ECEN 4013

*Design of Engineering Systems*

# Agenda

Tempco

Capacitors

OpAmp Basics

# Temperature coefficients

# Parts per million (ppm)

Commonly used to express small fractions

| | | |
|---|---|---|
| 100% | 1.00 | 1,000,000 ppm |
| 10% | 0.10 | 100,000 ppm |
| 1% | 0.01 | 10,000 ppm |
| 0.1% | 0.001 | 1,000 ppm |
| **0.01%** | **0.0001** | **100 ppm** |
| 0.001% | 0.00001 | 10 ppm |
| 0.0001% | 0.000001 | 1 ppm |

# Parts per million (ppm)

Assume a 20.0k resistor at 25ºC with -400 ppm/ºC tempco is heated to 100ºC. What is the resistance at temperature?

$\Delta R$ = (20.0k)(-400 ppm/ºC)(75ºC)

= $(1.5 \times 10^{6})(-4 \times 10^{-4})$= -600 ohms

Resistance at 100ºC is 19.4k.

# How to deal with tempco

Tempco can be a problem if the circuit depends on absolute value of the part.

Try to arrange circuits which depend on the ratio of resistors (or capacitors) of the same type.

Although absolute values of individual components change with temperature, component ratios will stay approximately constant if the parts have approximately identical tempcos and see the same temperature change.

# Capacitors

A DESIGNER’S LOOK AT CAPACITORS

# CAPACITORS

- In simplest form, a capacitor consists of two conductors separated by a dielectric. Capacitor types are often identified by their dielectric.

- Some capacitors are unintentional (parasitic) but very real, even they don’t show up on the schematic.  Often a source of problems.

# CAPACITORS

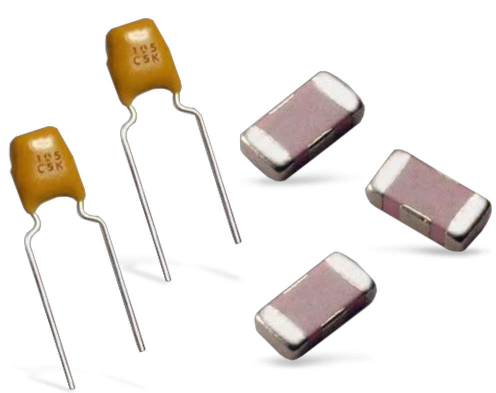
- As with resistors, a huge range of devices are available.  We will concern ourselves only with the types used for general analog and digital applications.  Power and some RF capacitors are special cases.

# CAPACITORS

- This discussion will concern itself with the following devices:
  - Ceramic (fixed)
  - Film (fixed)
  - Mica (fixed)
  - Tantalum (electrolytic)
  - Aluminum (electrolytic)

# CERAMIC CAPACITORS

- Ceramic capacitors are very common and can be considered a utility part. They are widely available as leaded and surface mount devices.
- "Ceramic" refers to the use of a ceramic material as the dielectric.
- A great many ceramic dielectrics are in common use.



# CERAMIC CAPACITORS

- Different ceramic formulations exist because no one formulation can do everything.

- Different ceramics are used to optimize thermal stability (low tempco), voltage rating, part volume, cost, and the largest capacitance achievable in a given package size.

# NP0/C0G CERAMIC CAPACITORS

- Type NP0/C0G is considered a stable formulation capable of operating with a low tempco over a wide temperature range. NP0/C0G types are relatively large for their size. The maximum available capacitance may not support some low-frequency applications.

# X7R/X5R CERAMIC CAPACITORS

- Type X7R is considered a semi-stable formulation capable of operating with low tempco over a fairly large temperature range. X7R types are available in a wide range of capacitance values and are a good overall choice for industrial applications in the -20°C to +80°C range.

# Y5U CERAMIC CAPACITORS

- Type Y5U (among others) has a more pronounced tempco and is typically employed over a more restricted temperatures (typically 0°C to +70°C).

- Y5U devices have good volumetric efficiency and will have higher maximum capacitance relative to X7R.

# Z5U CERAMIC CAPACITORS

- Type Z5U (among others) has a very pronounced tempco and is typically employed over restricted temperatures (typically 0°C to +70°C) where the highest possible capacitance in a given package size and voltage rating is needed .

- Z5U devices are good candidates for power supply decoupling, where actual capacitance is not a critical consideration.

# FILM CAPACITORS

- Usually a “wrap-and-fill” axial-lead construction made with thin dielectric films of mylar, polystyrene, polyester, polycarbonate, and polypropylene.

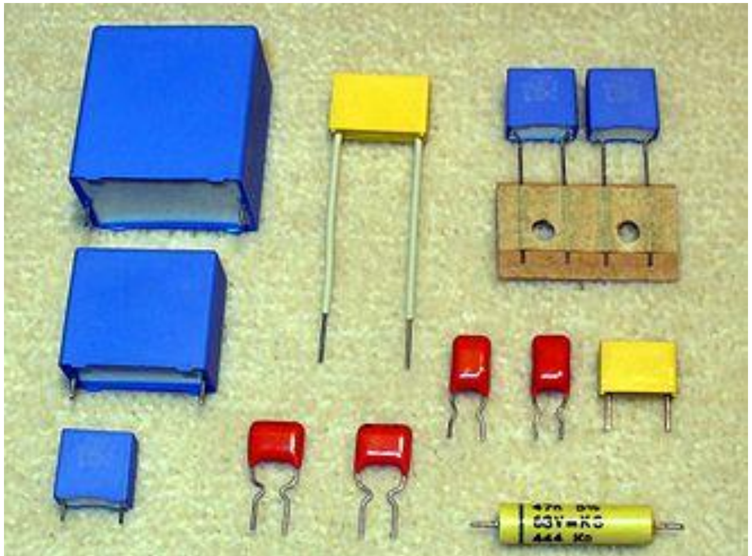
- Typically non-polarized and capable of high voltage ratings with good high frequency performance over a wide temperature range (often -55°C to +125°C).

