St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2023. Vol. 16. No. 3.1
Научно-технические ведомости СПбГПУ. Физико-математические науки. 16 (3.1) 2023

Conference materials
UDC 53.082.52; 621.3.084.2
DOI: https://doi.org/10.18721/JPM.163.142

Evaluation of quantum efficiency of InGaAs/InP single-photon detectors in quantum key distribution systems

A.A. Filyaev [1, 2 ,3] ✉, A.V. Losev [1, 2, 4], V.V. Zavodilenko [1, 2, 3], I.D. Pavlov [1, 2]
[1] National University of Science and Technology MISIS, Moscow, Russia;
[2] "QRate" LLC, Skolkovo, Russia;
[3] HSE University, Moscow, Russia;
[4] National Research University of Electronic Technology MIET, Zelenograd, Russia
✉ a.filyaev@goqrate.com

Abstract. In this paper an important parameter of single-photon detectors, such as quantum efficiency, is considered. Errors in determining this parameter lead to significant errors in the parameters of a quantum key distribution system, where such detectors find their application. Three models are proposed to estimate photon detection efficiency or quantum efficiency and their main advantages and disadvantages are considered. A special experimental setup has been developed to carry out validation of the presented models on experimental data. It was found that at low values of laser radiation power the dependent and empirical models give good results, and the independent model is not applicable.

Keywords: quantum efficiency, single-photon detector, quantum key distribution systems

Funding: The study was commissioned by JSCo "RZD".

Citation: Filyaev A.A., Losev A.V., Zavodilenko V.V., Pavlov I.D., Evaluation of quantum efficiency of InGaAs/InP single-photon detectors in quantum key distribution systems, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.1) (2023) 237–241. DOI: https://doi.org/10.18721/JPM.163.142

This is an open access article under the CC BY-NC 4.0 license (https://creativecommons.org/licenses/by-nc/4.0/)

Материалы конференции
УДК 53.082.52; 621.3.084.2
DOI: https://doi.org/10.18721/JPM.163.142

Оценка квантовой эффективности InGaAs/InP детекторов одиночных фотонов в составе системы распределения квантовых ключей

А.А. Филяев [1, 2, 3] ✉, А.В. Лосев [1, 2, 4], В.В. Заводиленко [1, 2, 3], И.Д. Павлов [1, 2]
[1] Национальный исследовательский технологический университет МИСиС, Москва, Россия;
[2] ООО «КуРэйт», Сколково, Россия;
[3] Национальный исследовательский университет «Высшая школа экономики», Москва, Россия;
[4] Национальный исследовательский университет МИЭТ, Зеленоград, Россия
✉ a.filyaev@goqrate.com

Аннотация. В работе рассматривается важный параметр детекторов одиночных фотонов, такой как квантовая эффективность, ошибки в определении которой приводят существенным погрешностям в параметрах системы квантового распределения ключей, где такие детекторы занимают ключевое положение. Для оценки квантовой эффективности или вероятности детектирования фотонов предложены три модели, рассмотрены их основные достоинства и недостатки.

Ключевые слова: квантовая эффективность, детектор одиночных фотонов, системы квантового распределения ключей

© Filyaev A.A., Losev A.V., Zavodilenko V.V., Pavlov I.D., 2023. Published by Peter the Great St. Petersburg Polytechnic University.

Финансирование: Исследовательская работа выполнена по заказу ОАО «РЖД».

Ссылка при цитировании: Филяев А.А., Лосев А.В., Заводиленко В.В., Павлов И.Д. Оценка квантовой эффективности InGaAs/InP детекторов одиночных фотонов в составе системы распределения квантовых ключей // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.1. С. 237–241. DOI: https://doi.org/10.18721/JPM.163.142

Статья открытого доступа, распространяемая по лицензии CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/)

Introduction

Currently single-photon detectors (SPDs) are widely used in various fields. For example, these devices have found application in quantum key distribution (QKD), where they are indispensable [1–3]. In addition, SPD are used in time-resolved emission measurements, where the device is used to: verify the operation of individual circuit elements without directly affecting them [4], to detect singlet oxygen luminescence [5] and other applications [6]. There are also other applications, such as photon quantum computing [7], the LIDAR system [8], fluorescence microscopy [9], etc. However, in these areas, the use of SPD allows exclusively improving the accuracy of measurements, but is not a key element in the operation of these systems. In this paper, we consider a SPD based on an InGaAs/InP single-photon avalanche diode [10], which is used in QKD systems.

A major problem in SPDs is the inaccuracy in determining their operational parameters. Significant errors in determining the quantum efficiency or photon detection efficiency (PDE) [11] cause the parameters of the entire QKD system to become more difficult to predict and acquire significant uncertainties [12]. For example, an incorrectly defined PDE parameter can cause the absolute safety of the system to be an order of magnitude lower than expected. For this reason, this paper explores approaches to estimating this parameter. In the following, models to account for this phenomenon both in terms of physical processes and an empirical approach are considered as calculation models.

Materials and Methods

The experiment was carried out on the setup shown schematically in Fig. 1. The laser pulses have a repetition rate of 100 kHz and full width at half maximum of 50 ns. The laser pulses are fed to an attenuator with a power controller (A_{var}), where it controls the output integral power (within 1 second).

