Secured Transportation of Quantum Codes Using Integrated PANDA-Add/drop and TDMA Systems

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Abstract

New system of quantum cryptography for communication networks is proposed. Multi optical Soliton can be generated and propagated via an add/drop interferometer system incorporated with a time division multiple access (TDMA) system. Here the transportation of quantum codes is performed. Chaotic output signals from the PANDA ring resonator are inserted into the add/drop filter system. Using the add/drop filter system multi dark and bright solitons can be obtained and used to generate entangled quantum codes for internet security. In this research soliton pulses with FWHM and FSR of 325 pm and 880 nm are generated, respectively.

Keywords: Nonlinear fiber optics; PANDA system; Add/drop filter; Multi soliton, TDMA Network Communication system

Introduction

TDMA is a channel access method for shared medium networks in which the users receive information with different time slots. This allows multiple stations to share the same transmission medium while using only a part of its channel capacity. It can be used in digital internet communications and satellite systems. Therefore, in the TDMA system, instead of having one transmitter connected to one receiver, there are multiple transmitters, where high secured signals of quantum codes along the users can be transmitted.

Soliton generation becomes an interesting subject [1]. The high optical output of the ring resonator system is of benefit to long distance communication links [2]. A Gaussian soliton can be generated in a simple system arrangement [3]. There are many ways to achieve powerful light, for instance, using a high-power light source or reducing the radius of ring resonator [4].

However, there are many research works reported in both theoretical and experimental works [5]. In practice, the intensive pulse is obtained by using erbium-doped fiber (EDF) and semiconductor amplifiers incorporated with the experimental setup [6]. Gaussian pulse is used to form a multi soliton using a ring resonator [7]. We propose a modified add/drop optical filter called PANDA system [8].

Theoretical Background

The PANDA ring resonator is connected to an add/drop filter system, shown in Figure 1.
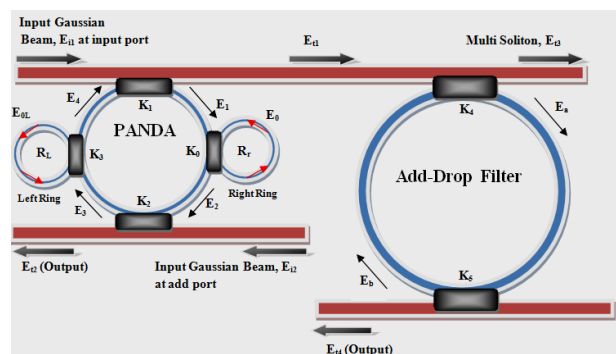

Figure 1: Schematic diagram of a PANDA ring resonator connected to an add/drop filter system

The laser Gaussian pulse input propagates inside the ring resonators system which is introduced by the nonlinear Kerr effect. The Kerr effect causes the refractive index (n) of the medium to vary as shown in Equation (1).

$$n = n_0 + n_2 I = n_0 + \frac{n_2}{A_{eff}} P \quad , \qquad (1)$$

where n_0 and n_2 are the linear and nonlinear refractive indexes, respectively. I and P are the optical intensity and the power, respectively. A_{eff} is the effective mode core area of the device [9]. For an add/drop optical filter design, the effective mode core areas range from 0.50 to 0.10 μm². The parameters were obtained by using practical parameters of used material (InGaAsP/InP) [10], [11]. Input optical fields of Gaussian pulses at the input and add ports of the system are given in Equation (2) [12].

$$E_{i1}(t) = E_{i2}(t) = E_{i0} \exp\left[\left(\frac{z}{2L_D} \right) - i\omega_0 t \right] , \qquad (2)$$

