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Long Distance Communication Using Localized Optical Soliton via Entangled Photon

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ABSTRACT: *A system of microring resonators (MRRs) is presented to generation entangled photon. Different time slot for continuous variable quantum key distribution (CVQKD) use is applicable in optical wireless link. Chaotic behavior of a soliton pulse within the device can be presented respect to the Kerr nonlinear type of light in the MRR devices. Continuous spatial and temporal signals are generated spreading over the spectrum. The CVQKD is formed using the localized spatial soliton pulse. Here localized temporal soliton with FWHM and FSR of 0.2 ps and 0.58 ns is obtained respectively. The spatial soliton pulse has a FWHM of 80 pm. Transmission of soliton pulse with FWHM of 1.5 ps is simulated along the long distance fiber optics where the polarized photons are formed incorporating with the polarization control unit into the MRRs, which allows different time slot entangled photons to be randomly formed.*
Keywords: *Microring Resonator, Spatial and Temporal Soliton, continuous variable quantum distribution*

I. INTRODUCTION

CVQKD can form requires information providing the perfect communication security [1]. Amiri et al. demonstrated that quantum security could be performed via the optical soliton pulses [2]. To generate a spectrum of light over a broad range [3], an optical soliton pulse is recommended as a powerful laser pulse that can be used to generate chaotic filter characteristics when propagating within nonlinear MRRs [4-7]. Using this technique, the capacity of the transmission data [8] can be secured and increased when the chaotic packet switching is employed [9]. This system is used to trap optical solitons in order to generate entangled photon pair required for CVQKD [10-13]. Generation of the localized soliton pulses for CVQKD application is presented. CVQKD system can be implemented within the optical communication [14-17], where the optical links can be set up using the optical soliton, generated by the chaotic signals [18]. Furthermore, the CVQKD can be generated using different time slot entangled photon pairs [19].

II. THEORETICAL MODELING

Schematic diagram of the proposed system is shown in Fig. 1. A soliton pulse with 20 ns pulse width, peak power at 500 mW is input into the system. The suitable ring parameters are used, for instance, ring radii R_1=10 µm, R_2=5µm, and R_3=2µm. In order to make the system associate with the practical device, the selected parameters of the system are fixed to λ_0=1555 nm, n_0=3.34, A_{eff}=0.50, 0.25µm^2 and 0.12µm^2, α=0.5dBmm^{-1} and γ=0.1. The coupling coefficient of the MRR ranged from 0.9 to 0.975.

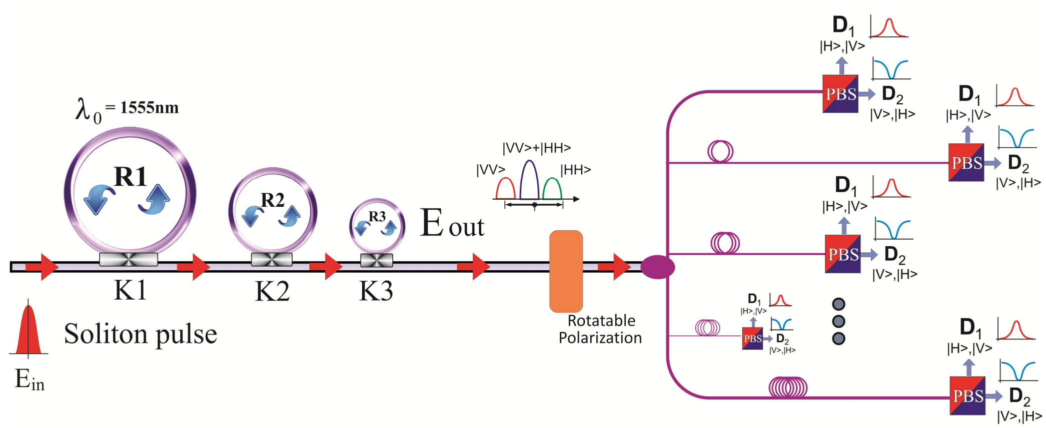

Fig.1: Schematic diagram of a CVQKD with the different time slot entangled photon encoding. PBS, polarizing beam splitter, Ds, detectors, Rs, ring radii and κs, coupling coefficients.

