4-6 Experimental Results of Polarization Characteristics Measurements through Satellite-to-Ground Propagation Paths toward Satellite Quantum Key Distribution

TOYOSHIMA Morio, TAKENAKA Hideki, SHOJI Yozo, TAKAYAMA Yoshihisa, KOYAMA Yoshisada, and KUNIMORI Hiroo

The polarization characteristics of a laser source from space were measured through space-to-ground atmospheric transmission paths. An existing Japanese laser communication satellite and the NICT's optical ground station were used to measure Stokes parameters and the degree of polarization of the laser beam transmitted from the satellite. As a result, the polarization was preserved within an rms error of 1.6°, and the degree of polarization was 99.4 ± 4.4% through the space-to-ground atmosphere. These results contribute to the link estimation for quantum key distribution via satellites and provide the potential for enhancements in quantum cryptography worldwide in the future.

Keywords
Atmospheric propagation, Laser beam transmission, Polarization, Free-space optical communication, Quantum key distribution

1 Introduction

Recently, there have been many dangers and threats to society, such as frequent large-scale disasters and accidents, worldwide infectious diseases, recurrent terrorism, and the deterioration of homeland security. Besides being intellectual and industrial inventions and innovations, science and technology are also a means to create social values and can help provide answers for these crises that threaten the world's security and safety [1]. Because of sophisticated eavesdropping technology, the information and communications technology sector needs to be able to prevent information leakage and illegal access; therefore, quantum cryptography technology has become more important to information security.

Novel methods have been studied that utilize the principles governing quantum cryptography to ensure unconditional security [2][3]; these include quantum teleportation between distant parties [4], which theoretically cannot be broken according to the laws of physics. Technologies for quantum teleportation and quantum channel coding that defeats the classical Shannon limit have been verified [5]. Fiber-based quantum cryptography systems for commercial use are already being sold by some venture companies: Cerberis, Vectis, and Clavis from Id Quantique in Switzerland; MagiQ QPN Security Gateway 7505 from MagiQ Technologies in the USA; and SQBox from SmartQuantum in France [6]-[8]. In Switzerland, an Internet vote using quantum cryptography was conducted in October 2007 for the mayoral election in Geneva [9]. These details show the maturity of the technology level for quantum key distribution (QKD).

QKD using optical fibres is limited to a distance of approximately 100 km due to transmission losses, nonlinearity, and background noise. Using free-space QKD would enable the long-distance transmission of photons; therefore, satellite quantum cryptography is an ideal application of QKD [10][11]. It is important to investigate the feasibility of such satellite QKD for future space applications. A low earth orbit (LEO) satellite usually orbits the Earth at about 7 km/s, which causes the Doppler shift. The polarization is the best means for satellite QKD to be used under the Doppler shift comparing with the time-bin method. However, the depolarization from space to ground has never been measured precisely so far.

In this paper, a highly polarized artificial laser source with a degree of polarization (DOP) of more than 99% onboard a satellite is used for measuring the polarization and the obtained polarization characteristics through space to ground are presented.

2 Earth scale global QKD using optical ground stations

2.1 Principle of QKD

Various quantum states can be used for QKD, however, the polarization is one of the most stable way. Figure 1 shows the detection of a polarized single photon. For example, the vertical polarized single photon can be reflected by the polarized beam splitter (PBS) and the detector "A" is always ON in the left-handed figure. The detector "B" is always OFF. On the other hand, in the right-handed figure, a θ-polarized single photon can be detected by the detectors "A" and "B" with the probabilities of $\sin^2 \theta$ and $\cos^2 \theta$. Here, the both detectors cannot be ON simultaneously and it is impossible to determine which polarization was sent after the detection. Therefore, we can say the followings:

— It is possible to distinguish a vertical polarized single photon,
— It is impossible to distinguish a θ-polarized single photon (perfect random when $\theta = 45°$),
— It is impossible to determine which polarization was sent after the detection.

QKD uses these characteristics. Figure 2 shows the key exchange between a transmitter (Alice) and a receiver (Bob) based on BB84. Alice has original bits and sends the transmitted states with two types of polarizations, e.g. rectilinear (vertical and horizontal) and diagonal (at 45° and 135°). Bob receives the transmitted states with the decision of rectilinear or diagonal in the polarization states. After the reception, Bob and Alice exchange only the information of the polarization states by public communication means and they select only the common bits with the same polarization states.

