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Influence of polarization reference frame rotation on ground-receiver error rate in satellite quantum key distribution

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Abstract. Quantum key distribution (QKD) in a space-Earth communication link is a difficult technical task. Aside from precise mutual pointing of the optical axes during the satellite QKD session, the polarization reference frame coincidence of the satellite and the receiving station is also required. Satellite motion causes a rotation of the polarization reference frame in respect to ground station measurements of quantum states, which contributes to the error rate in time. In order to reduce the quantum bit error rate, we designed and tested a polarization correction device for the receiving ground station that is included as a part of our data analysis and processing module. We have measured the polarization properties of the ground-based receiver and showed the evolution of four polarization states over time for a typical satellite passage. An average polarization extinction ratio is equal to 200:1 for the optical free-space receiver. We have calculated the maximum permitted deviation of the polarization reference frame at the performance of the compensation system, which is less than 5.8 degrees when bit error rate is equal to 1,5%.

Keywords: Quantum communications, quantum key distribution, polarimetry, extinction ratio, optical design, photon polarization, single photon detectors, free-space optics

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Материалы конференции
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Влияние вращения поляризационной системы отсчета на величину ошибок в эксперименте по квантовому распределению ключей со спутника на наземную станцию

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Аннотация. Квантовое распределение ключей по линии связи космос-Земля является сложной технической задачей. Помимо точного взаимного наведения оптических осей во время сеанса квантовой связи со спутником, также требуется совпадение поляризационной системы отсчета космического аппарата и приемной наземной станции. В статье представлены результаты тестов системы коррекции поляризации для наземной станции, которая входит в состав приемного модуля анализа и обработки данных. Проведены измерения поляризационных свойств наземной приемной станции для четырех поляризационных состояний от времени в ходе симуляции типичного пролёта спутника. Усредненный коэффициент поляризационной экстинкции для оптического приемника составил 200:1. Максимально допустимое отклонение поляризационной системы отсчета при работе системы компенсации составляет менее 5,8 градусов при ограничении итоговой величин ошибки в 1,5%.

Ключевые слова: Квантовые коммуникации, распределение квантовых ключей, поляриметрия, коэффициент экстинкции, оптическая схема, поляризация фотонов, детекторы одиночных фотонов, оптика свободного пространства

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Introduction

Quantum key distribution in a Space-Earth optical communication link is a challenging technical task [1,2]. The development of an equipment requires a solution of many issues including the precise optical axes pointing of a ground station and a satellite payload, but also the highly necessary polarization reference frame coincidence of them. The problem of pointing and tracking is successfully solved in our previous articles [3,4]. The solution to the polarization rotation problem is reported here.

The satellite reference frame has a time dependent rotation relatively at the ground station, even when the satellite system is stabilized along the nadir axis [5]. Such angular movement creates a shift in the angles of the polarization bases during a QKD communication with the satellite, which increases the error rate when decoding quantum states.

In this work we consider the effect of a time dependent rotation of the polarization basis and describe the method which helps to compensate this polarization deviation. The observed polarization characteristic of an optical ground station allows us to determine the maximum mismatch angle of polarization reference frames encoding and decoding photon states.

Methods

A ground-based receiver for QKD is located in the Zvenigorod observatory, about 80 km from Moscow. A Ritchey–Chretien Alt-Az telescope with an aperture of 0.6 m and a focal length of 4.8 m is used to gather a quantum signal. The main optical part of the receiver for satellite quantum key distribution with a satellite consists of a mirror telescope, an optical signal processing unit, and a polarization analyzer (PA).

The polarization analyzer acts as a free-space decoder of quantum states that allows using the BB84 protocol for satellite-to-ground QKD. The optical signal analysis and processing system (APS) includes a motorized half-wave plate. Its time-dependent angular motion may be regulated by a predicted function to correct the rotation of the reference frame of polarization bases measurements, as shown in figure 1. By altering the angle of the half-wave plate fast axis, a unit can align the decoder's polarization reference frame in relation to the transmitter's polarized photons.

In order to test the compensating system, we simulate the relative rotation of the satellite to the Alt-Azimuth telescope polarization reference frame. A polarized laser source with an intense output power and a wavelength of roughly 850 nm is positioned in front of our receiving ground station. This source is mounted in a high-precision rotary holder, altering the angle of the output linear polarization.

