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InGaAs/InP avalanche photodiode for infrared single photon detection using a time-to-voltage converter

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ABSTRACT

We demonstrated an efficient and robust technique for weak avalanche discrimination by using a time-to-voltage converter circuit for the infrared single photon detection based on InGaAs/InP single photon avalanche photodiodes (SPADs), which enabled a strong suppression of the afterpulse noise. At a gating frequency of 10 MHz, a detection efficiency of 20.1% was obtained with a dark count probability of 1.2×10^{-5} and an afterpulse probability of 1.22% without dead time, paving the way for the low-noise fast detection of infrared single photons.

1. Introduction

Single photon detector (SPD) is one of the key components for an increasing number of applications such as fiber-optic sensing [1], eye-safe ranging and timing [2], semiconductor device analysis [3], singlet oxygen detection [4], and quantum cryptography [5]. In quantum key distribution (QKD) systems over optical fiber links [6–9], the wavelength of 1550 nm is the most desirable for long-distance transmission, since optical fibers exhibit low dispersion and minimum loss (0.2 dB/km) at this wavelength. The most convenient detectors at 1550 nm are based on InGaAs/InP avalanche photodiodes (APDs) [10–13]. APDs used as SPDs are referred to as single photon avalanche photodiodes (SPADs) and have several advantages, they are compact, have lower operating voltages, cryogenic-free operation and also cost less. SPADs operate above their breakdown voltage (V_{BR}) in the so-called Geiger mode, in which a single photon can trigger a macroscopic current pulse, providing the ability to accurately sense the arrival at the detector of a single photon. However, fractions of the many carriers trapped in the multiplication layer of the APD are subsequently released, and may result in the triggering of avalanches in subsequent gates. Limited by the current semiconductor manufacturing techniques, InGaAs/InP SPADs have higher probability that these so-called “afterpulses” occur. To suppress the rate of these afterpulses, a long dead time setting bigger than the lifetime of the trapped carriers is necessary (few microseconds) [12,14]. Therefore, the gate repetition frequency and maximum count rate of InGaAs/InP APDs are both severely limited. This has made InGaAs/InP SPADs unsuitable for applications that require high-speed SPDs, such as the gigahertz clocked QKD systems.

The afterpulse effect is not only attributed to the crystallographic defects in the multiplication layer, it is also proportional to the total number of carriers flowing through the device during an avalanche event. Therefore, the traditional way to reduce the afterpulse noise is to decrease the excess bias voltage and thus limit the avalanche current. However, this will reduce the amplitude of the avalanche signal, makes it difficult to be discriminated from the APD capacitive response, especially when using fast gating signals. So far, there have been two methods to discriminate weak avalanche signals: the sine wave gating (SG) with filtering and the so-called self-differencing (SD) technique [15–19]. Using these techniques, compensating the APD capacitive response to the applied gate signal is realized. However, both methods have drawbacks, such as the errors caused by two successive avalanches and the difficulty of tuning the gate frequency continuously over a wide range for the SD technique, and the variation of the effective gate-width with the frequency for the SG technique. Recently, a simple method for weak avalanche discrimination was reported by Cho and Kang [20]. Contrarily to other reported methods that focus on removing the capacitive response of the APD, weak avalanches were discriminated by combining them with auxiliary signals. Its disadvantage is the difficulty of tuning the amplitude and the delay of the auxiliary signal. More recently, Bouzid et al. [21] presented a simple and practical method for

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weak avalanche discrimination. By this method, the time integral of the avalanche current is processed for photon detection. However, the gating frequency is still limited due to the bandwidth limitation of the analog integrator circuit.

In this paper, we experimentally demonstrate an efficient and robust technique for weak avalanche discrimination by using a time interval to voltage converter circuit. Comparing to other reported methods, the zero crossing time interval rather than the peak voltage of the APD output is monitored to sense the photon detection event, resulting in a sharp reduction of the afterpulse noise. The detection efficiency reached 20.1% while the afterpulse probability was controlled as low as 1.22% under the gating frequency of 10 MHz.

2. Discriminator with time-to-voltage converter circuit

In our method, the zero crossing time interval of the SPAD output is processed so that even a weak avalanche can be discriminated easily. Fig. 1 shows the timing diagram of the SPAD outputs for both cases: no avalanche (capacitive response) and weak avalanche event; the dashed line indicates the discrimination threshold. As shown in Fig. 1(b), many avalanche signals are buried in the capacitive response noise. However, by converting the zero crossing time interval of the APD output to a voltage, the resulting waveform [Fig. 1(f)] shows that even weak avalanches can be distinguished without difficulty.

