Continuous operation of a one-way quantum key distribution system over installed telecom fibre

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(Dated: April 1, 2022)

We demonstrate a robust, compact and automated quantum key distribution system, based upon a one-way Mach-Zender interferometer, which is actively compensated for temporal drifts in the photon phase and polarization. The system gives a superior performance to passive compensation schemes with an average quantum bit error rate of 0.87% and a duty cycle of 99.6% for a continuous quantum key distribution session of 19 hours over a 20.3 km installed telecom fibre. The results suggest that actively compensated quantum key distribution systems are suitable for practical applications.

Quantum cryptography, or more precisely quantum key distribution (QKD) [1], provides a secure way to distribute cryptographic keys on fibre optic networks, the secrecy of which can be guaranteed by the laws of quantum mechanics. Most QKD systems that have been realized so far have encoded the bit information as a phase delay in an interferometer [2, 3]. This is largely due to the availability of high-quality telecom phase modulators, as well as the fact that phase-encoded qubits are relatively resilient to decoherence in optical fibres [11]. Despite this, stabilising the interferometer path lengths to within the wavelength of the photons is a major technical problem, currently limiting the usefulness of many applications.

An early long distance demonstration of QKD was based upon two asymmetric Mach-Zender interferometers (AMZI) [2, 3]. Photons generated by the sender (Alice) travel through the first AMZI, followed by the optical fibre, before passing through a second AMZI at the receiver’s (Bob) site. Optical interference will take place if the phase delay of Bob’s AMZI cancels that of Alice’s. Alice and Bob can then perform QKD using phase modulators in each of the two interfering paths, provided there is a fixed phase relationship between the two paths without any modulation. In practice, maintaining a fixed path length difference (to within several tens of a nanometer) between the two AMZIs is very difficult. In particular, changes in the ambient conditions, such as the apparatus temperature, cause a slow drift of the phase difference. Consequently, one-way systems typically operate for only a few minutes at a time and require constant realignment [2, 3].

The phase drift problem was resolved using an ingenious passive compensation scheme [2, 3, 10]. Here the photons make a double pass through a single AMZI, ensuring passive compensation of any phase drifts occurring over time scales greater than the propagation time of the photons through the system. In the ‘plug-n-play’ scheme [2, 3], a bright laser pulse is divided into two by propagation through the AMZI at Bob and then transmitted to Alice. Alice modulates one of the two pulses, and after attenuating them to single photon level, reflects the pulses back along the same path back to Bob. The pulses then travel back through the AMZI, during which time Bob, modulates the other pulse of the pair. Such an arrangement automatically cancels any slow variations in the difference of the two paths in the AMZI and is now the basis of commercially available QKD systems [8].

Although the round-trip fibre architecture can reduce the problem of phase drift, it can degrade the system performance. Contamination of the quantum signal by photons from the strong pulse that are back-scattered by the fibre contributes to the quantum bit error rate (QBER). To minimise this, a round-trip system needs to operate by sending bursts of pulses spaced by long dead intervals [8]. This will reduce the duty cycle and bit rate of the system. The round trip layout also cannot be used with a single photon source. This is due not only to the effective doubling of the transmission loss, but also because of the Trojan horse attack [12]. Since Alice is simply a modulation station in such a scheme, an eavesdropper could insert Trojan photons to be modulated and gain information.

In this paper, we show that phase and polarization drifts in a one-way QKD system may be controlled using active compensation. In this scheme, each signal pulse is multiplexed with brighter reference pulses at the same wavelength. Alice and Bob modulate only the signal pulses, but leave the reference pulses un-modulated. Therefore, the interference of the reference pulse is used to detect any phase drift and provide a feedback signal to rebalance the double AMZI. The system is self-initiating and can operate continuously over long periods without user intervention.

Figure 1 illustrates a schematic of the optical layout in our system. In comparison with the setup we reported previously to achieve 122km QKD [8], we have added a pulse splitter into Alice’s arrangement and a reference detector at Bob’s setup (shown within the shaded inserts). The pulse splitter divides the input 1.55 µm DFB laser pulse (of 400 ps duration) into two pulses separated by a 40 ns delay. The reference (late) pulse is 24
times stronger than the signal (early) pulse. The output of the splitter is fed into the encoding AMZI. The signal (early) pulse is then attenuated to an average intensity of 0.2 photons per clock cycle, before multiplexing with pulses from the 1.3 μm clock laser, which serve as a timing reference. Bob’s set-up contains three InGaAs avalanche photodiodes (APD’s); APD0 and APD1 for the signal photons are cooled to -100°C by a compact Stirling cooler to achieve a dark count probability of $10^{-6}$, while APD2 for the strong reference pulse, cooled by a thermal-electric cooler to 40°C, has a dark count probability of $2 \times 10^{-5}$. The overall detection efficiency of APD0 and APD1 is around 11%. Their detection rate is balanced because of the higher intrinsic efficiency of APD1, despite of the 18% splitting loss to APD2. Active stabilization of the phase drift is achieved by using the count rate in the reference detector APD2 to control the bias applied to the fibre stretcher in Bob’s AMZI.

