MICRO-429: Metrology Practicals

T3- Dark count rate (DCR) and afterpulsing statistics in photon-counting devices

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Objective:

- Understanding single-photon avalanche diodes (SPADs) & photon counting
- DCR vs. (excess) bias voltage
- Inter-arrival statistics, dead time, and afterpulsing

Reading & reference material:

- Read reference [1] for 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] to understand the afterpulsing phenomena and estimate the dead time of a SPAD
- 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 laptop

Methodology:

- Power up the SPAD23™ module, set up the user interface, and explore the different display and data acquisition options in the dark and when exposed to (dim) light.
  - ★ Use the counter option from the interface and measure DCR.
  - ★ Modify the Matlab code to do DCR measurements.

★ Write a piece of Matlab code to record inter-arrival times, estimate dead time and measure the afterpulsing probability.

- 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] M. Hofbauer, B. Steindl, and H. Zimmermann, "Temperature dependence of dark count rate and afterpulsing of a single-photon avalanche diode with an integrated active quenching circuit in 0.35 μm CMOS." Journal of Sensors, (2018).

Theoretical Background – Afterpulsing:

During the avalanche process, a huge number of carriers flow through the device. Some of these carriers can be captured by the deep-level traps existing in the material. Depending on their lifetime, trapped carriers can ignite additional avalanche processes after releasing. This phenomenon is known as afterpulsing, which is a type of correlated noise.

There are multiple ways of measuring the afterpulsing probability of SPAD devices. In this experiment, you will learn and implement the inter-arrival time histogram method, which relies on extracting correlations between the rising edge of the time of avalanches. Please read Refs. 1 and 3 to learn more about utilizing this technique.

With the piece of Matlab code you will insert, a similar curve will be obtained as provided in Figure 1. Then, a fitting procedure should be performed, which will represent the inter-avalanche time behavior according to Poisson statistics in case of no afterpulsing. Finally, the afterpulsing probability (APP) will be defined/calculated as the area between the experimental data and the exponential fit curve divided by the total area under the experimental data.

$$APP\ (\%) = \frac{Area\ Between\ Blue\ and\ Green\ Curve}{Area\ Under\ Blue\ Curve} \times 100$$

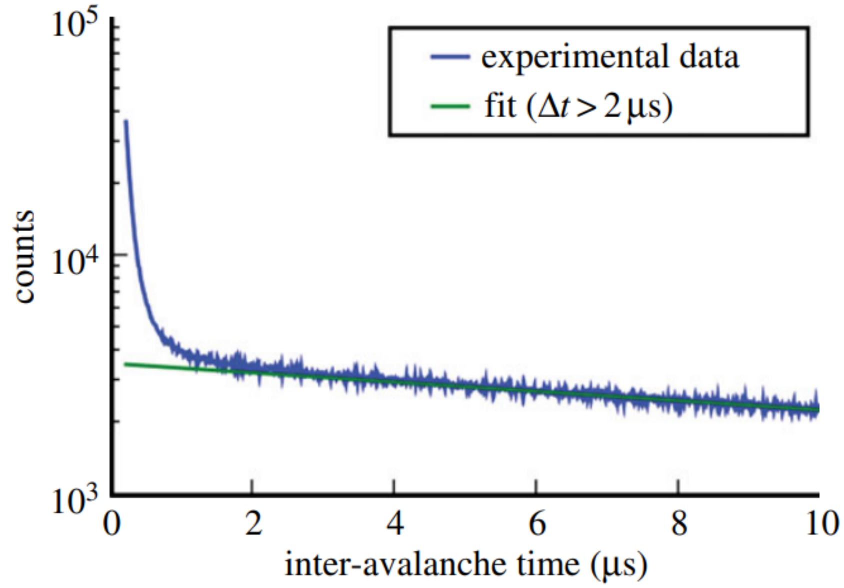


Figure 1: A histogram of inter-avalanche arrival times, along with an exponential fit.

