BY PAUL RAKO • TECHNICAL EDITOR

MEASURING nanoamperes

MEASURING LOW CURRENTS CAN BE TRICKY. CLEVER ANALOG-DESIGN TECHNIQUES AND THE RIGHT PARTS AND EQUIPMENT CAN HELP.

Thousands of applications require a circuit to measure a small current. One of the most common is the measurement of photodiode current to infer the light impinging on the diode. Scientific applications, such as CT (computer-tomography) scanners, gas chromatographs, and photo-multiplier and particle and beam monitoring, all require low-level current measurements. In addition to these direct applications, the manufacturers of semiconductors, sensors, and even wires must measure extraordinarily low currents to characterize their devices. Leakage current, insulation-resistance measurements, and other parameters require consistent, accurate measurements to establish data-sheet specifications.

Few engineers realize, however, that the data sheet of a part is a contractual document. It specifies the behavior of the device, and any disputes over the operation of the part always come down to the specs on the data sheet. Recently, a customer of a large analog-IC company threatened legal action against the manufacturer, claiming that the parts he had purchased exhibited far higher operating currents than the submicroampere levels that the company specified. It turned out that the PCB (printed-circuit-board)-assembly house was properly washing the board but that assemblers were picking up the PCB and leaving fingerprints on a critical node. Because it could measure these tiny currents, the semiconductor company proved that its parts were working correctly; the leakage current was due to dirty PCBs.

The difficulty with measuring small currents is that all kinds of other effects interfere with the measurement (see sidebar "History of current measurements" at www.edn.com/070426df). This article looks at two breadboard circuits that must handle surface leakage, amplifier-bias-current-induced errors, and even cosmic rays. As in almost all circuits, EMI (electromagnetic interference) or RFI (radio-frequency interference) can induce errors, but, at these low levels, even electrostatic coupling can cause a problem. As the currents you measure drop into the femtoampere range, the circuits are subject to even more interfering effects. Humidity changes the value of capacitors and causes higher surface leakage. Vibrations induce piezoelectric effects in the circuit. Minor temperature variations, even from a room fan, cause temperature gradients in the PCB that give false readings. Even room light can degrade the accuracy of measurements; light from fluorescent fixtures can enter the glass ends of a detector diode and cause interference (Reference 1).

Small currents require accurate measurement if you want to characterize the performance of quartz-crystal oscillators. Jim Williams, a staff scientist at Linear Technology and longtime *EDN* contributor, shares a circuit he designed for a customer who needed to measure the rms current in a 32-kHz watch crystal **(Figure 1)**. One difficulty with this measurement is that even a FET probe's 1-pF loading can affect the crystal oscillation. Indeed, one of the goals of current measurement is to establish the sizing of the low-value capacitor you use with every crystal oscillator. A further difficulty of this measurement is that it must measure accurately and in real time at 32 kHz, which rules out the use of an integrating capacitor. The signal is a complex ac signal that the system designer must convert to an rms value for evaluation.

"Quartz-crystal rms operating current is critical to long-term stability, temperature coefficient, and reliability," says Williams. The necessity of minimizing introduced parasitics, especially capacitance, complicates accurate determination of rms-crystal current, especially in micropower-crystal types, he says. **Figure 2**'s high-gain low-noise amplifier, he explains, combines with a commercially available closed-core current probe to permit the measurement, and an rms-to-dc converter supplies the rms value. The dashed lines indicate a quartz-crystal test circuit that exemplifies a typical measurement situation. Williams uses the Tektronix CT-1 current probe to monitor crystal current and introduce minimal parasitic loading. A coaxial cable feeds the probe's 50Ω output to A_1; A_1 and A_2 take a closed-loop gain of 1120, and the excess gain over a nominal gain of 1000 corrects for the CT-1's 12% low-frequency gain error at 32.768 kHz.

AT A GLANCE

- Physics and noise limit the measurement of small currents.
- Early mechanical meters could resolve femtoamperes.
- JFET and CMOS amplifiers are suitable for measurements.
- To measure femtoampere-level currents, integrate the current into a capacitor.
- Integrated parts can measure femtoamperes and provide 20-bit outputs.

