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Femtoammeter Design: Development Module for Charged Particle Detection

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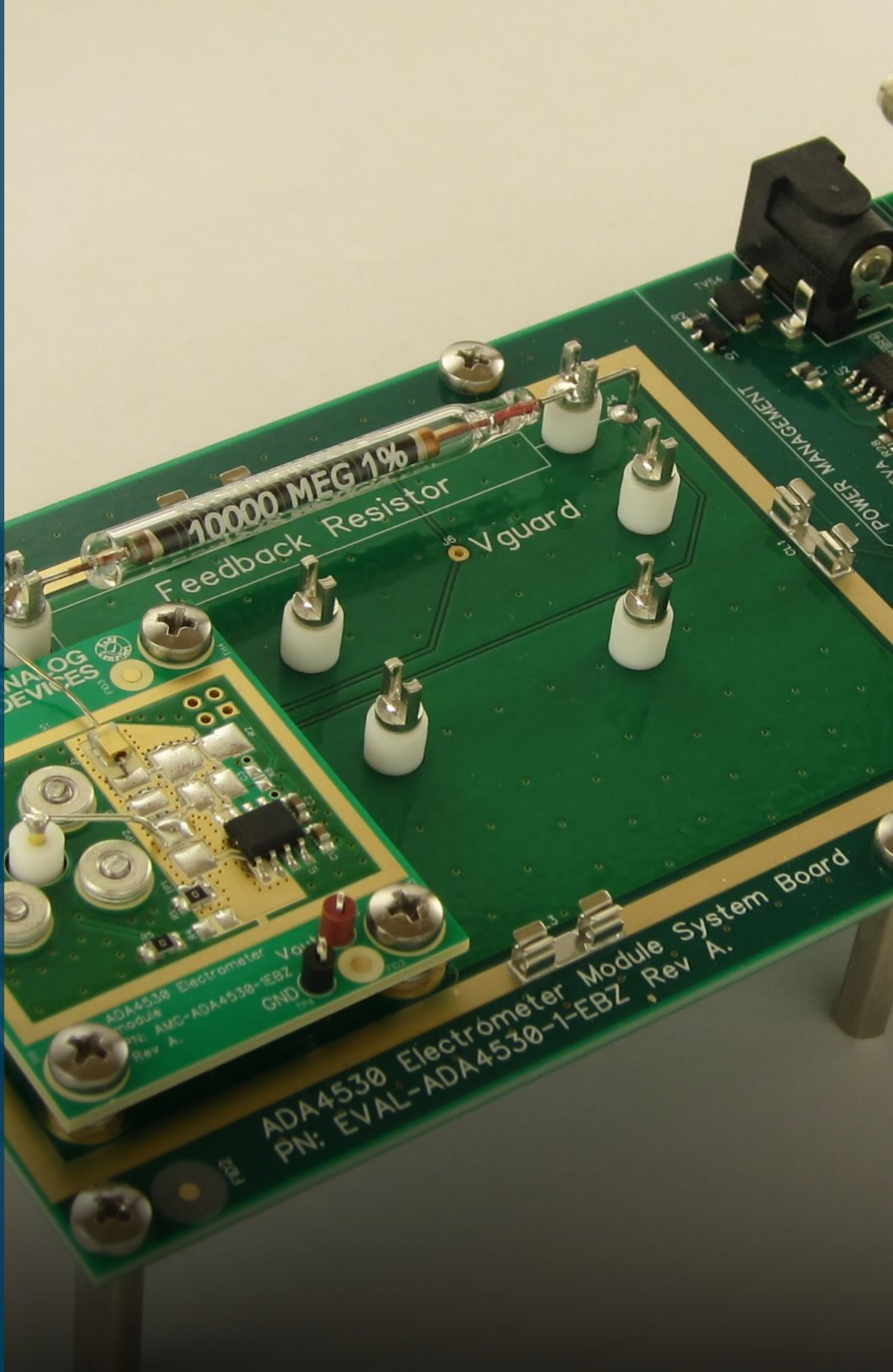
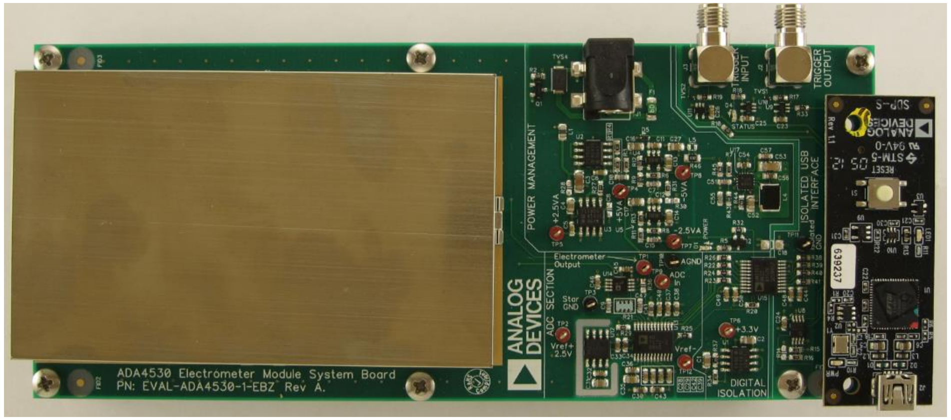
SYSTEM APPLICATIONS ENGINEER

