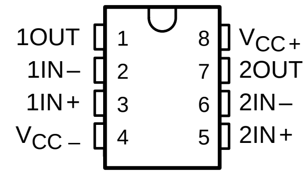
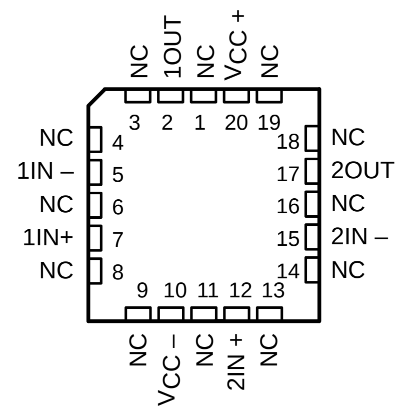
- **Maximum Offset Voltage**
  800 μV (TL052A)
- **High Slew Rate . . . 17.8 V/μs Typ at 25°C**
- **Low Total Harmonic Distortion**
  0.003% Typ at R_L = 2 kΩ
- **Low Noise Voltage . . . 19 nV/√Hz**
- **Low Input Bias Currents . . . 30 pA Typ**

D, JG, OR P PACKAGE
(TOP VIEW)



FK PACKAGE
(TOP VIEW)



NC – No internal connection

description

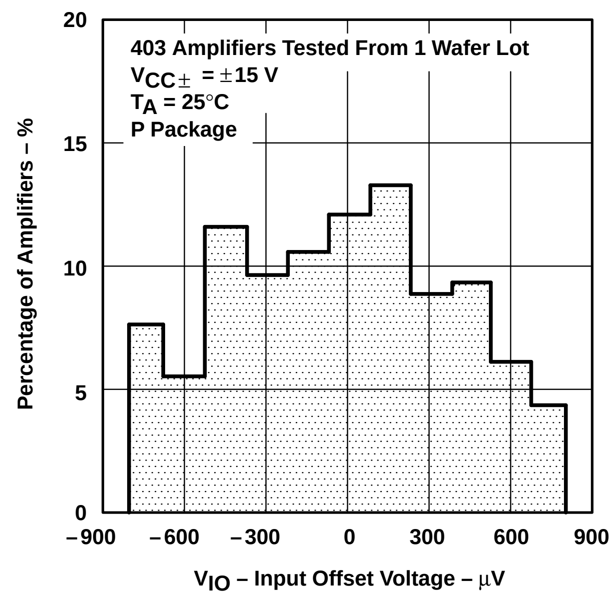
The TL052 and TL052A dual operational amplifiers incorporate well-matched, high-voltage JFET and bipolar transistors in a monolithic integrated circuit. These devices offer the significant advantages of Texas Instruments new enhanced-JFET process. This process affords not only low initial offset voltage due to the on-chip zener trim capability but also stable offset voltage over time and temperature. In comparison, traditional JFET processes are plagued by significant offset voltage drift.

This new enhanced process still maintains the traditional JFET advantages of fast slew rates and low input bias and offset currents. These advantages coupled with low noise and low harmonic distortion make the TL052 well suited for new state-of-the-art designs as well as existing design upgrades. The TL052 has been designed to be functionally compatible, as well as pin compatible, with the TL072 and TL082. Two offset voltage grades are available: TL052 (1.5 mV max) and TL052A (800 μV max).

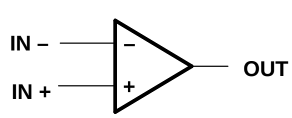
A variety of available packaging options includes small-outline and chip-carrier versions for high-density system applications.

The C-suffix devices are characterized for operation from 0°C to 70°C. The I-suffix devices are characterized for operation from –40°C to 85°C. The M-suffix devices are characterized for operation over the full military temperature range of –55°C to 125°C.

DISTRIBUTION OF TL052A
INPUT OFFSET VOLTAGE



symbol (each amplifier)



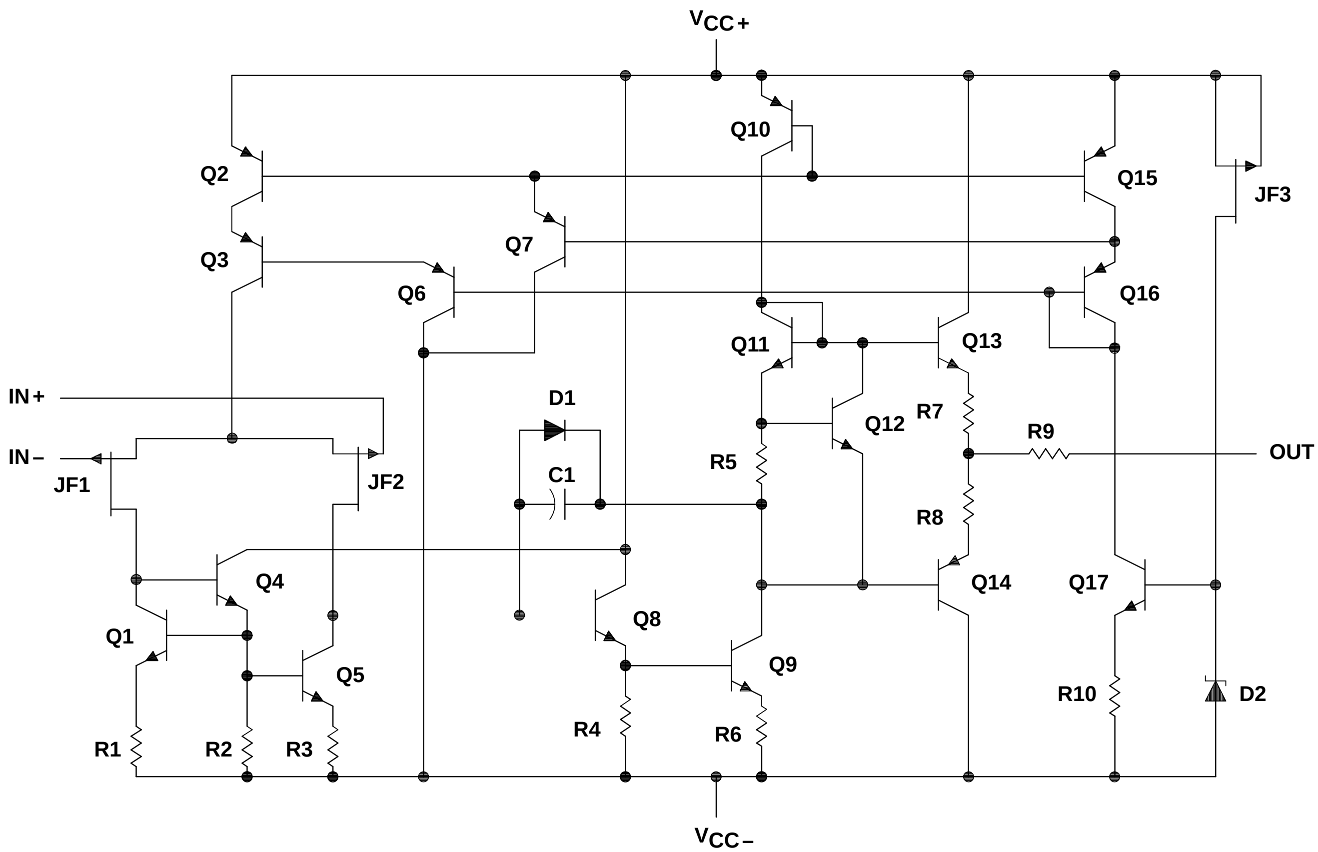
PRODUCTION DATA information is current as of publication date. Products conform to specifications per the terms of Texas Instruments standard warranty. Production processing does not necessarily include testing of all parameters.

AVAILABLE OPTIONS

T_A	V_{IO}max AT 25°C	PACKAGED DEVICES				CHIP FORM (Y)
		SMALL OUTLINE (D)	CHIP CARRIER (FK)	CERAMIC DIP (JG)	PLASTIC DIP (P)	
0°C to 70°C	800 µV 1500 µV	TL052ACD TL052CD	—	—	TL052ACP TL052CP	TL052Y
–40°C to 85°C	800 µV 1500 µV	TL052AID TL052ID	—	—	TL052AIP TL052IP	—
–55°C to 125°C	800 µV 1500 µV	TL052AMD TL052MD	TL052AMFK TL052MFK	TL052AMJG TL052MJG	TL052AMP TL052MP	—

The D packages are available taped and reeled. Add R suffix to device type (e.g., TL052CDR).

equivalent schematic (each amplifier)



COMPONENT COUNT†	
Transistors	34
Resistors	19
Diodes	3
Capacitors	2

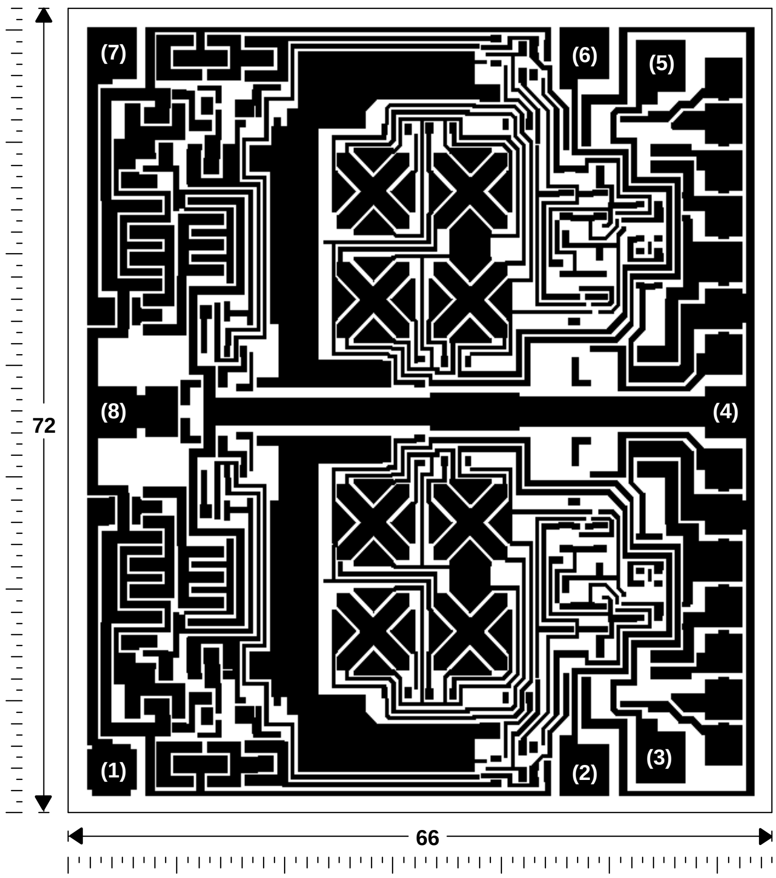
† Includes both amplifiers and all bias and trim circuitry

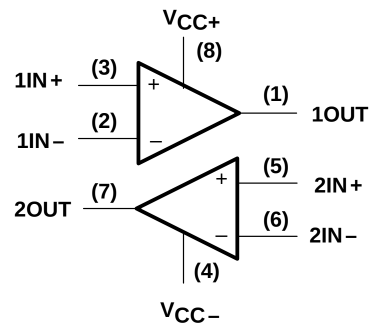
TEXAS INSTRUMENTS
POST OFFICE BOX 655303 • DALLAS, TEXAS 75265
POST OFFICE BOX 1443 • HOUSTON, TEXAS 77251–1443

TL052Y chip information

This chip, when properly assembled, displays characteristics similar to the TL052. Thermal compression or ultrasonic bonding may be used on the doped-aluminum bonding pads. Chips may be mounted with conductive epoxy or a gold-silicon preform.

BONDING PAD ASSIGNMENTS





CHIP THICKNESS: 15 TYPICAL

BONDING PADS: 4 × 4 MINIMUM

$T_J$max = 150°C

TOLERANCES ARE ±10%.

ALL DIMENSIONS ARE IN MILS.

PIN (4) IS INTERNALLY CONNECTED TO BACKSIDE OF CHIP.

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

Supply voltage, V_{CC+} (see Note 1)		18 V
Supply voltage, V_{CC-} (see Note 1)		–18 V
Differential input voltage (see Note 2)		±30 V
Input voltage range, V_I (any input, see Notes 1 and 3)		±15 V
Input current, I_I (each input)		±1 mA
Output current, I_O (each output)		±80 mA
Total current into V_{CC+}		160 mA
Total current out of V_{CC-}		160 mA
Duration of short-circuit current at (or below) 25°C (see Note 4)		unlimited
Continuous total dissipation		See Dissipation Rating Table
Operating free-air temperature range, T_A:	C suffix	0°C to 70°C
	I suffix	–40°C to 85°C
	M suffix	–55°C to 125°C
Storage temperature range		–65°C to 150°C
Case temperature for 60 seconds: FK package		260°C
Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds: D or P package		260°C
Lead temperature 1,6 mm (1/16 inch) from case for 60 seconds: JG package		300°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.

NOTES:
1. All voltage values, except differential voltages, are with respect to the midpoint between V_{CC+} and V_{CC-}.
2. Differential voltages are at IN+ with respect to IN–.
3. The magnitude of the input voltage must never exceed the magnitude of the supply voltage or 15 V, whichever is less.
4. The output may be shorted to either supply. Temperature and/or supply voltages must be limited to ensure that the maximum dissipation rating is not exceeded.

DISSIPATION RATING TABLE

PACKAGE	$T_A \le 25°C$ POWER RATING	DERATING FACTOR ABOVE $T_A = 25°C$	$T_A = 70°C$ POWER RATING	$T_A = 85°C$ POWER RATING	$T_A = 125°C$ POWER RATING
D	725 mW	5.8 mW/°C	464 mW	377 mW	145 mW
FK	1375 mW	11.0 mW/°C	880 mW	715 mW	275 mW
JG	1050 mW	8.4 mW/°C	672 mW	546 mW	210 mW
P	1000 mW	8.0 mW/°C	640 mW	520 mW	200 mW

recommended operating conditions

		C SUFFIX		I SUFFIX		M SUFFIX		UNIT
		MIN	MAX	MIN	MAX	MIN	MAX	
Supply voltage, $V_{CC\pm}$		±5	±15	±5	±15	±5	±15	V
Common-mode input voltage, V_{IC}	$V_{CC\pm} = \pm 5$ V	–1	4	–1	4	–1	4	V
	$V_{CC\pm} = \pm 15$ V	–11	11	–11	11	–11	11	
Operating free-air temperature, T_A		0	70	–40	85	–55	125	°C

electrical characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A†	TL052C, TL052AC						UNIT
					$V_{CC\pm} = \pm 5$ V			$V_{CC\pm} = \pm 15$ V			
					MIN	TYP	MAX	MIN	TYP	MAX	
V_{IO}	Input offset voltage	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$	TL052C	25°C		0.73	3.5		0.65	1.5	mV
				Full range			4.5			2.5	
			TL052AC	25°C		0.51	2.8		0.4	0.8	
				Full range			3.8			1.8	
α_{VIO}	Temperature coefficient of input offset voltage (see Note 5)		TL052C	25°C to 70°C		8			8		µV/°C
			TL052AC	25°C to 70°C		8			6	25	
	Input offset voltage long-term drift (see Note 6)	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$		25°C		0.04			0.04		µV/mo
I_{IO}	Input offset current	$V_O = 0$, $V_{IC} = 0$, See Figure 5		25°C		4	100		5	100	pA
				70°C		0.02	1		0.025	1	nA
I_{IB}	Input bias current	$V_O = 0$, $V_{IC} = 0$, See Figure 5		25°C		20	200		30	200	pA
				70°C		0.15	4		0.2	4	nA
V_{ICR}	Common-mode input voltage range			25°C	–1 to 4	–2.3 to 5.6		–11 to 11	–12.3 to 15.6		V
				Full range	–1 to 4			–11 to 11			
V_{OM+}	Maximum positive peak output voltage swing	$R_L = 10\ k\Omega$		25°C	3	4.2		13	13.9		V
				Full range	3			13			
		$R_L = 2\ k\Omega$		25°C	2.5	3.8		11.5	12.7		
				Full range	2.5			11.5			
V_{OM-}	Maximum negative peak output voltage swing	$R_L = 10\ k\Omega$		25°C	–2.5	–3.5		–12	–13.2		V
				Full range	–2.5			–12			
		$R_L = 2\ k\Omega$		25°C	–2.3	–3.2		–11	–12		
				Full range	–2.3			–11			
A_{VD}	Large-signal differential voltage amplification	$R_L = 2\ k\Omega$, See Note 7		25°C	25	59		50	105		V/mV
				0°C	30	65		60	129		
				70°C	20	46		30	85		
r_i	Input resistance			25°C		10^{12}			10^{12}		Ω
c_i	Input capacitance			25°C		10			12		pF
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}min$, $V_O = 0$, $R_S = 50\ \Omega$		25°C	65	85		75	93		dB
				0°C	65	84		75	92		
				70°C	65	84		75	91		

† Full range is 0°C to 70°C.

