Generation of Quantum Photon Information Using Extremely Narrow Optical Tweezers for Computer Network Communication

I. S. Amiri, A. Nikoukar, A. Shahidinejad, M. Ranjbar, J. Ali, P. P. Yupapin

Abstract: **A system of microring resonator (MRR) is presented to generate extremely narrow optical tweezers. An add/drop filter system consisting of one centered ring and one smaller ring on the left side can be used to generate extremely narrow pulse of optical tweezers. Optical tweezers generated by the dark-Gaussian behavior propagate via the MRRs system, where the input Gaussian pulse controls the output signal at the drop port of the system. Here the output optical tweezers can be connected to a quantum signal processing system (receiver), where it can be used to generate high capacity quantum codes within series of MRR's and an add/drop filter. Detection of the encoded signals known as quantum bits can be done by the receiver unit system. Generated entangled photon pair propagates via an optical communication link. Here, the result of optical tweezers with full width at half maximum (FWHM) of 0.3 nm, 0.8 nm and 1.6 nm, 1.3 nm are obtained at the through and drop ports of the system respectively. These results used to be transmitted through a quantum signal processor via an optical computer network communication link.**

Keywords: Internet security, optical tweezers, quantum cryptography, quantum signal processing, entangled photon pair

I. INTRODUCTION

Dark-Gaussian soliton controls within a semiconductor add/drop multiplexer has numerous applications in optical communication [1]. Optical tweezers technique is recognized as a powerful tool for manipulation of micrometer-sized particles in three spatial dimensions. It has the unique ability to trap and manipulate molecules at mesoscopic scales with widespread applications in biology and physical sciences [2].

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The output is achieved when the high optical field is set up as an optical tweezers [3]. In many research areas, the optical tweezers ismused to store and trap light, atom, molecule or particle within the proposed system. The tweezers are kept in the stable form within the add/drop filter. Schulz et al. [4] have shown that the transferring of trapped atoms between two optical tweezers could be performed. MRR's are of type of Fabry-Perot resonators which can be readily integrated in array geometries to implement many useful functions. Its nonlinear phase response can be readily incorporated into an interferometer system to produce specific intensity output function [5]. Several emerging technologies, such as integrated all optical signal processing and all-optical quantum information processing, require interactions between two distinct optical signals. Optical tweezer tools can be used to trap molecules or photons [6].

Internet security becomes an important function in the modern internet service. However, the security technique known as quantum cryptography has been widely used and investigated in many applications, using optical tweezers [7]. Yupapin et al. [8] have proposed a new technique for QKD (Quantum Key Distribution) which can be used to make the communication transmission security. It also can be implemented with a small device such as mobile telephone hand set. Mitatha et al. [9] have proposed a new design of secured packet switching. This method uses nonlinear behaviors of light in MRR which can be used for high-capacity and security switching. Recently quantum network shows promising usage for the perfect network security [10]. To date, QKD is the only form of information that can provide the perfect communication security. Yupapin et al. [11] have shown that the continuous wavelength can be generated by using a soliton pulse in a MRR. The secret key codes are generated via the entangled photon pair which is used to security purposes using the dark soliton pulse propagation. In this study, an optical tweezers generator system based on microring resonators is developed.

II. THEORETICAL MODELING

Soliton pulse of the form of dark soliton is introduced into the multiplexer system shown in Fig. 1. Dynamic behavior of the optical tweezers is appeared when the Gaussian soliton is input into the add port of the system. The dark and Gaussian solitons are propagating inside the proposed system with centre wavelength of $\lambda_0 = 0.6$ μm.