Williams investigates the validity of this gain-error correction at one sinusoidal frequency—32.768 kHz—with a seven-sample group of Tektronix CT-1s. He reports that device outputs are collectively within 0.5% of 12% down for a 1-μA, 32.768-kHz sinusoidal input current. Although these results tend to support the measurement scheme, Williams contends that it is worth noting that Tektronix measured the results. "Tektronix does not guarantee performance below the specified −3 dB, 25-kHz low-frequency roll-off. A_3 and A_4 contribute a gain of 200, resulting in total amplifier gain of 224,000. This figure results in a $1\text{V}/\mu\text{A}$ scale factor at A_4 referred to the CT-1's output. A_4's LTC1563-2 32.7-kHz bandpass-filtered output feeds A_5 through an LTC1968-based rms-to-dc converter that provides the circuit's outputs," he says. The signal-processing path, Williams explains, constitutes an extremely narrowband amplifier tuned to the crystal's frequency. **Figure 3** depicts typical circuit waveforms. According to Williams, the crystal drive at C_1's output (upper trace), causes a 530-nA rms crystal current that the A_4's output (middle trace) and the rms-to-dc-converter input (lower trace) represent. "Peaking visible in the middle trace's unfiltered presentation derives from parasitic paths shunting the crystal," he says.

Williams' circuit provides several lessons. Measuring nanoamperes is difficult even when using integrating techniques. This problem was far more difficult, because he had to complete the measurement in real time. Further complicating matters was the fact that this ac measurement required a bandwidth of 32 kHz to capture the bulk of energy in the oscillator current waveform. Williams addressed these problems by using a sensor. The Tektronix CT-1 sensor **(Reference 2)** can cost as much as $500, but, without a good sensor, Williams would not have been able able to recover the signal from all the noise. In addition to good sensitivity, the CT-1 has a 50Ω output impedance that allows for lower noise-signal paths than would a high-impedance output. Another important principle that this example demonstrates is that it is essential to limit the bandwidth of the signal path. By making a narrowband amplifier chain, Williams discarded all the noise contributions from frequencies that were not in his area of interest. Finally, Williams used good low-noise design principles in the circuit. Wiring critical nodes in air minimizes leakage paths, and the LT1028 is

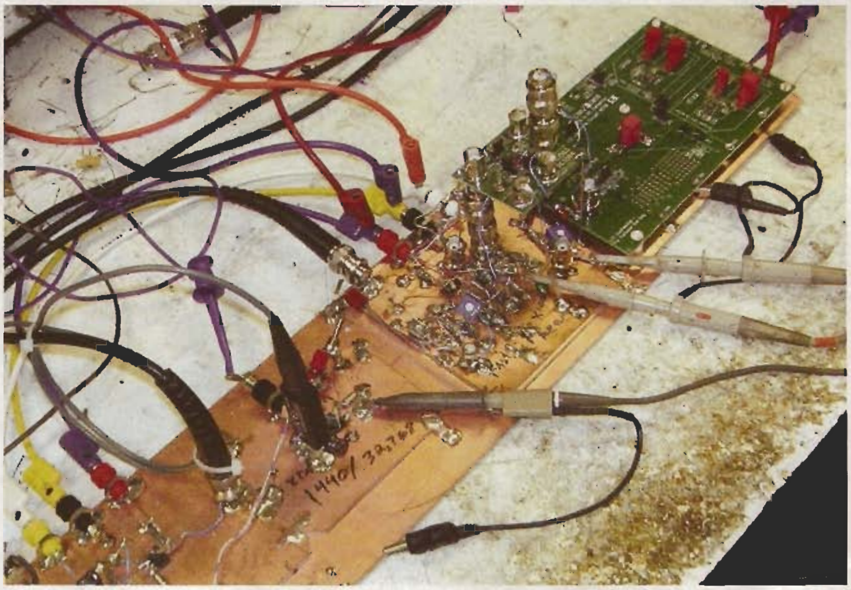


Figure 1 This breadboard measures the rms current in a watch crystal (courtesy Linear Technology).

