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Stable single-photon detection based on Si-avalanche photodiode in a large temperature variation range*

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In this paper, we present a stable single-photon detection method based on Si-avalanche photodiode (Si-APD) operating in Geiger mode with a large temperature variation range. By accurate temperature sensing and direct current (DC) bias voltage compensation, the single-photon detector can work stably in Geiger mode from −40 °C to 35 °C with an almost constant avalanche gain. It provides a solution for single-photon detection at outdoor operation in all-weather conditions.

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Single-photon detection based on the avalanche photodiode (APD) has gained a lot of research interest, and therefore great progress about that has been also made[1-7]. Among them, Si-APDs have been a good choice for the single-photon detection at visible wavelengths due to their practicality, high quantum efficiency and low dark count noise. Combined with single-photon frequency upconversion, Si-APDs could also be applied to the single-photon detection of infrared photons[8,9]. Moreover, the Si-APD single-photon detectors can be employed in lots of important applications, such as the laser ranging[10-12], three dimensional laser imaging[13,14], spectral analysis, optical fiber sensing, and quantum communication[15,16].

At present, most of the Si-APD single-photon detectors are designed to be operated at room temperature with Peltier cooling in temperature variation range from −10 °C to −20 °C. The temperature controlling accuracy is usually beyond ±0.5 °C in order to decrease the dark count noise of the detector and ensure the high stability. However, if the single-photon detector needs to work in low temperature situations which would be below the Peltier cooling controlling range, the low temperature operation would affect the detection performance or even damage the detector itself.

At a certain direct current (DC) bias voltage, with the decrease of temperature, the avalanche voltage will decrease as well, leading to the increase of the voltage difference, which would influence the avalanche gain and change the single-photon detection efficiency, dark count noise and so forth. As a result, the measurement errors would be enlarged due to the instability of the detector. To solve this problem, we develop a method to compensate the avalanche voltage drift resulting from the temperature variation in order to stabilize the avalanche gain of the Si-APD. Therefore, the detector can be operated in a large temperature variation range, especially in low temperature conditions. Comparing the digital feed-back controlling with monolithic processor[17], the analogue circuit we used here is much simpler and more reliable, which is more suitable for outdoor application in all-weather conditions.

In the experiment, we chose a high-performance Si-APD (SAP500T8, Laser Components) for the test. The temperature sensor and the Peltier cooler were integrated in the same Si-APD chip. We built the single-photon detector based on the Si-APD as shown in Fig.1. The high voltage is applied on the APD to operate it in Geiger mode. The arrival of the photon at the detection area of the APD can induce an avalanche pulse output at the resister R_s. With the capacitor C, the avalanche pulse will be picked out. The signal is sent to a comparator to form a digital pulse output. In order to increase the detection rate, once there is an avalanche pulse output, a quenching signal will be released to decrease the high voltage applied on the APD to be below the avalanche voltage to quench the avalanche process. And after that, a reset signal is sent out to initialize the APD at Geiger mode.

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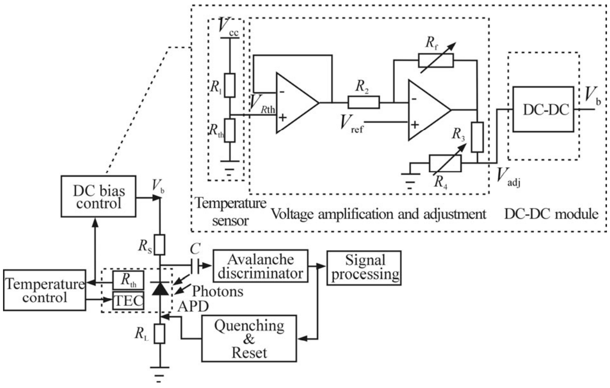


Fig.1 Schematic diagram of Si-APD single-photon detection circuit (The inset is the detailed schematic diagram of the DC bias voltage control module.)

When the operation temperature is set at −20 °C, the avalanche voltage is about 110 V, and the extra voltage (the difference between the DC bias voltage and the avalanche voltage) is about 6 V. Therefore, the DC bias voltage is set at 116 V. The detection efficiency is 50% at 532 nm, and the dark noise is about 1.5×10^3 counts per second. Considering the cooling limit of the temperature controlling component integrated in the APD chip, we set −20 °C as the target temperature for the feed-back. As shown in Fig.2, the avalanche voltage is increased with the temperature. With a linear fitting, we can get the relationship between the avalanche voltage V_a and the temperature T as

$$V_a=117.530+0.386T, \tag{1}$$

where T is in degree celsius.

