Ultralow-noise single-photon detection based on precise temperature controlled photomultiplier with enhanced electromagnetic shielding

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Received May 3, 2017; accepted June 6, 2017; posted online June 27, 2017

We demonstrate an ultralow-noise single-photon detection system based on a sensitive photomultiplier tube (PMT) with precise temperature control, which can capture fast single photons with intervals around 10 ns. By improvement of the electromagnetic shielding and introduction of the self-differencing method, the dark counts (DCs) are cut down to ~1%. We further develop an ultra-stable PMT cooling subsystem and observe that the DC goes down by a factor of 3.9 each time the temperature drops 10°C. At −20°C it is reduced 400 times with respect to the room temperature (25°C), that is, it becomes only 2 counts per second, which is on par with the superconducting nanowire detectors. Meanwhile, despite a 50% loss, the detection efficiency is still 13%. Our detector is available for ultra-precise single-photon detection in environments with strong electromagnetic disturbances.

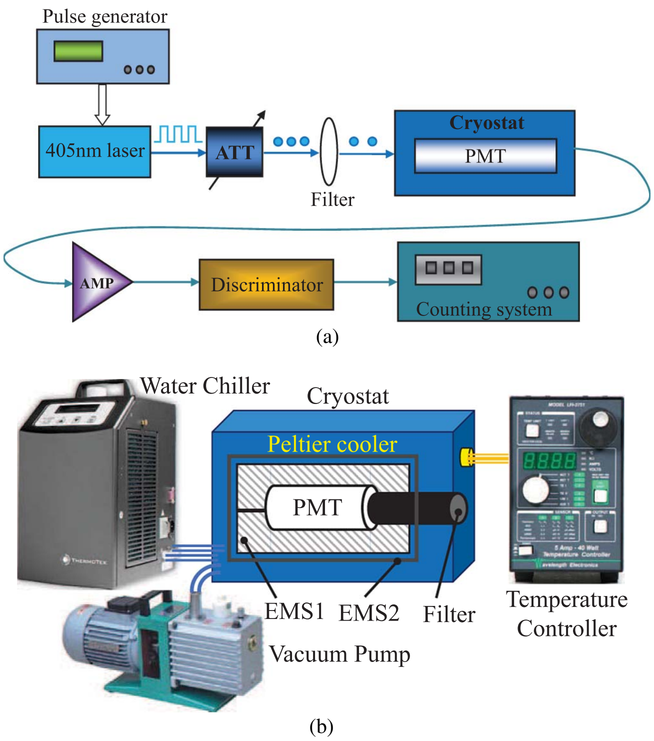
OCIS code: 030.5260, 040.5250.
doi: 10.3788/COL201715.100301.

Single-photon detection (SPD) is a crucial technique in a number of areas, such as quantum key distribution (QKD)[1,2], fluorescence laser scanning microscopy[3], high-resolution light detection and ranging (LIDAR)[4–6]. Although there are many schemes proposed to detect single photons[7,8], it is a long way to develop an ideal single-photon detector that has low detection noise and precise time resolution, but does not require a complicated cryostat system. Up to now, an avalanche photodiode (APD) has been widely investigated because it is easy to be cooled down, however, its high dark-count (DC) probability and strong after-pulse effect add more difficulties in signal processing[9–11]. The superconducting nanowire SPD (SNSPD) seems to satisfy most of the requirements, but it is necessary to be cooled down by expensive liquid helium[12,13]. Recently, a new kind of SPD based on the segmented single-photon avalanche detector (SPAD) has been attracting much interest, because it is equaling or even surpassing photomultiplier tubes (PMTs) for fast response and sensitivity, however, it is still lagging for acceptance area, linearity, and dark current[14].