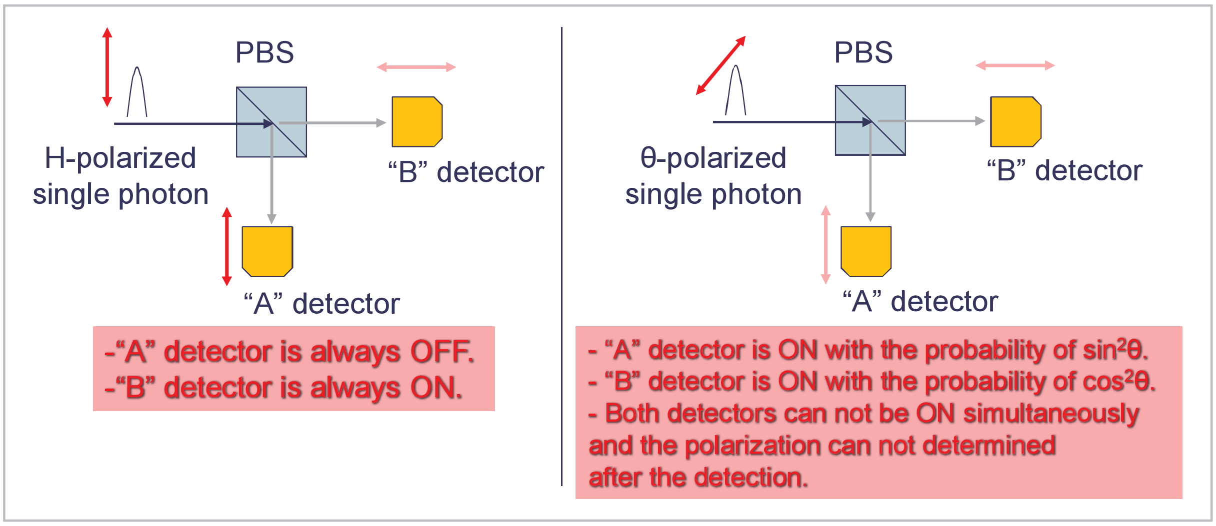
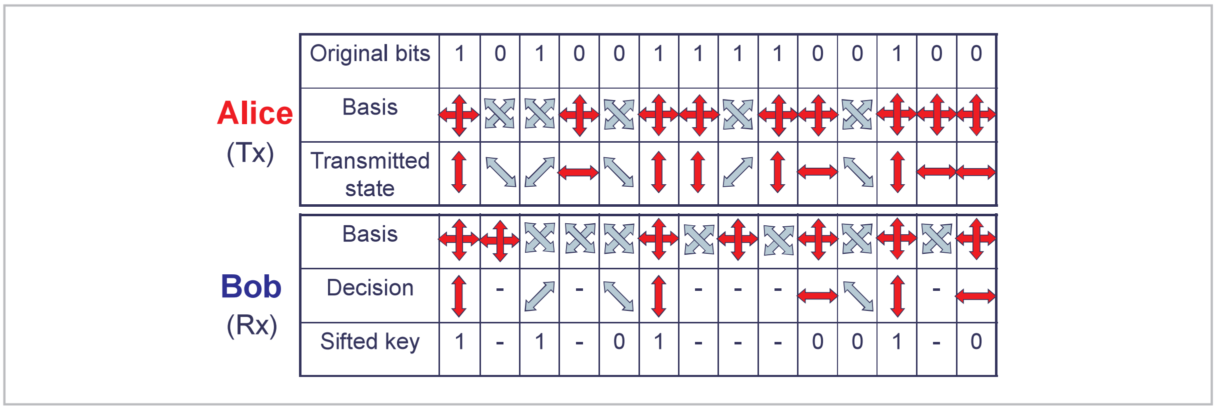


Fig.1 *Polarized single photon detection*



Alice (Tx)	Original bits	1	0	1	0	0	1	1	1	1	0	0	1	0	0
	Basis	✛	×	×	✛	×	✛	✛	×	✛	✛	×	✛	✛	✛
	Transmitted state	↕	⤡	⤢	↔	⤡	↕	↕	⤢	↕	↔	⤡	↕	↔	↔
Bob (Rx)	Basis	✛	✛	×	×	×	✛	×	✛	×	✛	×	✛	×	✛
	Decision	↕	-	⤢	-	⤡	↕	-	-	-	↔	⤡	↕	-	↔
	Sifted key	1	-	1	-	0	1	-	-	-	0	0	1	-	0

