第 35 卷第 6 期
2006 年 6 月
光 子 学 报
ACTA PHOTONICA SINICA
Vol. 35 No. 6
June 2006

Single Photon Detection at 1550 nm Wavelength at Temperature of Above 253 K*

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Abstract The selected APDs which have higher punch through voltage are used to prove single photon detection at 1550 nm communication wavelengths at temperature of above 253 K. In the experiment, a controllable nonlinear current limiting circuit is used to protect the APD operated in Geiger mode at high temperature. Single photon detection at 1550 nm communication wavelengths, cooled by a thermo-electrical cooler, were experimentally demonstrated at temperature of 257.8 K. Its dark count is 3.13$\times 10^{-5}$ ns and single photon detection efficiency is 2.08%. The experimental data indicate that it is possible to realize single photon detection at higher temperature. The APDs operated at the temperature of above 253 K can simplify the cooling device greatly.

Keywords Applied optics; Infrared single photon detectors; Dark counting; Peltier-cooler

CLCN TN247; TN29 **Document Code** A

0 Introduction

The single photon detectors used at 1550 nm wavelength quantum cryptography highly appeal for very high sensitivity and extremely low noise[1]. The best choice is the InGaAs/InP avalanche photodiode (APD) with separate absorption multiplication (SAM) at present. There are two techniques important for the single photon detection. One is cooling down the detector to decrease the dark counts, the other is to operate the APD above its breakdown voltage to obtain the highest sensitivity, which is so-called Geiger mode operation[2]. There basically are three techniques to practice Geiger mode operation: active quenching[3], passive quenching[4] and gated mode quenching[5]. Gated-mode operation can effectively decrease the dark counts by using the gating pulses synchronized with the arrival of photons[6]. Many efforts worldwide have been paid to improve the gated mode operation[7,8]. In order to obtain a tolerable dark count rate, these detectors must be cooled. The lowest dark count recorded at 77 K is only 1.8 $\times$ 10^{-5} in 50 ns time window[9]. It is important to use Peltier cooler to replace liquid nitrogen cooler in practical application. Therefore the temperature range must rises to about 203 K~243 K. A optimized quantum efficiency of 13.7% was reported at the temperature of 218 K though their study temperature range extends to 123 K by liquid nitrogen cooling[10]. The lifetime of the trapped carriers, which are the source of after-pulses and may result in dark counts, decreases with temperature increasing[11,12]. The lifetime of the trapped carriers at 201 K was found to be approximately 1 μs. Therefore the repeat rate of the gate pulses was limited to 10 kHz[13]. The earliest report that single photon detection operated at room temperature in Geiger mode with InGaAs/InP APD was in 1985[14], but that was at 1.3 μm with a quantum efficiency of only 0.4% and the detecting sensitive area was limited to be a miroplasma size of less than 10 μm in diameter. In fact, both the detection efficiency η and the dark counts P_{dark} increase (decrease) when the temperature or V_E increase (decrease)[11]. The maximum multiplication factor, the highest detection efficiency and the best signal-to-noise ratio appear at different temperature and bias condition[15]. In general, the breakdown voltage increases with temperature. Therefore a higher bias voltage should be used to obtain higher gain, faster response and to decrease the time jitter and after pulses. The detection efficiency and the frequency of the gating pulses can be increased due to the decrease of the lifetime of the trapped carriers. However, the dark counts increase with temperature even faster. For more practical and economical consideration, higher temperature is

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*Supported by National 973 program G2001039302; Guangong Province program 2003A1030405 and Guangzhou program 1999-Z-035-01

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Received date: 2005-07-22

better if the dark current can be decreased by the improvement of the device structure and the material growth method. Here we report the single photon detection experiment with the InGaAs/InP APD at 1550nm wavelength at temperature of 256.8K by using a passive quenching circuit which contains nonlinear current limiting element and gating discrimination.

1 Device structure and fabrication

The electronic circuit used in the experiment is shown in Fig. 1. The quenching resistor in the passive quenching circuit has been replaced by a nonlinear current limiting circuit. The components Q_1, Q_2, ic_1, W_i, W_{11}, R_{11}, C_{13}, C_{14} are integrated into a current limiting circuit. The current limiting circuit worked at nonlinear range so that its static resistance is small and the resistance will increase to a very large value immediately when the avalanche break down current appears. Without any feedback time, the avalanche current was quickly and effectively quenched. After the avalanche has been quenched, the small static resistance conduces to reset the APD quickly and decrease the dead time. The avalanche signal is amplified by an emitter feeding back transistor Q_3 and its collector is the output port.

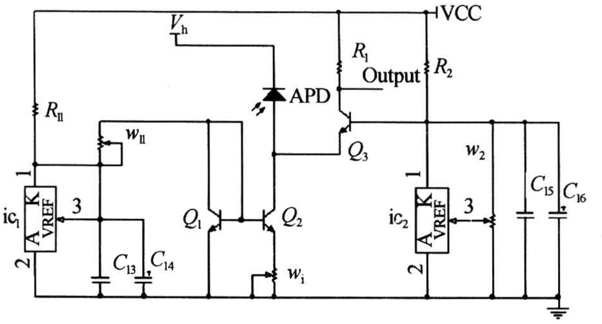

Fig. 1 The electrical control circuit of the APD containing a nonlinear quenching element

The APD used in the experiment was selected from JDS Uniphase, the part number is ETX 40 APD BA series ETX00408052-005 which is the replacement of the EPM 239 BA SS photodiode. The data from the manufactory are: Total dark current at 25℃ is −0.5 nA when biased at $V_r = V_b - 0.5$ V, The temperature coefficient of the breakdown voltage V_b is 0.18%/℃, the diode capacitance is only 0.6 pF, and the operation temperature ranges from −40℃ to 85℃.

