

Chapter 2

Mathematics of Soliton Transmission in Optical Fiber

Abstract Ring resonators are suitable for many applications in micro and nano optical communication. Optical soliton is a self-reinforcing solitary wave that maintains its shape while it travels at constant speed. Optical solitons are seen by a cancellation of nonlinear and dispersive effects in the medium which can be a fiber optic. In a Kerr effect medium such as fiber optics, high intensity of light causes a phase delay having similar temporal shape as the intensity. This nonlinear phenomenon occurs for a beam called self-phase modulation (SPM), which is generated by its intensity. Optical Chaos occurs in many nonlinear optical systems. One of the most common examples is a ring resonator. Chaotic behavior has been considered as a nonlinear property in physics, electronics, and communication. When a high-intensity short pulse is coupled to optical fiber, the instantaneous phase of optical pulse rapidly changes through the optical Kerr effect. The SPM and cross-phase modulation (CPM) effects change the phase of the pulse as a function of its intensity. Here, we derive the soliton equations based on solving the nonlinear Schrodinger and Maxwell equations. The main performance characteristics of ring resonators are transmittance, free spectral range, finesse, Q-factor, and group delay, which have been demonstrated.

Keywords Ring Resonators • Solitary Waves • Wavelength Division Multiplexing (WDM) • Self-phase Modulation (SPM) • Cross-Phase Modulation (CPM) • Bifurcation • Chaos • Dispersion • Diffraction • Nonlinear Schrodinger Equation • Maxwell Equation • Add/Drop Ring Resonator • PANDA Ring Resonator

2.1 Ring Resonators

The ring resonators are important devices in nanotechnology which are suitable for many applications in micro and nano optical communication. The nonlinear behaviors of light in a micro and nanoring resonator have been investigated and used for communication security. Moreover, the field buildup inside the ring cavity can be used for all optical signal processing functions based on enhanced nonlinear effects. Here the working principles of optical soliton propagating inside ring resonators are used. The novel concepts of ring resonator devices are given in this chapter.

2.2 Solitary Waves

Optical soliton is a self-reinforcing solitary wave that maintains its shape while it travels at constant speed [1, 2]. Optical solitons are seen by a cancellation of non-linear and dispersive effects in the medium which can be a fiber optic. Therefore, an optical soliton is a pulse that travels without distortion due to dispersion or other effects. The subject of solitary waves is therefore an important development in the field of optical communications. When solitons pulses are located mutually far apart, each of them is approximately a traveling wave with constant shape and velocity. If two pulses of optical soliton are brought together, they gradually deform and finally merge into a single wave packet. This wave packet, however, can be split into two solitary waves with the same shape and velocity before the collision. Optical solitons are used in telecommunication via Wavelength Division Multiplexing (WDM).

2.3 Wavelength Division Multiplexing (WDM) Technique

Wavelength Division Multiplexing (WDM) is a technique in which simultaneous transmission of signals occurs at different optical wavelength. In some applications of this technique, several optical signals combine, transmit together, and will be separated again based on different arrival times. To handle this technique, optical signals from separating lasers can be combined together or a broadband optical signal from for example a light emitting diode spectrally be sliced into smaller pulses. The use of multiple channels allows increased overall data transmission capacities without increasing the data rates of the single channels, where the time slot per bit must be reduced. Even if the bandwidth of the data modulator is limited, this can be done by using a train of ultra-short pulses (rather than a continuous optical wave) as the input of the modulator [3].

When the transmitted signals reach the receivers, the channel are de-multiplexed by means of optical wavelength filters like Mach-Zehnder interferometers, Fabry-Perot resonators or arrayed-waveguide gratings. This technique has the main advantage that the available bandwidth of an optical fiber can be used very efficiently [4]. Therefore DWDM is a technology that employs the properties of refracted light to combine or separate optical signals regarding to their wavelengths within the optical spectrum. DWDM increases the efficiency of using existing fiber by providing multiple optical paths along a fiber. WDM is normally applied to an optical carrier depicted by its wavelength, whereas frequency-division multiplexing (FDM) is applied to a radio carrier. Since wavelength and frequency are connected together through a simple relationship, they describe the same concept.

There are many applications on micro resonators in both fundamental and applied research. One of the existing and emerging micro resonator applications is the wavelength-selective components for WDM systems. The microring and micro-disk resonators are flexible building blocks for very large scale integrated photonic circuits, as they are ultra compact (10^5 devices/cm²) and can carry out a wide range

of optical signal processing functions such as filtering, splitting and combining of light, switching of channels in the space domain, as well as multiplexing and demultiplexing of channels in the wavelength domain. Vernier filter tuning by combining microring resonators of different radii has also been successfully used to suppress non-synchronous resonances of different microrings and extend the resulting filter FSR [5]. Linear arrays of optical micro resonators evanescently coupled to each other can also be used for optical power transfer. This type of coupled-resonator optical waveguide (CROW) has recently been proposed [6] and then demonstrated and studied in a variety of material and geometrical configurations.

2.4 Nonlinear Effect as Self-Phase Modulation (SPM)

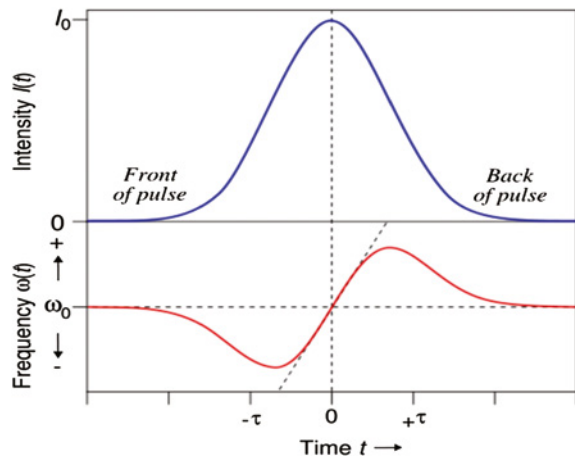
In a Kerr effect medium such as fiber optics, high intensity of light causes a phase delay having the similar temporal shape with the intensity. This nonlinear phenomenon occurs for a beam is called self phase modulation (SPM) which is generated by its intensity. This effect refers to nonlinear changes of the refractive index given by

$$\Delta n = n_2 I \quad (2.1)$$

where, n_2 is the nonlinear index and the optical intensity is shown by I . Therefore this phase shift is a temporal dependence effect, whereas the transverse dependence leads to the effect of self-focusing. In other words, the Kerr effect causes a time-dependent phase shift according to the time-dependent pulse intensity, where a temporally varying instantaneous frequency can be performed shown in Fig. 2.1.

For the initial up-chirped pulse, the SPM leads to spectral broadening, whereas a compression effect occurs for initially down-chirped pulse. In semiconductor lasers high signal intensity will result in reducing the carrier densities, which lead to a modification of the refractive index, where finally the phase will be changed.

