TEXAS INSTRUMENTS

OPA388-Q1 Automotive, Precision, Zero-Drift, Zero-Crossover, True Rail-to-Rail, Input/Output Operational Amplifier

1 Features

- AEC-Q100 qualified for automotive applications:
  - Temperature grade 1: -40°C to +125°C, T_A
- Functional-Safety Capable
  - Documentation available to aid functional safety system design
- Zero drift: ±0.005 µV/°C
- Zero crossover: 140-dB CMRR true RRIO
- Low noise: 7.0 nV$\sqrt{\text{Hz}}$ at 1 kHz
- No 1/f noise: 140 nV$_{PP}$ (0.1 Hz to 10 Hz)
- Fast settling: 2 µs (1 V to 0.01%)
- Gain bandwidth: 10 MHz
- Single supply: 2.5 V to 5.5 V
- Dual supply: ±1.25 V to ±2.75 V
- True rail-to-rail input and output
- EMI/RFI filtered inputs
- Industry-standard package: SOT-23-5

2 Applications

- HEV/EV inverter and motor control
- Battery management system (BMS)
- DC/DC converter
- Onboard (OBC) and wireless charger

3 Description

The OPA388-Q1 precision, operational amplifier is an automotive, low-noise, fast-settling, zero-drift device that provides rail-to-rail input and output operation. Excellent ac performance, combined with only 0.25 µV of offset and 0.005 µV/°C of drift over temperature, make the OPA388-Q1 a great choice for driving high-resolution, analog-to-digital converters (ADCs) with high accuracy. Zero-crossover technology minimizes any offset change over the common-mode range. The combination of low drift and very low 1/f noise allow the OPA388-Q1 to monitor and detect faulty conditions without compromising signal integrity.

The OPA388-Q1 is available in the SOT23-5 package. The device is specified over the industrial temperature range of –40°C to +125°C.

Device Information [(1)]

PART NUMBER	PACKAGE	BODY SIZE (NOM)
OPA388-Q1	SOT-23 (5)	2.90 mm × 1.60 mm

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

The OPA388-Q1 in a Bidirectional Current Shunt Monitor
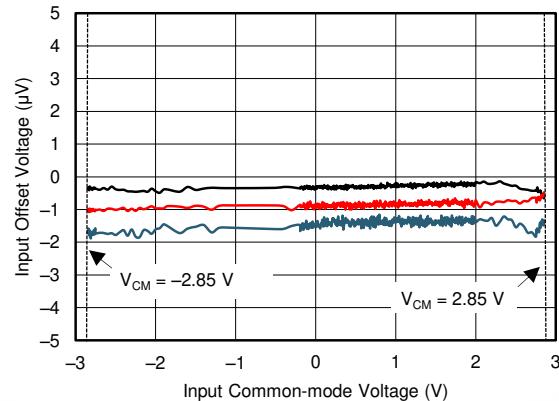
The OPA388-Q1 Features Ultra-Low Offset Across the Full Common-Mode Range

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4 Revision History

DATE	REVISION	NOTES
August 2020	*	Initial release.

Product Folder Links: *OPA388-Q1*

5 Pin Configuration and Functions
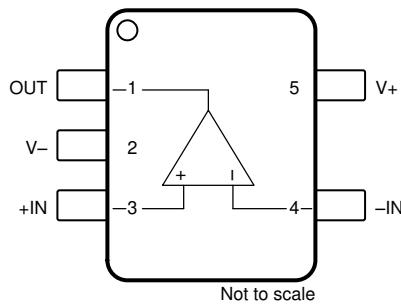
Figure 5-1. DBV Package, 5-Pin SOT-23, Top View

Pin Functions

PIN		I/O	DESCRIPTION
NAME	NO.		
–IN	4	I	Inverting input
+IN	3	I	Noninverting input
NC	—	—	No internal connection (can be left floating)
OUT	1	O	Output
V–	2	—	Negative (lowest) power supply
V+	5	—	Positive (highest) power supply

Product Folder Links: OPA388-Q1

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		(V+) – (V–) + 0.2	
	Current			±10	mA
Output short circuit[2]			Continuous	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 AEC Q100-002[1] HBM ESD classification level 2	±2000	V
		Charged-device model (CDM), per AEC Q100-011 CDM ESD classification level C5	±750	

(1) AEC Q100-002 indicates that HBM stressing shall be in accordance with the ANSI/ESDA/JEDEC JS-001 specification

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-Q1	UNIT
		DBV (SOT-23)	
THERMAL METRIC[1]		**5 PINS**	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	145.7	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	94.8	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	43.4	°C/W
Ψ_{JT}	Junction-to-top characterization parameter	24.7	°C/W
Ψ_{JB}	Junction-to-board characterization parameter	43.1	°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: VS = ±1.25 V to ±2.75 V (VS = 2.5 to 5.5 V)

at T_A = 25°C, V_{CM} = V_{OUT} = V_S / 2, and R_{LOAD} = 10 kΩ 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	
			T_A = –40°C to +125°C			±700	
I_{OS}	Input offset current	R_{IN} = 100 kΩ				±700	pA
			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/√Hz
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 ǁ 2		MΩ ǁ pF
z_{ic}	Common-mode input impedance				60 ǁ 4.5		TΩ ǁ pF
OPEN-LOOP GAIN							
A_{OL}	Open-loop voltage gain	(V–) + 0.15 V < V_O < (V+) – 0.15 V, R_{LOAD} = 10 kΩ		126	148		dB
			T_A = –40°C to +125°C	120	126		
		(V–) + 0.25 V < V_O < (V+) – 0.25 V, R_{LOAD} = 2 kΩ		126	148		
		(V–) + 0.30 V < V_O < (V+) – 0.30 V, R_{LOAD} = 2 kΩ	T_A = –40°C to +125°C	120	148		

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at T_A = 25°C, V_{CM} = V_{OUT} = V_S / 2, and R_{LOAD} = 10 kΩ connected to V_S / 2 (unless otherwise noted)

PARAMETER		TEST CONDITIONS		MIN	TYP	MAX	UNIT
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
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	25	
I_{SC}	Short-circuit current	V_S = 5.5 V			±60		mA
		V_S = 2.5 V			±30		
C_{LOAD}	Capacitive load drive	See Figure 6-25					
Z_O	Open-loop output impedance	f = 1 MHz, I_O = 0 A, see Figure 6-24			100		Ω
POWER SUPPLY							
I_Q	Quiescent current per amplifier	V_S = ±1.25 V (V_S = 2.5 V)	I_O = 0 A		1.7	2.4	mA
			T_A = –40°C to +125°C, I_O = 0 A		1.7	2.4	
		V_S = ±2.75 V (V_S = 5.5 V)	I_O = 0 A		1.9	2.6	
			T_A = –40°C to +125°C, I_O = 0 A		1.9	2.6	

6.6 Typical Characteristics

at T_A = 25°C, V_S = ±2.5 V, V_{CM} = V_S / 2, R_{LOAD} = 10 kΩ connected to V_S / 2, and C_L = 100 pF (unless otherwise noted)

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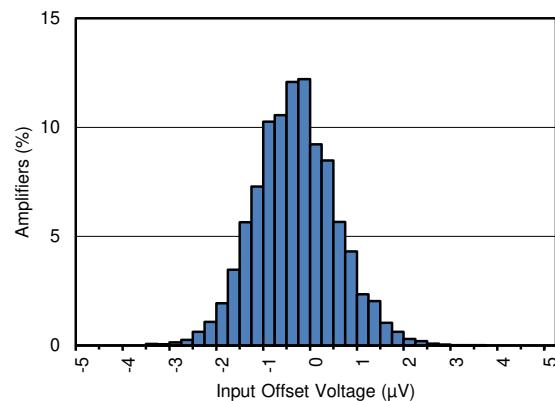
Figure 6-1. Offset Voltage Production Distribution
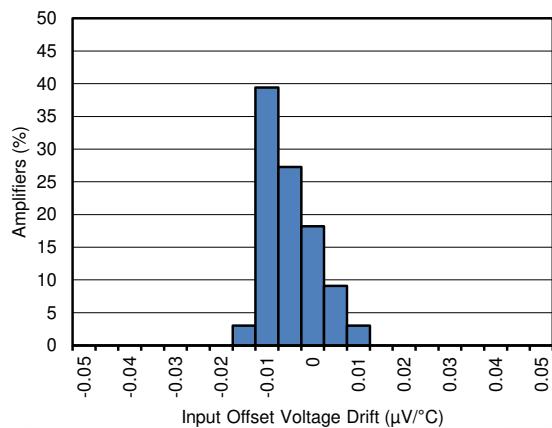
$T_A = -40°C$ to $+125°C$