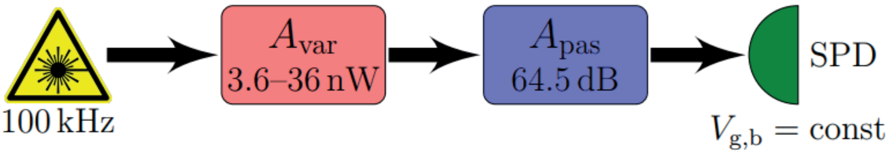

Fig. 1. Simplified schematic of the experimental setup

In the presented system, to obtain average number of photons per pulse $\mu = 0.1$ photon/pulse, the power $W \approx 3.6$ nW must be set, and to obtain $\mu = 1$ photon/pulse, the power $W \approx 36$ nW must be set. This value determined by the A_{var} attenuation is 64.5 dB, which includes the attenuation of the second attenuator and losses in the contacts and optical fiber. During all measurements with the change of W the detector parameters V_g and V_b (gate amplitude and bias voltage, which determine the detector characteristics) remained constant.

In the experiment the following data sets are to be obtained: R' is the count rate when the laser is switched off; R_i is the count rate when the laser is on and the output power μ_i from the set $\mu i \in \{\mu_1, ..., \mu_N\}$.

© Филяев А.А., Лосев А.В., Заводиленко В.В., Павлов И.Д., 2023. Издатель: Санкт-Петербургский политехнический университет Петра Великого.

Assuming mutual independence of photons in a k–photon state, the known theoretical prediction of detection probability is expressed as:

$$P_{det}(\mu)=\sum_{k=1}^{\infty}\frac{\mu^k}{k!}e^{-\mu}[1-(1-\eta)^k], \tag{1}$$

where the term $1-(1-\eta)^k$ denotes the probability that at least one photon will trigger the detector, assuming that simultaneous detecting of k-photons is considered as joint and independent events. The term $(\mu^k/k!)*e^{-\mu}$ denotes the probability that the laser pulse with energy μ will have k-photons.

If the k-photons interaction processes inside the detector are not independent (but still be joint), we can derive the laser pulse detection probability as:

$$P_{det}(\mu)=\sum_{k=1}^{\infty}\frac{\mu^k}{k!}e^{-\mu}\eta_k, \tag{2}$$

with some unknown detection probabilities η_k (in particular, $\eta_1=\eta$).

Three models are proposed in the paper:

1) The independent model, which assumes the independence of photons in the k-photon state. η_k is expressed as for such a model:

$$\eta_k=1-(1-\eta)^k, \tag{3}$$

where η is an unknown parameter.

2) The dependent model, which takes into account the photon interaction dependence. η_k is expressed as for such a model:

$$\eta_k=1-\prod_{i=1}^{k}(1-\rho_i\eta), \tag{4}$$

where η and ρ_i are unknown parameters. Parameter ρ_k denotes the amplification or loss of the probability of detecting the single-photon after $k-1$ unsuccessful detections. The independent model has only one unknown parameter, which has the physical meaning of PDE ($\{\eta\}$), and this model can be used in theoretical models for QKD. The dependent model has a more reasonable physical description and more appropriate parameters ($\{\eta, \rho_i\}$). The application of this model in theoretical studies is difficult, but the results obtained are more accurate. The main difficulties begin when the parameter μ is large enough (more than 1 photon/pulse). In this case, the number of used ρ_i should be more than 3.

3) An empirical model that includes only two unknown parameters η and ρ. η_k is expressed as for such a model:

$$\eta_k=\frac{1-(1-\rho\eta)^k}{\rho}, \tag{5}$$

This model is worth using if the independent model gives too coarse an estimate and the dependent model requires complex calculations.

Results and Discussion

We will validate the models by experimental data obtained from SPD measurements based on an InGaAs/InP single-photon avalanche photodiode PA19H262-0006 manufactured by Wooriro in gating mode, operating temperature $T=-50$ °C. Fig. 2 show the experimental data, and three curves corresponding to the models considered. The label η denotes the independent model, $\{\eta, \rho_i\}$ – the dependent model, $\{\eta, \rho\}$ – the empirical model. Fitted parameters for each model presented at the Table.

Table

Distinctive features of the studied samples

Model	η	ρ	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6
η	0.127	–	–	–	–	–	–
$\{\eta, \rho_i\}$	0.150	–	0.5	0.653	0.868	0.963	0.993
$\{\eta, \rho\}$	0.152	2.897	–	–	–	–	–

Analyzing Fig. 2, we can note that the independent model gives significantly different results from the experiment. However, in this case two other models are applicable. The empirical model gives the best result. We can see that η can differ for different models up to 0.02–0.03, that converted to PDE like Δη = 2–3%, which is a big enough value. Thus, for an accurate description of the detector's parameters, it is necessary to indicate within which model its PDE was determined.

