

Chapter X

Measuring VSWR and Gain in Wireless Systems

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Introduction

Measurement and control of gain and reflected power in wireless transmitters are critical auxiliary functions that are often overlooked. The power reflected back from an antenna is specified using either the Voltage Standing Wave Ratio (VSWR) or Reflection Coefficient (also referred to as Return Loss). Poor VSWR can cause shadowing in a TV broadcast system as the signal reflected off the antenna reflects again off the power amplifier and is then rebroadcast. In wireless communications systems, shadowing will produce multi-path-like phenomena. While poor VSWR can degrade transmission quality, the catastrophic VSWR that results from damage to co-axial cable or to an antenna can, at its worst, destroy the transmitter.

The gain of a signal chain is measured and controlled as part of the overall effort to regulate the transmitted power level. If too much or too little power is transmitted, the result will be either violation of emissions regulations or a poor quality link.

Reflection Coefficient is calculated by measuring the ratio between forward and reverse power. Gain, on the other hand, is calculated by measuring input and output power.

The high commonality of hardware used to measure gain and VSWR can reduce overall component count. This article will focus on techniques that can be used to perform these in-situ measurements in wireless transmitters.

A typical Wireless Transmitter

Figure 1 shows a typical wireless transmitter. This consists of mixed-signal baseband circuitry, an up-converter (which generally includes one or more intermediate frequencies or IFs), amplifiers, filters and a power amplifier. These components may be located on different PCBs or may even be physically separated. In Figure 1, for example, an indoor unit is connected to an outdoor unit with a cable. In such a configuration both units may be expected to have well defined, temperature stable gains (this is especially true if the two units were made by different vendors). Alternatively, each unit might be expected to deliver a well defined output power.

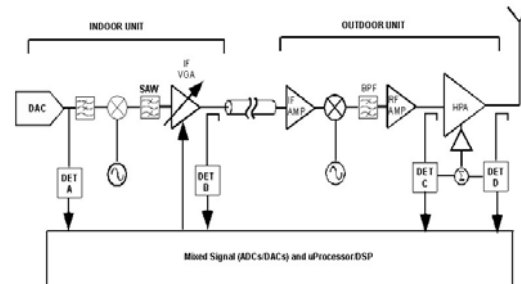


Figure 1. Output Power is regulated by measuring output power and then adjusting the VGA gain. Gain is regulated by measuring both input and output power and then adjusting the VGA gain.

So, there are two different approaches to the ultimate goal of delivering a known power level to the antenna; Power Control or Gain Control. With *Power Control*, the system relies on being able to precisely measure output power (using Detector D in this example). Once output power has been measured, the gain of some component in the system (in this case it might be the IF VGA) is varied until the correct output power is measured at the antenna. It is not necessary to know the gain of the circuit or the exact input signal amplitude; it's just a matter of varying gain or input signal until the output power is correct. This approach is often (incorrectly) referred to as Automatic Gain Control or AGC. To be correct, it should be referred to as Automatic Power Control or APC since it is power not gain that is being precisely regulated.

Gain Control takes a different approach. Here, at least two power detectors are used to precisely regulate the gain of the complete signal chain or a part thereof. The ultimate goal of precisely setting the output power is then achieved by applying a known input signal to the signal chain.

A number of factors ultimately determine which approach is used. *Power control* requires only one power detector and makes sense in a non-configurable transmitter whose components are fixed. So, for example, power could be measured

at the output of the RF HPA but adjustments would be made using the IF VGA.

Gain Control, on the other hand, may make more sense in a reconfigurable system whose components come from different vendors. In Figure 1 the input power and output power at the HPA are being measured (using Detectors C and D) so the gain can be regulated independent of the other blocks in the circuit. Note that the power/gain control loops can be all-analog or microprocessor based.

Using Gain Control to regulate the gain of the complete signal chain in Figure 1 would be less practical since the two required detector signals (Detector A and Detector D) are physically remote from one another. A more practical approach would be to independently control the gain of the Indoor and Outdoor units.

RF Detectors

Until recently, most RF power detectors were built using a temperature-compensated half-wave rectifying diode circuit. These devices deliver an output voltage that is proportional to the input voltage over a limited dynamic range (typically 20 to 30 dB). As a result, the relationship between output voltage and input power in dBm is exponential (Figure 2). While the temperature stability of a temperature-compensated diode detector is excellent at high input powers (+10 to +15 dBm), it degrades significantly as input drive is reduced.

