

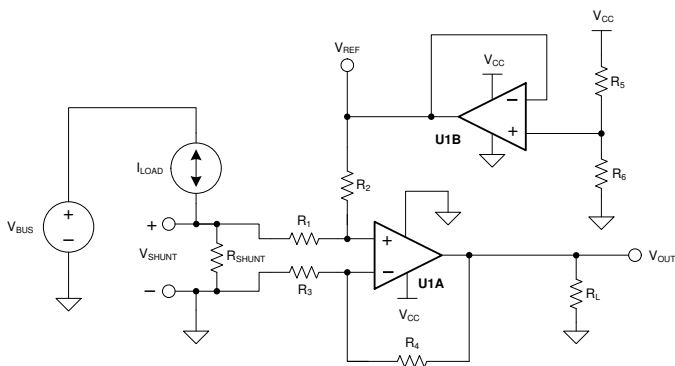
OPAx388-Q1 自动、精密、零漂移、零交叉、 真正的轨至轨输入/输出运算放大器

1 特性

- 符合面向汽车应用的 AEC-Q100 标准：
 - 温度等级 1：-40°C 至 +125°C，T_A
- 提供功能安全
 - 可帮助进行功能安全系统设计的文档 (OPA388-Q1)
 - 可帮助进行功能安全系统设计的文档 (OPA2388-Q1: VSSOP)
- 零漂移：±0.005μV/°C
- 零交叉：140dB CMRR 真正 RRIO
- 低噪声：1 kHz 时为 7.0 nV √Hz
- 无 1/f 噪声：140nV_{PP} (0.1Hz 至 10Hz)
- 快速稳定：2μs (1V, 0.01%)
- 增益带宽：10MHz
- 单电源：2.5V 至 5.5V
- 双电源：±1.25V 至 ±2.75V
- 真正的轨至轨输入
- 输入已滤除 EMI 和 RFI
- 行业标准封装：VSSOP-8、SOT-23-5

2 应用

- 混合动力汽车/电动汽车逆变器和电机控制
- 电池管理系统 (BMS)
- 直流/直流转换器
- 车载充电器 (OBC) 和无线充电器



双向电流分流监控器中的 OPA388-Q1

3 说明

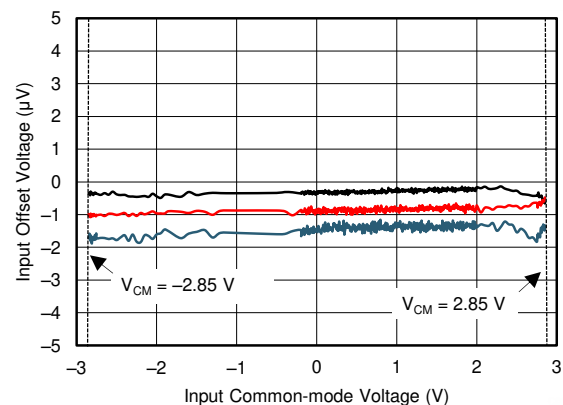
OPA388-Q1 和 OPA2388-Q1 (OPAx388-Q1) 是自动低噪声、快速稳定、零漂移高精度运算放大器，可实现轨到轨输入和输出运行。优异交流性能与仅为 0.25 μV 的失调电压以及 0.005μV/°C 的温度漂移相结合，使 OPAx388-Q1 成为驱动高精度高分辨率模数转换器 (ADC) 的理想选择。零交叉技术更大程度地减小了共模范围内的失调电压变化。低漂移和超低 1/f 噪声相结合，使 OPAx388-Q1 能够监视和检测故障情况，而不会影响信号完整性。

这些器件的额定工业温度范围均为 -40°C 至 +125°C。

器件信息

器件型号	封装 ⁽¹⁾	封装尺寸 (标称值)
OPA388-Q1	SOT-23 (5)	2.90mm × 1.60mm
OPA2388-Q1	SOIC (8) - 预发布	4.90mm × 3.90mm
	VSSOP (8)	3.00mm × 3.00mm

(1) 如需了解所有可用封装，请参阅数据表末尾的封装选项附录。



OPA388-Q1 在整个共模范围内采用超低失调电压



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4 Revision History

注：以前版本的页码可能与当前版本的页码不同

Changes from Revision * (August 2020) to Revision A (November 2021)	Page
• 添加了 OPA2388-Q1 量产数据 (正在供货) 器件和相关内容.....	1

5 Pin Configuration and Functions

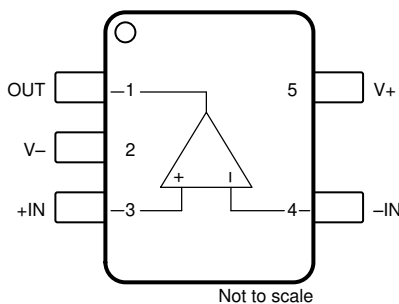


图 5-1. OPA388-Q1 DBV (5-Pin SOT-23) Package, Top View

Pin Functions: OPA388-Q1

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

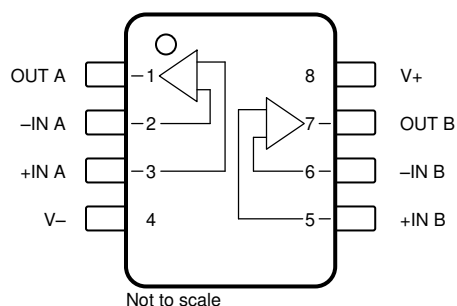


图 5-2. OPA2388-Q1 D (8-Pin SOIC, Preview) and DGK (8-Pin VSSOP) Packages, Top View

Pin Functions: OPA2388-Q1

PIN		TYPE	DESCRIPTION
NAME	NO.		
- IN A	2	Input	Inverting input, channel A
- IN B	6	Input	Inverting input, channel B
+IN A	3	Input	Noninverting input, channel A
+IN B	5	Input	Noninverting input, channel B
OUT A	1	Output	Output, channel A
OUT B	7	Output	Output, channel B
V -	4	Power	Negative (lowest) power supply
V+	8	Power	Positive (highest) power supply

6 Specifications

6.1 Absolute Maximum Ratings

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

			MIN	MAX	UNIT
V _S	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	
	Signal input pins current			±10	mA
	Output short circuit ⁽²⁾		Continuous	Continuous	
T _A	Operating temperature		– 55	150	°C
T _J	Junction temperature			150	°C
T _{stg}	Storage temperature		– 65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

(2) Short-circuit to 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
V _S	Supply voltage, V _S = (V ⁺) – (V [–])	Single-supply	2.5		5.5	V
		Dual-supply	±1.25		±2.75	
T _A	Specified temperature		– 40		125	°C

6.4 Thermal Information: OPA388-Q1

THERMAL METRIC ⁽¹⁾		OPA388-Q1	UNIT
		DBV (SOT-23)	
		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 Thermal Information: OPA2388-Q1

THERMAL METRIC ⁽¹⁾		OPA2388-Q1	UNIT
		DGK (VSSOP)	
		8 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance	165	°C/W
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance	53	°C/W
$R_{\theta JB}$	Junction-to-board thermal resistance	87	°C/W
Ψ_{JT}	Junction-to-top characterization parameter	4.9	°C/W
Ψ_{JB}	Junction-to-board characterization parameter	85	°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.

6.6 Electrical Characteristics

at $T_A = 25^\circ\text{C}$, $V_{CM} = V_{OUT} = V_S / 2$, $V_S = \pm 1.25\text{ V to } \pm 2.75\text{ V}$ (2.5 V to 5.5 V), 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	OPA388-Q1		±0.25	±5	μV	
		OPA2388-Q1		±1.5	±5		
		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 _S = ±2.75 V	124	140		
INPUT IMPEDANCE							
Z _{id}	Differential input impedance			100 2		M Ω pF	
Z _{ic}	Common-mode input impedance			60 4.5		T Ω pF	
OPEN-LOOP GAIN							
A _{OL}	Open-loop voltage gain	(V ⁻) + 0.15 V < V _O < (V ⁺) - 0.15 V		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 k Ω		126	148		
			T _A = - 40°C to +125°C	120	148		
		(V ⁻) + 0.30 V < V _O < (V ⁺) - 0.30 V, R _{LOAD} = 2 k Ω					
			T _A = - 40°C to +125°C				

6.6 Electrical Characteristics (continued)

at $T_A = 25^\circ\text{C}$, $V_{CM} = V_{OUT} = V_S / 2$, $V_S = \pm 1.25\text{ V to } \pm 2.75\text{ V}$ (2.5 V to 5.5 V), and $R_{LOAD} = 10\text{ k}\Omega$ 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	V _S = ±2.5 V, G = 1, 1-V step	To 0.1%	0.75			μs
			To 0.01%	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
				5		20	
			R _{LOAD} = 2 k Ω	20		50	
		Negative rail	No load	5		15	
				10		20	
			R _{LOAD} = 2 k Ω	40		60	
		T _A = - 40°C to +125°C, both rails, R _{LOAD} = 10 k Ω			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 图 6-25		
Z _O	Open-loop output impedance	f = 1 MHz, I _O = 0 A, see 图 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	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	1.9		2.6	

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)

表 6-1. Table of Graphs

DESCRIPTION	FIGURE
Offset Voltage Production Distribution	图 6-1
Offset Voltage Drift Distribution From -40°C to $+125^\circ\text{C}$	图 6-2
Offset Voltage vs Temperature	图 6-3
Offset Voltage vs Common-Mode Voltage	图 6-4
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Quiescent Current vs Temperature	图 6-22
Open-Loop Gain vs Temperature	图 6-23
Open-Loop Output Impedance vs Frequency	图 6-24
Small-Signal Overshoot vs Capacitive Load (10-mV Step)	图 6-25
No Phase Reversal	图 6-26
Positive Overload Recovery	图 6-27
Negative Overload Recovery	图 6-28
Small-Signal Step Response (10-mV Step)	图 6-29, 图 6-30
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Settling Time	图 6-33, 图 6-34
Short-Circuit Current vs Temperature	图 6-35
Maximum Output Voltage vs Frequency	图 6-36
EMIRR vs Frequency	图 6-37

