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ORIGINAL ARTICLE

Transmission performances of solitons in optical wired link

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Abstract Chaotic signal generation from microring resonators (MRRs) is presented. Two 1.5 μm Gaussians with spectral profile having powers of 600 mW are input into the system of MRRs. Using nonlinear conditions, the chaotic signals can be generated and propagated within the ring medium. Results show that the chaotic signals can be controlled and manipulated by using additional Gaussian input into the add port of the MRRs. A balance should be achieved between dispersion and nonlinear lengths when the propagating pulse is soliton. Chaotic output signals from the ring resonator can be converted to logic codes then inserted into an optical fiber transmission link which has a length of 180 km in order to perform the transmission performance. The transmitted signals in the form of spatial and temporal solitons can be detected at the end of the transmission link.

1. Introduction

Nonlinear light behavior inside a microring resonator (MRR) occurs when a strong signal of light is inputted into the ring system [1,2]; this is used for many applications in signal processing and communication such as wired/wireless cable systems and indoor–outdoor communication [3]. The optical Kerr effect manifests itself temporally as self-phase modulation, a self-induced phase- and frequency-shift of a pulse of light as it travels through a medium [4]. This process, along with dispersion, can produce optical solitons [5]. Spatially, an intense beam of light in a medium will produce a change in the medium's refractive index that mimics the transverse intensity pattern of the beam [6]. The pulse of optical soliton can be used to create a spectrum of light over a wide range [7–9]. They are powerful laser pulses that can be applied to generate chaotic filter features. Therefore, the solitons are considered as stable pulse. The solitons have been extensively investigated in many physics studies [10–12]. The MRR system that comprises one centered ring resonator connected to two smaller ring resonators on the right and left sides. MRRs can be used as filter devices where trapping of optical frequency or wavelength can be obtained using suitable system parameters. MRRs are simulated using waveguide, where the medium has Kerr effect-type nonlinearity [13]. The Kerr effect, also called the quadratic electro-optic effect (QEO effect), is a change in the refractive index of a material in response to an applied electric field [14].

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Advantage of using soliton pulses instead of conventional laser pulses in optical communication systems is to remain the shape of the pulse almost unaltered over a long distance [15–18]. The chaotic signals can be transmitted within an optical fiber transmission link, where the multi transmitted ultra-short spatial and temporal solitons can be generated [19,20]. The Generation of multi soliton pulses has become an interesting approach to enlarging communication channel capacity [21,22]. The dynamics of ultra-short pulse propagation in a MRR system have recently attracted research interest because such pulses are characterized by wide bandwidths and high speeds. One main advantage of a multiple soliton transmission system made of integrated microring resonator is the high data-rate transmission for short and long distance [23,24]. The narrower pulses of soliton are recommended in order to improve the system performances. The attenuation of such soliton signals during propagation is much lower compared to the conventional laser pulses which emit peaks of micrometer [25–27]. In this study chaotic signals in the form of logic codes are generated by the MRR system and are transmitted via fiber optics of 180 km, where the nonlinear behavior of the fiber causes the signals to be compressed along the transmission link. The simulation/modeling is performed using the MATLAB software, utilizing the iterative method to obtain the presented results in this communication.

2. Theoretical background

We will suppose, that a solution for electric filed E has a form of

$$E(r,t) = A(Z,t)F(X,Y)\exp(i\beta_0 Z) \tag{1}$$

where $F(X,Y)$ is transverse field distribution that corresponds to the fundamental mode of single mode fiber. $A(Z,t)$ is along propagation axis Z and on time t dependent amplitude of the mode. After some math manipulations one can come to the equation that governs pulse propagation in optical fibers.

$$\frac{\partial A}{\partial Z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial t^2} = i\gamma |A|^2 A \tag{2}$$

The parameters β_1 and β_2 include the effect of dispersion to first and second orders, respectively [28,29]. Physically, $\beta_1 = 1/v_g$, where v_g is group velocity associated with the pulse and β_2 takes into account the dispersion of group velocity. For this reason, β_2 is called the group velocity dispersion (GVD) parameter. The system to generate chaotic signal can be seen in Fig. 1, where an MRR consisting of three microring resonators is proposed. The Gaussians can be used as an input signal into the system via the input and add ports. Parameter γ is nonlinear parameter that takes into account the nonlinear properties of a fiber medium. Parameter β_1 is in real case always positive [30–32]. The dispersion parameter D (ps/nm/km) can be defined as follows:

