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Automation of Measuring Parameters of Single Photon Detectors at a Modular Research Quantum Key Distribution Setup

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***Abstract*—This paper considers the issue of developing software for automated measurement of single photon detectors at a modular research quantum key distribution setup. The results of measuring the parameters of single photon detectors are presented.**

Keywords*—single photon, detector, parameter, measurement, software, quantum communication.

I. Introduction

In various scientific and industrial fields, problems are solved in which it is necessary to register single photons. For this, single photon detectors (SPD) are used, which is based on various physical principles [1]. One of the rapidly developing areas that can ensure the safe transfer of information is quantum communication. In quantum key distribution (QKD) setups, SPD based on avalanche photodiodes are mainly used [2–4]. To determine the optimal operating mode of the SPD, it is necessary to measure its parameters.

The aim of this paper is developing software for automated measurement of SPD parameters based on avalanche photodiodes operating in the asynchronous photon detection mode at a modular research setup for quantum key distribution produced by QRate [5].

II. Experimental Setup

The modular research setup for quantum key distribution consists of two main units, Alice and Bob. Alice is in charge of the quantum signals preparation, whereas Bob measures the results [5]. Each unit contains motherboard with SMA connectors and two socket rows for add-on cards. The laser module and phase modulator drivers are implemented in the form of such cards. The main function of the motherboard is to provide commutation between add-on cards and the NI PCIe 7841R board, installed in a personal computer (PC). An optical circuit implementing the QKD protocol includes the circulator, beamsplitters, Faraday mirror, phase modulators, constant and variable optical attenuators.

Setup is controlled from a PC using the NI PCIe 7841R board and software written in LabVIEW which is a graphical program-development environment based on the G programming language. This approach makes it possible to build various optoelectronic circuits and provides a relatively quick and easy development of software that implements the logic of their work.

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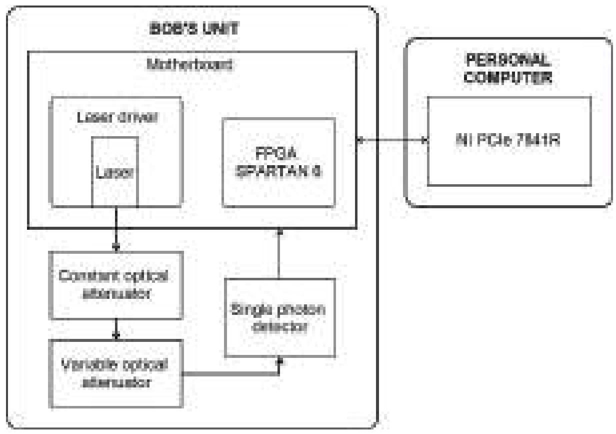

Fig. 1. Block diagram of an experimental setup for measuring SPD parameters.

Fig. 1 shows the optoelectronic circuit for measuring the SPD parameters assembled on the basis of the Bob's unit. A laser module including a laser driver and a thermostabilized semiconductor laser operating in a pulsed mode on the standard telecommunication wavelength $\lambda = 1550$ nm is installed in the motherboard. The radiation is attenuated by constant optical attenuator and variable optical attenuator taken from the Alice's unit. Attenuated radiation falls on the SPD.

III. Software and Measurement Method

The developed software for measuring SPD parameters can be divided into three parts.

The first part is a user interface, allowing to set the laser pulse repetition rate, attenuation coefficients of constant and variable optical attenuators, number of measurements, duration of one measurement, confidence probability, path to the file on the hard disk where the measurement results are saved.

The second part is the firmware for the Virtex-5 LX30 FPGA located on the NI PCIe 7841R board and is responsible for controlling the operation of the laser and processing the signals received from the SPD.

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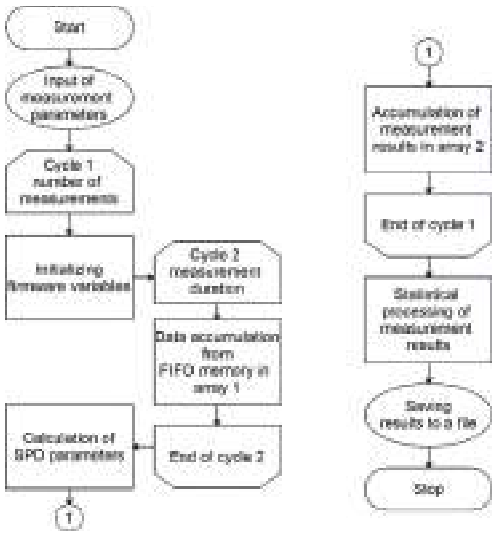


Fig. 2. Software flowchart.

The third part is the statistical processing of the collected measurement data, which includes determining the average value of the measured quantity, the absolute and relative measurement errors.