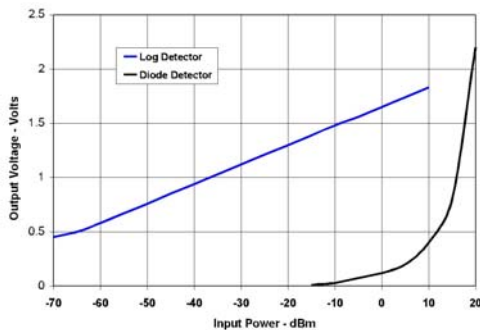


Figure 2. Diode Detectors measure signal strength over a narrow range and provide an output voltage which is exponentially related to input power in dBm. Log detectors provide an output voltage which is directly proportional to the input power in dBm.

A log detector, on the other hand, delivers an output voltage proportional to the log of the

input signal over a large dynamic range (up to 100 dB). Temperature stability is usually constant over the complete dynamic range. A log-responding device offers a key advantage in gain and VSWR measurement applications. In order to compute gain or reflection loss, the ratio of the two signal powers (either OUTPUT/INPUT or REVERSE/FORWARD) must be calculated (Figure 3). An analog divider must be used to perform this calculation with a linear-responding diode detector, but only simple subtraction is required when using a log-responding detector (since $\text{Log}(A/B) = \text{Log}(A) - \text{Log}(B)$).

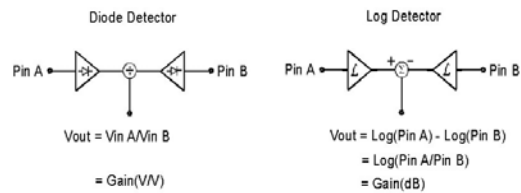


Figure 3. To perform a ratio (gain) calculation using linear in V/V responding diode detectors, analog division must be performed. Using log-responding detectors (log-amps), a ratio calculation can be performed using simple subtraction.

A dual RF Detector has an additional advantage compared to a discrete implementation. There is a natural tendency for two devices (RF Detectors in this case) to behave similarly when they are fabricated on a single piece of silicon, with both devices having similar temperature drift characteristics, for example. At the summing node, this drift will cancel to yield a more temperature-stable result.

A Dual RMS Responding RF Detector

The AD8364 is a true rms, responding, dual-channel RF power measurement subsystem for the precise measurement and control of signal power. The flexibility of the AD8364 allows communications systems, such as RF power amplifiers and radio transceiver AGC circuits, to be monitored and controlled with ease. Operating on a single 5 V supply, each channel is fully specified for operation up to 2.7 GHz over a dynamic range of 60 dB. The AD8364 provides accurately scaled, independent, rms outputs of both RF measurement channels. Difference output ports, which measure the difference between the two channels, are also available. The on-chip channel matching makes the rms channel

difference outputs extremely stable with temperature and process variations. The device also includes a useful temperature sensor with an accurately scaled voltage proportional to temperature, specified over the device operating temperature range. The AD8364 can be used with input signals having rms values from -55 dBm to $+5$ dBm referred to $50\ \Omega$ and large crest factors with no accuracy degradation.

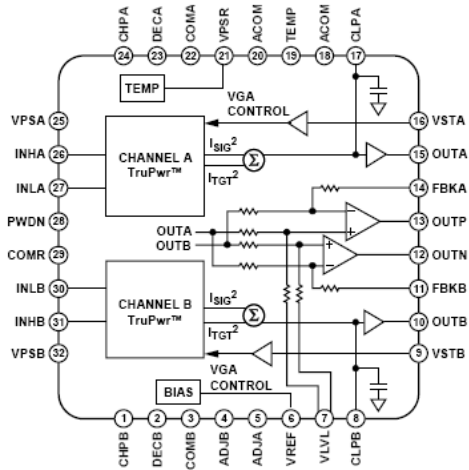


Figure 4. AD8364 Dual RMS Responding 60 dB RF Detector Functional Block Diagram

The device can easily be configured to provide four rms measurements simultaneously. Linear-in-dB rms measurements are supplied at OUTA and OUTB, with conveniently scaled slopes of 50 mV/dB. The rms difference between OUTA

and OUTB is available as differential or single-ended signals at OUTP and OUTN. An optional voltage applied to VLVL provides a common mode reference level to offset OUTP and OUTN above ground.