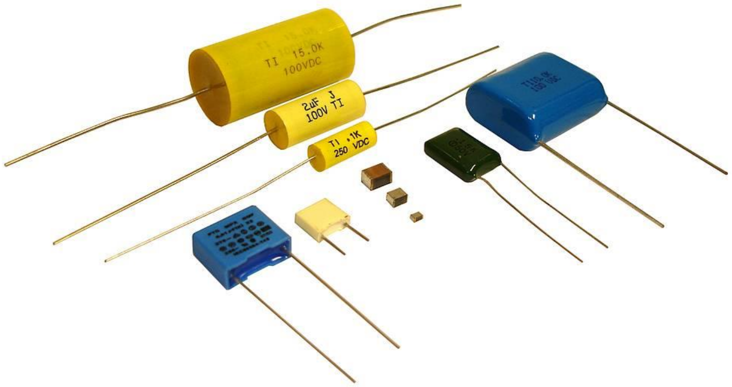
# FILM CAPACITORS

- Good tempcos, low leakage, and low dielectric loss make them useful for peak detectors, sample-and-hold circuits, low-power resonant circuits, and general analog filtering. Tight tolerances are available.

- Polypropylene capacitors are preferred for line-to-ground and line-to-line AC applications.

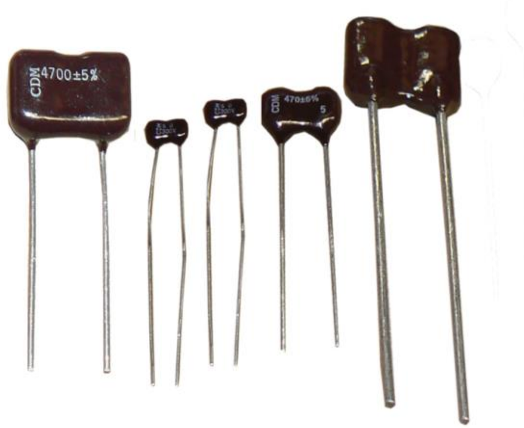
- Large in size compared to other types.

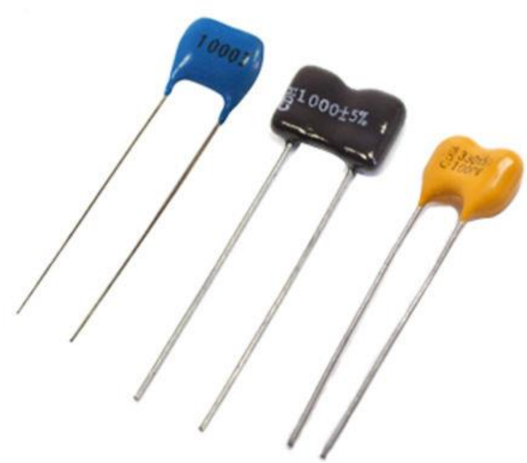




# MICA CAPACITORS

- Mica is a naturally-occurring mineral which is an excellent insulator.
- Mica capacitors are classic parts for RF, high frequency, and high voltage applications. Values are typically less than 1000 pF.
- Very stable with very low loss. Large and heavy compared to other types.



# ELECTROLYTIC CAPACITORS

- Polarized capacitors are used when very large capacitance in a small volume is essential. Tolerances are very wide.

- Widely used in power supply and other low frequency applications where bulk capacitance, small volume, and low cost are the primary considerations.

- Tantalum and aluminum electrolytics are especially common.

# ELECTROLYTIC CAPACITORS

Available with a wide range of temperature ratings. Surface mount parts are available.

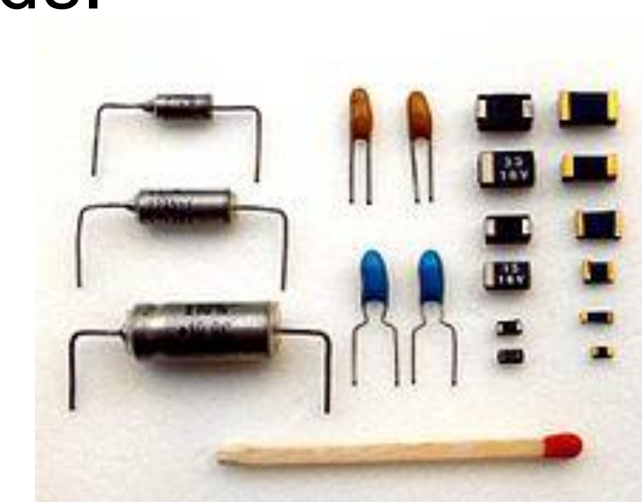
Electrolytics must not be used for bipolar signals. You <u>must</u> respect the polarity markings and the voltage ratings.

Electrolytics are safe when properly installed and used within their ratings. They can be dangerous when applied incorrectly.

# TANTALUM CAPACITORS

Available in many different package styles. Most leaded parts will be irregular little blobs, although military-rated and extended temperature parts may be cylindrical.

Tantalum capacitors can (and usually will) burn if installed backwards.



# ALUMINUM ELECTROLYTICS

Usually available in cylindrical aluminum cans with radial wire leads, snap-in prongs, or screw terminals on the bottom plate.

Larger devices will have scored tear lines and sometimes pressure vents. If exposed to sufficiently long overvoltage, aluminum electrolytics can explode.

# CAPACITOR DECADE VALUESS

As with resistors, capacitors are available in standard decade values, although there are frequent exceptions.

# CAPACITOR DECADE VALUESS

Decade values for lab stock will be:

1.0
2.2
3.3
4.7
5.6
6.8
8.2

# CAPACITOR PART NUMBERS

Typically lengthy, as with resistors.  If anything, capacitor part numbers are more involved than resistor part numbers.

# ABOUT THE PART NUMBERS

Random KEMET Example:

C0805C682K5RACTU

- C = Ceramic
- 0805 = 0805 case size, surface mount
- C = Standard series
- 682 = capacitance code in pF = 6800 pF
- K = capacitance tolerance, ±10%
- 5 = rated voltage, 50 VDC
- R = dielectric, X7R
- A = failure rate
- C = termination finish, 100% matte Sn
- TU = packaging, 7” reel/unmarked

# ABOUT THE PART NUMBERS

Capacitance codes are similar to the codes used for resistors, but the interpretation varies from type to type.

Ceramic, mica, and film capacitors are usually expressed in pF.

Electrolytics are often expressed in µF.

# OP AMP BASICS

# Op amp nonidealities

Contemporary op amps are very good but they are not ideal:

(1) Input impedance is high but not infinite.

(2) Output impedance is low but not zero.

(3) Gain is high but not infinite.

# Op amp nonidealities

(4) Frequency response is not infinite.

(5) Slew rate is not infinite.

(6) Inputs and outputs do not have rail-to-rail signal range (but some are close).

(7) Op amps produce internally-generated noise.

# Let's discuss specific issues

As always, the device spec sheet is the designer's friend.

This example will be an AD820. Two device grades, A and B, are available. We will use A grade specs.

Most specs are the same. The B grade has tighter specs in some cases.

