

TLC4501, TLC4501A, TLC4502, TLC4502A
FAMILY OF SELF-CALIBRATING (Self-Cal™)
PRECISION CMOS RAIL-TO-RAIL OUTPUT OPERATIONAL AMPLIFIERS

SLOS221B – MAY 1998 – REVISED APRIL 2001

- Self-Calibrates Input Offset Voltage to 40 μV Max
- Low Input Offset Voltage Drift . . . 1 $\mu\text{V}/^\circ\text{C}$
- Input Bias Current . . . 1 pA
- Open Loop Gain . . . 120 dB
- Rail-To-Rail Output Voltage Swing
- Stable Driving 1000 pF Capacitive Loads
- Gain Bandwidth Product . . . 4.7 MHz
- Slew Rate . . . 2.5 V/ μs
- High Output Drive Capability . . . ± 50 mA
- Calibration Time . . . 300 ms
- Characterized From -55°C to 125°C
- Available in Q-Temp Automotive HighRel Automotive Applications Configuration Control / Print Support Qualification to Automotive Standards

description

The TLC4501 and TLC4502 are the highest precision CMOS single supply rail-to-rail operational amplifiers available today. The input offset voltage is 10 μV typical and 40 μV maximum. This exceptional precision, combined with a 4.7-MHz bandwidth, 2.5-V/ μs slew rate, and 50-mA output drive, is ideal for multiple applications including: data acquisition systems, measurement equipment, industrial control applications, and portable digital scales.

These amplifiers feature *self-calibrating* circuitry which digitally trims the input offset voltage to less than 40 μV within the first 300 ms of operation. The offset is then digitally stored in an integrated successive approximation register (SAR). Immediately after the data is stored, the calibration circuitry effectively drops out of the signal path, shuts down, and the device functions as a standard operational amplifier.

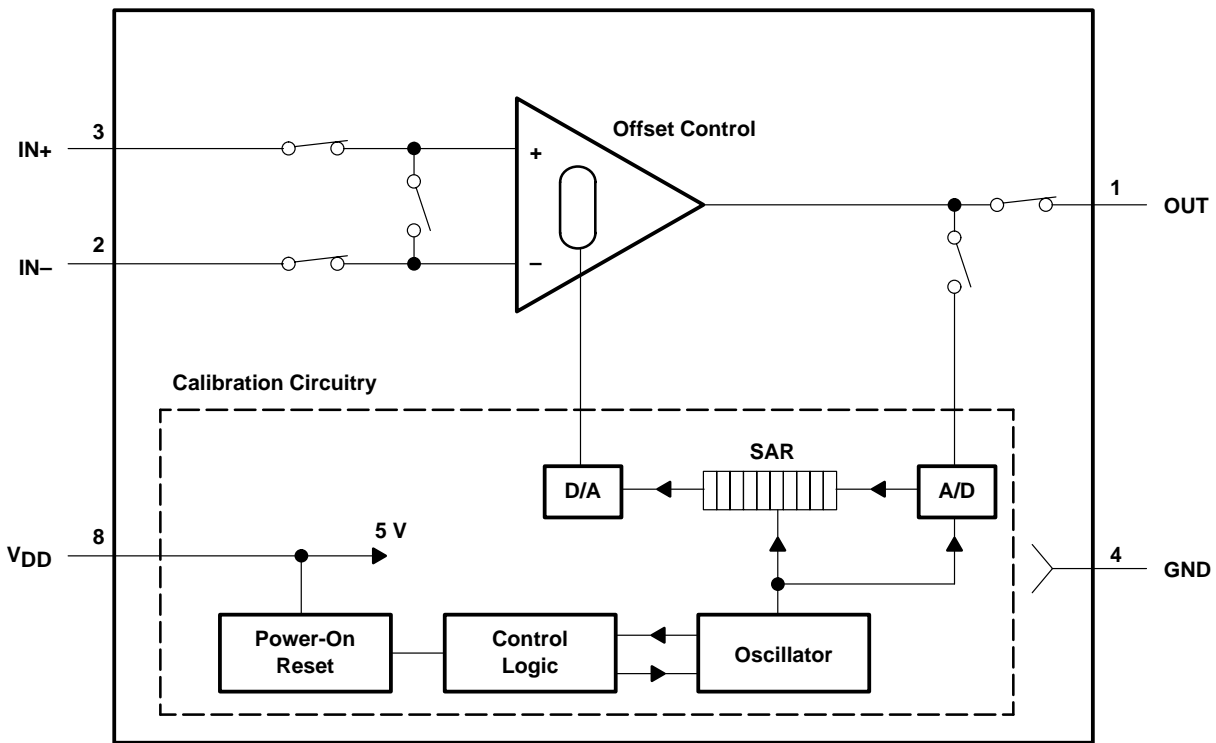


Figure 1. Channel One of the TLC4502



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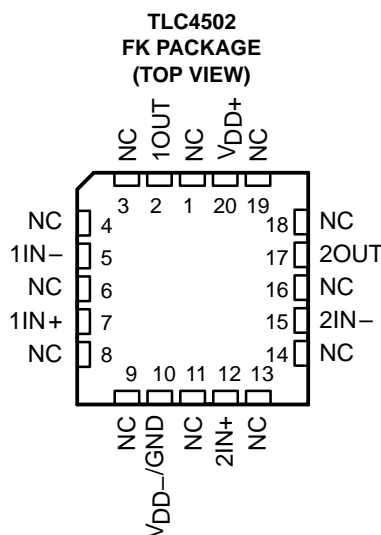
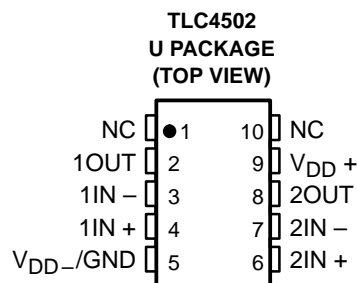
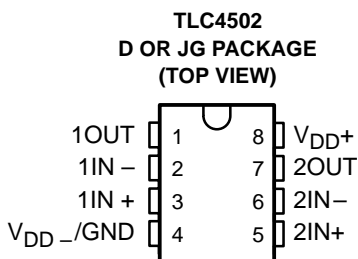
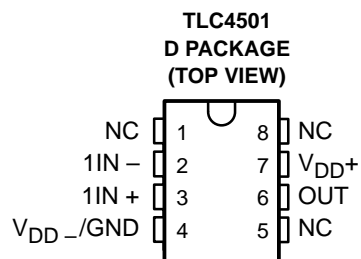
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 On products compliant to MIL-PRF-38535, all parameters are tested unless otherwise noted. On all other products, production processing does not necessarily include testing of all parameters.

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description (continued)

Using this technology eliminates the need for noisy and expensive chopper techniques, laser trimming, and power hungry, split supply bipolar operational amplifiers.



NC – No internal connection

AVAILABLE OPTIONS

| T _A | V _{IO} max AT 25°C | PACKAGED DEVICES | | | |
|----------------|-----------------------------|--------------------|-------------------|------------------|-----------------------|
| | | SMALL OUTLINE† (D) | CHIP CARRIER (FK) | CERAMIC DIP (JG) | CERAMIC FLAT PACK (U) |
| 0°C to 70°C | 40 μV | TLC4501ACD | — | — | — |
| | 50 μV | TLC4502ACD | — | — | — |
| | 80 μV | TLC4501CD | — | — | — |
| | 100 μV | TLC4502CD | — | — | — |
| -40°C to 125°C | 40 μV | TLC4501AID | — | — | — |
| | 50 μV | TLC4502AID | — | — | — |
| | 80 μV | TLC4501ID | — | — | — |
| | 100 μV | TLC4502ID | — | — | — |
| -40°C to 125°C | 50 μV | TLC4502AQD | — | — | — |
| | 100 μV | TLC4502QD | — | — | — |
| -55°C to 125°C | 50 μV | TLC4502AMD | TLC4502AMFKB | TLC4502AMJGB | TLC4502AMUB |
| | 100 μV | TLC4502MD | TLC4502MFKB | TLC4502MJGB | TLC4502MUB |

† The D package is also available taped and reeled.



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

| | |
|---|------------------------------|
| Supply voltage, V_{DD+} (see Note 1) | 7 V |
| Differential input voltage, V_{ID} (see Note 2) | ± 7 V |
| Input voltage range, V_I (any input, see Note 1) | –0.3 V to 7 V |
| Input current, I_I (each input) | ± 5 mA |
| Output current, I_O (each output) | ± 100 mA |
| Total current into V_{DD+} | ± 100 mA |
| Total current out of V_{DD-}/GND | ± 100 mA |
| Electrostatic discharge (ESD) | > 2 kV |
| Duration of short-circuit current at (or below) 25°C (see Note 3) | unlimited |
| Continuous total power dissipation | See Dissipation Rating Table |
| Operating free-air temperature range, T_A : TLC4502C | 0°C to 70°C |
| TLC4502I | –40°C to 125°C |
| TLC4502Q | –40°C to 125°C |
| TLC4502M | –55°C to 125°C |
| Storage temperature range, T_{stg} | –65°C to 150°C |
| Case temperature for 60 seconds, T_C : FK package | 260°C |
| Lead temperature 1,6 mm (1/16 inch) from case for 10 seconds | 260°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 V_{DD-}/GND .
2. Differential voltages are at $IN+$ with respect to $IN-$. Excessive current flows when an input is brought below $V_{DD-} - 0.3$ V.
3. 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 | $T_A \leq 25^\circ\text{C}$ POWER RATING | DERATING FACTOR ABOVE $T_A = 25^\circ\text{C}$ | $T_A = 70^\circ\text{C}$ POWER RATING | $T_A = 85^\circ\text{C}$ POWER RATING | $T_A = 125^\circ\text{C}$ 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 |
| U | 675 mW | 5.4 mW/°C | 432 mW | 350 mW | 135 mW |

recommended operating conditions

| | TLC4502C | | TLC4502I | | TLC4502Q | | TLC4502M | | UNIT |
|---------------------------------------|-----------|-----------------|-----------|-----------------|-----------|-----------------|-----------|-----------------|------|
| | MIN | MAX | MIN | MAX | MIN | MAX | MIN | MAX | |
| Supply voltage, V_{DD} | 4 | 6 | 4 | 6 | 4 | 6 | 4 | 6 | V |
| Input voltage range, V_I | V_{DD-} | $V_{DD+} - 2.3$ | V_{DD-} | $V_{DD+} - 2.3$ | V_{DD-} | $V_{DD+} - 2.3$ | V_{DD-} | $V_{DD+} - 2.3$ | V |
| Common-mode input voltage, V_{IC} | V_{DD-} | $V_{DD+} - 2.3$ | V_{DD-} | $V_{DD+} - 2.3$ | V_{DD-} | $V_{DD+} - 2.3$ | V_{DD-} | $V_{DD+} - 2.3$ | V |
| Operating free-air temperature, T_A | 0 | 70 | –40 | 125 | –40 | 125 | –55 | 125 | °C |



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electrical characteristics at specified free-air temperature, $V_{DD} = 5\text{ V}$, $GND = 0$ (unless otherwise noted)

| PARAMETER | TEST CONDITIONS | T_A † | TLC450xC | | | UNIT | |
|--|---|------------|------------|-----------|-----|------------------------------|---------------|
| | | | MIN | TYP | MAX | | |
| V_{IO} Input offset voltage | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | Full range | TLC4501 | -80 | 10 | 80 | μV |
| | | | TLC4501A | -40 | 10 | 40 | |
| | | | TLC4502 | -100 | 10 | 100 | |
| | | | TLC4502A | -50 | 10 | 50 | |
| α_{VIO} Temperature coefficient of input offset voltage | | Full range | | 1 | | $\mu\text{V}/^\circ\text{C}$ | |
| I_{IO} Input offset current | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | 25°C | | 1 | 60 | pA | |
| | | Full range | | | 500 | | |
| I_{IB} Input bias current | | 25°C | | 1 | 60 | pA | |
| | | Full range | | | 500 | | |
| V_{OH} High-level output voltage | $I_{OH} = -500\ \mu\text{A}$ | 25°C | | 4.99 | | V | |
| | $I_{OH} = -5\text{ mA}$ | 25°C | | 4.9 | | | |
| | | Full range | | 4.7 | | | |
| V_{OL} Low-level output voltage | $V_{IC} = 2.5\text{ V}$, $I_{OL} = 500\ \mu\text{A}$ | 25°C | | 0.01 | | V | |
| | $V_{IC} = 2.5\text{ V}$, $I_{OL} = 5\text{ mA}$ | 25°C | | 0.1 | | | |
| | | Full range | | | 0.3 | | |
| A_{VD} Large-signal differential voltage amplification | $V_{IC} = 2.5\text{ V}$, $V_O = 1\text{ V to }4\text{ V}$, $R_L = 1\text{ k}\Omega$, See Note 4 | 25°C | 200 | 1000 | | V/mV | |
| | | Full range | 200 | | | | |
| $R_{I(D)}$ Differential input resistance | | 25°C | | 10 | | k Ω | |
| R_L Input resistance | See Note 4 | 25°C | | 10^{12} | | Ω | |
| C_L Common-mode input capacitance | $f = 10\text{ kHz}$, P package | 25°C | | 8 | | pF | |
| Z_O Closed-loop output impedance | $A_V = 10$, $f = 100\text{ kHz}$ | 25°C | | 1 | | Ω | |
| CMRR Common-mode rejection ratio | $V_{IC} = 0\text{ to }2.7\text{ V}$, $V_O = 2.5\text{ V}$, $R_S = 1\text{ k}\Omega$ | 25°C | 90 | 100 | | dB | |
| | | Full range | 85 | | | | |
| k_{SVR} Supply-voltage rejection ratio ($\Delta V_{DD} \pm / \Delta V_{IO}$) | $V_{DD} = 4\text{ V to }6\text{ V}$, $V_{IC} = 0$, No load | 25°C | 90 | 100 | | dB | |
| | | Full range | 90 | | | | |
| I_{DD} Supply current | $V_O = 2.5\text{ V}$, No load | TLC4501/A | 25°C | 1 | 1.5 | mA | |
| | | | Full range | | 2 | | |
| | | TLC4502/A | 25°C | | 2.5 | | 3.5 |
| | | | Full range | | | | 4 |
| $V_{IT(CAL)}$ Calibration input threshold voltage | | Full range | 4 | | | V | |

† Full range is 0°C to 70°C.

NOTE 4: R_L and C_L values are referenced to 2.5 V.



