Towards Continuous Fiber Birefringence Compensation with Single-Photon-Level Light

Yicheng Shi[1,*], Thomas Gerrits[1], and Oliver Slattery[1]

[1] *National Institute of Standards and Technology, 100 Bureau Drive, Gaithersburg, MD 20899, USA*

[*] *yicheng.shi@nist.gov*

Abstract:
We propose a method for continuously compensating for the polarization state change of photons propagating in fibers. This technique operates at a single-photon-level intensity and therefore imposes minimal noise on the quantum channel.

1. Introduction

In a fiber-based quantum network, reliable transmission of polarization-encoded photons remains challenging due to the presence of fiber birefringence, which randomly alters the polarization states of propagating photons [1]. As shown in Fig. 1, the polarization state at the fiber output changes rapidly overtime and causes errors in measurements. As a result, active polarization compensation is required to ensure the stable operation of quantum network links.

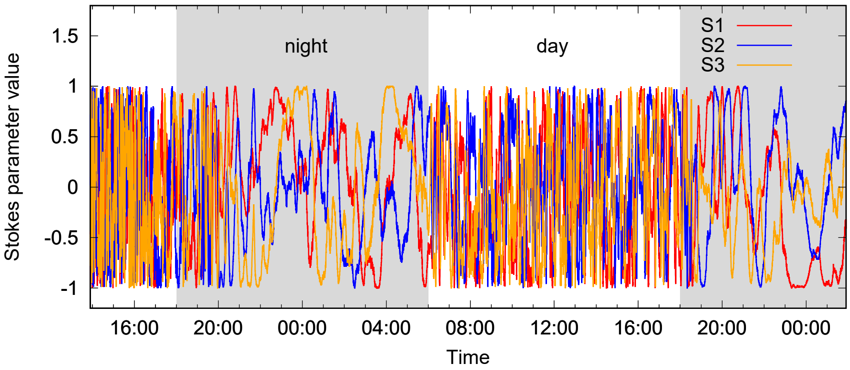

Fig. 1. Fiber polarization state change monitored over 36 hours. Shown in the figure are the Stokes parameters of a 1550.12 nm laser sent across a 120 km fiber loop-back between the National Institute of Standards and Technology (NIST) and the University of Maryland (UMD).

Various polarization compensation schemes have been implemented over the years and can be categorized into two types based on whether or not reference light is utilized. In the former case, reference light with modulated polarization states is sent across the optical fiber alongside the quantum signal [2, 3]. Based on the polarization measurement results on the receiving side, a polarization controller placed in the fiber link is set to invert the polarization change induced by the fiber. Alternatively, polarization compensation can be realized by utilizing the intrinsic parameter of a quantum system, such as quantum bit error rate or entanglement visibility, as the error signal in a control loop [4, 5]. While monitoring the error signal, the polarization controller is adjusted until the parameter is optimized.

If reference light is used, the compensation scheme can be performed rapidly within hundreds of milliseconds [4] at the cost of a hardware overhead. The bright reference light and the quantum signals are typically time-division multiplexed to avoid optical cross-talk, which in turn reduces the throughput of the quantum channel. In contrast, the parameter optimization method imposes no noise on the quantum channel and has a simple physical setup. However, its compensation time is usually limited to several minutes or longer due to the long integration time of each measurement.

We propose a method that could overcome the disadvantages in both types of compensation schemes. Our method utilizes reference light prepared in a defined polarization state at single-photon-level intensities which minimizes the noise imposed on the quantum channel. This technique can potentially have a high enough feedback bandwidth to compensate for rapidly changing fiber conditions on the order of hundreds of milliseconds.

