

## GENERATION OF QUANTUM CODES USING UP AND DOWN LINK OPTICAL SOLITON

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**Abstract.** In this study, a system of continuous variable quantum code via a wavelength router is presented. The optical Kerr type nonlinearity in the nonlinear microring resonator (NMRR) induces the chaotic behavior. In this proposed system chaotic signals are generated by an optical soliton or Gaussian pulse within a NMRR system. Large bandwidth signals of optical soliton are generated by the input pulse propagating within the MRRs, which is allowed to form the continuous wavelength or frequency with large tunable channel capacity. Therefore, distinguished up and down links of wavelength or frequency pulses can be generated by using localized spatial soliton via a quantum router and networks. These selected up and down links pulses are more suitable to generate high secured quantum codes because of the greater free spectral range (FSR). The continuous quantum codes can be generated by using the polarization control unit and beam splitter, incorporating into the MRRs. In this work, frequency band of 10.7 MHz and 16 MHz and wavelengths of 206.9 nm, 1.448  $\mu\text{m}$ , 2.169  $\mu\text{m}$  and 2.489  $\mu\text{m}$  can be obtained for QKD by using input optical soliton and Gaussian beam.

*Keywords:* Nonlinear microring resonator (NMRR); up and down links optical soliton, quantum codes

### 1.0 INTRODUCTION

Quantum network is becoming a promising technology for network security. QKD is an interesting tool that can provide suitable communication security and has been proposed in many research works [1, 2]. The applications in different forms such as point to point link [3], optical wireless [2], satellite [4], long distance communication [5] and network [6] have been reported. The use of continuous variable QKD with quantum router and network has been proposed [7-10].

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Recently, Yupapin et al. [11] have shown that the continuous wavelength and frequency can be generated using a soliton pulse in an MRR.

A new quantum code distribution protocol in which information is encoded on continuous variables of a single photon has been used [12]. Suchat et al. have proposed the use of QKD via optical wireless link, secured information transmission in telephone networks [13]. They also have proposed the system of quantum entangled photon generation [14, 15] in long-distance communication. Ma et al. [16] have demonstrated a one-way QKD scheme based on phase encoding and polarization measurement of single photons.

In this study, we are using the continuous variable QKD system, where the signal bands are generated by a technique called chaotic filtering scheme. The required frequency bands and wavelength can be selected and used. The continuous variable quantum codes are generated using different time slot entangled photon pairs. The entangled photon generation and behaviors within the proposed device are analyzed.

## 2.0 THEORETICAL MODELING

The input optical power is in the form of an optical soliton or a Gaussian beam. Optical soliton can be used to generate chaotic filter characteristics when propagating within the NMRRs [17]. When the input pulse is introduced into multi-stage MRRs as shown in Fig.1, the optical field ( $E_{in}$ ) can be expressed by

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

or

$$E_{in}(t) = E_0 \exp^{j\phi_0(t)} \quad . \quad (2)$$

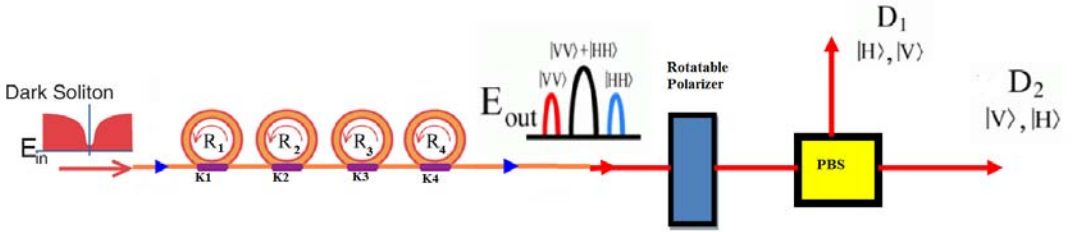
Here  $A$  and  $z$  are the optical field amplitude and propagation distance, respectively.  $T$  is the soliton pulse propagation time, and  $L_D = T_0^2 / |\beta_2|$  is the dispersion length of the soliton pulse.  $\beta_2$  is the propagation constant. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton. When soliton peak intensity  $(\beta_2 / \Gamma T_0^2)$  is given, then  $T_0$  is known.

