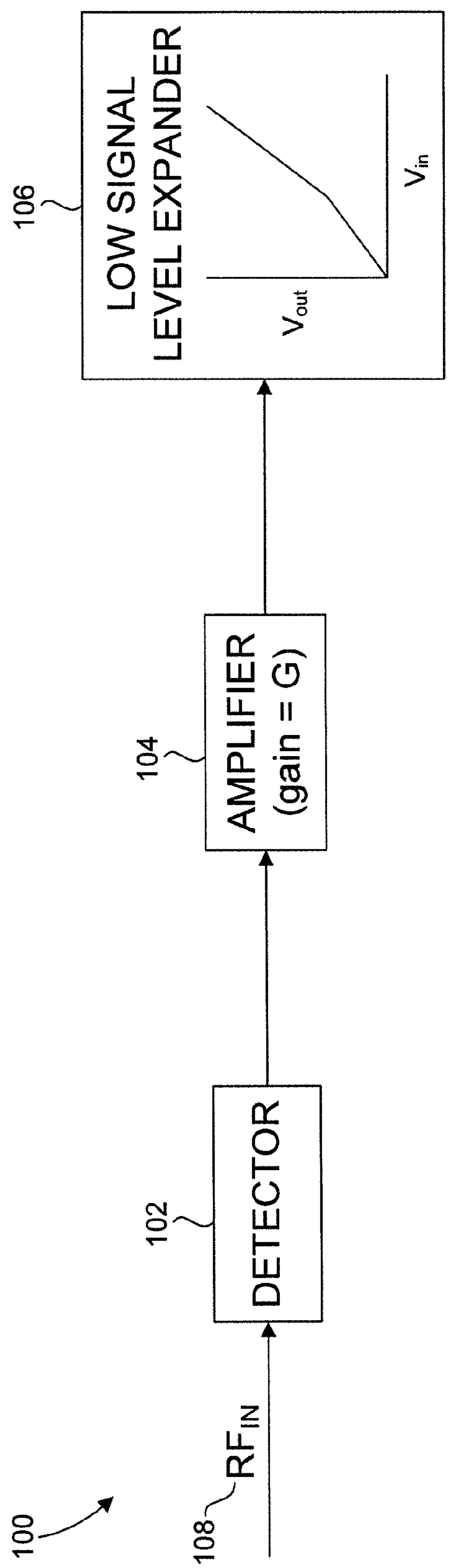

106
LOW SIGNAL
LEVEL EXPANDER
V_{out}
V_{in}
104
AMPLIFIER
(gain = G)
102
DETECTOR
RF_{IN}
108
100

FIG. 1

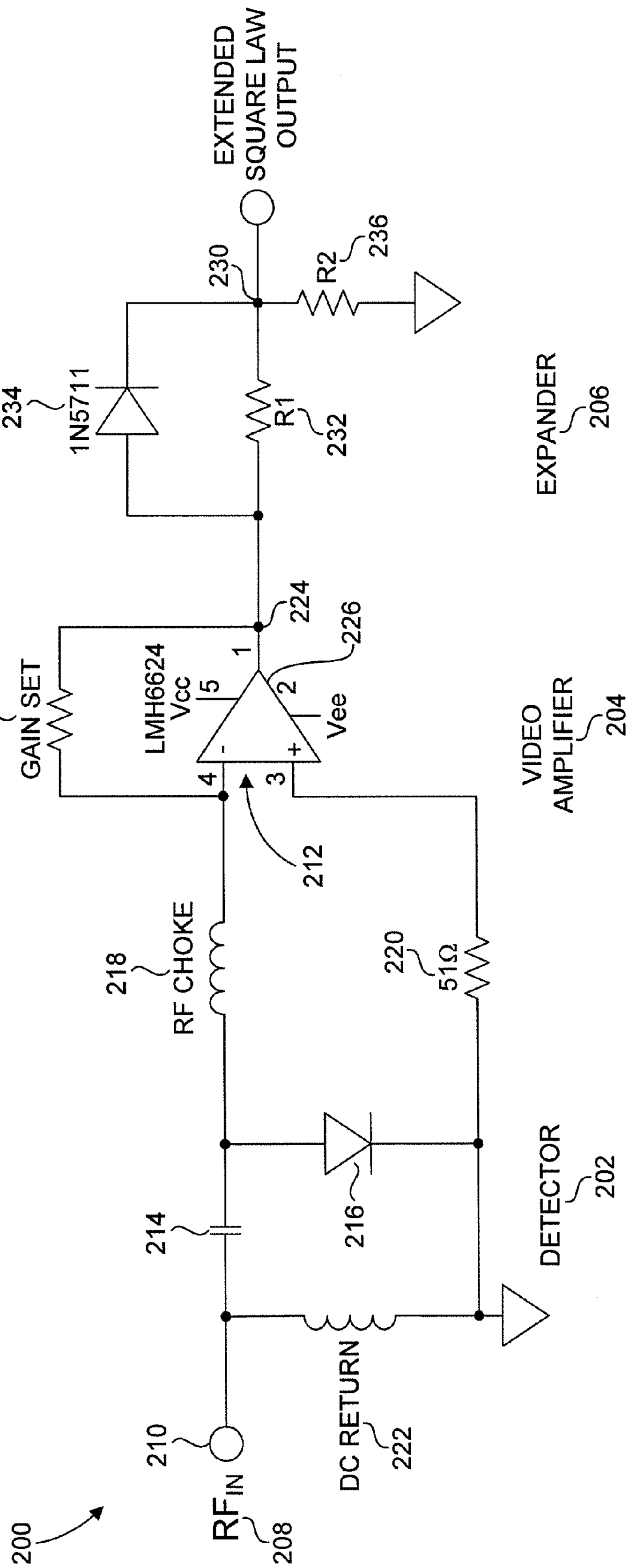

EXTENDED SQUARE LAW OUTPUT
230
R2
236
234
1N5711
R1
232
EXPANDER
206
224
226
LMH6624
Vcc
Vee
1
2
3
4
5
228
GAIN SET
VIDEO AMPLIFIER
204
212
218
RF CHOKE
220
51Ω
216
214
DETECTOR
202
DC RETURN
222
210
RF$_{IN}$
208
200

