

## High Speed Variable Gain Amplifiers (VGAs)

[High frequency variable gain amplifiers \(VGAs\)](#) must be fully specified not only in terms of traditional op amp ac specifications (bandwidth, slew rate, settling time), but also in terms of *communications-specific specifications*. These latter specifications include performance for harmonic distortion, spurious free dynamic range (SFDR), intermodulation distortion, intercept points (IP2, IP3), noise, and noise figure (NF). Figure 1 illustrates these specifications, below.

- ◆ **Noise**
  - **Noise referred to output (RTO)**
  - **Noise referred to input (RTI)**
- ◆ **Distortion**
  - **Second and third order intercept points ( IP2, IP3)**
  - **Spurious free dynamic range (SFDR)**
  - **Harmonic distortion**
    - ◆ **Single-tone**
    - ◆ **Multi-tone**
    - ◆ **Out-of-band**
  - **Multitone Power Ratio (MTPR)**
  - **Noise Factor (NF), Noise Figure (NF)**

### ***Figure 1: Dynamic Range Specifications in Communications Systems***

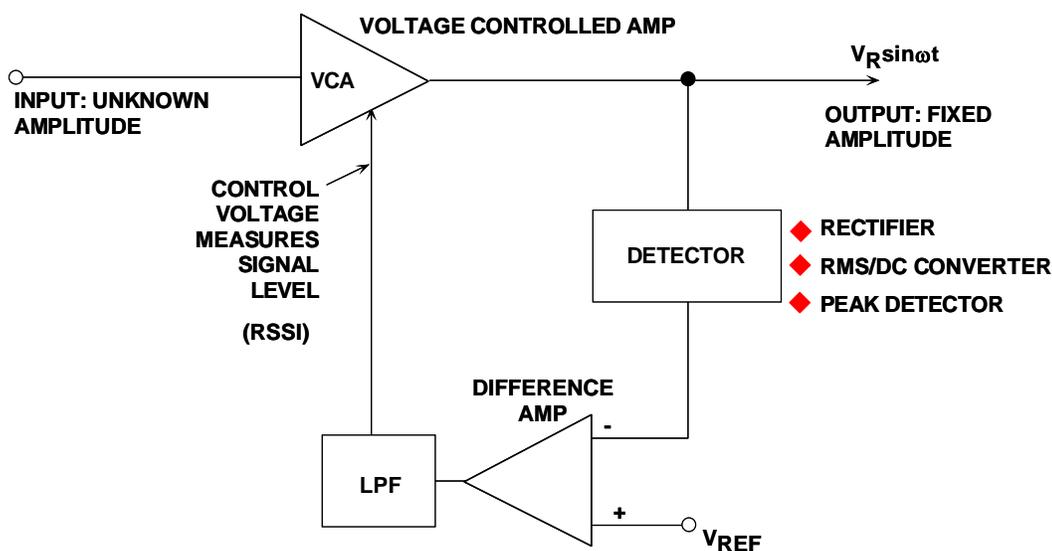
Within this tutorial we will focus on VGAs that are suitable for communications systems which depend upon these specifications to meet system performance objectives. Both analog-controlled and digitally-controlled VGAs will be examined.

## **VARIABLE GAIN AMPLIFIERS (VGAS) IN AUTOMATIC GAIN CONTROL (AGC) SYSTEMS**

Wideband, low distortion variable gain amplifiers find wide applications in communications systems. One example is automatic gain control (AGC) in radio receivers as shown in Figure 2 below. Typically, the received energy exhibits a large dynamic range due to the variability of the propagation path, requiring dynamic-range compression in the receiver.

In this case, the wanted information is in the modulation envelope (whatever the modulation mode), not in the absolute magnitude of the carrier. For example, a 1 MHz carrier modulated at 1 kHz to a 30% modulation depth would convey the same information, whether the received carrier level is at 0 dBm or -120 dBm. Some type of automatic gain control (AGC) in the receiver is generally utilized to restore the carrier amplitude to some normalized reference level, in the presence of large input fluctuations. AGC circuits are dynamic-range compressors which respond to some signal metric (often mean amplitude) acquired over an interval corresponding to many periods of the carrier.

