A novel single-photon detector based on capacitance-balancing technique

Xie Chao[1, a], Yanli Zhao[1]

[1]Wuhan National Laboratory of optoelectronics, Huazhong University of Science and Technology, Wuhan 430074, China

[a]M201372515@hust.edu.cn

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Abstract. A gated InGaAs/InP single-photon detector based on a novel capacitance balancing technique was demonstrated. The single-photon detector is based on a gated InGaAs/InP avalanche photodioe. A quantum efficiency of 10% at 1550nm was obtained with a dark count probability per gate of 1.82×10^{-6} and an afterpulsing probability of 3.6% at a detection rate of 100 MHz. Moreover, compared with traditional capacitance balancing technique, our scheme can reduce dark count probability obviously.

Introduction

Near infrared single-photon detectors (SPDs) are widely used in many fields, such as quantum secure communication, astronomy, and ultrasensitive spectroscopy. The InGaAs/InP avalanche photodiode (APD) has been the most practical device for SPDs at telecommunication wavelength[1]. Since a photo-excited carrier grows into a macroscopic current output via the carrier avalanche multiplication in an APD operated in the Geiger mode, a single photon can be detected efficiently. However, some carriers trapped in the APD are subsequently emitted, and trigger additional avalanches that cause erroneous events. The InGaAs/InP APD in Geiger mode has a particular high probability that these so called "afterpulses" occur. Therefore, the InGaAs/InP APD is usually operated in the gated mode in which the gate duration (gate-on time) is generally set to a few nanoseconds. Then the interval between two consecutive gates is set to more than the lifetime (in orders of microseconds) of the trapped carriers so that the afterpulse is suppressed.

The alternative SPDs at telecommunication wavelengths are frequency-upconversion-assisted Si-APD (upconversion detector) and a superconducting single-photon detectors (SSPD). Although these SPDs can be operated with greater voltages than gigahertz clock systems, they have drawbacks that make them difficult to apply to practical QKD systems. The upconversion detectors suffers from background noise counts with high detection efficiency, while the SSPD requires cryogenic below 4K.

Thus far, several techniques, such as self-differencing technique[2], and sinusoidal gating technique[3], have been invented for InGaAs/InP single-photon avalanche photodioses(SPADs) in the gated Geiger mode, increasing the working speed over GHz. With these methods, SPADs can sense much weaker photon-induced avalanches at a high speed with good performance. However, it is quite difficult to change the gating frequencies of these SPADs, limiting their applications. Here, we propose the capacitance-balancing technique to solve the problem, easily tuning the gating freque- ncies without changing any state of the SPAD. At a detection rate of 200 MHz, we obtained a single photon detection efficiency of 10% with an afterpulse probability of 3.6% and a low dark count rate (1.82×10^{-6} per pulse). These make the device suitable for quantum secure communication, which requires that the bit error rate is less than 5%.
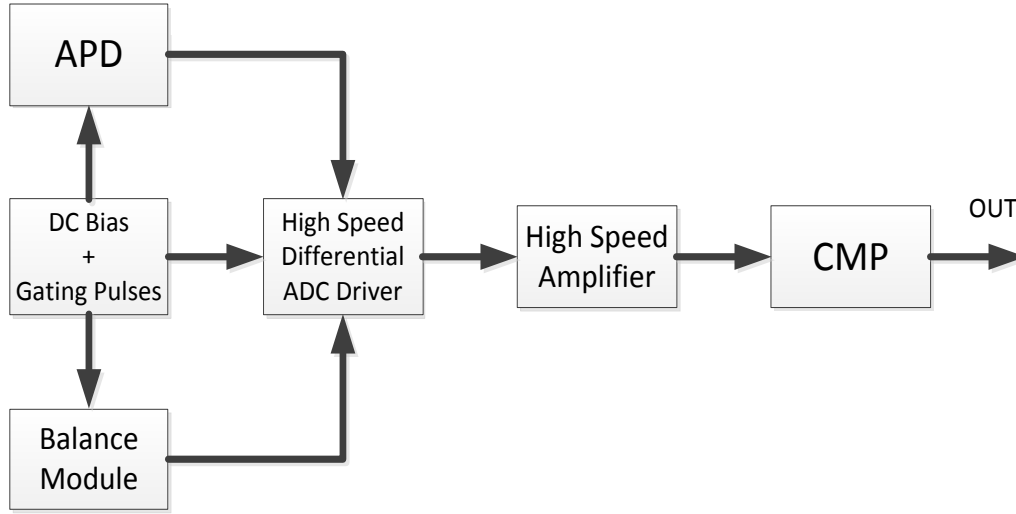
Experimental setup

Figure.1.Schematic of the capacitance-balancing single photon detector.

