Measuring Linearity of Detector Spectral Responsivity at Ultra-Low Incident Powers

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Agenda

• Background and Motivation
• Testing condition, setup and procedure
• Test results and analysis
• Discussion
Background

• Next-generation scatterometer development is underway at NASA/GSFC Code 618 Diffuser Calibration Lab (DCL)

• The detection system for scatterometer need to be characterized to meet the system requirements, including, but not limited to:
  1. Electronic Signal to Noise Ratio (S/N)
  2. Dynamic Range (4~5 magnitude orders)
  3. Non-Linearity from the pre-amp
  4. Non-Linearity of the detector spectral responsivity
  5. Etc.
Background

• The detection system works in AC-mode, and includes a New Focus 3502 optical chopper, a Stanford SR570 pre-amp, a Stanford SR830 lock-in amplifier and a set of detector heads

• The detectors* under test are:
  A. Si: S2281-04 s/n: 4G001 (190 nm ~1100 nm)
  B. Std-InGaAs: G12180-250A s/n: 45 (900 nm ~ 1700 nm)
  C. Ex-InGaAs: G12183-230A s/n: 251 (900 nm ~ 2500 nm)

*Products from Hamamatsu
Background

- The SR-570 pre-amp has a gain range from $1.0 \times 10^3$ to $1.0 \times 10^{12}$, and a maximum output ±5 Volt;
- The SR-830 is a DSP lock-in amplifier has a maximum input 1 Volt.
- The photon current from the detector was fed to the SR570 directly, and converted to voltage, then passed to SR830 as shown below.
Background

- To measure the non-linearity from the pre-amp, we set the light source to a fixed level, and its stability is monitored by a NIST linearity-characterized detector; by changing the pre-amp’s gains, we recorded the signal changes. The signal from the monitoring detector was used to correct any changes caused by the light source. This work was done and documented in a 2015 SPIE San Diego proceeding “Characterization and Application of a LED-driven Integrating Sphere Source” (Proc. Of SPIE Vol. 9607 96070Y-1).

- To measure the responsivity non-linearity from the detector, we set the pre-amp’s gain to a fixed value, say 1.0E+8. By changing the output level of the light source, we recorded both signals from the monitoring detector and the detector under test. The signal from the detector under test compared to the signal from linearity-characterized detector. This way, the spectral responsivity linearity of the detector under test was characterized.
Motivation

• While I was measuring the responsivity non-linearity from different detectors, two of the questions popping up were “how low of an incident power can the detection system detect, and how linear is the spectral responsivity of the detector under such low incident power?

• This work mainly focuses on answering these two questions.
Challenges

• To successfully make those measurements, some conditions need to be fulfilled
  1. Absolutely no stray light and ambient light
  2. The light source needs to be very stable under such low power levels
  3. The power level of the light source can be easily adjusted
Test setup
Light-Tight Enclosure
Uniform Light Source

- Integrating sphere 30.5 cm (12”) in diameter
- Lined with Spectralon
- 10 cm (4”) opening
- 4 ports for mounting LEDs
- 2 ports for mounting monitoring detectors
Component Description--LED

- Off-the-shelf products from Thorlabs.com
- A wide range choice
- Relatively narrow spectral band-pass
- Relatively high power output
- Work under constant current mode, easy to control and stable
## Component Description -- LED

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>InGaAs</th>
</tr>
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<tbody>
<tr>
<td>Wavelength</td>
<td>405 nm</td>
<td>565 nm</td>
</tr>
<tr>
<td>FWHM</td>
<td>20 nm</td>
<td>100 nm</td>
</tr>
<tr>
<td>Max Power</td>
<td>760 mW</td>
<td>150 mW</td>
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<tr>
<td>Adjustable Current</td>
<td>0~1000mA</td>
<td>0~500mA</td>
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</table>
Component Description--LED

- Stability of the LED output was measured by the mounted monitoring detector.
- The fluctuation level is less than 0.1% after half hour warm up.
Component Description—Monitoring Si Detector

