Dual, Ultralow Noise Variable Gain Amplifier

AD604

FEATURES

- Ultralow input noise at maximum gain:
  - 0.80 nV/√Hz, 3.0 pA/√Hz
- Two independent linear-in-dB channels
- Absolute gain range per channel programmable:
  - 0 dB to 48 dB (preamp gain = 14 dB)
  - through 6 dB to 54 dB (preamp gain = 20 dB)
- ±1.0 dB gain accuracy
- Bandwidth: 40 MHz (−3 dB)
- 300 kΩ input resistance
- Variable gain scaling: 20 dB/V through 40 dB/V
- Stable gain with temperature and supply variations
- Single-ended unipolar gain control
- Power shutdown at lower end of gain control
- Can drive ADCs directly

APPLICATIONS

- Ultrasound and sonar time gain control
- High performance AGC systems
- Signal measurement

FUNCTIONAL BLOCK DIAGRAM

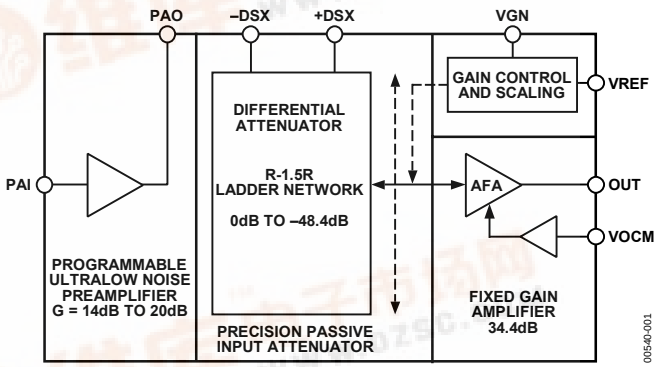

Figure 1.

GENERAL DESCRIPTION

The AD604 is an ultralow noise, very accurate, dual-channel, linear-in-dB variable gain amplifier (VGA) optimized for time-based variable gain control in ultrasound applications; however, it supports any application requiring low noise, wide bandwidth, variable gain control. Each channel of the AD604 provides a 300 kΩ input resistance and unipolar gain control for ease of use. User determined gain ranges, gain scaling (dB/V), and dc level shifting of output further optimize performance.

Each channel of the AD604 utilizes a high performance preamplifier that provides an input referred noise voltage of 0.8 nV/√Hz. The very accurate linear-in-dB response of the AD604 is achieved with the differential input exponential amplifier (DSX-AMP) architecture. Each of the DSX-AMPs comprise a variable attenuator of 0 dB to 48.36 dB followed by a high speed fixed gain amplifier. The attenuator is a 7-stage R-1.5R ladder network. The attenuation between tap points is 6.908 dB and 48.36 dB for the ladder network.

The equation for the linear-in-dB gain response is

$$G(\text{dB}) = (\textit{Gain Scaling}\ (\text{dB/V}) \times \textit{VGN}\ (\text{V})) + (\textit{Preamp Gain}\ (\text{dB}) - 19\ \text{dB})$$

Preamplifier gains between 5 and 10 (14 dB and 20 dB) provide overall gain ranges per channel of 0 dB through 48 dB and 6 dB through 54 dB. The two channels of the AD604 can be cascaded to provide greater levels of gain range by bypassing the second channel's preamplifier. However, in multiple channel systems, cascading the AD604 with other devices in the AD60x VGA family that do not include a preamplifier may provide a more efficient solution. The AD604 provides access to the output of the preamplifier, allowing for external filtering between the preamplifier and the differential attenuator stage.

Note that scale factors up to 40 dB/V are achievable with reduced accuracy for scales above 30 dB/V. The gain scales linearly-in-dB with control voltages of 0.4 V to 2.4 V with the 20 dB/V scale. Below and above this gain control range, the gain begins to deviate from the ideal linear-in-dB control law. The gain control region below 0.1 V is not used for gain control. In fact when the gain control voltage is <50 mV, the amplifier channel is powered down to 1.9 mA.

The AD604 is available in 24-lead SSOP, SOIC, and PDIP packages and is guaranteed for operation over the −40°C to +85°C temperature range.

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10/96—Revision 0: Initial Version

SPECIFICATIONS

Each amplifier channel at T_A = 25°C, V_S = ±5 V, R_S = 50 Ω, R_L = 500 Ω, C_L = 5 pF, V_{REF} = 2.50 V (scaling = 20 dB/V), 0 dB to 48 dB gain range (preamplifier gain = 14 dB), VOCM = 2.5 V, C1 and C2 = 0.1 µF (see Figure 37), unless otherwise noted.

Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS					
Preamplifier					
Input Resistance			300		kΩ
Input Capacitance			8.5		pF
Input Bias Current			−27		mA
Peak Input Voltage	Preamp gain = 14 dB		±400		mV
	Preamp gain = 20 dB		±200		mV
Input Voltage Noise	VGN = 2.9 V, R_S = 0 Ω				
	Preamp gain = 14 dB		0.8		nV/√Hz
	Preamp gain = 20 dB		0.73		nV/√Hz
Input Current Noise	Independent of gain		3.0		pA/√Hz
Noise Figure	R_S = 50 Ω, f = 10 MHz, VGN = 2.9 V		2.3		dB
	R_S = 200 Ω, f =10 MHz, VGN = 2.9 V		1.1		dB
DSX					
Input Resistance			175		Ω
Input Capacitance			3.0		pF
Peak Input Voltage			2.5 ± 2		V
Input Voltage Noise	VGN = 2.9 V		1.8		nV/√Hz
Input Current Noise	VGN = 2.9 V		2.7		pA/√Hz
Noise Figure	R_S = 50 Ω, f = 10 MHz, VGN = 2.9 V		8.4		dB
	R_S = 200 Ω, f =10 MHz, VGN = 2.9 V		12		dB
Common-Mode Rejection Ratio	f = 1 MHz, VGN = 2.65 V		−20		dB
OUTPUT CHARACTERISTICS					
−3 dB Bandwidth	Constant with gain		40		MHz
Slew Rate	VGN = 1.5 V, output = 1 V step		170		V/µs
Output Signal Range	R_L ≥ 500 Ω		2.5 ± 1.5		V
Output Impedance	f = 10 MHz		2		Ω
Output Short-Circuit Current			±40		mA
Harmonic Distortion	VGN = 1 V, V_{OUT} = 1 V p-p				
HD2	f = 1 MHz		−54		dBc
HD3	f = 1 MHz		−67		dBc
HD2	f = 10 MHz		−43		dBc
HD3	f = 10 MHz		−48		dBc
Two-Tone Intermodulation	VGN = 2.9 V, V_{OUT} = 1 V p-p				
Distortion (IMD)	f = 1 MHz		−74		dBc
	f = 10 MHz		−71		dBc
Third-Order Intercept	f = 10 MHz, VGN = 2.65 V, V_{OUT} = 1 V p-p, input referred		−12.5		dBm
1 dB Compression Point	f = 1 MHz, VGN = 2.9 V, output referred		15		dBm
Channel-to-Channel Crosstalk	V_{OUT} = 1 V p-p, f = 1 MHz, Channel 1: VGN = 2.65 V, inputs shorted, Channel 2: VGN = 1.5 V (mid gain)		−30		dB
Group Delay Variation	1 MHz < f < 10 MHz, full gain range		±2		ns
VOCM Input Resistance			45		kΩ

Parameter	Conditions	Min	Typ	Max	Unit
ACCURACY					
Absolute Gain Error					
0 dB to 3 dB	0.25 V < VGN < 0.400 V	−1.2	+0.75	+3	dB
3 dB to 43 dB	0.400 V < VGN < 2.400 V	−1.0	±0.3	+1.0	dB
43 dB to 48 dB	2.400 V < VGN < 2.65 V	−3.5	−1.25	+1.2	dB
Gain Scaling Error	0.400 V < VGN < 2.400 V		±0.25		dB/V
Output Offset Voltage	VREF = 2.500 V, VOCM = 2.500 V	−50	±30	+50	mV
Output Offset Variation	VREF = 2.500 V, VOCM = 2.500 V		30	50	mV
GAIN CONTROL INTERFACE					
Gain Scaling Factor	VREF = 2.5 V, 0.4 V < VGN < 2.4 V	19	20	21	dB/V
	VREF = 1.67 V		30		dB/V
Gain Range	Preamp gain = 14 dB		0 to 48		dB
	Preamp gain = 20 dB		6 to 54		dB
Input Voltage (VGN) Range	20 dB/V, VREF = 2.5 V		0.1 to 2.9		V
Input Bias Current			−0.4		µA
Input Resistance			2		MΩ
Response Time	48 dB gain change		0.2		µs
VREF Input Resistance			10		kΩ
POWER SUPPLY					
Specified Operating Range	One complete channel		±5		V
	One DSX only		5		V
Power Dissipation	One complete channel		220		mW
	One DSX only		95		mW
Quiescent Supply Current	VPOS, one complete channel		32	36	mA
	VPOS, one DSX only		19	23	mA
	VNEG, one preamplifier only	−15	−12		mA
Powered Down	VPOS, VGN < 50 mV, one channel		1.9	3.0	mA
	VNEG, VGN < 50 mV, one channel		−150		µA
Power-Up Response Time	48 dB gain change, V_{OUT} = 2 V p-p		0.6		µs
Power-Down Response Time			0.4		µs

ABSOLUTE MAXIMUM RATINGS

Table 2

Parameter[1, 2]	Rating
Supply Voltage $\pm V_S$	
Pins 17, 18, 19, 20 (with Pins 16, 22 = 0 V)	±6.5 V
Input Voltages	
Pins 1, 2, 11, 12	VPOS/2 ± 2 V Continuous
Pins 4, 9	±2 V
Pins 5, 8	VPOS, VNEG
Pins 6, 7, 13, 14, 23, 24	VPOS, 0 V
Internal Power Dissipation	
PDIP (N)	2.2 W
SOIC (RW)	1.7 W
SSOP (RS)	1.1 W
Operating Temperature Range	−40°C to +85°C
Storage Temperature Range	−65°C to +150°C
Lead Temperature, Soldering 60 sec	300°C
θ_{JA}[3]	
AD604AN	105°C/W
AD604AR	73°C/W
AD604ARS	112°C/W
θ_{JC}[3]	
AD604AN	35°C/W
AD604AR	38°C/W
AD604ARS	34°C/W

[1] Pins 1, 2, 11, 12, 13, 14, 23, and 24 are part of a single-supply circuit. The part will most likely be damaged if any of these pins are accidentally connected to VN.
[2] When driven from an external low impedance source.
[3] Using MIL STD 883 test method G43-87 with a 1S (2-layer) test board.

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

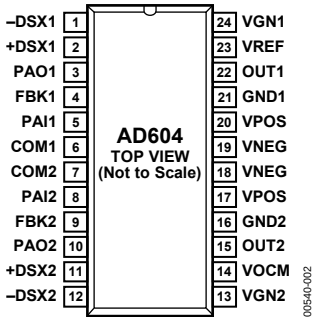


Figure 2.

Table 3. Pin Function Descriptions

Pin No.	Mnemonic	Description
1	–DSX1	CH1 Negative Signal Input to DSX1.
2	+DSX1	CH1 Positive Signal Input to DSX1.
3	PAO1	CH1 Preamplifier Output.
4	FBK1	CH1 Preamplifier Feedback Pin.
5	PAI1	CH1 Preamplifier Positive Input.
6	COM1	CH1 Signal Ground. When connected to positive supply, Preamplifier 1 will shut down.
7	COM2	CH2 Signal Ground. When connected to positive supply, Preamplifier 2 will shut down.
8	PAI2	CH2 Preamplifier Positive Input.
9	FBK2	CH2 Preamplifier Feedback Pin.
10	PAO2	CH2 Preamplifier Output.
11	+DSX2	CH2 Positive Signal Input to DSX2.
12	–DSX2	CH2 Negative Signal Input to DSX2.
13	VGN2	CH2 Gain-Control Input and Power-Down Pin. If grounded, device is off; otherwise, positive voltage increases gain.
14	VOCM	Input to this pin defines the common-mode of the output at OUT1 and OUT2.
15	OUT2	CH2 Signal Output.
16	GND2	Ground.
17	VPOS	Positive Supply.
18	VNEG	Negative Supply.
19	VNEG	Negative Supply.
20	VPOS	Positive Supply.
21	GND1	Ground.
22	OUT1	CH1 Signal Output.
23	VREF	Input to this pin sets gain-scaling for both channels to 2.5 V = 20 dB/V, 1.67 V = 30 dB/V.
24	VGN1	CH1 Gain-Control Input and Power-Down Pin. If grounded, the device is off; otherwise, positive voltage increases gain.

