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A simple method for afterpulse probability measurement in high-speed single-photon detectors

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HIGHLIGHTS

- A simple and fast method for afterpulse probability measurement is proposed.
- Theory and implementation of the in-laser-period counting method are presented.
- The proposed method is verified on a 1.25-GHz single-photon detector.
- Comparisons among the proposed method and common methods are presented.
- Accuracy and error analyses are provided.

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ABSTRACT

A simple statistical method is proposed for afterpulse probability measurement in high-speed single-photon detectors. The method is based on in-laser-period counting without the support of time-correlated information or delay adjustment, and is readily implemented with commercially available logic devices. We present comparisons among the proposed method and commonly used methods which use the time-correlated single-photon counter or the gated counter, based on a 1.25-GHz gated infrared single-photon detector. Results show that this in-laser-period counting method has similar accuracy to the commonly used methods with extra simplicity, robustness, and faster measuring speed.

1. Introduction

Infrared single-photon detectors (SPDs) based on InGaAs/InP single-photon avalanche diodes (SPADs) have been largely improved in the recent years. The SPAD is a special type of avalanche photodiodes (APDs) which operate with a bias voltage above the breakdown voltage, that is, in "Geiger mode" [1]. The SPAD running in Geiger mode should be quenched when an avalanche is triggered. Recently, a self-quenched avalanche quantum dot infrared photodetector (AQDIP) which does not require external quenching circuits was developed by Zavvari and Ahmadi [2] for mid-infrared single-photon detection, and this self-quenching technique is probably applied to AQDIPs for near infrared and long-wave infrared detection [3]. As for the SPAD, the gated passive quenching circuit (GPQC) [4] is an excellent approach to quench the SPAD. Since the gating frequency is as high as several GHz and the amplitude of the gating signal is large (i.e. more than 10 $V_{p\text{-}p}$), high-speed operation and high detection efficiency are achieved in InGaAs/InP SPDs [5,6], and hence their application in quantum key distribution (QKD) systems [7] is promoted.

However, high dark count rate and severe afterpulse effect are still their main drawbacks [5,6,8] compared to superconducting nanowire SPDs [9]. Different from HgCdTe electron-APDs whose dominant component of dark current is band-to-band tunneling [10], the dark counts of InGaAs/InP SPADs are mainly dominated by trap-assisted tunneling, especially when the excess bias voltage is high [11]. Moreover, the traps bring not only more dark counts, but also severe afterpulsing effects. When evaluating the key performance of the SPD, it is easy to measure dark count rate with general counters, but afterpulse probability is relatively complicated to be estimated [8].

One kind of popular methods for afterpulse probability measurement is based on the time-correlated single photon counting technique. Generally, devices used for this approach include the time-correlated single-photon counter (TCSPC) [12] and the

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multi-channel scalar (MCS) [13,14]. These devices are designed to precisely record the time when the avalanche occurs referred to a sync signal of the photon source. Dark counts, photon-induced counts, afterpulse counts, and their timing information are obtained from the recorded time tags, and hence the afterpulse probability can be demonstrated with the statistics [12–14]. Comprehensive characterizations of afterpulsing effects were presented with the support of time-correlated data. Power law [15,16] and Sinhc law [16] dependence of afterpulsing were discovered, and exponential law at short delays and low temperatures was supplemented later [17]. The de-trapping times of the trapped carriers were also investigated [18]. Moreover, the characterization and modeling of afterpulsing effects could even be done merely with time-correlated dark-count data [19,20]. However, when using the TCSPC or the MCS, attentions should be paid on the following two points. Firstly, as the count rate of a state-of-the-art high-speed SPD can be up to 500-MHz [5], TCSPCs or MCSs with low dead time should be adopted to avoid missing events; otherwise it may cause inaccurate results [5,6]. Secondly, the processing of such a large data set is off-line and time-consuming.

Another kind of commonly used methods is based on the gated counting technique, using gated counters [6,22]. Instead of recording the time-correlated information of avalanche pulses, the gated counter counts the avalanche pulses corresponding to the gate into which the incident photons fall. In this way, photon counts and non-photon counts can be discriminated, and one can measure the increase of non-photon-count events in non-illuminated gates to estimate afterpulse probability [6]. When using gated counters, the delay of the laser trigger signal and the gate width should be adjusted carefully because of the timing jitter and the environmental variance of the system, especially in long-distance experiments for QKD systems [23]. Improvements have been made to simplify the afterpulsing measurement using the gated counter by Yen et al. [8] through varying the detection gate width, so that non-illuminated gates are not required, but this method is not applicable to high-speed SPDs with GHz gating frequency.