Fig. 2.1 Spectral broadening of a pulse due to SPM [7]



Unlike the way that SPM affects the phase of the propagating pulse such phase changes in semiconductor lasers do not follow the temporal intensity profile. Therefore, this effect is declared for the pulse of picoseconds to a few nanoseconds. SPM is very efficient in mode-locked femtosecond lasers with the Kerr non-linearity effect medium. In materials with negligible or zero dispersion effects, the nonlinear phase shift is unstable, thus soliton pulse mode is employed which is a result of balancing SPM and dispersion [8, 9]. The intensity of a Gaussian ultra-short pulse at a time (t) can be expressed by

$$I(t) = I_0 \exp\left(-\frac{t^2}{\tau^2}\right), \quad (2.2)$$

where I_0 and τ are the peak intensity and pulse duration. In a Kerr type medium, the refractive index is given by

$$n(I) = n_0 + n_2 I, \quad (2.3)$$

where, n_0 and n_2 are the linear and nonlinear refractive indices. Regarding to the intensity profile of the propagating pulse, a time-varying refractive index is given by:

$$\frac{dn(I)}{dt} = n_2 \frac{dI}{dt} = n_2 \cdot I_0 \cdot \frac{-2t}{\tau^2} \cdot \exp\left(\frac{-t^2}{\tau^2}\right) \quad (2.4)$$

The phase of the pulse is defined by

$$\phi(t) = \omega_0 t - kx = \omega_0 t - \frac{2\pi}{\lambda_0} \cdot n(I) \cdot L \quad (2.5)$$

where ω_0 and λ_0 are the carrier frequency and wavelength of the pulse, and L is the distance in which the pulse propagates. Due to the change in refractive index, an instantaneous phase shift of the pulse occurs therefore:

$$\omega(t) = \frac{d\phi(t)}{dt} = \omega_0 - \frac{2\pi L}{\lambda_0} \cdot \frac{dn(I)}{dt} \quad (2.6)$$

Therefore

$$\omega(t) = \omega_0 + \frac{4\pi L n_2 I_0}{\lambda_0 \tau^2} \cdot t \cdot \exp\left(\frac{-t^2}{\tau^2}\right). \quad (2.7)$$

Thus, the leading edge shifts to lower frequencies where, trailing edge shifts to higher frequencies. In the center portion of the pulse (between $t = \pm\tau/2$), there is an approximately linear frequency shift (chirp) given by:

$$\omega(t) = \omega_0 + \alpha \cdot t \quad (2.8)$$

where α is:

$$\alpha = \left. \frac{d\omega}{dt} \right|_0 = \frac{4\pi L n_2 I_0}{\lambda_0 \tau^2} \quad (2.9)$$

In fact in any real medium the dispersion effects are existing and simultaneously will act on the pulse. In normal dispersion the front of the pulse moves faster than the back, broadening the pulse in time, while in anomalous dispersion, the pulse is compressed temporally and becomes shorter. This effect will result generation of ultra-short pulse. If the ultra-short pulse is of sufficient intensity, the spectral broadening process of SPM can balance with the temporal compression due to anomalous dispersion and reach an equilibrium state which is called an optical soliton [10, 11].

2.5 Nonlinear Effect as Cross-Phase Modulation (CPM)

Cross-Phase Modulation (CPM) is a nonlinear optical effect in which one wavelength of light affects the phase of another wavelength of light through the optical Kerr effect. In optical communication networks, CPM can be used as a technique for adding information to a light stream by modifying the phase of a coherent optical beam with another beam through interactions in an appropriate non-linear medium. Thus, it leads to an interaction of laser pulses in a medium in which the measurement of the optical intensity of one pulse can be performed by monitoring a phase change of the other one. This technique is applied in secured optical communication and can also be used for synchronizing two mode-locked lasers using the same gain medium, in which the pulses overlap and experience cross-phase modulation.

2.6 Developments of Bifurcation

The bifurcation is recognized as splitting of a main body of a optical pulse into two parts. A bifurcation occurs when a small change applied to the parameter values (bifurcation parameters) of a system causes a sudden qualitative or a topological change in its behavior. It represents the sudden appearance of a qualitatively different solution for a nonlinear system as some parameter is varied Bifurcations occur in both continuous and discrete systems.

2.7 Developments of Chaos

Optical Chaos occurs in many nonlinear optical systems. One of the most common examples is a ring resonator. Chaotic behavior has been considered as a nonlinear property in physics, electronics and communication [12, 13]. The chaotic communication has recently attracted great attention because of its potential application in secure communication, where it uses a noise-like broadband waveform as a carrier. The chaotic signals can be obtained after propagation of input pulse inside the nonlinear ring resonator [14–16].

Secure data transmission on the basis of chaotic signals is widely investigated in many research works [17, 18]. One of the potential approaches is data transmission using chaotic signals and sequences with modulated parameters. The major concern of this method is a reconstruction of the hidden information from received chaotic signals [19, 20]. Unique properties of chaotic signals serve a basis of application of new radical methods of coding and decoding an information component of chaotic carrying.

2.8 Focussing and Defocussing of Optical Beam

When a laser pulse such as a Gaussian beam propagates in a Kerr type medium along the z -direction, respect to increasing radius away from the center of the beam, the refractive index of the medium will change according to the intensity. Depending on the sign of the Kerr coefficient n_2 , with the positive sign, the refractive index decreases with the distance from the beam center and therefore the medium acts like a focusing lens, where the light beam will be compressed towards its center. This phenomena is called self-focusing because the focusing has caused the by light itself [21].

When there are no diffraction effect in the Kerr medium, the light will continue to focus cooperating with increasing in intensity until damage to the material results. If the light is strongly diffracted by the medium, the focusing is countered by the diffractive spreading effects, therefore balancing each other leading to self-trapping of the propagating pulse which is a simple explanation for the existence of the optical spatial soliton. If n_2 is negative, the refractive index increases with the distance from the beam center and the Kerr medium acts like a defocusing lens. This phenomenon is called self-defocusing, where under certain conditions dark spatial soliton pulse can be supported by the medium.

When a light beam in the transverse direction enters an optical Kerr media, the intensity dependent refractive index causes the pulses to be bent through the medium. Therefore, the beam will either experience a defocusing bending effect (if $n_2 < 0$) or a focusing bending effect (if $n_2 > 0$), causes the beam itself will create a self-induced waveguide in the medium.

The most important case is that when $n_2 > 0$. In this case, highly intense beams cause such a strong focusing which can be broken up again, due to strong diffraction effects for very narrow beams, or even due to material damage in the non-linear crystal. For some situations, however, there exist stationary solutions to the spatial light distribution that exactly balance between the self-focusing and the diffraction of the beam, where it is considered as a balance between two bending effects. The compression can be happened due to self-phase modulation (temporal analogue of self-focusing), where the expansion is due to dispersion. These forces balance and can create a soliton that is localized in the time dimension as well as in the direction of propagation.

2.9 Developments of Dispersion

Dispersion indicates the wavelength dependence of the refractive index in matter, $(dn/d\lambda)$, where n is the refractive index and λ is the wavelength. The spectral region shorter than the zero-dispersion wavelength λ_0 is recognized to a normal dispersion region. A spectral region longer than λ_0 is called an anomalous dispersion region, where the low frequency (or longer wavelength), causes smaller group velocity dispersion (GVD). This phenomenon occurs by interaction between the matter and light because an electromagnetic signal propagating within a physical medium is degraded due to having different propagation velocities of its various wave components such as frequency. Therefore material dispersion causes different wavelengths to travel at different speed because the refractive index of the fiber core varies with wavelength.

The part of light, which travels in the cladding of the fiber having different refractive indices, propagate through it at different speed to the core due to the waveguide dispersion. The Material and waveguide effects are combined to give an overall effect called “chromatic dispersion”, which is proportional to the square of the transmitted bit rate in an optical network. Chromatic dispersion is to emphasize its wavelength dependence nature, while group velocity dispersion (GVD) to emphasize the role of the group velocity. Any information-carrying signal included components from a range of wavelength. The group velocity of a signal is function of wavelength, therefore each spectral component travel independently and experiences a group delay, which ultimately results in pulse broadening [22]. Thus, overlapping of pulses will happen and after a certain amount of overlap, adjacent pulses cannot be identified at the receiver and error occurs.