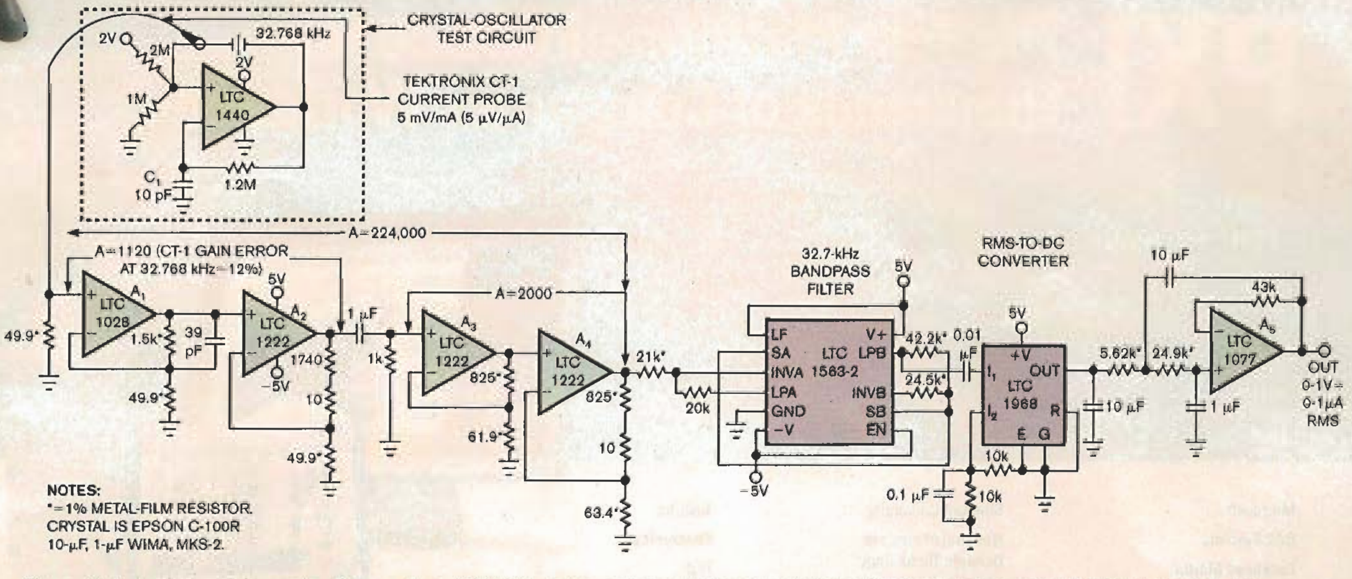


Figure 2 A_1 to A_4 furnish a gain of more than 200,000 to the current probe, permitting submicroampere current measurement. An LTC1563-2 bandpass filter smoothes residual noise and provides unity gain at 32.768 kHz. An LTC1968 supplies rms-calibrated output.

perhaps the lowest noise amplifier available from any manufacturer when working from 50Ω source impedance.

FEMTOAMPERE BIAS CURRENT

Paul Grohe, an application engineer at National Semiconductor, provides another remarkable example of measuring tiny currents. Years ago, National decided to sell the LMC6001, an amplifier that had a guaranteed bias current of 25 fA, implying that National needed to measure the bias current of each part to verify the specification. The test department could not accommodate test equipment in the setup; all the circuitry had to fit onto a standard probe card. Grohe and engineering colleague Bob Pease built a proof-of-concept fixture to demonstrate the feasibility of a small test circuit that could resolve to 1 fA **(Figure 4)**. Many books and resources discuss using an integrating capacitor to measure small currents **(Reference 3)**. The principle is that a small current can charge a small capacitor and that you can read that voltage to infer the current. In some cases, the current is an external current from a sensor. In this case, the current is leaving the amplifier-input pin. **Figure 5** shows a simple theoretical circuit in which the amplifier is measuring its own bias current.

