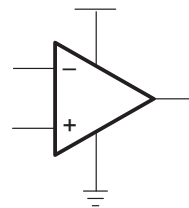


# TLV2401, TLV2402, TLV2404 FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION

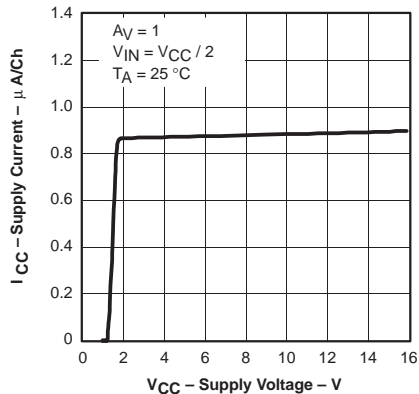
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- Micro-Power Operation . . .  $< 1 \mu\text{A}/\text{Channel}$
- Input Common-Mode Range Exceeds the Rails . . .  $-0.1 \text{ V}$  to  $V_{\text{CC}} + 5 \text{ V}$
- Reverse Battery Protection Up To 18 V
- Rail-to-Rail Input/Output
- Gain Bandwidth Product . . . 5.5 kHz
- Supply Voltage Range . . . 2.5 V to 16 V
- Specified Temperature Range
  - $T_{\text{A}} = 0^{\circ}\text{C}$  to  $70^{\circ}\text{C}$  . . . Commercial Grade
  - $T_{\text{A}} = -40^{\circ}\text{C}$  to  $125^{\circ}\text{C}$  . . . Industrial Grade
- Ultrasmall Packaging
  - 5-Pin SOT-23 (TLV2401)
  - 8-Pin MSOP (TLV2402)
- Universal OpAmp EVM (Refer to the EVM Selection Guide SLOU060)

Operational Amplifier



SUPPLY CURRENT  
vs  
SUPPLY VOLTAGE



## description

The TLV240x family of single-supply operational amplifiers has the lowest supply current available today at only 880 nA per channel. Reverse battery protection guards the amplifier from an over-current condition due to improper battery installation. For harsh environments, the inputs can be taken 5 V above the positive supply rail without damage to the device.

The low supply current is coupled with extremely low input bias currents enabling them to be used with mega- $\Omega$  resistors making them ideal for portable, long active life, applications. DC accuracy is ensured with a low typical offset voltage as low as 390  $\mu\text{V}$ , CMRR of 120 dB and minimum open loop gain of 130 V/mV at 2.7 V.

The maximum recommended supply voltage is as high as 16 V and ensured operation down to 2.5 V, with electrical characteristics specified at 2.7 V, 5 V and 15 V. The 2.5-V operation makes it compatible with Li-Ion battery-powered systems and many micro-power microcontrollers available today including TI's MSP430.

All members are available in PDIP and SOIC with the singles in the small SOT-23 package, duals in the MSOP, and quads in TSSOP.

### SELECTION OF SINGLE SUPPLY OPERATIONAL AMPLIFIER PRODUCTS†

DEVICE	$V_{\text{CC}}$ (V)	$V_{\text{IO}}$ (mV)	BW (MHz)	SLEW RATE (V/ $\mu\text{s}$ )	$I_{\text{CC}}/\text{ch}$ ( $\mu\text{A}$ )	RAIL-TO-RAIL
TLV240x‡	2.5–16	0.390	0.005	0.002	0.880	I/O
TLV224x	2.5–12	0.600	0.005	0.002	1	I/O
TLV2211	2.7–10	0.450	0.065	0.025	13	O
TLV245x	2.7–6	0.020	0.22	0.110	23	I/O
TLV225x	2.7–8	0.200	0.2	0.12	35	O

† All specifications are typical values measured at 5 V.

‡ This device also offers 18-V reverse battery protection and 5-V over-the-rail operation on the inputs.



Please be aware that an important notice concerning availability, standard warranty, and use in critical applications of Texas Instruments semiconductor products and disclaimers thereto appears at the end of this data sheet.

PRODUCTION DATA information is current as of publication date. Products conform to specifications per the terms of Texas Instruments standard warranty. Production processing does not necessarily include testing of all parameters.

**TEXAS  
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# TLV2401, TLV2402, TLV2404

## FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT

### OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION

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#### TLV2401 AVAILABLE OPTIONS

T <sub>A</sub>	V <sub>IOmax</sub> AT 25°C	PACKAGED DEVICES			
		SMALL OUTLINE† (D)	SOT-23† (DBV)	SYMBOLS	PLASTIC DIP (P)
0°C to 70°C	1500 μV	TLV2401CD	TLV2401CDBV	VAWC	—
-40°C to 125°C		TLV2401ID	TLV2401IDBV	VAWI	TLV2401IP

† This package is available taped and reeled. To order this packaging option, add an R suffix to the part number (e.g., TLV2401CDR).

#### TLV2402 AVAILABLE OPTIONS

T <sub>A</sub>	V <sub>IOmax</sub> AT 25°C	PACKAGED DEVICES			
		SMALL OUTLINE† (D)	MSOP† (DGK)	SYMBOLS	PLASTIC DIP (P)
0°C to 70°C	1500 μV	TLV2402CD	TLV2402CDGK	xxTIAIX	—
-40°C to 125°C		TLV2402ID	TLV2402IDGK	xxTIAIY	TLV2402IP

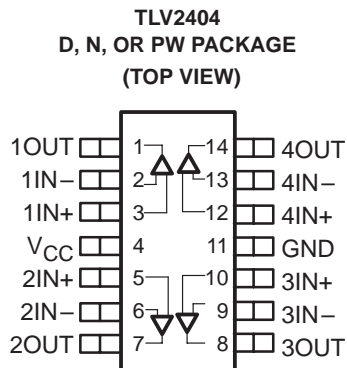
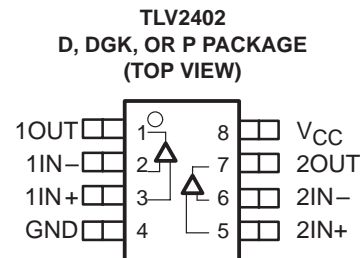
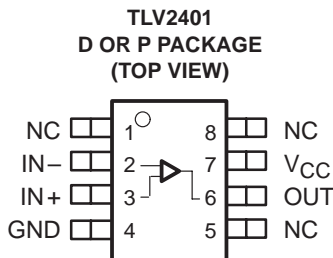
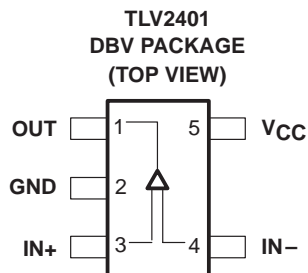
† This package is available taped and reeled. To order this packaging option, add an R suffix to the part number (e.g., TLV2402CDR).

#### TLV2404 AVAILABLE OPTIONS

T <sub>A</sub>	V <sub>IOmax</sub> AT 25°C	PACKAGED DEVICES		
		SMALL OUTLINE† (D)	PLASTIC DIP (N)	TSSOP (PW)
0°C to 70°C	1500 μV	TLV2404CD	TLV2404CN	TLV2404CPW
-40°C to 125°C		TLV2404ID	TLV2404IN	TLV2404IPW

† This package is available taped and reeled. To order this packaging option, add an R suffix to the part number (e.g., TLV2404CDR).

### TLV240x PACKAGE PINOUTS



NC – No internal connection



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**absolute maximum ratings over operating free-air temperature range (unless otherwise noted)†**

Supply voltage, $V_{CC}$ (see Note 1)	17 V
Differential input voltage range, $V_{ID}$	$\pm 20$ V
Input current range, $I_I$ (any input)	$\pm 10$ mA
Output current range, $I_O$	$\pm 10$ mA
Continuous total power dissipation	See Dissipation Rating Table
Operating free-air temperature range, $T_A$ : C suffix	$0^\circ\text{C}$ to $70^\circ\text{C}$
I suffix	$-40^\circ\text{C}$ to $125^\circ\text{C}$
Maximum junction temperature, $T_J$	$150^\circ\text{C}$
Storage temperature range, $T_{stg}$	$-65^\circ\text{C}$ to $150^\circ\text{C}$
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds	$260^\circ\text{C}$

† Stresses beyond those listed under “absolute maximum ratings” may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated under “recommended operating conditions” is not implied. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.

