Quantum key distribution with dissipative Kerr soliton generated by on-chip microresonators

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Quantum key distribution (QKD) can distribute symmetric key bits between remote legitimate users with the guarantee of quantum mechanics principles. For practical applications, the compact and robust photonic components for QKD are essential, and there are increasing attention to integrate the source, detector and modulators on a photonic chip. However, the massive and parallel QKD based on wavelength multiplexing are still challenge, due to the limited coherent light sources on the chip. Here, we introduce the Kerr dissipative soliton in a microresonator, which provides the locked coherent frequency comb with 49GHz frequency spacing, for QKD. We demonstrate the parallel QKD by demultiplexing the coherent comb lines form the soliton, and showing the potential of Gbps secret key rate if the hundreds of channels covering C and L bands are fully exploited. The demonstrated soliton based QKD architecture are compatible with the efforts of quantum photonic integrated circuits, which are compact, robust and low-cost, and provides a competitive platform of practical QKD chip.

I. INTRODUCTION

Quantum key distribution (QKD) can distribute symmetric key bits between remote legitimate users [1]. The security of key bits are information-theoretical benefiting from their physical generating process [2, 3]. A lot of research works have been devoted to get higher secure key rate (SKR), longer secure transmission distance in a QKD point-to-point link [4–8], as well as more flexible connections and higher user capacities in QKD networks [9–12]. The photonic layer, which can generate, modulate and detect photon pulses at the single photon level, is the kernel of QKD. Although the clocking rate of practical QKD systems have exceeded 1 GHz and the SKR can be more than 1 Mbps at the fiber quantum channel of 50 km [13], to increase the SKR is the most pressing task in QKD research. Wavelength division multiplexing (WDM) is an effective technique to increase the SKR in an end-to-end QKD system [14–16], or to route quantum signals in QKD networks [10, 11]. The emerging achievements of integrated photonic QKD chips [17–19] and single photon detector arrays [20] exhibit the potential to integrate large-scale information transmitting and receiving units in very small scales.

The maturest light source used in current real-life QKD systems is the weak coherent source (WCS), and arrays of lasers are deployed in the scenario of using WDM. However, for a integrated QKD chip [17, 19] for massive parallel and high speed communication, the locked laser sources are necessary but very challenging. Even for traditional off-chip QKD systems, such a source is cumbersome or costs too much. Recently, there is emerging a new research field on the frequency comb generation in microcavities [21–24], which provides abundant individual frequency resources in a wide bandwidth with only a single external laser pump. The dissipative Kerr soliton (DKS) soliton source [24–26] can provide high signal-to-noise ratio (SNR) individual optical comb lines in a wide bandwidth (∼150nm) covering C and L bands, with the repetition rate ≥ 50GHz, which is suitable for wavelength multiplexing, and thus has the potential to replace the laser arrays with a single and compact device. Such an attractive source has already been applied in classical optical communication and indicates a Tbps communication rate by wavelength multiplexing [27].

In this work, by utilizing a DKS source on a photonic chip, we demonstrated that ultra-high-key-rate QKD systems are feasible by frequency multiplexing and demultiplexing. We verified the soliton source by two scenarios. In the first scenario, one 1 GHz QKD system is running by using only one communication channel. In the second scenario, two 1 GHz QKD systems are running simultaneously but independently within different communication channels. According to these two scenarios, we realized an SKR of more than 200kbps with one 1GHz QKD system in the distance of 25km. By considering the frequency source and the potential application in integrated optics of the soliton, QKD systems with 100Mbps to 1Gbps SKR is promising.
II. DISSIPATIVE KERR SOLITON

Figure 1 schematically illustrates the concept of QKD networks based on the on-chip DKS source. In an integrated microring resonator, there are whispering gallery modes with almost equal frequency spacing and very high quality factor (Q) [28]. Due to the competition between the external pump laser, cavity dissipation and the intracavity Kerr effect, the resonator could evolve into a stable soliton state that a pulse circulating in the resonator with fixed pulse shape [24–26]. Through the external bus waveguide, the soliton could be coupled out and serve as the laser source for the QKD experiments. In the frequency domain, the stable pulse corresponds to a comb, consisting of many coherent laser lines with equal frequency spacing. Therefore, ultra-high speed and multi-user QKD network could potentially be realized through wavelength multiplexing.

