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Control of Quantum Noise for Optical Sensing and Communications

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Free-Space Quantum Communications in Harsh Environments

23/12/2022

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Abstract

Our project aims at exploring the possibility of all-weather secure quantum communication using macroscopic quantum states of light. To this end, the project has two goals: (a) experimental investigations and mathematical modeling of the propagation characteristics of macroscopic quantum states of light owing to atmospheric turbulence, and (b) basic research on quantum receivers for cryptographic applications in harsh environments. For the former, we conducted experiments that simulated fog in a laboratory environment to investigate the propagation characteristics of visible laser light, near-infrared laser light, and single-mode squeezed light. For the latter, we discussed an optical pre-processing method to improve the reception sensitivity of optical homodyne detection. We performed a proof-of-principle experiment for a modified homodyne detection method developped by us and performed a theoretical analysis of the technique. In addition, we developed a numerical analysis method for the error probability characteristics of the optical receivers in a turbulent free-space communication channel where the transmission coefficient varies probabilistically.

Introduction

More than half a century has passed since the birth of quantum signal detection theory, which is the cornerstone of modern quantum communication theory. Quantum stream cipher, the quantum-noise-based direct encryption scheme for optical communications at the center of our research, is based on the foundations of quantum communication theory. For quantum cryptography to progress from a theoretical possibility to a more realistic technology, experimental and theoretical research must be complementary. We have reported several experimental and theoretical studies on the quantum stream cipher connecting two points via optical fibers and also fabricated a prototype based on them.

To enhance the usability of a quantum stream cipher, free-space optical communications must be explored in addition to point-to-point optical communications connected by optical fibers. In the case of free-space optical communications, various environmental changes caused by the weather affect the communication channel. Therefore, quantum communications, including cryptographic applications, must be considered from experimental and theoretical perspectives under various harsh weather conditions such as fog, rain, snow, and turbulence.

Our project aims to explore the possibility of all-weather secure quantum communication using macroscopic quantum states of light. The goals of this project are the (a) experimental elucidation and mathematical modeling of the propagation characteristics of macroscopic quantum states of light owing to atmospheric turbulence and (b) basic research on quantum receivers for cryptographic applications in harsh environments. This study reports on the research activities conducted in our project.

Propagation characteristics of macroscopic quantum states of light

In the first year, we focused on uniform fog, among the effects of various atmospheric disturbances. First, preliminary experiments using visible and near-infrared laser light confirmed that the effect of uniform fog on light wave propagation was mainly energy attenuation owing to Mie scattering. Next, we used single-mode squeezed light as quantum light to investigate the effect of fog on light wave propagation [1]. FIG. 1 shows the results of detecting squeezed light passing through the fog by balanced homodyne measurement. The blue and red circles represent the anti-squeeze and noise level of the squeezing, respectively. The horizontal axis represents the light loss L (=1-T) owing to fog, calculated from measurements of the transmittance T. The solid line shows the calculated results of modeling the effect of energy attenuation because of fog using a beam splitter model of transmittance T. The agreement between the experimental and theoretical values indicates that the effect of uniform fog on the propagation of quantum light is primarily because of energy attenuation. Simultaneously, we also observed that the effect of uniform fog on the spatial modes of light waves was small, and the coherence between light waves did not deteriorate. These results suggest that uniform fog conditions do not significantly degrade the detection efficiency in the homodyne measurement of quantum light.

In the second year, we performed experimental studies in the case of non-uniform fog [2], by employing a temporally and spatially scrambled fog to reproduce a non-uniform fog environment. As in the case of the uniform fog, we first studied the propagation of visible and near-infrared laser light in this environment and confirmed that energy loss was also the primary effect in this case. FIG. 2 shows the experimental results of noise level fluctuations owing to non-uniform fog. Figures 2 (a) and (b) depict the temporal variations of the noise level when squeezed light passes through a uniform fog and a fog whose density varies with time, respectively. In this case too, energy loss was the most significant factor in light wave propagation.