Methodology:

Part 0: Preparation (*before the practical*)

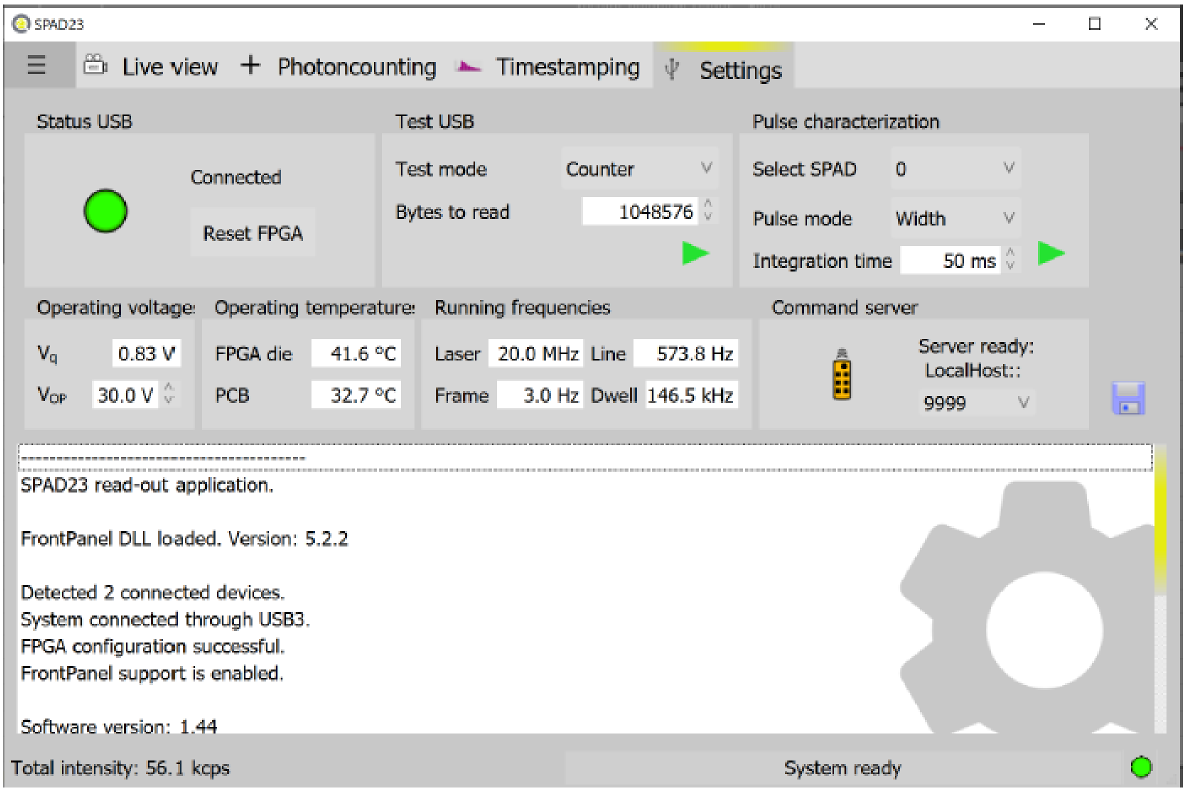
1) In the folder “Practice data/Part2”, you will find “msgvals.mat”. It should be used to prepare your code for “Part 2: DCR Measurement – Matlab” section. “msgvals.mat” contains pixel numbers in the first row and the number of counts corresponding to each pixel in the second row.
2) Edit the “T3_Part2_SC” code such that the count rate could be measured for different voltages, integration times, and the number of iterations. Refer to the comments in the code and related steps of this document for the required modifications.
3) In the folder “Practice data/Part3”, you will find “Histogram_Practice.mat” and “Pulse_Dist_Text_Practice.zip”. “Histogram_Practice.mat” contains the "time" variable, which represents the inter-arrival time bins, whereas "counts_tot" is the total number of counts corresponding to each inter-arrival time bin. Plot the total number of counts with respect to the inter-arrival times and calculate the afterpulsing probability as explained in the *Theoretical Background* section.

- NB: “Pulse_Dist_Text_Practice.zip” contains examples of the original raw data files (in text format) generated by the sensor. They have already been imported by the provided Matlab routines and are provided only for your reference.

4) Edit the “T3_Part3_SC” code such that a pulse distance measurement can be acquired for 2’000 times.