NOTES: 5. This parameter is tested on a sample basis. For other test requirements, please contact the factory. This statement has no bearing on testing or nontesting of other parameters.

6. Typical values are based on the input offset voltage shift observed through 168 hours of operating life test at $T_A = 150°C$ extrapolated to $T_A = 25°C$ using the Arrhenius equation and assuming an activation energy of 0.96 eV.

7. For $V_{CC\pm} = \pm 5$ V, $V_O = \pm 2.3$ V; at $V_{CC\pm} = \pm 15$ V, $V_O = \pm 10$ V.

electrical characteristics at specified free-air temperature (continued)

PARAMETER		TEST CONDITIONS	T_A†	TL052C, TL052AC						UNIT
				$V_{CC\pm} = \pm5$ V			$V_{CC\pm} = \pm15$ V			
				MIN	TYP	MAX	MIN	TYP	MAX	
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC\pm}/\Delta V_{IO}$)	$V_O = 0$, $R_S = 50\ \Omega$	25°C	75	99		75	99		dB
			0°C	75	98		75	98		
			70°C	75	97		75	97		
I_{CC}	Supply current (two amplifiers)	$V_O = 0$, No load	25°C		4.6	5.6		4.8	5.6	mA
			0°C		4.7	6.4		4.8	6.4	
			70°C		4.4	6.4		4.6	6.4	
V_{O1}/V_{O2}	Crosstalk attenuation	$A_{VD} = 100$	25°C		120			120		dB

operating characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A†	TL052C, TL052AC						UNIT
					$V_{CC\pm} = \pm5$ V			$V_{CC\pm} = \pm15$ V			
					MIN	TYP	MAX	MIN	TYP	MAX	
SR +	Slew rate at unity gain	$R_L = 2\ k\Omega$, $C_L = 100$ pF, See Figure 1 and Note 8		25°C		17.8		9	20.7		V/µs
				Full range				8			
SR –	Negative slew rate at unity gain			25°C		15.4		9	17.8		
				Full range				8			
t_r	Rise time	$V_{I(PP)} = \pm10$ mV, $R_L = 2\ k\Omega$, $C_L = 100$ pF, See Figures 1 and 2		25°C		55			56		ns
				0°C		54			55		
				70°C		63			63		
t_f	Fall time			25°C		55			57		
				0°C		54			56		
				70°C		62			64		
	Overshoot factor			25°C		24%			19%		
				0°C		24%			19%		
				70°C		24%			19%		
V_n	Equivalent input noise voltage (see Note 5)	$R_S = 20\ \Omega$, See Figure 3	f = 10 Hz	25°C		71			71		nV/√Hz
			f = 1 kHz	25°C		19			19	30	
$V_{N(PP)}$	Peak-to-peak equivalent input noise current		f = 10 Hz to 10 kHz	25°C		4			4		µV
I_n	Equivalent input noise current	f = 1 kHz		25°C		0.01			0.01		pA/√Hz
THD	Total harmonic distortion	$R_S = 1\ k\Omega$, f = 1 kHz,	$R_L = 2\ k\Omega$, See Note 9	25°C		0.003%			0.003%		
B_1	Unity-gain bandwidth	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2\ k\Omega$, See Figure 4	25°C		3			3		MHz
				0°C		3.2			3.2		
				70°C		2.6			2.7		
ϕ_m	Phase margin at unity gain	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2\ k\Omega$, See Figure 4	25°C		60°			63°		
				0°C		59°			63°		
				70°C		60°			63°		

† Full range is 0°C to 70°C.

NOTES: 5. This parameter is tested on a sample basis. For other test requirements, please contact the factory. This statement has no bearing on testing or nontesting of other parameters.

8. For $V_{CC\pm} = \pm5$ V, $V_{I(PP)} = \pm1$ V; for $V_{CC\pm} = \pm15$ V, $V_{I(PP)} = \pm5$ V.
9. For $V_{CC\pm} = \pm5$ V, $V_{O(RMS)} = 1$ V; for $V_{CC\pm} = \pm15$ V, $V_{O(RMS)} = 6$ V.

electrical characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A†	TL052I, TL052AI $V_{CC\pm} = \pm5$ V MIN	TYP	MAX	$V_{CC\pm} = \pm15$ V MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$	TL052I	25°C		0.73	3.5		0.65	1.5	mV
				Full range			5.3			3.3	
			TL052AI	25°C		0.51	2.8		0.4	0.8	
				Full range			4.6			2.6	
α_{VIO}	Temperature coefficient (see Note 5)		TL052I	25°C to 85°C		7			6		µV/°C
			TL052AI	25°C to 85°C		6			6	25	
	Input offset voltage long-term drift (see Note 6)	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$		25°C		0.04			0.04		µV/mo
I_{IO}	Input offset current	$V_O = 0$, $V_{IC} = 0$, See Figure 5		25°C		4	100		5	100	pA
				85°C		0.06	10		0.07	10	nA
I_{IB}	Input bias current	$V_O = 0$, $V_{IC} = 0$, See Figure 5		25°C		20	200		30	200	pA
				85°C		0.6	20		0.7	20	nA
V_{ICR}	Common-mode input voltage range			25°C	–1 to 4	–2.3 to 5.6		–11 to 11	–12.3 to 15.6		V
				Full range	–1 to 4			–11 to 11			
V_{OM+}	Maximum positive peak output voltage swing	$R_L = 10\ k\Omega$		25°C	3	4.2		13	13.9		V
				Full range	3			13			
		$R_L = 2\ k\Omega$		25°C	2.5	3.8		11.5	12.7		
				Full range	2.5			11.5			
V_{OM-}	Maximum negative peak output voltage swing	$R_L = 10\ k\Omega$		25°C	–2.5	–3.5		–12	–13.2		V
				Full range	–2.5			–12			
		$R_L = 2\ k\Omega$		25°C	–2.3	–3.2		–11	–12		
				Full range	–2.3			–11			
A_{VD}	Large-signal differential voltage amplification	$R_L = 2\ k\Omega$, See Note 7		25°C	25	59		50	105		V/mV
				–40°C	30	74		60	145		
				85°C	20	43		30	76		
r_i	Input resistance			25°C		10^{12}			10^{12}		Ω
c_i	Input capacitance			25°C		10			12		pF
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}min$, $V_O = 0$, $R_S = 50\ \Omega$		25°C	65	85		75	93		dB
				–40°C	65	83		75	90		
				85°C	65	84		75	93		

† Full range is –40°C to 85°C.

NOTES: 5. This parameter is tested on a sample basis. For other test requirements, please contact the factory. This statement has no bearing on testing or nontesting of other parameters

6. Typical values are based on the input offset voltage shift observed through 168 hours of operating life test at T_A = 150°C extrapolated to T_A = 25°C using the Arrhenius equation and assuming an activation energy of 0.96 eV.

7. At $V_{CC\pm} = \pm5$ V, $V_O = \pm2.3$ V; at $V_{CC\pm} = \pm15$ V, $V_O = \pm10$ V.

electrical characteristics at specified free-air temperature (continued)

PARAMETER		TEST CONDITIONS		T_A†	TL052I, TL052AI						UNIT
					$V_{CC\pm} = \pm5$ V			$V_{CC\pm} = \pm15$ V			
					MIN	TYP	MAX	MIN	TYP	MAX	
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC\pm}/\Delta V_{IO}$)	$V_O = 0$,	$R_S = 50\ \Omega$	25°C	75	99		75	99		dB
				–40°C	75	98		75	98		
				85°C	75	99		75	99		
I_{CC}	Supply current (two amplifiers)	$V_O = 0$,	No load	25°C		4.6	5.6		4.8	5.6	mA
				–40°C		4.5	6.4		4.7	6.4	
				85°C		4.4	6.4		4.6	6.4	
V_{O1}/V_{O2}	Crosstalk attenuation	$A_{VD} = 100$		25°C		120			120		dB

operating characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A†	TL052I, TL052AI						UNIT
					$V_{CC\pm} = \pm5$ V			$V_{CC\pm} = \pm15$ V			
					MIN	TYP	MAX	MIN	TYP	MAX	
SR +	Slew rate at unity gain	$R_L = 2\ k\Omega$, $C_L = 100$ pF, See Figure 1 and Note 8		25°C		17.8		9	20.7		V/µs
				Full range				8			
SR –	Negative slew rate at unity gain			25°C		15.4		9	17.8		
				Full range				8			
t_r	Rise time	$V_{I(PP)} = \pm10$ mV, $R_L = 2\ k\Omega$, $C_L = 100$ pF, See Figures 1 and 2		25°C		55			56		ns
				–40°C		52			53		
				85°C		64			65		
t_f	Fall time			25°C		55			57		
				–40°C		51			53		
				85°C		64			65		
	Overshoot factor			25°C		24%			19%		
				–40°C		24%			19%		
				85°C		24%			19%		
V_n	Equivalent input noise voltage (see Note 5)	$R_S = 20\ \Omega$, See Figure 3	f = 10 Hz	25°C		71			71		
			f = 1 kHz	25°C		19			19	30	
$V_{N(PP)}$	Peak-to-peak equivalent input noise current		f = 10 Hz to 10 kHz	25°C		4			4		µV
I_n	Equivalent input noise current	f = 1 kHz		25°C		0.01			0.01		pA/√Hz
THD	Total harmonic distortion	$R_S = 1\ k\Omega$, f = 1 kHz,	$R_L = 2\ k\Omega$, See Note 9	25°C		0.003%			0.003%		
B_1	Unity-gain bandwidth	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2\ k\Omega$, See Figure 4	25°C		3			3		MHz
				–40°C		3.5			3.6		
				85°C		2.5			2.6		
ϕ_m	Phase margin at unity gain	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2\ k\Omega$, See Figure 4	25°C		60°			63°		
				–40°C		58°			61°		
				85°C		60°			63°		

† Full range is –40°C to 85°C.

NOTES: 5. This parameter is tested on a sample basis. For other test requirements, please contact the factory. This statement has no bearing on testing or nontesting of other parameters.
8. For $V_{CC\pm} = \pm5$ V, $V_{I(PP)} = \pm1$ V; for $V_{CC\pm} = \pm15$ V, $V_{I(PP)} = \pm5$ V.
9. For $V_{CC\pm} = \pm5$ V, $V_{O(RMS)} = 1$ V; for $V_{CC\pm} = \pm15$ V, $V_{O(RMS)} = 6$ V.

electrical characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A†	TL052M, TL052AM $V_{CC\pm} = \pm 5$ V MIN	TYP	MAX	$V_{CC\pm} = \pm 15$ V MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$	TL052M	25°C		0.73	3.5		0.65	1.5	mV
				Full range			6.5			4.5	
			TL052AM	25°C		0.51	2.8		0.4	0.8	
				Full range			5.8			3.8	
α_{VIO}	Temperature coefficient of input offset voltage		TL052M	25°C to 125°C		10			9		µV/°C
			TL052AM	25°C to 125°C		9			8		
	Input offset voltage long-term drift (see Note 6)	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$		25°C		0.04			0.04		µV/mo
I_{IO}	Input offset current	$V_O = 0$, $V_{IC} = 0$, See Figure 5		25°C		4	100		5	100	pA
				125°C		1	20		2	20	nA
I_{IB}	Input bias current	$V_O = 0$, $V_{IC} = 0$, See Figure 5		25°C		20	200		30	200	pA
				125°C		10	50		20	50	nA
V_{ICR}	Common-mode input voltage range			25°C	–1 to 4	–2.3 to 5.6		–11 to 11	–12.3 to 15.6		V
				Full range	–1 to 4			–11 to 11			
V_{OM+}	Maximum positive peak output voltage swing	$R_L = 10$ kΩ		25°C	3	4.2		13	13.9		V
				Full range	3			13			
		$R_L = 2$ kΩ		25°C	2.5	3.8		11.5	12.7		
				Full range	2.5			11.5			
V_{OM-}	Maximum negative peak output voltage swing	$R_L = 10$ kΩ		25°C	–2.5	–3.5		–12	–13.2		V
				Full range	–2.5			–12			
		$R_L = 2$ kΩ		25°C	–2.3	–3.2		–11	–12		
				Full range	–2.3			–11			
A_{VD}	Large-signal differential voltage amplification	$R_L = 2$ kΩ, See Note 7		25°C	25	59		50	105		V/mV
				–55°C	30	76		60	149		
				125°C	10	32		15	49		
r_i	Input resistance			25°C		10^{12}			10^{12}		Ω
c_i	Input capacitance			25°C		10			12		pF
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}$min, $V_O = 0$, $R_S = 50\ \Omega$		25°C	65	85		75	93		dB
				–55°C	65	83		75	92		
				125°C	65	84		75	94		
k_{SVR}	Supply-voltage rejection ratio ($\Delta V_{CC\pm}/\Delta V_{IO}$)	$V_O = 0$, $R_S = 50\ \Omega$		25°C	75	99		75	99		dB
				–55°C	75	98		75	98		
				125°C	75	100		75	100		
I_{CC}	Supply current (two amplifiers)	$V_O = 0$, No load		25°C		4.6	5.6		4.8	5.6	mA
				–55°C		4.4	6.4		4.5	6.4	
				125°C		4.2	6.4		4.4	6.4	
V_{O1}/V_{O2}	Crosstalk attenuation	$A_{VD} = 100$		25°C		120			120		dB

† Full range is – 55°C to 125°C.

NOTES: 6. Typical values are based on the input offset voltage shift observed through 168 hours of operating life test at $T_A = 150$°C extrapolated to $T_A = 25$°C using the Arrhenius equation and assuming an activation energy of 0.96 eV.

7. For $V_{CC\pm} = \pm 5$ V, $V_O = \pm 2.3$ V; at $V_{CC\pm} = \pm 15$ V, $V_O = \pm 10$ V.

operating characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A†	TL052M, TL052AM						UNIT
					$V_{CC\pm} = \pm 5$ V			$V_{CC\pm} = \pm 15$ V			
					MIN	TYP	MAX	MIN	TYP	MAX	
SR +	Positive slew rate at unity gain	$R_L = 2$ kΩ, $C_L = 100$ pF, See Figure 1 and Note 8		25°C		17.8		9	20.7		V/μs
				Full range				8			
SR –	Negative slew rate at unity gain			25°C		15.4		9	17.8		
				Full range				8			
t_r	Rise time	$V_{I(PP)} = \pm 10$ mV, $R_L = 2$ kΩ, $C_L = 100$ pF, See Figures 1 and 2		25°C		55			56		ns
				–55°C		51			52		
				125°C		68			68		
t_f	Fall time			25°C		55			57		
				–55°C		51			52		
				125°C		68			69		
	Overshoot factor			25°C		24%			19%		
				–55°C		25%			19%		
				125°C		25%			19%		
V_n	Equivalent input noise voltage (see Note 5)	$R_S = 20$ Ω, See Figure 3	f = 10 Hz	25°C		71			71		nV/√Hz
			f = 1 kHz	25°C		19			19		
$V_{N(PP)}$	Peak-to-peak equivalent input noise current		f = 10 Hz to 10 kHz	25°C		4			4		μV
I_n	Equivalent input noise current	f = 1 kHz		25°C		0.01			0.01		pA/√Hz
THD	Total harmonic distortion	$R_S = 1$ kΩ, f = 1 kHz,	$R_L = 2$ kΩ, See Note 9	25°C		0.003%			0.003%		
B_1	Unity-gain bandwidth	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2$ kΩ, See Figure 4	25°C		3			3		MHz
				–55°C		3.6			3.7		
				125°C		2.3			2.4		
ϕ_m	Phase margin at unity gain	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2$ kΩ, See Figure 4	25°C		60°			63°		
				–55°C		57°			61°		
				125°C		60°			63°		

† Full range is – 55°C to 125°C.

