MICRO-429: Metrology Practicals

T4 - Sensitivity in photon-counting devices

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Objective:

- Photon detection probability (PDP) and efficiency (PDE)
- Poisson nature of photons, “hand diagram”
- Photo-response non-uniformity (PRNU)

Reading & reference material:

- Read reference [1] for a general understanding of SPAD technology
- Read MICRO-428 lecture notes on *Optical Image Sensors – Introduction to single-photon detection*
- Read reference [2] to learn about typical characteristics – breakdown voltage, DCR, photon detection probability (PDP), timing jitter, afterpulsing probability – of a SPAD23™ pixel

- Read reference [3] for a general understanding of SiPM technology
- Complementary information:
    - ★ SPAD23™ Operating Manual
    - ★ Training data (to optimize your own Matlab routines)
    - ★ MICRO-428 lecture notes on *Statistics* (SPAD related examples, basic statistics)

Setup:

- 1 SPAD23™ detection unit
- 1 x Pulsed laser source
- 1 Laser controller
- 1 NIM to TTL converter
- Absorptive neutral density filters
- 1 x Mirror
- 1x Diffuser
- 1 laptop

Methodology:

- Power up the SPAD23™ module, set up the user interface, and explore the SPAD/photon behavior under different illumination conditions.
    - Use the timestamping option from the interface and collect the timing data of the incident photons.
    - Write a Matlab code to investigate the effect of the incident light power on SPAD pixels and the nature of the photons.
    - Estimate the spatial photo-response uniformity.
- Document your findings in the *Lab Notebook* along the way.

References:

[1] E. Charbon, “Single-photon imaging in complementary metal-oxide semiconductor processes”, Phil. Trans. Royal Society, 28 March 2014. DOI: 10.1098/rsta.2013.0100.

[2] I. M. Antolovic, C. Bruschini, and E. Charbon, "Dynamic range extension for photon counting arrays." Optics Express 26.17 (2018): 22234-22248.

[3] Gundacker, Stefan, and Arjan Heering. "The silicon photomultiplier: fundamentals and applications of a modern solid-state photon detector." Physics in Medicine & Biology 65.17 (2020): 17TR01.

[4] Ulku, A. C., Bruschini, C., Antolović, I. M., Kuo, Y., Ankri, R., Weiss, S., Michalet, X. & Charbon, E. (2018). A 512× 512 SPAD image sensor with integrated gating for widefield FLIM. IEEE Journal of Selected Topics in Quantum Electronics, 25(1), 1-12.

Theoretical Background

Single SPAD vs. SiPM: A single (digital) SPAD is capable of generating only a single pulse even when several photons impinge on it at the same time. Therefore, some of the photons can be missed. A silicon photomultiplier (SiPM) on the other hand is composed of several SPADs connected in parallel. Its output is thus proportional to the number of incident photons. As a result, an SiPM can detect more than a single event even over a very short time duration (< SPAD deadtime). Please have a look at Ref. 3 to gain insight about SiPM basics.

In the first part of the experiment, SPAD23 will be treated as an SiPM in order to measure the number of events per laser period, which is correlated to the number of photons per optical pulse. Thus, we will be able to construct the photon probability distribution (detection PDF).

In order to convert SPAD23 to an SiPM, we will use coarse timestamps. When raw timestamp measurement is performed, a text file containing fine and coarse timestamps is saved. Coarse timestamps indicate at which laser period an event is detected. By investigating the coincidences in the detections of different pixels, it is possible to estimate how many events occurred for each laser period. A summary of what/how you will measure can be seen in Figure 1.

