TEXAS INSTRUMENTS

OPA1652, OPA1654

SBOS477B – DECEMBER 2011 – REVISED DECEMBER 2016

OPA165x SoundPlus™ Low Noise and Distortion, General-Purpose, FET-Input Audio Operational Amplifiers

1 Features

- Low Noise:
  4.5 nV/√Hz at 1 kHz
  3.8 nV/√Hz at 10 kHz
- Low Distortion: 0.00005% at 1 kHz
- Low Quiescent Current:
  2 mA per Channel
- Low Input Bias Current: 10 pA
- Slew Rate: 10 V/μs
- Wide Gain Bandwidth: 18 MHz (G = 1)
- Unity-Gain Stable
- Rail-to-Rail Output
- Wide Supply Range:
  ±2.25 V to ±18 V, or 4.5 V to 36 V
- Dual and Quad Versions Available
- Small Package Sizes:
  Dual: SO-8 and MSOP-8
  Quad: SO-14 and TSSOP-14

2 Applications

- Analog and Digital Mixers
- Audio Effects Processors
- Musical Instruments
- A/V Receivers
- DVD and Blu-Ray™ Players
- Car Audio Systems

3 Description

The OPA1652 (dual) and OPA1654 (quad) FET-input operational amplifiers achieve a low 4.5-nV/√Hz noise density with an ultra-low distortion of 0.00005% at 1 kHz. The OPA1652 and OPA1654 op amps offer rail-to-rail output swing to within 800 mV with a 2-kΩ load, which increases headroom and maximizes dynamic range. These devices also have a high output drive capability of ±30 mA.

These devices operate over a very-wide-supply range of ±2.25 V to ±18 V, or 4.5 V to 36 V, on only 2 mA of supply current per channel. The OPA1652 and OPA1654 op amps are unity-gain stable and provide excellent dynamic behavior over a wide range of load conditions.

These devices also feature completely independent circuitry for lowest crosstalk and freedom from interactions between channels, even when overdriven or overloaded.

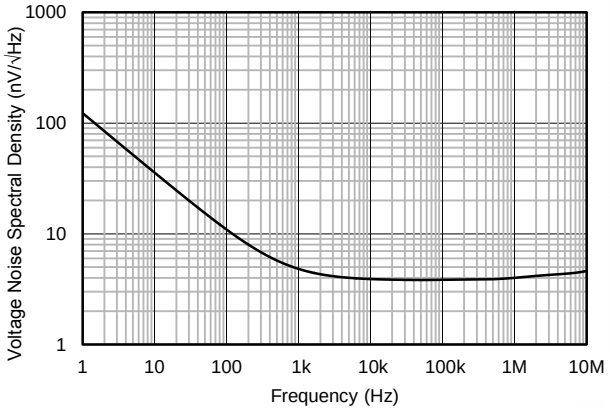
The OPA1652 and OPA1654 temperature ranges are specified from –40°C to +85°C.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
OPA1652	SOIC (8)	4.90 mm × 3.91 mm
	VSSOP (8)	3.00 mm × 3.00 mm
	WSON (8)	3.00 mm × 3.00 mm
OPA1654	SOIC (14)	8.65 mm × 3.91 mm
	TSSOP (14)	5.00 mm × 4.40 mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

Input Voltage Noise Spectral Density



An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.

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4 Revision History

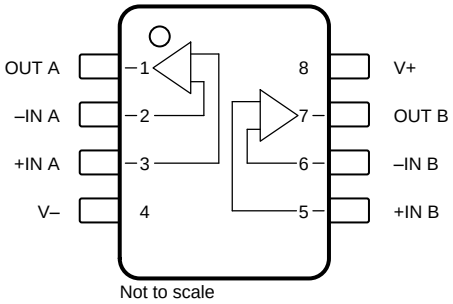
NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision A (August 2016) to Revision B	Page
• Added new SON (8) package and body size information to *Device Information* table	1
• Added new pinout drawing for OPA1652 DRG (WSON) package	3
• Added thermal information for the DRG (WSON) package in the *Thermal Information* table	6

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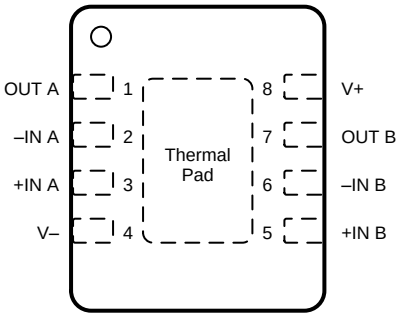
5 Pin Configuration and Functions

OPA1652 D and DGK Packages
8-Pin SOIC and VSSOP
Top View



Not to scale

OPA1652 DRG Package
8-Pin WSON With Exposed Thermal Pad
Top View



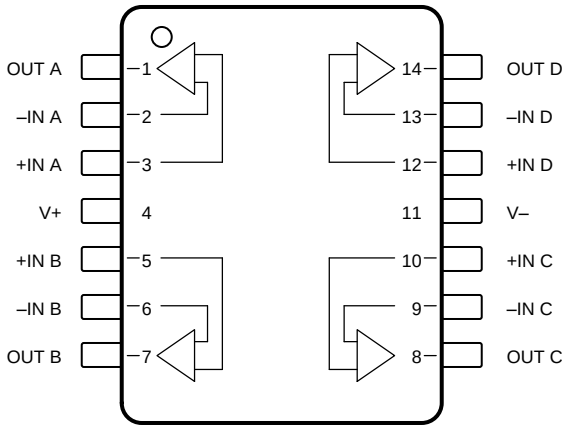
Not to scale

Pin Functions: OPA1652

PIN		I/O	DESCRIPTION
NAME	NO.		
–IN A	2	I	Inverting input, channel A
+IN A	3	I	Noninverting input, channel A
–IN B	6	I	Inverting input, channel B
+IN B	5	I	Noninverting input, channel B
OUT A	1	O	Output, channel A
OUT B	7	O	Output, channel B
V–	4	—	Negative (lowest) power supply
V+	8	—	Positive (highest) power supply
Thermal pad	—	—	Exposed thermal die pad on underside of DRG package; connect thermal die pad to V–. Soldering the thermal pad improves heat dissipation and provides specified performance

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OPA1654 D and PW Packages
14-Pin SOIC and TSSOP
Top View



Not to scale

Pin Functions: OPA1654

PIN		I/O	DESCRIPTION
NAME	NO.		
–IN A	2	I	Inverting input, channel A
+IN A	3	I	Noninverting input, channel A
–IN B	6	I	Inverting input, channel B
+IN B	5	I	Noninverting input, channel B
–IN C	9	I	Inverting input, channel C
+IN D	10	I	Noninverting input, channel C
–IN D	13	I	Inverting input, channel D
+IN D	12	I	Noninverting input, channel D
OUT A	1	O	Output, channel A
OUT B	7	O	Output, channel B
OUT C	8	O	Output, channel C
OUT D	14	O	Output, channel D
V–	11	—	Negative (lowest) power supply
V+	4	—	Positive (highest) power supply

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6 Specifications

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)

		MIN	MAX	UNIT
Voltage	Supply voltage, V_S = (V+) – (V–)		40	V
	Input	(V–) – 0.5	(V+) + 0.5	V
Current	Input (all pins except power-supply pins)	–10	10	mA
	Output short-circuit(2)	Continuous		
Temperature	Operating, T_A	–55	125	°C
	Junction, T_J		200	°C
	Storage, T_{stg}	–65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) Short-circuit to V_S / 2 (ground in symmetrical dual supply setups), one amplifier per package.

6.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001(1)	±2000	V
		Charged-device model (CDM), per JEDEC specification JESD22-C101(2)	±1000	
		Machine model (MM)	±200	

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
(2) JEDEC document JEP157 states that 250-V CDM allows safe manufacturing with a standard ESD control process.

6.3 Recommended Operating Conditions

over operating free-air temperature range (unless otherwise noted)

		MIN	NOM	MAX	UNIT
	Supply voltage	4.5 (±2.25)		36 (±18)	V
T_A	Operating temperature	–40		85	°C

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6.4 Thermal Information: OPA1652

THERMAL METRIC[1]		OPA1652			UNIT
		D (SOIC)	DGK (VSSOP)	DRG (WSON)	
		8 PINS	8 PINS	8 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	143.6	218.9	66.9	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	76.9	78.6	54.5	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	61.8	103.7	40.4	°C/W
ψ_{JT}	Junction-to-top characterization parameter	27.8	14.6	1.9	°C/W
ψ_{JB}	Junction-to-board characterization parameter	61.3	101.8	40.4	°C/W
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance	N/A	N/A	10.8	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report.

6.5 Thermal Information: OPA1654

THERMAL METRIC[1]		OPA1654		UNIT
		D (SOIC)	PW (TSSOP)	
		14 PINS	14 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	90.1	126.9	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	54.8	46.6	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	44.4	58.6	°C/W
ψ_{JT}	Junction-to-top characterization parameter	19.9	5.5	°C/W
ψ_{JB}	Junction-to-board characterization parameter	44.2	57.8	°C/W
$R_{\theta JC(bot)}$	Junction-to-case (bottom) thermal resistance	N/A	N/A	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report.

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6.6 Electrical Characteristics: V_S = ±15 V

at T_A = 25°C, R_L = 2 kΩ, and V_{CM} = V_{OUT} = midsupply, unless otherwise noted

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
AUDIO PERFORMANCE							
THD + N	Total harmonic distortion + noise				0.00005%		
		G = 1, f = 1 kHz, V_O = 3 V_{RMS}			–126		dB
IMD	Intermodulation distortion	G = 1, V_O = 3 V_{RMS}	SMPTE and DIN Two-Tone, 4:1 (60 Hz and 7 kHz)		0.00005%		
					–126		dB
			DIM 30 (3-kHz square wave and 15-kHz sine wave)		0.00005%		
					–126		dB
			CCIF Twin-Tone (19 kHz and 20 kHz)		0.00005%		
					–126		dB
FREQUENCY RESPONSE							
GBW	Gain-bandwidth product	G = 1			18		MHz
SR	Slew rate	G = –1			10		V/µs
	Full power bandwidth(1)	V_O = 1 V_P			1.6		MHz
	Overload recovery time	G = –10			1		µs
	Channel separation (dual and quad)	f = 1 kHz			–120		dB
NOISE							
e_n	Input voltage noise	f = 20 Hz to 20 kHz			4.0		μV_{PP}
	Input voltage noise density	f = 1 kHz			4.5		nV/√Hz
		f = 10 kHz			3.8		nV/√Hz
I_n	Input current noise density	f = 1 kHz			3		fA/√Hz
OFFSET VOLTAGE							
V_{OS}	Input offset voltage	V_S = ±2.25 V to ±18 V			±0.5	±1.5	mV
		V_S = ±2.25 V to ±18 V, T_A = –40°C to 85°C(2)			2	8	µV/°C
PSRR	Power-supply rejection ratio	V_S = ±2..25 V to ±18 V			3	8	µV/V
INPUT BIAS CURRENT							
I_B	Input bias current	V_{CM} = 0 V			±10	±100	pA
I_{OS}	Input offset current	V_{CM} = 0 V			±10	±100	pA
INPUT VOLTAGE RANGE							
V_{CM}	Common-mode voltage range			(V–) + 0.5		(V+) – 2	V
CMRR	Common-mode rejection ratio			100	110		dB
INPUT IMPEDANCE							
	Differential				100 || 6		MΩ || pF
	Common-mode				6000 || 2		GΩ || pF
OPEN-LOOP GAIN							
A_{OL}	Open-loop voltage gain	(V–) + 0.8 V ≤ V_O ≤ (V+) – 0.8 V, R_L = 2 kΩ		106	114		dB
OUTPUT							
V_{OUT}	Voltage output	R_L = 2 kΩ		(V–) + 0.8		(V+) – 0.8	V
I_{OUT}	Output current			See *Typical Characteristics*			mA
Z_O	Open-loop output impedance	f = 1 MHz		See *Typical Characteristics*			Ω
I_{SC}	Short-circuit current(3)				±50		mA
C_{LOAD}	Capacitive load drive				100		pF
POWER SUPPLY							
V_S	Specified voltage			±2.25		±18	V
I_Q	Quiescent current (per channel)	I_{OUT} = 0 A			2	2.5	mA
		I_{OUT} = 0 A, T_A = –40°C to 85°C(2)				2.8	mA
TEMPERATURE							
	Specified range			–40		85	°C
	Operating range			–55		125	°C

(1) Full-power bandwidth = SR / (2π × V_P), where SR = slew rate.
(2) Specified by design and characterization.
(3) One channel at a time.

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6.7 Typical Characteristics

at T_A = 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

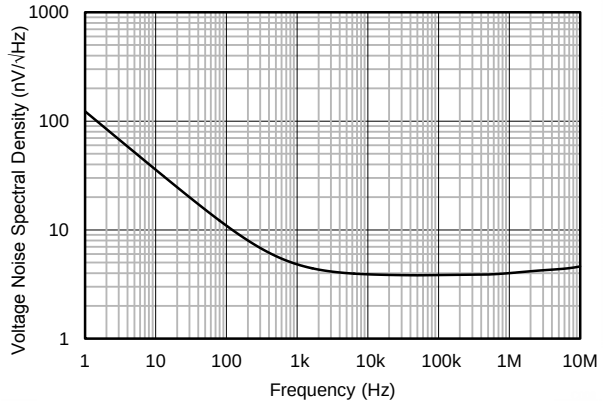


Figure 1. Input Voltage Noise Density vs Frequency

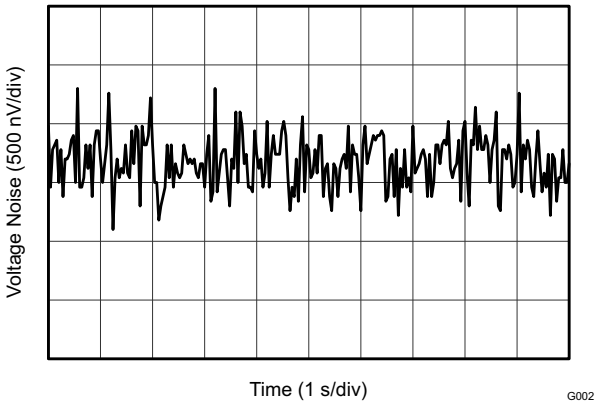


Figure 2. 0.1-Hz to 10-Hz Noise

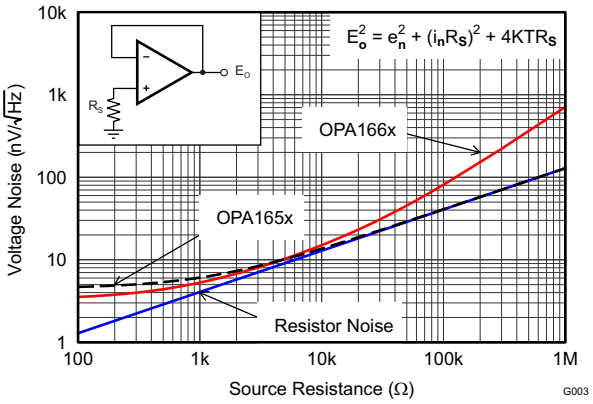


Figure 3. Voltage Noise vs Source Resistance

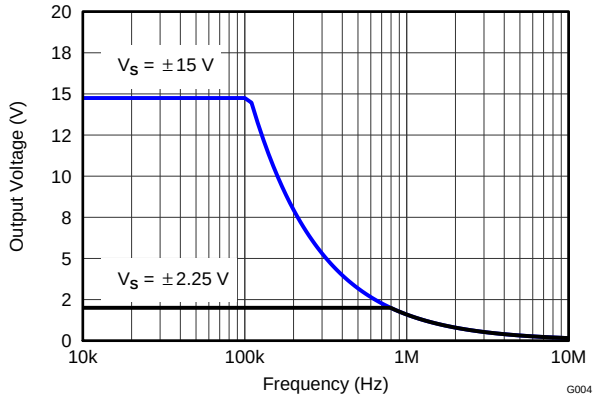


Figure 4. Maximum Output Voltage vs Frequency

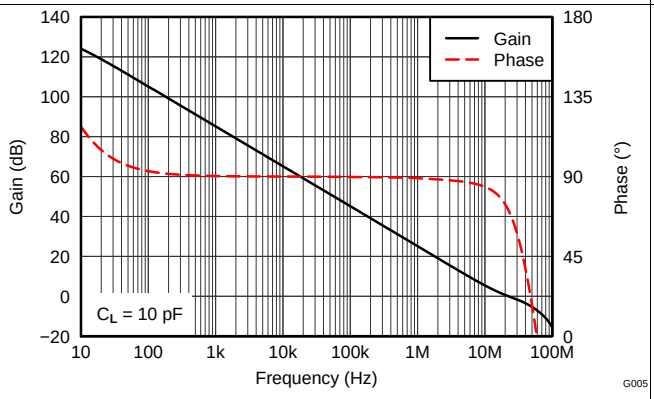


Figure 5. Gain and Phase vs Frequency

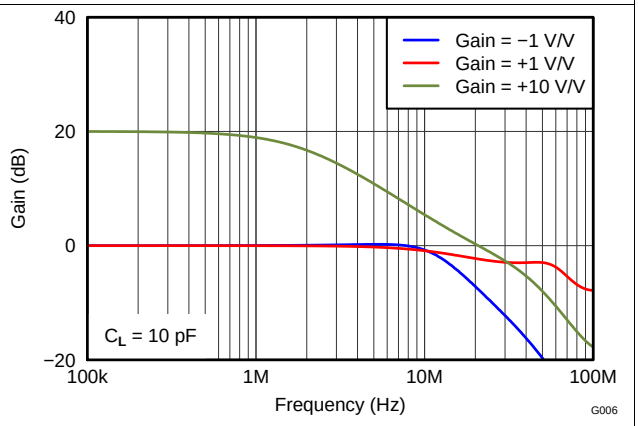


Figure 6. Closed-Loop Gain vs Frequency

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Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