6.7 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)

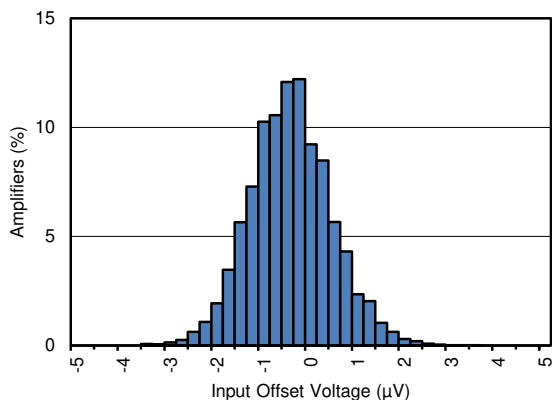


图 6-1. Offset Voltage Production Distribution

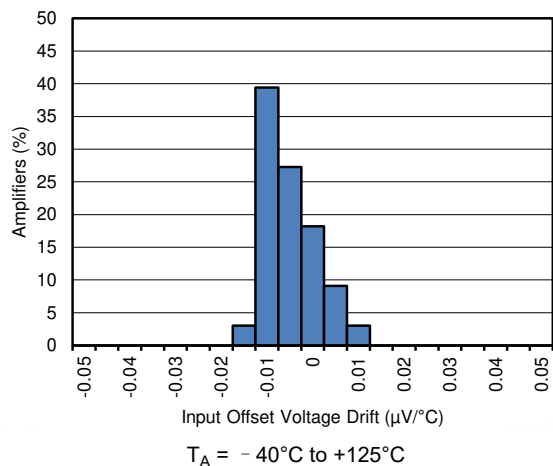


图 6-2. Offset Voltage Drift Distribution

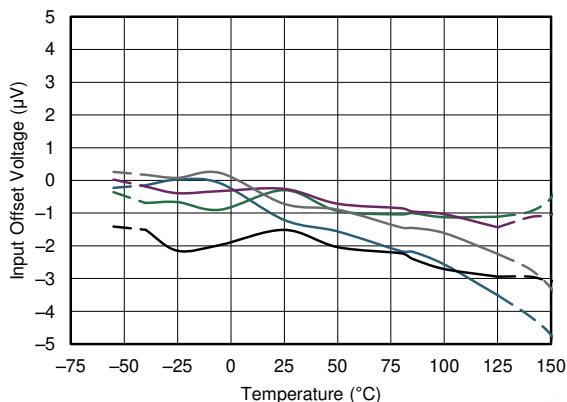


图 6-3. Offset Voltage vs Temperature

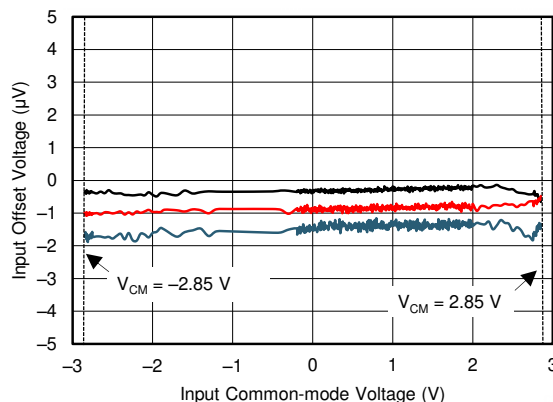


图 6-4. Offset Voltage vs Common-Mode Voltage

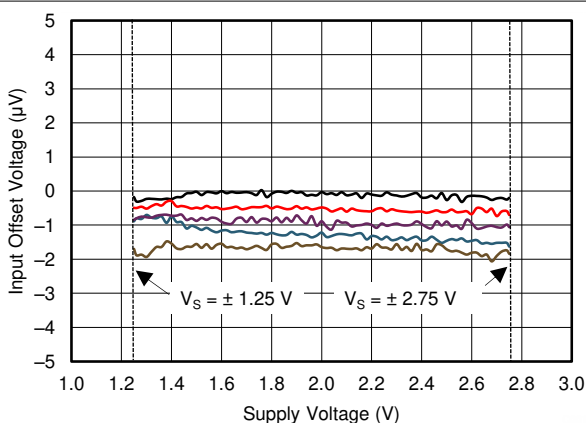


图 6-5. Offset Voltage vs Supply Voltage

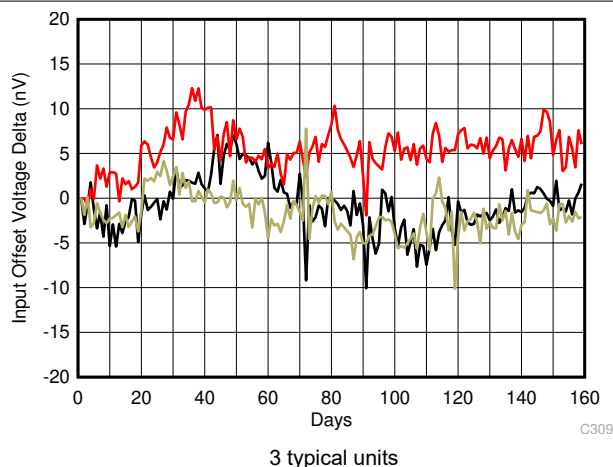


图 6-6. Offset Voltage Long Term Drift

6.7 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)

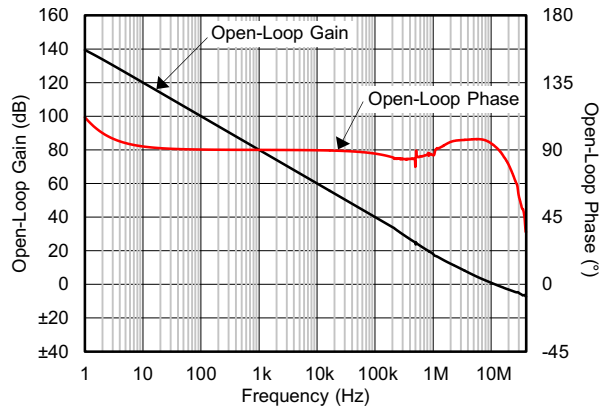


图 6-7. Open-Loop Gain and Phase vs Frequency

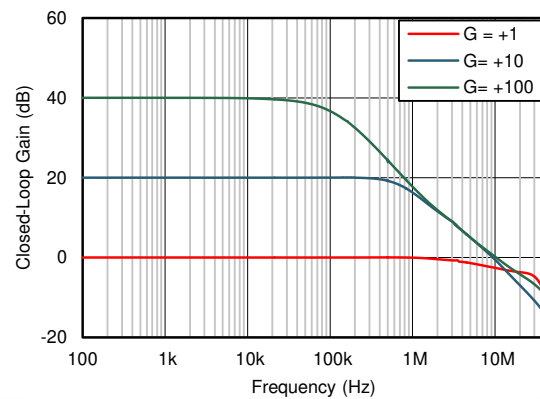


图 6-8. Closed-Loop Gain and Phase vs Frequency

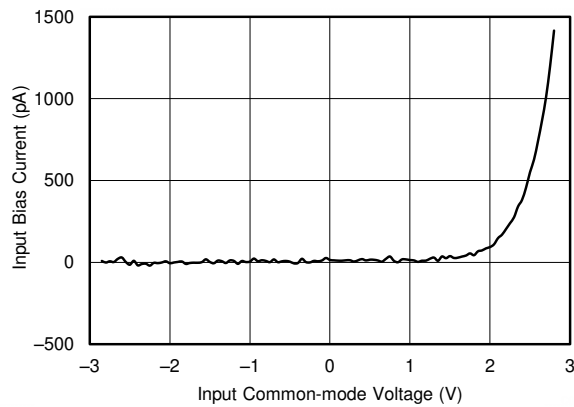


图 6-9. Input Bias Current vs Common-Mode Voltage

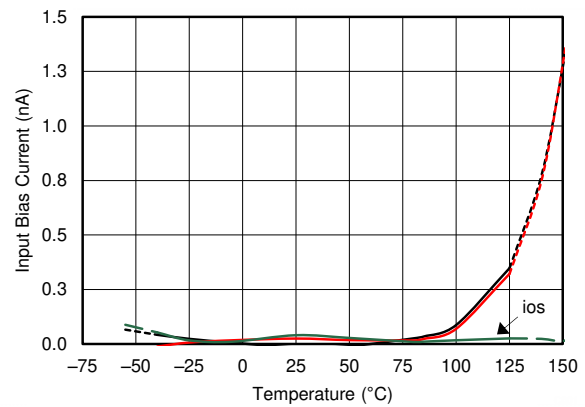


图 6-10. Input Bias Current vs Temperature

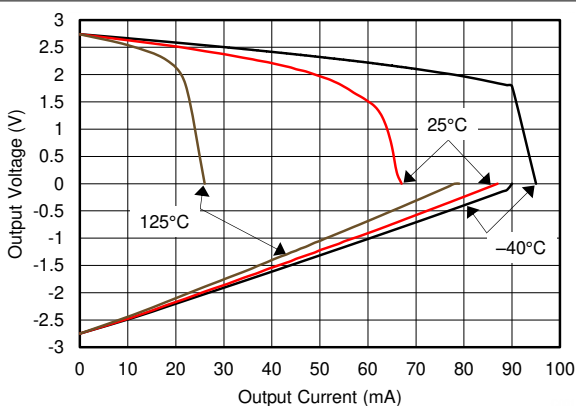


图 6-11. Output Voltage Swing vs Output Current (Maximum Supply)