Waveguide dispersion is only important in single mode fibers. It is caused by the fact that some light travels in the fiber cladding compared to most light travels in the fiber core. Since fiber cladding has lower refractive index than fiber core, light ray that travels in the cladding travels faster than that in the core. Waveguide dispersion is also a type of chromatic dispersion. While the difference in refractive indices of the single mode fiber core and cladding is minuscule, they can still become a factor over greater distances. It can also combine with material dispersion to create a nightmare in single mode chromatic dispersion.

2.10 Developments of Diffraction

In a single-mode fiber, the propagating light is confined to a circular area with a diameter of the order of micron size corresponds to the diameter of the fiber core. In the case of free space, this strong confinement would lead to a large divergence angle. In a fiber optic the spatially varying refractive index has a focusing effect which exactly balances diffraction effect for certain fiber modes. In a single-mode fiber, the waveguide effect is just strong enough to balance diffraction.

Thus, the diffraction becomes stronger for smaller modes, where the fibers with small mode areas require a larger numerical aperture (NA) for thoroughly guiding. The large mode area fibers require a small NA if the guidance of higher-order modes is to be kept. Therefore, single-mode fibers with large mode area are based on the balance of two weak effects which are diffraction and correspondingly guiding effect from the waveguide structure. Therefore, any additional effects, such as those from bending the fiber can have a strong impact in the form of bend losses.

2.11 Transmission Theory

If we introduce a pure monochromatic wave at frequency ω_0 into a length of optical fiber, the magnitude of the electric field vector associated with the wave would be given by

$$|E(r, t)| = J(x, y) \cos(\omega_0 t - \beta(\omega_0)z), \quad (2.10)$$

here the z is propagation direction and $J(x, y)$ is the distribution of the electric field along the fiber cross section and is determined by solving the wave equation. For the fundamental mode, the longitudinal component is of the form

$$E_z = 2\pi J_l(x, y) \exp(i\beta z), \quad (2.11)$$

Due to the cylindrical symmetry of the fiber, $J_l(x, y)$ is a function only of $\rho = \sqrt{x^2 + y^2}$ which is expressed in terms of Bessel functions. The transverse component of the fundamental mode is of the form

$$E_x(E_y) = 2\pi J_t(x, y) \exp(i\beta z), \quad (2.12)$$

where again $J_t(x, y)$ depends only on $\sqrt{x^2 + y^2}$. Thus, for each of the solutions corresponding to the fundamental mode, we can write

$$E(r, \omega) = 2\pi J(x, y) e^{i\beta(\omega)z} e(x, y), \quad (2.13)$$

where, $J(x, y) = \sqrt{J_l(x, y)^2 + J_t(x, y)^2}$ and the e is the unit vector along the direction of $E(r, \omega)$. In this equation, we have written β as a function of ω to emphasize this dependence. In general, the dependence of the J and e on ω can be neglected for pulses whose spectral width is much smaller than their center frequency. This condition is satisfied by pulses used in optical communication systems.

Consider a pulse whose shape, or envelope, is described by $A(z, t)$ and whose center frequency is ω_0 . Assume that the pulses have narrow spectral width. Therefore, most of the energy of the pulse is concentrated in a frequency band whose width is negligible compared to the center frequency ω_0 of the pulse. This assumption is usually satisfied for most pulses used in optical communication systems. Thus, the electric field vector associated with such a pulse is

$$|E(r, t)| = J(x, y) \Re \left[A(z, t) e^{-i(\omega_0 t - \beta_0 z)} \right], \quad (2.14)$$

where $\Re$ denotes the real part. Here β_0 is the value of the propagation constant β at the frequency ω_0 and $J(x, y)$ has the same significance as before. Considering the pulse envelope $A(z, t)$ to be complex valued and regarding to the phase shifts it can be written,

$$A(z, t) = |A(z, t)| \exp(i\varphi A(z, t)), \quad (2.15)$$

the phase of the pulse is given by

$$\varphi(t) = \omega_0 t - \beta_0 z - \varphi_A(z, t) \quad (2.16)$$

Here we have also assumed that the pulse is obtained by modulating a nearly monochromatic source at frequency ω_0 . We can derive the following partial differential equation for the evolution of the pulse shape $A(z, t)$ [22] as:

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} = 0, \quad (2.17)$$

where, $\beta_2 = \left. \frac{\partial^2 \beta}{\partial \omega^2} \right|_{\omega=\omega_0}$. If β is a linear function of ω , $\beta_2 = 0$, then arbitrary pulse shapes propagate without change in shape (and at velocity $1/\beta_1$). In other words, if the group velocity is independent of ω , n_0 broadening of the pulse occurs. Thus β_2 is the key parameter governing group velocity or chromatic dispersion. It is termed the group velocity dispersion parameter or, simply, GVD parameter.

2.12 Effects of Nonlinear Condition in Optical Fiber

When a high-intensity short pulse is coupled to optical fiber, the instantaneous phase of optical pulse rapidly changes through the optical Kerr effect. Self-phase modulation (SPM) and cross-phase modulation (CPM) effects change the phase of the pulse as a function of its intensity. For a monochromatic wave the refractive index becomes intensity dependent in the presence of SPM, where for non-monochromatic pulses with envelope A propagating in optical fiber, this relation must be modified so that the frequency and intensity-dependent refractive index is now given by

$$\hat{n}(\omega, E) = n(\omega) + \bar{n}|A|^2/A_{eff} \quad (2.18)$$

here, $n(\omega)$ is the linear refractive index, which is frequency dependent because of the chromatic dispersion, but also intensity independent, $\bar{n}$ is the nonlinear index coefficient and A_{eff} is the effective cross-sectional area of the fiber, typically $50 \mu\text{m}^2$. The expression for the frequency and intensity-dependent propagation constant is now given by

$$\hat{\beta}(\omega, E) = \beta(\omega) + \omega \cdot \bar{n}|A|^2/c \cdot A_{eff} \quad (2.19)$$

The unit for the nonlinear index coefficient is $\mu\text{m}^2/\text{W}$, therefore the intensity of the pulse $|A|^2$ must be expressed in watts (W). For more convenience, we assume that $\gamma = \omega \cdot \bar{n}/c \cdot A_e = 2\pi \cdot \bar{n}/\lambda \cdot A_e$, therefore, $\hat{\beta} = \beta + \gamma|A|^2$. Thus γ stands the same

relationship to the propagation constant β as the nonlinear index coefficient $\bar{n}$ does to the refractive index n . Hence, we call γ the nonlinear propagation. Considering the intensity dependence of the propagation constant, Eq. 2.91 must be modified to

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2} = i\gamma \cdot |A|^2 \cdot A \quad (2.20)$$

The term of $\frac{i}{2} \beta_2 \frac{\partial^2 A}{\partial t^2}$ incorporating the effect of chromatic dispersion, where, the term $i\gamma \cdot |A|^2 \cdot A$ incorporates the intensity-dependent phase shift. Here, the combined effects of chromatic dispersion and SPM on pulse propagation can be analyzed using this equation as the starting point. Regarding to new variable parameter such as $\tau = (t - \beta_1 z)/T_0$, $\xi = z/L_D = z/|\beta_2|/T_0^2$, $U = A/\sqrt{P_0}$, Eq. (2.90) can be written as

$$i \frac{\partial U}{\partial \xi} - \frac{\text{sgn}(\beta_2)}{2} \frac{\partial^2 U}{\partial \tau^2} + N^2 |U|^2 U = 0, \quad (2.21)$$

where

$$N^2 = \gamma P_0 L_D = \frac{\gamma P_0}{|\beta_2|/T_0^2}. \quad (2.22)$$

Equation (2.25) is called the nonlinear Schrödinger equation (NLSE). Here, the pulse propagates with velocity β_1 (in the absence of chromatic dispersion) and $(t - \beta_1 z)$ is the time axis in a reference frame moving with the pulse. The variable τ is the time in this reference frame but in units of T_0 , which is a measure of the pulse width. The variable ξ measures distance in units of the chromatic dispersion length which is defined as $L_D = T_0^2/|\beta_2|$. The quantity P_0 represents the peak power of the pulse, and thus U is the envelope of the pulse normalized to have unit peak power. The quantity of $1/\gamma P_0$ also has the dimensions of length what we call it the nonlinear length and can be shown by L_{NL} .