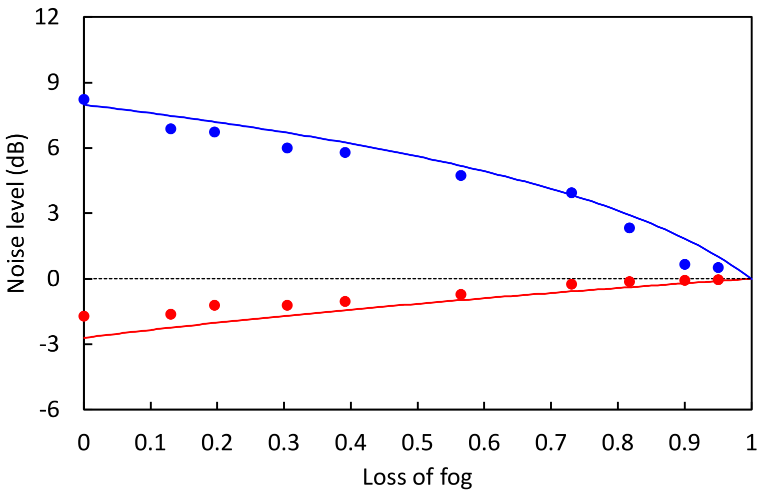


FIG.1 (Figure 4 of [1]): Noise level of anti-squeezed (blue) and squeezed light (red) vs. a loss of fog.

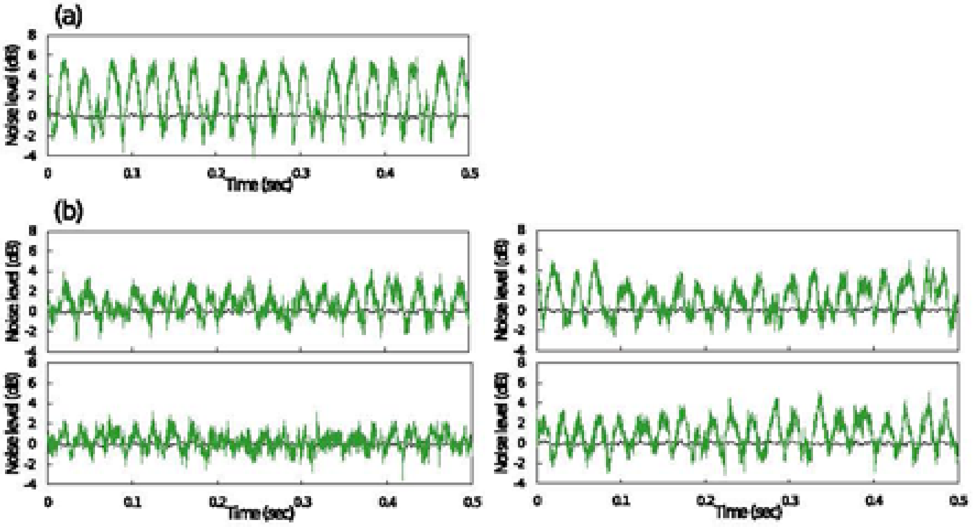


FIG. 2 (Figure 11 of [2]): Temporal noise level variations.
(a) uniform fog case. (b) non-uniform fog cases.

Basic research on quantum receivers for cryptographic use

We first discussed optical pre-processing for the cryptographic application of optical receivers in free-space optical communications. FIG 2 (a) shows a conventional receiver setup with an optical decryption process. First, the phase of the optical cipher signal is demodulated for decryption, followed by homodyne detection of the decrypted optical binary signal. The attenuation of the optical cipher signals owing to the phase modulator is a practical limitation of this setup. The typical loss of a high-speed $LiNbO_3$ phase modulator is a few dB, which degrades the signal-to-noise ratio of the optical signals. Therefore, most of the advantages of utilizing decryption in the optical domain are lost. We explored a new approach to solving this problem in the first year and proposed a homodyne receiver in which the phase of local light is modulated for decryption, as shown in FIG. 2(b). The phase manipulation of the local light can perform the same decryption function as the conventional one. Moreover, because the cipher signal is detected directly without further attenuation, simultaneous decryption and homodyne detection are expected in the shot noise limit. A patent application for the proposed method was filed in Japan [5].