# Typical cover sheet

ANALOG DEVICES

## Single-Supply, Rail-to-Rail, Low Power, FET Input Op Amp

## AD820

### FEATURES

**True single-supply operation**
- Output swings rail-to-rail
- Input voltage range extends below ground
- Single-supply capability from 5 V to 30 V
- Dual-supply capability from ±2.5 V to ±15 V

**Excellent load drive**
- Capacitive load drive up to 350 pF
- Minimum output current of 15 mA

**Excellent ac performance for low power**
- 800 μA maximum quiescent current
- Unity-gain bandwidth: 1.8 MHz
- Slew rate of 3 V/μs

**Excellent dc performance**
- 800 μV maximum input offset voltage
- 2 μV/°C typical offset voltage drift
- 25 pA maximum input bias current

**Low noise: 13 nV/√Hz @ 10 kHz**

### PIN CONFIGURATIONS

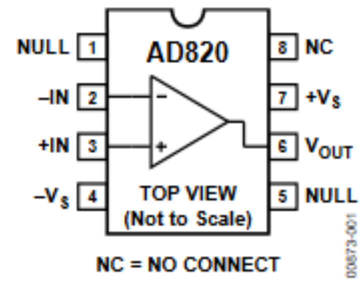



*Figure 1. 8-Lead PDIP*

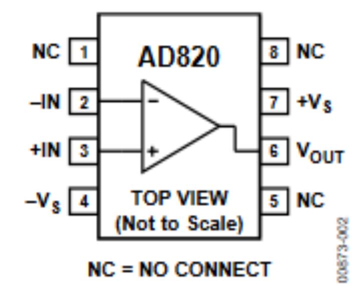



*Figure 2. 8-Lead SOIC_N and 8-Lead MSOP*

## APPLICATIONS

**Battery-powered precision instrumentation**
**Photodiode preamps**
**Active filters**
**12-bit to 14-bit data acquisition systems**
**Medical instrumentation**
**Low power references and regulators**

## GENERAL DESCRIPTION

The AD820 is a precision, low power FET input op amp that can operate from a single supply of 5 V to 36 V, or dual supplies of ±2.5 V to ±18 V. It has true single-supply capability, with an input voltage range extending below the negative rail, allowing the AD820 to accommodate input signals below ground in the single-supply mode. Output voltage swing extends to within 10 mV of each rail, providing the maximum output dynamic range.

Offset voltage of 800 μV maximum, offset voltage drift of 2 μV/°C, typical input bias currents below 25 pA, and low input voltage noise provide dc precision with source impedances up to 1 GΩ. 1.8 MHz unity gain bandwidth, −93 dB THD at 10 kHz, and 3 V/μs slew rate are provided for a low supply current of 800 μA. The AD820 drives up to 350 pF of direct capacitive load and provides a minimum output current of 15 mA. This allows the amplifier to handle a wide range of load conditions. This combination of ac and dc performance, plus the outstanding load drive capability, results in an exceptionally versatile amplifier for the single-supply user.

The AD820 is available in two performance grades. The A and B grades are rated over the industrial temperature range of −40°C to +85°C. The AD820 is offered in three 8-lead package options: plastic DIP (PDIP), surface mount (SOIC) and (MSOP).

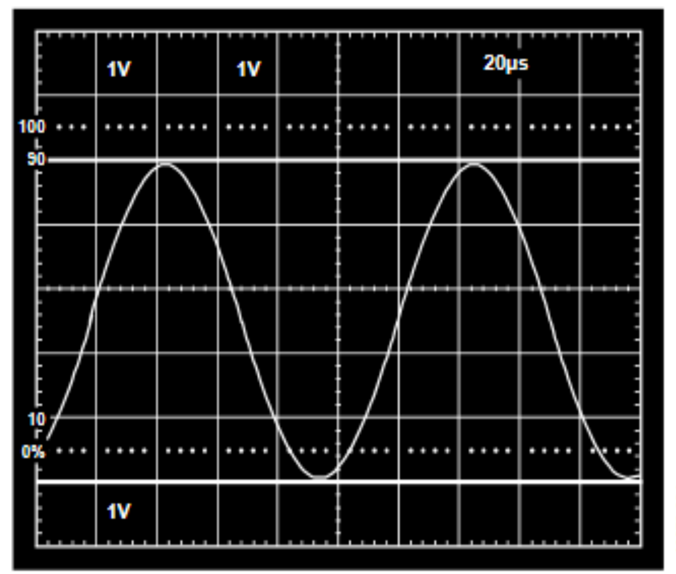



*Figure 3. Gain-of-2 Amplifier; $V_S$ = 5 V, 0 V, $V_{IN}$ = 2.5 V Sine Centered at 1.25 V*

# Let’s discuss specific issues

The AD820 is capable of dual supply or single supply operation.

Specifications are provided for several common power supply combinations:

+5V unipolar
±5V bipolar
±15V bipolar

# Let’s discuss specific issues

Using the specs for ±15V bipolar operation, following are major device specs of interest to the designer:

- Output offset: this is a static DC error appearing at the output when the output should be zero. It is troublesome when dealing with precision DC applications.
  - Inputs shorted together ideally should have 0v output
  - Instead, there is some output

$V_S = \pm 15$ V @ $T_A = 25°C$, $V_{CM} = 0$ V, $V_{OUT} = 0$ V, unless otherwise noted.

Table 3.

| | | AD820A | | | AD820B | | | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | **Conditions** | **Min** | **Typ** | **Max** | **Min** | **Typ** | **Max** | **Unit** |
| DC PERFORMANCE | | | | | | | | |
| Initial Offset | | | 0.4 | 2 | | 0.3 | 1.0 | mV |
| Maximum Offset over Temperature | | | 0.5 | 3 | | 0.5 | 2 | mV |
| Offset Drift | | | 2 | | | 2 | | μV/°C |

