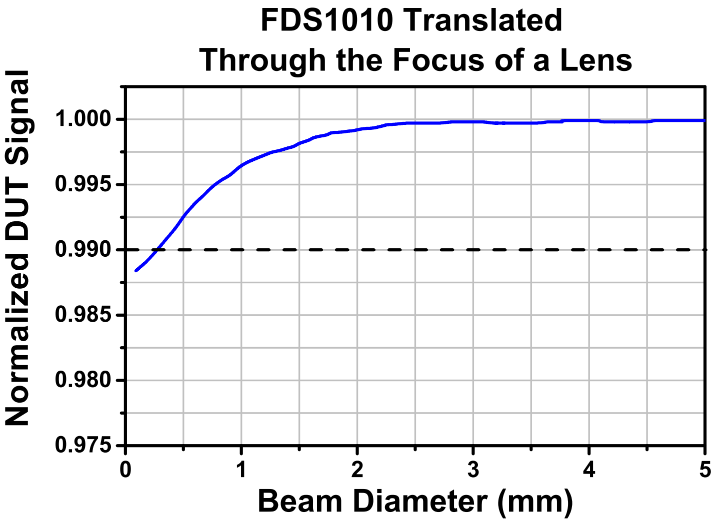
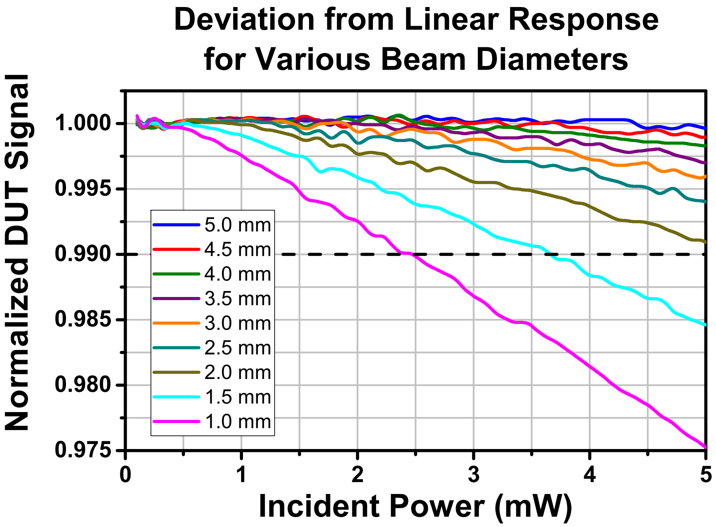
Effect of Beam Size on Photodiode Saturation

- Experiments were conducted to demonstrate a change in the saturation point for a FDS1010 silicon photodiode as a function of beam diameter.
- The saturation point was defined as a 1% deviation from the linear response.
- The smaller the beam diameter, the lower the power corresponding to a 1% deviation from the linear response. For example, when the FDS1010 had a 0 V bias and was illuminated at 830 nm, a Ø2 mm beam saturated at approximately 5 mW while a Ø1 mm beam saturated at approximately 2.5 mW.
- A control experiment was conducted to ensure the observed change in saturation power was not a function of the power density.
- These results suggest the user should be cognizant of the beam size when attempting to measure absolute power with a power sensor that has 0 V bias, such as our S130C power sensor.



FDS1010 Translated Through the Focus of a Lens

Figure 1: Normalized change in output current as the photodiode Device Under Test (DUT), FDS1010, was translated through the focus of a lens.



Deviation from Linear Response for Various Beam Diameters

Figure 2: Percent deviation from the linear response with increasing power for 1 – 5 mm beam diameters. The 1% deviation level is indicated with a dashed horizontal line.

Background

- Photodiodes convert incident optical power into an electrical current.
- As discussed in our Lab Fact "Photodiode Saturation and Noise Floor," the output from a photodiode follows an S-curve based on the noise floor and saturation limit. A typical S-curve, recorded using a load resistor to convert the output current to a voltage, is shown in Figure 3.
- Photodiodes are generally used within the linear response region in the middle of the S-curve to simplify the response and prevent ambiguities near the noise floor and the saturation limit.

