

Chapter 2

MRR Systems and Soliton Communication

Abstract The nonlinear Schrödinger equation (NLSE) is an appropriate equation for describing the propagation of light in optical fibers. The optical solitons are very stable against perturbations, where it is property of a fundamental soliton makes it an ideal candidate for optical communications. To have the secured communication, the performance of resonators should be considered in terms of resonance width, the free spectral range, the finesse, and the quality factor. When an optical soliton pulse input into the nonlinear microring resonator (MRR), the large optical bandwidth of the output signals can be generated, where the nonlinear behavior of self-phase modulation (SPM) keeps the large output power. High capacity of optical pulses can be obtained if the full width at half maximum (FWHM) of these pulses are very small, thus the intensity build up can be performed inside the micro and nanoring systems.

Keyword Nonlinear Schrödinger equation (NLSE) • Optical fibers • Microring resonators (MRRs) • Soliton communication • Self-phase modulation (SPM)

2.1 Evaluation of Soliton

The nonlinear Schrödinger equation (NLSE) is an appropriate equation for describing the propagation of light in optical fibers using normalization parameter such as: the normalized time T_0 , the dispersion length L_D and peak power of the pulse P_0 the nonlinear Schrödinger equation in the terms of normalized coordinates can be written as [1]:

$$i\left(\frac{\partial u}{\partial z}\right) - \frac{5}{2}\left(\frac{\partial^2 u}{\partial t^2}\right) + N^2|u|^2u + i\left(\frac{\alpha}{2}\right)u = 0 \quad (2.1)$$

where $u(z, t)$ is pulse envelope function, z is propagation distance along the fiber, N is an integer designating the order of soliton and α is the coefficient of energy gain per unit length, and with negative value it represents energy loss. Here, s is -1 for

Fig. 2.1 Evolution of soliton in normal dispersion regime

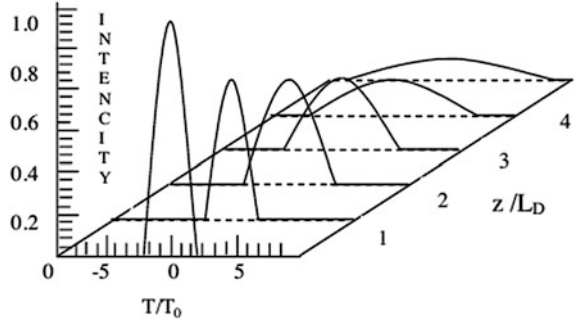
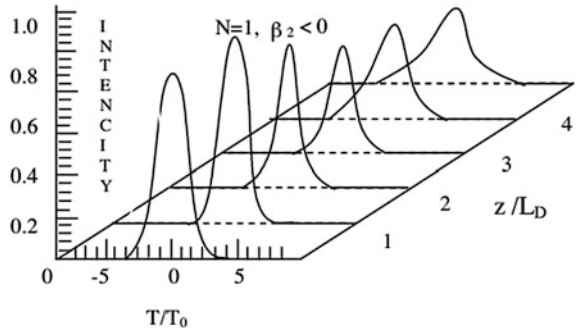


Fig. 2.2 Evolution of soliton in anomalous dispersion regime



negative β_2 (anomalous GVD-Bright soliton) and +1 for positive β_2 (normal GVD-Dark soliton) as shown in Figs. 2.1 and 2.2 [2],

$$N_2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|^2} \quad (2.2)$$

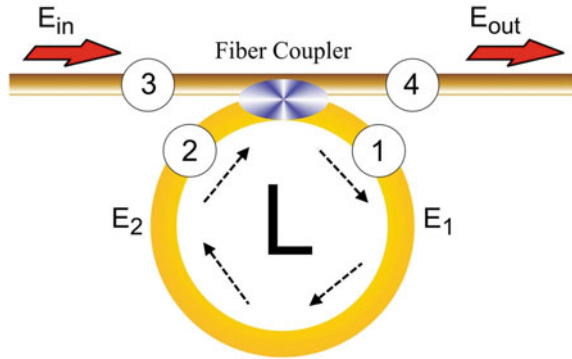
with nonlinear parameter γ and nonlinear length L_{NL} .

