Single-Measurement Characterization of SPAD Recovery and After-Pulsing Dynamics Using a Non-Homogeneous Poisson Process Model

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We introduce a method that allows the extraction of a wide variety of detector properties, including non-instantaneous recovery and after-pulsing, from a single measured inter-detection interval histogram of free-running single-photon avalanche diodes (SPADs). Our approach is based on non-homogeneous Poisson processes and works with continuous illumination over several orders of magnitude of incident photon rates, without the need for pulsed lasers or synchronized gating.

The general model is defined by the time-dependent rate of avalanches $\lambda(t)$, where we set the time $t = 0$ at the end of the SPAD dead-time τ_d. This function directly yields the probability density function $p(t) = \lambda(t)\,\exp\left(-\int_0^t \lambda(s)\,\mathrm{d}s\right)$ that describes the inter-detection interval distribution.

In a previous work [1], we used this framework to describe the non-instantaneous exponential recovery (characterized by the time constant τ_r) of the photon detection efficiency (PDE) following dead-time, demonstrating excellent agreement with experimental data and stable fits for incident photon rates covering more than three orders of magnitude.

Here, we extend this framework to also include after-pulsing with multiple charge carrier trap types [2]. An example model fit for $n = 2$ trap types is shown in Fig. 1, using

$$\lambda(t) = \left(R_\mathrm{dc} + R_\mathrm{i}\eta_0 + \sum_{k=1}^{n} \frac{N_k}{\tau_k}\, e^{-(t+\tau_\mathrm{d})/\tau_k}\right) \times \left(1 - e^{-t/\tau_\mathrm{r}}\right)\,, \tag{1}$$

where R_dc is the dark-count rate, R_i is the incident photon-rate, N_k (τ_k) is the average number of excitations (decay time constant) for traps of type k, and η_0 is the zero-flux PDE. Our approach offers a practical alternative to conventional pulsed-laser characterization methods, enabling detailed SPAD analysis using only continuous-wave illumination.

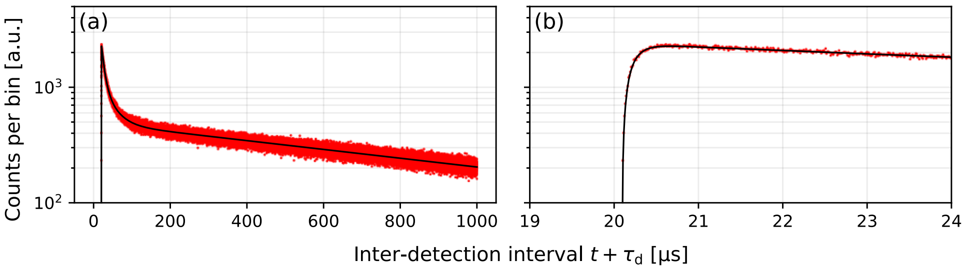

Fig. 1: *The model from Eq. (1) was fitted to the dark counts measured for a commercial InGaAs SPAD (ID Quantique, IDQube) with 20% PDE and 20µs dead-time, operated at* $-40°C$*, yielding* $R_\mathrm{dc} = 861.2(2)\mathrm{Hz}$*,* $\tau_\mathrm{d} = 20.09\mu\mathrm{s}$*,* $\tau_\mathrm{r} = 119.7(8)\mathrm{ns}$*,* $N_1 = 0.1983(9)$*,* $\tau_1 = 8.47(4)\mu\mathrm{s}$*,* $N_2 = 0.0636(5)$*,* $\tau_2 = 31.8(2)\mu\mathrm{s}$*. Panel (b) is a zoom-in on the rising slope from panel (a).*

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References

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