NOTES: 5. This parameter is tested on a sample basis. For other test requirements, please contact the factory. This statement has no bearing on testing or nontesting of other parameters.

8. For $V_{CC\pm} = \pm 5$ V, $V_{I(PP)} = \pm 1$ V; for $V_{CC\pm} = \pm 15$ V, $V_{I(PP)} = \pm 5$ V.

9. For $V_{CC\pm} = \pm 5$ V, $V_{O(RMS)} = 1$ V; for $V_{CC\pm} = \pm 15$ V, $V_{O(RMS)} = 6$ V.

electrical characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS	T_A	TL052Y $V_{CC\pm} = \pm 5$ V MIN	TYP	MAX	$V_{CC\pm} = \pm 15$ V MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	$V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$	25°C		0.73	3.5		0.65	1.5	mV
α_{VIO}	Temperature coefficient of input offset voltage		25°C to 70°C		8			8		μV/°C
	Input offset voltage long-term drift		25°C		0.04			0.04		μV/mo
I_{IO}	Input offset current	$V_O = 0$, $V_{IC} = 0$, See Figure 5	25°C		4	100		5	100	pA
I_{IB}	Input bias current	$V_O = 0$, $V_{IC} = 0$, See Figure 5	25°C		20	200		30	200	pA
V_{ICR}	Common-mode input voltage range		25°C	–1 to 4	–2.3 to 5.6		–11 to 11	–12.3 to 15.6		V
V_{OM+}	Maximum positive peak output voltage swing	$R_L = 10\ k\Omega$	25°C	3	4.2		13	13.9		V
		$R_L = 2\ k\Omega$		2.5	3.8		11.5	12.7		
V_{OM-}	Maximum negative peak output voltage swing	$R_L = 10\ k\Omega$	25°C	–2.5	–3.5		–12	–13.2		
		$R_L = 2\ k\Omega$		–2.3	–3.2		–11	–12		
A_{VD}	Large-signal differential voltage amplification	$R_L = 2\ k\Omega$, See Note 7	25°C	25	59		50	105		V/mV
r_i	Input resistance		25°C		10^{12}			10^{12}		Ω
c_i	Input capacitance		25°C		10			12		pF
CMRR	Common-mode rejection ratio	$V_{IC} = V_{ICR}min$, $V_O = 0$, $R_S = 50\ \Omega$	25°C	65	85		75	93		dB
k_{SVR}	Supply-voltage rejection ratio $(\Delta V_{CC\pm}/\Delta V_{IO})$	$V_O = 0$, $R_S = 50\ \Omega$	25°C	75	99		75	99		dB
I_{CC}	Supply current (two amplifiers)	$V_O = 0$, No load	25°C		4.6	5.6		4.8	5.6	mA
V_{O1}/V_{O2}	Crosstalk attenuation	$A_{VD} = 100$	25°C		120			120		dB

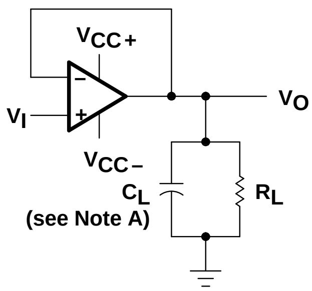
NOTE 7. For $V_{CC\pm} = \pm 5$ V, $V_O = \pm 2.3$ V; at $V_{CC\pm} = \pm 15$ V, $V_O = \pm 10$ V.

operating characteristics at specified free-air temperature

PARAMETER		TEST CONDITIONS		T_A	TL052Y $V_{CC\pm} = \pm5$ V MIN	TYP	MAX	TL052Y $V_{CC\pm} = \pm15$ V MIN	TYP	MAX	UNIT
SR +	Positive slew rate at unity gain	$R_L = 2$ kΩ, $C_L = 100$ pF, See Figure 1 and Note 8		25°C		17.8		9	20.7		V/μs
SR –	Negative slew rate at unity gain			25°C		15.4		9	17.8		V/μs
t_r	Rise time	$V_{I(PP)} = \pm10$ mV, $R_L = 2$ kΩ, $C_L = 100$ pF, See Figures 1 and 2		25°C		55			56		ns
t_f	Fall time					55			57		ns
	Overshoot factor					24%			19%		
V_n	Equivalent input noise voltage (see Note 5)	$R_S = 20$ Ω, See Figure 3	f = 10 Hz	25°C		71			71		nV/√Hz
			f = 1 kHz	25°C		19			19	30	
$V_{N(PP)}$	Peak-to-peak equivalent input noise current		f = 10 Hz to 10 kHz	25°C		4			4		μV
I_n	Equivalent input noise current	f = 1 kHz		25°C		0.01			0.01		pA/√Hz
THD	Total harmonic distortion	$R_S = 1$ kΩ, f = 1 kHz,	$R_L = 2$ kΩ, See Note 9	25°C		0.003%			0.003%		
B_1	Unity-gain bandwidth	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2$ kΩ, See Figure 4	25°C		3			3		MHz
ϕ_m	Phase margin at unity gain	$V_I = 10$ mV, $C_L = 25$ pF,	$R_L = 2$ kΩ, See Figure 4	25°C		60°			63°		

NOTES: 5. This parameter is tested on a sample basis. For other test requirements, please contact the factory. This statement has no bearing on testing or nontesting of other parameters.
8. For $V_{CC\pm} = \pm5$ V, $V_{I(PP)} = \pm1$ V; for $V_{CC\pm} = \pm15$ V, $V_{I(PP)} = \pm5$ V.
9. For $V_{CC\pm} = \pm5$ V, $V_{O(RMS)} = 1$ V; for $V_{CC\pm} = \pm15$ V, $V_{O(RMS)} = 6$ V.

PARAMETER MEASUREMENT INFORMATION



NOTE A: C_L includes fixture capacitance.

Figure 1. Slew Rate, Rise/Fall Time, and Overshoot Test Circuit

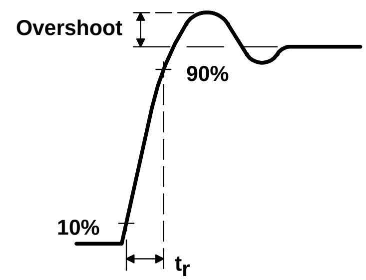


Figure 2. Rise Time and Overshoot Waveform

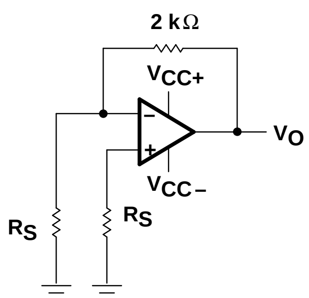
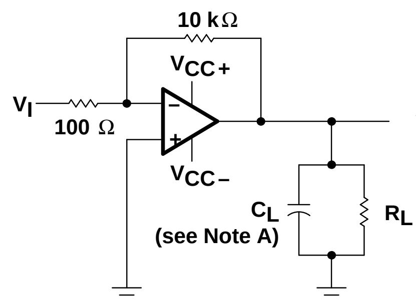


Figure 3. Noise-Voltage Test Circuit



NOTE A: C_L includes fixture capacitance.

Figure 4. Unity-Gain Bandwidth and Phase-Margin Test Circuit

typical values

Typical values as presented in this data sheet represent the median (50% point) of device parametric performance.

input bias and offset current

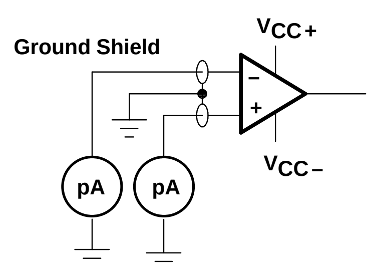


Figure 5. Input-Bias and Offset-Current Test Circuit

At the picoamp-bias-current level typical of the TL052 and TL052A, accurate measurement of the bias current becomes difficult. Not only does this measurement require a picoammeter, but test socket leakages can easily exceed the actual device bias currents. To accurately measure these small currents, Texas Instruments uses a two-step process. The socket leakage is measured using picoammeters with bias voltages applied but with no device in the socket. The device is then inserted in the socket, and a second test that measures both the socket leakage and the device input bias current is performed. The two measurements are then subtracted algebraically to determine the bias current of the device.

noise

Because of the increasing emphasis on low noise levels in many of today's applications, the input noise voltage density is sample tested at f = 1 kHz. Texas Instruments also has additional noise testing capability to meet specific application requirements. Please contact the factory for details.

TYPICAL CHARACTERISTICS

Table of Graphs

			FIGURE
V_{IO}	Input offset voltage	Distribution	6
α_{VIO}	Temperature coefficient of input offset voltage	Distribution	7
I_{IO}	Input offset current	vs Free-air temperature	8
I_{IB}	Input bias current	vs Common-mode input voltage vs Free-air temperature	9 8
V_{IC}	Common-mode input voltage	vs Supply voltage vs Free-air temperature	10 11
V_O	Output voltage	vs Differential input voltage	12, 13
V_{OM}	Maximum peak output voltage swing	vs Supply voltage vs Frequency vs Output current vs Free-air temperature	14 15, 16, 17 18, 19 20, 21
A_{VD}	Differential voltage amplification	vs Load resistance vs Frequency vs Free-air temperature	22 23 24, 25
z_o	Output impedance	vs Frequency	29
CMRR	Common-mode rejection ratio	vs Frequency vs Free-air temperature	26, 27 28
k_{SVR}	Supply-voltage rejection ratio	vs Free-air temperature	30
I_{OS}	Short-circuit output current	vs Supply voltage vs Time vs Free-air temperature	31 32 33
I_{CC}	Supply current	vs Supply voltage vs Free-air temperature	34 35
SR	Slew rate	vs Load resistance vs Free-air temperature	36, 37 38, 39
	Overshoot factor	vs Load capacitance	40
V_n	Equivalent input noise voltage	vs Frequency	41
THD	Total harmonic distortion	vs Frequency	42
B_1	Unity-gain bandwidth	vs Supply voltage vs Free-air temperature	43 44
ϕ_m	Phase margin	vs Supply voltage vs Load capacitance vs Free-air temperature	45 46 47
	Phase shift	vs Frequency	23
	Pulse response	Small-signal Large-signal	48 49