The soliton pulse is introduced into the proposed system, where the input optical field (E_{in}) of the bright soliton pulse can be expressed by [20-22],

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

A and z are the optical field amplitude and propagation distance, respectively [23]. T is a soliton pulse propagation time in a frame moving at the group velocity [24-26], $T = t\text{-}\beta_1{\times}z$ [27], where β_1 and β_2 are the coefficients of the linear and second order terms of the Taylor expansion of the propagation constant [28-32]. $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse [33-35]. The carrier frequency of the soliton is ω_0 [36-37]. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton [38-40]. When a soliton peak intensity $\left(|\beta_2/\Gamma T_0^2|\right)$ is given, then T_o is known [41-45]. For the soliton pulse in the micro ring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length (L_{NL}= (1/ $\Gamma\phi_{NL}$) [46], where $\Gamma = n_2{\times}k_0$, is the length scale over which disperse or nonlinear effects makes the beam becomes wider or narrower [47-50]. For a soliton pulse, there is a balance between dispersion and nonlinear lengths, hence L_D=L_{NL} [51-53]. When light propagates within the nonlinear medium, the refractive index (n) of light within the medium is given by [54-57]

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}}\right)P, \tag{2}$$

where n_0 and n_2 are the linear and nonlinear refractive indexes, respectively [58-62]. I and P are the optical intensity and optical power, respectively [63-65]. The effective mode core area of the device is given by A_{eff} [66]. For the MRR, the effective mode core areas range from 0.50 to 0.12 μm^2 [67-68]. When a soliton pulse is input and propagated within a MRR as shown 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) in each round-trip, which can be expressed by [69-72]

$$\left|\frac{E_{out}(t)}{E_{in}(t)}\right|^2 = (1-\gamma)\left[1 - \frac{(1-(1-\gamma)x^2)\kappa}{(1-x\sqrt{1-\gamma}\sqrt{1-\kappa})^2 + 4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2(\frac{\phi}{2})}\right] \tag{3}$$

κ is the coupling coefficient [73], and x=exp($-\alpha L/2$) represents a round-trip loss coefficient [74], Φ_0=kLn_0 and Φ_{NL}=$kLn_2|E_{in}|^2$ are the linear and nonlinear phase shifts [75], k=2π/λ is the wave propagation number in a vacuum [76]. Where L and α are the waveguide length and linear absorption coefficient, respectively [77]. In this work, the iterative method is introduced to obtain the results as shown in equation (3), similarly, when the output field is connected and input into the other ring resonators [78].

III. RESULT AND DISCUSSION

Large bandwidth within the MRRs device can be generated by using a soliton pulse input shown in Fig. 1, where the required signals can be generated and perform secure communication network. The nonlinear refractive index is n_2=2.5 x 10^{-17}m^2/W. In this case, the wave guided loss used is 0.5dBmm^{-1}. From Fig. 2, the signal is chopped (sliced) into a smaller signal spreading over the spectrum, which shows that the large bandwidth is formed within the first MRR. Compress bandwidth is obtained within the ring R_2. The amplified gain is obtained within a microring device (i.e. ring R_3). Temporal soliton is formed and trapped by using the constant gain condition. The attenuation of the optical power within a microring device is required in order to keep the constant output gain, where the next round input power is attenuated and kept the same level with the R_2 output. Here R_1=10µm, κ_1=0.95, A_{eff1}=50 µm^2, R_2=5µm, κ_2=0.975, A_{eff2}=25µm^2, R_3=2.5µm, κ_3=0.975, A_{eff3}=0.1µm^2. The total round trip is 40000 and the central wavelength has been selected to λ=1.55 µm.