FIG. 2

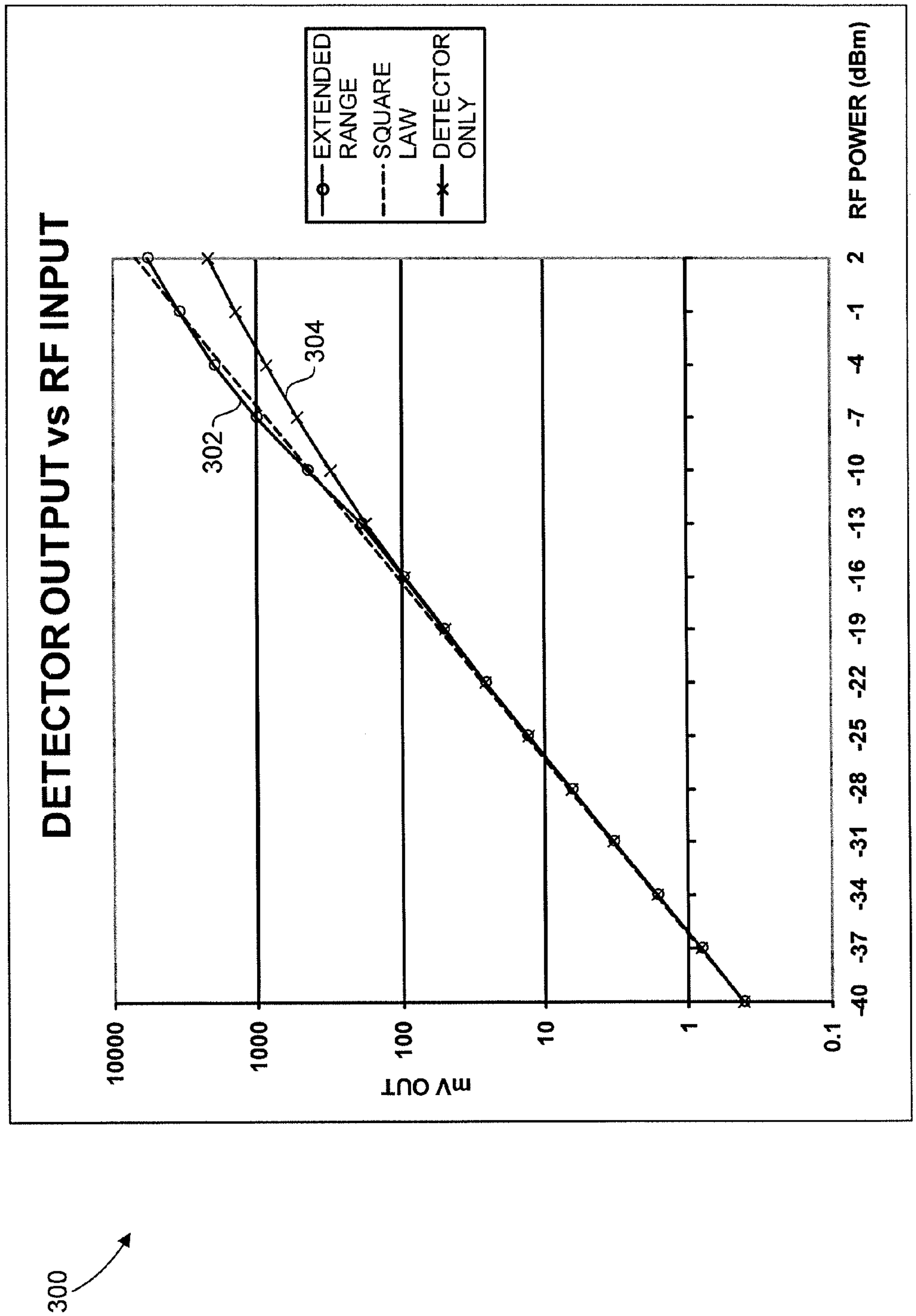

300
DETECTOR OUTPUT vs RF INPUT
mV OUT
10000
1000
100
10
1
0.1
-40
-37
-34
-31
-28
-25
-22
-19
-16
-13
-10
-7
-4
-1
2
RF POWER (dBm)
302
304
EXTENDED RANGE
SQUARE LAW
DETECTOR ONLY

FIG. 3

SQUARE LAW EXTENSION TECHNIQUE FOR HIGH SPEED RADIO DETECTION

CROSS REFERENCE TO RELATED APPLICATIONS

[0001] This application claims the benefit of commonly-owned copending U.S. provisional patent application Ser. No. 61/641,213, filed May 1, 2012, herein incorporated by reference.

FIELD OF THE INVENTION

[0002] This disclosure relates to radio signal power detection. More specifically, the disclosure relates to the accurate measurement of instantaneous power in high density signal environments to recover lower power signals.

BACKGROUND OF THE INVENTION

[0003] Square law detection is commonly employed to accurately measure the instantaneous power level of environments with multiple radio frequency (RF) signals. Conventional radio signal detection circuits are used to detect these RF signals and have small signal semiconductor diodes to demodulate amplitude-modulated and pulse-modulated RF signals in such multiple signal environments. However, the ability to measure two or more signals at widely different power levels in a multiple signal environment is limited. The ability to measure two or more signals at different power levels is also known as the instantaneous dynamic range of square law detection circuits. The absolute dynamic range of this process is limited by thermal noise at low power levels and breakdown at high power levels. The behavior of the ability to accurately measure two or more signals at widely different power levels changes considerably between these ultimate limits.

[0004] At low signal power levels, diode detectors demonstrate a "square-law" conversion in which the change in the detected output voltage is proportional to the change in RF input signal power of the detection circuit. The behavior of the signal at low power levels is generally referred to as the "square law" region. At high signal power levels, diode detectors demonstrate behavior consistent with rectification in which the change in the detected output voltage is proportional to the change in RF input signal voltage of the detection circuit. The rectification behavior is generally referred to as the "linear" or "linear-law" region. The change in the behavior of the ability to measure two or more signals at different power levels causes distortion in the detected output if the detector circuit is operated in the transition between the square law and linear law region or is operated across both regions.

