Simplified Model for a Single-Photon Detector Module

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Abstract—**In this work we propose a model for a Single-Photon Detector Module (SPDM), with an InGaAs/InP avalanche photodiode, to obtain the detection efficiency and to quantify the noise generated inside the detector, providing one important tool to increase the measurements accuracy.**

Index Terms— **Avalanche photodiodes, Infrared detectors, Optical communication.**

I. Introduction

The knowledge of the exact value for a photodetector efficiency, is essential to transmit confidence in the measurements. Normally the detector's manufacturer provides an efficiency value, which normally is the quantum efficiency, that is the probability for incident photon to be detected. The detection efficiency is related with several other factors, such as; optical coupling efficiency between the optical fibre and the active area of the detector; the photon absorption probability; the operation temperature; the working wavelength and, in the case of a SPDM (Single-Photon Detector Module) based on avalanche photodiodes (APD's), the probability that a photogenerated carrier triggers an avalanche when crossing the multiplication region. Another parameter that is essential to quantify is the noise generated inside the detector. In a SPDM, normally, this quantity is expressed by the value of its dark counts. In a APD, the avalanche can be triggered by an impinging photon, by randomly thermally generated carriers or by trapped charges during a previous avalanche by trap levels inside the high level field region of the junction. When the trapped carriers are released they can trigger a so-called after-pulse. Because the life time of the trapped charges is typically a few microseconds, if the frequency of the APD is limited to a few MHz it is possible to minimize the dark counts arising from this factor. Cooling the detector will also reduce the dark counts related with the thermally generated carriers and improve the detectors performance [1].

The APD principle of working is the following. If a photon is absorbed in the active region it generates a carrier who is accelerated, by a strong electric field, through the junction, this way, only one carrier is capable to generate an avalanche of carriers by impact ionization. This avalanche induces a macroscopic current that must be controlled in order to not destroy the device. Working in a 'gated mode' we can control the avalanches, the electric field will only be applied when the gate is 'open', and safely operate the device. The detector is 'blind' to the arrival of one or more photons per gate, an avalanche can be triggered by more than one photon and when it starts it only ends when the gate closes. If an avalanche occur in a gate, there will be an electric pulse at the detectors output. It is possible to obtain the average number of photons per gate by statistical methods. This way quantifying the detection efficiency is essential, in order to measure, precisely as possible, the average number of photons per pulse of a modulated optical signal.

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II. Experimental

A tuneable laser, NetTest Tunics Source, was used in order to produce a 1550nm optical signal in continuous mode and one optical attenuator was used to reduce the optical power. We also use a second optical attenuator, JSD Fitel, in witch we could control, and measure, some extra attenuation, this way we were able to obtain a reduced optical power (less then -110dBm) at the detector's entrance. The signal optical power was measured with an Advantest Q8384 Optical Spectrum Analyser. Next we measured the photons counting with the SPDM (id200 from Id Quantique), for several optical powers and gate periods. The SPDM internal trigger, set to a frequency of 100kHz, was used. The measured detection probability (fig.1) is the ratio between the counting value and the number of gates open per second. We made measurements for the five, different time duration, gates available; 2.5ns, 5ns, 20ns, 50ns and 100ns.

III. Theoretical Model

We assume that the photon counting fluctuations follows a Poisson probability distribution law that is given by:

$$P_r(n,T) = \frac{(\lambda T)^n e^{-\lambda T}}{n!} \tag{1}$$

where P_r is the probability of detecting an average number of photons, n, in the interval T. The probability of do not detect any photon, (n=0), during a time interval T. Time period during witch the gate is open, will be:

$$P_r(n=0,T)=e^{-\lambda T} \tag{2}$$

This way, the probability of detecting any number of photons in that time interval is:

$$P_r(n\neq 0,T)=1-e^{-\lambda T} \tag{3}$$

Assuming that:

