Two-Way Quantum Communication in a Single Optical Fiber with Active Polarization Compensation

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Abstract. We experimentally demonstrate a two-way stable transmission of polarization encoded qubits over 23 km of spooled dispersion-shifted fiber with active polarization control in both directions, while simultaneously exchanging classical data. Two classical reference channels (one containing a telecom 10 Gb/s data stream), wavelength-multiplexed with the quantum signal, are used as feedback. The feasibility of quantum communication is demonstrated in the two opposite directions over 6 hours of continuous operation, as well as a classical error rate better than 1.0 x 10^{-9}.

Keywords: Quantum communications, Polarization, Optical networks.

1 Introduction

Most quantum communication [1] experiments to date have used a dark optical fiber link for the transmission of qubits between Alice and Bob [2-5]. For a broader insertion of quantum technologies into classical optical telecom environments, it is important to be able to reliably transmit qubits in a fiber populated with telecom traffic. For telecom operators, this is of great interest, since employing a single fiber solely for quantum transmission is not economically attractive.

By far the most widely demonstrated application of quantum information has been quantum key distribution (QKD) [6] employing the BB84 [7] protocol. BB84 is simply a secure way of transmitting the key if the bits are encoded in orthogonal pairs of quantum states which are grouped in two non-orthogonal bases. The quantum channel only needs to be one-way, but a classical communication channel is also needed between Alice and Bob.

From a standard classical optical network point of view, two-way quantum communication makes sense since, in a reconfigurable environment, quantum signals may need to be sent back and forth between Alice, Bob and other eventual network users. In addition to that, the same optical fiber may be shared by many users on both ends, and two-way communication needs to be provisioned in advance by the network operators. Specifically for QKD, there are protocols that require two-way quantum channels [8-11].

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In this work we present, to the best of our knowledge, the first experimental demonstration of a two-way quantum communication channel with active continuous polarization control [12,13] in both directions in long-distance optical fibers. This experiment shows that it is possible to perform classical telecom activity and transmit quantum signals simultaneously in an optical fiber with active polarization control. These results can be used to the benefit of telecom operators as well as improving practical implementations of quantum communications.

2 Experimental Theory and Setup

Optical fibers have been extensively used in quantum communication experiments because their properties suit well the transmission of single-photons. In addition to that, they have been extensively optimized by the telecom industry such that one can obtain relatively cheap fibers having low attenuation and chromatic dispersion in the 1550 nm telecom window. They are also widely deployed making it easier to install QKD systems to many different users in the future.

The two most widely used encoding methods of information for quantum communications are polarization [7] and time-bin (phase) [14]. Polarization was the first one used in experimental demonstrations; however, its use in optical fibers was quickly discontinued because of residual birefringence present in the fibers. The process of manufacturing optical fibers is not perfect and therefore a residual birefringence remains present. The problem arises since it depends on environmental factors (temperature and mechanical stresses applied to the fiber), and therefore the polarization state of an optical field at the output of the fiber randomly changes with time. This makes polarization-based quantum communications in optical fibers unfeasible unless active control is employed, which opened the way to phase encoding.

In order to have continuous polarization control enabled, our control system employs two reference channels wavelength-multiplexed with the quantum channel. In order to have optimum control, they need to be located as close as possible to the quantum channel, and the mean differential group delay of the fiber link cannot be much higher than ~ 1 ps [13]. For compatibility purposes and easy availability of components, we place our wavelengths of choice in the ITU-T wavelength grid (International Telecommunication Union - Telecommunication Standardization Sector). We use the 100 GHz grid spacing, meaning that the channels are located 0.8 nm apart in the 1550 nm window. Our quantum channel is located at $\lambda_Q = 1546.12$ nm, with the reference channels located at $\lambda_1 = 1545.32$ and $\lambda_2 = 1546.92$ nm. The experimental setup is shown in Fig. 1.

We have respectively labeled Alice and Bob the transmitter and receiver of the classical information channels, as they only propagate in one direction in our setup. Alice has the classical lasers to transmit the two reference lasers at λ_1 and λ_2 wavelengths. The laser located at λ_1 is a standard telecom distributed feedback (DFB) laser diode operating in continuous wave (CW) mode. The other one is the laser output of a DFB laser inside a bit error rate (BER) test meter operating at 9.953 Gb/s, simulating real telecom traffic.