[0005] Many of the known detector circuits combine a detector and an amplifier to enhance the linear region of the circuit and are used to recover information from amplitude modulated RF signals. These linear extension circuits enhance the operation of the circuit over a range of temperature and input signal levels and are described in U.S. Pat. No. 4,490,681 to Turner, U.S. Pat. No. 4,502,015 to Nicolas, et al., U.S. Pat. No. 5,873,029 to Grondahl, et al., among other references. Some square law extension circuits are known, such as U.S. Pat. No. 3,241,079 to Snell, but these techniques do not address increasing the ability to accurately measure low level signals in the presence of large signals in a high density or multiple signal environment. Such known square law extension circuits cannot accurately detect low level signals when a large signal biases the parallel set of diodes in the linear region of the signal.

[0006] Improved methods of correcting the distortion of high modulation rate signals in multiple signal environments using analog techniques would be desired in the art.

SUMMARY OF THE INVENTION

[0007] An object of this invention is to provide methods and device structures suitable for accurately measuring instantaneous power in high density signal environments to facilitate the recovery of lower power signals that may otherwise be suppressed as the detector circuit enters the linear region from the square law region of the detector circuit's output. High density signal environments include multiple signals that can range over a wide range of power levels.

[0008] The foregoing and other objects, features and advantages of the invention will become more readily apparent from the following detailed description of embodiments of the invention which proceeds with reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] FIG. **1** is a block diagram that corresponds to elements of a square law extension circuit, according to embodiments of the disclosure.

[0010] FIG. **2** is a schematic of an example square law extension circuit in accordance with aspects of the disclosure.

[0011] FIG. **3** is a graphical representation of an output versus the RF input signal for corrected and uncorrected detector circuits, according to aspects of the disclosure.

DETAILED DESCRIPTION

[0012] In the drawings, which are not necessarily to scale, like or corresponding elements of the disclosed systems and methods are denoted by the same reference numerals.

[0013] Accurate analog measurement of instantaneous power in high density signal environments facilitates the recovery of lower power signals, specifically lower power pulsed signals for example, that would otherwise be suppressed as the detected signals enter the linear region from the square law region. A block diagram of a square law extension circuit **100** is shown in FIG. **1**, which includes a detector **102** that is coupled to an amplifier **104**. The output of the amplifier **104** is fed to a voltage dependent attenuator or expander **106** that expands the gain of the amplifier **104** coincidentally with the signal compression that occurs as the detector **102** transitions from a square law region into a linear law or rectification region. The detector **102** includes any conventional detector circuit and detects voltages of incoming RF signals **108** in a multiple signal environment in which the input power signal levels can span multiple orders of magnitude. The detector **102** is coupled to the amplifier **104** by a direct connection in the example shown in FIG. **1**. The amplifier **104** may be a high-speed, low-noise DC-coupled amplifier or any other suitable amplifier.

[0014] The expander **106** shown in FIG. **1** is a low signal level expander that can be depicted by a graph representing the output signal voltage (V_{out}) versus the input voltage (V_{in}). The V_{out} increases proportionately to the V_{in} of the expander while the detector signal's power level is relatively low and thus in the square law region. When the signal's power level becomes relatively high and thus transitions from the square law region to the linear region, the V_{out} slope gradually increases to approximate a continued square law transfer function. In some example square law extension circuits, an additional 20 decibels (dBm) of square law operation may be realized.