Among the existing detectors, the classical PMT has its own superiority due to internal huge gain ($\sim 1 \times 10^8$), which makes the thermal noise negligible with respect to the quantum noise. Furthermore, it has a very large sensitive area (up to many cm^2) and low dark current (down to $1 \times 10^{-18}\ \text{A/cm}^2$)[14]. Thus, it is able to realize ultralow-noise detection, which is only reached by SNSPD at present. Considering this point, we choose a low-noise PMT to establish the SPD system, and detect the single photons with high quantum efficiency at 405 nm. Reducing the noise by enhanced electromagnetic shielding and self-differencing, we can catch the photons at a much smaller level with short intervals of around 10 ns. To further suppress the DCs, we develop an ultra-stable thermoelectric cryostat system to cool down the PMT. The results show that the DCs become smaller and smaller as the temperature is decreasing. At −20°C and below, the DC number is pretty close to zero, which is on par with the superconducting nanowire detectors.

We start the investigation by measuring the detector system performance. The characterization setup is shown in Fig. 1.

A continuous wave (CW) laser emitting at 405 nm is firstly modulated by a pulse generator to produce 100 MHz optical pulses, which is attenuated to an average photon number per pulse of $\mu = 0.1$ before being launched into the PMT (R980, Hamamatsu) through an ambient-light filter. The temperature of the PMT is precisely controlled by a Peltier cooler with the driver (LFI3751, Wavelength Electronics) and separated from the external environment by a constant-temperature water chiller (T255 P, ThermoTek). Mainly, we use a vacuum pump to keep the PMT-located cavity lower pressure so that it almost has non aqueous vapor, which efficiently hedges the risk of any damage to the PMT resulting from freezing. Figure 1(b) illustrates the PMT cooling subsystem,



(a)

(b)

Fig. 1. Experimental setup of ultralow-noise SPD system: (a) principle; ATT, attenuator; AMP, amplifier; (b) PMT cooling subsystem; EMS1/EMS2, electromagnetic shielding.

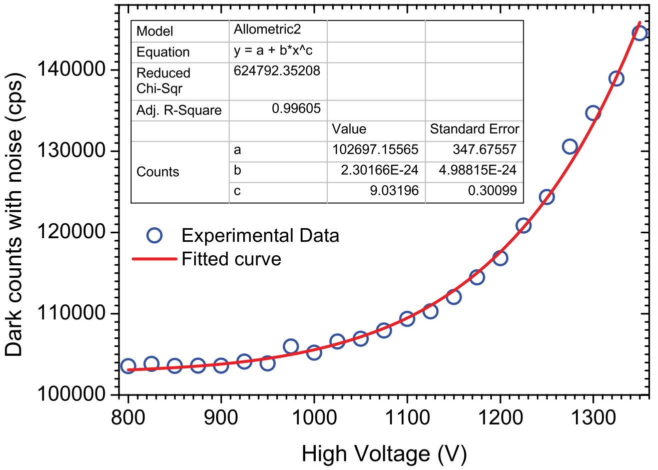


Fig. 2. DCs (cps) under different high voltage of the PMT without noise reduction.

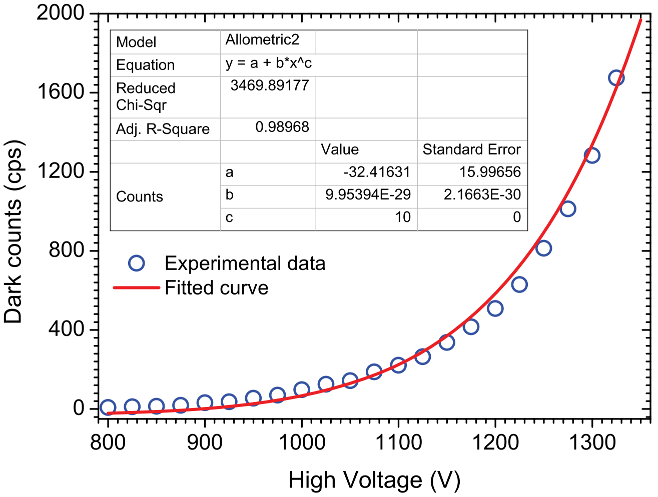


Fig. 3. DCs (cps) under different high voltage of the PMT after electromagnetic shielding and self-differencing.

which has high accuracy and can restrict the temperature fluctuation of the PMT as low as 0.01°C.