Second, we performed a proof-of-concept experiment of homodyne detection with the phase modulation of local light. We assumed a phase shift keying (PSK)-based quantum stream cipher in which the legitimate receiver detects a binary PSK (BPSK) coherent optical signal (phase: 0° and 180°) after decryption. The transmitter, which consisted of an arbitrary waveform generator (AWG) and Mach-Zehnder interferometer (MZI), generated a 5-Gbaud BPSK coherent optical signal. The wavelength was in the telecommunication wavelength band (1550.12 nm). After adjusting the power and polarization, the signals were detected using a homodyne setup with a real-time oscilloscope while changing the phase of the local light. FIG. 5 shows the experimental results. The vertical and horizontal axes indicate the received signal level and time, respectively. The leftmost figure shows the result when the phase of the BPSK coherent optical signal and local light match best. The right-most figure illustrates the case where the phase difference between the signal and local light is approximately 90°, i.e., out of phase. The two intermediate figures depict the results for the cases in between. The leftmost figure represents the most favorable situation for the legitimate receiver, where the receiver can distinguish between the two signal levels with negligibly small errors. In contrast, the right-most figure indicates that it is difficult to distinguish between the two signals. Thus, we demonstrated that homodyne detection with the phase modulation of local light succeeds in manipulating the phase of optical signals. In parallel, we analyzed the proposed homodyne receiver from the viewpoint of quantum signal detection theory [3]. The figure on the right in FIG. 6 illustrates the theoretical explanation of the phenomenon in which the average value shifts following the phase shift of the local light when the signaling phase is 0°. The leftmost and rightmost figures in FIG. 5 correspond to the cases where the phase of the local light is 0° (or 180°) and 90° in the right-hand side figure of FIG. 6, respectively. Thus, we confirmed that the experimental results were generally consistent with the theoretical analysis. The results of this study are yet to be published, and we plan to continue our experiments and report them elsewhere.

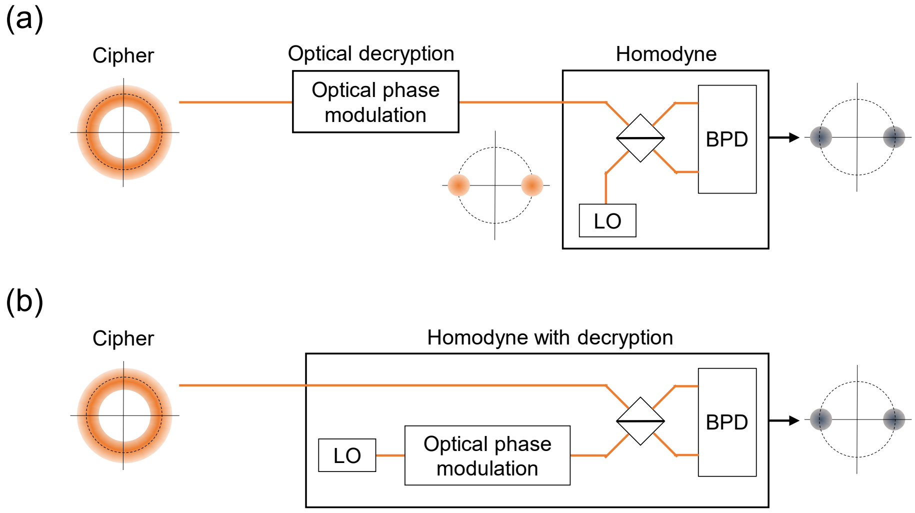


FIG. 3 (original/unpublished): Pre-processing for decryption. (a) conventional scheme. (b) proposed scheme.

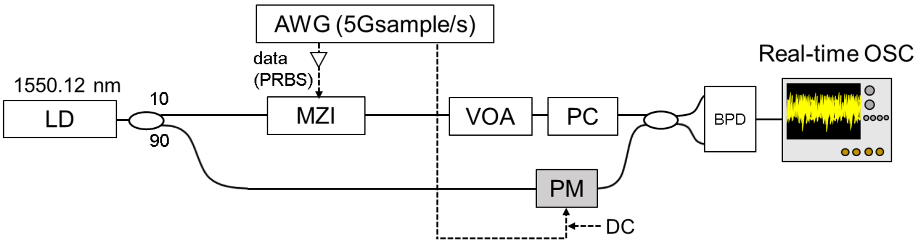
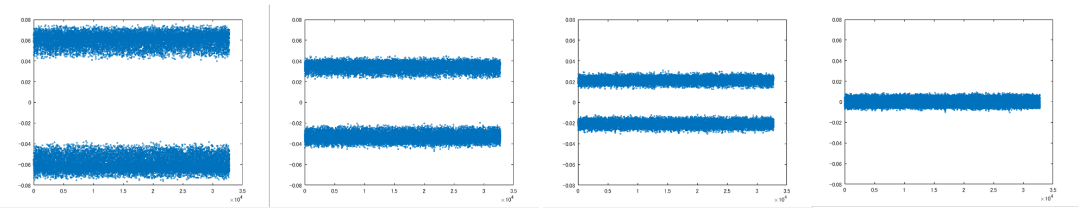


FIG. 4 (original/unpublished): Setup for a proof-of-concept experiment.