[0015] The square law extension circuit **100** shown in FIG. **1** operates over a wide range of frequencies and power levels, e.g., multiple orders of magnitude. The detector **102** of the square law extension circuit **100** has an input for receiving RF signals **108** in the multiple signal environment. The detector **102** then provides a detected signal output, which can be in part or entirely based on the received RF signal **108**. The amplifier **104** shown in FIG. **1** can be, for example, a video amplifier or another suitable amplifier that has an input that receives the detected signal output from the detector **102** and provides an output for an amplified detected signal. The amplified detected signal can be based at least in part on an amplification of the detected signal output. The expander **106** shown in FIG. **1** has an input that receives the amplified detected signal from the video amplifier **104** and is arranged to provide an expanded signal output that can be based at least in part on the received amplified detected signal. The expanded signal output is a signal that increases in a first proportion to the amplified detected signal up to a predetermined threshold and increases at a second proportion to the amplified detected signal when the expanded signal output exceeds the predetermined threshold. The second proportion is greater than the first proportion in some examples. The first proportion can indicate or track square law behavior of the expanded signal output and, above the threshold, the second proportion corrects for a deviation from square law behavior of the expanded signal output. The expanded signal output may increase linearly with respect to the detected signal output up to the predetermined threshold. The predetermined threshold may be any suitable threshold and will be discussed in greater detail below in reference to FIG. **2**.

[0016] FIG. **2** is a schematic of specific example of a square law extension circuit. This exemplary square law extension circuit **200** includes a detector **202**, a video amplifier **204**, and an expander **206**. In some embodiments, the RF signals **208** applied to the detector **202** operate in a frequency range between 1 mega Hertz (MHz) and 100 giga Hertz (GHz) with appropriate component values, although the frequency range may be expanded or narrowed as desired. The detected signal output of the detector **202** may include a power range that is at least 2 orders of magnitude, for example. The expanded output power associated with the expanded signal output extends over a range of at least 4 orders of magnitude in some examples and again this range can be expanded or narrowed as desired by selecting components of particular values in the square law extension circuit **200**.

[0017] The predetermined threshold described above in reference to FIG. **1** may be associated with an expanded signal output having a voltage of approximately 0.4 volts (V), although this value may be varied, depending on the values of the selected components shown in the schematic of the square law extension circuit **200** in FIG. **2**. In this example, the expander **206** caps the signal levels when the voltage of the expanded signal output reaches approximately 0.4V, or any other set threshold value.

[0018] The square law extension circuit **200** shown in FIG. **2** includes a detector **202**, a video amplifier **204**, and an expander **206**, as discussed above. The detector **202** has an input **210** for receiving the RF signals **208** and provides an output **212**, which is the input to the amplifier **204**. The detector **202** in this example square law extension circuit **200** includes a capacitor **214**, a detector diode **216**, an RF choke **218**, and a 51Ω resistor **220**, as shown in FIG. **2**. The capacitor **214** and the RF choke **218** are electrically connected in series with each other while the detector diode **216** and a DC return inductor **222** are in parallel with each other. The resistor **220** is electrically coupled in parallel with the RF choke **218** in this example. The detector diode **216** may be a Schottky diode, a tunnel diode, or any other suitable diode. An example detector diode **216** may be the 1N5711 diode manufactured by Microsemi®.

[0019] The output of the detector is the RF signal output **212** and is a voltage that is then input into the video amplifier **204**. The video amplifier **204** provides an output **224** for an amplified detected RF signal. As shown in the example square law detection circuit **200** in FIG. **2**, the amplifier **204** may include an operational amplifier **226**, such as the LMH6624 amplifier manufactured by National®, and a gain set resistor **228** electrically coupled in parallel to each other. The gain set resistor **228** allows for the gain of the amplifier **204** to be varied in a conventional manner. In general, the gain is selected to boost the lowest power input signals for easy detection. An example gain is G=10.

[0020] The expander **206** shown in FIG. **2** has an input that receives the amplified detected RF signal from the output **224** of the amplifier **204** and provides an expanded signal output **230**. In the example square law extension circuit **200** shown in FIG. **2**, the expander **206** includes a first resistor (R_1) **232** and an expander diode **234** that is electrically connected in parallel with the R_1 **232** to node **230**. A second resistor (R_2) **236** is electrically connected in series with the R_1 **232** and the expander diode **234** at node **230** and to ground. In this example, R_1 **232** and R_2 **236** form a voltage divider or a voltage attenuator that at least partially cancels the gain of the video amplifier **204** at relatively low RF power levels, i.e., the power of the RF_{in} **208** to the detector **202** is relatively low. The voltage divider reduces the expanded signal output proportionately equal to the gain that is necessary to correct for the square law deviation at higher input power levels. A voltage drop occurs across R_1 **232** and R_2 **236** in the voltage divider. The voltage drop across R_1 **232** increases to the threshold voltage discussed above (e.g., 0.4V) at which point the expander diode **234** begins to conduct current. The square law region of the detector signal can be extended by varying the threshold voltage at which the expander diode **234** begins to conduct current.