Firstly, we should define the zero point of our receiver, setting a horizontal |H⟩-polarization on the laser source. Rotating the half-wave plate of the compensation system in APS, we find its angular position that corresponds to the maximum number of clicks on the single photon detector coupled to the |H⟩-channel of the polarization decoder.

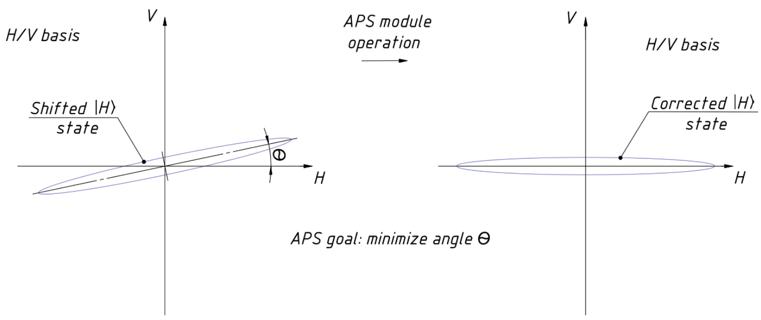

Fig. 1. Polarization conversion in APS module

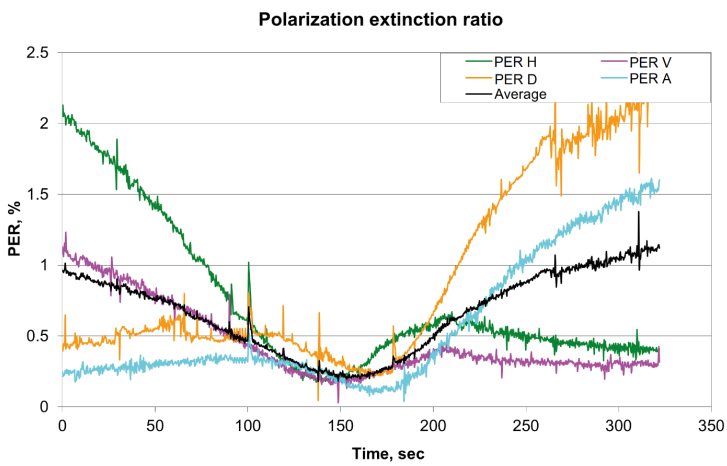

Fig.2. Polarization extinction ratio (PER) obtained in the local test

To obtain the expected error rate of the ground station, we measure the polarization characteristics of the optical receiver using an intense laser source with a polarization extinction ratio (PER) better than 4000:1. So, we start a polarization rotation of the laser source in a range of ±90 degrees according to the predicted function and compensate it on the receiver, simultaneously. Such measurements are carried out for |H⟩ — horizontal polarization, |V⟩ — vertical polarization, |D⟩ — diagonal polarization and |A⟩ — anti-diagonal polarization decoder channels. The results of polarization extinction coefficient depending on time for these channels are presented in figure 2. The average value of the PER of these polarization states for our setup turned out to be less than 0.5% (Fig. 2).

Results

Based on the PER values acquired from experiment for the stationary transmission of polarization states, the compensating mechanism appears to be operational. Because the simulation of the satellite QKD session was conducted in the presence of a strong optical signal, we can only estimate the optical *QBER* of our system without taking noise into account.

Let us estimate the permissible angular error of polarization reference frame rotation when the upper bound of expected *QBER* is under 1.5%:

$$QBER_{exp} = QBER_{opt} + \frac{ER-1}{ER+1}\sin^2\theta_{max}, \quad (1)$$

where ER – reciprocal of average PER, θ – angular error value, $QBER_{exp}$ – the specified (expected) limit parameter for error rate, $QBER_{opt}$ – optical part of error rate.

Hence, taking into account $ER = 200$ from local polarization test and consequently $QBER_{opt} = 0.5\%$, $QBER_{exp} = 1.5$ %, we can calculate θ_{max}, using estimated and experimental measurements as follows:

$$\theta_{max} = \arcsin\sqrt{\frac{(ER+1)\cdot QBER_{opt}}{ER-1}}, \quad (2)$$

$$\theta_{max} = 5.78^{o}. \quad (3)$$

Conclusion

We have demonstrated the work of the analysis and processing module in operating mode simulation. The APS module can successfully compensate for polarization reference frame rotation and the average optical *QBER* is 0.5%. Finally, we estimate the maximum allowed angular error for the compensation system, as a consequence of complexity of the precise satellite rotation prediction.

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