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TYPICAL CHARACTERISTICS†

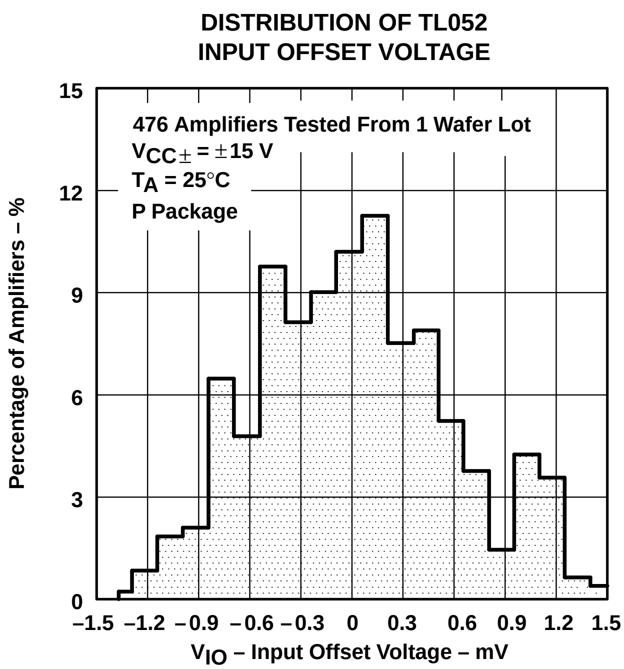

Figure 6

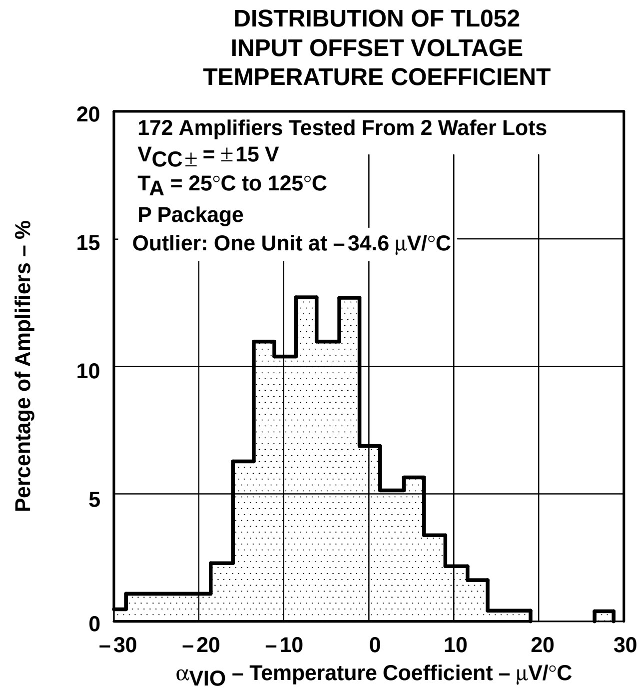

Figure 7

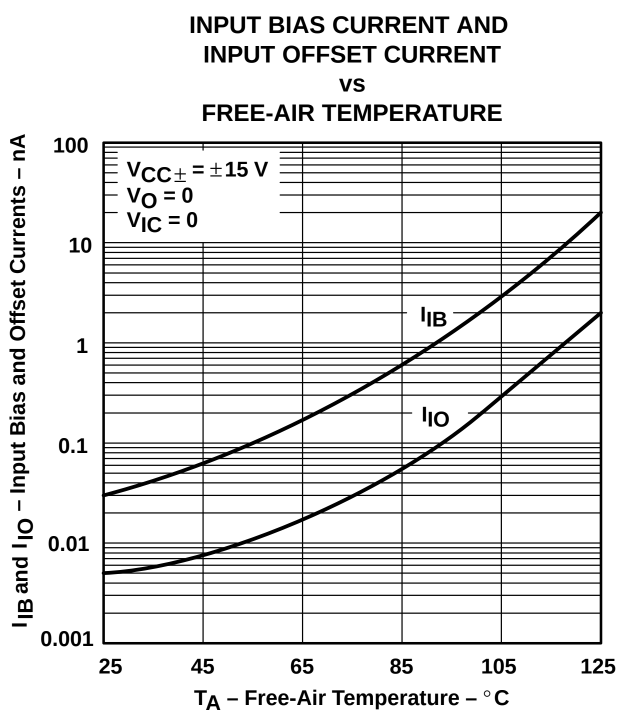

Figure 8

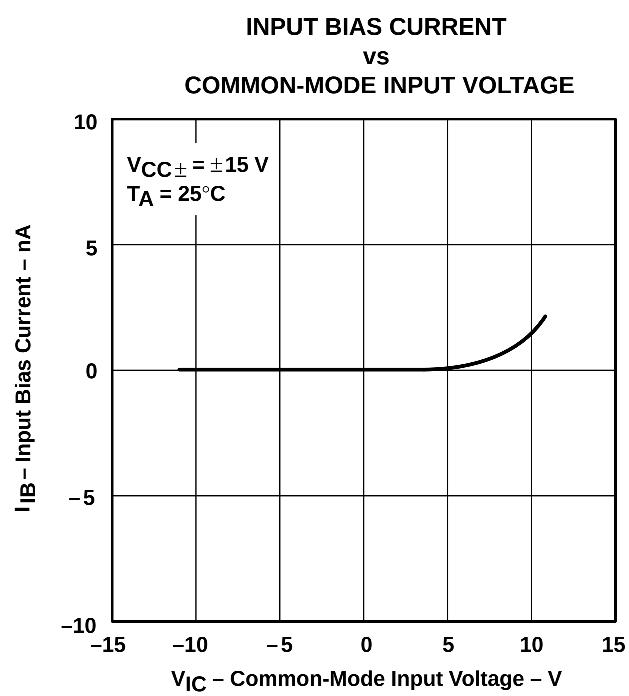

Figure 9

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

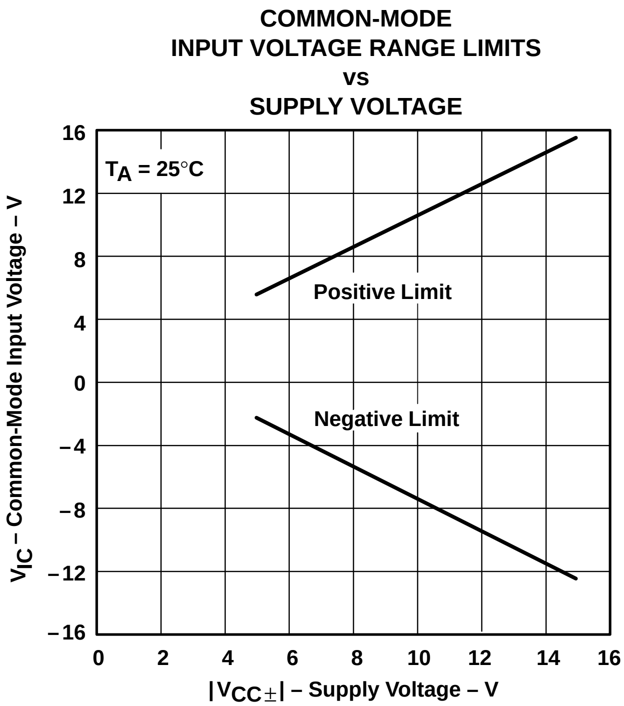

Figure 10

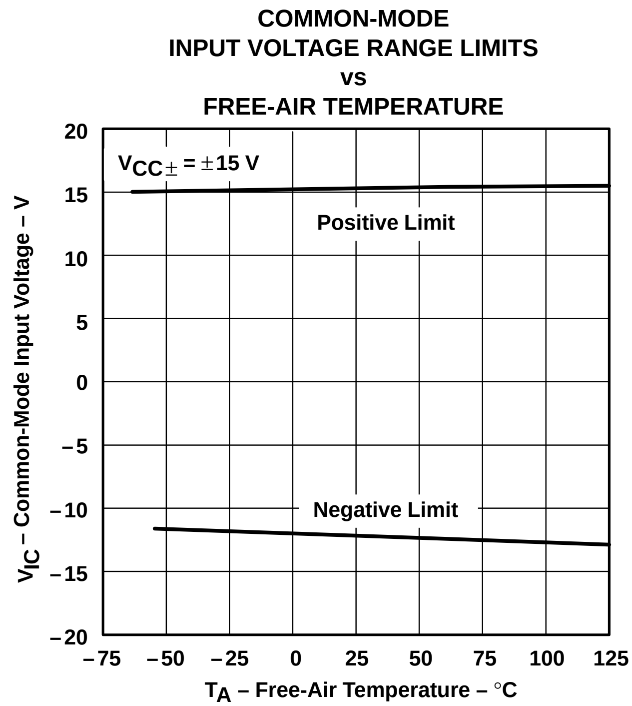

Figure 11

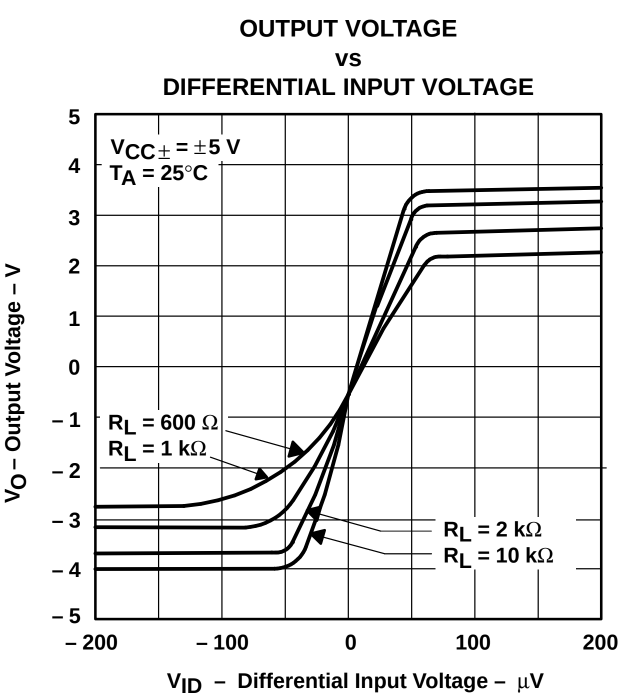

Figure 12

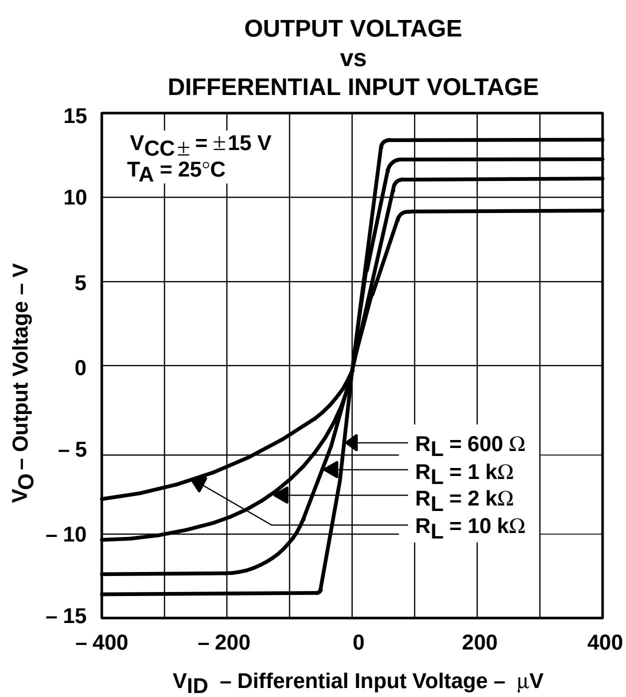

Figure 13

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

MAXIMUM PEAK OUTPUT VOLTAGE vs SUPPLY VOLTAGE

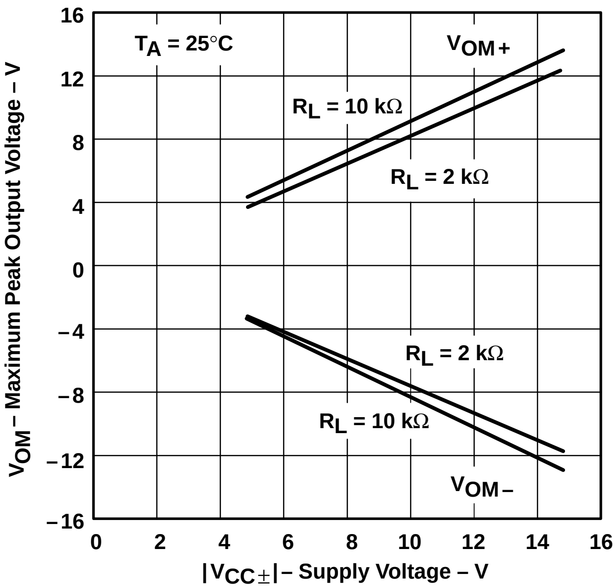

Figure 14

MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE vs FREQUENCY

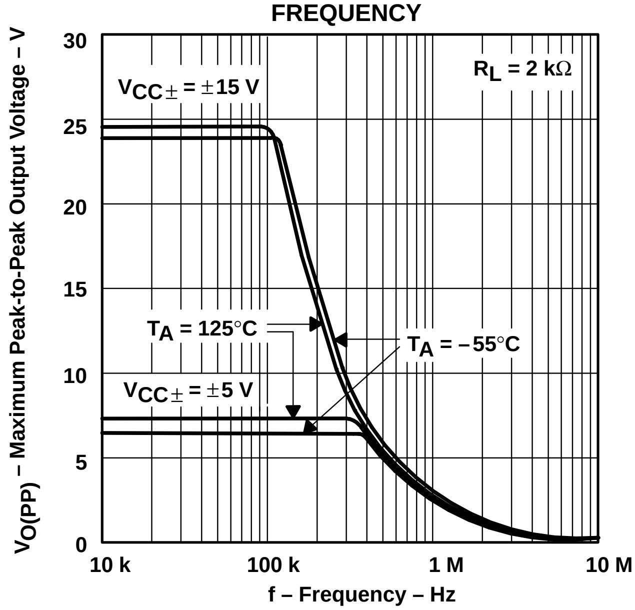

Figure 15

MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE vs FREQUENCY

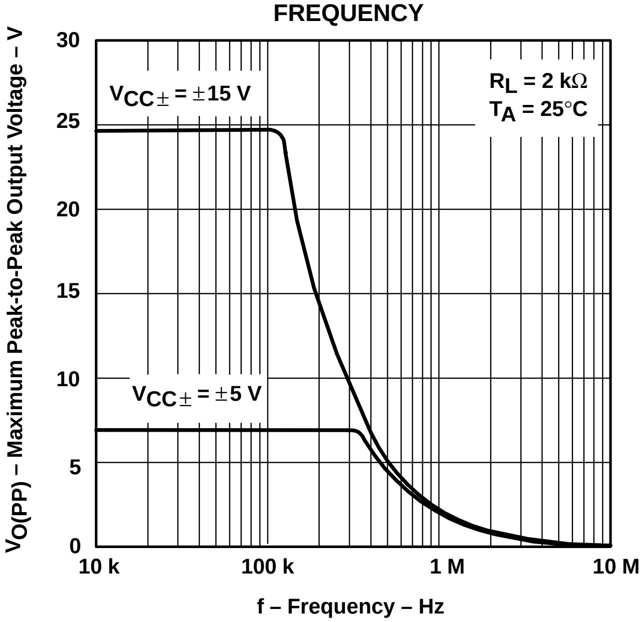

Figure 16

MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE vs FREQUENCY

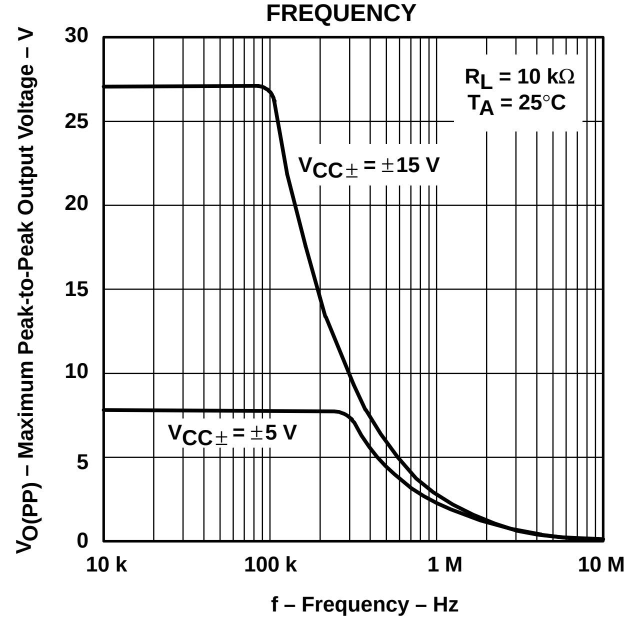

Figure 17

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

MAXIMUM PEAK OUTPUT VOLTAGE vs OUTPUT CURRENT

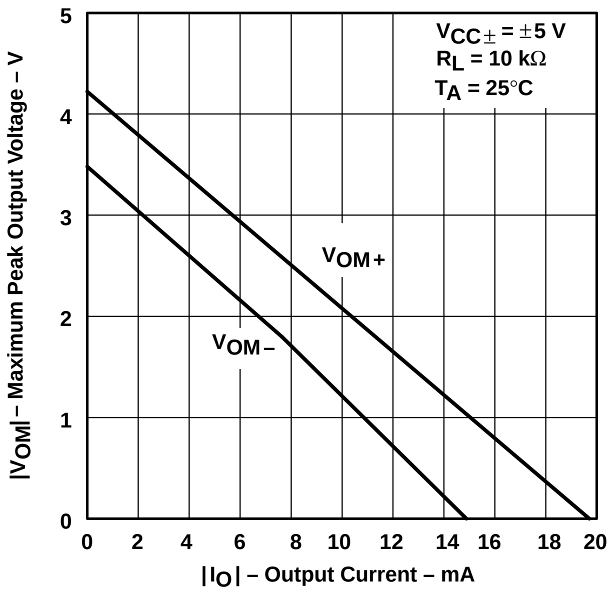

Figure 18

MAXIMUM PEAK OUTPUT VOLTAGE vs OUTPUT CURRENT

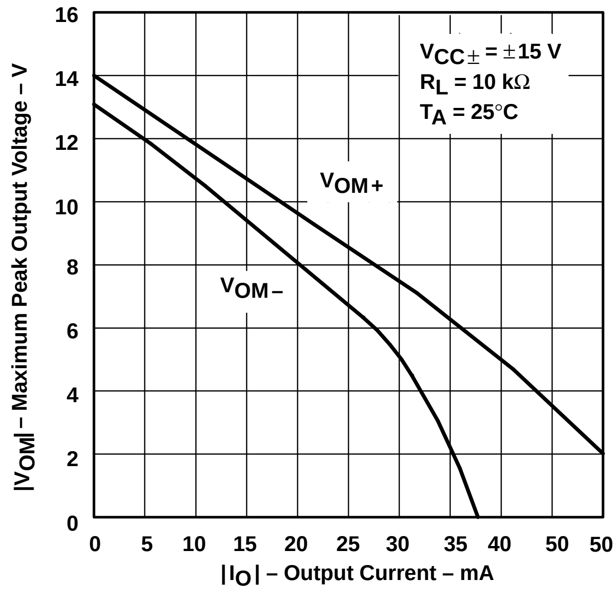

Figure 19

MAXIMUM PEAK OUTPUT VOLTAGE vs FREE-AIR TEMPERATURE

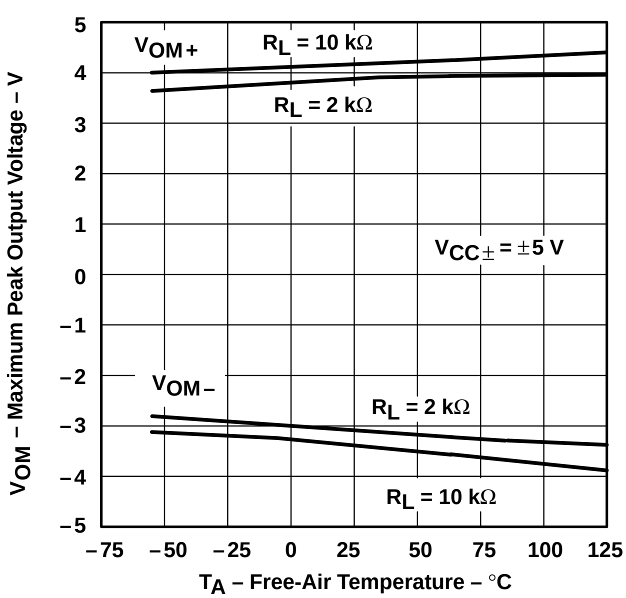

Figure 20

MAXIMUM PEAK OUTPUT VOLTAGE vs FREE-AIR TEMPERATURE

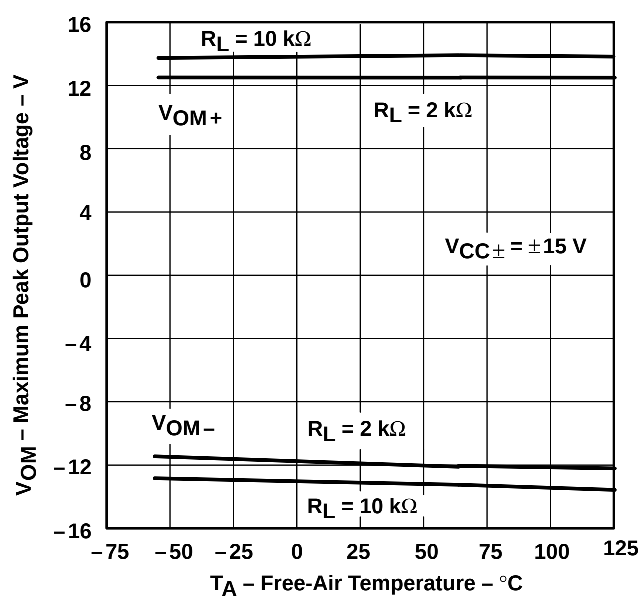

Figure 21

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

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TYPICAL CHARACTERISTICS†

LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION vs LOAD RESISTANCE

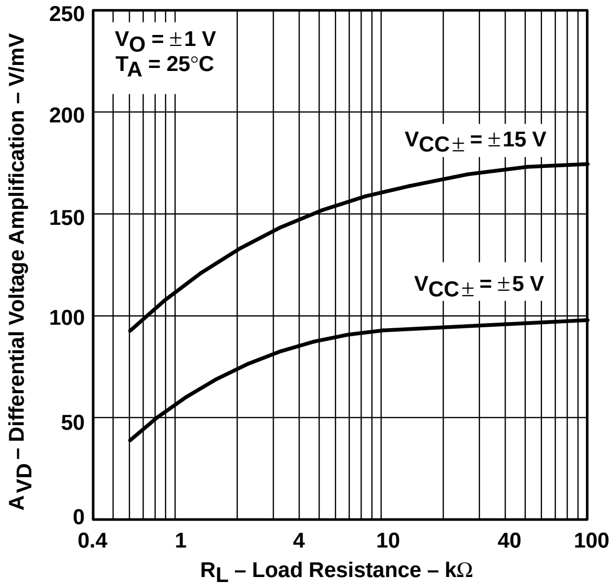

Figure 22

LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION AND PHASE SHIFT vs FREQUENCY

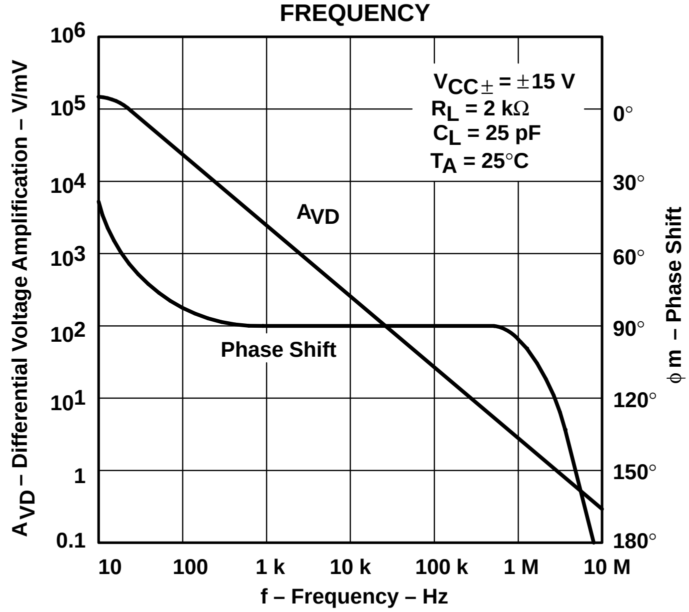

Figure 23

LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION vs FREE-AIR TEMPERATURE

