# Quantum cryptography coding system for optical wireless communication

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In this study, a system of microring resonators (MRRs) and an add/drop filter are used to generate a large bandwidth signal as a localized multi wavelength, applicable for highly secure optical wireless communication (OWC). This technique uses the Kerr nonlinear type of light in the MRR to generate multi wavelength of bright and dark soliton for quantum network cryptography. An applicable quantum key distribution (QKD) protocol is discussed in details. Results show that ranges of multi bright and dark soliton wavelengths from 1.4μm to 1.7μm with central wavelength of 1.55μm are simulated, where the FWHM and FSR of 26 pm and 940 pm are obtained, respectively.

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## 1. Introduction

Quantum communication refers to the distribution of quantum states between two parties, traditionally called Alice and Bob. The quantum states could be entangled states or quantum dense coding [1]. Many of the initial works in quantum communication applied discrete quantum variables. However, continuous variables are verified to be appropriate for a quantum communication [2]. QKD is another major branch of quantum communication. It concerns with the establishment of a joint secret key between Alice and Bob, through a quantum channel [3]. QKD techniques have been considered as a useful component in network communication systems that need high security [4]. Currently, there are large numbers of private networks around the world which offer consumers' desired secured and private communications. In the past two decades, wireless communications has attracted great popularity in which, Radio Frequency (RF) and Optical Wireless (OW) have been applied for transferring data [5]. OW has the potential to be an alternative to RF and fiber optic communication systems, because of the license-free operation (in contrast to the RF communication), immunity to electromagnetic interference, ease of deployment, low power consumption, high security caused by the high directionality and narrowness of the beam [6].

In fact, the Quantum channel establishes the key using quantum cryptography. Then the key will be used for the data encryption and data decryption in OWC channel. The quantum channel also can be wired or wireless. Optical wireless QKD uses the air as the medium for the transmission of photons between the quantum transmitter and receiver. Optical wireless QKD over the free space was first proposed in 1996 [7]. After that, a number of preparation, measurement and entanglement based structures have been investigated in free space [3]. The current longest quantum channel distance is 144 km [8] and satellite quantum communication was investigated in [9].

MRR consists of a single coupler and a microring resonator. Light of appropriate wavelength is injected to the loop by the input waveguide. Over multiple round-trip, the intensity will build up due to constructive interference. Since only some wavelength resonates within the loop, it functions as a filter. Characterization of light inside a MRR system is investigated in [10, 11].

Some MRR systems have been proposed which have different applications in which specific full width at half maximum (FWHM), free spectral range (FSR), and intensity are needed [12-22].

MRR has many interesting and effective applications because of its own nature. It shows an effective performance for generating mm-wave and micro wave generation [23, 24] and it can be an interesting tool to generate solitonic pulses needed in indoor WDM-based OWC systems. Shahidinejad et al. [25-27] have shown that MRR can be used to generate secured quantum key codes.

The entangled photon pair can be performed via the MRR system, where it can be used to generate secured key codes. Dense wavelength of optical pulses, whether bright or dark type can be generated when the soliton pulse is propagating within the nonlinear MRR system and causes large bandwidth signals to be achieved and offered for continuous dense coding and quantum packet switching applications [28, 29]. Therefore, signals encoding is implemented using multi orthogonal bright and dark soliton signals and Quantum key can be performed and generated using a nonlinear MRR system with appropriate parameters.

In this paper, a nonlinear MRR system is used to form the multi wavelength, applicable for digital code generation used in quantum communication and OWC system. By using the proposed system, orthogonal soliton pulses which are bright and dark soliton can be localized and transferred through a digital signal processing system. The rest of this paper is organized as follows. Section 2 presents the quantum cryptography protocol applicable for OWC. Section 3 describes the theoretical modeling of the proposed system and section 4 demonstrates simulation results and contribution. Finally conclusions are presented in section 5.

## 2. Quantum cryptography protocol

The security of conventional cryptography depends on the mathematical complexity of the encryption algorithms and the confidentiality of the keys used in those algorithms. However these days there are such strong algorithm like AES, which can guarantee the confidentiality of a communication for quite a while, but the problem, is that we need to refresh our keys from time to time. The security of the encrypted information in these schemes strongly depends on the secrecy of the key. The algorithm is known to everybody, and the issue of finding the key is only a matter of computing power. By the significant increasing of computing power, the time to reveal the key has been reduced significantly. So, distributing the keys needed in our encryption algorithms has become a major problem. Here is where quantum cryptography helps us to produce a shared random key between our two parties Alice and Bob, without Even being able to gather any information about the key.

