Phase stabilization with single photon detection for quantum networks

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Abstract: We demonstrate phase stabilization of a 3.2 km quantum network link with faint light. Our stabilization signal can empower phase-reliant quantum communication protocols and supports coexistent multiplexing of classical/quantum channels in a scaleable quantum network.

Coherence is one of the important features of quantum systems. Maintaining coherence in a quantum state is essential for quantum communication. Preserving phase reference in photonic quantum states is key to operating many quantum communication protocols. Optical fiber provides a convenient channel for photonic quantum networks, enabling light transmittance over long distances with high isolation from environmental noise and with modest loss. However, long fiber links suffer from instabilities of the optical path length due to their dependence on temperature and other environmental factors. The obvious solution to phase stabilization is to perform interference and extract the phase information. However, using classical signals to perform phase stabilization is not desirable, especially in a multiplexed quantum network with many coexisting quantum and classical signals in the same fiber. Studies show the classical signal induces Raman and other scattering noise into the quantum channel [1], introducing strict classical power limitations. Hence, it is imperative to reduce the power of all traffic to few-photon levels to avoid cross-talk between quantum and classical channels [2]. To this end, phase stabilization with super-weak coherent states is required to achieve co-existence in a scaleable quantum network. Here we design a stabilization method that takes advantage of single-photon detection (i.e. uses instrumentation that is uniquely available on a quantum network) and uses just a few hundred thousand photons per second. We report a time-multiplexed phase-stabilized optical link of up to 3.2 km with visibility of better than 93±1% using 65 photons per pulse. Thanks to time multiplexing built in to the stabilization protocol, this phase stabilizer is compatible with a broad range of quantum networking and quantum-inspired protocols, including quantum receivers for classical communications.

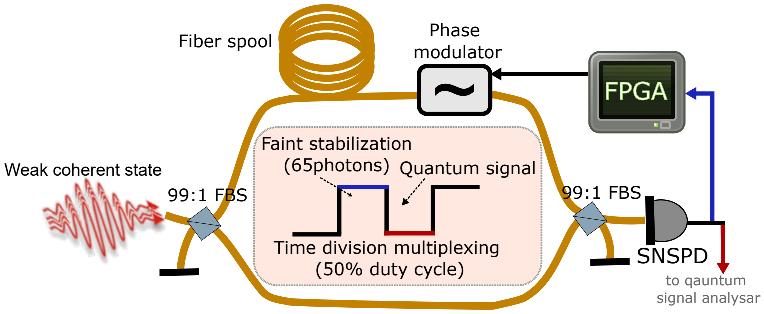

Fig. 1. Schematics of the experimental set-up for phase stabilization of quantum network fiber links.

The experimental setup is shown in Fig 1. We use a faint coherent signal in a C-band (1550nm) from the ultrastable laser to stabilize the long optical fiber link with single photon detection. The signal is split using a 99:1 fiber beam splitter (FBS) and 99% of the signal is sent to fiber spools and 1% is sent through the short fiber. An acousto-optic modulator (AOM) is used after the fiber spools to modulate the optical phase. Subsequently, the signals are combined at another 99:1 fiber beam splitter. The output from the fiber beam splitter is connected to a superconducting nanowire single photon detector (SNSPD). The electrical pulse generated after each photon detection at the SNSPD is sent to the FPGA for phase estimation. To maximize Fisher information of photon detection on phase estimation, the local oscillator displaces the input to the vacuum, and the FPGA adaptive algorithm, described below, computes the feedback for the AOM that keeps displacing the input to the vacuum. The weak optical pulse is then turned off to deliver the quantum payload. Here the pulse duration is 132 μS. With a 50% duty cycle, half of the time we send the phase stabilization signal, and the other half can be used to send the quantum signal. During the stabilization, the SNPSD output is fed into the feedback algorithm. By keeping the optimization signal low, the SNSPD is kept well below saturation, and it is readily available for detecting the quantum payload. Phase stabilization strategy consists of two parts: photon number collection and adaptive phase shift determination. The number of photons is counted during the time period "δt". After each measurement period of "δt", the number of photons is compared to the previous cycle measurement, which determines the most likely direction of adaptive phase shift is determined. The current photon count is stored for the next cycle. Finally, the correction to the phase shift is proportional to the total number of detected photons.