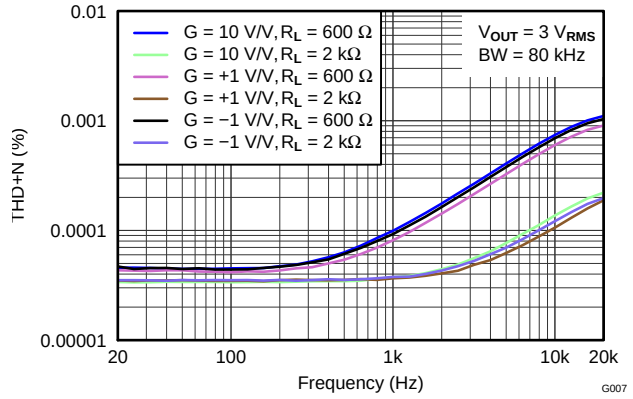


Figure 7. THD+N Ratio vs Frequency

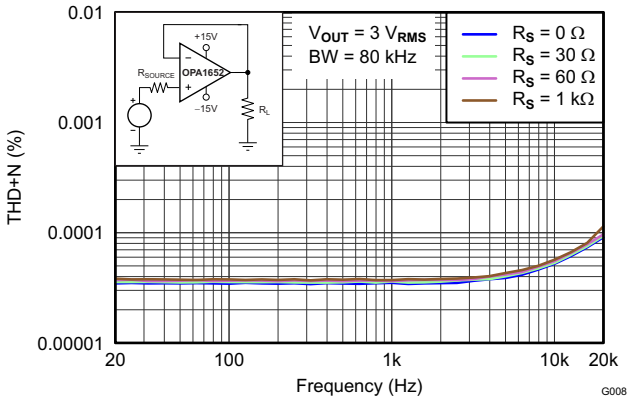


Figure 8. THD+N Ratio vs Frequency

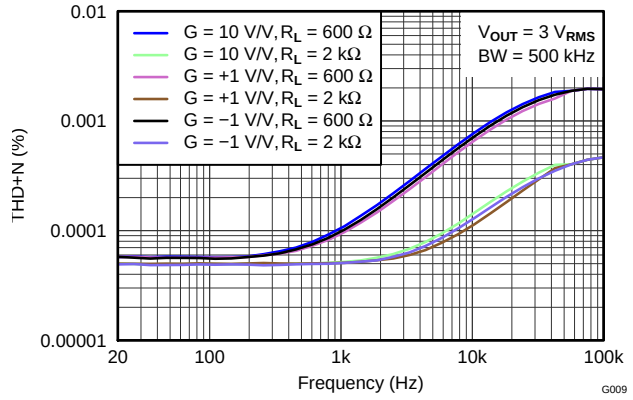


Figure 9. THD+N Ratio vs Frequency

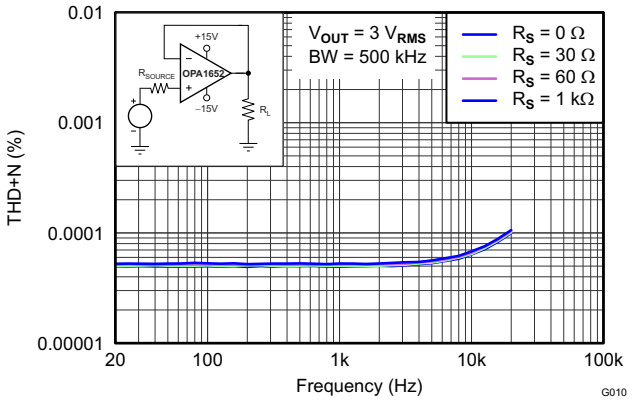


Figure 10. THD+N Ratio vs Frequency

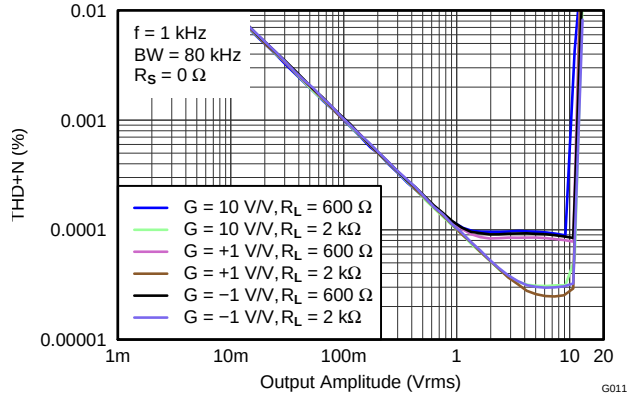


Figure 11. THD+N Ratio vs Output Amplitude

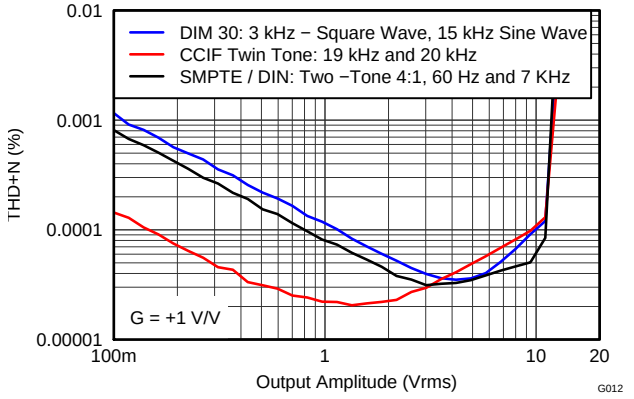


Figure 12. Intermodulation Distortion vs Output Amplitude

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Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

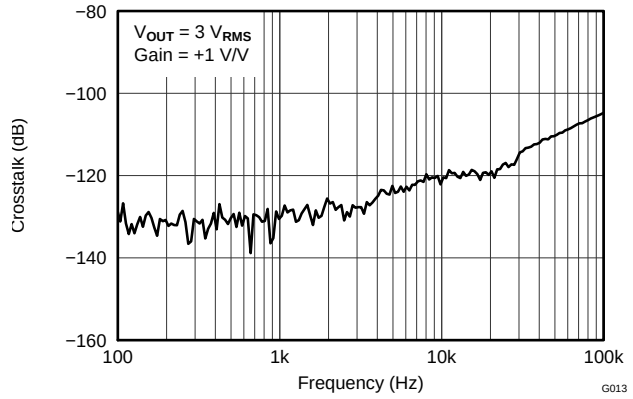


Figure 13. Channel Separation vs Frequency

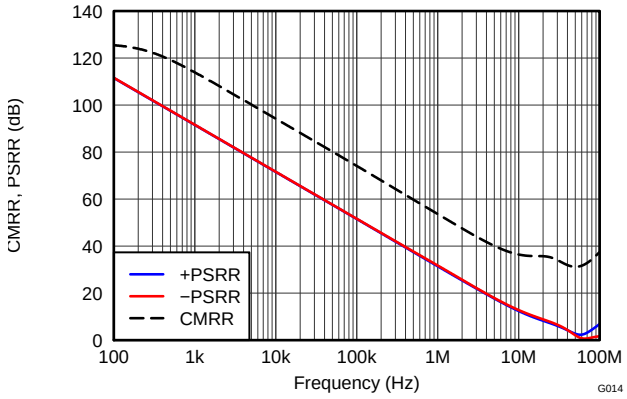


Figure 14. CMRR and PSRR vs Frequency (Referred to Input)

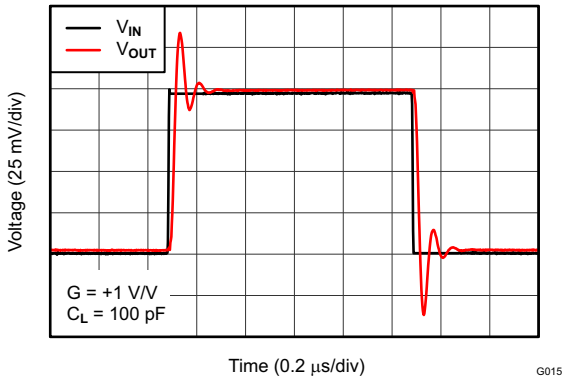


Figure 15. Small-Signal Step Response (100 mV)

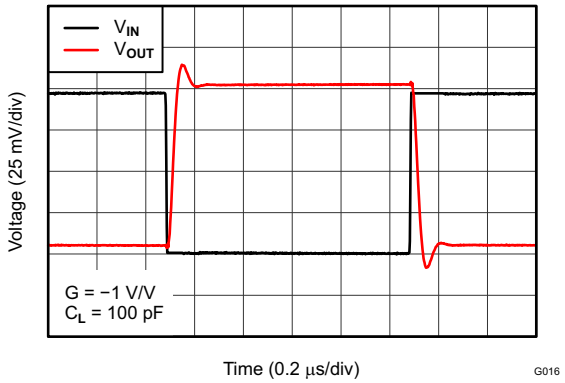


Figure 16. Small-Signal Step Response (100 mV)

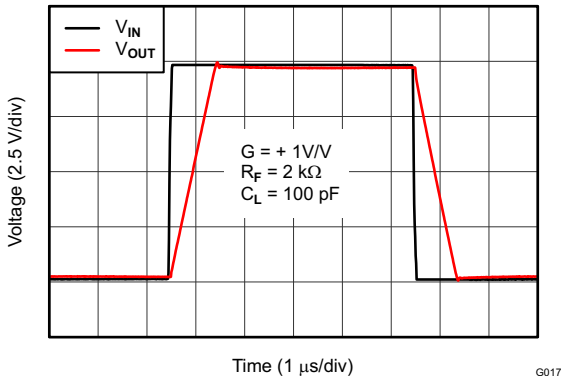


Figure 17. Large-Signal Step Response

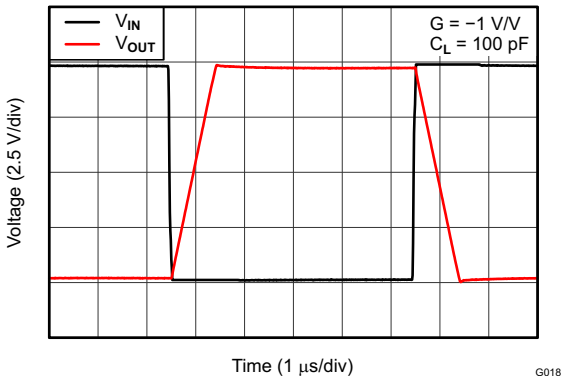


Figure 18. Large-Signal Step Response

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Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

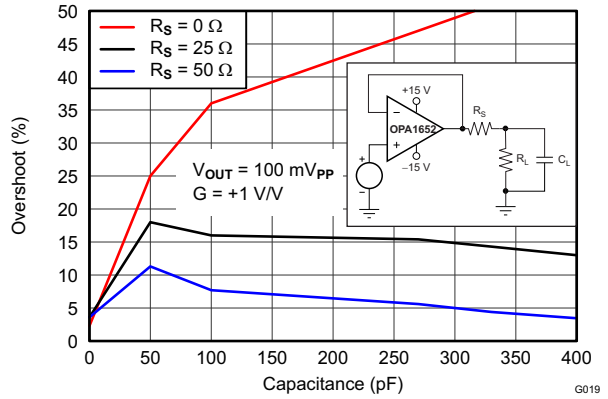


Figure 19. Small-Signal Overshoot vs Capacitive Load

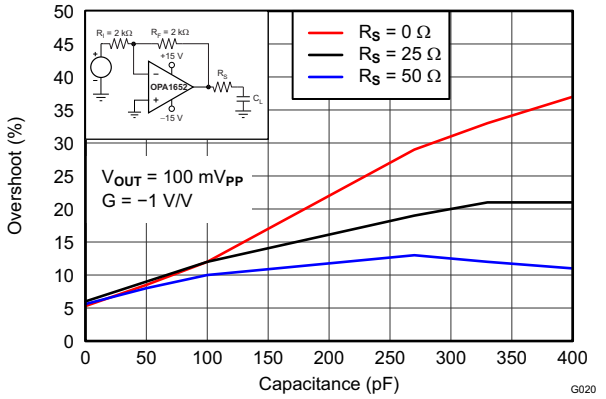


Figure 20. Small-Signal Overshoot vs Capacitive Load

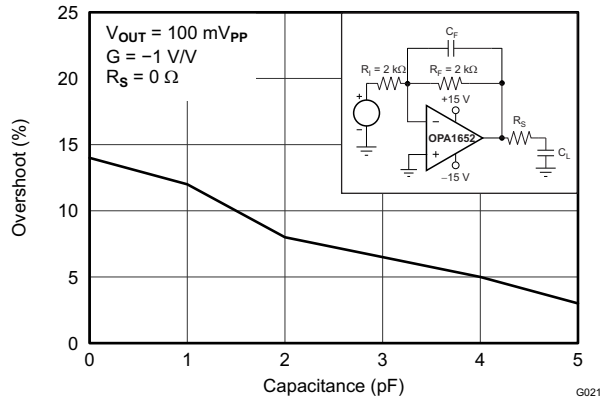


Figure 21. Small-Signal Overshoot vs Feedback Capacitor (100-mV Output Step)

