



OPAx388 Precision, Zero-Drift, Zero-Crossover, True Rail-to-Rail Input/Output, Operational Amplifiers

1 Features

- Ultra-Low Offset Voltage: $\pm 0.25 \mu\text{V}$
- Zero-Drift: $\pm 0.005 \mu\text{V}/^\circ\text{C}$
- Zero-Crossover: 140-dB CMRR True RRIO
- Low Noise: $7.0 \text{ nV}/\sqrt{\text{Hz}}$ at 1 kHz
- No $1/f$ Noise: $140 \text{ nV}_{\text{PP}}$ (0.1 Hz to 10 Hz)
- Fast Settling: $2 \mu\text{s}$ (1 V to 0.01%)
- Gain Bandwidth: 10 MHz
- Single Supply: 2.5 V to 5.5 V
- Dual Supply: $\pm 1.25 \text{ V}$ to $\pm 2.75 \text{ V}$
- True Rail-to-Rail Input and Output
- EMI/RFI Filtered Inputs
- Industry-Standard Packages:
 - Single in SOIC-8, SOT-23-5, and VSSOP-8
 - Dual in SOIC-8 and VSSOP-8
 - Quad in SOIC-14 and TSSOP-14

2 Applications

- Bridge Amplifiers
- Strain Gauges
- Test Equipment
- Current Shunt Measurement
- Thermocouples, Thermopiles
- Electronic Scales
- Medical Instrumentation
- Resistor Thermal Detectors
- Precision Active Filters

3 Description

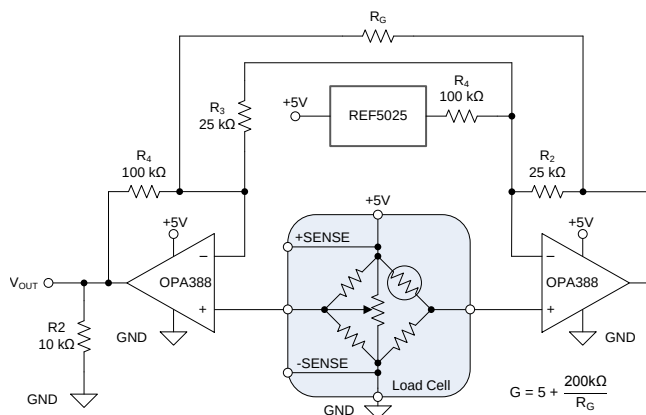
The OPAx388 (OPA388, OPA2388, and OPA4388) series of precision operational amplifiers are ultra-low noise, fast-settling, zero-drift, zero-crossover devices that provide rail-to-rail input and output operation. These features and excellent ac performance, combined with only $0.25 \mu\text{V}$ of offset and $0.005 \mu\text{V}/^\circ\text{C}$ of drift over temperature, makes the OPAx388 ideal for driving high-precision, analog-to-digital converters (ADCs) or buffering the output of high-resolution, digital-to-analog converters (DACs). This design results in superior performance when driving analog-to-digital converters (ADCs) without degradation of linearity. The OPA388 (single version) is available in the VSSOP-8, SOT23-5, and SOIC-8 packages. The OPA2388 (dual version) is offered in the VSSOP-8 and SO-8 packages. The OPA4388 (quad version) is offered in the TSSOP-14 and SO-14 packages. All versions are specified over the extended industrial temperature range (-40°C to $+125^\circ\text{C}$).

Device Information⁽¹⁾

PART NUMBER	PACKAGE	BODY SIZE (NOM)
OPA388	SOIC (8)	4.90 mm × 3.90 mm
	SOT-23 (5)	2.90 mm × 1.60 mm
	VSSOP (8)	3.00 mm × 3.00 mm
OPA2388	SOIC (8)	4.90 mm × 3.90 mm
	VSSOP (8)	3.00 mm × 3.00 mm
OPA4388	SOIC (14)	8.65 mm × 3.90 mm
	TSSOP (14)	5.00 mm × 4.40 mm

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

OPA388 in a High-CMRR, Instrumentation Amplifier Application



OPA388 Allows Precision, Low-Error Measurements

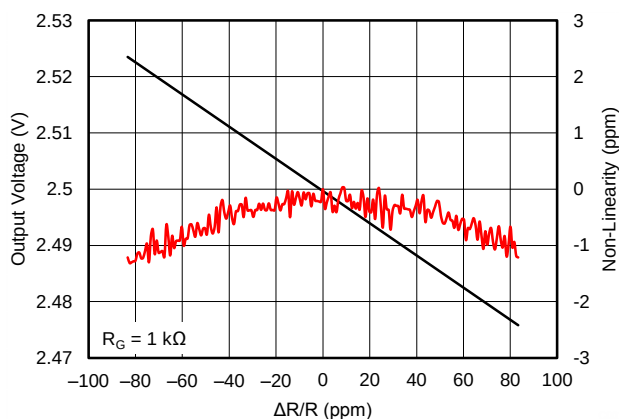


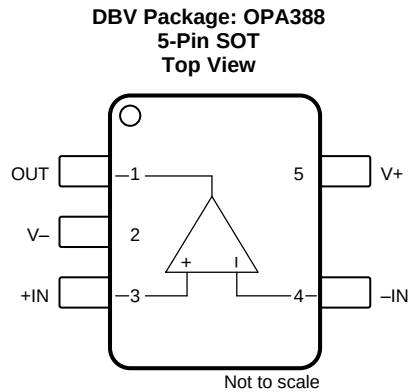
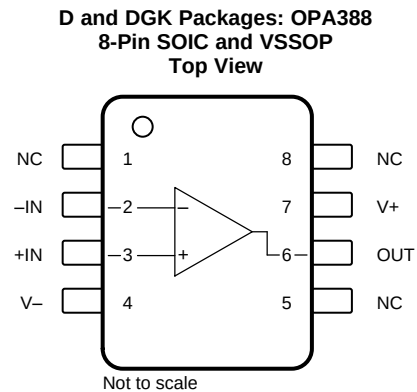
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4 Revision History

DATE	REVISION	NOTES
December 2016	*	Initial release.

5 Pin Configuration and Functions



Pin Functions: OPA388

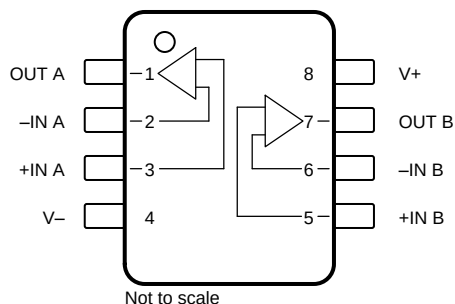
PIN			I/O	DESCRIPTION
NAME	OPA388			
	D (SOIC), DGK (VSSOP)	DBV (SOT)		
−IN	2	4	I	Inverting input
+IN	3	3	I	Noninverting input
NC	1, 5, 8	—	—	No internal connection (can be left floating)
OUT	6	1	O	Output
V−	4	2	—	Negative (lowest) power supply
V+	7	5	—	Positive (highest) power supply

OPA388, OPA2388, OPA4388

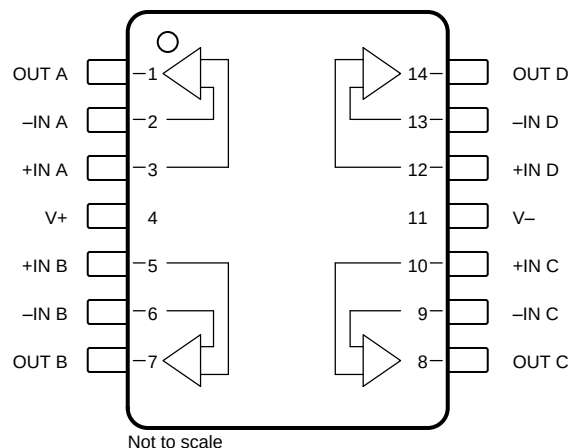
SBOS777 – DECEMBER 2016

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D and DGK Packages: OPA2388
8-Pin SOIC and VSSOP
Top View



D and PW Packages: OPA4388
14-Pin SOIC and TSSOP
Top View



Pin Functions: OPA2388 and OPA4388

NAME	PIN		I/O	DESCRIPTION
	OPA2388 D (SOIC), DGK (VSSOP)	OPA4388 D (SOIC), PW (TSSOP)		
-IN A	2	2	I	Inverting input, channel A
-IN B	6	6	I	Inverting input, channel B
-IN C	—	9	I	Inverting input, channel C
-IN D	—	13	I	Inverting input, channel D
+IN A	3	3	I	Noninverting input, channel A
+IN B	5	5	I	Noninverting input, channel B
+IN C	—	10	I	Noninverting input, channel C
+IN D	—	12	I	Noninverting input, channel D
OUT A	1	1	O	Output, channel A
OUT B	7	7	O	Output, channel B
OUT C	—	8	O	Output, channel C
OUT D	—	14	O	Output, channel D
V-	4	11	—	Negative (lowest) power supply
V+	8	4	—	Positive (highest) power supply

6 Specifications

6.1 Absolute Maximum Ratings

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

			MIN	MAX	UNIT
Supply voltage, $V_S = (V+) - (V-)$	Single-supply		6		V
	Dual-supply		± 3		
Signal input pins	Voltage	Common-mode	$(V-) - 0.5$	$(V+) + 0.5$	V
		Differential	± 0.5		
	Current		± 10		mA
Output short circuit ⁽²⁾			Continuous		
Temperature	Operating, T_A		-55	150	°C
	Junction, T_J			150	
	Storage, T_{stg}		-65	150	

- (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 ground, 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⁾		± 4000	V
	Charged-device model (CDM), per JEDEC specification JESD22-C101 ⁽²⁾		± 1000	

- (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, $V_S = (V+) - (V-)$	Single-supply	2.5		5.5	V
	Dual-supply	± 1.25		± 2.75	
Specified temperature		-40		125	°C

6.4 Thermal Information: OPA388

THERMAL METRIC ⁽¹⁾		OPA388	UNIT
		D (SOIC)	
		8 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	116	°C/W
$R_{\theta JC(top)}$	Junction-to-case(top) thermal resistance	60	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	56	°C/W
Ψ_{JT}	Junction-to-top characterization parameter	12.8	°C/W
Ψ_{JB}	Junction-to-board characterization parameter	55.9	°C/W
$R_{\theta JC(bot)}$	Junction-to-case(bottom) thermal resistance	N/A	°C/W

