Optical-Quantum Security using Dark-Bright Soliton Conversion in a Ring Resonator System

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Abstract

We present a new concept of quantum cryptography using dark-bright soliton conversion behaviors within a nonlinear ring resonator, in which the orthogonal soliton is established among the soliton conversion. A new model of add/drop filters is modified which is known as a PANDA Ring resonator is proposed. The entangled soliton/photon can work in the same way of the entangled photon, but in this case the entangle soliton is gained more power that give the advantage of long distance quantum communication. In application, the high capacity quantum communication is also variable by using the multivariable entangled solitons.

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Keywords: Entangled soliton; entangled photons; quantum computer; quantum cryptography; ring resonator

1. Introduction

We use data and information in our live every day, so the security of data is considered first, therefore, there are a lot of techniques are used to protect the secret data or information. Up to date, a quantum technique is recommended to provide such a requirement. However, the security technique known as
quantum cryptography has been widely used and investigated in many applications [1-3]. Recently, Suchat et al [4] have reported the interesting concept of continuous variable quantum key distribution via a simultaneous optical-wireless up-down-link system, where they have shown that the continuous variable quantum key could be performed via chaotic signals generated in a nonlinear micro-ring resonator system with appropriate soliton input power and micro-ring resonator parameters. They have also shown that the different time slot entangled photons can be formed randomly and can be used to select two different frequency bands for up-down-link converters within a single system. Yupapin et al [5] have proposed a new technique for QKD (Quantum Key Distribution) that can be used to make the communication transmission security and implemented with a small device such as mobile telephone hand set. This technique has proposed the Kerr nonlinear type of light in the micro ring resonator to generate the superposition of the chaotic signal via a four-wave mixing type that introduces the second-harmonic pulse. A technique used for communication security via quantum chaotic has been proposed by Yupapin and Chunpang [6], where the use of quantum-chaotic encoding of light traveling in a fiber ring resonator to generate two different codes i.e. quantum bits and chaotic signal is presented. Mitatha et al [7] have proposed the design of secured packet switching used nonlinear behaviors of light in micro ring resonator which can be made high-capacity and security switching. Such a system can also be used for the tunable band pass and band stop filters.

Both quantum communication and quantum information processing has been shown to be fundamentally different from its classical counterpart. Examples where this difference is highlighted are secure key distribution for cryptography, and the existence of fast algorithms for an idealized quantum computer. Quantum network has also been introduced and become the promising technology that can be used to fulfill the perfect network security. Some research works have been reported in various forms of applications [8, 9]. The use of quantum key distribution via optical network has been reported [10, 11]. To date quantum key distribution is the only form of information that can provide the perfect communication security. The use of QKD has been proposed in many research works, whereas the applications in different forms - such as point to point link [12], optical wireless [13], satellite [14], long distance [15] and network [16] - have been reported. However, a more reliable system for network security is needed, which is both high capacity and secure. The concept of continuous variable in the form of dense wavelength multiplexing is introduced to overcome such a problem. By using the continuous variable concept, the continuous QKD can be formed and available for a large demand. There are some works proposed the use of continuous variable QKD with quantum router and network [17, 18]. However, the requirement of large bandwidth signal and dense wavelength multiplexing become the practical problems. Yupapin et al [19] have also shown that the continuous wavelength can be generated by using a soliton pulse in a micro ring resonator, which can be used to overcome such problems.

In this paper, we have used a nonlinear micro ring resonator to form the correlated photons and quantum codes, where the secret key codes can be generated by using the entangled photon pair, which can be formed the secret key for two parties known as Alice and Bob by using the Gaussian light pulse propagating with the series of micro ring resonator. In application, the device can be embedded within the computer processing unit with using to increase the capacity and the speed for internet, where the internet security can be provided. Furthermore, such a concept is also available for hybrid communications, for instance, wire/wireless, satellite. However, the theoretical background of correlated photon source generation is reviewed.

In this paper, we have used dark-bright soliton conversion behaviors within a nonlinear ring resonator to form correlated photons and quantum codes, in which the orthogonal soliton is established among the soliton conversion. A new model of add/drop filters is modified which is known as a PANDA Ring resonator is proposed. The entangled soliton(photon) can work in the same way of the entangled photon, but in this case the entangle soliton is gained more power that give the advantage of long distance
quantum communication. In application, the high capacity quantum communication is also variable by using the multivariable entangled solitons.