It is apparent that SPM dominates for $N > 1$ while for $N < 1$ dispersion effects dominates. For $N \approx 1$ both SPM and GVD cooperate in such a way that the SPM-induced chirp is just right to cancel the GVD induced broadening of the pulse. The optical pulse would then propagate undistorted in the form of soliton. By integrating the NLS, the solution for the fundamental soliton can be written as [3, 4]

$$u(z, t) = \text{sech}(t) \exp(iz/2) \quad (2.3)$$

where, $\text{sech}(t)$ is hyperbolic scent function. Since the phase term $\exp(iz/2)$ has no influence on the shape of the pulse, the soliton is independent of z and hence is non dispersive in time domain. It is property of a fundamental soliton makes it an ideal candidate for optical communications. Optical solitons are very stable against perturbations [5]; therefore they can be created even when the pulse shape and peak

Fig. 2.3 Schematic diagram for a ring resonator coupled to a single waveguide



power deviates from ideal conditions (values corresponding to $N = 1$). Soliton can be used for Secured Communication. To have the secured communication, the performance of resonators should be considered in terms of resonance width, the free spectral range, the finesse, and the quality factor. A fiber optic ring resonator consists of a waveguide in a closed loop which is coupled to one or more input/output (or bus) waveguides. A simple MRR is shown in Fig. 2.3.

2.2 MRR Used to Generate Chaotic Signals

Ring resonator provides traveling wave procedure, unlike the standing wave characteristic of Fabry-Perot resonators (F-P) [6–8]. Ring resonator can be considered as an interferometer device, which resonates for light whose phase change is an integer multiple of 2π after each trip around the ring. Part of light that does not contribute this resonant condition will be transmitted through the bus waveguide. Signal loss occurs when light is transmitted through the fiber, especially over long distances such as undersea cables. The expression for the resonant wavelengths of the ring is very similar to that of the F-P and is given by

$$\lambda_r = \frac{2\pi R n_{eff}}{m} \quad (2.4)$$

where, R is the ring radius constructed with circular waveguide and m is an integer. In this situation the device will act as a phase filter where all wavelengths are transmitted and the resonant wavelengths, having also traversed the ring, acquires a phase change. To capture or separate the resonant wavelengths from the rest, an additional waveguide as an output bus, can be positioned on the opposite side of the ring. In this case the ring resonator is known as an add/drop filter system [9, 10]. The key performance parameters of the ring resonator include the free spectral

range (FSR), the extinction ratio (ER), and the finesse [11]. The expression for the FSR of a ring resonator is given by

$$\Delta\lambda = \frac{\lambda_r^2}{2\pi R n_g} \quad (2.5)$$

The nonlinearity of the fiber ring is of the Kerr-type, wherein the nonlinear refractive index is given by [12, 13]

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}} \right) P, \quad (2.6)$$

where n_0 and n_2 are the linear and nonlinear refractive indices, while I and P are the optical intensity and optical field power, respectively. Here, the fiber coupler is considered as a point device and is reciprocal. The linear and nonlinear phase shifts of the ring resonator can be expressed by $\phi_0 = kLn_0$ and $\phi_{NL} = kLn_2|E_1|^2$, where $k = 2\pi/\lambda$ is a wave number, and $L = 2\pi R$ is the circumference of the ring resonator, where R is the radius of the ring resonator. Mathematically, the subsequence equations of the round-trip within the system is given by [14, 15].

$$E_{n+1} = j\sqrt{(1-\gamma)\kappa}E_{in} + \sqrt{(1-\gamma)(1-\kappa)}xE_n \exp(-j(\phi_0 + \phi_{NL})) \quad (2.7)$$

Here, the subscript n denotes the number of round-trips inside the system. This equation has to be satisfied with boundary conditions appropriate for ring. The transmission around the single ring resonator is represented by

$$z^{-1} = \exp(-\alpha L/2 - jk_n L) \quad (2.8)$$

where k_n is the propagation constant and $\alpha L/2$ is the ring loss (round-trip loss), which includes propagation loss, losses resulting from transitions in the curvature, and bending losses. The value of α (unit length^{-1}) depends on the properties of the material and the waveguide used, and it is referred to as the intensity attenuation coefficient, where L is the circumference of the ring resonator. In order to describe this, we consider a ring resonator connected to a single coupler that extracts light from the ring into the output waveguides [16, 17].