In QKD we distribute and actually generate a random key between our parties via the quantum channel. The most significant advantage of quantum channel in compare with classical channel is certainly the ability of detecting the existence of any eavesdropper trying to gain some information on the quantum channel. If an intruder wants to listen to information being transmitted on the QC, he needs to do some measurement on the photons, and this will cause the photon to be destroyed, having more error rate than expected by two parties, makes them aware of being an eavesdropper in play. In this paper, we explain how BB84 protocol works in QC and helps us along with OWC channel to establish a highly secure connection. BB84 is one of the most basic protocols of quantum key distribution which has been proposed by Charles H. Bennett and Gilles Brassard in 1984.

As shown in Fig. 1, this paper proposes a quantum transmission procedure. The procedure includes the following steps.

1. At the first step Alice generates a string of random classical bits from which the main key will be derived later. In fact the final key will be one of any possible subset of this string

2. Then choosing randomly one of two bases (diagonal or rectilinear) for each of those bits, Alice encoded the classical bits to the polarized photons and sends them to Bob using the quantum channel.

3. At the other side Bob needs to measure the receiving photons whether with rectilinear detector or diagonal detector, as far as Bob doesn't know yet the original polarization of the photons, he should make a decision again randomly and independently of Alice for choosing a detector for each photon.

This is needless to say again that the information gained from diagonal polarization measurement of a rectilinear photon is worthless, or vice versa. So, only the information that Bob guessed a correct polarization basis for, would be meaningful.

4. Alice and Bob over the public communication channel which is the OWC here, find out which photons were successfully received with the correct basis.

Bob reports bases of received photons, and Alice says which bases were correct. And they can reveal and check some bits of their initial shared information together in order to make sure of the correctness of their final key.

Now the information can be encrypted and decrypted by any of symmetric encryption algorithm using this key. Confidentiality of our communication over the OWC channel is guaranteed for quite a while depending on the length of the key we generated by QKD, and the strength of the encryption algorithm in which we use our key. And then we need to repeat the protocol again and renew our key.

Besides all privileges mentioned above, another outstanding advantage of our scheme is the high level security of our communication system based on quantum cryptography which can be implemented in our system much easier than any other systems.

As far as we are generating both OWC pulses and quantum pulses, we could use all the privileges that quantum cryptography brings to us for the security reasons by just simply switching between OWC and Quantum channel.

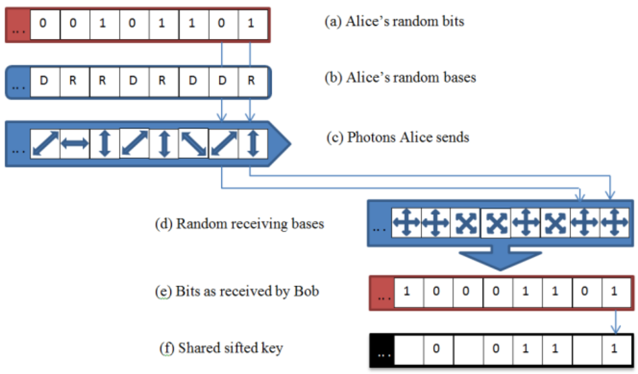


*Fig. 1. Quantum transmission, (a): Alice chooses a random string of bits, (b): for each of bits Alice decides a polarization bases (rectilinear or diagonal) randomly, (c): she then produce a sequence of polarized photons, each representing one bit of string based on the basis chosen, and sends to Bob, (d): Bob try to guess the correct detector (rectilinear or diagonal detector) and measure the photons, (e): result of Bob's measurement as a binary zero or one, (f): after discussion over OWC channel they discard all the data for which Bob used wrong basis. Resulting to initial shared random information.*

### 3. Theoretical modeling

An optical soliton pulse can be inputted into the nonlinear MRRs, where large optical bandwidth of the output signals can be generated. The nonlinear behavior of self-phase modulation (SPM) keeps the large output power. Chaotic signals cancelation can be performed using an optical add/drop filter system [30]. The schematic of the proposed systems is shown in Fig. 2.