**Figure 6-2. Offset Voltage Drift Distribution**
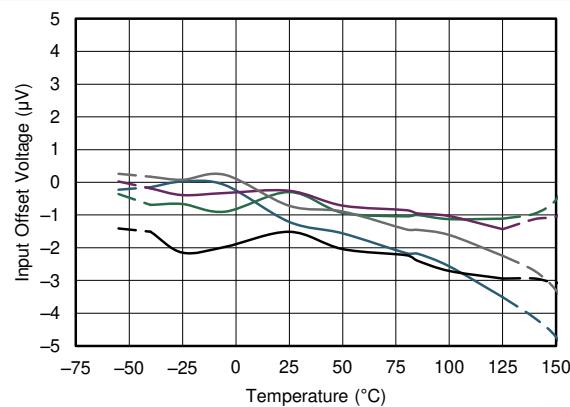
Figure 6-3. Offset Voltage vs Temperature
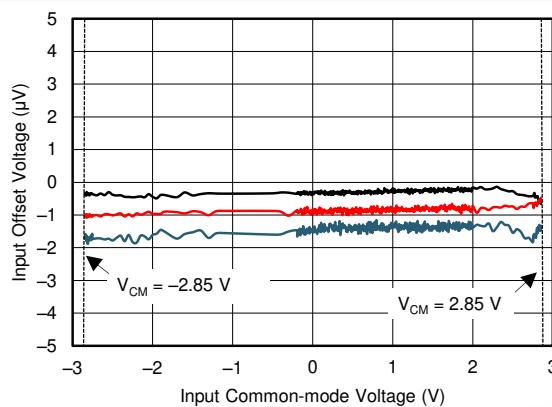

Figure 6-4. Offset Voltage vs Common-Mode Voltage
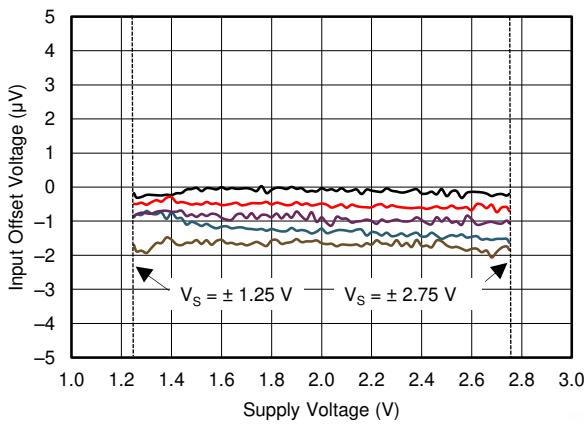

Figure 6-5. Offset Voltage vs Supply Voltage

3 typical units
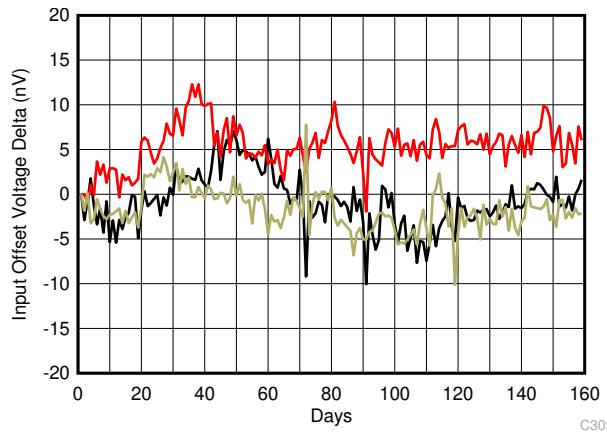
Figure 6-6. Offset Voltage Long Term Drift

Product Folder Links: *OPA388-Q1*
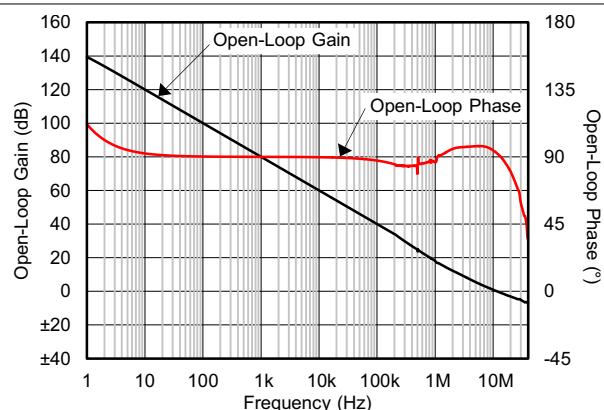
Figure 6-7. Open-Loop Gain and Phase vs Frequency
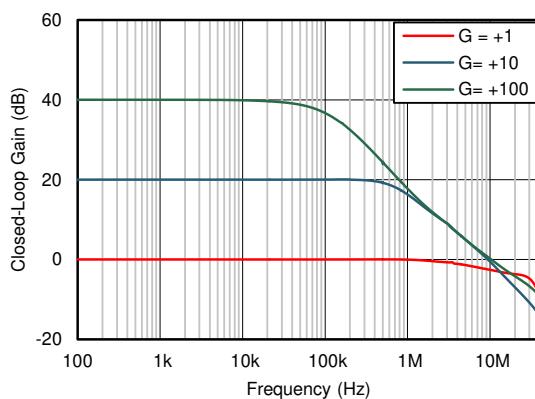
Figure 6-8. Closed-Loop Gain and Phase vs Frequency
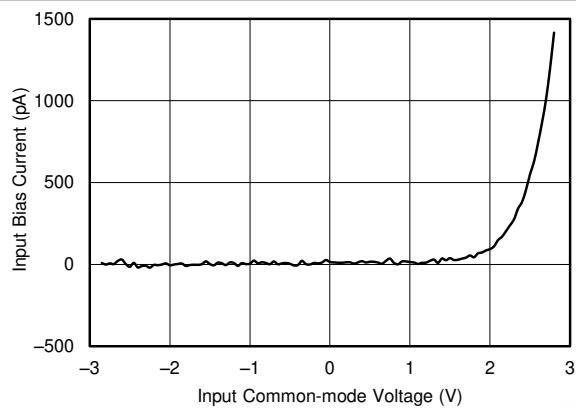
Figure 6-9. Input Bias Current vs Common-Mode Voltage
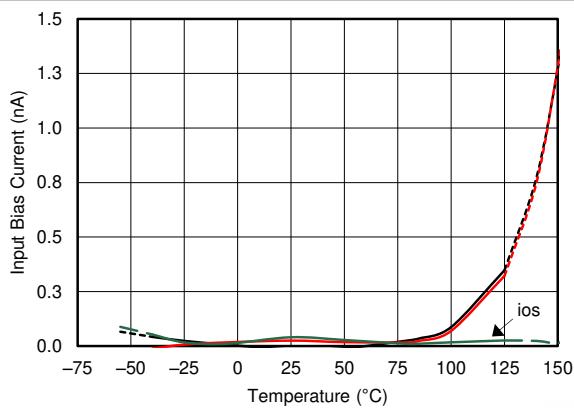
Figure 6-10. Input Bias Current vs Temperature
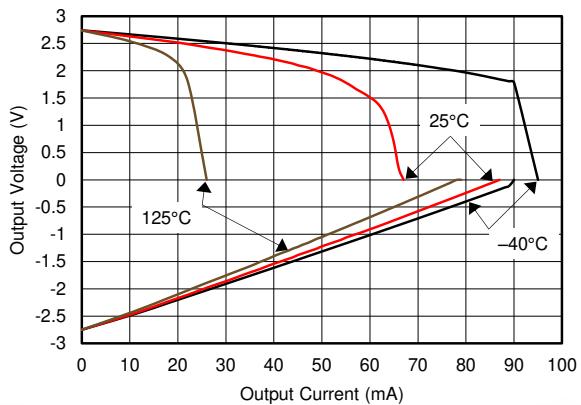
Figure 6-11. Output Voltage Swing vs Output Current (Maximum Supply)
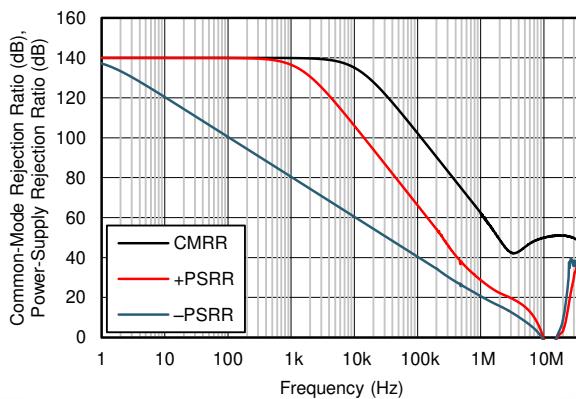
Figure 6-12. CMRR and PSRR vs Frequency
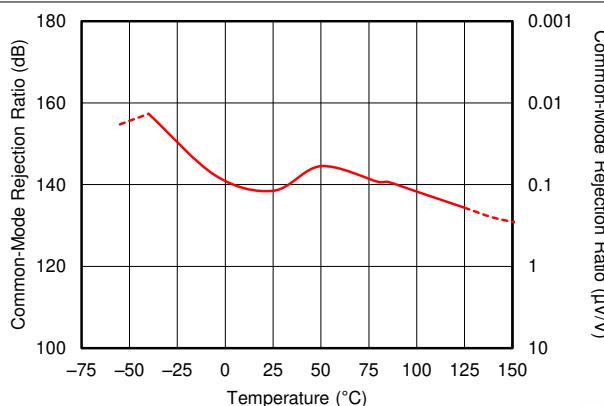
Figure 6-13. CMRR vs Temperature
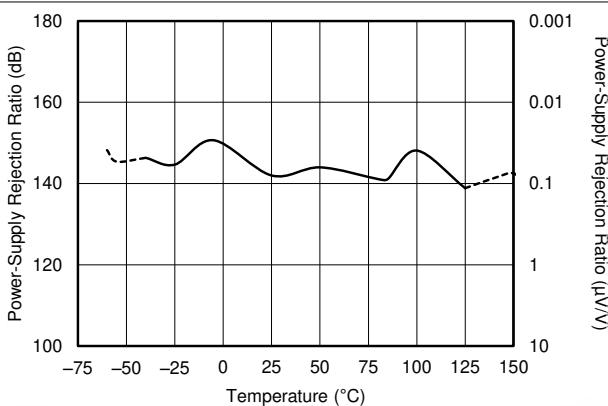
Figure 6-14. PSRR vs Temperature
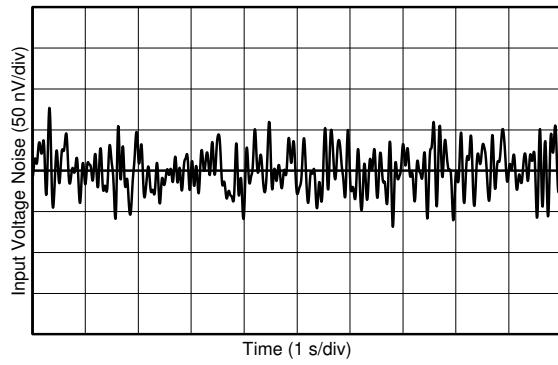