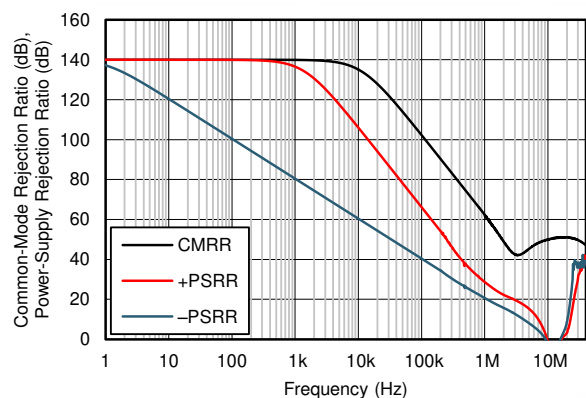


图 6-12. CMRR and PSRR vs Frequency

6.7 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)

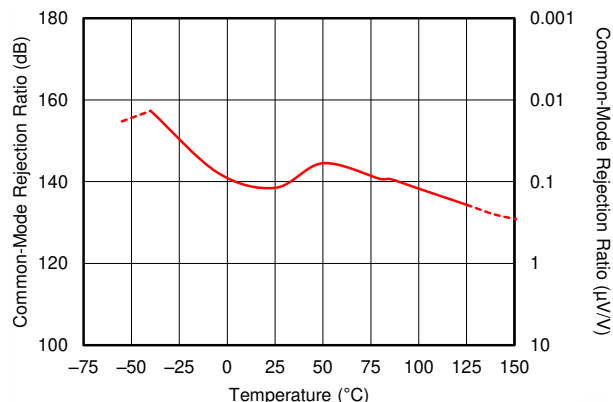


图 6-13. CMRR vs Temperature

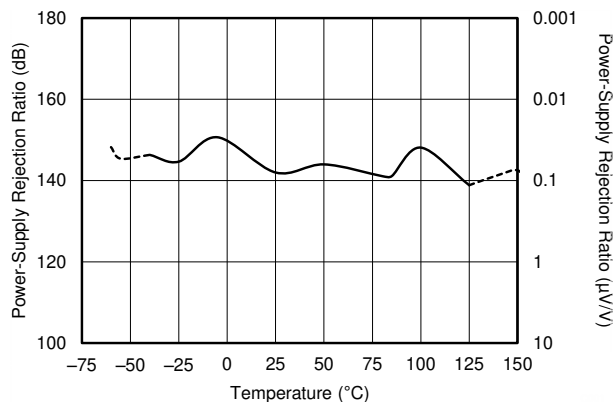


图 6-14. PSRR vs Temperature

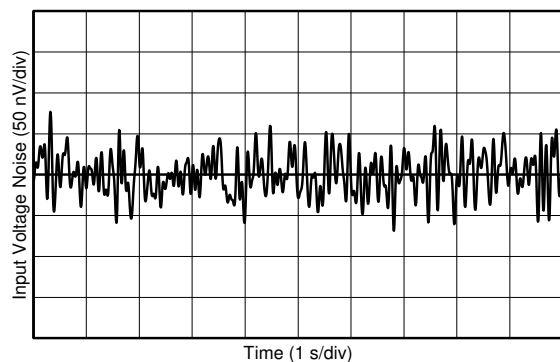


图 6-15. 0.1-Hz to 10-Hz Noise

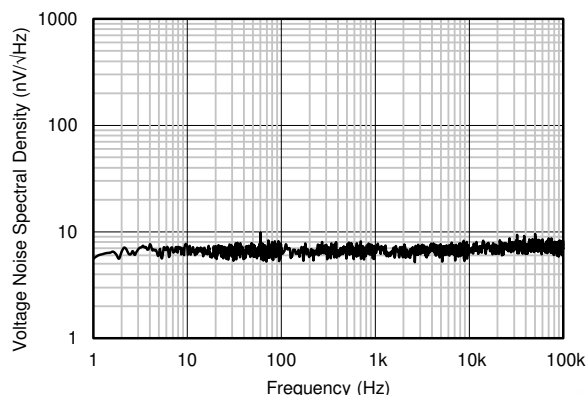


图 6-16. Input Voltage Noise Spectral Density vs Frequency

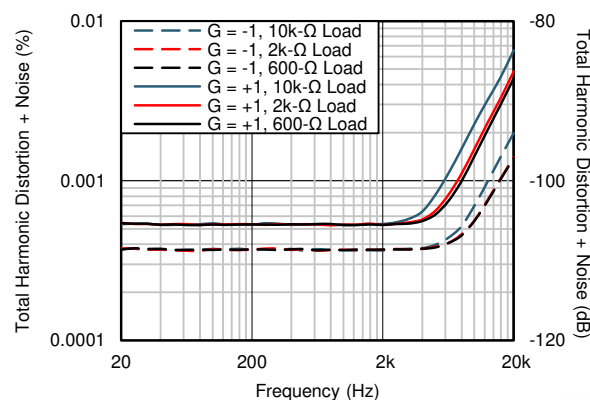


图 6-17. THD+N Ratio vs Frequency

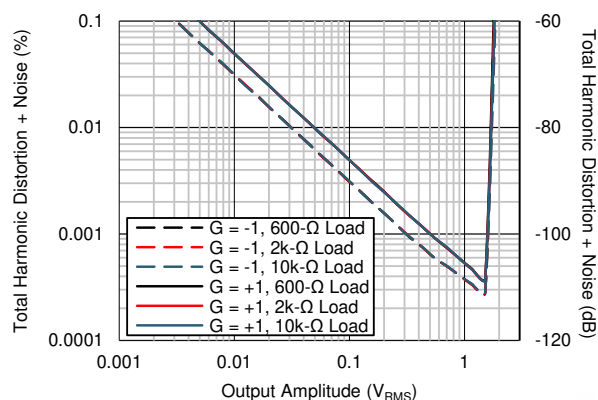
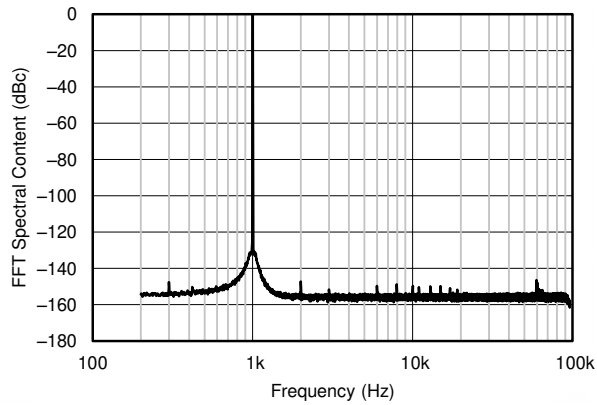


图 6-18. THD+N vs Output Amplitude

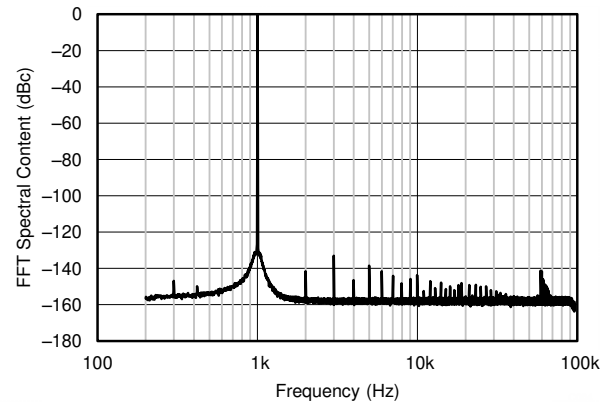
6.7 Typical Characteristics (continued)

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)



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

图 6-19. Spectral Content (With 10-k Ω Load)



$G = +1$, $f = 1\text{ kHz}$, $V_O = 4.5\text{ V}_{PP}$, $R_L = 2\text{ k}\Omega$, $BW = 90\text{ kHz}$

图 6-20. Spectral Content (With 2-k Ω Load)