TYPICAL PERFORMANCE CHARACTERISTICS

Unless otherwise noted, G (preamp) = 14 dB, VREF = 2.5 V (20 dB/V scaling), f = 1 MHz, R_L = 500 Ω, C_L = 5 pF, T_A = 25°C, V_{SS} = ±5 V

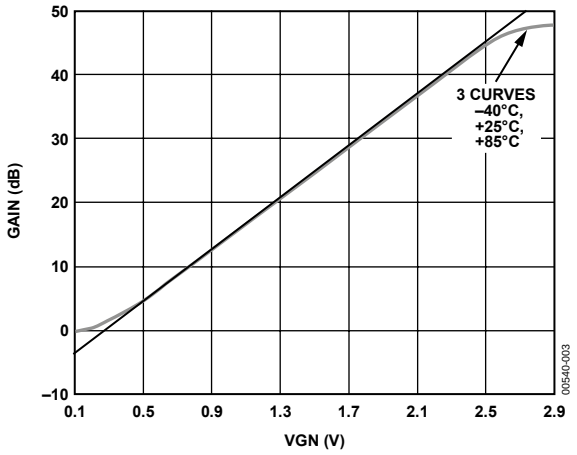


Figure 3. Gain vs. VGN for Three Temperatures

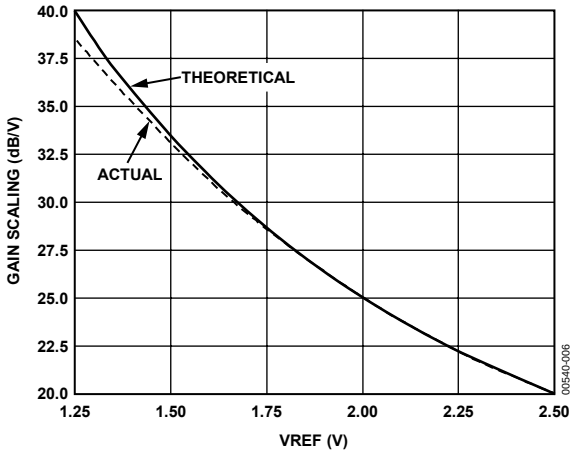


Figure 6. Gain Scaling vs. VREF

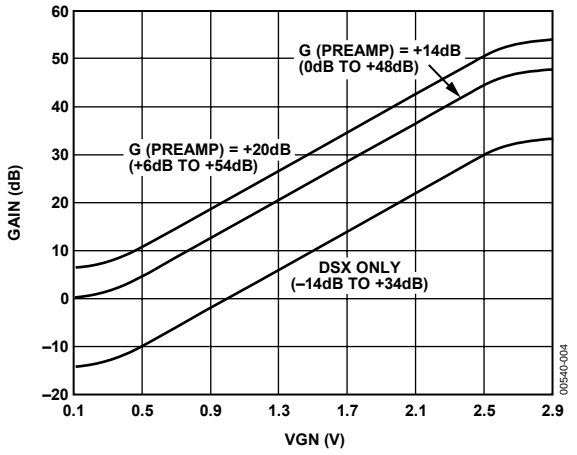


Figure 4. Gain vs. VGN for Different Preamp Gains

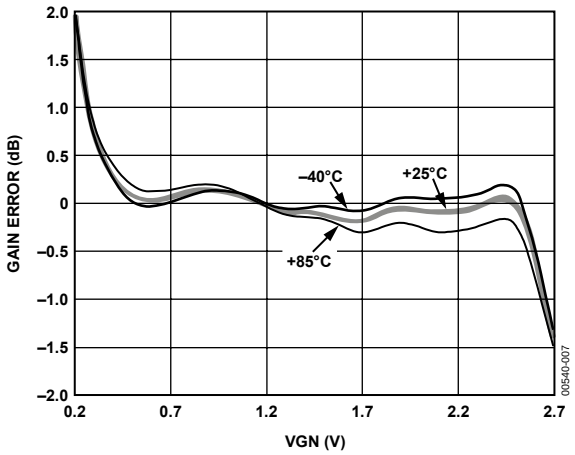


Figure 7. Gain Error vs. VGN

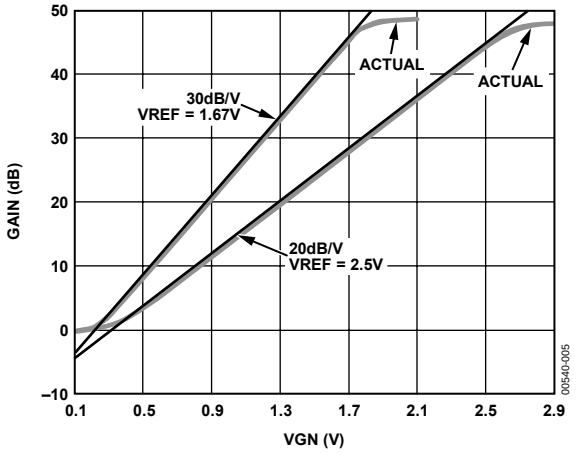


Figure 5. Gain vs. VGN for Different Gain Scalings

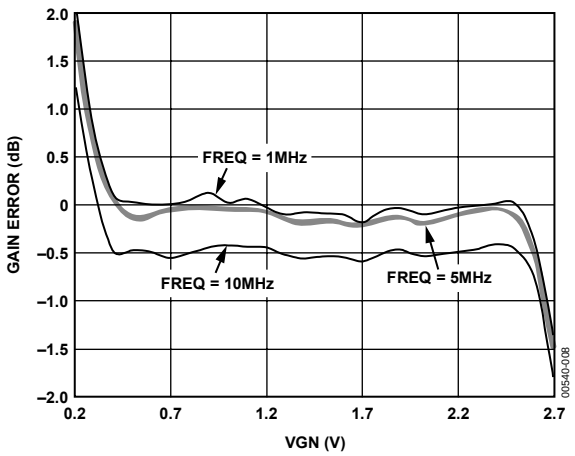


Figure 8. Gain Error vs. VGN at Different Frequencies

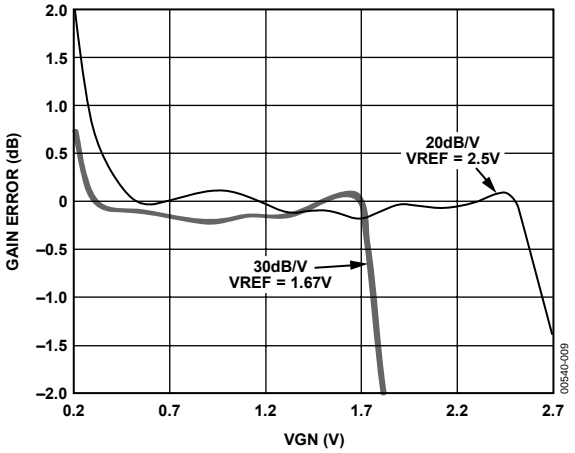


Figure 9. Gain Error vs. VGN for Two Gain Scaling Values

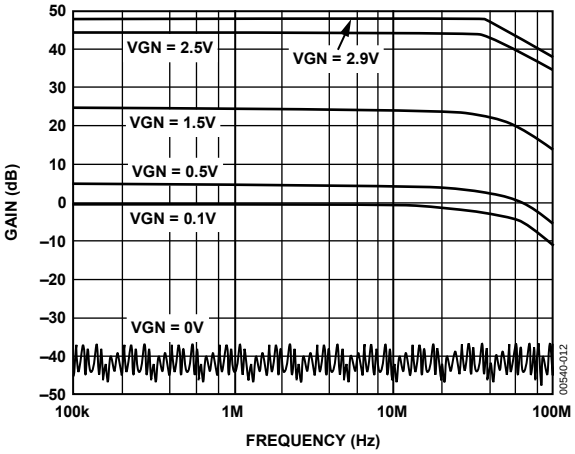


Figure 12. AC Response for Various Values of VGN

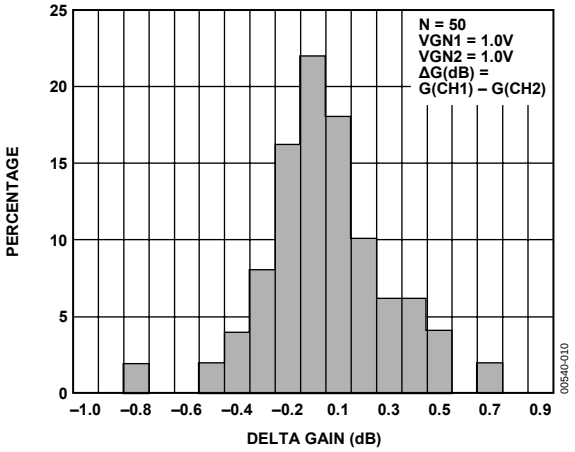


Figure 10. Gain Match; VGN1 = VGN2 = 1.0 V

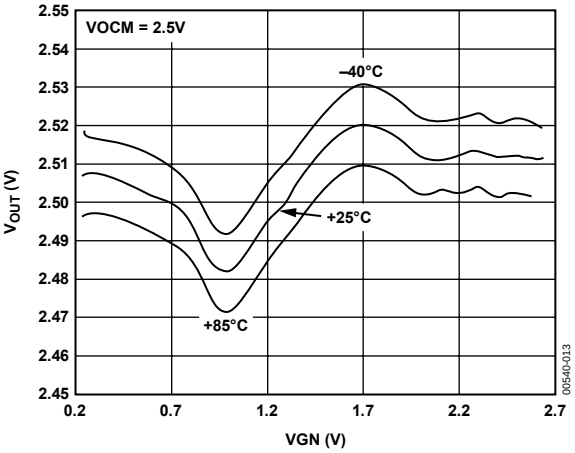


Figure 13. Output Offset vs. VGN for Three Temperatures

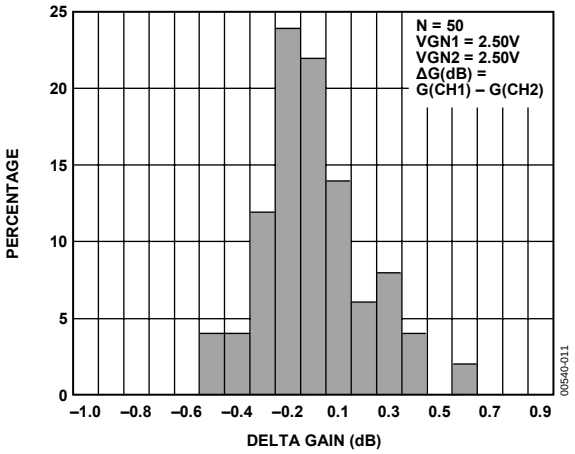


Figure 11. Gain Match: VGN1 = VGN2 = 2.50 V

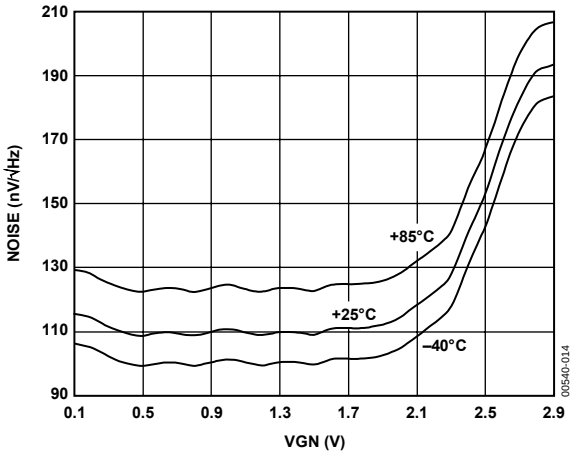


Figure 14. Output Referred Noise vs. VGN for Three Temperatures

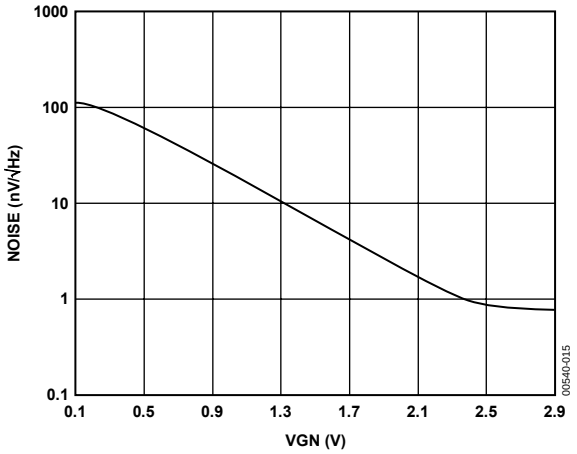


Figure 15. Input Referred Noise vs. VGN

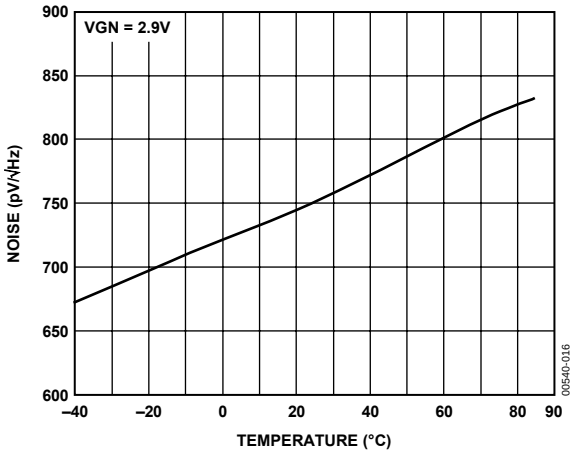


Figure 16. Input Referred Noise vs. Temperature

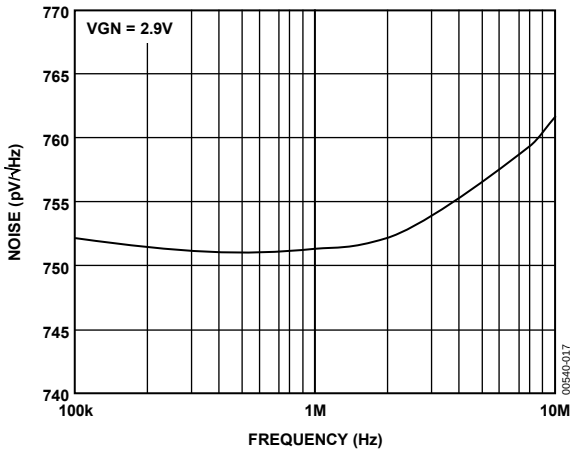


Figure 17. Input Referred Noise vs. Frequency

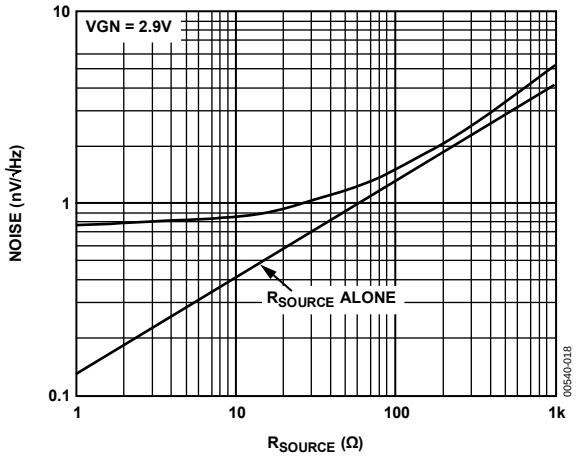


Figure 18. Input Referred Noise vs. R_{SOURCE}

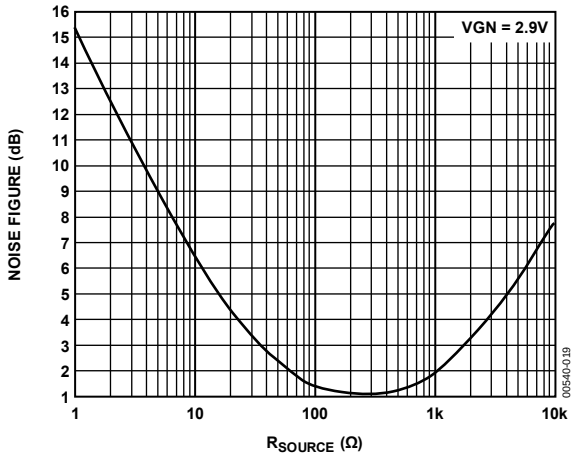


Figure 19. Noise Figure vs. R_{SOURCE}

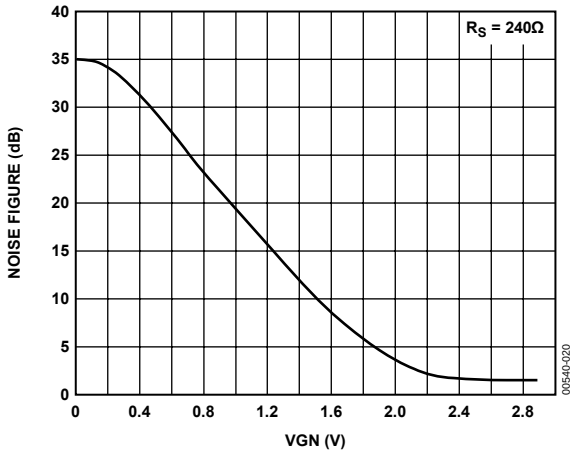


Figure 20. Noise Figure vs. VGN

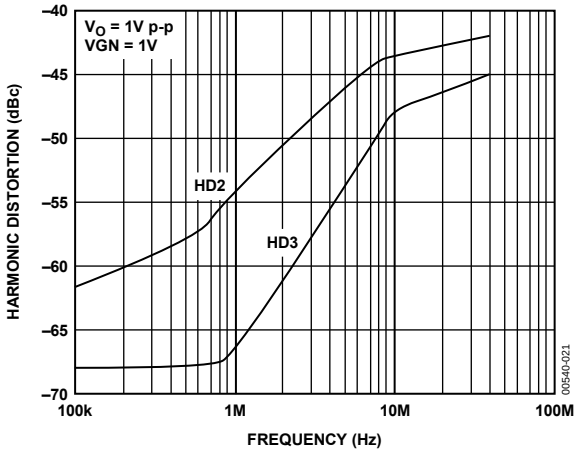


Figure 21. Harmonic Distortion vs. Frequency

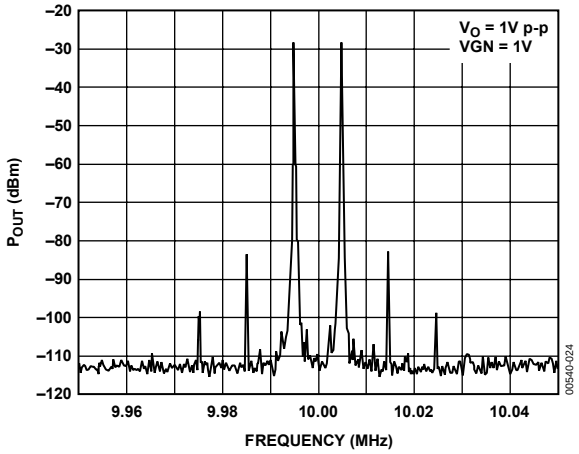


Figure 24. Intermodulation Distortion

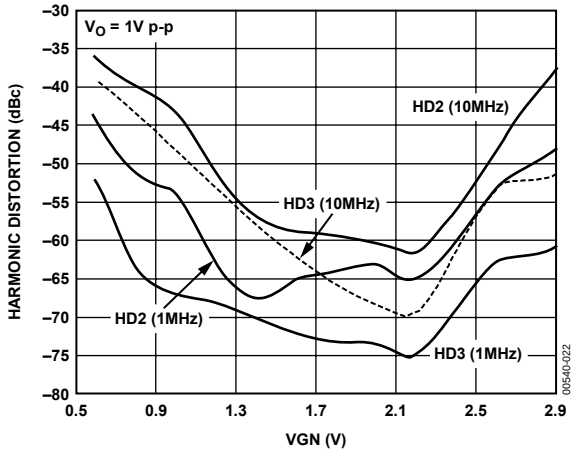


Figure 22. Harmonic Distortion vs. VGN

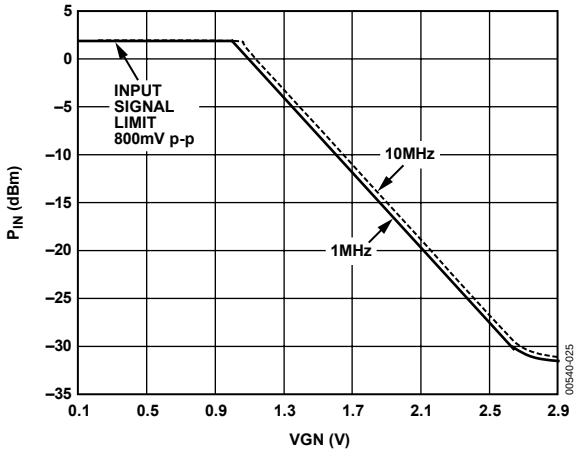


Figure 25. 1 dB Compression vs. VGN

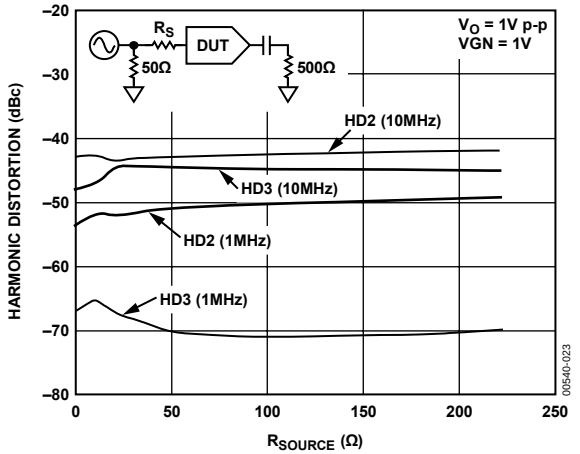


Figure 23. Harmonic Distortion vs. R_{SOURCE}

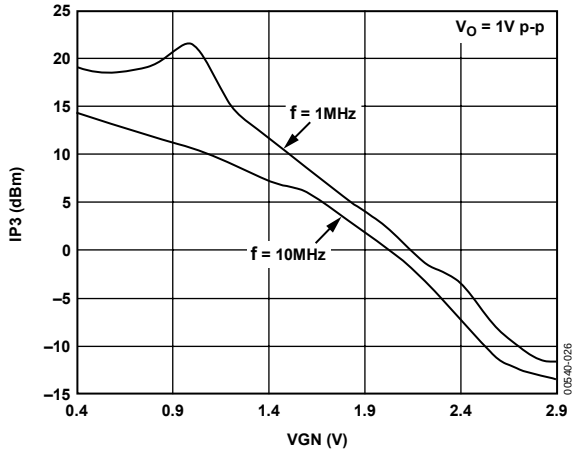


Figure 26. Third-Order Intercept vs. VGN

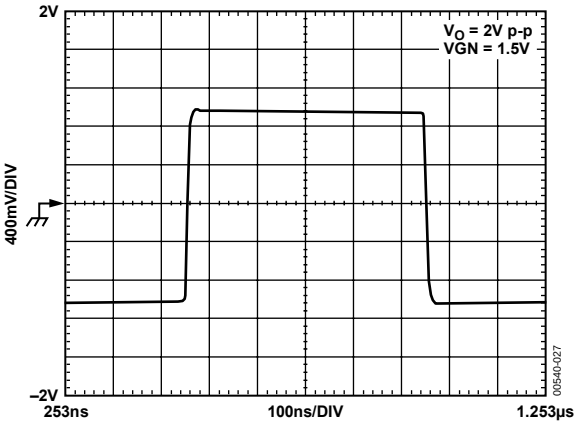


Figure 27. Large Signal Pulse Response

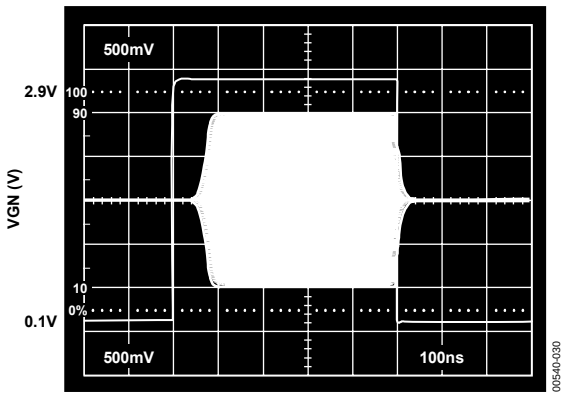


Figure 30. Gain Response

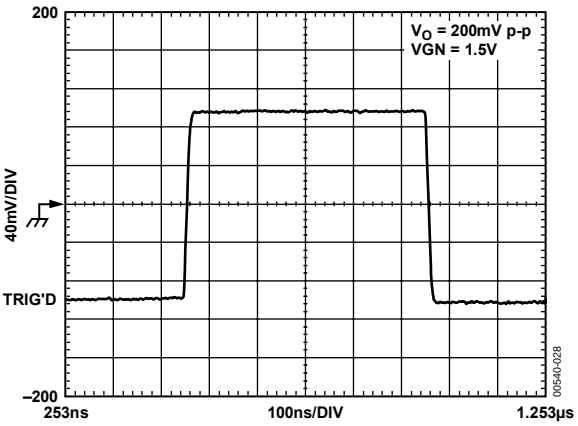


Figure 28. Small Signal Pulse Response

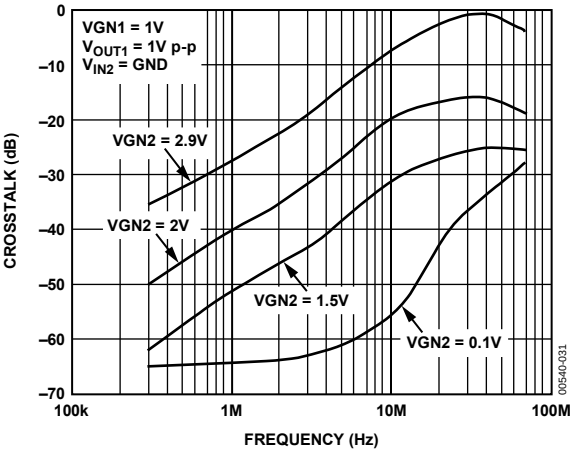


