Conference materials
UDC 29.31.00
DOI: https://doi.org/10.18721/JPM.173.216

Polarization extinction ratio conversion due to pointing system impact in satellite quantum key distribution

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Abstract. Quantum key distribution via satellites enables the technology to be applied at transcontinental scale; nevertheless, in contrast to fiber systems, using a free-space optical communication channel presents certain extra technological obstacles. The contribution of the acquisition, pointing and tracking system's operation to the potential quantum bit error value is investigated in this research. The polarization extinction ratio measurements varying with the pointing mirror angular position are reported, based on these data, the upper limit of the quantum bit error is predicted for several types of satellite passages.

Keywords: quantum key distribution, polarimetry, polarization extinction ratio, free-space optics

Funding: This work was supported by the Ministry of Education and Science of the Russian Federation in the framework of the Program of Strategic Academic Leadership "Priority 2030" (Strategic Project "Quantum Internet").

Citation: Duplinsky A.V., Khmelev A.V., Bakhshaliev R.M., Sevryukov D.O., Barbyshev K.A., Kurochkin V.L., Polarization extinction ratio conversion due to pointing system impact in satellite quantum key distribution, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 17 (3.2) (2024) 88–92. DOI: https://doi.org/10.18721/JPM.173.216

Материалы конференции
УДК 29.31.00
DOI: https://doi.org/10.18721/JPM.173.216

Влияние системы наведения на изменение коэффициента поляризационной экстинкции в спутниковой квантовой криптографии

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Аннотация. Квантовое распределение ключей с использованием спутника позволяет применять эту технологию на трансконтинентальных масштабах; тем не менее, в отличие от оптоволоконных систем, использование оптического канала связи в свободном пространстве сопряжено с определенными дополнительными техническими препятствиями. Нами исследуется величина ошибок, вносимых в процессе работы системы сбора, наведения и слежения в величину потенциальной ошибки квантового бита. Приведены результаты измерений коэффициента поляризационной экстинкции, изменяющиеся в зависимости от углового положения наведения зеркала, и на основе этих данных прогнозируется верхний предел ошибки квантового бита для нескольких типов пролетов спутников.

Ключевые слова: квантовое распределение ключей, поляриметрия, коэффициент поляризационной экстинкции, оптика свободного пространства

Финансирование: Работа выполнена при поддержке Министерства образования и науки РФ в рамках Программы стратегического академического лидерства «Приоритет 2030» (Стратегический проект «Квантовый Интернет»).

Ссылка при цитировании: Дуплинский А.В., Хмелёв А.В., Бахшалиев Р.М., Севрюков Д.О., Барбышев К.А., Курочкин В.Л. Влияние системы наведения на изменение коэффициента поляризационной экстинкции в спутниковой квантовой криптографии // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2024. Т. 17. № 3.2. С. 88–92. DOI: https://doi.org/10.18721/JPM.173.2.16

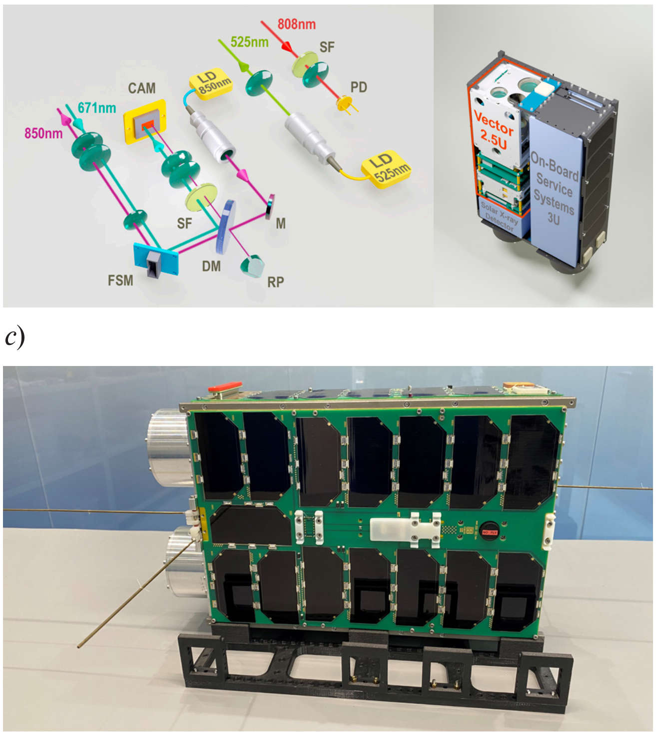
Introduction

Satellite quantum key distribution (QKD) requires acquisition, pointing and tracking system (APT) on both sides of the communication link, most often it is a closed feedback loop consisting of a controlled fast mirror and a camera [1, 2]. However, angular inclinations of the mirror cause polarization extinction ratio (PER) conversion during system operation, which negatively affects the quantum bit error (QBER).

