Internal cancellation of spikes using two avalanche photodiodes in series for single photon detection*

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We propose a method of improving the performance of InGaAs/InP avalanche photodiodes by using two avalanche photodiodes in series as single photon detectors for 1550-nm wavelength. In this method, the raw single photon avalanche signals are not attenuated, thus a high signal-to-noise ratio can be obtained compared with the existing results. The performance of the scheme is investigated and the ratio of the dark count rate to the detection efficiency is obtained to be 1.3×10^{-4} at 213 K.

Keywords: quantum information, quantum key distribution, single photon detection, single photon counting

PACC: 0367, 2940, 2970

1. Introduction

Single-photon detection is an important technique in many fields, such as optical time domain reflectometer,[1,2] quantum key distribution (QKD),[3−5] high time resolution spectroscopy, and fluorescence measurement. Normally, photomultiplier tubes (PMTs) are well-known single-photon detectors with low dark counts and high timing resolution. While in the near infrared region beyond 1 μm, PMTs are unsuitable for implementing single photon counting due to their low quantum efficiencies. Silicon avalanche photodiodes (APDs) have been used as single-photon sensors in a range from 400 nm to 900 nm. However, they do not respond to the wavelength beyond 1 μm because of their wide band-gap. Germanium APDs have been tested for single photon counting at 1300 nm earlier.[6,7] In order to obtain an appropriate dark count rate, germanium APDs should be cooled to 77 K. At this temperature, the cut-off wavelengths of germanium APDs will drop to 1450 nm, thus they cannot be used to detect the photons at 1550 nm. Although InGaAs–Si and InGaAs–InAlAs APDs have been used for single photon counting at 1550 nm,[8,9] current experimental results show that they are not good for such a kind of detection.

Up to now, single-photon detectors (SPDs) at 1550 nm have been mostly based on InGaAs/InP separate absorption, grading, charge and multiplication (SAGCM) APDs.[10,11] The cut-off wavelengths of these kinds of APDs are up to 1700 nm, which satisfy the requirement of the telecom communication. When these APDs are used for single-photon detection, they should be operated in the Geiger mode to achieve single-photon sensitivity, and in the gated mode to keep low dark counts. When it works in the gated mode, a gate pulse with steeply rising and falling edges, which will induce transient spikes by the charging and the discharging of the junction capacitance of the APD, is applied to the APD. The spikes will be superposed on the single-photon avalanche signals. Usually the amplitudes of the spikes are larger than those of the avalanche signals, which makes it hard to discriminate the avalanche signals from the spikes. Therefore, to suppress the spikes is a crucial requirement for using APDs in single-photon detection. There are several methods to avoid the spikes effects: (i) to use a coincidence circuit;[12] (ii) to cancel the spikes;[13−15] (iii) to count the discharge pulses[16] and (iv) to use a band elimination filter.[17] To cancel the spikes, a differential amplifying circuit was used on the output of the APDs.[13] Since there are several amplifiers, the circuit is complex and the noise is large. Bethune *et al.* used two coaxial cable reflection lines to cancel the spikes.[14] The electronic circuit is simple

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and the cancelling effect is determined only by these two cables, while the single-photon avalanche signals will be attenuated due to the reflection of the short coaxial cable. Moreover, the widths of the gate pulses applied to the APDs should be shorter than the delay time of the open line, which is normally about 10 ns. Sometimes we need a wider gate pulse for debugging, such as synchronizing the time of the gate pulse with that of the arrived photons. Tomita and Nakamura have suggested a method of cancelling the spikes by using two APDs and a hybrid junction to cancel the spikes.[15] The rejection ratio of the spikes is high and the cancelling circuit is simple. This scheme can be used to detect two paths of single-photon signals, which is suitable for quantum key distribution and other applications with differential detection. However in this method, a 180° hybrid junction is required to balance the outputs of the two APDs. The single-photon avalanche signals will also pass through the hybrid junction and be attenuated over 6 dB. Actually, the raw avalanche signals are very weak because the excessive bias voltages applied to the APDs should be as low as possible so as to reduce the dark counts. So any signal attenuation will lead to a reduction in signal-to-noise ratio and an increase in discrimination threshold.

2. Experiment and results

We propose a novel scheme, in which two APDs in series are used to cancel the spikes. The schematic diagram is shown in Fig. 1. The two APDs (JDSU EXT40) are cooled to about 213 K by semiconductor cooling sub-system. Since the APDs were produced in the same batch, they show almost the same electric characteristics. For example, their junction capacitances are both 0.25 pF at the same dc bias. In our implementation, positive short gate pulse and positive dc bias voltage are applied to the APD1, and negative electric signals are applied to the APD2, as shown in Fig. 1. In this way, the phases of the spikes induced by the APD1 are exactly reverse to those induced by the APD2. Thus at the output of point A, the spikes are cancelled and the avalanche signals become predominant. Comparing our method with other methods of cancelling the spike noises,[13−15] we can find all the shortcomings mentioned above to be avoided. For example, the single-photon avalanche signals are not attenuated and higher signal-to-noise ratio can be obtained, so that a lower discriminating threshold of the immediate circuit is needed. When using two APDs in series, we should make the positive and the negative gate pulses exactly symmetric and synchronic. A hybrid junction, which divides a gate pulse into a positive gate pulse and a negative gate, is used to obtain the symmetry and two cables with the same lengths are used to connect the hybrid junction outputs to the APDs. The effect of the spike cancelling is shown in Fig. 2. The solid curve indicates the output signals of point A without generating avalanche, and the dot and dash curves indicate the spikes of APD1 and APD2 respectively. The result shown in Fig. 2 clearly indicates that the spikes are suppressed efficiently. In a typical condition, the amplitudes of the spikes can be reduced from 260 mV to 13 mV, thus the achieved cancelling ratio is about 26 dB. Thus a lower APD bias voltage can be used, so that the dark counts are remarkably reduced.