Fig.2 *Key generation based on BB84*

In this scenario, they did only the information exchange of not original bits but the polarization states, therefore, the eavesdropper (Eve) cannot succeed to know the information of the original bits. These common bits are called the sifted key and shared only between Alice and Bob. If Eve would read the transmitted states with the random polarization states, copy them and send them correctly, however, half of the information would be random and Bob can recognize the eavesdropping due to the increase of the bit error ratio.

2.2 QKD with two arbitrary optical ground stations

A global QKD that uses two arbitrary ground stations is shown in Fig. 3.

1) A satellite sends a quantum key $\alpha = 1001$ to a ground station A (OGS A) using quantum entanglement. The satellite and OGS A save the same quantum key α.
2) Then, the satellite generates the quantum key $\beta = 1010$ when it is over optical ground station B (OGS B) after completing half an orbit. The satellite and OGS B save the same quantum key β.
3) Then, the satellite sends information in the form of the equation $\gamma = \alpha$ xor $\beta = 1001$ xor $1010 = 0011$ to both the optical ground stations over public communication links. It is secure if one can eavesdrop the information γ.
4) At each optical ground station, the quantum key for the other ground station can be resolved by an exclusive OR with γ and each saved quantum key.

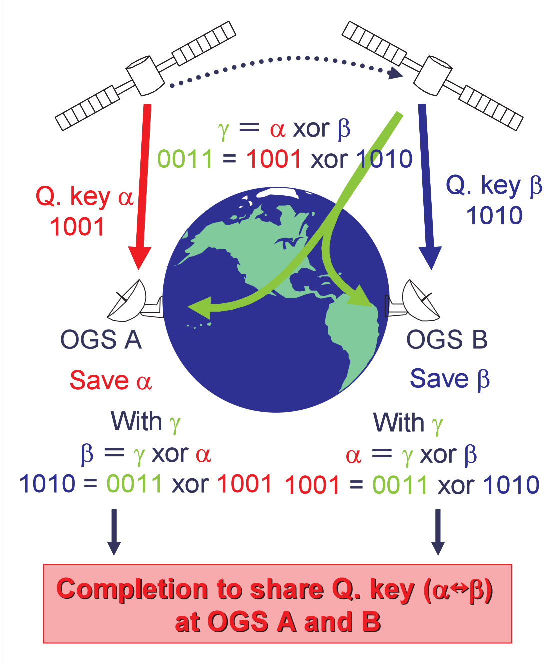


Fig.3 *Quantum key distribution between two arbitrary optical ground stations*

A global quantum key distribution can be conducted between two arbitrary optical ground stations over the Earth, especially for when the ground stations are located on opposite sides of the earth, e.g., in Japan and Europe. Future use of quantum cryptography in long-distance transmission will be significant in space communications because the transmission distance will be significantly greater than that offered by present-day optical fiber-based systems.

3 Experimental system

3.1 Configuration of the ground-to-satellite laser communications experiments

The National Institute of Information and Communications Technology (NICT, formerly CRL) measured the polarization characteristics using an artificial laser source in space. A LEO satellite, the Optical Inter-Orbit Communications Engineering Test Satellite (OICETS) Kirari, was used for this purpose [12]. The laser communications experiments between the optical ground station developed by NICT—located in Koganei of downtown Tokyo—and OICETS were conducted in cooperation with the Japan Aerospace Exploration Agency (JAXA) in March, May and September of 2006; these were called the Kirari Optical Communication Demonstration Experiments with the NICT optical ground station (KODEN). The OICETS satellite was controlled by JAXA from the Kirari operation center in Tsukuba. The optical ground station has a 1.5-m telescope located in Koganei, Tokyo and operated by NICT. The optical antenna onboard OICETS is a 26-cm diameter center-feed Cassegrain mirror-type telescope. The laser beam from the satellite is transmitted with a wavelength of 847 nm and the beam divergence of the downlink laser beam was only about 6 μrad, so the footprint of the optical beam was only 6 m on the ground at the link distance of 1,000 km.