Figure 31. Crosstalk (CH1 to CH2) vs. Frequency

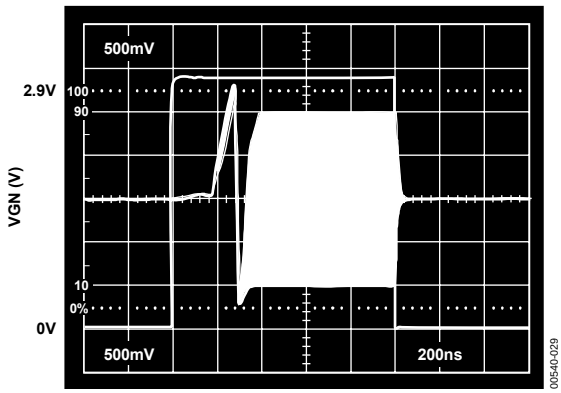


Figure 29. Power-Up/Down Response

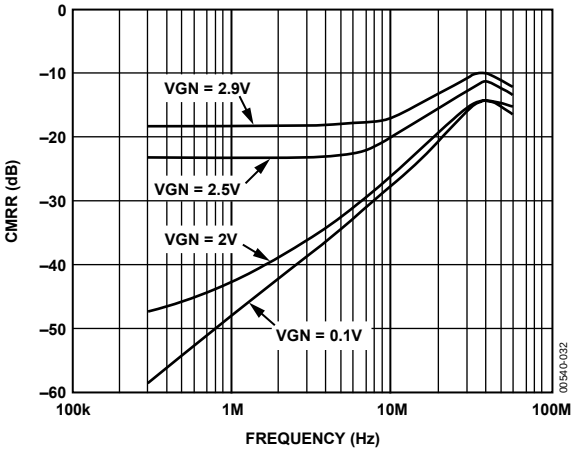


Figure 32. DSX Common-Mode Rejection vs. Frequency

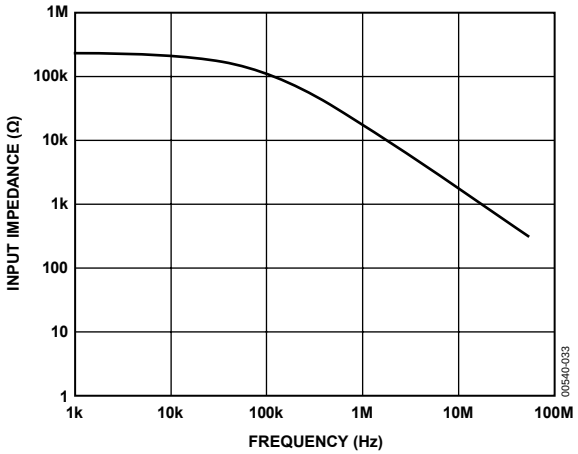


Figure 33. Input Impedance vs. Frequency

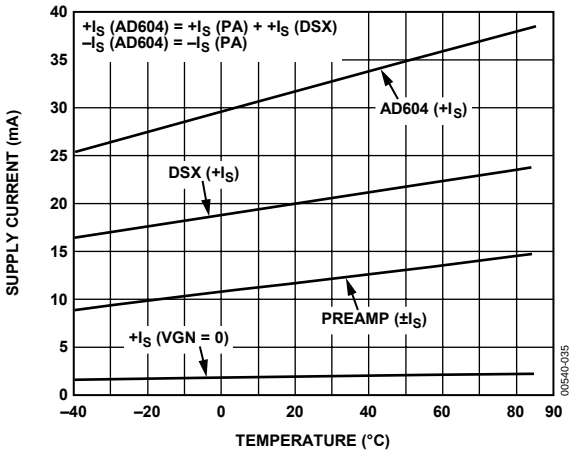


Figure 35. Supply Current (One Channel) vs. Temperature

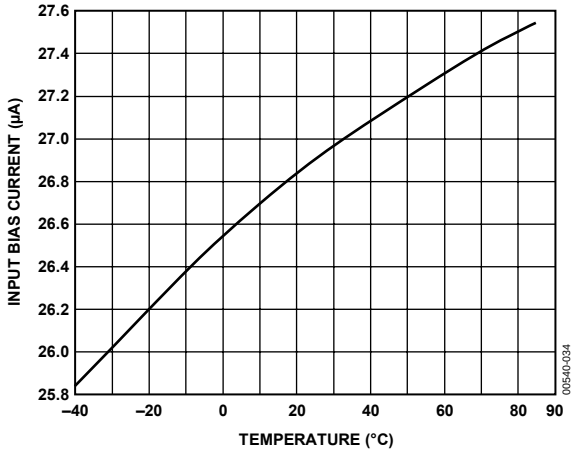


Figure 34. Input Bias Current vs. Temperature

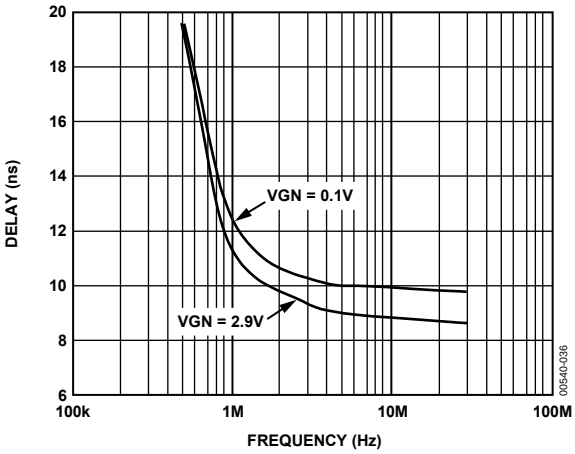


Figure 36. Group Delay vs. Frequency

THEORY OF OPERATION

The AD604 is a dual-channel, variable gain amplifier with an ultralow noise preamplifier. Figure 37 shows the simplified block diagram of one channel. Each channel consists of:

1. A preamplifier with gain setting resistors (R5, R6, and R7).
2. A single-supply X-AMP® (hereafter called DSX, differential single-supply X-AMP), made up of:
   - A precision passive attenuator (differential ladder).
   - A gain control block.
   - A VOCM buffer with supply splitting resistors (R3 and R4).
   - An active feedback amplifier (AFA) with gain setting resistors (R1 and R2). (To understand the active-feedback amplifier topology, refer to the AD830 data sheet. The AD830 is a practical implementation of the idea.)

The preamplifier is powered by a ±5 V supply, while the DSX uses a single +5 V supply. The linear-in-dB gain response of the AD604 can generally be described by

$$G\ (\text{dB}) = \textit{Gain Scaling}\ (\text{dB/V}) \times \textit{Gain Control}\ (\text{V}) + (\textit{Preamp Gain}\ (\text{dB}) - 19\ \text{dB}) \quad (1)$$

Each channel provides between 0 dB to 48.4 dB through 6 dB to 54.4 dB of gain, depending on the user determined preamplifier gain. The center 40 dB of gain is exactly linear-in-dB while the gain error increases at the top and bottom of the range. The gain of the preamplifier is typically either 14 dB or 20 dB but can be set to intermediate values by a single external resistor (see the Preamplifier section for details). The gain of the DSX can vary from −14 dB to +34.4 dB, as is determined by the gain control voltage (VGN). The VREF input establishes the gain scaling; the useful gain scaling range is between 20 dB/V and 40 dB/V for a VREF voltage of 2.5 V and 1.25 V, respectively. For example, if the preamp gain was set to 14 dB and VREF was set to 2.50 V (to establish a gain scaling of 20 dB/V), the gain equation would simplify to

$$G\ (\text{dB}) = 20\ (\text{dB/V}) \times \textit{VGN}\ (\text{V}) - 5\ \text{dB}$$

