Noise reduction methods of single photon detector based on InGaAs/InP avalanche photodiodes

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Abstract. This work is dedicated to the problem of noise reduction of single photon detector development based on InGaAs-InP avalanche photodiodes. Dark count probability and quantum efficiency of the detectors have been measured. We present the experimental fiber based quantum key distribution setup with phase coding of single photon states. The autocompensation two way optical scheme (plug&play) is used. The single photon source is the strongly attenuated laser pulse which goes through two paths of Mach-Zehnder interferometer where it undergoes the phase coding. Quantum channel is formed by 25 km single mode fiber. To generate the quantum key the four phases BB84 protocol is used.

1. Introduction
The telecommunication wavelength photodetectors are primarily made on the base of InGaAs photodiodes. Photon counting is the key part of quantum communication as the need arise to transmit single photons over long distances using optical fibers. InGaAs/InP single-photon avalanche diode detectors are favoured in a number of applications for single-photon detection at wavelengths around 1550 nm, e.g. quantum key distribution [1]. Gated quenching, in various realization, including the use of active quenching circuits [1,2], has been implemented in many of these applications to limit the charge flow per event to reduce the detrimental effects of the afterpulsing phenomenon. In this work the commercially available InGaAs avalanche diode ERM 547NT is used to design as single-photon detector. We implement the noise reduction methods proposed and measure dark count probability and quantum efficiency of the detectors have been measured. Experimental results of quantum key distribution on the fiber setup obtained with these detectors are given.

2. Single photon detectors based on InGaAs avalanche diodes
To detect individual photons, avalanche photodiode (APD) operates in the Geiger mode [1,2]. For this purpose, the reverse supply voltage in them is raised above the threshold breakdown voltage of the diode. The higher the voltage above the threshold the higher the probability to detect a photon. However, voltage augmentation is usually accompanied by an increase in the noise clicks without any incoming signal (dark noise) and the probability of the noise due the so-called afterpulsing effect.
During the passage of the avalanche current after an operation of the photodiode from a photon or thermal noise pulse, the so-called traps in the semiconductor volume can be charged and then, with a delay, they begin to discharge spontaneously and lead to a new avalanche of the charge. This causes the photodetector to operate falsely. The effect of afterpulses strongly restricts the maximal click rate of photon counting.

To reduce the influence of these undesirable effects, some special solutions are implemented. For example, APD cooling yields a significant decrease of dark noises. To decrease the probability of the appearance of afterpulses, active avalanche quenching is used. Another way is to operate in the mode with pulse supply when the voltage at the APD is sustained lower than the threshold and, to detect single photons, the voltage is raised above the threshold for a short time (for a few nanoseconds) [2,3]. After the passage of the avalanche, the voltage is decreased lower than the threshold for dead time 5–20 μs so that the traps could discharge.

The Figure 1 presents a block diagram of our quantum detector that is based on avalanche photodiode ERM547NT (VD1). Breakdown voltage of the avalanche photodiode can be adjusted with a precision 1 mV. The pulse widths of an avalanche gate (LE) and an avalanche detection strobe (QDET_IMP) can be adjusted using pulse shapers. Delay lines allow to adjust time lags from AVB_REQ pulse to LE and QDET_IMP. This time lags are required to shift an avalanche boost pulse (AVB) and LE to the time moment when the expected photon can cause the avalanche. Comparator DA3 is used to separate the avalanche pulses from the noise. The comparator discrimination threshold (Vth) can be adjusted with a precision less than 1 mV. The Figure 2 presents a timing diagram of the quantum detector. The diagram shows the sequence of changes in the main signals of the detector. T_{le.ws} – adjusted LE pulse width. T_{avb.ws} – fixed AVB pulse width, the pulse amplitude is 3.5 V and width is 1 ns. T_{le.dls}, T_{avb.dls} – adjusted delays from AVB_REQ pulse to LE and AVB pulses, respectively.

**Figure 1** – The quantum detector block diagram.
3. Single photon detectors: experimental results

We have measured of the dark noise and quantum efficiency for the used single-photon APD detectors ERM 547NT. Measurement of the dark noise was organized as follows. The measurements have been carried out in a dark room to protect APD from spurious photons. APD was cooled down to the -50°C temperature. The repetition rate $f_{\text{PULSES}}$ of the voltage pulses was 1 or 10 MHz. The pulses had a trapezoid form with the average duration of 2.5 ns and amplitude of 3.5V. This voltage was added to the DC bias voltage of the APD. The amplifier gave dark count pulses at the output. The average frequency of dark counts was measured by a controller FPGA. The articles often use the term the dark count probability per gate $P_D$ was calculated from the measured $f_{\text{DURK}}$ frequency as:

$$P_D = \frac{f_{\text{DARK}}}{f_{\text{PULSES}}}$$

(1)

To decrease the probability of the appearance of afterpulses after the passage of the avalanche, the voltage is decreased lower than the threshold for dead time 5–20 μs so that the traps could discharge. Figure 3 shows the plot of dark counts per second versus dead time. From this plot we obtain that optimal dead time equals to 5 μs.