Gain Measurement Example

Figure 5 shows a transmitter whose gain is regulated using a dual power detector. The simplified transmit signal chain shown consists of a high-performance IF-synthesizing DAC, VGA, mixer/upconverter, and High-Power Amplifier. High-performance DACs, such as the AD9786 and AD9779, that run at sampling frequencies up to 500 MSPS and beyond are capable of synthesizing Intermediate Frequency outputs (100 MHz in this example).

The output of the DAC is Nyquist filtered using a band-pass filter before being applied to a ADL5330 variable gain amplifier. Conveniently, the amplifier accepts a differential input that can be tied directly to the output of the differential filter. This, in turn, is tied to the DAC output.

The VGA output is converted from differential to single-ended using a balun transformer, and is then applied to the ADL5350 mixer. After appropriate filtering (not shown), the signal is amplified and transmitted at a maximum output power level of 30 watts (approximately +45 dBm).

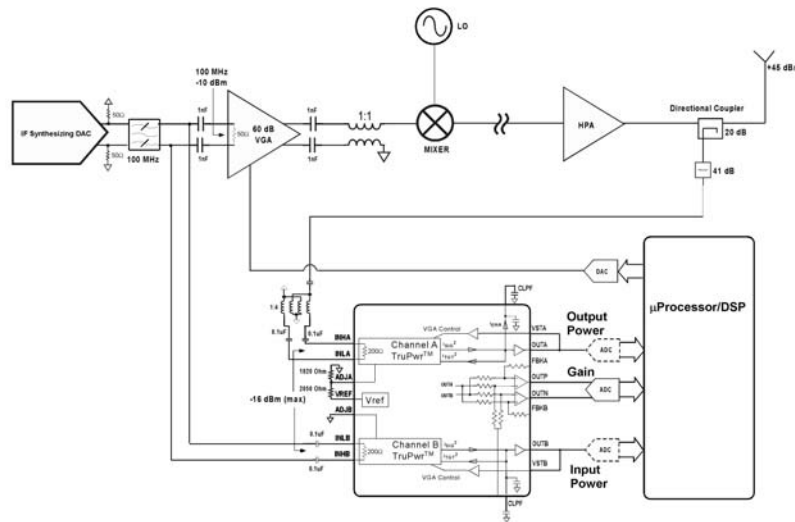


Figure 5. A dual Power Detector can be used to measure and control the gain of a signal chain even when the input and output frequencies are different.

The gain of the signal chain is measured by detecting the power at the DAC output and at the output of the HPA. Gain is then regulated by adjusting the gain of a VGA.

At the DAC and PA outputs, a sample of the signal is taken and fed to the detectors. At the HPA output, a directional coupler is used to tap off some of the power going to the antenna. While an asymmetrical power splitter could also be used, a directional coupler results in lower insertion loss (little or no power is consumed in the coupler) and tends to reject any signals that are received on the antenna (in-band or out-of-band blockers).

A 20 dB directional coupler is used in this example, but the coupling factor could be much lower, since the signal must be attenuated before being applied to the power detector. Directional couplers with lower coupling factors have the added advantage of even lower insertion loss.

The transfer function of the AD8364 dual detector shows that at the output frequency used (2140 MHz in this case), the detector has the best linearity and most stable temperature drift at power levels below -10 dBm. Thus, the power coming from the directional coupler ($+25$ dBm max) must be attenuated before being applied to the detector. If maximizing detector dynamic range is not critical to the application, the attenuation can be conservatively set at 41 dB so that the detector sees a maximum input power of -16 dBm. This still leaves about 34 dB of useful dynamic range over which the gain can be controlled.

When using single-chip dual power detectors, attention must be paid to RF feed through. In general, when one input power is about 40 dB below the other, measurement accuracy suffers. In this application, the input power levels to both detectors are equal when the system is at full power. So, the maximum power level at the input detector has also been set to -16 dBm.

To detect the input Power level at the DAC output, a directional coupler is impractical at this low frequency. In addition, directional coupling is not necessary since there will be little or no reflected signal at this point in the circuit. Furthermore, the power being delivered to the VGA is -10 dBm, so the power to be delivered to the detector is only 6 dB lower. The detector

has an input impedance of 200 ohms and the VGA has an input impedance of 50 ohms, so it quickly becomes clear that the two devices can simply be connected in parallel. With the same voltage present at both inputs, the 50-to-200 ohm impedance ratio will result in a convenient 6 dB power difference.