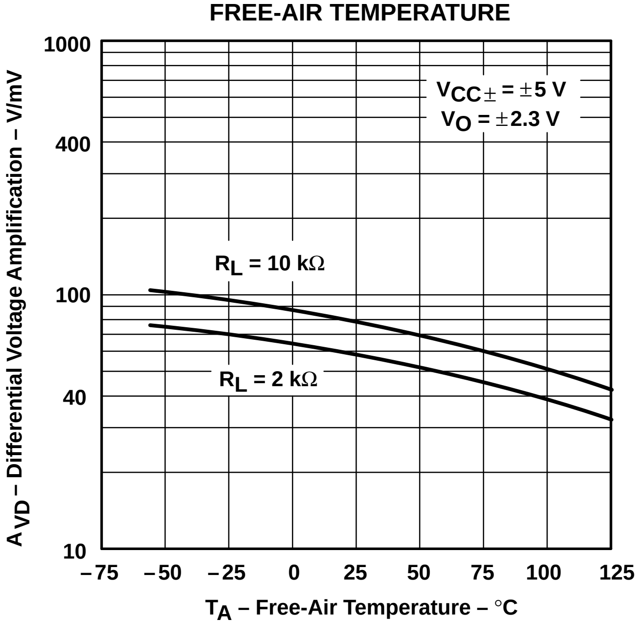

Figure 24

LARGE-SIGNAL DIFFERENTIAL VOLTAGE AMPLIFICATION vs FREE-AIR TEMPERATURE

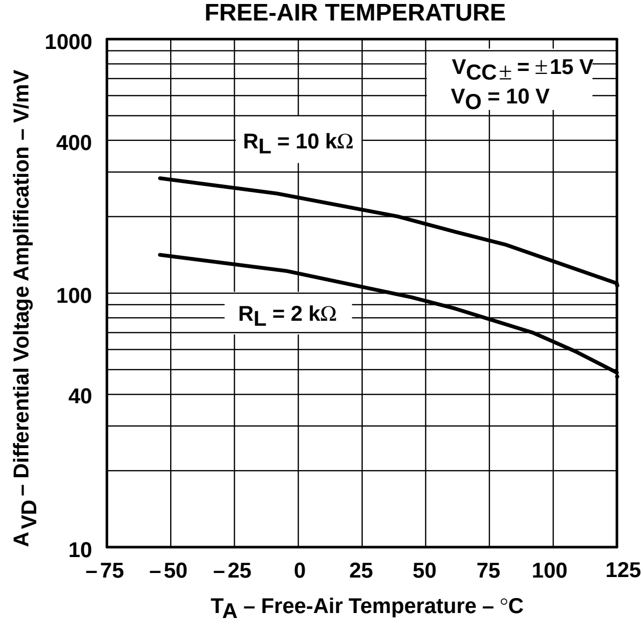

Figure 25

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

COMMON-MODE REJECTION RATIO
vs
FREQUENCY

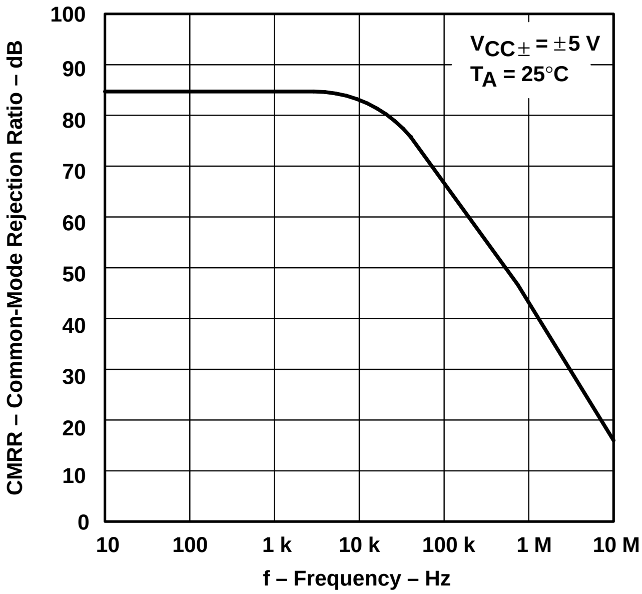

Figure 26

COMMON-MODE REJECTION RATIO
vs
FREQUENCY

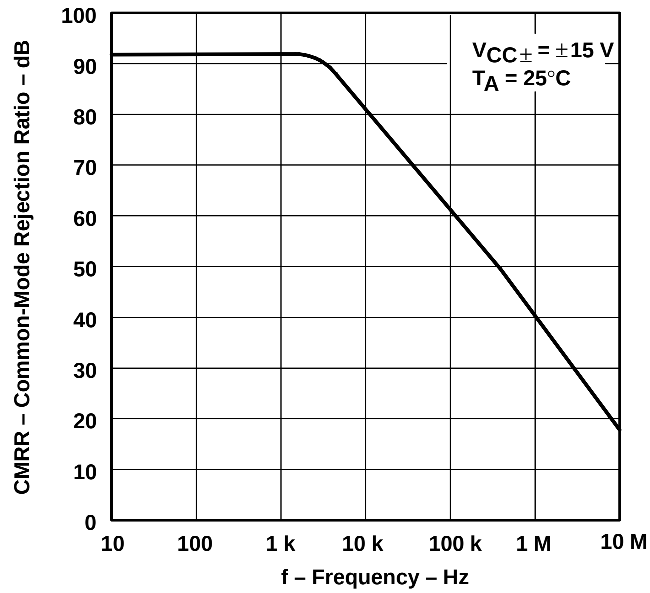

Figure 27

COMMON-MODE REJECTION RATIO
vs
FREE-AIR TEMPERATURE

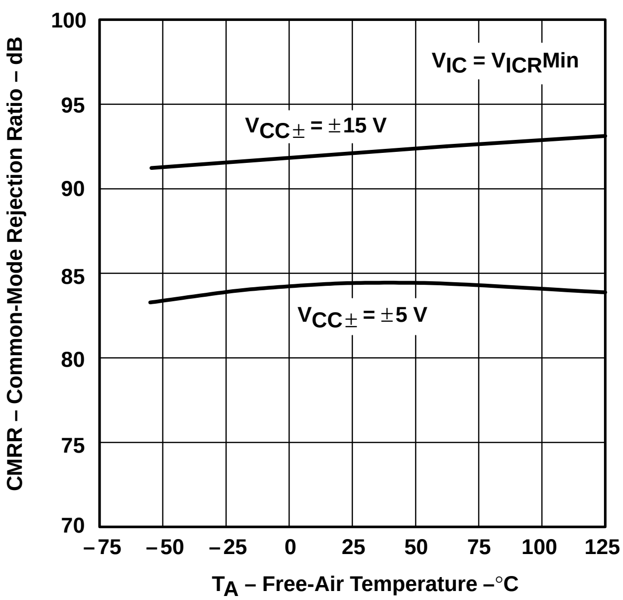

Figure 28

OUTPUT IMPEDANCE
vs
FREQUENCY

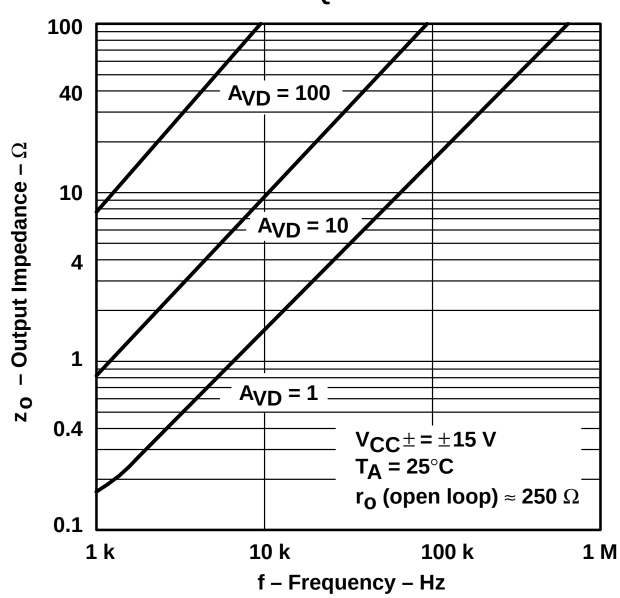

Figure 29

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

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TYPICAL CHARACTERISTICS†

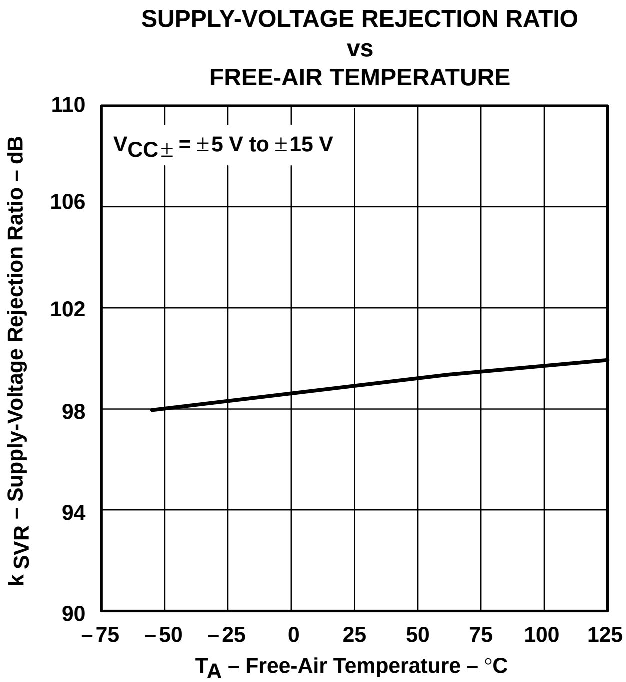

Figure 30

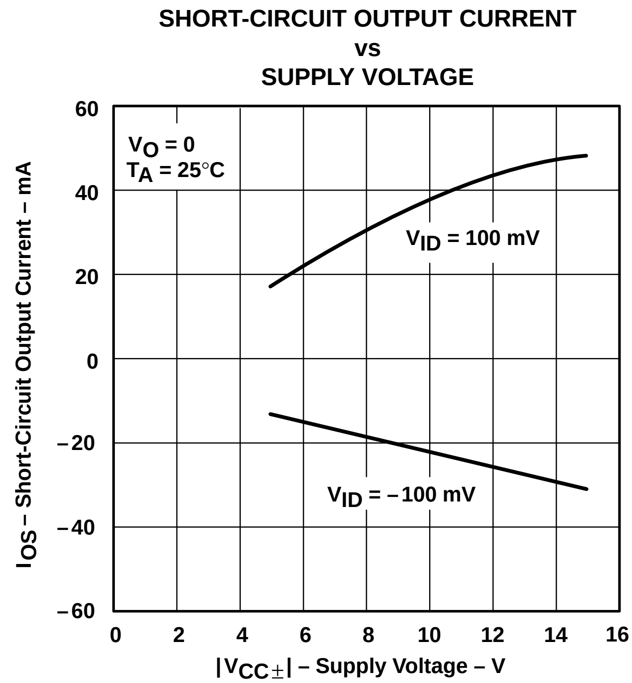

Figure 31

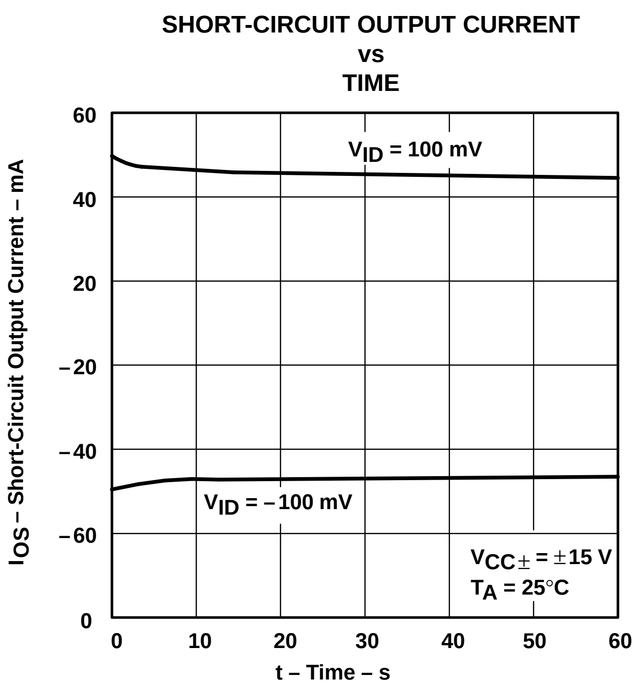

Figure 32

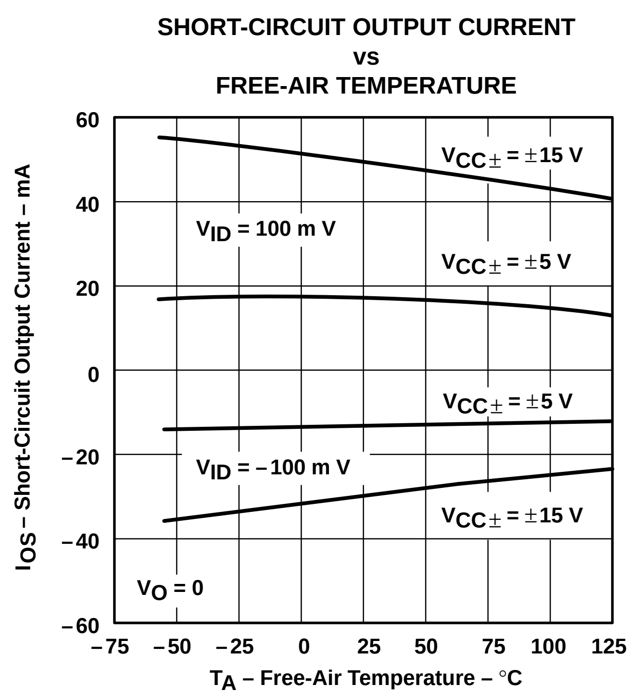

Figure 33

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

SUPPLY CURRENT vs SUPPLY VOLTAGE

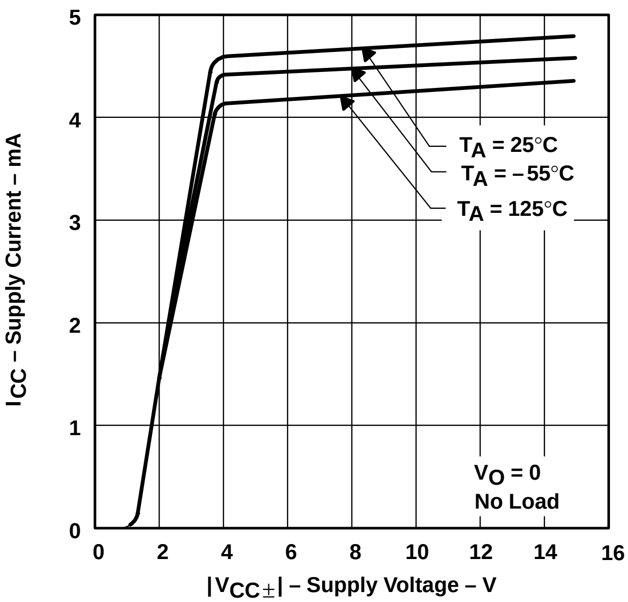

Figure 34

SUPPLY CURRENT vs FREE-AIR TEMPERATURE

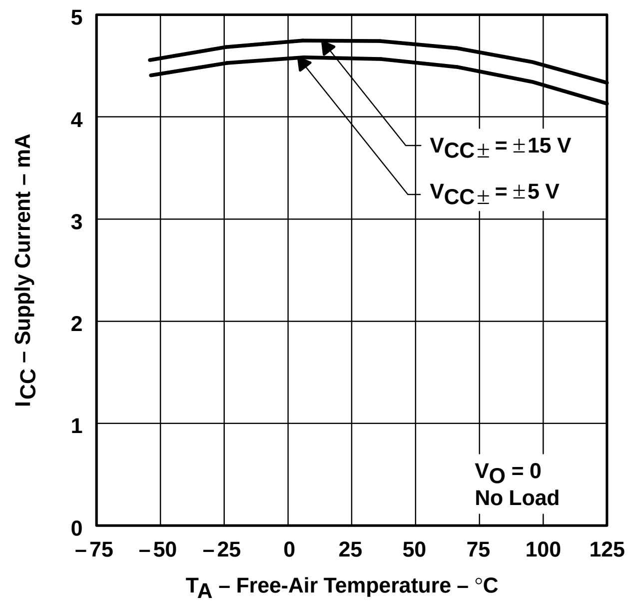

Figure 35

SLEW RATE vs LOAD RESISTANCE

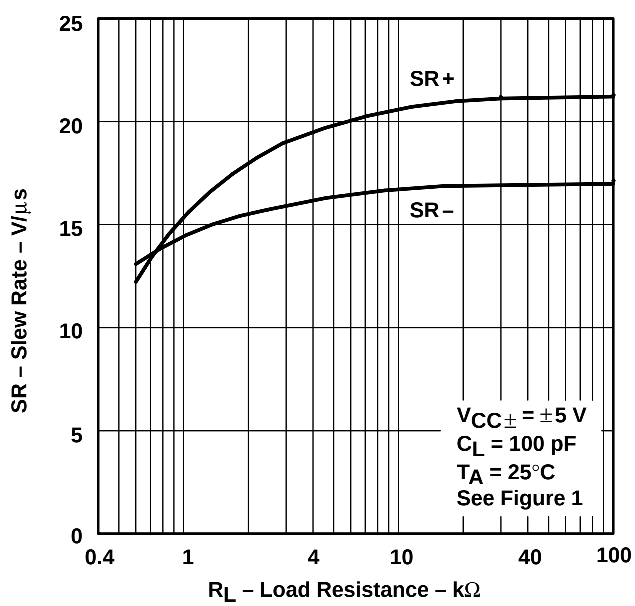

Figure 36

SLEW RATE vs LOAD RESISTANCE

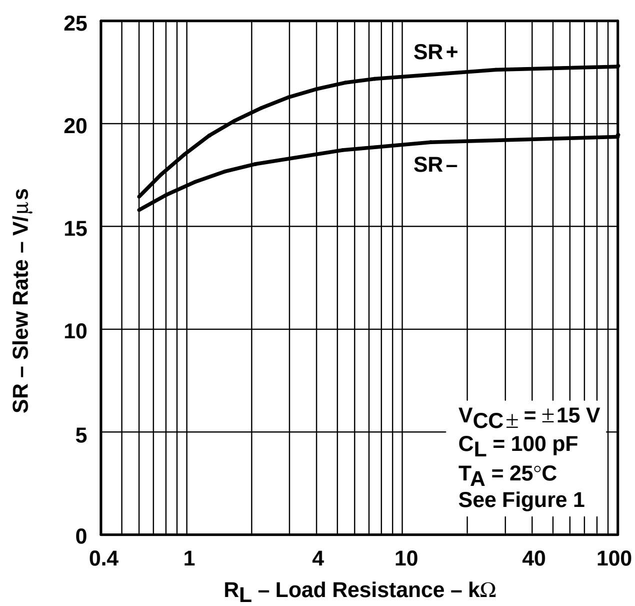

Figure 37

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

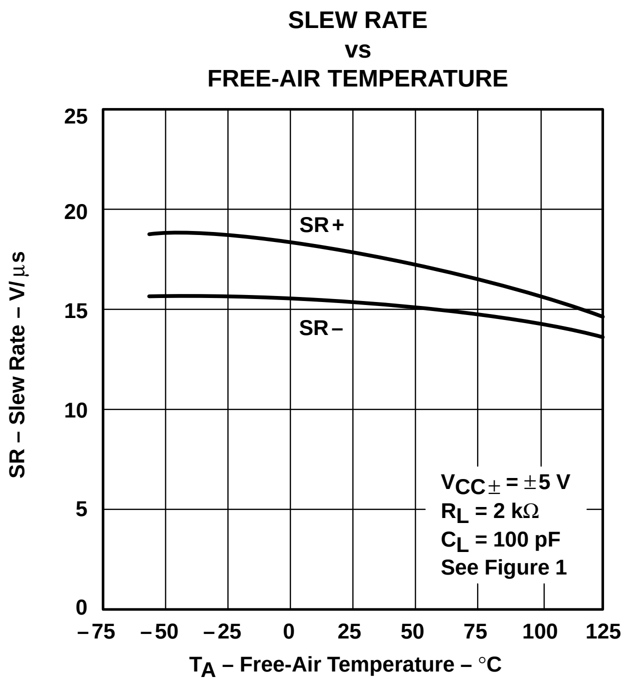

Figure 38

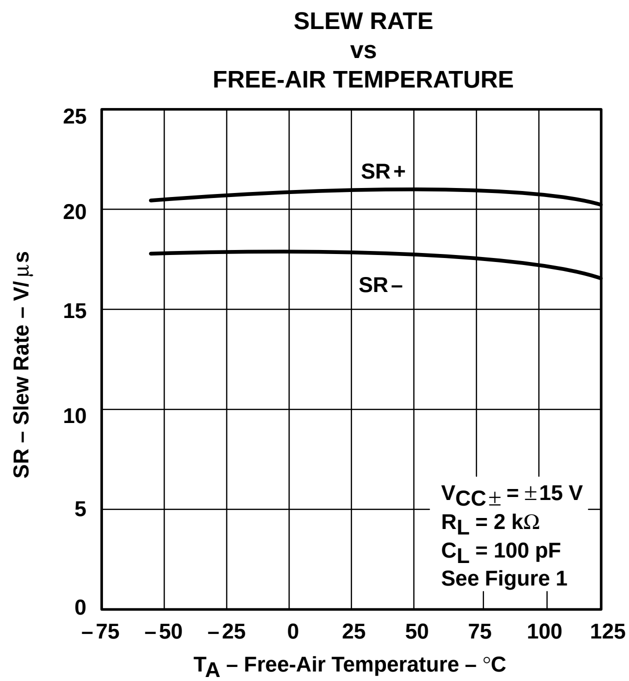

Figure 39

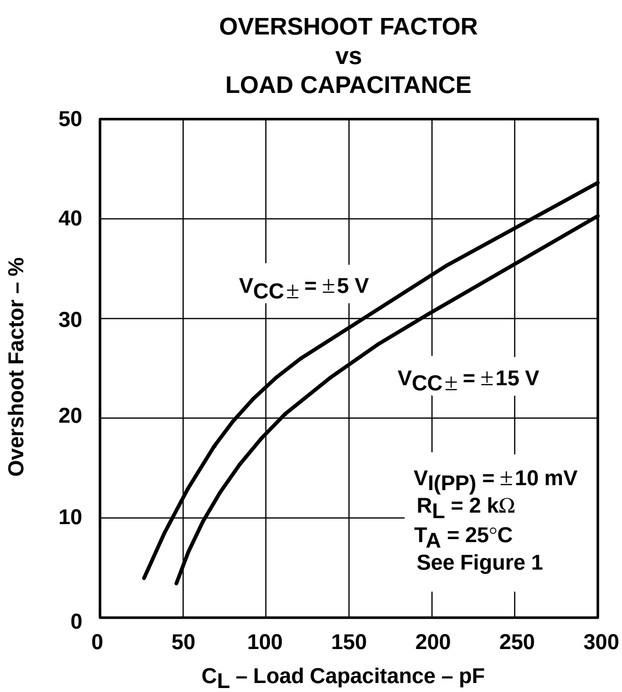

Figure 40

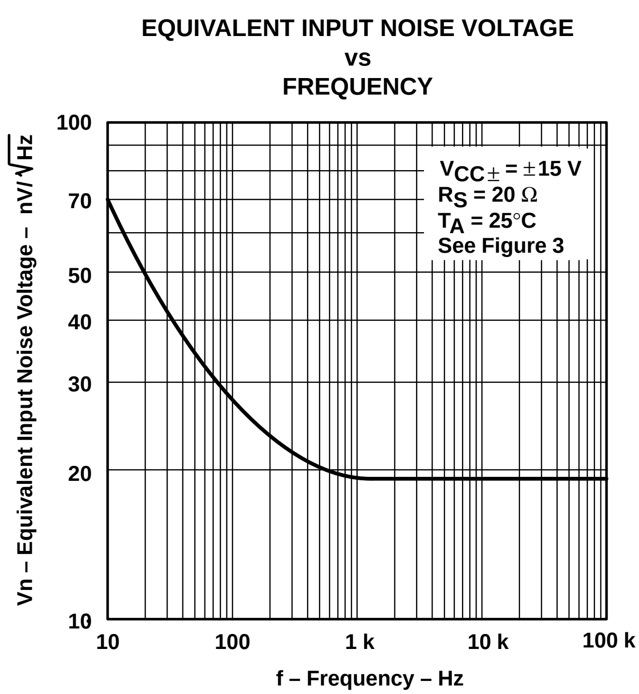

Figure 41

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

TYPICAL CHARACTERISTICS†

TOTAL HARMONIC DISTORTION