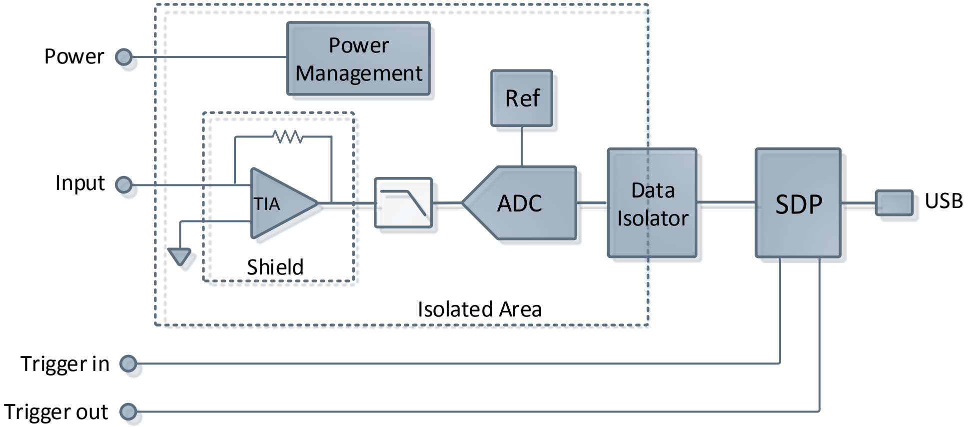
PRECISION INSTRUMENTATION



Femtoammeter Module

- Development module for sensors with low-level current output
  - Direct interface to photodiodes, faraday cups through SMA connector
- Features
  - **<10fA sensitivity** with 10GΩ transimpedance
    - 400pA measurement range
    - Shielding
    - Isolation with **ADuM3151**
  - Femtoampere input bias op amp
    - **ADA4530-1**
  - 24-bit resolution ADC
    - **AD7172-2**
  - USB interface to PC via SDP
  - Simple power supply: 9VDC input
    - **ADP7118, ADP2442, ADP7182**
  - Measurement synchronization
    - Trigger in/out signals
  - Can be reconfigured as electrometer front-end





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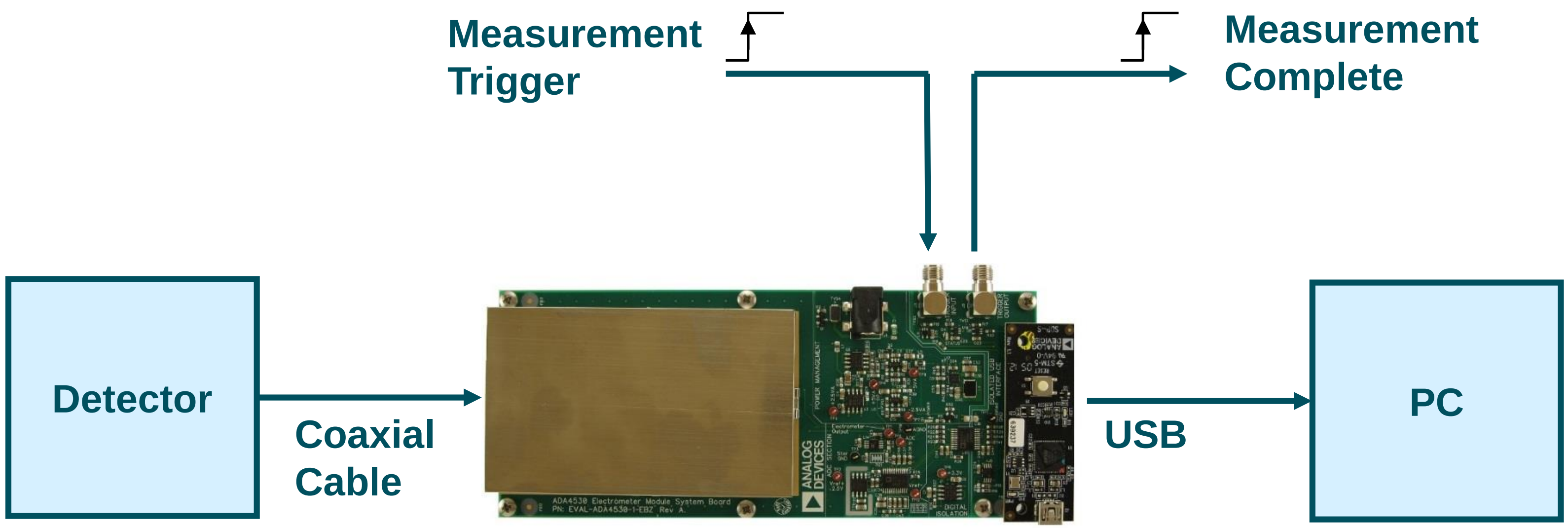
Example Application