Where high measurement precision is required, care must be paid to the temperature stability of the power detectors. This issue is further complicated if the temperature drift characteristics of the detectors change with frequency. The dual detector shown provides temperature compensation nodes.

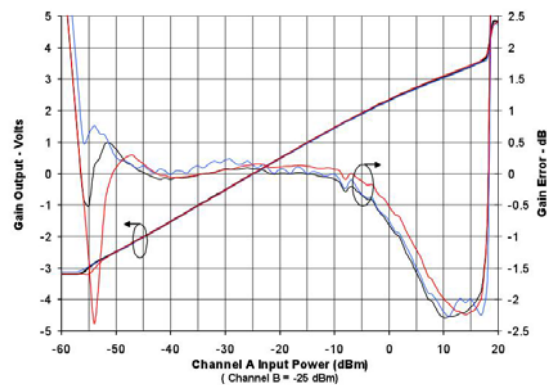


Figure 6. The operating input range of a detector should be chosen so that the detector always sees a power level which is well within its linear operating range, between -10 dBm and -50 dBm in this case.

Temperature compensation is activated by connecting a voltage to the ADJ pins of each detector (this voltage can be conveniently derived using a resistor divider from the 2.5 V on-chip reference). No compensation is required for the low frequency input (ADJB is grounded), while a 1.0-V compensation voltage is required at ADJA to minimize temperature drift at 2.1 GHz.

While the focus of the application circuit in Figure 5 is gain measurement, it should be noted that input power and output power can also be measured. The outputs of the individual detectors are available and can be separately sampled.

Because the detectors are log-responding, their outputs can be simply subtracted to yield gain. This subtraction is performed on chip and the gain result is delivered as a differential voltage. The full-scale differential voltage is

approximately ± 4 V (biased up to 2.5 V) with a slope of 100 mV/dB. Digitizing with a 10-bit ADC with an LSB size of ~ 10 mV (± 5 V fullscale), 0.1-dB measurement resolution is achievable.

An Analog Gain Control Loop

A dual RMS-responding detector operating in Controller Mode can also be used to control the gain of an HPA very accurately vs. input power, temperature, and crest factor. If the gain of an HPA module is controlled with enough accuracy over input power, temperature, and crest factor, the HPA module's output power would not have to be reported but would be directly related to the power feeding it. If both inputs of a dual detector are put in Controller Mode, the detector determines the power at each input and adjusts the gain of a VGA until the power detected on one input is equal to the power on the other.

Figure 7 shows a basic schematic of the AD8364 (dual RMS detector) used to control the gain of a system. Figure 8 shows the performance of this setup. Everything that needs to be accurately controlled should be included between the two couplers. Note that a VGA, variable attenuator, or even the bias of the HPA can be used to control the gain. If the control levels between the detector and VGA are set properly and power levels are properly designed for, the usable input power range will be close to the detectable power range of the detector (60 dB, in the case of the AD8364).

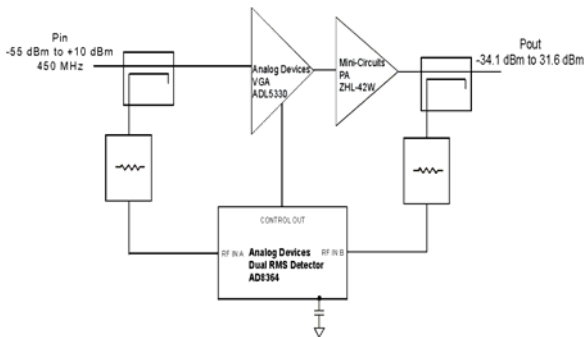


Figure 7. When both inputs of a dual detector are used in Controller Mode, the detector will control a VGA (or VVA, etc.) in such a way as to equalize the power it detects at both RF inputs. The gain of the system will be determined by the couplers and attenuators used to set the power being detected by the dual detector.