Consequently, they require time to adjust to variations in received signal level. The time required to respond to a sudden increase in signal level can be reduced by using peak detection methods, but with some loss of robustness, since transient noise peaks can now activate the AGC detection circuits. Nonlinear filtering and the concept of "delayed AGC" can be useful in optimizing an AGC system. Many tradeoffs are found in practice.

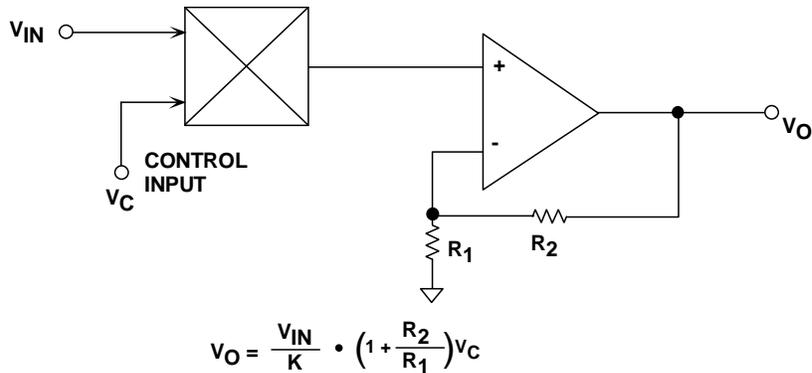


**Figure 2: A Typical Automatic Gain Control (AGC) System**

It is interesting to note that an AGC loop actually has *two* outputs. The more obvious output is of course the amplitude-stabilized signal. The less obvious output is the control voltage to the VCA. In reality, this voltage is a measure of the average amplitude of the input signal. If the system is precisely scaled, the control voltage may be used as a measure of the input signal, which is sometimes also known as a *received signal strength indicator* (RSSI). This latter point, given a suitably precise VCA gain control law, allows implementation of a receiving system which is calibrated for incoming signal level.