The reality of measuring small currents is far more involved than the figure would suggest. First, Grohe could

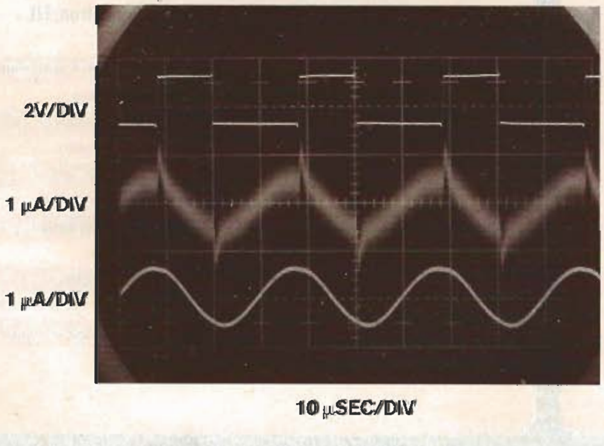


Figure 3 The upper trace shows C_1's 32.768-kHz output. A_4's output (middle trace) shows the crystal current. The lower trace shows the rms-converter input. Peaks in the middle trace's unfiltered presentation derive from parasitic paths shunting the crystal (courtesy Linear Technology).

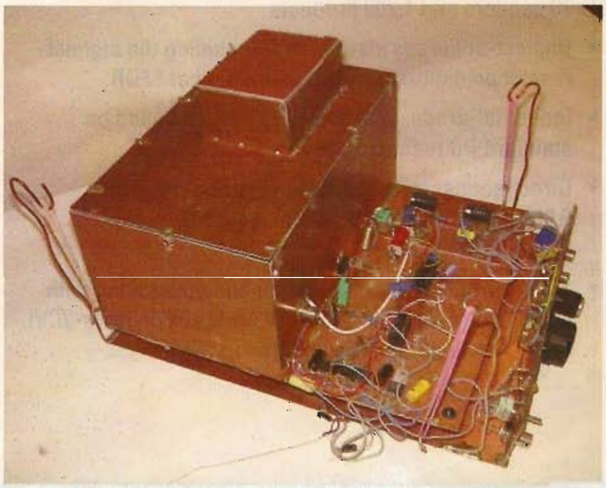


Figure 4 This prototype can resolve 1 fA of an amplifier's bias current. The breadboard has several levels of shielding made by soldering together copper-clad PCBs. Note the rubber-band suspension to shield the electronics from vibration (courtesy National Semiconductor).

not use the part itself to measure its own bias current. If he had tried to use the part itself as the integrator, there would have been no way to calibrate the effects of a socket and other leakages associated with the test fixture. Doing so required a separate low-bias-current part as the integrator **(Figure 6)**. Using a CMOS LMC660 amplifier ensured that the bias-current contribution would be less than 2 fA. By employing this technique, Grohe could simply remove any DUT (device under test), and the integrator would then have measured its own bias current as well as all the leakages from the test socket and the PCB on which the integrator was mounted.

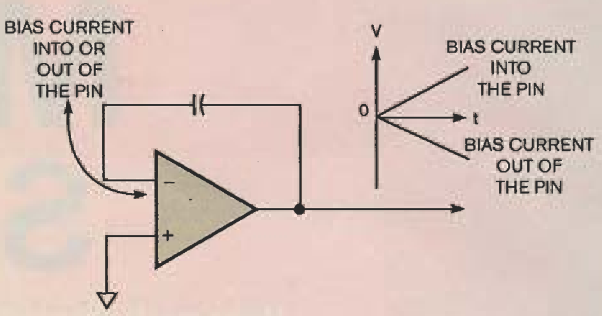


Figure 5 This integrator exemplifies the theory of using a capacitor in the feedback path of an amplifier to measure small currents.

Figure 7 shows that Grohe did not insert the DUT into a socket and that none of the pins are in contact with a PCB. To minimize leakage, Grohe brought up just two power pins as long, separate individual sockets that he did not mount to a PCB. Likewise, he hooked the pin to be tested to a socket and a 2-in. flying lead and connected that pin-and-socket combination to the integrating-amplifier input. To keep the DUT from running as an open loop, Grohe soldered together two sockets to bridge the output pins, which are suspended in air. Air currents can carry charged ions that can give false readings, so Grohe enclosed the entire DUT in a shielded copper-clad box.