Fig. 2 shows the time interval to voltage converter scheme that we used in our experiment. It typically consists of a current source I_{ref}, a comparator, a capacitor C, and two analog switches S_1 and S_2. The start signal is used to charge the capacitor and the stop signal is used to discharge the capacitor by closing the analog switch (S_2) in order to reset the circuit for the next detection. An event (response to the gate signal) turns on the analog switch S_1 and charges the capacitor C with the current I_{ref} until the next zero crossing time of the APD output. The time between the rising edge and the falling edge of the APD output is therefore represented as a voltage on the capacitor C. More specifically, the time-to-voltage converter generates a voltage proportional to the zero crossing time period of the APD output. As can be seen in Fig. 1, the zero crossing time period is much larger in the case of an avalanche event comparing to the case when there is no avalanche. As a result of this operation, it is possible to discriminate the avalanche event without any compensation of the transient spikes.

3. Experimental setup

The experimental setup of the single photon detector using the time-to-voltage converter circuit is shown in Fig. 3. The InGaAs/InP APD under test is the AGD-25-SE-1-T8 (Princeton Lightwave). The APD chip is mounted on a three-stage thermoelectric cooler (TEC), and they are together housed in a TO-8 can package. The APD is cooled to

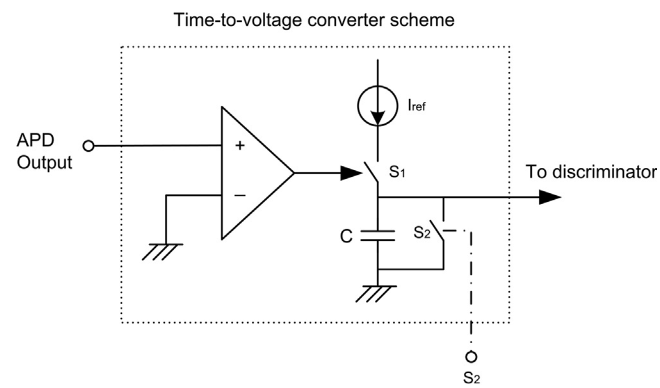

Fig. 2. An example of electrical circuit to realize the time interval to voltage converter method.

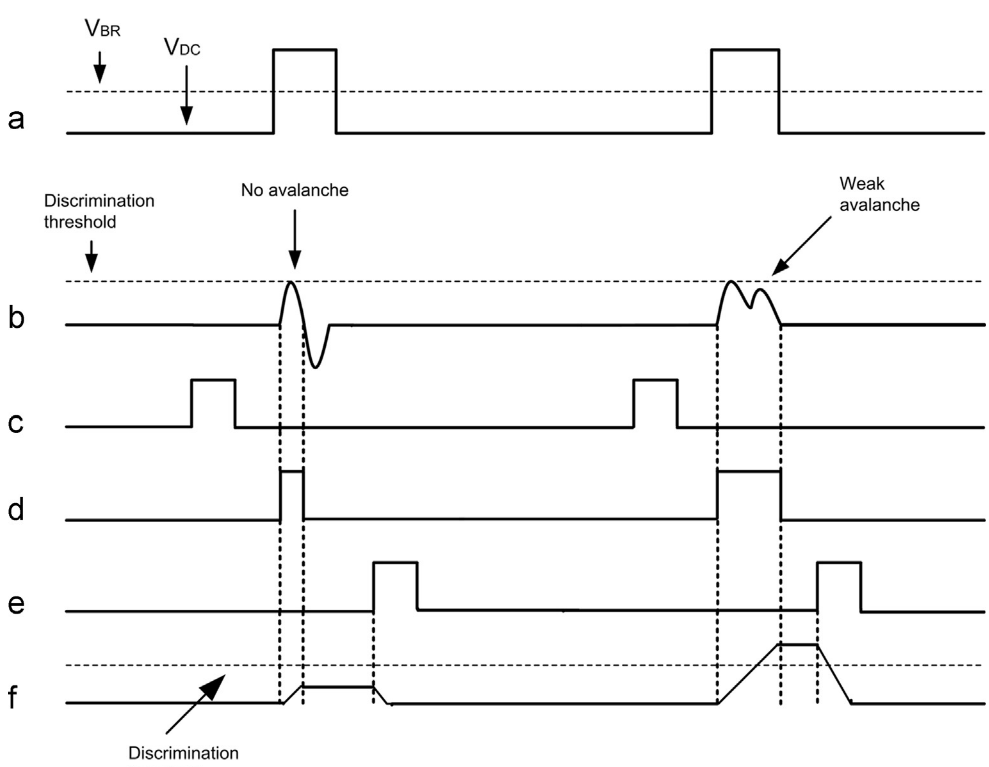

Fig. 1. Concept of the time interval to voltage converter method and its timing diagram. (a) APD input, (b) APD output, (c) Start signal, (d) Comparator output, (e) Stop signal, and (f) Discriminator input.