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operating characteristics, $V_{DD} = 5\text{ V}$

| PARAMETER | | TEST CONDITIONS | | T_A^\dagger | TLC450xC, TLC450xAC | | | UNIT |
|------------------------|---|--|-------------------------------------|---------------|---------------------|-------|-----|------------------------------|
| | | | | | MIN | TYP | MAX | |
| SR | Slew rate at unity gain | $V_O = 0.5\text{ V to }2.5\text{ V}, C_L = 100\text{ pF}$ | | 25°C | 1.5 | 2.5 | | $\text{V}/\mu\text{s}$ |
| | | | | Full range | 1 | | | $\text{V}/\mu\text{s}$ |
| V_n | Equivalent input noise voltage | f = 10 Hz | | 25°C | 70 | | | $\text{nV}/\sqrt{\text{Hz}}$ |
| | | f = 1 kHz | | 25°C | 12 | | | |
| $V_{N(PP)}$ | Peak-to-peak equivalent input noise voltage | f = 0.1 to 1 Hz | | 25°C | 1 | | | μV |
| | | f = 0.1 to 10 Hz | | 25°C | 1.5 | | | |
| I_n | Equivalent input noise current | | | 25°C | 0.6 | | | $\text{fA}/\sqrt{\text{Hz}}$ |
| THD + N | Total harmonic distortion plus noise | $V_O = 0.5\text{ V to }2.5\text{ V}, f = 10\text{ kHz}, R_L = 1\text{ k}\Omega, C_L = 100\text{ pF}$ | | $A_V = 1$ | 25°C | 0.02% | | |
| | | | | $A_V = 10$ | 25°C | 0.08% | | |
| | | | | $A_V = 100$ | 25°C | 0.55% | | |
| Gain-bandwidth product | | f = 10 kHz, $C_L = 100\text{ pF}$ | $R_L = 1\text{ k}\Omega,$ | 25°C | 4.7 | | | MHz |
| B_{OM} | Maximum output swing bandwidth | $V_{O(PP)} = 2\text{ V},$ $R_L = 1\text{ k}\Omega,$ | $A_V = 1,$ $C_L = 100\text{ pF}$ | 25°C | 1 | | | MHz |
| t_s | Settling time | $A_V = -1,$ Step = 0.5 V to 2.5 V, $R_L = 1\text{ k}\Omega,$ $C_L = 100\text{ pF}$ | | to 0.1% | 25°C | 1.6 | | μs |
| | | | | to 0.01% | 25°C | 2.2 | | |
| ϕ_m | Phase margin at unity gain | $R_L = 1\text{ k}\Omega,$ | $C_L = 100\text{ pF}$ | 25°C | 74 | | | |
| Calibration time | | | | 25°C | 300 | | | ms |

† Full range is 0°C to 70°C.

NOTE 4: R_L and C_L values are referenced to 2.5 V.

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electrical characteristics at specified free-air temperature, $V_{DD} = 5\text{ V}$, $GND = 0$ (unless otherwise noted)

| PARAMETER | TEST CONDITIONS | T_A † | TLC450xI | | | UNIT | |
|--|---|---------------|------------|-----------|-----|------------------------------|---------------|
| | | | MIN | TYP | MAX | | |
| V_{IO} Input offset voltage | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | Full range | TLC4501 | -80 | 10 | 80 | μV |
| | | | TLC4501A | -40 | 10 | 40 | |
| | | | TLC4502 | -100 | 10 | 100 | |
| | | | TLC4502A | -50 | 10 | 50 | |
| α_{VIO} Temperature coefficient of input offset voltage | | Full range | | 1 | | $\mu\text{V}/^\circ\text{C}$ | |
| I_{IO} Input offset current | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | 25°C | | 1 | 60 | pA | |
| | | -40°C to 85°C | | | 500 | pA | |
| | | Full range | | | 5 | nA | |
| I_{IB} Input bias current | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | 25°C | | 1 | 60 | pA | |
| | | -40°C to 85°C | | | 500 | pA | |
| | | Full range | | | 10 | nA | |
| V_{OH} High-level output voltage | $I_{OH} = -500\ \mu\text{A}$ | 25°C | | 4.99 | | V | |
| | $I_{OH} = -5\text{ mA}$ | 25°C | | 4.9 | | | |
| | | Full range | | 4.7 | | | |
| V_{OL} Low-level output voltage | $V_{IC} = 2.5\text{ V}$, $I_{OL} = 500\ \mu\text{A}$ | 25°C | | 0.01 | | V | |
| | $V_{IC} = 2.5\text{ V}$, $I_{OL} = 5\text{ mA}$ | 25°C | | 0.1 | | | |
| | | Full range | | 0.3 | | | |
| A_{VD} Large-signal differential voltage amplification | $V_{IC} = 2.5\text{ V}$, $V_O = 1\text{ V to }4\text{ V}$, $R_L = 1\text{ k}\Omega$, See Note 4 | 25°C | 200 | 1000 | | V/mV | |
| | | Full range | 200 | | | | |
| $R_{I(D)}$ Differential input resistance | | 25°C | | 10 | | $\text{k}\Omega$ | |
| R_L Input resistance | See Note 4 | 25°C | | 10^{12} | | Ω | |
| C_L Common-mode input capacitance | $f = 10\text{ kHz}$, P package | 25°C | | 8 | | pF | |
| Z_O Closed-loop output impedance | $A_V = 10$, $f = 100\text{ kHz}$ | 25°C | | 1 | | Ω | |
| CMRR Common-mode rejection ratio | $V_{IC} = 0\text{ to }2.7\text{ V}$, $V_O = 2.5\text{ V}$, $R_S = 1\text{ k}\Omega$ | 25°C | 90 | 100 | | dB | |
| | | Full range | 85 | | | | |
| k_{SVR} Supply-voltage rejection ratio ($\Delta V_{DD} \pm / \Delta V_{IO}$) | $V_{DD} = 4\text{ V to }6\text{ V}$, $V_{IC} = 0$, No load | 25°C | 90 | 100 | | dB | |
| | | Full range | 90 | | | | |
| I_{DD} Supply current | $V_O = 2.5\text{ V}$, No load | TLC4501/A | 25°C | 1 | 1.5 | mA | |
| | | | Full range | | 2 | | |
| | | TLC4502/A | 25°C | 2.5 | 3.5 | | |
| | | | Full range | | 4 | | |
| $V_{IT(CAL)}$ Calibration input threshold voltage | | Full range | 4 | | | V | |

† Full range is -40°C to 125°C.

NOTE 4: R_L and C_L values are referenced to 2.5 V.



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operating characteristics, $V_{DD} = 5\text{ V}$

| PARAMETER | | TEST CONDITIONS | | T_A † | TLC450xI, TLC450xAI | | | UNIT |
|------------------------|---|--|--------------------------------|-------------|---------------------|-------|-----|------------------------------|
| | | | | | MIN | TYP | MAX | |
| SR | Slew rate at unity gain | $V_O = 0.5\text{ V to }2.5\text{ V}, C_L = 100\text{ pF}$ | | 25°C | 1.5 | 2.5 | | $\text{V}/\mu\text{s}$ |
| | | | | Full range | 1 | | | $\text{V}/\mu\text{s}$ |
| V_n | Equivalent input noise voltage | $f = 10\text{ Hz}$ | | 25°C | 70 | | | $\text{nV}/\sqrt{\text{Hz}}$ |
| | | $f = 1\text{ kHz}$ | | 25°C | 12 | | | |
| $V_{N(PP)}$ | Peak-to-peak equivalent input noise voltage | $f = 0.1\text{ to }1\text{ Hz}$ | | 25°C | 1 | | | μV |
| | | $f = 0.1\text{ to }10\text{ Hz}$ | | 25°C | 1.5 | | | |
| I_n | Equivalent input noise current | | | 25°C | 0.6 | | | $\text{fA}/\sqrt{\text{Hz}}$ |
| THD + N | Total harmonic distortion plus noise | $V_O = 0.5\text{ V to }2.5\text{ V}, f = 10\text{ kHz}, R_L = 1\text{ k}\Omega, C_L = 100\text{ pF}$ | | $A_V = 1$ | 25°C | 0.02% | | |
| | | | | $A_V = 10$ | 25°C | 0.08% | | |
| | | | | $A_V = 100$ | 25°C | 0.55% | | |
| Gain-bandwidth product | | $f = 10\text{ kHz}, C_L = 100\text{ pF}$ | $R_L = 1\text{ k}\Omega,$ | 25°C | 4.7 | | | MHz |
| B_{OM} | Maximum output swing bandwidth | $V_{O(PP)} = 2\text{ V}, R_L = 1\text{ k}\Omega,$ | $A_V = 1, C_L = 100\text{ pF}$ | 25°C | 1 | | | MHz |
| t_s | Settling time | $A_V = -1, \text{ Step} = 0.5\text{ V to }2.5\text{ V}, R_L = 1\text{ k}\Omega, C_L = 100\text{ pF}$ | | to 0.1% | 25°C | 1.6 | | μs |
| | | | | to 0.01% | 25°C | 2.2 | | |
| ϕ_m | Phase margin at unity gain | $R_L = 1\text{ k}\Omega,$ | $C_L = 100\text{ pF}$ | 25°C | 74 | | | |
| Calibration time | | | | 25°C | 300 | | | ms |

† Full range is -40°C to 125°C .

NOTE 4: R_L and C_L values are referenced to 2.5 V.

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electrical characteristics at specified free-air temperature, $V_{DD} = 5\text{ V}$, $GND = 0$ (unless otherwise noted)

| PARAMETER | TEST CONDITIONS | T_A † | TLC4502Q, TLC4502M | | | UNIT | |
|--|---|---------------------|-----------------------|-------------|------------------|-----------|------------------------------|
| | | | MIN | TYP | MAX | | |
| V_{IO} Input offset voltage | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | TLC4502 TLC4502A | Full range | -100 -50 | 10 10 | 100 50 | μV |
| α_{VIO} Temperature coefficient of input offset voltage | | | Full range | | 1 | | $\mu\text{V}/^\circ\text{C}$ |
| I_{IO} Input offset current | $V_{DD} = \pm 2.5\text{ V}$, $V_O = 0$, $V_{IC} = 0$, $R_S = 50\ \Omega$ | | 25°C | | 1 | 60 | nA |
| I_{IB} Input bias current | | | 125°C | | | 5 | nA |
| | | | 25°C | | 1 | 60 | nA |
| | | | 125°C | | | 10 | nA |
| V_{OH} High-level output voltage | $I_{OH} = -500\ \mu\text{A}$ | | 25°C | | | 4.99 | V |
| | $I_{OH} = -5\text{ mA}$ | | 25°C | | | 4.9 | V |
| | | | Full range | | | 4.7 | V |
| V_{OL} Low-level output voltage | $V_{IC} = 2.5\text{ V}$, $I_{OL} = 500\ \mu\text{A}$ | | 25°C | | | 0.01 | V |
| | $V_{IC} = 2.5\text{ V}$, $I_{OL} = 5\text{ mA}$ | | 25°C | | | 0.1 | V |
| | | | Full range | | | 0.3 | V |
| A_{VD} Large-signal differential voltage amplification | $V_{IC} = 2.5\text{ V}$, $V_O = 1\text{ V to }4\text{ V}$, $R_L = 1\text{ k}\Omega$, See Note 4 | | 25°C | 200 | 1000 | | V/mV |
| | | | Full range | 200 | | | V/mV |
| $R_{I(D)}$ Differential input resistance | | | 25°C | | 10 | | k Ω |
| R_L Input resistance | See Note 4 | | 25°C | | 10 ¹² | | Ω |
| C_L Common-mode input capacitance | $f = 10\text{ kHz}$, P package | | 25°C | | 8 | | pF |
| z_O Closed-loop output impedance | $A_V = 10$, $f = 100\text{ kHz}$ | | 25°C | | 1 | | Ω |
| CMRR Common-mode rejection ratio | $V_{IC} = 0\text{ to }2.7\text{ V}$, $V_O = 2.5\text{ V}$, $R_S = 1\text{ k}\Omega$ | | 25°C | 90 | 100 | | dB |
| | | | Full range | 85 | | | dB |
| k_{SVR} Supply-voltage rejection ratio ($\Delta V_{DD} \pm / \Delta V_{IO}$) | $V_{DD} = 4\text{ V to }6\text{ V}$, $V_{IC} = V_{DD} / 2$, No load | | 25°C | 90 | 100 | | dB |
| | | | Full range | 90 | | | dB |
| I_{DD} Supply current | $V_O = 2.5\text{ V}$, No load | | 25°C | | 2.5 | 3.5 | mA |
| | | | Full range | | | 4 | mA |
| $V_{IT(CAL)}$ Calibration input threshold voltage | | | Full range | 4 | | | V |

† Full range is -40°C to 125°C for Q suffix, -55°C to 125°C for M suffix.

NOTE 4: R_L and C_L values are referenced to 2.5 V.



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operating characteristics, $V_{DD} = 5\text{ V}$

| PARAMETER | | TEST CONDITIONS | | T_A † | TLC4502Q, TLC4502M, TLC4502AQ, TLC4502AM | | | UNIT |
|------------------------|---|---|---------------------------|-------------------------------------|--|-------|------------------------|------------------|
| | | | | | MIN | TYP | MAX | |
| SR | Slew rate at unity gain | $V_O = 0.5\text{ V to }2.5\text{ V},$ See Note 4 | | $C_L = 100\text{ pF}$ | 25°C | 1.5 | 2.5 | V/ μs |
| | | | | | Full range | 1 | | V/ μs |
| V_n | Equivalent input noise voltage | $f = 10\text{ Hz}$ | | 25°C | 70 | | nV/ $\sqrt{\text{Hz}}$ | |
| | | $f = 1\text{ kHz}$ | | 25°C | 12 | | | |
| $V_{N(PP)}$ | Peak-to-peak equivalent input noise voltage | $f = 0.1\text{ to }1\text{ Hz}$ | | 25°C | 1 | | μV | |
| | | $f = 0.1\text{ to }10\text{ Hz}$ | | 25°C | 1.5 | | | |
| I_n | Equivalent input noise current | | | 25°C | 0.6 | | fA/ $\sqrt{\text{Hz}}$ | |
| THD + N | Total harmonic distortion plus noise | $V_O = 0.5\text{ V to }2.5\text{ V},$ $f = 10\text{ kHz},$ $R_L = 1\text{ k}\Omega,$ $C_L = 100\text{ pF}$ | | $A_V = 1$ | 25°C | 0.02% | | |
| | | | | $A_V = 10$ | 25°C | 0.08% | | |
| | | | | $A_V = 100$ | 25°C | 0.55% | | |
| Gain-bandwidth product | | $f = 10\text{ kHz},$ $C_L = 100\text{ pF}$ | $R_L = 1\text{ k}\Omega,$ | 25°C | 4.7 | | MHz | |
| BOM | Maximum output swing bandwidth | $V_{O(PP)} = 2\text{ V},$ $R_L = 1\text{ k}\Omega,$ | | $A_V = 1,$ $C_L = 100\text{ pF}$ | 25°C | 1 | | MHz |
| t_s | Settling time | $A_V = -1,$ Step = 0.5 V to 2.5 V, $R_L = 1\text{ k}\Omega,$ $C_L = 100\text{ pF}$ | | to 0.1% | 25°C | 1.6 | | μs |
| | | | | to 0.01% | 25°C | 2.2 | | |
| ϕ_m | Phase margin at unity gain | $R_L = 1\text{ k}\Omega,$ | $C_L = 100\text{ pF}$ | 25°C | 74 | | | |
| Calibration time | | | | 25°C | 300 | | ms | |

† Full range is -40°C to 125°C for Q suffix, -55°C to 125°C for M suffix.