Here  $\Gamma = n_2 \times k_0$ , is the length scale over which dispersive or nonlinear effects makes the beam become wider or narrower. For instance, a soliton pulse is input into a micro ring resonator with a 550 mW of peak power. For the soliton pulse in

the micro ring device, a balance should be achieved between the dispersion length ( $L_D$ ) and the nonlinear length ( $L_{NL}=(1/\gamma\phi_{NL})$ , where  $\gamma$  and  $\phi_{NL}$  are a coupling loss of the field amplitude and nonlinear phase shift. Here  $\phi_0 = kLn_0$  is linear phase shifts. These are the length scales over which dispersive or nonlinear effects make the beam becomes wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear length. Hence  $L_D=L_{NL}$ .

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

where  $n_0$  and  $n_2$  are the linear and nonlinear refractive indices, respectively.  $I$  is the optical intensity and  $P$  is the optical power. The effective mode core area of the device is given by  $A_{eff}$ . For the micro ring and nano-ring resonators, the effective mode core area ranges from  $0.50$  to  $0.1 \mu\text{m}^2$  [18]. The proposed system is consisting of series of ring resonators connected to rotatable polarizer and beam splitter which is used to generate up and down links optical soliton pulses and quantum codes, shown at Figure (1).



**Figure 1** Schematic of a continuous variable quantum code distribution, PBS; polarizing beam splitter; Ds, detectors; Rs, ring radii and  $\kappa_s$ , coupling coefficients.

In this system, a soliton pulse is input and allowed to propagate within a micro ring resonator as shown in Fig. 1. The resonant output is formed in the series of MRRs. Thus, the normalized output of the light field can be expressed as

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

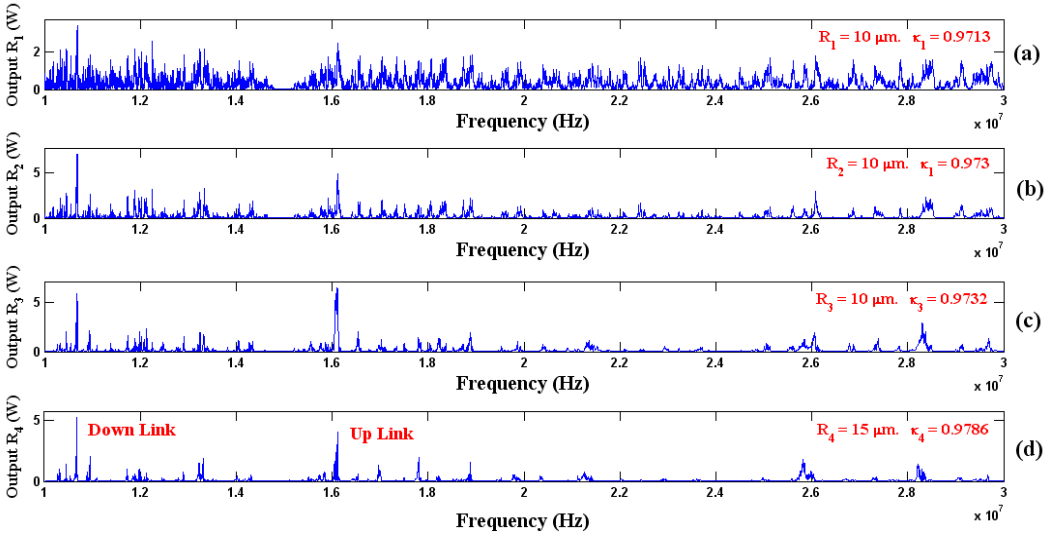
The close form of Eq. (4) indicates that a ring resonator in this particular case is comparable to a Fabry-Perot cavity, with an input and output mirror with a field reflectivity,  $(1-\kappa)$ , and a fully reflecting mirror. Here  $\kappa$  is the coupling coefficient, and  $x=\exp(-\alpha L/2)$  represents a roundtrip loss coefficient.  $k=2\pi/\lambda$  is the wave propagation number,  $\phi_0 = kLn_0$  and  $\phi_{NL} = kLn_2|E_{in}|^2$  are the linear and nonlinear phase shifts. Equation (4) shows the output power from each ring resonator which is recognized as an input power for the next ring resonator. The simulation programs of the mathematical equations can produce suitable optical soliton pulses to generate quantum codes, applicable for the secured communication.