In 2023, the Vector [2] payload was developed and successfully launched into orbit to demonstrate classical satellite laser communication. Moreover, it is also aimed at testing technical solutions and service systems for the future satellite payload to perform QKD, including APT. Vector's APT system uses a 671 nm laser beacon from a ground receiving station as a reference signal, detecting it on the camera matrix. APT's purpose is to tilt the MEMS mirror so that the detected point on the matrix match with the target point, resulting in parallelism between both optical axis of the satellite's transmitting scheme and ground station receiving scheme. Simultaneously, a similar procedure occurs at the ground station, which operates using a 525 nm beacon laser mounted aboard the satellite. The payload optical scheme and satellite general view are shown in Fig. 1

To communicate with the satellite, we use customized Zvenigorod ground station, which was previously successfully utilized as receiver during satellite QKD experiments with Micius satellite [3].

a) *b*)



c)

Fig. 1. Vector optical scheme. The payload has three apertures: two for downlink and uplink laser communications and one for downlink beacon laser operation. LD is the laser diode, M is the mirror, DM is the dichroic mirror, RP is the 180° reflective prism, SF is the spectral filters, CAM is the camera, FSM is the fast steering mirror, PD is the photodetector (*a*); 3D satellite model (*b*); general view of the satellite (*c*)

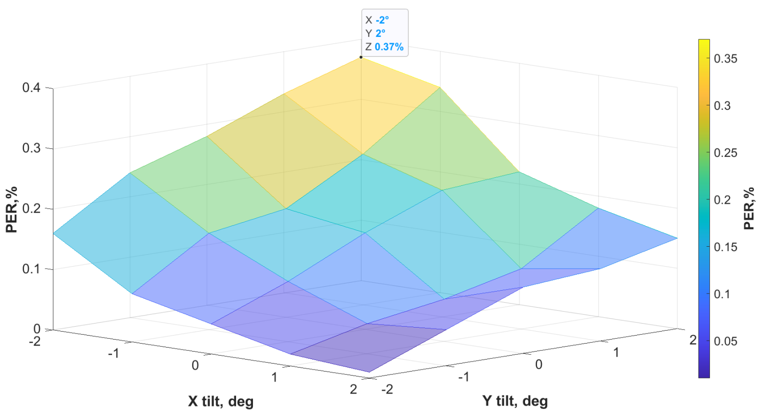


Fig. 2. Scanning results for different MEMS angles

Methods and Results

To assess the expected APT impact, Vector payload optical prototype was used. Its APT active element is performed by an aluminum-coated MEMS mirror with 5 mm aperture diameter. The optical signal of the prototype was measured using a polarimeter with ±2° deflection angles with a step of 1° for both axes. Thus, the entire working area of the MEMS mirror was scanned and PER for these points were measured. The scanning results are presented in Fig. 2.

The lowest PER point angular coordinates are (−2°; 2°), and its value is 0.37 %. Using this PER as the upper bound of the transmitter error, we estimate the potential maximum QBER.

$$e_{det}^{U} = e_{det}^{Rx} + e^{Tx,U}, \quad (1)$$

where e^{Rx}_{det} is the intrinsic error of the receiver when the input beam is perfectly polarized, $e^{Tx,U}$ is the upper bound of the transmitter error.

Utilizing the previously published model [4], we estimate the upper bound of the simulated QBER during a quantum key distribution session for a prospective satellite using a similar APT optical architecture.

$$\mathrm{QBER}(t) = \frac{e_0 Y_0 + e_{det}^{U}\left(1 - e^{-\mu\eta(t)}\right)}{Y_0 + 1 - e^{-\mu\eta(t)}}, \quad (2)$$

where μ is the intensity of signal states, e_0 is the error rate of the background, Y_0 is the background signal, η(*t*) is the link efficiency, e^{U}_{det} is the upper bound of an intrinsic error caused by measurement fidelity.

The predicted QBER function for two satellite passages with different maximum elevation angles $\theta_{El}^{max} = 32.5°$ and $\theta_{El}^{max} = 90°$, using $\mu = 0.8$, $e_0 = 0.5$, $Y_0 = 5 \cdot 10^{-6}$ clicks are presented in Fig. 3. The elevation angle reaches its maximum during the passage at 0 (s) - point, which also happens to be the instant with the lowest QBER value. The largest QBER occurs at the edges, when the angle between satellite and the ground station is at its minimum and the distance is at its maximum.

Fig. 3 shows that, during these QKD sessions, the QBER value remains under 3%; for any higher PER values, these lines will pass below.

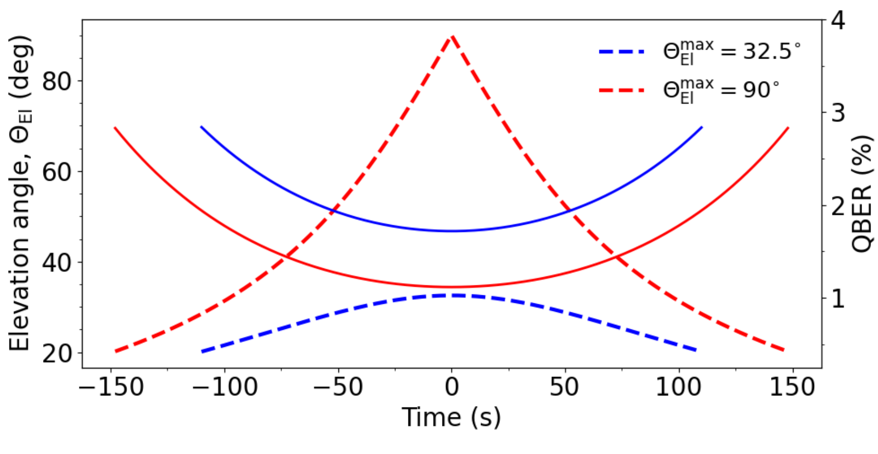


Fig. 3. QBER modeling results for two different passages

Conclusion

Polarization extinction ratio scanning and quantum bit error rate modeling show the possibility of using such an APT technical solution in the payload design for satellite quantum key distribution realization.

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Received 31.07.2024. Approved after reviewing 12.08.2024. Accepted 19.08.2024.