# Typical offset distribution

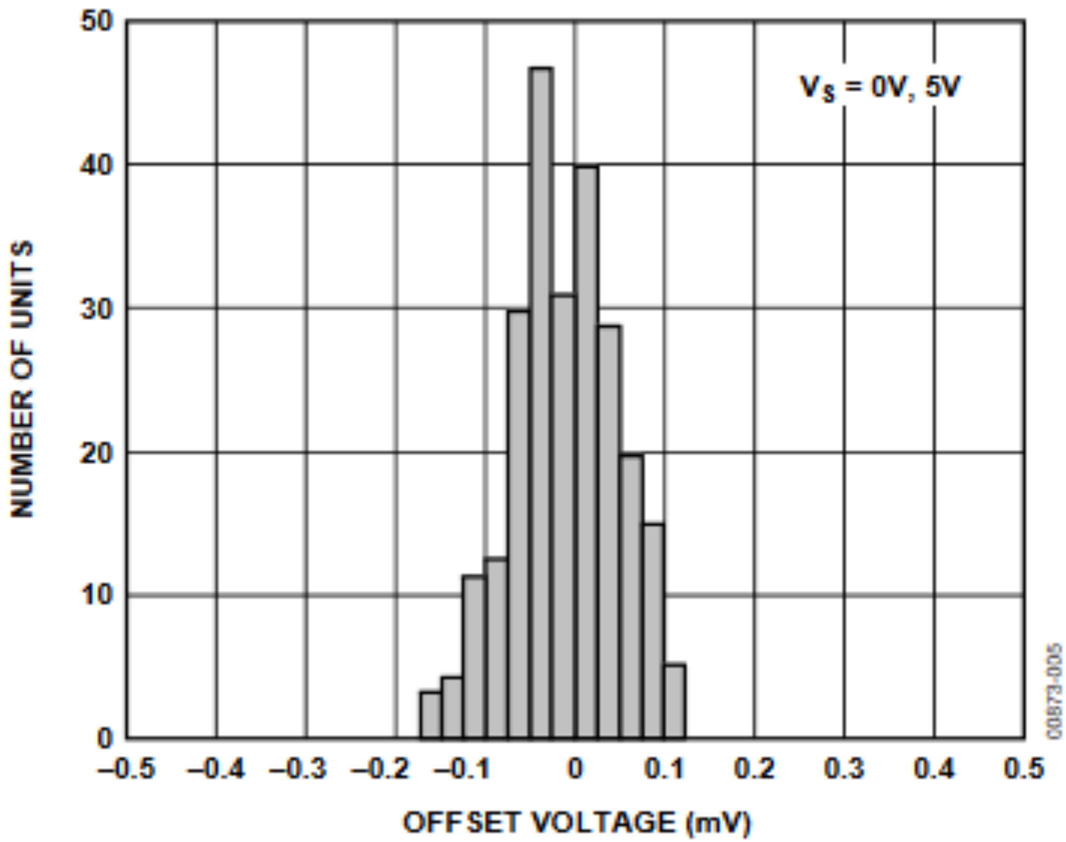



*Figure 4. Typical Distribution of Offset Voltage (248 Units)*

- Input bias current: each input has a small bias current that will go to circuit common through external impedances. This gives rise to additional offset error and is a function of temperature. Spec given is the average current into both terminals at a constant output level.

| | | | | | | |
|---|---|---|---|---|---|---|
| Input Bias Current | $V_{CM} = 0V$ | 2 | 25 | 2 | 10 | pA |
| | $V_{CM} = -10V$ | 40 | | 40 | | pA |
| At $T_{MAX}$ | $V_{CM} = 0V$ | 0.5 | 5 | 0.5 | 2.5 | nA |

- Vcm is common mode voltage (average of voltages at the inputs)

