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Simple silicon photodiode based femto-watt measurement system and its implication

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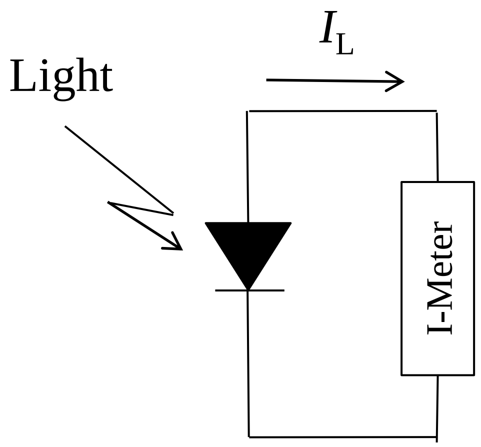
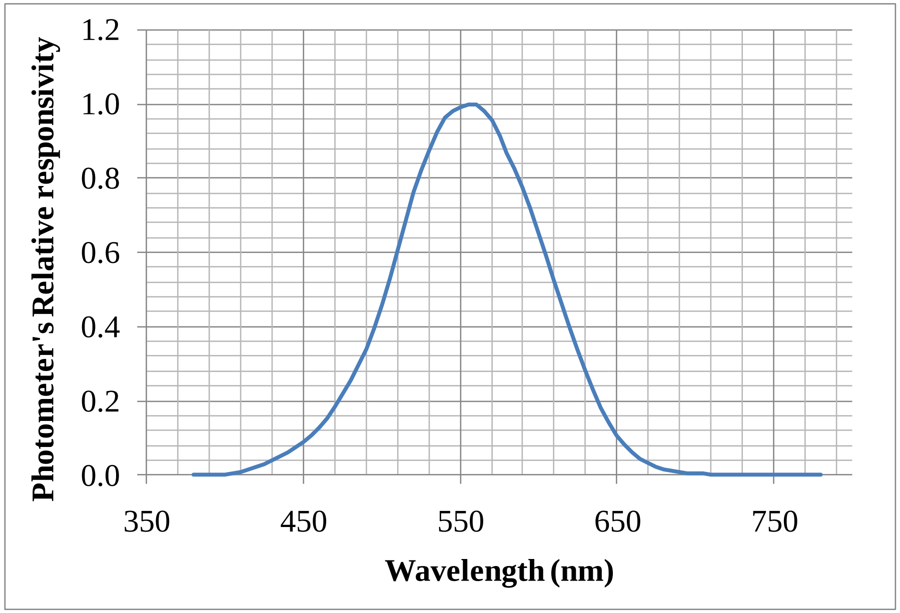
Characteristics of Si photodiodes

- Femto-ampere (10^{-15} A) noise level.
- Excellent linearity.
- Low dark current.
- Lowest measurement uncertainty
- Good long-term stability.
- Wide spectral response.
- Used in many applications in photometry, colorimetry, and UV radiometry.

Measurement issues

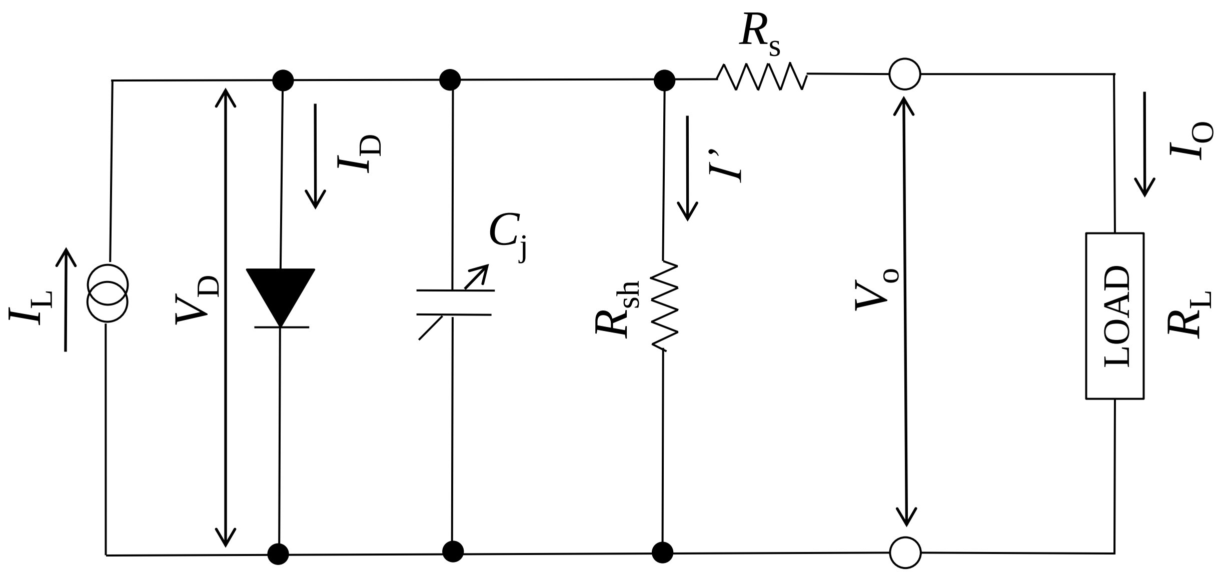
- No internal gain → relatively low responsivity.
- Lowest detection limit is determined by a current measuring circuitry (Orders of magnitude higher than the noise level of the photodiode itself).