The nonlinear length serves as a convenient normalizing measure for the distance z in discussing nonlinear effects, just as the chromatic dispersion length does for the effects of chromatic dispersion. Thus for pulses propagating over distances $z \ll L_{NL}$, the effect of SPM on pulses can be neglected. Then we can write the quantity N introduced in the NLSE as $N^2 = L_D/L_{NL}$. If the compression of an optical pulse due to the SPM balances with and cancels the pulse broadening caused by the dispersion, the optical pulse propagates through the fiber while maintaining its original pulse shape. This is called an optical soliton.

2.13 Soliton Solving Based on Nonlinear Schrödinger Equation

The starting point for the analysis of temporal soliton is the time-dependent wave equation for the spatial envelopes of the electromagnetic fields in optical Kerr-media, here for simplicity taken for linearly polarized light in isotropic media,

$$\left(i\frac{\partial}{\partial z} + i\frac{1}{v_g}\frac{\partial}{\partial t} - \frac{\beta}{2}\frac{\partial^2}{\partial t^2}\right)\vec{A}_\omega(z, t) = -\frac{\omega n_2}{c}|\vec{A}_\omega(z, t)|^2\vec{A}_\omega(z, t), \quad (2.23)$$

where, as previously, $v_g = (\frac{dk}{d\omega})^{-1}$, is the linear group velocity, and the $\beta = \frac{d^2k}{d\omega^2}$ introduced for the second order linear dispersion of the medium. For the intensity-dependent refractive index $n = n_0 + n_2|E_\omega|^2$. Since we here are considering wave propagation in isotropic media, with linearly polarized light (for which no polarization state cross-talk occur), this equation is conveniently taken in a scalar form as

$$\left(i\frac{\partial}{\partial z} + i\frac{1}{v_g}\frac{\partial}{\partial t} - \frac{\beta}{2}\frac{\partial^2}{\partial t^2}\right)A_\omega(z, t) = -\frac{\omega n_2}{c}|A_\omega(z, t)|^2A_\omega(z, t), \quad (2.24)$$

where it consists of three terms that interact. The first two terms contain first order derivatives of the envelope, and these terms can be seen as the homogeneous part of a wave equation for the envelope, giving travelling wave solutions that depend on the other two terms, which rather act like source terms. The third term contains a second order derivative of the envelope, and this term is also linearly dependent on the dispersion β of the medium, that is to say, the change of the group velocity of the medium with respect to the angular frequency ω of the light. This term is generally responsible for smearing out a short pulse as it traverses a dispersive medium. Finally, the fourth term is a nonlinear source term, which depending on the sign of n_2 will concentrate higher frequency components either at the leading or trailing edge of the pulse [23, 24].

2.14 Ordinary Solitons Generation

The Nonlinear Schrödinger equation, or NLS can be written in another form of

$$-i\frac{\partial u}{\partial z} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2} + |u|^2u, \quad (2.25)$$

which is Maxwell's equations, adapted to field propagation in single-mode optical fiber. In a single-mode fiber, there is only one possible spatial behavior in the transverse dimensions x and y , so that we need to deal only with appropriate averages of the field quantities over those dimensions. Thus, the NLS equation involves only distance along the propagation direction, z , and time, t . The absolute magnitude of u represents the amplitude envelope of the pulse and the complex quantity $u(z, t)$ is proportional to the light field and the mean time of flight to location z so that the pulse always remains in view.

The first term on the right of the NLS equation, the one involving the second derivative with respect to time, describes the effects of chromatic dispersion. It is important to note that this linear term, when acting by itself, does nothing to change the frequency spectrum of the pulse. It serves only to broaden (or narrow) the pulse

in time. The second term on the right of this equation is the nonlinear term. Note that it is just the pulse's intensity envelope times u itself. It is based on the fact that the index of refraction, is dependent on the light intensity. It is important to note that this term, when acting by itself, does nothing to change the pulse shape in time. It serves only to broaden (or narrow) the pulse in the frequency domain. The major problem is the power loss in the fiber. It occurs primarily due to the absorption and scattering. When loss or gain is taken into account, the NLS equation becomes

$$-i \frac{\partial u}{\partial z} = \frac{1}{2} \frac{\partial^2 u}{\partial t^2} + |u|^2 u - i \frac{1}{2} \alpha u, \quad (2.26)$$

where a positive or negative value of α implies, respectively, gain or loss. The factor of one-half in the α term causes α itself to represent power (or energy) loss or gain per unit length. This equation is one of the few that support solitons. Solitons are a class of solitary wave pulses that can pass through one another with no scattering. This equation has a special solution of

$$u(z, t) = \sec h(t) \exp\left(\frac{iz}{2}\right), \quad (2.27)$$

which is known as the fundamental soliton. It has a shape similar to the more familiar Gaussian function, but it has a narrower peak and broader wings. Since the phase term is not dependent on t , the soliton is a completely nondispersive pulse; therefore, its shape does not change with z . This invariance with propagation occurs, for the soliton, since the dispersive and nonlinear terms of the NLS equation cancel each other's effects, causing only a phase shift of the whole pulse. Therefore, the dispersive term, which affects the pulse only in the time domain, can cancel the nonlinear term, which affects the pulse only in the frequency domain. Over very short distances both terms modify only the phase of the pulse [25, 26]. Regarding to the solution of the NLS equation in the regime of $\beta < 0$, a temporal soliton solution can be obtained when the pulse $u(z, t)$ has the initial shape of

$$u(0, t) = N \sec h(t), \quad (2.28)$$

where $N \geq 1$ is an integer number. Depending on the value of N , solitons of different order can be formed, where the fundamental soliton is given for $N = 1$. For higher values of N , the solitons are called "higher order solitons". When $N = 1$, therefore

$$u(z, t) = \sec h(t) \exp(iz/2) \quad (2.29)$$

This solution is called "bright solitons". Bright soliton is characterized as a localized intense peak above a continuous wave (CW) background. This type of optical soliton can be when the group velocity dispersion is negative ($\frac{d^2 k}{d\omega^2}$) or in other words, in the presence of anomalous dispersion. Since the CW plane-wave solution is unstable in self-focusing Kerr medium, bright solitons are a good candidate.

There are a lot of techniques are used to secure secret data or information. Communication security has become the popular technique in modern

communication requirement, where the idea of using a dark soliton to be a communication carrier where the recovery can be retrieved by the dark-bright soliton conversion [27–29].