The desired gain can then be achieved by setting the unipolar gain control (VGN) to a voltage within its nominal operating range of 0.25 V to 2.65 V (for 20 dB/V gain scaling). The gain is monotonic for a complete gain control voltage range of 0.1 V to 2.9 V. Maximum gain can be achieved at a VGN of 2.9 V.

Since the two channels are identical, only Channel 1 will be used to describe their operation. VREF and VOCM are the only inputs that are shared by the two channels, and since they are normally ac grounds, crosstalk between the two channels is minimized. For highest gain scaling accuracy, VREF should have an external low impedance voltage source. For low accuracy 20 dB/V applications, the VREF input can be decoupled with a capacitor to ground. In this mode, the gain scaling is determined by the midpoint between VPOS and GND, so care should be taken to control the supply voltage to 5 V. The input resistance looking into the VREF pin is 10 kΩ ± 20%.

The DSX portion of the AD604 is a single-supply circuit, and the VOCM pin is used to establish the dc level of the midpoint of this portion of the circuit. VOCM needs only an external decoupling capacitor to ground to center the midpoint between the supply voltages (5 V, GND); however, if the dc level of the output is important to the user (see the Applications section for AD9050 example), then VOCM can be specifically set. The input resistance looking into the VOCM pin is 45 kΩ ± 20%.

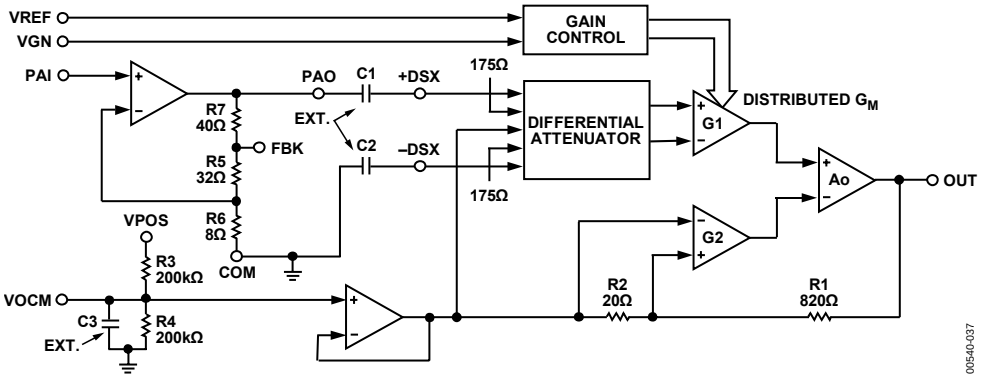


Figure 37. Simplified Block Diagram of a Single Channel of the AD604

PREAMPLIFIER

The input capability of the following single-supply DSX (2.5 ± 2 V for a +5 V supply) limits the maximum input voltage of the preamplifier to ±400 mV for the 14 dB gain configuration or ±200 mV for the 20 dB gain configuration.

The preamplifier gain can be programmed to 14 dB or 20 dB by either shorting the FBK1 node to PAO1 (14 dB) or by leaving node FBK1 open (20 dB). These two gain settings are very accurate since they are set by the ratio of on-chip resistors. Any intermediate gain can be achieved by connecting the appropriate resistor value between PAO1 and FBK1 according to Equation 2 and Equation 3:

$$G = \frac{V_{OUT}}{V_{IN}} = \frac{(R7 \| R_{EXT}) + R5 + R6}{R6} \quad (2)$$

$$R_{EXT} = \frac{[R6 \times G - (R5 + R6)] \times R7}{R7 - (R6 \times G) + (R5 + R6)} \quad (3)$$

Since the internal resistors have an absolute tolerance of ±20%, the gain can be in error by as much as 0.33 dB when R_{EXT} is 30 Ω, where it was assumed that R_{EXT} is exact.