Fig. 2 shows a software flowchart that implements a technique for measuring SPD parameters.

After starting the program, the variables assigned through the user interface are assigned to the variables.

The SPD parameters are measured several tens of times, which are realized by a single measurement of the SPD parameters in cycle 1. The procedure for a single measurement of the SPD parameters consists of the following. During a given time, the laser generates pulses with a given repetition rate from the range from 0.5 kHz to 15 kHz (cycle 2). SPD responses are fixed. Statistics are accumulated in array 1 over a time equal to the pulse repetition period. Using the obtained time distribution of SPD responses, the time (t_{count}) and number of SPD responses (N_{count}) at the moment of arrival of pulses, the time of occurrence (t_{ap}), and the number of afterpulses (N_{ap}) are determined.

Based on the measured values, the following SPD parameters can be determined: the photon detection probability (p_{count}), the afterpulse probability (p_{ap}) and the dead time (t_{dead}).

The photon detection probability is defined as the ratio of the number of registered photons by SPD to the total number of photons (N) arriving at it

$$p_{count} = \frac{N_{count}}{N}, \qquad (1)$$

$$N = N_1 N_{imp} 10^{-(\alpha_{const}+\alpha_{var})/10} \infty, \qquad (2)$$

$$N_1 = \frac{E_{imp}}{E_1} = \frac{P_{imp}\lambda}{\nu hc}, \qquad (3)$$

where N_1 is the number of photons in one pulse, N_{imp} is the number of pulses, E_{imp} is the pulse energy, E_1 is the energy of one photon, P_{imp} is the pulses power, ν is pulse repetition rate, h and c are fundamental physical constants.

The afterpulse probability is the ratio of the number of afterpulses to the number of registered photons

$$p_{ap} = \frac{N_{ap}}{N_{count}}. \qquad (4)$$

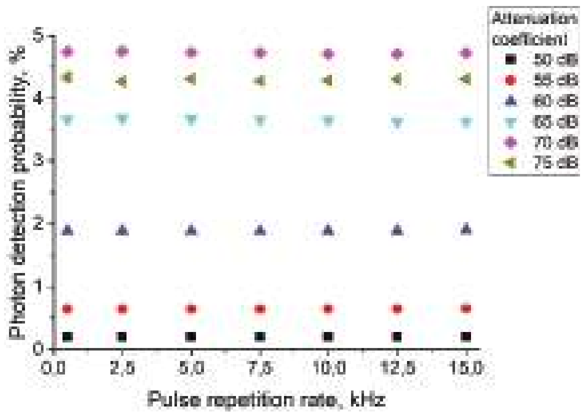
The dead time of the SPD corresponds to the time after the photon is recorded, during which the detector is unable to register new photons, and is equal to the difference between the time of occurrence of the afterpulses and the time of registration of incoming photons

$$t_{dead} = t_{ap} - t_{count}. \qquad (5)$$

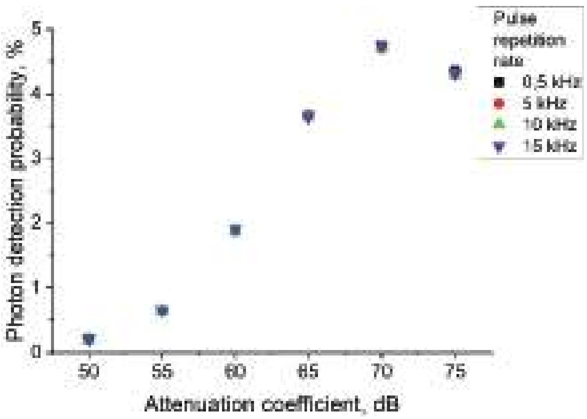
It should be noted that the correct measurement results using this technique can be obtained only with a certain measurement mode, which can be determined by a series of measurements of the SPD parameters at different settings of the experimental setup.

IV. Results and Discussion

Using the developed software, the dependences of the SPD parameters on the pulse repetition rate, the degree of attenuation of laser radiation, the duration of one measurement are analyzed.



(a)



(b)

Fig. 3. Dependences of the photon detection probability on the pulse repetition rate (a) and the degree of attenuation of laser radiation (b).

Fig. 3 shows the results of measurements of the photon detection probability depending on the pulse repetition rate and the degree of attenuation of laser radiation. The photon detection probability is practically independent of the pulse repetition rate, but has an extremum dependence on the degree of radiation attenuation.

SPD is intended for registration of single photons. Therefore, if a pulse containing many photons arrives at the SPD, then only one response of the detector still occurs. Thus, it can be roughly said that the SPD registers pulses with a certain probability.