[0021] The parallel current paths of the expander diode **234** and R_1 **232** increase the voltage drop across R_2 **236**. The expander diode **234** may include a Schottky diode in some examples. Further increases in RF power will cause the expander diode **234** to conduct more heavily and produce an exponential decrease in attenuation as the detector signal transitions from the square law region to the linear law region of the signal. Specifically, the voltage drop across the expander diode **234** is determined as follows: when the voltage drop across R_1 **232** is below the threshold voltage, the voltage drop across the expander diode **234** is: $V_{expander\ diode}=I*R_1$ or $V_{in}*R1/(R1+R2)$. When the voltage drop across R_1 reaches the threshold voltage of the expander diode **234**, the voltage drop across the expander diode **234** and R_1 becomes fixed at the characteristic voltage drop of the expander diode **234** or the threshold voltage ($V_{f(diode)}$). As the current through the expander diode **234** increases, the voltage across R_2 continues to increase with the current: $I=(V_{in}-V_{f(diode)})*R_2$.

[0022] The gain of the video amplifier **204** is set so that expander diode **234** begins to conduct current at the voltage level where the detector signal begins to deviate from square law behavior. As the RF power level that is applied to the detector **202** shown in FIG. **2** increases, the voltage drop across R_1 **232** increases until it reaches the threshold voltage. When the voltage drop across R_1 **232** reaches the threshold voltage, the expander diode **234** receives current and the voltage drop across R_1 **232** remains at the threshold voltage while a voltage drop across R_2 **236** begins to increase. The output at node **230** of the expander **206** may terminate in a high-impedance device so that essentially no current flows through that expanded square law output node and that all of the current flows through R_2 **236**.

[0023] FIG. **3** is a graphical representation **300** of a detector circuit's output versus the RF input for corrected **302** and uncorrected **304** detector circuits. By employing the square law extension circuit discussed above with reference to FIGS. **1** and **2**, the square law region of the detector circuit's output may be extended over a broader power range than the detector alone provides. Without the square law extension circuit, the output signal **304** of the detector circuit alone begins to deviate from square law behavior at approximately −22 dBm in the example shown in FIG. **3**, while the output signal **302** from the square law detection circuit begins to deviate from square law behavior at approximately −1 dBm. In this example, the threshold is set to begin correction at about −13 dBm.

[0024] Methods implementing the above square law detection circuit also measure power in a multiple RF signal environment over a wide range of frequencies and power levels. Such methods can detect RF power in a multiple RF signal environment, amplify the detected voltage output of the RF power to create an amplified voltage output having a predetermined gain, and expand the amplified voltage output by causing an expanded output signal to increase in a first proportion to the amplified voltage output up to a predetermined threshold and increase at a second proportion to the amplified voltage output that is more than the first proportion when the expanded output signal exceeds the predetermined threshold. The multiple signal environment can include signals at different frequencies and power levels. In some examples, one signal has a power level that is greater than a second signal and the power levels between the two signals may differ by at least 2 orders of magnitude. In other examples, the power levels of the various signals may differ by the entire detected range. Any of the signals may be a pulsed signal. In some examples, the detected signal with a lower power level is a pulsed signal.

[0025] Having described and illustrated the principles of the invention in a preferred embodiment thereof, it should be apparent that the invention can be modified in arrangement and detail without departing from such principles. We claim all modifications and variations coming within the spirit and scope of the following claims.