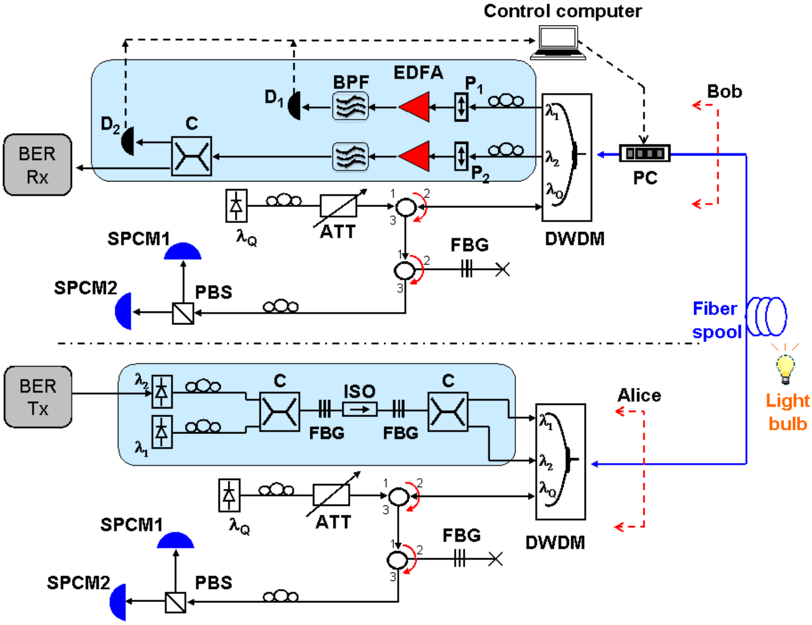

Fig. 1. Experimental setup. The light blue bounded areas at both Alice and Bob's stations represent the control and classical components. The classical channels propagate from Alice to Bob, while the quantum signals propagate simultaneously in both directions. ATT: Optical attenuator; BER Rx and Tx: Bit error rate meter receiver and transmitter respectively; BPF: Band pass filter; D1 and D2: Classical p-i-n photodetectors; DWDM: Dense wavelength division multiplexer; EDFA: Erbium doped fiber amplifier; FBG: Fiber Bragg grating; ISO: Optical isolator; SPCM: Single photon counting module; P1 and P2: Linear polarizers; PC: $LiNbO_3$ polarization controller; PBS: Polarizing beam splitter.

The states of polarization (SOPs) of both channels need to be adjusted with non-orthogonal states using manual polarization controllers before being multiplexed and entering the fiber link [11]. Both channels are combined in a 50/50 coupler, before going through two identical fiber Bragg gratings (FBG) filters, each reflecting 99.9% at λ_Q = 1546.12 nm. The two FBGs provide ~ 60 dB attenuation at λ_Q, thus reducing the cross-channel amplified spontaneous emission (ASE) noise to ~ 100 dB below the power at the center wavelength of the lasers. One isolator is used between the two FBGs to avoid the creation of a Fabry-Perot cavity. Finally another 50/50 coupler splits the two signals and they are multiplexed in the optical link together with the quantum wavelength λ_Q. The loss the two reference channels suffer when passing through both 50/50 couplers is not of importance since we need to attenuate both channels before inserting them in the optical link to minimize Raman spontaneous scattering noise [15, 16]. The launch powers for both channels after the multiplexer are of -19.8 dBm each.

Alice and Bob are separated by 23 km of dispersion-shifted spooled fiber. The SOPs of the three channels are actively compensated by a $LiNbO_3$ polarization controller (PC) located close to Bob. An incandescent light bulb is used to randomly heat the fiber to simulate temperature changes. Alice and Bob have identical optical hardware to prepare the polarization qubits to be sent and decode the received ones: attenuated lasers at λ_Q, circulators and polarizing beam splitters (PBS), all shown in Fig. 1. Filtering is done using FBGs located at λ_Q (isolation > 35 dB) and the DWDMs, and it was verified that no cross-talk took place by performing photon counting measurements in both directions without the fiber spool. The output ports of the PBS are connected to commercial SPCMs (single-photon counting modules). They operate in Geiger mode [6] at a gate frequency of 100 kHz, with a quantum efficiency of 15% at 1550 nm and a gate width of 2.5 ns. The measured dark count probability is 3.7×10^{-5} and 3.2×10^{-5} per gate for each SPCMs respectively.

Within Bob's setup, the classical channels are split and pass through linear polarizers P_1 and P_2 oriented at 45° from each other using manual polarization controllers [12, 13]. λ_1 and λ_2 are amplified with EDFAs before detections at classical *pin* photodiodes D_1 and D_2 (300 kHz bandwidth). λ_2 is also split by a 50/50 coupler so that it can also feed the receiver unit of the BER test meter to monitor the error rate of the 10 Gb/s data stream. The two electrical outputs of D_1 and D_2 are fed back into the control computer to close the feedback loop, allowing us to undo any birefringence rotations the fiber may cause for *any* input SOP [13].

3 Experimental Results

A single SOP is sent from each end of the fiber, and the manual polarization controllers before each PBS are adjusted to maximize the counts on one of the SPCMs (the SOP matches the measurement basis). The counts are recorded as a function of time, and the results are plotted in Fig. 2. Initially, the active control system was switched off and the counts recorded by Alice's detectors. We observe that the counts almost immediately begin to drift due to the birefringence variation. The system is then switched on, the states realigned and the counts recorded over a similar time period. The two SPCMs were moved to Bob's side, the counts are recorded and the results from both controlled cases also plotted in Fig. 2. It is clear that the counts in both SPCMs remain stable throughout the experimental runs with the active polarization control switched on. It is also worth mentioning that the BER rate stayed better than 1.0×10^{-9} during all measurements, showing that our control system is compatible with simultaneous telecom traffic. The long-term drift observed in the SPCM1 Alice curve is believed to have been caused by a small change in the SOPs before or after the DWDMs. The drop in the count rate when comparing Bob's and Alice's SPCMs is due to ~ 3 dB attenuation caused by the $LiNbO_3$ polarization controller, since in the Alice-Bob path, the controller increases the attenuation of the quantum channel, while in the opposite direction it does not (it is a part of Bob's setup). The launched mean photon number per gate was 1.0 on both sides. It should be noted that our polarization stabilization system is able to compensate for any input polarization state [13]. The visibility can be calculated for the case when the received SOP is compatible with the measurement basis as a function of time. The two controlled cases (co- and counter-propagating) exhibit average visibilities of 0.916 ± 0.025 and 0.931 ± 0.016 respectively, with the deviation from perfect visibility stemming from detector dark counts,