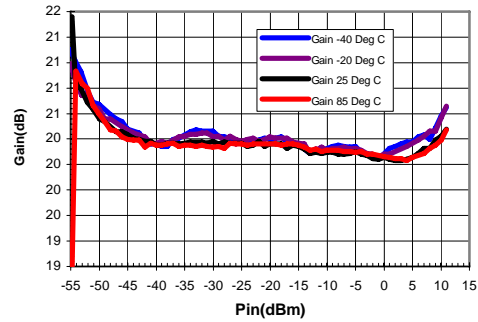


Figure 8. When both inputs of Analog Devices dual RMS detector (AD8364) are put in Controller Mode, the gain is controlled to better than ± 15 dB vs. temperature and input power, with a dynamic range almost equal to the dynamic range of the RMS detector.

A 60 dB Gain/Phase Detector

The AD8302 is a fully integrated system for measuring gain/loss and phase in receive, transmit, and instrumentation applications. It requires few external components and a single supply of 2.7 V–5.5 V. The ac-coupled input signals can range from -60 dBm to 0 dBm from low frequencies up to 2.7 GHz. The outputs provide an accurate measurement of either gain or loss over a ± 30 dB range scaled to 30 mV/dB, and of phase over a 0° – 180° range scaled to 10 mV/degree. The AD8302 can be used in controller mode to force the gain and phase of a signal chain toward predetermined setpoints.

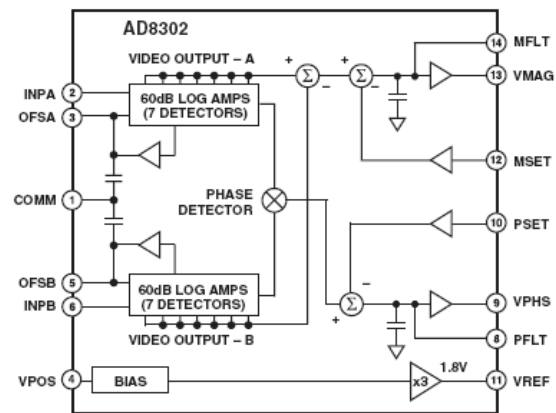


Figure 9. AD8302 60 dB Gain/Phase Detector

The AD8302 comprises a closely matched pair of demodulating logarithmic amplifiers, each having a 60 dB measurement range. By taking the difference of their outputs, a measurement of

the magnitude ratio or gain between the two input signals is available. These signals may even be at different frequencies, allowing the measurement of conversion gain or loss. The AD8302 may be used to determine absolute signal level by applying the unknown signal to one input and a calibrated ac reference signal to the other. With the output stage feedback connection disabled, a comparator may be realized, using the setpoint pins MSET and PSET to program the thresholds.

The AD8302 includes a phase detector of the multiplier type, but with precise phase balance driven by the fully limited signals appearing at the outputs of the two logarithmic amplifiers. Thus, the phase accuracy measurement is independent of signal level over a wide range.

In controller applications, the connection between the gain output pin VMAG and the setpoint control pin MSET is broken. The desired setpoint is presented to MSET and the VMAG control signal drives an appropriate external variable gain device. Likewise, the

feedback path between the phase output pin VPHS and its setpoint control pin PSET may be broken to allow operation as a phase controller.

VSWR Measurement Example

A dual log detector can also be used to measure the reflection coefficient of an antenna. In Figure 10, two directional couplers are used, one to measure forward power and one to measure reverse power. Additional attenuation is required before applying these signals to the detectors. The AD8302 dual detector has a measurement range of ± 30 dB. Each detector has a recommended input power range for good linearity and temperature stability, and care must be taken in setting the attenuation levels so the reflection coefficient can be measured over the desired output power range. The level planning used in this example is graphically depicted in Figure 11.