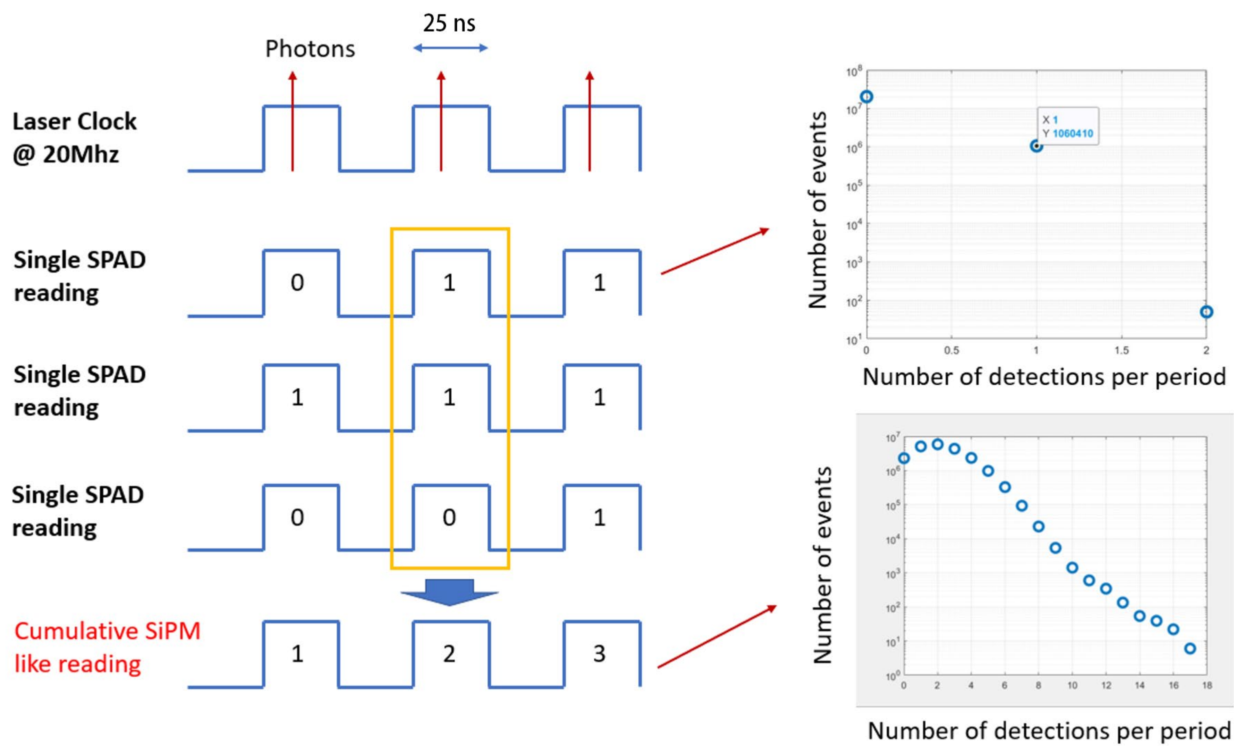


Figure 1: Timing diagram of photon detection events for a single SPAD pixel, and conversion to SiPM-like reading (*left*). Example of number of detected avalanche pulses for a single pixel when operating with a 20 MHz laser repetition rate over a 1 s integration time (*upper right*). Number of total detected avalanche pulses from all 23 pixels under the same configuration (*lower right*).

Note: In photon counting optical devices, due to the particle nature of light, Poisson noise or shot noise is observed. When we consider a light beam coming out from a laser, a stream of discrete photons will be hitting the detector array, with the photon emissions from the laser occurring at random times. In case of high optical power, the variation of the number of emitted photons per unit time is very small. However, in the *single-photon regime* – i.e. when the laser power is reduced so that only a small number of photons hit the array every second (and on average much less than one per pulse) – the relative fluctuations in the number of detected photons will be important. These fluctuations are called shot noise. The shot noise magnitude can be quantified with the square root of the expected number of events.

In the second part of the experiment, you will estimate the PRNU (photo-response non-uniformity) of the SPAD23 array by measuring its signal-to-noise ratio (SNR). In an ideal case, i.e. when operating with uniform illumination and uniformly distributed pixel sensitivity, and in absence of other noise sources, the SNR of the detector array would be limited by shot noise. An example can be observed in Figure 2. Please read the first paragraph in the "Performance Characterization/Dynamic Performance" section of Ref. 4.