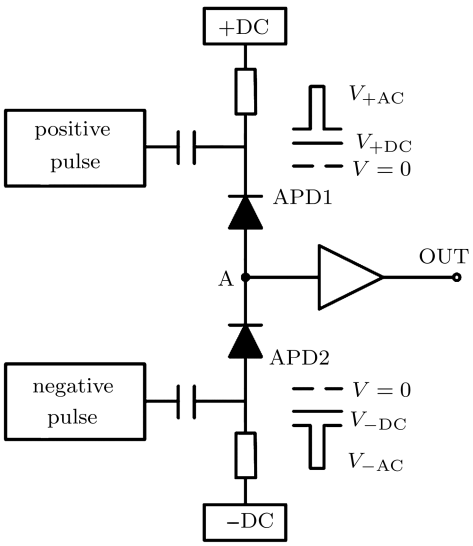


Fig. 1. Schematic diagram of photon detector with two APDs in series.

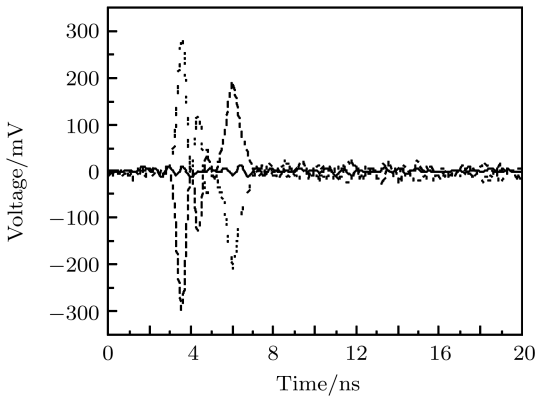


Fig. 2. Spike cancelling results, where dot curve is for APD1, dash curve for APD2, and solid curve for cancelling results.

In our method, each of the two APDs in series can be used to detect single-photons. The APD1 gives a positive avalanche signal and the APD2 gives a negative one. These opposite signals can be easily discriminated by the following electric circuits. When detecting single-photons, the two APDs should not absorb photons at the same time, otherwise the avalanche signals produced by the APDs will also be cancelled. The method can be applied to some cases such as QKD, in which the useful single-photons will not trigger two APDs at the same time.

Figure 3 shows the experiment setup of our single-photon detection. The delay generator acts as a master clock of the system and the repetition rate is kept at 100 kHz. It triggers a 1550-nm diode laser, which generates short light pulses of about 100-ps FWHM (full-width at half-maximum). The light pulses are attenuated to an average value of 0.1 photon/pulse by a variable attenuator, then they are coupled to the APDs for detection. At the same time, the delay generator triggers positive and negative pulse generators, which generate short gate pulses of 2.5 ns with an amplitude of 5 V and the pulses are applied to the two APDs each with DC offset. When the avalanche occurs, the output signals are amplified and discriminated by the following circuit and recorded by the counters.

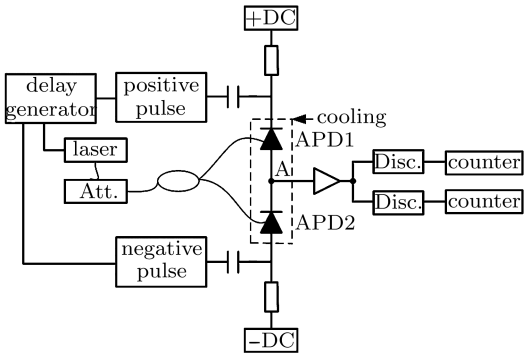


Fig. 3. Experimental setup, where Att. denotes attenuator and Disc. represents discriminator.

The detection efficiency (DE) and the dark count rate (DCR) are two important parameters when single-photon detectors are applied to the QKD. According to the QKD theory,[18,19] the quantum bit error rate should be kept below 11%,[20] so that the smaller the DCR/DE is, the longer the transmission distance will be. We have measured the two APD characters separately, and figure 4 shows the DCR and the DE each as a function of operation total voltage (the sum of the gate pulse and the DC voltage) of APDs. The result indicates that both the DCR and the DE increase with the increase of the sum of the gate voltage and the DC bias, while the DCR increases faster than the DE, which makes the DCR/DE increase with the total voltage increasing.