The next issue was selecting an integrating capacitor. Initially, Grohe felt that the best capacitor would be an air-dielectric capacitor, so he fashioned two large plates, measuirng about 4×5 in., for the integrator capacitor. The size of this capacitor accounts for the size of the second copper-clad box on which the DUT box is mounted. Using a large capacitor proved to be a bad idea. The large area provides an ample target for cosmic radiation, creating ionized charges that interfere with the measurement **(Figure 8)**. Grohe then minimizied the capacitor's size while still using a good dielectric. It occurred to him that RG188 coax cable uses Teflon insulation. A 2-in. section of this cable provided the 10 pF for the integration capacitor **(Figure 9)**. As a further benefit, the outside braiding would serve as shield. Grohe therefore hooked it to the low-impedance-output side of the amplifier. With the switch to this capacitor, the cosmic rays struck only once every 30 seconds or so. Grohe took the integrated measurement for 15 seconds and, by taking five measurements, negated their effect. He then discarded any single outlying measurement. Any ionizing radiation sources, even an old watch with a radium dial, can cause cosmic-ray problems. Note that Grohe pried up the input pin of the amplifier to prevent leakage from the PCB.

Before taking a measurement, you need to reset the integrating capacitor to zero. Using a semiconductor switch is impractical, because of leakage currents and the 5- to 20-pF capacitance most analog switches offer. That capacitance exhibits the varactor effect, as well; it changes with applied voltage, further complicating measurement. To minimize these problems, Grohe used a Coto-reed relay. Knowing that the coil might couple to the internal reed when the relay was open, he specified a relay with an electrostatic shield. Much to his dismay, there still was a large jump in the measurement when the relay opened due to charge injection. It turns out that you can also look at a reed relay as a transformer, with the reed assembly representing a single turn. This phenomenon explains the failure of the electrostatic shield to prevent the interference. Magnetic fields inducing voltages in the high-impedance side of the circuit caused the charge injection.

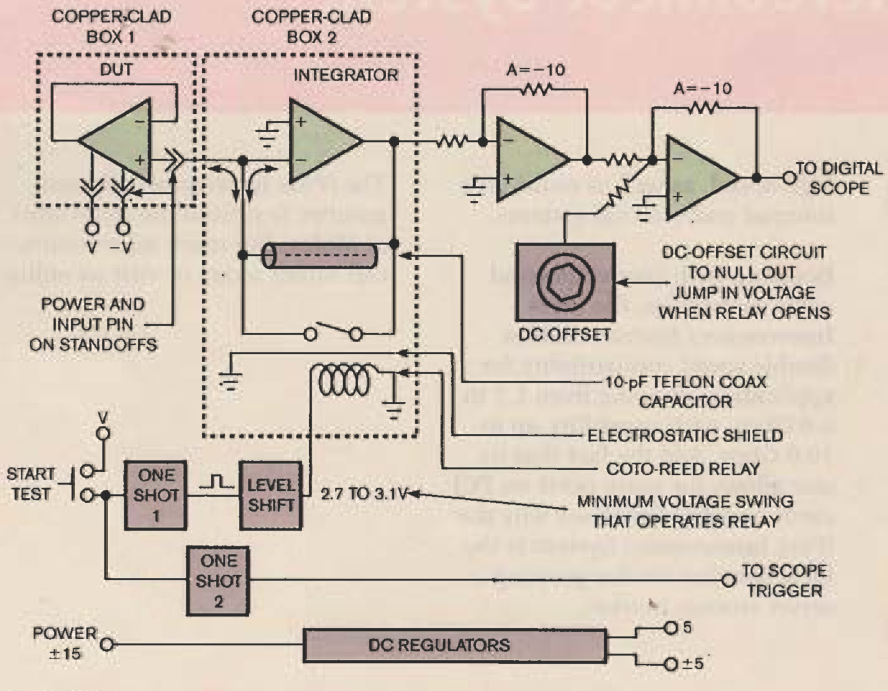


Figure 6 This circuit can resolve 1-fA bias currents coming out of the DUT.

Figure 7 This configuration mounts the DUT on long standoffs that do not touch the PCB. Copper-clad boards serve as shielding (courtesy National Semiconductor).