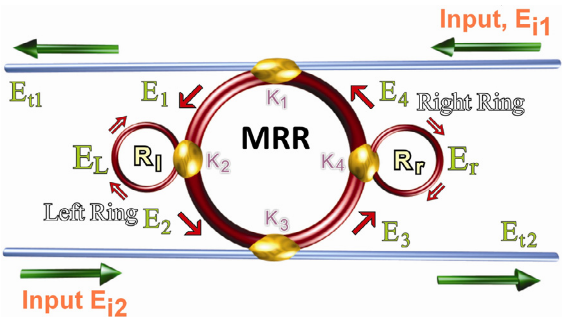

Figure 1 Microring resonator system.

$$D = \frac{d}{d\lambda}\left[\frac{1}{v_g}\right] = -\frac{2\pi c}{\lambda^2}\beta_2 \tag{3}$$

As we know, dispersion parameter D is a monotonically increasing function of wavelength. Eq. (3) has only two solutions, in the form of either dark or bright soliton. The bright soliton corresponds to the light pulse but dark soliton is rather a pulse shaped dip in CW light "background". In other words, the dark soliton is in a fact negation of the bright soliton [33–35]. Where there is maximum of light in the bright soliton, there is minimum of the light in the dark soliton and vice versa. Eq. (2) can be normalized in the form of

$$i\frac{\partial u}{\partial z} - \frac{s}{2}\frac{\partial^2 u}{\partial \tau^2} \pm |u|^2 u \tag{4}$$

using the transform of

$$\tau = (t - \beta_1 Z)/T_0, z = Z/L_D, u = \sqrt{|\gamma| L_D} A \tag{5}$$

where T_0 is moving time window width (very often set to the pulse width) and $L_D = T_0^2/\beta_2$ is dispersion length [36–38]. Using inverse scattering method reveals that solution of above-mentioned equation has a form of

$$u(z,\tau) = N\frac{2}{e^{\tau} + e^{-\tau}}e^{iz/2} = N\sec h(\tau)e^{iz/2} \tag{6}$$

If N is an integer, it represents the order of the soliton pulse. Very interesting situation comes when $N = 1$. In this case of first order soliton, the pulse does not change its shape at all as it propagates in optical fiber [39–41]. It is evident that for telecommunication purposes is the soliton of first order most suitable, because in this application it is necessary to keep a pulse shape stable [42–44]. We define N as

$$N = T_0\sqrt{\frac{P_0\gamma}{|\beta_2|}} \tag{7}$$

T_0 [s] corresponds to input pulse width, P_0 [W] is peak power, β_2 [s^2/m] takes into account group velocity dispersion and γ [(Wm)$^{-1}$] is nonlinear parameter of the fiber material. The system of MRRs is shown in Fig. 1.

The refractive index (n) of the medium varies due to the Kerr effect caused by the nonlinear condition [45]. It can be expressed by Eq. (8). The electric field of the left and right rings of the MRRs system is given by Eqs. (10) and (11). The interior signals can be expressed by Eqs. (12)–(15). Output electric fields of the MRRs system given by E_{t1} and E_{t2} are expressed by Eqs. (16) and (17) [46–49]:

$$n = n_0 + n_2 I = n_0 + \frac{n_2}{A_{eff}}P \tag{8}$$

$$E_{i1}(t) = E_{i2}(t) = E_0 \exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right], \tag{9}$$

$$E_L = (E_1\sqrt{1-\gamma_2}) \times \frac{\sqrt{1-\kappa_2} - \sqrt{1-\gamma_2}e^{-\frac{\alpha}{2}L_L - jk_n L_L}}{1 - \sqrt{(1-\gamma_2)(1-\kappa_2)}e^{-\frac{\alpha}{2}L_L - jk_n L_L}}. \tag{10}$$

$$E_r = (E_3\sqrt{1-\gamma_4})\frac{\sqrt{1-\kappa_4}-\sqrt{1-\gamma_4}e^{-\frac{\alpha}{2}L_R-jk_nL_R}}{1-\sqrt{1-\gamma_4}\sqrt{1-\kappa_4}e^{-\frac{\alpha}{2}L_R-jk_nL_R}}, \tag{11}$$

$$E_1 = \frac{jx_1\left[\sqrt{\kappa_1}E_{i1}+x_2y_1\sqrt{\kappa_3}E_rE_{i2}e^{-\frac{\alpha L}{4}-jk_n\frac{L}{2}}\right]}{1-x_1x_2y_1y_2E_LE_re^{-\frac{\alpha}{2}L-jk_nL}}, \tag{12}$$