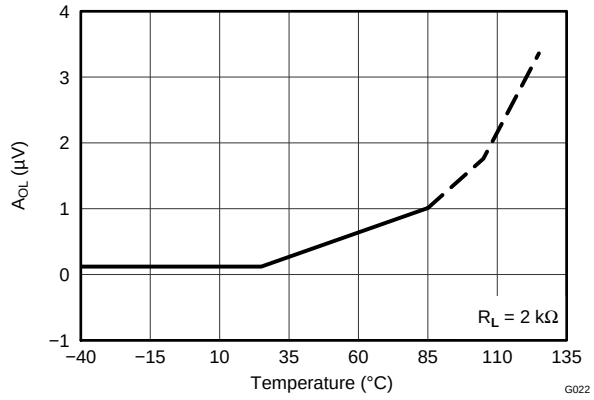


Figure 22. Open-Loop Gain vs Temperature

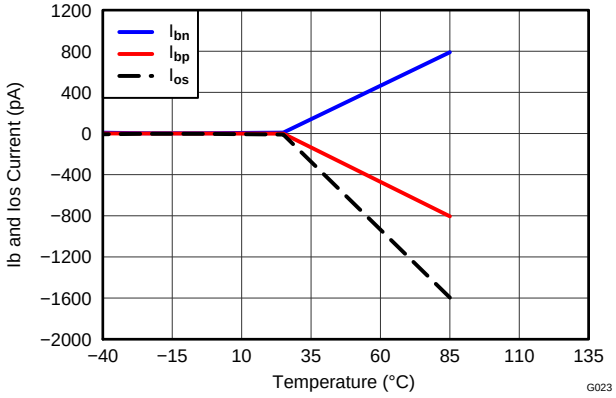


Figure 23. I_B and I_{OS} vs Temperature

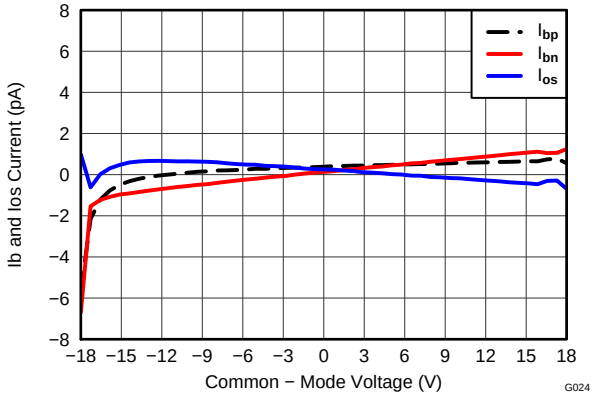


Figure 24. I_B and I_{OS} vs Common-Mode Voltage

Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

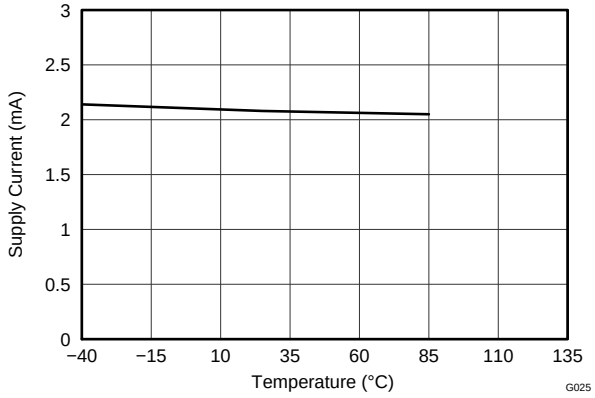


Figure 25. Supply Current vs Temperature

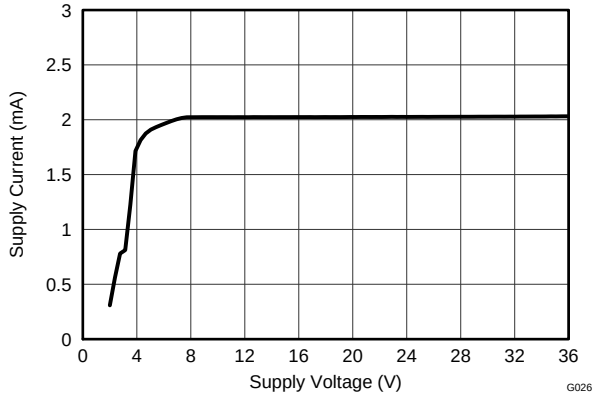


Figure 26. Supply Current vs Supply Voltage

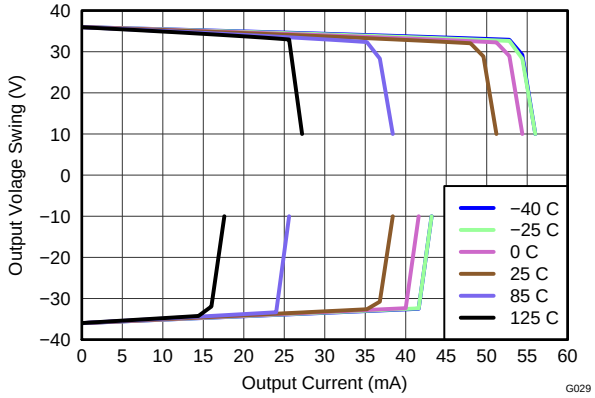


Figure 27. Output Voltage vs Output Current

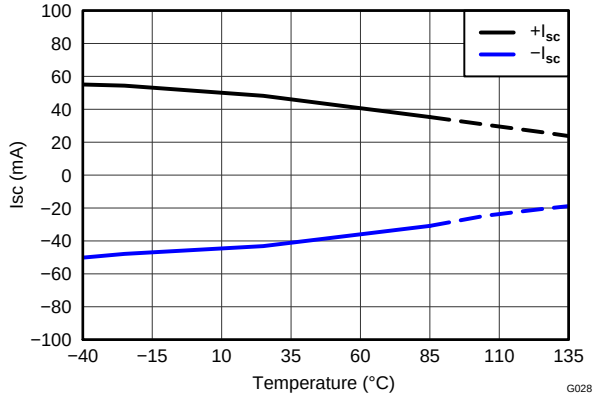


Figure 28. Short-Circuit Current vs Temperature

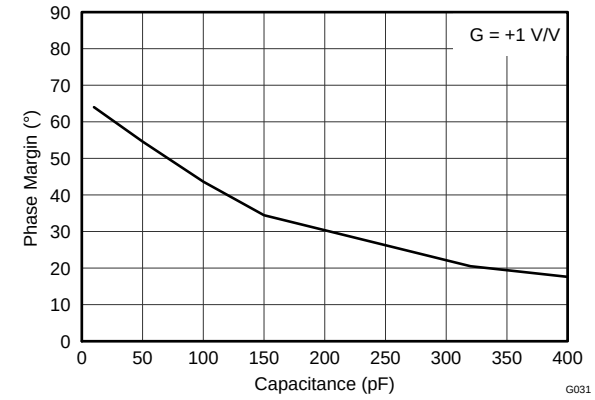


Figure 29. Phase Margin vs Capacitive Load

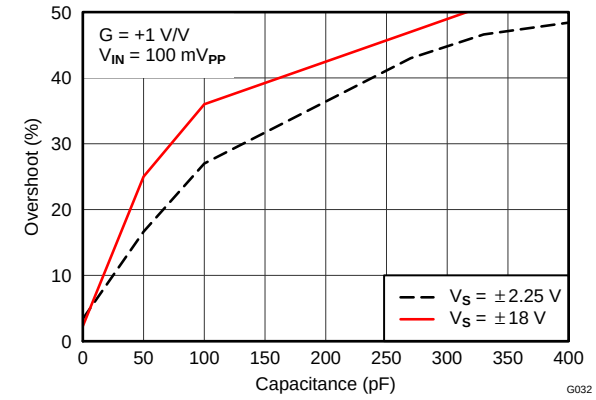


Figure 30. Percent Overshoot vs Capacitive Load

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Typical Characteristics (continued)

at T_A = 25°C, V_S = ±15 V, and R_L = 2 kΩ, unless otherwise noted.

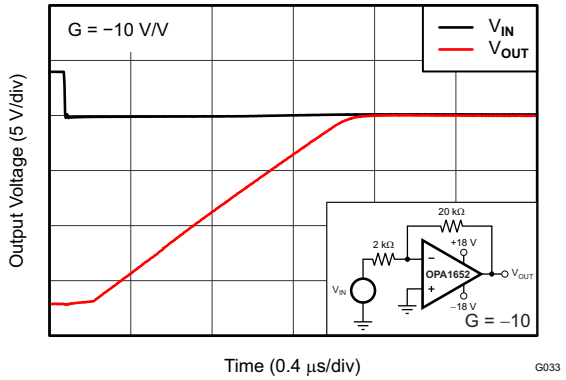


Figure 31. Negative Overload Recovery

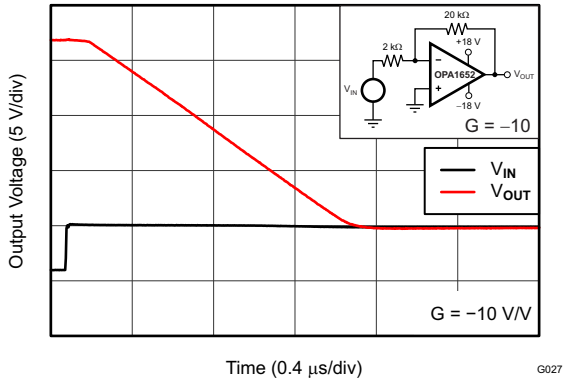


Figure 32. Positive Overload Recovery

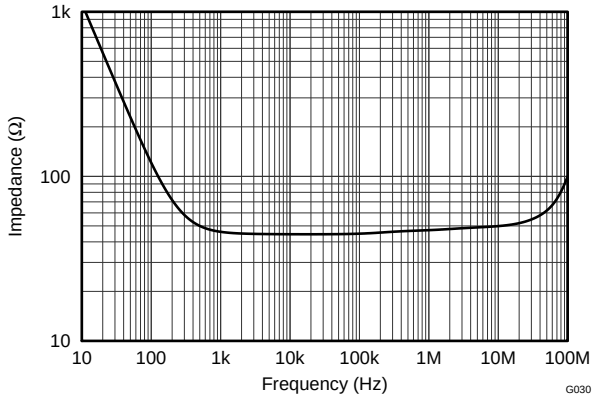


Figure 33. Open-Loop Output Impedance vs Frequency

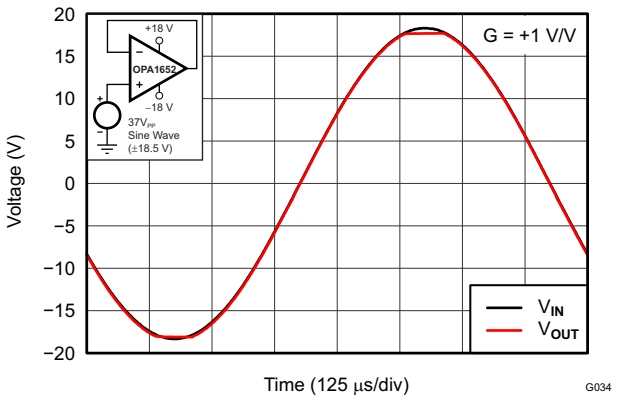


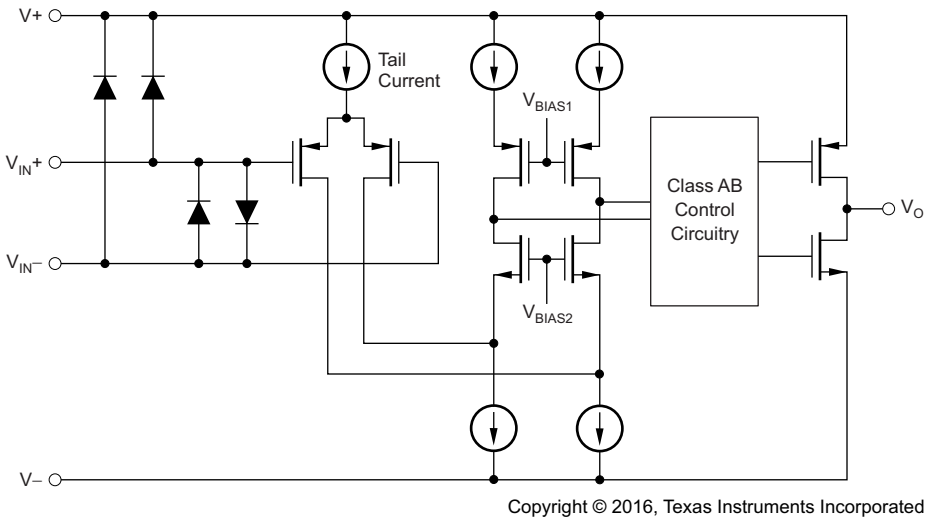
Figure 34. No Phase Reversal

7 Detailed Description

7.1 Overview

The OPA1652 and OPA1654 are unity-gain stable, precision dual and quad op amps with very low noise. The *Functional Block Diagram* shows a simplified schematic of the OPA165x (with one channel shown). The device consists of a very low noise input stage with a folded cascode and a rail-to-rail output stage. This topology exhibits superior noise and distortion performance across a wide range of supply voltages not previously delivered by audio operational amplifiers.

7.2 Functional Block Diagram



7.3 Feature Description

7.3.1 Phase Reversal Protection

The OPA165x family has internal phase-reversal protection. Many op amps exhibit phase reversal when the input is driven beyond the linear common-mode range. This condition is most often encountered in noninverting circuits when the input is driven beyond the specified common-mode voltage range, causing the output to reverse into the opposite rail. The input of the OPA165x prevents phase reversal with excessive common-mode voltage. Instead, the appropriate rail limits the output voltage. This performance is shown in Figure 35.

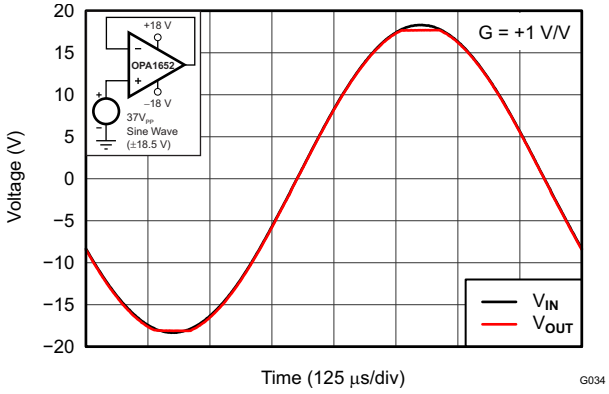


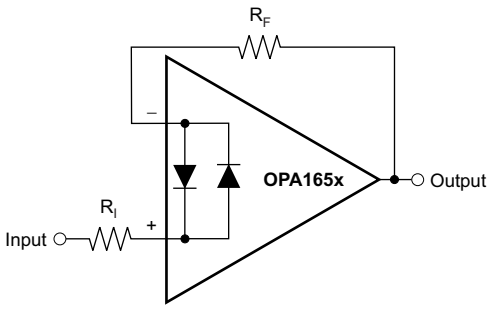
Figure 35. Output Waveform Devoid of Phase Reversal During an Input Overdrive Condition

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Feature Description (continued)

7.3.2 Input Protection

The input terminals of the OPA1652 and OPA1654 are protected from excessive differential voltage with back-to-back diodes, as Figure 36 illustrates. In most circuit applications, the input protection circuitry has no consequence. However, in low-gain or G = 1 circuits, fast ramping input signals can forward bias these diodes because the output of the amplifier cannot respond rapidly enough to the input ramp. If the input signal is fast enough to create this forward bias condition, the input signal current must be limited to 10 mA or less. If the input signal current is not inherently limited, an input series resistor (R_I) or a feedback resistor (R_F) can limit the signal input current. This resistor degrades the low-noise performance of the OPA165x, and is examined in the *Noise Performance* section. Figure 36 shows an example configuration when both current-limiting input and feedback resistors are used.



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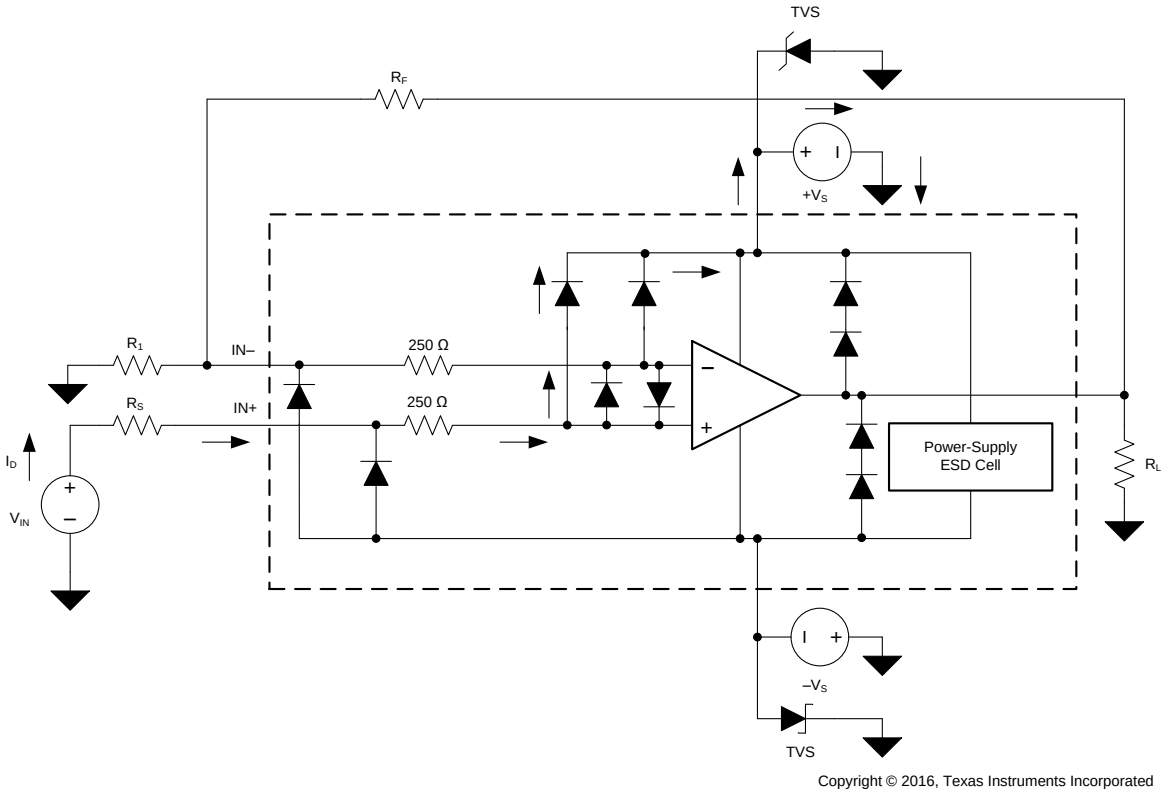
Figure 36. Pulsed Operation

7.3.3 Electrical Overstress

Designers typically ask questions about the capability of an operational amplifier to withstand electrical overstress. These questions tend to focus on the device inputs, but can involve the supply voltage pins or the output pin. Each of these different pin functions have electrical stress limits determined by the voltage breakdown characteristics of the particular semiconductor fabrication process and specific circuits connected to the pin. Additionally, internal electrostatic discharge (ESD) protection is built into these circuits to protect them from accidental ESD events both before and during product assembly.

A good understanding of this basic ESD circuitry and the relevance to an electrical overstress event is helpful. Figure 37 illustrates the ESD circuits contained in the OPA165x (indicated by the dashed line area). The ESD protection circuitry involves several current-steering diodes connected from the input and output pins and routed back to the internal power-supply lines, where the diodes meet at an absorption device internal to the operational amplifier. This protection circuitry is intended to remain inactive during normal circuit operation.

Feature Description (continued)



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Figure 37. Equivalent Internal ESD Circuitry Relative to a Typical Circuit Application

An ESD event produces a short-duration, high-voltage pulse that is transformed into a short-duration, high-current pulse when discharging through a semiconductor device. The ESD protection circuits are designed to provide a current path around the operational amplifier core to prevent damage. The energy absorbed by the protection circuitry is then dissipated as heat.

When an ESD voltage develops across two or more amplifier device pins, current flows through one or more steering diodes. The absorption device activates depending on the path that the current takes. The absorption device has a trigger, or threshold voltage, that is above the normal operating voltage of the OPA165x, but below the device breakdown voltage level. When this threshold is exceeded, the absorption device quickly activates and clamps the voltage across the supply rails to a safe level.

When the operational amplifier connects into a circuit (refer to Figure 37), the ESD protection components are intended to remain inactive and do not become involved in the application circuit operation. However, circumstances may arise where an applied voltage exceeds the operating voltage range of a given pin. If this condition occurs, there is a risk that some internal ESD protection circuits can turn on and conduct current. Any such current flow occurs through steering-diode paths and rarely involves the absorption device.

Figure 37 shows a specific example where the input voltage (V_{IN}) exceeds the positive supply voltage (V+) by 500 mV or more. Much of what happens in the circuit depends on the supply characteristics. If V+ can sink the current, one of the upper input steering diodes conducts and directs current to V+. Excessively high current levels can flow with increasingly higher V_{IN}. As a result, the data sheet specifications recommend that applications limit the input current to 10 mA.

If the supply is not capable of sinking the current, V_{IN} begins sourcing current to the operational amplifier, and then becomes the source of positive supply voltage. The danger in this case is that the voltage can rise to levels that exceed the absolute maximum ratings of the operational amplifier.

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Feature Description (continued)

Another common question explains what happens to the amplifier if an input signal is applied to the input when the power supplies (V+ or V–) are at 0 V. This depends on the supply characteristic when at 0 V, or at a level below the input signal amplitude. If the supplies appear as high impedance, then the input source supplies the operational amplifier current through the current-steering diodes. This state is not a normal bias condition; most likely, the amplifier does not operate normally. If the supplies are at low impedance, then the current through the steering diodes can become quite high. The current level depends on the ability of the input source to deliver current, and any resistance in the input path.

If there is any uncertainty about the ability of the supply to absorb this current, add external Zener diodes to the supply pins; see Figure 37. Select the Zener voltage so the diode does not turn on during normal operation. However, the Zener voltage must be low enough so that the Zener diode conducts if the supply pin rises above the safe-operating, supply-voltage level.