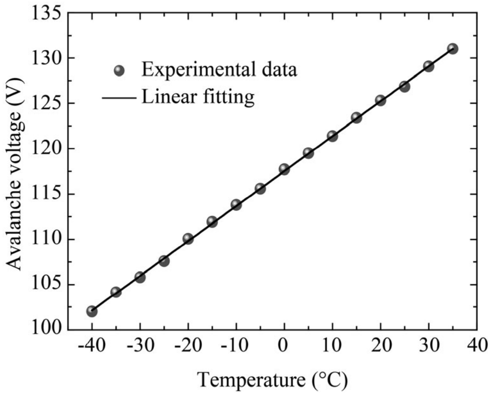


Fig.2 Avalanche voltage as a function of the temperature

When the temperature is higher than the target, the Peltier cooler will work to stabilize the temperature at the target with a proportional-integral-derivative (PID) circuit. Meanwhile, the DC bias voltage is kept constant as 116 V so that the APD can maintain the same performance. But when the temperature is lower than the target, instead of heating the APD to the target temperature, we stabilize the APD by adjusting the DC bias voltage. By this means, we can take the advantage of the low temperature environment to decrease the dark noise of the detector. According to Eq.(1), the DC bias voltage should vary with the avalanche voltage to maintain the same voltage difference of 6 V in order to keep the same avalanche gain. Therefore, in the real application, Eq.(1) can be modified to

$$V_a=\begin{cases}117.530+0.386T & (-40\ ^\circ\mathrm{C}\le T<-20\ ^\circ\mathrm{C})\\ 110 & (T\ge -20\ ^\circ\mathrm{C})\end{cases}. \tag{2}$$

To adjust the DC bias voltage, we build a voltage control module as shown in the inset of Fig.1. The thermistor R_{th} will convert the temperature to voltage, followed by voltage amplification and adjustment unit which is composed of a voltage follower and a differential amplifier. Resistor R_f is used to adjust the gain of differential amplifier. The output V_{adj} is used to control the final output of the DC-DC module. The output DC bias voltage V_b should be

$$V_b=a+bV_{adj}. \tag{3}$$

When the temperature is below −20 °C, the resistor value of R_{th} can be considered to decrease linearly with the increase of temperature. With a much larger resistance in series R_1, the voltage on R_{th} decreases linearly with the temperature, as the voltage V_{Rth} is sent to the inverting input of the differential amplifier, so the output DC bias voltage V_b increases linearly with the increase of temperature. As shown in Tab.1, the parameters of the resistors and the reference voltage are selected in order that the DC bias voltage changes in the same way as the avalanche voltage with the temperature, and when the temperature is above −20 °C, V_{adj} maintains the same due to the output saturation of amplifier as shown in Fig.3.

Tab.1 The parameters of the circuit for the DC bias voltage control module

Parameter	Value	Parameter	Value
R_1	100.0 kΩ	V_{ref}	6.4 V
R_2	39.2 kΩ	a	0.196
R_3	2.0 kΩ	b	41.528
R_4	2.7 kΩ	R_f	31.2 kΩ

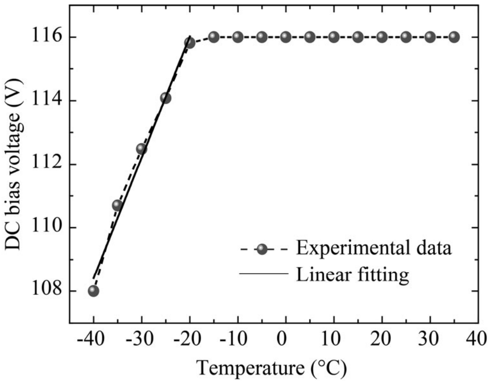


Fig.3 Output of the DC bias voltage control module as a function of the temperature

By fitting the experimental data in Fig.3, we can obtain

$$V_{\mathrm{b}} = \begin{cases} 123.628 + 0.380T & (-40\ ^\circ\mathrm{C} \le T < -20\ ^\circ\mathrm{C}) \\ 116 & (T \ge -20\ ^\circ\mathrm{C}) \end{cases} . \quad (4)$$