$$E_2 = E_LE_1e^{-\frac{\alpha L}{4}-jk_n\frac{L}{2}}, \tag{13}$$

$$E_3 = x_2\left[y_2E_LE_1e^{-\frac{\alpha L}{4}-jk_n\frac{L}{2}}+j\sqrt{\kappa_3}E_{i2}\right], \tag{14}$$

$$E_4 = E_rE_3e^{-\frac{\alpha L}{4}-jk_n\frac{L}{2}}. \tag{15}$$

$$E_{t1} = AE_{i1}-\frac{G^2BE_{i2}e^{-\frac{\alpha L}{4}-jk_n\frac{L}{2}}}{1-FG^2}[CE_{i1}+DE_{i2}G], \tag{16}$$

$$E_{t2} = \frac{Gx_2y_2E_{i2}\sqrt{\kappa_1\kappa_3}}{1-FG^2}\left[AE_LE_{i1}+\frac{D}{x_1\kappa_1\sqrt{\kappa_3}E_r}E_{i2}G\right], \tag{17}$$

where

$$A = x_1x_2, \quad B = x_1x_2y_2\sqrt{\kappa_1}E_r, \quad C = x_1^2x_2\kappa_1\sqrt{\kappa_3}E_LE_r,$$
$$G = \left(e^{-\frac{\alpha L}{4}-jk_n\frac{L}{2}}\right), \quad D = (x_1x_2)^2y_1y_2\sqrt{\kappa_1\kappa_3}E_LE_r^2,$$
$$F = x_1x_2y_1y_2E_LE_r, \quad x_1 = (1-\gamma_1)^{1/2}, \quad x_2 = (1-\gamma_3)^{1/2},$$
$$y_1 = (1-\kappa_1)^{1/2}, \quad \text{and} \quad y_2 = (1-\kappa_3)^{1/2}.$$

with n_0 and n_2 that are indexes. The optical intensity and the power are presented by I and P. E_0 and z are the amplitude of optical field and propagation distance respectively [50–52]. L_D is the dispersion length where, frequency shift of the signal is ω_0. κ is the intensity coupling coefficient, $k = 2\pi/\lambda$ is the wave propagation, $L_L = 2\pi R_l$, and here, $L_R = 2\pi R_r$ and R_r is the radius of right ring, and L is the circumference of the MRRs [53–56].

3. Result and discussion

The Gaussians with centered wavelength 1.55 μm and 600 mW power are inputs. In order to form the multi-function operations, for instance, control, tune, amplify, the additional input such as Gaussian with spectral profile is introduced into the system. The ring system exhibits a nonlinear Kerr effect, where the linear and nonlinear refractive indices of the system are $n_0 = 3.34$ and $n_2 = 2.7 \times 10^{-17}$, respectively [57–59]. The selected radius of the centered ring resonator is $R_{\mathrm{MRR}} = 5$ μm, where the right/left rings have equal radius of 1 μm, respectively. To make a compact ring, a small bend radius is required [60–62]. The coupling coefficients of the MRRs are chosen as $\kappa_1 = 0.35$, $\kappa_2 = 0.2$, $\kappa_3 = 0.1$, and $\kappa_4 = 0.95$. Considering the MRR with radius of 5 μm and coupling coefficient of 0.1, the result of bistability and bifurcation due to the nonlinear condition of the medium is presented in Fig. 2.

The interior intensities within the MRRs system (Fig. 1) are presented in Fig. 3.

By generating large bandwidth of chaotic signals, more channel capacity can be obtained and controlled [63–65]. Therefore, stable signals of the chaotic signals and multi soliton signals can be seen within the through and drop ports of the system respectively shown in Fig. 4.

Fig. 4 shows the through port chaotic signals where the expansion of the signals can be seen in Fig. 4(b). The generated chaotic signals are distributed over the wavelength ranges from 1.48 μm to 1.52 μm. These types of signals can be used as carrier signals, where information can be carried out by the signals via an optical communication link [66–68]. In order to transmit the signals, a fiber optic transmission link can be used; therefore, multi soliton pulses can be generated and used in many applications in optical communications [69–71]. Generated logic code is as "0010100010010000010110110110001001 011101101101001" within the chaotic signals shown by Fig. 5.

The potential of multi soliton pulses can be used for many applications such as high capacity and secured optical communication [72–74]. Thus, the chaotic signals from the through port of the system in the form of codes can be input into the fiber optic transmission link to perform the optical quantum transmission process [75–78]. The transmission link system is shown in Fig. 6.

The attenuation of the fiber is 0.4 dB/km, and it has a dispersion of 1.67 ps/nm/km and group delay of 0.2 ps/km [79–81]. Fig. 7 shows the transmitted chaotic signals in the communication system, which leads to generate spatial multi solitons.