Part 1: DCR Measurement – User Interface

5) Place the SPAD23™ unit inside the black box.
6) Connect the power cable of the SPAD23™ unit to a power plug.
7) Connect the data cable of the SPAD23™ unit to the computer.
8) Close the lid of the black box before moving on to the DCR measurements.
9) 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:



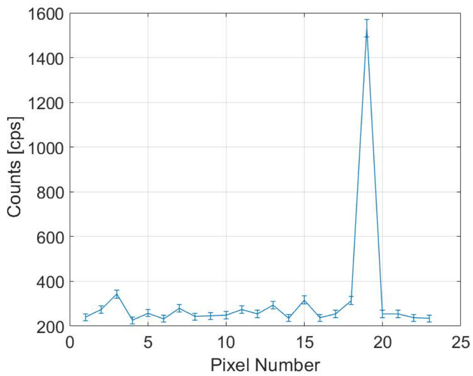
10) Check the “Operating voltages” sub-section, and take note of the “Vop” voltage (bias voltage).

11) Go to the “Live View” tab on the interface, and observe the counts of each pixel. Determine and note hot pixels if there are any.
12) Go to the “Photoncounting” tab on the interface. You will run a classical DCR measurement with an integration time of your choice (specified in ms), and save your data. Saved data can be seen in the data/counters sub-folder. This folder contains the dark count rate of each pixel. The DCR of pixel is usually higher.
13) Repeat step 12 for 2 other “Vop” voltages. Vop voltage can be set in the range 26.0 - 31.5 V.
14) Comment on a) the DCR and distribution of the hot pixels, b) the trend of DCR with respect to the operating voltage.

Part 2: DCR Measurement – Matlab

15) Perform a count rate measurement. Run the code “T3_Part2_SC” such that your operating voltage and integration time are set as 30.0 V and 500 ms, respectively.

16) Plot DCR vs. pixel number and verify that the results obtained with the user interface and Matlab are similar. Add error bars assuming a Poissonian process.



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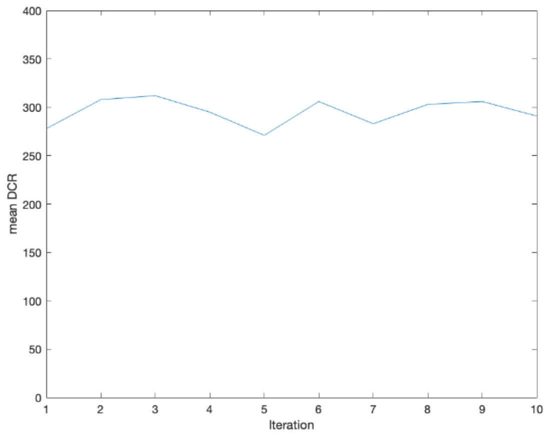
17) Run the code “T3_Part2_SC” to repeat the DCR measurement 10 times for the same operating voltage and integration time. For each iteration, calculate the mean DCR of all pixels, including and excluding hot pixels. Then you can get a plot with mean DCRs versus iterations.

NB: from now on, exclude hot pixels from the calculation of the mean values.



18) Calculate the standard deviation of the previous mean DCR measurements.

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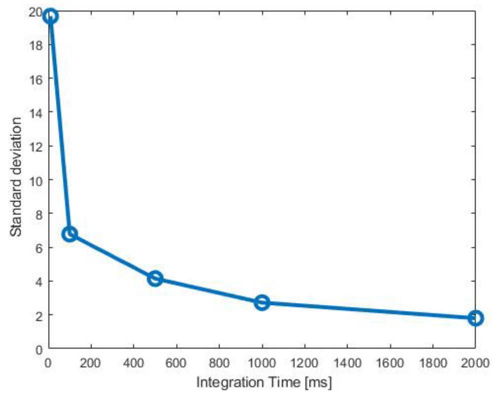
19)Run the code "T3_Part2_SC" to also sweep the integration time (10 ms to 2000 ms) such that the mean DCR is measured 10 times for each selected integration time.

20)Calculate and plot the standard deviation of the mean DCR for each integration time.



21)Comment on the result.