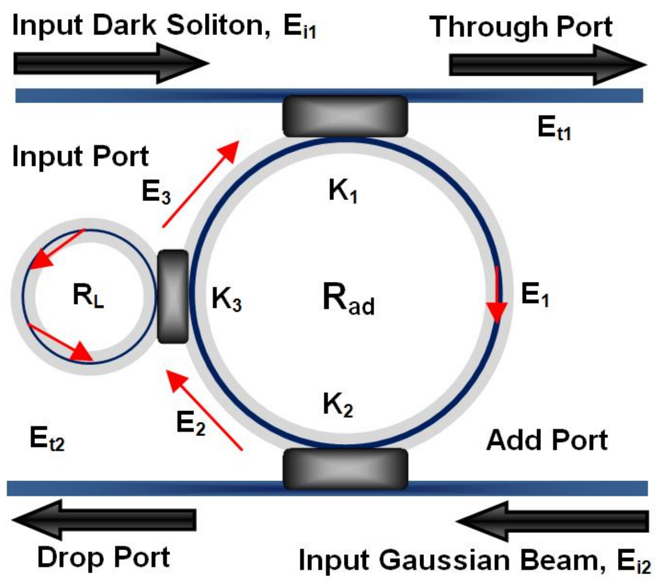

Fig.1. A schematic diagram of an add/drop filter [12].

The input optical field (E_{in}) of the dark soliton and add optical field (E_{add}) of the Gaussian soliton pulses are given by [13]

$$E_{in} = A\tanh\left[\frac{T}{T_0}\right]\exp\left[\left(\frac{z}{2L_D}\right)-i\omega_0 t\right], \quad (1)$$

$$E_{add}(t) = E_0\exp\left[\left(\frac{z}{2L_D}\right)-i\omega_0 t\right] \quad (2)$$

In Equations (1) and (2), A and z are the optical field amplitude and propagation distance, respectively. T is defined as soliton pulse propagation time in a frame moving at the group velocity, $T = t-\beta_1\times z$, where β_1 and β_2 are the coefficients of the linear and second order terms of Taylor expansion of the propagation constant. $L_D = T_0^2/|\beta_2|$ represent the dispersion length of the soliton pulse. The frequency carrier of the soliton is ω_0. For the intensity of soliton peak as $\left(\left|\beta_2/\Gamma T_0^2\right|\right)$, T_o is known. A balance should be achieved between the dispersion length (L_D) and the nonlinear length ($L_{NL}= (1/\gamma\varphi_{NL})$, where γ and φ_{NL} are the coupling loss of the field amplitude and nonlinear phase shift. They are the length scale over which dispersive or nonlinear effects makes the beam becomes wider or narrower. It means that the $L_D=L_{NL}$ should be satisfied. During the propagating of light within the nonlinear medium, the refractive index (n) is given by

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}}\right)P, \quad (3)$$

In Equation (3), n_0 and n_2 are the linear and nonlinear refractive indexes, respectively. I and P represent the optical intensity and optical power, respectively. The effective mode core area of the device is given by A_{eff}. For the MRR and NRR, the effective mode core area ranges from 0.50 to 0.10 μm^2 [14]. In Fig. 1, the resonant output is formed, thus, the normalized output of the light field is the ratio between the output and input fields $E_{out}(t)$ and $E_{in}(t)$. The output and input signals in each roundtrip of the nanoring resonator at the left side can be calculated using equation (4).

$$\left|\frac{E_{out}(t)}{E_{in}(t)}\right|^2 = (1-\gamma)\times \left[1-\frac{(1-(1-\gamma)x^2)\kappa}{(1-x\sqrt{1-\gamma}\sqrt{1-\kappa})^2+4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2(\frac{\phi}{2})}\right] \quad (4)$$

Here κ is the coupling coefficient, and $x=\exp(-\alpha L/2)$ represents a roundtrip loss coefficient, $\phi_0 = kLn_0$ and $\phi_{NL} = kLn_2|E_{in}|^2$ are the linear and nonlinear phase shifts, $k = 2\pi/\lambda$ is the wave propagation number in a vacuum. L and α are a waveguide length and linear absorption coefficient, respectively. In this work, an iterative method is inserted to obtain the needed results using equation (4).

