SPAD Measurements

Eduardo Barroso[1] Eikin Kisilkan[2]

[1] *École Polytechnique Fédérale de Lausanne (EPFL)*
[2] *Novoviz*

Abstract

This report documents the experimental setup for the characterization of Single Photon Avalanche Diodes (SPADs). The objectives are to measure the timing jitter of the detectors and to perform coincidence detection experiments. Measurements are conducted using a femtosecond pulsed laser and a continuous-wave pseudothermal light source. This document outlines the hardware configuration, optical pathways, and data acquisition parameters required for the lab session.

Introduction

Characterization of single photon avalanche diodes (SPAD) is a practice that consists on experimentaly quantifying its four main performance indicators known as: jitter, photon detection probability (PDP), dark count rate (DCR) and deadtime. This is done with multiple techiques such as retroluminecence [?], microscopic techniques [?], and Time-Correlated single photon counting (TCSPC).

This Lab-Report is focused on measuring SPAD's performance indicators through a series of TCSPC experiments using different light sources. The goal is to report the temporal response of integrated SPAD detectors together with the statistical properties of the light sources.

0.1 Timing SPAD Detector Response Function: Jitter

A photon incident of the active area of a SPAD detector, triggers an avalanche of charge carriers creating a current signal. The current is later detected and converted to a digital signal; typicaly within less than $100ps$. This temporal delay between the time of photon arrival and signal detection is called jitter.

Timing jitter is quantified by measuring delay Δt between the emission of a LASER pulse (recorded by a Laser Clock), and the detection signal from the SPAD. Accumulating these events in a histogram it is possible to extract the instrument response function (IRF). The jitter is then reported as the Full Width at Half Maximum (FWHM) of this distribution.

Detection Probabilities (Pulsed Source)

A pulsed LASER can be described by its repetition rate f_{rep}. Thus, a total number of pulses N_{pulses} in an exposure time t_{exp}, is given by $N_{pulses} = f_{rep} \times t_{exp}$. If a SPAD registers C_A total counts during this exposure, the average probability of detecting a photon per pulse is:

$$P_A = \frac{C_A}{N_{pulses}} = \frac{R_A}{f_{rep}} \tag{1}$$

where $R_A = C_A/T_{exp}$ is the average count rate in counts per second (cps). P_A also known as Photon Detection Probability (PDP), is typically < 0.05.

Statistical Properties of Light

Second Order Coherence $g^{(2)}$

The second order correlation function $g^{(2)}$ quantifies intensity correlations, photon statistics and time separated probability of detecting two photons. A value for $g^{(2)} < 1$, is an indicator of antibuching; a quantum characteristic of the respective light source.

Experimentally – for a pulsed LASER setup, $g^{(2)}$ can be calculated using:

$$g^{(2)}(0) = \frac{P_{AB}}{P_A P_B} = \frac{C_{AB} \cdot f_{rep}}{R_A R_B T_{exp}} \quad (2)$$

For an ideal coherent state (Poissonian statistics), $g^{(2)}(0) = 1$.

For the CW LASER and rotating diffuser setup, the delay τ is continuous. The normalized coincidence rate across a bin width $\Delta\tau$ is:

$$g^{(2)}(\tau) = \frac{C_{AB}(\tau)}{R_A R_B \Delta\tau T_{exp}}$$

True thermal light exhibits photon bunching. As the delay approaches zero, the statistics shift from Poissonian to Bose-Einstein, yielding a theoretical limit of:

$$g^{(2)}(0) = 2$$

The decay of $g^{(2)}(\tau)$ back to 1 as τ increases maps the coherence time (τ_c) of the pseudothermal source, which is strictly governed by the rotational speed of the optical diffuser.