1. A square law extension circuit operating over a range of frequencies and power levels, comprising:

a detector having an input for receiving radio frequency (RF) signals and providing a detected signal output;

an amplifier having an input that receives the detected signal output and providing an output for an amplified detected signal; and

an expander having an input that receives the amplified detected signal and is arranged to provide an expanded signal output, wherein the expanded signal output is a signal that increases in a first proportion to the amplified detected signal up to a predetermined threshold and increases at a second proportion to the amplified detected signal that is more than the first proportion when the expanded signal output exceeds the predetermined threshold.

2. The square law extension circuit of claim **1**, wherein the expanded signal output increases linearly with respect to the detected signal output up to the predetermined threshold.

3. The square law extension circuit of claim **1**, wherein the first proportion indicates square law behavior of the expanded signal output and the second proportion corrects for a deviation from square law behavior of the expanded signal output.

4. The square law extension circuit of claim **1**, wherein the RF signals applied to the detector operates in a frequency range between 1 MHz and 100 GHz.

5. The square law extension circuit of claim **1**, wherein the detected signal output includes a power range of at least 2 orders of magnitude.

6. The square law extension circuit of claim **5**, wherein an expanded output power associated with the expanded signal output extends over a range of at least 4 orders of magnitude.

7. The square law extension circuit of claim **1**, wherein the expander includes a first resistor, a diode electrically connected in parallel with the first resistor, and a second resistor electrically connected in series with the first resistor and the diode, and wherein the first resistor and the second resistor form a voltage divider.

8. A method of measuring power in a multiple radio frequency signal environment over a wide range of frequencies and power levels, comprising:

detecting radio frequency power in the multiple radio frequency signal environment;

amplifying a detected voltage output of the radio frequency power to create an amplified voltage output having a predetermined gain;

expanding the amplified voltage output by causing an expanded output signal to increase in a first proportion to the amplified voltage output up to a predetermined threshold and increase at a second proportion to the amplified voltage output that is more than the first proportion when the expanded output signal exceeds the predetermined threshold.

9. The method of claim **8**, wherein the multiple radio frequency environment includes a first signal having a first power level and a second signal having a second power level that is lower than the first power level.

10. The method of claim **9**, wherein the second signal includes a pulsed signal.

11. The method of claim **9**, wherein the second power level is lower than the first power level by at least 2 orders of magnitude.

12. The method of claim **8**, wherein the first proportion indicates square law behavior of the expanded output signal and the second proportion indicates a correction for a deviation from square law behavior of the expanded output signal.

13. The method of claim **8**, wherein amplifying a voltage output of the detected radio frequency power is performed by a high-speed, low-noise direct current coupled amplifier.

14. The method of claim **8**, wherein the low level of the radio frequency power is defined at −13 dBm or less.

15. A square law extension circuit operating over a range of frequencies and power levels, comprising:

a detector having an input for receiving radio frequency (RF) signals and providing a detected RF signal output;

an amplifier having an input that receives the detected RF signal and providing an output for an amplified detected RF signal; and

an expander having an input that receives the amplified detected RF signal and providing an expanded signal output, wherein the expander includes a first resistor, a diode electrically connected in parallel with the first resistor, and a second resistor electrically connected in series with the first resistor and the diode, and wherein the first resistor and the second resistor form a voltage divider,

wherein increasing power applied to the detector input causes a voltage drop across the first resistor to increase, and wherein when a voltage drop across the first resistor reaches a first threshold voltage, the first diode receives current and the voltage drop across the first resistor remains at the first threshold voltage while a voltage drop across the second resistor increases.

16. The square law extension circuit of claim **15**, wherein the power applied to the detector operates in a frequency range between 1 MHz and 100 GHz.

17. The square law extension circuit of claim **15**, wherein the video amplifier defines a gain that is set so the diode starts conducting current when the detected output signal begins deviating from square law behavior.

18. The square law extension circuit of claim **15**, wherein the voltage divider reduces the expanded signal output by a proportion equal to the gain necessary to correct for the square law deviation.

19. The square law extension circuit of claim **15**, wherein the expander diode includes a Schottky diode.

20. The square law extension circuit of claim **15**, wherein the first threshold voltage is approximately 0.4V.

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