E_{i0} and z are the optical field amplitude and propagation distance respectively. L_D is the dispersion length of the soliton pulse where t is the soliton phase shift time, and where the carrier frequency of the signal is ω_0 [13]. Soliton pulses propagate within the microring device when the balance between the dispersion length (L_D) and the nonlinear length ($L_{NL}=1/\Gamma\phi_{NL}$) is achieved. Therefore $L_D = L_{NL}$, where $\Gamma=n_2\times k_0$, is the length scale over which dispersive or nonlinear effects make the beam become wider or narrower [14]. For the PANDA ring resonator, the output signals inside the system are given as follows [15], [16]:

$$E_1 = \sqrt{1-\gamma_1} \left(\sqrt{1-\kappa_1} E_4 + j\sqrt{\kappa_1} E_{i1} \right) \qquad (3)$$

$$E_2 = E_0 E_1 e^{\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}} \quad , \qquad (4)$$

where κ_1, γ_1 and α are the intensity coupling coefficient, fractional coupler intensity loss and attenuation coefficient respectively. $k_n = \frac{2\pi}{\lambda}$ is the wave propagation number, λ is the input wavelength light field and $L = 2\pi R_{PANDA}$ where, R_{PANDA} is the radius of the PANDA system, which is 300 nm. The electric field of the small ring at the right side of the PANDA rings system is given as:

$$E_0 = E_1 \frac{\sqrt{(1-\gamma)(1-\kappa_0)} - (1-\gamma)e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}{1 - \sqrt{1-\gamma}\sqrt{1-\kappa_0}e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}, \qquad (5)$$

where $L_1 = 2\pi R_r$ and R_r is the radius of right ring. Light fields of the left side of PANDA ring resonator can be expressed as:

$$E_3 = \sqrt{1-\gamma_2}\left(\sqrt{1-\kappa_2} E_2 + j\sqrt{\kappa_2} E_{i2} \right), \qquad (6)$$

$$E_4 = E_{0L} E_3 e^{\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}, \qquad (7)$$

where,

$$E_{0L} = E_3 \frac{\sqrt{(1-\gamma)(1-\kappa_3)} - (1-\gamma)e^{-\frac{\alpha}{2}L_2 - jk_n L_2}}{1 - \sqrt{1-\gamma}\sqrt{1-\kappa_3}e^{-\frac{\alpha}{2}L_2 - jk_n L_2}} , \qquad (8)$$

Here, $L_2 = 2\pi R_L$ and R_L is the left ring radius. In order to simplify these equations, the parameters of x_1, x_2, y_1 and y_2 are defined as: $x_1 = \sqrt{(1-\gamma_1)}$, $x_2 = \sqrt{(1-\gamma_2)}$, $y_1 = \sqrt{(1-\kappa_1)}$, and $y_2 = \sqrt{(1-\kappa_2)}$. Therefore, the output powers from through and drop ports of the PANDA ring resonator can be expressed as E_{t1} and E_{t2} and are given as:

$$E_{t1} = AE_{i1} - BE_{i2}e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}\left[\frac{CE_{i1}G^2 + DE_{i2}G^3}{1-FG^2} \right], \quad (9)$$

$$E_{t2} = x_2 y_2 E_{i2}\left[\frac{A\sqrt{\kappa_1\kappa_2}E_0 E_{i1}G + \frac{D}{x_1\sqrt{\kappa_1}E_{0L}}E_{i2}G^2}{1-FG^2} \right], \qquad (10)$$

where, $A = x_1 x_2$, $B = x_1 x_2 y_2 \sqrt{\kappa_1}E_{0L}$, $C = x_1^2 x_2 \kappa_1 \sqrt{\kappa_2}E_0 E_{0L}$, $D = (x_1 x_2)^2 y_1 y_2 \sqrt{\kappa_1 \kappa_2}E_0 E_{0L}^2$, $G = \left(e^{\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}} \right)$ and $F = x_1 x_2 y_1 y_2 E_0 E_{0L}$.

E_{t1}, output from the PANDA system can be input into the add/drop filter system which is made of a ring resonator coupled to two fiber waveguides with proper parameters [17].

