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Achieving high visibility in subcarrier wave quantum key distribution system

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Abstract. We study influence of quantum signal polarization distortions in the optical fiber on the interference pattern visibility in a subcarrier wave quantum key distribution system. An optical scheme of the polarization compensation unit is suggested, and dynamics of the QBER depending on the unit architecture is explored.

1. Introduction
Quantum cryptography allows distributing secure keys in a way that any eavesdropping in the channel is inevitably detected [1]. An important practical problem in the development of quantum cryptography systems is to enable their integration to the existing telecommunications lines. A subcarrier wave quantum key distribution system (SCW QKD) is one the most perspective solutions of that problem [2-5]. In this system a quantum signal is not generated directly by the source, but it is put to the sideband as a result of the phase-frequency modulation. Its advantages include high phase stability, broad multiplexing capabilities, and possibility to function in standard telecom optical cables.

It is well known that conventional optical fibers have birefringence, which randomly fluctuates in space and time. Moreover, the electro-optical phase modulators used, in practical implementations of fiber-optics phase-coding quantum key distribution systems, are sensitive to the polarization of light. Therefore, the distortions of the quantum signal leads to a decrease in visibility of the interference pattern and a subsequent raise of quantum bit error rate (QBER), which is used as a criterion for the detection of eavesdropping in QKD systems.

In order to compensate the polarization distortion introduced by the fiber in the SCW QKD system, an improved double-pass scheme was earlier proposed [6, 7]. The main principle was in connection of two electro-optical modulators in the receiving module with a Faraday mirror. After passing through the modulators, the signal was reflected from the Faraday mirror, where its polarization was rotated, and the signal was send back. In this design both polarizing modes were modulated, and the interference pattern visibility increased to 95%. However, a significant disadvantage of this setup was high insertion losses induced by two passes through modulators (about 6.5 dB, equal to additional 38 km of Corning ULL optical fiber [8]).

The aim of this work is the development of the optimal scheme of the polarization distortion compensation unit (PDCU) for SCW QKD, and studying the impact of polarization distortions on QBER and the visibility.

2. Theoretical analysis

In practice, the limiting factors for the security of quantum key distribution systems are the loss ratio in the channel, and QBER. It is known that an eavesdropper (Eve) is able to mask her actions by errors that inevitably arise in the process of key distribution. QBER value depends on the design of the optical circuit and the equipment used. In particular, the most important are the parameters of the receiving device, such as loss of system components. Threshold performance for the quantum key distribution system is an error rate of 6.4% for the four states with "strong reference" protocol [9]. The error rate of the cryptographic key in a four-state phase system is determined by the following formula:

$$QBER = \frac{1-V}{2} + \frac{p}{4\mu\eta \cdot 10^{-\frac{\alpha L + \beta}{10}}}, \qquad (1)$$

where V is interference pattern visibility, β are the losses in the receiving module, p is the dark count probability per bit, μ is the mean photon number per pulse, α is the optical fiber attenuation coefficient at the central wavelength of the photon source, L is the optical fiber length and η is the detection efficiency.

There are two terms in (1): the first one depends on the quality of optical phase matching in the Alice (sender) and Bob (receiver) modules and is responsible for incorrect photon registration due to imperfect interference or depolarization. The second one characterizes the dark count as a fraction of all the registered counts. The latter increases with distance, since the number of photons reaching the detector decreases as transmission loss grows, whilst the dark count rate remains unchanged. The factor of four is introduced because the photons have a probability of being in the correct basis and a probability of returning from sidebands to the carrier. Thus, it is possible to form the lower threshold of the quantum bit error, in the absence of external factors [1]:

$$QBER_{min} = \frac{1-V_{mean}}{2}, \qquad (2)$$

where V_{mean} is the mean value of visibility obtained from the experiment.

To assess the impact of distortions, a polarization controller (PC) was connected into the transmission channel. In order to measure the angles of induced polarization rotation, a standard protractor with a range of angles from 0 to 180 degrees was attached to each of the PC plates used for manipulation. In the experiment, we used in the step of 30 degrees. Thus, each of the plates had 7 possible positions. The combined system of two PC plates gave 49 options. In each position of the PC the value of constructive and destructive interference of signals in the quantum channel was measured, thus determined the visibility of the interference pattern [1]:

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}, \qquad (3)$$

where I_{max} − constructive interference signal's intensity, I_{min} − destructive interference signal's intensity.

3. Experimental results

For the experimental investigation of the mechanism of compensation of the polarization signal distortion in fiber-optic communication lines in SCW QKD we assembled experimental models of PDCU in three versions:

- SCW QKD system without any PDCU;
- SCW QKD system with double-pass PDCU described in the introduction;
- SCW QKD system with single-pass PDCU proposed in this paper.

Let us discuss the proposed scheme. The main principle of this subsystem is to divide signal coming from the communication line into two orthogonal polarization components for subsequent