Photodiode
Faraday cup
Photomultiplier tubes (PMT)
Electron-multiplier
…

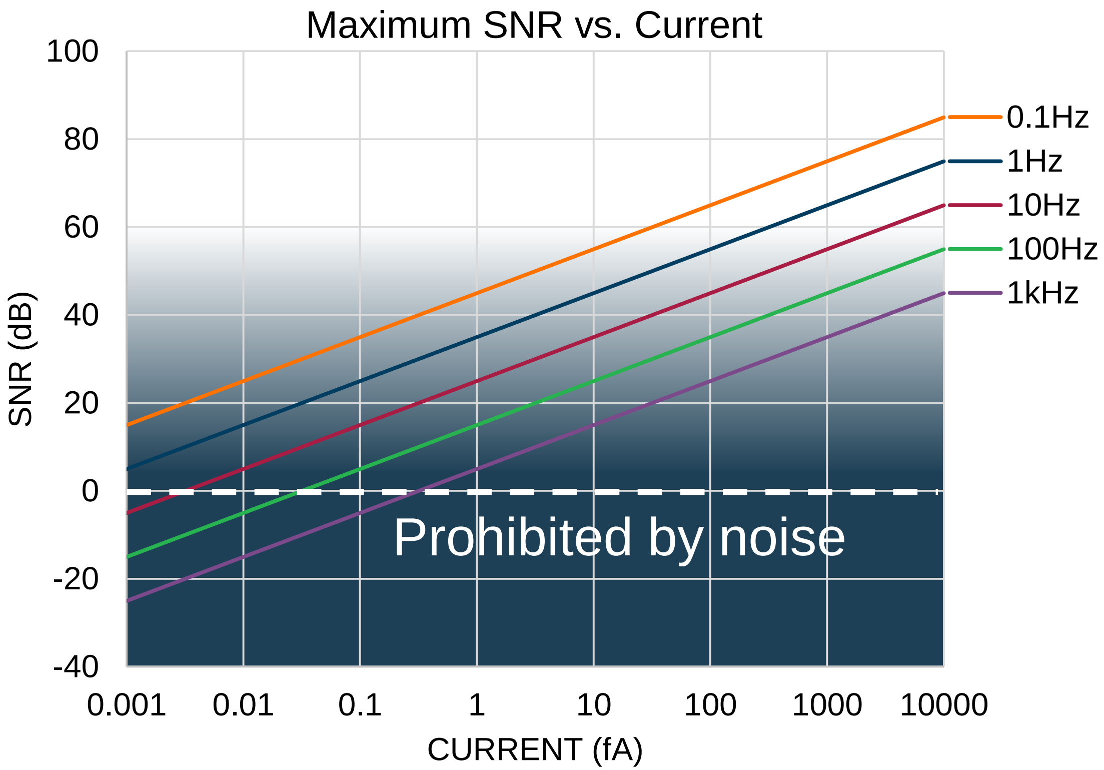
Fundamental Measurement Limits

- The discrete nature of electrical current generates "shot noise"
- Shot noise increases as the square root of current

$$i_i = \sqrt{2qI\Delta f}$$

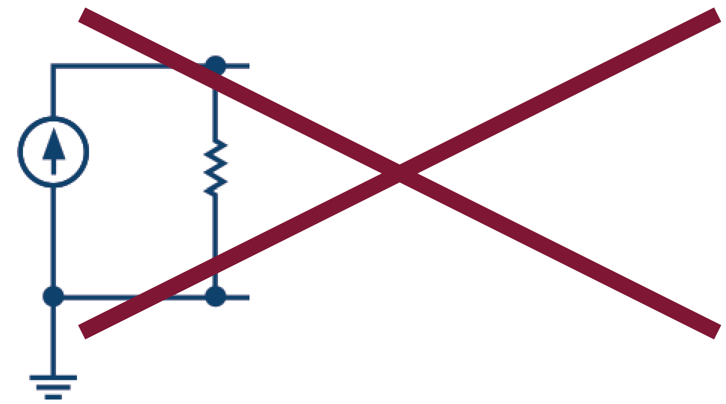
- At very low-level currents, shot noise can be greater than the measurement
  - Lower bandwidth; longer measurement times are required

$$SNR = \sqrt{\frac{I}{2q\Delta f}}$$

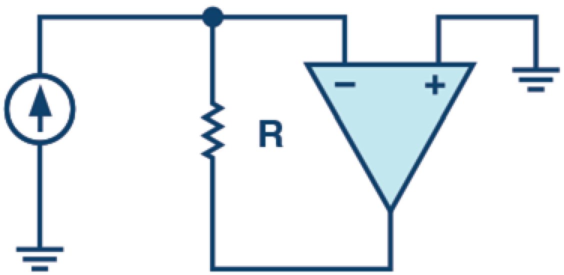


Measuring Low-Level Currents

- Option 1: resistor + buffer/amplifier
  - The current can flow through a resistor and then amplify
  - Increases burden voltage
  - Increases noise



- Option 2: transimpedance amplifier
  - The current still flows through a resistor
  - The op amp is used to reduce burden voltage
  - Keeps amplifier noise and error contribution low