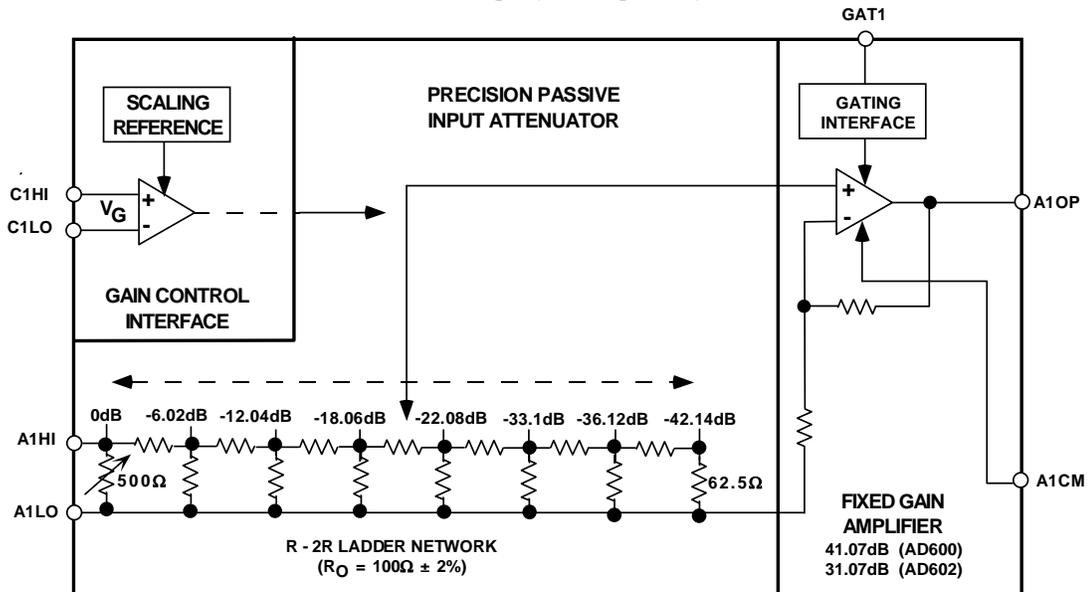
**VOLTAGE CONTROLLED VARIABLE GAIN AMPLIFIERS**

An analog multiplier, such as the [ADL5391](#), can be used as a variable-gain amplifier, as shown in Figure 3 below. The control voltage is applied to one input, and the signal to the other. In this configuration, the gain is directly proportional to the control voltage.



**Figure 3: Using a Multiplier as a Voltage-Controlled Variable Gain Amplifier**

Most VCAs made with analog multipliers have gain which is *linear in volts* with respect to the control voltage, moreover they tend to be noisy. There is a demand, however, for a VCA which combines a wide gain range with constant bandwidth and phase, low noise with large signal-handling capabilities, and low distortion with low power consumption, while providing accurate, stable, *linear-in-dB* gain. [The X-AMP™ family](#) achieve these demanding and conflicting objectives with a unique and elegant solution (for *exponential amplifier*). The concept is simple: a fixed-gain amplifier follows a passive, broadband attenuator equipped with special means to alter its attenuation under the control of a voltage (see Figure 4).



**Figure 4: X-Amp Block Diagram**

The amplifier is optimized for low input noise, and negative feedback is used to accurately define its moderately high gain (about 30 to 40 dB) and minimize distortion. Since this amplifier's gain is fixed, so also are its ac and transient response characteristics, including distortion and group delay; since its gain is high, its input is never driven beyond a few millivolts. Therefore, it is always operating within its small signal response range.

The attenuator is a 7-section (8-tap) R-2R ladder network. The voltage ratio between all adjacent taps is exactly 2, or 6.02 dB. This provides the basis for the precise linear-in-dB behavior. The overall attenuation is 42.14 dB. As will be shown, the amplifier's input can be connected to any one of these taps, or even *interpolated* between them, with only a small deviation error of about  $\pm 0.2$  dB. The overall gain can be varied all the way from the fixed (maximum) gain to a value 42.14 dB less. For example, in the AD600, the fixed gain is 41.07 dB (a voltage gain of 113); using this choice, the full gain range is  $-1.07$  dB to  $+41.07$  dB. The gain is related to the control voltage by the relationship  $G_{dB} = 32V_G + 20$  where  $V_G$  is in volts.

The gain at  $V_G = 0$  is laser trimmed to an absolute accuracy of  $\pm 0.2$  dB. The gain scaling is determined by an on-chip bandgap reference (shared by both channels), laser trimmed for high accuracy and low temperature coefficient. Figure 5 shows the gain versus the differential control voltage for both the [AD600](#) and the [AD602](#).