Dark soliton can be used to perform the communication transmission for security, whereas the required information can be retrieved by the dark-bright soliton conversion. Dark soliton is distinguished by being made from a localized reduction of intensity compared to a more intense continuous wave background. The linear polarized dark soliton can be formed in all normal dispersion fiber laser mode-locked by the non-linear polarization rotation method and can be rather stable. Dark soliton is one of the soliton properties where the soliton amplitude vanished during the propagation in transmission line, thus the dark soliton detection is extremely hard. To date, several papers have investigated the dark soliton behavior [30, 31] and one interesting result is that the dark soliton can be converted to into bright soliton and finally detected. This means that the dark soliton penalty can be used as a communication carrier [32]. Another solution which gives another type of soliton called dark solitons, is expressed as

$$u(z, t) = [\eta \tan h(\eta(t - \kappa z)) - i\kappa] \cdot \exp(iu_0^2 z), \quad (2.30)$$

where u_0 is the normalized amplitude of the continuous-wave background, ϕ is an internal phase angle in the range of $0 \leq \phi \leq \pi/2$, $\eta = u_0 \cos \phi$ and $\kappa = u_0 \sin \phi$. A dark soliton can be realized as a black soliton (for $\phi = 0$), which drops down to zero intensity in the middle of the pulse, and the grey soliton (for $\phi = 0$), which do not drop down to zero. The black soliton, the solution for $\phi = 0$ takes this simpler form of

$$u(z, t) = u_0 \tan h(u_0 t) \exp(iu_0^2 z) \quad (2.31)$$

Another important difference between the bright and the dark soliton is that the dark soliton propagates through the internal phase angle $u_0 z$ with a velocity which depends on the amplitude, where the bright soliton propagates with the same velocity.

2.15 Soliton Solving Based on Maxwell Equation

Considering the Maxwell equations, following assumptions can be applied to these equations, leading to We start from the Maxwell equations with the following assumptions:

- Propagation of electric field in the propagation direction can be negligible compared to the transverse electric field.
- The monochromatic electro-magnetic wave is applied, where the frequency is ω .
- The transverse electric field is given by $E(x, y, z, t) = \psi(x, y, z) \exp[i(\omega t - kz)]$, where $\psi(x, y, z)$ changes much slower than $\exp[i(\omega t - kz)]$.
- The refractive index will be changed, where the change is smaller than one.

In the Kerr-type materials, the intensity dependent refractive index is followed by $n(I) = n_0 + n_2 I$. Considering the above assumptions on the Maxwell equation, the nonlinear Schrödinger equation can be derived as

$$\frac{\partial}{\partial z} \psi(x, y, z) = \left[\frac{i}{2k} \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) + \frac{ik \times n_2}{n_0} |\psi(x, y, z)|^2 \right] \psi(x, y, z), \quad (2.32)$$

where, z is the propagation direction, k is the wave number, and ψ is the amplitude of the electric field. Particular interest which is soliton equation can be derived and expressed by

$$\psi = \sqrt{\psi_0} \sec h \left[\frac{x}{W_0} \right] \exp \left[i \left(\frac{z}{4z_0} \right) \right], \quad (2.33)$$

where, $W_0 = \sqrt{\frac{2n_0}{n_2}} \times \frac{1}{k\psi_0}$ is the beam width and $z_0 = \frac{kW_0^2}{2}$ is the diffraction length. The intensity of this equation can be defined by ($I(x, y) = |\psi|^2$) which is independent of z direction. The beam width (W_0) is a function of the peak intensity, where it is wider for lower peak intensities. Therefore, these solutions lead to come out with wave equation which will maintain their shape and size invariant along the propagation direction. If the solution is represented only a state of stationary propagation then it can be considered as a soliton [33–35]. Most phenomenon or nonlinear effects in an optical fiber occur when short pulses with widths ranging from a few ns to a few fs are input into the system, where both dispersive and nonlinear effects contribute to determine the shape and spectrum of the propagating pulses. In 1995, Agrawal could solve the electric field wave equation and derive the governing equation for a light pulse propagating in an optical fiber. This equation is given by

$$\frac{\partial \psi}{\partial z} = \left(\frac{-i\beta_2}{2} \frac{\partial^2}{\partial T^2} + i\gamma |\psi|^2 \right) \psi \quad (2.34)$$

where ψ and β_2 are the amplitude of the electric field and second-order dispersion of the wave number. T and γ are the temporal profile with the same velocity with pulse group velocity ($T = t - z/v_g$) and nonlinearity coefficient of the medium respectively. Solution of this equation gives solitary waves that keep their profile unchanged when propagating. Considering a negative sign of β_2 and the pulse width of T_0 , the solitary solution can be obtained expressed by

$$\psi = \sqrt{\psi_0} \sec h \left[\frac{T}{T_0} \right] \exp \left[i \left(\frac{z}{2L_D} \right) \right] \quad (2.35)$$

where ψ_0 is the peak power, $L_D = T_0^2/|\beta_2|$ is the dispersion length of the pulse. This solution, which describes a soliton pulse, shows a pulse that keeps its temporal width invariant as it propagates and hence is called a temporal soliton. It should be taken into account that for any given pulse width, T_0 , the peak intensity can be expressed by ($\frac{|\beta_2|}{\gamma T_0^2}$) and it will make the pulse propagating as a solitary wave. The temporal power profile for this soliton is given by

$$I(t, z) = |\psi|^2 = \psi_0 \sec^2 h \left[\frac{t - z/v_g}{T_0} \right]. \quad (2.36)$$

For the fiber soliton, a balance should be achieved between the dispersion length $L_D = T_0^2/|\beta_2|$ and the nonlinear length $L_{NL} = 1/\gamma\psi_0$, which are the length scales

over which disperse or nonlinear effects make the beam become wider or narrower. For a soliton, there is balance between the two and hence $L_D = L_{NL}$, which leads to:

$$T_0^2 \psi_0 = \frac{|\beta_2|}{\gamma} = \text{const}, \quad (2.37)$$

which entails that variations in the power can be compensated by changes in the pulse width and vice versa. This property is responsible for the strength of this type of solitons. Optical excitation having similar parameters to the soliton parameters usually develops with propagation into a stable soliton. For the spatial soliton case for simplicity we will reduce the NLS equation based on the Maxwell assumption to only two dimensions (x, z) which gives

$$\frac{\partial \psi}{\partial z} = \left[\frac{-i}{2k} \left(\frac{\partial^2}{\partial x^2} - i \frac{k \times \Delta n_0}{n_0} \right) |\psi|^2 \right] \psi \quad (2.38)$$

Solution of this equation gives the

$$\psi = \sqrt{\psi_0} \sec h \left[\frac{x}{W_0} \right] \exp \left[i \left(\frac{z}{4z_0} \right) \right], \quad (2.39)$$

Therefore, this solution describes a beam profile which is uniform in y , bell-shaped in x , and propagating in z with stable shape. The intensity structure in x is equal to the mode of a graded-index waveguide with refractive index expressed by

$$n(x) = n_0 \left(1 + \frac{\sec^2 h(x/W_0)}{k^2 W_0^2} \right), \quad (2.40)$$

Thus, while it propagates, this beam will disintegrate in $\hat{y}$, and some spatial frequency will start to form in $\hat{y}$ due to modulation. This instability can be eliminated by applying the input beam into a slab waveguide made of Kerr nonlinear material.