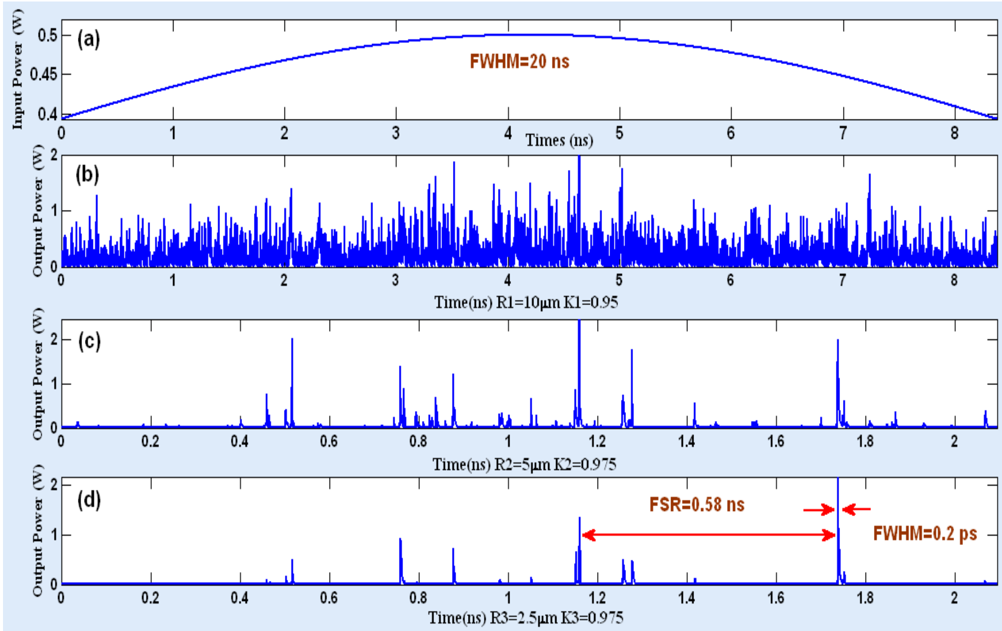

Fig. 2: Results obtained when temporal soliton is localized within a microring device with 40,000 roundtrips where (a): Input bright soliton, (b): Output signal from R_1, (c): Output signal from R_2, (d): Output signal from R_3 with FWHM and FSR of 0.2 ps and 0.58 ns respectively

Similarly, the spatial soliton is obtained as shown in Fig. 3. Here R_1=10µm, κ_1=0.975, A_{eff1}=50 µm^2, R_2=5µm, κ_2=0.975, A_{eff2}=25µm^2, R_3=4µm, κ_3=0.975, A_{eff3}=0.1µm^2. The central wavelength has been selected to λ=1.525µm.