Thus, for correct measurements it is necessary that the laser pulse arriving at the SPD ideally contains one photon, i.e. the number of photons arriving at the SPD should be equal to the number of pulses sent ($N = N_{imp}$). This is only possible when using the so-called single photon source. In the case of laser radiation, the distribution of the number of photons in a pulse obeys the Poisson statistics. Therefore, it is necessary to attenuate the radiation so that the pulse contains approximately one photon. Moreover, according to Poisson statistics, there will be several photons in some of the pulses, and some pulses will be completely empty (there is not a single photon).

If the attenuation coefficient is zero, then each laser pulse contains a large number of photons. Accordingly, in (1) $N = N_1 N_{imp}$, $N_{count} = p_{count} N_{imp}$ and $N_{count} << N$.

Consequently, the photon detection probability tends to zero. An increase in the attenuation coefficient leads to a decrease in the number of photons in pulses, as a consequence, the denominator in (1) decreases. At the same time, the numerator in (1) remains unchanged. Thus, there is an increase in the the photon detection probability in Fig. 3.

At a certain moment, we achieve a situation where each pulse contains approximately one photon. According to Fig. 3, this happens when the attenuation coefficient is 70 dB and corresponds to a maximum photon detection probability of 5%. The correct value of the measured parameter is obtained precisely with such an attenuation of the laser pulses.

Equation (1) assumes that all sent pulses reach the SPD. A further increase in the attenuation of laser pulses, according to Poisson statistics, leads to an increase in empty pulses, i.e. to a decrease in the pulses reaching the detector. In this case, $N_{count} = p_{count} (N_{imp} – N_{empty})$, where N_{empty} is the number of empty pulses. Thus, the numerator in (1) decreases, and faster than the denominator. Therefore, in Fig. 3, with an attenuation coefficient greater than 70 dB, a decrease in the photon detection probability is observed.

Fig. 4 illustrates the dependence of the afterpulse probability on the pulse repetition rate. The dependence of dead time on the pulse repetition rate is shown in Fig. 5.

The afterpulse probability and the dead time of the SPD decrease with increasing pulse repetition rate and tend to the corresponding constant values that are true. Let us consider further the reason for this dependence of the SPD parameters.

On the time distribution of SPD responses after the end of the dead time, parasitic detector responses are observed at different times, which are random in nature and are caused, for the most part, by multiple reflections on plug connections.

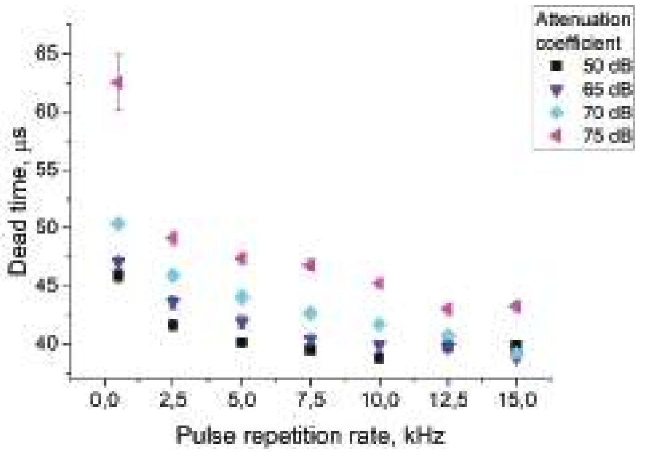


Fig. 4. Dependences of the afterpulse probability on the pulse repetition rate.

Since the dead time of the SPD is a priori selected so that the probability of occurrence of afterpulses tends to zero, in order to detect the afterpulse (response of the detector immediately after the dead time), a sufficiently large number of pulses must be sent. This can be achieved either by increasing the laser pulse repetition rate or by increasing the time of one measurement, which was 2000 ms in the measurements and, as will be shown further, is too short for the correct measurement of the dead time and the afterpulse probability.

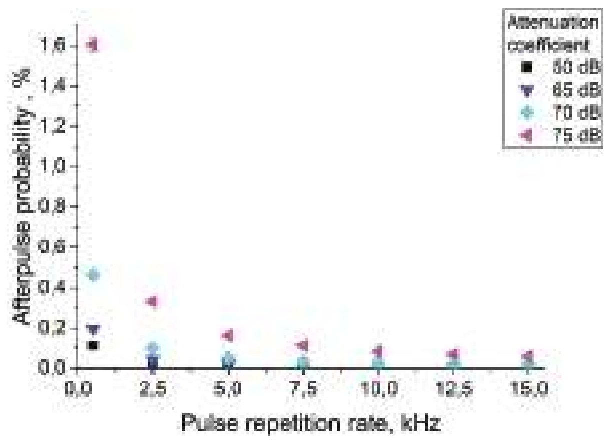
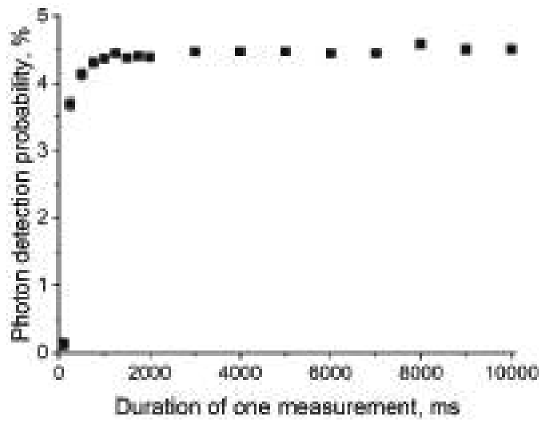