- Hamamatsu S2592-03 UV Enhanced Si Detector
- Spectral range 190 ~ 1100 nm
- 2.4X2.4 mm² active area
- TE cooled to -10°C
- Secured in aluminum socket for heat dissipation, set-screw mounted to the detector port on sphere
Component Description—Monitoring Si Detector

Photocurrent vs. Relative Irradiance at 850 nm

% Residual to Linear Fit at 850 nm

Table:

<table>
<thead>
<tr>
<th>Value</th>
<th>Error</th>
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<tbody>
<tr>
<td>m1</td>
<td>-2.2088e-15</td>
</tr>
<tr>
<td>m2</td>
<td>1.6937e-8</td>
</tr>
<tr>
<td>Chisq</td>
<td>189.96</td>
</tr>
<tr>
<td>R</td>
<td>1</td>
</tr>
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</table>
Component Description—Monitoring Std-InGaAs Detector

- Hamamatsu G12180-230A standard InGaAs detector
- Spectral range 900 nm ~ 1650 nm
- Ø 3.0 mm active area
- TE cooled to -20°C
- Secured in aluminum socket for heat dissipation, set-screw mounted to the detector port on sphere
Component Description—Monitoring Std-InGaAs Detector

• This detector was characterized for spectral-response-linearity by NIST using their Beamconjoiner Apparatus under those four IR wavelengths

• The photon current range in the NIST characterization was from $10^{-6} \sim 10^{-11}$ amperes

• The measured non-linearity was within 0.1% in the $10^{-6} \sim 10^{-10}$ ampere photon current range

• The measured non-linearity was within 0.5% in the $10^{-10} \sim 10^{-11}$ ampere photon current range
<table>
<thead>
<tr>
<th>Component Description-Detectors under Test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model #</strong></td>
</tr>
<tr>
<td><strong>Active Area (mm)</strong></td>
</tr>
<tr>
<td><strong>Spectral Range (nm)</strong></td>
</tr>
<tr>
<td><strong>TE temp (°C)</strong></td>
</tr>
<tr>
<td><strong>Shunt Resistance (MΩ)</strong></td>
</tr>
<tr>
<td><strong>Terminal Capacitance (pF)</strong></td>
</tr>
<tr>
<td><strong>NEP (W/Hz$^{1/2}$)</strong></td>
</tr>
</tbody>
</table>
Fore Optics

- The fore optics were configured in radiance mode to accommodate the situation in the BRDF measurements.
- Black Delrin was used to make the fore optics.
- This configuration was used for preliminary measurement purpose only, the final configuration will include a lens.
Inside the Light-Tight Enclosure
Measurement Procedure

- Set up all the components inside the light-tight enclosure;
- Determine the highest gain that the SR-570 pre-amp can be used with each detector;
- With the highest gain set in the SR-570, and the lowest LED current set in the LED controller (usually is 1 mA), put one or more ND filters in front of the fore optics so that the output of lock-in amplifier SR-830 is close to the noise floor of the whole electronic system (or dark signal, around 1 µV);
- Gradually increase the LED controller’s output current, record the output from SR-830 and the monitoring signal from KE6485
- Use the monitoring signal as reference to compare the output from SR-830, draw the linearity fitting function and calculate the linearity fitting error
Benefits of This Procedure

- The measurement results won’t be affected by stray light or ambient light due to the light-tight enclosure;
- The integrating sphere can reduce the output level greatly while the LED source maintains its stability;
- The ND filters provide even more flexibility to drop the light level that finally enters the fore optics and reaches the detector active area;
- They also make sure the monitoring detector is working in the light level in which it was characterized, while the detector under test is working in the much lower light level.
Instrument and Set up
How to Estimate Incident Power

- Use Ex-InGaAs G12183-230K as an example. Left chart shows its spectral response.
- At 1550 nm, its photosensitivity is about 0.75A/W.
- If the Lock-in SR830 readout is 10 µV with 1.0E+06 gain for pre-amp SR570, the incident power is estimated as $10 \div (10^6 \times 10^6) \div 0.75 = 13.3\text{pW}$.
Some of Test Results--Si

