Software for measuring parameters of single photon detectors at a modular research quantum key distribution setup

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Abstract. This article considers the issue of developing software for automated measurement of single photon detectors parameters at a modular research quantum key distribution setup. Using the developed software, a technique for measuring single photon detector parameters was tested. The dependences of the parameters on the pulse repetition rate, the degree of attenuation of laser radiation, and the duration of one measurement are analyzed.

1. 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].

2. 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.

Figure 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 \( \lambda = 1550 \text{ nm} \) 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.

![Block diagram of an experimental setup for measuring SPD parameters.](image)

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

3. **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 setting 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.

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.

Figure 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 (figure 3) of SPD responses, the time ($t_{\text{count}}$) and number of SPD responses ($N_{\text{count}}$) at the moment of arrival of pulses, the time of occurrence ($t_{\text{ap}}$), and the number of afterpulses ($N_{\text{ap}}$) are determined.

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

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.
\[ P_{\text{count}} = \frac{N_{\text{count}}}{N}, \]
\[ N = N_N N_{\text{imp}} 10^{-1} \alpha \mu + \alpha_{\text{ave}}/10, \]
\[ N_1 = \frac{E_{\text{imp}}}{E_1} = \frac{P_{\text{imp}} \lambda}{\nu h c}, \]

where \( N_N \) is the number of photons in one pulse, \( N_{\text{imp}} \) is the number of pulses, \( E_{\text{imp}} \) is the pulse energy, \( E_1 \) is the energy of one photon, \( P_{\text{imp}} \) is the pulses power, \( \nu \) 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

\[ P_{\text{ap}} = \frac{N_{\text{ap}}}{N_{\text{count}}}. \]

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

\[ t_{\text{dead}} = t_{\text{ap}} - t_{\text{count}}. \]

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.

**Figure 2.** Software flowchart.
4. 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.

Figure 4 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. This behaviour is explained by the fact that for correct measurements it is necessary that the laser pulse arriving at the SPD ideally contains one photon, which is achieved approximately when the attenuation coefficient is 70 dB and corresponds to a maximum photon detection probability of 5%.

The afterpulse probability and the dead time of SPD decrease with increasing frequency and tend to the corresponding true constant values (figure 5). This is due to the need to send a relatively large number of pulses to the detector for the correct measurement of these SPD parameters, which can be achieved either by increasing the laser pulse repetition rate, or by increasing the duration of one measurement, which was 2000 ms in the measurements.
Afterpulse probability tends to zero. 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.

Figure 5. Dependences of the afterpulse probability (a) and the dead time (b) on the pulse repetition rate.

Figure 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.

Figure 6. Dependences of the photon detection probability (a), the afterpulse probability (b) and dead time (c) on the duration of one measurement.

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 the dead time, the duration of one measurement should be at least 8000 ms.

5. 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.

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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