- Noise often causes difficulty in spectral responsivity calibrations, eg, photometers

Equivalent circuit of a photodiode



$$I_O = I_L - I_D - I'$$
$$= I_L - I_s \times (e^{\frac{eV_D}{kT}} - 1) - I'$$

I_L: Photocurrent generated by the incident light
I_D: Diode current
C_j: Junction capacitor
R_{sh}: Shunt resistor
R_s: Series resistor
I': Shunt resistor current
V_D: Voltage across the diode
I_O: Output current
V_O: Output voltage
I_s: Photodiode reverse saturation current

Short circuit current, I_{sc}

$$I_{sc} = I_L - I_s \times (e^{\frac{e \times (I_{sc} \times R_s)}{kT}} - 1) - \frac{I_{sc} \times R_s}{R_{sh}} \approx I_L$$

Require the measurement circuitry to have "0" input impedance for linearity.

Noise characteristics of photodiodes

Noise, i_n,

$$i_n = \sqrt{i_j^2 + i_{SD}^2 + i_{SL}^2}$$

$$i_j = \sqrt{\frac{4kTB}{R_{sh}}}$$

$$i_{SD} = \sqrt{2qI_D B}$$

$$i_{SL} = \sqrt{2qI_L B}$$

Noise equivalent power (NEP),

$$\mathrm{NEP} = \frac{i_n}{R_\lambda} \quad (\mathrm{W/Hz^{1/2}})$$

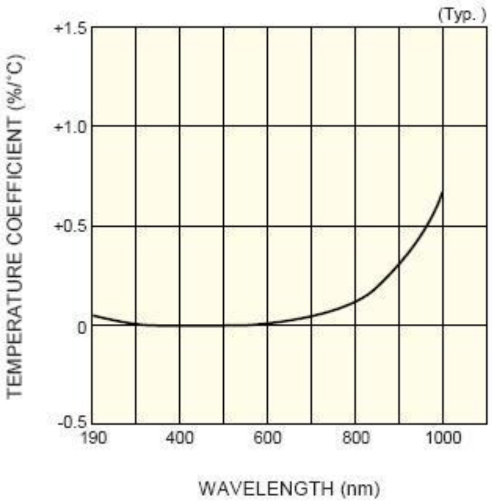
k: Boltzmann's constant
T: Absolute temperature
B: Noise bandwidth
R_{sh}: Shunt resistance
q: Electron charge
i_j: Thermal noise (Johnson noise)
i_D: Dark current
i_L: Photocurrent

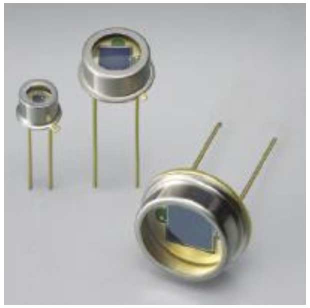
NEP is on the order of femto-amperes.

High shunt resistance reduces noise of photocurrent.

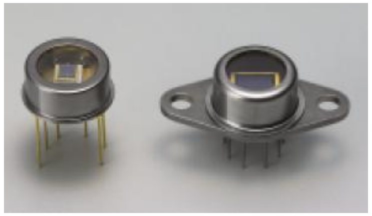
Si photodiodes with high shunt resistance

- High shunt resistance photodiodes
  (*eg*, S1226/S1227, 5 GΩ,
  6 mm x 6 mm),
  Typically don't have
  good thermal stability
  in red and NIR regions!





- Use Si photodiodes with a built-in thermoelectric cooler.
  - commercially available from multiple sources.
  - increases shunt resistance
    by more than two orders of magnitude
    (*eg*, S2592/S3477 (0.4 G with 6 mm x 6 mm area)