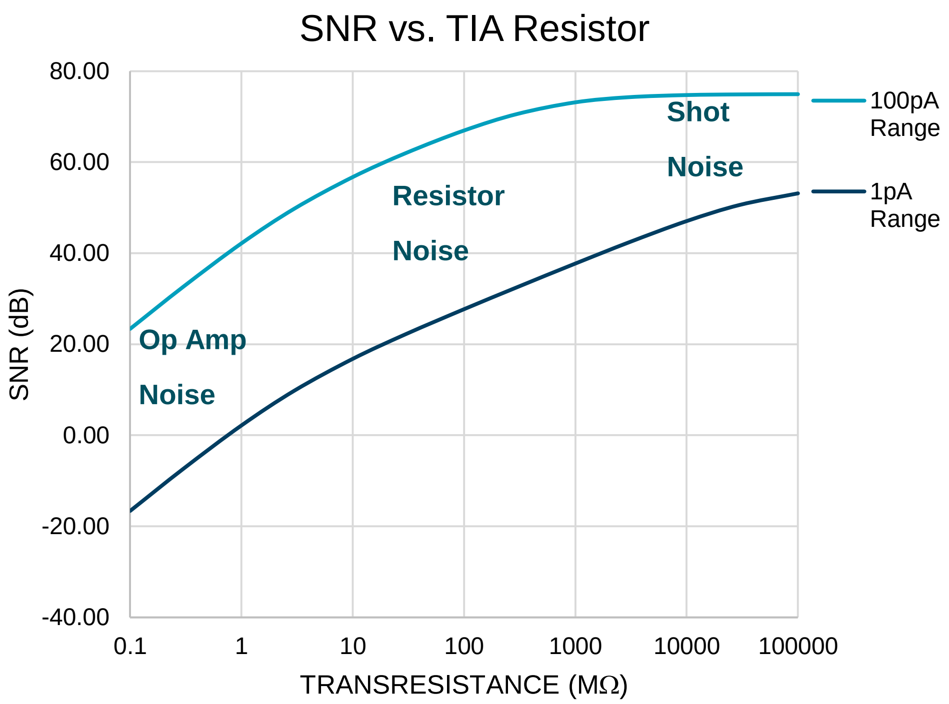
Resistor and Op Amp Noise

- Resistor
- The greater the resistor, the better SNR
  - Signal increases proportional to resistor value (Ohm's law)
  - Noise increases per square-root of resistor value (Johnson noise)

$$i_r = \sqrt{\frac{4kT}{R}\Delta f}$$

- Op Amp
- At low bandwidth, TIA has unity noise gain
  - The op amp's voltage noise contribution to current noise gets divided by resistor value

$$i_a = {}^{e_a}/_{R}$$



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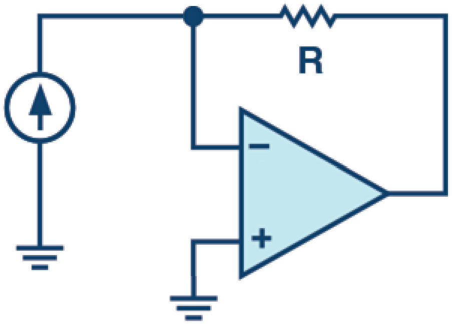
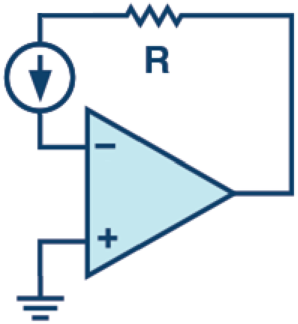
Resistor and Op Amp Noise

- In conclusion, to measure small currents, use
  - A large resistor
  - A very low noise op amp
  - A very low input-bias op amp like the **ADA4530-1**



- With large resistors
  - The amplifier will become slower (due to frequency compensation)
  - The op amp's input bias current can saturate the output
  - Doubles every 10°C