Output powers from the add/drop filter system are given by Equations (16) and (17), where E_{t3} and E_{t4} are the electric field outputs of the through and drop ports of the system respectively.

$$\frac{I_{t3}}{I_{t1}} = \left| \frac{E_{t3}}{E_{t1}} \right|^2 = \frac{1-\kappa_4 - 2\sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{-\frac{\alpha}{2}L_{ad}}\cos(k_n L_{ad}) + (1-\kappa_5)e^{-\alpha L_{ad}}}{1+(1-\kappa_4)(1-\kappa_5)e^{-\alpha L_{ad}} - 2\sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{-\frac{\alpha}{2}L_{ad}}\cos(k_n L_{ad})}$$
$$(11)$$

$$\frac{I_{t4}}{I_{t1}} = \left| \frac{E_{t4}}{E_{t1}} \right|^2 = \frac{\kappa_4 . \kappa_5 e^{-\frac{\alpha}{2}L_{ad}}}{1+(1-\kappa_4)(1-\kappa_5)e^{-\alpha L_{ad}} - 2\sqrt{1-\kappa_4}\sqrt{1-\kappa_5}e^{-\frac{\alpha}{2}L_{ad}}\cos(k_n L_{ad})}$$
$$(12)$$

where, κ_4 and κ_5 are the coupling coefficients of the add/drop filter system, $L_{ad} = 2\pi R_{ad}$ and R_{ad} is the radius of the add/drop system.

Result and Discussion

Gaussian beams with center wavelength of 1.55 μm and power of 600 mW are introduced into the add and input ports of the PANDA ring resonator. The simulated result has been shown in Figure 2. The linear and

nonlinear refractive indices of the system are $n_0 = 3.34$ and $n_2 = 3.2 \times 10^{-17}$ respectively. In Figure 2, the coupling coefficients of the PANDA ring resonator are given as $\kappa_0 = 0.2$, $\kappa_1 = 0.35$, $\kappa_2 = 0.1$ and $\kappa_3 = 0.95$, respectively and $\gamma = \gamma_1 = \gamma_2 = 0.1$. Here $R_{PANDA} = 300\ nm$ where $R_r = 180\ nm$ and $R_L = 200\ nm$ respectively. Figures 2(a) and 2(b) show the powers in the form of chaotic signals before entering the right ring of the PANDA system and amplification of signals during propagation of light inside right ring respectively, where Figures 2(c) and 2(d) show the powers before entering the left ring and amplification of signals within the right ring respectively. We found that the signals are stable and seen within the system where the chaotic signals are generated at the through port shown in Figure 2(e).
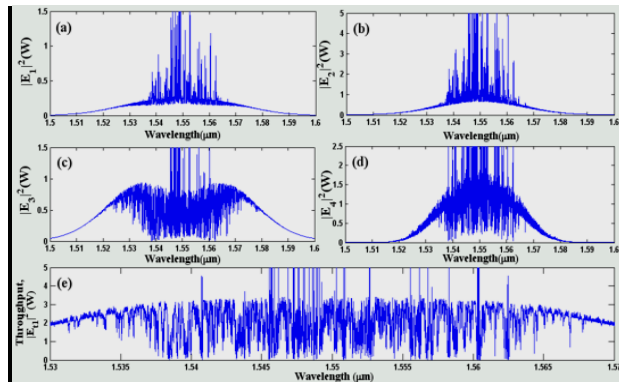

Figure 2: Multi soliton signal generation using PANDA ring resonator system where (a), (b), (c) and (d) are powers inside the PANDA system and (e) is the output power from the throughput.