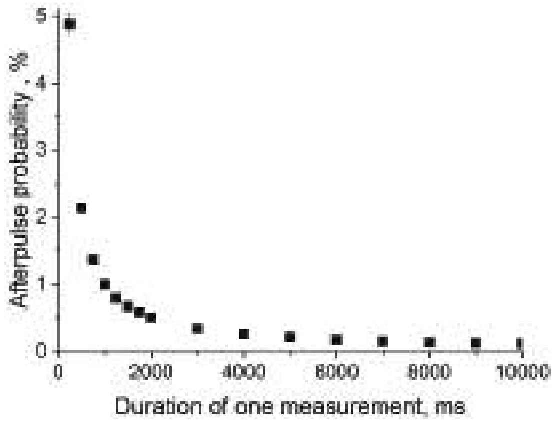
Fig. 5. Dependences of the dead time on the pulse repetition rate.

The algorithm inherited in the software is designed in such a way that the first response of the detector is sought after the registration of the laser pulse. If sufficient statistics of SPD responses is not collected, then instead of the afterpulse, the first response due to multiple reflections will be taken for calculation. This leads to an increase in the value of dead time. Moreover, the less attenuated the laser pulse, the higher the probability of the detector response due to multiple reflections. As a consequence, there is a smaller value of the dead time in Fig. 5, which increases with an increase in the attenuation coefficient.

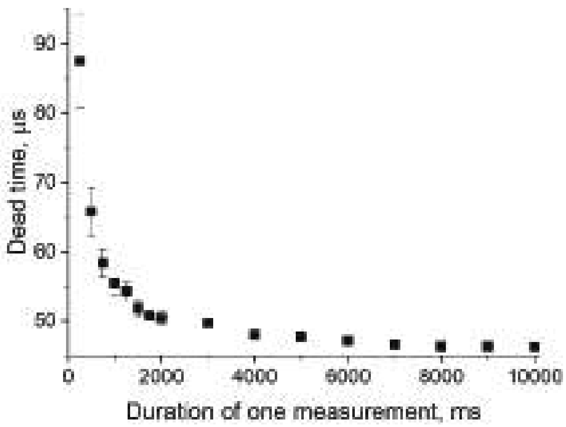
What was said above similarly leads to an incorrect determination of the afterpulse probability, which is actually close to zero. This is confirmed by the tendency to zero of the afterpulse probability with an increase in the pulse repetition rate in Fig. 4. Such a small afterpulse probability can be explained by the fact that the approximately 40 μs dead time is large enough so that all unwanted avalanche processes end and are not accepted by the detector.



(a)



(b)



(c)

Fig. 6. Dependences of the photon detection probability (a), afterpulse probability (b) and dead time (c) on the pulse repetition rate.

We do not exclude the possibility that those responses of the detector, which are taken as afterpulses, can also be caused by multiple reflections. But, in spite of this, adequate values of the SPD parameters corresponding to reality are obtained.

Fig. 6 shows the dependences of the photon detection probability, the afterpulse probability, and dead time on the duration of one measurement, obtained with a pulse repetition rate of 0.5 kHz and a total attenuation coefficient of laser radiation of 70 dB.

To measure the photon detection probability, duration of one measurement of 2000 ms is sufficient. At the same time, for the correct measurement of the afterpulse probability and dead time, the duration of one measurement should be at least 8000 ms.

V. Conclusion

Thus, as a result of this research, software was created to automate the measurement of parameters of single photon detectors at a modular research quantum key distribution setup. Using the developed software, the dependences of the SPD parameters such as photon detection probability, afterpulse probability and dead time on the pulse repetition rate, the degree of attenuation of laser radiation, and the duration of one measurement are measured. The operating mode of the experimental setup is determined, which ensures the correctness of measurements of the SPD parameters.

It should be noted that the considered technique for measuring the SPD parameters does not pretend to be precise, but it makes it possible to estimate the value of these parameters with sufficient accuracy. The values of the SPD parameters obtained in this study correspond to the values of these parameters declared by the manufacturer.

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