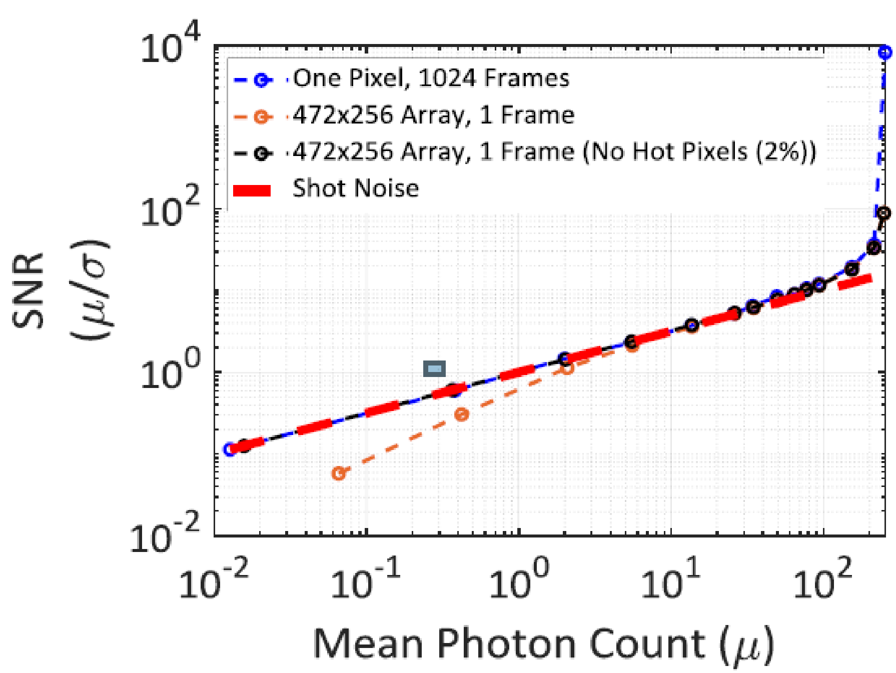
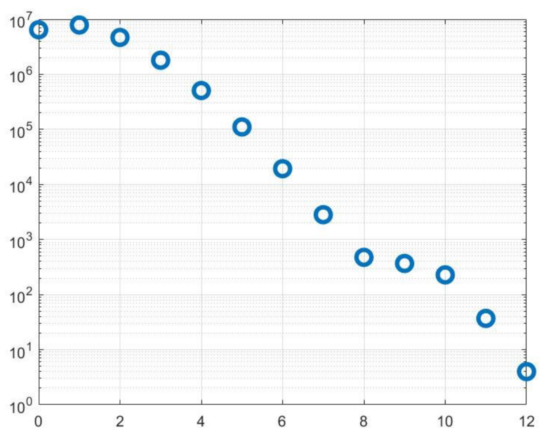


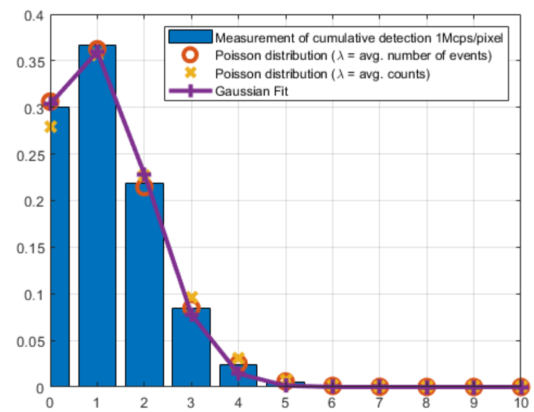
Figure 2: Temporal and spatial SNR of a SPAD array under different illumination levels.