NOTE 4: R_L and C_L values are referenced to 2.5 V.

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Table of Graphs

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|-----------------|---|-------------------------------|-------------------------|
| V_{IO} | Input offset voltage | Distribution | 2, 3, 4 |
| | | vs Common-mode input voltage | 5 |
| αV_{IO} | Input offset voltage temperature coefficient | Distribution | 6, 7 |
| V_{OH} | High-level output voltage | vs High-level output current | 8 |
| V_{OL} | Low-level output voltage | vs Low-level output current | 9 |
| $V_{O(PP)}$ | Maximum peak-to-peak output voltage | vs Frequency | 10 |
| I_{OS} | Short-circuit output current | vs Free-air temperature | 11 |
| V_O | Output voltage | vs Differential input voltage | 12 |
| A_{VD} | Large-signal differential voltage amplification | vs Free-air temperature | 13 |
| | | vs Frequency | 14 |
| z_o | Output impedance | vs Frequency | 15 |
| CMRR | Common-mode rejection ratio | vs Frequency | 16 |
| | | vs Free-air temperature | 17 |
| SR | Slew rate | vs Load capacitance | 18 |
| | | vs Free-air temperature | 19 |
| | Inverting large-signal pulse response | | 20 |
| | Voltage-follower large-signal pulse response | | 21 |
| | Inverting small-signal pulse response | | 22 |
| | Voltage-follower small-signal pulse response | | 23 |
| V_n | Equivalent input noise voltage | vs Frequency | 24 |
| | | Over a 10-second period | 25 |
| THD + N | Total harmonic distortion plus noise | vs Frequency | 26 |
| | | Gain-bandwidth product | vs Free-air temperature |
| ϕ_m | Phase margin | vs Load capacitance | 28 |
| | | vs Frequency | 14 |
| | | Gain margin | vs Load capacitance |
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| | Calibration time at -40°C | | 31 |
| | Calibration time at 25°C | | 32 |
| | Calibration time at 85°C | | 33 |
| | Calibration time at 125°C | | 34 |