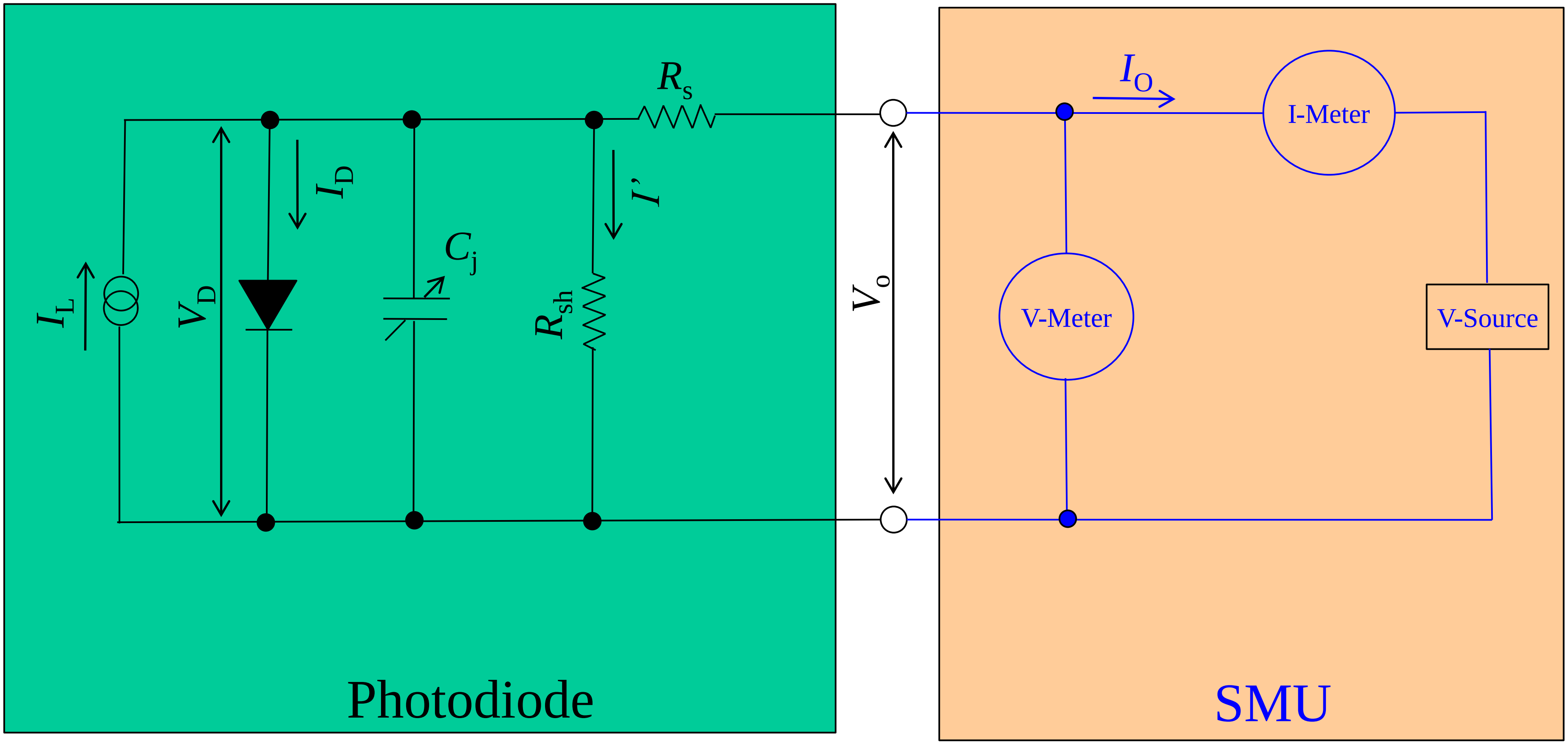


NIST

Measurement circuitry

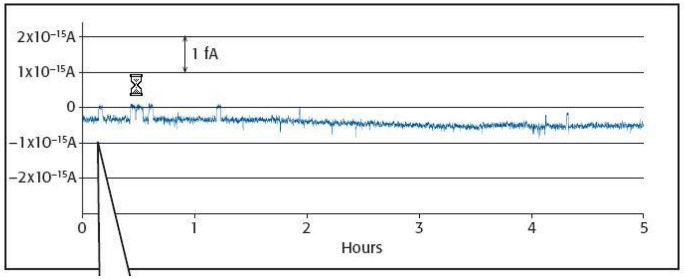
- Typically the dominant source of noise for the measurement system.
- A detector with high shunt resistance effectively reduces noise and improves stability of the measurement system.

Source Measure Unit (SMU) based system



Automated feedback control can be used to minimize the burden voltage V_O (<3 μV) so that it is virtually "0", → R_L=0

A sub-femtoamp SMU



CURRENT MEASUREMENT ACCURACY (2- OR 4-WIRE SENSE)[4]

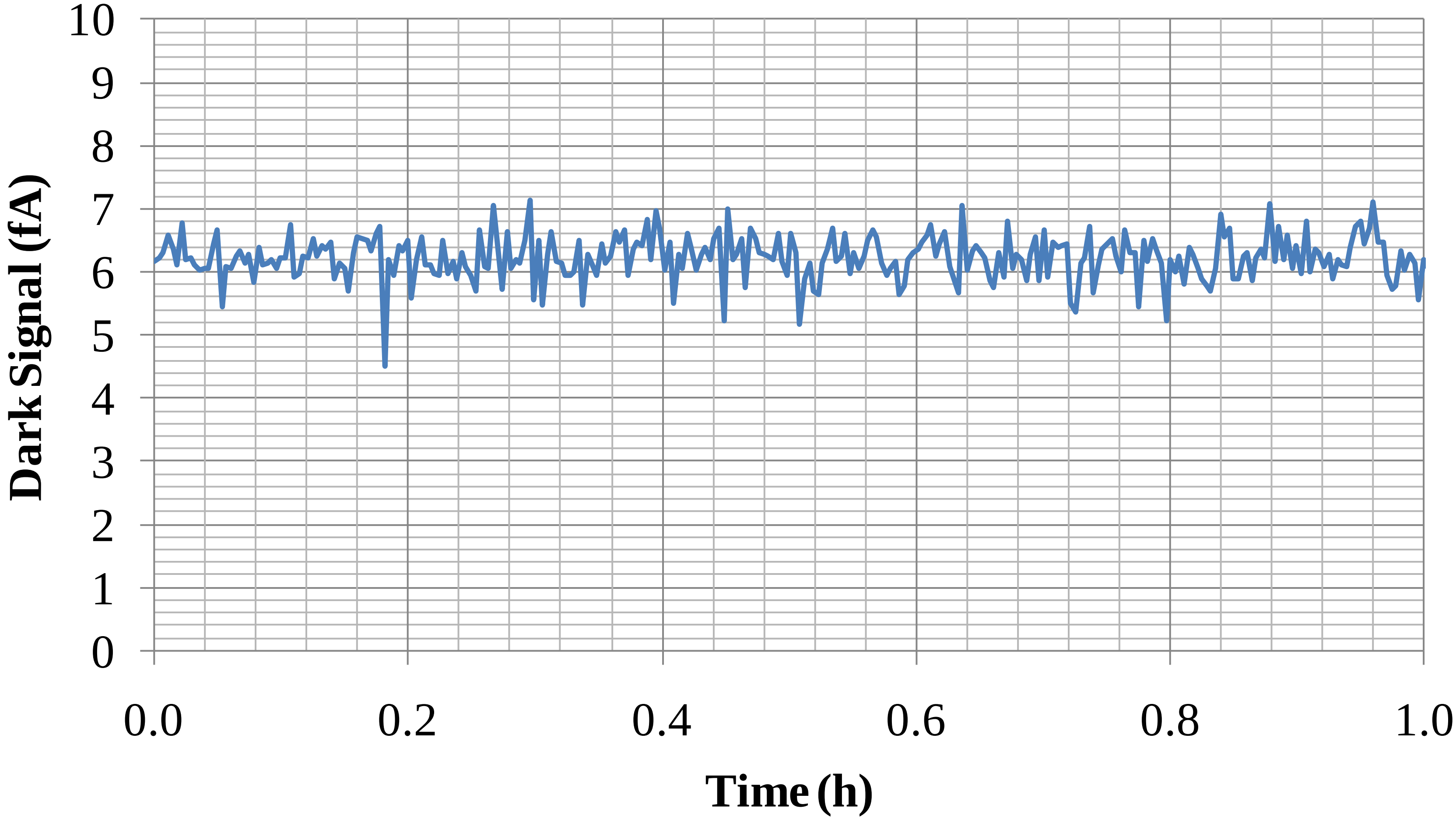
Range	Max. Resolution	Voltage Burden[5]	Accuracy (23°C ± 5°C) 1 Year ±(%rdg + amps)
1.00000 pA	10 aA	< 1mV	1.0 % + 7 fA
10.0000 pA	100 aA	< 1mV	0.50 % + 7 fA
100.000 pA	1 fA	< 1mV	0.15 % + 30 fA
1.00000 nA	10 fA	< 1mV	0.050 % + 200 fA
10.0000 nA	100 fA	< 1mV	0.050 % + 2 pA
100.000 nA	1 pA	< 1mV	0.050 % + 20 pA
1.00000 μA	10 pA	< 1mV	0.050 % + 300 pA
10.0000 μA	100 pA	< 1mV	0.050 % + 2 nA
100.000 μA	1 nA	< 1mV	0.025 % + 6 nA
1.00000 mA	10 nA	< 1mV	0.027 % + 60 nA
10.0000 mA	100 nA	< 1mV	0.035 % + 600 nA
100.000 mA	1 μA	< 1mV	0.055 % + 6 μA