Equipment and Materials

LASER and Light Sources

- Pulsed LASER
  - **NKT Photonics**
  - Model: [Origami XP / Origami HP] (Femtosecond)
  - Wavelength: [ ] nm (e.g., 1030 nm or 515 nm)
  - Pulse Duration: [ ] fs
  - Repetition Rate: 50 MHz
- **Continuous Wave (CW) LASER**
  - Brand / Model: [ ]
  - Wavelength: [ ] nm
  - Operating Power: [ ] mW
- **Pseudothermal Light Simulator**
  - Components: Rotating ground glass diffuser and pinhole aperture.
  - Diffuser Motor Speed / Coherence Time: [ ] ms

Timing Electronics

- Swabian Instruments Time Tagger
  - Connection: USB 3.0
  - Max Data Transfer Rate: 90 MTags/s
  - Max Input Frequency: 475 MHz
  - Dead Time: 2.1 ns
  - Base Jitter: 42 ps RMS (100 ps FWHM)
  - Physical Inputs: 4 (50 Ω impedance)
  - Trigger Level Range: -2.5 V to +2.5 V
- **Fast Photodiode (Laser Clock)**
  - Brand / Model: [ ]
  - Function: Generates the 50 MHz electrical clock signal from the pulsed laser.
  - Bandwidth / Rise Time: [ ] GHz / [ ] ps

Detectors and Optical Components

- **Single Photon Avalanche Diodes (SPADs)**
  - Brand / Model: [ ]
  - Active Area: [ ] μm
- **Neutral Density (ND) Filters**
  - Optical Density (OD) values applied: [ ]
- **Connectivity**
  - Type: High-bandwidth SMA Cables
  - Impedance: 50 Ω

Instrument Response Function and Timing Jitter

To establish the baseline temporal resolution of the detection system, the intrinsic timing jitter is measured using a synchronized start-stop protocol.

1. **Optical Setup:** The 50 MHz femtosecond laser is heavily attenuated using Neutral Density (ND) filters. The attenuation is tuned such that the SPAD detection probability remains strictly under 5% per pulse to prevent pile-up distortion.

2. **Electronic Routing:** The synchronization clock (fast photodiode) is routed to Channel 1 of the Time Tagger. The SPAD output is routed to Channel 2.

3. **Data Acquisition:** A continuous correlation measurement is executed between Channel 1 (Start) and Channel 2 (Stop) over a defined exposure time, accumulating a delay histogram.

4. **Analysis:** The resulting peak is fitted with a Gaussian distribution. The Full Width at Half Maximum (FWHM) of this peak defines the total system jitter (comprising the laser pulse width, SPAD jitter, and the 42 ps intrinsic jitter of the Swabian Time Tagger).

Pulsed Coincidence and $g^{(2)}$ Statistics

With the temporal boundaries defined, the setup is expanded to evaluate the second-order correlation and multi-photon events.

1. **Optical Setup:** The attenuated pulsed beam is split using a 50:50 beamsplitter and directed into multiple SPAD pixels.

2. **Coincidence Window Definition:** The temporal coincidence window (Δt_c) is strictly defined based on the Phase 1 results, typically set to 2σ or 3σ of the measured system jitter to ensure genuine coincidences while rejecting background dark counts.

3. **Data Acquisition:** Time tags are continuously streamed. The hardware clock remains on Channel 1, while SPAD pixels are routed to Channels 2, 3, and 4.

4. **Statistical Processing:**

    - **Probabilities:** Independent count rates for each channel are extracted to calculate the per-pulse detection probability (P_A, P_B).
    - **Second-Order Coherence:** The discrete cross-correlation between channels is computed to extract the experimental $g^{(2)}(0)$ value, verifying the Poissonian nature of the source.
    - **Multi-Fold Coincidences:** A coincidence matrix is generated to identify 2-fold, 3-fold, and 4-fold simultaneous detection events across the pixel array.

5. **Hardware Verification:** The externally tagged coincidences from the Swabian instrument are cross-referenced against the on-chip coincidence counting logic of the Novoviz SPAD module to validate the payload's internal processing fidelity.

Conclusion

References

[Einstein, 1905] Einstein, A. (1905). On the electrodynamics of moving bodies. *Annalen der Physik*, 17:891–921.