Figure 6-15. 0.1-Hz to 10-Hz Noise
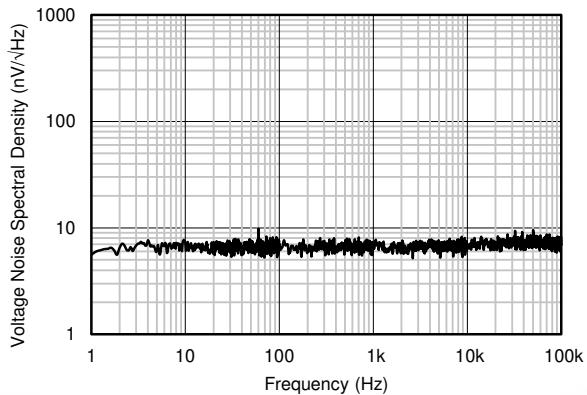

Figure 6-16. Input Voltage Noise Spectral Density vs Frequency
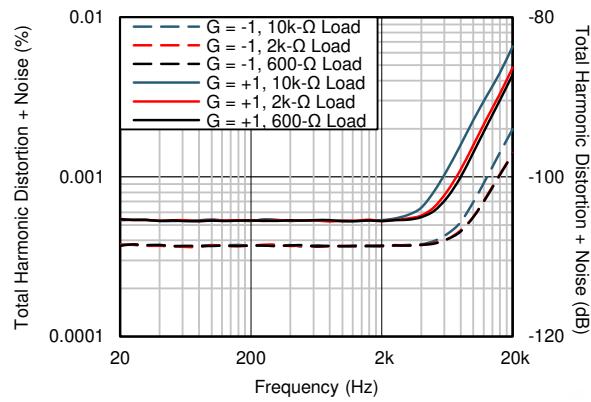
Figure 6-17. THD+N Ratio vs Frequency
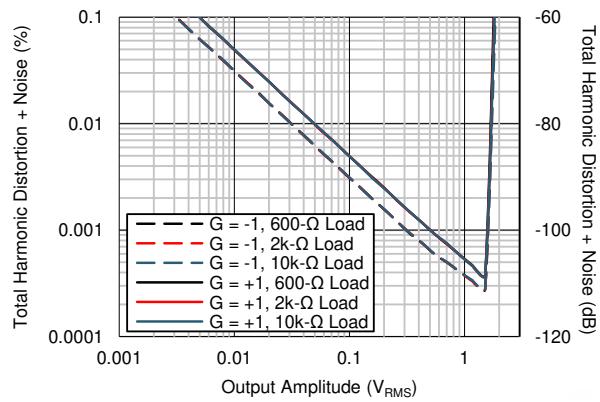
Figure 6-18. THD+N vs Output Amplitude

Product Folder Links: *OPA388-Q1*
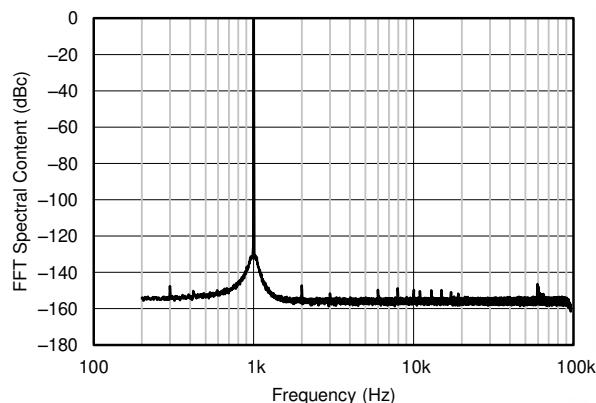
G = +1, f = 1 kHz, V_O = 4.5 V_{PP}, R_L = 10 kΩ, BW = 90 kHz

Figure 6-19. Spectral Content (With 10-kΩ Load)
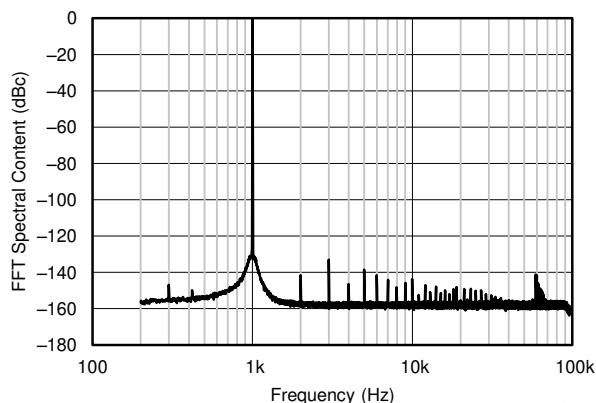
G = +1, f = 1 kHz, V_O = 4.5 V_{PP}, R_L = 2 kΩ, BW = 90 kHz

Figure 6-20. Spectral Content (With 2-kΩ Load)
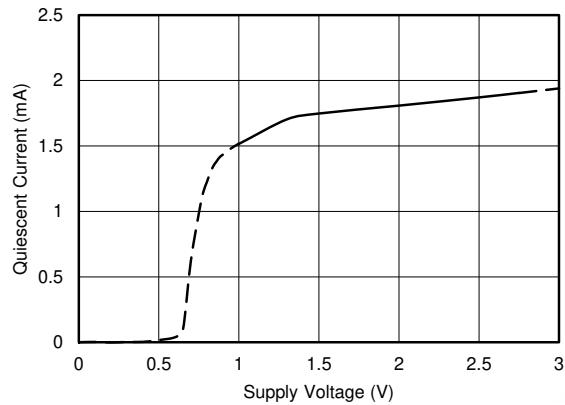
Figure 6-21. Quiescent Current vs Supply Voltage
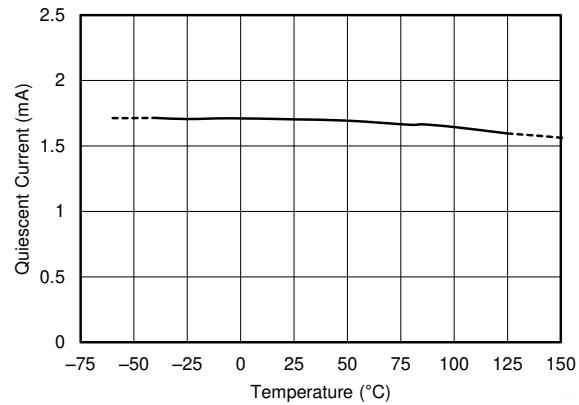