NOTE 1: All voltage values, except differential voltages, are with respect to GND

**DISSIPATION RATING TABLE**

PACKAGE	$\Theta_{JC}$ ( $^\circ\text{C}/\text{W}$ )	$\Theta_{JA}$ ( $^\circ\text{C}/\text{W}$ )	$T_A \leq 25^\circ\text{C}$ POWER RATING	$T_A = 125^\circ\text{C}$ POWER RATING
D (8)	38.3	176	710 mW	142 mW
D (14)	26.9	122.6	1022 mW	204.4 mW
DBV (5)	55	324.1	385 mW	77.1 mW
DGK (8)	54.2	259.9	481 mW	96.2 mW
N (14)	32	78	1600 mW	320.5 mW
P (8)	41	104	1200 mW	240.4 mW
PW (14)	29.3	173.6	720 mW	144 mW

**recommended operating conditions**

		MIN	MAX	UNIT
Supply voltage, $V_{CC}$	Single supply	2.5	16	V
	Split supply	$\pm 1.25$	$\pm 8$	
Common-mode input voltage range, $V_{ICR}$		-0.1	$V_{CC}+5$	V
Operating free-air temperature, $T_A$	C-suffix	0	70	$^\circ\text{C}$
	I-suffix	-40	125	

**TLV2401, TLV2402, TLV2404**  
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**electrical characteristics at recommended operating conditions,  $V_{CC} = 2.7, 5 \text{ V}$ , and  $15 \text{ V}$  (unless otherwise noted)**

**dc performance**

PARAMETER		TEST CONDITIONS	$T_A^\dagger$	MIN	TYP	MAX	UNIT
$V_{IO}$	Input offset voltage	$V_O = V_{CC}/2 \text{ V}$ , $V_{IC} = V_{CC}/2 \text{ V}$ , $R_S = 50 \Omega$	25°C	390	1200		$\mu\text{V}$
			Full range		1500		
$\alpha V_{IO}$	Offset voltage draft		25°C	3			$\mu\text{V}/^\circ\text{C}$
CMRR	Common-mode rejection ratio	$V_{IC} = 0 \text{ to } V_{CC}$ , $R_S = 50 \Omega$	$V_{CC} = 2.7 \text{ V}$	25°C	63	120	dB
				Full range	60		
			$V_{CC} = 5 \text{ V}$	25°C	70	120	
				Full range	63		
			$V_{CC} = 15 \text{ V}$	25°C	80	120	
				Full range	75		
AVD	Large-signal differential voltage amplification	$V_{CC} = 2.7 \text{ V}$ , $V_{O(pp)} = 1 \text{ V}$ , $R_L = 500 \text{ k}\Omega$	25°C	130	400	V/mV	
			Full range	30			
			$V_{CC} = 5 \text{ V}$ , $V_{O(pp)} = 3 \text{ V}$ , $R_L = 500 \text{ k}\Omega$	25°C	300		1000
				Full range	100		
			$V_{CC} = 15 \text{ V}$ , $V_{O(pp)} = 6 \text{ V}$ , $R_L = 500 \text{ k}\Omega$	25°C	1000		1800
				Full range	120		

$^\dagger$  Full range is 0°C to 70°C for the C suffix and -40°C to 125°C for the I suffix. If not specified, full range is -40°C to 125°C.

**input characteristics**

PARAMETER		TEST CONDITIONS	$T_A^\dagger$	MIN	TYP	MAX	UNIT	
$I_{IO}$	Input offset current	$V_O = V_{CC}/2 \text{ V}$ , $V_{IC} = V_{CC}/2 \text{ V}$ , $R_S = 50 \Omega$	25°C	25	250		pA	
			Full range	TLV240xC		300		
				TLV240xI		400		
$I_{IB}$	Input bias current	$V_O = V_{CC}/2 \text{ V}$ , $V_{IC} = V_{CC}/2 \text{ V}$ , $R_S = 50 \Omega$	25°C	100	300		pA	
			Full range	TLV240xC		350		
				TLV240xI		900		
$r_{i(d)}$	Differential input resistance		25°C	300		$\text{M}\Omega$		
$C_{i(c)}$	Common-mode input capacitance	$f = 100 \text{ kHz}$	25°C	3		pF		

$^\dagger$  Full range is 0°C to 70°C for the C suffix and -40°C to 125°C for the I suffix. If not specified, full range is -40°C to 125°C.



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electrical characteristics at recommended operating conditions,  $V_{CC} = 2.7, 5 \text{ V}$ , and  $15 \text{ V}$  (unless otherwise noted) (continued)

**output characteristics**

PARAMETER	TEST CONDITIONS	$T_A$ †	MIN	TYP	MAX	UNIT
$V_{OH}$ High-level output voltage	$V_{IC} = V_{CC}/2$ , $I_{OH} = -2 \mu\text{A}$	$V_{CC} = 2.7 \text{ V}$	25°C	2.65	2.68	V
			Full range	2.63		
		$V_{CC} = 5 \text{ V}$	25°C	4.95	4.98	
			Full range	4.93		
		$V_{CC} = 15 \text{ V}$	25°C	14.95	14.98	
			Full range	14.93		
	$V_{IC} = V_{CC}/2$ , $I_{OH} = -50 \mu\text{A}$	$V_{CC} = 2.7 \text{ V}$	25°C	2.62	2.65	
			Full range	2.6		
		$V_{CC} = 5 \text{ V}$	25°C	4.92	4.95	
			Full range	4.9		
		$V_{CC} = 15 \text{ V}$	25°C	14.92	14.95	
			Full range	14.9		
$V_{OL}$ Low-level output voltage	$V_{IC} = V_{CC}/2$ , $I_{OL} = 2 \mu\text{A}$	25°C		90	150	mV
		Full range			180	
	$V_{IC} = V_{CC}/2$ , $I_{OL} = 50 \mu\text{A}$	25°C		180	230	
		Full range			260	
$I_O$ Output current	$V_O = 0.5 \text{ V}$ from rail	25°C		$\pm 200$		$\mu\text{A}$

† Full range is 0°C to 70°C for the C suffix and -40°C to 125°C for the I suffix. If not specified, full range is -40°C to 125°C.

**power supply**

PARAMETER	TEST CONDITIONS	$T_A$ †	MIN	TYP	MAX	UNIT
$I_{CC}$ Supply current (per channel)	$V_O = V_{CC}/2$	$V_{CC} = 2.7 \text{ V}$ or $5 \text{ V}$	25°C	880	950	nA
			Full range		1290	
		$V_{CC} = 15 \text{ V}$	25°C	900	990	
			Full range		1350	
Reverse supply current	$V_{CC} = -18 \text{ V}$ , $V_{IN} = 0 \text{ V}$ , $V_O = \text{Open circuit}$	25°C		50	nA	
PSRR Power supply rejection ratio ( $\Delta V_{CC}/\Delta V_{IO}$ )	$V_{CC} = 2.7$ to $5 \text{ V}$ , $V_{IC} = V_{CC}/2 \text{ V}$ , No load,	TLV240xC	25°C	100	120	dB
			Full range	96		
		TLV240xI	Full range	85		dB
	$V_{CC} = 5$ to $15 \text{ V}$ , $V_{IC} = V_{CC}/2 \text{ V}$ , No load	25°C	100	120	dB	
		Full range	100			

† Full range is 0°C to 70°C for the C suffix and -40°C to 125°C for the I suffix. If not specified, full range is -40°C to 125°C.



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**electrical characteristics at recommended operating conditions,  $V_{CC} = 2.7, 5 \text{ V}$ , and  $15 \text{ V}$  (unless otherwise noted) (continued)**

**dynamic performance**

PARAMETER		TEST CONDITIONS		$T_A$	MIN	TYP	MAX	UNIT
UGBW	Unity gain bandwidth	$R_L = 500 \text{ k}\Omega$ ,	$C_L = 100 \text{ pF}$	$25^\circ\text{C}$		5.5		kHz
SR	Slew rate at unity gain	$V_{O(pp)} = 0.8 \text{ V}$ ,	$R_L = 500 \text{ k}\Omega$ , $C_L = 100 \text{ pF}$	$25^\circ\text{C}$		2.5		V/ms
$\phi M$	Phase margin	$R_L = 500 \text{ k}\Omega$ , $C_L = 100 \text{ pF}$		$25^\circ\text{C}$	60°			
	Gain margin				15			dB
$t_s$	Settling time	$V_{CC} = 2.7 \text{ or } 5 \text{ V}$ , $V(\text{STEP})_{PP} = 1 \text{ V}$ , $C_L = 100 \text{ pF}$ , $A_V = -1$ , $R_L = 100 \text{ k}\Omega$		$25^\circ\text{C}$	0.1%			ms
		$V_{CC} = 15 \text{ V}$ , $V(\text{STEP})_{PP} = 1 \text{ V}$ , $C_L = 100 \text{ pF}$ , $A_V = -1$ , $R_L = 100 \text{ k}\Omega$			0.1%			
		$V_{CC} = 15 \text{ V}$ , $V(\text{STEP})_{PP} = 1 \text{ V}$ , $C_L = 100 \text{ pF}$ , $A_V = -1$ , $R_L = 100 \text{ k}\Omega$			0.01%			

**noise/distortion performance**

PARAMETER		TEST CONDITIONS	$T_A$	MIN	TYP	MAX	UNIT
$V_n$	Equivalent input noise voltage	$f = 10 \text{ Hz}$	$25^\circ\text{C}$	800			$\text{nV}/\sqrt{\text{Hz}}$
		$f = 100 \text{ Hz}$		500			
$I_n$	Equivalent input noise current	$f = 100 \text{ Hz}$		8			$\text{fA}/\sqrt{\text{Hz}}$



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**TYPICAL CHARACTERISTICS**

**Table of Graphs**

			<b>FIGURE</b>
$V_{IO}$	Input Offset Voltage	vs Common-mode input voltage	1, 2, 3
$I_{IB}$	Input Bias Current	vs Free-air temperature	4, 6, 8
		vs Common-mode input voltage	5, 7, 9
$I_{IO}$	Input Offset Current	vs Free-air temperature	4, 6, 8
		vs Common-mode input voltage	5, 7, 9
CMRR	Common-mode rejection ratio	vs Frequency	10
$V_{OH}$	High-level output voltage	vs High-level output current	11, 13, 15
$V_{OL}$	Low-level output voltage	vs Low-level output current	12, 14, 16
$V_{O(PP)}$	Output voltage peak-to-peak	vs Frequency	17
$Z_o$	Output impedance	vs Frequency	18
$I_{CC}$	Supply current	vs Supply voltage	19
PSRR	Power supply rejection ratio	vs Frequency	20
$A_{VD}$	Differential voltage gain	vs Frequency	21
	Phase	vs Frequency	21
	Gain-bandwidth product	vs Supply voltage	22
SR	Slew rate	vs Free-air temperature	23
$\phi_m$	Phase margin	vs Capacitive load	24
	Gain margin	vs Capacitive load	25
	Supply current	vs Reverse voltage	26
	Voltage noise over a 10 Second Period		27
	Large signal follower pulse response		28, 29, 30
	Small signal follower pulse response		31
	Large signal inverting pulse response		32, 33, 34
	Small signal inverting pulse response		35
	Crosstalk	vs Frequency	36