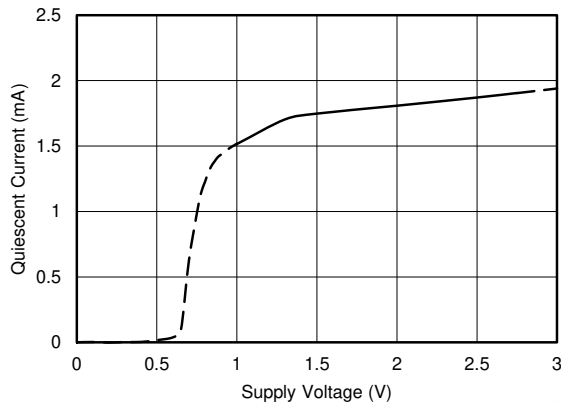


图 6-21. Quiescent Current vs Supply Voltage

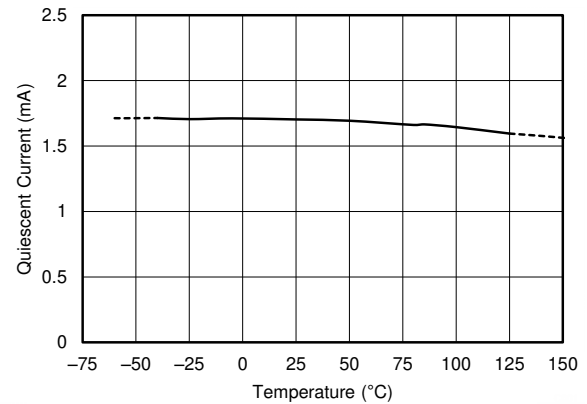


图 6-22. Quiescent Current vs Temperature

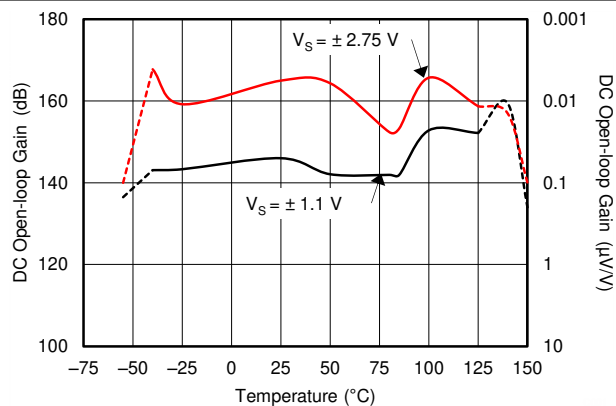


图 6-23. Open-Loop Gain vs Temperature

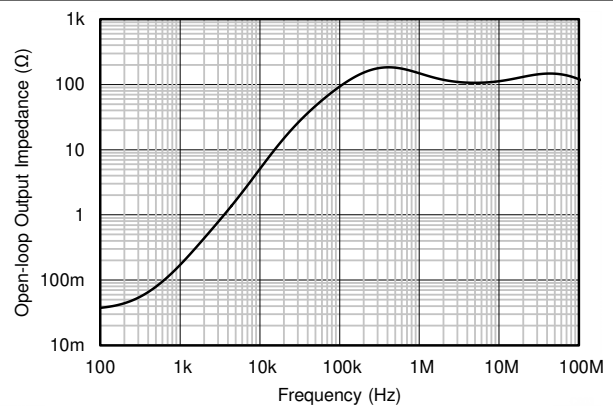


图 6-24. Open-Loop Output Impedance vs Frequency

6.7 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)

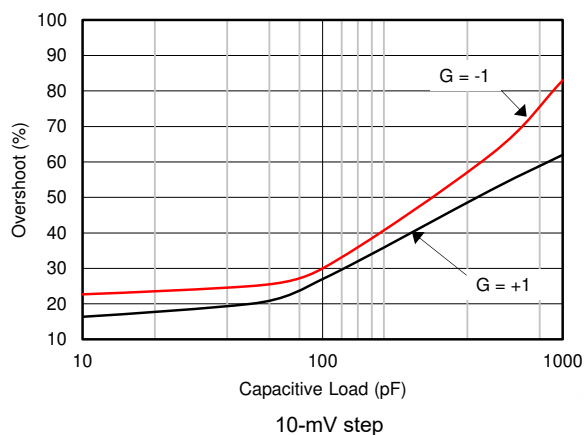


图 6-25. Small-Signal Overshoot vs Capacitive Load

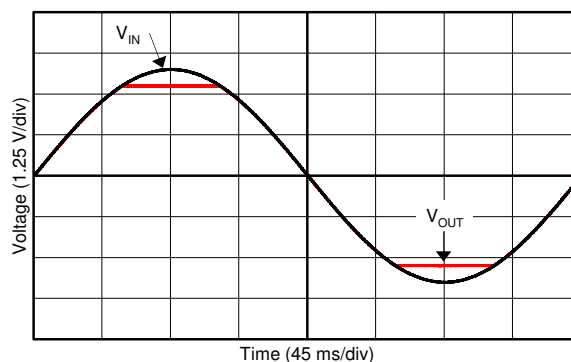


图 6-26. No Phase Reversal

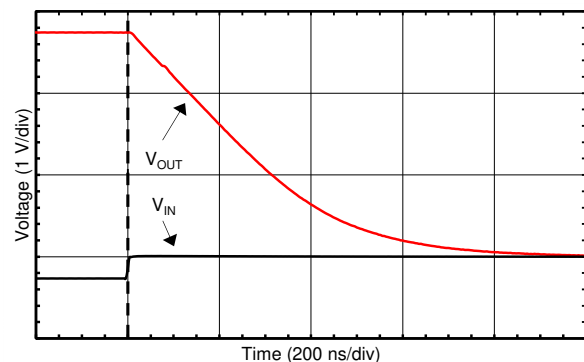


图 6-27. Positive Overload Recovery

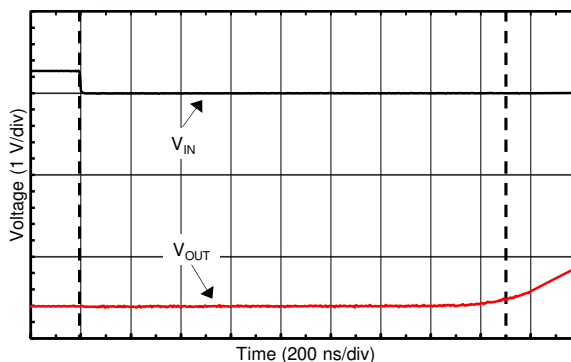
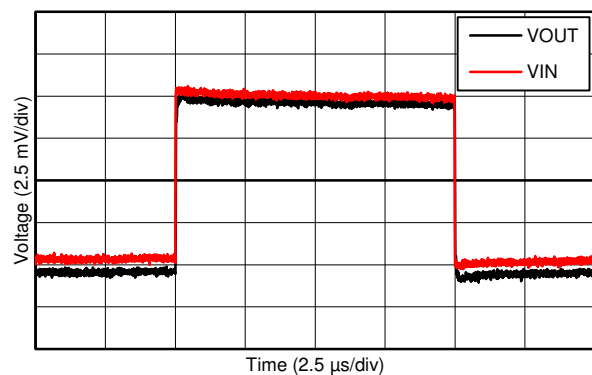
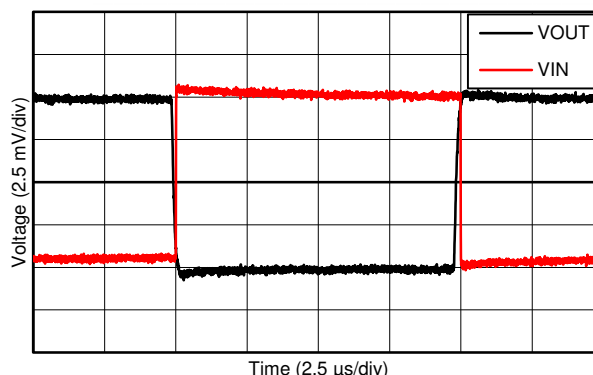


图 6-28. Negative Overload Recovery



$G = +1$, 10-mV step

图 6-29. Small-Signal Step Response

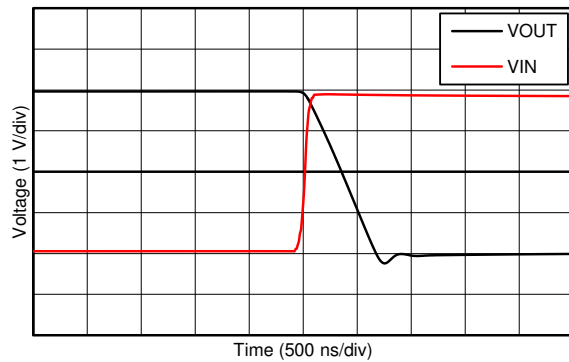


$G = -1$, 10-mV step

图 6-30. Small-Signal Step Response

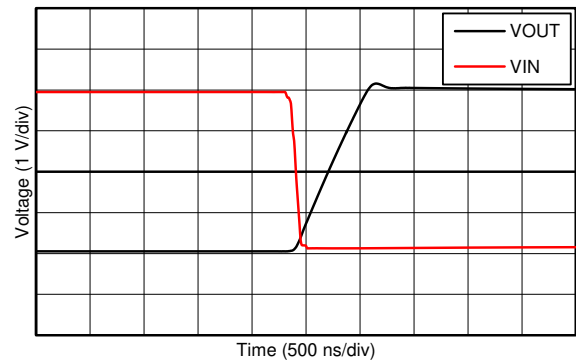
6.7 Typical Characteristics (continued)

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)



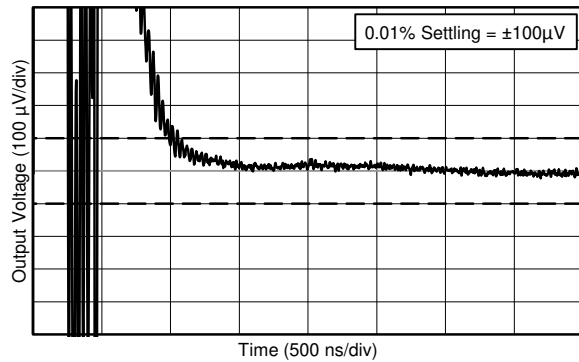
Falling output, 4-V Step

图 6-31. Large-Signal Step Response



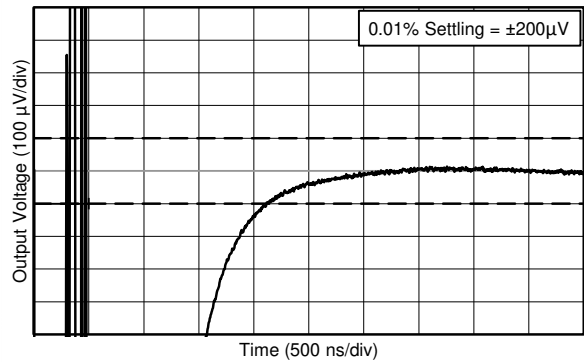
Rising output, 4-V step

图 6-32. Large-Signal Step Response



0.01% settling = $\pm 100\text{ }\mu\text{V}$, 1-V positive step

图 6-33. Settling Time



0.01% settling = $\pm 200\text{ }\mu\text{V}$, 1-V negative step

图 6-34. Settling Time

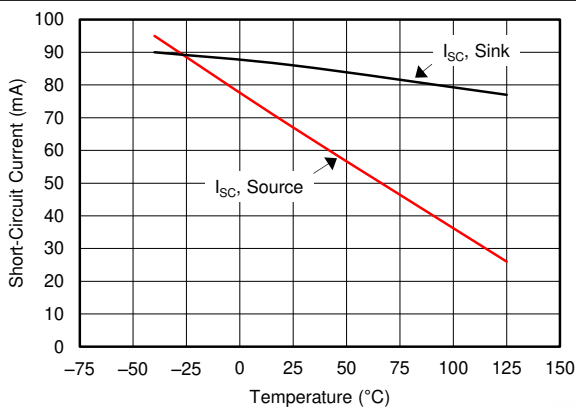


图 6-35. Short-Circuit Current vs Temperature

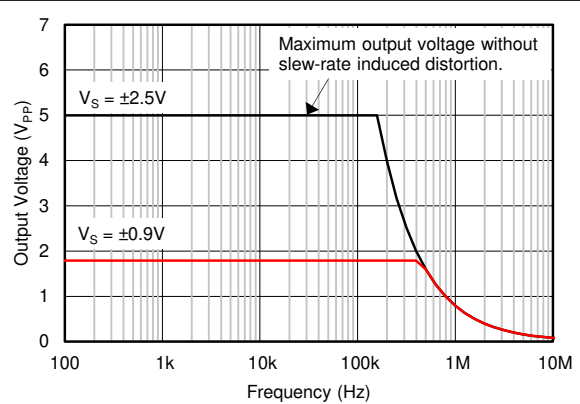


图 6-36. Maximum Output Voltage vs Frequency

6.7 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)