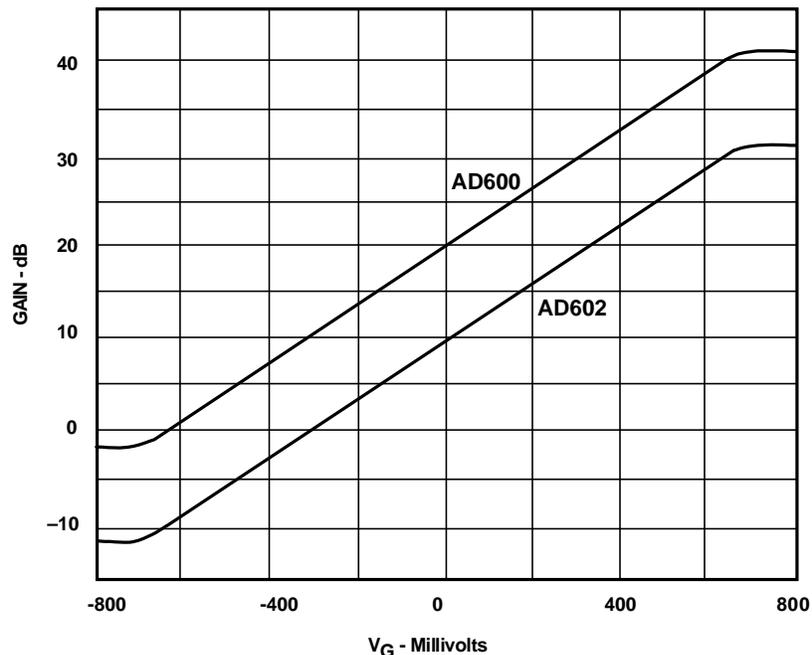
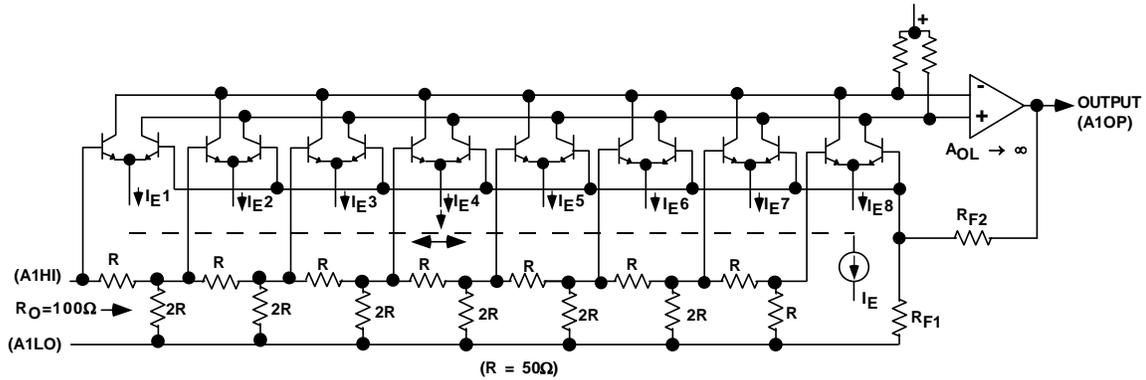


Figure 5: X-Amp Transfer Function

In order to understand the operation of the X-AMP™ family, consider the simplified diagram shown in Figure 6. Notice that each of the eight taps is connected to an input of one of eight bipolar differential pairs, used as current-controlled transconductance ( $g_m$ ) stages; the other input of all these  $g_m$  stages is connected to the amplifier's gain-determining feedback network,  $R_{F1}/R_{F2}$ . When the emitter bias current,  $I_E$ , is directed to one of the 8 transistor pairs (by means not shown here), it becomes the input stage for the complete amplifier.



**Figure 6: X-Amp Simplified Schematic**

When  $I_E$  is connected to the pair on the left-hand side, the signal input is connected directly to the amplifier, giving the maximum gain. The distortion is very low, even at high frequencies, due to the careful open-loop design, aided by the negative feedback. If  $I_E$  were now to be abruptly switched to the second pair, the overall gain would drop by exactly 6.02 dB, and the distortion would remain low, because only one  $g_m$  stage remains active.

In reality, the bias current is *gradually* transferred from the first pair to the second. When  $I_E$  is equally divided between two  $g_m$  stages, both are active, and the situation arises where we have an op amp with two input stages fighting for control of the loop, one getting the full signal, and the other getting a signal exactly half as large.

Analysis shows that the effective gain is reduced, not by 3 dB, as one might first expect, but rather by  $20 \log 1.5$ , or 3.52 dB. This error, when divided equally over the whole range, would amount to a gain ripple of  $\pm 0.25$  dB; however, the interpolation circuit actually generates a Gaussian distribution of bias currents, and a significant fraction of  $I_E$  always flows in adjacent stages. This smooths the gain function and actually lowers the ripple. As  $I_E$  moves further to the right, the overall gain progressively drops.