Si Spectral Responsivity Linearity Fitting @ 850nm with Gain 1.0E+8

\[ y = 130.29x - 3E-06 \]

<table>
<thead>
<tr>
<th>KE6485 Reading (A)</th>
<th>SR830 Reading (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0E+00</td>
<td>0.0E+00</td>
</tr>
<tr>
<td>5.0E-06</td>
<td>5.0E-06</td>
</tr>
<tr>
<td>1.0E-05</td>
<td>1.0E-05</td>
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<tr>
<td>1.5E-05</td>
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<td>3.5E-05</td>
<td>3.5E-05</td>
</tr>
<tr>
<td>4.0E-05</td>
<td>4.0E-05</td>
</tr>
</tbody>
</table>

SR830
Linear (SR830)
Some of Test Results -- Si

Si Linearity Fitting Error vs. Measurement uncertainty (1.0E+8 @ 850nm)

Measurement Uncertainty and Fitting Error (%) vs. Incident Power (Watt)

- SR830 Error
- Fitting Error
Some of Test Results – Std-InGaAs

Std-InGaAs Spectral Responsivity Linearity Fitting @1300nm With Gain 1.0E+08

\[ y = 104.65x - 5E-07 \]
Some of Test Results – Std-InGaAs

Std-InGaAs Linearity Fitting Error vs. Measurement Uncertainty (1.0E+8 @1300nm)

- SR830 Error
- Fitting Error
Some of Test Results – Ex-InGaAs

Ex-InGaAs Spectral Responsivity Linearity Fitting @ 1550nm with Gain 1.0E+06

\[ y = 23.434x - 4E-07 \]
Some of Test Results – Ex-InGaAs

Ex-InGaAs Linearity Fitting Error vs. Measurement Uncertainty (1.0E+6.0 @1550nm)

- SR830 Error
- Fitting Error
Results Analysis

• The tests present results where the incident powers are getting very close to the NEP (Noise Equivalent Power) of each detector;

• The linearity fitting error is getting higher while the measurement uncertainty is getting worse;

• But that does not mean the response linearity is getting worse when the incident power drops close to detector’s NEP.
Results Analysis

• The higher measurement uncertainty close to NEP level can surely contribute to the higher fitting error
• The fitting error calculation method also makes a big contribution to the higher fitting error when the incident power is close to the NEP level
Fitting Error Analysis

- Using $\Delta$ to represent the absolute fitting error in my case, the fitting error shown in the chart was calculated by $\Delta/(\text{Value B})$, or say relative fitting error.
- The fitting program will try to make the sum of all the $\Delta^2$ minimum, which will cause the uniform distribution of $\Delta^2$.
- When the Value B gets smaller and smaller, it will make the relative fitting error bigger and bigger.
Look Back at the Ex-InGaAs

Ex-InGaAs Linearity Fitting Error vs. Measurement Uncertainty (1.0E+6.0 @ 1550nm)

- SR830 Error
- Fitting Error
Look Back at the Ex-InGaAs
Summary

• The measurements at the power levels that are close to the detector’s NEP level can be performed and the results show that at such low incident power levels, the spectral responsivity of different detectors maintains linear.

• We also are interested in testing the detectors’ linearity of responsivity at very high incident power levels, to find out the power limits and the power density limits that can cause the detector to saturate.
Thanks for Attending

Q&A

Comments
Backup

- Two factors to determine the highest gain that can be used in the pre-amp:
  
  1. The shunt resistance of the photodiode detector
     
     1. The pre-amp gain setting requires that the highest gain can not be set to be higher than the detector’s shunt resistance
     
     2. Terminal (PN junction of detector) temperature makes huge contribution to detector’s shunt resistance and can be adjusted through a temperature controller

  2. The chopping frequency also affects the highest gain setting
Shunt resistance vs. element temperature

(Typ. $V_R=10$ mV)

Element temperature (°C)

Shunt resistance

- G12183-003K/-103K/-203K
- G12183-005K/-105K/-205K
- G12183-010K/-110K/-210K
- G12183-020K/-120K/-220K
- G12183-030K/-130K/-230K