TEMPERATURE COEFFICIENT (0°–18°C and 28°–40°C): ±[(0.15 × accuracy specification) + 1fA]/°C.

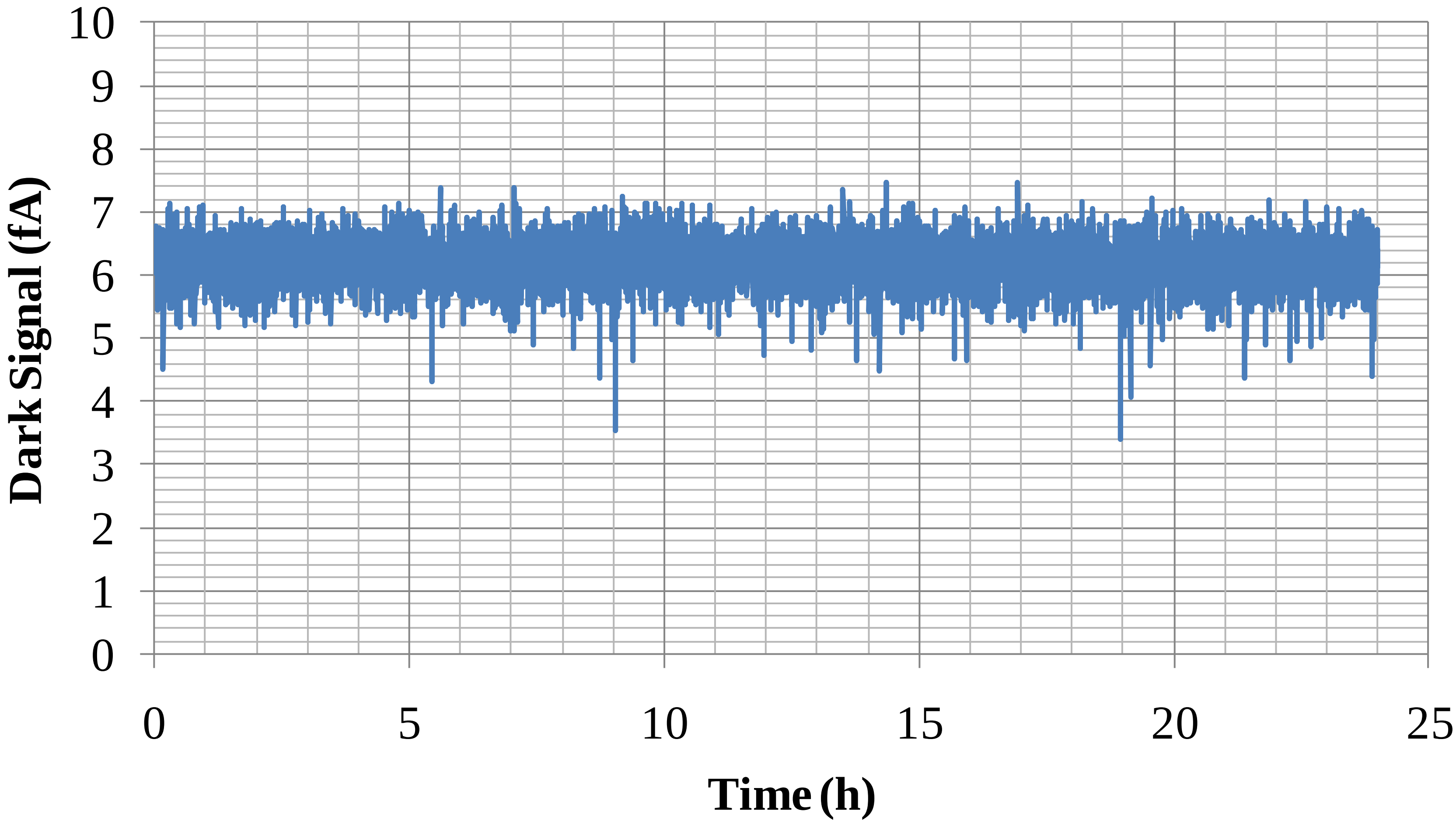
INPUT CURRENT: <3fA at 23°C, <40% RH; typically ±0.5fA/°C around 23°C, <40% RH.