Our work uses an integrated high-index doped silica glass microresonator [29, 30] for DKS frequency comb generation. By carefully designing the waveguide cross-section (2 μm × 3 μm) of the microring resonator, a flat anomalous group velocity dispersion in communication bands is realized, which is beneficial for broadband frequency comb generation. The radius of the microring is 592.1 μm, corresponding to a free spectral range of about 49 GHz, and the typical Q-factor of our device is about 1.7 million. By gluing the photonic integrated chip with optical fiber, the microring resonator can be efficiently excited and the DKS can be collected directly through fiber. Additionally, our device is packaged with a thermoelectric cooler (TEC) for enhancing the environmental adaptability of the DKS source [30].

The experimental setup of our integrated DKS source is shown in Fig. 2(a). An external pump laser is amplified by an erbium-doped fiber amplifier (EDFA) and coupled to the microring resonator. Due to the ultrahigh Q-factor enhanced Kerr nonlinearity in the microring, the whispering gallery modes start to lase through the hyperparametric oscillation [21]. By carefully tuning the relative frequency detuning of the pump laser and the microring resonance, the DKS could be realized [24, 25, 31]. Here, we adopt the auxiliary laser assisted soliton switching method to kick the microring to the multi-soliton state [32, 33]. Since the comb spacing of the N-soliton state is N-times of the FSR, we manually switch the system to the single soliton state for a full comb by annihilating the number of soliton step by step [32, 34]. It is worth noting that, the auxiliary laser is coupled with the microring counter-propagates with respect to the soliton, and the polarization of the laser is also orthogonal with the soliton, thus the auxiliary laser is filtered using a polarizing beam splitter (PBS) and has little influence to the soliton source. The soliton comb states are stable over several hours by maintaining the comb power with frequency control of the auxiliary laser or with temperature control of the TEC.

Figure 2(b) presents the spectrum of the single soliton state achieved in our experiment. The DKS exhibits a 3-dB spectral bandwidth as broad as 3.2 THz and more than 200 comb lines with 20 dB signal to noise ratio (SNR). The single-soliton state showing features, i.e. comb spacing are exactly equal and the spectrum envelop is very smooth, that are very attractive for communications. It already demonstrates that ultra-high speed optical communication with frequency multiplexing is feasible [27].

III. SOLITON-BASED WAVELENGTH MULTIPLEXING QKD

To demonstrate the feasibility of our integrated DKS source for the QKD applications, the wavelength multiplexing of the DKS was tested. The power spectra of five channels (CH1-CH5 of the demultiplexing (DEMUX) are shown in Fig. 2(c). The soliton comb line interval is 49 GHz and the channel interval is 98 GHz. The power spectra cross talks of the DEMUX are shown in Fig. 2(d) (from left to right: CH1 to CH5). Our experimental results indicates that the cross talk between adjacent channels is less than 20 dB for all channels (CH1-CH5), and there is no cross talk between non-adjacent channels. Therefore, our DKS source promises high secret key for QKD.

The experimental setup for the proof-of-principle demonstration of the DKS-based QKD is shown in Fig. 3(b). For each transmitter on Alice’s side, a demultiplexing (DEMUX) is connected to the DKS source to select a working bandwidth, as shown in Fig. 2(a), the output light from different channels of the DEMUX are selected comb lines, which are actually continuous lasers. An intensity modulator (IM) (IM1 in Fig. 3(b)) is used to chop the continuous light into pulses and a polarization controller (PC) is connected before IM1 to get maximum extinction ratio (ER) of light pulses. A phase modulator (PM) is cascaded to randomize the global phase of each pulses [35]. Then the classical random bits are phase-encoded onto the photons based on BB84 protocol with decoy state method.