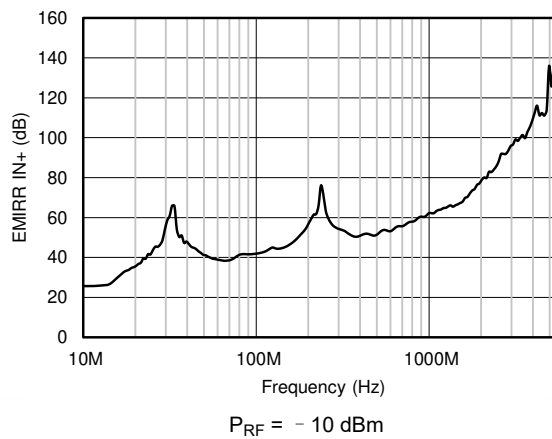


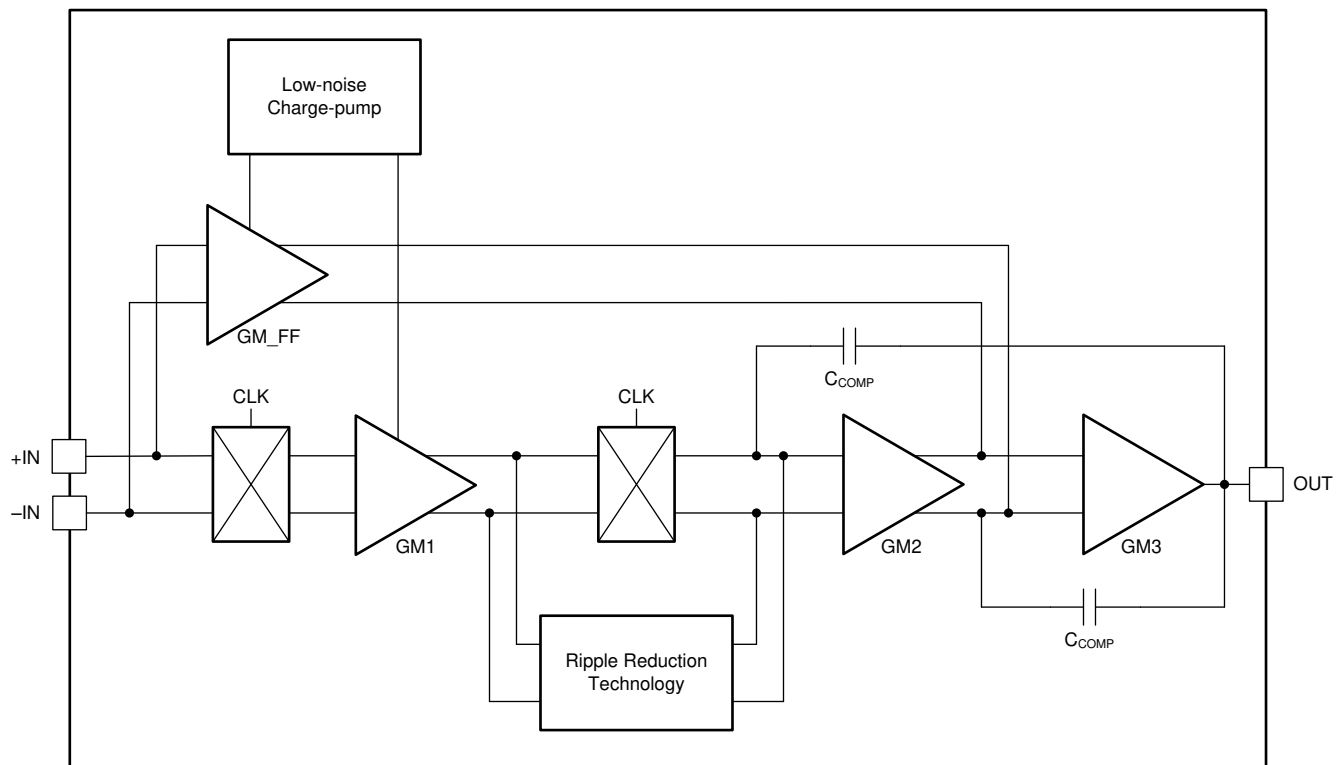
图 6-37. EMIRR vs Frequency

7 Detailed Description

7.1 Overview

The OPAx388-Q1 zero-drift amplifiers are 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 OPAx388-Q1 operate from 2.5 V to 5.5 V, are unity-gain stable, and are designed 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-Q1 strengths also include 10-MHz bandwidth, $7\text{-nV}/\sqrt{\text{Hz}}$ noise spectral density, and no $1/f$ noise, making these devices an excellent choice 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 Input Voltage and Zero-Crossover Functionality

The OPAx388-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. 图 7-1 and 图 7-2 contrast the performance of a traditional complementary rail-to-rail input stage amplifier with the performance of the zero-crossover OPAx388-Q1. Significant harmonic content and distortion is generated during the differential pair transition (such a transition does not exist in the OPAx388-Q1). Crossover distortion is eliminated through the use of a single differential pair coupled with an internal low-noise charge pump. The OPAx388-Q1 maintain 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.

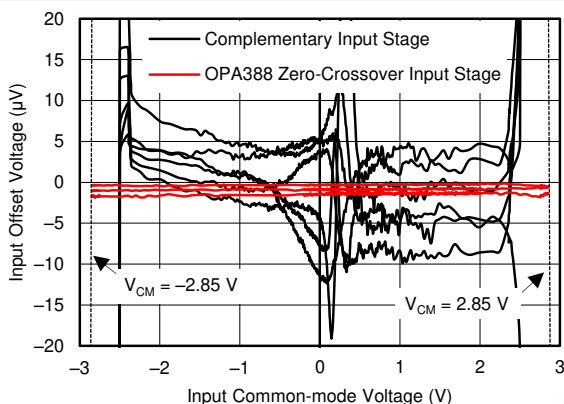


图 7-1. Input Crossover Distortion Nonlinearity

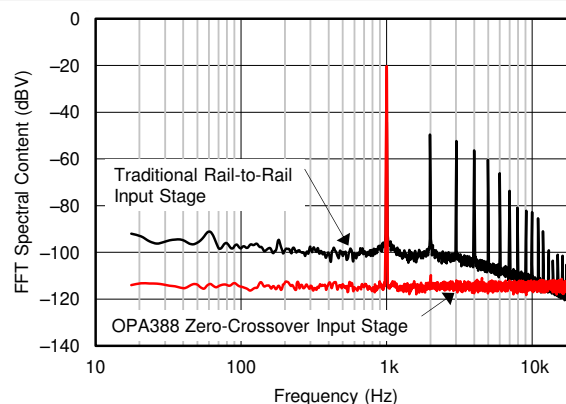
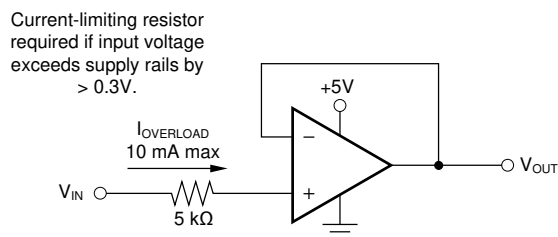


图 7-2. Input Crossover Distortion Spectral Content

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 图 7-3.



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图 7-3. Input Current Protection

7.3.2 Input Differential Voltage

The typical input bias current of the OPAx388-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 an 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-k Ω electromagnetic interference (EMI) filter resistors to create the equivalent circuit shown in 图 7-4. Notice that the input bias current remains within specification in the linear region.

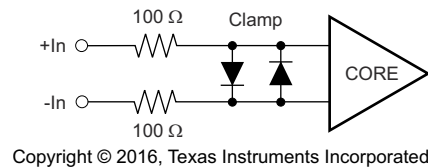


图 7-4. Equivalent Input Circuit

7.3.3 Internal Offset Correction

The OPAx388-Q1 operational amplifiers use an auto-calibration technique with a time-continuous, 200-kHz operational amplifier in the signal path. These amplifiers are zero-corrected every 5 μ s using a proprietary technique. At power up, the amplifiers require approximately 1 ms to achieve the specified V_{OS} accuracy. This design has no aliasing or flicker noise.

7.3.4 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-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 OPAx388-Q1 have a single functional mode and are operational when the power-supply voltage is greater than 2.5 V (± 1.25 V). The maximum specified power-supply voltage for the OPAx388-Q1 is 5.5 V (± 2.75 V).