When an input electric field, E_i is coupled to the ring waveguide through an external bus waveguide, a positive feedback is induced and the field inside the ring resonator, E_2 starts to build up. The feedback mechanism will be induced by the ring waveguide [18], therefore does not need any further requirements such as Bragg gratings, mirrors, or distributed feedback waveguides with difficult fabrication process. Due to on-resonant certain wavelength of the input signals inside the

ring waveguide, frequency selectivity is obtained. The inserted and transmitted electric fields into the ring resonator are expressed by

$$E_1 = (1 - \gamma)^{\frac{1}{2}} \left[jE_i \sqrt{\kappa} + E_2 \sqrt{1 - \kappa} \right] \quad (2.9)$$

$$E_2 = E_1 \exp \left(-\frac{\alpha}{2} L - jk_n L \right) \quad (2.10)$$

where $k_n = \frac{2\pi n_{eff}}{\lambda}$ and γ denotes the intensity insertion loss coefficient of the directional coupler and n_{eff} is the effective refractive index. Therefore, the refractive index n quantifies the increase in the wave number (phase change per unit length) caused by the medium [19, 20]. Here, the effective refractive index n_{eff} has the similar meaning with light propagation in a waveguide, where it depends not only on the wavelength but also on the mode, in which the light propagates. The ratio of the output and input powers which is E_t/E_i can be calculated as [21, 22].

$$\frac{E_t}{E_i} = (1 - \gamma)^{\frac{1}{2}} \cdot \left[\frac{\sqrt{1 - \kappa} - (1 - \gamma)^{\frac{1}{2}} \cdot \exp \left(-\frac{\alpha}{2} L - jk_n L \right)}{1 - (1 - \gamma)^{\frac{1}{2}} \cdot \sqrt{1 - \kappa} \cdot \exp \left(-\frac{\alpha}{2} L - jk_n L \right)} \right] \quad (2.11)$$

In the following new parameter will be used for simplifying:

$$D = (1 - \gamma)^{\frac{1}{2}}, \quad x = D \cdot \exp \left(-\frac{\alpha}{2} \cdot L \right), \quad y = \sqrt{1 - \kappa}, \quad \phi = k_n L$$

Intensity relation to the output port is given by:

$$T = \frac{I_t}{I_i}(\varphi) = \frac{|E_t|^2}{|E_i|^2} = D^2 \cdot \left[1 - \frac{(1 - x^2) \cdot (1 - y^2)}{(1 - xy)^2 + 4xy \cdot \sin^2 \left(\frac{\phi}{2} \right)} \right] \quad (2.12)$$

Maximum and minimum transmission can be calculated when $\sin^2 \left(\frac{\phi}{2} \right)$ is “1” and “0” respectively. Therefore;

$$T_{\max} = D^2 \cdot \frac{(x + y)^2}{(1 + x \cdot y)^2} \quad (2.13)$$

$$T_{\min} = D^2 \cdot \frac{(x - y)^2}{(1 - x \cdot y)^2} \quad (2.14)$$

The minimum transmission, $T_{\min}$ occurs at the resonant point when the circumference of the ring L , is an integer number of the guide wavelength, which is given by

$$\begin{aligned} \phi &= k_n \cdot L = 2m\pi, m = \text{integer}, \\ m \cdot \lambda_m &= n \cdot L \end{aligned} \quad (2.15)$$

Here, m is the mode number, λ_m is the resonant mode wavelength. The on-off ratio for the single ring resonator is defined as the ratio of the on-resonance intensity to the off-resonance intensity which is maximum at $T_{\min} = 0$. Therefore $x = y$ and

$$\alpha = -\frac{1}{L} \times \ln\left(\frac{1 - \kappa}{D^2}\right) \quad (2.16)$$

This relationship given by Eq. (2.16) is also referred to as critical coupling, where the maximum on-off ratio $\frac{I_i}{I_o}(2m\pi) = 0$ can be obtained by varying the coupling coefficient (κ) or the intensity attenuation coefficient (α).

2.3 Resonance Bandwidth

Resonance bandwidth determines how fast optical data can be processed by a ring resonator. The resonator bandwidth is given by the full-width at half-maximum (FWHM or 3 dB bandwidth) $\delta\phi$ [$I/I_i(\phi) = 0.5$] and the finesse F of the resonator is given by:

$$\delta\phi = \frac{2(1 - xy)}{\sqrt{xy}} \quad (2.17)$$

To understand how the bandwidth of the resonator is affected by the coupling coefficient κ , we will consider critically coupled ring resonator [23, 24]. In such a case,

$$\delta\phi = \frac{2k}{\sqrt{1 - k}} \quad (2.18)$$

Therefore, the lower coupling coefficient, the smaller resonance bandwidth is obtained.