### 3.0 RESULTS AND DISCUSSION

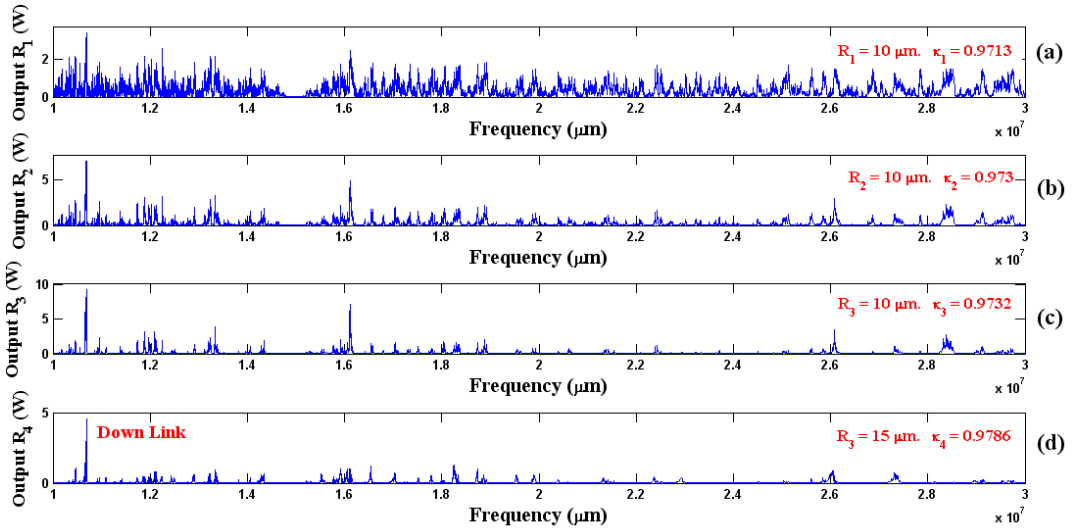
The single-mode soliton pulse becomes multimode noisy signals after circulating within the first MRR device due to the nonlinear Kerr effect. The large bandwidth signals are generated, in which the chaotic filtering characteristics of the signals are formed in the other ring resonators within the system. Using the material of InGaAsP/InP, the specified frequency bands are obtained based on appropriate ring parameters. The soliton waveform with center frequency at  $f_0 = 20$  MHz is input into the first MRR.

The optical power is fixed to 550 mW and  $n_0=3.34$ ,  $n_2=2.2\times 10^{-17}$  m<sup>2</sup> W<sup>-1</sup>,  $A_{\text{eff}}=0.50$  μm<sup>2</sup>,  $\alpha=0.5$  dB mm<sup>-1</sup>,  $\gamma=0.1$ , with 20,000 roundtrips. The chaotic signals are generated within the first ring ( $R_1$ ), where the broad frequency band is observed in ring  $R_2$ . The filtering signals are seen in rings  $R_3$  and  $R_4$ . Fig. 2 shows the profile of the simultaneous frequencies generation, for the related parameters of  $R_1=10$  μm,  $\kappa_1=0.9713$ ,  $R_2=10$  μm,  $\kappa_2=0.973$ ,  $R_3=10$  μm,  $\kappa_3=0.9732$ ,  $R_4=15$  μm, and  $\kappa_4=0.9786$ . In application, the upstream and downstream communication information can be linked via proposed system, for the up-down-link converters.