# TLV2401, TLV2402, TLV2404

## FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT

### OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION

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#### TYPICAL CHARACTERISTICS

**INPUT OFFSET VOLTAGE**  
vs  
**COMMON-MODE INPUT VOLTAGE**

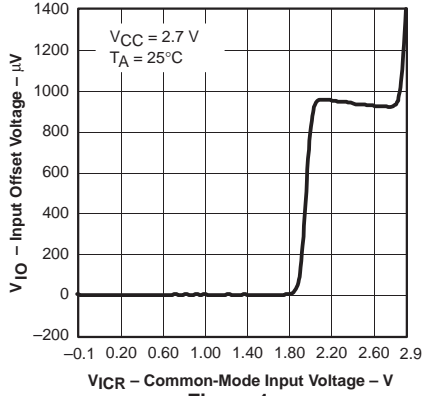


Figure 1

**INPUT OFFSET VOLTAGE**  
vs  
**COMMON-MODE INPUT VOLTAGE**

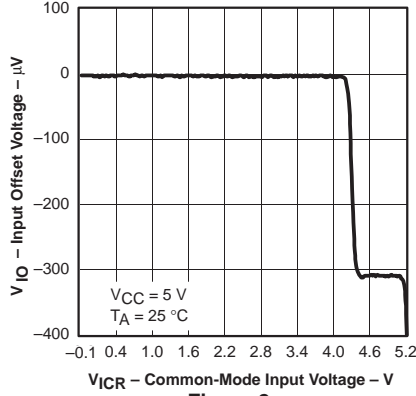


Figure 2

**INPUT OFFSET VOLTAGE**  
vs  
**COMMON-MODE INPUT VOLTAGE**

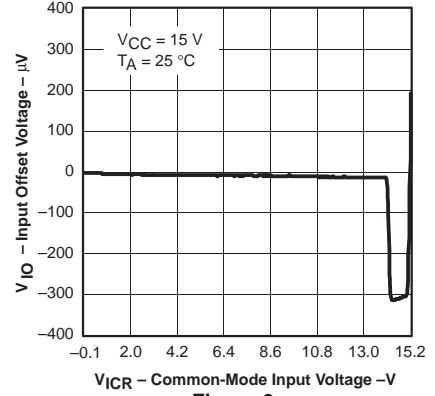


Figure 3

**INPUT BIAS / OFFSET CURRENT**  
vs  
**FREE-AIR TEMPERATURE**

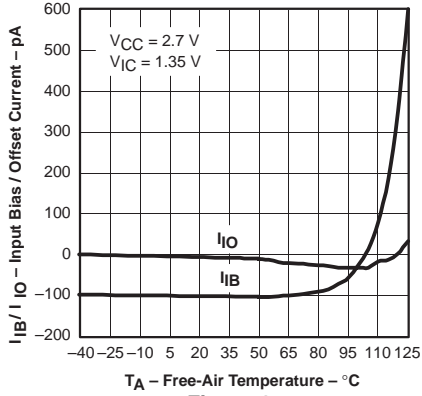


Figure 4

**INPUT BIAS / OFFSET CURRENT**  
vs  
**COMMON MODE INPUT VOLTAGE**

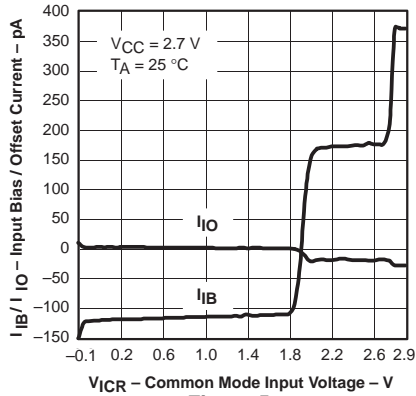


Figure 5

**INPUT BIAS / OFFSET CURRENT**  
vs  
**FREE-AIR TEMPERATURE**

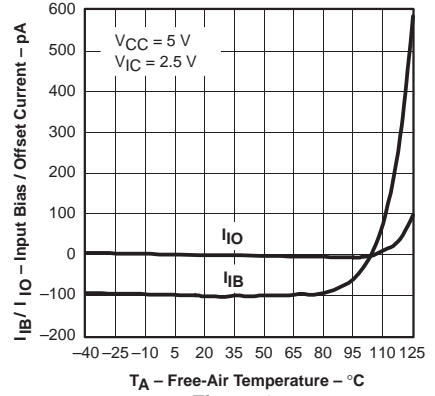


Figure 6

**INPUT BIAS / OFFSET CURRENT**  
vs  
**COMMON-MODE INPUT VOLTAGE**

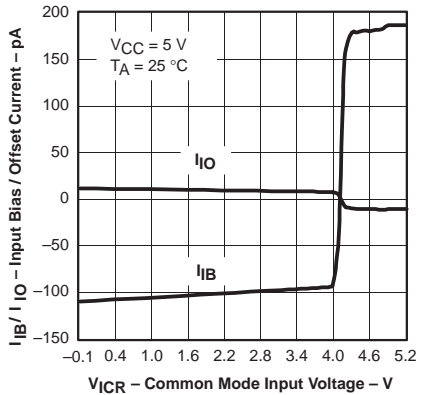


Figure 7

**INPUT BIAS / OFFSET CURRENT**  
vs  
**FREE-AIR TEMPERATURE**

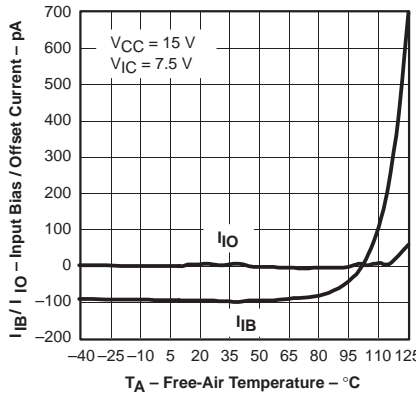


Figure 8

**INPUT BIAS / OFFSET CURRENT**  
vs  
**COMMON-MODE INPUT VOLTAGE**

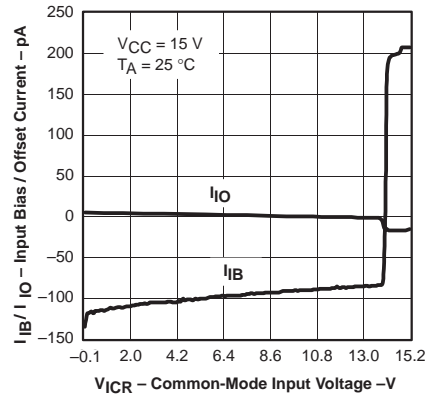


Figure 9





# TLV2401, TLV2402, TLV2404 FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION

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## TYPICAL CHARACTERISTICS

**COMMON-MODE REJECTION RATIO  
vs  
FREQUENCY**

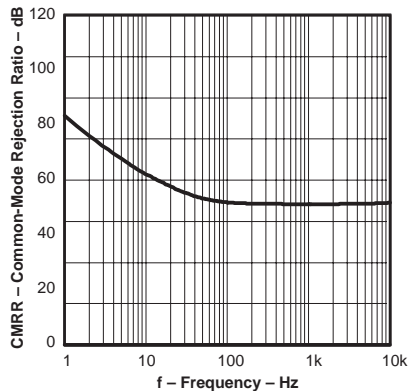