2.4 Finesse

The finesse of the resonator is defined as a ratio of the free spectral range and the full width at half maximum of the resonance. For the Fig. 2.2 using FSR (frequency spacing between two resonance) in terms of the is equal to 2π and thus the finesse is given by [25–27]

$$F = \frac{2\pi}{\delta\phi} = \frac{\pi\sqrt{xy}}{1 - xy} \quad (2.19)$$

2.5 Free Spectral Range (FSR)

The frequency spacing between two resonance peaks is called the free spectral range which can be calculated. The phase constant which corresponds to $\phi = 2(m + 1)\pi$ is defined as $\mathbb{Q}$. The phase constant corresponds to $\phi = 2(m + 1)\pi$ is defined as $\mathbb{Q} + \Delta\mathbb{Q}$. The frequency shift Δf and the wavelength shift $\Delta\lambda$ are related to the variation of the phase constant $\Delta\mathbb{Q}$ as $\Delta f = (c/2\pi) \cdot \Delta\mathbb{Q}$ and $\Delta\lambda = -(\lambda^2/2\pi) \cdot \Delta\mathbb{Q}$. The resonance spacing in terms of the frequency f and the wavelength λ are given by [28, 29]

$$\Delta f = \frac{c}{n_{gr} \cdot L} \quad (2.20)$$

and

$$\Delta\lambda = \left| -\frac{\lambda^2}{n_{gr} \cdot L} \right| \quad (2.21)$$

where n_{gr} is the group refractive index, which is defined as;

$$n_{gr} = n_{eff} - \lambda \frac{dn_{eff}}{d\lambda} \quad (2.22)$$

2.6 Quality Factor

Another value for characterization of ring resonator is the Q factor, The Q factor of the resonator is a measure of the sharpness of the resonance. In analogy with electrical circuit, the quality factor of an optical waveguide due it stored energy and the power lost per optical cycle. The Q factor is defined as [30–32]

$$Q = \omega \frac{\text{stored energy}}{\text{Power Loss}} \quad (2.23)$$

where ω is the frequency of the light coupled to the resonator. The Q factor of the resonator can be calculated from.

$$Q = \frac{f_0}{\delta f} = \frac{\lambda_0}{\delta \lambda} \quad (2.24)$$

The Q factor is the ratio of the absolute frequency f_0 or absolute wavelength λ_0 to the 3 dB bandwidth (δf or $\delta \lambda$). The shape and the bandwidth of the fiber response is determined by Q factor. The finesse and the Q factor are both important when one

is interested in both the FSR (Δf or $\Delta\lambda$) and the 3 dB bandwidth (δf or $\delta\lambda$). They are related by

$$\frac{Q}{F} = \frac{f_0}{\Delta f} = \frac{\lambda_0}{\Delta\lambda} \quad (2.25)$$

2.7 Chaotic Soliton Signal Generator

SMRR consists of a single coupler and a microring resonator. The nonlinearity of the fiber ring is of the Kerr-type wherein the nonlinear refractive index is given by [33, 34]

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{\text{eff}}} \right) P, \quad (2.26)$$

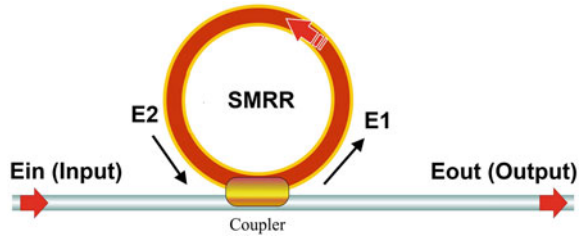
where n_0 and n_2 are the linear and nonlinear refractive indices, respectively. I and P are the optical intensity and optical field power, respectively. The effective mode core area of the fiber is A_{eff} . Schematic of SMRR is illustrated in Fig. 2.4.