- Example: 100pA*10GΩ = 1V

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The Implementation Problems

Surface contamination

Leakage

Stability

Dielectric absorption

Humidity

Triboelectricity

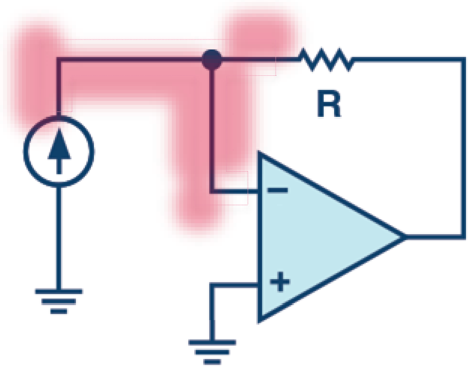
Light

Radiated noise

RF

Power-line noise

Ground noise



Input bias current

Noise

Offset drift

Output swing

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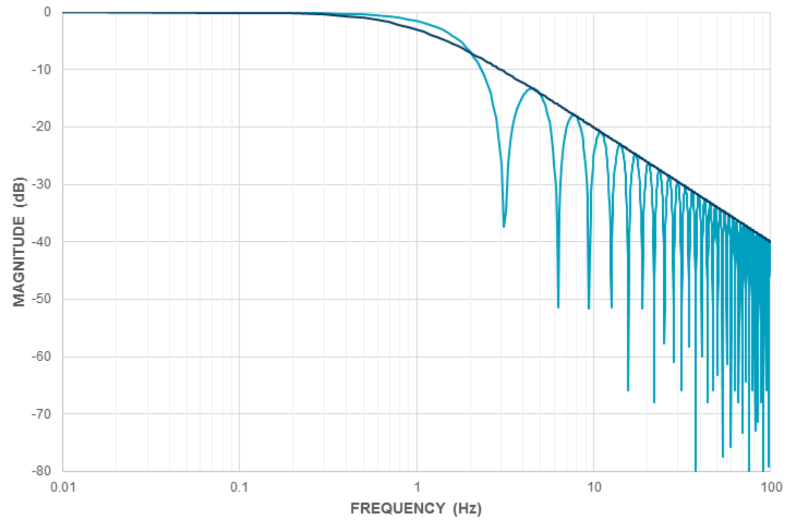
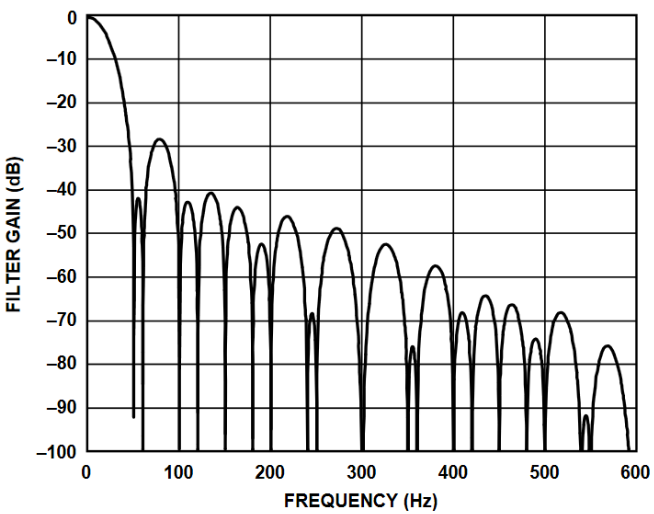
Noise Reduction: The Effect of Averaging vs. Filtering

- Sensitivity requires minimizing the noise
- Averaging and filtering reduce measurement bandwidth but work a little different
- The average of N samples:
  - Reduces the noise by √N (flat-band noise)
  - Reduces the effective maximum frequency by 2^N
  - Increases measurement time
  - Rejects frequencies at the notches
    - Good for power-line noise rejection
  - Produces aliasing above the notches
- Effectively a simple FIR filter
  - Can be arbitrarily short/long
  - Very popular these days
- Sigma-delta ADCs like AD7172 perform this function internally using specialized filters

1st Order Filter vs. Average



Example Filter Transfer Function in **AD7172-2**



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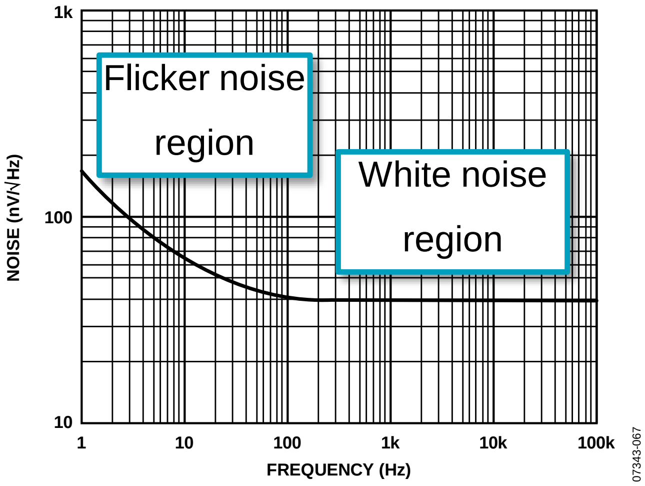
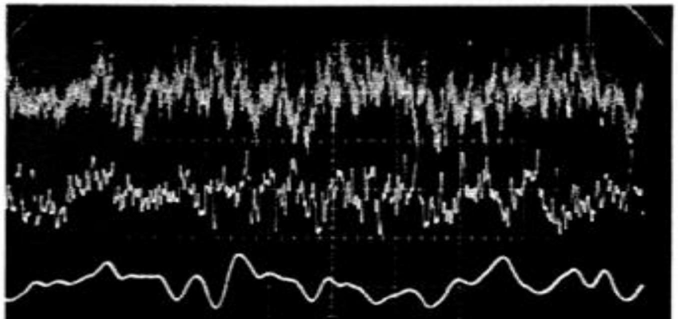
Flicker Noise and Low-Level Measurements

- Flicker (1/f) noise often limits measurement front-end sensitivity
- Noise reduction by filtering or averaging fails upon reaching the 1/f corner
  - Averaging reduces flat-band noise
  - Noise amplitude is not reduced by √N after reaching this region
  - The longer the average, the longer we look at the signal, the lower we move on the frequency band
- Common flicker noise sources:
  - ICs and semiconductor devices
    - Op amps, references, diodes…
  - Resistor excess noise
    - Noise index sometimes available from manufacturers