# Typical input bias current distribution

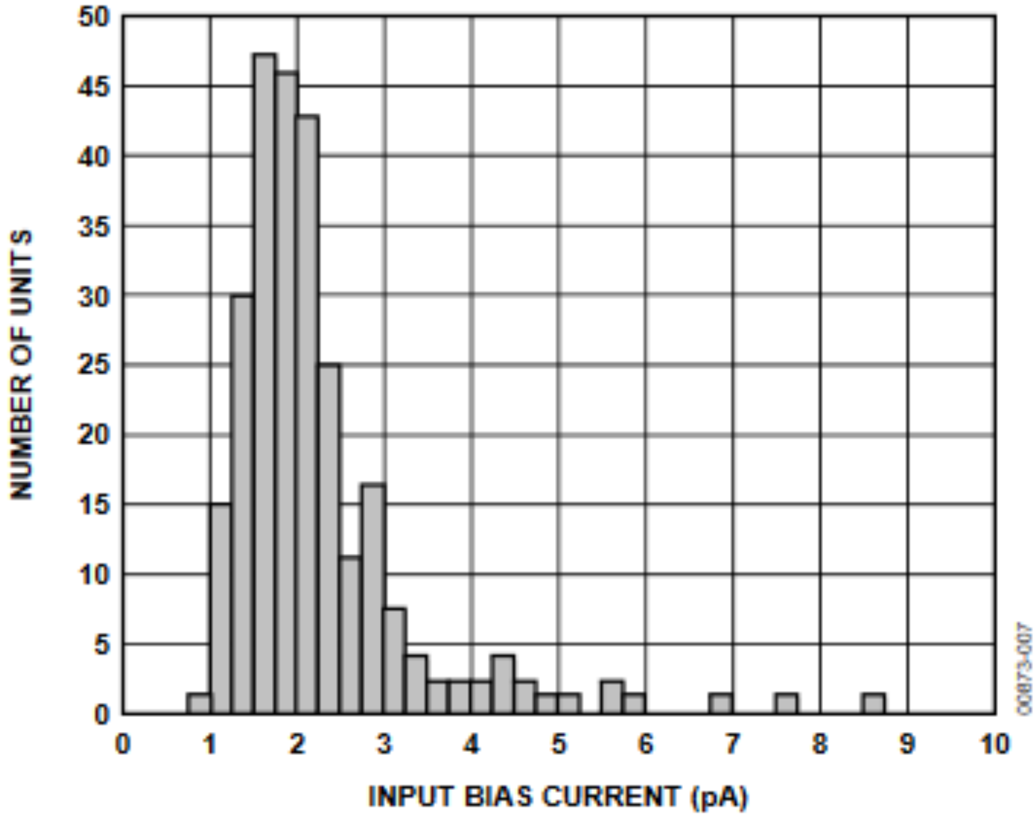



*Figure 6. Typical Distribution of Input Bias Current (213 Units)*

# Bias current is temperature sensitive!!

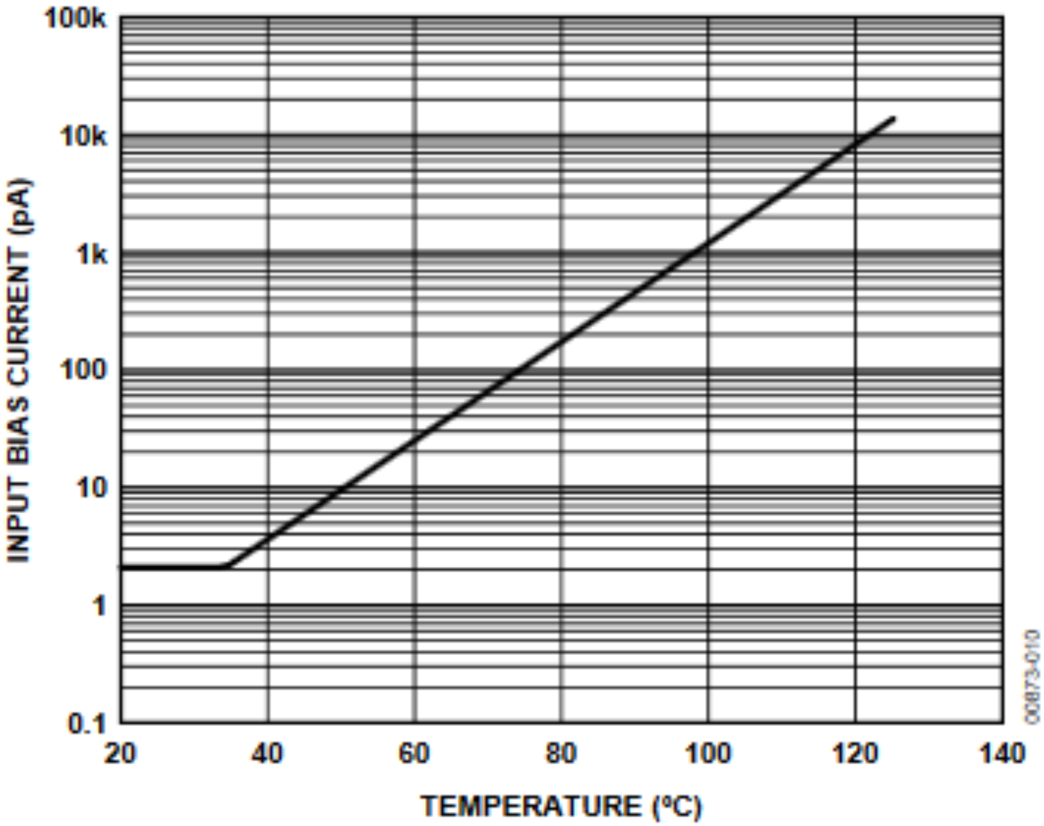



*Figure 9. Input Bias Current vs. Temperature; $V_S = 5\ V$, $V_{CM} = 0\ V$*

- Open loop gain: the maximum gain the amplifier is capable of producing. Gain when no feedback is used. It is affected by temperature and load.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Open-Loop Gain | $V_{OUT} = -10\ V$ to $+10\ V$ | | | | | | | |
| | $R_L = 100\ k\Omega$ | 500 | 2000 | | 500 | 2000 | | V/mV |
| $T_{MIN}$ to $T_{MAX}$ | | 500 | | | 500 | | | V/mV |
| | $R_L = 10\ k\Omega$ | 100 | 500 | | 100 | 500 | | V/mV |
| $T_{MIN}$ to $T_{MAX}$ | | 100 | | | 100 | | | V/mV |
| | $R_L = 1\ k\Omega$ | 30 | 45 | | 30 | 45 | | V/mV |
| $T_{MIN}$ to $T_{MAX}$ | | 20 | | | 20 | | | V/mV |

# Open loop gain

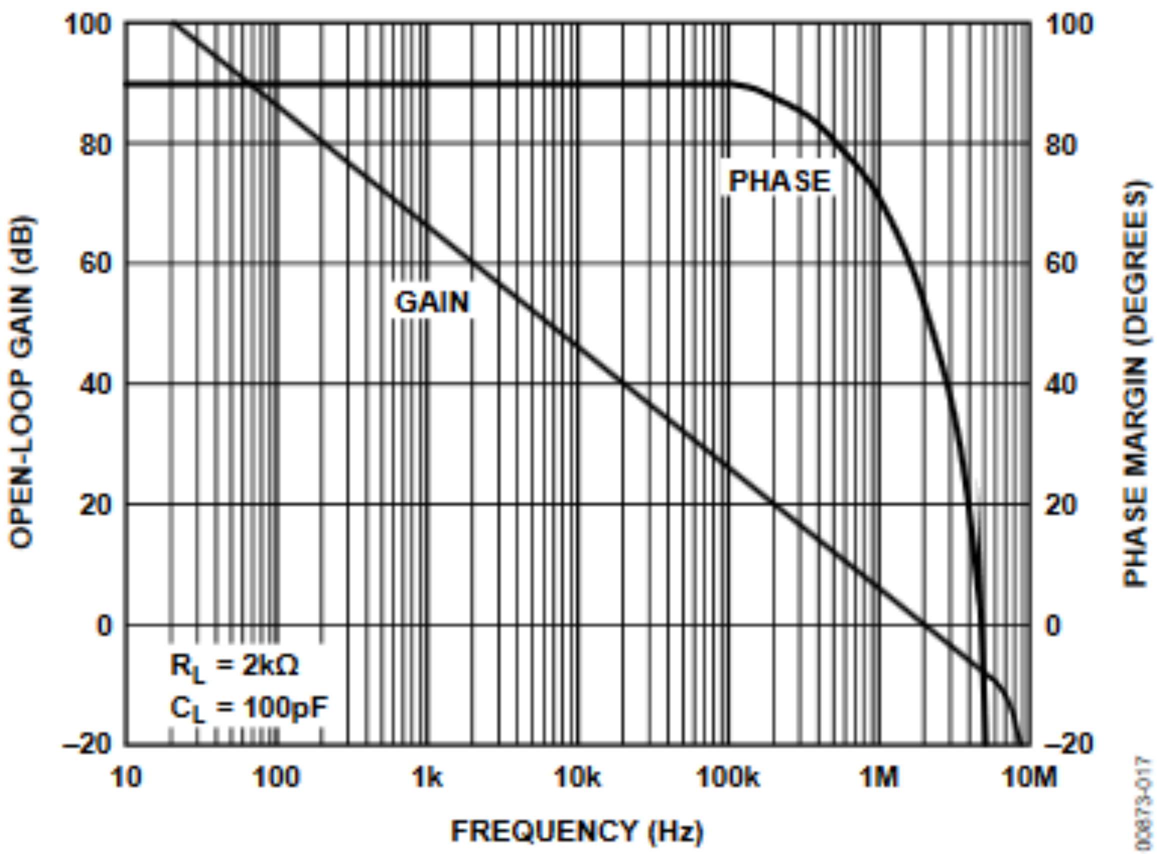



*Figure 16. Open-Loop Gain and Phase Margin vs. Frequency*

- Input voltage noise:  amplifiers have small internal noise sources. Noise performance can be a  very important consideration.