The total input-referred noise of the X-AMP™ is  $1.4 \text{ nV}/\sqrt{\text{Hz}}$ ; only slightly more than the thermal noise of a  $100 \text{ } \Omega$  resistor which is  $1.29 \text{ nV}/\sqrt{\text{Hz}}$  at  $25^\circ\text{C}$ . The input-referred noise is constant regardless of the attenuator setting, therefore the output noise is always constant and independent of gain.

A summary of many of the X-AMP family characteristics is given in Figure 7.

	BANDWIDTH	DISTORTION	NOISE	INPUT Z	SUPPLY
AD600/602	35MHz	-60dBc @ 10MHz	1.4nV/ $\sqrt{\text{Hz}}$	100 $\Omega$	$\pm 5\text{V}$
AD603	90MHz	-60dBc @ 10MHz	1.3nV/ $\sqrt{\text{Hz}}$	100 $\Omega$	$\pm 5\text{V}$
AD604	40MHz	-43dBc @ 10MHz	0.8nV/ $\sqrt{\text{Hz}}$	300k $\Omega$	$\pm 5\text{V}$
AD605	40MHz	-51dBc @ 10MHz	1.8nV/ $\sqrt{\text{Hz}}$	200 $\Omega$	+5V
AD8367	500MHz	IP3 = +33dBm @140MHz	NF = 7.5dB @140MHz	200 $\Omega$	+2.7 to +5.5V
AD8368	800MHz	IP3 = +33dBm @ 140MHz	NF = 9.5dB @ 140MHz	50 $\Omega$	+4.5 to +5.5V

Figure 7: X-AMP™ Family Key Specifications

**DIGITALLY CONTROLLED VGAs**

In some cases it may be advantageous to have the control of the signal level under digital control. One example is an upstream cable modem driver, such as the [AD8325](#).

Cable modems offer much higher data rates than standard dial-up connections and have become very popular. In addition to receiving data (*downstream*), the cable modem also transmits data (*upstream*). This requires a low distortion digitally controlled variable gain amplifier capable of driving the 75  $\Omega$  coaxial cable at a nominal level of 1 V rms (+11.2 dBm, or 60 dBmV). The [AD8325](#) is a member of a family of CATV upstream line drivers suitable for this application. The AD8325 gain is controlled by an 8-bit serial word that determines the desired gain over a 59.45 dB range, resulting in gain changes of 0.7526 dB/LSB. The AD8325 block diagram is shown Figure 8 below.