After the first trials, NICT noticed that it would be important to measure the polarization characteristics through the atmosphere for satellite QKD [13][14]. Then, NICT initiated the KODEN experiments again and conducted the revival experiments from October 2008 to February 2009 for the confirmation of the polarization characteristics through space-to-ground atmospheric paths.

3.2 System description

Figure 4 shows the configuration of the polarization measurement setup at the NICT optical ground station. A polarimeter with a 1.5-cm aperture diameter was equipped beside the 1.5-m telescope. Data—such as the received optical power, Stokes parameters, and DOP—were directly measured through the beam expander and recorded at a rate of 10 Hz. The specifications of the polarimeter are an input power range of –60 dBm to +10 dBm, normalized Stokes accuracy of less than 0.005, and DOP accuracy of less than ±0.5% at the wavelengths between 700 to 1,000 nm. The backscattered lights from the uplink beams did not influence the polarization measurements because the aperture of the polarimeter was different from that of the uplink beams.

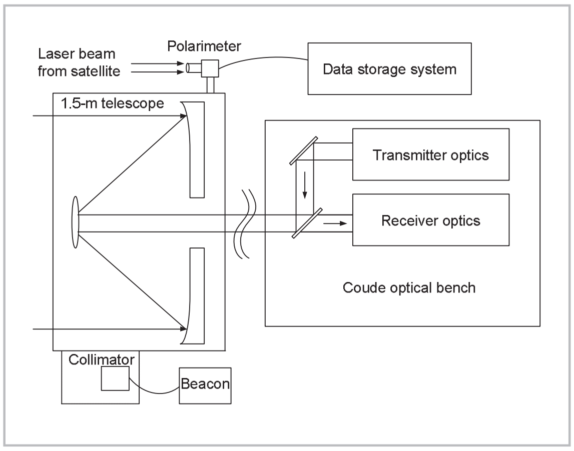


Fig.4 Configuration of the NICT optical ground station

3.3 Polarization measurements on the ground before the launch

The polarization characteristics of the laser beam onboard the OICETS satellite was measured during the thermal vacuum test before launch [15]. The polarization of the emitted laser beam was right-handed circular polarization ($\mathrm{RHCP}|_{\mathrm{Optical}}$) by the classical optics viewpoint, DOP was 99.4%, and the depolarization was within 0.49%. The definition of the polarization here is defined as Stokes parameters of (S0, S1, S2, S3) = (1, 0, 0, 1), which is $\mathrm{RHCP}|_{\mathrm{Optical}}$ by the classical optical viewpoint [16]. Circular polarization is usually used for laser communications terminals because the received weak laser beam can be isolated from the transmitted powerful laser beam with orthogonal polarization by using a quarter wave plate in front of the internal optics. If we follow the definition by the Institute of Electrical and Electronics Engineers (IEEE), the classical optics definition of circular polarization is just the opposite of the IEEE definition [17]. The left-handed circular polarization for RF signals ($LHCP|_{RF}$) is defined as the counter-clockwise direction of the electro-magnetic field at the fixed observation plane from the back-side view of the propagation direction. This definition is common for satellite communications; however, $LHCP|_{RF}$ is regarded as $RHCP|_{Optical}$ and vice versa according to convention.

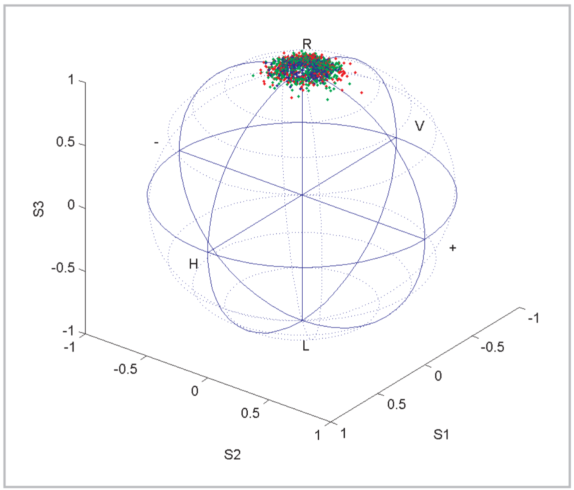


Fig.5 Polarization characteristics of the downlink laser beam from the satellite. The blue, green and red dots show the data when the optical powers were received at –39 to –35, –41 to –39 and –43 to –41 dBm, respectively