7.4 Device Functional Modes

7.4.1 Operating Voltage

The OPA165x series op amps operate from ±2.25 V to ±18 V supplies while maintaining excellent performance. The OPA165x series can operate with as little as 4.5 V between the supplies and with up to 36 V between the supplies. However, some applications do not require equal positive and negative output voltage swing. With the OPA165x series, power-supply voltages do not need to be equal. For example, the positive supply can be set to 25 V with the negative supply at –5 V.

In all cases, the common-mode voltage must be maintained within the specified range. In addition, key parameters are assured over the specified temperature range of T_A = –40°C to +85°C. Parameters that vary significantly with operating voltage or temperature are shown in the *Typical Characteristics* section.

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8 Application and Implementation

NOTE

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

8.1 Application Information

8.1.1 Noise Performance

Figure 38 shows the total circuit noise for varying source impedances with the op amp in a unity-gain configuration (no feedback resistor network, and therefore no additional noise contributions).

The OPA165x (Gain bandwidth = 18 MHz, G = 1) is shown with total circuit noise calculated. The op amp contributes a voltage noise component and a current noise component. The voltage noise is commonly modeled as a time-varying component of the offset voltage. The current noise is modeled as the time-varying component of the input bias current, and reacts with the source resistance to create a voltage component of noise. Therefore, the lowest noise op amp for a given application depends on the source impedance. For low source impedance, current noise is negligible, and voltage noise typically dominates the total noise of the circuit. The voltage noise of the OPA165x series op amps makes the series a suitable choice for source impedances greater than or equal to 1-kΩ.

The equation in Figure 38 shows the calculation of the total circuit noise, with these parameters:

- e_n = Voltage noise
- i_n = Current noise
- R_S = Source impedance
- k = Boltzmann's constant = 1.38 × 10^{-23} J/K
- T = Temperature in Kelvins (K)

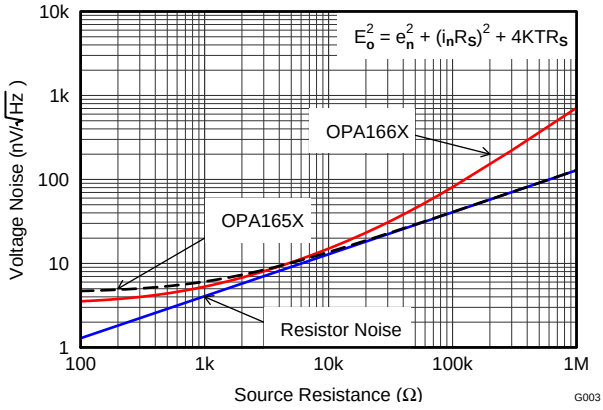


Figure 38. Noise Performance of the OPA165x in Unity-Gain Buffer Configuration

Design of low-noise op amp circuits requires careful consideration of a variety of possible noise contributors: noise from the signal source, noise generated in the op amp, and noise from the feedback network resistors. The total noise of the circuit is the root-sum-square combination of all noise components.

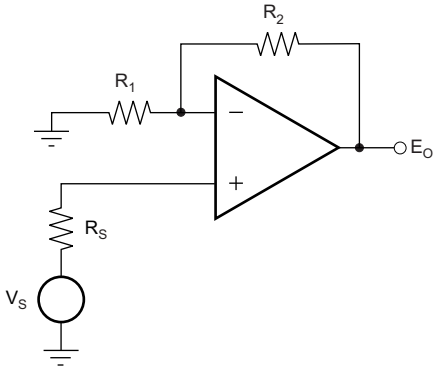
The resistive portion of the source impedance produces thermal noise proportional to the square root of the resistance. Figure 38 plots this equation. The source impedance is typically fixed; consequently, select the op amp and the feedback resistors to minimize the respective contributions to the total noise.

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Application Information (continued)

Figure 39 illustrates both inverting (Figure 39 B) and noninverting (Figure 39 A) op amp circuit configurations with gain. In circuit configurations with gain, the feedback network resistors contribute noise. The current noise of the op amp reacts with the feedback resistors, creating additional noise components. The feedback resistor values can generally be selected to make these noise sources negligible. The equations for total noise are shown for both configurations.

A) Noise in Noninverting Gain Configuration



Noise at the output:

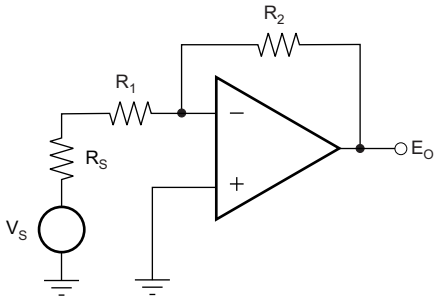
$$E_O^2 = \left(1 + \frac{R_2}{R_1}\right)^2 e_n^2 + \left(\frac{R_2}{R_1}\right)^2 e_1^2 + e_2^2 + \left(1 + \frac{R_2}{R_1}\right)^2 e_s^2$$

Where $e_S = \sqrt{4kTR_S}$ = thermal noise of R_S

$e_1 = \sqrt{4kTR_1}$ = thermal noise of R_1

$e_2 = \sqrt{4kTR_2}$ = thermal noise of R_2

B) Noise in Inverting Gain Configuration



Noise at the output:

$$E_O^2 = \left(1 + \frac{R_2}{R_1 + R_S}\right)^2 e_n^2 + \left(\frac{R_2}{R_1 + R_S}\right)^2 e_1^2 + e_2^2 + \left(\frac{R_2}{R_1 + R_S}\right)^2 e_s^2$$

Where $e_S = \sqrt{4kTR_S}$ = thermal noise of R_S

$e_1 = \sqrt{4kTR_1}$ = thermal noise of R_1

$e_2 = \sqrt{4kTR_2}$ = thermal noise of R_2

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Note: For the OPA165x series of op amps at 1 kHz, $e_n = 4.5\ nV/\sqrt{Hz}$.

Figure 39. Noise Calculation in Gain Configurations

8.1.2 Total Harmonic Distortion Measurements

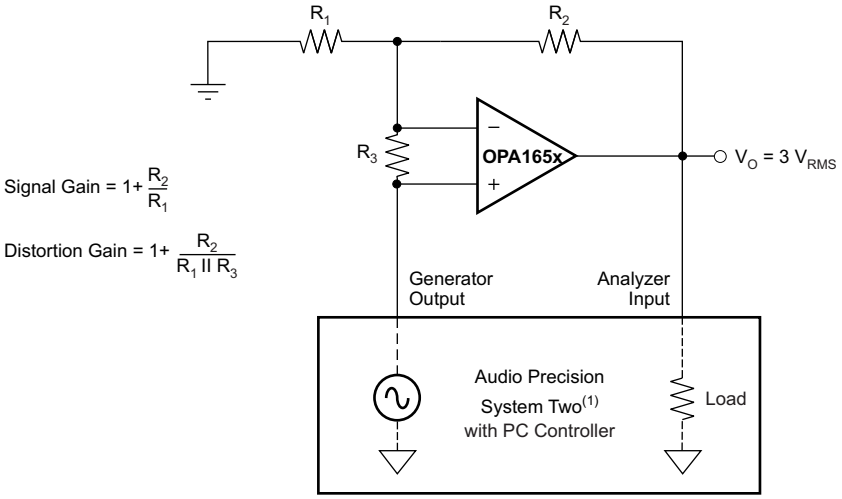
The OPA165x series op amps have excellent distortion characteristics. THD + noise is below 0.0002% (G = 1, $V_O = 3\ V_{RMS}$, bandwidth = 80 kHz) throughout the audio frequency range, 20 Hz to 20 kHz, with a 2-kΩ load (see Figure 7 for characteristic performance).

The distortion produced by the OPA165x series op amps is below the measurement limit of many commercially available distortion analyzers. However, a special test circuit (such as Figure 40 shows) can extend the measurement capabilities.

Op amp distortion can be considered an internal error source that refers to the input. Figure 40 shows a circuit that causes the op amp distortion to be gained up (refer to the table in Figure 40 for the distortion gain factor for various signal gains). The addition of R_3 to the otherwise standard noninverting amplifier, configuration alters the feedback factor or noise gain of the circuit. The closed-loop gain is unchanged, but the distortion gain factor reduces the feedback available for error connection, that extends the resolution by the same amount. Note that the input signal and load applied to the op amp are the same as with conventional feedback without R_3. The value of R_3 must be kept small to minimize the effect on the distortion measurements.

Application Information (continued)

The validity of this technique can be verified by duplicating measurements at high gain or high frequency where the distortion is within the measurement capability of the test equipment. The Audio Precision System Two distortion and noise analyzer calculated the measurements for this data sheet, which significantly simplifies repetitive measurements. Manual distortion measurement instruments performs this measurement technique.



SIGNAL GAIN	DISTORTION GAIN	R_1	R_2	R_3
+1	101	∞	1 kΩ	10 Ω
–1	101	4.99 kΩ	4.99 kΩ	49.9 Ω
+10	110	549 Ω	4.99 kΩ	49.9 Ω

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(1) For measurement bandwidth, see Figure 7 through Figure 12.

Figure 40. Distortion Test Circuit

8.1.3 Capacitive Loads

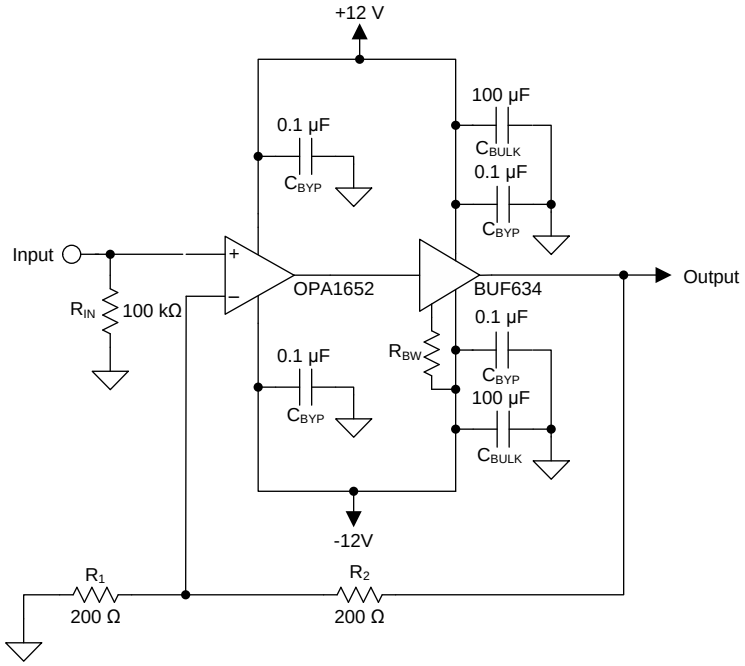
The dynamic characteristics of the OPA1652 and OPA1654 are optimized for commonly encountered gains, loads, and operating conditions. The combination of low closed-loop gain and high capacitive loads decreases the phase margin of the amplifier and can lead to gain peaking or oscillations. As a result, heavier capacitive loads must be isolated from the output. The simplest way to achieve this isolation is to add a small resistor (R_S equal to 50 Ω, for example) in series with the output.

This small series resistor also prevents excess power dissipation if the output of the device becomes shorted. Figure 19 illustrates a graph of *Small-Signal Overshoot vs Capacitive Load* for several values of R_S. For more details about analysis techniques and application circuits, see *Feedback Plots Define Op Amp AC Performance* (SBOA015), available for download from the TI website (www.ti.com).

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8.2 Typical Application

The low noise and distortion of the OPA165x family of audio operational amplifiers make them an excellent choice for a number of analog audio circuits. Figure 41 illustrates a power amplifier circuit suitable for high-fidelity headphone applications.



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Figure 41. Composite Power Amplifier for Headphones

8.2.1 Design Requirements

- Gain: 6 dB
- Output Voltage: > 2 V_{RMS}, 32-Ω Load
- Output Impedance: < 1 Ω
- THD+N: < –110dB (1 kHz, 2 V_{RMS}, 32-Ω Load)

8.2.2 Detailed Design Procedure

The power amplifier circuit (single channel shown) features a BUF634 high-speed buffer amplifier inside the feedback loop of an OPA1652 to increase the amount of available output current. The bandwidth and power consumption of the BUF634 can be set with an external resistor (R_{BW}). For this circuit, R_{BW} uses a 0-Ω resistor that configures the BUF634 for the widest bandwidth and highest performance. Feedback resistors R_1 and R_2 (as shown in Equation 1) calculate the gain of the circuit:

$$A_V = 1 + \frac{R_2}{R_1} \quad (1)$$

To achieve the design goal of a 6-dB voltage gain (2 V/V), R_1 and R_2 must have equal values. These resistors also contribute noise thermal noise to the circuit. The voltage noise spectral density of the feedback resistors, referred to the amplifier input, is given in Equation 2:

$$e_{NR} = \sqrt{4kT\left(R_2 \parallel R_1\right)} \quad (2)$$

Ideally, the thermal noise contributions of the resistors do not significantly degrade the noise performance of the circuit. Selecting resistor values so the resistor noise is less than one-third the input voltage noise of the op amp (Equation 3) ensures that any increase in the circuit noise as a result of the feedback resistor contributions is minimal.

Typical Application (continued)

$$e_{NR} \le \frac{e_{OA}}{3} \tag{3}$$

To calculate the required resistor values, Equation 3 is inserted into Equation 2, and the resulting equation is rearranged to solve for the parallel combination of R_1 and R_2 , as shown in Equation 4. Using a value of 3.8 nV/√Hz as the broadband voltage noise of the OPA1652 results in a value of 96.8 Ω for the parallel combination of R_1 and R_2. R_1 and R_2 use standard value 200-Ω resistors, resulting in a parallel value of 100 Ω, which is suitably close to the required value.

$$R_1 || R_2 \le \frac{{e_{OA}}^2}{36kT} \le \frac{\left(3.8\ nV/\sqrt{Hz}\right)^2}{36 \times 1.381 \times 10^{-23} \times 300} \le 96.8\ \Omega \tag{4}$$

Because of the extremely wide bandwidth and high slew rate of the BUF634, no additional components are required to maintain stability in the circuit or prevent latch-up conditions. This circuit is stable with capacitive loads over 1-nF, which is suitable for headphone applications.

8.2.3 Application Curves

The measured performance of the circuit is shown in Figure 42 through Figure 46. The frequency response is extremely flat over the full audio bandwidth, deviating only 0.004 dB over the audible range. The decrease in gain shown at low frequency is a result of the test equipment, and not the amplifier circuit. The amplifier output impedance, calculated from the change in gain in the loaded and unloaded conditions, is 0.036 Ω. The maximum output power (before clipping) is displayed in Figure 43. For a 32-Ω load, the power amplifier delivered 781 mW before clipping. The best THD+N performance achieved with a 32-Ω load was –117.2 dB at 678 mW (1 kHz, 22-kHz measurement bandwidth). THD+N vs frequency is shown in Figure 44 for a 2-V_{RMS} output level measured in a 90-kHz bandwidth. The worst-case measurement was for a 16-Ω load (250 mW), 20-kHz input frequency, –91.8 dB (0.0026%). The amplifier output spectrum for a 2-V_{RMS}, 1 kHz, fundamental into two different loads is shown in Figure 45 and Figure 46. All distortion harmonics are below –120 dB relative to the fundamental for both loading conditions.