Mochtenbacher and Connelly. Low-Noise Electronic System Design. Wiley, 1993

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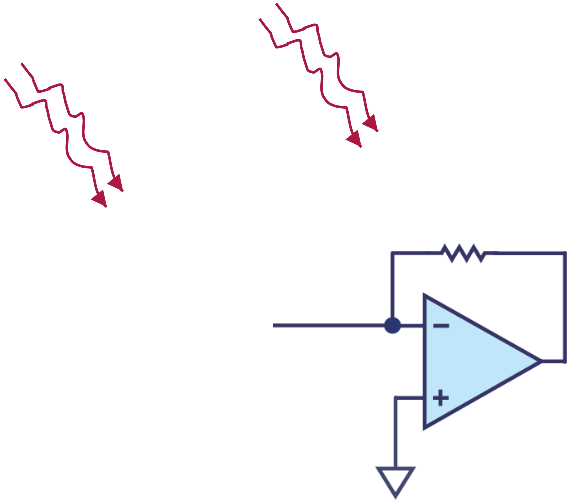
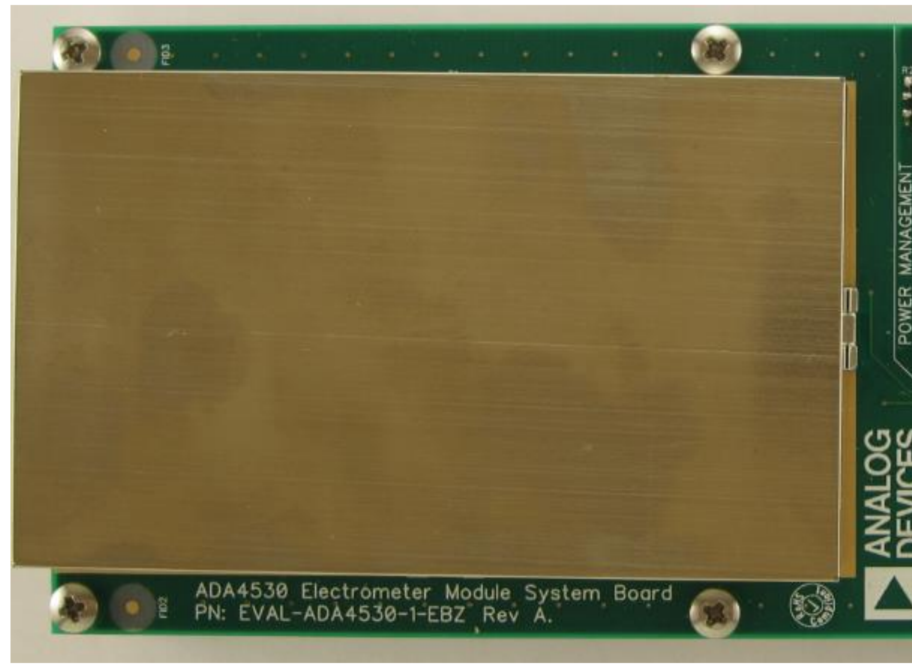
Extrinsic Noise

- Main sources:
  - Power lines (50/60Hz)
  - RF (e.g. wireless communications)
- Reaches the circuit via
  - Emission
  - Conduction
- Reduced by
  - Shielding
  - Minimize inductive loops (e.g. twist wires)
  - Proper layout and grounding
  - Isolation
  - Power supply decoupling
  - Filtering



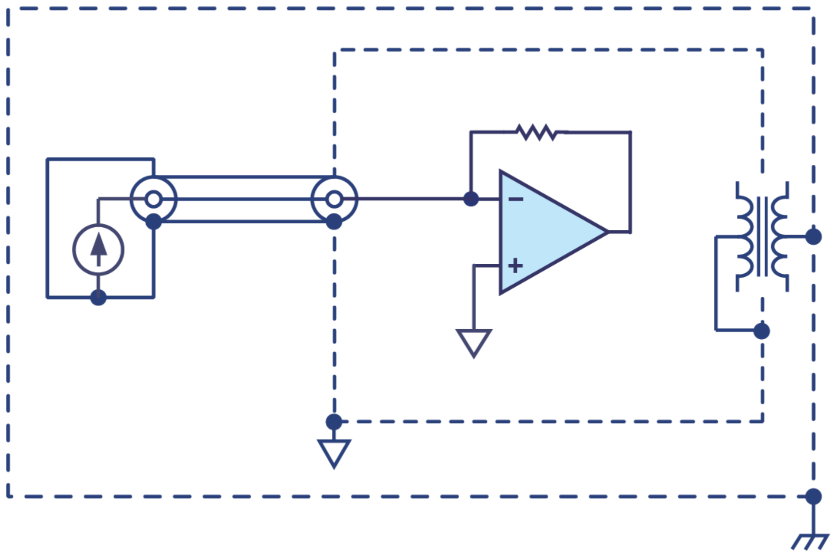
Shielding

- Shields help keep stray fields away from sensitive nodes
- Shields should be grounded when exposed to operators for safety



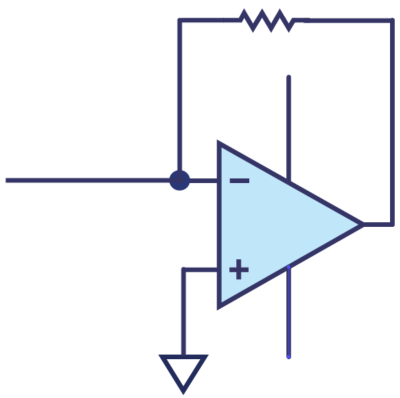
Isolation

- Great for breaking ground loops, reduce noise
- But must bring data (**ADuM3151**) and power across isolation barrier
- Proper connections are required to avoid coupling of the common-mode current into the measurement
  - Or use batteries
- Shields can couple noise into isolated circuits
  - Keep shields away from sensitive nodes
  - Or use a driven shield (guard) inside the shield



Surface and Board Leakage

- The surface of dielectrics has better conduction properties due to contamination, humidity, etc
  - This includes FR-4 and PTFE board materials, no matter how good their bulk properties are
- Sources of contamination:
  - Solder flux residue from assembly process
    - No-clean solder residue is difficult to remove
  - Dust and other particulate accumulation
- Washing assemblies is recommended after assembly
- Moisture reduces insulation properties of PCB and cables
  - Bake after wash to eliminate moisture absorption
  - Choose appropriate materials and perform measurements in controlled environments