8 Application and Implementation

备注

以下应用部分中的信息不属于 TI 器件规格的范围，TI 不担保其准确性和完整性。TI 的客户应负责确定器件是否适用于其应用。客户应验证并测试其设计，以确保系统功能。

8.1 Application Information

The OPAx388-Q1 are unity-gain stable, precision operational amplifiers 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-Q1 are 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-Q1 precision amplifiers are 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 design example detects load currents from -1 A to $+1\text{ A}$. 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.

图 8-1 shows the circuit drawing.

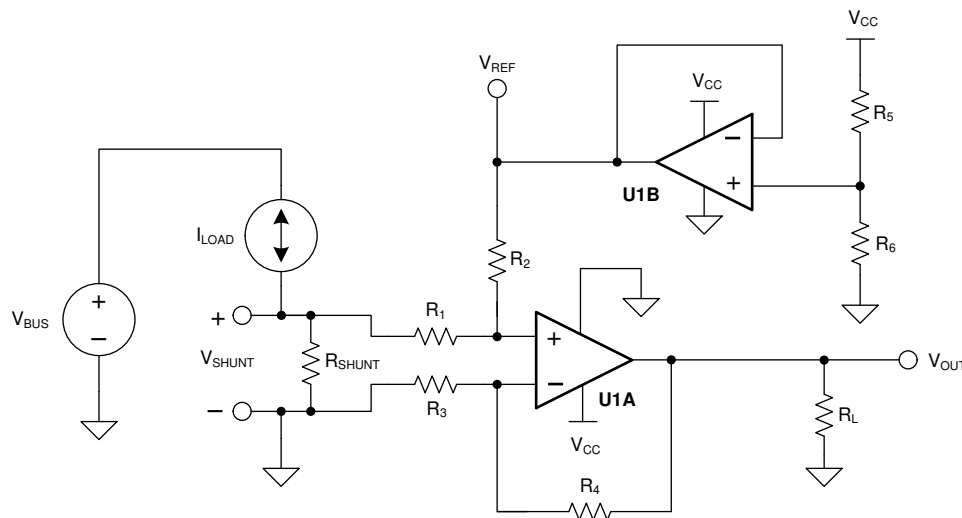


图 8-1. Bidirectional Current-Sensing

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 [方程式 1](#).

$$V_{OUT} = V_{SHUNT} \times \text{Gain}_{\text{Diff_Amp}} + V_{REF} \quad (1)$$

where

- $V_{SHUNT} = I_{LOAD} \times R_{SHUNT}$
- $\text{Gain}_{\text{Diff_Amp}} = \frac{R_4}{R_3}$
- $V_{REF} = V_{CC} \times \left(\frac{R_6}{R_5 + R_6} \right)$

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.

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

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. Make sure 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, 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 are 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.

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

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

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

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

The resistor value selected for R_1 and R_3 was $1 \text{ k}\Omega$. $15.4 \text{ k}\Omega$ 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

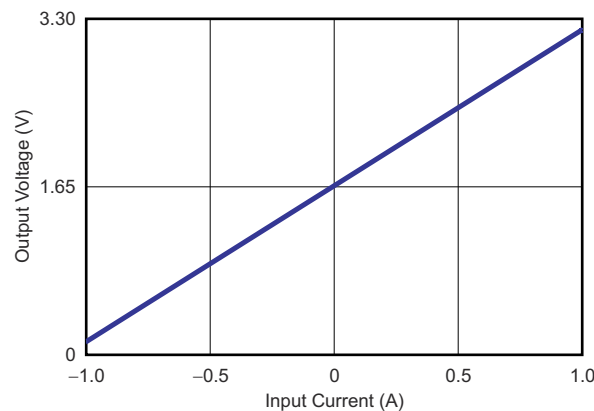


图 8-2. Bidirectional Current-Sensing Circuit Performance: Output Voltage vs Input Current

9 Power Supply Recommendations

The OPAx388-Q1 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 ($\pm 2.75\text{ V}$). Key parameters that vary over the supply voltage or temperature range are shown in [节 6.7](#).

CAUTION

Supply voltages greater than 7 V can permanently damage the device (see [节 6.1](#)).

10 Layout

10.1 Layout Guidelines

Pay attention to good layout practice. Keep traces short and, if possible, use a printed-circuit board (PCB) ground plane with surface-mount components placed as close as possible to the device pins. Place a $0.1\text{-}\mu\text{F}$ capacitor closely across the supply pins. Apply these guidelines 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, optimize the circuit layout and mechanical conditions. 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 making sure these potentials 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.

Follow these guidelines to reduce the likelihood of junctions being at different temperatures, which can cause thermoelectric voltage drift of $0.1\text{ }\mu\text{V}/^\circ\text{C}$ or greater, depending on the materials used.

10.2 Layout Example

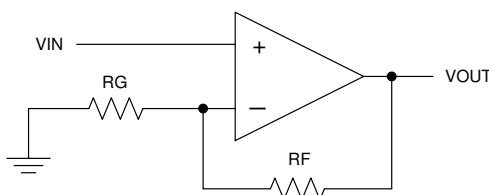


图 10-1. Schematic Representation

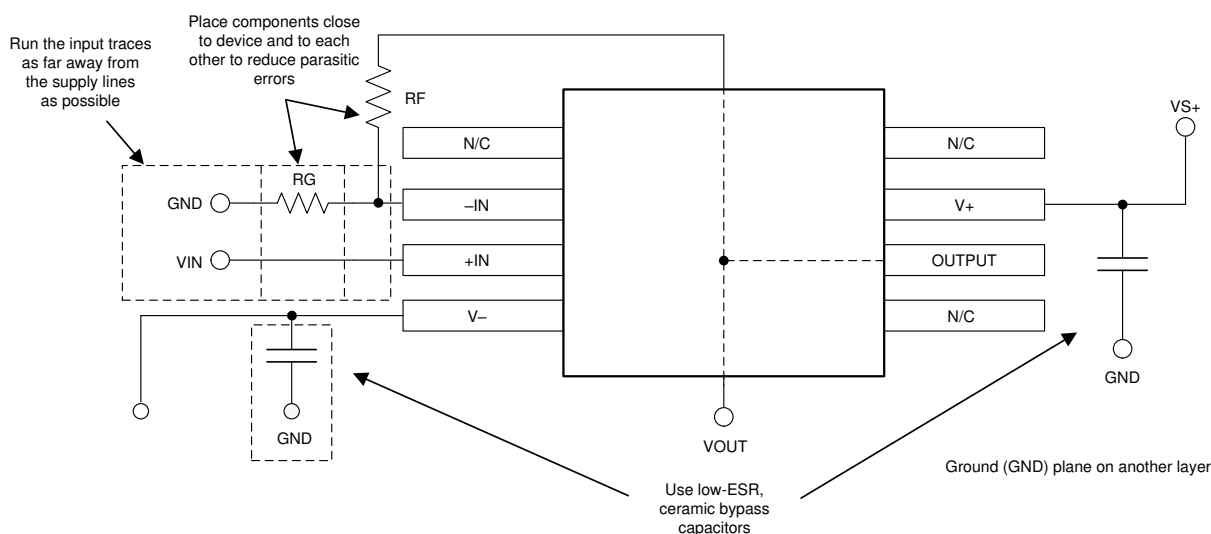


图 10-2. Layout Example

11 Device and Documentation Support

11.1 Device Support

11.1.1 Development Support

11.1.1.1 TINA-TI™ Simulation Software (Free Download)

TINA-TI™ simulation software is a simple, powerful, and easy-to-use circuit simulation program based on a SPICE engine. TINA-TI simulation software 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 simulation software 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 simulation software 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.

备注

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

11.1.1.2 PSpice® for TI

PSpice® for TI is a design and simulation environment that helps evaluate performance of analog circuits. Create subsystem designs and prototype solutions before committing to layout and fabrication, reducing development cost and time to market.

11.1.1.3 TI Precision Designs

The OPAx388-Q1 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: Texas Instruments, [Circuit board layout techniques](#)

11.3 接收文档更新通知

要接收文档更新通知，请导航至 ti.com 上的器件产品文件夹。点击 [订阅更新](#) 进行注册，即可每周接收产品信息更改摘要。有关更改的详细信息，请查看任何已修订文档中包含的修订历史记录。

11.4 支持资源

[TI E2E™ 支持论坛](#) 是工程师的重要参考资料，可直接从专家获得快速、经过验证的解答和设计帮助。搜索现有解答或提出自己的问题可获得所需的快速设计帮助。

链接的内容由各个贡献者“按原样”提供。这些内容并不构成 TI 技术规范，并且不一定反映 TI 的观点；请参阅 TI 的《使用条款》。

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11.6 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.

11.7 术语表

[TI 术语表](#) 本术语表列出并解释了术语、首字母缩略词和定义。

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 part number	Status (1)	Material type (2)	Package Pins	Package qty Carrier	RoHS (3)	Lead finish/ Ball material (4)	MSL rating/ Peak reflow (5)	Op temp (°C)	Part marking (6)
OPA2388QDGKRQ1	Active	Production	VSSOP (DGK) 8	2500 LARGE T&R	Yes	SN	Level-2-260C-1 YEAR	-40 to 125	O28Q
OPA2388QDGKRQ1.B	Active	Production	VSSOP (DGK) 8	2500 LARGE T&R	Yes	SN	Level-2-260C-1 YEAR	-40 to 125	O28Q
OPA388QDBVRQ1	Active	Production	SOT-23 (DBV) 5	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	388Q
OPA388QDBVRQ1.B	Active	Production	SOT-23 (DBV) 5	3000 LARGE T&R	Yes	NIPDAU	Level-2-260C-1 YEAR	-40 to 125	388Q

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

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

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

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

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

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

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

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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.