The encoding processes are implemented by a Faraday-Sagnac-Michelson interferometer (FSMI), in which the Faraday mirror in its long arm is replaced by a Sagnac configuration with a modulator [36]. The quantum states carried by the photons can be divided into two mutually unbiased bases (MUB) Z and X, which are defined as \((1/\sqrt{2})(|s⟩ ± |l⟩)\) and \((1/\sqrt{2})(|s⟩ ± i|l⟩)\), respectively. Here, the pulses passing through the short and long paths of the FSMI, respectively, and the phase difference between the two pulses are randomly modulated by the PM in the Sagnac configuration with the phases of \(\{0, \pi/2, \pi, 3\pi/2\}\). The pulses escaping from FSMI are randomly modulated to different intensities by IM2 to implement decoy state method [37, 38]. The pulses are attenuated to the single-photon level by an attenuator (ATT) before entering the quantum channel.

After transmitting through a quantum channel of 25 km length, another DEMUX is used to demultiplex different channels into corresponding QKD receivers on Bob.
structures of Receiver1 and Receiver2 are shown in Figs. 3(d) and 3(e), respectively. The decoders in QKD receivers are the same FSMI unit as in the transmitter. The receiver measure the qubits either in the Z basis or X basis by randomly mod- ulating the PM in its decoder with the probabilities \( p_Z \) and \( p_X \), respectively. The decoding results are detected by single- photon detectors (SPD). The only difference between the two receivers is the number of single-photon detector (SPD). It is worth noting that although photon detection efficiency of about 3dB is sacrificed in single SPD receiver scheme, it does not weaken the security and verification of the experiments, and the less SPD number required may be valuable in massive networks.

IV. RESULTS

Our DKS-based QKD are implemented in two different sce- narios. In the first scenario, the performance of single-channel QKD are characterized. Thus, only a single communication channel of the DKS in Fig. 2(a) is used to implement the QKD. In the second scenario, multi-channel QKD are demonstrated by employing two communications channels of the DKS. In this scenario, two QKD systems are running simultaneously while independently, so that cross talk between different channels can be estimated.

The QKD system utilizes one signal and two decoy states and the clock rates of the QKD system is 1GHz. The average photon number per transmitted pulse of the first QKD system TR1 (Transmitter1&Receiver1) is \( \lambda_{\mu,1} = 0.50, \lambda_{\nu_{1,1}} = 0.16 \) and \( \lambda_{\nu_{1,2}} = 0.008 \), respectively, where \( \mu \) represents the signal state, \( \nu_1 \) and \( \nu_2 \) represent the decoy states. The corresponding values of the second system TR2 (Transmitter2&Receiver2) are \( \lambda_{\mu,2} = 0.60, \lambda_{\nu_{1,2}} = 0.06 \) and \( \lambda_{\nu_{2,2}} = 0.008 \), respectively. The sending ratio of \( \mu \), \( \nu_1 \) and \( \nu_2 \) is 29:2:1 for both systems.

In the first scenario, the single-channel QKD systems are verified. We run TR1 and TR2 independently within a single channel of the DEMUX in Fig.2(a). The quantum bit error rates (QBERs) of TR1 and TR2 are 2.66 ± 0.48 nd 2.66 ± 0.33, respectively, within one hour, as shown in Figs. 4(a) and 4(b). The average SKRs of TR1 and TR2 are 78.764kbps and 195.360kbps, respectively, where all time overhead including the post-processing procedure has been considered. The post- processing efficiencies of TR2 is higher than that of TR1, thus the SKR of TR2 is larger than twice of that of TR1. The one-hour real-time QBER of TR1 for signal and decoy states are shown in Fig.4(c). It shows that QBERs of all states increase little after one hour’s running and demonstrates that the sys- tem is stable for the single-channel scenario.

In the second scenario, we verified the multi-channel QKD systems. Two QKD systems are running simultaneously but independently within different channels. The experimental re- sults show that there is no significant difference for QBER and SKR between adjacent and nonadjacent channels, as shown in Figs. 4(d)-4(f). It shows that the average QBERs of the signal state are within 3% and the SKRs are in the same level to that of the single-channel experiments. There is no significant dif- ference between the single and multi-channel experiments. It demonstrates the performance of the first and second scenar- ios are well matched.