Cancelation of the chaotic signals noise can be done using the add-drop device with the appropriate parameters. This is given in details as follows. The two complementary optical circuits of ring-resonator add-drop filters can be given by the Eqs. (5) and (6).

$$\left|\frac{E_{t1}}{E_{in}}\right|^2 = \frac{(1-\kappa_1)-2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos(k_nL)+(1-\kappa_2)e^{-\alpha L}}{1+(1-\kappa_1)(1-\kappa_2)e^{-\alpha L}-2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos(k_nL)} \quad (5)$$

and

$$\left|\frac{E_{t2}}{E_{in}}\right|^2 = \frac{\kappa_1\kappa_2 e^{-\frac{\alpha}{2}L}}{1+(1-\kappa_1)(1-\kappa_2)e^{-\alpha L}-2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}\,e^{-\frac{\alpha}{2}L}\cos(k_nL)} \quad (6)$$

where E_{t1} and $_{2t}E$ represent the optical fields of the throughput and drop ports respectively. $\beta = kn_{eff}$ is the propagation constant, n_{eff} is the effective refractive index of the waveguide and the circumference of the ring is $L=2\pi R$. R is the radius of the ring. The phase constant can be simplified as $\Phi=\beta L$. The chaotic noise cancellation can be managed by using the specific parameters of the add-drop device in which required signals can be retrieved by the specific users. The waveguide (ring resonator) loss is $\alpha = 0.5\ dBmm^{-1}$. The fractional coupler intensity loss is $\gamma = 0.01$. In the case of add-drop device, the nonlinear refractive index is neglected [15]. The electric fields inside the proposed system are expressed as:

$$E_1 = \sqrt{1-\gamma_1}\left[\sqrt{1-\kappa_1}E_3 + j\sqrt{\kappa_1}E_{i1}\right], \quad (7)$$

$$E_2 = \sqrt{1-\gamma_2}\left[\sqrt{1-\kappa_2}E_1 + j\sqrt{\kappa_2}E_{i2}\right], \quad (8)$$

$$E_3 = E_{0L}E_2 e^{-\alpha L_{ad}/4 - jk_nL_{ad}/2}, \quad (9)$$

and the output fields E_{t1} and E_{t2} at the throughput and drop parts of the system are derived by

$$E_{t1} = -x_1x_2y_2\sqrt{\kappa_1}E_{i2}e^{-\frac{\alpha L}{2}} - jk_n\frac{L}{2} + \left[\frac{x_2x_3\kappa_1\sqrt{\kappa_2}E_{0L}E_{i1}(e^{-\frac{\alpha L}{2}} - jk_n\frac{L}{2})^2 + x_3x_4y_1y_2\sqrt{\kappa_1}\sqrt{\kappa_2}E_{0L}E_{i2}(e^{-\frac{\alpha L}{2}} - jk_n\frac{L}{2})^3}{1 - x_1x_2y_1y_2E_{0L}(e^{-\frac{\alpha L}{2}} - jk_n\frac{L}{2})^2}\right] \quad (10)$$

and

$$E_{t2} = x_2y_2E_{i2} + \left[\frac{x_1x_2\kappa_1\sqrt{\kappa_1}\sqrt{\kappa_2}E_{0L}E_{i1}e^{-\frac{\alpha L}{2} - jk_n\frac{L}{2}} + x_1x_3y_1y_2\sqrt{\kappa_2}E_{0L}E_{i2}(e^{-\alpha\frac{L}{2} - jk_n\frac{L}{2}})^2}{1 - x_1x_2y_1y_2E_{0L}(e^{-\frac{\alpha L}{2} - jk_n\frac{L}{2}})^2}\right]. \quad (11)$$