**Figure 6-22. Quiescent Current vs Temperature**
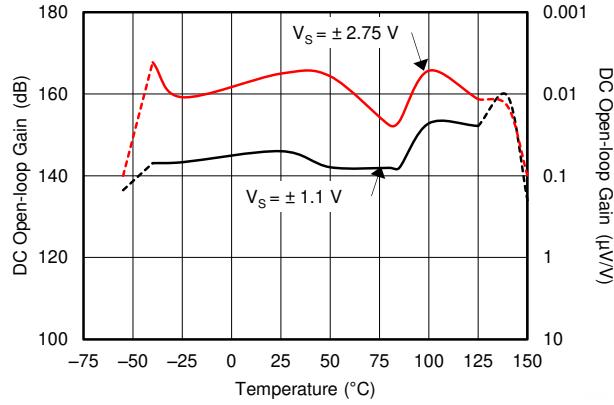
Figure 6-23. Open-Loop Gain vs Temperature
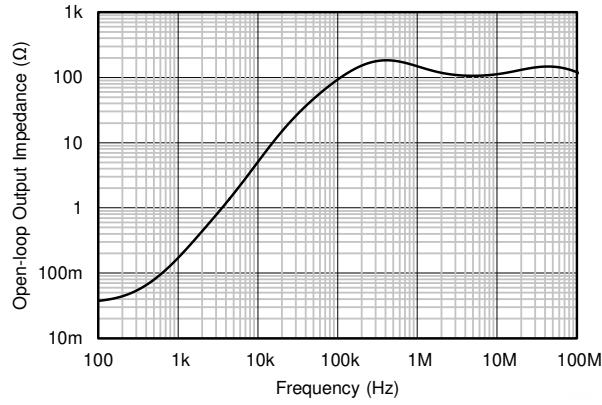
Figure 6-24. Open-Loop Output Impedance vs Frequency

Product Folder Links: *OPA388-Q1*
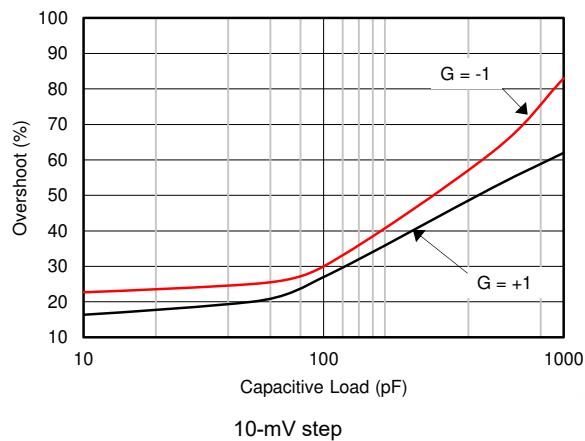
Figure 6-25. Small-Signal Overshoot vs Capacitive Load
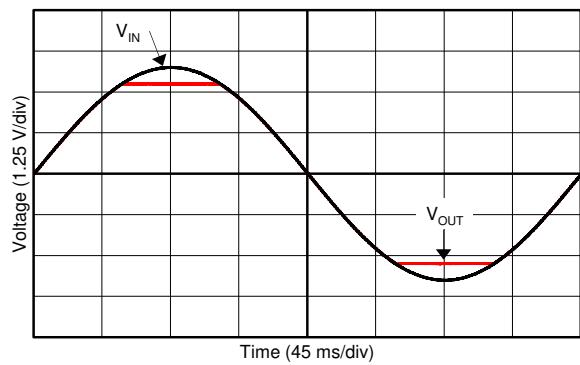
Figure 6-26. No Phase Reversal
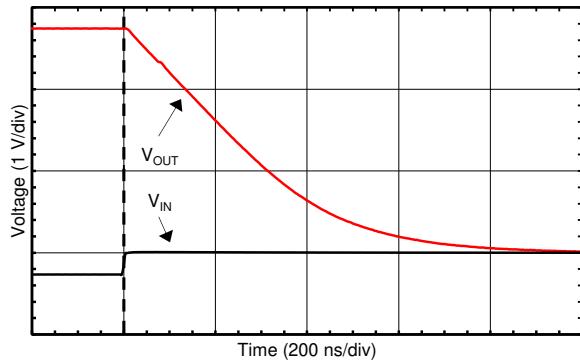
Figure 6-27. Positive Overload Recovery
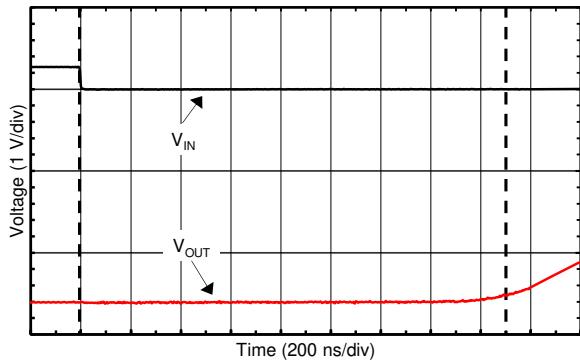
Figure 6-28. Negative Overload Recovery

G = +1, 10-mV step
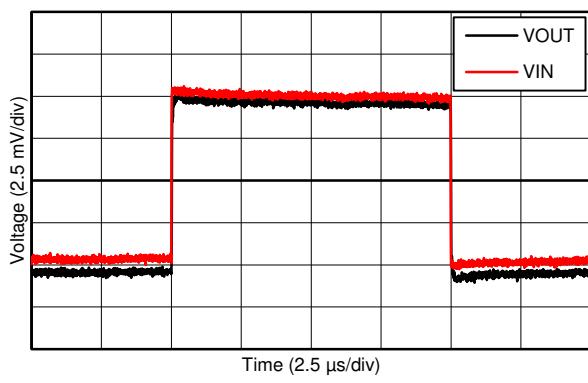
Figure 6-29. Small-Signal Step Response

G = –1, 10-mV step
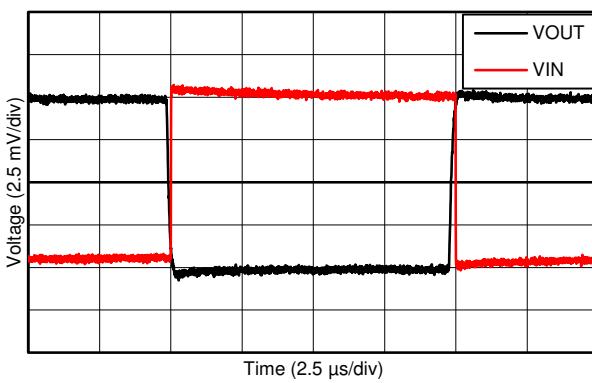
Figure 6-30. Small-Signal Step Response

Product Folder Links: *OPA388-Q1*
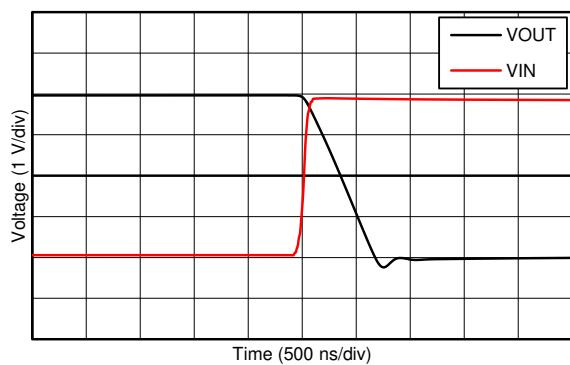
Falling output, 4-V Step

Figure 6-31. Large-Signal Step Response
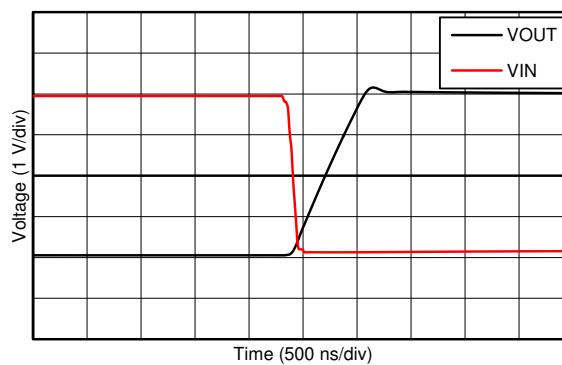
Rising output, 4-V step