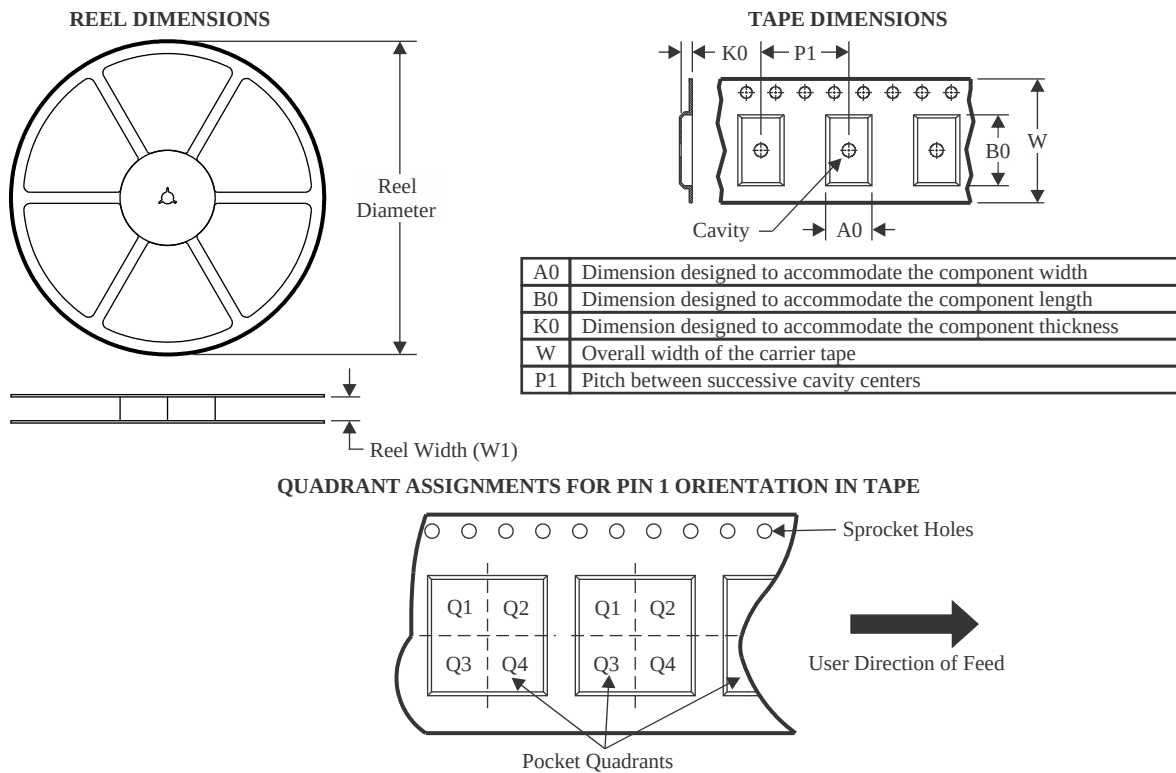
OTHER QUALIFIED VERSIONS OF OPA2388-Q1, OPA388-Q1 :

- Catalog : [OPA2388](#), [OPA388](#)

NOTE: Qualified Version Definitions:

- Catalog - TI's standard catalog product

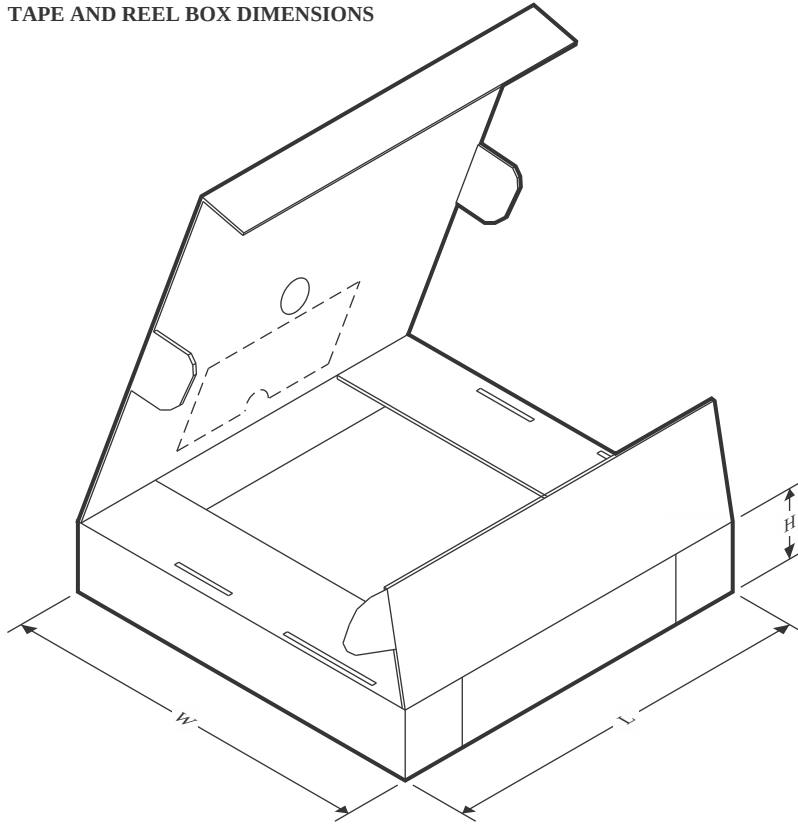
TAPE AND REEL INFORMATION



*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
OPA2388QDGKRQ1	VSSOP	DGK	8	2500	330.0	12.4	5.25	3.35	1.25	8.0	12.0	Q1
OPA388QDBVRQ1	SOT-23	DBV	5	3000	180.0	8.4	3.23	3.17	1.37	4.0	8.0	Q3

TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

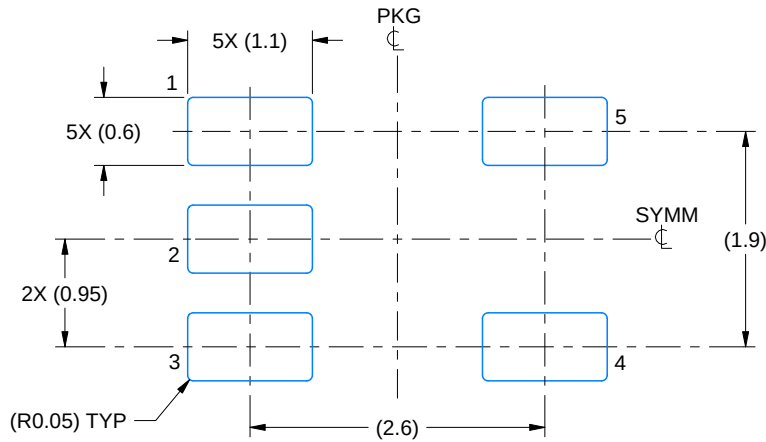
Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
OPA2388QDGKRQ1	VSSOP	DGK	8	2500	366.0	364.0	50.0
OPA388QDBVRQ1	SOT-23	DBV	5	3000	213.0	191.0	35.0

EXAMPLE BOARD LAYOUT

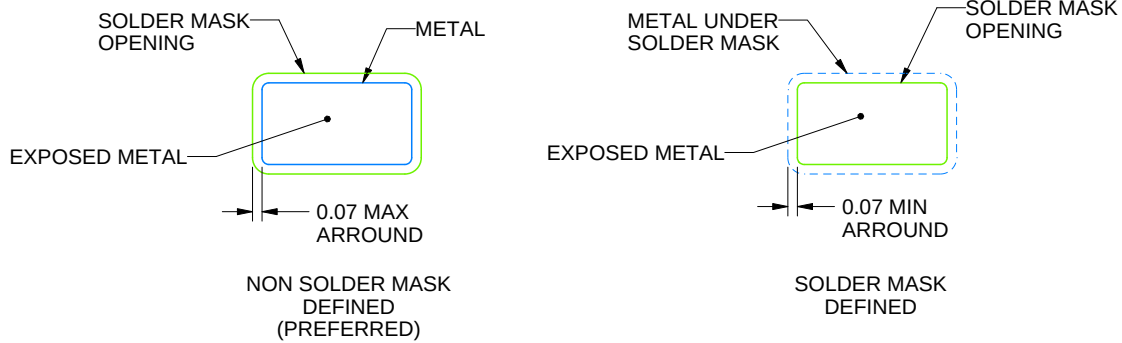
DBV0005A

SOT-23 - 1.45 mm max height

SMALL OUTLINE TRANSISTOR



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE:15X



SOLDER MASK DETAILS

4214839/K 08/2024

NOTES: (continued)

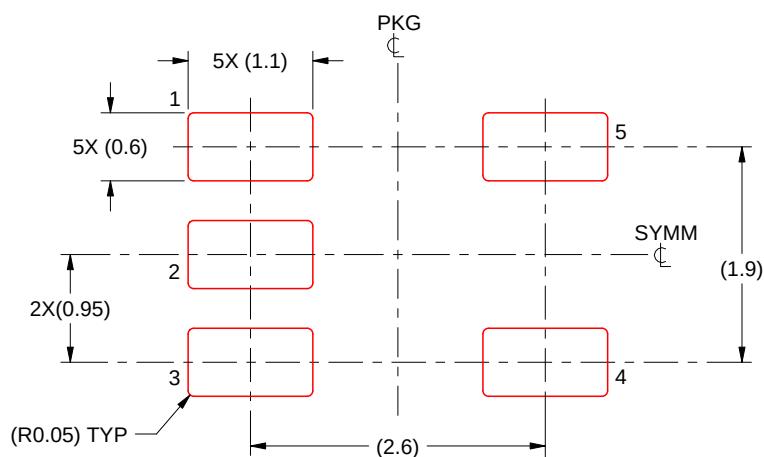
6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.