The ultra-short soliton signals can be obtained after the chaotic signals were transmitted along the fiber optic transmission link, where finally the signals are received by suitable optical receiver; thus, the detection process can be performed via the optical receiver. The FWHM and FSR of the spatial multi soliton signals are 1.34 pm and 80 pm respectively. The temporal shape of the multi soliton pulses can be seen in Fig. 8. Here the temporal pulses with FWHM of 100 ps could be generated.

Therefore, transmission of the chaotic signals along the fiber optics is performed, where the spatial and temporal solitons can be generated and detected using a suitable optical receiver. A further investigation on system performance was conducted using a bit-error-rate (BER) calculation. As illus-

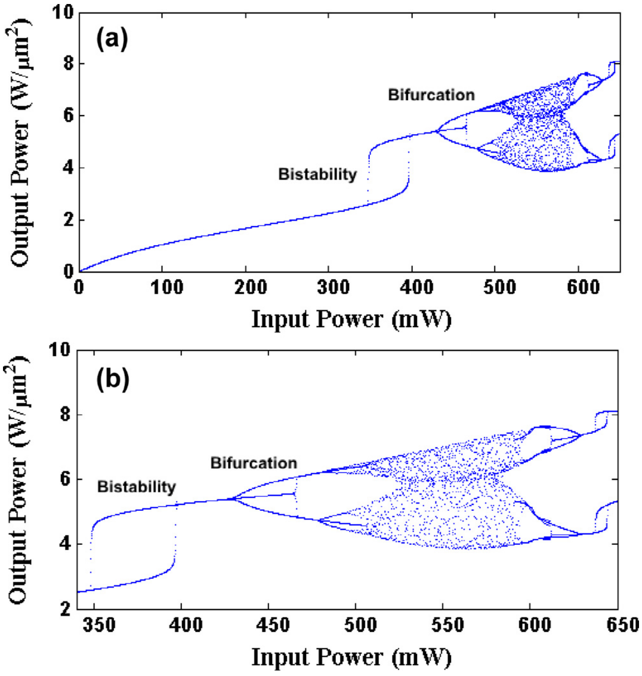

Figure 2 (a) Bifurcation and bistability; input poser versus output power and (b) magnifying (a).

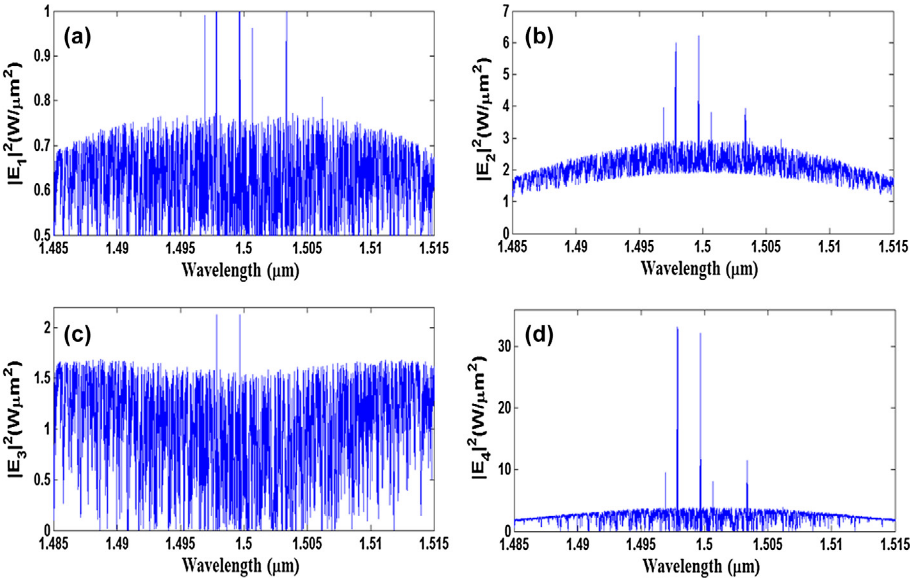

Figure 3 Interior signal generation in the MRRs system, where (a) intensity before R_l, (b) intensity after R_l, (c) intensity before R_r and (d) intensity after R_r.

