Femtoammeter Design: Development Module for Charged Particle Detection

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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
Example Application

- Detector
- Coaxial Cable
- Measurement Trigger
- Measurement Complete
- USB
- PC
- 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
  \[ SNR = \frac{I}{\sqrt{2q\Delta f}} \]
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

\[ i_a = \frac{e_a}{R} \]
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: $100\text{pA} \times 10\text{G}\Omega = 1\text{V}$
The Implementation Problems

- Input bias current
- Noise
- Offset drift
- Output swing
- Leakage
- Dielectric absorption
- Surface contamination
- Stability
- Humidity
- Light
- Triboelectricity
- Radiated noise
- RF
- Power-line noise
- Ground noise
- Power-line noise
- Noise
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 $\sqrt{N}$ (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
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 $\sqrt{N}$ 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

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
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
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

<table>
<thead>
<tr>
<th>Material</th>
<th>Moisture Absorption (%)</th>
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</thead>
<tbody>
<tr>
<td>Hi Pref FR-4</td>
<td>0.50</td>
</tr>
<tr>
<td>Nearly pure PTFE</td>
<td>0.02</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Problem</th>
<th>Cause</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage on PCB</td>
<td>Moisture and contamination</td>
<td>Guard rings, board cuts, dust covers</td>
</tr>
<tr>
<td></td>
<td>Solder flux contamination</td>
<td>Avoid no-clean solder; wash and bake</td>
</tr>
<tr>
<td>Dielectric absorption</td>
<td>Charge trapped in dielectrics</td>
<td>Use PTFE in boards and cables, guarding</td>
</tr>
<tr>
<td>Cable leakage</td>
<td>Poor-quality insulation between conductors</td>
<td>Use PTFE-insulated cables or triax cables</td>
</tr>
<tr>
<td>Extrinsic noise</td>
<td>E/M fields, Powerline interference</td>
<td>Shielding and guarding</td>
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<td></td>
<td>Ground noise</td>
<td>Isolation</td>
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<td></td>
<td>Light-induced charge</td>
<td>Shielding/covers</td>
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<td></td>
<td>Mechanical vibrations, triboelectricity</td>
<td>Cable tie-downs</td>
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A femtoammeter module solves many problems and enables quick and simple prototyping and evaluation.
QUESTIONS?

THANK YOU!