Input light of monochromatic Gaussian laser beam is introduced into the system. The fiber has a nonlinear refractive index of n_2 and a linear absorption coefficient of α . The intensity coupling coefficient of the fiber coupler is κ , where γ is a coupling loss of the field amplitude. The fiber ring has resonant condition for the specific wavelength in linear case. Here the fiber coupler is considered as a point device and is reciprocal. The relation between the electric fields E_1 and E_2 , can be expressed using the nonlinear form as [35, 36]:

$$E_2 = E_1 x \exp\{-j(\phi_0 + \phi_{NL})\}, \quad (2.27)$$

where $\phi_0 = kLn_0$ and $\phi_{NL} = kLn_2|E_1|^2$ are expressed as linear and nonlinear phase shift, $k = 2\pi/\lambda$ is a wave number and L is the circumference of the ring resonator. $x = \exp(-\alpha L/2)$ represents a round trip loss for the input pulse propagating inside

Fig. 2.4 Nonlinear silicon microring resonator (SMRR)



the SMRR. Mathematically, the subsequence Equations of the round trip within the system is given by [37, 38]

$$E_{n+1} = j\sqrt{(1-\gamma)\kappa}E_{in} + \sqrt{(1-\gamma)(1-\kappa)}xE_n \exp(-j(\phi_0 + \phi_{NL})), \quad (2.28)$$

where the subscript “n” denotes the number of round trip inside the SMRR. This equation has to be satisfied with boundary conditions appropriate to SMRR. In order to definiteness, we consider a SMRR connected to a single coupler that extracts light from the ring into the output waveguides, as schematically shown in Fig. 2.4. Here, general case with external field, injected into the SMRR has been studied. To have more simplicity, we consider that the coupler device is ideal, where it simply splits the input fields without internal losses at the operating wavelength. We also ignore reflectivities at the coupler–waveguide interface, which is usually a good approximation due to the same structure of the output waveguides and the coupler. Regards to steady situation, the output field can be expressed as [39–41]:

$$E_{out} = \sqrt{1-\gamma} \cdot E_{in} \left[\sqrt{1-\kappa} - \frac{\sqrt{1-\gamma}\kappa x \exp(-j(\phi_0 + \phi_{NL}))}{1 - \sqrt{(1-\gamma)(1-\kappa)} x \exp(-j(\phi_0 + \phi_{NL}))} \right]. \quad (2.29)$$

Thus the output power of the light field is given by

$$P_{out} = |E_{out} \cdot E_{out}^*| \quad (2.30)$$

Equation (2.29) is mathematical relation used for characterizing of nonlinear effects of the ring resonator system. Therefore, nonlinear refractive index, coupling coefficient, and the radius of the SMRR system are variable parameters that cause the nonlinear behavior to be seen in different roundtrip and input power.

MRR’s input optical power can be in the form of an optical soliton pulse or a laser Gaussian beam expressed by Eqs. 2.31 and 2.32. The advantage of using optical soliton is that, it can be used to generate chaotic filter characteristics while propagating within the MRRs [42]. When the input pulse is brought into the MRRs system shown in Fig. 2.6.

$$E_{in} = A \tan h \left[\frac{T}{T_0} \right] \exp \left[\left(\frac{z}{2L_D} \right) - i\omega_0 t \right] \quad (2.31)$$

$$E_{in}(t) = E_0 \exp^{i\phi_0(t)} \quad (2.32)$$

A and z are optical field amplitude and propagation distance, respectively. T is the time of soliton pulse propagation, where $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse and, β_2 is the propagation constant. Therefore, a soliton pulse describes a pulse, which keeps its temporal or spatial width invariance while it propagates inside the MRRs system. Soliton peak intensity is expressed by

$(|\beta_2/\Gamma T_0^2|)$, where $\Gamma = n_2 \times k_0$, is the length scale over which dispersive or nonlinear effects causes the beam to be wider or narrower. For a temporal 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 γ and ϕ_{NL} are a coupling loss of the field amplitude and nonlinear phase shift. Here $\phi_0 = kL n_0$ is linear phase shifts. The refractive index (n) is given by [43, 44]:

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}} \right) P, \quad (2.33)$$

In which n_0 and n_2 are the linear and nonlinear refractive indices, respectively. I is the optical intensity and P is the optical power. For the micro ring and nano-ring resonators, the effective mode core area ranges from 0.50 to 0.1 μm^2 . MRRs proposed system is consisting of series of ring resonators. This system can be connected to a rotatable polarizer and a beam splitter, which is used to generate distinct optical soliton pulses and quantum codes with greeter free spectrum range (FSR), shown by Fig. 2.5.