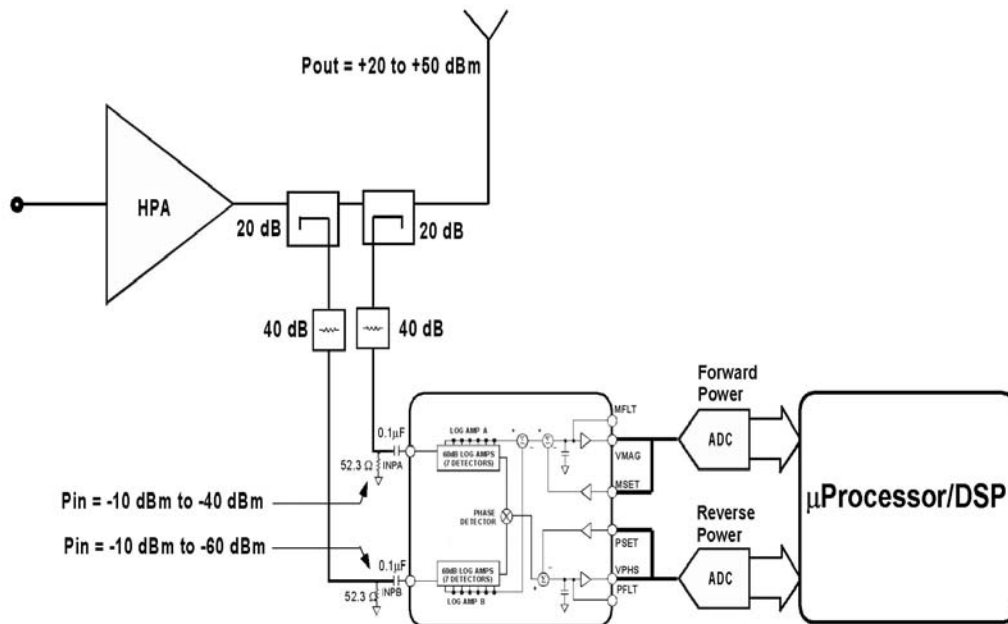


Figure 10. A dual log detector can be used to measure reflection coefficient of an antenna. The detector also provides a reading of the phase between forward and reverse power over a 180 degree range

In this example, the expected output power range from the HPA is 30 dB, from +20 dBm to +50 dBm. Over this power range, we would like to be able to accurately measure reflection coefficients from 0 dB (short or open load) up to -20 dB.

Each of the AD8302's detectors has a nominal input range from 0 dBm to -60 dBm. In this example, the maximum forward power of +50 dBm is padded down to -10 dBm at the detector input (this is achieved through the combined coupling factor of the directional coupler and the

subsequent attenuation). This puts the maximum power at the detector comfortably within its linear operating range. Also, when the HPA is transmitting at its lowest power level of +20 dBm, the detector sees a power of -40 dBm, still well within its input range.

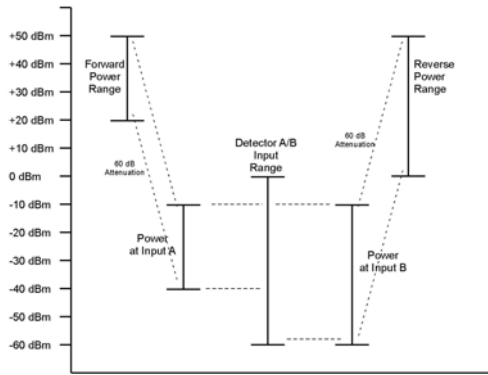


Figure 11. Careful level planning should be used to match the input power levels in a dual detector and to place these power levels within the linear operating range of the detectors.

The power from the reverse path is padded down by the same amount. This means that the system is capable of measuring reflected power up to 0 dB. This may not be necessary if the system is designed to shut down when the reflection coefficient degrades below a certain minimum (e.g. 10 dB), but it is permissible because the detector has so much dynamic range. For example, when the HPA is transmitting +20 dBm, the reverse path detector will see an input power of -60 dBm if the antenna has a return loss of 20 dB.

The application circuit in Figure 10 provides a direct reading of return loss, but no information is provided about the absolute forward or reverse power. If this information is required, the dual detector used in Figure 4 would be more useful because it would provide a measure of absolute forward and reflected power along with the reflection coefficient.

The AD8302 dual detector used in Figure 10 also provides a phase output. Because of the large gain in the main signal path of a progressive compression log amp, a limited (amplitude saturated) version of the input signal is a natural by product. These limiter outputs are multiplied together to yield a phase detected output with a range of 180 degrees centered around an ideal

operating point of 90 degrees. In a VSWR application, this information constitutes the phase angle of the reflected signal (with respect to the incident signal) and may be of use in optimizing power delivered to the antenna.