A diagram of our SPD is shown in Figure 1.The tested APD is PGA300 (Princeton Lightwave). The APD is cooled by a three-stage peltier. The APD module was used as the single-photon detection element after it was fiber pigtailed. In order to supply an AC voltage superposed on the DC reverse bias voltage V_{DC} to the APD, we used a gated passive quenching circuit (GPQC). The sinusoidal voltage at a frequency of wg was produced by a signal generator (SG:Agilent 83630B) and used as the gated voltage. Here the balance module was used to produce the similar response as the APD. The avalanche signal was discriminated by the ultra high speed comparator (CMP:MAXIM MAX9600). We finally obtained the logic output in the emitted-coupled-logic (ECL) level.

We evaluated the SPD performance for weak laser pulses at 1550nm. The laser pulses were triggered by the clock signal given by the SG. Here the phase of the sinusoidal gate voltage was synchronized with that of the 10 MHz standard clock. The relative phase delay between the sinusoidal voltage and the laser pulse was adjusted by the phase shifter. In order to obtain the highest quantum efficiency, the timing (laser pulse delay) of the optical pulses at the APD must be carefully tuned by the phase shifter.

To evaluate the quantum efficiency η, the dark count probability P_d, and the afterpulsing probability P_a of our SPD , the detection events (logic outputs from the SPD) were registered by a multi-channel scaler that gave the time histogram of the detection events. As described above, the the repetition frequency w_L of the laser pulses was set to 10 MHz , which was lower than the frequency wg of the sinusoidal gate. Therefore, there are many nonilluminated gates , and the photon detection events occur only in the illuminated gates, as shown in Fig.2. The number of events in the illuminated gates is consequently much larger than that in the nonilluminated gates (see Histogram in Fig.2), since only dark counts and afterpulse events occur in the nonilluminated gates. The histogram of the dark counts can be easily obtained with the laser switched off (see Histogram in Fig.2). We must note that there are actually not only the dark counts but also the afterpulse events correlated with the dark count events. However, such afterpulse events were treated here as dark count events. The number of events in nonilluminated gates with the laser switched on is higher than that with the laser switched off, since afterpulse events correlated with the photon detection events occur. The afterpulsing probability P_a, defined as the ratio of the total afterpulse events to photon detection events, is given by the expression.

$$Pa = \frac{(C_{NI} - C_D)R}{C_I - C_{NI}} ,$$ (1)

$$R = \frac{w_g}{w_L},\qquad(2)$$

Where C_{NI} and CI are the number of the events per nonilluminated gate, respectively, and CD is the number of events per gate with the laser switched off. R is the ratio of the gating frequency of the laser pulse repetition frequency, and corresponds to the number of the gates that are applied to the APD during one period of the laser pulse.

The quantum efficiency and the dark count probability are easily evaluated using the relations

$$\mu\eta Ns = C_I - C_{NI},\qquad(3)$$

$$PdNs = C_D\qquad(4)$$

Where μ is the average photon number per optical pulse, and Ns is the number of the measurements using the MCS. In our experiment, $\mu\ and\ Ns$ was set to 0.1 and 10^8, respectively.
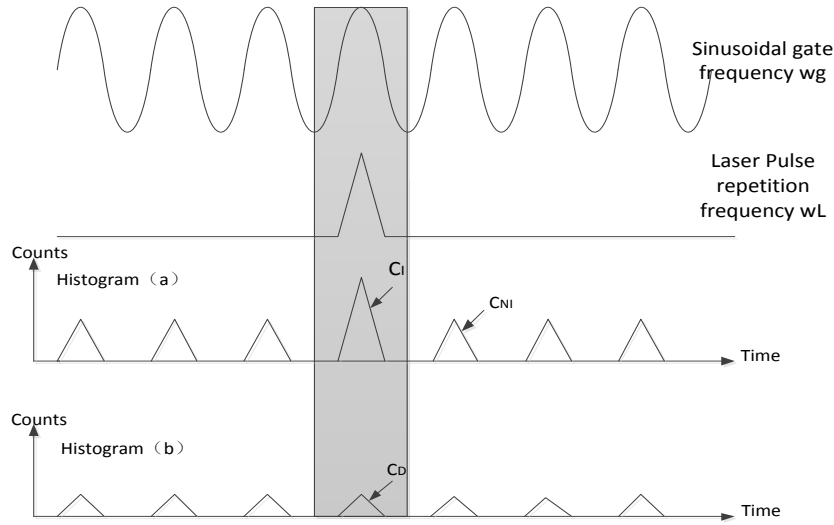