Figure 6-32. Large-Signal Step Response
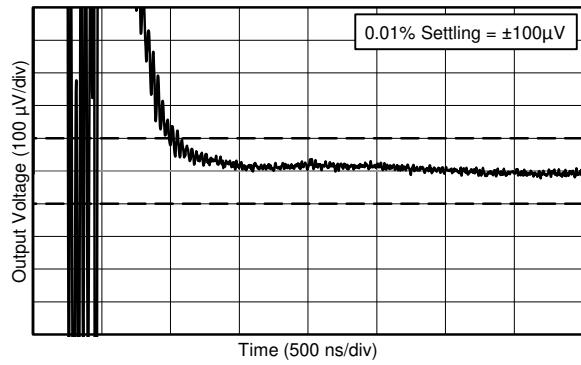
0.01% settling = ±100 µV, 1-V positive step

Figure 6-33. Settling Time
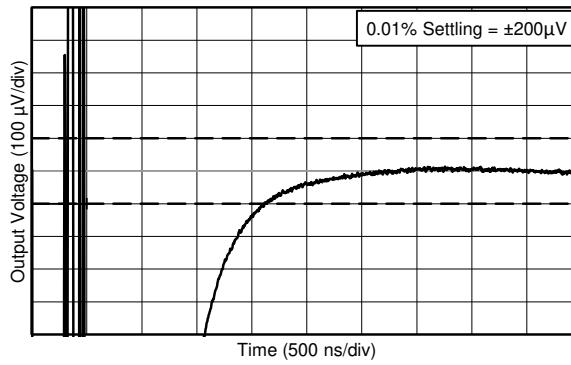
0.01% settling = ±200 µV, 1-V negative step

Figure 6-34. Settling Time
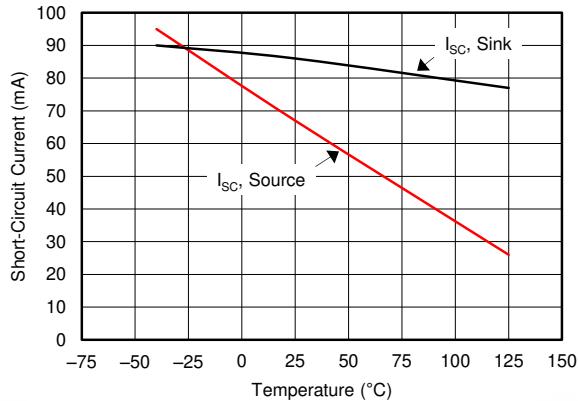
Figure 6-35. Short-Circuit Current vs Temperature
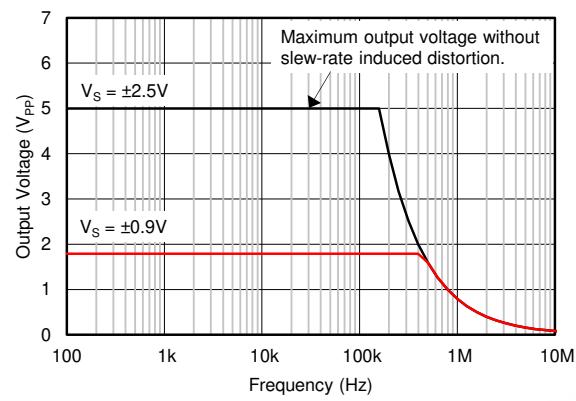
Figure 6-36. Maximum Output Voltage vs Frequency

Product Folder Links: OPA388-Q1
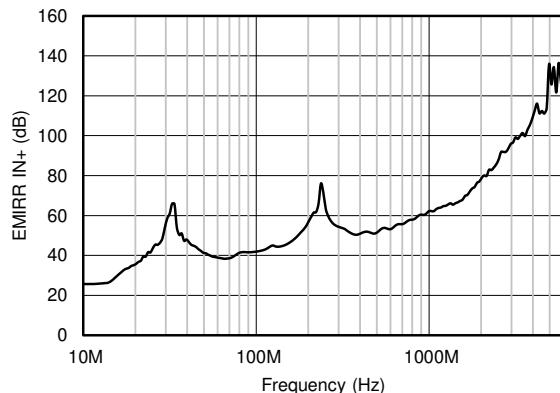
$P_{RF} = -10$ dBm

Figure 6-37. EMIRR vs Frequency

Product Folder Links: *OPA388-Q1*

7 Detailed Description

7.1 Overview

The OPA388-Q1 zero-drift amplifier is engineered with the unique combination of a proprietary precision auto-calibration technique and 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 OPA388-Q1 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 OPA388-Q1 strengths also include 10-MHz bandwidth, 7-nV/$\sqrt{Hz}$ noise spectral density, and no 1/f noise, making the OPA388-Q1 optimal for interfacing with sensor modules and buffering high-fidelity, digital-to-analog converters (DACs).

7.2 Functional Block Diagram

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Product Folder Links: OPA388-Q1
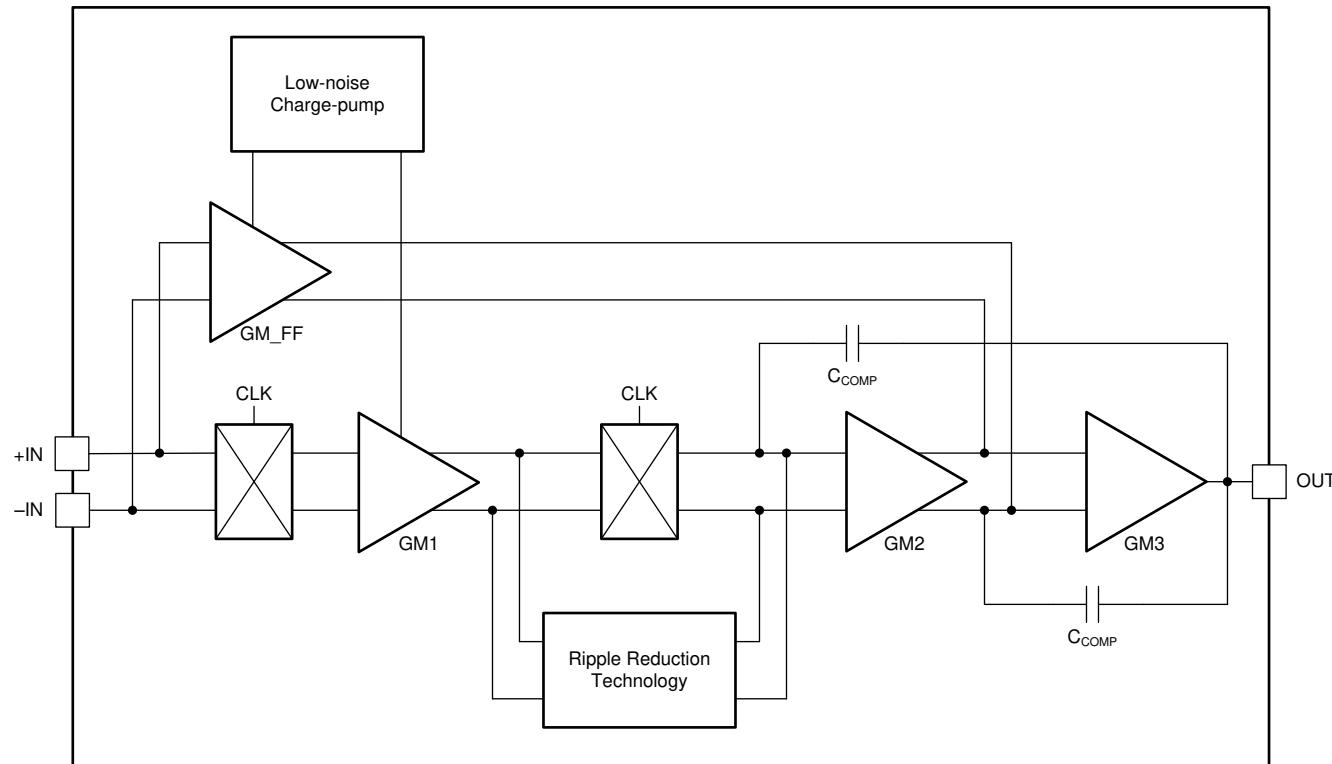
7.3 Feature Description

7.3.1 Operating Voltage

The OPA3x88 family of operational amplifiers can be used with single or dual supplies from an operating range of V_S = 2.5 V (±1.25 V) up to 5.5 V (±2.75 V). Supply voltages greater than 7 V can permanently damage the device (see Section 6.1). Key parameters that vary over the supply voltage or temperature range are shown in *Section 6.6*.