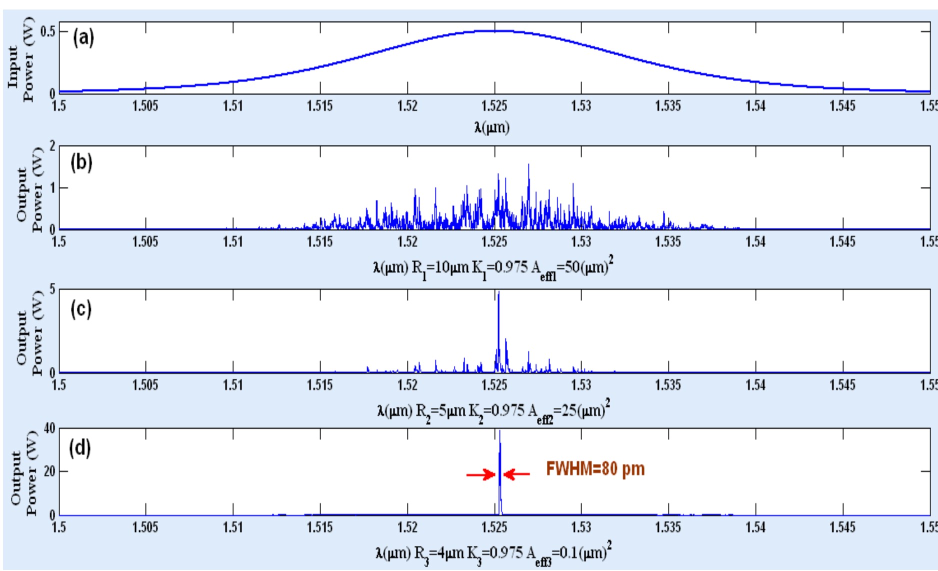

Fig.3: Results obtained when a spatial soliton is localized within a microring device with 40,000 roundtrips, where (a): input bright soliton, (b): output signal from R_1, (c): output signal from R_2, (d): output signal from R_3 with FWHM of 80 pm

Soliton pulse with FWHM=1.5 ps and 10 pm can be propagated along long distance fiber optics with nonlinear refractive index of n_2=2.6 x 10^{-20} m^2/W and attenuation coefficient of α=0.4 dB/km. The simulation results of the transmission through a length of 60 km and 80 km are presented shown in Figs. 4 and 5 respectively.

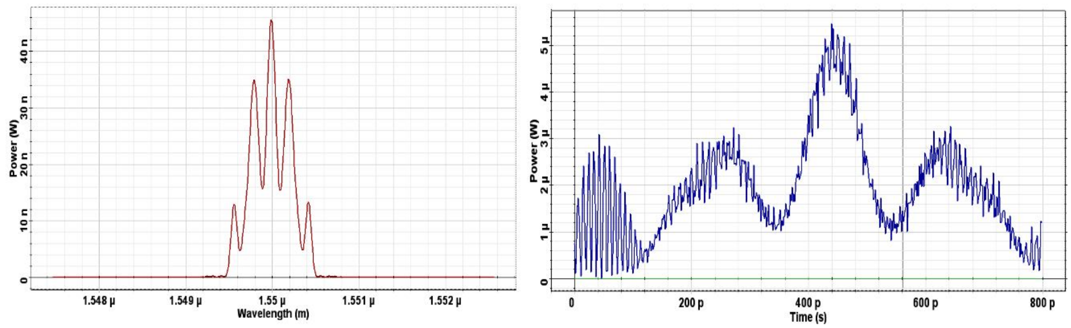

Fig.4: Results obtained when soliton is transmitting along long fiber distance 60 km

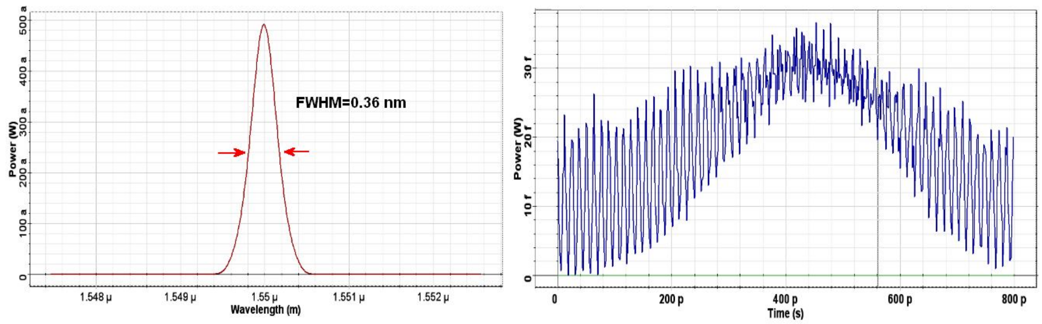

Fig.5: Results obtained when soliton is transmitting along long fiber distance 80 km

