

# Designing femtoampere circuits requires special considerations

*New levels of performance in high-impedance, low-current applications are possible, but only if you follow these very important design rules.*

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One femtoampere is  $10^{-15}$  amperes, or, to put it in another perspective, it is one millionth of a nanoampere. It's difficult for most people to conceive of such a small current. Yet, varactor-input op amps, vibrating capacitor amplifiers, electrometer tubes and MOSFET amplifiers can be used to measure and manipulate femtoampere currents.

Choosing the right amplifier and then obtaining optimum performance from it requires careful considerations and trade-offs. First we'll examine the choice of amplifiers. And then we will discuss the ways to realize the full potential of the amplifier.

## Low-bias current is the key specification

The bias current of the measurement amplifier is the most important source of error in high-impedance, low-current applications. These applications generally fall into two basic categories: Inverting or non-inverting. Inverting configurations are used to measure small signal currents. Non-inverting circuits are utilized to measure voltages, usually in connection with high-impedance signal sources where source-loading is a problem.

Inverting applications often employ the "current to voltage converter" configuration, shown in Fig. 1. Teledyne Philbrick Model 1702 varactor op amp is used for the example shown. Included in this category are photomulti-

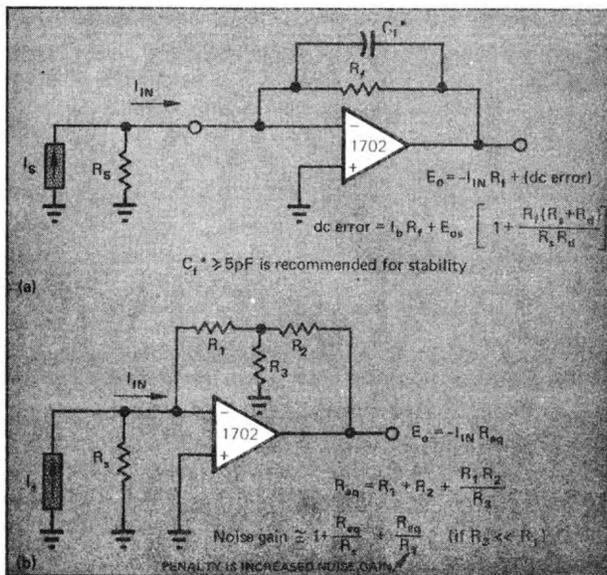


Fig. 1—A simple current-to-voltage converter (a) can be used for many applications. If  $R_f$  becomes too high to be realized with a single component, a T-network may be used (b). In either case, the important amplifier specifications are low bias current ( $I_b$ ) temperature coefficient and high input impedance ( $Z_D$ ). The bias current must be much less than the input current ( $I_{IN}$ ).

plier tube preamps, ionization gages, gas chromatographs and radiation detectors. Special inverting applications include integrators and charge amplifiers.

In inverting applications, a dc error is produced at the output by the bias current at the inverting ( $-$ ) input. This error is equal in magnitude to the bias current times the feedback impedance. That is, it appears that the bias current flows through the feedback impedance to cause an output voltage error. Further, the bias current limits the ultimate resolution of current-measuring circuits, and causes an output drift in integrator and charge-amplifier circuits. For integrators, the drift rate equals the bias current divided by the feedback capacitance ( $I_b/C$ ).

Non-inverting applications, such as buffer amplifiers, PH meters, microvoltmeters, and long-term track-and-hold devices, use the "follower" configuration of Fig. 2. A dc

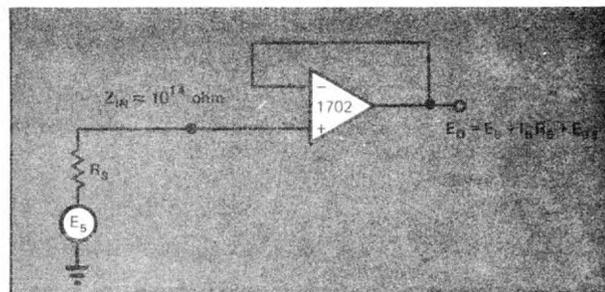


Fig. 2—The non-inverting input is used to obtain an ultra-high-impedance buffer follower. The bias current following into the impedance of the signal source causes an output error.

error due to bias current is developed in this type of circuit when the bias current of the non-inverting input flows into the impedance of the signal source. This error is referred to the output by the gain of the circuit ( $1 + R_f/R_i$ ). In applications which have a capacitive source, such as a track-and-hold circuit, the bias current of the amplifier will cause an apparent drift at the output as it charges up the source capacitor (Fig. 3).