2. Operator principle

A dark-bright soliton conversion system using a ring resonator optical channel dropping filter is composed with two sets of coupled waveguides, as shown in Fig. 1. The relative phase of the two output light signals after coupling into the optical coupler is $\pi/2$. This means that the signals coupled into the drop and through ports have acquired a phase of $\pi$ with respect to the input port signal. In application, if we engineer the coupling coefficients appropriately, the field coupled into the through port on resonance would completely extinguish the resonant wavelength, and all the power would be coupled into the drop port. The input and control fields at the input and add ports are formed by the dark and bright optical solitons and described by Equations (1) and (2), respectively [20, 21].

$$E_\text{in}(t) = A_0 \tanh \left( \frac{T}{T_0} \right) \exp \left[ \left( \frac{z}{2L_D} \right) - io_0 t \right] \quad (1)$$

$$E_\text{in}(t) = A_0 \text{sech} \left( \frac{T}{T_0} \right) \exp \left[ \left( \frac{z}{2L_D} \right) - io_0 t \right] \quad (2)$$

Here $A_0$ and $z$ are the optical field amplitude and propagation distance, respectively. $T=t-\beta_1 z$, where $\beta_1$ and $\beta_2$ are the coefficients of the linear and second-order terms of Taylor expansion of the propagation constant. $L_D=2T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. $T_0$ in equation is a soliton pulse propagation time at initial input (or soliton pulse width), where $t$ is the soliton phase shift time, and the frequency shift of the soliton is $\omega_0$. The optical fields of the system within the device as shown in Fig. 1 are obtained and expressed in following forms

![Fig. 1. Schematic diagram of a proposed PANDA ring resonator](image_url)

$$E_1 = -j\kappa_1 E_1 + \tau_1 E_4,$$  

(3)
Here $E_i$ is the input field, $E_a$ is the add(control) field, $E_j$ is the through field, $E_d$ is the drop field, $E_1$...$E_4$ are the fields in the ring at points 1...4, $\kappa_i$ is the field coupling coefficient between the input bus and ring, $\kappa_j$ is the field coupling coefficient between the ring and output bus, $L$ is the circumference of the ring, $T$ is the time taken for one round trip(roundtrip time), and $\alpha$ is the power loss in the ring per unit length. We assume that this is the lossless coupling, i.e., $\tau_{i,j} = \sqrt{1-\kappa_{i,j}^2}$, $T = L n_{eff} / c$.

3. Entangled Photon

In Fig. 2, a single dark-bright soliton pair is plotted at the center wavelength by using the add-drop filter with the input power is 0.15W. The inversion of dark and bright soliton pulses is formed and detected by the through and drop ports as shown in Fig. 2(a), where the control field can be added via the Add port. The orthogonal solitons in terms of phase changes are plotted in Fig. 2(b), where we found that their behaviors can provide the similar manner of the entangled photon pair, which can be used in quantum information application, but in this case the advantage is that the long distance quantum communication link can be provided due to the soliton property of the generated entangled photon source.

Fig. 3 shows the orthogonal soliton pairs generated by a dark soliton pump input into a PANDA ring resonator at the center wavelength 1.45\micron, where (a) a bright soliton at $E_1$, (b) a dark-soliton at $E_2$, (c) a dark soliton at $E_3$, (d) a bright soliton at $E_4$, and (e) the transmittance at through (Th) and reflectance at drop (Dr) ports, respectively.

\begin{align*}
E_2 &= \exp\left(j\omega T/2\right)\exp\left(-\alpha L/4\right)E_i, \\
E_3 &= \tau_z E_2 - j\kappa_2 E_a, \\
E_4 &= \exp\left(j\omega T/2\right)\exp\left(-\alpha L/4\right)E_3, \\
E_r &= \tau_r E_i - j\kappa_r E_4, \\
E_d &= \tau_d E_a - j\kappa_d E_2,
\end{align*}

Fig. 2. Shows the normalized intensity of a single dark-bright soliton pair at the center wavelength by using the add-drop filter, with the input dark soliton power (red) is 0.15W.
When we consider the case when the photon output is input into the quantum processor unit. Generally, there are two pairs of possible polarization entangled photons forming within the ring device, which are represented by the two polarization orientation angles as $[0^\circ, 90^\circ]$. These can be formed by using the optical component called the polarization rotatable device and a polarizing beam splitter (PBS). In this concept, we assume that the polarized photon can be performed by using the proposed arrangement. Where each pair of the transmitted qubits can be randomly formed the entangled photon pairs. To begin this concept, we introduce the technique that can be used to create the entangled photon pair (qubits) as shown in Fig. 4, a polarization coupler that separates the basic vertical and horizontal polarization states corresponds to an optical switch between the short and the long pulses. We assume those horizontally polarized pulses with a temporal separation of $\Delta t$. The coherence time of the consecutive pulses is larger than $\Delta t$. Then the following state is created by Eq. (9) [22].

