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Free-space subcarrier wave quantum communication

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Abstract. We experimentally demonstrate quantum communication in 10 dB loss outdoor atmospheric channel with 5 kbit/s bitrate using subcarrier wave coding method. Free-space link was organized by telescoping system with symmetric fiber-optic collimators.

1. Introduction

Quantum communication (QC) is a new technique of secure key exchanging between parties in communication network. Nowadays different groups demonstrating quantum communication in optical fibers up to 404 km [1] and up to 144 km in free space [2]. Free space experiments demonstrating the feasibility of QC for sattelite-to-sattelite and ground-to-ground application. For expample in ground-to-ground applications free space QC can solve last-mile problem in quantum networks. To date, mostly method based on polarization-coding has been implemented in free space[3- 5]. In this work we show that subcarrier wave coding technique [6-8] can be adapted to free space quantum communication.

2. Experimental setup

Experimental setup is shown in figure 1. Free-space subcarrier wave QC system consists of Alice and Bob modules connected by free-space atmospheric quantum channel.

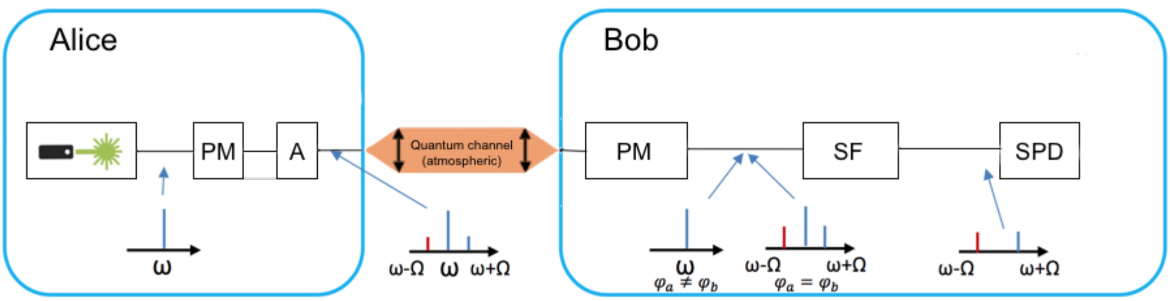

Figure 1. Experimental setup of free-space subcarrier wave quantum communication system. PM – phase modulator, A – attenuator, SF – spectral filter, SPD – single photon detector.

Semiconductor laser at the Alice module emits a signal at optical frequency ω which is directly modulated in $LiNbO_3$ phase modulator by an electrical signal with frequency Ω and modulation depth m<<1. The optical spectra are composed of central peak and two subcarriers at frequencies ω + Ω and ω – Ω with phase shift φ_A randomly chosen from four-state protocol. After modulation signal is attenuated and passed through beam expander and to receiver side by atmospheric quantum channel. The total optical power at the output of Alice module was equal to mean photon number 1 per pulse at subcarriers.

Free space atmospheric quantum channel was organized by telescoping system with symmetric fiber-optic collimators (Fig. 2.) An ideal atmospheric channel can be descripted by Gaussian beam solution of paraxial wave equation. Maximal length between Alice and Bob modules is limited by beam diffraction and depended on the collimator lens diameter.

$$L = \frac{2\pi\omega^2}{\lambda}\frac{\omega_0}{\omega}\sqrt{1-\left(\frac{\omega_0}{\omega}\right)^2},$$

where ω is the beam waist, and ω_0 – radius of the beam at the lens. The length is maximized when $\omega_0/\omega = \frac{1}{\sqrt{2}}$.

At the receiver side signal is collected by symmetric beam collimator and coupled in an optical fiber and passed to Bob module. Here signal passed through phase modulator where random phase shift φ_B is introduced according to four-state protocol. Then signal transmitted to an optical spectral filter that separates the carrier from subcarriers. After spectral filter two subcarriers at frequencies ω + Ω and ω - Ω passed to single photon detector. When Alice and Bob introduced equal phase shifts (φ_A - φ_B = 0), constructive interference was observed in the side frequency optical signal. When the difference in phase shifts was a multiple of π, destructive interference was observed. Key generation and sifting was performed experimentally using the BB84 protocol.