The sending and receiving units were housed in compact 3U-height 19-inch rack mounts containing both the optics and associated electronics. We found that the scheme could compensate for changes in the ambient temperature inside the housing due to the drive electronics. The BB84 protocol [1] for QKD was used, with the required classical information exchanged over the Ethernet. The measurements results are sifted, and the QBER monitored, in real-time. Bob also monitors the photon detection rate, the phase drift/compensation rate, and the coincidence rate of APD0 and APD1. The key distribution stations were connected using installed telecom fibre serving our laboratory on the Cambridge Science Park. Its total length was measured to be 20.3 km, and its transmission loss was 5.3dB for 1.55 μm. This is rather more than the specified attenuation of the fibre (0.2 dB/km) due to connector and splice losses.

Figure 2 illustrates data recorded over an uninterrupted 19-hour experimental run, during which 29.7 Mbit of sifted key material was formed at an average rate of 0.43 kbits/s. This data was recorded with a relatively low clock rate of 250kHz, in order to minimize the APD afterpulse counts [2] and thereby characterize contributions of the active compensation scheme to the QBER.

Figure 2 plots the QBER sampled over 5-kbits block-size as a function of key position. Notice that most of the measured QBER lies between 0.5% and 1.2%, while the minimum value is just 0.32%. The QBER averaged over the whole QKD session is 0.87%, which is among the lowest reported values so far. The few points with slightly higher QBER are related to times when the interferometer was highly unstable due to the fibre-stretcher resets discussed below. However, even during these periods, the averaged QBER remained less than 2.5%, demonstrating that the system is able to recover quickly. The probability of the QBER exceeding 1.5% is low, as shown by the distribution of measured values in the inset of Fig. 2.

Figure 3(a) shows the voltage applied to the fibre stretcher as a function of time. The drive voltage varies in the range from -5V to 5V. With a phase compensation co-efficient of 294°/V, the fibre stretcher is able to give around a maximum of 8-wavelength compensation. When the phase drifts beyond this range, the stretcher is programmed to reset to 0V. From the data collected, it is
the classical interference fringe visibility was recorded to be 99.12%, suggesting the QBER due to the optical imperfection is 0.44%. This error source can be reduced to be less than 0.1% in an optimized double AMZI [5].

The QBER due to the residual mismatch in the phase delay between the two AMZIs is an important parameter to evaluate the success of the active compensation scheme. Figure 4 shows the same data as in Fig. 3(a), but over a much shorter timescale. Notice that the voltage applied to the fibre stretcher oscillates around an average value with an amplitude of 70 mV, which corresponds to maximum error in the phase compensation of 10.3°. The QBER due to mis-compensation can be approximated by

\[ QBER_{\text{phase}} = \int_{-\Delta\varphi}^{+\Delta\varphi} \frac{1 - \cos \varphi}{2} d\varphi \]  

where \( \Delta\varphi \) is the phase variation range due to mis-compensation. Using the recorded data, phase mis-compensation is found to contribute only 0.27% to the QBER. The remaining contribution to the QBER, of around 0.15%, is attributed to the erroneous counts in the single photon detectors, including dark counts, stray photons and after-pulsing.

We have also tested the system at a clock frequency of 1 MHz, and obtained a sifted bit rate of 1.7 kbit/s. However, the average QBER was found to increase to 1.8%, due to an increase in afterpulse noise in the APDs. We stress that this increase in the QBER is due to the APDs and is not a limitation of the active compensation scheme. Given a sufficiently improved APD [14], clock rates in excess of 10 MHz may be expected. Finally, we point out that the active compensation scheme is compatible with a single photon source by only a slight modification to the set-up. Single photons can be combined with reference pulses from an attenuated laser using a
highly asymmetric coupler. Alternatively, they can be multiplexed by shining the reference laser pulse through the lower input port of Alice’s encoding AMZI.

In summary, we present an automated and compact QKD system with active compensation for both polarization and phase drifts. The compensation scheme gives a QBER of 0.87% averaged over 19 hours key distribution session with an averaged duty cycle of 99.6%. The results demonstrate that actively compensated QKD systems are suitable for practical applications.

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