Figure 38 shows how the preamplifier is set to gains of 14 dB, 17.5 dB, and 20 dB. The gain range of a single channel of the AD604 is 0 dB to 48 dB when the preamplifier is set to 14 dB (Figure 38a), 3.5 dB to 51.5 dB for a preamp gain of 17.5 dB (Figure 38b), and 6 dB to 54 dB for the highest preamp gain of 20 dB (Figure 38c).

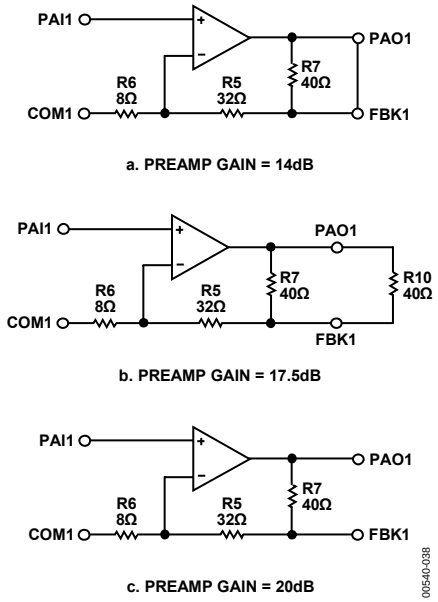


Figure 38. Preamplifier Gain Programmability

For a preamplifier gain of 14 dB, the preamplifier's −3 dB small signal bandwidth is 130 MHz; when the gain is at the high end (20 dB), the bandwidth is reduced by a factor of two to 65 MHz. Figure 39 shows the ac responses for the three preamp gains discussed above; note that the gain for an R_{EXT} of 40 Ω should be 17.5 dB, but the mismatch between the internal resistors and the external resistor has caused the actual gain for this particular preamplifier to be 17.7 dB. The −3 dB small signal bandwidth of one complete channel of the AD604 (preamplifier and DSX) is 40 MHz and is independent of gain.

To achieve its optimum specifications, power and ground management are critical to the AD604. Large dynamic currents result because of the low resistances needed for the desired noise performance. Most of the difficulty is with the very low gain setting resistors of the preamplifier that allow for a total input referred noise, including the DSX, as low as 0.8 nV/√Hz. The consequently large dynamic currents have to be carefully handled to maintain performance even at large signal levels.

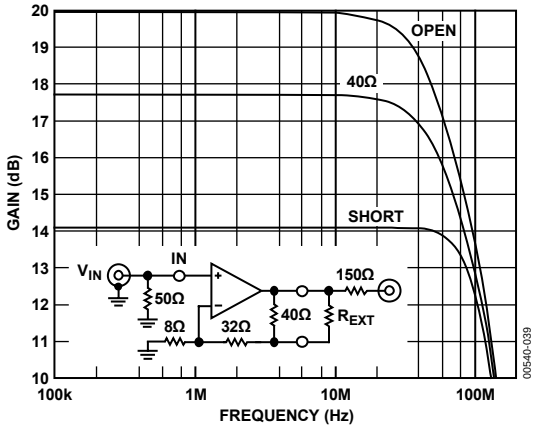


Figure 39. AC Response for Preamplifier Gains of 14 dB, 17.5 dB, and 20 dB

The preamplifier uses a dual ±5 V supply to accommodate large dynamic currents and a ground referenced input. The preamplifier output is also ground referenced, and requires a common-mode level shift into the single-supply DSX. The two external coupling capacitors (C1 and C2 in Figure 37) connected to nodes PAO1 and +DSX, and −DSX and ground, respectively, perform this function (see the AC Coupling section). In addition, they eliminate any offset that would otherwise be introduced by the preamplifier. It should be noted that an offset of 1 mV at the input of the DSX is amplified by 34.4 dB (× 52.5) when the gain control voltage is at its maximum; this equates to 52.5 mV at the output. AC coupling is consequently required to keep the offset from degrading the output signal range.

The internal feedback resistors that set the gain of the preamplifier are so small (nominally 8 Ω and 32 Ω) that even an additional 1 Ω in the "ground" connection at Pin COM1, which serves as the input common-mode reference, will seriously degrade gain accuracy and noise performance. This node is very sensitive and careful attention is necessary to minimize the ground impedance. All connections to node COM1 should be as short as possible.

The preamplifier, including the gain setting resistors, has a noise performance of 0.71 nV/√Hz and 3 pA/√Hz. Note that a significant portion of the total input referred voltage noise is due to the feedback resistors. The equivalent noise resistance presented by R5 and R6 in parallel is nominally 6.4 Ω, which

contributes 0.33 nV/√Hz to the total input referred voltage noise. The larger portion of the input referred voltage noise is coming from the amplifier with 0.63 nV/√Hz. The current noise is independent of gain and depends only on the bias current in the input stage of the preamplifier—it is 3 pA/√Hz.

The preamplifier can drive 40 Ω (the nominal feedback resistors) and the following 175 Ω ladder load of the DSX with low distortion. For example, at 10 MHz and 1 V at the output, the preamplifier has less than −45 dB of second and third harmonic distortion when driven from a low (25 Ω) source resistance.

In some cases, more than 48 dB of gain range is needed, in which case two AD604 channels could be cascaded. Since the preamplifier has a limited input signal range, consumes over half (120 mW) of the total power (220 mW), and its ultralow noise is not necessary after the first AD604 channel, a shutdown mechanism that disables only the preamplifier is built in. All that is required to shut down the preamplifier is to tie the COM1 and/or COM2 pin to the positive supply. The DSX will be unaffected and can be used as before (see the Applications section for further details).

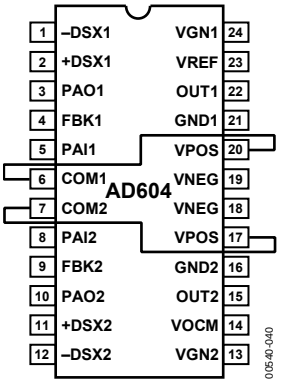


Figure 40. Shutdown of Preamplifiers Only

DIFFERENTIAL LADDER (ATTENUATOR)

The attenuator before the fixed gain amplifier of the DSX is realized by a differential 7-stage R-1.5R resistive ladder network with an untrimmed input resistance of 175 Ω single-ended or 350 Ω differential. The signal applied at the input of the ladder network (Figure 41) is attenuated by 6.908 dB per tap; thus, the attenuation at the first tap is 0 dB, at the second, 13.816 dB, and so on, all the way to the last tap where the attenuation is 48.356 dB. A unique circuit technique is used to interpolate continuously between the tap points, thereby providing continuous attenuation from 0 dB to −48.36 dB. The ladder network, together with the interpolation mechanism, can be considered a voltage-controlled potentiometer.

Since the DSX is a single-supply circuit, some means of biasing its inputs must be provided. Node MID together with the VOCM buffer to perform this function. Without internal biasing, the user would have to dc bias the inputs externally. If not done carefully, the biasing network can introduce additional noise and offsets. By providing internal biasing, the user is relieved of this task and only needs to ac couple the signal into the DSX. It should be made clear again that the input to the DSX is still fully differential if driven differentially, that is, pins +DSX and −DSX see the same signal but with opposite polarity (see the Ultralow Noise, Differential Input-Differential Output VGA section). What changes is the load as seen by the driver; it is 175 Ω when each input is driven single ended, but 350 Ω when driven differentially. This can be easily explained when thinking of the ladder network as just two 175 Ω resistors connected back-to-back with the middle node, MID, being biased by the VOCM buffer. A differential signal applied between nodes +DSX and −DSX results in zero current into node MID, but a single-ended signal applied to either input, +DSX or −DSX, while the other input is ac grounded causes the current delivered by the source to flow into the VOCM buffer via node MID.

The ladder resistor value of 175 Ω was chosen to provide the optimum balance between the load driving capability of the preamplifier and the noise contribution of the resistors. One feature of the X-AMP architecture is that the output referred noise is constant vs. gain over most of the gain range. This can be easily explained by looking at Figure 41 and observing that the tap resistance is equal for all taps after only a few taps away from the inputs. The resistance seen looking into each tap is 54.4 Ω, which makes 0.95 nV/√Hz of Johnson noise spectral density. Since there are two attenuators, the overall noise contribution of the ladder network is √2 times 0.95 nV/√Hz or 1.34 nV/√Hz, a large fraction of the total DSX noise. The rest of the DSX circuit components contribute another 1.20 nV/√Hz, which together with the attenuator produces 1.8 nV/√Hz of total DSX input referred noise.

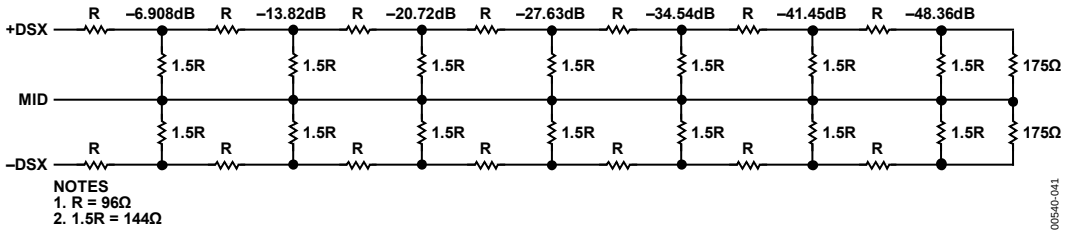


Figure 41. R-1.5R Dual Ladder Network

AC COUPLING

As already mentioned, the DSX portion of the AD604 is a single-supply circuit and, therefore, its inputs need to be ac-coupled to accommodate ground-based signals. External capacitors C1 and C2 in Figure 37 level shift the ground referenced preamplifier output from ground to the dc value established by VOCM (nominal 2.5 V). C1 and C2, together with the 175 Ω looking into each of the DSX inputs (+DSX and −DSX), act as high-pass filters with corner frequencies depending on the values chosen for C1 and C2. For example, if C1 and C2 are 0.1 µF, then together with the 175 Ω input resistance seen into each side of the differential ladder of the DSX, a −3 dB high-pass corner at 9.1 kHz is formed.

If the AD604 output needs to be ground referenced, another ac coupling capacitor is required for level shifting. This capacitor also eliminates any dc offsets contributed by the DSX. With a nominal load of 500 Ω and a 0.1 µF coupling capacitor, this adds a high-pass filter with −3 dB corner frequency at about 3.2 kHz.

The choice for all three of these coupling capacitors depends on the application. They should allow the signals of interest to pass unattenuated, while at the same time, they can be used to limit the low frequency noise in the system.

GAIN CONTROL INTERFACE

The gain control interface provides an input resistance of approximately 2 MΩ at Pin VGN1 and gain scaling factors from 20 dB/V to 40 dB/V for VREF input voltages of 2.5 V to 1.25 V, respectively. The gain scales linearly-in-dB for the center 40 dB of gain range, which for VGN is equal to 0.4 V to 2.4 V for the 20 dB/V scale, and 0.2 V to 1.2 V for the 40 dB/V scale. Figure 42 shows the ideal gain curves for a nominal preamplifier gain of 14 dB, which are described by the following equations:

$$G\ (20\ \text{dB/V}) = 20 \times VGN - 5,\ VREF = 2.500\ \text{V} \quad (4)$$

$$G\ (20\ \text{dB/V}) = 30 \times VGN - 5,\ VREF = 1.666\ \text{V} \quad (5)$$

$$G\ (20\ \text{dB/V}) = 40 \times VGN - 5,\ VREF = 1.250\ \text{V} \quad (6)$$

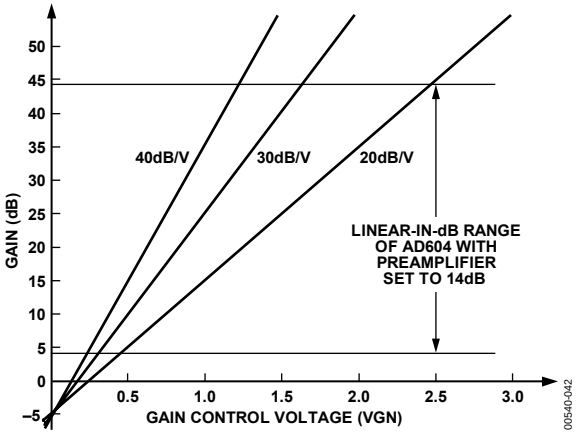


Figure 42. Ideal Gain Curves vs. VGN

From these equations, it can be seen that all gain curves intercept at the same −5 dB point; this intercept will be +6 dB higher (+1 dB) if the preamplifier gain is set to +20 dB or +14 dB, lower (−19 dB) if the preamplifier is not used at all. Outside of the central linear range, the gain starts to deviate from the ideal control law but still provides another 8.4 dB of range. For a given gain scaling, V_{REF} can be calculated as shown in Equation 7:

$$VREF = \frac{2.500\ \text{V} \times 20\ \text{dB/V}}{Gain\ Scale} \quad (7)$$

Usable gain control voltage ranges are 0.1 V to 2.9 V for 20 dB/V scale and 0.1 V to 1.45 V for the 40 dB/V scale. VGN voltages of less than 0.1 V are not used for gain control since below 50 mV, the channel (preamp and DSX) is powered down. This can be used to conserve power and, at the same time, to gate off the signal. The supply current for a powered-down channel is 1.9 mA; the response time to power the device on or off is less than 1 µs.