When the input pulse introduced into the MRRs system as shown in Fig. 2.5, the resonant output is built up in the series of MRRs, where Eq. (2.34) can express the normalized output of the light field [45, 46].

$$\left| \frac{E_{out}(t)}{E_{in}(t)} \right|^2 = (1 - \gamma) \left[1 - \frac{(1 - (1 - \gamma)x^2)\kappa}{(1 - x\sqrt{1 - \gamma}\sqrt{1 - \kappa})^2 + 4x\sqrt{1 - \gamma}\sqrt{1 - \kappa}\sin^2(\frac{\phi_0 + \phi_{NL}}{2})} \right] \quad (2.34)$$

Equation (2.34) points that a ring resonator in this exacting case is comparable to a Fabry-Perot cavity which is consisting of an input and output mirror with a field reflectivity, $(1 - \kappa)$, and a fully reflecting mirror. Equation (2.34) shows the output power from each ring resonator, which is realized as input power for the next ring resonator. Simulation results of the mathematical equations provide applicable

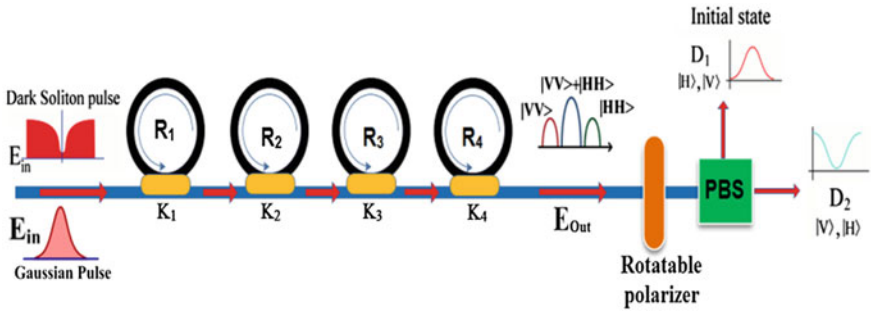


Fig. 2.5 System of a discrete pulses generation, where *PBS* polarizing Beam splitter, *Ds* detectors, *Rs* ring radii and κ_s coupling coefficients

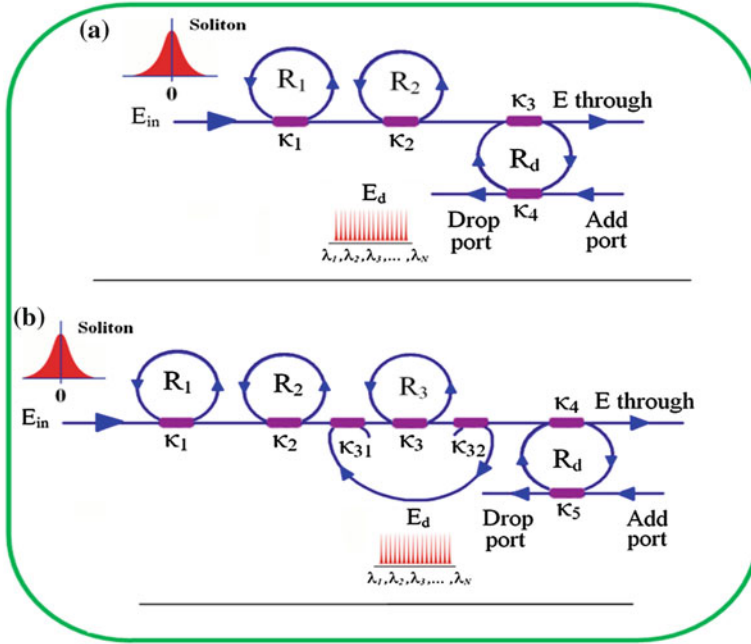


Fig. 2.6 Systems of multi optical soliton pulse generation **a** multi soliton generation, **b** multi soliton trapping and storage, R_s ring radii, κ_s coupling coefficients, κ_{31} and κ_{32} are coupling losses

optical soliton pulses to generate quantum codes, used for the secured networks communication.

When an optical soliton pulse input into the nonlinear MRR, the large optical bandwidth of the output signals can be generated, where the nonlinear behavior of self-phase modulation (SPM) keeps the large output power. Chaotic signals cancellation can be done using an optical add/drop filter system. The schematic of the two proposed systems are shown in Fig. 2.6.