Measurement of the quantum efficiency was organized as follows. The measurements have been carried out in a dark room to protect APD from spurious photons. APD was cooled down to the -50°C temperature. The repetition rate $f_{\text{PULSES}}$ of laser pulses and of the voltage pulses was set to 1 or 10 MHz. The delays of detected laser pulses and voltage pulses were synchronized. The average output power $P$ of laser 1550 nm was measured by a calibrated Coherent power meter. The corresponding mean photon number $\mu$ emitted per laser pulse is calculated from the formula:
\[ \mu = \frac{P}{\hbar \omega f_L} \]  
where \( \hbar \omega \) is the 1550 nm photon energy. The power \( P \) was set up to be \( 10^6 \) photons emitted per laser pulse on the average. After passage through a combination of fiber attenuators with the total loss of 70 dB the photon flux was attenuated to \( \mu \approx 0.1 \) photons per laser pulse. The photon statistics, i.e., probability \( P_n \) to find \( n \) photons in a laser pulse, is given by the Poisson distribution:

\[ P_n = \frac{\mu^n}{n!} e^{-\mu} \]

For \( \mu = 0.1 \) one obtains \( P_0 = 0.905 \), \( P_1 = 0.0905 \), \( \Sigma P_{n>1} = 0.0045 \). This means that the probability to receive more than one photon is negligibly small in comparison with the probability of single-photon laser pulses. The output of the 70 dB attenuator was directly connected to the input of APD ERM 547NT. The average total frequency \( f_C \) of the counts was measured by a controller FPGA. The quantum efficiency \( \eta \) was calculated as follows:

\[ \eta = \frac{1}{\mu} \left[ \frac{f_C}{f_L} - P_D \right] \]

The measured dependences of quantum efficiency versus APD bias voltage at the 1 MHz repetition rates and -50°C temperature is presented on Figure 4. From these dependences one finds that the APD breakdown voltage at -50°C is close to 55 V (given by the sum of the bias and gate voltages).

**Figure 3.** Measured number of dark counts per second versus dead time for quantum detector based on APD ERM 547NT.

**Figure 4.** Quantum efficiency dependence on reverse voltage for quantum detector based on APD ERM 547NT.

4. **Quantum key distribution: experimental results**

From the practical standpoint, quantum cryptography is today the most mature area of quantum informatics. The essential purpose of quantum key distribution (QKD) is to create a secure communication process between two legal users, Alice and Bob, even with an eavesdropper Eve in the
channel [1, 4, 5]. The first QKD protocol was proposed in 1984 [6]. This protocol is known as BB84. The first experimental demonstration was in 1992 [7].

We constructed a fiber based quantum cryptography setup to investigate the quantum key generation in the fiber channel [2,3]. This setup is controlled by the integrated processor and operates on the standard telecom wavelength. Quantum key distribution was implemented on the base of phase coding of the quantum states of single photons, emitted from a pulsed semiconductor laser, in the two alternative non-orthogonal bases. All the optical elements including laser, phase modulators and high speed attenuators are integrated to the single mode fiber. The optical scheme of the setup is designed in a two-pass autocompensating scheme [1,8]. This scheme consists of transmitter Alice and receiver Bob which are connected with the 25 km quantum channel made of the single mode fiber SMF-28. The quantum key generation process is totally guided by the standard computers (PC). These computers are setting the optolectromic components adjustments with the use of the high speed programmable array (FPGA) totally integrated in the setup. Photons were counted by single photon detector.

In this optical circuit with pulses traveling forward and back, Rayleigh backscattering can considerably increase the noise recorded by the single-photon APD detectors operating in the single-photon counting mode during quantum key distribution. Therefore, the laser does not continuously generate pulses but emits pulse trains in each transmission cycle, and the length of these trains corresponds to the length of the storage line which is inserted in Alice’s optical circuit. Due to this, the single-photon pulses propagating back in the quantum channel do not overlap with the multiphoton pulses going from Bob to Alice. For a storage line 25 km long, the train contains ~2400 pulses at a laser pulse clock frequency of 10 MHz. In experiment, random numbers are generated by both sides using a pseudo-random number generator.

Alice stores the serial number of each pulse and the value of bit. Bob buffers both the serial number of the pulse and the measurement basis of the single photons detected, and sends them to a computer. Based on these data and using the public channel between the computers, Alice and Bob generate the same quantum key. The key generation process is completely operated and controlled by standard PCIs, which set the operating mode of the optoelectronic components by means of a high-integration high-speed programmable array.

We performed test quantum key distribution experiments on the our experimental setup [2,3]. Preliminary measurements were made to assess the contrast of the interferometer, which is the source of additional errors in key distribution [8]. The measurements were performed in a multiphoton mode in which there was no noise due to the self-noise of the single-photon detectors operating in the Geiger mode. The measured interferometer contrast was not worse than 98.5%, which is sufficient to minimize the errors due to imperfection of the optical circuit. On an extended fiber optic communication line with a length of 25 km the 3.2 kbit/s bit rate was obtained on the quantum key distribution setup. The total amount of errors in the key did not exceed 8%. Considering that error rate in the quantum key distribution should be lower than 11% [1,5] result achieved on this setup can be considered as suitable for the real key distribution.

5. Conclusion

A processor-controlled fiber-optic experimental setup for quantum key distribution at telecom wavelength was designed. The self-compensated two-channel optical circuit allows operation with a communication channel 25–100 km long [1-3,8]. The setup uses specially designed single-photon detectors based on InGaAs : InP avalanche photodiodes ERM 547NT. Quantum efficiency and dark noise levels were measured. Low noise avalanche photodiodes improves the singlephoton detector
parameters and allows to achieve higher bit rate of quantum key distribution. For example the photodiodes of Princeton lightwave demonstrate outstanding parameters. Experimental studies in quantum cryptography are attracting steadily increasing interest in the world. Intensive practical studies are in progress in many scientific establishments and telecommunication companies.

Acknowledgments

This work was supported by RFBR (Grant No. 14-07-00809) and by the Siberian Branch of the Russian Academy of Sciences.

6. References

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