7.3.2 Input Voltage and Zero-Crossover Functionality

The OPA388-Q1 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 7-1 and Figure 7-2 contrast the performance of a traditional complementary rail-to-rail input stage amplifier with the performance of the zero-crossover OPA388-Q1. Significant harmonic content and distortion is generated during the differential pair transition (such a transition does not exist in the OPA388-Q1). Crossover distortion is eliminated through the use of a single differential pair coupled with an internal low-noise charge pump. The OPA388-Q1 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.
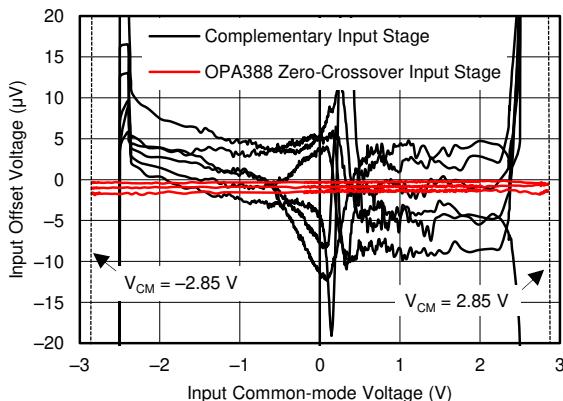

Figure 7-1. Input Crossover Distortion Nonlinearity
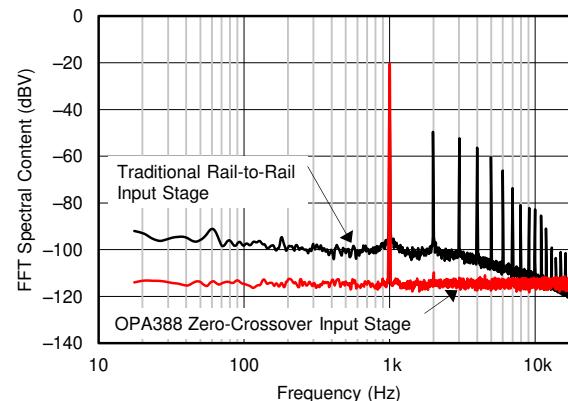
Figure 7-2. Input Crossover Distortion Spectral Content

Product Folder Links: *OPA388-Q1*

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 7-3.
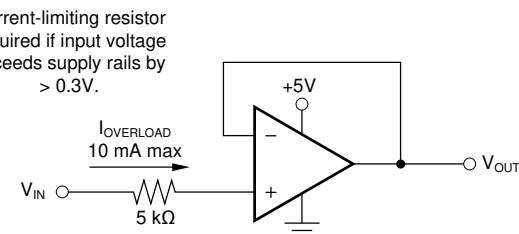

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Figure 7-3. Input Current Protection

7.3.3 Input Differential Voltage

The typical input bias current of the OPA388-Q1 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 7-4. Notice that the input bias current remains within specification in the linear region.
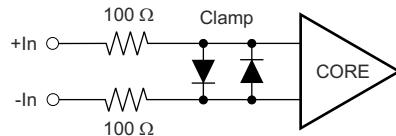
Copyright © 2016, Texas Instruments Incorporated

Figure 7-4. Equivalent Input Circuit

7.3.4 Internal Offset Correction

The OPA388-Q1 operational amplifier uses an auto-calibration technique with a time-continuous, 200-kHz operational amplifier in the signal path. This amplifier is zero-corrected every 5 μs 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 OPA388-Q1 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-Q1 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 OPA388-Q1 is 5.5 V (±2.75 V).

Product Folder Links: *OPA388-Q1*

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 OPA388-Q1 is a unity-gain stable, precision operational amplifier 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 OPA388-Q1 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 OPA388-Q1 precision amplifier is designed 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 OPA388-Q1 because of the 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 8-1 shows the solution.
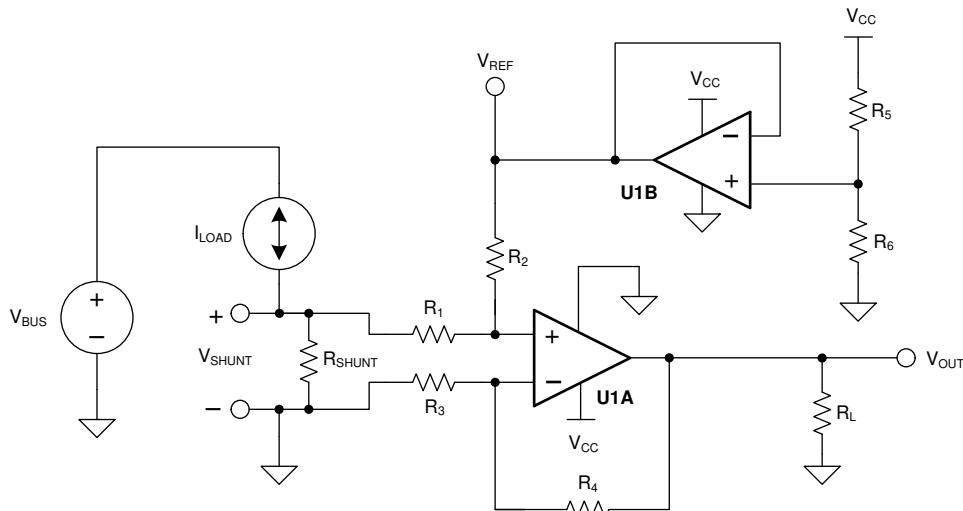
Figure 8-1. Bidirectional Current-Sensing

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 ±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.

$$V_{OUT} = V_{SHUNT} \times Gain_{Diff\_Amp} + V_{REF} \tag{1}$$

where

- $V_{SHUNT} = I_{LOAD} \times R_{SHUNT}$
- $Gain_{Diff\_Amp} = \dfrac{R_4}{R_3}$
- $V_{REF} = V_{CC} \times \left(\dfrac{R_6}{R_5 + R_6} \right)$

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.

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

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-Q1, that has a common-mode range that extends below the negative supply voltage. Finally, to minimize offset error, note that the OPA388-Q1 has a typical offset voltage of merely ±0.25 μV (±5 μV 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-kΩ resistors were used.

To set the gain of the difference amplifier, the common-mode range and output swing of the OPA388-Q1 must be considered. Equation 3 and Equation 4 depict the typical common-mode range and maximum output swing, respectively, of the OPA388-Q1 given a 3.3-V supply.

$$-100 \text{ mV} < V_{CM} < 3.4 \text{ V} \tag{3}$$

$$100 \text{ mV} < V_{OUT} < 3.2 \text{ V} \tag{4}$$

The gain of the difference amplifier can now be calculated as shown in Equation 5.

$$\text{Gain}_{\text{Diff\_Amp}} = \frac{V_{OUT\_Max} - V_{OUT\_Min}}{R_{SHUNT} \times (I_{MAX} - I_{MIN})} = \frac{3.2 \text{ V} - 100 \text{ mV}}{100 \text{ m}\Omega \times [1 \text{ A} - (-1\text{A})]} = 15.5 \frac{V}{V} \tag{5}$$

The resistor value selected for R_1 and R_3 was 1 kΩ. 15.4 kΩ 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
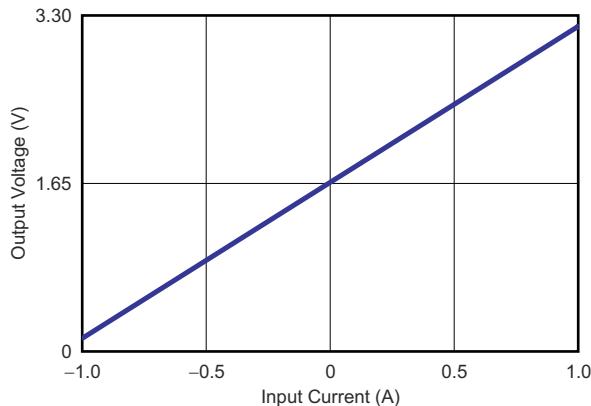
Figure 8-2. Bidirectional Current-Sensing Circuit Performance: Output Voltage vs Input Current

Product Folder Links: *OPA388-Q1*

8 Power Supply Recommendations

The OPA388-Q1 device is specified for operation from 2.5 V to 5.5 V (±1.25 V to ±2.75 V). Parameters that can exhibit significant variance with regard to operating voltage are presented in *Section 6.6*.

9 Layout

9.1 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-µF 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 µV/°C or higher, depending on materials used.