The bright soliton pulse is introduced into the proposed system. The input optical field (E_{in}) of the optical bright soliton can be expressed as,

$$E_{in} = A \operatorname{sech} \left[\frac{T}{T_0} \right] \exp \left[\left(\frac{z}{2L_D} \right) - i\omega_0 t \right] \quad (2.35)$$

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, $T = t - \beta_1 \times z$, where β_1 and β_2 are the coefficients of the linear and second order terms of Taylor expansion of the propagation constant. $L_D = T_0^2 / |\beta_2|$ is the dispersion length of the soliton pulse [47, 48]. The frequency shift of the soliton is ω_0 . This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton. When a soliton peak intensity

($|\beta_2/\Gamma T_0^2|$) 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 ($L_{NL} = (1/\Gamma\phi_{NL})$, where $\Gamma = n_2 \times k_0$, is the length scale over which dispersive or nonlinear effects makes the beam becomes wider or narrower, hence $L_D = L_{NL}$. When light propagates within the nonlinear medium, the refractive index (n) of light within the medium is given by [49]

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}} \right) P, \quad (2.36)$$

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 range from 0.50 to 0.10 μm^2 . 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 [50, 51]

$$\left| \frac{E_{out}(t)}{E_{in}(t)} \right|^2 = (1 - \gamma) \left[1 - \frac{(1 - (1 - \gamma)x^2)\kappa}{(1 - x\sqrt{1 - \gamma}\sqrt{1 - \kappa})^2 + 4x\sqrt{1 - \gamma}\sqrt{1 - \kappa}\sin^2(\frac{\phi}{2})} \right] \quad (2.37)$$

In this investigation, the iterative method is introduced to obtain the results as shown in Eq. (2.37), 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.

$$\left| \frac{E_t}{E_{in}} \right|^2 = \frac{(1 - \kappa_1) - 2\sqrt{1 - \kappa_1} \cdot \sqrt{1 - \kappa_2} e^{-\frac{\alpha}{2}L} \cos(k_n L) + (1 - \kappa_2)e^{-\alpha L}}{1 + (1 - \kappa_1)(1 - \kappa_2)e^{-\alpha L} - 2\sqrt{1 - \kappa_1} \cdot \sqrt{1 - \kappa_2} e^{-\frac{\alpha}{2}L} \cos(k_n L)} \quad (2.38)$$

and

$$\left| \frac{E_d}{E_{in}} \right|^2 = \frac{\kappa_1 \kappa_2 e^{-\frac{\alpha}{2}L}}{1 + (1 - \kappa_1)(1 - \kappa_2)e^{-\alpha L} - 2\sqrt{1 - \kappa_1} \cdot \sqrt{1 - \kappa_2} e^{-\frac{\alpha}{2}L} \cos(k_n L)} \quad (2.39)$$

E_t and E_d represent the optical fields of the through port 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 $L = 2\pi R$, 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. κ_1 and κ_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

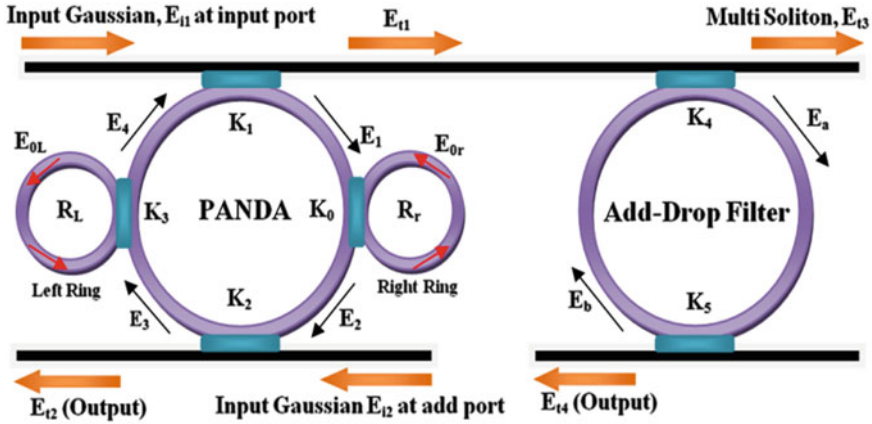


Fig. 2.7 Schematic diagram of a PANDA ring resonator connected to an add/drop filter system

resonator) loss is $\alpha = 0.5 \text{ dBmm}^{-1}$. The fractional coupler intensity loss is $\gamma = 0.1$. In the case of the add/drop device, the nonlinear refractive index is neglected. High capacity of optical pulses can be obtained when the full width at half maximum (FWHM) of these pulses are very small, where the intensity build up can be performed inside the micro or nanoring system. The proposed system consists of a PANDA ring resonator connected to an add/drop filter system, shown in Fig. 2.7.