Here, the $x_1 = \sqrt{1-\gamma_1}$, $x_2 = \sqrt{1-\gamma_2}$, $x_3 = 1-\gamma_1$, $x_4 = 1-\gamma_2$, $y_1 = \sqrt{1-\kappa_1}$, $y_2 = \sqrt{1-\kappa_2}$,

$$E_{0L} = E_2\frac{\sqrt{(1-\gamma)(1-\kappa_3)} - (1-\gamma)e^{-\frac{\alpha}{2}L_L - jk_nL_L}}{1 - \sqrt{1-\gamma}\sqrt{1-\kappa_3}e^{-\frac{\alpha}{2}L_L - jk_nL_L}}.$$

$L_L = 2\pi R_L$, where R_L is the left ring radius

III. RESULT AND DISCUSSION

In operation dark soliton pulse with maximum power of 1 W is inputted into the interferometer system, where the Gaussian beam has power of 600 mW. The suitable ring parameters are ring radii, where $R_{ad} = 100$ μm and $R_L = 800$ nm. The coupling coefficients of the centered ring are given by $\kappa_1 = 0.7$ and $\kappa_2 = 0.2$, where the ring resonator at the left side has coupling coefficient of $\kappa_3 = 0.35$.

In order to make the system associate with the practical device, the selected parameters of the system are fixed to $\lambda_0 = 0.6$ μm, $n_0 = 3.34$ (InGaAsP/InP). The effective core areas range from $A_{eff} = 0.50$ to 0.10 μm^2. The nonlinear refractive index is $n_2 = 1.3\times10^{-13}$ m^2/W. The dynamic dark soliton control can be configured to be an optical dynamic tool known as an optical tweezers.

After the Gaussian pulse is added into the system via add port, the dark-Gaussian soliton collision is seen in which extremely narrow optical tweezers can be generated shown in Fig. 2. Figure 2(a) shows the inserted dark soliton and Gaussian pulse at the input and add ports of the system with center wavelength of $\lambda_0 = 0.6\mu m$. Figures 2(b), 2(c) and 2(d) show the interior generated optical tweezers with different amplitudes. The output signals from the through and drop ports of the system can be seen in Figs 2(e) and 2(f), respectively.

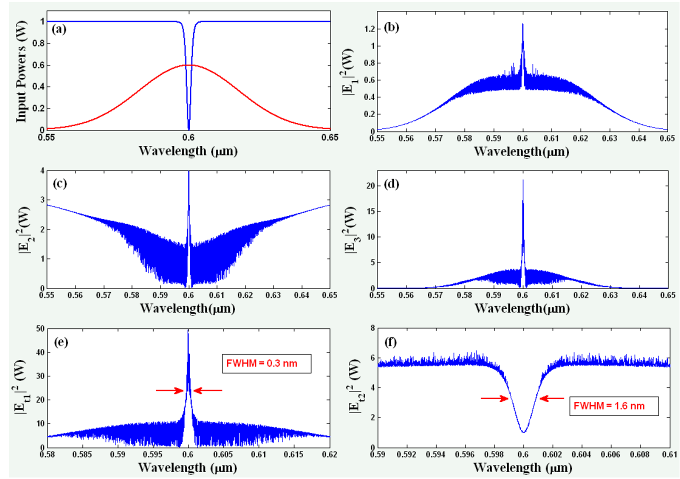

Fig. 2: Results of the optical tweezers generation (a): input dark soliton and Gaussian pulse, (b), (c) and (d): interior signals, (e) and (f): through and drop port output signals with FWHM of 0.3 nm and 1.6 nm respectively, where $\kappa_1 = 0.7$, $\kappa_2 = 0.2$ and $\kappa_3 = 0.35$

Figure (3) shows the extremely narrow optical tweezers (potential wells), where the powers of the inputs Gaussian pulse and the optical dark soliton are 400 mW and 4 W respectively. Here $\kappa_1 = 0.2$, $\kappa_2 = 0.4$, $\kappa_3 = 0.15$, $n_2 = 1.3\times10^{-21}$ m^2/W, $A_{eff} = 0.50$ μm^2, where the radius of the left ring has been selected to $R_L = 5$ μm.