In order to generate multi optical soliton, the chaotic signals from the PANDA ring resonator are input into the add/drop filter system. Figures 3(a) and 3(b) show the generation of multi soliton in the form of dark soliton and expansion of the through port signals respectively, where Figures 3(c) and 3(d) represent multi soliton in the form of bright solitons and expansion of the drop port signals respectively. The coupling coefficients of the add/drop filter system are given as $\kappa_4 = 0.9$, $\kappa_5 = 0.5$, where the radius of the ring is $R_{ad} = 130$ μm.
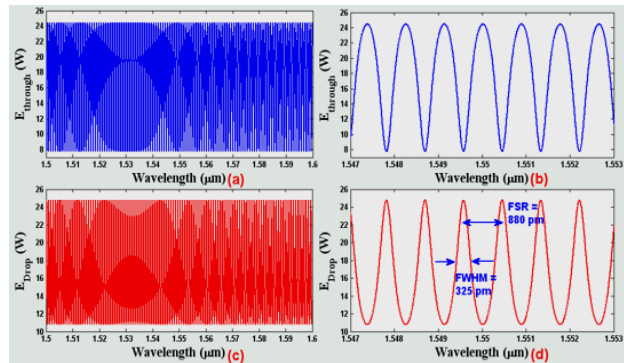

Figure 3: Output multi soliton signal generation using an add/drop filter system, where (a): dark soliton at through port, (b): expansion of multi dark soliton, (c) bright soliton at drop port, and (d): expansion of multi bright soliton with FWHM and FSR of 325 pm and 880 pm respectively

Generated multi optical soliton can be input into an optical receiver unit which is a quantum processing system used to generate high capacity packet of quantum codes within the series of MRR's. In operation, the computing data can be modulated and input into the receiver unit which is encoded to the quantum signal processing system. The receiver unit can be used to detect the quantum bits, which is operated by the add/drop filter (R_{dN1}). Therefore entangled photon can be provided, where the required data can be retrieved via the drop port of the add/drop filter in the router. A schematic of the quantum processing system which is used to generate entangled photon is shown in Figure 4.
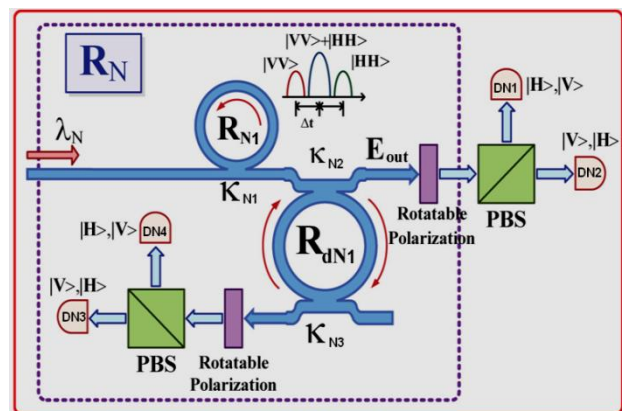

Figure 4: A schematic of an entangled photon pair manipulation within a ring resonator. The quantum state is propagating to a rotatable polarizer and then is split by a beam splitter (PBS) flying to detector D_{N1}, D_{N2}, D_{N3} and D_{N4}

From Figure 4 it can be seen that there are two pairs of possible polarization entangled photons forming within the MRR device, which are the four polarization orientation angles as [0°, 90°], [135° and 180°]. These can be done by using the optical component, called the polarization rotatable device and a polarizing beam splitter (PBS). Polarization coupler separates the basic

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vertical and horizontal polarization states. Each one corresponds to an optical switch between the short and the long pulses. The horizontally polarized pulses have a temporal separation of Δt. The coherence time of the consecutive pulses is larger than Δt. Then the following state is created by Equation (18).

$$|\Phi>_p = |1, H>_s |1, H>_i + |2, H>_s |2, H>_i \qquad (13)$$

Here k is the number of time slots (1 or 2), which denotes the state of polarization (horizontal $|H>$ or vertical $|V>$). The subscript identifies whether the state is the signal (s) or the idler (i) state. This two-photon state with $|H>$ polarization are input into the orthogonal polarization-delay circuit. The delay circuit consists of coupler and the difference between the round-trip times of the microring resonator, which is equal to Δt. The microring is tilted by changing the roundtrip of the ring and is converted into $|V>$ at the delay circuit output. The delay circuit converts $|k, H>$ into

$$r|k, H> + t_2 \exp(i\Phi) |k+1, V> + rt_2 \exp(i_2\Phi) |k+2, H> + r_2 t_2 \exp(i_3\Phi) |k+3, V>$$