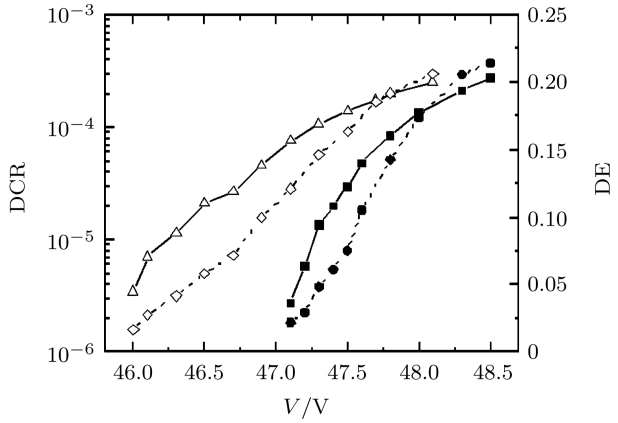


Fig. 4. Curves for dark count rate per pulse (DCR) and detection efficiency (DE) versus total voltage separately, where solid circles are for DE of APD1, solid squares for DCR of APD1, open diamonds for DE of APD2, open triangles for DCR of APD2.

So the DCR/DE can be reduced with a lower total voltage, which means a longer QKD transmission distance. On the other hand, a low total voltage leads to a low DE, which will reduce the raw key rate of QKD. In practical applications, the balance of the two parameters should be evaluated according to their real effects. Figure 5 shows the DCR/DE as a function of the DE, and the minimum DCR/DE of 1.3×10^{-4} is obtained at DE = 2%. When this single-photon

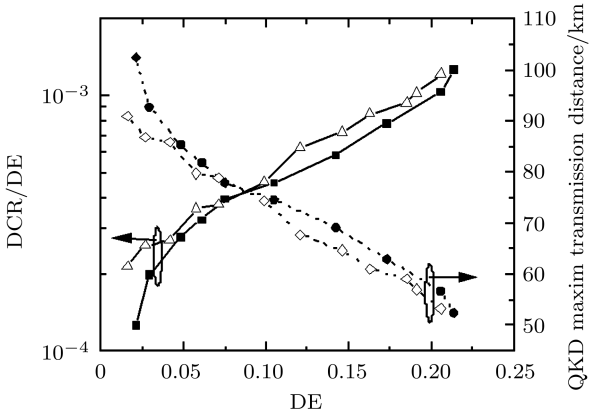


Fig. 5. Curves for ratio of dark count rate per pulse to detection efficiency (DCR/DE) and QKD maxim transmission distance ($L_{\max}$) versus detection efficiency, separately, where solid squares are for DCR/DE of APD1, open triangles for DCR/DE of APD2, filled circles for $L_{\max}$ of APD1, open diamonds for $L_{\max}$ of APD2.

detector is used in a QKD system,[19] the maximum transmission distance of QKD can exceed 90 km, with an APD detection efficiency being 2%. To obtain a better raw key rate, the APD detection efficiency is usually fixed at about 10%. Under this condition, the ratio of DCR to DE of this single-photon detector is lower than 5×10^{-4} and the transmission distance is longer than 70 km.

Compared with other detection schemes such as the Tomita's scheme,[15] our scheme has a higher DCR/DE at the same temperature of 213 K, which we attribute to the inherent characters of the APDs. To demonstrate the supposition, we made two identical APDs based on the Bethune's scheme and we obtain a minimum DCR/DE of 5×10^{-4}, nearly four times larger than that with our scheme. On the other hand, we have measured ten APDs manufactured in the same batch based on our scheme and the results are shown in Fig. 6. It is clear that all the ratios of DCR to DE are between 3×10^{-4} and 6.5×10^{-4} when the quantum efficiencies are 10%. At some time, these results show that the stable performance of single-photon detectors can be obtained with our scheme.

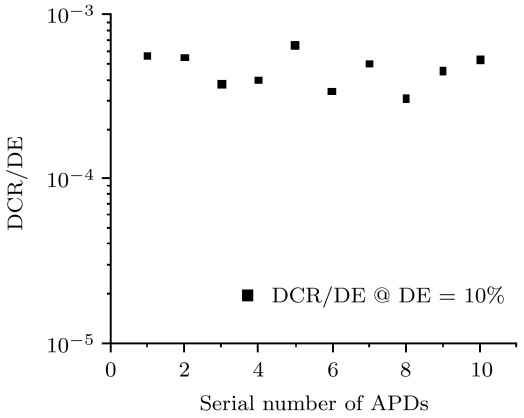


Fig. 6. Ratio of dark count rate per pulse to detection efficiency (DCR/DE) of ten APDs.

3. Conclusions

We presented a simple scheme to cancel the spikes. A good cancelling result is obtained by using two APDs in series. With the method, we can reduce the threshold of the discriminators and the APD bias voltage, so that a better performance of single-photon detection can be achieved. Moreover, the width of the gate pulse can be adjusted conveniently, so that it will be easier to synchronize gate pulses with photons.

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