If minimizing bias-current errors was the only consideration it would be very easy to choose a particular type of amplifier for any application. But, as is the usual case, there are other considerations—bandwidth, stability, noise, size and cost. Table 1 lists the basic types of low bias current amplifiers and rates their relative performance with regard to several of the most important parameters.

## Optimize circuit performance

Once an amplifier is chosen, the next step is to optimize circuit performance. Because the amplifier's extraordinary sensitivity makes possible high-performance applications,

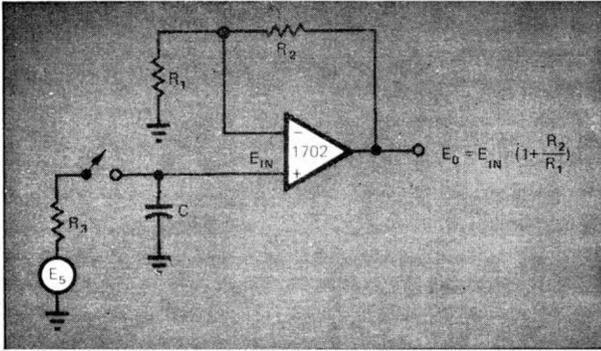


Fig. 3—A non-inverting configuration can provide gain as in this track-and-hold amplifier. The amplifier's bias current causes an apparent output drift as it charges the source capacitor. If C is 10  $\mu$ F, the drift rate, due to the 1702 only, is less than 100  $\mu$ V/day.

error considerations which are insignificant in less sophisticated applications now become the limiting factor in circuit operation. For example, even a  $10^{14}$ -ohm insulation resistance between the signal input of the 1702 and a power-supply lead can cause a leakage current to flow that is 75 times the bias current of the amplifier!

Since total circuit performance is strongly dependent upon the amount of careful consideration given to the selection and layout of components, we have listed several of the most important factors.

**Wiring.** Hard wiring with good quality insulation (teflon, etc.) is preferable to printed-circuit wiring. For example, the amplifier should be plugged into a socket with teflon insulators rather than soldered directly onto a PC board. Insulated wiring would then connect input terminals to external components. If possible, it would be advisable in inverting applications to solder the feedback components directly between the pins of the socket. If a PC board layout must be used, a high insulation resistance coating should be applied to the entire circuit to minimize the detrimental effects of dirt and moisture.

Further, all hard wiring should be short and supported in such a way that movement due to vibration is limited as

much as possible, because motion of input wiring will cause corresponding variations in parasitic capacitance. Such variations produce changes in stored charge (assuming that the voltage potential on the wire remains constant), which effectively look like noise currents to the circuit.

A guard is a signal shield which is designed to float at the common-mode voltage of the critical signal points which it protects. Its purpose is to minimize the effects of both parasitic capacitances and leakage resistances. For high impedance op-amps, a guard is normally a foil on the printed-circuit board which surrounds all points connected to the "hot" input terminal of the amplifier. If the op-amp is connected in an inverting configuration, the "hot" terminal is the inverting (or "-") input, and a guard around this terminal would normally be connected to signal ground. For non-inverting applications, a guard surrounding the non-inverting (or "+") input and connected to the amplifier output is normally employed. Fig. 4 illustrates typical guarding schemes.

Coaxial cable should be used wherever possible to minimize RFI pickup. A type with an internal graphite coating or conductive tape will also minimize any noise generated in vibration environments.

**Switches.** Reed relays make good switches for many applications where reset or hold operations are required. Ceramic switches should also be considered. Use guarding around the switch.

**Resistors.** Many applications require extremely large resistors, typically up to  $10^{14}$  ohms. Several firms manufacture special components which can be used. These include Victoreen Instrument Div. of VLN, Cleveland, Ohio; Pyrofilm Corp., Whippany, N. J.; Electra/Midland Corp., San Diego, Calif.; and Mini Systems Inc., North Attleboro, Mass.

Table 2 lists the advantages and disadvantages of each type. Critical parameters include tolerance, temperature coefficient, long term stability, and physical size. Price and delivery also may be of great importance.