The detected signals from the PMT are amplified by a fast timing preamplifier (VT120, Ortec), then processed in a constant-fraction 200 MHz discriminator (model 935, Ortec), and finally recorded through a computer controlled counter (model 974 A, Ortec). First, we measure the noise or DCs of the system operated at room temperature (25°C), however, the result is larger than expected. The background noise is rather large, which is around 92 kcps (cps: counts per second). The reason is that there is a high-power base station close to our lab. Moreover, by increasing the operating voltage applied on the PMT, the DCs grow up quickly. At 1350 V, it is over 145 kcps, as shown in Fig. 2(a), from which we can find that the DC has exponential growth along with the high voltage increasing. Analysis shows that the index is nine, but the stage number of the PMT is 10 in our experiment, so the serious noise has distorted the real rule of the PMT detection.

In order to reduce the noise, we add double electromagnetic shielding for the PMT detector. Moreover, we introduce the self-differencing module before the preamplifier (VT120), which is mainly used in APD-based SPD[15]. The module is composed of a 50:50 power splitter, a 2 ns delay line, and a subtracter. The signal is first split into two equal parts, and after being delayed 2 ns in one arm, they are combined in the subtracter. Because the noise will be partly reduced due to subtraction, the signal-to-noise ratio is further improved. Figure 3 illustrates the DC number versus the high voltage of the PMT, which shows that it is only 1.6 kcps (nearly 1% of that before processing) at 1350 V, and the index is just 10, which is the same as the gain stages of the PMT. Thus, the system is now available for SPD.

It is reasonable to subsequently characterize the input single photons and the response of the PMT-based SPD. When turning on the 100 MHz generator, the laser emits the optical pulses with the same frequency. After being attenuated to single photons, they will be captured by the SPD and output corresponding counting signals. We record the single photon counts and obtain its statistical photon-number distribution, which is plotted in Fig. 4(a). Meanwhile, we employ a high-speed oscilloscope to measure the detected single-photon signals, while comparing them with the synchronized 100 MHz trigger. Only when they are superposed are the detected signals

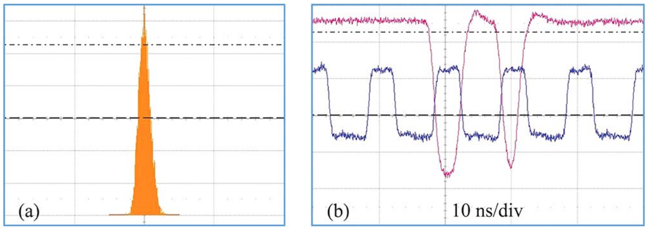


Fig. 4. (Color online) (a) Photon-number distribution of single photons under test, (b) detected single photons (red line) and 100 MHz synchronized trigger (blue line).

generated by incident single photons. We find some of these cases and illustrate one in Fig. 4(b), where the interval of adjacent single-photon signals is around 10 ns, which indicates that the SPD has fast temporal response and is available to detect high-speed single photons up to 100 MHz.

As we all know, the rate of QKD is only a few thousand cps at present[1,2]. If the DC is hundreds of or even 1000 cps, it is impossible to distribute the quantum keys properly. On the other hand, the DC is mainly contributed by thermal noise, which means reducing the temperature of the PMT is an efficient way to further reduce the DC number.

At the beginning, we turn on the vacuum pump to reduce pressure of the cavity to about 15 kPa, and set the high voltage of the PMT at 1250 V, while keeping it stead. For the temperature range from 25°C to 15°C, we use the water chiller to control the temperature of the PMT. While below 15°C, we power on the Peltier cooler and set the temperature, which will be automatically controlled and locked. At each test point, we measure and record the DC number. Experimental results confirm that decreasing the temperature will reduce the DC greatly, which is partly shown in Fig. 5. To find the rate of DC reduction, we produce the log-log plot, which is inserted in Fig. 5, where the unit of temperature is Kelvin. Further analysis shows that the DC is reduced by a factor of 3.9 each time the temperature drops 10°C, which is reasonable according to Ref. [16].