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

6.5 Electrical Characteristics: $V_S = \pm 1.25\text{ V to } \pm 2.75\text{ V}$ ($V_S = 2.5\text{ to } 5.5\text{ V}$)

at $T_A = 25^\circ\text{C}$, $V_{CM} = V_{OUT} = V_S / 2$, and $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$ (unless otherwise noted)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
OFFSET VOLTAGE							
V _{OS}	Input offset voltage			±0.25	±5	μV	
		T _A = −40°C to +125°C			±7.5		
dV _{OS} /dT	Input offset voltage drift	T _A = −40°C to +125°C		±0.005	±0.05	μV/°C	
PSRR	Power-supply rejection ratio	T _A = −40°C to +125°C		±0.1	±1	μV/V	
INPUT BIAS CURRENT							
I _B	Input bias current	R _{IN} = 100 kΩ		±30	±350	pA	
			T _A = 0°C to +85°C		±400	pA	
			T _A = −40°C to +125°C		±700		
I _{OS}	Input offset current			±60	±700		
			T _A = 0°C to +85°C		±800		
			T _A = −40°C to +125°C		±800		
NOISE							
E _N	Input voltage noise	f = 0.1 Hz to 10 Hz		0.14		μV _{PP}	
e _N	Input voltage noise density	f = 10 Hz		7		nV/√Hz	
		f = 100 Hz		7			
		f = 1 kHz		7			
		f = 10 kHz		7			
I _N	Input current noise density	f = 1 kHz		100		fA/rtHz	
INPUT VOLTAGE							
V _{CM}	Common-mode voltage range			(V−) − 0.1	(V+) + 0.1	V	
CMRR	Common-mode rejection ratio	(V−) − 0.1 V < V _{CM} < (V+) + 0.1 V	V _S = ±1.25 V	124	138	dB	
			V _S = ±2.75 V	124	140		
		(V−) < V _{CM} < (V+) + 0.1 V, T _A = −40°C to +125°C	V _S = ±1.25 V	114	134		
		(V−) − 0.05 V < V _{CM} < (V+) + 0.1 V, T _A = −40°C to +125°C	V _S = ±2.75 V	124	140		
INPUT IMPEDANCE							
Z _{id}	Differential input impedance			100 2		MΩ pF	
Z _{ic}	Common-mode input impedance			60 4.5		TΩ pF	
OPEN-LOOP GAIN							
A _{OL}	Open-loop voltage gain	(V−) + 0.1 V < V _O < (V+) − 0.1 V, R _{LOAD} = 10 kΩ		126	148	dB	
		(V−) + 0.1 V < V _O < (V+) − 0.1 V, R _{LOAD} = 10 kΩ, T _A = −40°C to +125°C		120	126		
		(V−) + 0.2 V < V _O < (V+) − 0.2 V, R _{LOAD} = 2 kΩ		126	148		
		(V−) + 0.25 V < V _O < (V+) − 0.25 V, R _{LOAD} = 2 kΩ, T _A = −40°C to +125°C		120	126		
FREQUENCY RESPONSE							
GBW	Unity-gain bandwidth			10		MHz	
SR	Slew rate	G = +1, 4-V step		5		V/μs	
THD+N	Total harmonic distortion + noise	G = 1, f = 1 kHz, V _O = 1 V _{RMS}		0.0005%			
t _S	Settling time	To 0.1%	V _S = ±2.5 V, G = +1, 1-V step	0.75		μs	
		To 0.01%	V _S = ±2.5 V, G = +1, 1-V step	2			
t _{OR}	Overload recovery time	V _{IN} × G = V _S		10		μs	

Electrical Characteristics: $V_S = \pm 1.25\text{ V}$ to $\pm 2.75\text{ V}$ ($V_S = 2.5$ to 5.5 V) (continued)

 at $T_A = 25^\circ\text{C}$, $V_{CM} = V_{OUT} = V_S / 2$, and $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$ (unless otherwise noted)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
OUTPUT							
V _O	Voltage output swing from rail	Positive rail	No load		1	15	mV
			R _{LOAD} = 10 kΩ		5	20	
			R _{LOAD} = 2 kΩ		20	50	
		Negative rail	No load		5	15	
			R _{LOAD} = 10 kΩ		10	20	
			R _{LOAD} = 2 kΩ		40	60	
		T _A = −40°C to +125°C, both rails, R _{LOAD} = 10 kΩ				10	
I _{SC}	Short-circuit current	V _S = 5.5 V			±60	mA	
		V _S = 2.5 V			±30		
C _{LOAD}	Capacitive load drive	See Typical Characteristics					
Z _O	Open-loop output impedance	f = 1 MHz, I _O = 0 A, see Figure 23			150		Ω
POWER SUPPLY							
I _Q	Quiescent current per amplifier	T _A = −40°C to +125°C, I _O = 0 A	V _S = ±1.25 V (V _S = 2.5 V)		1.7	2.4	mA
			V _S = ±2.75 V (V _S = 5.5 V)		1.9	2.6	
TEMPERATURE							
T _A	Specified range				−40	125	°C

6.6 Typical Characteristics

Table 1. Table of Graphs

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EMIRR vs Frequency	Figure 36

6.7 Typical Characteristics

at $T_A = 25^\circ\text{C}$, $V_S = \pm 2.5\text{ V}$, $V_{CM} = V_S / 2$, $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$, and $C_L = 100\text{ pF}$ (unless otherwise noted)

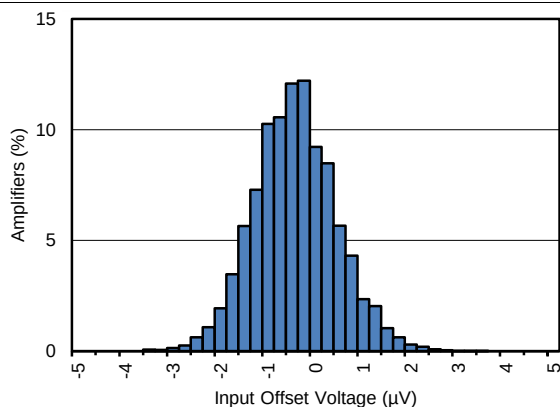


Figure 1. Offset Voltage Production Distribution

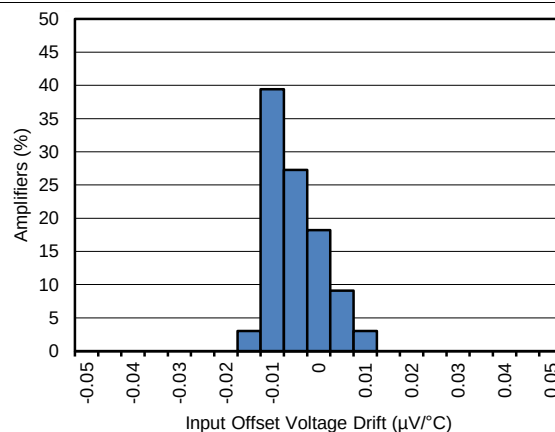


Figure 2. Offset Voltage Drift Distribution From -40°C to $+125^\circ\text{C}$

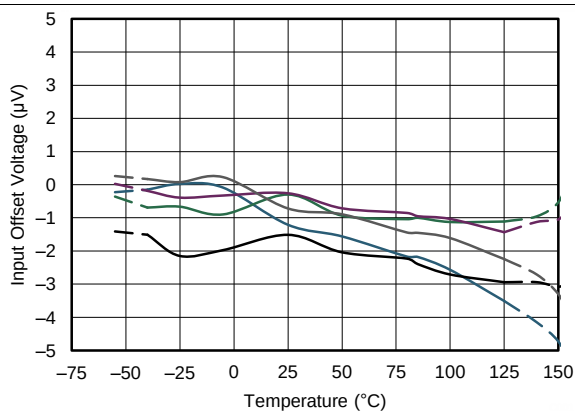


Figure 3. Offset Voltage vs Temperature

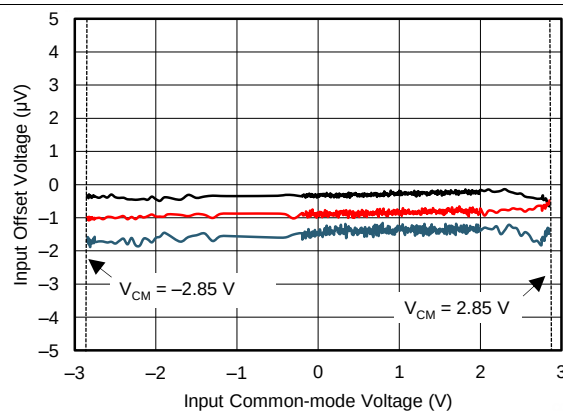


Figure 4. Offset Voltage vs Common-Mode Voltage

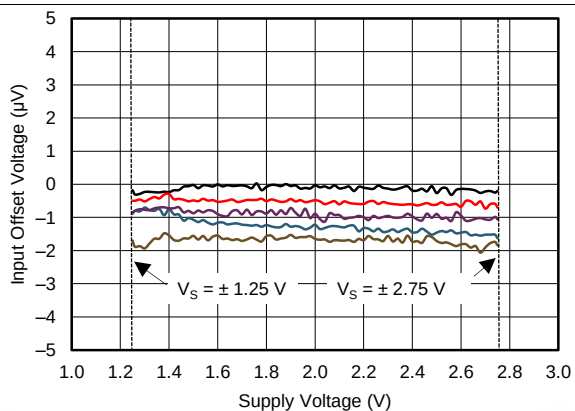


Figure 5. Offset Voltage vs Supply Voltage

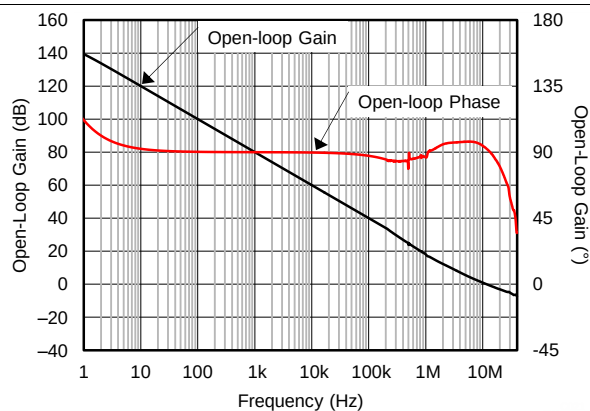


Figure 6. Open-Loop Gain and Phase vs Frequency

Typical Characteristics (continued)

at $T_A = 25^\circ\text{C}$, $V_S = \pm 2.5\text{ V}$, $V_{CM} = V_S / 2$, $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$, and $C_L = 100\text{ pF}$ (unless otherwise noted)

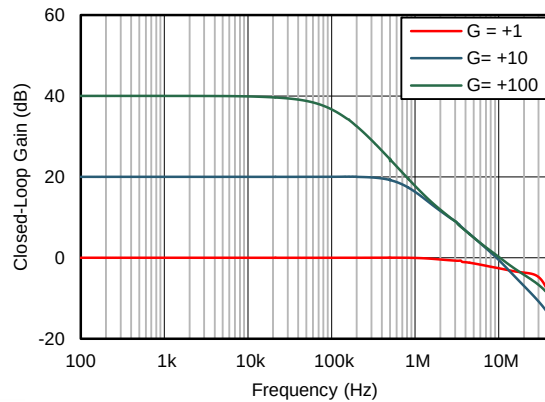


Figure 7. Closed-Loop Gain and Phase vs Frequency

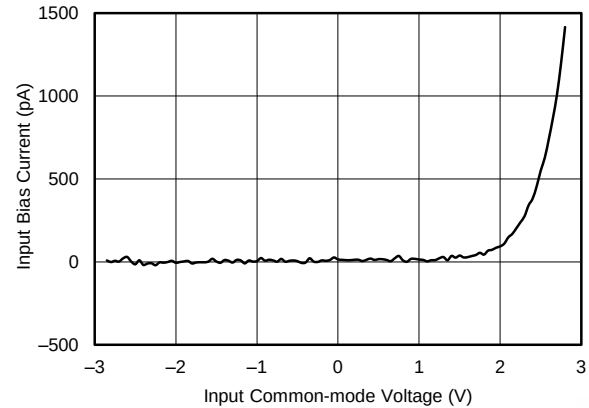


Figure 8. Input Bias Current vs Common-Mode Voltage

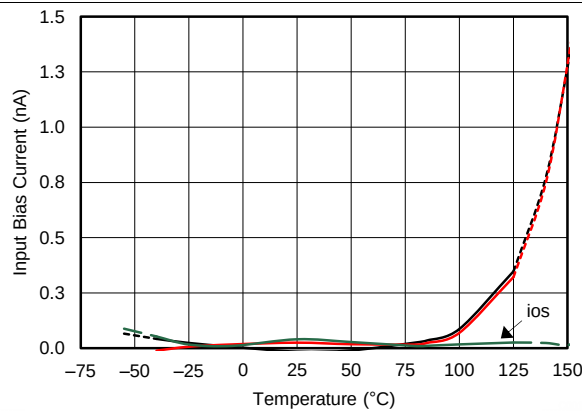


Figure 9. Input Bias Current vs Temperature

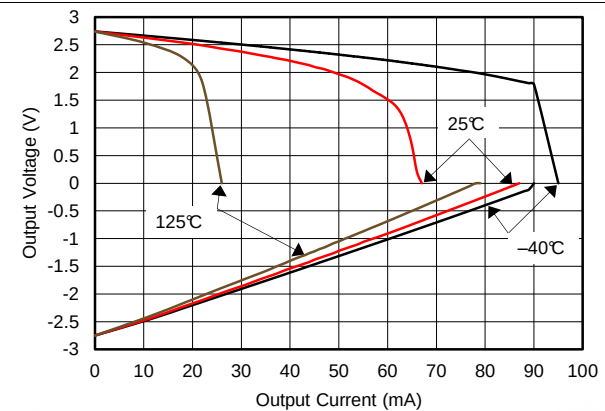


Figure 10. Output Voltage Swing vs Output Current (Maximum Supply)