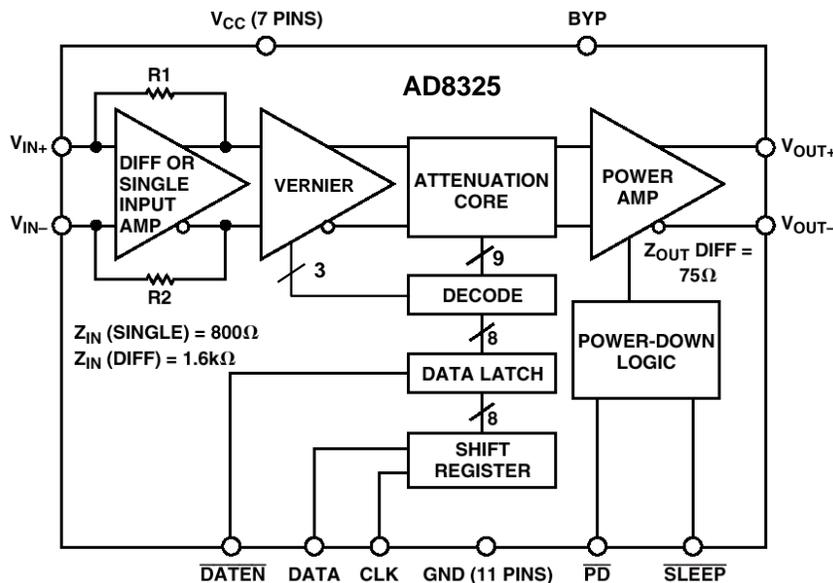


Figure 8: AD8325 CATV Digitally Controlled Variable Gain Amplifier

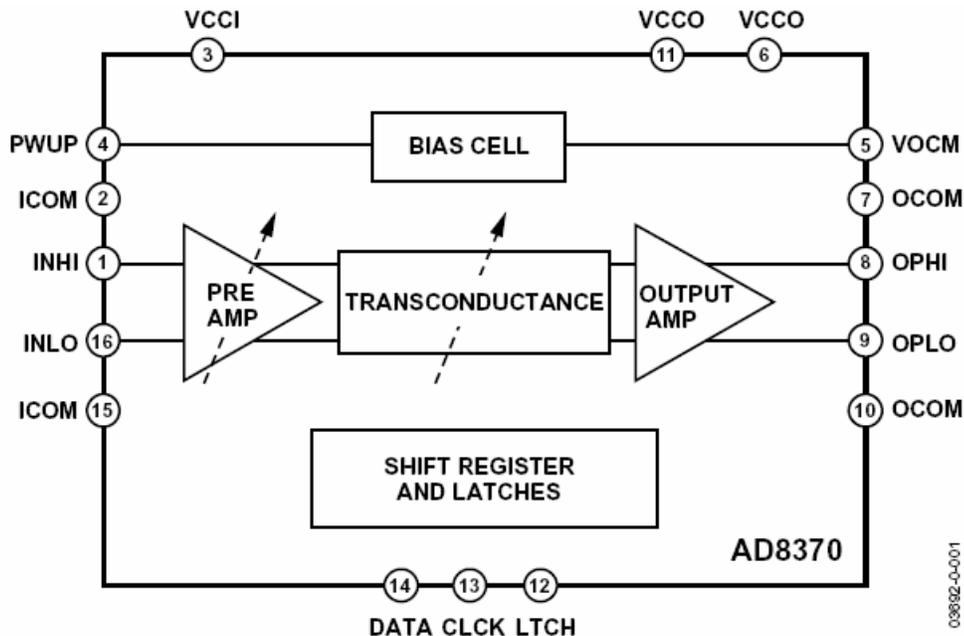
The AD8325 has a variable attenuator core where the attenuation is digitally controlled from 0 dB to -59.45 dB. The input buffer has a gain of approximately +30 dB, therefore the resulting overall gain range is from -29.45 dB to +30.0 dB. The AD8325 is composed of four analog functions in the power-up mode. The input amplifier (preamp) can be used either single-ended or differentially. The 8-bit control word is decoded into a 3-bit word which drives the vernier stage (fine tune gain adjustment) and a 9-bit word which drives the attenuation core (DAC). The 0.7526 dB/LSB resolution is implemented in the vernier stage and provides a total of approximately 5.25 dB of attenuation. After the vernier stage, a DAC provides the bulk of the AD8325's attenuation (9-bits, or 54 dB).

The signals in the preamp and vernier gain blocks are differential to improve the PSRR and linearity. A differential current is fed from the DAC to the output stage, which amplifies these currents to the appropriate levels necessary to drive the 75 Ω load.

A key performance and cost advantage of the AD8325 results from the ability to maintain a constant dynamic output impedance of 75 Ω during power-up and power-down conditions. The output stage utilizes negative feedback to implement a differential 75 Ω dynamic output impedance. This eliminates the need for an external 75 Ω termination, resulting in twice the effective output voltage when compared to a standard op amp.

These features allow the AD8325 to operate on a single +5 V supply and still deliver the required output power. Distortion performance of -57 dBc is achieved with an output level up to 1 V rms (+11.2 dBm) at a 21 MHz bandwidth.