ACTIVE FEEDBACK AMPLIFIER (FIXED GAIN AMP)

To achieve single-supply operation and a fully differential input to the DSX, an active-feedback amplifier (AFA) is utilized. The AFA is basically an op amp with two g_m stages; one of the active stages is used in the feedback path (therefore the name), while the other is used as a differential input. Note that the differential input is an open-loop g_m stage that requires it to be highly linear over the expected input signal range. In this design, the g_m stage that senses the voltages on the attenuator is a distributed one; for example, there are as many g_m stages as there are taps on the ladder network. Only a few of them are on at any one time, depending on the gain-control voltage.

The AFA makes a differential input structure possible since one of its inputs (G1) is fully differential; this input is made up of a distributed g_m stage. The second input (G2) is used for feedback. The output of G1 will be some function of the voltages sensed on the attenuator taps, which is applied to a high gain amplifier (A0). Because of negative feedback, the differential input to the high gain amplifier has to be zero; this in turn implies that the differential input voltage to G2 times g_{m2} (the transconductance of G2) has to be equal to the differential input voltage to G1 times g_{m1} (the transconductance of G1).

Therefore, the overall gain function of the AFA is

$$\frac{V_{OUT}}{V_{ATTEN}} = \frac{g_{m1}}{g_{m2}} \times \frac{R1 + R2}{R2} \quad (8)$$

where:

V_{OUT} is the output voltage.
V_{ATTEN} is the effective voltage sensed on the attenuator.
$(R1+R2)/R2 = 42$
$g_{m1}/g_{m2} = 1.25$

The overall gain is thus 52.5 (34.4 dB).

The AFA has additional features:

1. Inverting the signal by switching the positive and negative input to the ladder network.
2. The possibility of using the DSX1 input as a second signal input.
3. Fully differential high impedance inputs when both preamplifiers are used with one DSX (the other DSX could still be used alone).
4. Independent control of the DSX common-mode voltage.

Under normal operating conditions, it is best to connect a decoupling capacitor to Pin VOCM, in which case the common-mode voltage of the DSX is half the supply voltage; this allows for maximum signal swing. Nevertheless, the common-mode voltage can be shifted up or down by directly applying a voltage to VOCM. It can also be used as another signal input, the only limitation being the rather low slew rate of the VOCM buffer.

If the dc level of the output signal is not critical, another coupling capacitor is normally used at the output of the DSX; again this is done for level shifting and to eliminate any dc offsets contributed by the DSX (see the AC Coupling section).

APPLICATIONS

The most basic circuit in Figure 43 shows the connections for one channel of the AD604. The signal is applied at Pin 5. RGN is normally 0, in which case the preamplifier is set to a gain of 5 (14 dB). When Pin FBK1 is left open, the preamplifier is set to a gain of 10 (20 dB) and the gain range shifts up by 6 dB. The ac coupling capacitors before Pin −DSX1 and Pin +DSX1 should be selected according to the required lower cutoff frequency. In this example, the 0.1 µF capacitors, together with the 175 Ω seen looking into each of the DSX input pins, provide a −3 dB high-pass corner of about 9.1 kHz. The upper cutoff frequency is determined by the bandwidth of the channel, which is 40 MHz. Note that the signal can be simply inverted by connecting the output of the preamplifier to Pin −DSX1 instead of +DSX1; this is due to the fully differential input of the DSX.

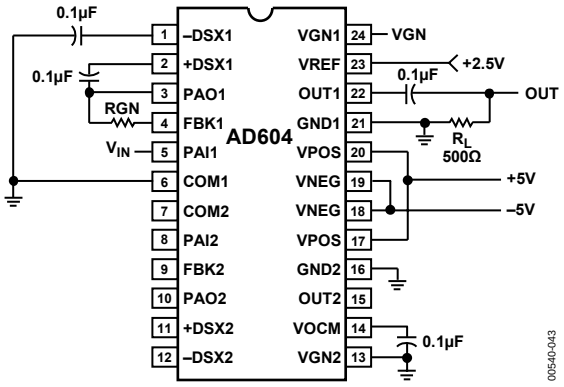


Figure 43. Basic Connections for a Single Channel

As shown here, the output is ac-coupled for optimum performance. In the case of connecting to the AD9050, ac coupling can be eliminated as long as Pin VOCM is biased by the same 3.3 V common-mode voltage as the AD9050 (see Figure 52).

Pin VREF requires a voltage of 1.25 V to 2.5 V, with between 40 dB/V and 20 dB/V gain scaling, respectively. Voltage VGN controls the gain; its nominal operating range is from 0.25 V to 2.65 V for 20 dB/V gain scaling and 0.125 V to 1.325 V for 40 dB/V scaling. When this pin is taken to ground, the channel will power down and disable its output.

Pin COM1 is the main signal ground for the preamplifier and needs to be connected with as short a connection as possible to the input ground. Since the internal feedback resistors of the preamplifier are very small for noise reasons (8 Ω and 32 Ω nominally), it is of utmost importance to keep the resistance in this connection to a minimum. Furthermore, excessive inductance in this connection may lead to oscillations.

As a consequence of the ultralow noise and wide bandwidth of the AD604, large dynamic currents flow to and from the power supply. To ensure the stability of the part, extreme attention to supply decoupling is required. A large storage capacitor in parallel with a smaller high frequency capacitor connected right at the supply pins, together with a ferrite bead coming from the supply, should be used to ensure high frequency stability.

To provide for additional flexibility, Pin COM1 can be used to depower the preamplifier. When COM1 is connected to VP, the preamplifier is off, yet the DSX portion can be used independently. This may be of value when one desires to cascade the two DSX stages in the AD604. In this case, the first DSX output signal with respect to noise is large and using the second preamplifier at this point would waste power (see Figure 44).

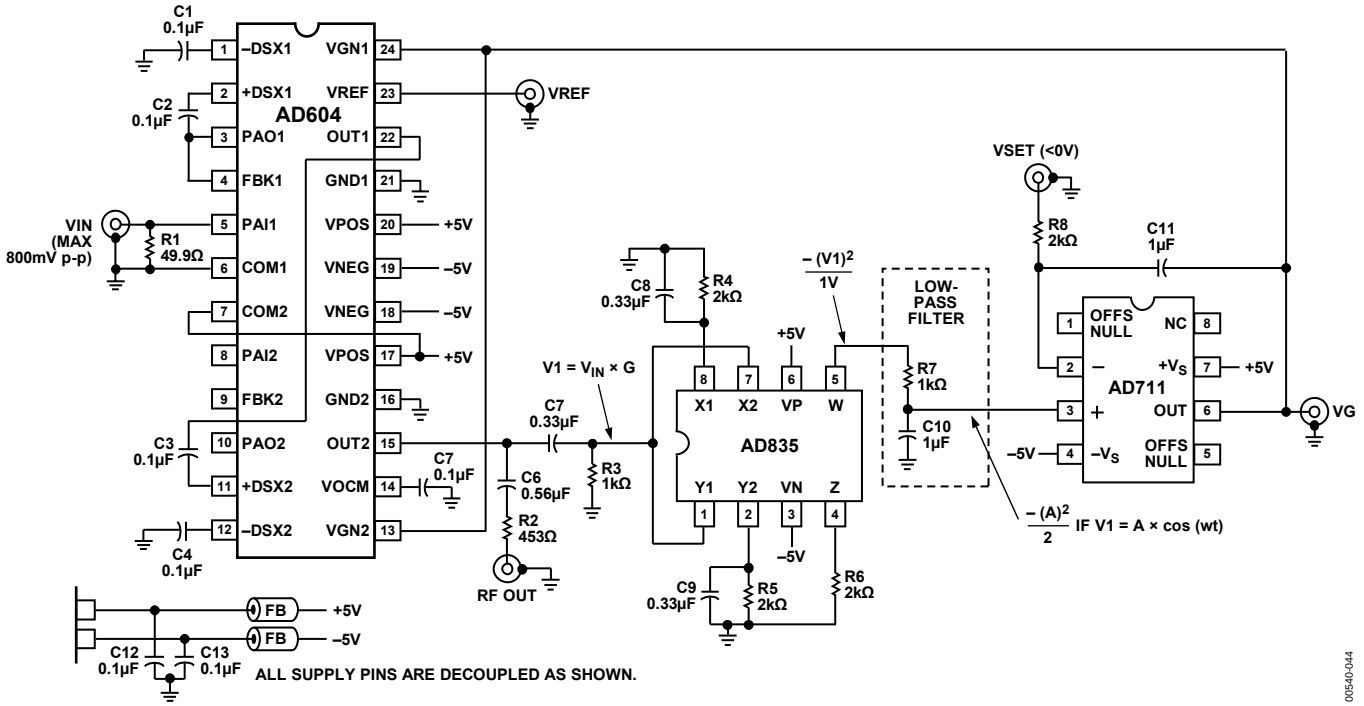


Figure 44. AGC Amplifier with 82 dB of Gain Range

AN ULTRALOW NOISE AGC AMPLIFIER WITH 82 dB TO 96 dB GAIN RANGE

Figure 44 shows an implementation of an AGC amplifier with 82 dB of gain range using a single AD604. First, the connections for the two channels of the AD604 are discussed; second, how the detector circuitry that closes the loop works is discussed.

The signal is applied to connector VIN, and since the signal source was 50 Ω, a terminating resistor (R1) of 50 Ω was added. The signal is then amplified by 14 dB (Pin FBK1 shorted to PAO1) through the Channel 1 preamplifier and is further processed by the Channel 1 DSX. Next, the signal is applied directly to the Channel 2 DSX. The second preamplifier is powered down by connecting its COM2 pin to the positive supply as explained in the Preamplifier section. Capacitor C1 and Capacitor C2 level shift the signal from the preamplifier into the first DSX and at the same time eliminate any offset contribution of the preamp. C3 and C4 have the same offset cancellation purpose for the second DSX. Each set of capacitors, together with the 175 Ω input resistance of the corresponding DSX, provides a high-pass filter with −3 dB corner frequency of about 9.1 kHz. Pin VOCM is decoupled to ground by a 0.1 µF capacitor, while VREF can be externally provided; in this application, the gain scale is set to 20 dB/V by applying 2.500 V. Since each of the DSX amplifiers operates from a single 5 V supply, the output is ac-coupled via C6 and C7. The output signal can be monitored at the connector labeled RF OUT.

Figure 45 and Figure 46 show the gain range and gain error for the AD604 connected as shown. The gain range is −14 dB to +82 dB; the useful range is 0 dB to +82 dB if the RF output amplitude is controlled to ±400 mV (+2 dBm). The main limitation on the lower end of the signal range is the input capability of the preamplifier. This can be overcome by adding an attenuator in front of the preamplifier, but that would defeat the advantage of the ultralow noise preamplifier. It should be noted that the second preamplifier is not used since its ultralow noise and the associated high power consumption are overkill after the first DSX stage. It is disabled in this application by connecting the COM2 pin to the positive supply. Nevertheless, the second preamplifier can be used, if so desired, and the useful gain range will shift up by 14 dB to encompass 0 dB to 96 dB of gain. For the same +2 dBm output, this allows signals as small as −94 dBm to be measured.