4 Experimental results of polarization characteristics through space-to-ground atmospheric paths

4.1 Measurements of DOP

Polarization measurements from the spacecraft were conducted from October 2008 to February 2009. The data were measured in the night from 16:16:08 to 16:21:58 in the Universal Time on December 23, 2008. The minimum distance between the ground station and the satellite was 959.8 km at the maximum elevation angle of 35.3°. The duration of the experiment was 350 sec above 15° in the elevation angle of the satellite. The scintillation indices ranged from 0.05 to 0.4 according to the elevation angles and there was no cloud. DOP with an rms error was measured to be 99.4 ± 4.4%. The error of DOP could be attributed to the instrumental error, the backscattered light from the uplink beams, and the polarization effect in the atmosphere. The polarization effect in the atmosphere due to ice crystals might be negligible because no significant difference as a function of the elevation angles could be observed. Therefore, the instrumental error is considered to be dominant in this measurement.

4.2 Measurements of Stokes parameters

Figure 5 shows the polarization characteristics on the Poincaré sphere as a function of the Stokes parameters of (S1, S2, S3) measured during the experiment. The rms angular error on the Poincaré sphere was measured to be within 3.2° in this experiment. One revolution of 360° on the Poincaré sphere experiences 180° in the rotation angle of the polarization; therefore, the rms angular error for the linear polarization becomes half of 3.2°. This value includes both the nature of the atmospheric slant path and the instrument error; however, if we calculate $\tan(3.2°/2) = 0.028$, the cross leak component of the orthogonal polarization will be 2.8% from the main component, which can be considered as a quantum bit error ratio (QBER) for QKD. QKD using optical fibres is limited to a distance of approximately 100 km [18], and in the past polarization measurements of a laser beam after propagation over a horizontal 144 km path, the QBER was measured to be 4.8 ± 1% which was caused by the various imperfection of their experimental setup [19]. According to QKD theory, the maximal tolerated error has an upper bound of 11% [20]. Therefore, the error budget can be considered to be within this maximal tolerated error for the satellite-to-ground QKD systems. Thus, it is useful to estimate the link budget for satellite-to-ground QKD scenarios by using the results presented here.

5 Conclusion

The polarization characteristics of an artificial laser source in space were measured through space-to-ground atmospheric transmission paths. A LEO satellite and an optical ground station were used to measure Stokes parameters and the degree of polarization of the laser beam transmitted from the satellite. The polarization was preserved within an rms error of 1.6°, and the degree of polarization was 99.4 ± 4.4% through the space-to-ground atmosphere. These results contribute to the link estimation for QKD via space and provide the upper bound based on the measurements and the potential for enhancements in quantum cryptography worldwide in the future.

Acknowledgements

The authors express their appreciation to the team members of the Japan Aerospace Exploration Agency, Space Engineering Development Co. Ltd. and NEC Toshiba Space Systems, Ltd., for their support in conducting the experiments.

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(Accepted March 14, 2012)

***TOYOSHIMA Morio**, Ph.D.*

Director, Space Communication Systems Laboratory, Wireless Network Research Institute

Satellite Communications, Atmospheric Turbulence, Laser Communications, Quantum Cryptography

TAKENAKA Hideki

Limited Term Technical Expert, Space Communication Systems Laboratory, Wireless Network Research Institute

Satellite Communications, Laser Communications

***SHOJI Yozo**, Ph.D.*

Planning Manager, New Generation Network Laboratory, Network Research Headquarters

Millimeter-wave Communications System, Microwave-Photonics Systems, Coherent Laser Communications System, Wired & Wireless Network Virtualization

***TAKAYAMA Yoshihisa**, Dr. Eng.*

Senior Researcher, Space Communication Systems Laboratory, Wireless Network Research Institute

Nonlinear Optics, Phase Conjugate Optics, Photonic Crystals, Computational Electromagnetics, Space Laser Communications

KOYAMA Yoshisada

Expert Researcher, Space Communication Systems Laboratory, Wireless Network Research Institute

Optical Communications, Onboard Equipment

KUNIMORI Hiroo

Senior Researcher, Space Communication Systems Laboratory, Wireless Network Research Institute

Satellite Laser Ranging