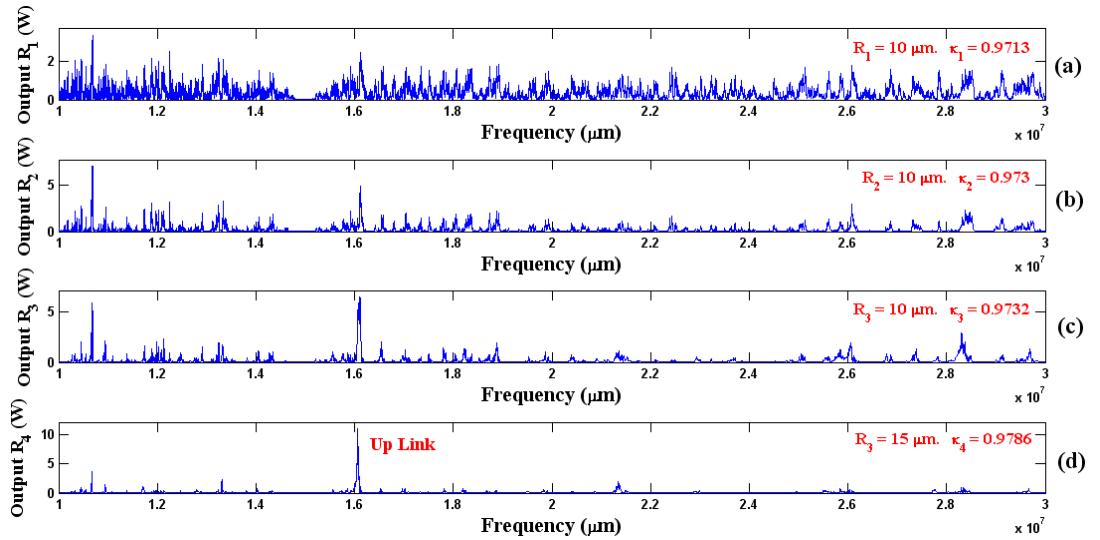
In the system, the up-link and down-link frequency bands can be simultaneously generated. Therefore, the specified frequencies can be selected (filtered) to form the required link converters. Fig. 3 shows the frequency profile generated for a down-link converter, in which the parameters used are the same but with different effective areas,  $A_{\text{eff}}$  for  $R_3$  and  $R_4$ . Fig. 4 shows the frequency generation for an up-link converter.



**Figure 2** Graph simultaneous of specific frequencies generation, (a) noisy chaotic signals, (b) frequency bands, (c) filtering signals, (d) Up-down-link signals.



**Figure 3** Graph simultaneous of specific frequencies generation, (a) noisy chaotic signals, (b) frequency bands, (c) filtering signals, (d) down-link signal(10.7 MHz).