V. DISCUSSION

Increasing the SKR is an essential aim of the QKD community. Frequency multiplexing is one of the most common approach. Recently, the development of optical integrated chip makes on-chip QKD becoming a prospective branch to realize miniaturized and affordable QKD systems [17–19]. An- other advantage of on-chip QKD is that QKD system with dense multiplexing is much easier to implement but cost much less. Intra-cavity soliton source is part of an integrated optical chip and supports dense multiplexing in the domain of frequency. More importantly, the soliton is much superior than multi-laser sources. For multi-laser source, every laser should be monitored to fit the corresponding communication channel. However, we only need to monitor the temperature of the cavity and the frequency of the pump and auxiliary lasers to make sure hundreds of frequency comb lines fit the corre- sponding communication channels. This work makes it possi- ble to achieve Gbps SKR QKD system with soliton source by combining with the ultrafast on-chip modulation technology.

VI. CONCLUSION

In conclusion, we have demonstrated the QKD based on an on-chip DKS source. Through the wavelength multiplexing, the single-channel and multi-channel QKD experiments are performed, and the experiments demonstrated a SKR exceeding 200kbps by one channel. Our experiments reveal the potential of DKS-based QKD system for high SKR based on the massive and parallel communication channels. Combining with the exciting progresses achieved in the quantum photonic integrated circuits, the DKS source, high speed modulators, and high-efficiency detectors could be potentially realized on a single chip. Such a QKD chip possesses the advantages of compact, low-cost, robust and high efficiency, and will greatly promote the popularization of QKD in personal equipment and networks.

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FIG. 1. The concept setup of the Soliton based QKD. The narrow linewidth pump laser generates the dissipative Kerr soliton (DKS) within the on-chip resonator. The soliton comb is then be used as the light source to realize the ultra-high speed (multi-user) QKD system by frequency multiplexing/demultiplexing.

FIG. 2. (a) The experimental setup of the DKS source for frequency multiplexing and demultiplexing. The pump (Pump) and auxiliary (Aux) lasers are used to generate the DKS and to timely balance the heat fluctuation within the microresonator, respectively. The optical spectrum analyzer (OSA) and powermeter are used to monitor the output spectrum and power of the microresonator, respectively. The temperature of the microresonator is manually tuned by a temperature controller (TC) with the feedback of the OSA and powermeter. The laser polarizations before and after the microresonator are controlled by polarization controllers (PC1-PC3). The DKS is then be demultiplexed into a frequency source. (b) The measured power spectra of the soliton comb. (c) The measured power spectra of the output channels of the demultiplexing (DEMUX) in (a). (d) Channel crosstalk of the DEMUX. For left to right: the power spectra crosstalk of CH1 to CH5.
FIG. 3. The experimental setup of the soliton-based QKD system. (a) The schematic setup of the multi-channel QKD system. Two QKD systems run independently with different channels. All channels are multiplexed and demultiplexed by the dense wavelength division multiplexing (DWDM). The length of the quantum channel is 25 km. (b) The encoding setup of the transmitters. (c) The structure of the Faraday-Sagnac-Michelson interferometer (FSMI). The blue line of the Sagnac loop is the polarization maintaining fiber. (d) and (e) The decoding setup of receivers with single and double single-photon detectors (SPDs), respectively. (DE)MUX: (de)multiplexing; BS: non-polarizing beam splitter; PBS: polarizing beam splitter; M: Faraday mirror; PM: phase modulator; IM: intensity modulator; Att: attenuator; Cir: circulator.

FIG. 4. The QBER of the signal state ($e_\mu$), raw key rate (RKR), sifted key rate (SfKR) and secret key rate (SKR) of the (a)-(b) single-channel and (d)-(f) multi-channel QKD systems. The regular triangle and square represent the experimental data of TR1. The inverted triangle and circle represent the experimental data of TR2. (c) The one hour real-time QBER of TR1 by CH1. The red star, black circle and blue regular triangle represent $\mu$, $\nu_1$ and $\nu_2$, respectively. The sending ratio of $\mu$, $\nu_1$ and $\nu_2$ of the transmitter is 29:2:1. "TR1 CH1&TR2 CH2" means that system TR1 runs within CH1, while TR2 runs within CH2 simultaneously but independently.