Q = 19.6 dB

Q = 19.0 dB

Q = 17.9 dB

Q = 5.73 dB
BER = 0.03

FIG. 5 (original/unpublished): Detection level of BPSK coherent optical signal.

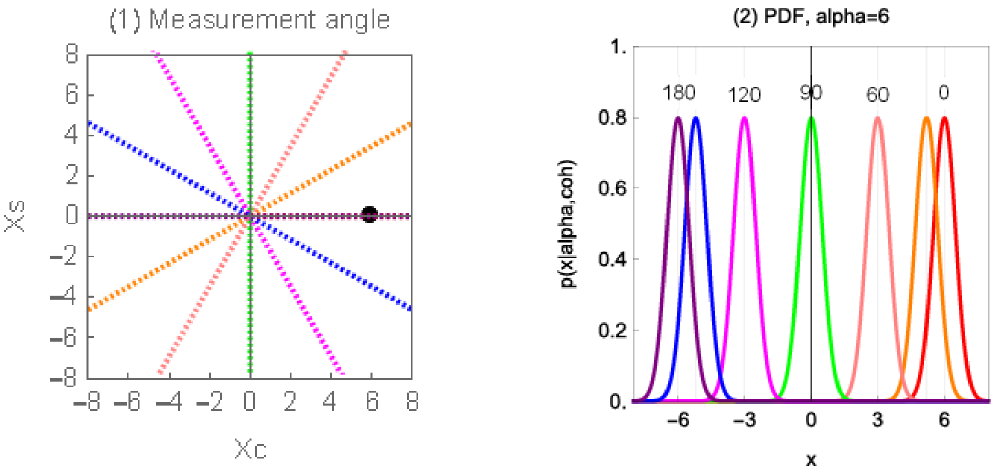
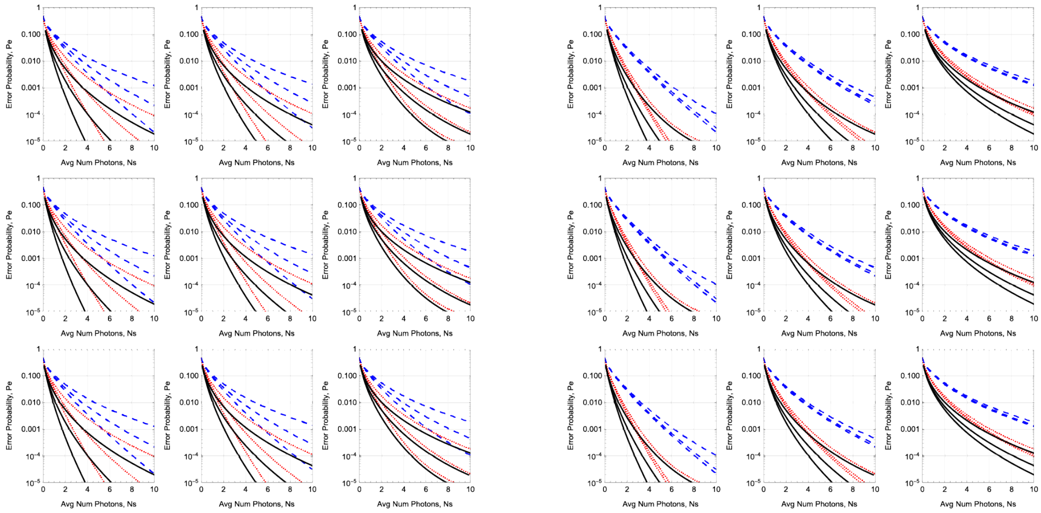


FIG 6 (Fig. 2 of [3]): Signal and measurement angle on Xc-Xs plane (left). Expected value vs. measurement angle (right)