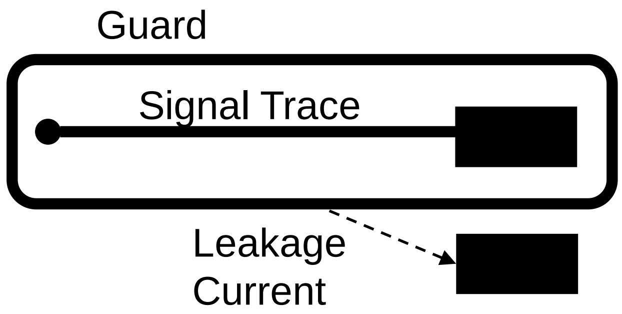


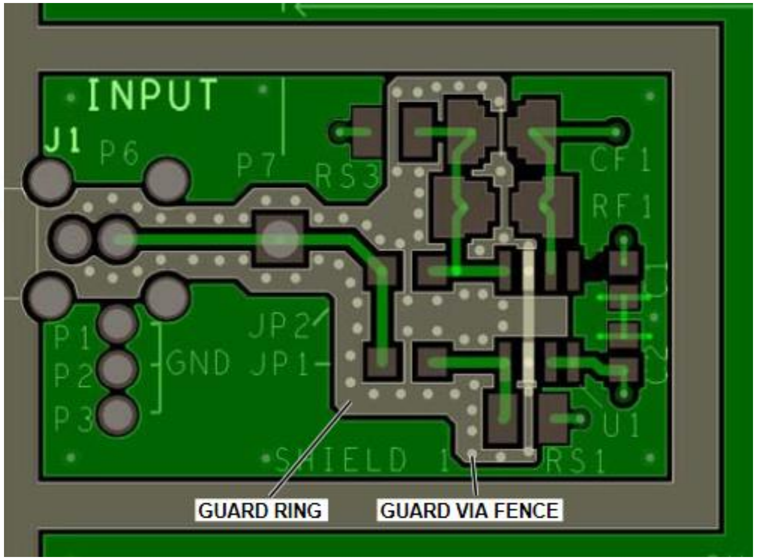
Material	Moisture Absorption (%)
Hi Pref FR-4	0.50
Nearly pure PTFE	0.02

Source: Rogers Corp.

Dealing with Leakage on the PCB

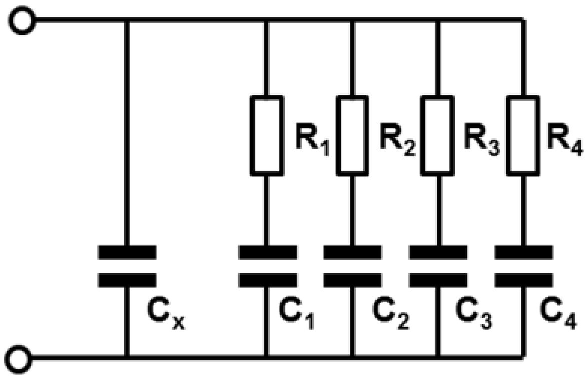
- Better layout yields better performance over time and environmental conditions
- Guard rings
  - Prevents sensitive current to flow through unwanted paths
  - Needs to be driven by an amplifier at the same potential as the input (e.g. a buffer)
- Remove solder mask
  - Eliminates the conduction path over the guard ring
  - Solder mask absorbs moisture too
- Board cuts