The bright soliton pulse is inserted into the proposed system as the laser source. The temporal form of the bright soliton can be presented as Eq. (1). The input optical field ($E_{in}$) of the optical powers can be expressed as [31] follow, where Eq. (1) shows the optical bright soliton.

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

A and z are the optical field amplitude and propagation distance, respectively. $T$ is a soliton pulse propagation time in a frame moving at the group velocity, $T = t\text{-}\beta_1 \times z$, where $\beta_1$ and $\beta_2$ are the coefficients of the linear and second order terms of Taylor expansion of the propagation constant. $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse. The frequency shift of the soliton is $\omega_0$. This soliton describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton. When soliton peak intensity $\left(|\beta_2/\Gamma T_0^2|\right)$ is given then, $T_o$ is known. For the temporal optical soliton pulse in the microring device, a balance should be achieved between the dispersion length ($L_D$) and the nonlinear length of $L_{NL} = (1/\Gamma_{\Phi NL})$, where $\Gamma = n_2 \times k_0$ is the length scale over which dispersive or nonlinear effects makes the beam becoming wider or narrower, hence $L_D = L_{NL}$.

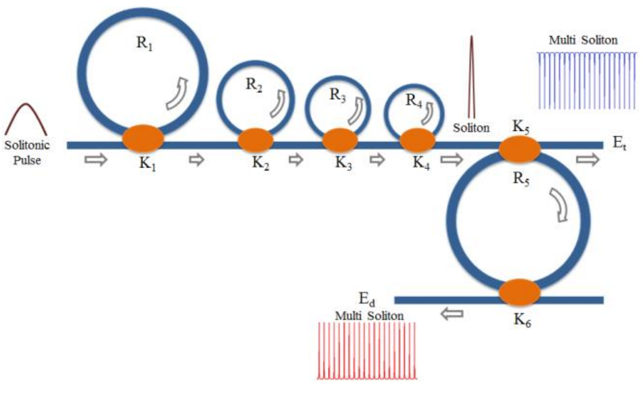


*Fig. 2. Systems of multi optical soliton pulse generation, where, $R_s$: ring radii, $\kappa_s$: coupling coefficients.*

When light propagates within the nonlinear medium, the refractive index (n) of light within the medium is given by [32]

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

$n_0$ and $n_2$ are the linear and nonlinear refractive indexes, respectively. $I$ and $P$ are 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 areas ranges from 0.50 to 0.10 μm$^2$ [33]. The resonant output can be formed; therefore the normalized output signals of the light field which is the ratio between the output and input fields ($E_{out}$ (t) and $E_{in}$ (t)) in each roundtrip can be expressed by [34]

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

Equation (3) specifies that a ring resonator in the exacting case is very similar to a Fabry-Perot cavity, which has an input and output mirror with a field reflectivity *(1-κ)*, and a fully reflecting mirror. $\kappa$ 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 and $k = 2\pi/\lambda$ is the wave propagation number in a vacuum. $L$ and $\alpha$ are waveguide length and linear absorption coefficient, respectively. In this investigation, the iterative method is introduced to obtain the results as shown in Eq. (3), similarly, when the output field is connected and input into the next ring resonators. In order to retrieve the signals from the chaotic noise, we propose to use the add/drop device with the appropriate parameters. The optical outputs of a ring resonator add/drop filter are given by Eq. (4) and Eq. (5) [35]

$$\left|\frac{E_t}{E_{in}}\right|^2 = \frac{(1-\kappa_1) - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}L}\cos(k_n L) + (1-\kappa_2)e^{-\alpha L}}{1 + (1-\kappa_1)(1-\kappa_2)e^{-\alpha L} - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}L}\cos(k_n L)} \tag{4}$$

and

$$\left|\frac{E_d}{E_{in}}\right|^2 = \frac{\kappa_1\kappa_2 e^{-\frac{\alpha}{2}L}}{1 + (1-\kappa_1)(1-\kappa_2)e^{-\alpha L} - 2\sqrt{1-\kappa_1}\cdot\sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}L}\cos(k_n L)} \tag{5}$$