$$|\Phi\rangle_s = |1,H\rangle_s|1,H\rangle_s + |2,H\rangle_s|2,H\rangle_s$$

In the expression $|k,H\rangle$, $k$ is the number of time slots (1 or 2), where denotes the state of polarization [horizontal $|H\rangle$ or vertical $|V\rangle$], and the subscript identifies whether the state is the signal (s) or the idler (i) state. In Eq. (9), for simplicity, we have omitted an amplitude term that is common to all product states. We employ the same simplification in subsequent equations in this paper. This two-photon state with $|H\rangle$ polarization shown by Eq. (9) is input into the orthogonal polarization-delay circuit shown schematically. The delay circuit consists of a coupler and the difference between the round-trip times of the micro ring resonator, which is equal to $\Delta t$. The micro ring is tilted by changing the round trip of the ring is converted into $|V\rangle$ at the delay circuit output. That is the delay circuits convert $|k,H\rangle$ to be

$$r|k,H\rangle + t_q \exp(i\phi)|k+1,V\rangle + r_t \exp(i\phi)|k+2,H\rangle + r_t \exp(i\phi)|k+3,V\rangle$$
Where t and r is the amplitude transmittances to cross and bar ports in a coupler. Then Eq. (9) is converted into the polarized state by the delay circuit as

\[
\begin{align*}
|\Phi\rangle &= \left[ |1, H\rangle + \exp(i\phi)|2, V\rangle, |1, H\rangle + \exp(i\phi)|2, V\rangle, |1, H\rangle + \exp(i\phi)|3, V\rangle, |1, H\rangle + \exp(i\phi)|3, V\rangle \right] \\
&\times \left[ |2, H\rangle + \exp(i\phi)|2, V\rangle, |2, H\rangle + \exp(i\phi)|3, V\rangle, |2, H\rangle + \exp(i\phi)|3, V\rangle, |2, H\rangle + \exp(i\phi)|3, V\rangle \right] \\
= & \left[ |1, H\rangle + \exp(i\phi)|1, H\rangle, |2, V\rangle, |1, H\rangle + \exp(i\phi)|2, V\rangle, |1, H\rangle + \exp(i\phi)|3, V\rangle, |2, H\rangle + \exp(i\phi)|3, V\rangle \\
&+ |2, H\rangle, |2, H\rangle \right] + \exp(i\phi)|2, H\rangle, |3, V\rangle, + \exp(i\phi)|3, V\rangle, |2, H\rangle + \exp(i\phi)|3, V\rangle, |3, V\rangle \\
= & \left[ |2, H\rangle, |2, H\rangle \right] + \exp(i\phi)|2, V\rangle, |2, V\rangle, |2, V\rangle, |2, V\rangle \right].
\end{align*}
\] (10)

By the coincidence counts in the second time slot, we can extract the fourth and fifth terms. As a result, we can obtain the following polarization entangled state as

\[
|\Phi\rangle = \left[ |2, H\rangle, |2, H\rangle \right] + \exp(i\phi)|2, V\rangle, |2, V\rangle, |2, V\rangle, |2, V\rangle \right].
\] (11)

We assume that the response time of the Kerr effect is much less than the cavity round-trip time. Because of the Kerr nonlinearity of the optical device, the strong pulses acquire an intensity dependent phase shift during propagation. The interference of light pulses at a coupler introduces the output beam, which is entangled. Due to the polarization states of light pulses are changed and converted while circulating in the delay circuit, where the polarization entangled photon pairs can be generated. The entangled photons of the nonlinear ring resonator are separated to be the signal and idler photon probability. The polarization angle adjustment device is applied to investigate the orientation and optical output intensity, this concept is well described by the published work [23].

Fig. 4. A system of the entangled photon pair manipulation of the receiver part. The quantum state is propagating to a rotatable polarizer and then is split by a beam splitter (PBS) flying to detector D3 and D4.

4. conclusion

We have proposed an interesting concept of quantum cryptography using dark-brighth soliton, a system consists a new model of add/drop filters is modified which is known as a PANDA ring resonator connect to rotatable polarization and polarization beam splitter (PBS) at through port and drop port. We can generate the pair of photon within PANDA ring resonator, the entangle soliton is gained more power
that give the advantage of long distance quantum communication. In application, the high capacity quantum communication is also variable by using the multivariable entangled solitons.

References