| | | | | |
|---|---|---|---|---|
| NOISE/HARMONIC PERFORMANCE | | | | |
| Input Voltage Noise | | | | |
| f = 0.1 Hz to 10 Hz | | 2 | 2 | μV p-p |
| f = 10 Hz | | 25 | 25 | nV/√Hz |
| f = 100 Hz | | 21 | 21 | nV/√Hz |
| f = 1 kHz | | 16 | 16 | nV/√Hz |
| f = 10 kHz | | 13 | 13 | nV/√Hz |

- Dynamic performance: different measurements related to the speed of the device – usually a major consideration.
  - Unity Gain Frequency – frequency at which gain drops off to 0dB
  - Full Power Response – range of frequencies where Op Amp operates at full power
  - Slew Rate – change in voltage per unit of time
  - Settling Time – time to settle to within a certain error band (often chosen by manufacturer)

| DYNAMIC PERFORMANCE | | | | |
|---|---|---|---|---|
| Unity Gain Frequency | | 1.9 | 1.9 | MHz |
| Full Power Response | $V_{OUT}$ p-p = 20 V | 45 | 45 | kHz |
| Slew Rate | | 3 | 3 | V/μs |
| Settling Time | $V_{OUT}$ = 0 V to ±10 V | | | |
| To 0.1% | | 4.1 | 4.1 | μs |
| To 0.01% | | 4.5 | 4.5 | μs |

# Open loop gain

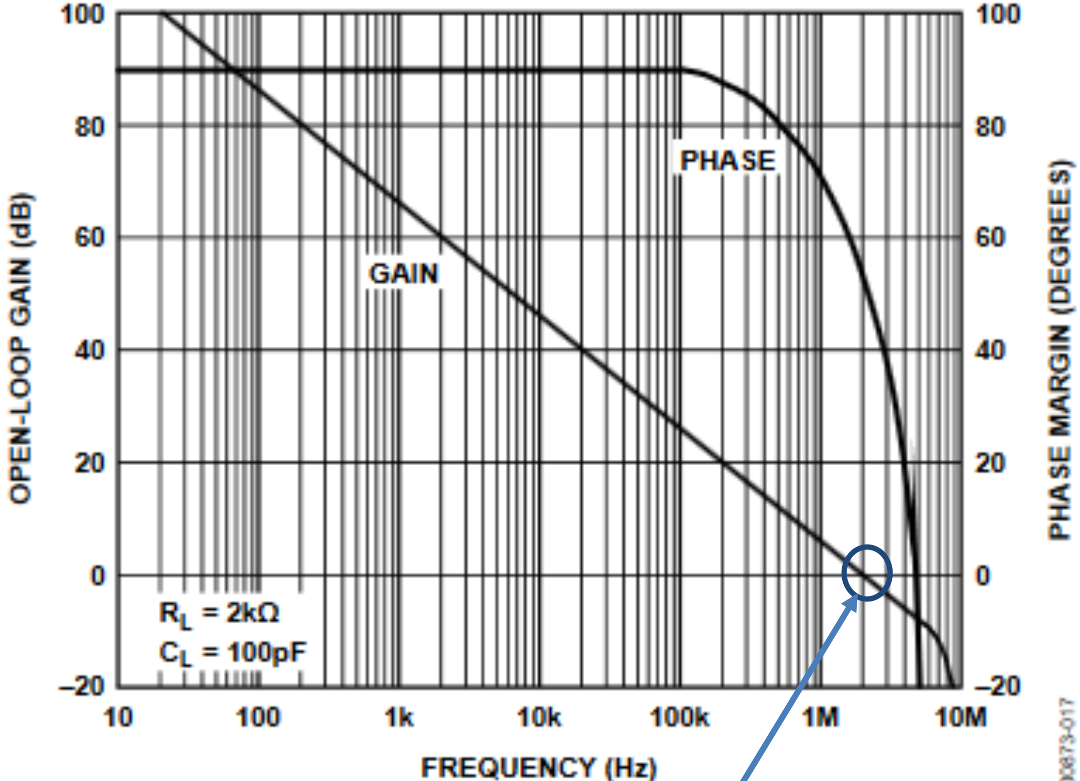



*Figure 16. Open-Loop Gain and Phase Margin vs. Frequency*

Unity Gain Frequency

# Large signal response (related to slew rate)

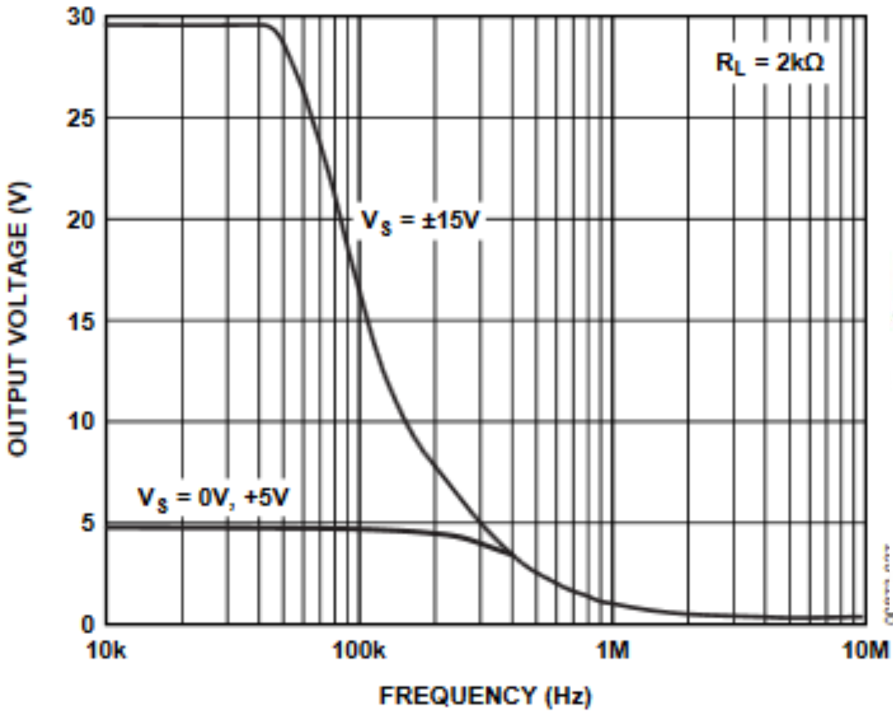
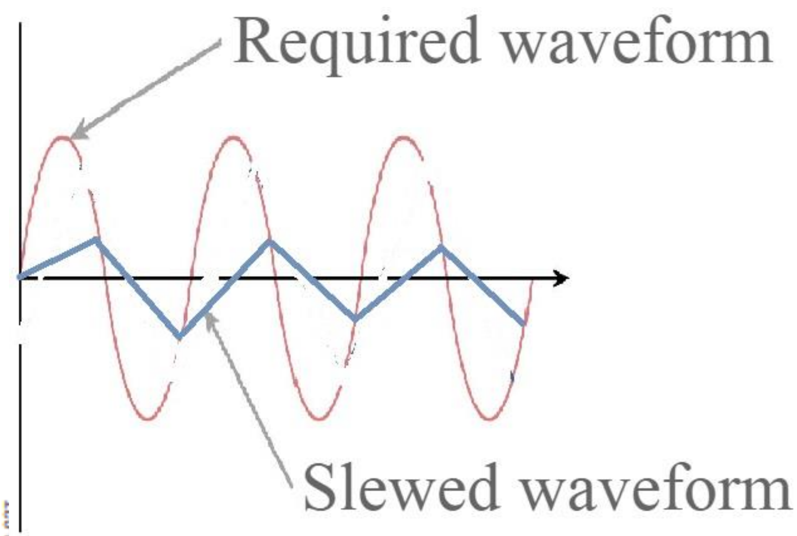