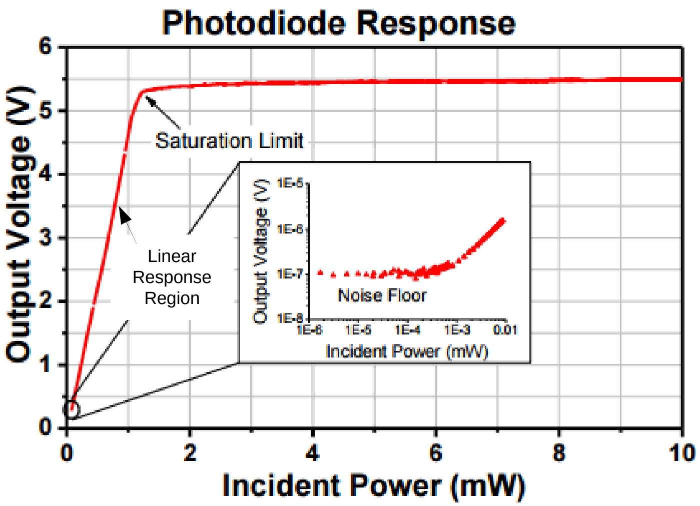


Figure 3: Measured response of a Si photodiode with a 5 V bias and 10 kΩ load resistor showing the linear region between the noise floor and saturation limit.

- In this Lab Fact, we investigated the change in saturation at the top of the S-curve with respect to the beam diameter incident upon a silicon photodiode (FDS1010) with a 0 V bias.
- It is important to note that for the purposes of this Lab Fact, we have defined saturation as a 1% deviation from the linear region.
- Additional control experiments were conducted to demonstrate that the observed effects were the result of beam size and not power density or local saturation.

Experimental Design

- An 830 nm superluminescent diode (SLD830S-A20) was used to minimize coherent effects, such as speckle.
- The SLD was collimated with a fiber collimator (F810APC-842) and the beam traveled through a linear polarizer (LPNIR100-MP), achromatic half-wave plate (AHWP05-980), and linear polarizer (LPNIR100-MP) in order to control the incident power without changing the drive current applied to the SLD.
- An 80:20 beamsplitter (BSN11R) reflected 20% of the signal to a monitor photodiode (SM1PD1A) in order to remove any power instabilities. The photodiode had a 2 V reverse bias and the incident beam was Ø7.5 mm for all measurements.
- The 80% transmitted beam was focused by a lens (ACA254-150-B). Power values were determined by first calibrating the system with an integrating sphere (S142C) placed after the lens. A translation stage (LTS150) was then used to move a CCD beam profiler (BC106N-VIS) through the lens focus to calibrate the beam diameter versus stage position. Beam diameters were measured to the 5% clip level.
- Then the device under test (DUT), an FDS1010 photodiode with 0 V bias, was mounted on the stage and translated along the focused beam. Two datasets were recorded:
  1) A 1 mW beam was scanned to provide continuous measurements over 0.06 – 5 mm beam diameters in order to calibrate the photodiode position, assuming the minimum signal corresponds to the smallest beam diameter.
  2) The stage was scanned to provide measurements for 1 mm – 5 mm beam diameters while the optical power incident upon the DUT was varied between 0.12 – 5 mW.
- Output current from the monitor and the photodiode under test were recorded with an ammeter to remove the need for load resistors.

