Experimental Implementation of 1310-nm Differential Phase Shift QKD System with Up-conversion Detectors

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Abstract: We have experimentally implemented a differential phase shift quantum-key distribution system with up-conversion detectors operating at a 2.5 Gbps clock rate. A Michelson interferometer with Faraday mirrors is used to increase the system stability.

OCIS codes: (270.5568) Quantum Cryptography; (270.5570) Quantum Detectors

1. Introduction

Quantum Key Distribution (QKD) systems offer the promise of unconditional security for communication, but currently it suffers from limited speed and distance due to the low efficiency of single photon detectors and the fragility of photons. To increase both speed and distance of a QKD system, one needs to reduce the photon transmission loss, improve protocol, and increase the clock rate and detection efficiency. For fiber-based QKD systems, the wavelength of the quantum signal needs to be in the low transmission loss windows (around 1310 nm and 1550 nm) of the telecommunications fiber in order to propagate more than 10 km. With the aid of frequency up-conversion devices [1], silicon avalanche photo diodes (Si-APDs) can detect the photons in these telecom low-loss wavelength bands and can operate in the free running mode at over GHz. In the differential phase shift (DPS) protocol [2], one does not need to sift off the photons detected with incompatible bases, and thus increases the sifted key rate. Therefore, the DPS QKD system with up-conversion detectors [3] is a very effective scheme to achieve long-distance fiber propagation. In this paper, we report an experimental implementation of a high speed 1310-nm DPS QKD system, in which we applied an up-conversion technique using a 1550-nm pump. In this system, we use an unbalanced Michelson interferometer with two Faraday mirrors to implement the differential phase shift, which makes the system polarization insensitive to temperature and suitable for field applications.

2. System configuration

Figure 1 shows schematically the QKD system (a), the 1-bit Michelson Interferometer (b), and the up-conversion unit (c).

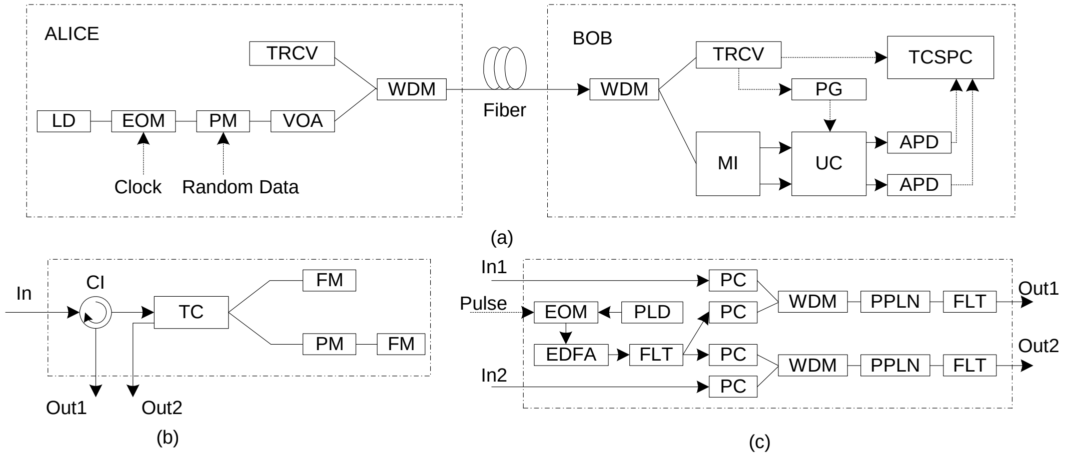
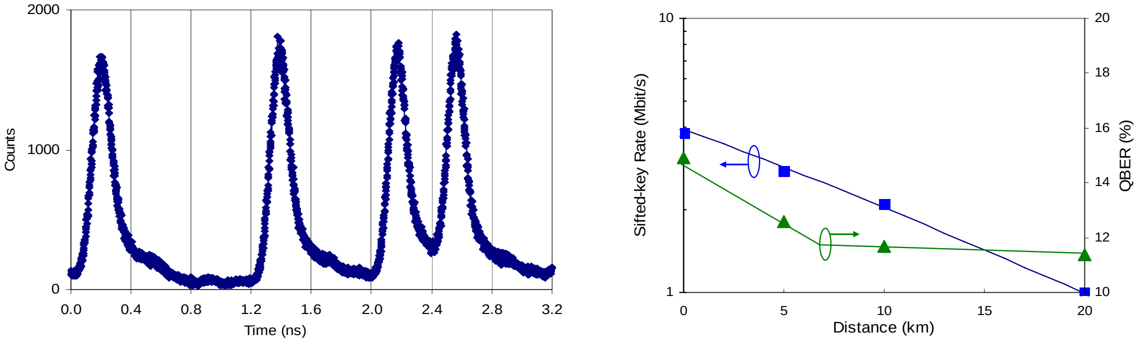


