Advances in Computer Science Research, volume 71
4th International Conference on Machinery, Materials and Information Technology Applications (ICMMITA 2016)

1.25 GHz Single-photon Detection with Sinusoidally Gated InGaAs/InP Avalanche Photodiode

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Keywords: single-photon detection; sine-wave gating; dark count rate; afterpulse

Abstract. The InGaAs/InP avalanche photodiodes (APDs) are one of the most practical devices for single-photon detection at the near-infrared wavelengths. In this paper, we report a Chinese-made InGaAs/InP APD based single-photon detector operated at 1.25 GHz. The combining technique of sine-wave gating and low-pass filtering was employed to suppress the spike noise. Detection efficiency of 20% was attained with the dark count rate of 2.34×10^{-6} per gate and the afterpulse probability of 2.1% at -25°C. These performance parameters were measured to be approximately the same as the imported APD, showing that the manufacturing technology and performance of the InGaAs/InP APD had a great progress in China.

Introduction

Single-photon detectors (SPDs) are now widely used in numerous fields of great importance, such as quantum key distribution, optical time-domain reflectometry, astronomy and deep-space communication, and biological imaging [1-3]. Considering the compact structures and low-power consumption, the InGaAs/InP avalanche photodiodes (APDs) have been one of the most practical devices for efficient near-infrared single-photon detection. InGaAs/InP APDs are generally operated in gated Geiger mode to reduce error counts. In the operation mode, the weak photon-induced avalanche signals are usually buried in the spike noise produced by the APD’s capacitive responses. Some artful techniques, such as sine-wave gating, self-differencing, and the combination of both, have been demonstrated to suppress the spike noise efficiently while the gating repetition rate over 1 GHz [4-6]. Due to the relative backward semiconductor production technology in China, most of InGaAs/InP APDs used were imported, limiting the development of single-photon detection in China.

In this paper, we demonstrated a gated single-photon detector based on a domestic InGaAs/InP APD with different detection efficiencies at different temperatures. The detector was 1.25 GHz gated and employed the combining technique of the sine-wave gating and low-pass filtering for the suppression of the spike noise. When it was cooled to be -25°C, we obtained the detection efficiency of 20% with the dark count rate of 2.34×10^{-6} per gate and the afterpulse probability of 2.1%. Meanwhile, the timing jitter was measured to be 140 ps. Compared with the imported InGaAs/InP APD, the manufacturing technology and performance of InGaAs/InP APD have made a great progress recently in China, but there is still room for improvement.

Experimental Setup

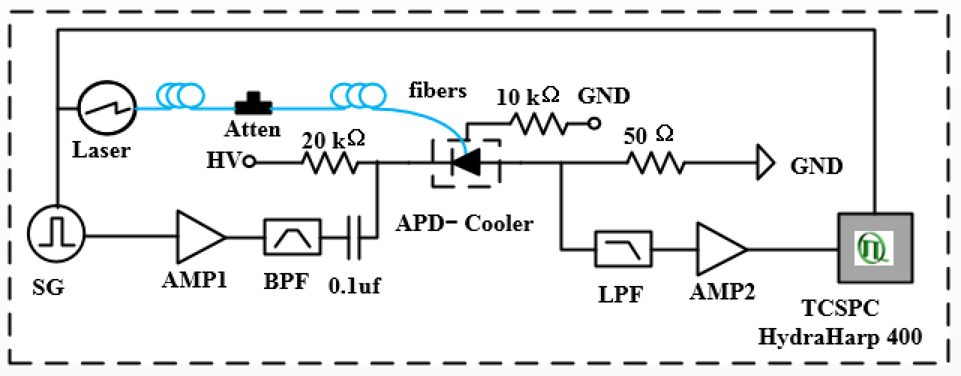
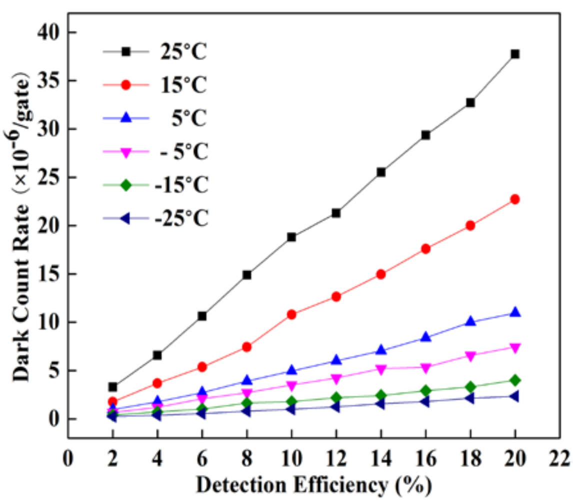


Fig. 1 Experimental setup of the single-photon detector with an InGaAs/InP APD based on sine-wave gating combining with low-pass filtering technique. SG: signal generator; AMP1, AMP2: RF amplifier; BPF: band-pass filter; LPF: low-pass filter; Attn: tunable optical attenuator; TCSPC: Time-correlated single-photon counting system (PicoQuant, HydraHarp 400).