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TYPICAL CHARACTERISTICS

**DISTRIBUTION OF TLC4502 INPUT
OFFSET VOLTAGE**

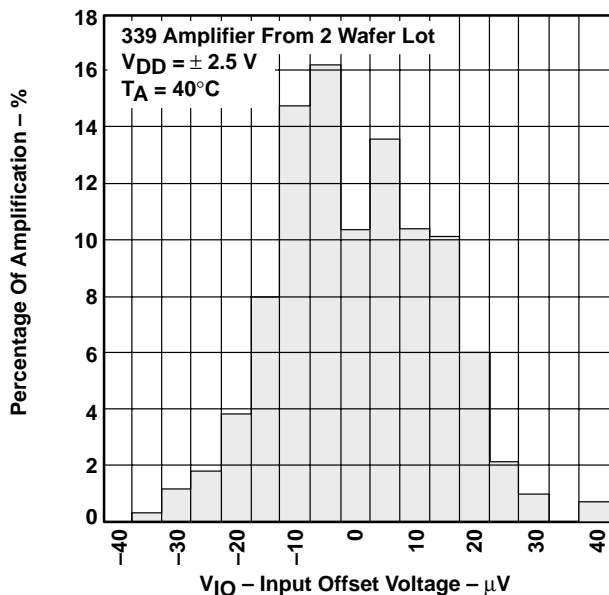


Figure 2

**DISTRIBUTION OF TLC4502 INPUT
OFFSET VOLTAGE**

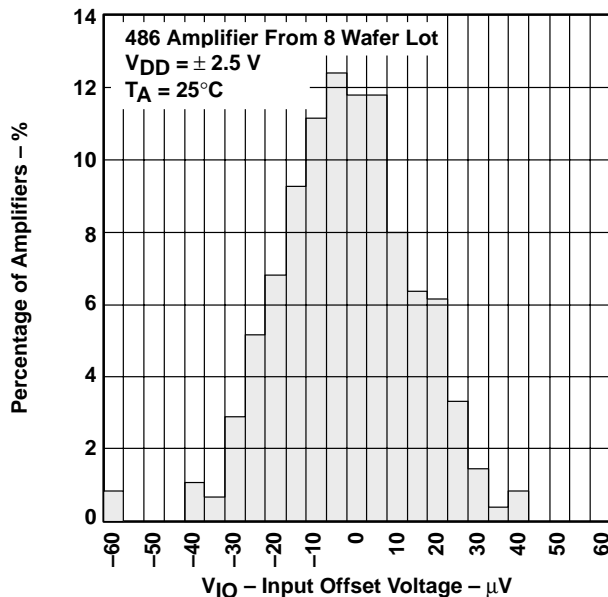


Figure 3

**DISTRIBUTION OF TLC4502 INPUT
OFFSET VOLTAGE**

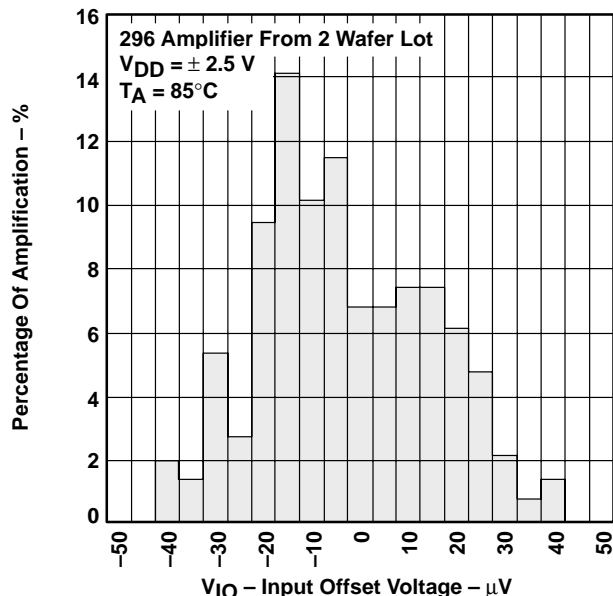


Figure 4

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

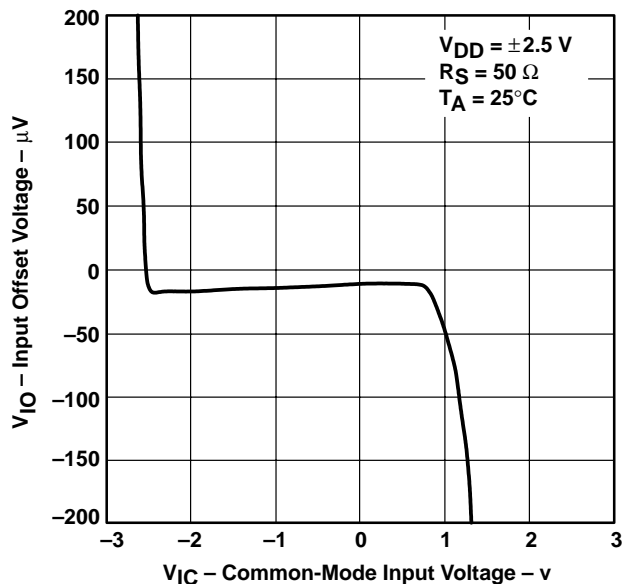


Figure 5

TLC4501, TLC4501A, TLC4502, TLC4502A
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TYPICAL CHARACTERISTICS

DISTRIBUTION OF TLC4502 INPUT OFFSET VOLTAGE TEMPERATURE COEFFICIENT

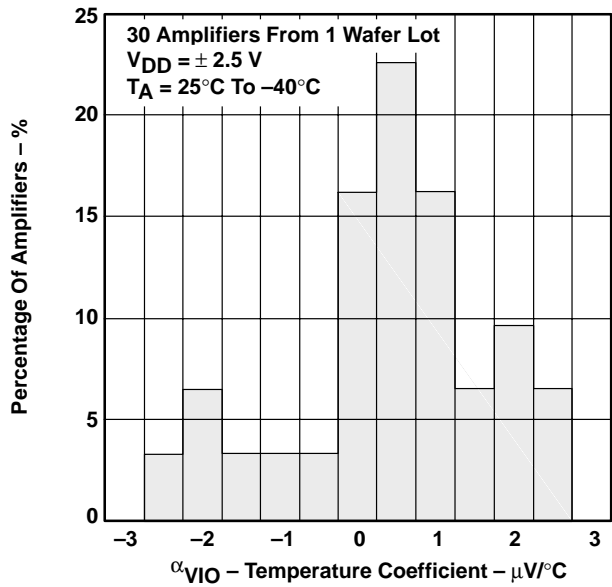


Figure 6

DISTRIBUTION OF TLC4502 INPUT OFFSET VOLTAGE TEMPERATURE COEFFICIENT

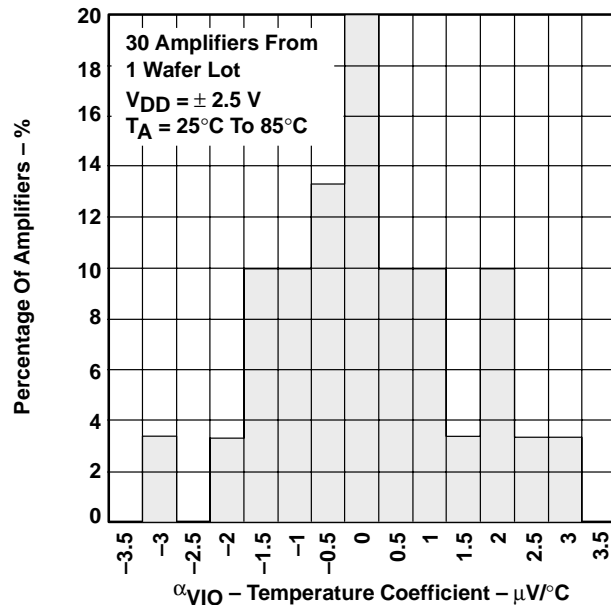


Figure 7

HIGH-LEVEL OUTPUT VOLTAGE vs HIGH-LEVEL OUTPUT CURRENT

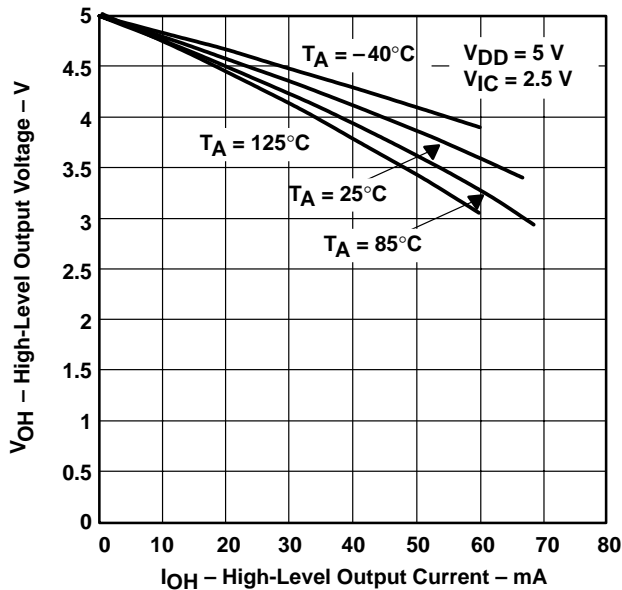


Figure 8

LOW-LEVEL OUTPUT VOLTAGE vs LOW-LEVEL OUTPUT CURRENT

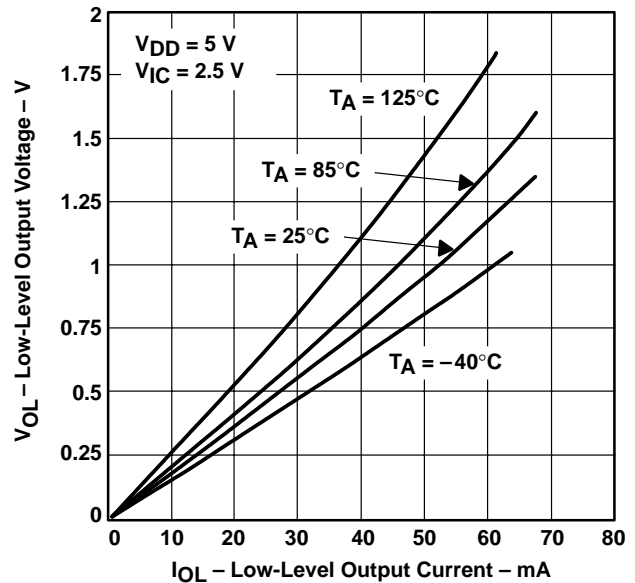


Figure 9



TLC4501, TLC4501A, TLC4502, TLC4502A
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TYPICAL CHARACTERISTICS

MAXIMUM PEAK-TO-PEAK OUTPUT VOLTAGE
 VS
 FREQUENCY

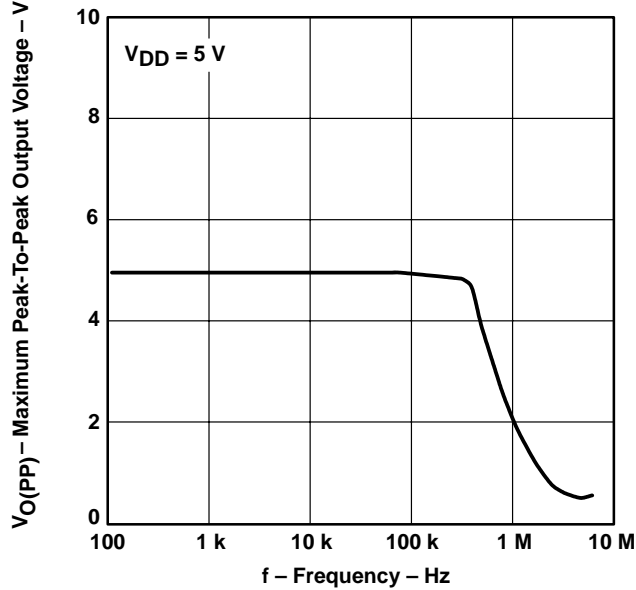


Figure 10

SHORT-CIRCUIT OUTPUT CURRENT
 VS
 FREE-AIR TEMPERATURE

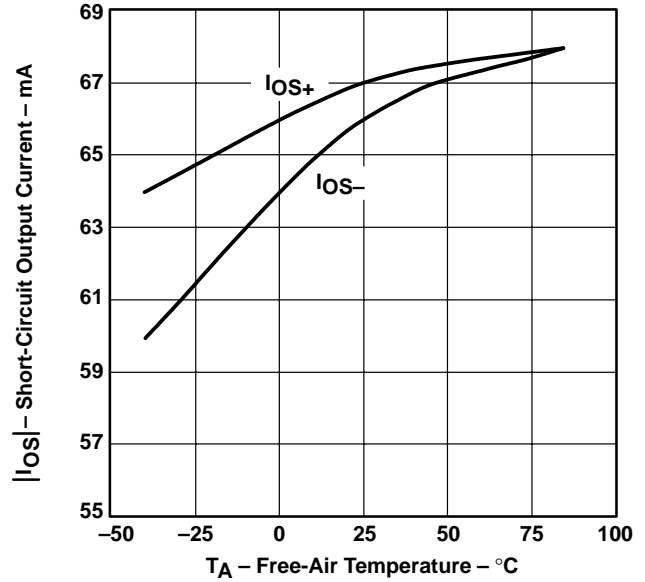


Figure 11

OUTPUT VOLTAGE
 VS
 DIFFERENTIAL INPUT VOLTAGE

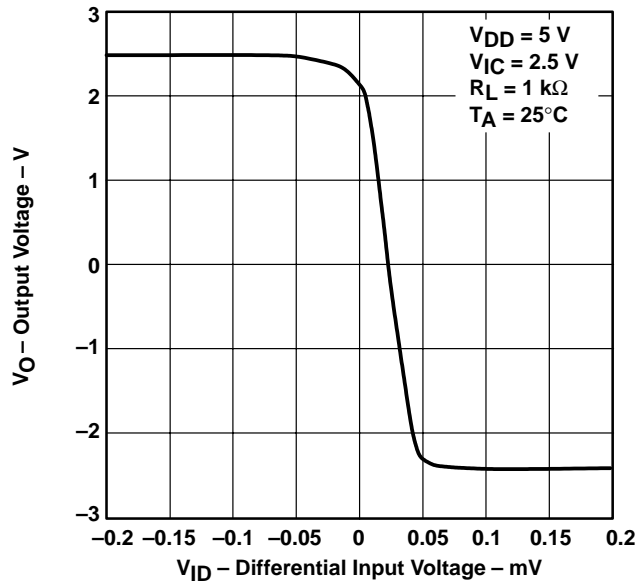


Figure 12

LARGE-SIGNAL DIFFERENTIAL
 VOLTAGE AMPLIFICATION
 VS
 FREE-AIR TEMPERATURE

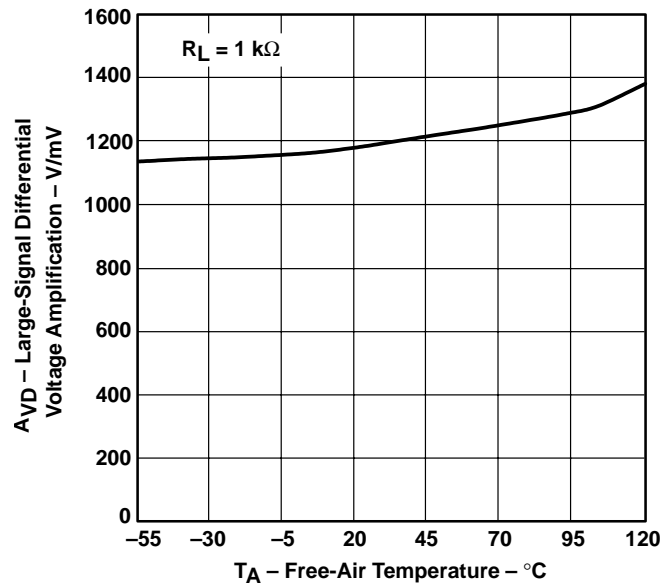


Figure 13

TYPICAL CHARACTERISTICS

LARGE-SIGNAL DIFFERENTIAL VOLTAGE
 AMPLIFICATION AND PHASE MARGIN

vs
 FREQUENCY

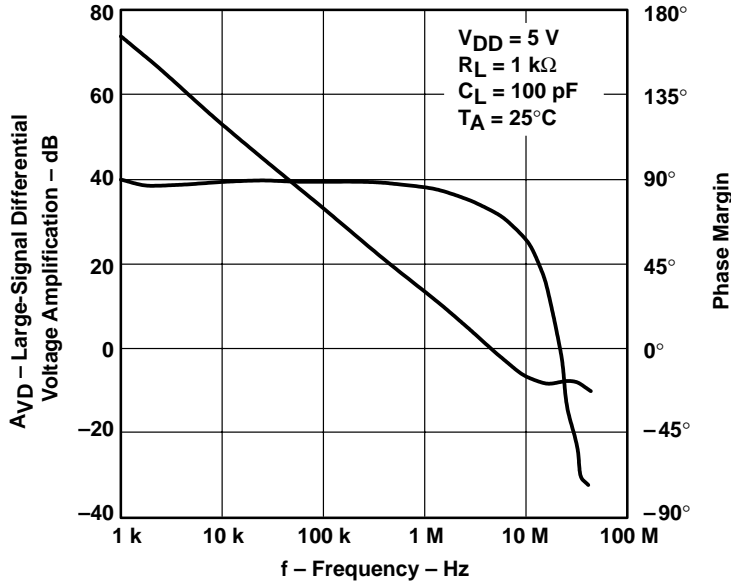


Figure 14

OUTPUT IMPEDANCE

vs
 FREQUENCY

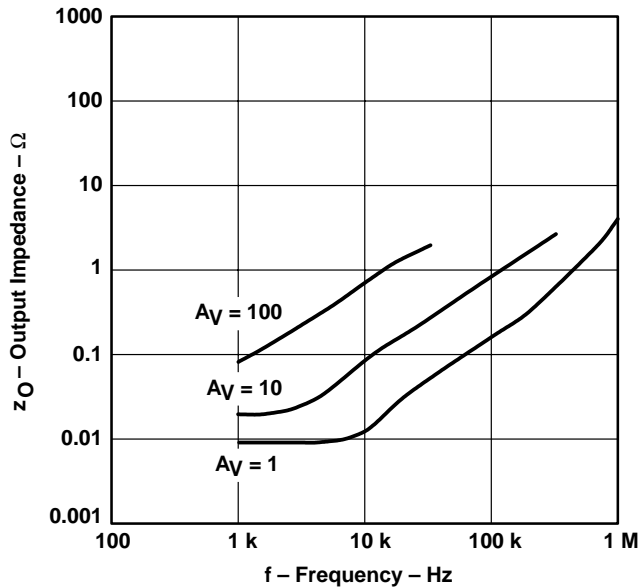


Figure 15

TYPICAL CHARACTERISTICS

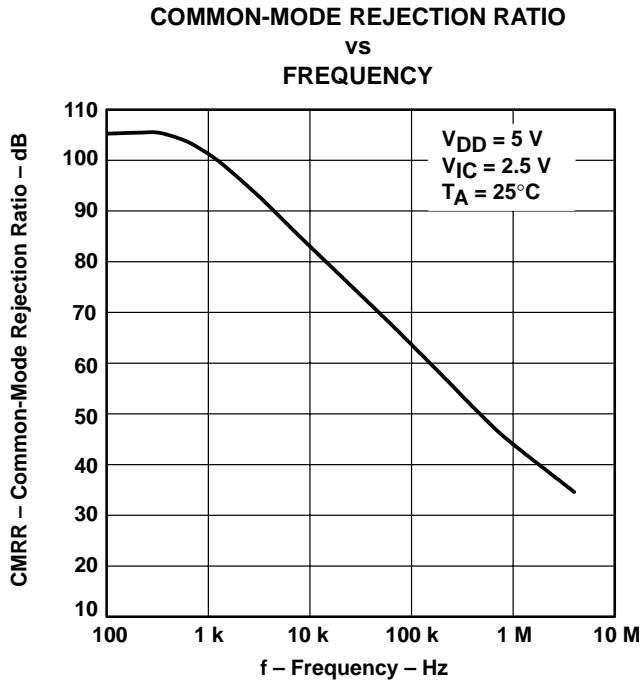


Figure 16

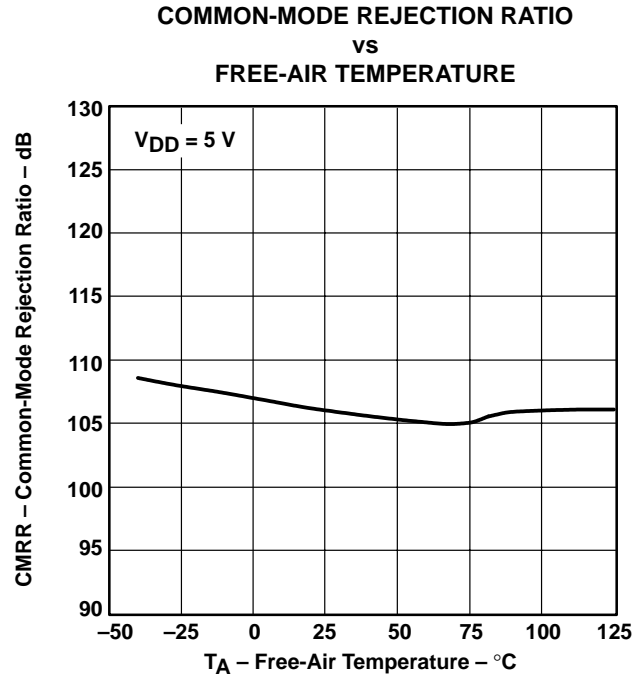


Figure 17

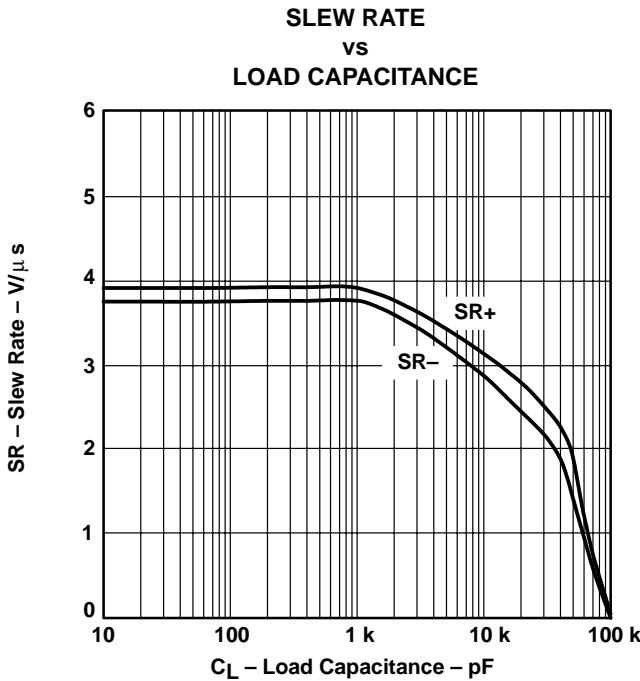


Figure 18

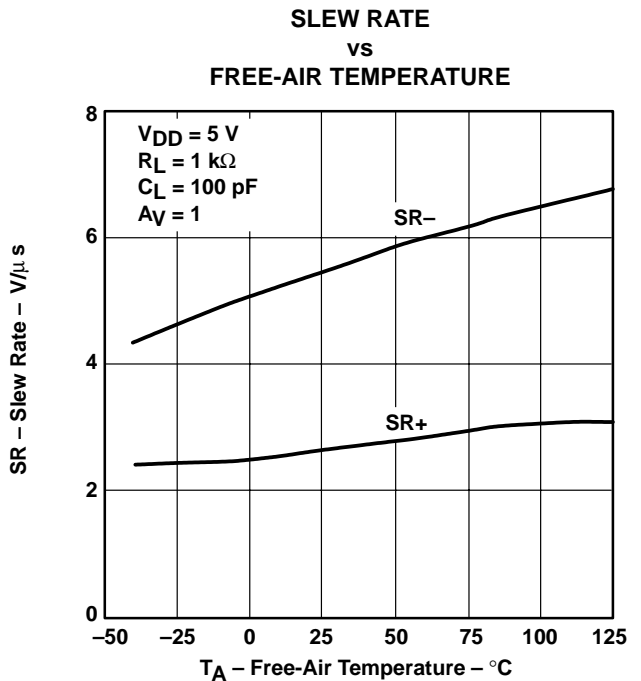


Figure 19

TYPICAL CHARACTERISTICS

INVERTING LARGE-SIGNAL PULSE RESPONSE

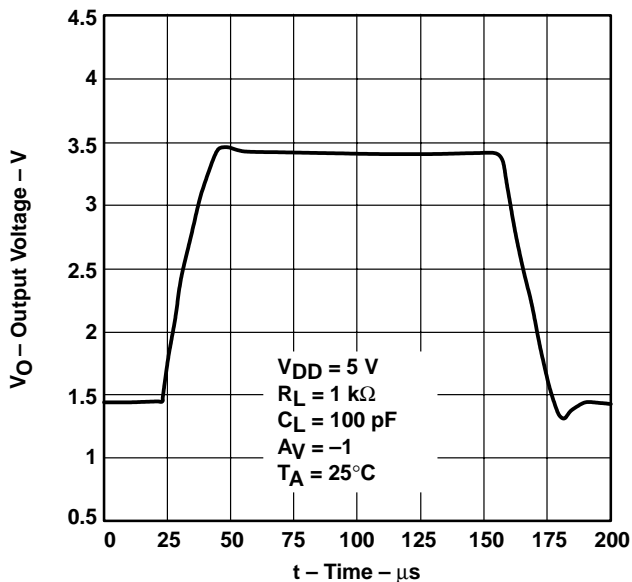


Figure 20

VOLTAGE-FOLLOWER LARGE-SIGNAL PULSE RESPONSE

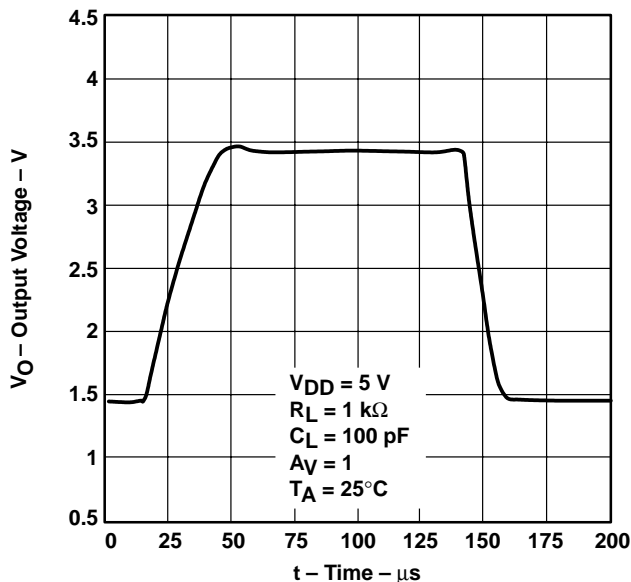


Figure 21

INVERTING SMALL-SIGNAL PULSE RESPONSE

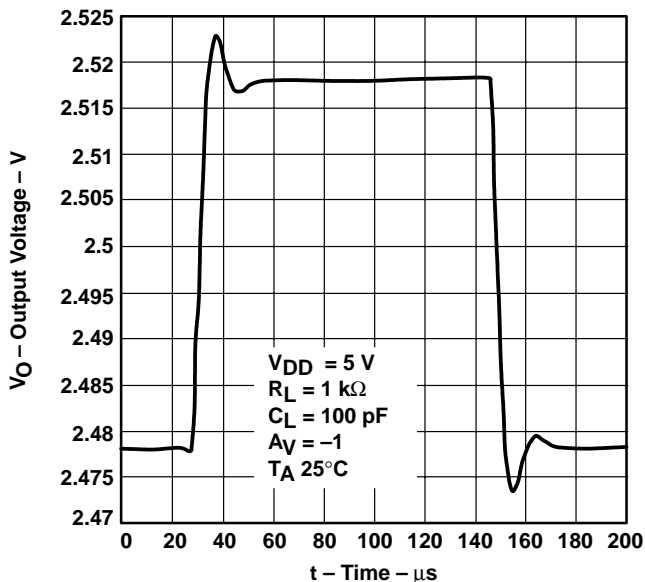


Figure 22

VOLTAGE-FOLLOWER SMALL-SIGNAL PULSE RESPONSE

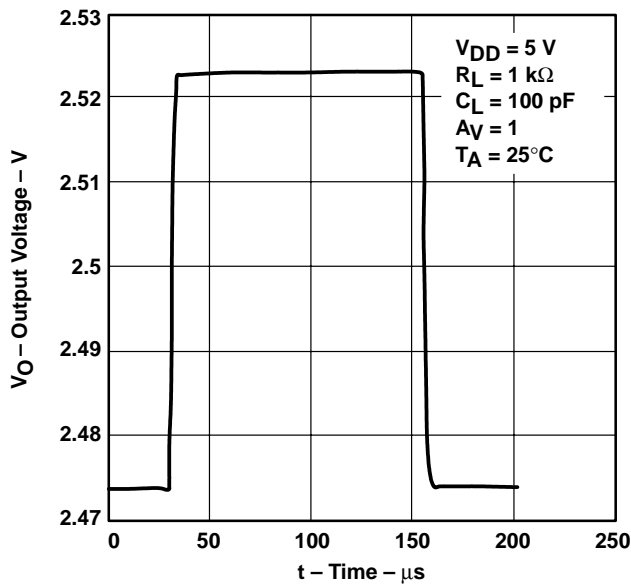


Figure 23

TYPICAL CHARACTERISTICS

EQUIVALENT INPUT NOISE VOLTAGE
 vs
 FREQUENCY

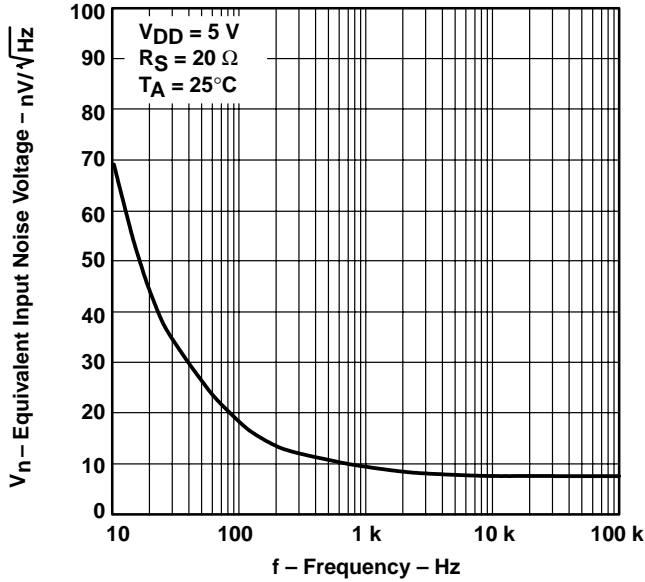


Figure 24

INPUT NOISE VOLTAGE OVER
 A 10-SECOND PERIOD

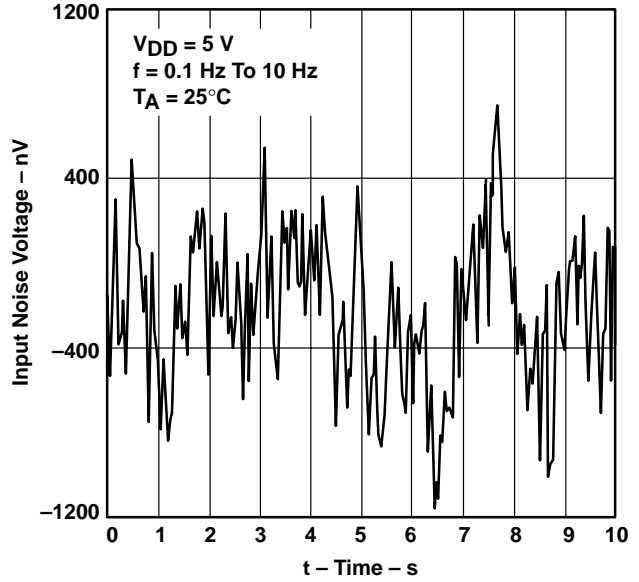


Figure 25

TOTAL HARMONIC DISTORTION PLUS NOISE
 vs
 FREQUENCY

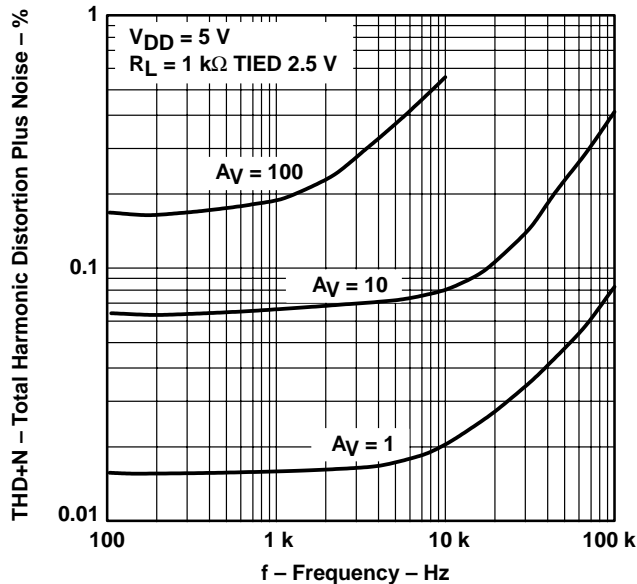


Figure 26

GAIN-BANDWIDTH PRODUCT
 vs
 FREE-AIR TEMPERATURE

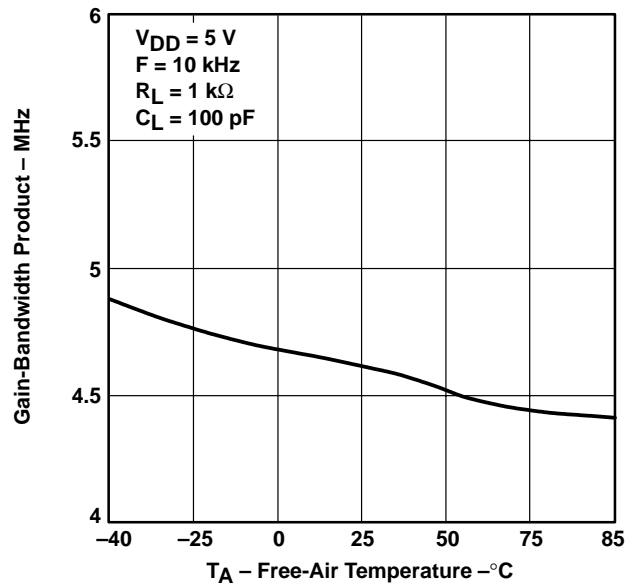


Figure 27

TYPICAL CHARACTERISTICS

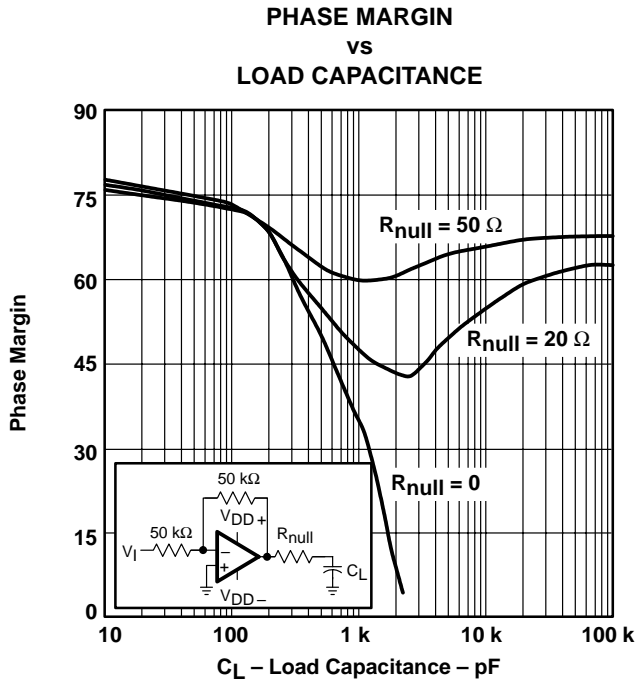


Figure 28

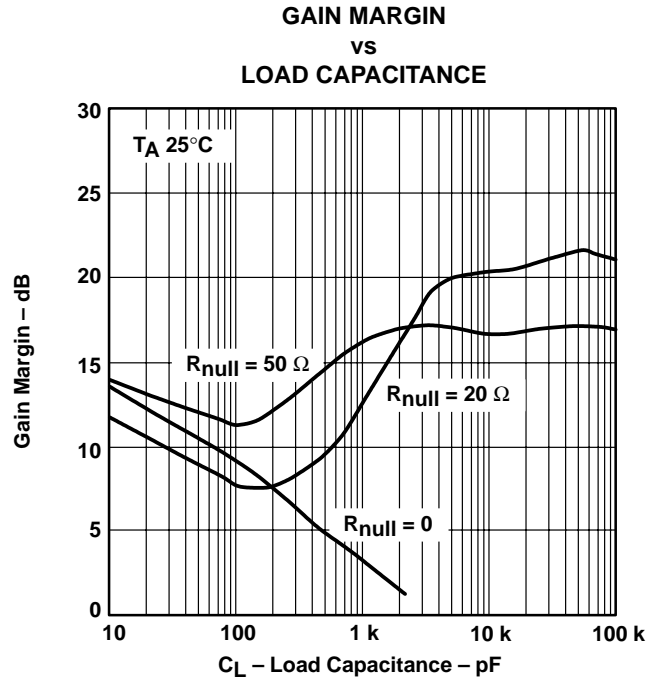


Figure 29

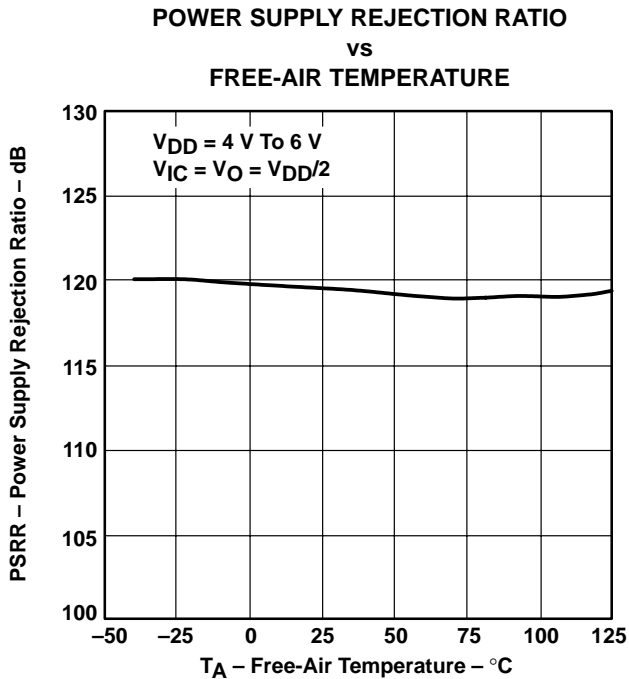


Figure 30

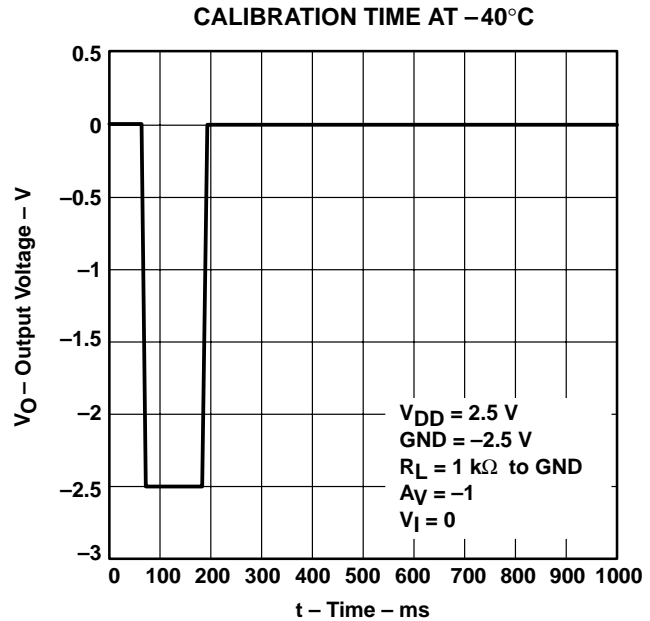


Figure 31

TYPICAL CHARACTERISTICS