Fig. 1 (a). Schematic diagram of the DPS-QKD system; (b) Schematic diagram of Michelson Interferometer; (c) Schematic diagram of up-conversion Unit. LD: CW laser Diode; EOM: Electric-optic Modulator; PM: Phase Modulator; VOA: Variable optical attenuator; TRCV: Optical transceiver; WDM: Wavelength-Division Multiplexer; PG: Pulse train generator; APD: Silicon avalanche photodiode. ; MI: Michelson Interferometer, see (b); UC: Up-conversion unit, see fig. 1 (c); TCSPC: time-correlated single photon counting; TC: Tunable Coupler; FM: Faraday Mirror; CI: Circulator. PLD: Laser Diode for pump; EDFA: Erbium-doped fiber amplifier, FLT: Optical Filter, PC: Polarization controller, PPLN: Periodically-poled $LiNbO_3$ waveguide; Dotted line: Electric cable; Solid Line: Optical Fiber

At Alice, a CW 1310-nm laser beam was modulated into 2.5-GHz pulse train with a FWHM of 100 ps by an amplitude modulator, and the pulses are then further phase-modulated to 0 and π by a random data streams. The phase-encoded pulse trains are attenuated into single photon level, combined with classical channel laser (1550 nm) via a WDM and transmitted over a standard telecommunication single-mode fiber. At Bob, another WDM is used to de-multiplex the quantum and the classical channels. The quantum signal then passes through a polarization-insensitive 1-bit delay Michelson interferometer, whose outputs are dependent on the phase difference of consecutive pulses. The scheme of Michelson interferometer with two Faraday rotation mirrors helps to minimize the polarization sensitivity to temperature, which is important for its field application. The extinction ratio is maintained via a tunable coupler around 50/50, which helps to equalize the power in the two arms. A phase modulator compensates static phase difference to achieve maximal extinction ratio as well. The output signal photons at 1310 nm from the interferometer pass though a periodically-poled $LiNbO_3$ (PPLN) waveguide and are converted to 710-nm photons by a strong 1550-nm pump, which is a 2.5-GHz, 200-ps FWHM pulse train synchronized to the quantum signal via the clock extracted from the classical signal. After passing through noise-reduction filters, the 710-nm photons are detected by Si-APDs (MPD photon counting detector module) [4] and counted by a time-correlated single photon counting (TCSPC) module.

3. Results and discussion

Figure 2 (a) shows a histogram of the output at detector 1 for a repetitive pattern of 10010110. For each detection event, Bob returns bit position (the time bin), but not the bit value, of the detected photons to Alice through public channel, and Alice can obtain the bit value. Figure 2 (b) shows the QKD system performance, including sifted-key rate and quantum bit error (QBER). During the measurements, the mean photon number per pulse at the output of Alice is set to 0.1 and the data are collected at distances of 0, 5, 10, and 20 km. The measured sifted-key rate is over Mbits/s at 20 km and the data agrees well with calculations that consider the loss of transmission and interferometer, detection efficiency and the influence of the dead time of APD and TCSPC. However, the QBER is relatively high (>10%) at all distances, even though the up-conversion detector dark counts have been reduced to less than 2000 per second. The low dark count rate is achieved with longer wavelength pump and pulse modulation form [2]. The measured extinction rate of the interferometer and modulators are about 18 dB. Therefore, the dark counts and imperfect extinction contributions is estimated to induce an error rate of only about 2~3%. The main cause of the high error rate is the timing jitter. Although the optical pulse FWHM is 100 ps and the jitter of APD is about ~30 ps (FWHM), which is significantly less than the system time bin (400 ps), a long tail of the APD response results in strong inter-symbol photon leakage. Besides, the count-rate dependent jitter of APD [5] causes even higher error rates in short distance experiments, i.e., the jitter increases as the receiving photon rates become higher.



(a) (b)

Fig. 2. (a) Histogram of the output at detector 1 for a repetitive pattern of 10010110. (b) The system performance of the 1310nm DPS QKD system. Left blue square is the sifted-key rate measured in the system; left blue line is the calculated sifted-key rate; right green triangle is the measured QBER; right green line is the trend-line of QBER.

In conclusion, we have experimentally implemented a fiber-based 1310 nm DPS QKD system using 1550 nm pump up-conversion detectors and generated more than 1Mbit/s sifted-key rate over 20 km. The QBER of the system is dominated by the long tail of the APD response. The system error rate is expected to be reduced significantly by improving this jitter performance.

4. References

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