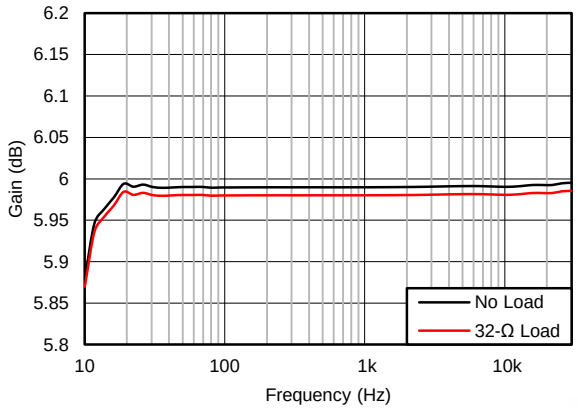


Figure 42. Amplifier Transfer Function

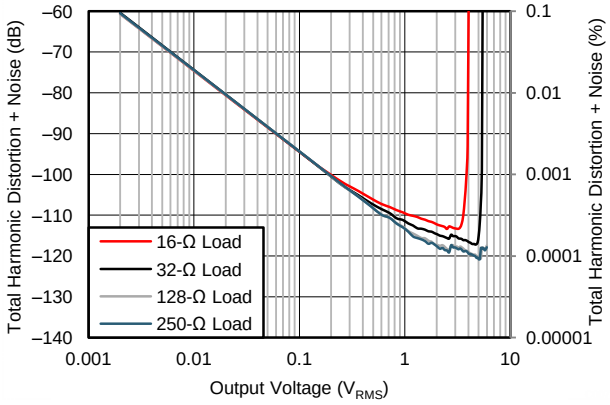
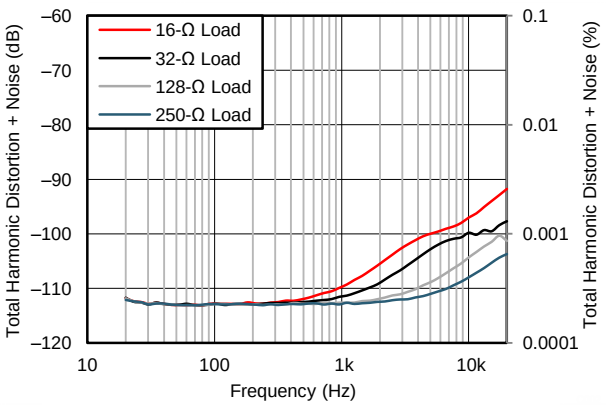


Figure 43. THD+N vs Frequency for Various Loads

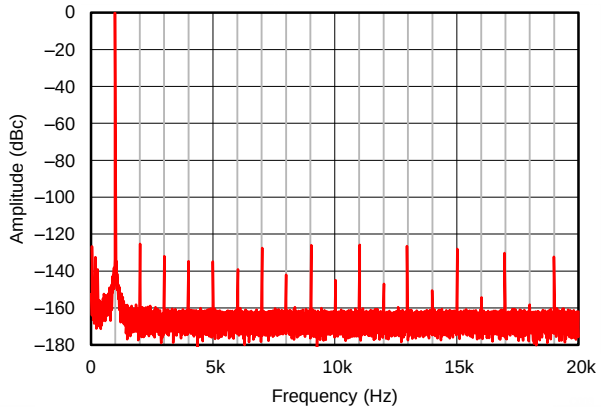
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Typical Application (continued)



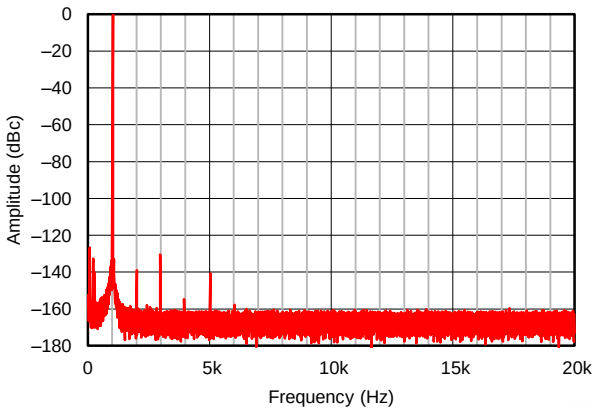
90-kHz measurement bandwidth, 2-V_{RMS} output

Figure 44. THD+N vs Frequency for Various Loads



1 kHz, 32-Ω load, 2-V_{RMS} output

Figure 45. Output Spectrum



1 kHz, 250-Ω load, 2 V_{RMS}

Figure 46. Output Spectrum

9 Power Supply Recommendations

The OPA165x series is specified for operation from 4.5 V to 36 V (±2.25 V to ±18 V); many specifications apply from –40°C to +85°C. Parameters that can exhibit significant variance with regard to operating voltage or temperature are presented in the *Typical Characteristics* section. Applications with noisy or high-impedance power supplies require decoupling capacitors close to the device pins. In most cases, 0.1-µF capacitors are adequate.

10 Layout

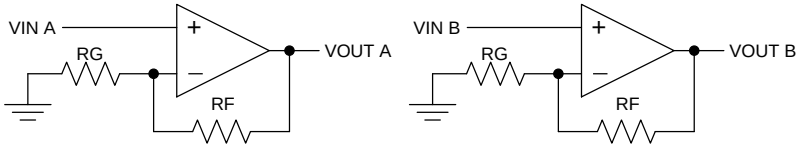
10.1 Layout Guidelines

For best operational performance of the device, use good printed-circuit board (PCB) layout practices, including:

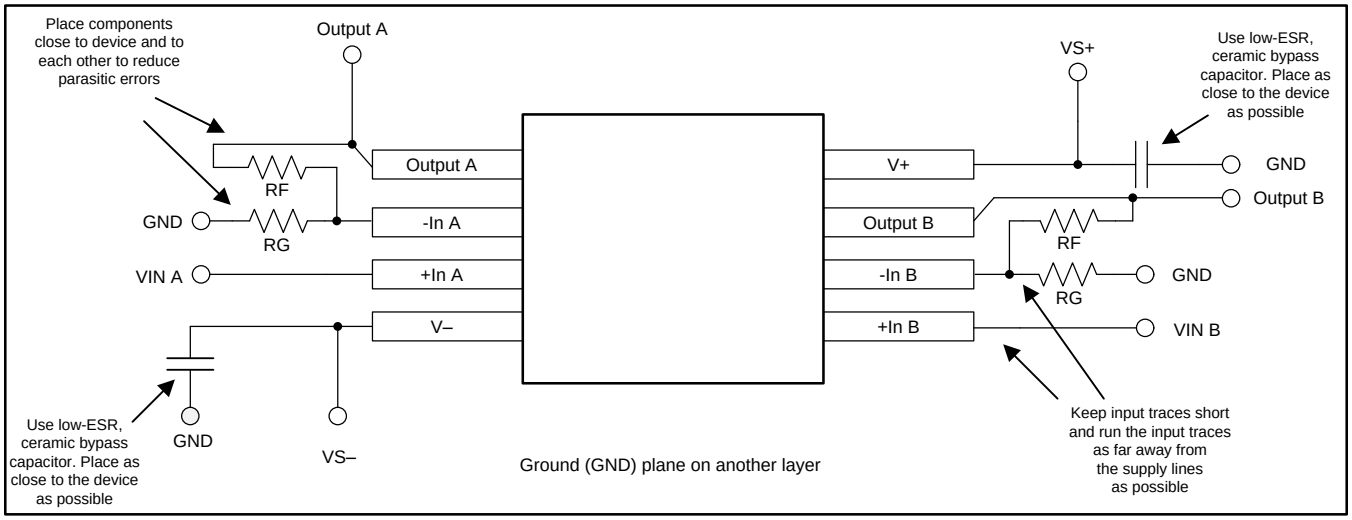
- Noise can propagate into analog circuitry through the power pins of the circuit as a whole and of op amp itself. Bypass capacitors are used to reduce the coupled noise by providing low-impedance power sources local to the analog circuitry.
  - Connect low-ESR, 0.1-µF ceramic bypass capacitors between each supply pin and ground, placed as close to the device as possible. A single bypass capacitor from V+ to ground is applicable for single-supply applications.
- Separate grounding for analog and digital portions of circuitry is one of the simplest and most-effective methods of noise suppression. One or more layers on multilayer PCBs are typically devoted to ground planes. A ground plane helps distribute heat and reduces electromagnetic interference (EMI) noise pickup. Physically separate digital and analog grounds, observing the flow of the ground current.
- To reduce parasitic coupling, run the input traces as far away from the supply or output traces as possible. If these traces cannot be kept separate, crossing the sensitive trace perpendicular is much better as opposed to in parallel with the noisy trace.
- Place the external components as close to the device as possible. As illustrated in Figure 47, keeping R_F and R_G close to the inverting input minimizes parasitic capacitance.
- Keep the length of input traces as short as possible. Always remember that the input traces are the most sensitive part of the circuit.
- Consider a driven, low-impedance guard ring around the critical traces. A guard ring can significantly reduce leakage currents from nearby traces that are at different potentials.
- Cleaning the PCB following board assembly is recommended for best performance.
- Any precision integrated circuit can experience performance shifts resulting from moisture ingress into the plastic package. Following any aqueous PCB cleaning process, TI recommends baking the PCB assembly to remove moisture introduced into the device packaging during the cleaning process. A low temperature, post-cleaning bake at 85°C for 30 minutes is sufficient for most circumstances.

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10.2 Layout Example



(Schematic Representation)



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Figure 47. Operational Amplifier Board Layout for Noninverting Configuration

10.3 Power Dissipation

The OPA1652 and OPA1654 series op amps are capable of driving 2-kΩ loads with a power-supply voltage up to ±18 V and full operating temperature range. Internal power dissipation increases when operating at high supply voltages. Copper leadframe construction used in the OPA165x series op amps improves heat dissipation compared to conventional materials. Circuit board layout minimizes junction temperature rise. Wide copper traces help dissipate the heat by acting as an additional heat sink. Temperature rise is further minimized by soldering the devices to the circuit board rather than using a socket.

11 Device and Documentation Support

11.1 Device Support

11.1.1 Development Support

11.1.1.1 TINA-TI™ (Free Software Download)

TINA™ is a simple, powerful, and easy-to-use circuit simulation program based on a SPICE engine. TINA-TI™ is a free, fully-functional version of the TINA software, preloaded with a library of macro models in addition to a range of both passive and active models. TINA-TI provides all the conventional DC, transient, and frequency domain analysis of SPICE, as well as additional design capabilities.

Available as a free download from the WEBENCH® Design Center, TINA-TI offers extensive post-processing capability that allows users to format results in a variety of ways. Virtual instruments offer the ability to select input waveforms and probe circuit nodes, voltages, and waveforms, creating a dynamic quick-start tool.

NOTE

These files require that either the TINA software (from DesignSoft™) or TINA-TI software be installed. Download the free TINA-TI software from the TINA-TI folder.

11.1.1.2 DIP Adapter EVM

The DIP Adapter EVM tool provides an easy, low-cost way to prototype small surface mount devices. The evaluation tool these TI packages: D or U (SOIC-8), PW (TSSOP-8), DGK (VSSOP-8), DBV (SOT23-6, SOT23-5 and SOT23-3), DCK (SC70-6 and SC70-5), and DRL (SOT563-6). The DIP Adapter EVM may also be used with terminal strips or may be wired directly to existing circuits.

11.1.1.3 Universal Operational Amplifier EVM

The Universal Op Amp EVM is a series of general-purpose, blank circuit boards that simplify prototyping circuits for a variety of IC package types. The evaluation module board design allows many different circuits to be constructed easily and quickly. Five models are offered, with each model intended for a specific package type. PDIP, SOIC, VSSOP, TSSOP and SOT-23 packages are all supported.

NOTE

These boards are unpopulated, so users must provide their own devices. TI recommends requesting several op amp device samples when ordering the Universal Op Amp EVM.

11.1.1.4 Smart Amplifier Speaker Characterization Board Evaluation Module

The Smart Amplifier Speaker Characterization Board, when used in conjunction with a supported TI Smart Amplifier and PurePath Console software, provides users the ability to measure speaker excursion, temperature and other parameters for use with a TI Smart Amplifier products.

11.1.1.5 TI Precision Designs

TI Precision Designs are analog solutions created by TI's precision analog applications experts and offer the theory of operation, component selection, simulation, complete PCB schematic and layout, bill of materials, and measured performance of many useful circuits. TI Precision Designs are available online at http://www.ti.com/ww/en/analog/precision-designs/.

11.1.1.6 WEBENCH® Filter Designer

WEBENCH® Filter Designer is a simple, powerful, and easy-to-use active filter design program. The WEBENCH Filter Designer allows the user to create optimized filter designs using a selection of TI operational amplifiers and passive components from TI's vendor partners.

Available as a web-based tool from the WEBENCH® Design Center, WEBENCH® Filter Designer allows the user to design, optimize, and simulate complete multistage active filter solutions within minutes.

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11.2 Documentation Support

11.2.1 Related Documentation

The following documents are relevant to using the OPA165x, and recommended for reference. All are available for download at www.ti.com unless otherwise noted.

- *OPA1652, OPA1654 EMIR Immunity Performance* (SBOT007)
- *Source resistance and noise considerations in amplifiers* (SLYT470)
- *Single-Supply Operation of Operational Amplifiers* (SBOA059)
- *Op Amp Performance Analysis* (SBOA054)
- *Compensate Transimpedance Amplifiers Intuitively* (SBOA055)
- *Tuning in Amplifiers* (SBOA067)
- *Feedback Plots Define Op Amp AC Performance* (SBOA015)
- *Active Volume Control for Professional Audio* (TIDU034)

11.3 Related Links

Table 1 lists quick access links. Categories include technical documents, support and community resources, tools and software, and quick access to sample or buy.

Table 1. Related Links

PARTS	PRODUCT FOLDER	SAMPLE & BUY	TECHNICAL DOCUMENTS	TOOLS & SOFTWARE	SUPPORT & COMMUNITY
OPA1652	Click here	Click here	Click here	Click here	Click here
OPA1654	Click here	Click here	Click here	Click here	Click here

11.4 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. In the upper right corner, click on *Alert me* to register and receive a weekly digest of any product information that has changed. For change details, review the revision history included in any revised document.

11.5 Community Resource

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's Terms of Use.

TI E2E™ Online Community ***TI's Engineer-to-Engineer (E2E) Community.*** Created to foster collaboration among engineers. At e2e.ti.com, you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

Design Support ***TI's Design Support*** Quickly find helpful E2E forums along with design support tools and contact information for technical support.

11.6 Trademarks

TINA-TI, E2E are trademarks of Texas Instruments.
SoundPlus is a trademark of Texas Instruments Incorporated.
WEBENCH is a registered trademark of Texas Instruments.
Blu-Ray is a trademark of Blu-Ray Disc Association.
TINA, DesignSoft are trademarks of DesignSoft, Inc.
All other trademarks are the property of their respective owners.

11.7 Electrostatic Discharge Caution



These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

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11.8 Glossary

SLYZ022 — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

12 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

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PACKAGING INFORMATION

Orderable part number	Status (1)	Material type (2)	Package | Pins	Package qty | Carrier	RoHS (3)	Lead finish/ Ball material (4)	MSL rating/ Peak reflow (5)	Op temp (°C)	Part marking (6)
OPA1652AID	Active	Production	SOIC (D) | 8	75 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AID.A	Active	Production	SOIC (D) | 8	75 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AID.B	Active	Production	SOIC (D) | 8	75 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDGK	Active	Production	VSSOP (DGK) | 8	80 | TUBE	Yes	NIPDAUAG	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGK.A	Active	Production	VSSOP (DGK) | 8	80 | TUBE	Yes	NIPDAUAG	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGK.B	Active	Production	VSSOP (DGK) | 8	80 | TUBE	Yes	NIPDAUAG	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGKR	Active	Production	VSSOP (DGK) | 8	2500 | LARGE T&R	Yes	NIPDAU | SN | NIPDAUAG	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGKR.A	Active	Production	VSSOP (DGK) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGKR.B	Active	Production	VSSOP (DGK) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGKRG4	Active	Production	VSSOP (DGK) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGKRG4.A	Active	Production	VSSOP (DGK) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDGKRG4.B	Active	Production	VSSOP (DGK) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-1-260C-UNLIM	-40 to 85	OUPI
OPA1652AIDR	Active	Production	SOIC (D) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDR.A	Active	Production	SOIC (D) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDR.B	Active	Production	SOIC (D) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRG4	Active	Production	SOIC (D) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRG4.A	Active	Production	SOIC (D) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRG4.B	Active	Production	SOIC (D) | 8	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRGR	Active	Production	SON (DRG) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRGR.A	Active	Production	SON (DRG) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRGR.B	Active	Production	SON (DRG) | 8	3000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRGT	Active	Production	SON (DRG) | 8	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRGT.A	Active	Production	SON (DRG) | 8	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1652AIDRGT.B	Active	Production	SON (DRG) | 8	250 | SMALL T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OP1652
OPA1654AID	Active	Production	SOIC (D) | 14	50 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AID.A	Active	Production	SOIC (D) | 14	50 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIDR	Active	Production	SOIC (D) | 14	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIDR.A	Active	Production	SOIC (D) | 14	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654

Orderable part number	Status (1)	Material type (2)	Package | Pins	Package qty | Carrier	RoHS (3)	Lead finish/ Ball material (4)	MSL rating/ Peak reflow (5)	Op temp (°C)	Part marking (6)
OPA1654AIDRG4	Active	Production	SOIC (D) | 14	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIDRG4.A	Active	Production	SOIC (D) | 14	2500 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIPW	Active	Production	TSSOP (PW) | 14	90 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIPW.A	Active	Production	TSSOP (PW) | 14	90 | TUBE	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIPWR	Active	Production	TSSOP (PW) | 14	2000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIPWR.A	Active	Production	TSSOP (PW) | 14	2000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIPWRG4	Active	Production	TSSOP (PW) | 14	2000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654
OPA1654AIPWRG4.A	Active	Production	TSSOP (PW) | 14	2000 | LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 85	OPA1654

(1) **Status:** For more details on status, see our product life cycle.

(2) **Material type:** When designated, preproduction parts are prototypes/experimental devices, and are not yet approved or released for full production. Testing and final process, including without limitation quality assurance, reliability performance testing, and/or process qualification, may not yet be complete, and this item is subject to further changes or possible discontinuation. If available for ordering, purchases will be subject to an additional waiver at checkout, and are intended for early internal evaluation purposes only. These items are sold without warranties of any kind.

(3) **RoHS values:** Yes, No, RoHS Exempt. See the TI RoHS Statement for additional information and value definition.

(4) **Lead finish/Ball material:** Parts may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead finish/Ball material values may wrap to two lines if the finish value exceeds the maximum column width.

(5) **MSL rating/Peak reflow:** The moisture sensitivity level ratings and peak solder (reflow) temperatures. In the event that a part has multiple moisture sensitivity ratings, only the lowest level per JEDEC standards is shown. Refer to the shipping label for the actual reflow temperature that will be used to mount the part to the printed circuit board.

(6) **Part marking:** There may be an additional marking, which relates to the logo, the lot trace code information, or the environmental category of the part.

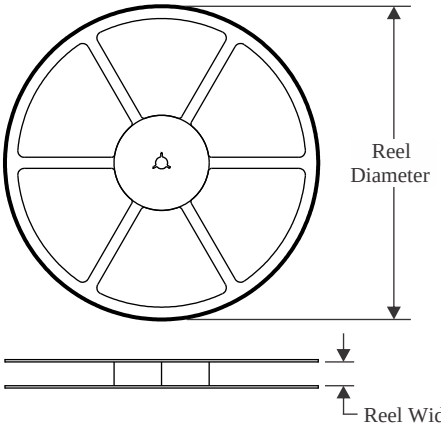
Multiple part markings will be inside parentheses. Only one part marking contained in parentheses and separated by a "~" will appear on a part. If a line is indented then it is a continuation of the previous line and the two combined represent the entire part marking for that device.