- 0.05 % accuracy.
- 5 s time constant.
- Good stability.
- Fully automated.

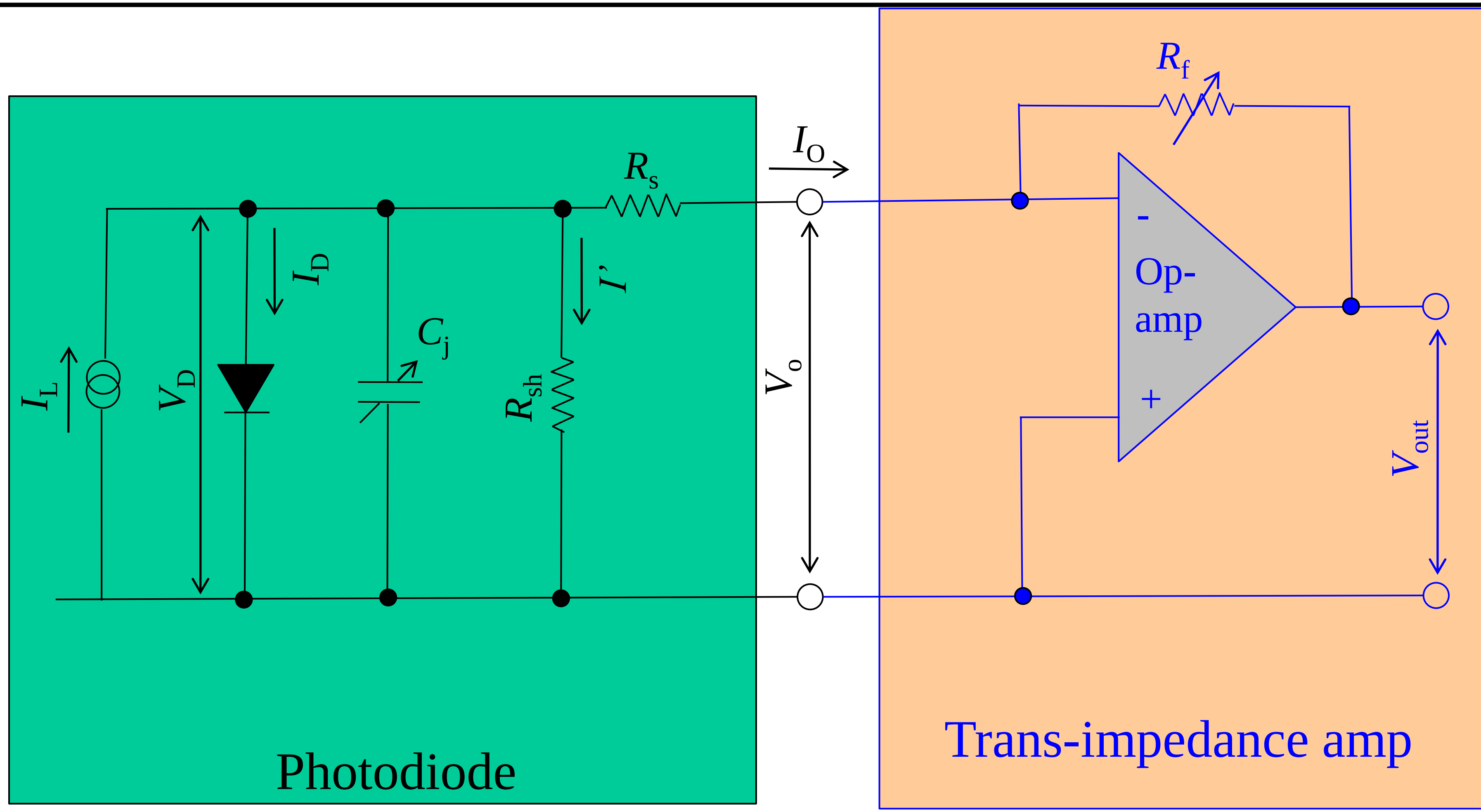
Si photodiode - SMU
Dark signal stability with a cooled detector (-10 °C)



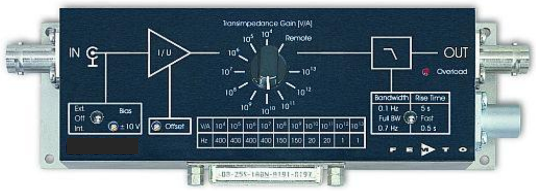
Si photodiode – SMU
Dark signal stability with a cooled detector (-10 °C)