Figure 10

**HIGH-LEVEL OUTPUT VOLTAGE  
vs  
HIGH-LEVEL OUTPUT CURRENT**

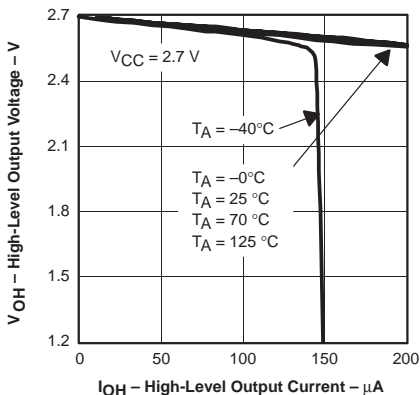


Figure 11

**LOW-LEVEL OUTPUT VOLTAGE  
vs  
LOW-LEVEL OUTPUT CURRENT**

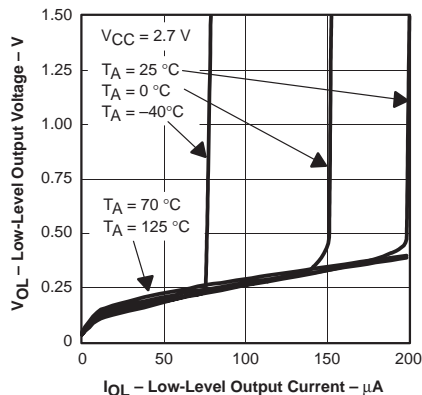


Figure 12

**HIGH-LEVEL OUTPUT VOLTAGE  
vs  
HIGH-LEVEL OUTPUT CURRENT**

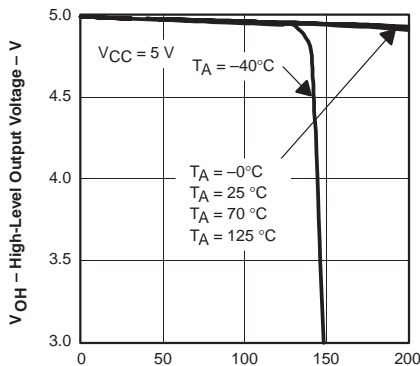


Figure 13

**LOW-LEVEL OUTPUT VOLTAGE  
vs  
LOW-LEVEL OUTPUT CURRENT**

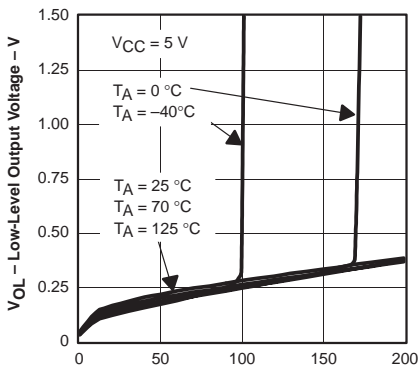


Figure 14

**HIGH-LEVEL OUTPUT VOLTAGE  
vs  
HIGH-LEVEL OUTPUT CURRENT**

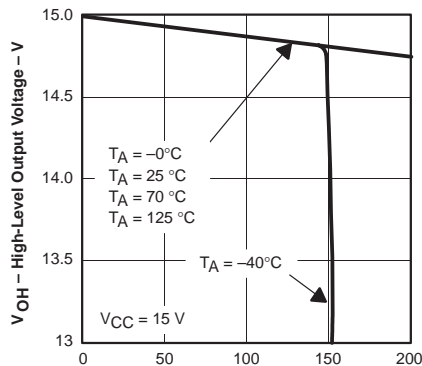


Figure 15

**LOW-LEVEL OUTPUT VOLTAGE  
vs  
LOW-LEVEL OUTPUT CURRENT**

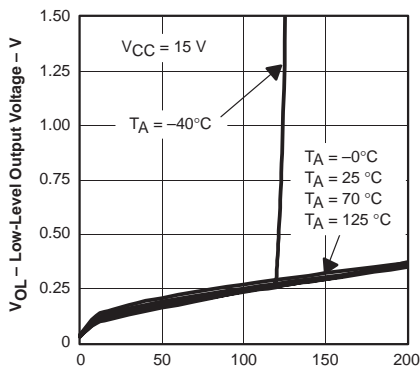


Figure 16

**OUTPUT VOLTAGE  
PEAK-TO-PEAK  
vs  
FREQUENCY**

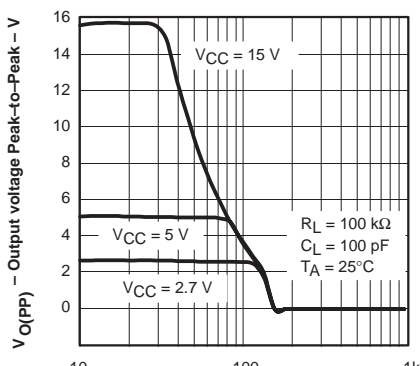


Figure 17

**OUTPUT IMPEDANCE  
vs  
FREQUENCY**

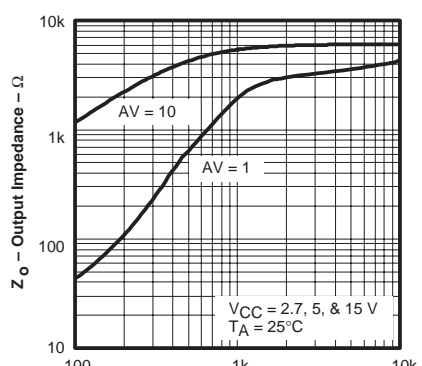


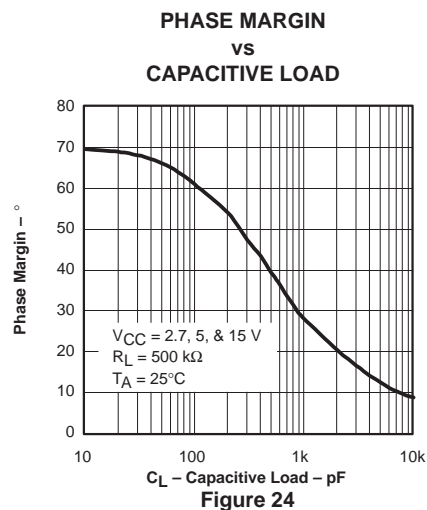
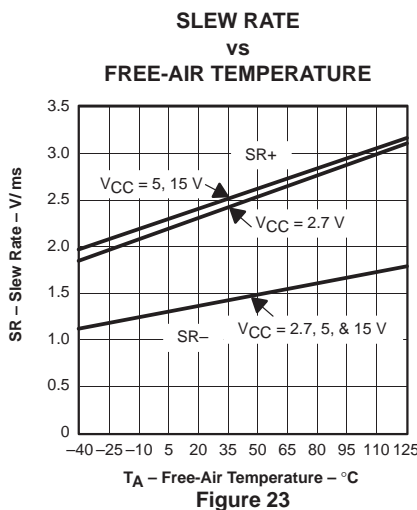
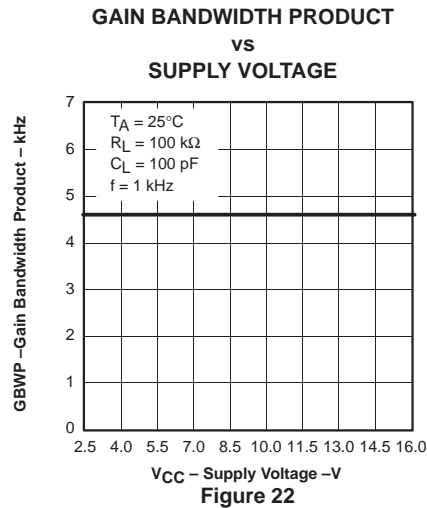
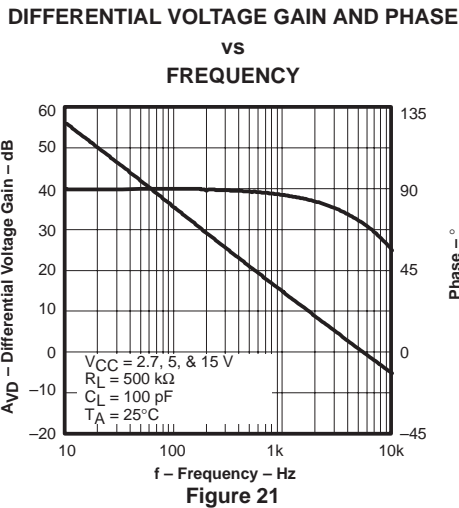
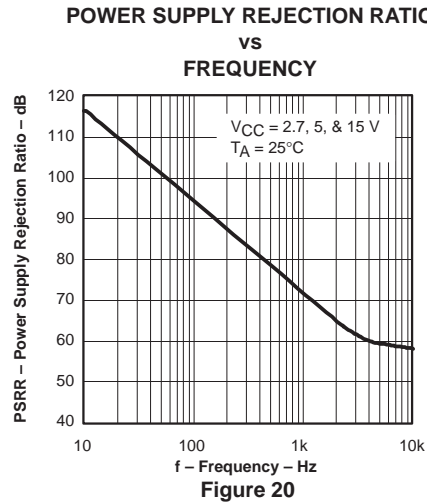
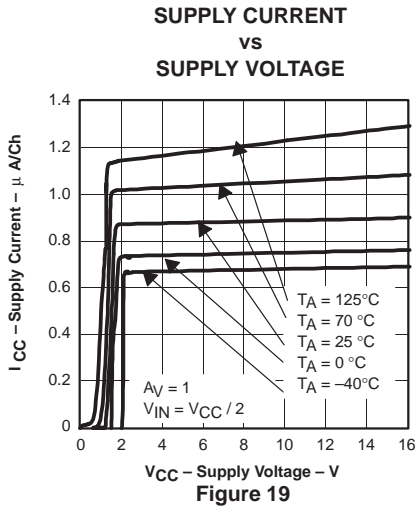
Figure 18



**TLV2401, TLV2402, TLV2404**  
**FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT**  
**OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION**

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**TYPICAL CHARACTERISTICS**



**TLV2401, TLV2402, TLV2404**  
**FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT**  
**OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION**