vs
FREQUENCY

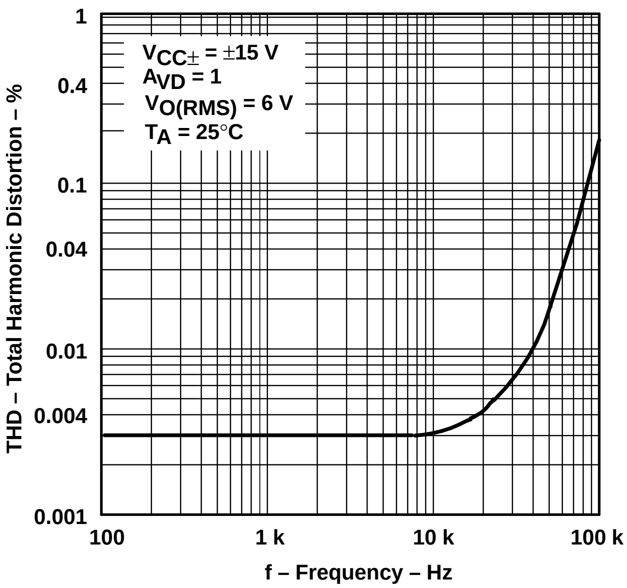

Figure 42

UNITY-GAIN BANDWIDTH
vs
SUPPLY VOLTAGE

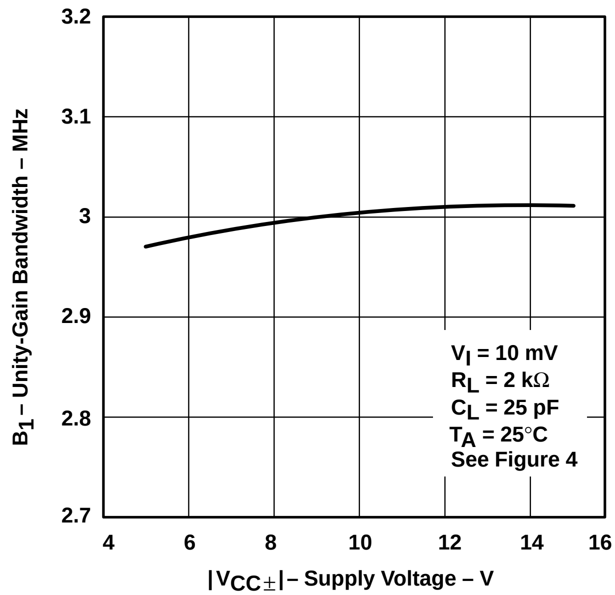

Figure 43

UNITY-GAIN BANDWIDTH
vs
FREE-AIR TEMPERATURE

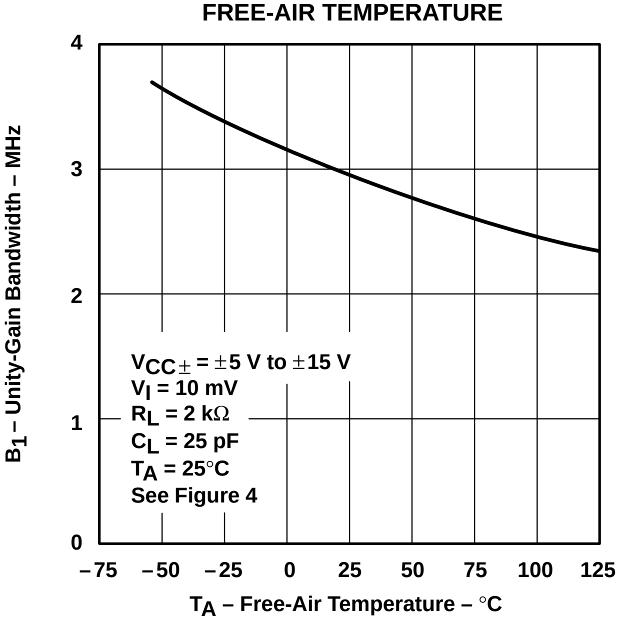

Figure 44

PHASE MARGIN
vs
SUPPLY VOLTAGE

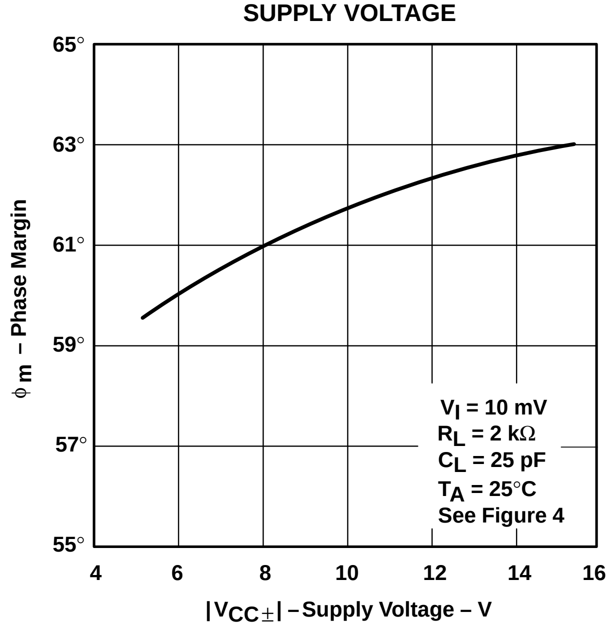

Figure 45

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

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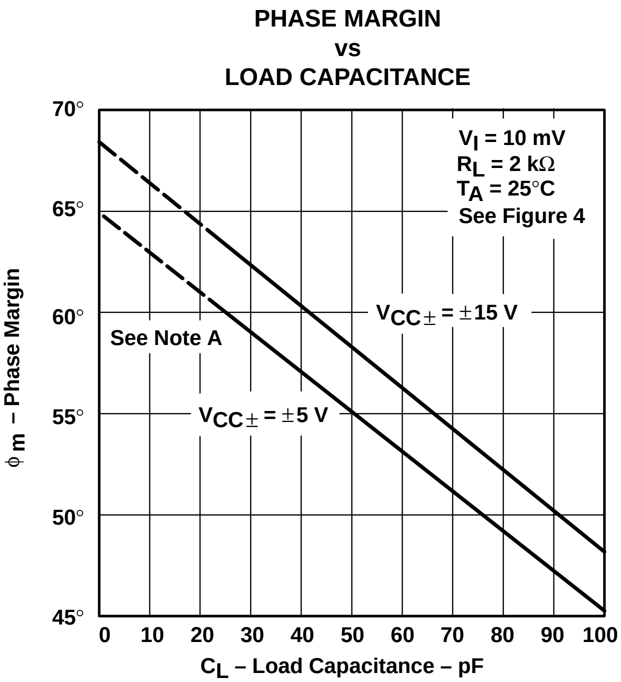
TYPICAL CHARACTERISTICS†



NOTE A: Values of phase margin below a load capacitance of 25 pF were estimated.

Figure 46

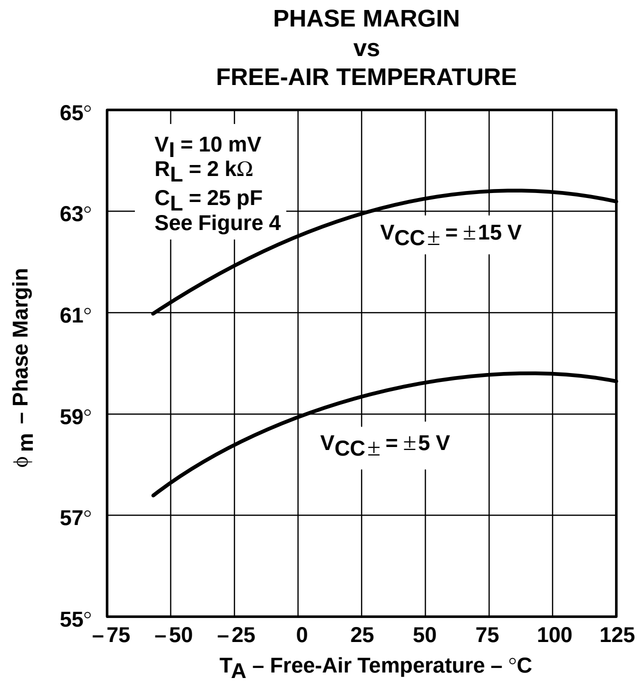


Figure 47

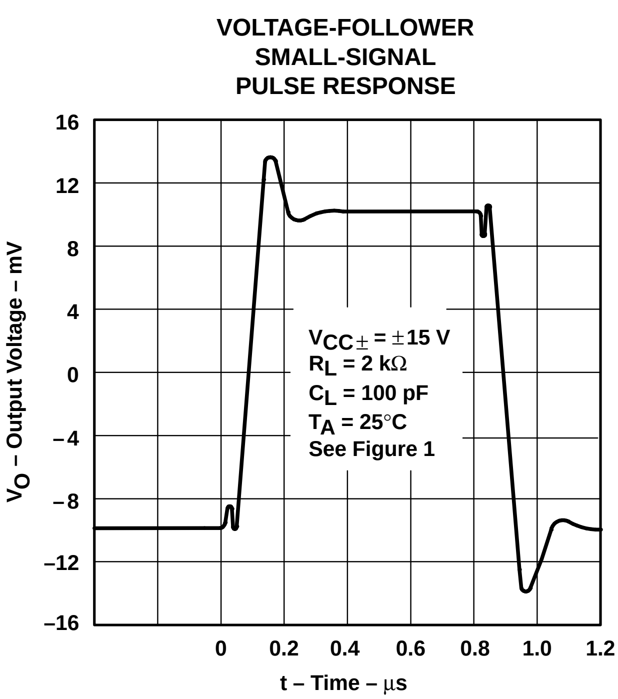


Figure 48

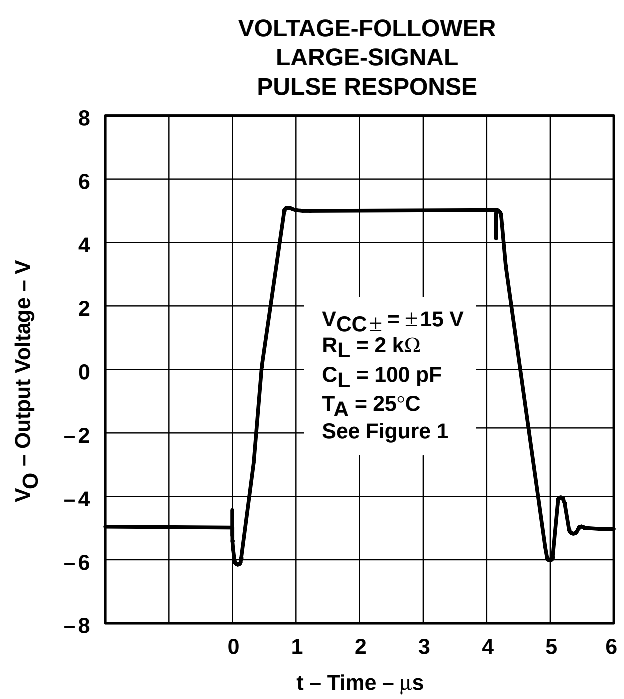


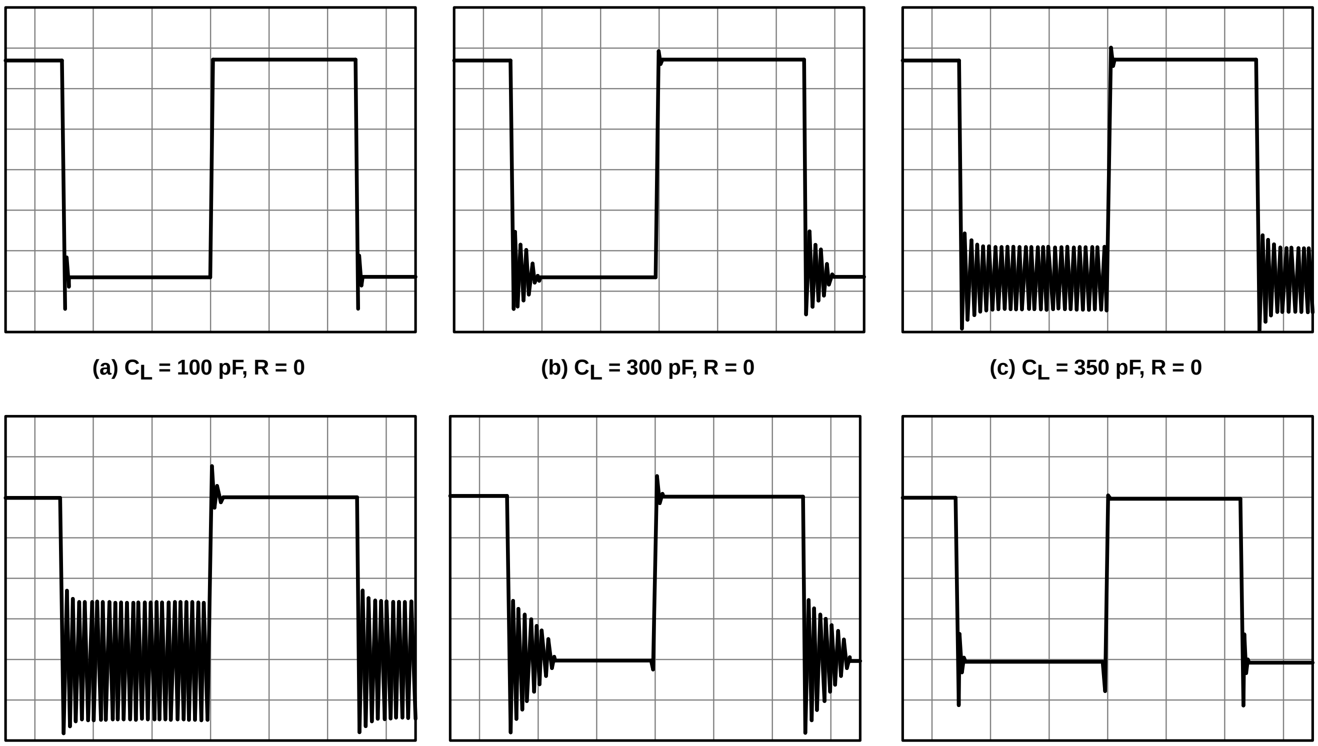
Figure 49

† Data at high and low temperatures are applicable only within the rated operating free-air temperature ranges of the various devices.

APPLICATION INFORMATION

output characteristics

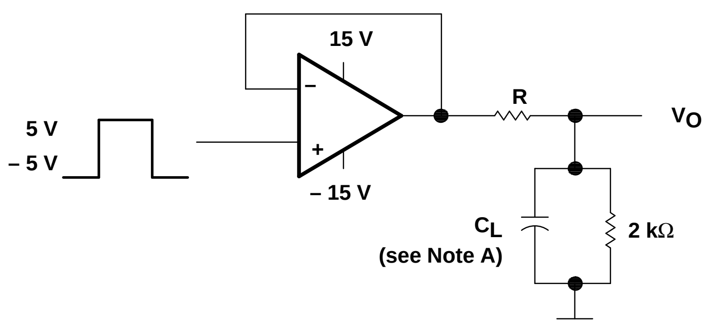
All operating characteristics (except bandwidth and phase margin) are specified with 100-pF load capacitance. The TL052 and TL052A drive higher capacitive loads; however, as the load capacitance increases, the resulting response pole occurs at lower frequencies, thereby causing ringing, peaking, or even oscillation. The value of the load capacitance at which oscillation occurs varies with production lots. If an application appears to be sensitive to oscillation due to load capacitance, adding a small resistance in series with the load should alleviate the problem. Capacitive loads of 1000 pF and larger may be driven if enough resistance is added in series with the output (see Figure 50).