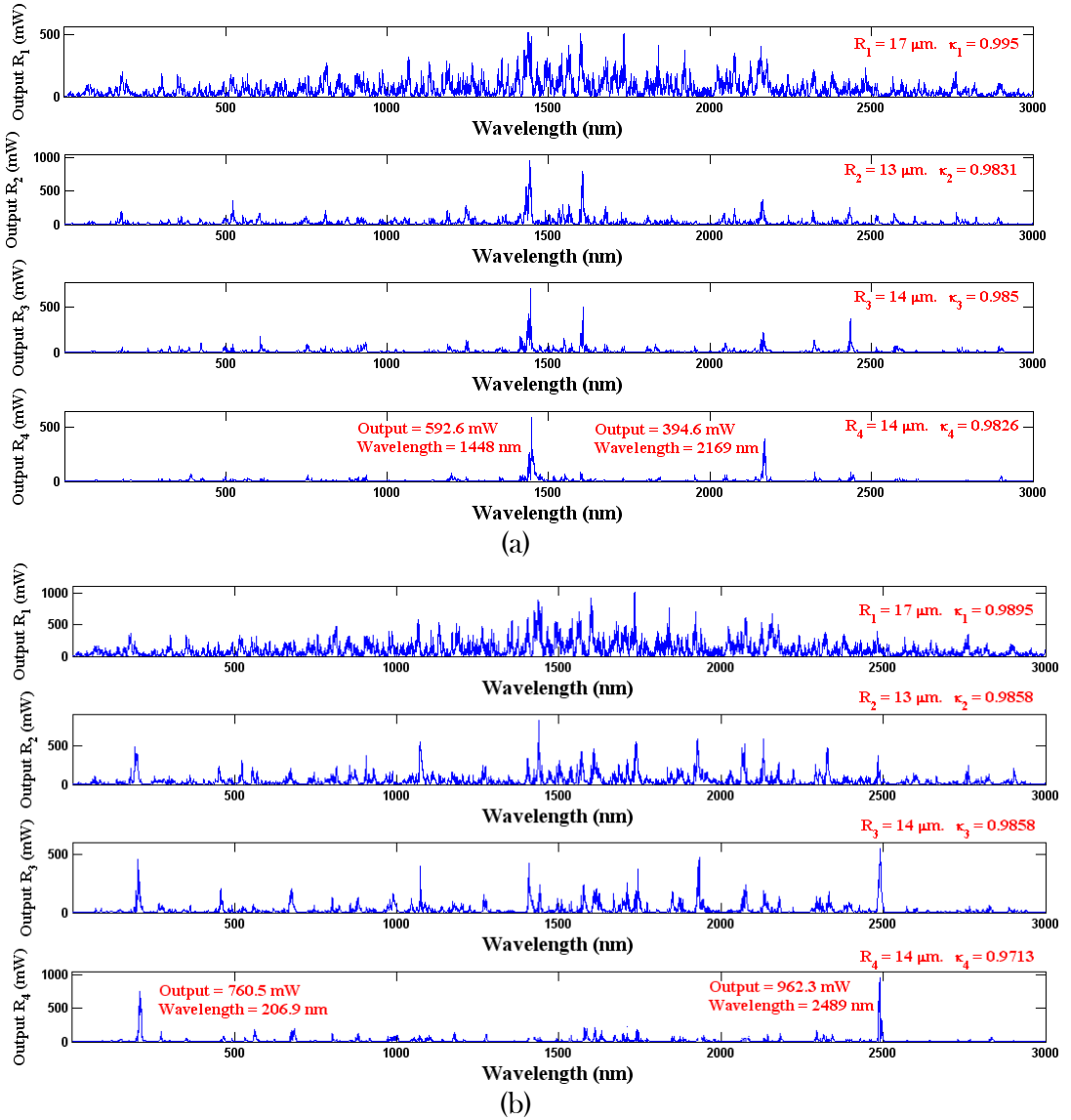


**Figure 4** Graph simultaneous of specific frequencies generation, (a) noisy chaotic signals, (b) frequency bands, (c) filtering signals, (d) up-link signal(16 MHz).

Using the proposed system, we can also generate the wide range of the spread wavelength domain where the wavelength multiplexing, especially dense wavelength division multiplexing (DWDM) via optical wireless link, is probable. Moreover, the use of the quantum code distribution via an optical wireless link is confirmed by Suchat et al. [19]. However, they have proposed the system of FORR. The quantum code distribution can be generated within the MRR device.

In principle, the specific wavelength mode is required in this technique, therefore, the chaotic signal is recommended to generate within the series MRRs [20]. Here the input power is in the form of Gaussian beam and expressed by Equation (2). After the Gaussian pulse is input into the first MRR device as shown in Fig.5, there are some light modes generated with smaller spectral width than the input pulse, which is obtained by the generated chaotic signals. The selected modes at the specific wavelength are required to obtain the desired use. The optical filter characteristics is employed by using the appropriate ring parameters such as input power and, ring material, refractive index, radius and coupling constant, etc. In this analysis, the Gaussian input power is 450 mW, with centre wavelength at  $\lambda_0=1.5 \mu\text{m}$ ,  $n_2=2.2 \times 10^{-15} \text{ m}^2 \text{ W}^{-1}$  and  $A_{\text{eff}} = 25 \mu\text{m}^2$ . In Figure 5(a), the Gaussian pulse is input into the first ring device ( $R_1$ ). The series ring radii  $R_1$ ,  $R_2$ ,  $R_3$  and  $R_4$  are 17, 13, 14 and 14  $\mu\text{m}$ , respectively. The coupling constants  $\kappa_1$ ,  $\kappa_2$ ,  $\kappa_3$ ,  $\kappa_4$  are 0.995, 0.9831, 0.985 and 0.9826, respectively.