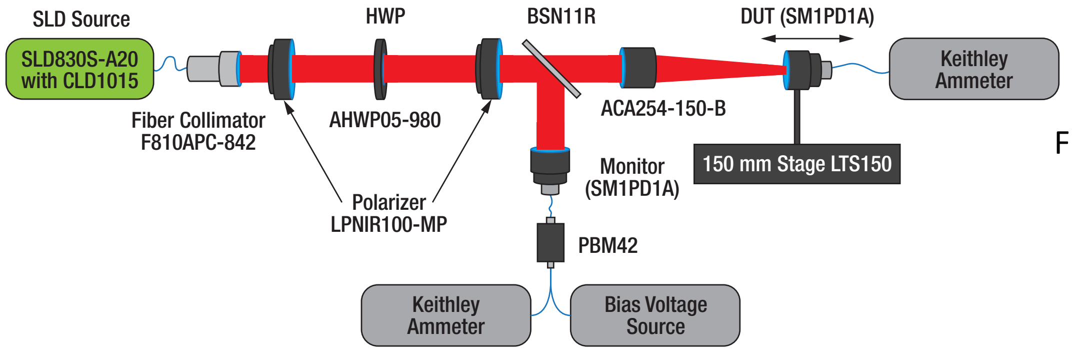


Figure 4: Block diagram of experiment

Experiment Setup

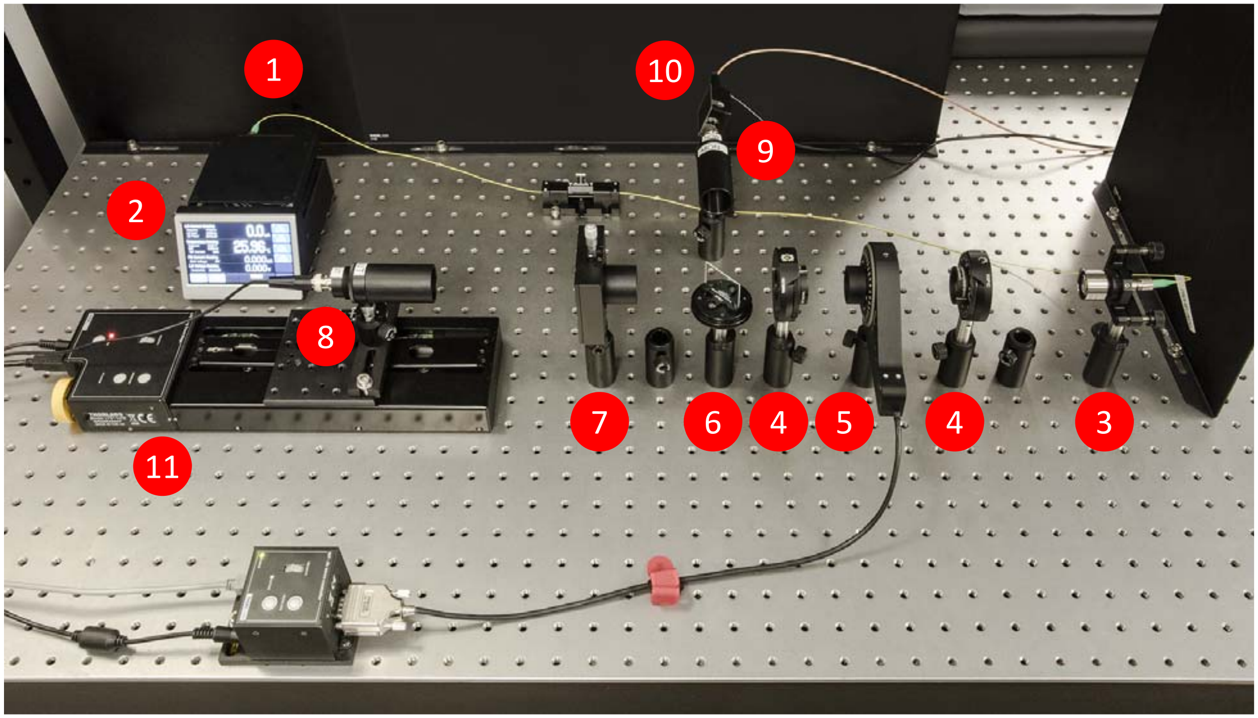


Figure 5: Experimental Setup

1. SLD source: SLD830S-A20
2. LD Current Controller: CLD1015
3. Fiber Collimator: F810APC-842
4. Linear Polarizer: LPNIR100-MP2
5. Half Wave Plate: AHWP05M-980
6. Plate Beamsplitter: BSN11R
7. Focusing Lens: ACA254-150-B
8. Photodiode DUT: SM1PD1A (FDS1010)*
9. Monitor Photodiode: SM1PD1A (FDS1010)*
10. Bias Module: PBM42 (Modified)
11. Translation Stage: LTS150

*SM1PD1A consists of the FDS1010 photodiode in an SM1-threaded housing.