(a) C_L = 100 pF, R = 0 **(b) C_L = 300 pF, R = 0** **(c) C_L = 350 pF, R = 0**

(d) C_L = 1000 pF, R = 0 **(e) C_L 1000 pF, R = 50 Ω** **(f) C_L = 1000 pF, R = 2 kΩ**

Figure 50. Effect of Capacitive Loads



NOTE A: C_L includes fixture capacitance.

Figure 51. Test Circuit for Output Characteristics

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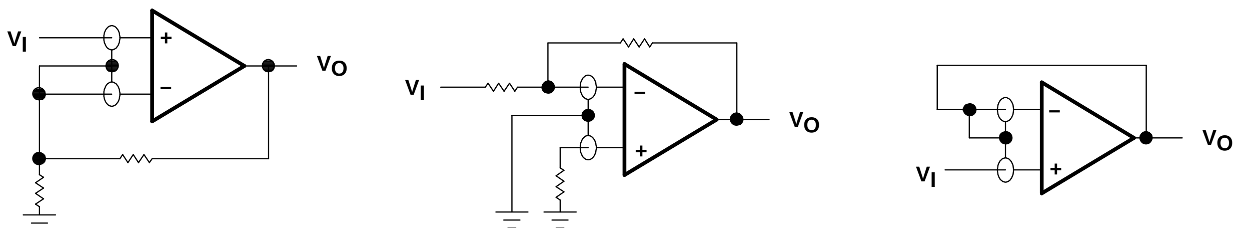
APPLICATION INFORMATION

input characteristics

The TL052 and TL052A are specified with a minimum and a maximum input voltage that, if exceeded at either input, could cause the device to malfunction.

Because of the extremely high input impedance and resulting low bias current requirements, the TL052 and TL052A are well suited for low-level signal processing; however, leakage currents on printed-circuit boards and sockets can easily exceed bias current requirements and cause degradation in system performance. It is good practice to include guard rings around inputs (see Figure 52). These guards should be driven from a low-impedance source at the same voltage level as the common-mode input.

Unused amplifiers should be connected as grounded unity-gain followers to avoid possible oscillation.



(a) NONINVERTING AMPLIFIER **(b) INVERTING AMPLIFIER** **(c) UNITY-GAIN AMPLIFIER**

Figure 52. Use of Guard Rings

noise performance

The noise specifications in operational amplifier circuits are greatly dependent on the current in the first-stage differential amplifier. The low input bias current requirements of the TL052 and TL052A result in a very low current noise. This feature makes the devices especially favorable over bipolar devices when using values of circuit impedance greater than 50 kΩ.