In addition, there are methods which do not require discrimination of photon and non-photon counts. A method proposed by Zhang et al. [24] uses the Poisson distribution of the photon-count and dark-count events, which is deduced from a method by Campbell [25] for afterpulse probability measurement in photo-multiplier tubes. In this method, the results were dependent to the incident light intensity, which affects the accuracy of the measurement. Recently, a method proposed by Tzou et al. [26] made use of the distribution of only dark counts. It is very easy to implement this method, though the actual afterpulse probability should be small enough (<20%) in practical use. Besides, Jiang et al. [27] presented an interesting method to extract the de-trapping times through varying the intensity of the photon flux in a free-running SPD, but the total afterpulse probability was not provided.

In this paper, we propose a simple statistical method to estimate afterpulse probability in high-speed SPDs using a counter which we call the in-laser-period counter. This method eliminates the need of discrimination of photon and non-photon counts, and it does not require complicated data processing, which makes it extremely suitable to be integrated into the single-photon detector for on-line performance monitoring. The theory of the method is described in Section 2. In order to verify the proposed method, we present a comparison among methods using a low-dead-time TCSPC, a gated counter, and an in-laser-period counter. The results of different methods are obtained through varying the excess bias voltage of a high-speed 1.25-GHz gated SPD which we build for the measurements. Detailed experimental setup including the description of the in-laser-period counter is demonstrated in Section 3. Results show that the in-laser-period statistical method has similar accuracy to the commonly used methods, and it allows shorter data acquisition time.

2. Method of afterpulse probability measurement

Afterpulse probability is the probability that a second avalanche pulse caused by the release of the trapped carriers generated from a previous pulse [24]. Because we are able to know in which gate the pulse is generated, the increased portion of dark counts generated in the non-illuminated gates can be regarded as afterpulse counts. Starting from this concept, an equation for calculating afterpulse probability is raised and often used [4,12,13,22], that is

$$P_{ap} = \frac{(P_{NI} - P_D)R_L}{P_I - P_{NI}}, \tag{1}$$

where P_D is the dark-count event probability per gate measured without laser, P_I and P_{NI} are the count event probability per illuminated gate and per non-illuminated gate, respectively, and R_L is the ratio of the gating frequency to the laser repetition frequency. This method requires the differentiation of the photon or non-photon-count events in illuminated gates and non-illuminated gates, and hence the gated counter and the TCSPC are often used when calculating with (1).

In order to simplify the measurement, we propose a statistical method using an in-laser-period counter which we describe in Section 3. From the definition of the afterpulse probability, we can calculate it basically using

$$P_{ap} = C_{ap}/C_{ph}, \tag{2}$$

where C_{ap} is the count rate of afterpulses due to photon-induced pulses, and C_{ph} is the count rate of photon-induced pulses. C_{ap} can be calculated in a simple way if C_{ph} is known, that is

$$C_{ap} = C_{total} - C_{dark} - C_{ph}, \tag{3}$$

where C_{total} is the total count rate, and C_{dark} is the dark count rate. Now the key is to calculate C_{ph}.

Firstly, we define R_d as the ratio of the dark count rate to the total count rate, that is

$$R_d = C_{dark}/C_{total}, \tag{4}$$

which denotes the probability that a count event is a dark count. Then we define C_n as the number of laser periods where n avalanche pulses occur. For example, C_2 is the number of laser periods where two avalanche pulses occur in one second. The probability that all of n avalanche pulses in a laser period are dark counts can be estimated as R_d^n, and then the probability that at least one non-dark count occurs is $(1 - R_d^n)$. If the laser period is longer than the life time of the trapped carrier, one of the non-dark counts in n counts is probably a photon-count event. Thus, C_{ph} is estimated using

$$C_{ph} = \sum_{n=1}^{\infty} C_n(1 - R_d^n) \approx C_1(1 - R_d) + C_{2+}(1 - R_d^2), \tag{5}$$

where C_{2+} is used to simplify the calculation and data acquisition, which denotes the number of laser periods in which more than one count event occurs. Note that C_1 and C_{2+} are the statistical result obtained from the in-laser-period counter directly and simultaneously. Thus, the afterpulse probability can be calculated approximately using

$$P_{ap} = \frac{C_{total} - C_{dark}}{C_1(1 - R_d) + C_{2+}(1 - R_d^2)} - 1. \tag{6}$$

Because this method does not require deliberate discrimination of photon-induced avalanche pulses, it depends on timing the least – only an auxiliary laser frequency reference signal is used. Neither