independent modulation of each polarization mode. This is achieved by the use of fiber polarization beam splitter with a division ratio of 50/50. As shown in the diagram (Fig. 1) after the beam splitter the polarization modes of the original signal follow two different arms. All fiber connections inside the system are polarization-preserving. Each arm contains a phase modulator, which provides a sinusoidal high frequency modulation signal, and optical circulator in conjunction with faraday mirror. We assume that in the first arm of a preferred direction in a lithium niobate crystal coincides with the polarization mode of the signal coming from the polarization beam splitter.
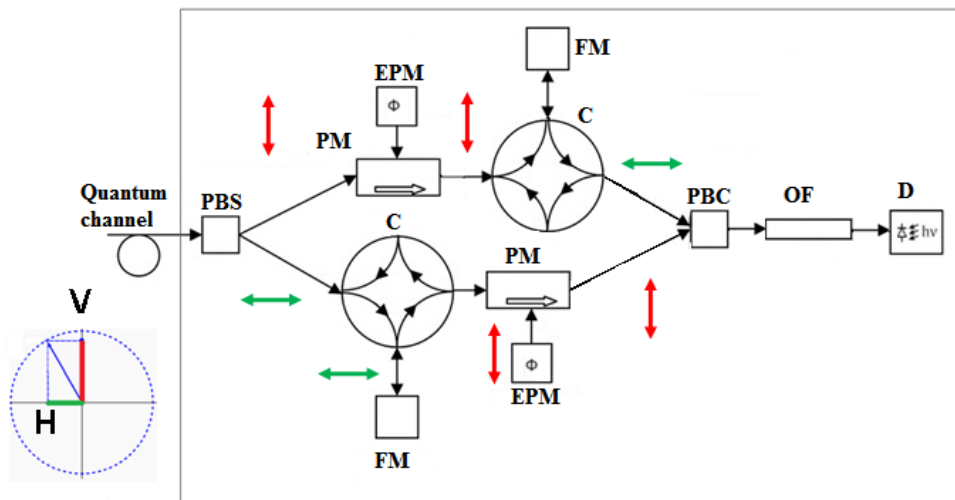

Figure 1. Principal scheme of receiving part of the subcarrier wave quantum cryptography system with single-pass polarization distortion compensation unit (PBS - polarizing beam splitter, PM – phase modulator, EPM – electrical phase modulator, PBC – polarizing beam combiner, C – circulator, OF – optical filter, D – detector. On the insets one can see signal polarization modes at different ports).

The second arm contains an important difference. The beam splitter divides the signal into two polarization modes. The mode distributed in the first arm coincides with the preferred direction in the phase modulator. After modulation it should be rotated by FM, so it becomes orthogonal to incoming mode. Therefore, the mode in the second arm needs to be rotated by 90° in order to coincide with the crystal axis and introduce no difference in modulation efficiency of the components. His rotation is achieved by a Faraday mirror and a circulator, as shown in Fig. 1. Thanks to this addition, both polarization modes undergo equal phase shifts, if we take into account delays between PMs in different arms and fix them by EPM. After the modulation, the pulse components from the shoulders are connected by a polarization maintaining optical coupler. And because of FMs they don't interfere with each other. Then the spectral filter separates sideband frequencies and the reference carrier, according to the SCW protocol. The result of sidebands interference from Alice and Bob is measured on a single photon detector.

The received experimental data in the form of six surfaces is presented on two graphs (Fig. 2, 3) corresponding to the values of the visibility and QBER. The average value of visibility of the interference pattern without compensation (purple surface) is 88%, which corresponds to QBER 6%. Thus, the QBER value is close to the theoretical limit, which significantly decreases the secure key rate. For the double-pass PDCU (blue surface) the average value of the visibility of the interference pattern is equal to 95.5%, which corresponds to QBER - 2.21%. Finally, the single-pass PDCU proposed in this work the average value of the visibility of the interference pattern is 98.8%, with QBER as low as 0.58%.
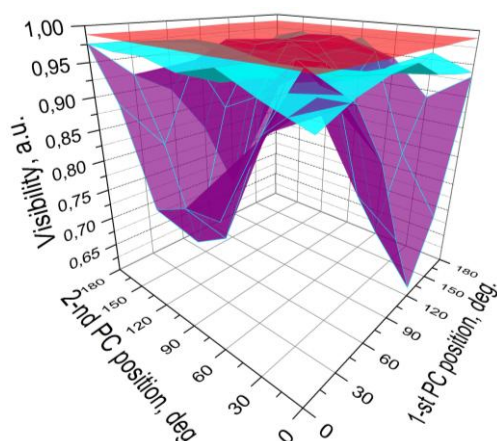
Figure 2. Dependence of the interference pattern visibility on polarization controller's position for SCW-QKD without any PDCU (violet), with double-pass PDCU (blue), with single-pass PDCU (red).
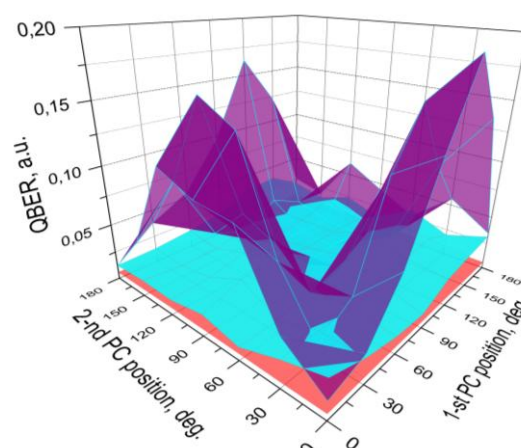

Figure 3. Dependence of QBER value on polarization controller's position for SCW-QKD without any PDCU (violet), with double-pass PDCU (blue), with single-pass PDCU (red).

4. Conclusion

The main motivation of this work lies in the necessity of integrating QKD devices into existing telecommunication environment. We developed a SCW QKD system module that makes it fully insensitive to polarization fluctuations and robust to environmental changes. The feasibility of single-pass polarization distortion compensation unit was proved experimentally using as criteria the interference pattern visibility that describes the quality of optical phase matching in the Alice and Bob modules; and QBER that is responsible for errors in the quantum key distribution process and robustness to the eavesdropping. The proposed module also decreases the insertion losses in the receiving party. This will allow increasing the distance of SCW QKD in standard telecommunication optical fibers.

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