9.2 Layout Example
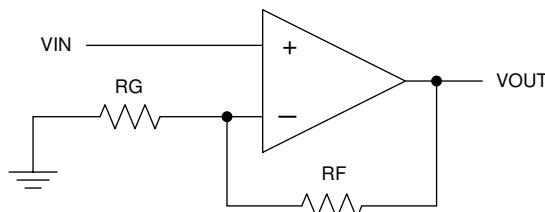
**Figure 9-1. Schematic Representation**
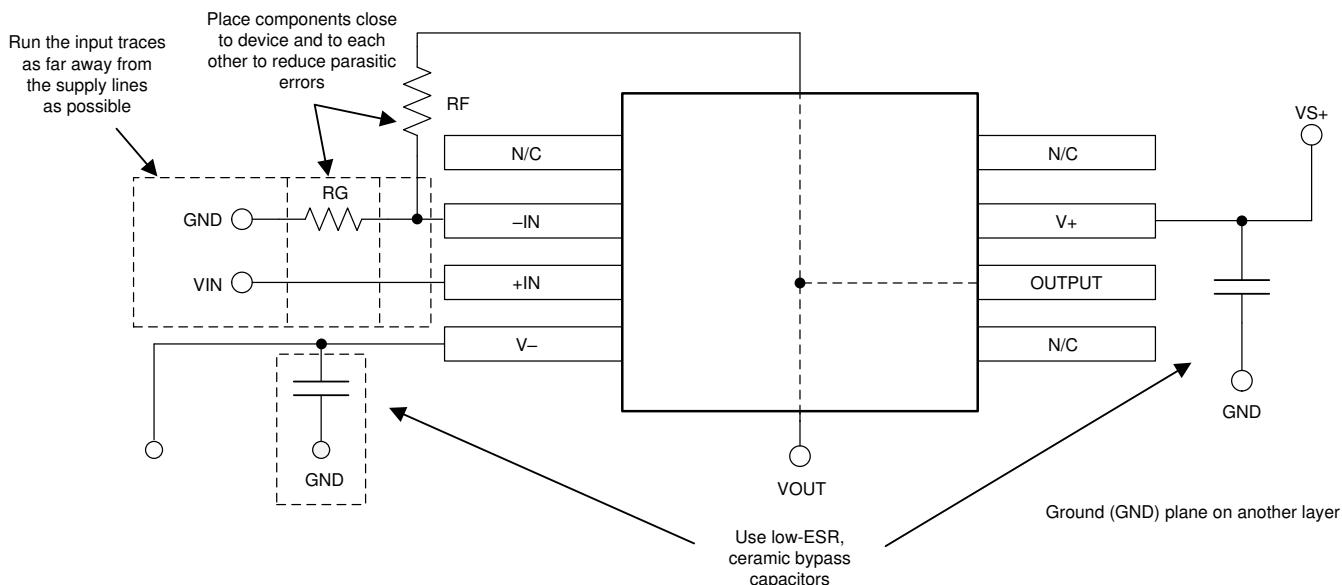
Figure 9-2. Layout Example

10 Device and Documentation Support

10.1 Device Support

10.1.1 Development Support

10.1.1.1 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.

10.1.1.2 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.

10.2 Documentation Support

10.2.1 Related Documentation

For related documentation see the following: Texas Instruments, *Circuit board layout techniques*

10.3 Receiving Notification of Documentation Updates

To receive notification of documentation updates, navigate to the device product folder on ti.com. Click on *Subscribe to updates* 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.

10.4 Support Resources

TI E2E™ support forums are an engineer's go-to source for fast, verified answers and design help — straight from the experts. Search existing answers or ask your own question to get the quick design help you need.

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10.6 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.

10.7 Glossary

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

11 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 finish/ Ball material (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
OPA388QDBVRQ1	ACTIVE	SOT-23	DBV	5	3000	RoHS & Green	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	388Q	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) **RoHS:** TI defines "RoHS" to mean semiconductor products that are compliant with the current EU RoHS requirements for all 10 RoHS substances, including the requirement that RoHS substance do not exceed 0.1% by weight in homogeneous materials. Where designed to be soldered at high temperatures, "RoHS" products are suitable for use in specified lead-free processes. TI may reference these types of products as "Pb-Free".

RoHS Exempt: TI defines "RoHS Exempt" to mean products that contain lead but are compliant with EU RoHS pursuant to a specific EU RoHS exemption.

Green: TI defines "Green" to mean the content of Chlorine (Cl) and Bromine (Br) based flame retardants meet JS709B low halogen requirements of <=1000ppm threshold. Antimony trioxide based flame retardants must also meet the <=1000ppm threshold requirement.

(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 finish/Ball material - Orderable Devices 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.

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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.

OTHER QUALIFIED VERSIONS OF OPA388-Q1 :

● Catalog: OPA388

NOTE: Qualified Version Definitions:

   ● Catalog - TI's standard catalog product

PACKAGE MATERIALS INFORMATION

TAPE AND REEL INFORMATION

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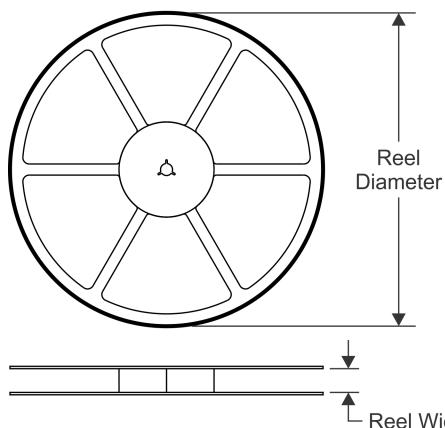
TAPE DIMENSIONS
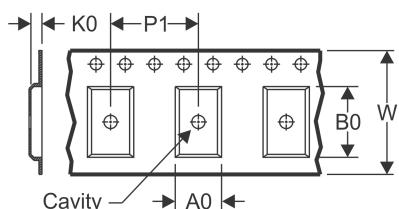
A0	Dimension designed to accommodate the component width
B0	Dimension designed to accommodate the component length
K0	Dimension designed to accommodate the component thickness
W	Overall width of the carrier tape
P1	Pitch between successive cavity centers

QUADRANT ASSIGNMENTS FOR PIN 1 ORIENTATION IN TAPE
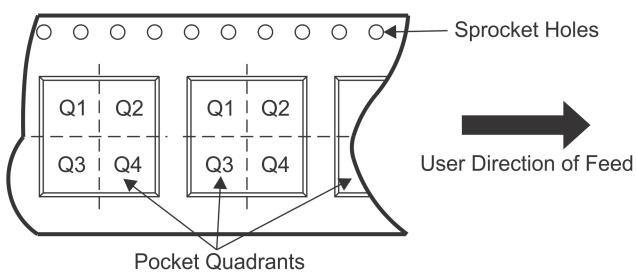
*All dimensions are nominal

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
OPA388QDBVRQ1	SOT-23	DBV	5	3000	180.0	8.4	3.23	3.17	1.37	4.0	8.0	Q3