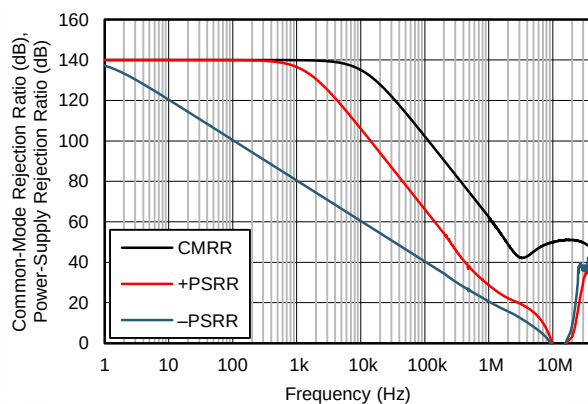


Figure 11. CMRR and PSRR vs Frequency

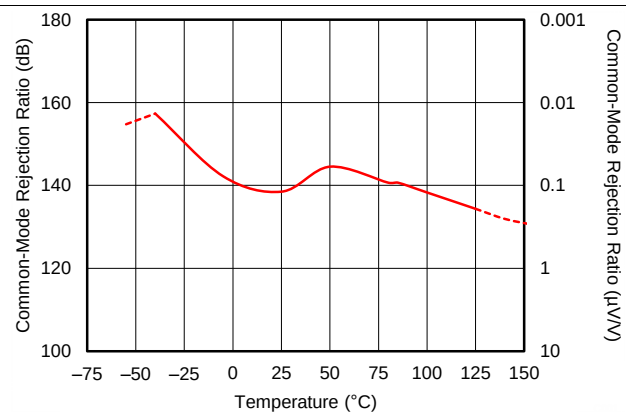


Figure 12. CMRR vs Temperature

Typical Characteristics (continued)

at $T_A = 25^\circ\text{C}$, $V_S = \pm 2.5\text{ V}$, $V_{CM} = V_S / 2$, $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$, and $C_L = 100\text{ pF}$ (unless otherwise noted)

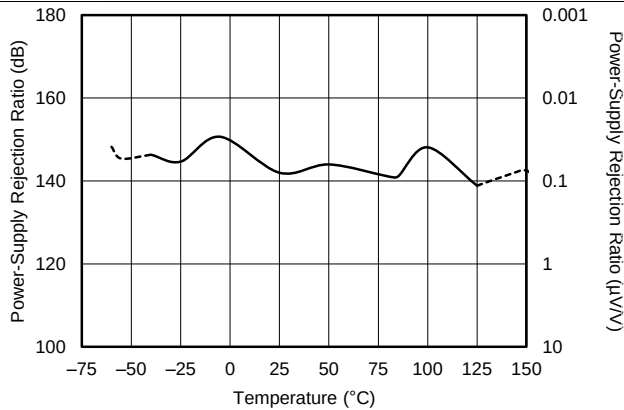


Figure 13. PSRR vs Temperature

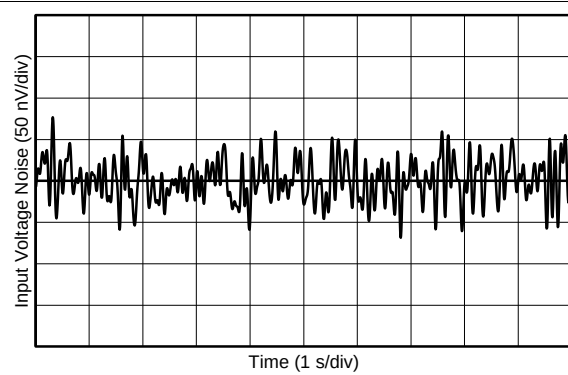


Figure 14. 0.1-Hz to 10-Hz Noise

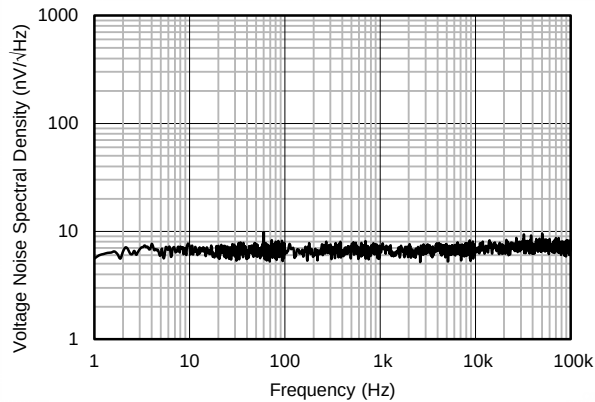


Figure 15. Input Voltage Noise Spectral Density vs Frequency

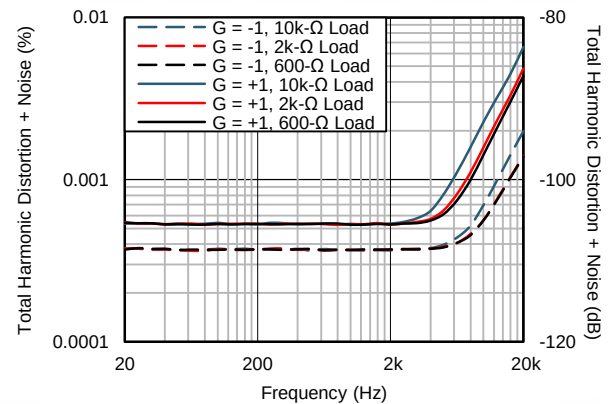


Figure 16. THD+N Ratio vs Frequency

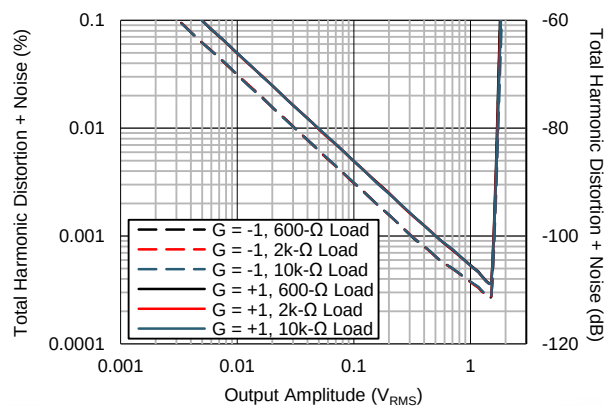
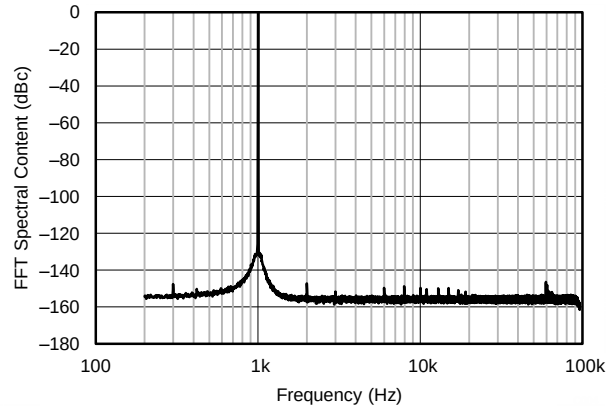


Figure 17. THD+N vs Output Amplitude



$G = +1$, $f = 1\text{ kHz}$, $V_O = 4.5\text{ V}_{PP}$, $R_L = 10\text{ k}\Omega$, $BW = 90\text{ kHz}$

Figure 18. Spectral Content (With 10-kΩ Load)

Typical Characteristics (continued)

at $T_A = 25^\circ\text{C}$, $V_S = \pm 2.5\text{ V}$, $V_{CM} = V_S / 2$, $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$, and $C_L = 100\text{ pF}$ (unless otherwise noted)

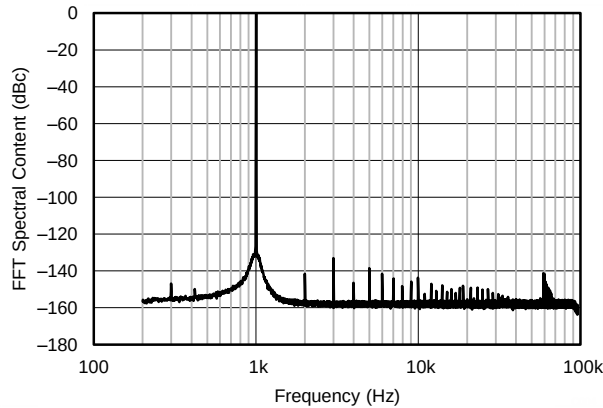


Figure 19. Spectral Content (With 2-k Ω Load)