We study the phase noise of the fiber spools of different lengths. We expect that the longer fiber suffers from more phase noise. We use a laser with a coherence length that is significantly larger than the longest link, the phase noise originating from the source is negligible. We observe that with the length of the fiber the magnitude of phase noise increases, so the requirements on the feedback bandwidth increase. In Fig 2 (a,b) we show the effect of phase noise on the interference fringes in 400m optical fiber. Before the stabilization, the interference fringes fluctuate significantly. After the stabilization algorithm is enabled the phase is locked to attain destructive interference. The measured visibility for a 400m fiber is 96.6±1%.

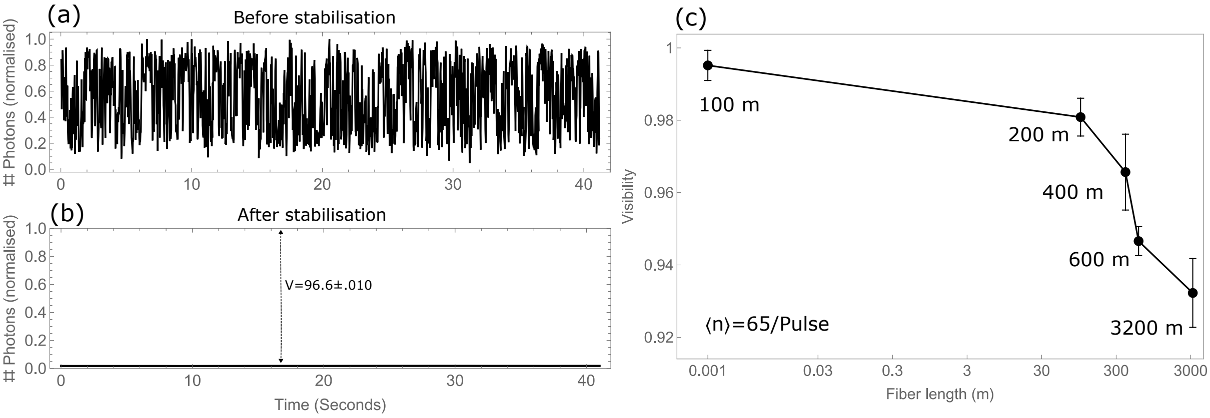

Fig. 2. Phase stabilization and the visibility achieved at different optical fiber lengths. (a) the intensity fluctuation due to phase noise in the 400 m fiber spool with no stabilization and (b) same link, with phase stabilization using 500,000 telecom photons per second (c) experimentally achieved visibility at different lengths of fiber links.

To test our phase stabilization algorithm we have used different lengths of optical fiber spools. We measured visibility at different fiber lengths and plotted in Fig. 2(c). For 100m, 200m, 400m, 600m, and 3200m fiber lengths the measured visibilities are 99.5±0.4%, 98.1±0.5%, 96.6±1%, 94.7±0.4% and 93.2±1%. The feedback bandwidth of this algorithm is not sufficient to fully stabilize longer fiber lengths, hence resulting in lower stability. However, it is to be noted that we have achieved more than 90% visibility even with 3.2 km fiber. Improving the phase stability can be achieved in the same or similar arrangement and by using the availible technology. Particularly, the cycle length could be significantly shortened, while still maintaining the same duty factor for the quantum payload. We are also exploring the single photon measurements with two SNSPD detectors for quadrature measurement-based phase stabilization.

In conclusion, we demonstrated the phase stabilization of optical fiber links in quantum networks with faint light, sufficient to empower many phase-stabilization-reliant quantum protocols. In doing so, we stabilized an optical link length of 3.2 km with single photon detection using just an average of ≈500,000 photons per second. Beyond sharing phase reference between two parties, this protocol enables multiplexing of quantum and coexistent classical links in the same fiber.

References

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