Methodology:

Part 0: Preparation (*before the practical*)

1) The practice data file “hh.mat” includes a histogram of detection events for 0, 1, 2 … 20 events. For example, the first number shows how many times zero events are detected per period. Import “hh.mat” to your Matlab and prepare a code which:
   a) Plots “hh” in log scale.





   b) Calculates a normalized histogram by dividing the “hh.mat” data with the total number of events and plots it as bars (see figure above). This calculation converts the histogram (hh) to a probability distribution. For example, the first point of the calculated curve shows the probability of detecting zero events within a period.
   Hint: check “bar()”.
   c) Makes a Gaussian fit to the probability distribution calculated in step 1.b.
   Hint: “fit(x',y','gauss1')”.

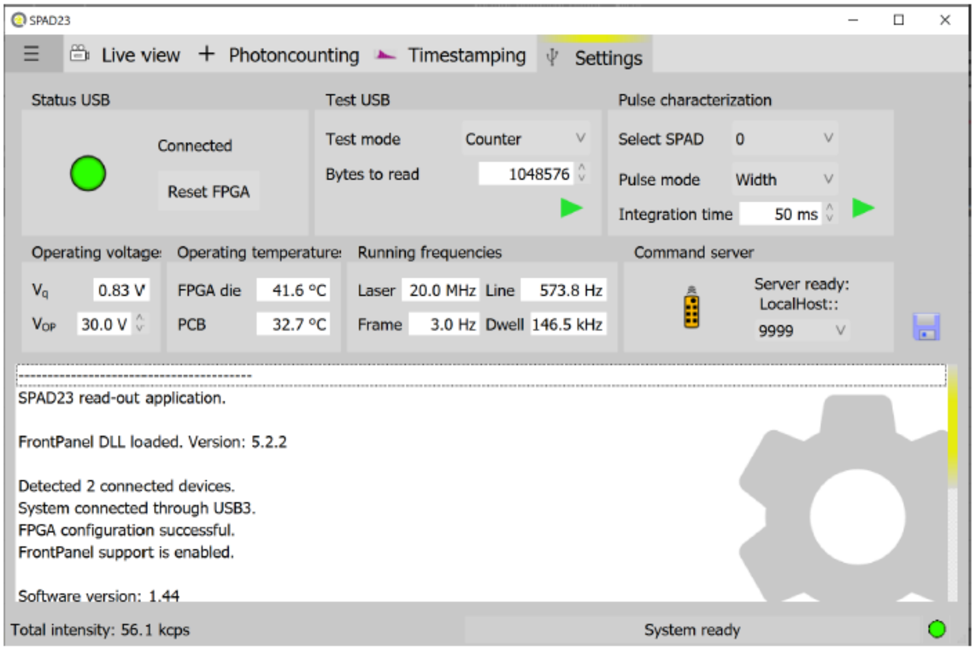
d) Calculates the expected value of the probability distribution (step 1.b) and plots a Poissonian distribution whose mean is equal to calculated expected value.
Hint: "poisspdf()".

e) Plots a Poissonian distribution whose mean is equal to 1.275 , which is the average counts (total counts / number of periods) read directly from GUI. The final figure should look like the one above (right).
NB: Please note the slight difference between the average counts (step 1.e) and average number of events (step 1.d). Some events are filtered out due to corrupted data, therefore the latter will be smaller than the former.