In nonlinear optics subject, soliton can be classified to temporal or spatial, depending on whether the confinement of light occurs in time or space. Temporal soliton is introduced to optical pulse which maintain its shape, whereas spatial soliton represent self-guided beams that remain confined in the transverse directions orthogonal to the direction of propagation. A spatial soliton is formed when self-focusing of an optical beam balances its natural diffraction-induced spreading. In contrast, it is the self-phase modulation that counteracts the natural dispersion-induced broadening of an optical pulse and leads to the formation of a temporal soliton. Therefore, whether the soliton pulse is of temporal or spatial type, they evolve from a nonlinear change in the refractive index of an optical material induced by the light intensity. This phenomenon is known as optical Kerr effect and optical material that exhibit this property is known as a Kerr medium.

On the other hand, the effect of anomalous dispersion (with $\beta < 0$) and the effect of a nonlinear, intensity dependent refractive index (with $n_2 > 0$) are opposite of each other. The transmission bit rate in optical fibers is limited strongly by group velocity dispersion. It is because generated impulses have a non-zero

bandwidth and the medium they are propagating through has a refractive index that depends on frequency (or wavelength). When these two effects (dispersion and nonlinear effects) combined, for example considering pulse propagation in a medium, giving a pulse that can propagate without altering its shape. This is the basic principle of the temporal soliton.

2.16 System of Micro Ring Resonator

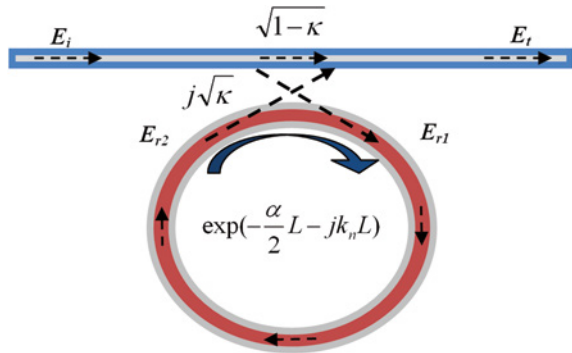
A fiber optic ring resonator consists of a waveguide in a closed loop which is coupled to one or more input/output (or bus) waveguides [36–38]. A simple microring resonator is shown in Fig. 2.2.

Ring resonator provides traveling wave procedure, unlike the standing wave characteristic of Fabry-Perot resonators (F-P). 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 [39–41]. 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

$$\lambda_r = \frac{2\pi R n_{eff}}{m} \quad (2.41)$$

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. The key performance parameters of the ring resonator include the FSR , the ER , and the finesse. The expression for the FSR of a ring resonator is given by

Fig. 2.2 Schematic diagram for a ring resonator coupled to a single waveguide



$$\Delta\lambda = \frac{\lambda_r^2}{2\pi R n_g} \quad (2.42)$$

The nonlinearity of the fiber ring is of the Kerr-type, wherein the nonlinear refractive index is given by [42–44]

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}}\right)P, \quad (2.43)$$

where n_0 and n_2 are the linear and nonlinear refractive indices [45, 46], while I and P are the optical intensity and optical field power, respectively [47, 48]. 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 [49–52]. Mathematically, the subsequence equations of the round-trip within the system is given by

$$E_{n+1} = j\sqrt{(1-\gamma)\kappa}E_{in} + \sqrt{(1-\gamma)(1-\kappa)}xE_n \exp(-j(\phi_0 + \phi_{NL})). \quad (2.44)$$

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

$$z^{-1} = \exp(-\alpha L/2 - jk_n L) \quad (2.45)$$

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 [53, 54]. 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 define this, we consider a ring resonator connected to a single coupler that extracts light from the ring into the output waveguides.

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_{r2} starts to build up. The feedback mechanism will be induced by the ring waveguide, 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 [55, 56]. The inserted and transmitted electric fields into the ring resonator are expressed by

$$E_{r1} = (1-\gamma)^{\frac{1}{2}} \left[jE_i\sqrt{\kappa} + E_{r2}\sqrt{1-\kappa} \right] \quad (2.46)$$

$$E_{r2} = E_{r1} \exp\left(-\frac{\alpha}{2}L - jk_n L\right) \quad (2.47)$$

where $k_n = \frac{2\pi \cdot n_{eff}}{\lambda}$ and γ denotes the intensity insertion loss coefficient of the directional coupler and n_{eff} is the effective refractive index [57, 58]. Therefore,

the refractive index n quantifies the increase in the wavenumber (phase change per unit length) caused by the medium. 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 [59–61]

$$\frac{E_t}{E_i} = (1 - \gamma)^{\frac{1}{2}} \cdot \left[\frac{\sqrt{1 - \kappa} - (1 - \gamma)^{\frac{1}{2}} \cdot \exp(-\frac{\alpha}{2}L - jk_n L)}{1 - (1 - \gamma)^{\frac{1}{2}} \cdot \sqrt{1 - \kappa} \cdot \exp(-\frac{\alpha}{2}L - jk_n L)} \right] \quad (2.48)$$

In the following new parameter will be used for simplifying [62, 63]:

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

Intensity relation to the output port is given by [64]:

$$T = \frac{I_t}{I_i}(\varphi) = \left| \frac{E_t}{E_i} \right|^2 = D^2 \cdot \left[1 - \frac{(1 - x^2) \cdot (1 - y^2)}{(1 - xy)^2 + 4xy \cdot \sin^2(\frac{\varphi}{2})} \right] \quad (2.49)$$

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

$$T_{\max} = D^2 \cdot \frac{(x + y)^2}{(1 + x \cdot y)^2} \quad (2.50)$$

$$T_{\min} = D^2 \cdot \frac{(x - y)^2}{(1 - x \cdot y)^2} \quad (2.51)$$

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

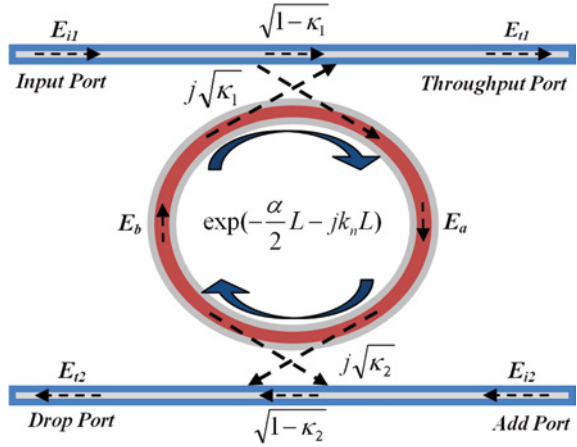
$$\begin{aligned} \phi &= k_n \cdot L = 2m\pi, \quad m = \text{integer}, \\ m \cdot \lambda_m &= n \cdot L \end{aligned} \quad (2.52)$$

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

$$\alpha = -\frac{1}{L} \times \ln\left(\frac{1 - \kappa}{D^2}\right) \quad (2.53)$$

This relationship given by Eq. (2.26) is also referred to as critical coupling, where the maximum on-off ratio $\frac{I_t}{I_i}(2m\pi) = 0$ can be obtained by varying the coupling coefficient (κ) or the intensity attenuation coefficient (α).

Fig. 2.3 Ring resonator with two adjacent waveguide



2.17 Ring Resonator as Add/Drop Filter

Recently, optical ring resonators (ORR) have numerous applications in single mode lasers, biosensors, optical switching, add/drop filters, tunable lasers, signal processing and dispersion compensators [65–67]. In any WDM system, optical filters are used for separating one optical channel from the combined signals. The basic ORR with two couplers is illustrated in Fig. 2.3. The main performance characteristics of these resonators are the transmittance, free spectral range, finesse, Q-factor, and the group delay, which have been demonstrated both theoretically and experimentally in many works. Structural design of a single ring resonator (SRR) add/drop filter system is shown in Fig. 2.3, which is constructed by 2×2 optical couplers.