A Single 1 MHz to 10 GHz 60 dB Log Detector

The AD8318 is a demodulating logarithmic amplifier, capable of accurately converting an RF input signal to a corresponding decibel-scaled output voltage. It employs the progressive compression technique over a cascaded amplifier chain, each stage of which is equipped with a detector cell. The device can be used in measurement or controller mode. The AD8318 maintains accurate log conformance for signals of 1 MHz to 6 GHz and provides useful operation to 8 GHz. The input range is typically 60 dB with error less than ± 1 dB. The AD8318 has a 10 ns response time that enables RF burst detection to beyond 60 MHz. The device provides unprecedented logarithmic intercept stability versus ambient temperature conditions. A 2 mV/K slope temperature sensor output is also provided for additional system monitoring. A single supply of +5 V is required. Current consumption is typically 68 mA. Power consumption decreases to <1.5 mW when the device is disabled.

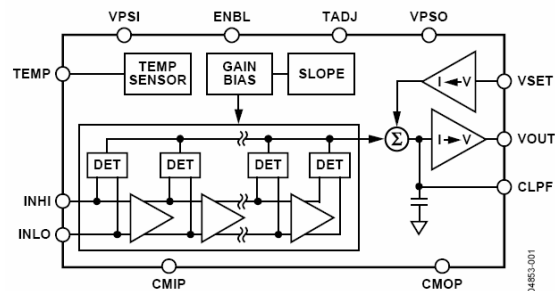


Figure 12. 8318 Dual RMS Responding 60 dB RF Detector Functional Block Diagram

The AD8318 can be configured to provide a control voltage to a VGA, such as a power amplifier or a measurement output, from pin VOUT. Since the output can be used for controller applications, special attention has been paid to minimize wideband noise. In this mode, the setpoint control voltage is applied to VSET. The feedback loop through an RF amplifier is closed via VOUT; the output of which regulates the amplifier's output to a magnitude

corresponding to V_{SET} . The AD8318 provides 0 V to 4.9 V output capability at the VOUT pin, suitable for controller applications. As a measurement device, VOUT is externally connected to VSET to produce an output voltage V_{OUT} that is a decreasing linear-in-dB function of the RF input signal amplitude.

Amplifier Gain Measurement Using a Single Log Detector and an RF Switch

Figure 13 shows an alternative approach to Gain measurement which is also applicable to VSWR measurement. In this application, we again want to measure and control the gain of a PA. The PA in the example is running at 8 GHz and has an output power range from +20 dBm to +50 dBm. This is a fixed-gain PA, so the output power is adjusted by changing input power.

Two directional couplers are used to detect input and output power. There is only a single log detector, however, so the two signals are alternately connected to the detector using a single-pole, double-throw RF switch. The AD8317 detector has a 0 dBm to -50 dBm input range at this frequency. To measure Gain, the input and output powers are alternately measured and digitized. The results are then simply subtracted to yield gain. Once gain is known, this digital control loop is completed by making any necessary adjustments to the gain of the PA via a bias adjustment. The level planning for this example is shown in Figure 14. Attenuation is used so that the two input power levels at the RF switch are close together and within the input range of the detector.

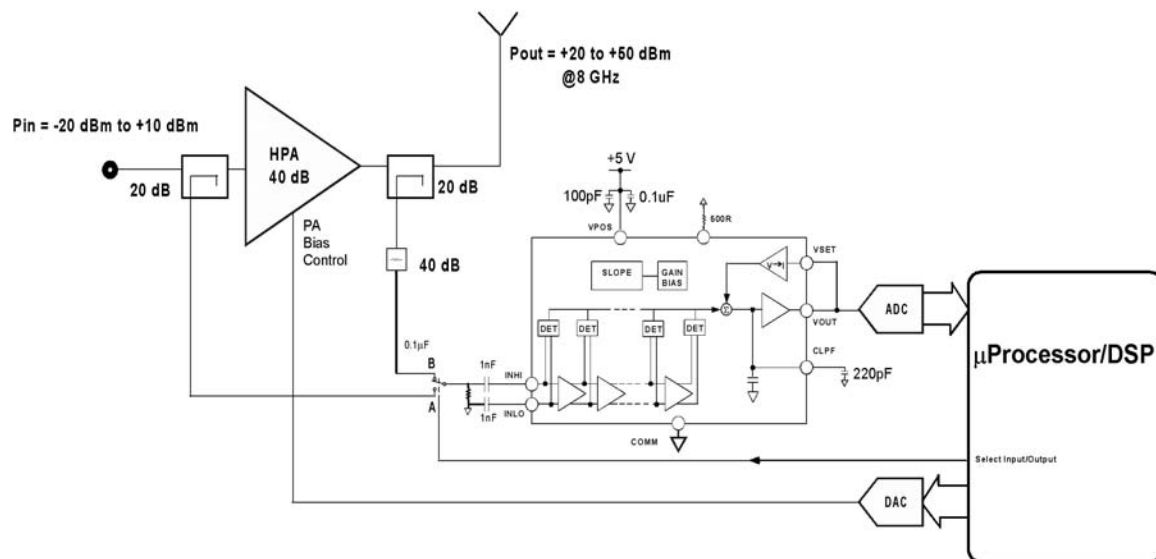


Figure 13. A single detector and RF switch can be used to measure gain.