Third, we discussed a numerical calculation method for evaluating free-space optical communication systems in terms of quantum signal detection [4]. As the first step, we employed a turbulence model described in the literature [Semenov & Vogel, Phys. Rev. A 2009, 80.2: 021802(R)] which considers the case where numerous small eddies form turbulence and formulates the appropriate probability distribution of the transmission coefficient. We developed a numerical calculation method for evaluating the error probability characteristics of the homodyne and optimal quantum receivers for the given probability distribution of the transmission coefficient of a channel and performed several numerical simulations using it. FIG. 7 shows the simulation results, in which the vertical and horizontal axes represent the average probability of error and average number of received signal photons, respectively. We used the simulations to investigate the performance degradation of the receivers in turbulence under the following two conditions: (A) several standard deviations of the amplitude of the transmission coefficient were chosen for a fixed standard deviation of the phase of the transmission coefficient, and (B) several standard deviations of the amplitude of the transmission coefficient were chosen for a fixed standard deviation of the phase of transmission coefficient. Under these conditions, we considered the following three types of receivers:

- Optimal quantum receiver (black)
- Homodyne receiver with one-component measurement (red)
- Homodyne receiver with two-component measurement (blue)

Simulation results confirmed that the optimal quantum receiver was sensitive to fluctuations in the phase of the transmission coefficient. In contrast, the homodyne receivers were more robust against fluctuations of the phase of transmission coefficient.



Case A

Case B

FIG 7 (Figures 5 and 6 of [4]): Error probability of a turbulent channel. Optimal quantum receiver (black). Homodyne 1 (red). Homodyne 2 (blue).

Conclusions

- We built a simulation chamber for a uniform and non-uniform fog and experimentally observed the propagation characteristics of visible, near-infrared, and single-mode squeezed light, respectively. The experiments confirmed that the effect of fog appeared mainly in the form of energy loss (Refs. [1, 2]). Future work is required to simulate other environments, not limited to fog, and experiment with entangled light, such as two-mode squeezed light.

- We devised an optical processing method that simultaneously performed decryption of quantum stream cipher and homodyne detection. The proposed method that manipulates the phase of local light can perform the same decryption function as the conventional one. Furthermore, since the cryptographic signal is directly detected without additional attenuation, it is expected to simultaneously achieve decryption and homodyne detection in the shot noise limit (patent [5]).

- We conducted a proof-of-concept experiment of the proposed decryption method (unpublished). In addition, theoretical analysis was also performed (Ref. [3]). Therefore, we confirmed that the experiments and theory were consistent. However, future work is needed to improve the experimental accuracy and closely align experiments and theory by conducting theoretical analyses that include more practical conditions.

- We developed a simple method for numerically determining the error probability characteristics of homodyne receivers and optimal quantum receivers when the model of a turbulent communication channel is given by the probability distribution of the transmission coefficient (Ref. [4]). Using the model in reference [Semenov & Vogel], we investigated the error probability characteristics of the homodyne receivers and the optimal quantum receiver under certain turbulent conditions. Future issues include treating various free-space communication channels, designing a system that leverages the robustness of the homodyne receiver confirmed in this study, and the realization problem of an optimal quantum receiver for the harsh environments encountered in free-space optical communications.

List of Publications and Significant Collaborations that resulted from your AOARD supported project:

[1] Genta Masada, “Investigation of light wave propagation in atmospheric disturbance toward quantum illumination,” Proc. SPIE, 118350E (2021) [Peer-reviewed]

[2] Genta Masada, “Investigation of propagation characteristics of laser light and squeezed light in fog,” Proc. SPIE, 1223804 (2022) [Peer-reviewed]

[3] Kentaro Kato, “Homodyne measurement with angle $¥phi$ rotation and its application to the detection of squeezed state signal,” to be published in Tamagawa University Quantum ICT Research Institute Bulletin 2022 [Peer-reviewed]

[4] Kentaro Kato, “A study on quantum communication through turbulent atmosphere,” Proceedings of the 45th Symposium on Information Theory and its Applications (SITA2022) [Oral presentation].

[5] Ken Tanizawa and Fumio Futami, Signal Processing System, Japanese Patent Application No. 2022-062535, Apr. 4, 2022.

Attachments:
・Copy of Ref.[1]
・Copy of Ref.[2]
・Copy of Ref [3]
・Copy of Ref.[4]
・Invention Report of Patent Application [5]
・SF425, signed by Mr.Hidemaro Saito, Administrative Staff, Tamagawa University