SLOS244B – FEBRUARY 2000 – REVISED NOVEMBER 2000

**TYPICAL CHARACTERISTICS**

**GAIN MARGIN  
VS  
CAPACITIVE LOAD**

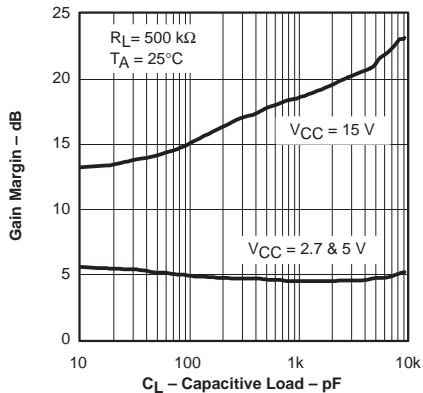


Figure 25

**SUPPLY CURRENT  
VS  
REVERSE VOLTAGE**

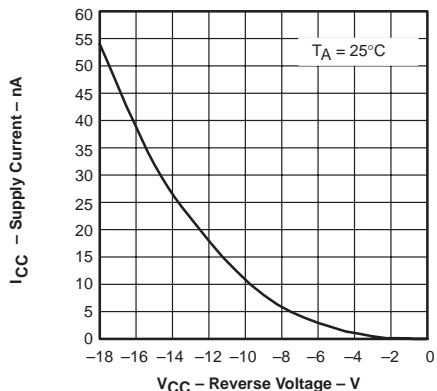


Figure 26

**VOLTAGE NOISE  
OVER A 10 SECOND PERIOD**

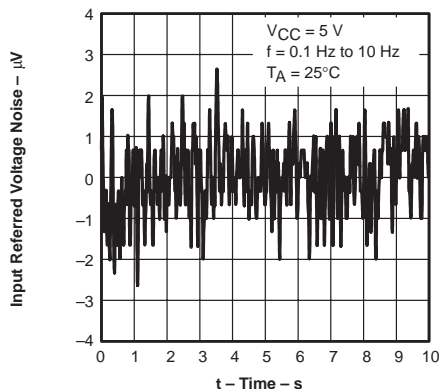


Figure 27

**LARGE SIGNAL FOLLOWER  
PULSE RESPONSE**

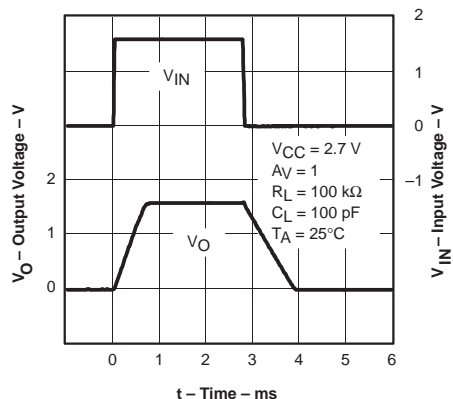


Figure 28

**LARGE SIGNAL FOLLOWER  
PULSE RESPONSE**

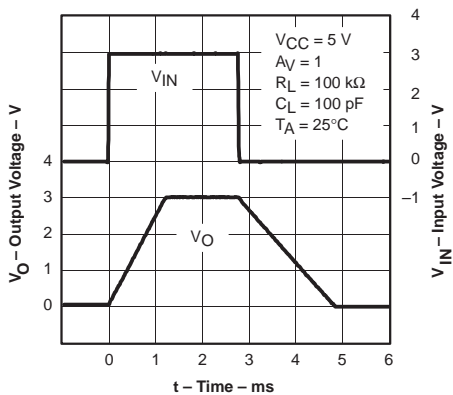


Figure 29

**LARGE SIGNAL FOLLOWER  
PULSE RESPONSE**

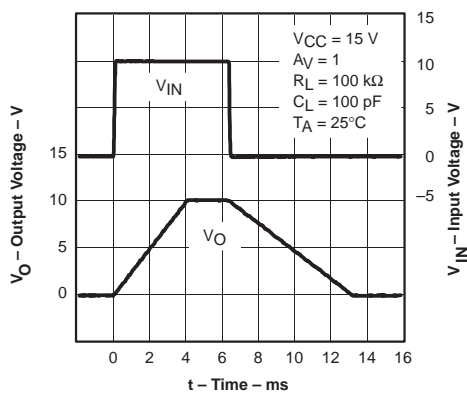


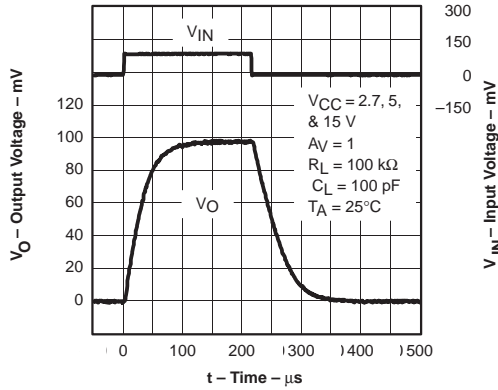
Figure 30

**TLV2401, TLV2402, TLV2404**  
**FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT**  
**OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION**

SLOS244B – FEBRUARY 2000 – REVISED NOVEMBER 2000

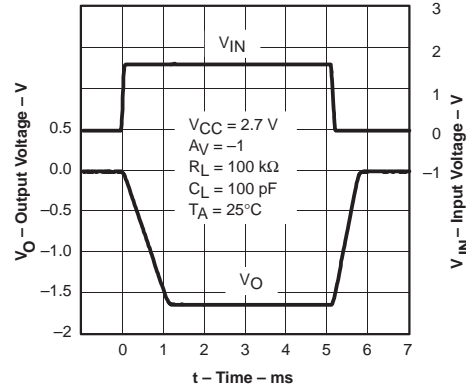
**TYPICAL CHARACTERISTICS**

**SMALL SIGNAL FOLLOWER PULSE RESPONSE**



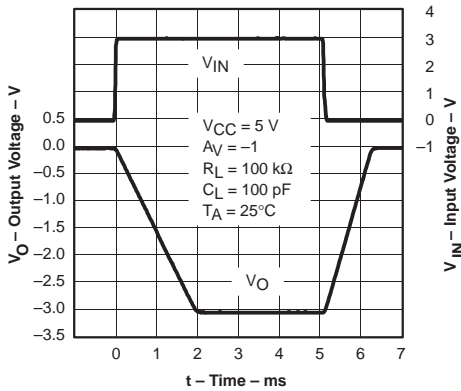
**Figure 31**

**LARGE SIGNAL INVERTING PULSE RESPONSE**



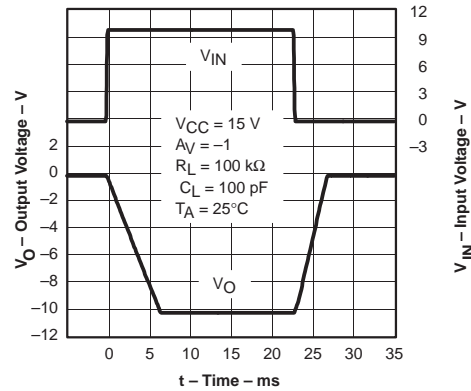
**Figure 32**

**LARGE SIGNAL INVERTING PULSE RESPONSE**



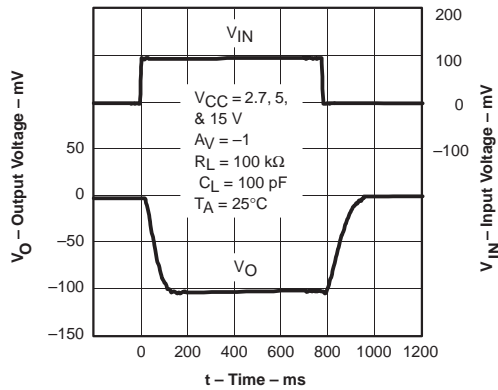
**Figure 33**

**LARGE SIGNAL INVERTING PULSE RESPONSE**



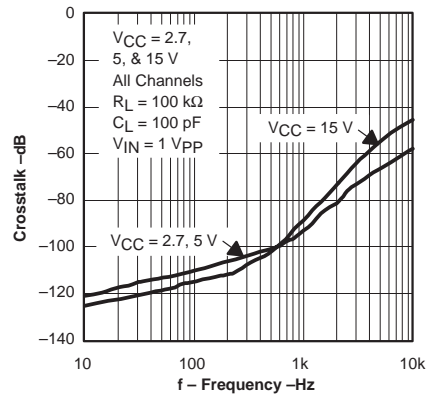
**Figure 34**

**SMALL SIGNAL INVERTING PULSE RESPONSE**



**Figure 35**

**CROSSTALK vs FREQUENCY**



**Figure 36**

## APPLICATION INFORMATION

### reverse battery protection

The TLV2401/2/4 are protected against reverse battery voltage up to 18 V. When subjected to reverse battery condition the supply current is typically less than 100 nA at 25°C (inputs grounded and outputs open). This current is determined by the leakage of 6 Schottky diodes and will therefore increase as the ambient temperature increases.

When subjected to reverse battery conditions and negative voltages applied to the inputs or outputs, the input ESD structure will turn on—this current should be limited to less than 10 mA. If the inputs or outputs are referred to ground, rather than midrail, no extra precautions need be taken.

### common-mode input range

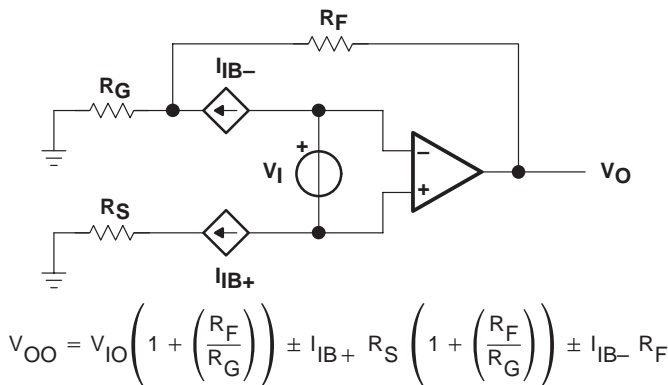
The TLV2401/2/4 has rail-to-rail input and outputs. For common-mode inputs from  $-0.1\text{ V}$  to  $V_{CC} - 0.8\text{ V}$  a PNP differential pair will provide the gain.