Conventional trans-impedance amplifier based system



A sub femtoamp trans-impedance amplifier

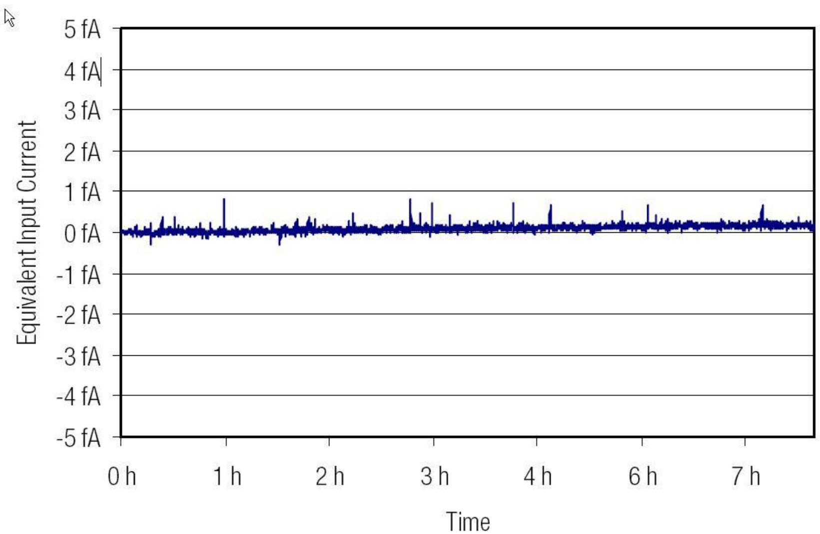


Variable Gain: 10^4 to 10^{13}

Gain accuracy: 1 %.

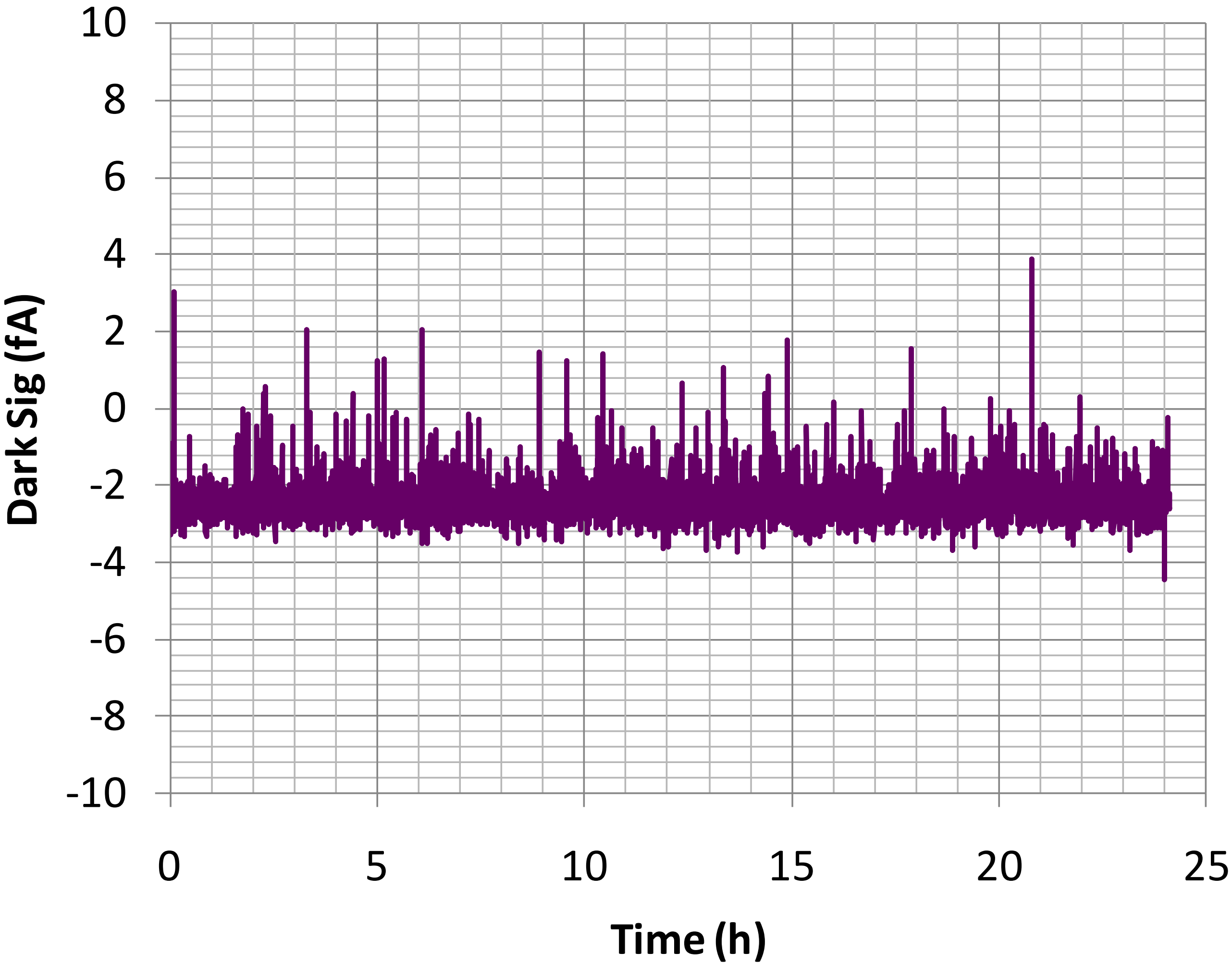
Gain Drift: 0.01 % - 0.03 % /°C

Rise/Fall Time: < 1 s at 10^{12} -10^{13}



- A low cost solution.