APPLICATION INFORMATION

instrumentation amplifier with adjustable gain/null

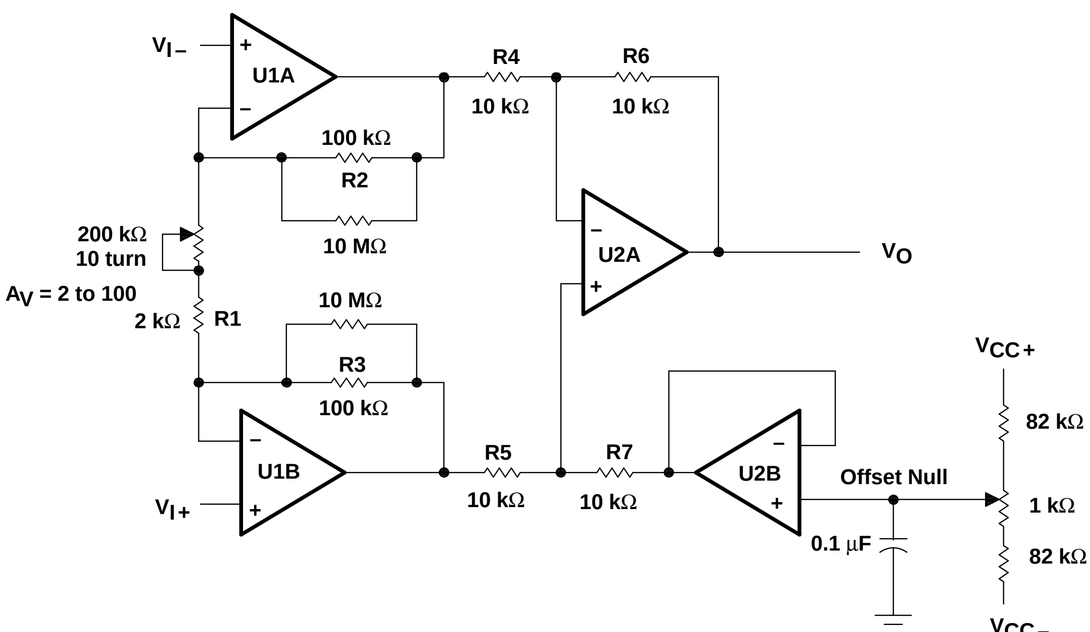
The instrumentation amplifier in Figure 53 benefits greatly from the high input impedance and stable input offset voltage of the TL052A. Amplifiers U1A, U1B, and U2A form the actual instrumentation amplifier, while U2B provides offset null. Potentiometer R1 provides gain adjust. With R1 = 2 kΩ, the circuit gain equals 100, while with R1 = 200 kΩ, the circuit gain equals two. The following equation shows the instrumentation amplifier gain as a function of R1:

$$A_V = 1 + \left(\frac{R2 + R3}{R1}\right)$$

Readjusting the offset null is necessary whenever the circuit gain is changed. If U2B is needed for another application, R7 can be terminated at ground. The low input offset voltage of the TL052A minimizes the dc error of the circuit. For best matching, all resistors should be one percent tolerance. The matching between R4, R5, R6, and R7 controls the CMRR of this application.

The following equation shows the output voltages when the input voltage equals zero. This dc error can be nulled by adjusting the offset null potentiometer; however, any change in offset voltage over time or temperature also creates an error. To calculate the error from changes in offset, consider the three offset components in the equation as delta offsets rather than initial offsets. The improved stability of Texas Instruments enhanced JFETs minimizes the error resulting from change in input offset voltage with time. Assuming V_I equals zero, V_O can be shown as a function of the offset voltage:

$$V_O = V_{IO2}\left[\left(1 + \frac{R3}{R1}\right)\left(\frac{R7}{R5 + R7}\right)\left(1 + \frac{R6}{R4}\right) + \frac{R2}{R1}\left(\frac{R6}{R4}\right)\right]$$
$$-V_{IO1}\left[\frac{R3}{R1}\left(\frac{R7}{R5 + R7}\right)\left(1 + \frac{R6}{R4}\right) + \frac{R6}{R4}\left(1 + \frac{R2}{R1}\right)\right] + V_{IO3}\left(1 + \frac{R6}{R4}\right)$$



NOTE: U1 and U2 = TL052A; $V_{CC\pm} = \pm 15$ V.

Figure 53. Instrumentation Amplifier

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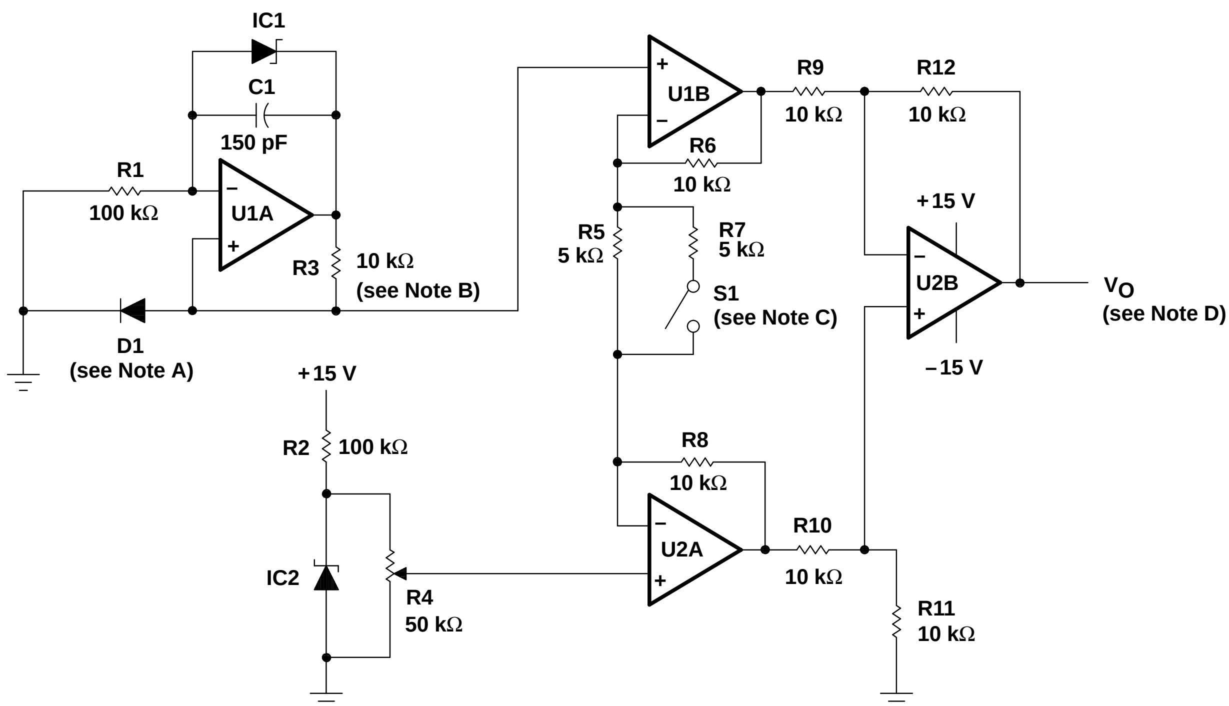
APPLICATION INFORMATION

analog thermometer

By combining a current source that does not vary over temperature with an instrumentation amplifier, a precise analog thermometer can be built (see Figure 54). Amplifier U1A and IC1 establish a constant current through the temperature-sensing diode D1. For this section of the circuit to operate correctly, the TL052 must use split supplies and R3 must be a metal-film resistor with a low temperature coefficient.

The temperature-sensitive voltage from the diode is compared to a temperature-stable voltage reference set by IC2. R4 should be adjusted to provide the correct output voltage when the diode is at a known temperature. Although this potentiometer resistance varies with temperature, the divider ratio of the potentiometer remains constant.

Amplifiers U1B, U2A, and U2B form the instrumentation amplifier that converts the difference between the diode and reference voltage to a voltage proportional to the temperature. With switch S1 closed, the amplifier gain equals 5 and the output voltage is proportional to temperature in degrees Celsius. With S1 open, the amplifier gain is 9 and the output is proportional to temperature in degrees Fahrenheit. Every time that S1 is changed, R4 must be recalibrated. By setting S1 correctly, the output voltage equals 10 mV per degree (C or F).



NOTES: A. Temperature-sensing diode ≈ (–2 mV/°C)
B. Metal-film resistor (low temperature coefficient)
C. Switch open for °F and closed for °C
D. V_O α temperature; 10 mV/°C or 10 mV/°F
E. U1, U2 = TL052. IC1, IC2 = LM385, LT1004, or LT1009 voltage reference

Figure 54. Analog Thermometer

APPLICATION INFORMATION

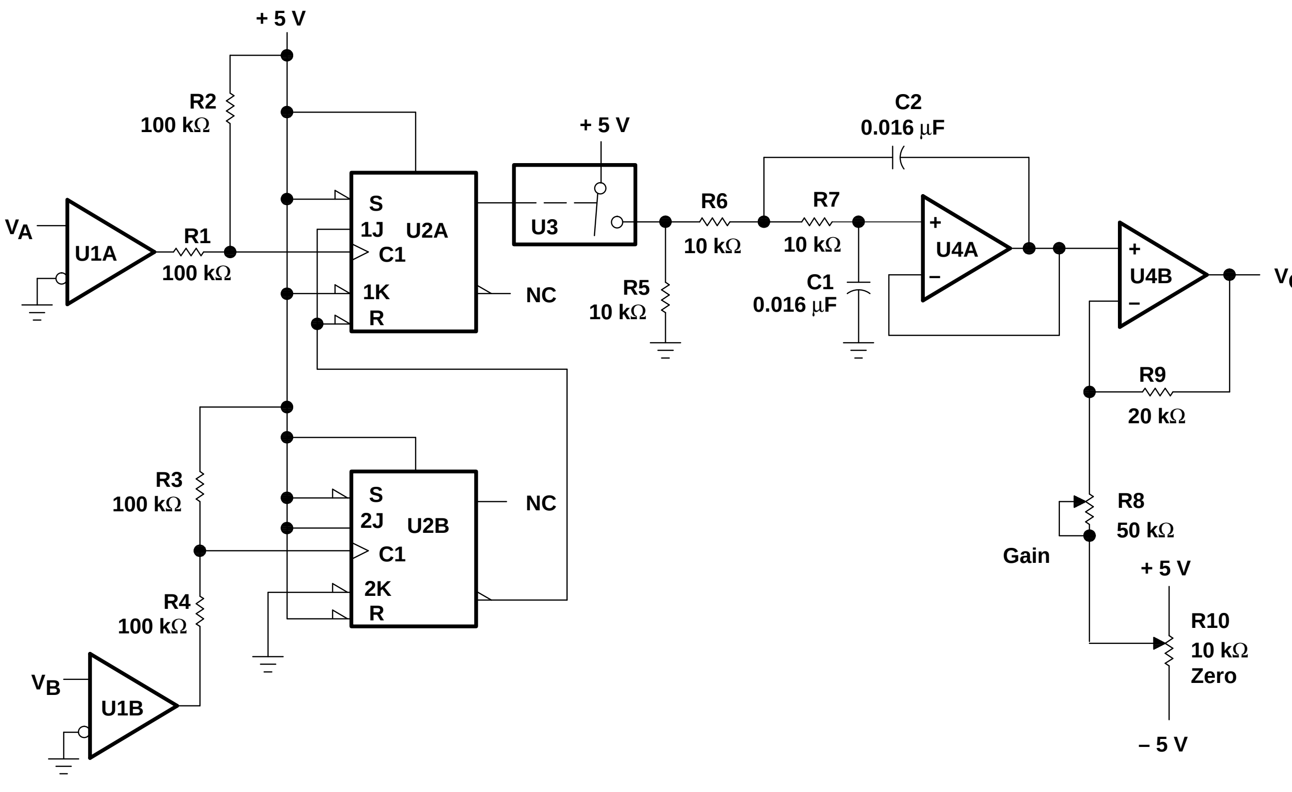
phase meter

The phase meter in Figure 55 produces an output voltage of 10 mV per degree of phase delay between the two input signals V_A and V_B. The reference signal V_A must be the same frequency as V_B. The TLC3702 comparators (U1) convert these two input sine waves into ±5-V square waves. Then R1 and R4 provide level shifting prior to the SN74HC109 dual J-K flip flops.

Flip-flop U2B is connected as a toggle flip-flop and generates a square wave at half the frequency of V_B. Flip-flop U2A also produces a square wave at half the input frequency. The pulse duration of U2A varies from zero to half the period, where zero corresponds to zero phase delay between V_A and V_B and half the period corresponds to V_B lagging V_A by 360 degrees.

The output pulse from U2A causes the TLC4066 (U3) switch to charge the TL052 (U4) integrator capacitors C1 and C2. As the phase delay approaches 360 degrees, the output of U4A approximates a square wave and U2A has an output of almost 2.5 V. U4B acts as a noninverting amplifier with a gain of 1.44 in order to scale the 0- to 2.5-V integrator output to a 0- to 3.6-V output range.

R8 and R10 provide output gain and zero-level calibration. This circuit operates over a 100-Hz to 10-kHz frequency range.



NOTES: U1 = TLC3702; $V_{CC\pm}$ = ±5 V
U2 = SN74HC109
U3 = TLC4066
U4, U5 = TL051; $V_{CC\pm}$ = ±5 V

Figure 55. Phase Meter

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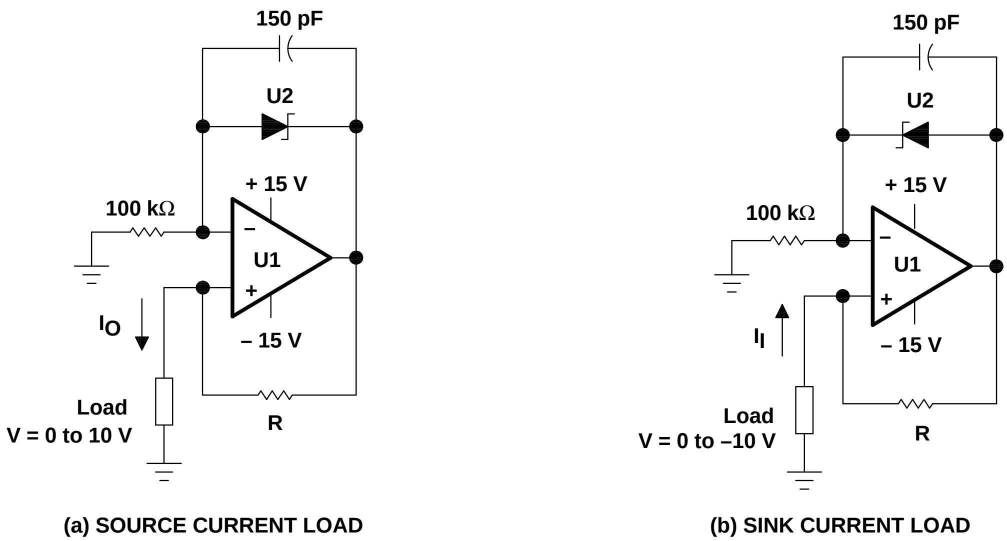
APPLICATION INFORMATION

precision constant-current source over temperature

A precision current source benefits from the high input impedance and stability of Texas Instruments enhanced-JFET process. A low-current shunt regulator maintains 2.5 V between the inverting input and the output of the TL052. The negative feedback then forces 2.5 V across the current setting resistor R; therefore, the current to the load is simply 2.5 V divided by R.

Possible choices for the shunt regulator include the LT1004, LT1009, and LM385. If the regulator's cathode connects to the operational amplifier output, this circuit sources load current. Similarly, if the cathode connects to the inverting input, the circuit sinks current from the load. To minimize output current change with temperature, R should be a metal film resistor with a low temperature coefficient. Also, this circuit must be operated with split-voltage supplies.



NOTES: U1 = 1/2 TL052
U2 = LM385, LT1004, or LT1009 voltage reference
$I = \frac{2.5\ V}{R}$, R = Low temperature coefficient metal film resistor

Figure 56. Precision Constant-Current Source