$E_t$ and $E_d$ represent the optical fields of the through port and drop ports, respectively. $\beta = kn_{\text{eff}}$ is the propagation constant, $n_{\text{eff}}$ is the effective refractive index of the waveguide, and the circumference of the ring is $L = 2\pi R$, with $R$ as the radius of the ring. New parameters are introduced for simplification with $\phi = \beta L$ as the phase constant. By using the specific parameters of the add/drop device, the chaotic noise cancellation can be obtained and the required signals can be retrieved by the specific users. $\kappa_1$ and $\kappa_2$ are the coupling coefficients of the add/drop filters, $k_n = 2\pi/\lambda$ is the wave propagation number in a vacuum, and the waveguide (ring resonator) loss is $\alpha = 0.5$ dBmm$^{-1}$ [36]. The fractional coupler intensity loss is $\gamma =$

0.1. In the case of the add/drop device, the nonlinear refractive index is neglected [37]. High capacity of optical pulses can be obtained when the full width at half maximum (FWHM) of these pulses are very small, where the amplification is performed inside the micro or Nano-ring system [38].

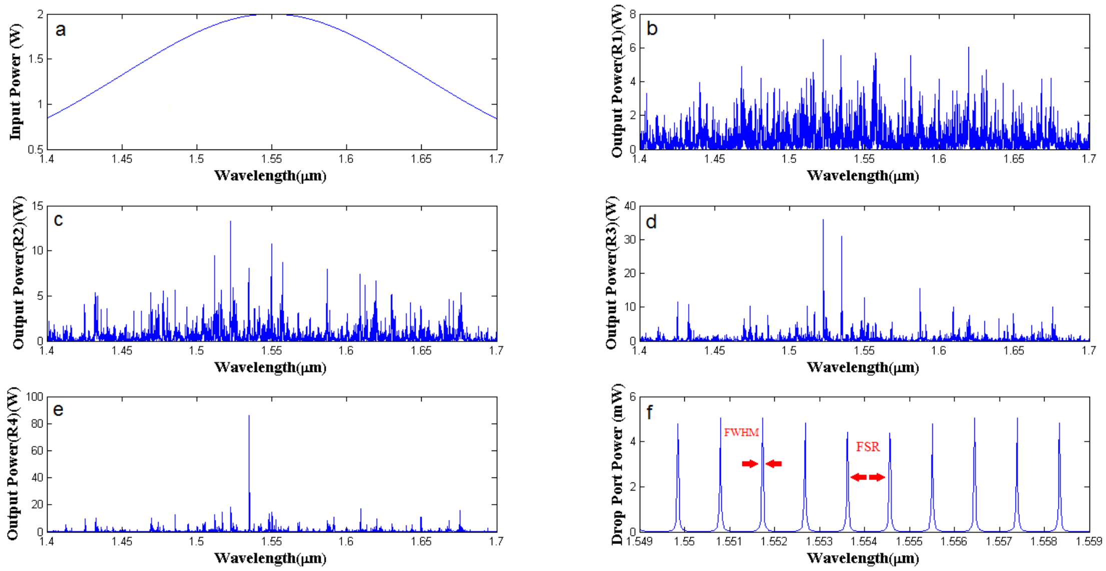


*Fig. 3. Results of the multi-soliton pulse generation, (a): input bright soliton, (b): large bandwidth signals, (c-e): soliton trapping (f): bright multi-soliton with FSR of 940 pm, and FWHM of 26 pm.*

## 3. Results and discussion

From Fig. 1, the input bright soliton pulse with center wavelength of 1550 nm and peak power of 2W is inputted to the system. The ring radii are $R_1$= 50 µm, $R_2$= 10 µm, $R_3$= 1 µm, $R_2$= .5 µm and $R_5$ = 70 µm. The fixed parameters are selected to $\lambda_0$ = 1.55 µm, $n_0$ = 3.34 (InGaAsP/InP), $A_{eff}$ = 0.25 µm$^2$, $\alpha$ = 0.5 dBmm$^{-1}$, and $\gamma$ = 0.1. The coupling coefficients range from 0.1 to 0.96, where the nonlinear refractive index is $n_2 = 2.2 \times 10^{-17}$ m$^2$/W and the wave guided loss used is 0.5 dBmm$^{-1}$. Optical signals are sliced into smaller signals broadening over the band as shown in Fig. 3(b). Therefore, a large bandwidth signal is formed within the first ring device, where a compress bandwidth with smaller group velocity is attained inside the ring $R_2$, $R_3$ and $R_4$, such as filtering signals. Afroozeh et al. [39] have shown how to determine soliton FWHM for soliton trapping. Localized soliton pulses are formed within the add/drop filter system, where resonant condition is performed, given in Fig. 3(f). As can be seen from Fig.3, input pulse after circulating inside the rings is amplified. In fact, the soliton pulse is generated by the forth ring in the system and then when the soliton passes the add/drop filter, multi-soliton pulses are generated.