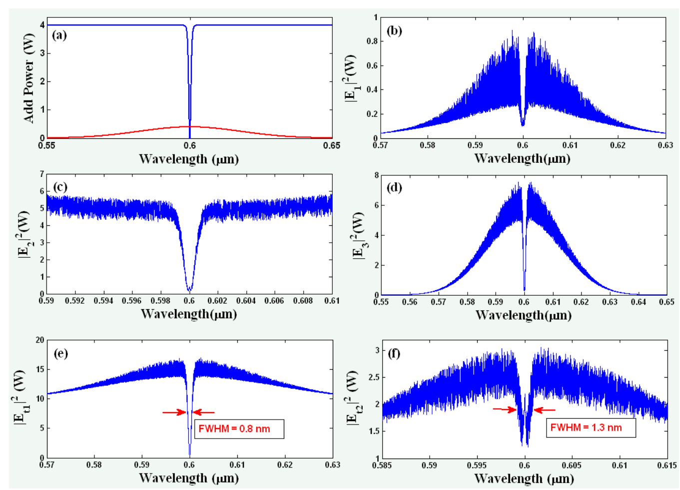

Fig. 3: Results of the optical tweezers generation (a): input dark soliton and Gaussian pulse, (b), (c) and (d): interior signals, (e) and (f): through and drop port output signals with FWHM of 0.8 nm and 1.3 nm respectively, where $\kappa_1 = 0.2$, $\kappa_2 = 0.4$ and $\kappa_3 = 0.15$

Soliton signals can be used in optical communication where the capacity of the output signals can be improved by generation of peaks with smaller FWHM [16]. In application, such a behavior can be used to confine the suitable size of light pulse or molecule. The proposed receiver unit is a quantum processing system that can be used to generate high capacity packet of quantum codes within the series of MRR's shown in Fig. 3 [17].

In operation, the computing data can be modulated and input into the system via a receiver unit, which is known as a quantum signal processing system. The receiver unit can be used to detect the quantum bits, where the reference states can be recognized by using the cloning unit, which is operated by the add/drop filter (R_{dN1}) shown in Fig. 4. By using suitable dark-Gaussian soliton input power, the tunable optical tweezers can be controlled. This provides the entangled photon as the dynamic optical tweezers probe [18]. The required data can be retrieved via the through and drop ports of the add/drop filter in the router, where the high capacity of data can be applied by using more wavelength carriers provided by the correlated photon generated.

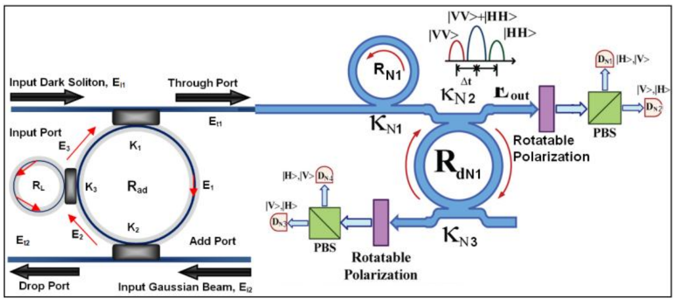

Fig.4: A schematic of an entangled photon pair manipulation within a ring resonator. The quantum state is propagating to a rotatable polarizer and then is split by a beam splitter (PBS) flying to detector D_{N1}, D_{N2}, D_{N3} and D_{N4}

From figure 4, there are two pairs of possible polarization entangled photons forming within the MRR device, which are the four polarization orientation angles as [0^o, 90^o], [135^o and 180^o]. These can be done by using the optical component, called the polarization rotatable device and a polarizing beam splitter (PBS). The polarized photon is used in the proposed arrangement. Each pair of the transmitted qubits can itself forms the entangled photon pairs. Polarization coupler separates the basic 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 (12) [19].