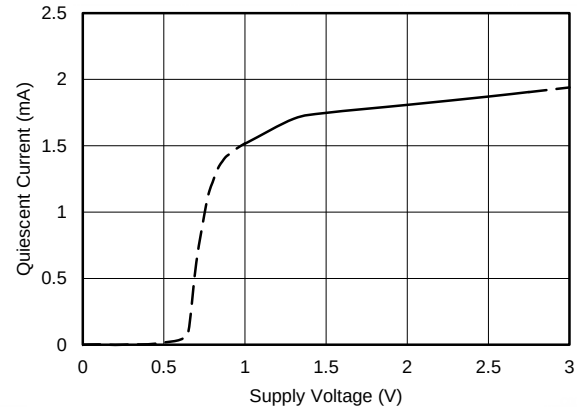


Figure 20. Quiescent Current vs Supply Voltage

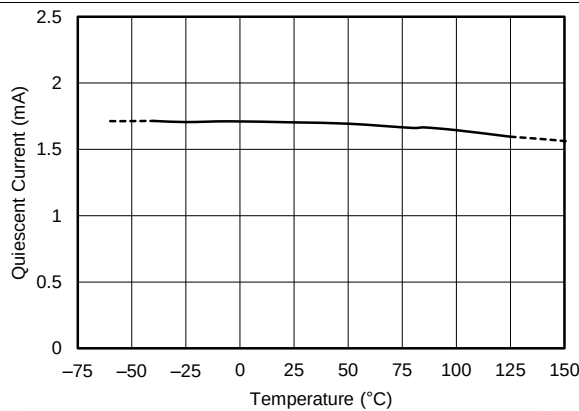


Figure 21. Quiescent Current vs Temperature

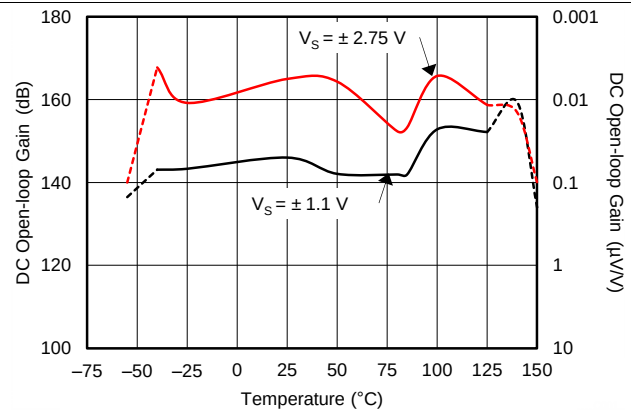


Figure 22. Open-Loop Gain vs Temperature

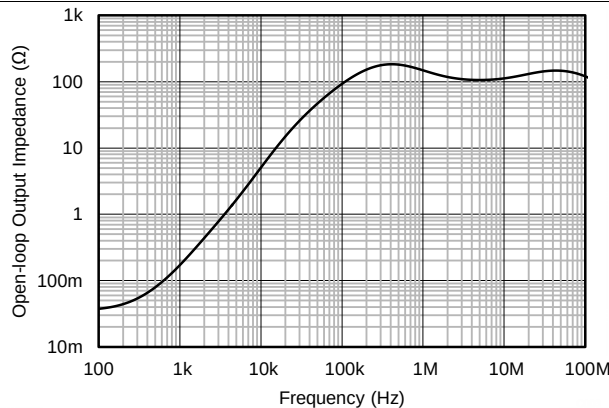


Figure 23. Open-Loop Output Impedance vs Frequency

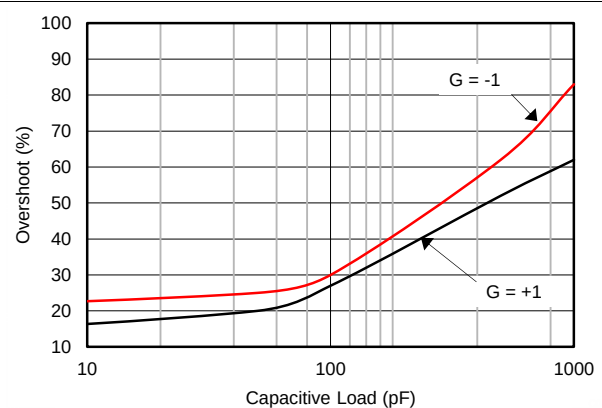


Figure 24. Small-Signal Overshoot vs Capacitive Load (10-mV Step)

Typical Characteristics (continued)

at $T_A = 25^\circ\text{C}$, $V_S = \pm 2.5\text{ V}$, $V_{CM} = V_S / 2$, $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$, and $C_L = 100\text{ pF}$ (unless otherwise noted)

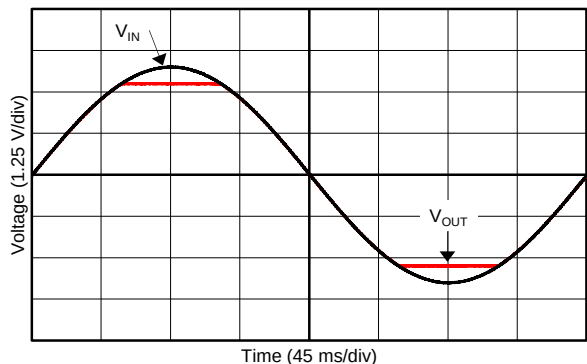


Figure 25. No Phase Reversal

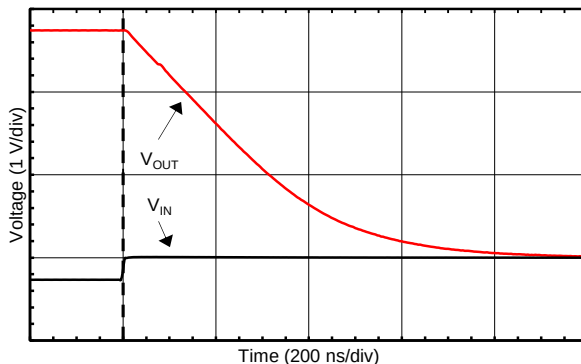


Figure 26. Positive Overload Recovery

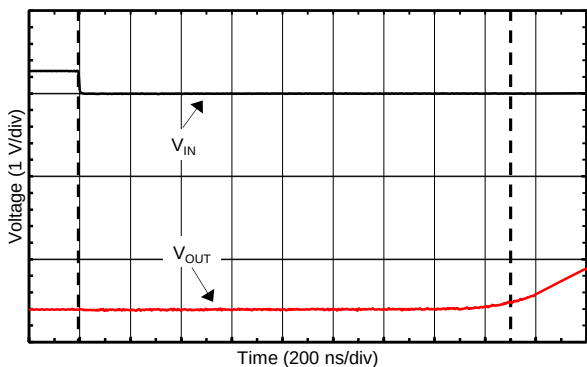
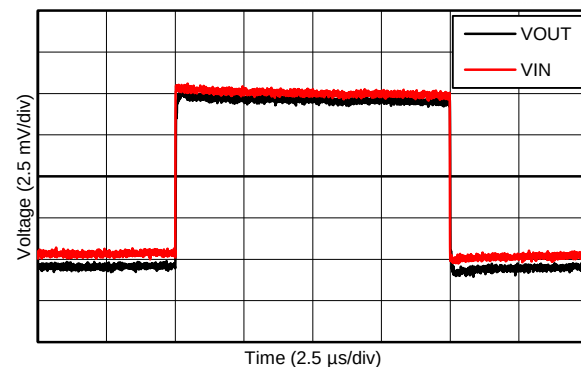
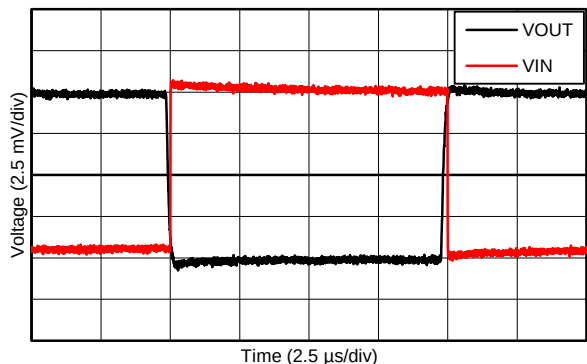


Figure 27. Negative Overload Recovery



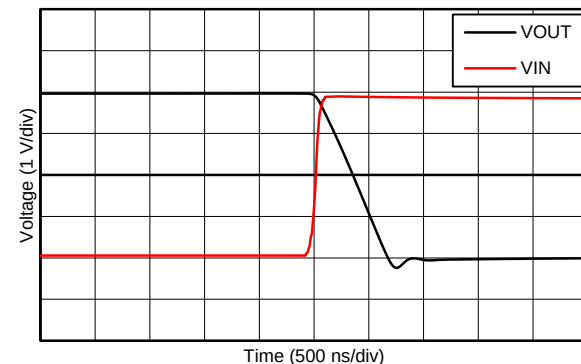
$G = +1$

Figure 28. Small-Signal Step Response (10-mV Step)



$G = -1$

Figure 29. Small-Signal Step Response (10-mV Step)

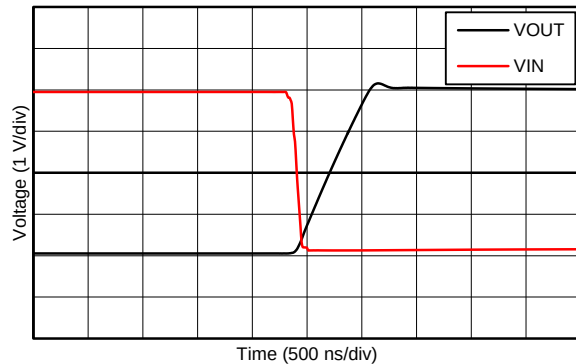


Falling output

Figure 30. Large-Signal Step Response (4-V Step)

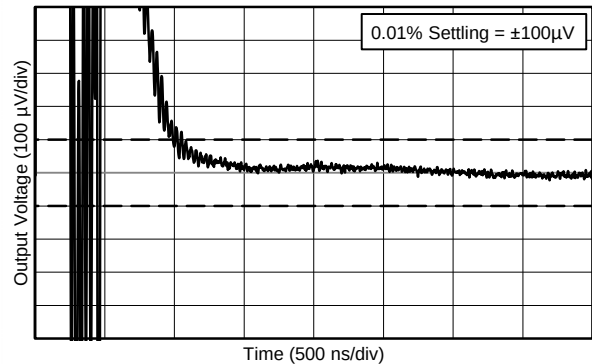
Typical Characteristics (continued)

at $T_A = 25^\circ\text{C}$, $V_S = \pm 2.5\text{ V}$, $V_{CM} = V_S / 2$, $R_{LOAD} = 10\text{ k}\Omega$ connected to $V_S / 2$, and $C_L = 100\text{ pF}$ (unless otherwise noted)



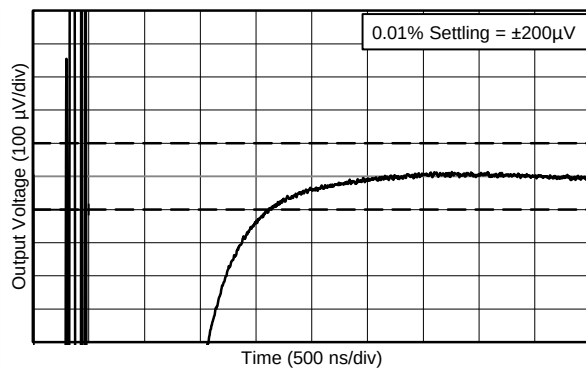
Rising output

Figure 31. Large-Signal Step Response (4-V Step)



0.01% settling = $\pm 100\text{ }\mu\text{V}$

Figure 32. Settling Time (1-V Positive Step)



0.01% settling = $\pm 200\text{ }\mu\text{V}$

Figure 33. Settling Time (1-V Negative Step)