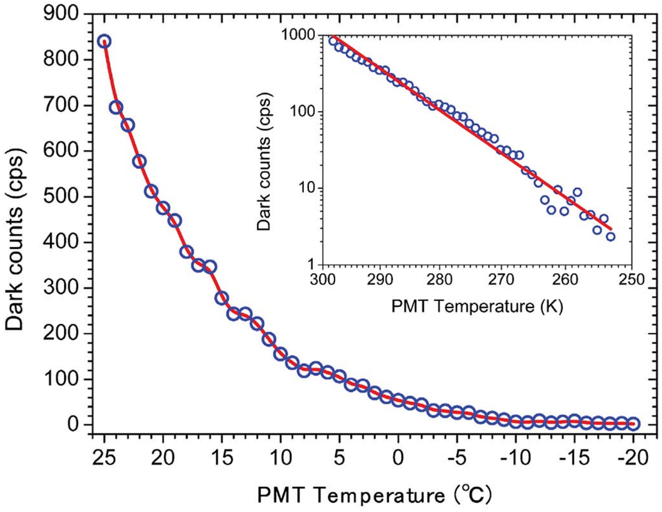


Fig. 5. DCs (cps) at different temperatures and its log-log plot (inset).

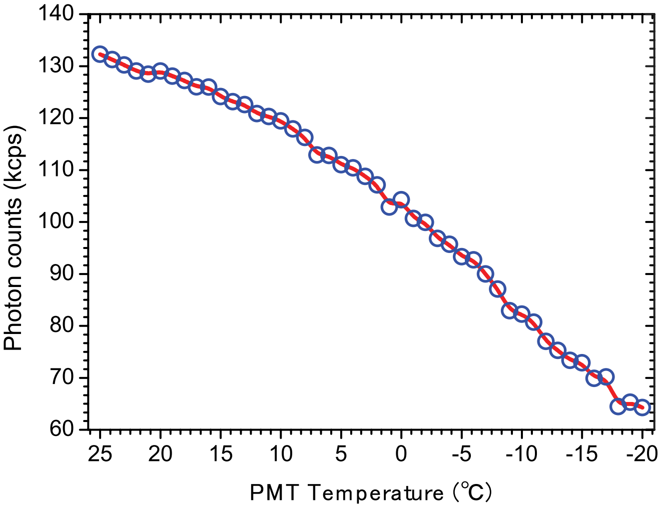


Fig. 6. Photon counts (kcps) at different temperatures.

Furthermore, we execute photon detection at above the temperature range. To ensure that almost every pulse is attenuated to single photons, we increase the attenuation factor and generate a single-photon train with a rate about 500 kcps from 100 MHz optical pulses. At room temperature (25°C), the photons counted by our SPD are ~133 kcps, from which we can infer that the detection efficiency is around 23.6%. However, as the temperature decreases, it goes down gradually, as shown in Fig. 6. At −20°C, we can find it becomes 13%, which is about half of that at 25°C. Compared with the large decrease (~400 times) of the DC number, the reduced detection efficiency is acceptable because it is still beyond 10% at the lower temperature of −20°C, while the DC is only 2 cps.

In conclusion, we develop and demonstrate ultralow-noise SPD based on a sensitive PMT with precise temperature control, which can capture fast single photons with intervals around 10 ns. To reduce the DC noise, we first improve the electromagnetic shielding, while applying the self-differencing method, which cuts down the DC to ~1%. Furthermore, we develop an ultra-stable cooling subsystem for the PMT and observe that the DC goes down by a factor of 3.9 each time the temperature drops 10°C. At −20°C it is further reduced 400 times with respect to the room temperature, that is, it becomes only 2 cps, which is on par with the superconducting nanowire detectors. Meanwhile, although the detection efficiency is decreased 50%, it is still 13%. Our results are available for realizing ultra-precise SPD and high-speed QKD, especially in environments with strong electromagnetic disturbances.

This work was supported by the National Natural Science Foundation of China (Nos. 11574026 and 11274037), the Program for New Century Excellent Talents in

University, MOE of China (No. NCET-12-0765), and the Foundation for the Author of National Excellent Doctoral Dissertation, China (No. 201236).

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