PACKAGE MATERIALS INFORMATION

TAPE AND REEL BOX DIMENSIONS
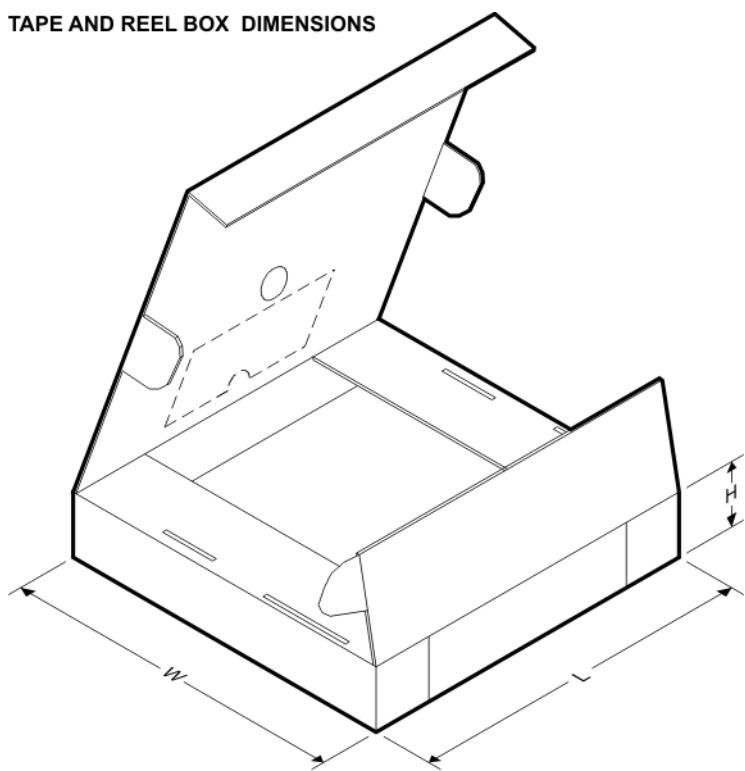
*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
OPA388QDBVRQ1	SOT-23	DBV	5	3000	213.0	191.0	35.0
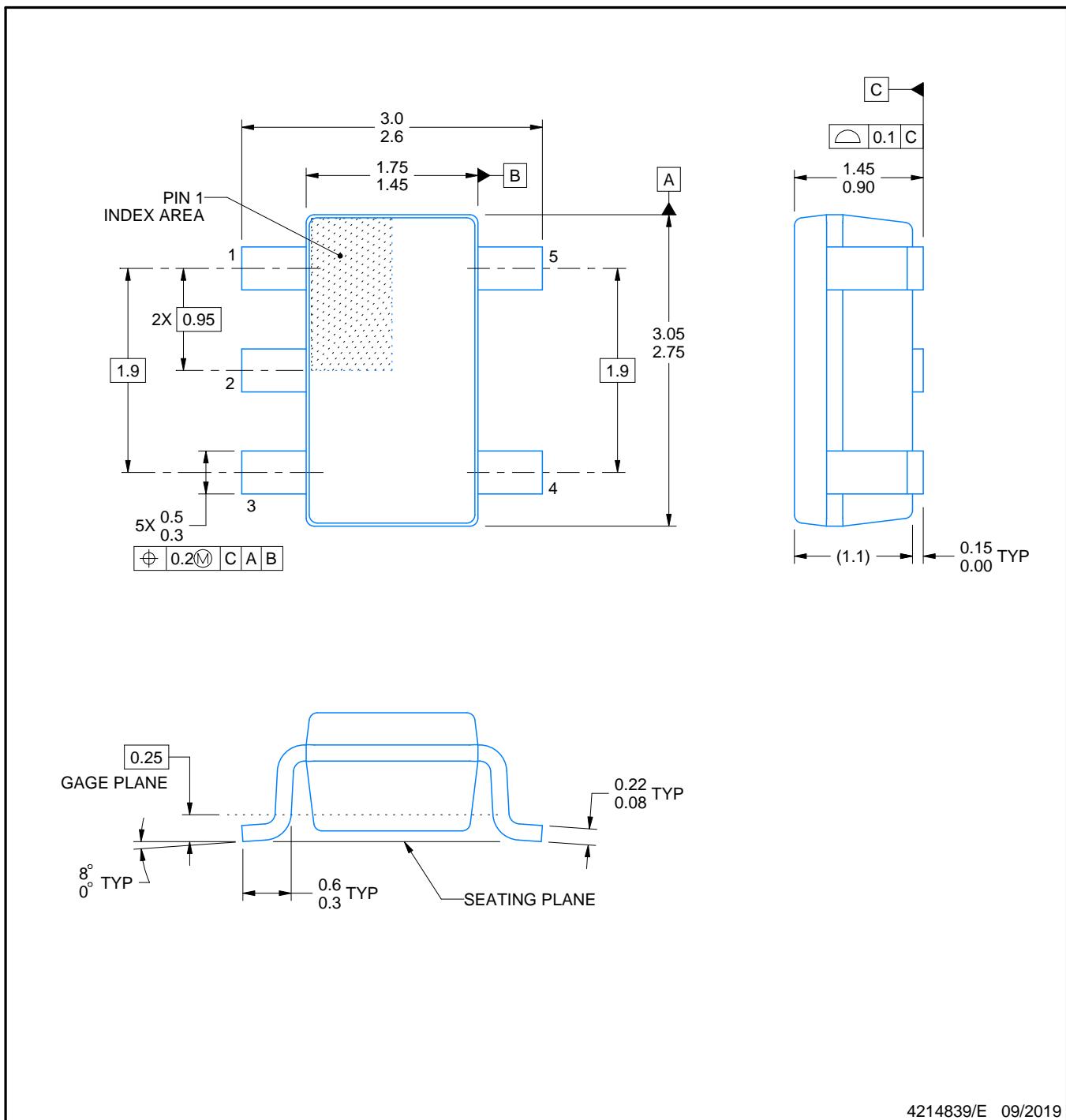
4214839/E   09/2019

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. Refernce JEDEC MO-178.
4. Body dimensions do not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0.15 mm per side.

PKG ℄

5X (1.1)

1

5X (0.6)

5

SYMM ℄

2

(1.9)

2X (0.95)

3

4

(R0.05) TYP

(2.6)
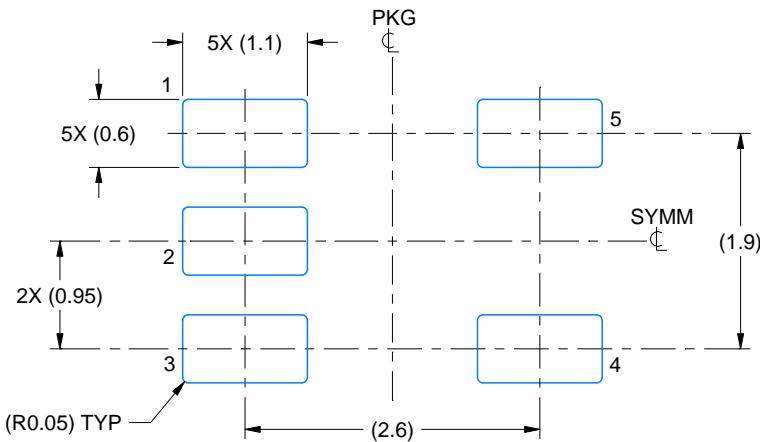
LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:15X

SOLDER MASK OPENING

METAL

METAL UNDER SOLDER MASK

SOLDER MASK OPENING

EXPOSED METAL

EXPOSED METAL

0.07 MAX ARROUND

0.07 MIN ARROUND

NON SOLDER MASK DEFINED (PREFERRED)

SOLDER MASK DEFINED
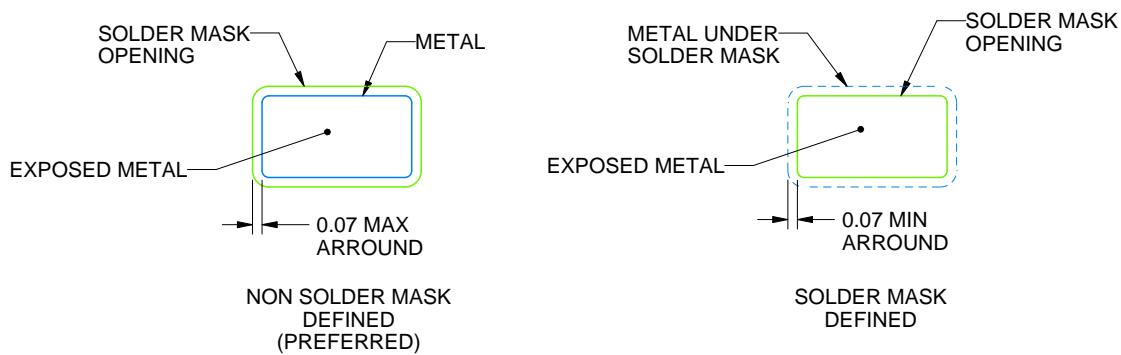
SOLDER MASK DETAILS

4214839/E   09/2019

NOTES: (continued)

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

PKG

5X (1.1)

1

5X (0.6)

5

2

SYMM

(1.9)

2X(0.95)

3

4

(R0.05) TYP

(2.6)
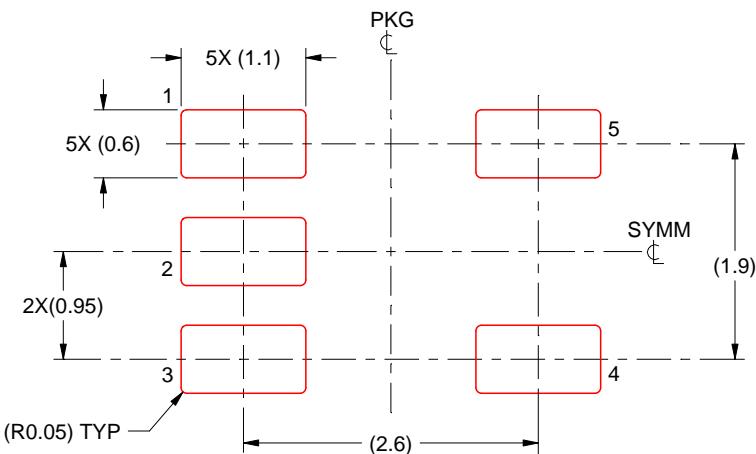
SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE:15X

4214839/E   09/2019

NOTES: (continued)

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

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