For inputs between  $V_{CC} - 0.8\text{ V}$  and  $V_{CC}$ , two NPN emitter followers buffering a second PNP differential pair provide the gain. This special combination of NPN/PNP differential pair enables the inputs to be taken 5 V above the rails, because as the inputs go above  $V_{CC}$ , the NPNs switch from functioning as transistors to functioning as diodes. This will lead to an increase in input bias current. The second PNP differential pair continues to function normally as the inputs exceed  $V_{CC}$ .

The TLV2401/2/4 has a negative common-input range that exceeds ground by 100 mV. If the inputs are taken much below this, reduced open loop gain will be observed with the ultimate possibility of phase inversion.

### offset voltage

The output offset voltage, ( $V_{OO}$ ) is the sum of the input offset voltage ( $V_{IO}$ ) and both input bias currents ( $I_{IB}$ ) times the corresponding gains. The following schematic and formula can be used to calculate the output offset voltage:



**Figure 37. Output Offset Voltage Model**

APPLICATION INFORMATION

general configurations

When receiving low-level signals, limiting the bandwidth of the incoming signals into the system is often required. The simplest way to accomplish this is to place an RC filter at the noninverting terminal of the amplifier (see Figure 38).

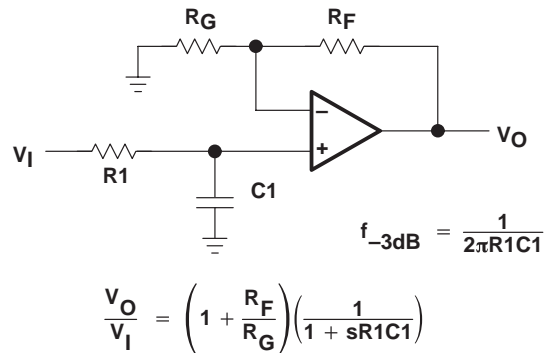


Figure 38. Single-Pole Low-Pass Filter

If even more attenuation is needed, a multiple pole filter is required. The Sallen-Key filter can be used for this task. For best results, the amplifier should have a bandwidth that is 8 to 10 times the filter frequency bandwidth. Failure to do this can result in phase shift of the amplifier.

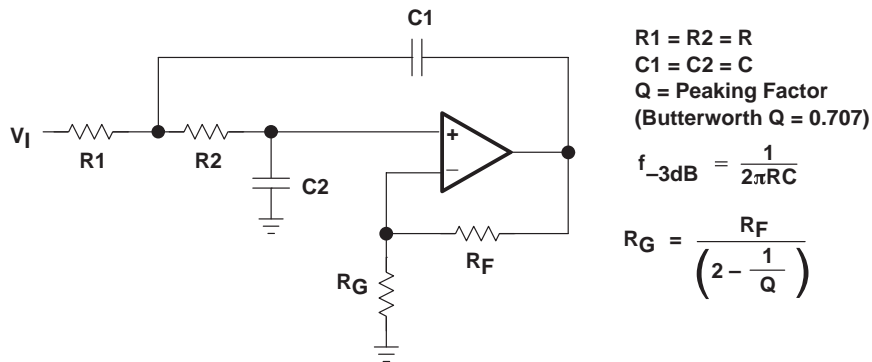


Figure 39. 2-Pole Low-Pass Sallen-Key Filter

## APPLICATION INFORMATION

### circuit layout considerations

To achieve the levels of high performance of the TLV240x, follow proper printed-circuit board design techniques. A general set of guidelines is given in the following.

- Ground planes – It is highly recommended that a ground plane be used on the board to provide all components with a low inductive ground connection. However, in the areas of the amplifier inputs and output, the ground plane can be removed to minimize the stray capacitance.
- Proper power supply decoupling – Use a 6.8- $\mu$ F tantalum capacitor in parallel with a 0.1- $\mu$ F ceramic capacitor on each supply terminal. It may be possible to share the tantalum among several amplifiers depending on the application, but a 0.1- $\mu$ F ceramic capacitor should always be used on the supply terminal of every amplifier. In addition, the 0.1- $\mu$ F capacitor should be placed as close as possible to the supply terminal. As this distance increases, the inductance in the connecting trace makes the capacitor less effective. The designer should strive for distances of less than 0.1 inches between the device power terminals and the ceramic capacitors.
- Sockets – Sockets can be used but are not recommended. The additional lead inductance in the socket pins will often lead to stability problems. Surface-mount packages soldered directly to the printed-circuit board is the best implementation.
- Short trace runs/compact part placements – Optimum high performance is achieved when stray series inductance has been minimized. To realize this, the circuit layout should be made as compact as possible, thereby minimizing the length of all trace runs. Particular attention should be paid to the inverting input of the amplifier. Its length should be kept as short as possible. This will help to minimize stray capacitance at the input of the amplifier.
- Surface-mount passive components – Using surface-mount passive components is recommended for high performance amplifier circuits for several reasons. First, because of the extremely low lead inductance of surface-mount components, the problem with stray series inductance is greatly reduced. Second, the small size of surface-mount components naturally leads to a more compact layout thereby minimizing both stray inductance and capacitance. If leaded components are used, it is recommended that the lead lengths be kept as short as possible.

**TLV2401, TLV2402, TLV2404**  
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**APPLICATION INFORMATION**

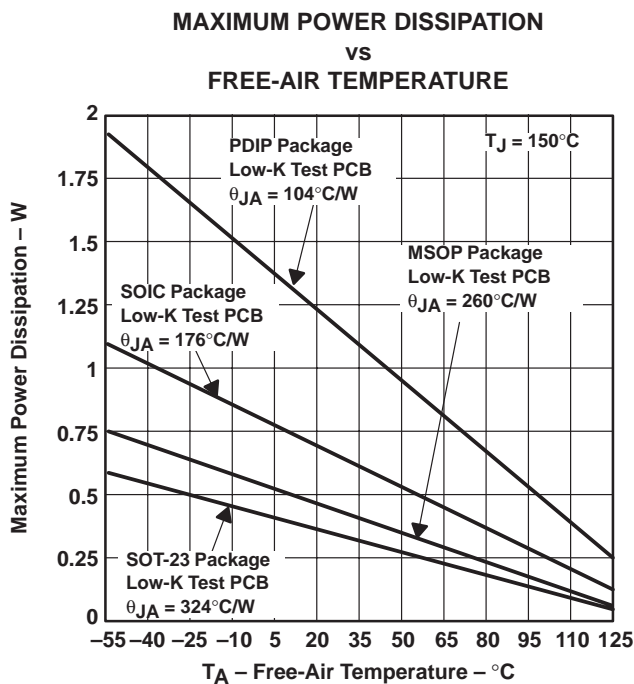
**general power dissipation considerations**

For a given  $\theta_{JA}$ , the maximum power dissipation is shown in Figure 40 and is calculated by the following formula:

$$P_D = \left( \frac{T_{MAX} - T_A}{\theta_{JA}} \right)$$

Where:

- $P_D$  = Maximum power dissipation of THS240x IC (watts)
- $T_{MAX}$  = Absolute maximum junction temperature (150°C)
- $T_A$  = Free-ambient air temperature (°C)
- $\theta_{JA}$  =  $\theta_{JC} + \theta_{CA}$
- $\theta_{JC}$  = Thermal coefficient from junction to case
- $\theta_{CA}$  = Thermal coefficient from case to ambient air (°C/W)



NOTE A: Results are with no air flow and using JEDEC Standard Low-K test PCB.

**Figure 40. Maximum Power Dissipation vs Free-Air Temperature**





# TLV2401, TLV2402, TLV2404 FAMILY OF 880-nA/Ch RAIL-TO-RAIL INPUT/OUTPUT OPERATIONAL AMPLIFIERS WITH REVERSE BATTERY PROTECTION