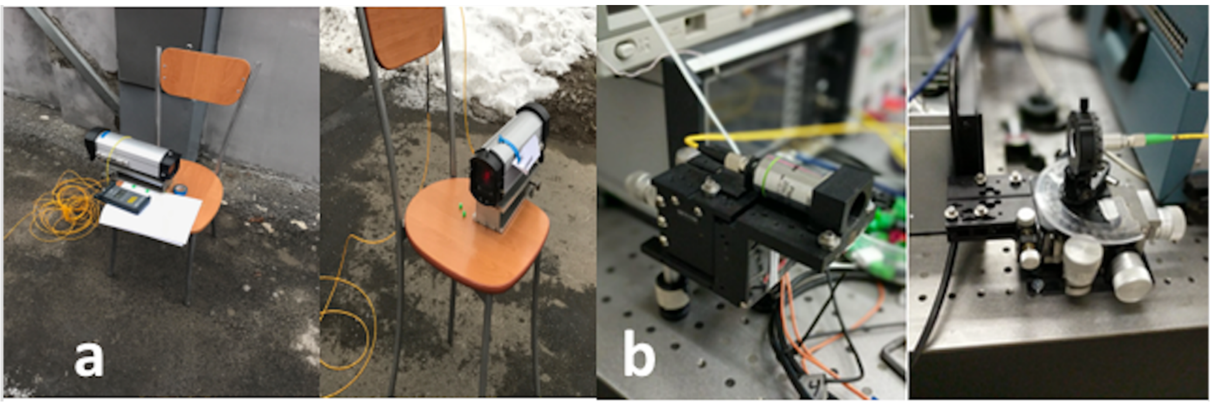

Figure 2. Free-space channels with beam collimators in outdoor (a) and indoor (b) experiments.

The experiment was perfomed two times: indoor in lab with 1 m on-table-link (Fig.2a.) and outdoor on a cloudy day (Fig. 2b.) with atmospheric channel between two beam collimators ~20 m. . QC system parameters are shown in Table 1.

Table 1. QC system parameters.

Parameter	Value
Central wavelength	1550 nm
Modulation clock frequency	100 MHz
Modulation frequency	4.8 GHz
Mean photon number	1
Measured losses in quantum channel	20 dB
Losses in Bob module	7 dB
Quantum efficiency of detector	20%
Spectral filter coefficient	99,99%
Spectral filter band	7.5 GHz

For measured losses in outdoor 20 m free-space link of 10 dB the sifted key rate was about 5kbit/s and QBER value was 6%.

For measured losses in indoor 1 m free-space link of 8 dB the sifted key rate was about 15 kbit/s and average QBER value was 3,28 %. At the reciever side beam collimator was rotated 45 degrees 8 times. Figure 3 shows that QBER pproximately the same for different positions of the telescope system.

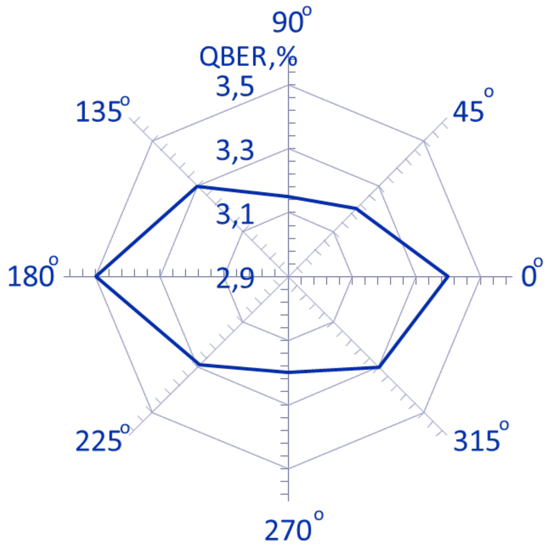

Figure 3. Dependence of QBER on collimator rotation angle

3. Conclusion

In this work we have implemented subcarrier wave technique for free-space quantum communication using standard fiber-optical components in Alice and Bob modules. In free-space regime this technique offers invariance to rotation of the telescope system and good capabilities in multiplexing.

Acknowledgments

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Erratum: Free-space subcarrier wave quantum communication

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Our paper «Free-space subcarrier wave quantum communication» in *Journal of Physics: Conf. Series* **917** (2017) 052003 contains the following misprints we would like to correct:

1. The expression for L on page 2, line 12 must be in the following form:

$$L = \frac{2\pi\theta^2}{\lambda}\frac{\theta_0}{\theta}\sqrt{1-\left(\frac{\theta_0}{\theta}\right)^2},$$

2. On page 2, line 13 should be as follows: «where θ is the beam waist, and θ_0 is the radius of the beam at the lens. The length is maximized when $\theta_0/\theta = 1/\sqrt{2}$».

3. The Acknowledgments section must be read as follows: This work was financially supported by the Ministry of Education and Science of Russian Federation (project № 14.578.21.0112, RFMEFI57815X0112).