The output of the dropt port is shown in Fig. 3 (f) which is bright soliton and the output of the throughput port of add/drop is dark soliton. Therefore, by using suitable add/drop filter system, powerful bright and dark soliton can be generated. Amplification of optical soliton is an advantage for long transmission links. The power distribution of the output pulses can be executed via the add/drop filter with radius of $R_5$. The multi soliton pulses with FSR and FHWM of 940 pm, and 26 pm are simulated.

An optical soliton communication has been realized as a good candidate for long distance communication. Therefore, increasing soliton wavelengths is recommended, where the security aim can be obtained by using the dark soliton signals. Generated multi soliton pulses can be transmitted into the OWC systems. Increasing communication capacity is provided by increasing soliton pulses ($\lambda_i$), which can be performed by generating bright and dark optical soliton pulses. Furthermore, the communication security is formed by using the dark soliton. Therefore, the high capacity and secured signals can be transmitted and retrieved via quantum codes. Here the quantum codes can be generated by using of dark and bright optical solitons.

Generated dark and bright soliton pulses can be converted to digital codes of “0” and “1” by using analog to digital electronic convertor system. This system is known as optical binary to decimal convertor system which is applicable to generate digital codes. Therefore, in operation, the large bandwidth within the MRR can be generated by using an optical soliton input into the device. The localized soliton pulse is generated, whereas the required signals, included specific wavelengths, can perform the secure communication network. The security code can be formed by using the spatial soliton pulses.

The generation of logic codes of “0” and “1” can be easily done by using series of beam splitters (B.S) connected to the proposed binary to decimal convertor system by [25].

As shown in Fig. 4, a highly secured OWC consists of two different channels; quantum channel and a classical channel. OWC is chosen as the classical channel. The quantum channel is the line of sight optical wireless path which can apply the proposed system to transmit polarization photons. First of all, the quantum channel determines the key used for the data encryption and decryption using quantum cryptography. After the quantum handshake which was discussed in detail in section 2, OWC system will either refuse or confirm the data communication via the OWC channel. As can be seen in Fig. 4, the applied OWC system as the OWC channel can be an indoor [40] or outdoor [41] OWC system . An outdoor OWC system is mostly utilized for bridging two different networks. While, an indoor optical wireless can be used to connect PCs, laptops, shopping areas, manufacturing floors and so on.

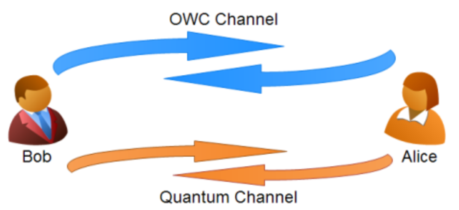


*Fig. 4. Block diagram of a highly secure OWC network.*

On the other hand, *Balsells et al* proposed solitonic pulse shape for OWC for the first time and they mathematically analyzed a solitonic pulse shape for an OWC system. Their results confirm the significant superiority of the solitonic pulse shape for atmospheric an OWC links. However they stated that solitonic pulse generation is more complicated than generating other pulses and new techniques are needed to generate solitonic pulse shape appropriate for OWC systems [42]. The obtained results in this research (as shown in Fig. 3 (e)) can be used for OWC system as well. In fact, the proposed system can be integrated to the existing OWC transmitter. It can generate solitonic pulses, which show better performance compared to other pulse shapes applied in OWC systems.

## 4. Conclusions

We proposed an interesting concept of the digital codes generation, where the system of micro ring resonator was used to generate high capacity of multi optical bright and dark soliton, connected to an analog to digital convertor system. A chaotic signal generation using a soliton pulse in the nonlinear MRRs was presented. Optical communication capacity can be increased by the multi soliton pulses generation, where more soliton channels can be generated by using the MRR system. The required channels were obtained by filtering the large bandwidth signals using an add/drop filter system. The advantage of the system is that the clear signal can be retrieved by the specific add/drop filter. Generated results can be applied for both the QKD and OWC systems. For realizing the quantum handshake the discussed protocol can be applied.

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