EXAMPLE STENCIL DESIGN

DBV0005A

SOT-23 - 1.45 mm max height

SMALL OUTLINE TRANSISTOR



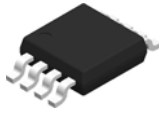
SOLDER PASTE EXAMPLE
BASED ON 0.125 mm THICK STENCIL
SCALE:15X

4214839/K 08/2024

NOTES: (continued)

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

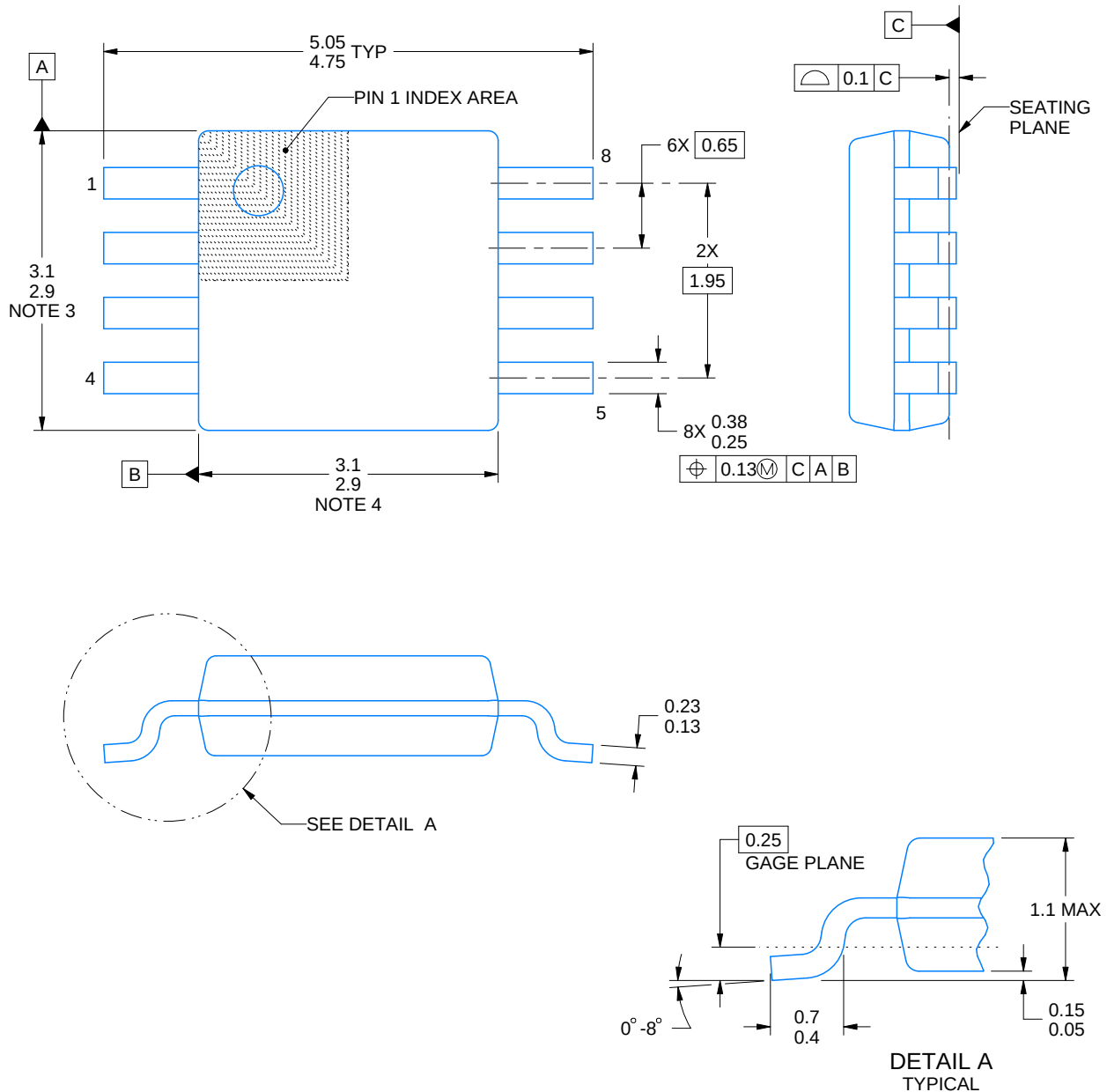
DGK0008A



PACKAGE OUTLINE

VSSOP - 1.1 mm max height

SMALL OUTLINE PACKAGE



4214862/A 04/2023

NOTES:

PowerPAD is a trademark of Texas Instruments.

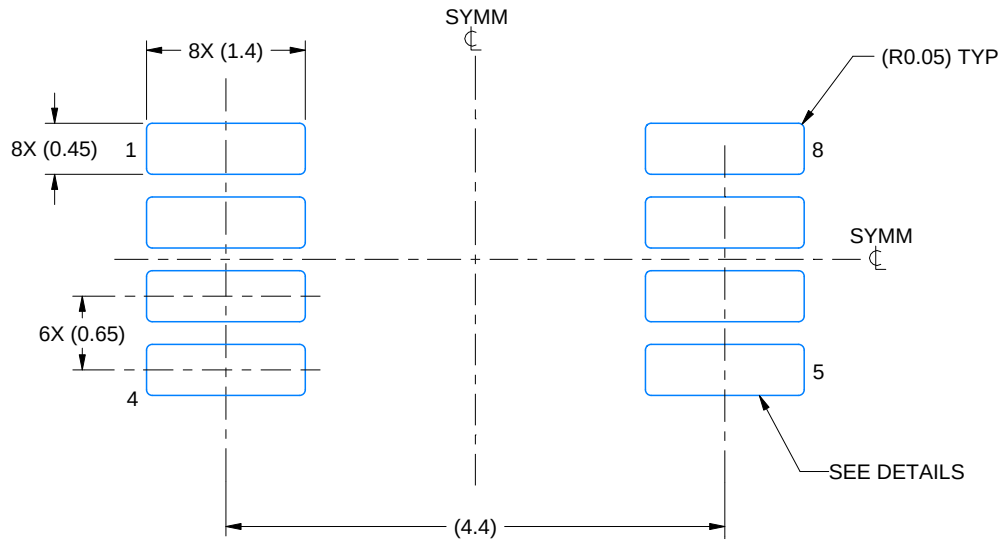
1. All linear dimensions are in millimeters. Any dimensions in parenthesis are for reference only. Dimensioning and tolerancing per ASME Y14.5M.
2. This drawing is subject to change without notice.
3. This dimension does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or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

EXAMPLE BOARD LAYOUT

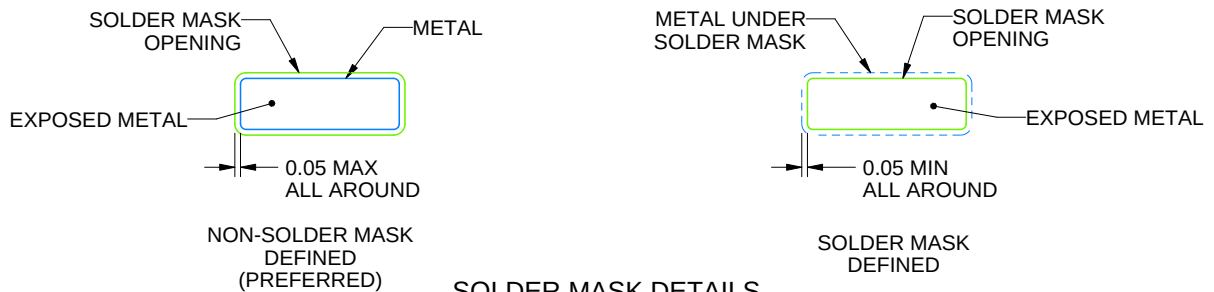
DGK0008A

TM VSSOP - 1.1 mm max height

SMALL OUTLINE PACKAGE



LAND PATTERN EXAMPLE
EXPOSED METAL SHOWN
SCALE: 15X



SOLDER MASK DETAILS

4214862/A 04/2023

NOTES: (continued)

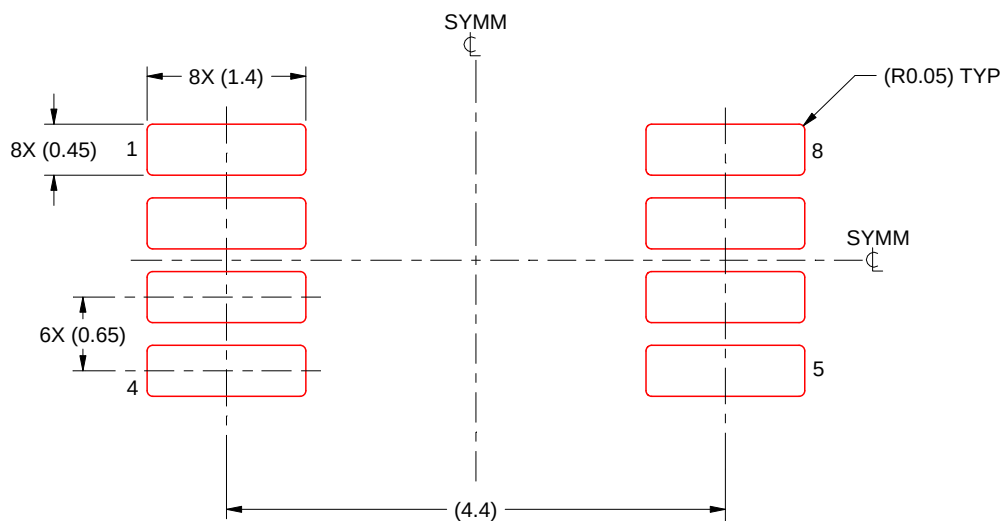
6. Publication IPC-7351 may have alternate designs.
7. Solder mask tolerances between and around signal pads can vary based on board fabrication site.
8. Vias are optional depending on application, refer to device data sheet. If any vias are implemented, refer to their locations shown on this view. It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

EXAMPLE STENCIL DESIGN

DGK0008A

TM VSSOP - 1.1 mm max height

SMALL OUTLINE PACKAGE



SOLDER PASTE EXAMPLE
SCALE: 15X

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NOTES: (continued)

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

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