Important Information and Disclaimer: The information provided on this page represents TI's knowledge and belief as of the date that it is provided. TI bases its knowledge and belief on information provided by third parties, and makes no representation or warranty as to the accuracy of such information. Efforts are underway to better integrate information from third parties. TI has taken and continues to take reasonable steps to provide representative and accurate information but may not have conducted destructive testing or chemical analysis on incoming materials and chemicals. TI and TI suppliers consider certain information to be proprietary, and thus CAS numbers and other limited information may not be available for release.

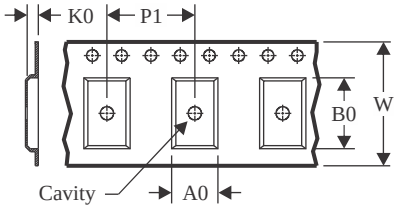
In no event shall TI's liability arising out of such information exceed the total purchase price of the TI part(s) at issue in this document sold by TI to Customer on an annual basis.

TAPE AND REEL INFORMATION

REEL DIMENSIONS

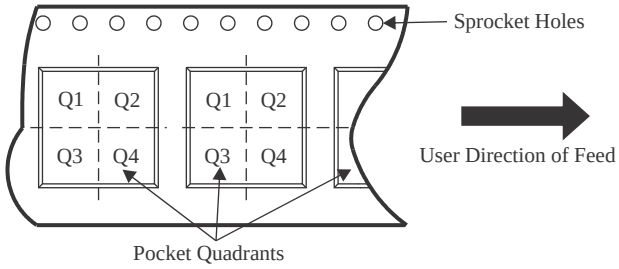


TAPE DIMENSIONS



A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

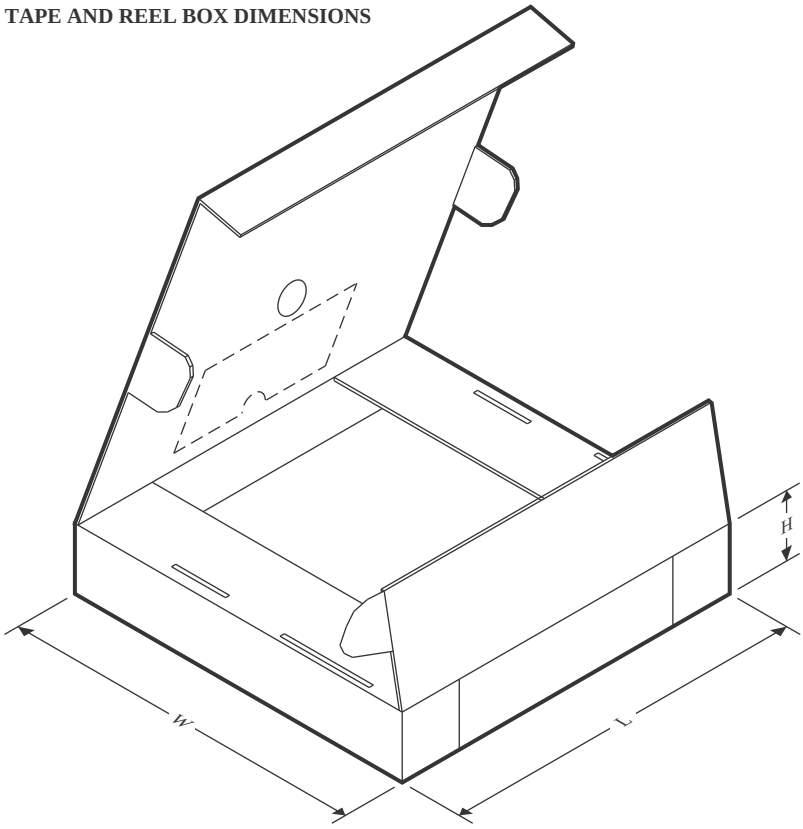
QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
OPA1652AIDGKR	VSSOP	DGK	8	2500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
OPA1652AIDGKR	VSSOP	DGK	8	2500	330.0	12.4	5.25	3.35	1.25	8.0	12.0	Q1
OPA1652AIDGKRG4	VSSOP	DGK	8	2500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
OPA1652AIDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
OPA1652AIDRG4	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
OPA1652AIDRGR	SON	DRG	8	3000	330.0	12.4	3.3	3.3	1.1	8.0	12.0	Q2
OPA1652AIDRGT	SON	DRG	8	250	180.0	12.4	3.3	3.3	1.1	8.0	12.0	Q2
OPA1654AIDR	SOIC	D	14	2500	330.0	16.4	6.5	9.0	2.1	8.0	16.0	Q1
OPA1654AIDRG4	SOIC	D	14	2500	330.0	16.4	6.5	9.0	2.1	8.0	16.0	Q1
OPA1654AIPWR	TSSOP	PW	14	2000	330.0	12.4	6.9	5.6	1.6	8.0	12.0	Q1
OPA1654AIPWRG4	TSSOP	PW	14	2000	330.0	12.4	6.9	5.6	1.6	8.0	12.0	Q1

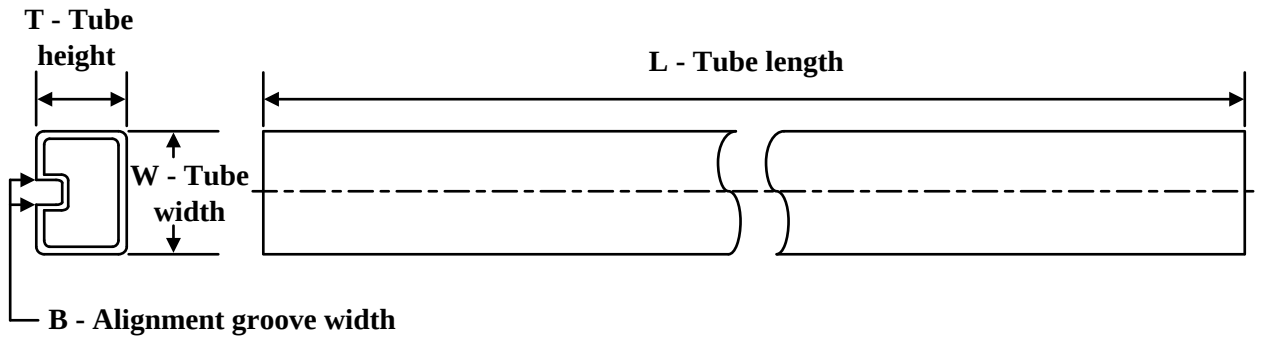
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

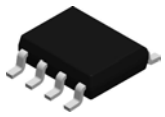
Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
OPA1652AIDGKR	VSSOP	DGK	8	2500	353.0	353.0	32.0
OPA1652AIDGKR	VSSOP	DGK	8	2500	366.0	364.0	50.0
OPA1652AIDGKRG4	VSSOP	DGK	8	2500	353.0	353.0	32.0
OPA1652AIDR	SOIC	D	8	2500	353.0	353.0	32.0
OPA1652AIDRG4	SOIC	D	8	2500	353.0	353.0	32.0
OPA1652AIDRGR	SON	DRG	8	3000	346.0	346.0	33.0
OPA1652AIDRGT	SON	DRG	8	250	210.0	185.0	35.0
OPA1654AIDR	SOIC	D	14	2500	353.0	353.0	32.0
OPA1654AIDRG4	SOIC	D	14	2500	353.0	353.0	32.0
OPA1654AIPWR	TSSOP	PW	14	2000	353.0	353.0	32.0
OPA1654AIPWRG4	TSSOP	PW	14	2000	353.0	353.0	32.0

TUBE



*All dimensions are nominal

Device	Package Name	Package Type	Pins	SPQ	L (mm)	W (mm)	T (µm)	B (mm)
OPA1652AID	D	SOIC	8	75	506.6	8	3940	4.32
OPA1652AID.A	D	SOIC	8	75	506.6	8	3940	4.32
OPA1652AID.B	D	SOIC	8	75	506.6	8	3940	4.32
OPA1652AIDGK	DGK	VSSOP	8	80	330	6.55	500	2.88
OPA1652AIDGK.A	DGK	VSSOP	8	80	330	6.55	500	2.88
OPA1652AIDGK.B	DGK	VSSOP	8	80	330	6.55	500	2.88
OPA1654AID	D	SOIC	14	50	506.6	8	3940	4.32
OPA1654AID.A	D	SOIC	14	50	506.6	8	3940	4.32
OPA1654AIPW	PW	TSSOP	14	90	530	10.2	3600	3.5
OPA1654AIPW.A	PW	TSSOP	14	90	530	10.2	3600	3.5

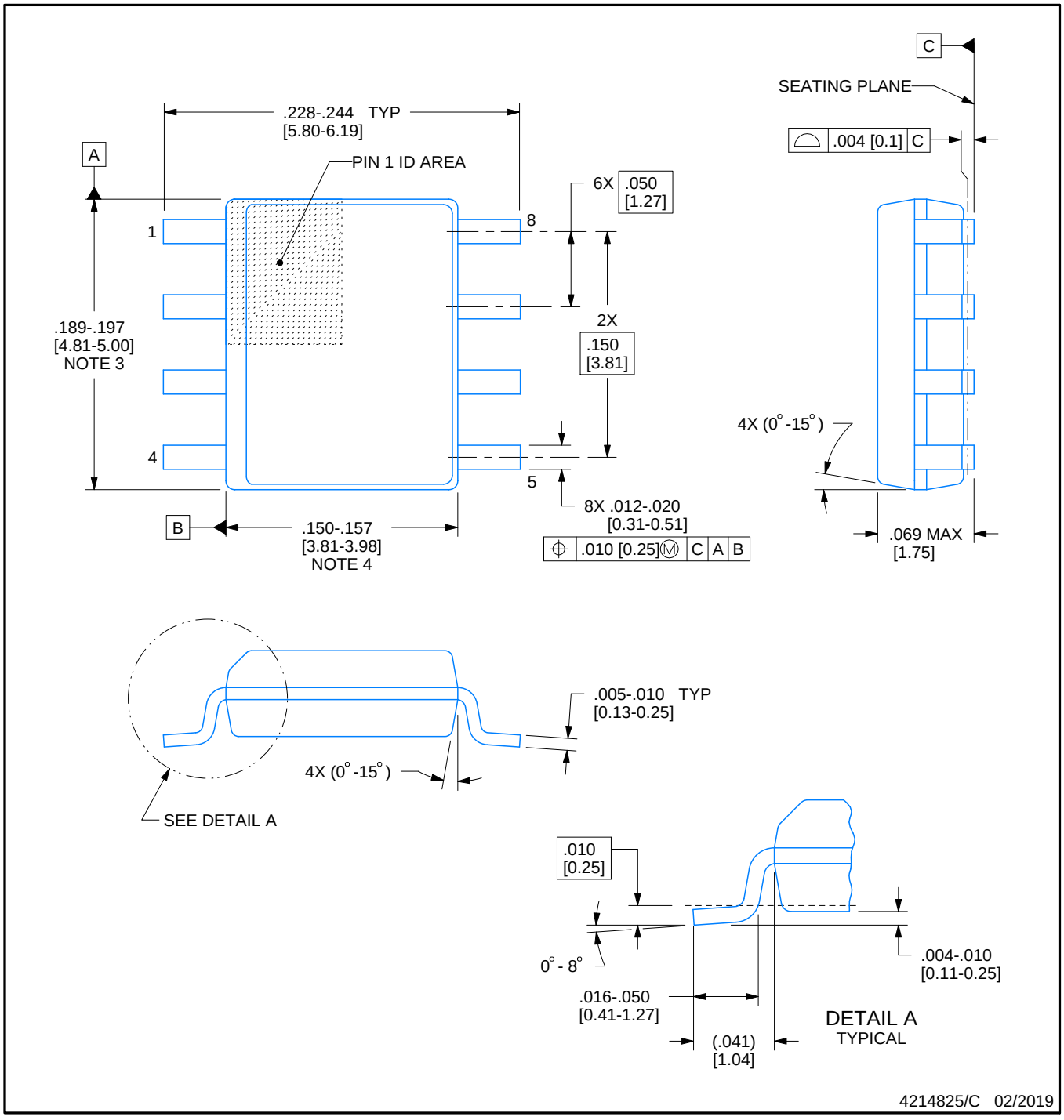


PACKAGE OUTLINE

D0008A

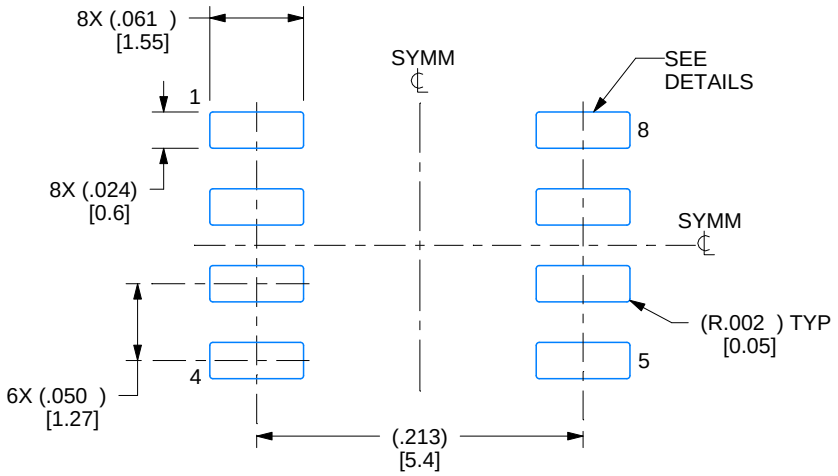
SOIC - 1.75 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT

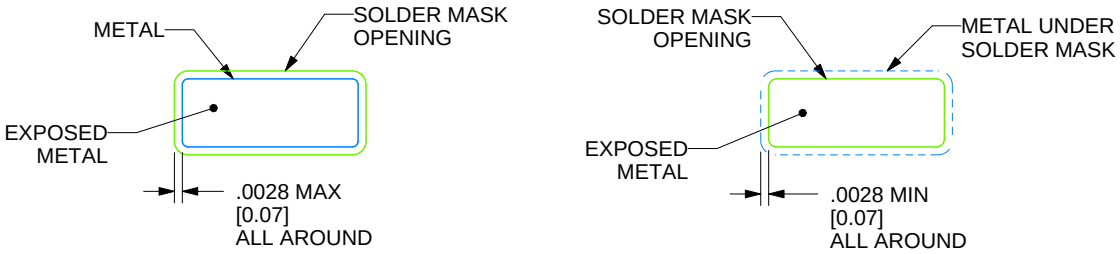


NOTES:

1. Linear dimensions are in inches [millimeters]. Dimensions in parenthesis are for reference only. Controlling dimensions are in inches. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed .006 [0.15] per side.
4. This dimension does not include interlead flash.
5. Reference JEDEC registration MS-012, variation AA.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:8X



SOLDER MASK DETAILS

4214825/C 02/2019

NOTES: (continued)

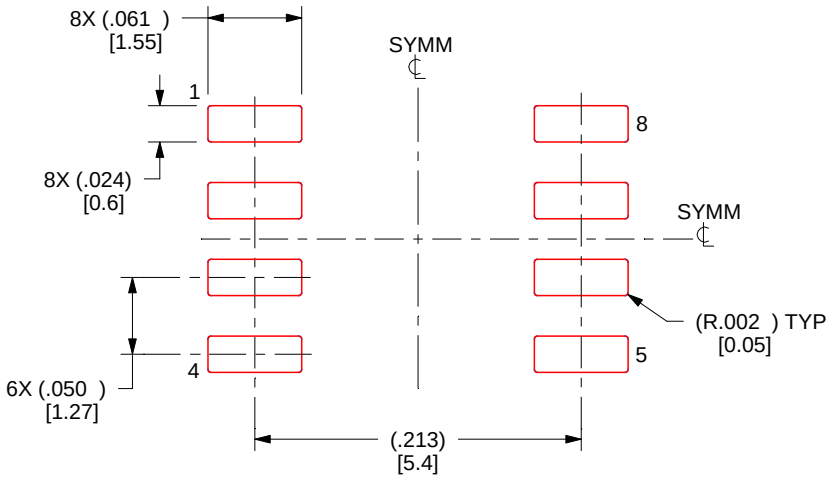
6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.