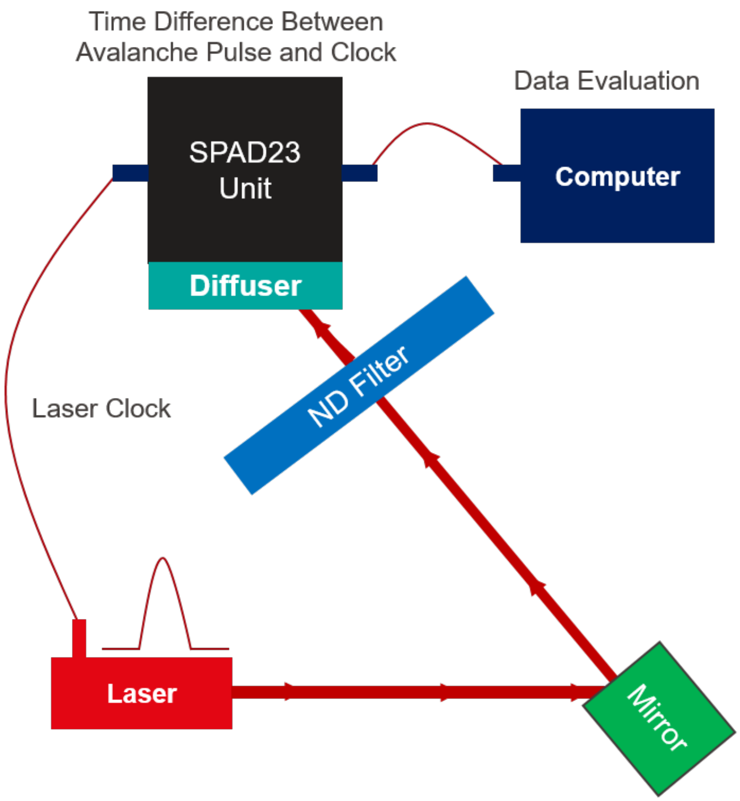
f) Plot the same figure also in log scale (which is not shown above).
Hint: "set(gca,'YScale','log')"

Part 1: Understanding the Poisson Nature of Photons with a Pulsed Source - System Set-up

2) Connect the power cable of the SPAD23™ unit to a power plug.
3) Place the SPAD23™ unit inside the black box.
4) Connect the power cable of the SPAD23™ unit to a power plug.
5) Connect the data cable of the SPAD23™ unit to the computer.
6) Open the SPAD23™ user interface. Go to the "Settings" tab and check if the unit is recognized by the software. "Status USB" sub-section should turn green. The screen should be seen as follows:



7) Check the “Operating voltages” sub-section, and set the “Vop” voltage to 30 V.
8) Disable the “Vop” from the interface.
9) You will use the optical setup to direct the laser light onto the SPAD23 unit. You will either use filters or tuning capability of your laser to change the irradiance of your SPAD module.



10)**WEAR GOGGLES**, **first, according to your laser wavelength for your eye protection**.

11)Power on the pulsed light source:

510 nm laser diode (Edinburgh Instruments): Turn the key of the laser to power it up, and wait for “Laser Ready” to go completely yellow without blinking. Set the period of your laser to 1 μs (1 MHz frequency).

12)When you click on:

“Laser On/Off” on the laser head (510 nm),

the laser light will be fired. The optical alignment is already done for this experiment, but in order to spot where the laser beam is, use your “Detector Card” available on your table. Thanks to this card you will be able to see the laser beam while you are wearing goggles.

13) To check if the laser clock is synchronized with the SPAD23 interface, click on "Change clock SMA mapping" from the upper left-most tab on the SPAD23 interface. Observe that the "Laser clk" on SMA2 becomes:
1 MHz (1 μs period) once the 510 nm laser is on.
14) On the SPAD23 interface, navigate to the "Live View" section.
Insert your NE240B neutral density filter (ND4) between the mirror and the module to achieve around 10~20 kcps count rate for a single pixel, and take note of total count rate from SPAD23 interface. (510 nm)

Part 2: Understanding the Poisson Nature of Photons with a Pulsed Source – single SPAD vs. SiPM and "Hand Diagram"

15) On the SPAD23 interface, navigate to the "Timestamping" section. Set your integration time to 1 second (1'000 ms). Choose "Calibrate" from the TDC settings and run. Then, choose "Align pixels" and run.
16) Choose "SPAD input" as the TDC setting. Run a measurement to acquire **raw** timestamps. The data will be saved to the "SPAD23_standalone_win64/data/tdc" folder. Delete the text file named "pix23.txt".
17) In order to calculate the histogram of events per period for a single pixel, run "T4_Part2_1" code. It will process the data and give you the "hh" variable which is similar to the practice data.
18) By using the code you prepared in advance, plot the histogram in log scale. Comment on the plot. For an integration time of 1s, what should the total number of non-zero events correspond to? Considering the laser period and SPAD dead-time, what should be the maximum number of events you can observe from a single pixel?
19) Normalize the histogram to calculate the probability distribution of events by dividing it by the total number of events.
20) Estimate the distribution.