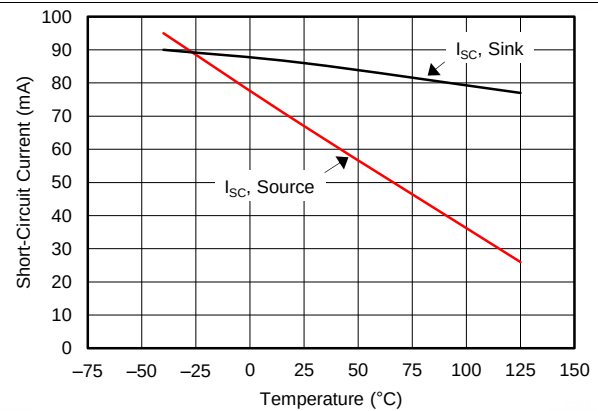


Figure 34. Short-Circuit Current vs Temperature

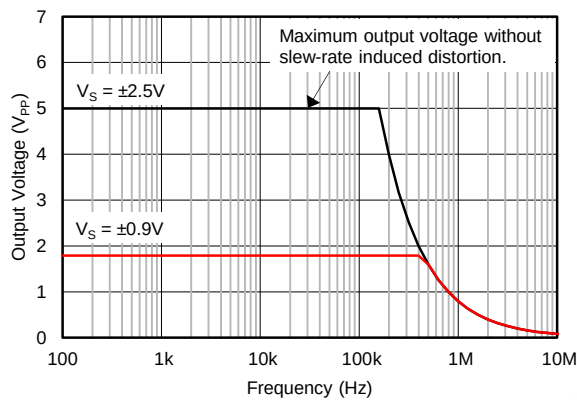


Figure 35. Maximum Output Voltage vs Frequency

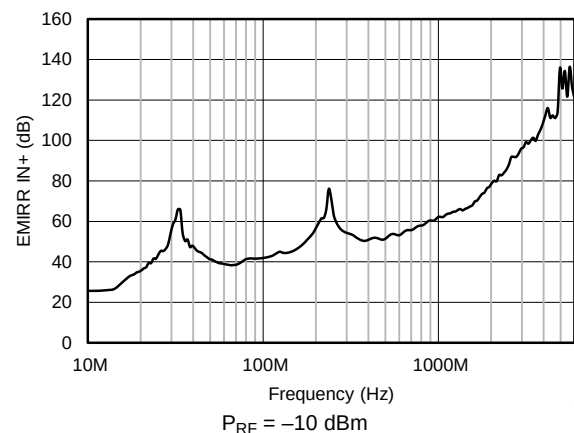


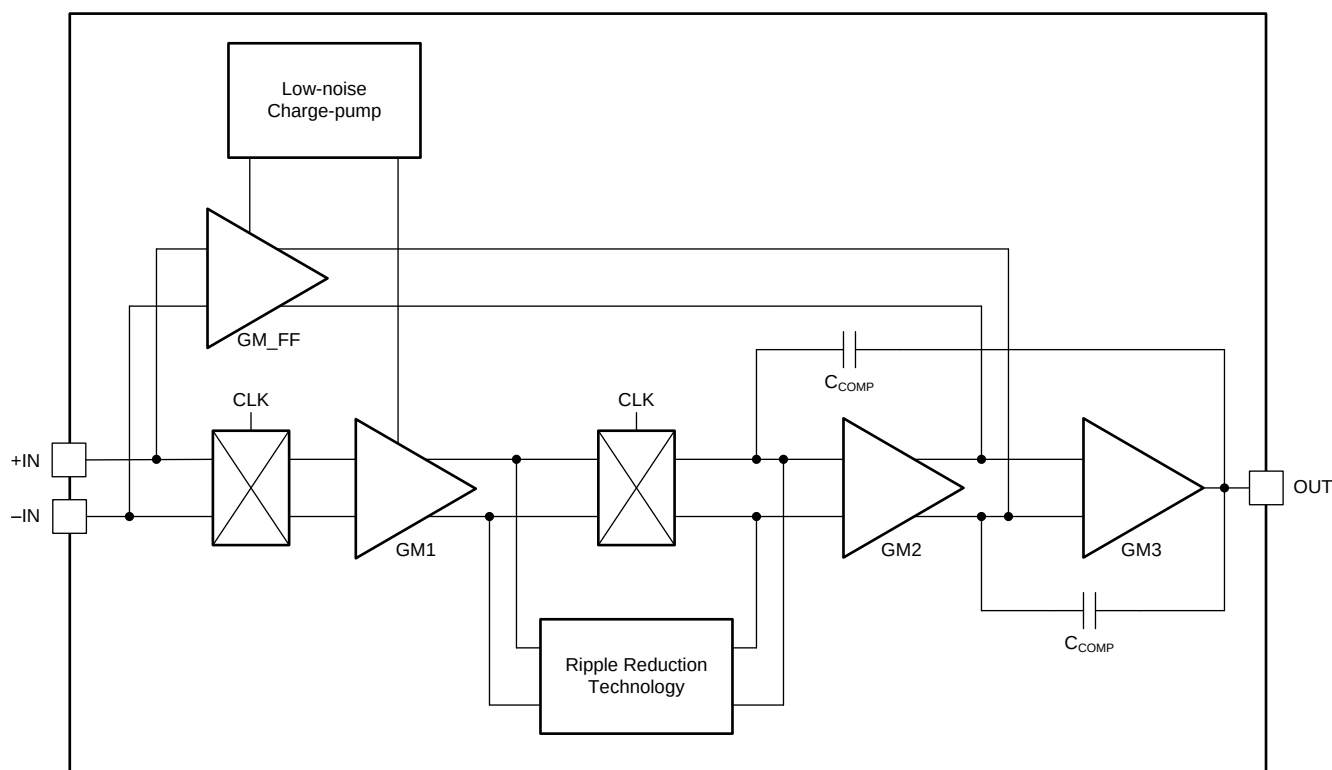
Figure 36. EMIRR vs Frequency

7 Detailed Description

7.1 Overview

The OPAx388 family of zero-drift amplifiers is engineered with the unique combination of a proprietary precision auto-calibration technique paired with a low-noise, low-ripple, input charge pump. These amplifiers offer ultra-low input offset voltage and drift and achieve excellent input and output dynamic linearity. The OPAx388 operates from 2.5 V to 5.5 V, is unity-gain stable, and is suitable for a wide range of general-purpose and precision applications. The integrated, low-noise charge pump allows true rail-to-rail input common-mode operation without distortion associated with complementary rail-to-rail input topologies (input crossover distortion). The OPAx388 strengths also include 10-MHz bandwidth, 7-nV/ $\sqrt{\text{Hz}}$ noise spectral density, and no 1/f noise, making the OPAx388 optimal for interfacing with sensor modules and buffering high-fidelity, digital-to-analog converters (DACs).

7.2 Functional Block Diagram



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7.3 Feature Description

7.3.1 Operating Voltage

The OPAx388 family of operational amplifiers can be used with single or dual supplies from an operating range of $V_S = 2.5 \text{ V}$ ($\pm 1.25 \text{ V}$) up to 5.5 V ($\pm 2.75 \text{ V}$). Supply voltages greater than 7 V can permanently damage the device (see [Absolute Maximum Ratings](#)). Key parameters that vary over the supply voltage or temperature range are shown in the [Typical Characteristics](#) section.

Feature Description (continued)

7.3.2 Input Voltage and Zero-Crossover Functionality

The OPAx388 input common-mode voltage range extends 0.1 V beyond the supply rails. This amplifier family is designed to cover the full range without the troublesome transition region found in some other rail-to-rail amplifiers. Operating a complementary rail-to-rail input amplifier with signals traversing the transition region results in unwanted non-linear behavior and polluted spectral content. [Figure 37](#) and [Figure 38](#) contrast the performance of a traditional complementary rail-to-rail input stage amplifier with the performance of the zero-crossover OPA388. Significant harmonic content and distortion is generated during the differential pair transition (such a transition does not exist in the OPA388). Crossover distortion is eliminated through the use of a single differential pair coupled with an internal low-noise charge pump. The OPAx388 maintains noise, bandwidth, and offset performance throughout the input common-mode range, thus reducing printed circuit board (PCB) and bill of materials (BOM) complexity through the reduction of power-supply rails.

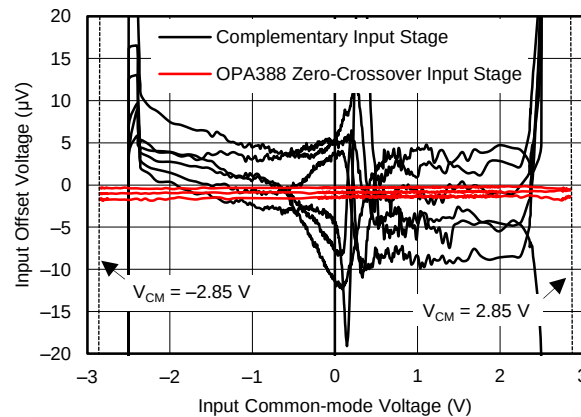


Figure 37. Input Crossover Distortion Nonlinearity

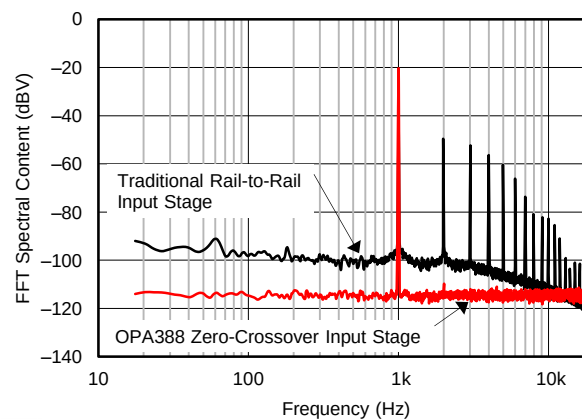


Figure 38. Input Crossover Distortion Spectral Content

Feature Description (continued)

Typically, input bias current is approximately ± 30 pA. Input voltages exceeding the power supplies, however, can cause excessive current to flow into or out of the input pins. Momentary voltages greater than the power supply can be tolerated if the input current is limited to 10 mA. This limitation is easily accomplished with an input resistor, as shown in Figure 39.

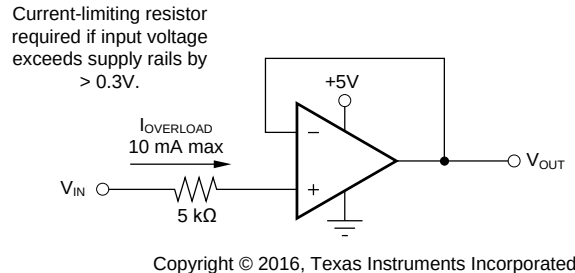


Figure 39. Input Current Protection

7.3.3 Input Differential Voltage

The typical input bias current of the OPAx388 during normal operation is approximately 30 pA. In overdriven conditions, the bias current can increase significantly. The most common cause of an overdriven condition occurs when the operational amplifier is outside of the linear range of operation. When the output of the operational amplifier is driven to one of the supply rails, the feedback loop requirements cannot be satisfied and a differential input voltage develops across the input pins. This differential input voltage results in activation of parasitic diodes inside the front-end input chopping switches that combine with 10-kΩ electromagnetic interference (EMI) filter resistors to create the equivalent circuit shown in Figure 40. Notice that the input bias current remains within specification in the linear region.

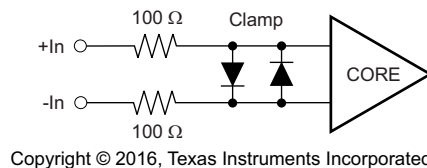


Figure 40. Equivalent Input Circuit

7.3.4 Internal Offset Correction

The OPA388 family of operational amplifiers uses an auto-calibration technique with a time-continuous, 200-kHz operational amplifier in the signal path. This amplifier is zero-corrected every 5 μ s using a proprietary technique. At power-up, the amplifier requires approximately 1 ms to achieve the specified V_{OS} accuracy. This design has no aliasing or flicker noise.