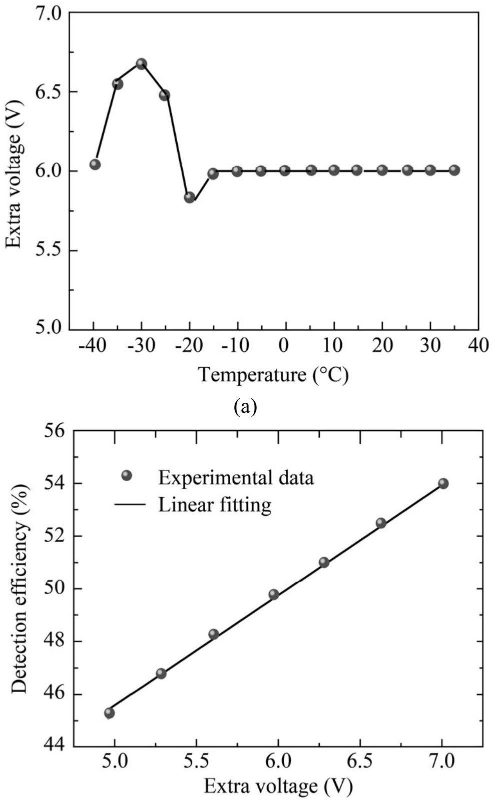
According to Eq.(2), the voltage difference $V_{\mathrm{b}}-V_{\mathrm{a}}$ is almost kept constant as 6 V. Therefore, the avalanche gain can be maintained in the large temperature tuning range.

As only one amplifier is used in the DC bias voltage module, the actual extra voltage will fluctuate as shown in Fig.4(a). The maximum extra voltage is 6.69 V, and the minimum is 5.77 V. There is a difference of 0.92 V due to the fluctuation. By fitting the experimental data in Fig.4(b), we get

$$\eta = 24.732 + 4.170\Delta V , \quad (5)$$

where η is the detection efficiency, and ΔV is the extra voltage.

To verify the stability of the single-photon detector, we test the whole single-photon detection system in a high-low temperature test chamber. At first, we record the dark noise without any light illumination.



(a)

(b)

Fig.4 (a) Extra voltage as a function of the temperature; (b) Detection efficiency as a function of the extra voltage

As shown in Fig.5, when the temperature of the test chamber is below −20 °C, the dark noise decreases with the decrease of temperature and reaches the minimum of 500 counts per second at the temperature of −35 °C. At even lower temperature, the dark noise does not change. And when the temperature of the test chamber is above −20 °C, the dark noise is maintained at about 2.0×10^3 counts per second since the APD is still operated at −20 °C by the Peltier cooler. But when the temperature of the test chamber is above 35 °C, the Peltier cooler can not be stabilized at −20 °C due to the large temperature difference, leading to the temperature increase of the APD. Since the avalanche voltage increases as the temperature but the DC bias voltage is kept constant as 116 V, the effective avalanche gain is decreased, leading to the decrease of the dark noise.

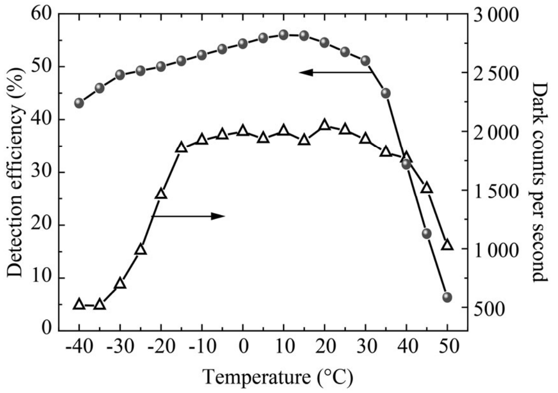


Fig.5 Dark noise and detection efficiency of the APD as a function of the test temperature

Then, we send the attenuated 532 nm laser signal at single-photon level to the detector for the measurement of detection efficiency. As shown in Fig.5, since the extra voltage is kept the same for the temperature tuning range from −40 °C to 35 °C, the avalanche gain is almost the same, resulting in an almost constant detection efficiency of 51%±4%. According to Eq.(5), the change of detection efficiency caused by the fluctuation of extra voltage should be less than 3.8%. Considering that the whole testing process lasted about 3 h, the change on the measurement results of detection efficiency may be mostly caused by the light source intensity fluctuation. The actual effect of temperature compensation should be better than the test results in real applications. When the temperature of the test chamber is above 35 °C, the detection efficiency will decrease due to the same reason of the dark noise.

In conclusion, we develop a practical method by combining the DC bias voltage compensating and Peltier cooling to realize the stable single-photon detection based on Si-APD in a large temperature variation range. At low temperatures, the adjustment on the DC bias voltage is applied to keep the same avalanche gain, while at high temperatures, the Peltier cooler is employed to maintain the operating temperature at −20 °C. By this means, we can operate the single-photon detector in a large temperature variation range, especially for low temperatures. This kind of technique can also be applied to InGaAs-APD based infrared single-photon detectors for outdoor application in all-weather conditions.

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