Results: Beam Size

- The plot in Figure 6 shows a typical normalized response for the photodiode DUT as it was scanned through the focus with an incident power of 1 mW.
- Starting on the right, the photodiode provided a constant current with the beam size decreasing from 5 mm to approximately 3 mm. After that point, the output current begins to decrease with decreasing beam size until reaching a minimum at the focus.
- With saturation defined as a 1% deviation from the constant signal on the right side of the plot, the photodiode was saturated with beam sizes <300 µm.
- The plot in Figure 7 shows normalized output current versus incident power for beam sizes between Ø1 and Ø5 mm in steps of 0.5 mm. The plot only shows incident power up to 5 mW because that is the specified maximum incident power for the photodiode in the S130C power sensor.
- Here we can see that beam diameters ≥2 mm did not reach the saturation limit for the power range investigated, while the 1.5 mm beam saturated at approximately 3.75 mW and the 1.0 mm beam saturated at approximately 2.5 mW.

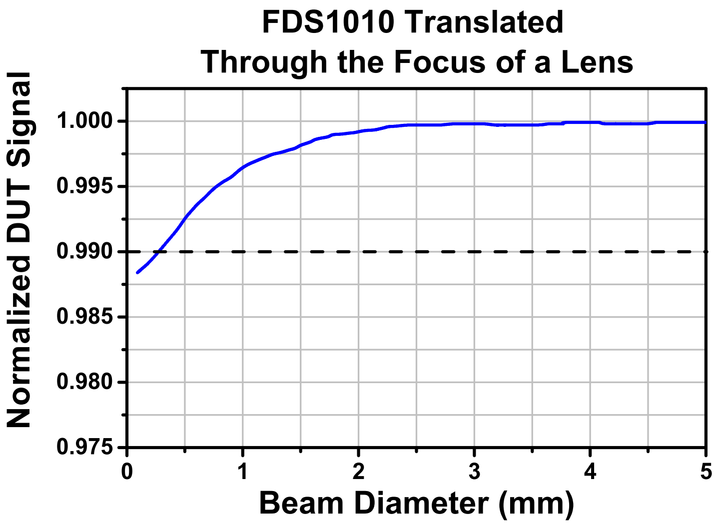


Figure 6: Photodiode output versus beam size normalized to signal at 5 mm beam diameter.

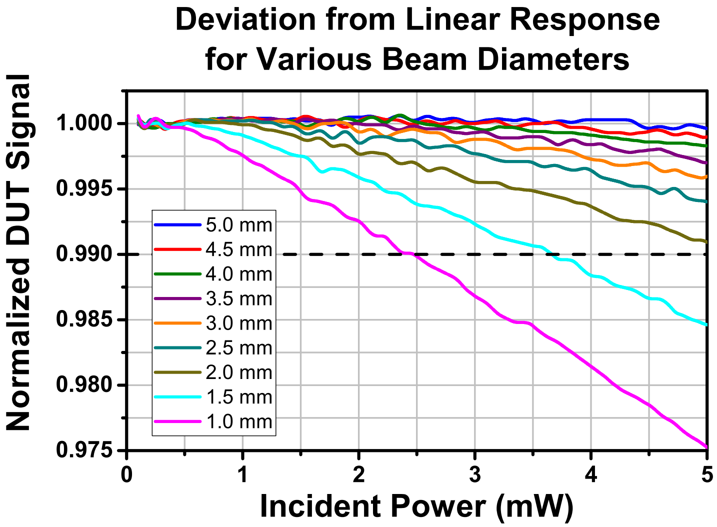


Figure 7: Normalized output current versus optical power for 1 – 5 mm beam diameters showing the 1 and 1.5 mm diameter beams saturate at 1% from the normalized response prior to 5 mW.