7.3.5 EMI Susceptibility and Input Filtering

Operational amplifiers vary in susceptibility to EMI. If conducted EMI enters the operational amplifier, the dc offset at the amplifier output can shift from its nominal value when EMI is present. This shift is a result of signal rectification associated with the internal semiconductor junctions. Although all operational amplifier pin functions can be affected by EMI, the input pins are likely to be the most susceptible. The OPAx388 operational amplifier family incorporates an internal input low-pass filter that reduces the amplifier response to EMI. Both common-mode and differential-mode filtering are provided by the input filter. The filter is designed for a cutoff frequency of approximately 20 MHz (-3 dB), with a rolloff of 20 dB per decade.

7.4 Device Functional Modes

The OPA388 has a single functional mode and is operational when the power-supply voltage is greater than 2.5 V (± 1.25 V). The maximum specified power-supply voltage for the OPAx388 is 5.5 V (± 2.75 V).

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

The OPAx388 is a unity-gain stable, precision operational amplifier family free from unexpected output and phase reversal. The use of proprietary zero-drift circuitry gives the benefit of low input offset voltage over time and temperature, as well as lowering the 1/f noise component. As a result of the high PSRR, these devices work well in applications that run directly from battery power without regulation. The OPAx388 family is optimized for full rail-to-rail input, allowing for low-voltage, single-supply operation or split-supply use. These miniature, high-precision, low-noise amplifiers offer high-impedance inputs that have a common-mode range 100 mV beyond the supplies without input crossover distortion and a rail-to-rail output that swings within 5 mV of the supplies under normal test conditions. The OPAx388 series of precision amplifiers is suitable for upstream analog signal chain applications in low or high gains, as well as downstream signal chain functions such as DAC buffering.

8.2 Typical Application

This single-supply, low-side, bidirectional current-sensing solution detects load currents from -1 A to 1 A . The single-ended output spans from 110 mV to 3.19 V. This design uses the OPAx388 because of its low offset voltage and rail-to-rail input and output. One of the amplifiers is configured as a difference amplifier and the other amplifier provides the reference voltage.

Figure 41 shows the solution.

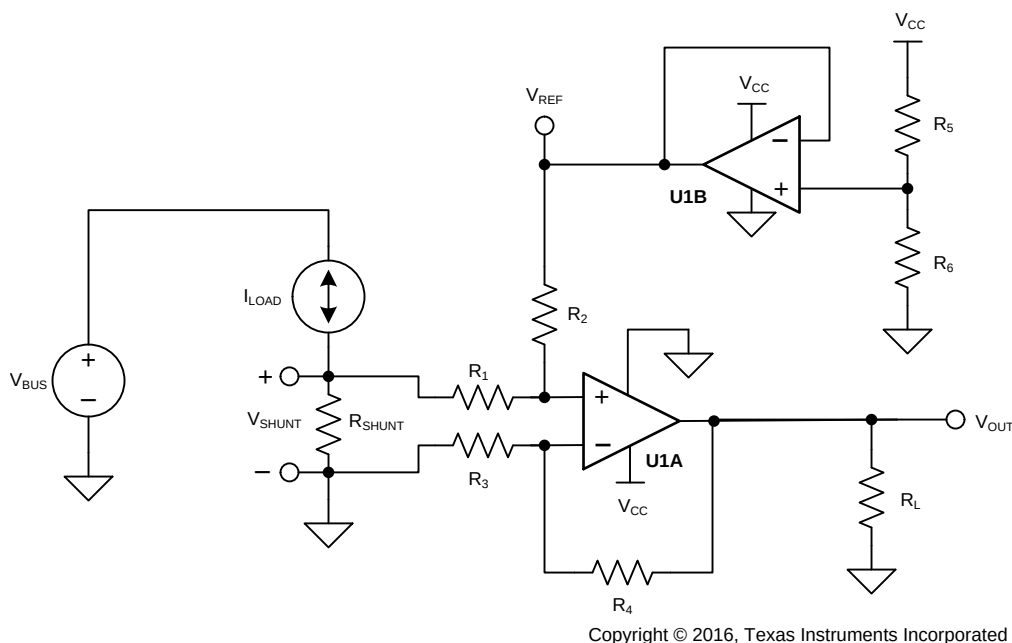


Figure 41. Bidirectional Current-Sensing Schematic

Typical Application (continued)

8.2.1 Design Requirements

This solution has the following requirements:

- Supply voltage: 3.3 V
- Input: –1 A to 1 A
- Output: 1.65 V $\pm$ 1.54 V (110 mV to 3.19 V)

8.2.2 Detailed Design Procedure

The load current, I_{LOAD} , flows through the shunt resistor (R_{SHUNT}) to develop the shunt voltage, V_{SHUNT} . The shunt voltage is then amplified by the difference amplifier consisting of U1A and R_1 through R_4 . The gain of the difference amplifier is set by the ratio of R_4 to R_3 . To minimize errors, set $R_2 = R_4$ and $R_1 = R_3$. The reference voltage, V_{REF} , is supplied by buffering a resistor divider using U1B. The transfer function is given by [Equation 1](#).

$$V_{OUT} = V_{SHUNT} \times \text{Gain}_{\text{Diff_Amp}} + V_{REF}$$

where

$$\begin{aligned} \bullet \quad V_{SHUNT} &= I_{LOAD} \times R_{SHUNT} \\ \bullet \quad \text{Gain}_{\text{Diff_Amp}} &= \frac{R_4}{R_3} \\ \bullet \quad V_{REF} &= V_{CC} \times \left(\frac{R_6}{R_5 + R_6} \right) \end{aligned} \quad (1)$$

There are two types of errors in this design: offset and gain. Gain errors are introduced by the tolerance of the shunt resistor and the ratios of R_4 to R_3 and, similarly, R_2 to R_1 . Offset errors are introduced by the voltage divider (R_5 and R_6) and how closely the ratio of R_4 / R_3 matches R_2 / R_1 . The latter value affects the CMRR of the difference amplifier, ultimately translating to an offset error.

The value of V_{SHUNT} is the ground potential for the system load because V_{SHUNT} is a low-side measurement. Therefore, a maximum value must be placed on V_{SHUNT} . In this design, the maximum value for V_{SHUNT} is set to 100 mV. [Equation 2](#) calculates the maximum value of the shunt resistor given a maximum shunt voltage of 100 mV and maximum load current of 1 A.

$$R_{SHUNT(\text{Max})} = \frac{V_{SHUNT(\text{Max})}}{I_{LOAD(\text{Max})}} = \frac{100 \text{ mV}}{1 \text{ A}} = 100 \text{ m}\Omega \quad (2)$$

The tolerance of R_{SHUNT} is directly proportional to cost. For this design, a shunt resistor with a tolerance of 0.5% was selected. If greater accuracy is required, select a 0.1% resistor or better.

The load current is bidirectional; therefore, the shunt voltage range is –100 mV to 100 mV. This voltage is divided down by R_1 and R_2 before reaching the operational amplifier, U1A. Take care to ensure that the voltage present at the noninverting node of U1A is within the common-mode range of the device. Therefore, use an operational amplifier, such as the OPA388, that has a common-mode range that extends below the negative supply voltage. Finally, to minimize offset error, note that the OPA388 has a typical offset voltage of merely $\pm 0.25 \mu\text{V}$ ($\pm 5 \mu\text{V}$ maximum).

Given a symmetric load current of –1 A to 1 A, the voltage divider resistors (R_5 and R_6) must be equal. To be consistent with the shunt resistor, a tolerance of 0.5% was selected. To minimize power consumption, 10-k Ω resistors were used.

To set the gain of the difference amplifier, the common-mode range and output swing of the OPA388 must be considered. [Equation 3](#) and [Equation 4](#) depict the typical common-mode range and maximum output swing, respectively, of the OPA388 given a 3.3-V supply.

$$-100 \text{ mV} < V_{CM} < 3.4 \text{ V} \quad (3)$$

$$100 \text{ mV} < V_{OUT} < 3.2 \text{ V} \quad (4)$$

The gain of the difference amplifier can now be calculated as shown in [Equation 5](#).

$$\text{Gain}_{\text{Diff_Amp}} = \frac{V_{OUT_Max} - V_{OUT_Min}}{R_{SHUNT} \times (I_{MAX} - I_{MIN})} = \frac{3.2 \text{ V} - 100 \text{ mV}}{100 \text{ m}\Omega \times [1 \text{ A} - (-1 \text{ A})]} = 15.5 \frac{\text{V}}{\text{V}} \quad (5)$$

Typical Application (continued)

The resistor value selected for R_1 and R_3 was 1 k Ω . 15.4 k Ω was selected for R_2 and R_4 because this number is the nearest standard value. Therefore, the ideal gain of the difference amplifier is 15.4 V/V.

The gain error of the circuit primarily depends on R_1 through R_4 . As a result of this dependence, 0.1% resistors were selected. This configuration reduces the likelihood that the design requires a two-point calibration. A simple one-point calibration, if desired, removes the offset errors introduced by the 0.5% resistors.

8.2.3 Application Curve

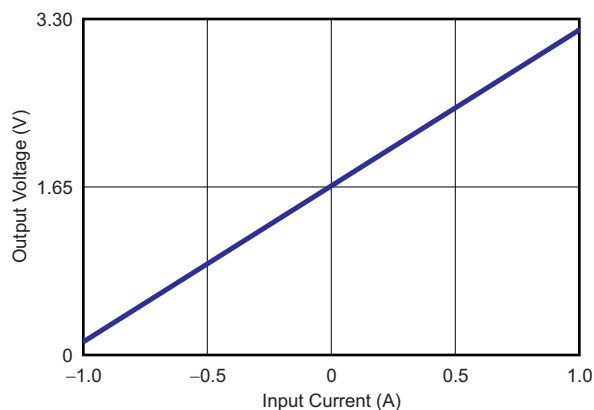
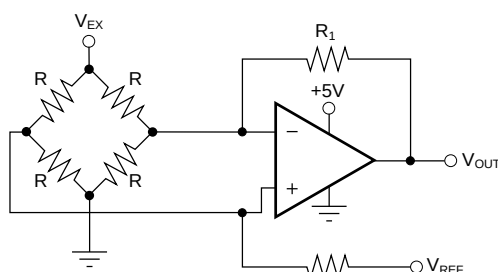


**Figure 42. Bidirectional Current-Sensing Circuit Performance:
Output Voltage vs Input Current**

8.3 System Examples

8.3.1 Single Operational Amplifier Bridge Amplifier

Figure 43 shows the basic configuration for a bridge amplifier.



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Figure 43. Single Operational Amplifier Bridge Amplifier Schematic

System Examples (continued)

8.3.2 Precision, Low-Noise, DAC Buffer

The OPA388 can be used for a precision DAC buffer, as shown in Figure 44, in conjunction with the DAC8830.

The OPA388 provides an ultra-low drift, precision output buffer for the DAC. A wide range of DAC codes can be used in the linear region because the OPA388 employs zero-crossover technology. A precise reference is essential for maximum accuracy because the DAC8830 is a 16-bit converter.