Fig. 2 is a schematic diagram of the experimental setup for single photon counting. The laser pulses at 1550 nm wavelength are attenuated by a variable attenuator FVA-3100 from EXFO. The attenuated weak pulses are divided into two parts by a 50/50 beam splitter. One part is sent to power meter PM-1600 from EXFO, the other is further attenuated by a fixed attenuator which has previously been calibrated to have an attenuation of 57.581 dB. The final very weak optical pulses were detected by the InGaAs/InP avalanche photodiode. The APD was cooled at the temperature range from 230 K to 263 K by a Peltier-cooler. The amplified signal is sent to photon counter SR-400 from Stanford Research and monitored by oscilloscope TDS-1012.

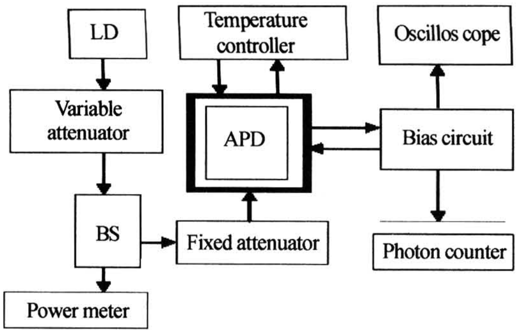

Fig. 2 Schematic diagram of the experimental setup for single photon counting

2 Results

The energy of the optical pulse is attenuated to different levels, so the average photons per pulse are different. The experimental results of the photon counting are shown in Fig. 3, when the operation temperature of the APD was stabilized at 256.8 K.

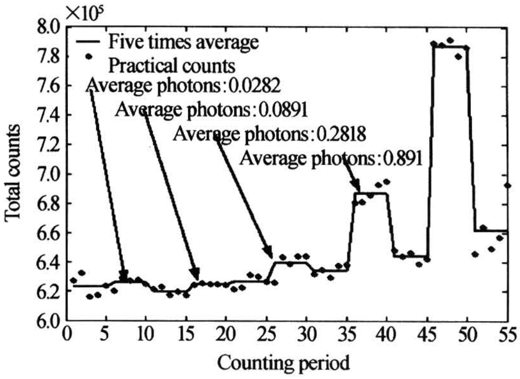

Fig. 3 The experimental data by SR-400 scan counting

The laser was modulated at a frequency of 220 kHz. The counting periods were 10 ms×2000, so the total counting time is 20 seconds. The counting with and without optical signals were performed alternately. The counts with optical signals were the total counts containing photon counts and dark counts. Therefore the total counts minus the dark counts is the pure photon counts. The counts began from dark counts when the temperature had been stabilized at 256.8 K and the dark count rate measured was 3.13×10^{-5} ns. The pure photon counts were 2587 when the input light pulses attenuated to −121 dBm were switched on. Though the case of the APD keeps stably at temperature of 256.8 K, the dark counts increased with the input power. It indicated that the core of the APD was warming up due to the avalanche current. The dots show the original record data. The lines show the average value of five times. Both of these data indicate clearly the statistics of the photon counts.

The final average optical power input to APD can be calculated and controlled with precisely controlled heavy attenuation technique[16]. The energy of a photon at 1550 nm wavelength is 1.28×10^{-19} J. When the input power is −121 dBm and modulation frequency is 220 kHz/s, the average photons per pulse is 0.028. In according to Poison statistics of the photons, the probability of single photon is 97.2% in the recorded data. The experimental data indicates clearly the single photon counts. The pure single photon counts on average for five times are 2587 in 20 seconds period. The photon detection efficiency is 2.08%.

The dark counts decreased to 1.87×10^{-5} ns when temperature dropped from 256.8 K to 253.2 K. But we did not see much improvement in signal-to-noise ratio. The operation temperature of APD for single photon detection at the 1550 nm wavelength in infrared region which have been reported were all below 243 K lately.

3 Conclusion

The recent study in using EPM 239 InGaAs APD for single photon detection which worked at 223 K, whose single photon detection efficiency was 10% with a dark count of about 2.5×10^{-5} ns[17]. In compare with these results, the dark counts of 3.13×10^{-5} ns in our experiment at 256.8 K is quite reasonable. The higher working temperature will ease or release the cooling need. Instead of multiple stage Peltier device, a single stage of Peltier device maybe is enough and it is not necessary to use electric fan or water circulator to dissipate the heat which is produced by the Peltier device. It will make the single photon detector smaller in size and convenient for practical use. The detection efficiency and signal-to-noise ratio should have potential to increase at this temperature by optimizing the parameters of the detector. What it emphasizes is the importance of the synchronizing technique if concerning with the intercept-resend attack from eavesdropper. Instead of simply cooling down the devices, it needs more efforts in studying the time jitter and improve the synchronizing techniques to increase the detection efficiency and signal-to-noise ratio at higher temperature.

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在高于253 K温度下的1550 nm波长单光子探测实验

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收稿日期:2005-07-22

摘 要 介绍了在高于253 K的温度下,实现红外单光子探测的实验．选用拉通电压较高的雪崩光电二极管(APD),设计制作了非线性限流技术保护高温工作的APD,利用半导体热电制冷器,在256.8K的温度下,实现了1550 nm波段的单光子探测实验．单光子探测的暗记数率为3.13×10^{-5} ns,在220 kHz/s的单光子脉冲速率下,探测效率为2.08%.

关键词 应用光学;红外单光子探测;暗计数;热电制冷

Wei Zhengjun was born in 1977. He received his bachelor degree in the department of physics of South China Normal University in 2004. He is carrying out his master degree research on the practical technique of quantum cryptography system. His current research is on the single photon detection.