- Make a Gaussian fit to the probability distribution.

- Calculate the expected value of the probability distribution and use it as the average of a Poissonian distribution.
- Calculate the mean number of events by dividing the count rate of the pixel with the laser frequency and use it as the mean of a Poissonian distribution.

21) Plot all the curves you calculated at the previous step together with the probability distribution (as bars) on both linear and log scales.
22) Comment on the plot. Which distribution explains best the probability distribution and why? Explain the possible reasons for any mismatch.

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23) Acquire raw data at higher count rates. After each measurement delete the text file named “pix23.txt”.

    Run a raw timestamp measurement for approximately 60 kcps and 150-200 kcps per pixel. Set the count rates by changing your ND filter to ND3+ND0.3 and ND3, respectively. Don’t forget to take note of total count rate from SPAD23 interface. (510 nm)
24) **In the previous steps, the probability distribution is plotted for a single pixel. Now, you will consider the SPAD23 as an SiPM**, and calculate a histogram which includes the detection events of all pixels simultaneously.
25) For each raw timestamp data you acquired (including the one at Step 12), run “T4_Part2_2” code to calculate the histogram of the number of events for all pixels.
26) Normalize the histogram to the calculate probability distribution of events by dividing it by the total number of events for each measurement.
27) Estimate the distribution of each measurement.

- Make a Gaussian fit to the probability distribution.
- Calculate the expected value of the probability distribution and use it as the average of a Poissonian distribution.
- Calculate the mean number of events by dividing the total count rate of SPAD23 with laser frequency and use it as the mean of a Poissonian distribution.

28) Plot all the curves you calculated at the previous step together with the probability distribution (as bars) on both linear and log scales for each measurement.

29) Comment on the plot. Which distribution explains best the probability distribution and why? Which quantity will you use to measure the quality of the fitting? Explain the possible reasons for any mismatch. Considering the laser period and SPAD dead-time, what should be the maximum number of events you can observe in total?

Part 3: Estimation of Photo-Response Uniformity with a Pulsed Source

30) In this part of the experiment, you will utilize the same setup, and will perform photon counting measurements under different incident photon power.

31) Insert a combination of ND4 and ND0.5 (ND4+ND0.5) filters between the mirror and the module. (510 nm)

32) On the SPAD23 interface, navigate to the "Photoncounting" section.

33) Set your integration time to 1'000 ms.

34) Run the measurement. The data will be saved to the "SPAD23_standalone_win64/data/counters" folder.

35) In order to sweep the power, perform the same measurement:
With ND4, ND3+ND0.5, ND3. (510 nm)

36) Modify the provided "T4_Part3" Matlab code to read the generated text files. Also, in the code, exclude your hot pixels from the "mean" and "std" functions.

37) Run the code to obtain the graphs. Analyze the "Figure 1" (no need to print this figure). What can you say about the photo-response uniformity of your SPAD23 module?

38) Observe the "Figure 2" (and print it). Comment on both curves depicted. What do they represent? Which one is the ideal condition for a detector array? Do you think that your detector module has a uniform photo-response? What could be the possible reasons for deviation from the ideal detector performance?

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39) (Optional) Refer to reference 2, and note the photon detection probability (PDP) corresponding to your laser wavelength, and the area of one pixel. By using the

mean photon count rate you obtained in any of the above measurements, calculate the irradiance per unit area for a pixel. Use the ideal attenuation rates for filters and diffusers from the datasheet.