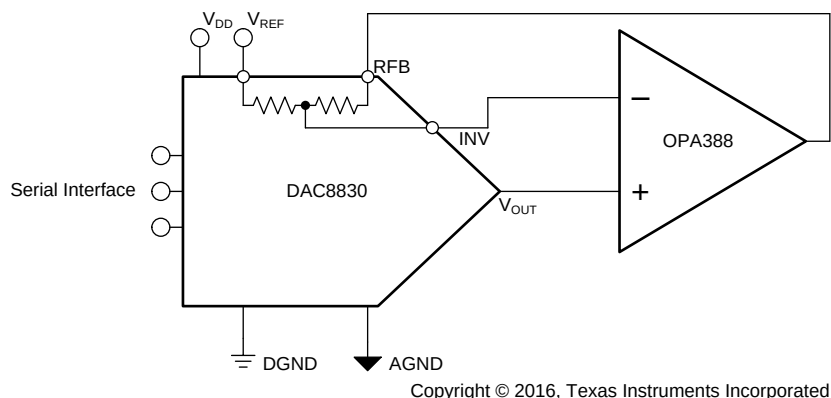


Figure 44. Precision DAC Buffer

8.3.3 Load Cell Measurement

Figure 45 shows the OPA388 in a high-CMRR dual-op amp instrumentation amplifier with a trim resistor and 6-wire load cell for precision measurement. Figure 46 illustrates the output voltage as a function of load cell resistance change, along with the nonlinearity of the system.

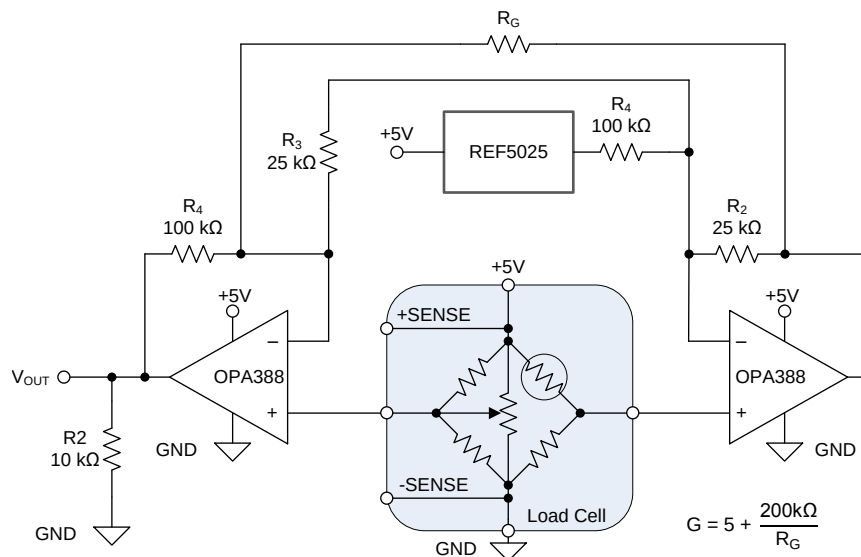


Figure 45. Load Cell Measurement Schematic

System Examples (continued)

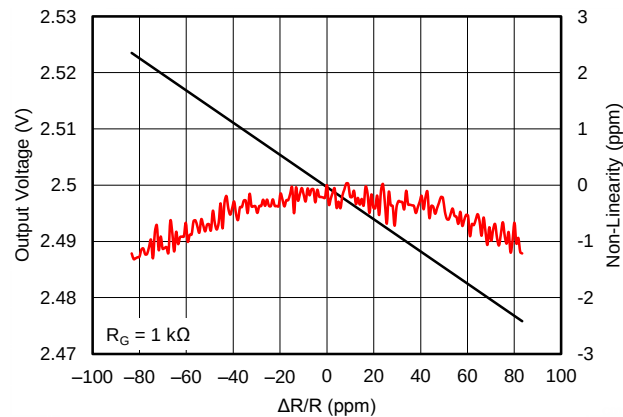


Figure 46. Load Cell Measurement Output

9 Power Supply Recommendations

The OPAx388 family of devices is specified for operation from 2.5 V to 5.5 V ($\pm 1.25 \text{ V}$ to $\pm 2.75 \text{ V}$). Parameters that can exhibit significant variance with regard to operating voltage are presented in the [Typical Characteristics](#) section.

10 Layout

10.1 Layout Guidelines

Paying attention to good layout practice is always recommended. Keep traces short and, when possible, use a printed-circuit board (PCB) ground plane with surface-mount components placed as close to the device pins as possible. Place a 0.1- μ F capacitor closely across the supply pins. These guidelines must be applied throughout the analog circuit to improve performance and provide benefits such as reducing the electromagnetic interference (EMI) susceptibility.

For lowest offset voltage and precision performance, circuit layout and mechanical conditions must be optimized. Avoid temperature gradients that create thermoelectric (Seebeck) effects in the thermocouple junctions formed from connecting dissimilar conductors. These thermally-generated potentials can be made to cancel by assuring they are equal on both input terminals. Other layout and design considerations include:

- Use low thermoelectric-coefficient conditions (avoid dissimilar metals).
- Thermally isolate components from power supplies or other heat sources.
- Shield operational amplifier and input circuitry from air currents, such as cooling fans.

Following these guidelines reduces the likelihood of junctions being at different temperatures, which can cause thermoelectric voltage drift of 0.1 μ V/ $^{\circ}$ C or higher, depending on materials used.

10.2 Layout Example

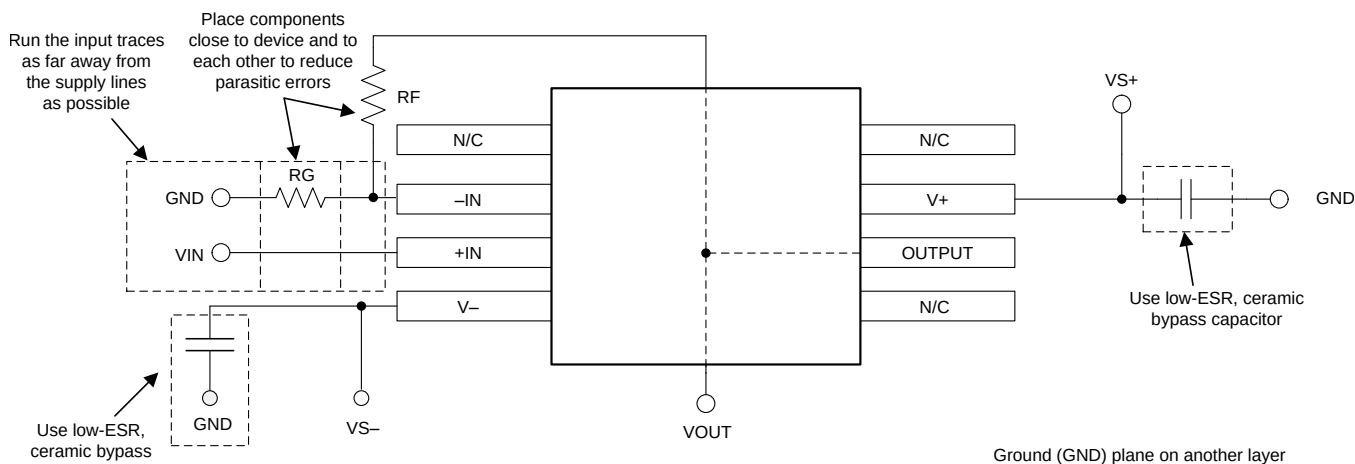


Figure 47. OPA388 Layout Example

11 Device and Documentation Support

11.1 Device Support

11.1.1 Development Support

11.1.1.1 TINA-TI™ (Free Software Download)

TINA-TI™ 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 macromodels 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 Analog eLab 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 TI Precision Designs

The OPAx388 family is featured on TI Precision Designs, available online at www.ti.com/ww/en/analog/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.

11.2 Documentation Support

11.2.1 Related Documentation

For related documentation see the following:

- [Circuit Board Layout Techniques](#) (SLOA089)
- [DAC883x 16-Bit, Ultra-Low Power, Voltage-Output Digital-to-Analog Converters](#) (SLAS449)

11.3 Related Links

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

Table 2. Related Links

PARTS	PRODUCT FOLDER	SAMPLE & BUY	TECHNICAL DOCUMENTS	TOOLS & SOFTWARE	SUPPORT & COMMUNITY
OPA388	Click here	Click here	Click here	Click here	Click here
OPA2388	Click here	Click here	Click here	Click here	Click here
OPA4388	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 Resources

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](#).

Community Resources (continued)

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.

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11.7 Electrostatic Discharge Caution



This integrated circuit can be damaged by ESD. Texas Instruments recommends that all integrated circuits be handled with appropriate precautions. Failure to observe proper handling and installation procedures can cause damage.

ESD damage can range from subtle performance degradation to complete device failure. Precision integrated circuits may be more susceptible to damage because very small parametric changes could cause the device not to meet its published specifications.

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.

PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
OPA388ID	ACTIVE	SOIC	D	8	1500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 105	OPA388	Samples
OPA388IDR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-2-260C-1 YEAR	-40 to 125	OPA388	Samples

(1) The marketing status values are defined as follows:

ACTIVE: Product device recommended for new designs.

LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.

NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.

PREVIEW: Device has been announced but is not in production. Samples may or may not be available.

OBsolete: TI has discontinued the production of the device.

(2) Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check <http://www.ti.com/productcontent> for the latest availability information and additional product content details.

TBD: The Pb-Free/Green conversion plan has not been defined.

Pb-Free (RoHS): TI's terms "Lead-Free" or "Pb-Free" mean semiconductor products that are compatible with the current RoHS requirements for all 6 substances, including the requirement that lead not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, TI Pb-Free products are suitable for use in specified lead-free processes.

Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.

Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

(3) MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

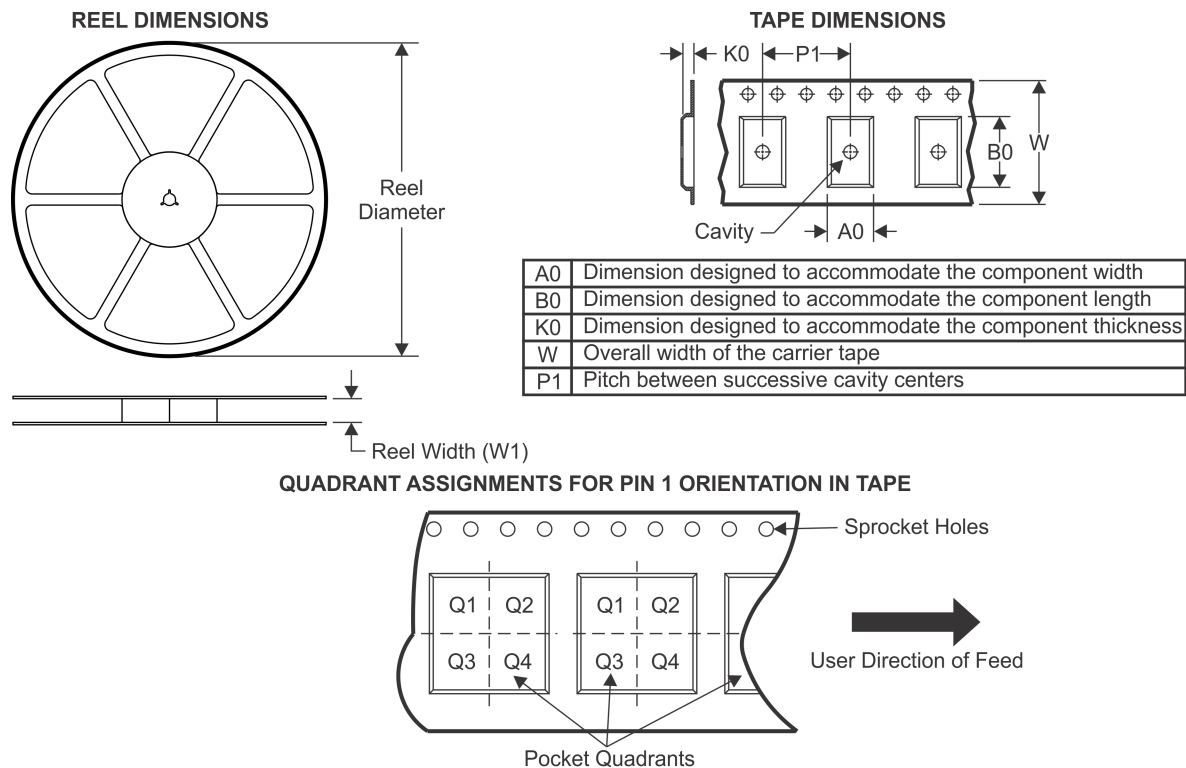
(4) There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