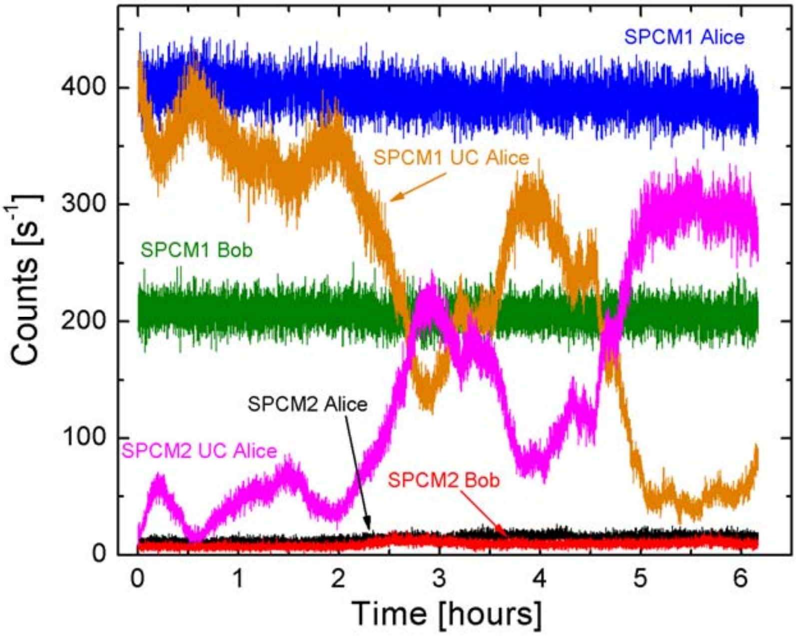

Fig. 2. Experimental results with and without polarization control as a function of time. SPCM1 UC Alice and SPCM2 UC Alice are measurements with the system control turned off.

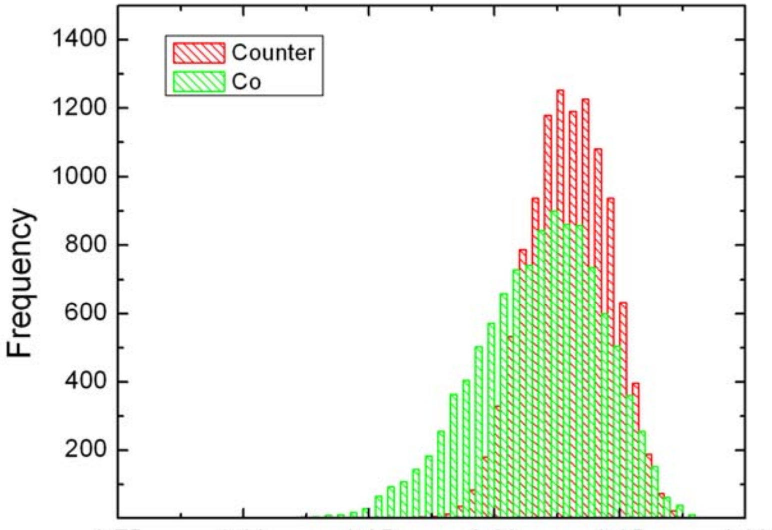

Fig. 3. Distribution of calculated visibilities obtained from the data in figure 2 for co- and counter-propagating directions.

Raman noise, fluctuations added by the polarization stabilizer and imperfect manual alignment of the PBSs with the single photons SOPs. Unsurprisingly the visibility for the uncontrolled measurement wanders randomly across all possible values, showing once again that quantum communication using polarization states without active control is unfeasible.

We now plot in Fig. 3 the histograms of the calculated visibilities from the data of the two controlled directions shown in Fig. 2. It shows that the visibility never goes below 0.8, allowing continuous uninterruptable QKD [6]. As expected from the results in the experiment, visibilities for the co-propagating case are worse when compared to the counter-propagating case because of the extra attenuation in the Alice-Bob direction (due to the $LiNbO_3$ polarization controller).

We have shown that stable fiber optical two-way transmission of polarization encoded qubits is possible in two simultaneous directions in a single long-distance optical fiber, shared with two classical optical channels (one of them containing a 10 Gb/s data stream), used to provide feedback to the active polarization compensation system. Limitations of distance were estimated for our current setup performing simultaneous quantum and classical communications. These results are important for any quantum protocols requiring two-way exchange of qubits, as well as future implementations of hybrid classical-quantum optical networks.

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