$$|\Phi\rangle_p = |1, H\rangle_s |1, H\rangle_i + |2, H\rangle_s |2, H\rangle_i \qquad (12)$$

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 shown by Equation (12) is 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 is converted into |V> at the delay circuit output. The delay circuit converts |k, H> into

$$r|k, H\rangle + t_2 \exp(i\Phi)\, |k+1, V\rangle + rt_2 \exp(i_2\Phi)\, |k+2, H\rangle + r_2t_2 \exp(i_3\Phi)\, |k+3, V\rangle$$

Here t and r are the amplitude transmittances to cross and bar ports in a coupler. Equation (12) is converted into the polarized state by the delay circuit as

$$|\Phi\rangle = [|1, H\rangle_s + \exp(i\Phi_s)\, |2, V\rangle_s] \times [|1, H\rangle_i + \exp(i\Phi_i)\, |2, V\rangle_i] + [|2, H\rangle_s + \exp(i\Phi_s)\, |3, V\rangle_s \times [|2, H\rangle_i + \exp(i\Phi_i)\, |2, V\rangle_i] = [|1, H\rangle_s |1, H\rangle_i + \exp(i\Phi_i)\, |1, H\rangle_s |2, V\rangle_i] + \exp(i\Phi_s)\, |2, V\rangle_s |1, H\rangle_i + \exp[i(\Phi_s+\Phi_i)]\, |2, V\rangle_s |2, V\rangle_i + |2, H\rangle_s |2, H\rangle_i + \exp(i\Phi_i)\, |2, H\rangle_s |3, V\rangle_i + \exp(i\Phi_s)\, |3, V\rangle_s |2, H\rangle_i + \exp[i(\Phi_s+\Phi_i)]\, |3, V\rangle_s |3, V\rangle_i \qquad (13)$$

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

$$|\Phi\rangle = |2, H\rangle_s |2, H\rangle_i + \exp[i(\Phi_s+\Phi_i)]\, |2, V\rangle_s |2, V\rangle_i \qquad (14)$$

Strong pulses acquire an intensity dependent phase shift during propagation. The interference of light pulses at the coupler introduces the entangled output beam. 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. The entangled photons of the nonlinear ring resonator are then separated into the signal and idler photon probability.

In application, the variable quantum codes can be generated using the PBS. The used beam splitters reflect (and transmit) 50% of the light that is incident, for all polarizations of the incident light. This interconnection can also be done with fiber couplers. In this concept, we assume that the polarized photon can be performed by using the proposed arrangement. In operation, the encoded quantum secret codes computing data can be modulated and input into the optical network communication system. Schematic of the network system is shown in Figure (5), in which quantum cryptography for internet security can be obtained.

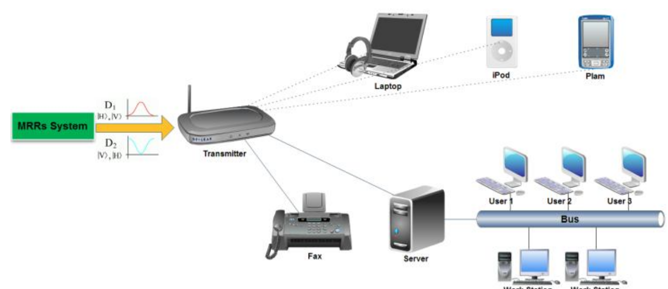

Fig. 5: Networks communication system, where the transmission of information can be implemented using generated quantum optical codes

IV. CONCLUSION

Novel system of microring resonator for secured optical communication has been demonstrated. The optical tweezers are generated by the dark soliton propagating in a MRR. The quantum signal processing unit is connected to the optical tweezers, which is able to generate qubits, thus providing secured and high capacity of information. This secured coded information can be easily transmitted via a optical network communication system. In order to enhance the capacity of transmission data codes, the multi optical tweezers can be generated when the dark soliton propagating inside the PANDA ring resonator.

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