In this paper, we used an InGaAs/InP APD made by the No. 44 Research Institute of China Electronic Technology Corporation(CETC) for the research, and the model is GD65211. The pigtailed APD applied TO-8 package and was integrated with a three-stage thermoelectric cooler(TEC) and a current mode temperature-sensitive sensor. Figure 1 illustrated the schematic of the test system employing sine-wave gating combined with low-pass filtering technique. Before being applied on the APD, the sine wave which came out from the signal generator, was amplified by AMP1 and then filtered by a band-pass filter (BPF) to eliminate the sideband noise and harmonic noise. Here, we set the repetition frequency of the sine-wave signal to be 1.25 GHz to characterize the single-photon detector. A 1550-nm pulsed laser at 10 MHz was attenuated to contain 0.1 photon per pulse before coupling into the APD as the photon source. The laser pulse was synchronously triggered with the gating pulse, while their delay was adjusted to gain the highest detection efficiency for optimal operation. The reverse bias voltage applied on the APD was changed to obtain different efficiencies. The output of the APD was filtered by the low-pass filtering cutting off at 700 MHz with the attenuation higher than 35 dB at 1.25 GHz. Since the spectrum of the avalanche signal distributed mostly at low frequency under 1 GHz, while the spike noise concentrated at 1.25 GHz and its harmonic frequencies, we could acquire the avalanche signal after the low-pass filter. Finally, the avalanche signal was extracted and acquired by the time-correlated single-photon counting(TCSPC) system after amplification by an RF amplifier.

Results and Discussion



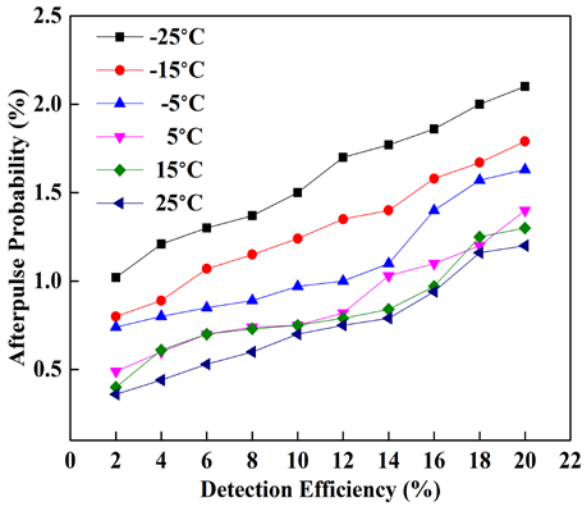


Fig. 2 Dark count rate as a function of the detection efficiency at different temperatures (-25°C ~25 °C).

Fig. 3 Afterpulse probability as a function of the detection efficiency at different temperatures (-25°C ~25 °C).

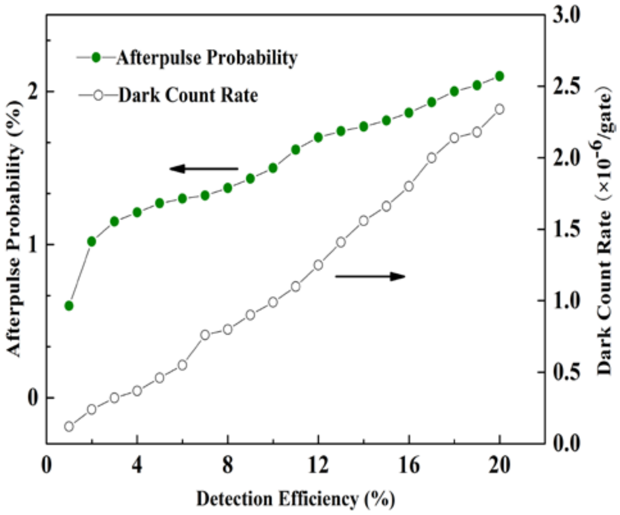


Fig. 4 Afterpulse probability and dark count rate as a function of detection efficiency at -25 °C.

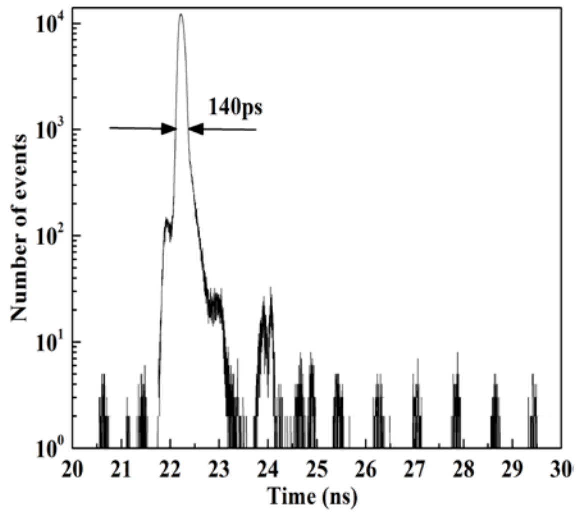


Fig. 5 Time histogram of detection events recorded by the TCSPC.