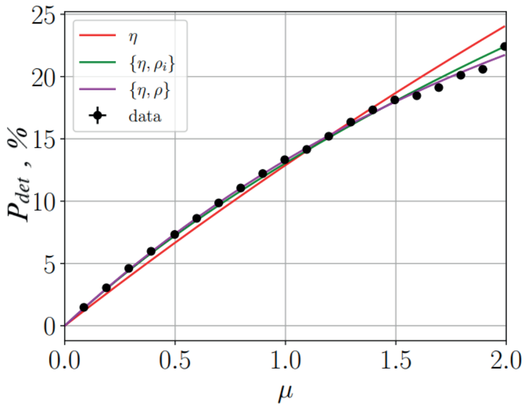

Fig. 2. Dependencies of detection probability P_{det}, obtained using the models considered, and experimental data for μ from 0 to 2 photon/pulse

Conclusion

Three models have been proposed to estimate the quantum efficiency. As a result of the research, it is found that:

1) The independent model approximates the experimental data rather poorly. This means that there are photon interaction effects inside the single-photon avalanche diode structure;

2) The dependent model is more physically sound, but a lot of experimental studies are required to obtain all necessary parameters ρ_i. If the range of interest μ is [0.1, 1] photon/pulse, this model is recommended. If μ > 1 photon/pulse, application of this model is not appropriate;

3) The use of an empirical model may be convenient for large ranges of μ, since it requires only two empirical parameters and approximates the experimental data reasonably well.

Acknowledgments

The study was commissioned by JSCo "RZD".

REFERENCES

1. **Kiktenko E.O., Pozhar N.O., Anufriev M.N., Trushechkin A.S., Yunusov R.R., Kurochkin Y.V., Lvovsky A.I., Fedorov A.K.,** Quantum-secured blockchain, Quantum Science and Technology. 3 (3) (2018) 035004.

2. **Fan-Yuan G.J., Teng J., Wang S., Yin Z.Q., Chen W., He D.Y., Guo G C., Han, Z.F.,** Optimizing single-photon avalanche photodiodes for dynamic quantum key distribution networks, Physical review applied. 13 (5) (2020) 054027.

3. **Zhang Y., Chen Z., Pirandola S., Wang X., Zhou C., Chu B., Zhao Y., Xu B., Yu S., Guo H.,** Long-distance continuous-variable quantum key distribution over 202.81 km of fiber, Physical review letters. 125 (1) (2020) 010502.

4. **Stellari F., Weger A.J., Kim S., Maliuk D., Song P., Ainspan H.A., Kwark Y., Baks C.W., Kindereit U., Anant V., Lundquist T.,** A Superconducting nanowire Single-Photon Detector (SnSPD) system for ultra low voltage Time-Resolved Emission (TRE) measurements of VLSI circuits, Int. Symp. for Testing and Failure Analysis (ISTFA). (2013) 182–188.

5. **Boso G., Ke D., Korzh B., Bouilloux J., Lange N., Zbinden H.,** Time-resolved singlet-oxygen luminescence detection with an efficient and practical semiconductor single-photon detector, Biomedical optics express. 7 (1) (2016) 211–224.

6. **Zhang H., Xiao L., Luo B., Guo J., Zhang L., Xie J.,** The potential and challenges of time-resolved single-photon detection based on current-carrying superconducting nanowires, Journal of Physics D: Applied Physics. 53 (1) (2019) 013001.

7. **You L.,** Superconducting nanowire single-photon detectors for quantum information, Nanophotonics. 9 (9) (2020) 2673–2692.

8. **Beer M., Haase J. F., Ruskowski J., Kokozinski R.,** Background light rejection in SPAD-based LiDAR sensors by adaptive photon coincidence detection, Sensors. 18 (12) (2018) 4338.

9. **Slenders E., Castello M., Buttafava M., Villa F., Tosi A., Lanzanт L., Koho S. V., Vicidomini G.,** Confocal-based fluorescence fluctuation spectroscopy with a SPAD array detector, Light: Science & Applications. 10 (1) (2021) 31.

10. **Sanzaro M., Calandri N., Ruggeri A., Tosi A.,** InGaAs/InP SPAD with monolithically integrated zinc-diffused resistor, IEEE journal of quantum electronics. 52 (7) (2016) 1—7.

11. **Hadfield R.H.,** Single-photon detectors for optical quantum information applications, Nature photonics. 3 (12) (2009) 696—705.

12. **Zhao L.Y., Wu Q.J., Qiu H.K., Qian J.L., Han Z.F.,** Practical security of wavelength-multiplexed decoy-state quantum key distribution, Physical Review A. 103 (2) (2021) 022429.

THE AUTHORS

FILYAEV Alexandr A.
a.filyaev@goqrate.com
ORCID: 0000-0001-7319-8001

ZAVODILENKO Vladimir V.
v.zavodilenko@goqrate.com
ORCID: 0000-0002-3252-2984

LOSEV Anton V.
a.losev@goqrate.com
ORCID: 0000-0002-6030-2532

PAVLOV Igor D.
ip@goqrate.com
ORCID: 0000-0001-8865-556X

Received 25.07.2023. Approved after reviewing 24.08.2023. Accepted 25.08.2023.

© Peter the Great St. Petersburg Polytechnic University, 2023