Here t and r are the amplitude transmittances to cross and bar ports in a coupler. Equation (18) is converted into the polarized state by the delay circuit as

$$|\Phi> = [|1, H>_s + \exp(i\Phi_s) |2, V>_s] \times [|1, H>_i + \exp(i\Phi_i) |2, V>_i]$$
$$+ [|2, H>_s + \exp(i\Phi_s) |3, V>_s \times [|2, H>_i + \exp(i\Phi_i) |2, V>_i]$$
$$=$$
$$[|1, H>_s |1, H>_i + \exp(i\Phi_i) |1, H>_s |2, V>_i] + \exp(i\Phi_s) |2, V>_s |1, H>_i +$$
$$\exp[i(\Phi_s+\Phi_i)] |2, V>_s |2, V>_i + |2, H>_s |2, H>_i + \exp(i\Phi_i) |2, H>_s |3, V>_i +$$
$$\exp(i\Phi_s) |3, V>_s |2, H>_i + \exp[i(\Phi_s+\Phi_i)] |3, V>_s |3, V>_I$$
$$(14)$$

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 [18]

$$|\Phi> = |2, H>_s |2, H>_i + \exp[i(\Phi_s+\Phi_i)] |2, V>_s |2, V>_i$$
$$(15)$$

The polarization states of light pulses are changed and converted during the circulation in the delay circuit, leading to the formation of the polarized entangled photon pairs. In operation, the encoded quantum secret codes computing data can be generated, where the different orders of the quantum codes can be made to generate different signal information and propagated in the network communication via TDMA transmission system shown in Figure 5. This system uses data in the form of secured logic codes to be transferred into the singular users via different length of the fiber optics line to the TDMA transmitter; thus quantum cryptography for internet security can be obtained.
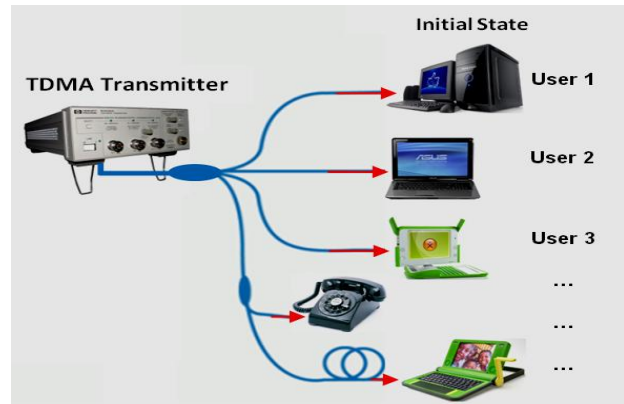

Figure 5. Schematic of the TDMA system

Therefore, same digital information of codes can be shared between users with different time slots. The transmission unit is a part of quantum processing system that can be used to transfer high capacity packet of quantum codes. Moreover, high capacity of data can be performed by using more wavelength carriers, whereas the sensitivity of the nano or microring resonator systems can be improved by increasing of the free spectrum range and decreasing of the FWHM applicable for laser sensing systems [19].

Conclusion

Extensive pulses in the form of chaotic signals can be generated. The proposed system is connected to an add/drop filter system in order to generate highly multi optical soliton. Interior signals of the PANDA system can be controlled and tuned. Generated chaotic signals can be input into the add/drop filter system. Therefore the multi pulses of soliton with FWHM and FSR of 325 pm and 880 pm can be generated and used widely in secured quantum codes applicable to quantum network communication. In fact we have proposed an interesting concept of internet security based on quantum codes where the use of data encoding for high capacity communication via optical network link is plausible.

Acknowledgements

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