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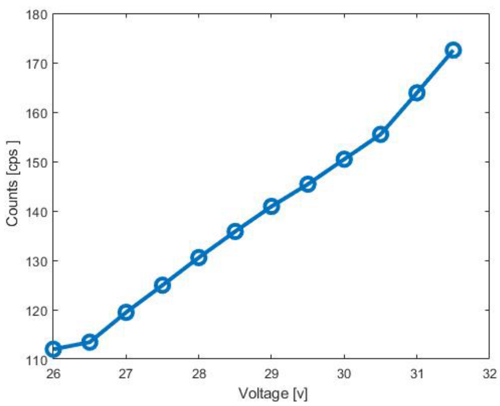
22)Set the integration time based on the previous result and justify your choice.

23)Modify the code such that the number of counts is measured for different Vops (26 - 31.5 V with 0.5 V step) 10 times.

24)Plot mean DCR vs. Vop.



25)Compare the DCR vs. bias voltage trend you observe with the one in Step 13-14. Explain why the DCR has such a behavior.

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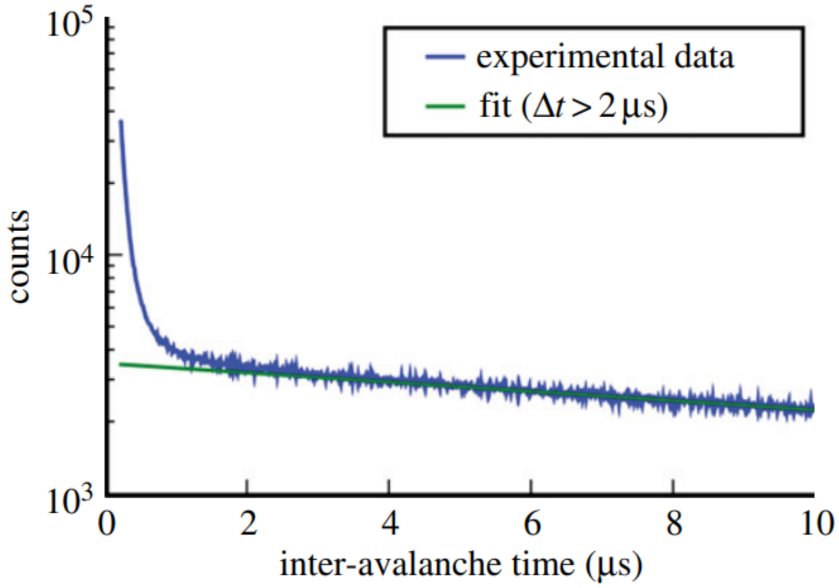
Part 3: Afterpulsing Probability Measurement

NB: Turn on the lamp. Before removing the device cap, make sure Vop is disabled to avoid saturation.

26) In order to perform afterpulsing analysis, first set the Vop to 31.5 V on the interface, and then, use the code “T3_Part3_SC” to perform inter-arrival time measurements (corresponding to the *pulse distance measurements* in the manual). In the code, set the integration time to 80 ms (maximum), set the number of repetitions to at least 2’000, and select a hot pixel.
27) Run the related sections of “T3_Part3_SC” code on the selected hot pixel such that count rate is ~50k cps due to illumination. Then the text files are saved at SPAD23_standalone_win64/data/.
28) This measurement data will be saved to the data/debug sub-folder as text files. The left column of the histograms shows the time interval (in ns) between subsequent pulses, and the right column shows the number of counts. Analyze some of these text files to understand what they represent.
29) Run the related sections “T3_Part3_SC” code to import the data contained in all of the generated text files.
30) Plot the total number of counts vs. pulse distance time in log scale (see Figure 1).
31) Compare the behavior of the curve with what expected from theory.
32) Estimate the SPAD dead time.
33) Calculate the afterpulsing probability in percentage. While doing that, you can remove the outliers at the beginning and end of the histogram.



34)Cut the text files from .../data/debug folder and paste them into another folder.

35)Repeat steps 27-34 for a regular pixel (not a hot one) under the same illumination conditions. Compare the results and comment.

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36)(Optional) Change the Vop to 27 V and repeat steps 27-34 for both the selected hot and regular pixel.