(5) Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "-" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

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

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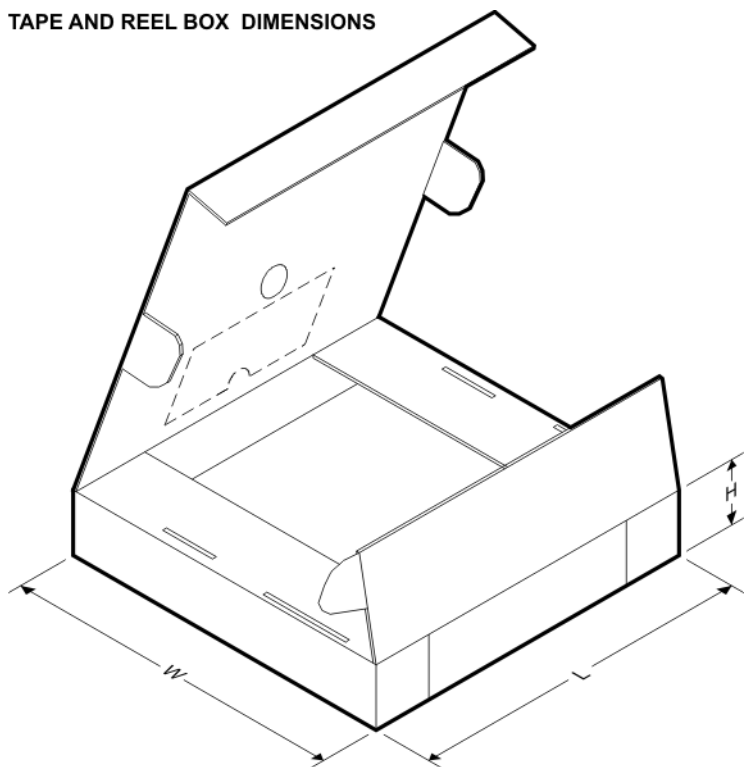
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TAPE AND REEL INFORMATION


*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
OPA388IDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1

TAPE AND REEL BOX DIMENSIONS

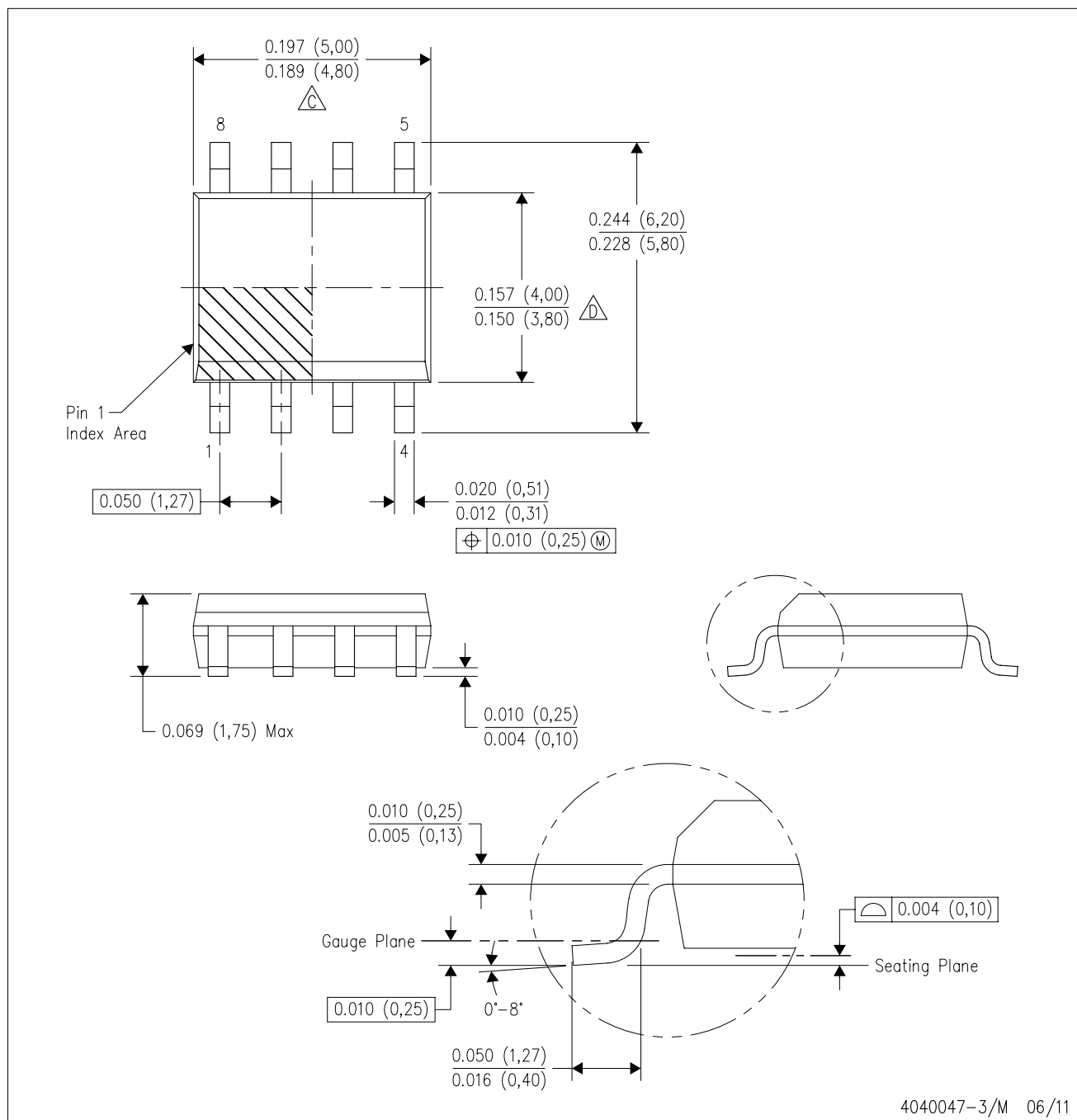


*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
OPA388IDR	SOIC	D	8	2500	367.0	367.0	35.0

D (R-PDSO-G8)

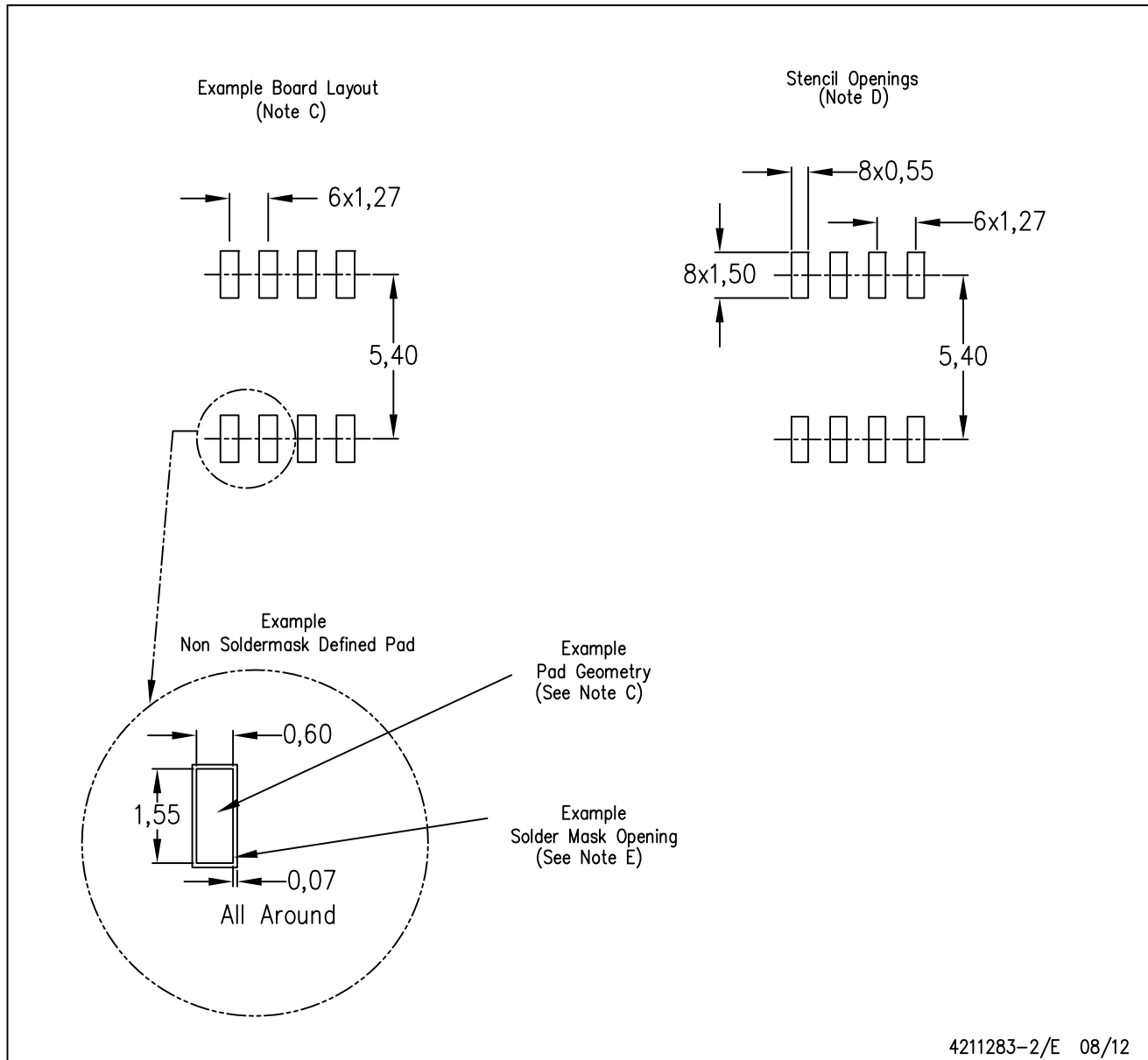
PLASTIC SMALL OUTLINE



- NOTES:
- A. All linear dimensions are in inches (millimeters).
 - B. This drawing is subject to change without notice.
 - $\triangle C$ Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.006 (0,15) each side.
 - $\triangle D$ Body width does not include interlead flash. Interlead flash shall not exceed 0.017 (0,43) each side.
 - E. Reference JEDEC MS-012 variation AA.

D (R-PDSO-G8)

PLASTIC SMALL OUTLINE



- NOTES:
- A. All linear dimensions are in millimeters.
 - B. This drawing is subject to change without notice.
 - C. Publication IPC-7351 is recommended for alternate designs.
 - D. Laser cutting apertures with trapezoidal walls and also rounding corners will offer better paste release. Customers should contact their board assembly site for stencil design recommendations. Refer to IPC-7525 for other stencil recommendations.
 - E. Customers should contact their board fabrication site for solder mask tolerances between and around signal pads.

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