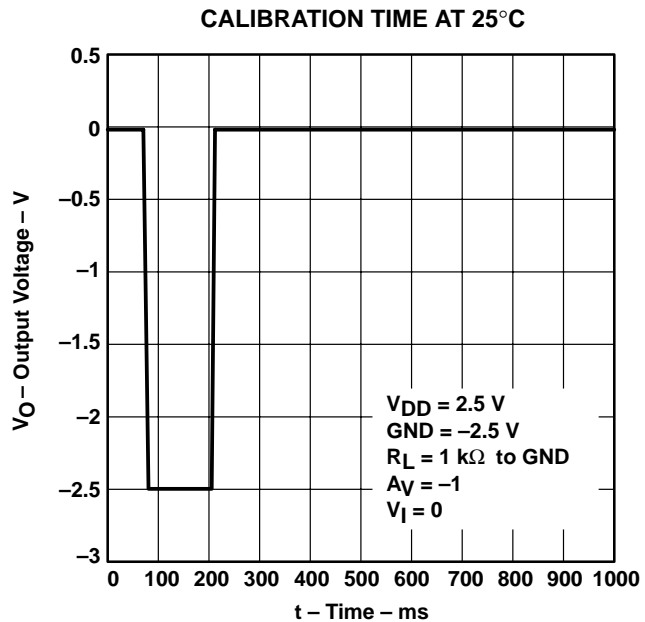


Figure 32

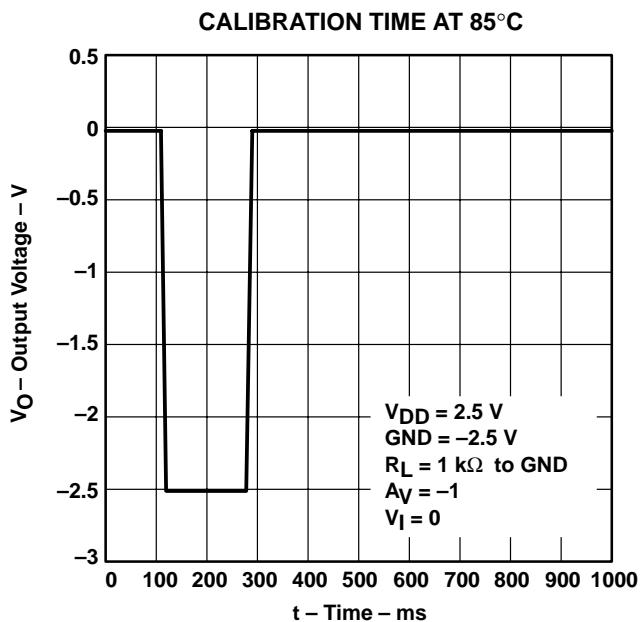


Figure 33

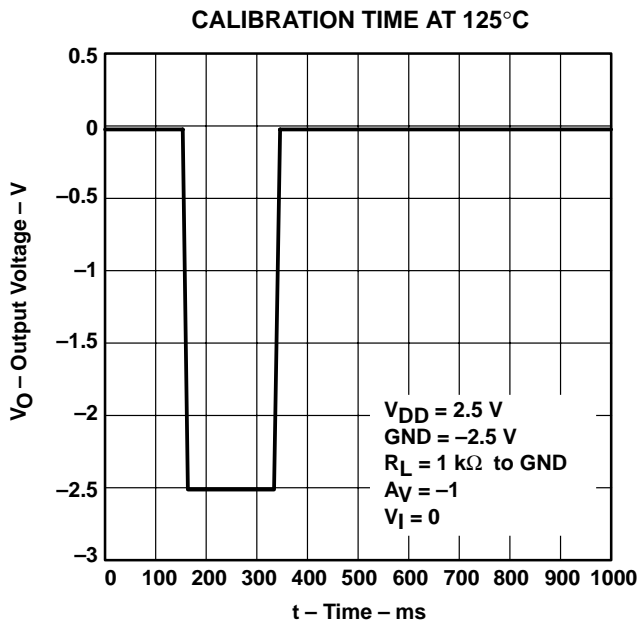


Figure 34

TLC4501, TLC4501A, TLC4502, TLC4502A
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APPLICATION INFORMATION

- The TLC4502 is designed to operate with only a single 5-V power supply, have true differential inputs, and remain in the linear mode with an input common-mode voltage of 0.
- The TLC4502 has a standard dual-amplifier pinout, allowing for easy design upgrades.
- Large differential input voltages can be easily accommodated and, as input differential-voltage protection diodes are not needed, no large input currents result from large differential input voltage. Protection should be provided to prevent the input voltages from going negative more than -0.3 V at 25°C . An input clamp diode with a resistor to the device input terminal can be used for this purpose.
- For ac applications, where the load is capacitively coupled to the output of the amplifier, a resistor can be used from the output of the amplifier to ground. This increases the class-A bias current and prevents crossover distortion. Where the load is directly coupled, for example in dc applications, there is no crossover distortion.
- Capacitive loads, which are applied directly to the output of the amplifier, reduce the loop stability margin. Values of 500 pF can be accommodated using the worst-case noninverting unity-gain connection. Resistive isolation should be considered when larger load capacitance must be driven by the amplifier.

The following typical application circuits emphasize operation on only a single power supply. When complementary power supplies are available, the TLC4502 can be used in all of the standard operational amplifier circuits. In general, introducing a pseudo-ground (a bias voltage of $V_I/2$ like that generated by the TLE2426) allows operation above and below this value in a single-supply system. Many application circuits shown take advantage of the wide common-mode input-voltage range of the TLC4502, which includes ground. In most cases, input biasing is not required and input voltages that range to ground can easily be accommodated.

description of calibration procedure

To achieve high dc gain, large bandwidth, high CMRR and PSRR, as well as good output drive capability, the TLC4502 is built around a 3-stage topology: two gain stages, one rail-to-rail, and a class-AB output stage. A nested Miller topology is used for frequency compensation.

During the calibration procedure, the operational amplifier is removed from the signal path and both inputs are tied to GND. Figure 35 shows a block diagram of the amplifier during calibration mode.



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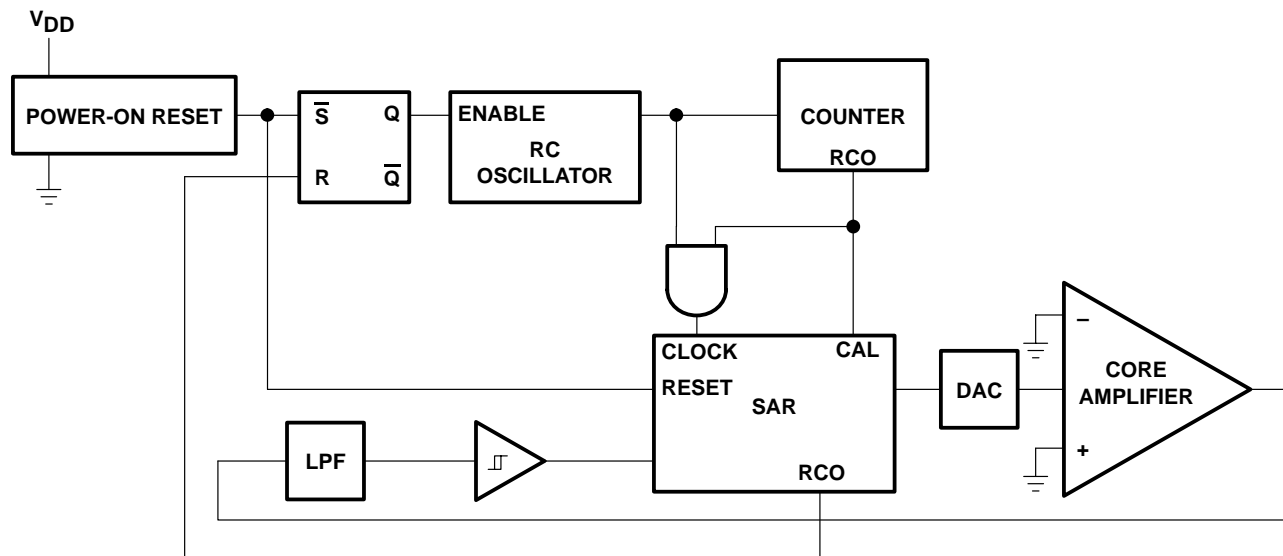


Figure 35. Block Diagram During Calibration Mode