Results: Local Saturation

- An initial thought was that the results we obtained were the result of local saturation, where a large power density locally depleted or reduced the population of available carriers.
- To determine if this was the case, we plotted the normalized output current versus power density by finding the quotient of the measured power and the beam diameter in Figure 7.
- If the results were mainly a result of power density/local saturation, we would expect all of the beam diameters to overlap along a single function and saturation to occur at a single power density.
- However, this was not the case in Figure 8; in fact, every beam diameter began to deviate from the normalized value of 1 at a different power density. This result suggested that the saturation changes we observed were not the result of an incident power density limit for the photodiode.
- It is important to note that this set of measurements coupled beam size change with a change in optical power. In the next slide, we attempted to vary the power density of the beam while keeping both beam envelope and power constant. This was accomplished by creating a "comb-like" structure within the beam profile.

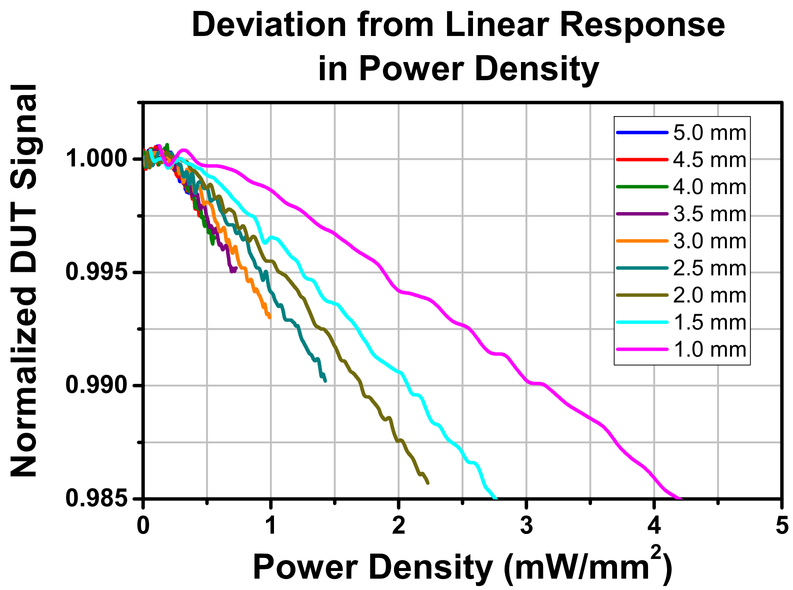


Figure 8: Normalized output current versus power density for the same beam diameters. This shows the saturation effect does not appear to be based on a single power density.

Results: Beam Shape

- We segmented the Gaussian beam into an array of beamlets within the Gaussian envelope using a microlens array (MLA300-14AR-M) positioned 18.6 mm in front of the photodiode under test.
- The plots in Figure 9 show sample cross sections of the beam profiles with and without the microlens array for the 4 mm diameter beam.
- By including the microlens array, the overall optical power was concentrated into smaller spots within the Gaussian envelope, thereby creating larger power densities at the focus locations while maintaining a similar electrical path length to the sensor leads for the electrons to travel.
- The normalized output versus incident power plot in Figure 10 shows the same solid lines for the unaltered Gaussian beam ≥2 mm with the results from the microlens array shown in the same color dashed lines.
  - It is important to note that data was not acquired with the microlens array for beam diameters <2 mm because the beam size was too close to the 300 µm pitch of the microlens array. The transmission of the MLA was also measured to ensure the same power levels were compared.