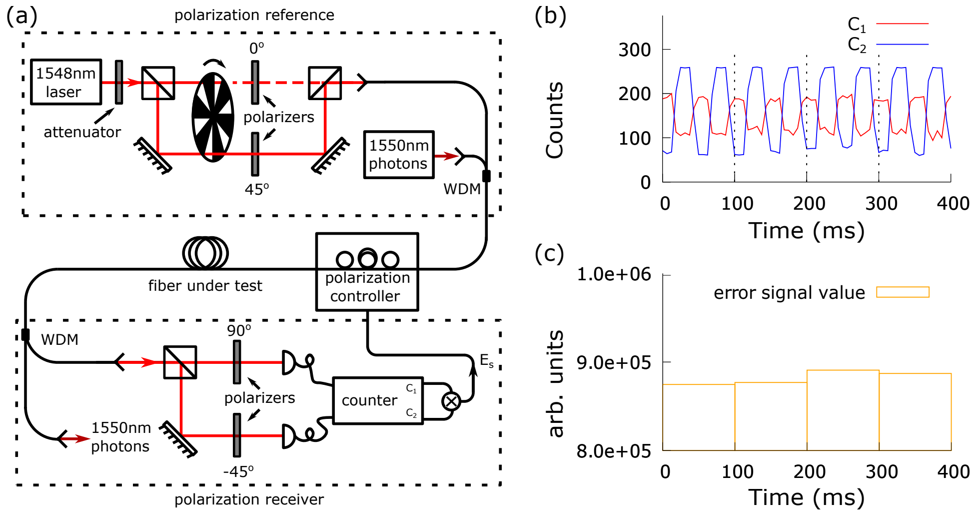

Fig. 2. (a) Experimental setup of the proposed polarization compensation scheme. (b) Photon count rates measured with two single photon detectors on the receiving side. (c) Error signal samples generated by multiplying the count rates between two measurement channels and integrating over 100 ms, which corresponds to two polarization modulation periods.

2. Fiber Compensation at a Single-Photon-Level Intensity

The experimental setup of the proposed compensation scheme is shown in Fig. 2a. The polarization reference light is generated by strongly attenuating a 1548.52 nm laser to an intensity level of about 10^5 photons per second. The photons are split into two paths and recombined using non-polarizing beam splitters. Two polarizers are placed in the optical paths and are set to $0°$ and $45°$, which prepare the photons with states $|H\rangle$ and $|+\rangle$ respectively. A rotating optical chopper is placed between the two paths such that only one of the paths is transmitting at any moment. As a result, the output light has a polarization state modulated between $|H\rangle$ and $|+\rangle$ at a frequency of 20 Hz, which is set by the rotation speed of the optical chopper.

The polarization reference light co-exists with the quantum signal at 1550.12 nm via Wavelength-Division Multiplexing (WDM). On the receiving side, the reference light is split and measured with two polarizers set at $90°$ and -$45°$ respectively, which corresponds to projection measurements onto $|V\rangle$ and $|-\rangle$ states. The transmitted photons are detected with two single-photon avalanche detectors, and the photon count rates C_1 and C_2 are recorded by a counting unit with an integration time of 2.5 ms (Fig. 2b). An error signal E_s is generated by summing the multiplication between C_1 and C_2 over 100 ms (or 2 polarization modulation periods, as shown in Fig. 2c).

The error signal E_s is proportional to $|\langle V|\hat{U}|H\rangle|^2 \cdot |\langle -|\hat{U}|H\rangle|^2 + |\langle V|\hat{U}|+\rangle|^2 \cdot |\langle -|\hat{U}|+\rangle|^2$, where $\hat{U}$ represents the unknown unitary polarization rotation induced by the fiber and the polarization controller. Polarization compensation can be achieved when E_s is minimized to zero, which occurs when the fiber induced rotation is neutralized by the polarization controller and $\hat{U}$ becomes the identity transformation.

This proposed compensation technique operates at a single-photon-level intensity ($\sim 10^5\ \mathrm{s}^{-1}$), which minimizes cross-talk and Raman scattering in fiber and contributes a negligible amount of noise to the quantum channel at 1550.12 nm. In this setup, the error signal is measured at a relatively high rate (10 Hz as shown in Fig. 2c) and can be further increased by using a higher modulation frequency, allowing for a shorter compensation time. In addition, as the count rates are measured continuously, our scheme does not require synchronization between the sender and receiver in contrast to other reference-light implementations utilizing classical-intensity-level light.

References

1. Gisin, N., Ribordy, G., Tittel, W. & Zbinden, H. Quantum cryptography. *Rev. Mod. Phys.*. **74**, 145-195 (2002)
2. Ma, L., Xu, H. & Tang, X. Polarization recovery and auto-compensation in quantum key distribution network. *Quantum Communications And Quantum Imaging IV*. **6305** pp. 630513 (2006)
3. Xavier, G., Faria, G., Temporão, G. & Weid, J. Full polarization control for fiber optical quantum communication systems using polarization encoding. *Opt. Express*. **16**, 1867-1873 (2008)
4. Ding, Y., Chen, W., Chen, H., Wang, C., Li, Y., Wang, S., Yin, Z., Guo, G. & Han, Z. Polarization-basis tracking scheme for quantum key distribution using revealed sifted key bits. *Opt. Lett.*. **42**, 1023-1026 (2017).
5. Shi, Y., Poh, H., Ling, A. & Kurtsiefer, C. Fibre polarisation state compensation in entanglement-based quantum key distribution. *Opt. Express*. **29**, 37075-37080 (2021).