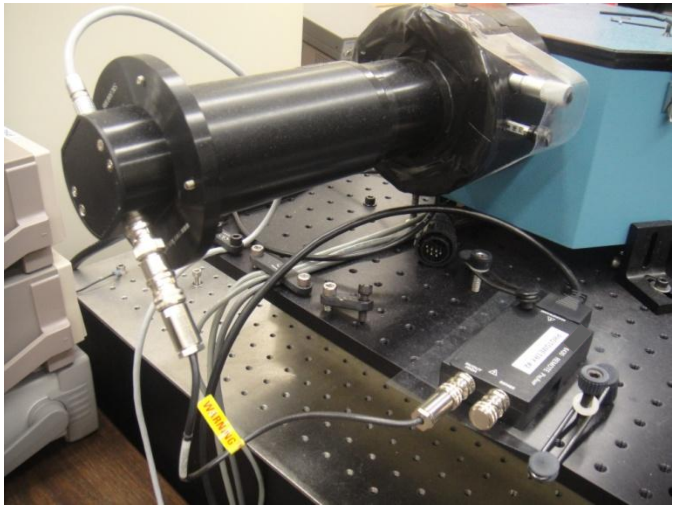
Si photodiode – transimpedance amplifer
Dark signal stability with a cooled detector (-10 °C)

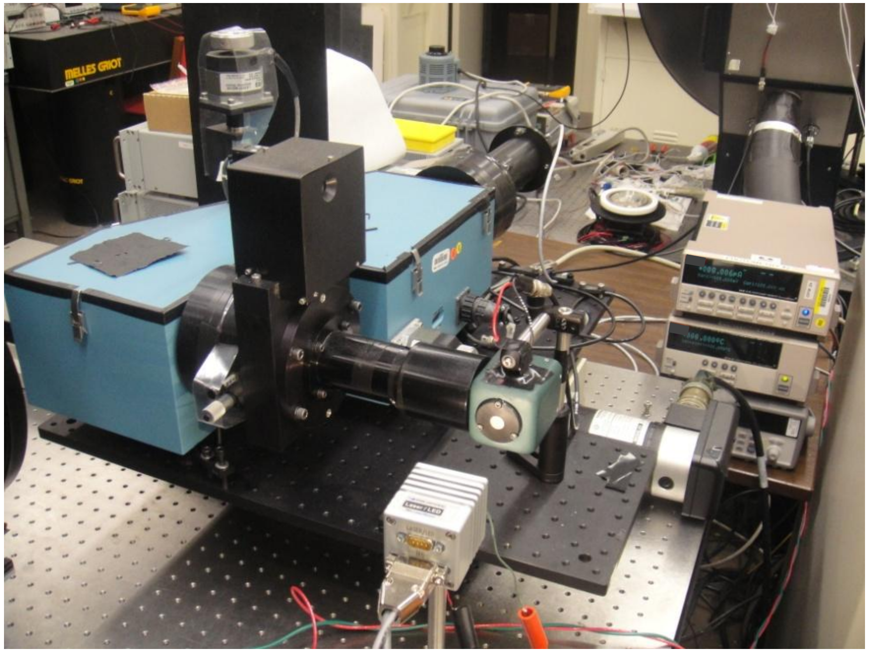


Application examples

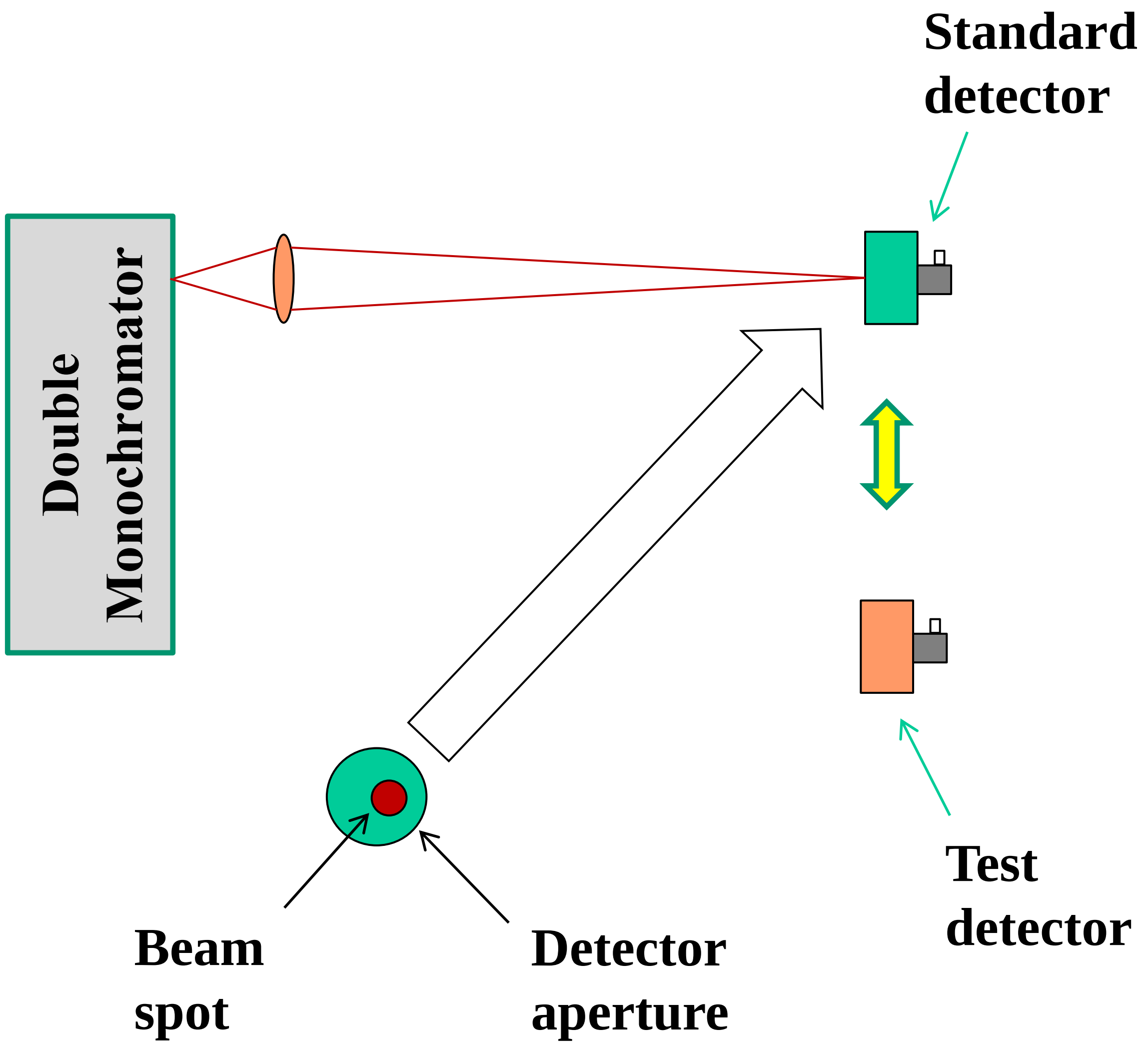
- A double monochromator for measurement of LEDs.
- Spectral irradiance/radiance responsivity calibration by using a laser-based or even a double monochromator based uniform source (eg, an integrating sphere source).