Fig.2.Schematic diagram of the histogram measurements. The illuminated gates are highlighted. Histogram (a) and (b) show the time histograms of the detection events when the laser was switched on and off, respectively. C_I and C_{NI} denote the number of events in the illuminated and nonilluminated gates, respectively, with the laser switched on. C_D denotes the number of events per gate with the laser switched off.
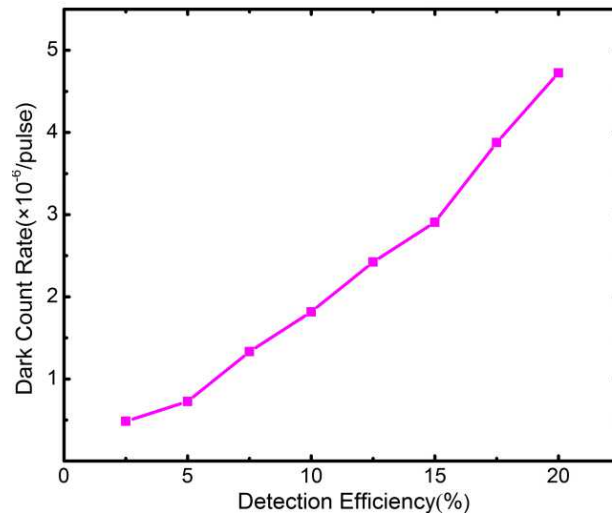

Fig.3.Dark count rate versus detection efficiency

Figure 3 shows the relation between dark count rate and the detection efficiency. It can be seen that the dark count rate rise smoothly when the detection efficiency is relatively low. The dark count rate

was 7.26×10^{-7} per gate when the detection efficiency was 5%, then it rose to 2.9×10^{-6} per gate when the detection efficiency was 15%. Nevertheless, when the DC bias increase to a high degree, the dark count rate rise sharply. The dark count rate at 20% detection efficiency was 4.72×10^{-6} per gate.
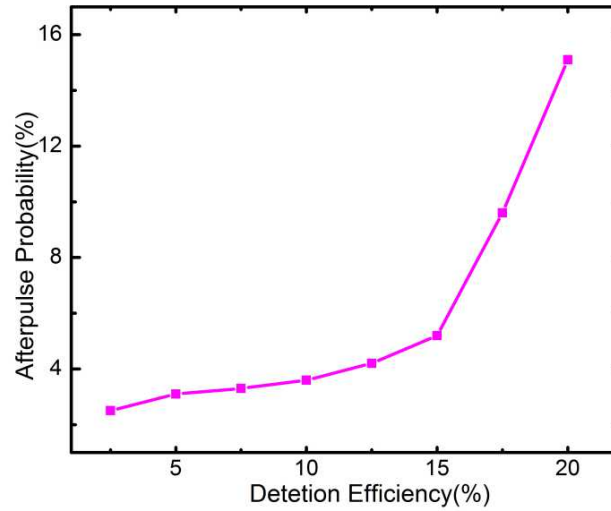

Fig.4. Afterpulse probability versus detection efficiency

Figure 4 shows the relation between afterpulse probability and the detection efficiency. We can also see that the afterpulse probability rise slowly when the detection efficiency is relatively low. The afterpulse probability at 5% detection efficiency was approximately 3.1%, and it rose to 5.2% when the detection efficiency was 15%. However, when the detection efficiency exceeded 15%, the afterpulse probability rise sharply. The afterpulse probability at 20% detection efficiency was 15.1%.

Summary

In conclusion, we have developed a single-photon detector at 1550nm using a sinusoidal gated capacitance balancing InGaAs/InP APD. A gated repetition of 100MHz was achieved with high quantum efficiency, low dark count probability, and low afterpulsing probability. The single-photon detector can be easily applied to QKD systems.

Acknowledgements

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