To achieve the highest gains, the input signal has to ultimately be bandlimited to reduce the noise; this is especially true if the second preamplifier is used. If the maximum signal at Pin OUT2 of the AD604 is limited to ±400 mV (+2 dBm), the input signal level at the AGC threshold is +25 µV rms (−79 dBm). The circuit as shown has about 40 MHz of noise bandwidth; the 0.8 nV/√Hz of input referred voltage noise spectral density of the AD604 results in an rms noise of 5.05 µV in the 40 MHz bandwidth. The 50 Ω termination resistor, together with the 50 Ω source resistance of the signal generator, combine to an effective resistance as seen by the input of the preamplifier of 25 Ω, which makes 4.07 µV of rms noise in 40 MHz. The noise floor of this channel is consequently the rms sum of these two main noise sources, 6.5 µV rms. This means that the minimum detectable signal (MDS) for this circuit is +6.5 µV rms (−90.7 dBm). As a general rule, the measured signal should be about a factor of three larger than the noise floor, in this case 19.5 µV rms. As we can see, the 25 µV rms signal that this AGC circuit can correct for is just slightly above the MDS. Of course, the sensitivity of

the input can be improved by bandlimiting the signal; if the noise bandwidth is reduced by a factor of four to 10 MHz, the noise floor of the AGC circuit with a 50 Ω termination resistor drops to +3.25 μV rms (−96.7 dBm). Further noise improvement can be achieved by an input matching network or by transformer coupling of the input signal.

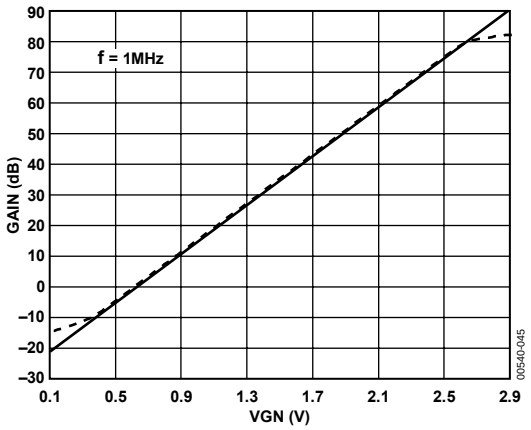


Figure 45. AD604 Cascaded Gain vs. VGN

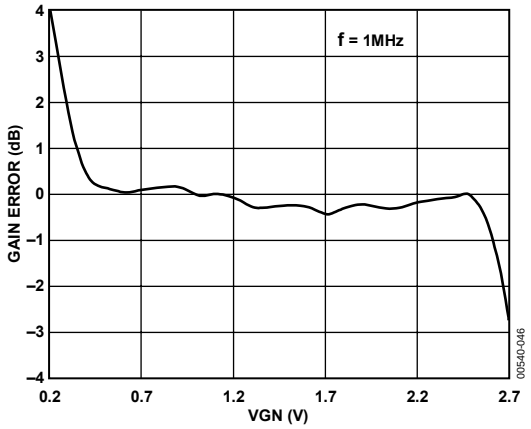


Figure 46. AD604 Cascaded Gain Error vs. VGN

The descriptions of the detector circuitry functions, comprised of a squarer, a low-pass filter, and an integrator, follow. At this point, it is necessary to make some assumptions about the input signal. The following explanation of the detector circuitry presumes an amplitude modulated RF carrier where the modulating signal is at a much lower frequency than the RF signal. The AD835 multiplier functions as the detector by squaring the output signal presented to it by the AD604. A low-pass filter following the squaring operation removes the RF signal component at twice the incoming signal frequency, while passing the low frequency AM information. The following integrator with a time constant of 2 ms set by R8 and C11 integrates the error signal presented by the low-pass filter and changes VG until the error signal is equal to V_{SET}.

For example, if the signal presented to the detector is $V1 = A \times \cos(\omega t)$ as indicated in Figure 44, the output of the squarer is $-(V1)^2/1$ V. The reason for all the minus signs in the detection circuitry comes from the necessity of providing negative feedback in the control loop; actually, if V_{SET} becomes greater than 0 V, the control loop provides positive feedback. Squaring $A \times \cos(\omega t)$ results in two terms, one at dc and one at 2ω; the following low-pass filter passes only the $-(A)^2/2$ dc term. This dc voltage is now forced equal to the voltage, V_{SET}, by the control loop. The squarer, together with the low-pass filter, functions as a mean-square detector. As should be evident by controlling the value of V_{SET}, we can set the amplitude of the voltage V1 at the input of the AD835; if V_{SET} equals −80 mV, the AGC output signal amplitude will be ±400 mV.

Figure 47 shows the control voltage, VGN, vs. the input power at frequencies of 1 MHz (solid line) and 10 MHz (dashed line) at an output regulated level of 2 dBm (800 mV p-p). The AGC threshold is evident at a P_{IN} of about −79 dBm; the highest input power that could still be accommodated was about +3 dBm. At this level, the output starts being distorted because of clipping in the preamplifier.

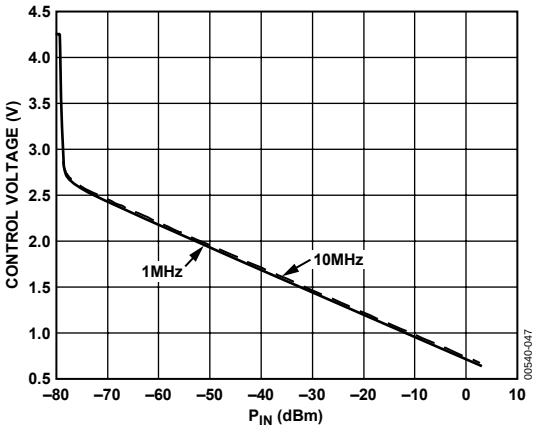


Figure 47. Control Voltage vs. Input Power of Circuit in Figure 44

As mentioned already, the second preamplifier can be used to extend the range of the AGC circuit in Figure 44. Figure 48 shows the modifications that need to be made to Figure 46 to achieve 96 dB of gain and dynamic range. Because of the extremely high gain, the bandwidth needs to be limited to reject some of the noise; furthermore, limiting the bandwidth helps suppress high frequency oscillations. The added components act as a low-pass filter and dc block (C5 level shifts the output of the first DSX from 2.5 V to ground); the ferrite bead has an impedance of about 5 Ω at 1 MHz, 30 Ω at 10 MHz, and 70 Ω at 100 MHz. Together with R2 and C6, the bead makes a low-pass filter that attenuates higher frequencies; at 1 MHz the attenuation is about −0.2 dB, while at 10 MHz, it increases to −6 dB, on to −28 dB at 100 MHz. Signals now have to be less than about 1 MHz to not be significantly affected by the added circuitry.

Figure 49 shows the control voltage vs. the input power at 1 MHz to the circuit in Figure 48; note that the AGC threshold is at −95 dBm. The output signal level was set to 800 mV p-p by applying −80 mV to the V_{SET} connector.

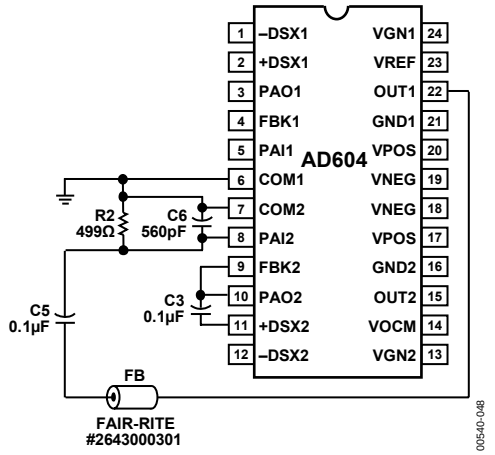


Figure 48. Modifications of AGC Amplifier to Create 96 dB of Gain Range

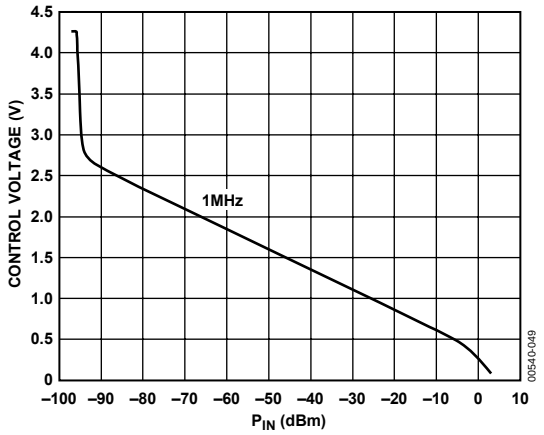


Figure 49. Control Voltage vs. Input Power of Circuit in Figure 48

ULTRALOW NOISE, DIFFERENTIAL INPUT-DIFFERENTIAL OUTPUT VGA

Figure 50 shows how to use both preamplifiers and DSXs to create a high impedance, differential input-differential output variable gain amplifier. This application takes advantage of the differential inputs to the DSXs. It should be pointed out that the input is not truly differential, in the sense that the common-mode voltage needs to be at ground to achieve maximum input signal swing. This has mainly to do with the limited output swing capability of the output drivers of the preamplifiers; they clip around ±2.2 V due to having to drive an effective load of about 30 Ω. If a different input common-mode voltage needs to be accommodated, ac coupling (as was done in Figure 48) is recommended. The differential gain range of this circuit runs from 6 dB to 54 dB. This is 6 dB higher than each individual channel of the AD604 because the DSX inputs now see twice the signal amplitude compared to when they are driven single ended.

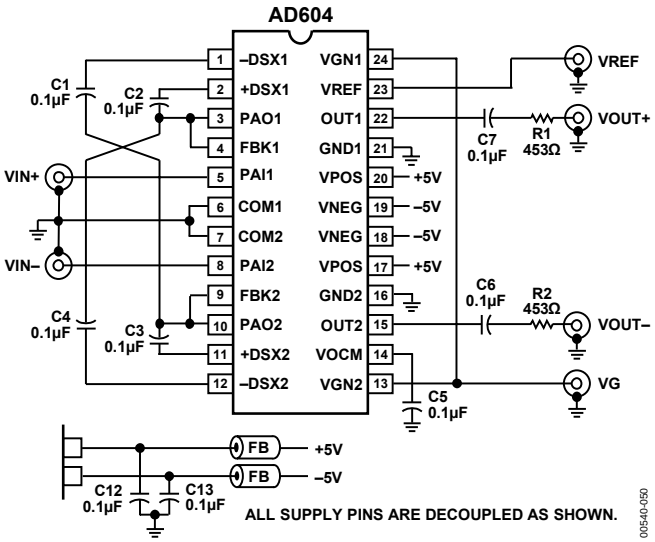


Figure 50. Ultralow Noise, Differential Input-Differential Output VGA

Figure 51 displays the output signals VOUT+ and VOUT– after a −20 dB attenuator formed between the 453 Ω resistors shown in Figure 50 and the 50 Ω loads presented by the oscilloscope plug-in. R1 and R2 were inserted to ensure a nominal load of 500 Ω at each output. The differential gain of the circuit was set to 20 dB by applying a control voltage, VGN, of 1 V; the gain scaling was 20 dB/V for a VREF of 2.500 V; the input frequency was 10 MHz and the differential input amplitude 100 mV p-p. The resulting differential output amplitude was 1 V p-p as can be seen on the scope photo when reading the vertical scale as 200 mV/div.

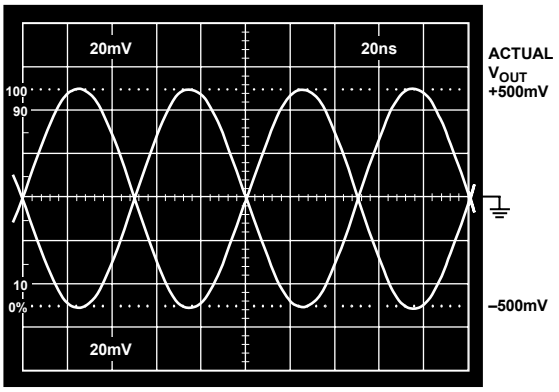


Figure 51. Output of VGA in Figure 50 for VGN = 1 V

MEDICAL ULTRASOUND TGC DRIVING THE AD9050, A 10-BIT, 40 MSPS ADC

The AD604 is an ideal candidate for the time gain control (TGC) amplifier that is required in medical ultrasound systems to limit the dynamic range of the signal that is presented to the ADC. Figure 52 shows a schematic of an AD604 driving an AD9050 in a typical medical ultrasound application.

The gain is controlled by means of a digital byte that is input to an AD7226 DAC that outputs the analog gain control signal.

The output common-mode voltage of the AD604 is set to VPOS/2 by means of an internal voltage divider. The VOCM pin is bypassed with a 0.1 µF capacitor to ground.

The DSX output is optionally filtered and then buffered by an AD9631 op amp, a low distortion, low noise amplifier. The op amp output is ac-coupled into the self-biasing input of an AD9050 ADC that is capable of outputting 10 bits at a 40 MSPS sampling rate.