Figure 26. Large Signal Frequency Response



# Simple derivation of slew rate

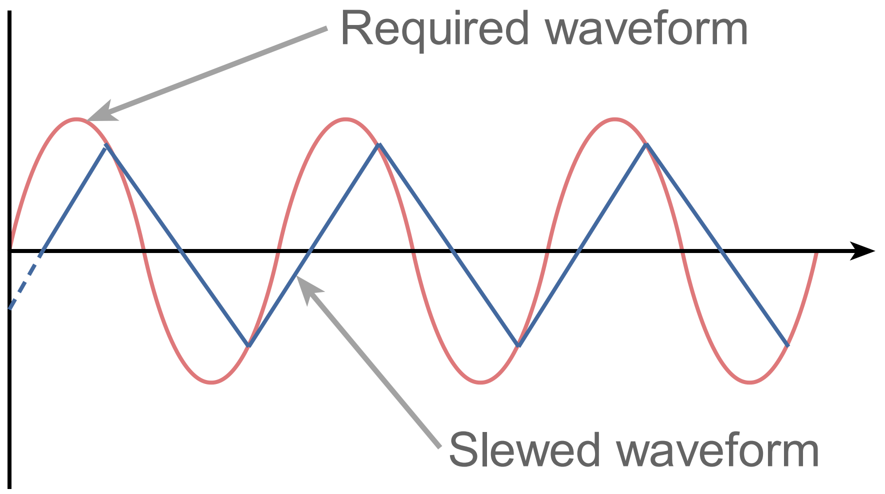
Let $V_{out} = A\sin(2\pi f t)$

$\frac{d}{dt}(V_{out}) = 2\pi f A \cos(2\pi f t)$

Derivative (slew rate) is maximum at t=0:

$$SR = 2\pi f A$$

Your device slew rate would need to be at or above this value to represent this function. Otherwise, distortion occurs.



# Output is limited by slew rate

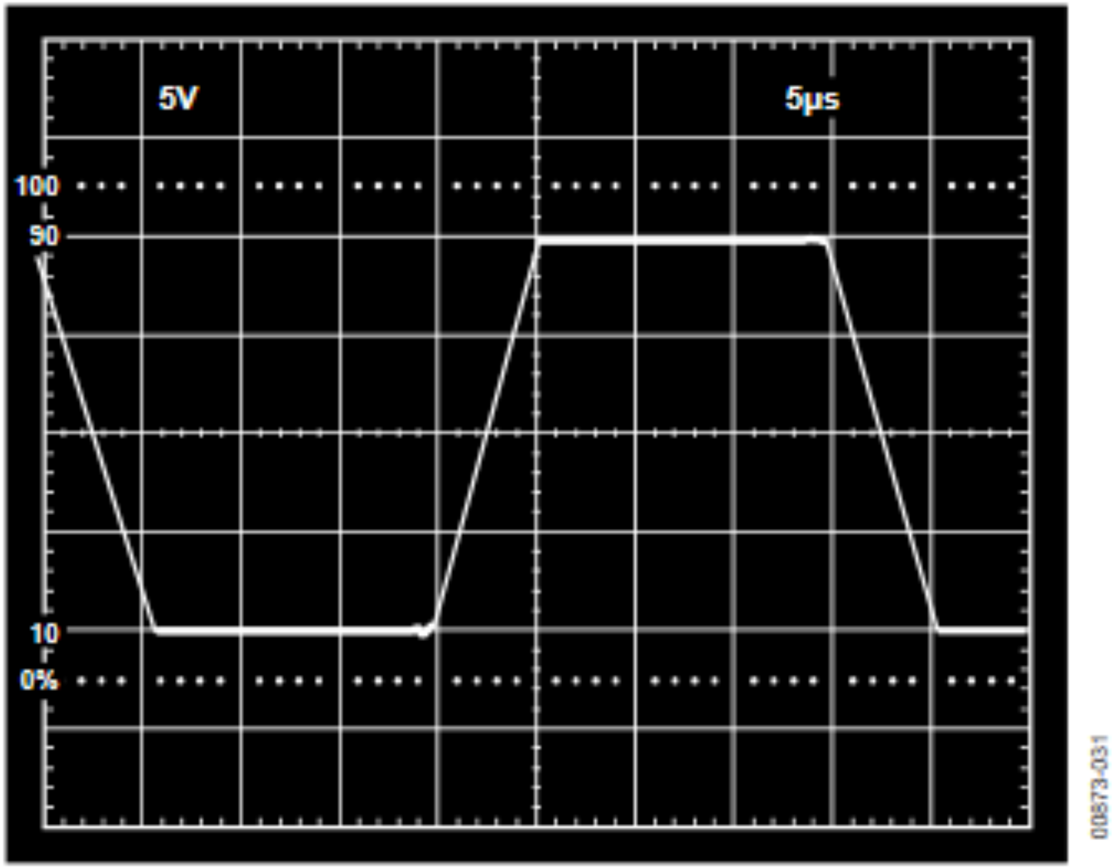



*Figure 30. Large Signal Response Unity-Gain Follower; $V_S = \pm 15$ V, $R_L = 10$ kΩ*