The class AB output stage features rail-to-rail voltage swing and incorporates additional switches to put the output node into a high-impedance mode during the calibration cycle. Small-replica output transistors (matched to the main output transistors) provide the amplifier output signal for the calibration circuit. The TLC4502 also features built-in output short-circuit protection. The output current flowing through the main output transistors is continuously being sensed. If the current through either of these transistors exceeds the preset limit (60 mA – 70 mA) for more than about 1 μ s, the output transistors are shut down to approximately their quiescent operating point for approximately 5 ms. The device is then returned to normal operation. If the short circuit is still in place, it is detected in less than 1 μ s and the device is shut down for another 5 ms.

The offset cancellation uses a current-mode digital-to-analog converter (DAC), whose full-scale current allows for an adjustment of approximately ± 5 mV to the input offset voltage. The digital code producing the cancellation current is stored in the successive-approximation register (SAR).

During power up, when the offset cancellation procedure is initiated, an on-chip RC oscillator is activated to provide the timing of the successive-approximation algorithm. To prevent wide-band noise from interfering with the calibration procedure, an analog low-pass filter followed by a Schmitt trigger is used in the decision chain to implement an averaging process. Once the calibration procedure is complete, the RC oscillator is deactivated to reduce supply current and the associated noise.

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The key operational-amplifier parameters CMRR, PSRR, and offset drift were optimized to achieve superior offset performance. The TLC4502 calibration DAC is implemented by a binary-weighted current array using a pseudo-R-2R MOSFET ladder architecture, which minimizes the silicon area required for the calibration circuitry, and thereby reduces the cost of the TLC4502.

Due to the performance (precision, PSRR, CMRR, gain, output drive, and ac performance) of the TLC4502, it is ideal for applications like:

- Data acquisition systems
- Medical equipment
- Portable digital scales
- Strain gauges
- Automotive sensors
- Digital audio circuits
- Industrial control applications

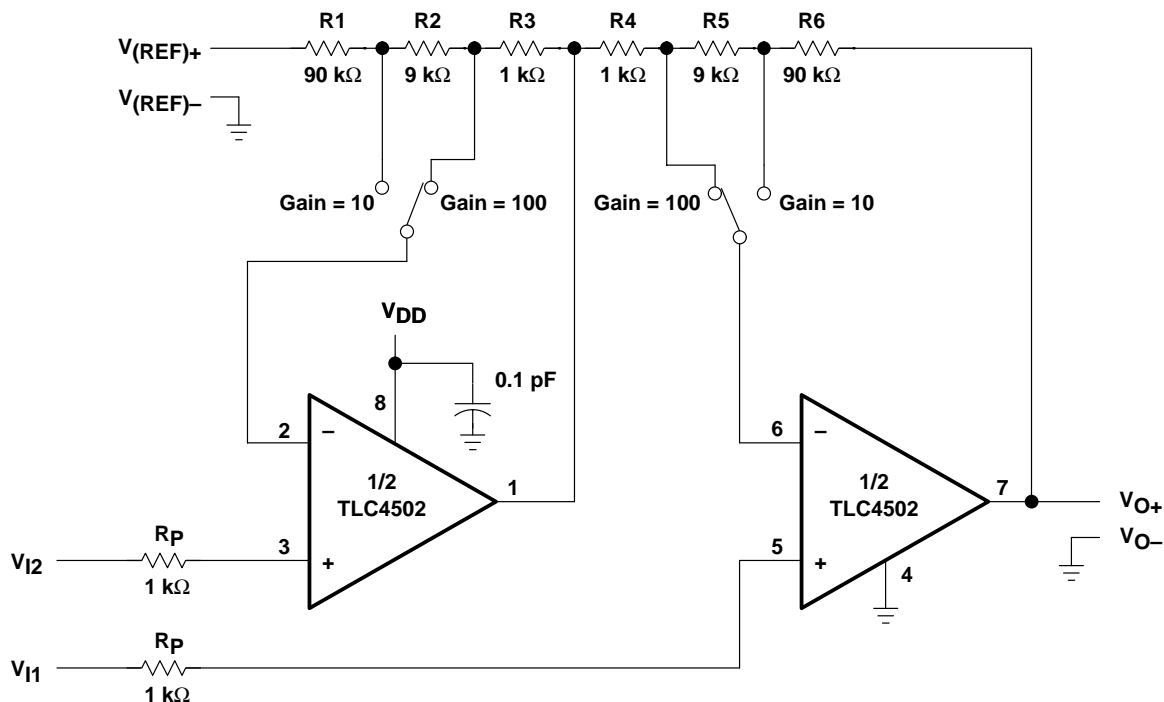
It is also ideal in circuits like:

- A precision buffer for current-to-voltage converters, a/d buffers, or bridge applications
- High-impedance buffers or preamplifiers
- Long term integration
- Sample-and-hold circuits
- Peak detectors

The TLC4502 self-calibrating operational amplifier is manufactured using Texas instruments LinEPIC process technology and is available in an 8-pin SOIC (D) Package. 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 125°C. The M-suffix devices are characterized for operation from –55°C to 125°C.



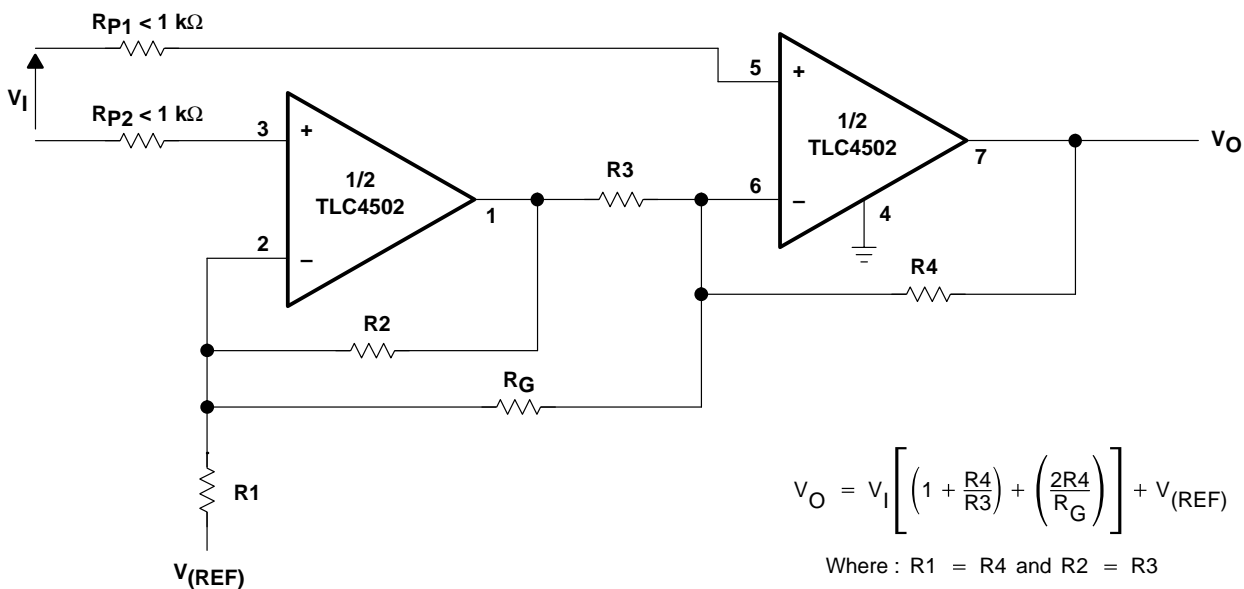
APPLICATION INFORMATION



$$\text{(Gain = 10)} \quad V_O = (V_{I1} - V_{I2}) \left(1 + \frac{R_6}{R_4 + R_5} \right) + V_{(REF)} \quad \text{Where } R_1 = R_6, R_2 = R_5, \text{ and } R_3 = R_4$$

$$\text{(Gain = 100)} \quad V_O = (V_{I1} - V_{I2}) \left(1 + \frac{R_5 + R_6}{R_4} \right) + V_{(REF)} \quad \text{Where } R_1 = R_6, R_2 = R_5, \text{ and } R_3 = R_4$$

Figure 36. Single-Supply Programmable Instrumentation Amplifier Circuit



$$V_O = V_I \left[\left(1 + \frac{R_4}{R_3} \right) + \left(\frac{2R_4}{R_G} \right) \right] + V_{(REF)}$$