EXAMPLE STENCIL DESIGN

D0008A

SOIC - 1.75 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT



SOLDER PASTE EXAMPLE
BASED ON .005 INCH [0.125 MM] THICK STENCIL
SCALE:8X

4214825/C 02/2019

NOTES: (continued)

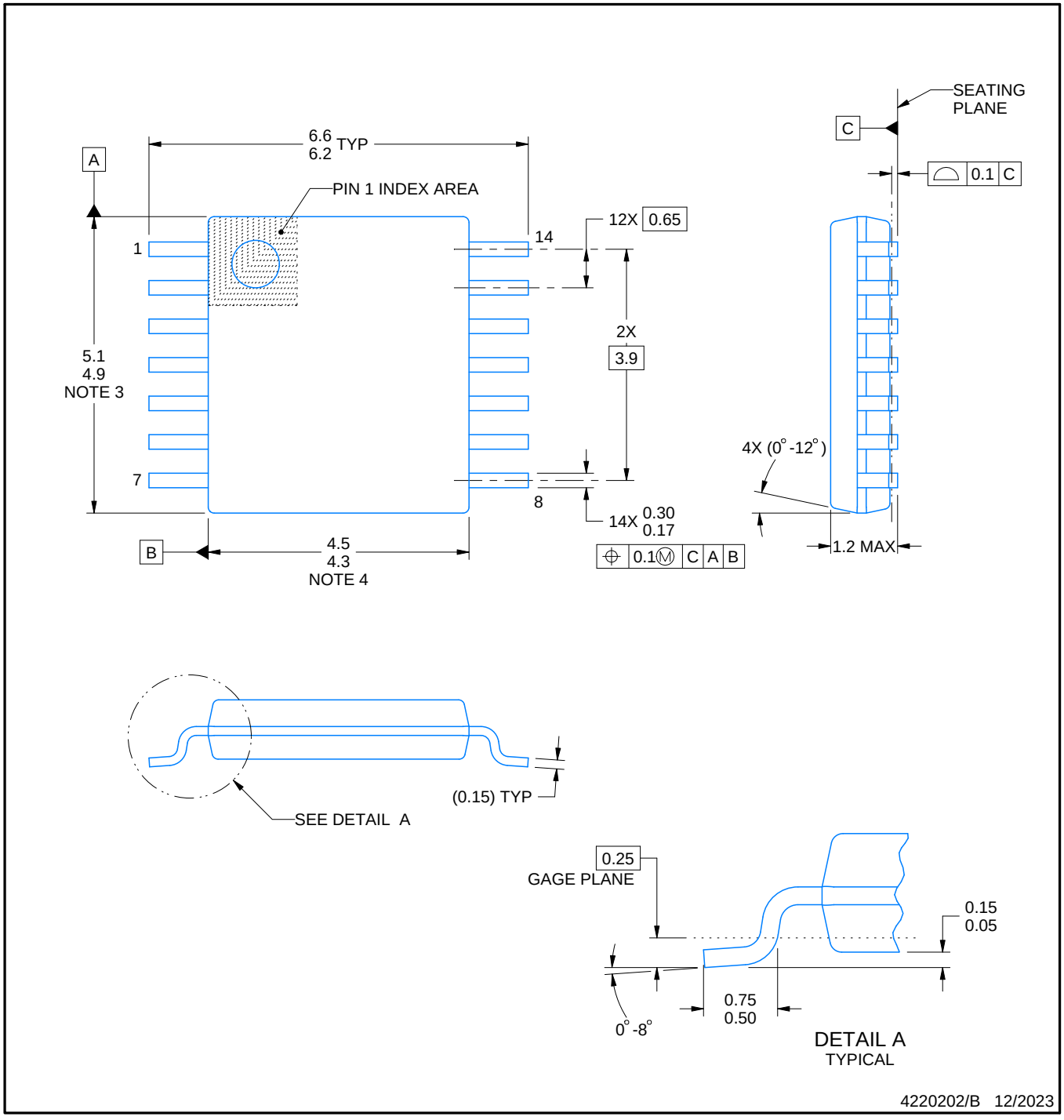
8. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
9. Board assembly site may have different recommendations for stencil design.

PACKAGE OUTLINE

PW0014A

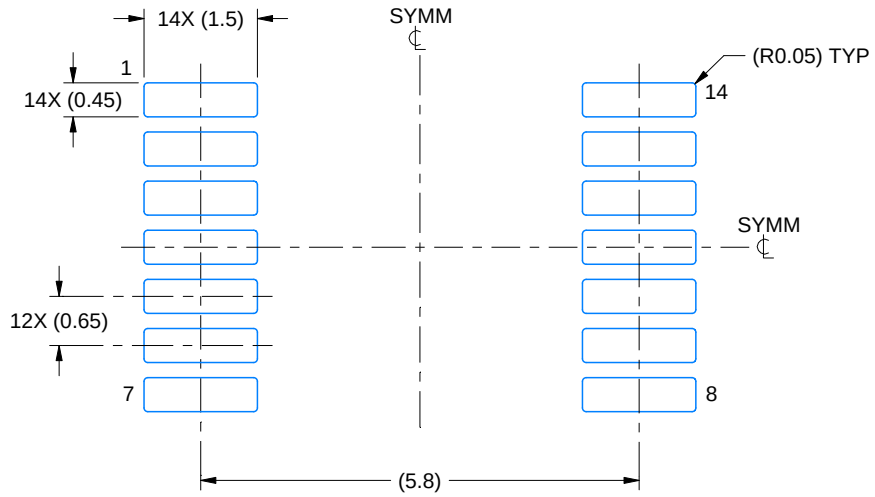
TSSOP - 1.2 mm max height

SMALL OUTLINE PACKAGE

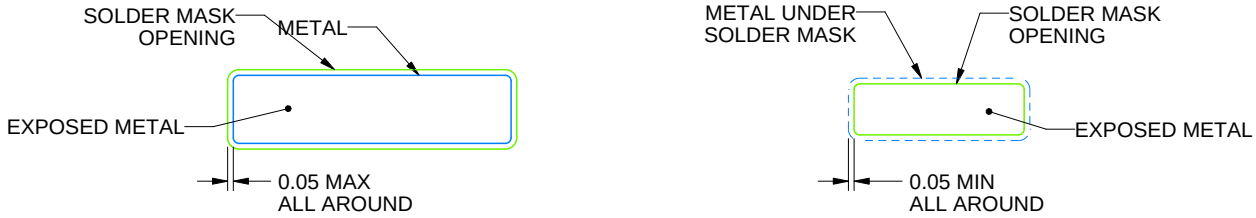


NOTES:

1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.
4. This dimension does not include interlead flash. Interlead flash shall not exceed 0.25 mm per side.
5. Reference JEDEC registration MO-153.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 10X

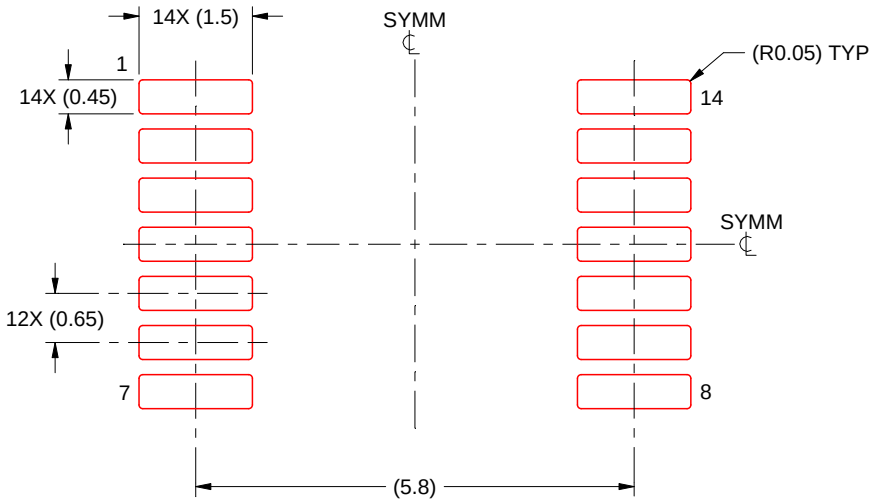


SOLDER MASK DETAILS

4220202/B 12/2023

NOTES: (continued)

6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE: 10X

4220202/B 12/2023

NOTES: (continued)

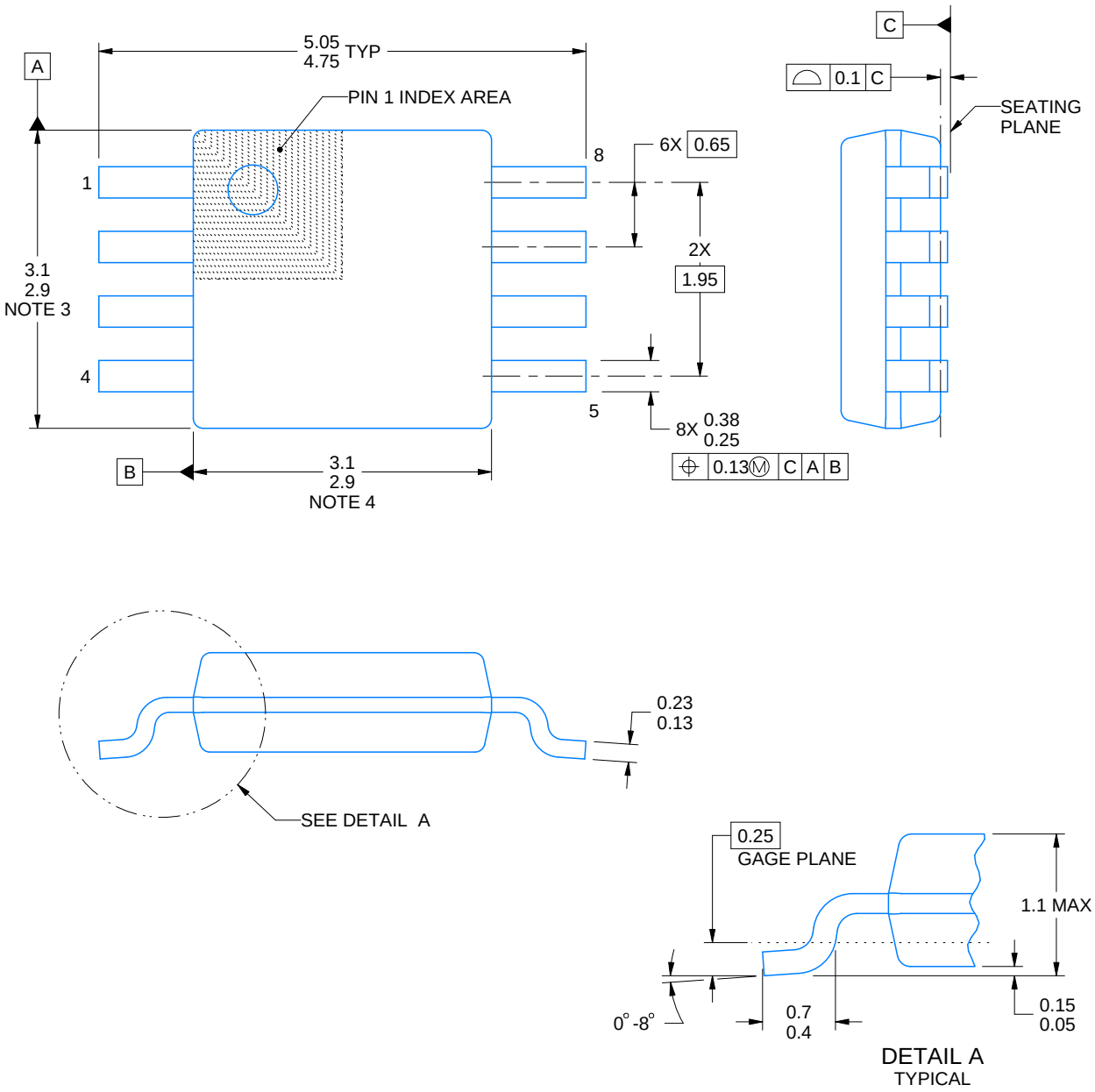
8. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
9. Board assembly site may have different recommendations for stencil design.

PACKAGE OUTLINE

DGK0008A

VSSOP - 1.1 mm max height

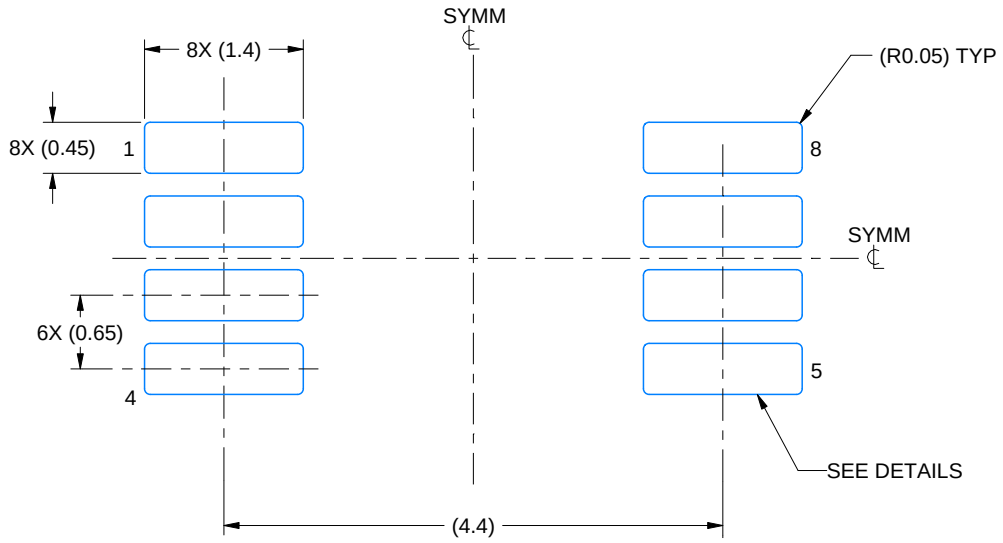
SMALL OUTLINE PACKAGE



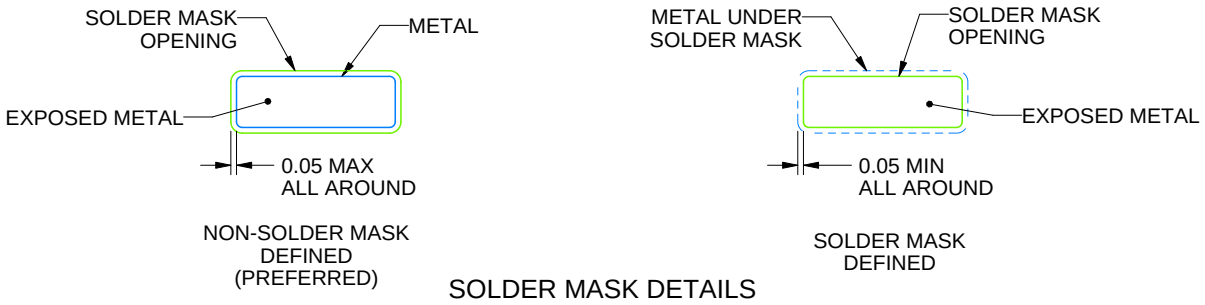
PowerPAD is a trademark of Texas Instruments.

NOTES:

1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.
4. This dimension does not include interlead flash. Interlead flash shall not exceed 0.25 mm per side.
5. Reference JEDEC registration MO-187.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 15X

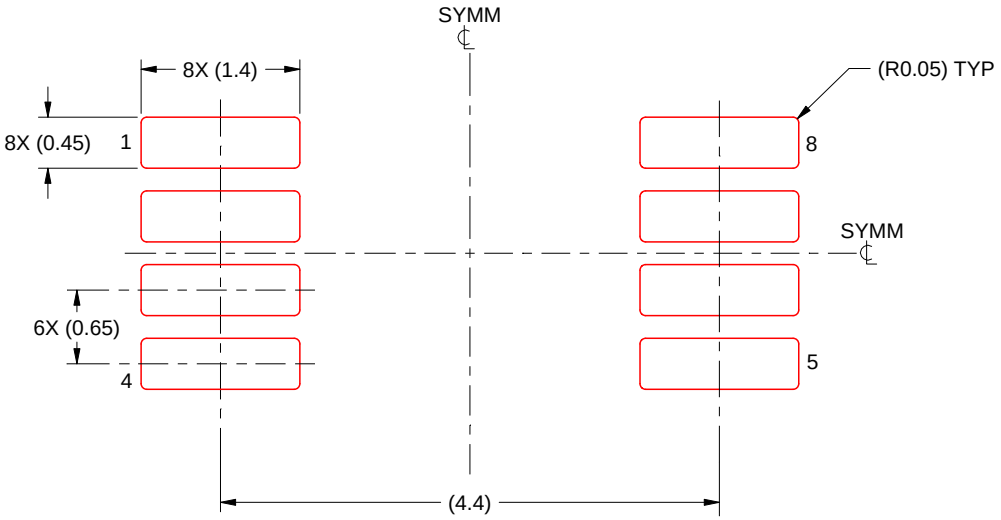


SOLDER MASK DETAILS

4214862/A 04/2023

NOTES: (continued)

6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.
8. Vias are optional depending on application, refer to device data sheet. If any vias are implemented, refer to their locations shown on this view. It is recommended that vias under paste be filled, plugged or tented.
9. Size of metal pad may vary due to creepage requirement.



SOLDER PASTE EXAMPLE
SCALE: 15X

4214862/A 04/2023

NOTES: (continued)

11. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
12. Board assembly site may have different recommendations for stencil design.

GENERIC PACKAGE VIEW

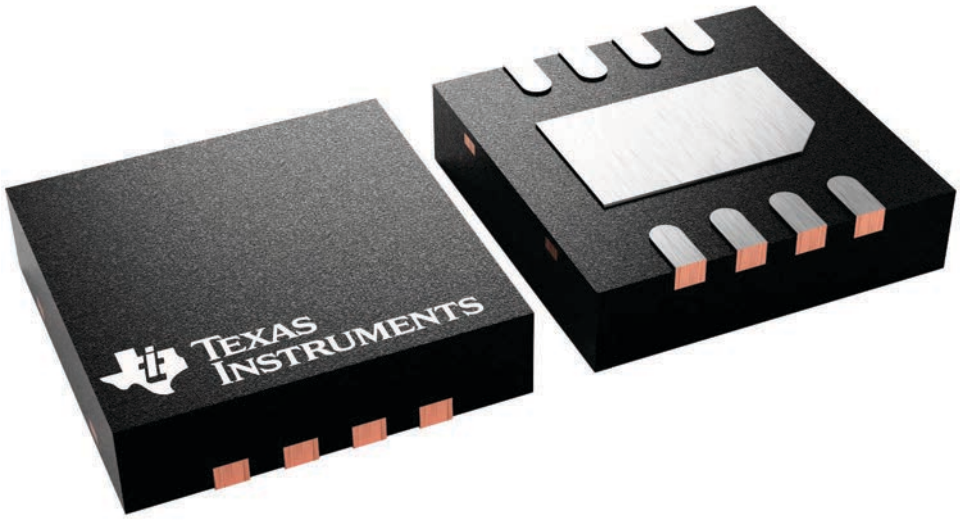
DRG 8

WSON - 0.8 mm max height

3 x 3, 0.5 mm pitch

PLASTIC SMALL OUTLINE - NO LEAD

This image is a representation of the package family, actual package may vary.
Refer to the product data sheet for package details.