# Settling time

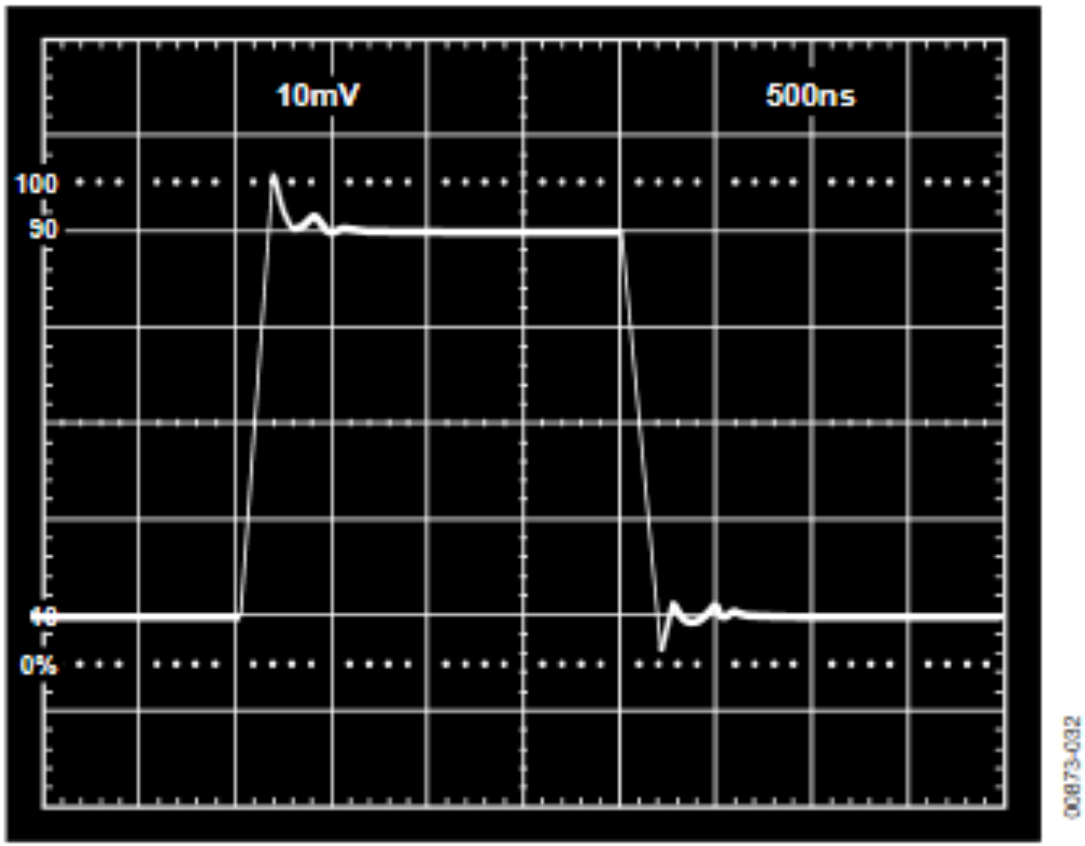



*Figure 31. Small Signal Response Unity-Gain Follower; $V_S = \pm 15$ V, $R_L = 10$ kΩ*

- Output saturation characteristics: related to maximum voltage swing (headroom). In this case, it's very close to true rail-to-rail. Note it's a function of load current.
  - Vol – Vee: difference between lowest possible voltage and negative supply
  - Vcc – Voh: difference between highest output and positive voltage supply

| | | | | | | |
|---|---|---|---|---|---|---|
| OUTPUT CHARACTERISTICS | | | | | | |
| Output Saturation Voltage[2] | | | | | | |
| $V_{OL} - V_{EE}$ | $I_{SINK} = 20\ \mu A$ | 5 | 7 | 5 | 7 | mV |
| $T_{MIN}$ to $T_{MAX}$ | | | 10 | | 10 | mV |
| $V_{CC} - V_{OH}$ | $I_{SOURCE} = 20\ \mu A$ | 10 | 14 | 10 | 14 | mV |
| $T_{MIN}$ to $T_{MAX}$ | | | 20 | | 20 | mV |
| $V_{OL} - V_{EE}$ | $I_{SINK} = 2\ mA$ | 40 | 55 | 40 | 55 | mV |
| $T_{MIN}$ to $T_{MAX}$ | | | 80 | | 80 | mV |
| $V_{CC} - V_{OH}$ | $I_{SOURCE} = 2\ mA$ | 80 | 110 | 80 | 110 | mV |
| $T_{MIN}$ to $T_{MAX}$ | | | 160 | | 160 | mV |

- Output current: how much current is the amplifier capable of sourcing?
  - Operating output current – typical operating minimum
  - Short-Circuit Current – how much current (sink or source) typically at output pin
  - Capacitive Load Drive – If capacitive load is too high, can become an unstable oscillator

| | | | | | | |
|---|---|---|---|---|---|---|
| Operating Output Current | | 20 | | 20 | | mA |
| $T_{MIN}$ to $T_{MAX}$ | | 15 | | 15 | | mA |
| Short-Circuit Current | | | 45 | | 45 | mA |
| Capacitive Load Drive | | | 350 | | 350 | pF |

- Power supply:  how much quiescent operating current is required for the amplifier?  Quiescent power is quiescent current multiplied by source voltage.  This is a major consideration for portable instruments.  Power to load not included.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| POWER SUPPLY | | | | | | | | |
| Quiescent Current | $T_{MIN}$ to $T_{MAX}$ | | 700 | 900 | | 700 | 900 | μA |

# Absolute Maximums

## ABSOLUTE MAXIMUM RATINGS

Table 4.

| Parameter | Rating |
|---|---|
| Supply Voltage | ±18 V |
| Internal Power Dissipation | |
| 8-Lead PDIP (N) | 1.6 W |
| 8-Lead SOIC_N (R) | 1.0 W |
| 8-Lead MSOP (RM) | 0.8 W |
| Input Voltage[1] | ((V+) + 0.2 V) to (V−) − 20 V |
| Output Short-Circuit Duration | Indefinite |
| Differential Input Voltage | ±30 V |
| Storage Temperature Range | |
| 8-Lead PDIP (N) | −65°C to +125°C |
| 8-Lead SOIC_N (R) | −65°C to +150°C |
| 8-Lead MSOP (RM) | −65°C to +150°C |
| Operating Temperature Range | |
| AD820A/AD820B | −40°C to +85°C |
| Lead Temperature(Soldering, 60 sec) | 260°C |

Tolerance ratings. Not operational ratings

# Questions?