Where : $R_1 = R_4$ and $R_2 = R_3$

Figure 37. Two Operational-Amplifier Instrumentation Amplifier Circuit

APPLICATION INFORMATION

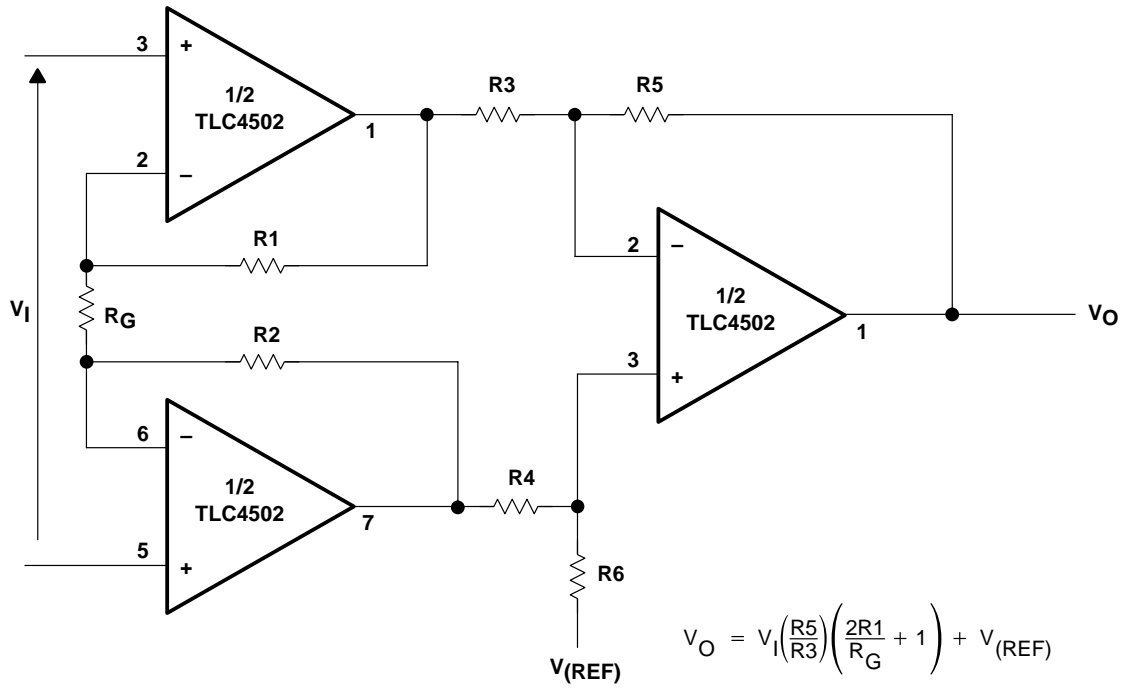


Figure 38. Three Operational-Amplifier Instrumentation Amplifier Circuit

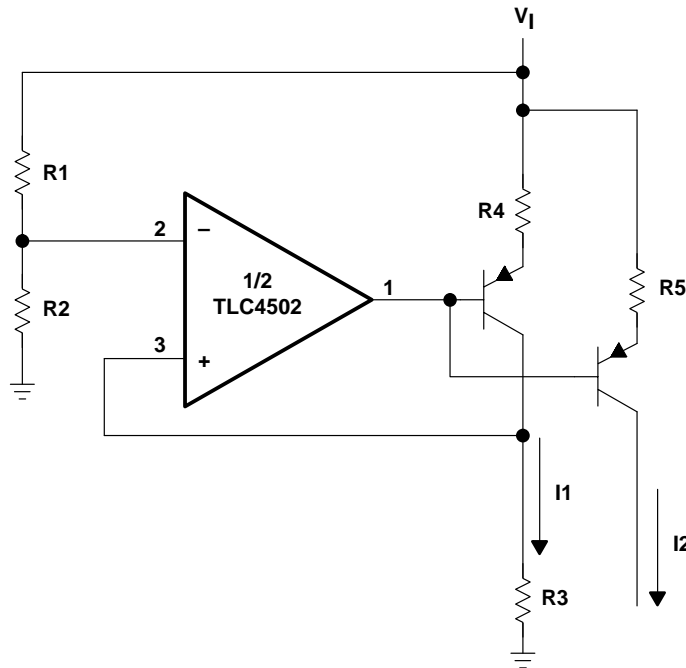


Figure 39. Fixed Current-Source Circuit

APPLICATION INFORMATION

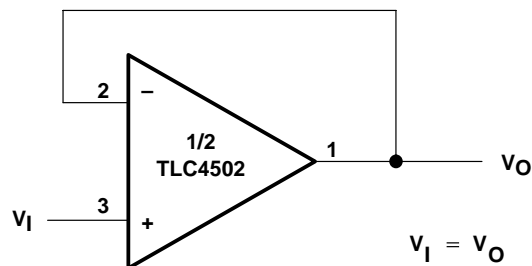


Figure 40. Voltage-Follower Circuit

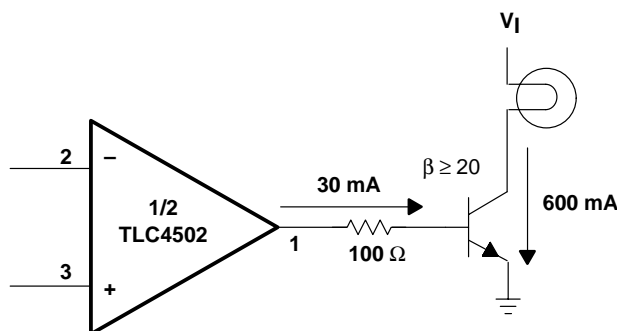


Figure 41. Lamp-Driver Circuit

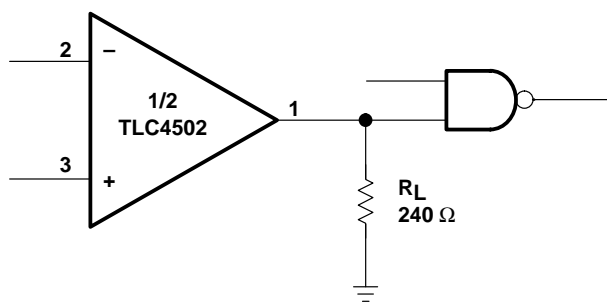


Figure 42. TTL-Driver Circuit

APPLICATION INFORMATION

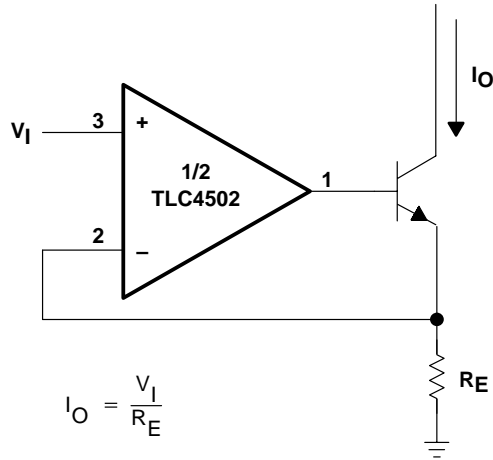


Figure 43. High-Compliance Current-Sink Circuit

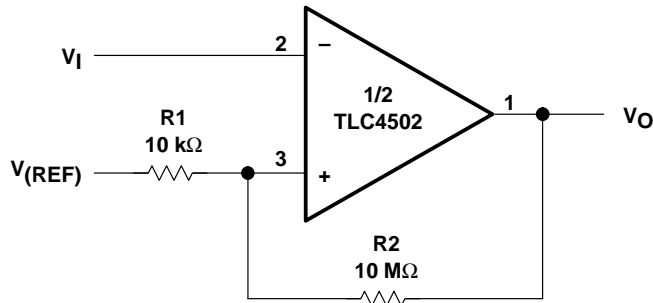


Figure 44. Comparator With Hysteresis Circuit

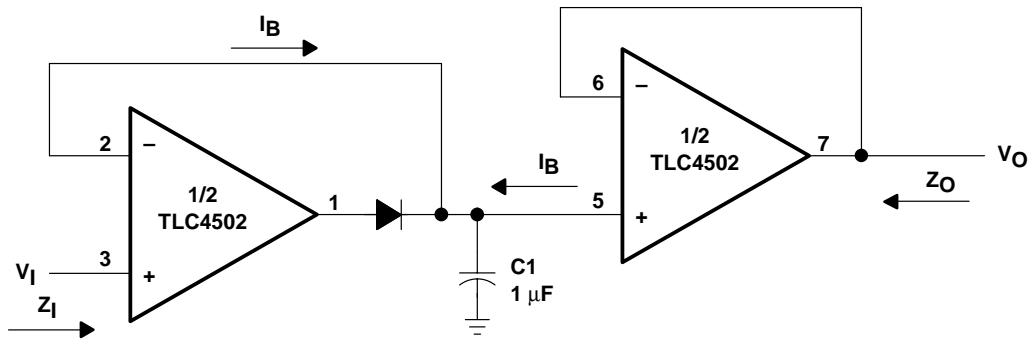


Figure 45. Low-Drift Detector Circuit

TLC4501, TLC4501A, TLC4502, TLC4502A FAMILY OF SELF-CALIBRATING (Self-Cal™) PRECISION CMOS RAIL-TO-RAIL OUTPUT OPERATIONAL AMPLIFIERS

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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 4) and subcircuit in Figure 46 are generated using the TLC4501 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 4: 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).

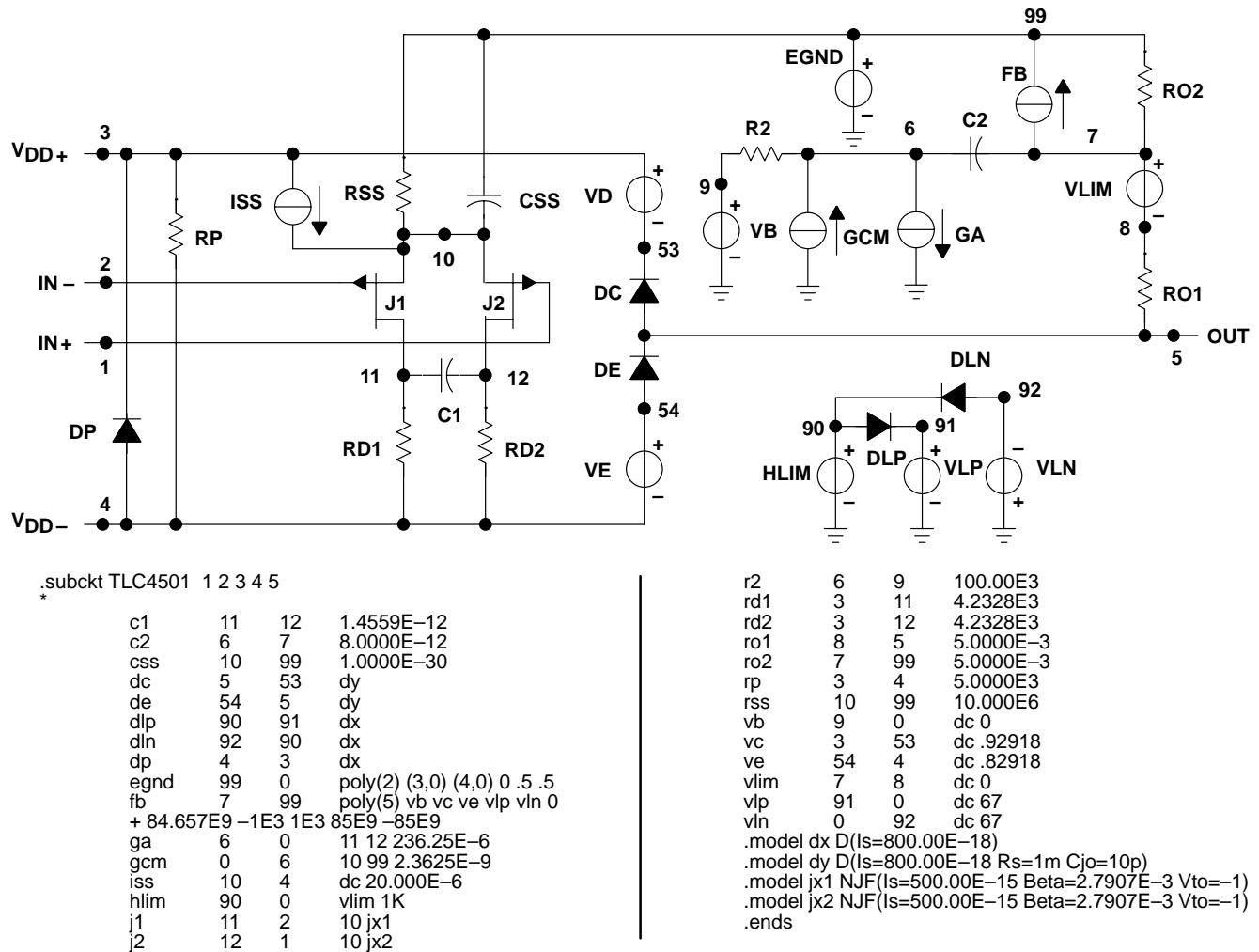


Figure 46. Boyle Macromodel and Subcircuit

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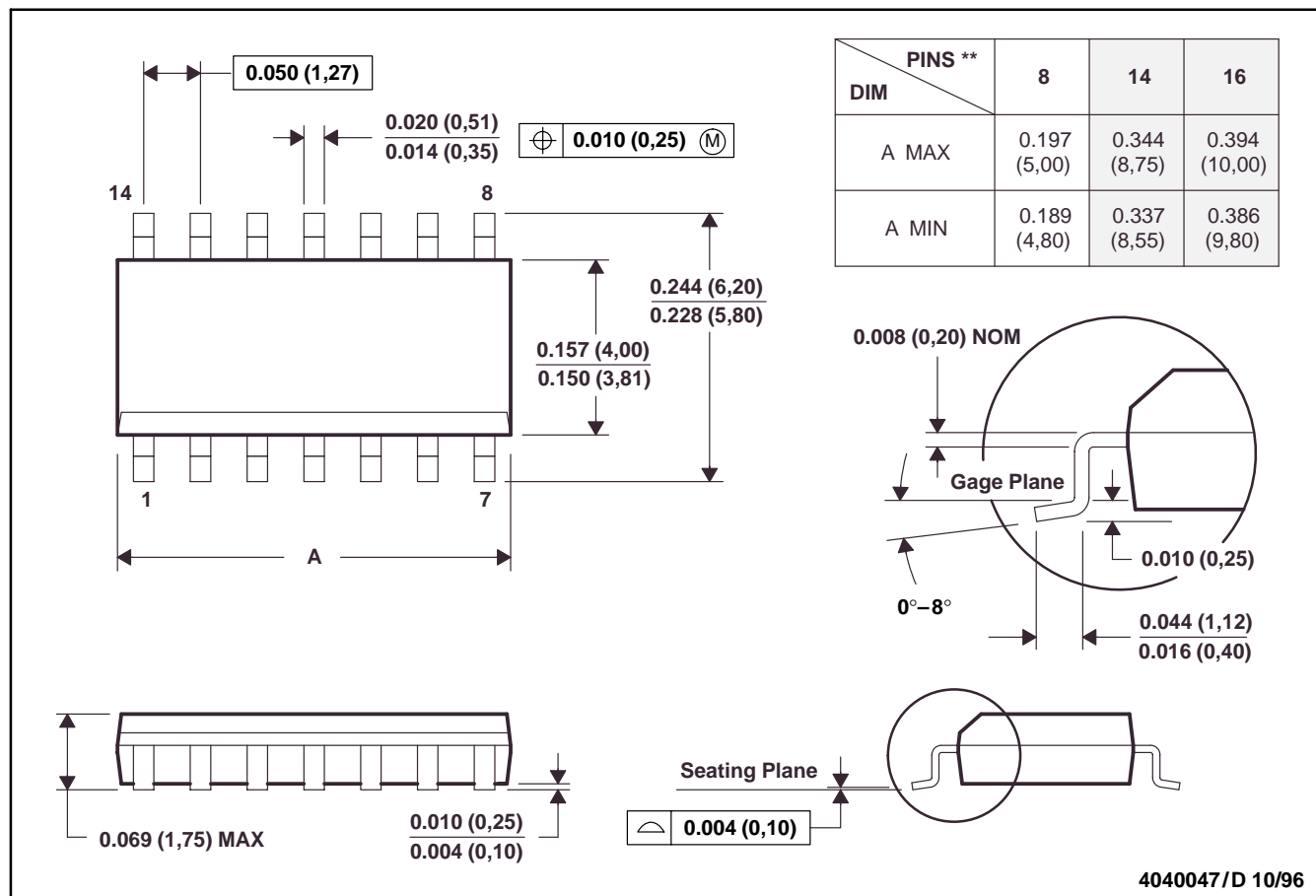
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MECHANICAL INFORMATION