A Si photodiode based double monochromator system



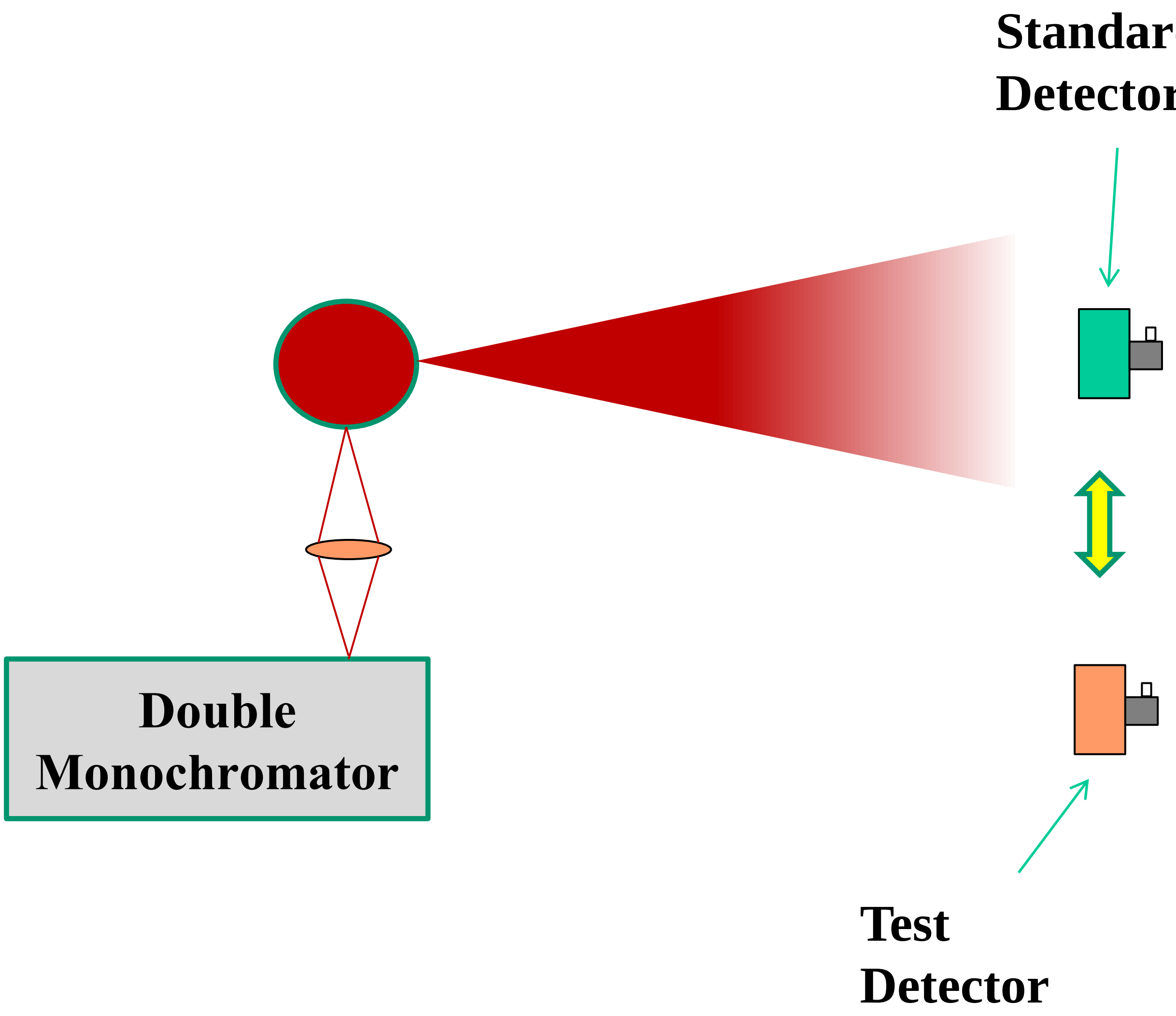


Conventional spectral power/irradiance responsivity calibration system



- Underfilled geometry.
- Indirectly for irradiance responsivity:
  -need accurate measurement of aperture area,
  - need to scan the entire aperture area.
- Difficult to achieve small uncertainties.

Preferred spectral irradiance and radiance calibration



- Overfilled geometry.
- Directly obtain irradiance resp.
- Measurement of aperture area is not to needed.
- No scan is required.

Conclusions

- Femto-ampere detectors such as photometers, colorimeters, and UV radiometers can be developed simply by using commercially available Si photodiodes and low noise instruments.
- Cost may not be high if one instrument is shared by multiple detectors.
- Femto-ampere detectors can be calibrated for spectral irradiance/radiance responsivity by using a laser-based or even a double monochromator based uniform source (*eg*, an integrating sphere source).
  - simplify calibration procedure,
  - reduce calibration uncertainty.

THANK YOU