For simplification, the intensity relation [68] does not take into account coupling losses ($D^2 = 1$).

$$E_a = E_{i1}j\sqrt{\kappa_1} + E_b\sqrt{1-\kappa_1}e^{-\frac{\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}} \quad (2.54)$$

$$E_b = E_a\sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}} \quad (2.55)$$

$$E_a = \frac{E_{i1}j\sqrt{\kappa_1}}{1 - \sqrt{1-\kappa_1}\sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}L-jk_nL}} \quad (2.56)$$

$$E_b = \frac{E_{i1}j\sqrt{\kappa_1}}{1 - \sqrt{1-\kappa_1}\sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}L-jk_nL}} \cdot \sqrt{1-\kappa_2}e^{-\frac{\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}} \quad (2.57)$$

$$E_{t1} = E_b e^{-\frac{\alpha}{2}\frac{L}{2}-jk_n\frac{L}{2}} j\sqrt{\kappa_1} + E_{i1}\sqrt{1-\kappa_1} \quad (2.58)$$

$$E_{t2} = E_a e^{\frac{-\alpha}{2} \frac{L}{2} - jk_n \frac{L}{2}} j \sqrt{\kappa_2} \quad \text{at } E_{i2} = 0 \quad (2.59)$$

$$\begin{aligned} \frac{E_{t1}}{E_{i1}} &= \frac{-\kappa_1 \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L - jk_n L} + \sqrt{1 - \kappa_1} - (1 - \kappa_1) \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L - jk_n L}}{1 - \sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L - jk_n L}} \\ &= \frac{-\sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L - jk_n L} + \sqrt{1 - \kappa_1}}{1 - \sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L - jk_n L}} \end{aligned} \quad (2.60)$$

$$\frac{E_{t2}}{E_{i1}} = \frac{-\sqrt{\kappa_1 \cdot \kappa_2} e^{\frac{-\alpha}{2} \frac{L}{2} - jk_n \frac{L}{2}}}{1 - \sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L - jk_n L}} \quad (2.61)$$

where κ_1 and κ_2 are the coupling coefficients, $L = 2\pi R$ and R is the radius of the add/drop filter device [69, 70]. The normalized outputs of the add/drop filter system are expressed as [71, 72]:

$$\frac{I_{t1}}{I_{i1}} = \left| \frac{E_{t1}}{E_{i1}} \right|^2 = \frac{1 - \kappa_1 - 2\sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L} \cos(k_n L) + (1 - \kappa_2) e^{-\alpha L}}{1 + (1 - \kappa_1)(1 - \kappa_2) e^{-\alpha L} - 2\sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L} \cos(k_n L)} \quad (2.62)$$

$$\frac{I_{t2}}{I_{i1}} = \left| \frac{E_{t2}}{E_{i1}} \right|^2 = \frac{\kappa_1 \cdot \kappa_2 e^{\frac{-\alpha}{2} L}}{1 + (1 - \kappa_1)(1 - \kappa_2) e^{-\alpha L} - 2\sqrt{1 - \kappa_1} \sqrt{1 - \kappa_2} e^{\frac{-\alpha}{2} L} \cos(k_n L)} \quad (2.63)$$

Using $y_1 = \sqrt{1 - \kappa_1}$ and $y_2 = \sqrt{1 - \kappa_2}$, the intensity relations are then given by:

$$\frac{I_{t1}}{I_{i1}}(\varphi) = \left| \frac{E_{t1}}{E_{i1}} \right|^2 = 1 - \frac{(1 - y_1^2) \cdot (1 - y_2^2 x^2)}{(1 - y_1 y_2 x)^2 + 4y_1 y_2 x \sin^2\left(\frac{\varphi}{2}\right)} \quad (2.64)$$

$$\frac{I_{t2}}{I_{i1}}(\varphi) = \left| \frac{E_{t2}}{E_{i1}} \right|^2 = \frac{(1 - y_1^2) \cdot (1 - y_2^2) \cdot x}{(1 - y_1 y_2 x)^2 + 4y_1 y_2 x \sin^2\left(\frac{\varphi}{2}\right)} \quad (2.65)$$

The full-width at half-maximum (FWHM) is given in this configuration by:

$$\delta\phi = 2 \frac{1 - y_1 y_2 x}{\sqrt{y_1 y_2 x}}, \quad (2.66)$$

where the finesse F is given by:

$$F = \frac{2\pi}{\delta\phi} = \frac{\pi \sqrt{y_1 y_2 x}}{1 - y_1 y_2 x} \quad (2.67)$$

The maximum and minimum transmission are calculated as follows. For the throughput port:

$$T_{\max} = \frac{(y_1 + y_2 x)^2}{(1 + y_1 y_2 x)^2} \quad (2.68)$$

$$T_{\min} = \frac{(y_1 - y_2 x)^2}{(1 - y_1 y_2 x)^2} \quad (2.69)$$

And for the drop port:

$$T_{\max} = \frac{(1 - y_1^2) \cdot (1 - y_2^2) \cdot x}{(1 - y_1 y_2 x)^2} \quad (2.70)$$

$$T_{\min} = \frac{(1 - y_1^2) \cdot (1 - y_2^2) \cdot x}{(1 + y_1 y_2 x)^2} \quad (2.71)$$

The on-off ratio of an add/drop filter system is given by:

$$\frac{T_{\max}(\text{throughput port})}{T_{\min}(\text{drop port})} = \frac{(y_1 + y_2 x)^2}{(1 - y_1^2) \cdot (1 - y_2^2) \cdot x} \quad (2.72)$$

The output intensity, I_{t1} at the throughput port will be zero at resonance ($k_n L = 2m\pi$) which indicates that the resonance wavelength is fully extracted by the resonator when $\kappa_1 = \kappa_2$ and $\alpha = 0$. The loss of signal power resulting from the insertion of a device in a transmission line for example an optical fiber is defined insertion loss and usually expressed in *dBs*. Therefore, it is a measure of attenuation. Attenuation can include loss due to the source and load impedances not matching, but is not included in insertion loss since this is a loss that was already present before the “insertion” was made. If the power transmitted to the load before insertion is P_T and the power received by the load after insertion is P_R , then the insertion loss in *dB* is given by,

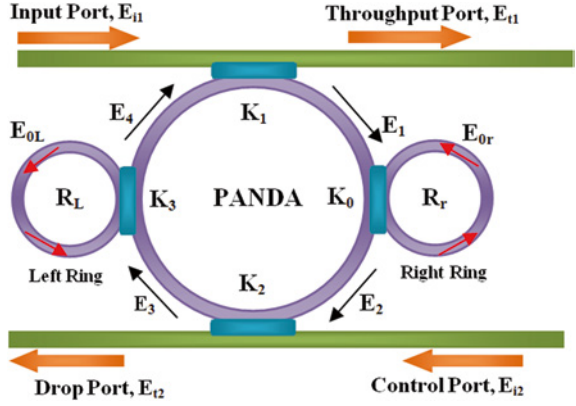
$$IL = 10 \log_{10} \frac{P_T}{P_R} \quad (2.73)$$

2.18 Ring Resonator as PANDA

This system consists of one add/drop interferometer system connected to two ring resonators in the left and right sides. This system represents a new technique of combination and integration of micro ring resonators in which it can be widely used to improve the secure communication and the high capacity of optical signal proceeding in network communications [73–75]. Here the derived equations of the system is introduced which show that how does the input pulse propagates inside the rings systems [76–78]. The proposed system is shown in Fig. 2.4.