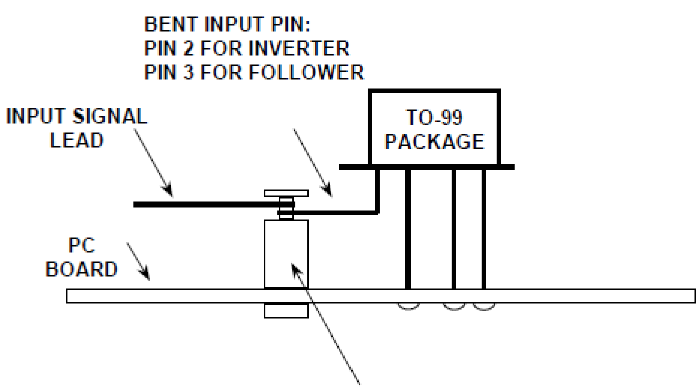
Dielectric Absorption

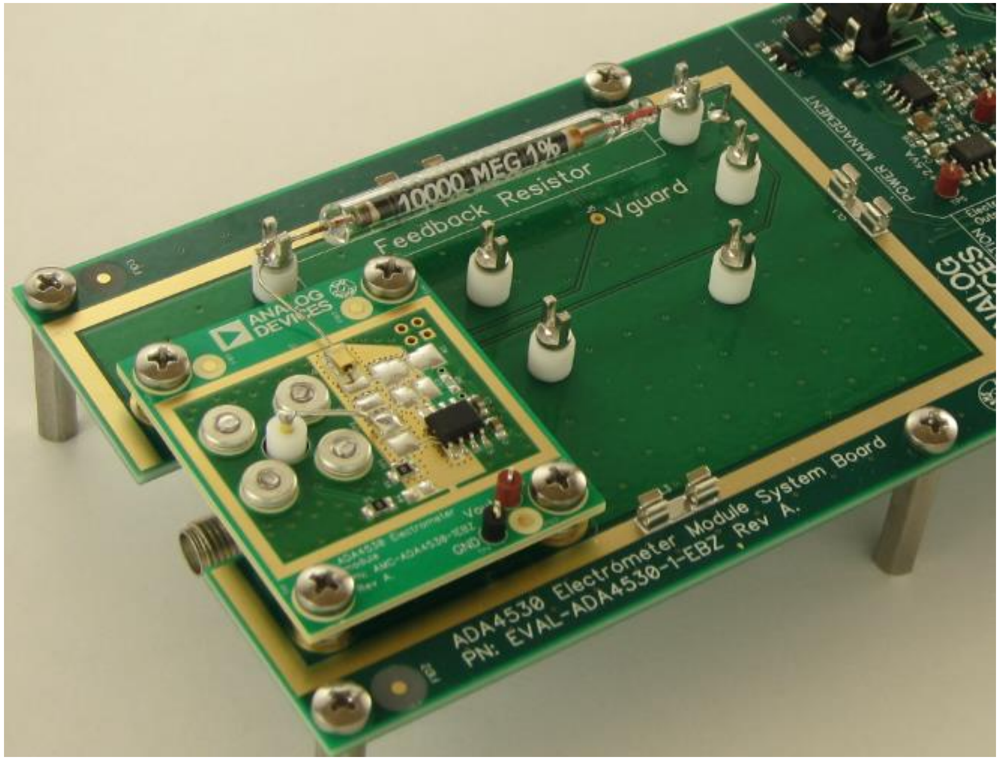
- Caused by the polarization of the dielectric between conductor plates upon application of an electric field
- Commonly observed in
  - Capacitors
  - Multilayer PCBs
- The polarization relaxation has a longer time constant than the capacitance formed by the plates
- Often modeled as an RC in parallel with the "ideal" capacitor
- This is also why large capacitors are handled with a bleeding resistor or a short (safety)



Dealing with Dielectric Absorption in PCBs

- Use PTFE (Teflon™) laminates (Rogers Corp.)
- Stand-offs available for air-wiring
- Minimize absorbing material: board cuts





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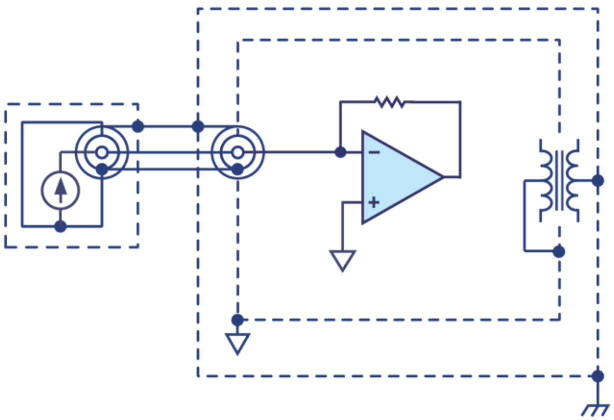
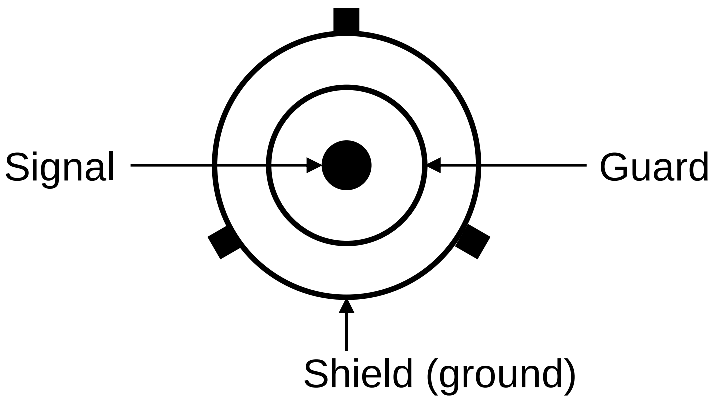
Interconnects for Low-Current Measurement

- Cables and connectors
  - Shielding is a must
- BNC, SMA and coaxial cables are OK as long as there is very little potential difference between center conductor and shield
  - Cost effective
  - Some RF materials (PTFE) have also good low-leakage, low DA properties
  - Beware of safety with ground-isolated measurements
- Best: use triax connectors and cables
  - BNC to triax adapters available for interfacing to sensors





Summary

- Design of low-level current measurement hardware requires attention to many details!

Problem	Cause	Solution
Leakage on PCB	Moisture and contamination	Guard rings, board cuts, dust covers
	Solder flux contamination	Avoid no-clean solder; wash and bake
Dielectric absorption	Charge trapped in dielectrics	Use PTFE in boards and cables, guarding
Cable leakage	Poor-quality insulation between conductors	Use PTFE-insulated cables or triax cables
Extrinsic noise	E/M fields, Powerline interference	Shielding and guarding
	Ground noise	Isolation
	Light-induced charge	Shielding/covers
	Mechanical vibrations, triboelectricity	Cable tie-downs

- A femtoammeter module solves many problems and enables quick and simple prototyping and evaluation

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QUESTIONS?

THANK YOU!