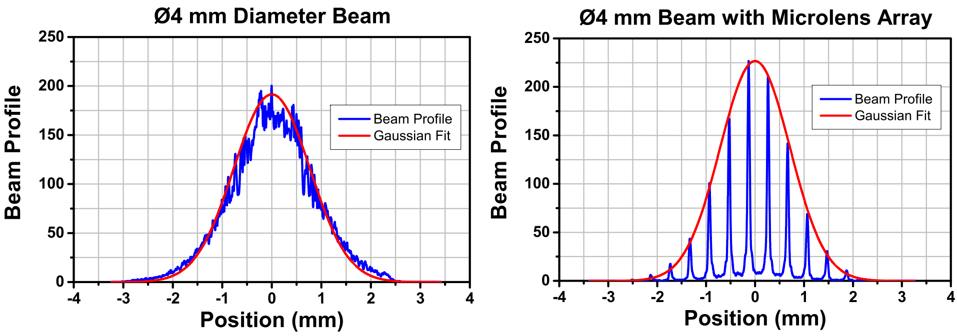


Figure 9: (Left) Gaussian fit to beam profiler measurement of Ø4 mm beam. (Right) Gaussian envelope fit to beam profiler measurement of Ø4 mm beam incident upon microlens array.

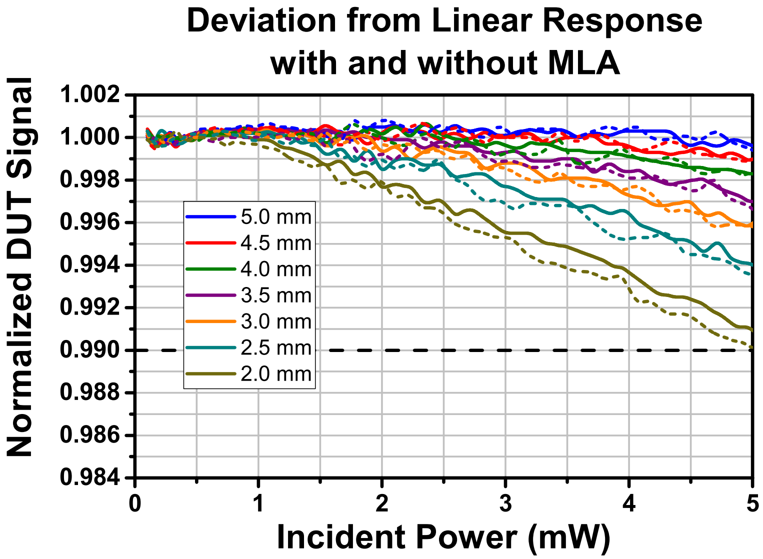


Figure 10: Normalized output current versus optical power for 2 – 5 mm beam diameters with (dashed line) and without (solid line) microlens array prior to photodiode.

- Here, we can see the microlens array data was nearly identical to the original Gaussian beam for all beam diameters, further suggesting the measured saturation seems to be dependent on the overall diameter of the light incident upon the photodiode under test and independent of power density.

Series Resistance and Saturation

- One possible explanation for the change in saturation with beam size is that the series resistance changes with beam size.
- A common circuit model for the internal components of a photodiode adapted from Korde *et al*. is shown in Figure 4 [1].
- In this model, the output current I can be calculated:

  $$I = I_L - I_0(\exp(eV_D / nkT) - 1) \qquad (1)$$

  where I_L is the internal photocurrent, I_0 is the reverse saturation current, e is the electron charge, V_D is the induced voltage drop across the resistive elements in the circuit, n is the emission coefficient, k is Boltzmann's constant, and T is temperature [1].