The [AD8370](#) is a low cost, digitally controlled, variable gain amplifier that provides precision gain control, high IP3, and low noise figure. A block diagram is shown in Figure 9.

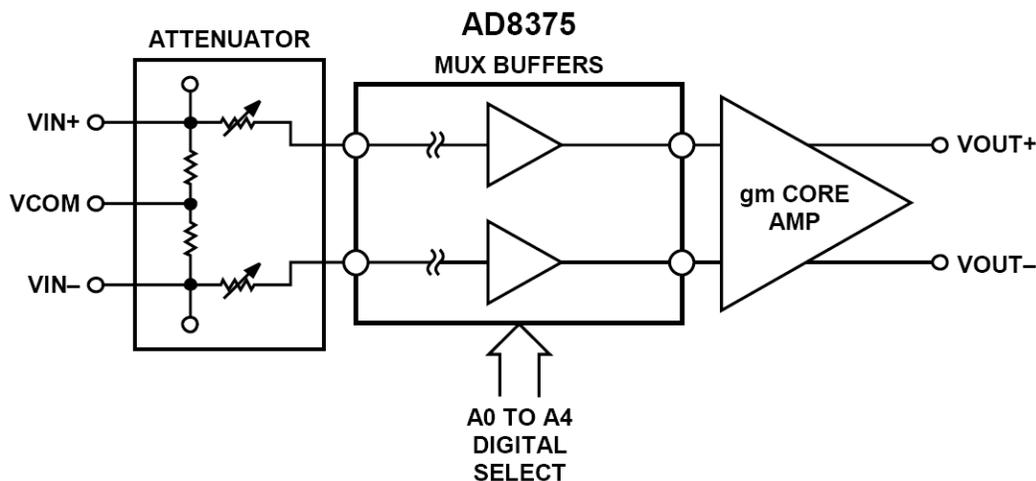


**Figure 9: AD8370 750MHz Digitally Controlled VGA**

The [AD8370](#) has excellent distortion performance and wide bandwidth. For wide input, dynamic range applications, the AD8370 provides two input ranges: high gain mode and low gain mode. A vernier 7-bit transconductance ( $G_m$ ) stage provides 28 dB of gain range at better than 2 dB resolution, and 22 dB of gain range at better than 1 dB resolution. A second gain range, 17 dB higher than the first, can be selected to provide improved noise performance. The AD8370 is powered on by applying the appropriate logic level to the PWUP pin. When powered down, the AD8370 consumes less than 4 mA and offers excellent input to output isolation. The gain setting is preserved when operating in a power-down mode.

Gain control of the AD8370 is through a serial 8-bit gain control word. The MSB selects between the two gain ranges, and the remaining 7 bits adjust the overall gain in precise linear gain steps.

The [AD8375](#) is a differential variable gain amplifier consisting of a 150  $\Omega$  digitally controlled passive attenuator followed by a highly linear transconductance amplifier as shown in Figure 10.



**Figure 10: AD8375 630MHz Low Distortion Digitally Controlled VGA**

A 5-bit binary code changes the attenuator setting in 1 dB steps such that the gain of the device changes from 20 dB (Code 0) to -4 dB (Code 24 and higher). The noise figure of the device is about 8 dB at maximum gain setting and it increases as the gain is reduced. The increase in noise figure is equal to the reduction in gain. The linearity of the part measured at the output is first-order independent of the gain setting. From 0 dB to 20 dB gain, OIP3 is approximately 50 dBm into 150  $\Omega$  load at 140 MHz (3 dBm per tone). At gain settings below 0 dB, it drops to approximately 45 dBm.

**REFERENCES**

1. Hank Zumbahlen, *Basic Linear Design*, Analog Devices, 2006, ISBN: 0-915550-28-1. Also available as [Linear Circuit Design Handbook](#), Elsevier-Newnes, 2008, ISBN-10: 0750687037, ISBN-13: 978-0750687034. Chapter 4.
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