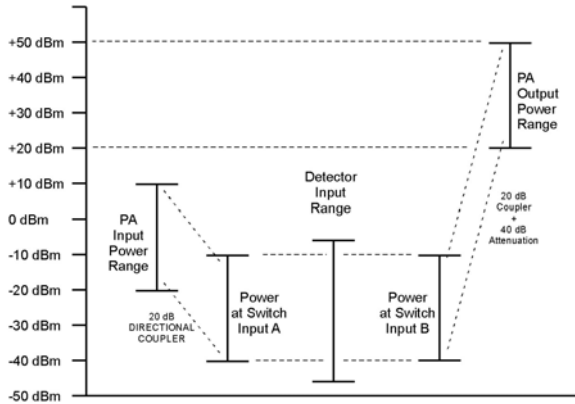


Figure 14. The signal detected at the output of the PA is heavily attenuated so that it maps into the input range of the detector. The signal levels at the switch inputs will always be close together, making RF feed through unlikely.

Precise Gain Measurement without Factory Calibration

In addition to reducing component count, this gain measurement method shown in Figure 13 has a number of interesting features. Because the same circuit is being used to measure input and output power, it is possible to make precise, temperature-stable gain measurements without ever calibrating the circuit. To understand why, let's take a look at the nominal transfer function of a log detector (Figure 15).

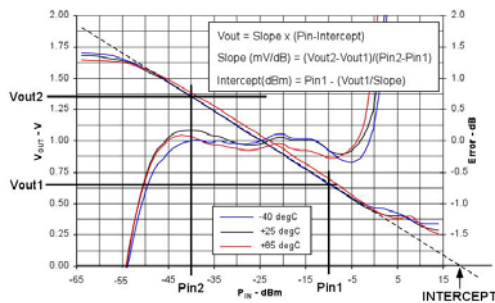


Figure 15. Log detectors provide a convenient $y=mx+b$ transfer function within their linear operating range at frequencies up to 10 GHz. Slope and Intercept can be calculated if necessary using a simple two-point calibration

We know the standard equation that describes the operation of the device in its linear region.

$$V_{OUT1} = SLOPE \times (P_{IN1} - INTERCEPT)$$

To figure out the unknown, P_{IN} , the equation can be rewritten as

$$P_{IN1} = (V_{OUT1}/SLOPE) - INTERCEPT$$

Since gain is the difference in the measured input powers (we still have to factor in the different attenuation levels of the two paths), we can write

$$GAIN = (V_{OUT1} - V_{OUT2})/SLOPE$$

So the Intercept of the detector is not required to calculate the gain. Even though the slope of a detector will change from device to device and over temperature, if V_{out1} and V_{out2} are close to one another (we endeavor to do this with good level planning and because of the finite input range of the detector), a typical value for the slope can be taken directly from the datasheet and used in the above calculation.

Output Power Monitoring

In Figure 13, power is being measured in order to calculate gain, so the system shown can also be used to monitor output power. However, this cannot be done precisely without factory calibration. To calibrate the circuit, the antenna must be temporarily replaced with a power meter. Output power and detector voltage are then be measured at two points within the linear range of the detector. These numbers would then be used to calculate the Slope and Intercept of the detector. For optimum precision, the detector includes a temperature compensation pin. A resistor is connected between this pin and ground to reduce the temperature drift to approximately ± 0.5 dB at the frequency of operation (8 GHz in the example shown). As a result, it is not necessary to do any additional calibration over temperature.

Conclusions

Because of their linear-in-dB transfer function, log amps can be easily used to measure gain and return loss. When dual devices are used very high measurement precision is achievable. In some cases, this can be achieved without factory calibration. In all cases, careful power level planning is necessary so that the power detectors are driven at power levels that offer good linearity and temperature stability.