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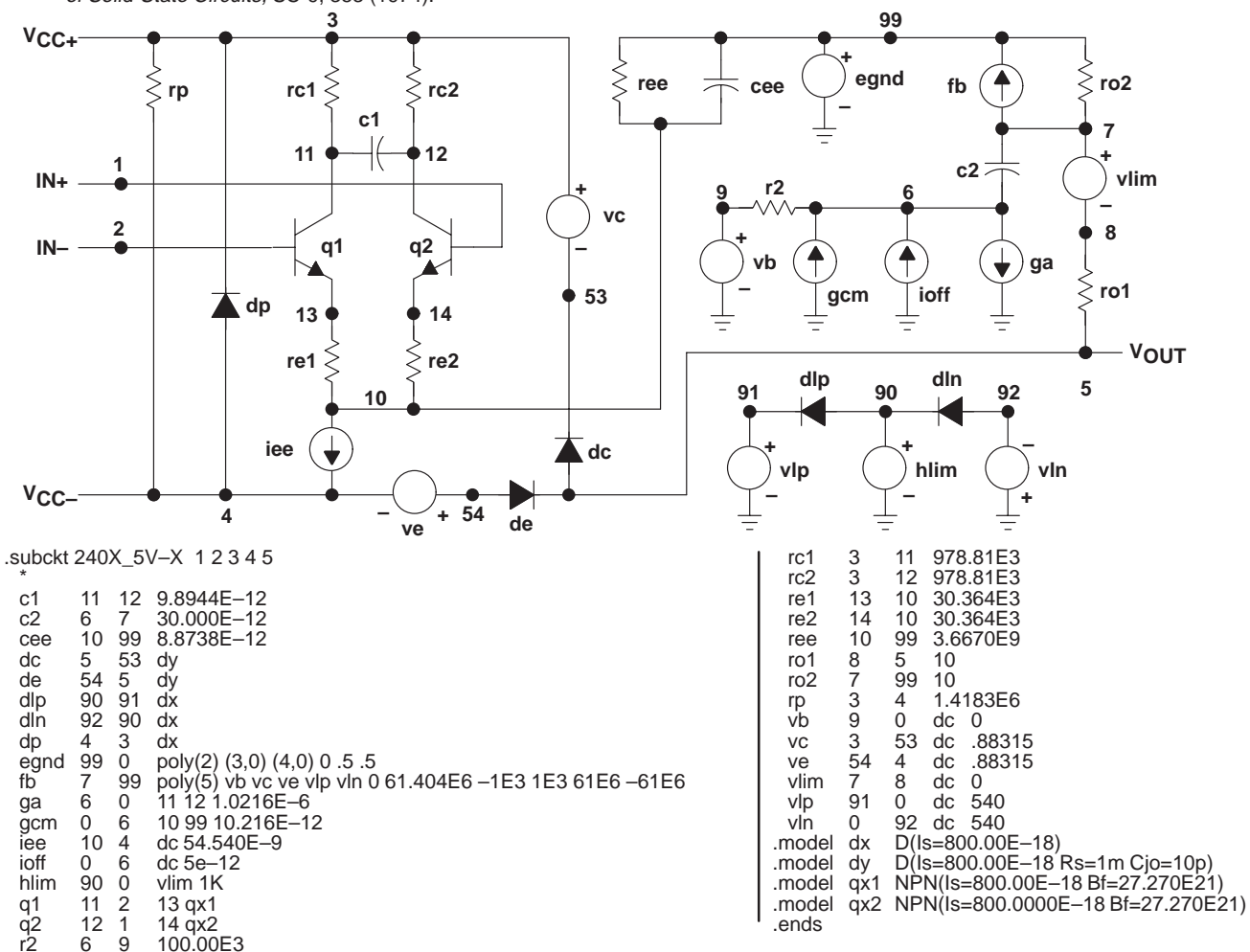
## APPLICATION INFORMATION

### macromodel information

Macromodel information provided was derived using Microsim *Parts*™ Release 8, the model generation software used with Microsim *PSpice*™. The Boyle macromodel (see Note 2) and subcircuit in Figure 41 are generated using the TLV240x typical electrical and operating characteristics at  $T_A = 25^\circ\text{C}$ . Using this information, output simulations of the following key parameters can be generated to a tolerance of 20% (in most cases):

- Maximum positive output voltage swing
- Maximum negative output voltage swing
- Slew rate
- Quiescent power dissipation
- Input bias current
- Open-loop voltage amplification
- Unity-gain frequency
- Common-mode rejection ratio
- Phase margin
- DC output resistance
- AC output resistance
- Short-circuit output current limit

NOTE 2: G. R. Boyle, B. M. Cohn, D. O. Pederson, and J. E. Solomon, "Macromodeling of Integrated Circuit Operational Amplifiers", *IEEE Journal of Solid-State Circuits*, SC-9, 353 (1974).



**Figure 41. Boyle Macromodels and Subcircuit**

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**PACKAGING INFORMATION**

Orderable Device	Status <sup>(1)</sup>	Package Type	Package Drawing	Pins	Package Qty	Eco Plan <sup>(2)</sup>	Lead/ Ball Finish	MSL Peak Temp <sup>(3)</sup>	Samples (Requires Login)
TLV2401CD	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDBVR	ACTIVE	SOT-23	DBV	5	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDBVRG4	ACTIVE	SOT-23	DBV	5	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDBVT	ACTIVE	SOT-23	DBV	5	250	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDBVTG4	ACTIVE	SOT-23	DBV	5	250	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDG4	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401CDRG4	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401ID	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDBVR	ACTIVE	SOT-23	DBV	5	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDBVRG4	ACTIVE	SOT-23	DBV	5	3000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDBVT	ACTIVE	SOT-23	DBV	5	250	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDBVTG4	ACTIVE	SOT-23	DBV	5	250	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDG4	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IDRG4	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2401IP	ACTIVE	PDIP	P	8	50	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	
TLV2401IPE4	ACTIVE	PDIP	P	8	50	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	

Orderable Device	Status <sup>(1)</sup>	Package Type	Package Drawing	Pins	Package Qty	Eco Plan <sup>(2)</sup>	Lead/ Ball Finish	MSL Peak Temp <sup>(3)</sup>	Samples (Requires Login)
TLV2402CD	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDG4	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDGK	ACTIVE	VSSOP	DGK	8	80	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDGKG4	ACTIVE	VSSOP	DGK	8	80	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDGKR	ACTIVE	VSSOP	DGK	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDGKRG4	ACTIVE	VSSOP	DGK	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402CDRG4	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402ID	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDG4	ACTIVE	SOIC	D	8	75	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDGK	ACTIVE	VSSOP	DGK	8	80	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDGKG4	ACTIVE	VSSOP	DGK	8	80	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDGKR	ACTIVE	VSSOP	DGK	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDGKRG4	ACTIVE	VSSOP	DGK	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDR	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IDRG4	ACTIVE	SOIC	D	8	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2402IP	ACTIVE	PDIP	P	8	50	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	
TLV2402IPE4	ACTIVE	PDIP	P	8	50	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	
TLV2404AIN	OBSOLETE	PDIP	N	14		TBD	Call TI	Call TI	

Orderable Device	Status <sup>(1)</sup>	Package Type	Package Drawing	Pins	Package Qty	Eco Plan <sup>(2)</sup>	Lead/ Ball Finish	MSL Peak Temp <sup>(3)</sup>	Samples (Requires Login)
TLV2404CD	ACTIVE	SOIC	D	14	50	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404CDG4	ACTIVE	SOIC	D	14	50	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404CPW	ACTIVE	TSSOP	PW	14	90	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404CPWG4	ACTIVE	TSSOP	PW	14	90	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404CPWR	ACTIVE	TSSOP	PW	14	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404CPWRG4	ACTIVE	TSSOP	PW	14	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404ID	ACTIVE	SOIC	D	14	50	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IDG4	ACTIVE	SOIC	D	14	50	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IDR	ACTIVE	SOIC	D	14	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IDRG4	ACTIVE	SOIC	D	14	2500	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IN	ACTIVE	PDIP	N	14	25	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	
TLV2404INE4	ACTIVE	PDIP	N	14	25	Pb-Free (RoHS)	CU NIPDAU	N / A for Pkg Type	
TLV2404IPW	ACTIVE	TSSOP	PW	14	90	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IPWG4	ACTIVE	TSSOP	PW	14	90	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IPWR	ACTIVE	TSSOP	PW	14	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	
TLV2404IPWRG4	ACTIVE	TSSOP	PW	14	2000	Green (RoHS & no Sb/Br)	CU NIPDAU	Level-1-260C-UNLIM	

<sup>(1)</sup> 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.

**OBSELETE:** TI has discontinued the production of the device.

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<sup>(2)</sup> 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)

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

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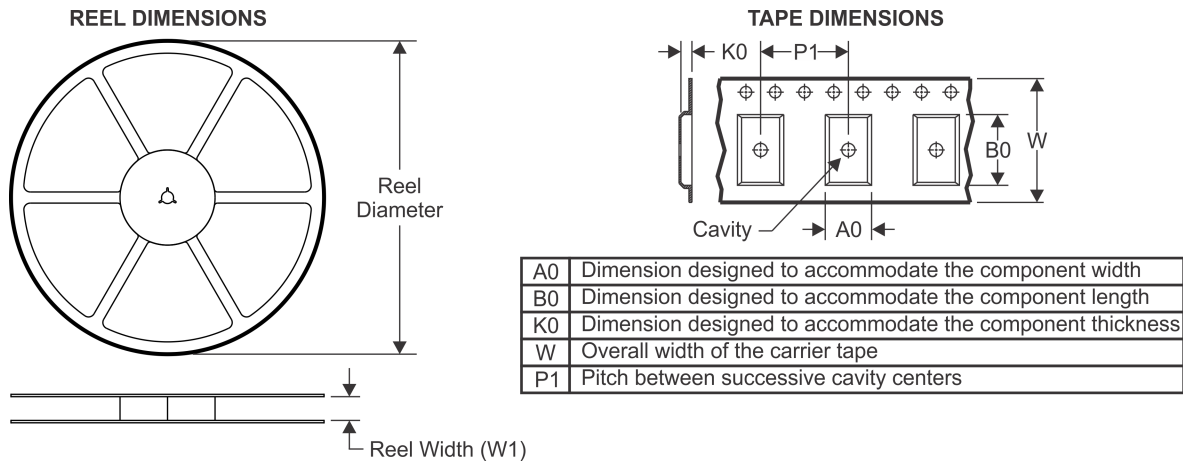
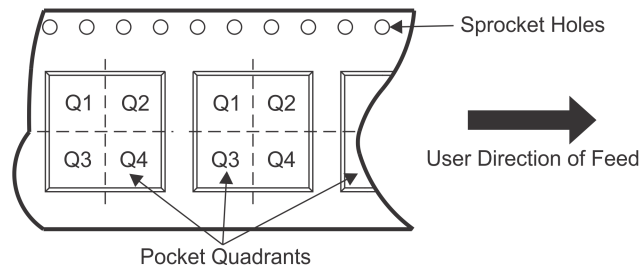
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**OTHER QUALIFIED VERSIONS OF TLV2402 :**

- Automotive: [TLV2402-Q1](#)

NOTE: Qualified Version Definitions:

- Automotive - Q100 devices qualified for high-reliability automotive applications targeting zero defects