By using the appropriate ring radius and the coupling coefficient, this system can be used to design and select the specific output signals. When the Gaussian



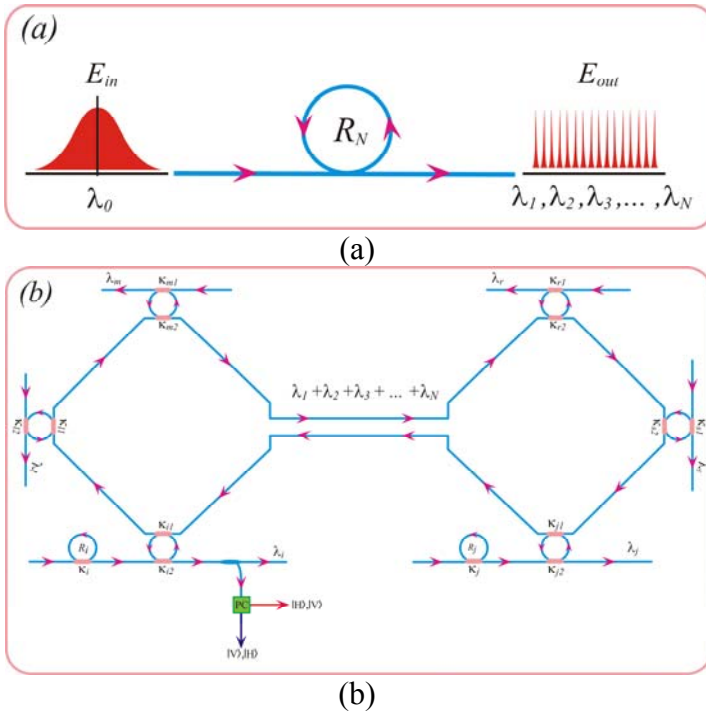
**Figure 5** Shows the chaotic signals generated by a series of 4 micro ring resonators, and (b) show generation of different wavelengths where  $R$  is the radius of the ring and  $\kappa$  is the coupling coefficient.  $\lambda$

power is input into the first ring, the chaotic signal is generated. The filtering signals are obtained by the second and third ring resonator as shown in Fig.5. Fig.5 (b) shows the filtering chaotic signal is obtained with the lower wavelength of  $\lambda_L=206.9 \text{ nm}$ , using the appropriate parameters. The higher wavelength of  $\lambda_H=2,489 \text{ nm}$  is also achieved. The obtained results are combined via the PBS as

shown in Fig.1. In application the continuous variable entangled photon can be generated where it is required to provide continuous variable codes. It means that the continuous wavelength or frequency generation is allowed for the continuous variable quantum codes.

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.

Quantum codes via localized up and down links optical solitons can be connected into a network system and quantum router shown in Fig.6. In operation, the large bandwidth within the MRR can be generated by using an optical soliton or Gaussian pulse input into the device. The localized signals up and down links optical soliton pulse are generated whereas the required signals included specific wavelengths or frequencies can form the secure communication network. The security code can be formed by using the spatial soliton pulses. Furthermore, the applications such as quantum repeater, quantum entangled photon source are available, which can complete the concept of quantum optical communication networks.



**Figure 6** Schematic of a large bandwidth signal generation system (a), and (b) a Schematic of a wavelength router and network system, where  $R_s$  is the ring radii and  $\kappa_s, \kappa_{s1}, \kappa_{s2}$  are the coupling coefficients



## 4.0 CONCLUSION

In conclusion, we have proposed a system using a new concept in which continuous variable codes can be performed. The system consists of a series of NMRR incorporated with rotatable polarizer and beam splitter. In application, such devices can be used to obtain the secured optical soliton pulses which are applicable for public networks. Here the entangled photon which are recognized as quantum codes are generated by chaotic signals in the series of MRRs devices.

We have shown that a large bandwidth of the arbitrary wavelength and frequency of light pulse can be generated for produce different quantum codes. The selected optical spatial pulse can be localized and used to perform the secured communication network. The optical input power in the system is generated using an optical soliton or Gaussian pulse within the nonlinear Kerr-type MRR devices. Further, more frequency and wavelength bands are available, which is suitable for implementing more applications.

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