The relay does not open instantaneously, and the pulse needed to energize the coil makes a significant current injection just before the relay opens. Grohe minimized this problem by characterizing the absolute minimum voltage swing needed to operate the relay he had installed. It turned out that the relay would pull in with 3.2V and drop out with 2.7V. He used a set of resistor taps on an LM317 adjustable regulator to control the output between these two values. By choosing not to energize the relay with a full 5V, he minimized the jump in the integrator output and made it repeatable. He then nulled out the jump by injecting a small current into the second gain-stage amplifier.

The gain stages are two low-noise amplifiers—the LMV751 or perhaps a chopper amplifier, such as the LM2011, would be suitable. Grohe sent this gained-up signal to a digital scope, which could record data and subtract the slope of the calibration run from the test runs to give a valid measurement. Grohe used two LS123-style one-shot circuits—one to trigger the relay and another to provide a suitable and repeatable time delay that triggered the digital scope.

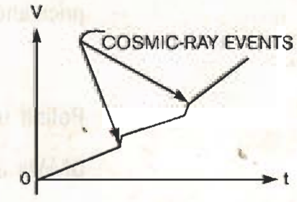


Figure 8 Cosmic rays impinge on the input node and capacitor, creating ions that make the measurement jump.

Grohe also understood that good low-noise-design principles also include the power rails to the parts, so he chose not to power the relay or digital circuits from the same power he used for the integrator and DUT. He used a handful of fixed and variable regulators to provide ±5V for the DUT and integrator, 8V for the relay-drive circuit, and a separate 5V for the digital circuits.

Using this circuit, Grohe was easily able to resolve 1 fA of current and found that most of the LMC6001 parts he tested had less than 5 fA of bias current, far exceeding the spec. He used this breadboard as the basis for a production-test circuit mounted on a standard probe card. (See **references 4, 5,** and **6** for more about his design, including a video of the system.)

Grohe would not use this circuit to measure femtoampere currents in his lab. "I would wheel out the Keithley 2400 electrometer," he says. "We would have used that instrument to test the LMC6001 in manufacturing had the

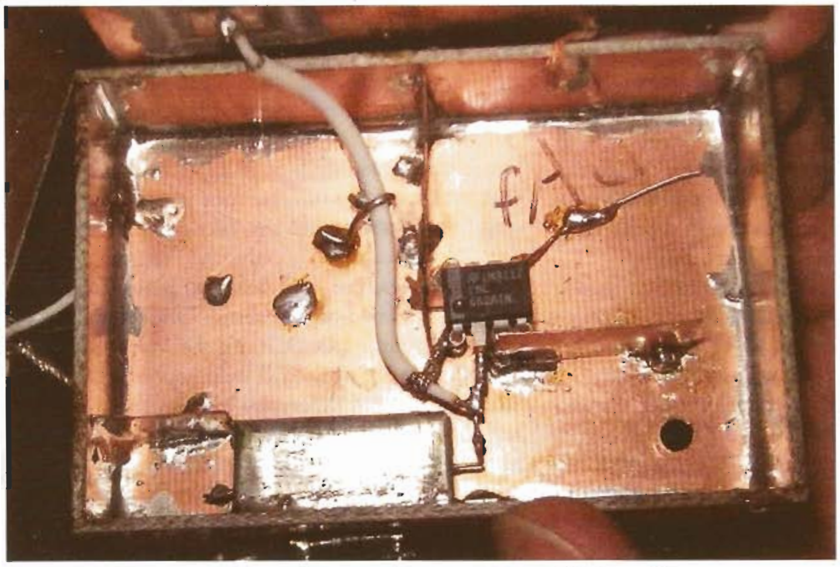


Figure 9 This copper-clad box mounts directly below the DUT box of Figure 7. Note the Teflon coaxial cable to create the integrating capacitor, as well as to provide a wire to bring the current to the input pin (courtesy National Semiconductor).

fab allowed us to use external test equipment." His faith in Keithley is well-placed. The company offers free on its Web site an excellent article on measuring attoamperes (**Reference 7**), as well as a book on delicate measurements (**Reference 8**).