For inverting applications, if electrical, mechanical, or

Parameter	Amplifier type				
	Varactor Bridge	Vibrating Capacitor	Electrometer Tube	MOS FET	Junction FET
I bias	very good ( $10^{-15}$ )	excellent ( $10^{-16}$ )	good ( $10^{-14}$ )	good ( $10^{-14}$ )	good ( $10^{-13}$ )
I bias vs time	very good	excellent	good	good	fair
Eos vs time	excellent	good	poor	poor	good
Bandwidth	narrow	narrow	wide	wide	wide
CMRR	excellent	excellent	poor	fair	good
Noise (.01Hz to 1 Hz)	excellent	excellent	good	fair	good
Size	small	large	large	small	small
Price	low	high	medium	medium	low
Overload protection	easy	easy	easy	difficult	easy
Microphonics	good	fair	poor	good	good
Warm-up	fast	fast	slow	fast	fast

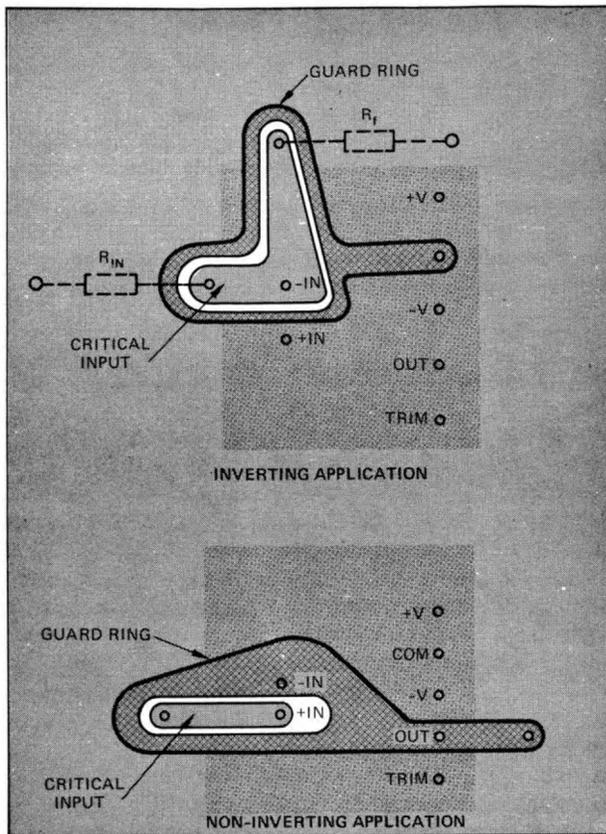


Fig. 4—Typical PC-board guard ring configuration shows the guard is referenced to the common (or ground) for inverting applications (a) and to the output for non-inverting applications (b). The small break in the guard ring prevents current loops.

economic considerations rule out a single feedback resistor, a T-Network should be considered (Fig. 1). Note, however, that because such a network increases the noise gain of the circuit, the noise and drift at the output will increase.

**Capacitors.** Capacitors are critical components in integrators, sample-and-hold circuits, etc. Key parameters to consider when selecting the optimum capacitor for a specific application include leakage resistance and dielectric absorption. Mica types are recommended for small capacitance values and polystyrene and teflon for larger ones. The maximum recommended capacitance is 10  $\mu$ F. The decreased leakage resistance of larger capacitors can cause significant problems in most circuits. □

### Author's biography

**Walter Patstone** is product manager at Teledyne Philbrick in Dedham, Mass., where his duties include initiation of product development projects and customer applications assistance. He was previously with Microsonics Corp. and Hughes Aircraft. Walter received a BSEE from Rensselaer Polytechnic Institute, an MSEE from Northeastern Univ. and is currently studying for an MBA.



TABLE 2 RESISTOR TYPES

Type	Advantages	Disadvantages
Wire-wound	High initial accuracy Excellent stability Excellent T.C. Excellent T.C. tracking Low noise	Expensive above 1M $\Omega$ Relatively large size Relatively high shunt capacitance and series inductance, depending on particular construction
Metal film	Low noise Very good temperature stability Low shunt capacitance and series inductance Relatively low cost	Relatively large size over 300k $\Omega$
Glass enclosed deposited carbon (Pyrofilm and Victoreen types)	Specifically designed for very high values up to 10 <sup>14</sup> $\Omega$ Low flicker noise Good stability Very good high frequency operation $\pm$ 1% precision available up to 10 <sup>14</sup> $\Omega$	Relatively noisy Relatively expensive Only fair T.C. Extremely large Fragile Sensitive to handling
Carbon composition	Low cost High reliability Small sizes available	Poor T.C. Easily affected by humidity Moderate tolerances only