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 by

$$n = n_0 + n_2 I = n_0 + \frac{n_2}{A_{eff}} P, \quad (2.40)$$

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. For an add/drop optical filter design, the effective mode core areas range from 0.50 to $0.10 \mu\text{m}^2$. The parameters were obtained by using practical parameters of used material (InGaAsP/InP) [52, 53]. Input optical fields of Gaussian pulses at the input and add ports of the system are given in Eq. (2.41).

$$E_{i1}(t) = E_{i2}(t) = E_{i0} \exp \left[\left(\frac{z}{2L_D} \right) - i\omega_0 t \right], \quad (2.41)$$

E_i 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 . 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. For the PANDA ring resonator, the output signals inside the system are given as follows:

$$E_1 = \sqrt{1 - \gamma_1} \left(\sqrt{1 - \kappa_1} E_4 + j\sqrt{\kappa_1} E_{i1} \right) \quad (2.42)$$

$$E_2 = E_0 E_1 e^{-\frac{\alpha L}{2} - jk_n \frac{L}{2}}, \quad (2.43)$$

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 [54, 55]:

$$E_0 = E_1 \frac{\sqrt{(1 - \gamma)(1 - \kappa_0)} - (1 - \gamma)e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}{1 - \sqrt{1 - \gamma}\sqrt{1 - \kappa_0}e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}, \quad (2.44)$$

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:

$$E_3 = \sqrt{1 - \gamma_2} \left[\sqrt{1 - \kappa_2} E_2 + j\sqrt{\kappa_2} E_{i2} \right], \quad (2.45)$$

$$E_4 = E_{0L} E_3 e^{-\frac{\alpha L}{2} - jk_n \frac{L}{2}}, \quad (2.46)$$

where,

$$E_{0L} = E_3 \frac{\sqrt{(1 - \gamma)(1 - \kappa_3)} - (1 - \gamma)e^{-\frac{\alpha}{2}L_2 - jk_n L_2}}{1 - \sqrt{1 - \gamma}\sqrt{1 - \kappa_3}e^{-\frac{\alpha}{2}L_2 - jk_n L_2}}, \quad (2.47)$$

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 [56–58]

$$E_{t1} = A E_{i1} - B E_{i2} e^{-\frac{\alpha L}{2} - jk_n \frac{L}{2}} \left[\frac{C E_{i1} G^2 + D E_{i2} G^3}{1 - F G^2} \right], \quad (2.48)$$

$$E_{t2} = x_2 y_2 E_{i2} \left[\frac{A \sqrt{\kappa_1 \kappa_2} E_0 E_{i1} G + \frac{D}{x_1 \sqrt{\kappa_1} E_{0L}} E_{i2} G^2}{1 - F G^2} \right], \quad (2.49)$$

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

Output powers from the add/drop filter system are given by Eqs. (2.50) and (2.51), where E_{t3} and E_{t4} are the electric field outputs of the through and drop ports of the system respectively.

$$\frac{I_{t3}}{I_{t1}} = \left| \frac{E_{t3}}{E_{t1}} \right|^2 = \frac{1 - \kappa_4 - 2\sqrt{1 - \kappa_4}\sqrt{1 - \kappa_5}e^{\frac{\alpha}{2}L_{ad}} \cos(k_n L_{ad}) + (1 - \kappa_5)e^{-\alpha L_{ad}}}{1 + (1 - \kappa_4)(1 - \kappa_5)e^{-\alpha L_{ad}} - 2\sqrt{1 - \kappa_4}\sqrt{1 - \kappa_5}e^{\frac{\alpha}{2}L_{ad}} \cos(k_n L_{ad})} \quad (2.50)$$

$$\frac{I_{t4}}{I_{t1}} = \left| \frac{E_{t4}}{E_{t1}} \right|^2 = \frac{\kappa_4 \cdot \kappa_5 e^{\frac{\alpha}{2}L_{ad}}}{1 + (1 - \kappa_4)(1 - \kappa_5)e^{-\alpha L_{ad}} - 2\sqrt{1 - \kappa_4}\sqrt{1 - \kappa_5}e^{\frac{\alpha}{2}L_{ad}} \cos(k_n L_{ad})} \quad (2.51)$$

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.

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