DDC112

Grohe and Pease's integration approach is not limited to laboratory setups. Texas Instruments has created a line of parts that can measure in the femtoampere range and provide a digital output to boot. The line includes a single-channel DDC101 as well as the improved-sensitivity, dual-channel DDC112, which provides for external integrating capacitors. The four- and eight-channel DDC114 and DDC118 have a charge sensitivity of 12 pC (**Reference 9**). The sample rate for these 20-bit parts reaches 3 kHz.

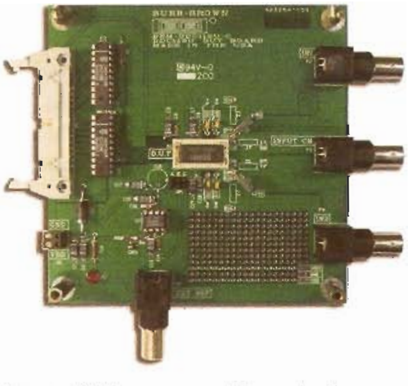
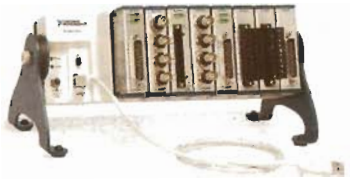


Figure 10 You can use this evaluation board for the DDC112 to measure femtoamperes of current. The DDC114 is even more sensitive (courtesy Texas Instruments).

You must be cognizant of physics to attempt these measurements. If the DDC112 can measure 12 pC of charge and you want to measure 12 pA of current, you need to set the integrating time to 1 second, the maximum the DDC114 allows. It is impossible to obtain a 3-kHz update rate if the part's integration interval is a full second. However, using the part configured in this fashion yields a 20-bit value at the end of the conversion. In other words, the DDC (direct digital converter) can resolve femtoampere currents, although at reduced accuracy. The input bias of the part is 20 fA, but your system's software can calibrate out this value, so the part should still be able to resolve to very low levels. Bear in mind that this type of sensitivity makes it difficult to calibrate the system just once in the factory and then have it work for all time. As temperature increases, the bias current increases, doubling every 10°C, and leakages as well as sensor drift can develop on your board. Providing the means for field calibration at power-up or more frequently is always a good idea



when measuring currents in the femtoampere range. Texas Instruments offers evaluation boards for these parts that you can get up and running in hours, measuring currents too small for even a good handheld digital voltmeter (**Figure 10**).

According to Jim Todsen, product-line manager for oversampling converters at TI and patent holder on the technology that the part uses, the DDC line's development started with the Burr-Brown ACF2101—a dual switched integrator front end that provides a single-chip option for the current-to-voltage function. The benefit of a dual integrator, Todsen explains, is that it is always collecting input current. While one integrator is sampling the input, the other side is presenting its integrated value to the ADC, and this process continues for as long as you need measurements. "After the ACF2101 converts the input current to a voltage," he says, "a discrete high-resolution ADC digitizes it. The DDC112 brought together both the current-to-voltage function of the ACF2101 and the digitization of the high-resolution ADC in one chip." He attributes this achievement to advances in wafer processing that allow high levels of mixed-signal integration as well as TI's development of a high-speed delta-sigma core that can provide the required speed and resolution to measure the front-end signals. "In addition," he notes, "we took advantage of having all the circuit elements under our control to optimize for very-low-leakage inputs and very stable performance over long integration periods."

These applications should convince you of the difficulty of measuring small currents. They should also convince you of the value of using proven parts and equipment—whether Analog Devices' AD549, National Semiconductor's LMC660, TI's DDC114 integrated circuits, Keithley's 2400 parameter-measurement unit, or Agilent's 4156 parameter-measurement unit—in this demanding application. Remember, though, that these remarkable parts and instruments are not magic boxes. You can take advantage of them only by removing noise sources and leakage paths from your board or test setup. Understanding op-amp specifications for voltage and current noise will help you select the right part (**Reference 10**). In the meantime, if your boss wants to know why you need $5 or $10 for a chip or thousands of dollars for an electrometer, you can now explain that, with the challenges entailed in measuring small currents, this equipment is a bargain. EDN

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