$$nE=\lambda T=\frac{P}{h\nu}T \tag{4}$$

Then,

$$P_r(n\neq 0,T)=1-e^{-\frac{P}{h\nu}T} \tag{5}$$

E is the energy, h the Planck's constant and ν the incident photons frequency. But we must have in mind that, due to several effects inside the detector, like said before, there are dark counts. Then the total optical power, P, will be given by:

$$P=\eta\times P_{in}+P_N \tag{6}$$

Were η is the detector's efficiency, P_{in} the optical power at the detector entrance and P_N is an optical power correlated with the dark counts. This way, adjusting this model with the experimental data of $P_r(t)$ as a function of P_{in}, it is possible to obtain η and P_N, for the detection system. Replacing expression (6) in expression (5), we get:

$$P_r(n\neq 0,T)=1-e^{-\frac{\eta\times P_{in}+P_N}{h\nu}T} \tag{7}$$

In order to simplify we can work expression (7), and by this way obtain:

$$-\frac{h\nu}{t}\ln\left[1-P_r(n\neq 0,T)\right]=\eta\times P_{in}+P_N \tag{8}$$

Representing $\left[-\frac{h\nu}{t}\ln\left[1-P_r(n\neq 0,T)\right]\right]$ as a function of P_{in} (fig. 2), we can obtain η and P_N (Table I) by a simple linear regression.

IV. Results and Discussion

The comparison between experimental and theoretical results is shown in figs 1 and 2.

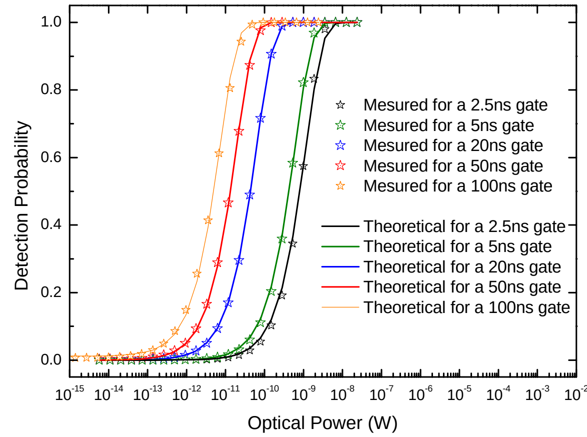

Fig.1. Measured detection probability, and calculated by expression (7), as function of the optical power for several gate periods.

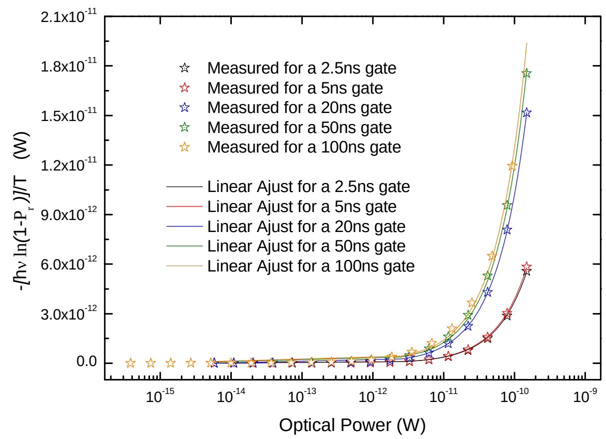

Fig. 2: Fitting of the experimental data with expression (8).

TABLE I
ESTIMATED PARAMETERS VALUES

Gate (ns)	***η (%)***	***P_N (W)***
2.5	3.71±0.08	4.91×10^{-92}
5	3.89±0.02	9.98×10^{-33}
20	10.20±0.01	4.28×10^{-15}
50	11.86±0.08	7.61×10^{-14}
100	12.94±0.02	1.11×10^{-13}

V. Conclusion

We have obtained an accurate model witch allows us to predict the detection efficiency of one SPDM and also the quantification the generated noise.

References

[1] Id Quantique, "Single-Photon Detector Module, Application Note v4.5" Carouge Switzerland, 2004, unpublished.