The operation temperature of the InGaAs/InP APD was vital to the performance of the single-photon detector. The InGaAs/InP APD was cooled to work at different temperatures from -25 ℃ to 25 ℃, and the single photon detection efficiency was tuned by varying the DC bias. Figure 2 and Figure 3 respectively showed the dark count rate and afterpulse probability as a function of detection efficiency. The results showed that, the dark count rate and afterpulse probability increased with the detection efficiency at the same test temperature. Meanwhile, we could figure out that the dark count rate was higher at the same detection efficiency at higher temperature, when the operation temperature of APD rose from -25 ℃ to -5 ℃, the change of dark count rate with temperature at the same detection efficiency was fairly minor. Once when the temperature exceeded 5 ℃, the dark count rate increased obviously with the temperature. However, the change trend of afterpulse probability was just the opposite, it decreased with the increasing temperature. When the operation temperature of APD rose from -25 ℃ to -5 ℃, the afterpulse probability rate decreased rapidly with rising of temperature at the same detection efficiency. Once when the temperature exceeded 5 ℃, the change of afterpulse probability with temperature was so subtle.

To observe performance of the domestic InGaAs/InP APD detailedly and make a better comparison with the imported APDs, we measured the dark counts and afterpulse probability as a function of the detection efficiency at -25 °C. As shown in the Fig. 4, the afterpulse probability increased slowly with the detection efficiency, it was 1.5% when the detection efficiency was about 10%; and it climbed to just 2.1% when the detection efficiency reached about ~20%. Meanwhile, the dark count rate increased gradually with the detection efficiency, which appeared an approximately linear relationship, it was just 2.34×10^{-6} per gate when the detection efficiency was ~20%.

We employed a TCSPC system (PicoQuant, HydraHarp 400) with the resolution of 2 ps to test the timing jitter of the single-photon detector. We set the operation temperature of the APD at -25 °C. While the detection efficiency was kept at 10%. We connected the synchronic signal of laser to the “START” input of the TCSPC, and the output of AMP2 was connected to the “STOP” input, the time histogram of detection events was recorded by the TCSPC as shown in Fig. 5. The count peak in the illuminated gating pulse was much higher than the other peaks. The time interval between the peaks was 0.8 ns, matching with the 1.25 GHz repetition frequency of the sine-wave gating. And the timing jitter of the avalanche signal showed an FWHM of 140 ps. Moreover, this parameter contained the timing jitter of whole system, we used the TCSPC to test timing jitter of signal generator’s two outputs channel, and the timing jitter is ~30 ps. If we choose smaller timing jitter signal generator, we could further improve the whole system’s timing jitter characteristics.

After we collected the performance parameters of domestic InGaAs/InP APD (No. 44 Research Institute of CETC, GD6521), we selected an imported InGaAs/InP APD (Princeton Lightwave, PGA300) for comparison as shown in Table 1[7]. When the detection efficiency was about ~10%, the dark count rate and afterpulse probability of GD6521 were only a little higher than PGA300, the dark count rate of GD6521 was just 0.99×10^{-6} per gate and the afterpulse probability was 1.50%. When the detection efficiency reached about ~20%, the dark count rate of GD6521 was 2.34×10^{-6} per gate and afterpulse probability was only 2.10%, which were even superior to PGA300. The only drawback is that the timing jitter of GD6521 was higher than PGA300, the former was 140 ps, the latter was 40~80 ps.

Table 1 The parameter comparison between domestic InGaAs/InP APD(GD6521) and domestic InGaAs/InP APD(PGA300)

Type of APD	Tempe-rature [°C]	Gating repetition rate [GHz]	Detection efficiency: 10%		Detection efficiency: 20%		Timing jitter [ps]
			Dark count rate [$\times10^{-6}$/gate]	Afterpulse probability [%]	Dark count rate [$\times10^{-6}$/gate]	Afterpulse probability [%]	
GD6521	-25	1.250	0.99	1.50	2.34	2.10	140
PGA300	-50	1.244	0.71	0.61	3.00	1.50	40~80

Conclusion

In general, we have demonstrated an infrared single-photon detector based on a domestic InGaAs/InP APD operated at 1.25 GHz by using the combining technique of the sine-wave gating and low-pass filtering. By measuring the performance parameters of domestic InGaAs/InP APD and comparing the results with the imported one, we could conclude that not only the detection efficiency, but also the dark count rate and afterpulse probability of domestic InGaAs/InP APD have reach the international advanced level. However, there is still room for improvement in terms of the timing jitter.

Acknowledgements

This work was financially supported by the National Natural Science Fund of China (Grant No. 61127014, 11404212, 11604209) and the National Key Scientific Instrument Project (Grant No. 2012YQ150092), General Financial Grant from the China Postdoctoral Science Foundation (Grant No. 2014M560347), Hujiang Foundation of China under Grant D15014.

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