**TAPE AND REEL INFORMATION**

**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
TLV2401CDBVR	SOT-23	DBV	5	3000	180.0	9.0	3.15	3.2	1.4	4.0	8.0	Q3
TLV2401CDBVT	SOT-23	DBV	5	250	180.0	9.0	3.15	3.2	1.4	4.0	8.0	Q3
TLV2401CDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
TLV2401IDBVR	SOT-23	DBV	5	3000	180.0	9.0	3.15	3.2	1.4	4.0	8.0	Q3
TLV2401IDBVT	SOT-23	DBV	5	250	180.0	9.0	3.15	3.2	1.4	4.0	8.0	Q3
TLV2401IDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
TLV2401IDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
TLV2402CDGKR	VSSOP	DGK	8	2500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
TLV2402CDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
TLV2402IDGKR	VSSOP	DGK	8	2500	330.0	12.4	5.3	3.4	1.4	8.0	12.0	Q1
TLV2402IDR	SOIC	D	8	2500	330.0	12.4	6.4	5.2	2.1	8.0	12.0	Q1
TLV2404CPWR	TSSOP	PW	14	2000	330.0	12.4	6.9	5.6	1.6	8.0	12.0	Q1
TLV2404IDR	SOIC	D	14	2500	330.0	16.4	6.5	9.0	2.1	8.0	16.0	Q1
TLV2404IPWR	TSSOP	PW	14	2000	330.0	12.4	6.9	5.6	1.6	8.0	12.0	Q1

**TAPE AND REEL BOX DIMENSIONS**


\*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
TLV2401CDBVR	SOT-23	DBV	5	3000	182.0	182.0	20.0
TLV2401CDBVT	SOT-23	DBV	5	250	182.0	182.0	20.0
TLV2401CDR	SOIC	D	8	2500	340.5	338.1	20.6
TLV2401IDBVR	SOT-23	DBV	5	3000	182.0	182.0	20.0
TLV2401IDBVT	SOT-23	DBV	5	250	182.0	182.0	20.0
TLV2401IDR	SOIC	D	8	2500	340.5	338.1	20.6
TLV2401IDR	SOIC	D	8	2500	367.0	367.0	35.0
TLV2402CDGKR	VSSOP	DGK	8	2500	358.0	335.0	35.0
TLV2402CDR	SOIC	D	8	2500	340.5	338.1	20.6
TLV2402IDGKR	VSSOP	DGK	8	2500	358.0	335.0	35.0
TLV2402IDR	SOIC	D	8	2500	340.5	338.1	20.6
TLV2404CPWR	TSSOP	PW	14	2000	367.0	367.0	35.0
TLV2404IDR	SOIC	D	14	2500	367.0	367.0	38.0
TLV2404IPWR	TSSOP	PW	14	2000	367.0	367.0	35.0

P (R-PDIP-T8)

PLASTIC DUAL-IN-LINE PACKAGE



4040082/E 04/2010

- NOTES:
- A. All linear dimensions are in inches (millimeters).
  - B. This drawing is subject to change without notice.
  - C. Falls within JEDEC MS-001 variation BA.



DBV (R-PDSO-G5)

PLASTIC SMALL-OUTLINE PACKAGE



- NOTES:
- A. All linear dimensions are in millimeters.
  - B. This drawing is subject to change without notice.
  - C. Body dimensions do not include mold flash or protrusion. Mold flash and protrusion shall not exceed 0.15 per side.
  - D. Falls within JEDEC MO-178 Variation AA.

DBV (R-PDSO-G5)

PLASTIC SMALL OUTLINE



- NOTES:
- A. All linear dimensions are in millimeters.
  - B. This drawing is subject to change without notice.
  - C. Customers should place a note on the circuit board fabrication drawing not to alter the center solder mask defined pad.
  - D. Publication IPC-7351 is recommended for alternate designs.
  - E. 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. Example stencil design based on a 50% volumetric metal load solder paste. Refer to IPC-7525 for other stencil recommendations.





D (R-PDSO-G14)

PLASTIC SMALL OUTLINE



4040047-5/M 06/11

- NOTES:
- A. All linear dimensions are in inches (millimeters).
  - B. This drawing is subject to change without notice.
  -  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.
  -  Body width does not include interlead flash. Interlead flash shall not exceed 0.017 (0,43) each side.
  - E. Reference JEDEC MS-012 variation AB.

PW (R-PDSO-G14)

PLASTIC SMALL OUTLINE

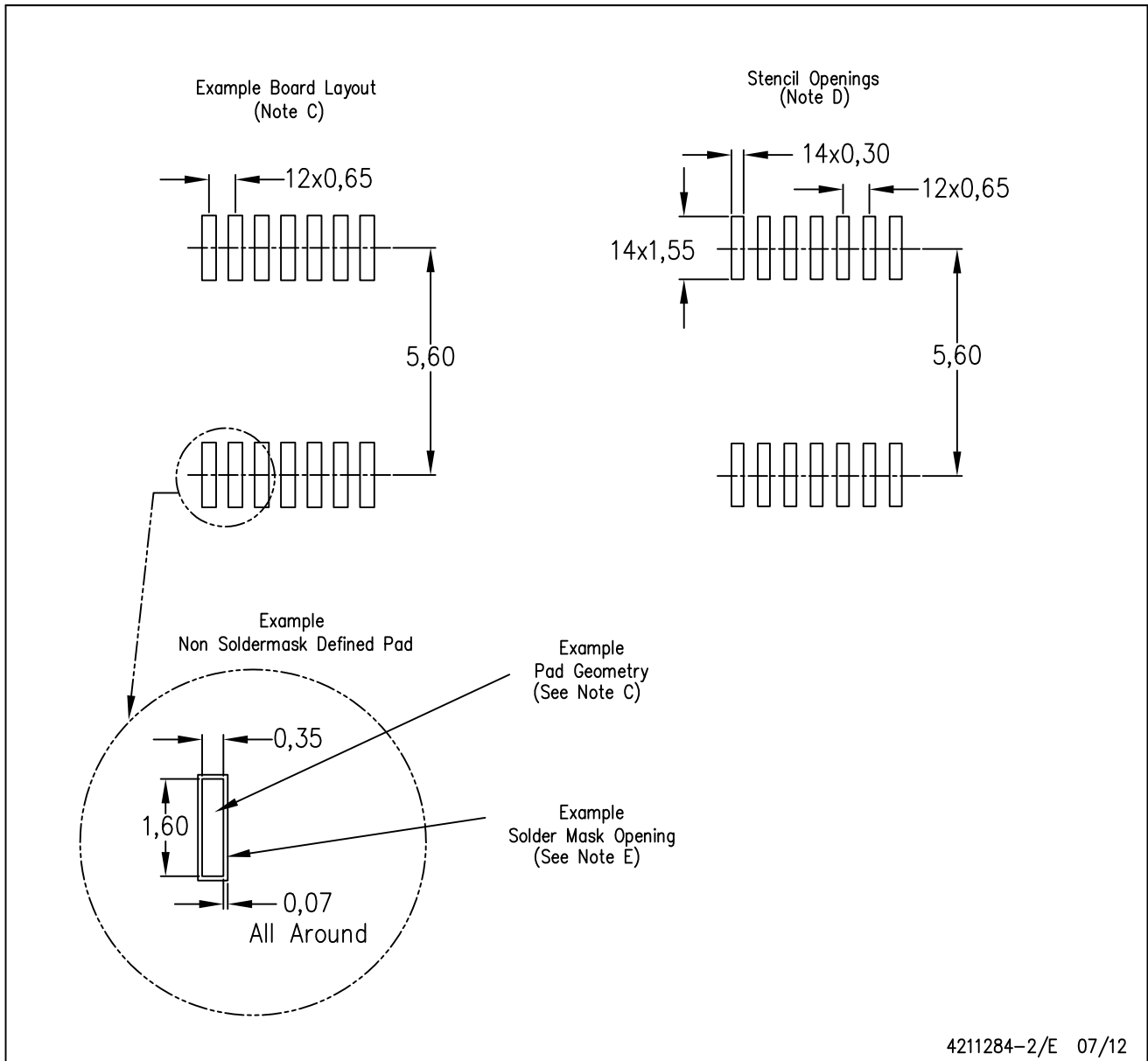


4040064-3/G 02/11

- NOTES:
- A. All linear dimensions are in millimeters. Dimensioning and tolerancing per ASME Y14.5M-1994.
  - B. This drawing is subject to change without notice.
  - C. Body length does not include mold flash, protrusions, or gate burrs. Mold flash, protrusions, or gate burrs shall not exceed 0,15 each side.
  - D. Body width does not include interlead flash. Interlead flash shall not exceed 0,25 each side.
  - E. Falls within JEDEC MO-153

PW (R-PDSO-G14)

PLASTIC SMALL OUTLINE



- NOTES:
- All linear dimensions are in millimeters.
  - This drawing is subject to change without notice.
  - Publication IPC-7351 is recommended for alternate designs.
  - 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.
  - Customers should contact their board fabrication site for solder mask tolerances between and around signal pads.

D (R-PDSO-G8)

PLASTIC SMALL OUTLINE



D (R-PDSO-G8)

PLASTIC SMALL OUTLINE



4211283-2/E 08/12

- NOTES:
- All linear dimensions are in millimeters.
  - This drawing is subject to change without notice.
  - Publication IPC-7351 is recommended for alternate designs.
  - 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.
  - Customers should contact their board fabrication site for solder mask tolerances between and around signal pads.



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