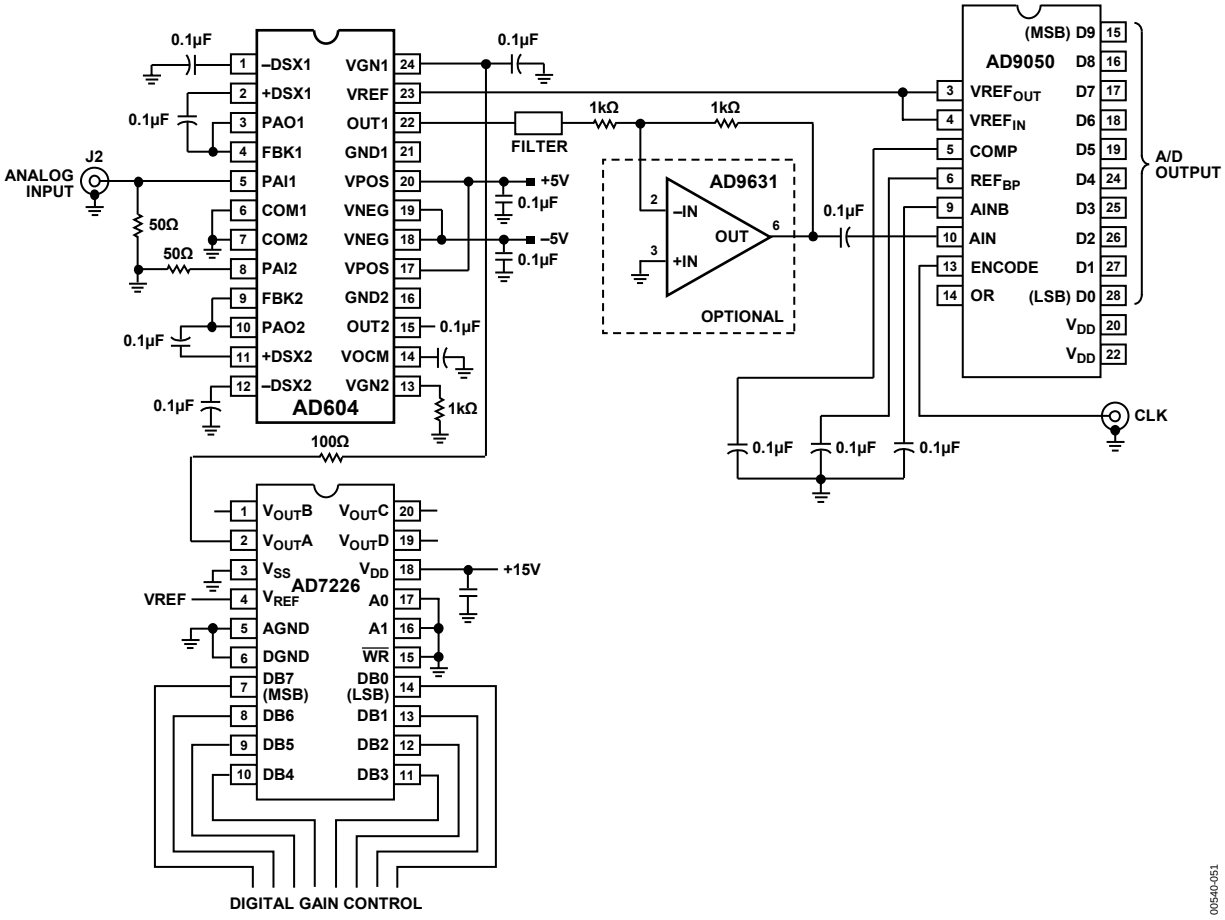


Figure 52. TGC Circuit for Medical Ultrasound Application

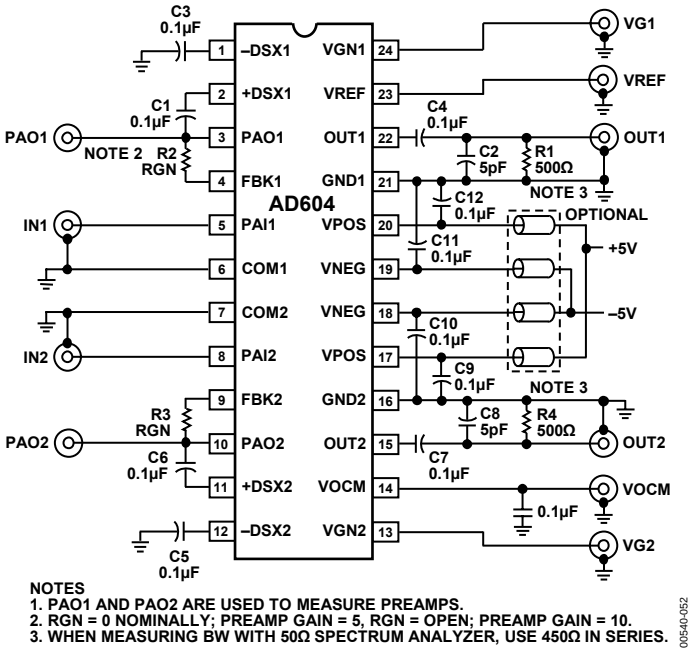


Figure 53. Basic Test Board

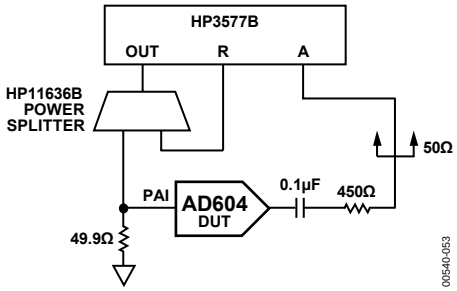
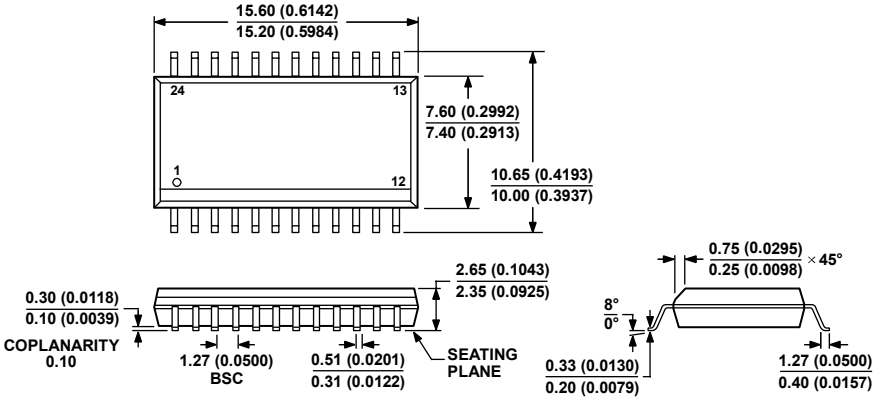


Figure 54. Setup for Gain Measurements

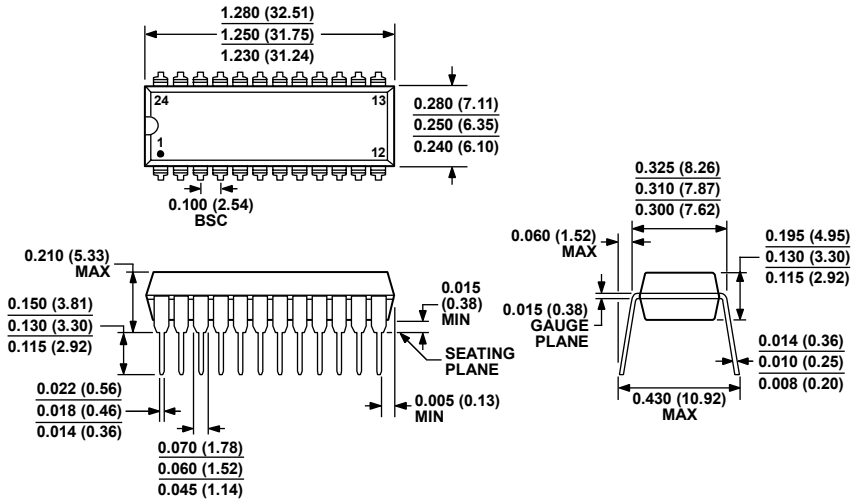
OUTLINE DIMENSIONS



COMPLIANT TO JEDEC STANDARDS MS-013-AD
CONTROLLING DIMENSIONS ARE IN MILLIMETERS; INCH DIMENSIONS
(IN PARENTHESES) ARE ROUNDED-OFF MILLIMETER EQUIVALENTS FOR
REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN.

060706-A

Figure 55. 24-Lead Standard Small Outline Package [SOIC_W]
Wide Body
(RW-24)
Dimensions shown in millimeters and (inches)



COMPLIANT TO JEDEC STANDARDS MS-001
CONTROLLING DIMENSIONS ARE IN INCHES; MILLIMETER DIMENSIONS
(IN PARENTHESES) ARE ROUNDED-OFF INCH EQUIVALENTS FOR
REFERENCE ONLY AND ARE NOT APPROPRIATE FOR USE IN DESIGN.
CORNER LEADS MAY BE CONFIGURED AS WHOLE OR HALF LEADS.

071006-A

Figure 56. 24-Lead Plastic Dual In-Line Package [PDIP]
Narrow Body
(N-24-1)
Dimensions shown in inches and (millimeters)

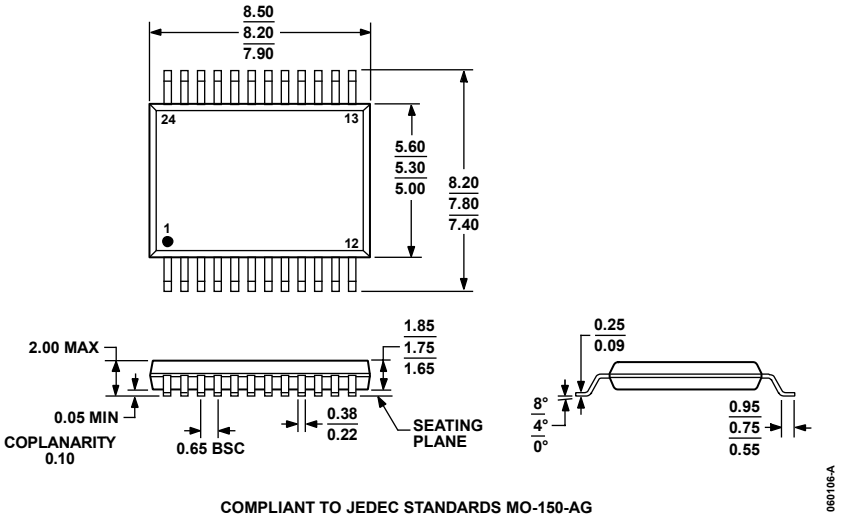


Figure 57. 24-Lead Shrink Small Outline Package [SSOP]
(RS-24)
Dimensions shown in millimeters

ORDERING GUIDE

Model	Temperature Range	Package Description	Package Option
AD604AN	−40°C to +85°C	24-Lead Plastic Dual In-Line Package [PDIP]	N-24-1
AD604ANZ[1]	−40°C to +85°C	24-Lead Plastic Dual In-Line Package [PDIP]	N-24-1
AD604AR	−40°C to +85°C	24-Lead Standard Small Outline Package [SOIC_W]	RW-24
AD604AR-REEL	−40°C to +85°C	24-Lead Standard Small Outline Package [SOIC_W]	RW-24
AD604ARZ[1]	−40°C to +85°C	24-Lead Standard Small Outline Package [SOIC_W]	RW-24
AD604ARZ-RL[1]	−40°C to +85°C	24-Lead Standard Small Outline Package [SOIC_W]	RW-24
AD604ARS	−40°C to +85°C	24-Lead Shrink Small Outline Package [SSOP]	RS-24
AD604ARS-REEL	−40°C to +85°C	24-Lead Shrink Small Outline Package [SSOP]	RS-24
AD604ARS-REEL7	−40°C to +85°C	24-Lead Shrink Small Outline Package [SSOP]	RS-24
AD604ARSZ[1]	−40°C to +85°C	24-Lead Shrink Small Outline Package [SSOP]	RS-24
AD604ARSZ-RL[1]	−40°C to +85°C	24-Lead Shrink Small Outline Package [SSOP]	RS-24
AD604ARSZ-RL7[1]	−40°C to +85°C	24-Lead Shrink Small Outline Package [SSOP]	RS-24
AD604-EB		Evaluation Board	

[1] Z = Pb-free part.

AD604

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