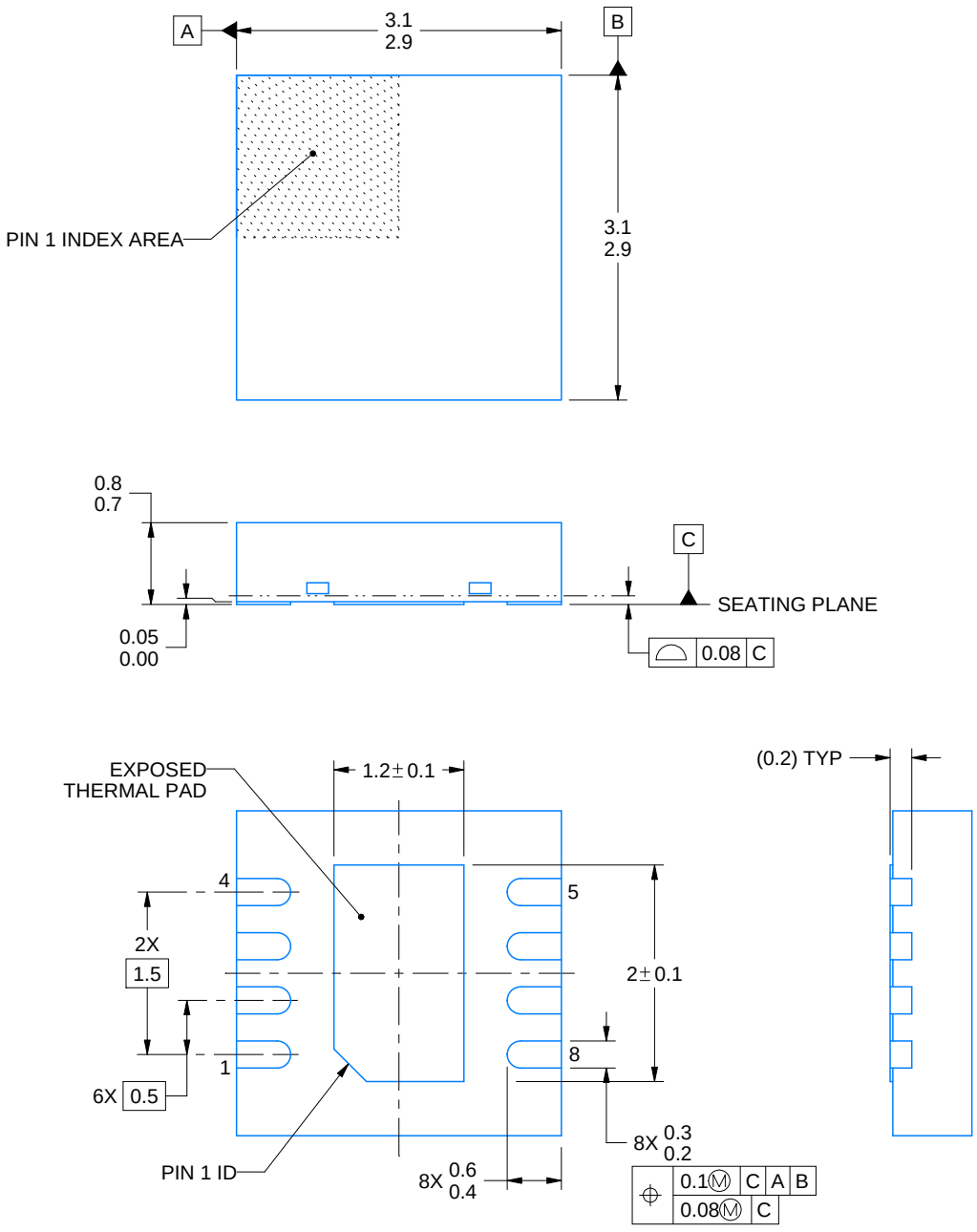
4225794/A

PACKAGE OUTLINE

DRG0008A

WSON - 0.8 mm max height

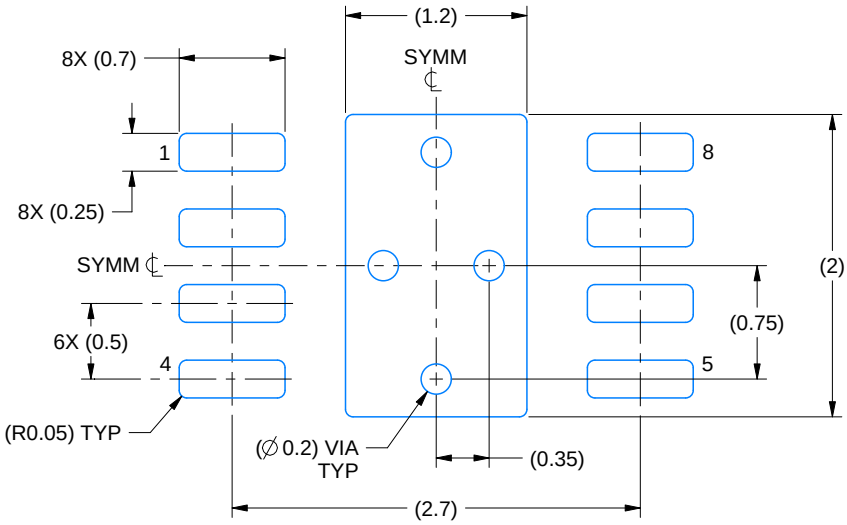
PLASTIC SMALL OUTLINE - NO LEAD



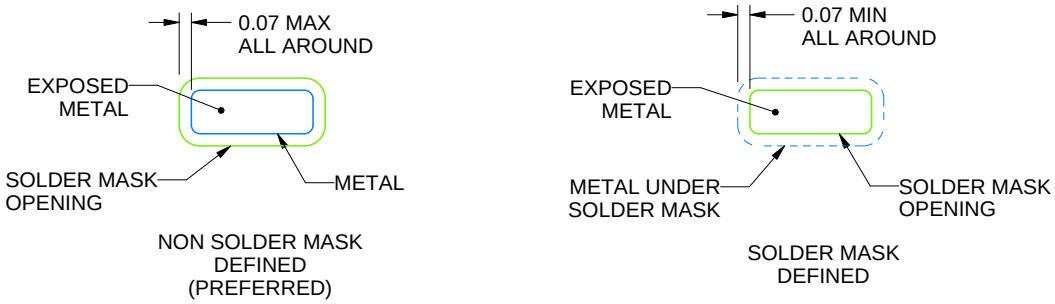
4218885/A 03/2020

NOTES:

1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. The package thermal pad must be soldered to the printed circuit board for thermal and mechanical performance.



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:20X

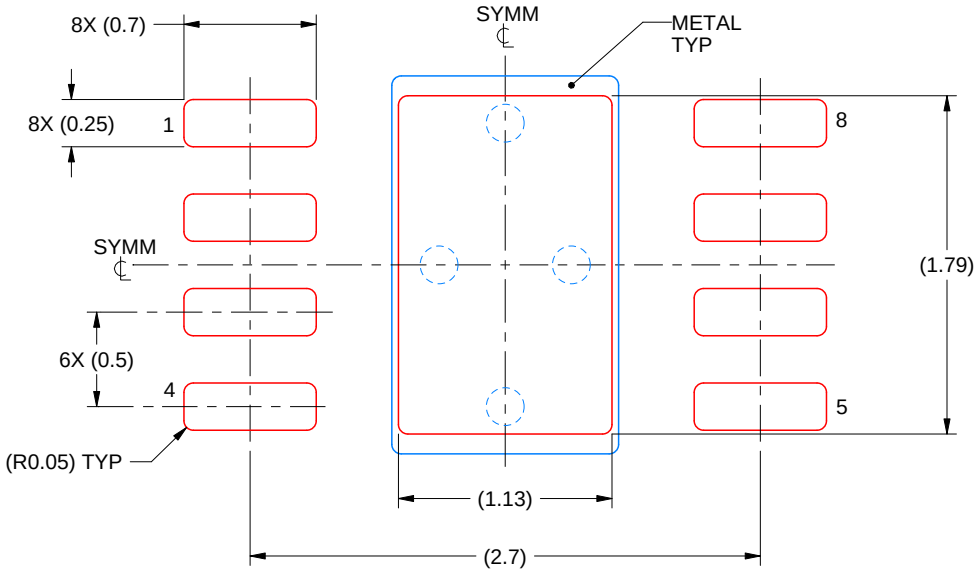


SOLDER MASK DETAILS

4218885/A 03/2020

NOTES: (continued)

4. This package is designed to be soldered to a thermal pad on the board. For more information, see Texas Instruments literature number SLUA271 (www.ti.com/lit/slua271).
5. Vias are optional depending on application, refer to device data sheet. If any vias are implemented, refer to their locations shown on this view. It is recommended that vias under paste be filled, plugged or tented.



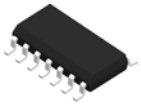
SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL

EXPOSED PAD
84% PRINTED SOLDER COVERAGE BY AREA
SCALE:25X

4218885/A 03/2020

NOTES: (continued)

6. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.

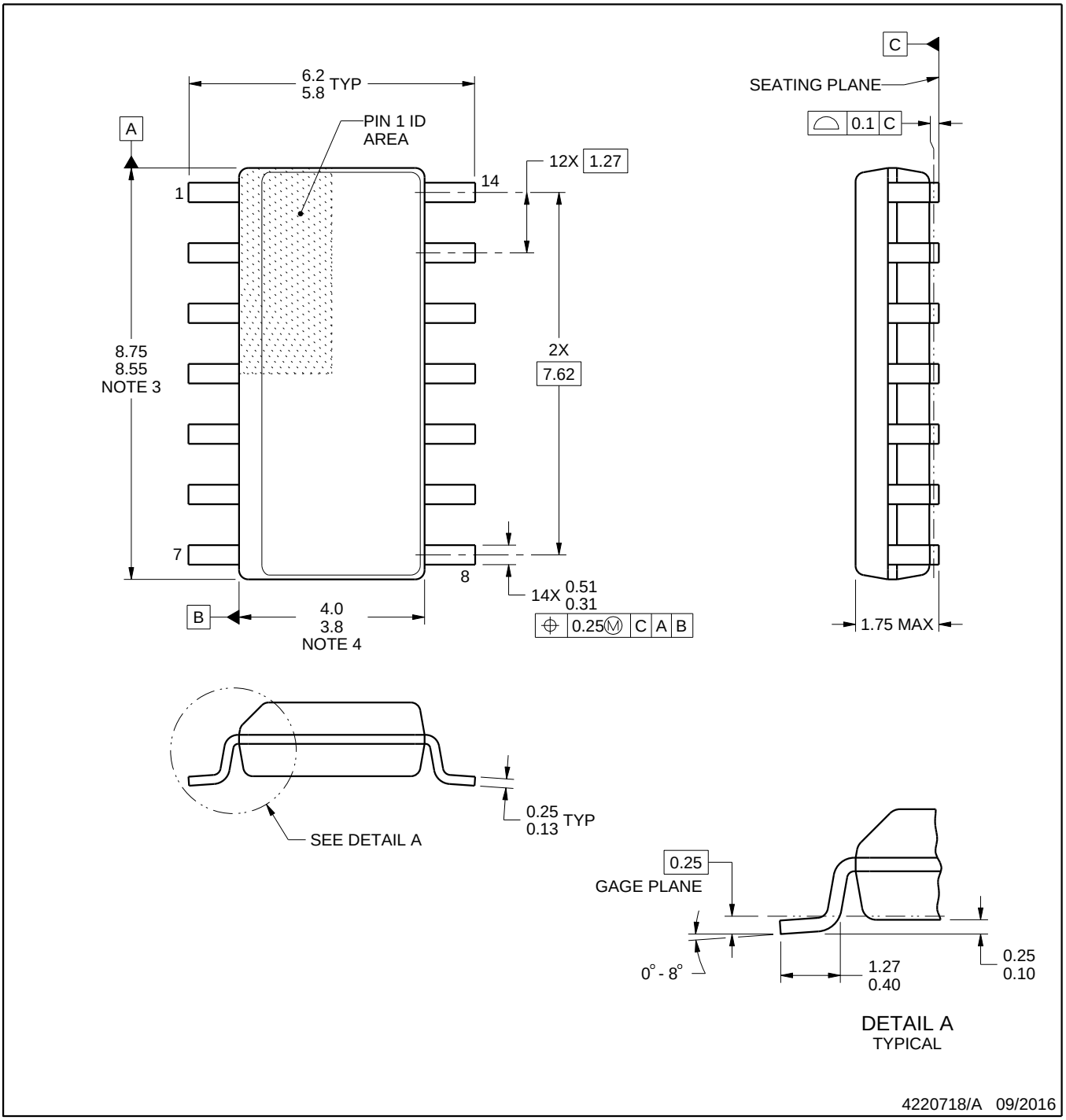


PACKAGE OUTLINE

D0014A

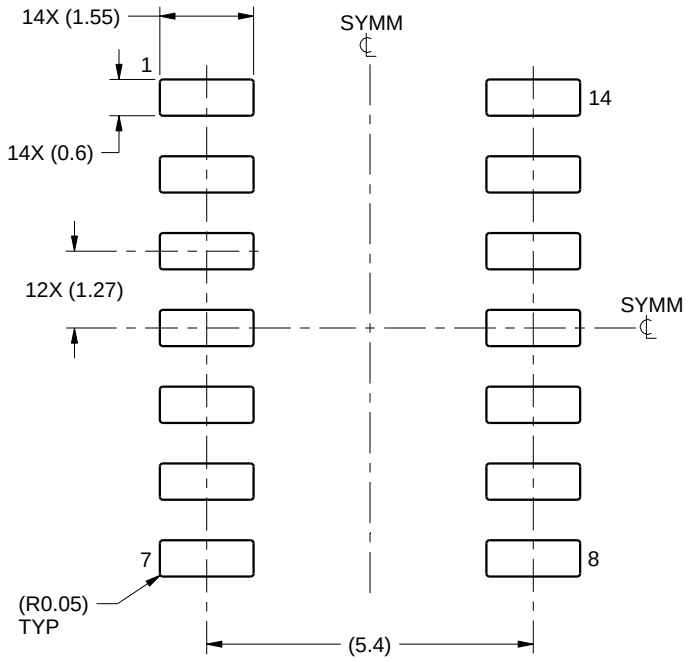
SOIC - 1.75 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT

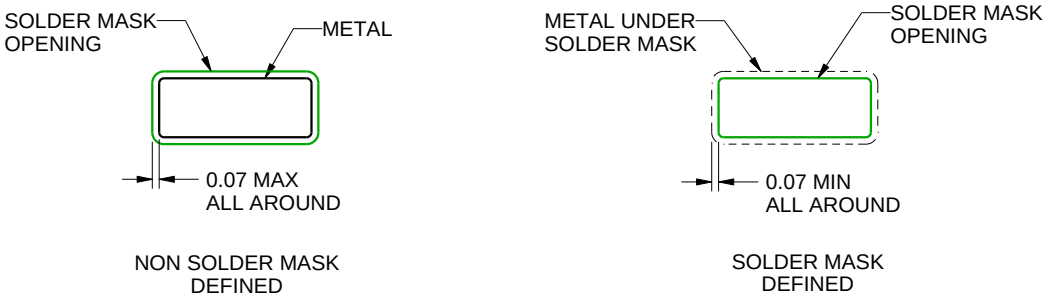


NOTES:

1. All linear dimensions are in millimeters. Dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm, per side.
4. This dimension does not include interlead flash. Interlead flash shall not exceed 0.43 mm, per side.
5. Reference JEDEC registration MS-012, variation AB.



LAND PATTERN EXAMPLE
SCALE:8X



SOLDER MASK DETAILS

4220718/A 09/2016

NOTES: (continued)

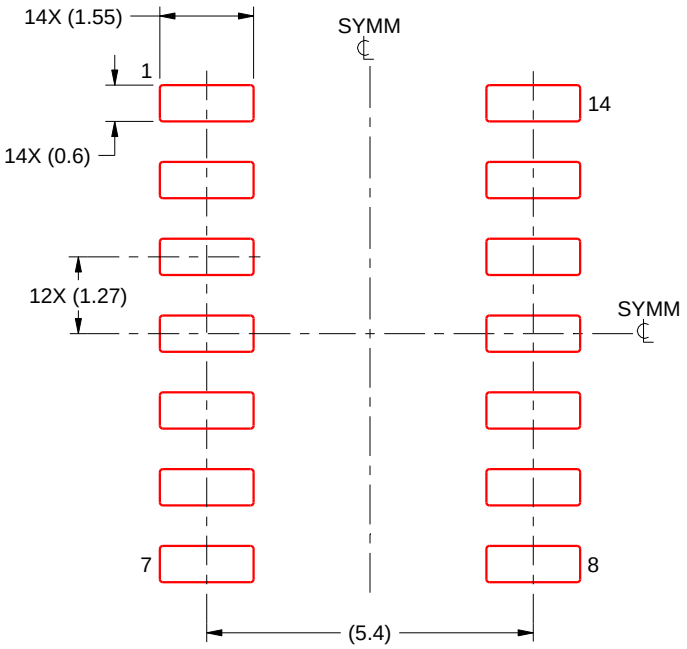
6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.

EXAMPLE STENCIL DESIGN

D0014A

SOIC - 1.75 mm max height

SMALL OUTLINE INTEGRATED CIRCUIT



SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE:8X

4220718/A 09/2016

NOTES: (continued)

8. Laser cutting apertures with trapezoidal walls and rounded corners may offer better paste release. IPC-7525 may have alternate design recommendations.
9. Board assembly site may have different recommendations for stencil design.

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