D (R-PDSO-G)**

PLASTIC SMALL-OUTLINE PACKAGE

14 PIN SHOWN



- NOTES: A. All linear dimensions are in inches (millimeters).
 B. This drawing is subject to change without notice.
 C. Body dimensions do not include mold flash or protrusion, not to exceed 0.006 (0,15).
 D. Falls within JEDEC MS-012

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FAMILY OF SELF-CALIBRATING (Self-Cal™)
PRECISION CMOS RAIL-TO-RAIL OUTPUT OPERATIONAL AMPLIFIERS

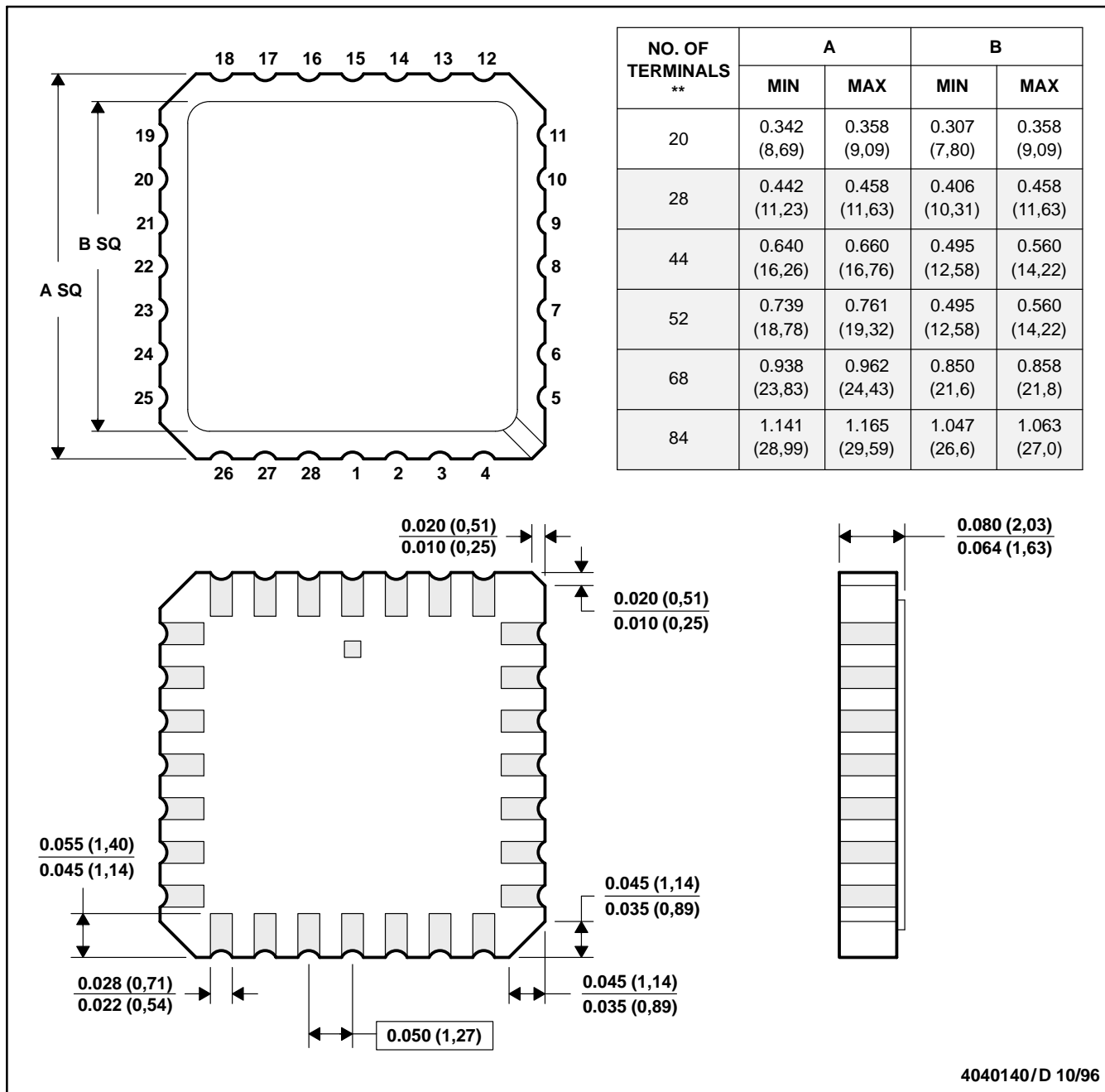
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MECHANICAL INFORMATION

FK (S-CQCC-N)**

LEADLESS CERAMIC CHIP CARRIER

28 TERMINAL SHOWN



- NOTES: A. All linear dimensions are in inches (millimeters).
 B. This drawing is subject to change without notice.
 C. This package can be hermetically sealed with a metal lid.
 D. The terminals are gold plated.
 E. Falls within JEDEC MS-004

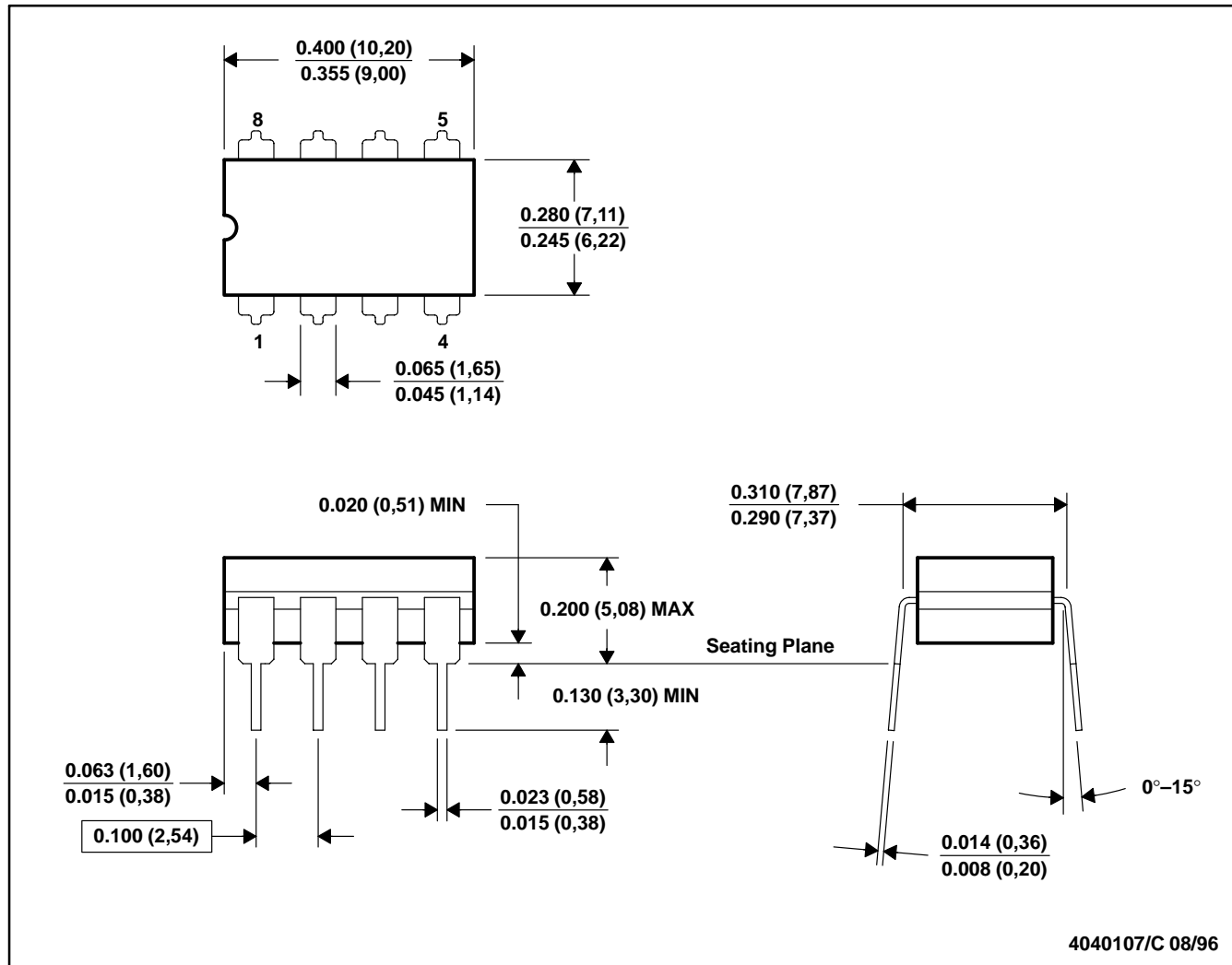
TLC4501, TLC4501A, TLC4502, TLC4502A
FAMILY OF SELF-CALIBRATING (Self-Cal™)
PRECISION CMOS RAIL-TO-RAIL OUTPUT OPERATIONAL AMPLIFIERS

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MECHANICAL INFORMATION

JG (R-GDIP-T8)

CERAMIC DUAL-IN-LINE PACKAGE



- NOTES: A. All linear dimensions are in inches (millimeters).
 B. This drawing is subject to change without notice.
 C. This package can be hermetically sealed with a ceramic lid using glass frit.
 D. Index point is provided on cap for terminal identification on press ceramic glass frit seal only.
 E. Falls within MIL-STD-1835 GDIP1-T8

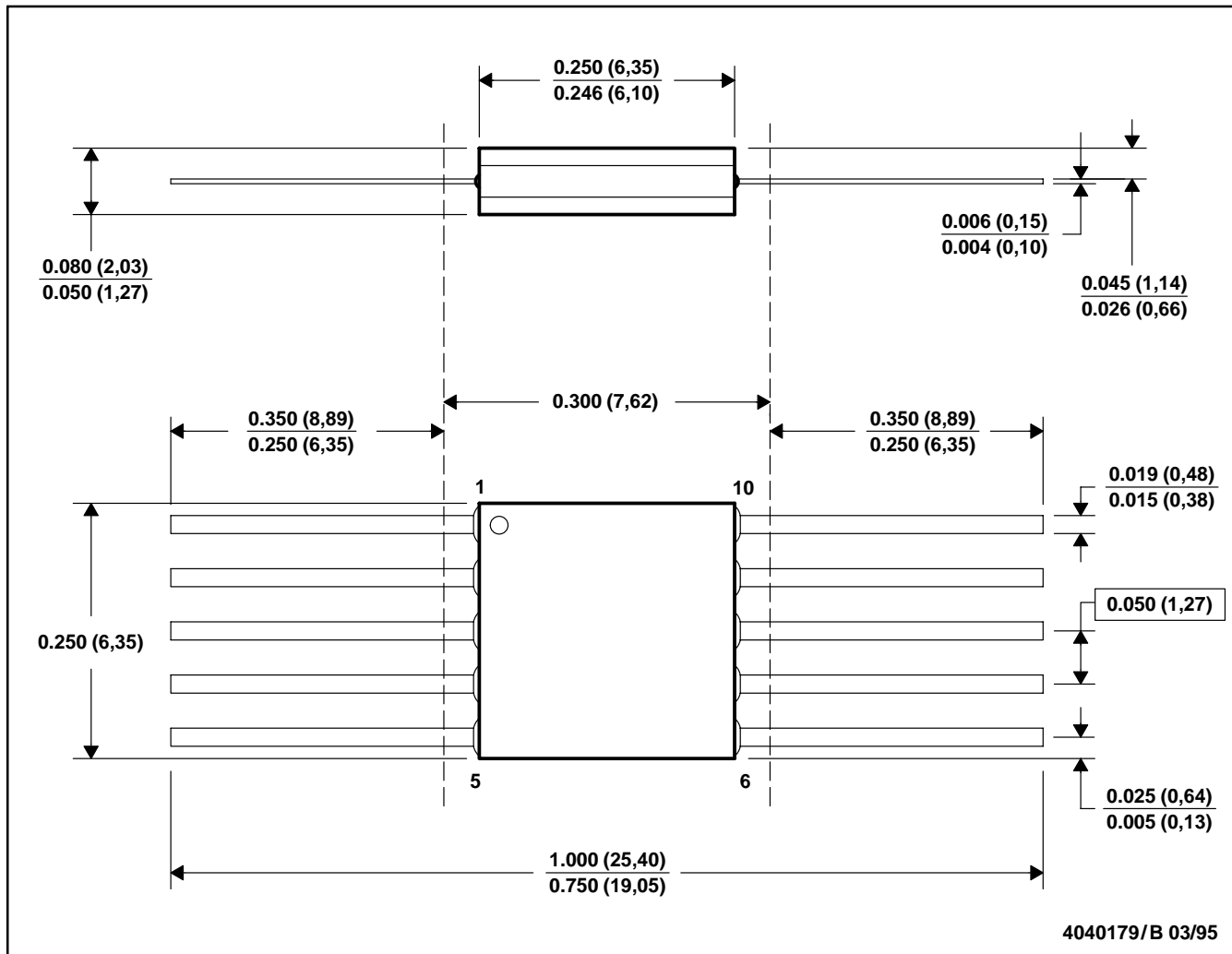
TLC4501, TLC4501A, TLC4502, TLC4502A
FAMILY OF SELF-CALIBRATING (Self-Cal™)
PRECISION CMOS RAIL-TO-RAIL OUTPUT OPERATIONAL AMPLIFIERS

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MECHANICAL INFORMATION

U (S-GDFP-F10)

CERAMIC DUAL FLATPACK



- NOTES: A. All linear dimensions are in inches (millimeters).
 B. This drawing is subject to change without notice.
 C. This package can be hermetically sealed with a ceramic lid using glass frit.
 D. Index point is provided on cap for terminal identification only.
 E. Falls within MIL STD 1835 GDFP1-F10 and JEDEC MO-092AA

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