The resonator output fields, E_{t1} and E_l consist of the transmitted and circulated components within the add/drop optical filter system, given by [79–81]

Fig. 2.4 Schematic of a PANDA ring resonator system



$$E_{t1} = \sqrt{1 - \gamma_1} \left[\sqrt{1 - \kappa_1} E_{i1} + j\sqrt{\kappa_1} E_4 \right], \quad (2.74)$$

$$E_1 = \sqrt{1 - \gamma_1} \left[\sqrt{1 - \kappa_1} E_4 + j\sqrt{\kappa_1} E_{i1} \right], \quad (2.75)$$

$$E_2 = E_{0r} E_1 e^{-\frac{\alpha}{2} \frac{L}{\lambda} - jk_n \frac{L}{\lambda}}, \quad (2.76)$$

where κ_1 is the intensity coupling coefficient, γ_1 is the fractional coupler intensity loss, α is the attenuation coefficient, $k_n = \frac{2\pi}{\lambda}$ is the wave propagation number, λ is the input wavelength light field, $L = 2\pi R_{ad}$ and R_{ad} is the radius of the add/drop system. For the second coupler of the add/drop system [82, 83],

$$E_{i2} = \sqrt{1 - \gamma_2} \left[\sqrt{1 - \kappa_2} E_{i2} + j\sqrt{\kappa_2} E_2 \right], \quad (2.77)$$

$$E_3 = \sqrt{1 - \gamma_2} \left[\sqrt{1 - \kappa_2} E_2 + j\sqrt{\kappa_2} E_{i2} \right], \quad (2.78)$$

$$E_4 = E_{0L} E_3 e^{-\frac{\alpha}{2} \frac{L}{\lambda} - jk_n \frac{L}{\lambda}}. \quad (2.79)$$

E_{0r} and E_{0L} are the light fields circulated components of the nanoring radii R_r and R_L are the coupled rings into the right and left sides of the add/drop optical filter system, respectively. Transmitted and circulated components of the light fields in the right nanoring, R_r are given by

$$E_2 = \sqrt{1 - \gamma} \left[\sqrt{1 - \kappa_0} E_1 + j\sqrt{\kappa_0} E_{r2} \right], \quad (2.80)$$

$$E_{r1} = \sqrt{1 - \gamma} \left[\sqrt{1 - \kappa_0} E_{r2} + j\sqrt{\kappa_0} E_1 \right], \quad (2.81)$$

$$E_{r2} = E_{r1} e^{-\frac{\alpha}{2} L_1 - jk_n L_1}. \quad (2.82)$$

or

$$E_{r1} = \frac{j\sqrt{1-\gamma}\sqrt{\kappa_0}E_1}{1 - \sqrt{1-\gamma}\sqrt{1-\kappa_0}e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}, \quad (2.83)$$

$$E_{r2} = \frac{j\sqrt{1-\gamma}\sqrt{\kappa_0}E_1 e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}{1 - \sqrt{1-\gamma}\sqrt{1-\kappa_0}e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}, \quad (2.84)$$

where $L_1 = 2\pi R_r$ and R_r is the radius of the right side nanoring. Thus, the output circulated light field, E_{0r} , for the right side nanoring is given by [84, 85]

$$E_{0r} = E_1 \frac{\sqrt{(1-\gamma)(1-\kappa_0)} - (1-\gamma)e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}{1 - \sqrt{1-\gamma}\sqrt{1-\kappa_0}e^{-\frac{\alpha}{2}L_1 - jk_n L_1}}. \quad (2.85)$$

Similarly, the output circulated light field, E_{0L} , for the left side nanoring of the add/drop system is given by

$$E_{0L} = E_3 \frac{\sqrt{(1-\gamma_3)(1-\kappa_3)} - (1-\gamma_3)e^{-\frac{\alpha}{2}L_2 - jk_n L_2}}{1 - \sqrt{1-\gamma_3}\sqrt{1-\kappa_3}e^{-\frac{\alpha}{2}L_2 - jk_n L_2}}, \quad (2.86)$$

where $L_2 = 2\pi R_L$ and R_L is the radius of the left side nanoring. Regarding to more simplification such as $x_1 = (1-\gamma_1)^{1/2}$, $x_2 = (1-\gamma_2)^{1/2}$, $y_1 = (1-\kappa_1)^{1/2}$, and $y_2 = (1-\kappa_2)^{1/2}$, the interior circulated light fields, E_1 , E_3 and E_4 are given by

$$E_1 = \frac{jx_1\sqrt{\kappa_1}E_{i1} + jx_1x_2y_1\sqrt{\kappa_2}E_{0L}E_{i2}e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}}{1 - x_1x_2y_1y_2E_{0r}E_{0L}e^{-\frac{\alpha}{2}L - jk_n L}}, \quad (2.87)$$

$$E_3 = x_2y_2E_{0r}E_1e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}} + jx_2\sqrt{\kappa_2}E_{i2}, \quad (2.88)$$

$$E_4 = x_2y_2E_{0r}E_{0L}E_1e^{-\frac{\alpha}{2}L - jk_n L} + jx_2\sqrt{\kappa_2}E_{0L}E_{i2}e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}. \quad (2.89)$$

Thus, the throughput port (E_{t1}) output is expressed by

$$E_{t1} = AE_{i1} - BE_{i2}e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}} \left[\frac{CE_{i1}\left(e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}\right)^2 + DE_{i2}\left(e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}\right)^3}{1 - F\left(e^{-\frac{\alpha}{2}\frac{L}{2} - jk_n\frac{L}{2}}\right)^2} \right] \quad (2.90)$$

where, $A = x_1x_2$, $B = x_1x_2y_2\sqrt{\kappa_1}E_{0L}$, $C = x_1^2x_2k_1\sqrt{\kappa_2}E_{0r}E_{0L}$, $D = (x_1x_2)^2y_1y_2\sqrt{\kappa_1\kappa_2}E_{0r}E_{0L}^2$ and $F = x_1x_2y_1y_2E_{0r}E_{0L}$. The power output of the throughput port (P_{t1}) is given by

$$P_{t1} = (E_{t1}) \cdot (E_{t1})^* = |E_{t1}|^2 \quad (2.91)$$

Similarly, the output optical field of the drop port (E_{t2}) is given by,

$$E_{t2} = x_2 y_2 E_{i2} \left[\frac{x_1 x_2 \sqrt{\kappa_1 \kappa_2} E_{0r} E_{i1} e^{-\frac{\alpha}{2} \frac{L}{2} - j k_n \frac{L}{2}} + x_1 x_2^2 y_1 y_2 \sqrt{\kappa_2} E_{0r} E_{0L} E_{i2} \left(e^{-\frac{\alpha}{2} \frac{L}{2} - j k_n \frac{L}{2}} \right)^2}{1 - x_1 x_2 y_1 y_2 E_{0r} E_{0L} \left(e^{-\frac{\alpha}{2} \frac{L}{2} - j k_n \frac{L}{2}} \right)^2} \right], \quad (2.92)$$

where the power output of the drop port (P_{t2}) is expressed by

$$P_{t2} = (E_{t2}) \cdot (E_{t2})^* = |E_{t2}|^2 \quad (2.93)$$

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