The continuous variable of photon can be generated within the proposed system, where each pair of the possible polarization entangled photons is formed within different time frames by using the polarization control unit as shown in Fig. 1, thus they can be represented by the four polarization orientation angles as [0°,90°] and [135°,180°] [79-80]. They can be formed by using the optical component called the polarization rotatable device and PBS [81]. Using this system, we assume that the polarized entangle photon can be performed by applying the proposed arrangement where each pair of the transmitted entangled photon pair (qubits) with different time slot ($t_1, t_2, t_3, \ldots, t_n$) can randomly form the entangled pairs [82-83]. Here we introduce the technique that is used to generate the qubits as shown in Fig. 1 [84-85]. A polarization coupler (i.e. last ring, R_3) that separates the basic vertical and horizontal polarization states corresponds to an optical switch between the short and the long pulses [86]. We assume those horizontally polarized pulses with a temporal separation of Δt. The coherence time of the consecutive pulses is larger than Δt. Then the following state at time t_1 is created by equation (4) [87].

$$|\Phi>_p = |1, H>_s |1, H>_i + |2, H>_s |2, H>_i \tag{4}$$

In the expression |k, H>, k is defined as the number of time slots (1 or 2), where it 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 with considering the assumption that an amplitude term is common to all product states mentioned in the equation (4). We will use the same assumption in subsequent equations in this paper. This two-photon state with |H> polarization shown by equation (4) is input into the orthogonal polarization-delay circuit shown schematically in Fig. 1. The delay circuit consists of a coupler and the difference between the round-trip times of the MRR, which is equal to Δt. The microring is tilted by changing the round trip of the ring is converted into |V> at the delay circuit output. That is the delay circuits convert

$$r|k, H> + t_2 \exp(i\Phi) |k+1, V> + rt_2 \exp(i_2\Phi) |k+2, H> + r_2 t_2 \exp(i_3\Phi) |k+3, V> \tag{5}$$

Where *t* and *r* is the amplitude transmittances to cross and bar ports in a coupler. Then equation (4) is converted into the polarized state by the delay circuit as

$$\begin{aligned}
|\Phi> &= [|1, H>_s + \exp(i\Phi_s) |2, V>_s] \times [|1, H>_i + \exp(i\Phi_i) |2, V>_i] \\
&+ [|2, H>_s + \exp(i\Phi_s) |3, V>_s \times [|2, H>_i + \exp(i\Phi_i) |2, V>_i] = \\
&[|1, H>_s |1, H>_i + \exp(i\Phi_i) |1, H>_s |2, V>_i] + \exp(i\Phi_s) |2, V>_s |1, H>_i + \\
&\exp[i(\Phi_s+\Phi_i)] |2, V>_s |2, V>_i + |2, H>_s |2, H>_i + \exp(i\Phi_i) |2, H>_s |3, V>_i + \\
&\exp(i\Phi_s) |3, V>_s |2, H>_i + \exp[i(\Phi_s+\Phi_i)] |3, V>_s |3, V>_i
\end{aligned} \tag{6}$$

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

$$|\Phi\rangle = |2, H\rangle_s |2, H\rangle_i + \exp[i(\Phi_s+\Phi_i)]\, |2, V\rangle_s |2, V\rangle_i \tag{7}$$

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 [88-90], 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 [91-92]. 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 described by.

IV. CONCLUSION

An interesting concept in which continuous variable quantum key distribution can be performed using a remarkably simple system was presented. Proposed system consists of a series of nonlinear MRR and NRR devices. Balance between dispersion and nonlinear lengths of the soliton pulse exhibits the self-phase modulation, which introduces the optical output constant, which means that light pulses can be trapped, localized coherently within the nano-waveguide. We have shown that a large bandwidth of the arbitrary soliton pulses can be generated and compressed within a micro waveguide. The chaotic signal generation using a soliton pulse in the nonlinear MRRs has been presented. The selected light pulse can be localized and used to perform the secure communication network. Localized spatial and temporal soliton pulse propagates along long distance communication where it can be used to generate entangled photon pair providing CVQKD applicable for communication networks. We have analyzed the entangled photon generated by chaotic signals in the series MRR devices. The classical information and security code can be formed by using the temporal and spatial soliton pulses, respectively.

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