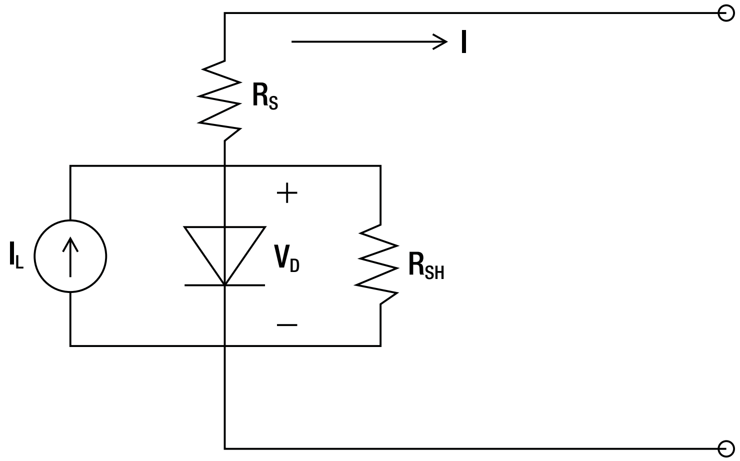


Figure 4: Circuit model for a photodiode with generated current I_L, voltage drop V_D, parallel resistance R_{SH}, series resistance R_S, and output current *I*.

- Using Ohm's law we can substitute:

  $$V_D = IR_S \qquad (2)$$

  into Eq. (1) assuming the current through the shunt resistance, R_{SH}, is negligible compared to the current through the series resistance, R_S (for a Silicon photodiode, R_{SH} is on the order of GΩ while R_S is tens to hundreds of Ω) :

  $$I = I_L - I_0(\exp(eIR_S / nkT) - 1). \qquad (3)$$

- Assuming constant temperature, Eq. (3) shows the maximum current I (saturation) is dependent on the series resistance, R_S. It is important to note that when a load resistance is used in series with a photodiode, the total resistance in Eq. (2) becomes the sum of the series resistance and load resistance.
- Series resistance is a function of several parameters such as semiconductor material and structure, temperature, and beam size. Scholze *et al*. suggests that the smaller the beam, the larger the series resistance due to the longer path length that the photo-generated charge carriers must travel to reach the sensor leads [2].

[1] R. Korde, C. Prince, D. Cunningham, R.E. Vest, E. Gullikson, Present status of radiometric quality silicon photodiodes. Metrologia **40**, S145 (2003)

[2] F. Scholze, R. Klein, R. Muller, Linearity of silicon photodiodes for EUV radiation. 2004 Proc. SPIE 5374 926–34

Experimental Limitations

- Only one type of silicon photodiode was tested.
- Results are only presented from one stock SM1PD1A, however we have qualitatively observed similar trends with other units.
- Only a single superluminescent diode with a center wavelength around 830 nm was used. Because the photodiode's responsivity at 830 nm is high, we expect the observed change in saturation to be larger than had we used a wavelength with a lower responsivity (lower responsivity results in a smaller I in Eq. (3)).
- Tests were only conducted with a 0 V bias to model the S130C photodiode power sensors, because that is where we originally noticed saturation effects. If bias voltage is applied to the photodiode, then Eq. (3) becomes:

  $$I = I_L - I_0(\exp(e[V_{bias} + IR_S]/ nkT) - 1) \qquad (4)$$

  and therefore the contribution from IR_S required to obtain a 1% change to the linearity will also increase.
- We refrained from fitting our data to model a series resistance, because we felt it was beyond the scope of this Lab Fact. Our intention is to characterize the response of the FDS1010 so the user is aware of possible discrepancies in the measured power due to saturation when performing their own measurements.

Summary

- Measurements were carried out to demonstrate a change in measured power with the FDS1010 Si photodiode with a change to the incident beam size.
- Our results indicate that beam diameters <2 mm result in a saturation power that is less than 5 mW when the photodiode has a 0 V bias, which is the maximum power specified for the FDS1010 photodiode packaged within the S130C power sensor.
- Control tests suggest the effect is separate from local saturation and not related to the maximum power density specification. One possible explanation is that the series resistance of the photodiode is beam size dependent.
- Overall, the user should be cognizant of the beam size when attempting to obtain absolute power measurements with a photodiode at 0 V bias. Small beams are subject to changes in the saturation power and larger beams are subject to spatial non-uniformities to the response. As a point of reference, Thorlabs' photodiode sensors are calibrated with a beam diameter of approximately 1.5 – 2 mm and optical powers <1 mW.