Simulation modelling for the analysis and the optimal design of SPAD detectors for time-resolved fluorescence measurements

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Typical fluorescence measurement setup

- The photodetector determines the accuracy of the measurements.
- General performance of measurement setup are defined by all part: from light source to software.
The simulation model consists of a set of independent blocks, each of them simulates an appropriate part of the experiment.

Optimization algorithm provides an opportunity to fit SPAD and experimental setup parameters to achieve the optimal system performance.
Simulation workflow

1. **Light source**
   - Duration of experiment
   - Repetition rate
   - Time and frequency characteristics

2. **Fluorescence sample**
   - Emis. spectrum
   - Ext. coefficient
   - Quantum yield
   - Lifetime
   - Concentration

3. **Filter simulation**
   - Transfer function

4. **Read-out circuit**
   - Afterpulsing probability
   - DCR

5. **SPAD**
   - Time response
   - Dead time
   - PDP
Simulation workflow

**Light source**

- Duration of experiment
- Repetition rate

**Fluorescence sample**

- Emis. spectrum
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**Filter simulation**

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**SPAD**

- Time response
- Dead time
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- PDP

Light spectrum

- FWHM
- Wavelength in nm

Power

Time in ns

FWHM
Simulation workflow

Assumptions:
- the light absorption obeys the Beer-Lambert law;
- fluorophores have uniform distribution;
- the optical density of the fluorescent sample is negligible;
- fluorescence decay is monoexponential;
- there are no other processes influencing light emission except fluorescence.

\[ t^* = t + (-\tau \ln z) \]
Simulation workflow

Fluorescence spectrum

Filter transfer function

Power

Wavelength in nm

Probability

Wavelength

Power in rel. units

Time in nanoseconds

Extinction coefficient

Quantum yield

Lifetime

Concentration

Simulation function

Filter simulation

Probability

Wavelength in nm

SPAD
Simulation workflow

Photon detection probability

Afterpulsing probability density

DCR

Dead time

Transfer function

Filter simulation

Read-out

SPAD

Afterpulsing probability

Time response

DCR

P*** t, λ

P** t, λ

Time response

Dead time

PDP
Simulation workflow

Light Intensity

LASER
Fluorescence Decay
Observation Window N
Observation Window N+1

Quantum yield
Lifetime
Concentration

Filter simulation

P_{t, \lambda}^*

Read-out circuit

SPAD

P_{t, \lambda}^{***}

Afterpulsing probability
DCR

Time response
Dead time
PDP

Time in ns

Power in con. un.

0 10 20 30 40 50

1 10 100 1000 10000 100000
Simulation results

- The practical and simulated laser pulses (Picoquant LDH-P-C-470 pulsed diode laser with 80-ps FWHM)

- Fluorescence decay simulated and measured with SPAD (time-gated technique with 10ns observation window and 60ps shift)

![Graph showing measured and simulated counts over time](image1)

- Measured
- Simulated

![Graph showing measured and simulated power over time](image2)

- Experimental lifetime = 16.21 ns
- Simulated lifetime = 16.39 ns

![Graph showing time in nanoseconds](image3)
Future work

- Further improvement of SPAD simulation
  - Geometry
  - Effects related to passive quenching
  - Temperature dependence

- Including additional setup characteristics
  - Light source intensity
  - Optical lenses

- Implementation of optimization algorithm
Thank you Questions?