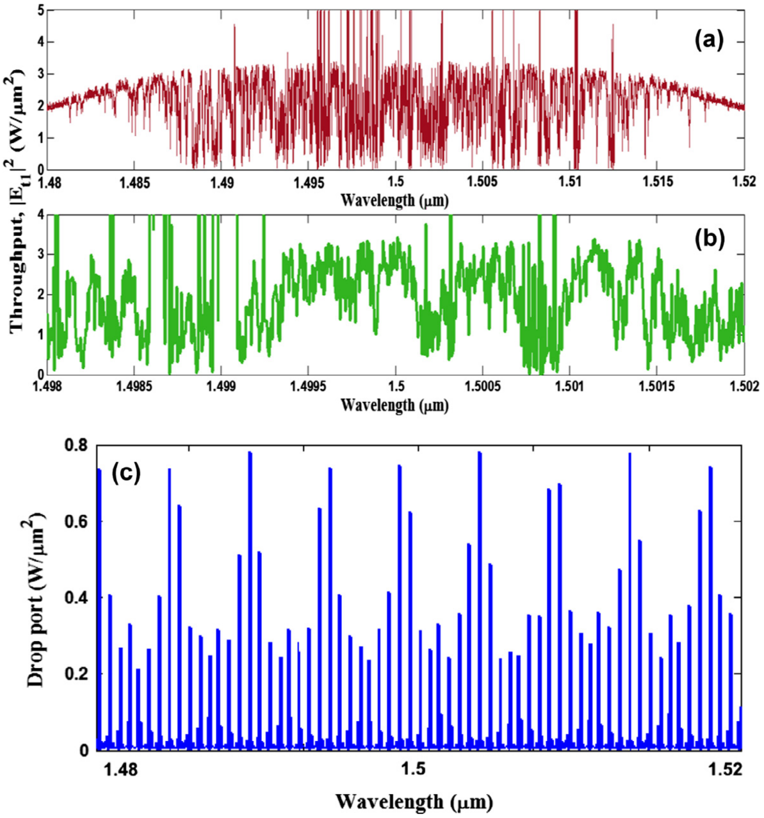

Figure 4 (a) Throughput chaotic signals, (b) expansion of the throughput chaotic signals, and (c) drop port signals.

trated in Fig. 9, the system performance was investigated under three fiber lengths (50, 120 km and 180 km). The 3.8×10^{-3} of BER in Fig. 8 is the threshold for successful transmission. At the threshold BER there are −22.2, −21.2, and −20 dBm sensitivities for the receiver at fiber transmissions at 50, 120 km and 180 km respectively.

Therefore, generation of multi soliton pulses and logic code are performed using the microring resonator (MRR) system which is considered as waveguide based device, where the transmission link uses the fiber optics in order to transmit the multi soliton pulses in the form of code thus performing the optical quantum transmission process.

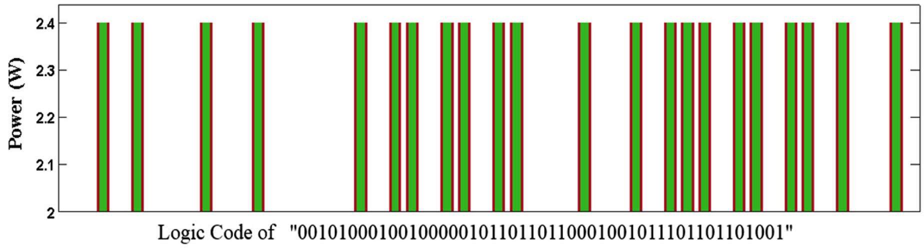

Figure 5 Randomly generated logic codes within the chaotic signals with minimum and maximum intensity power of 2 and 2.4 W/μm^2.

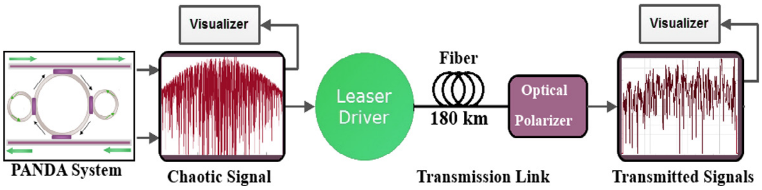

Figure 6 Optical transmission link.

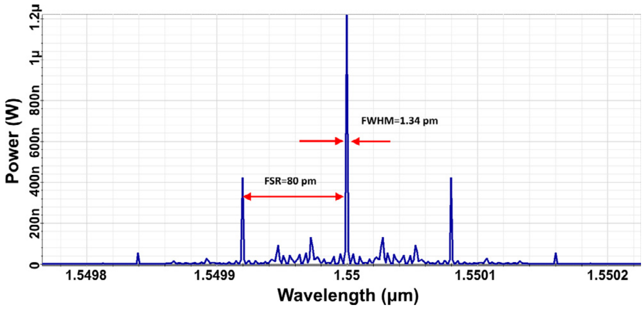

Figure 7 Spatial multi solitons with FWHM = 1.34 pm and FSR = 80 pm.

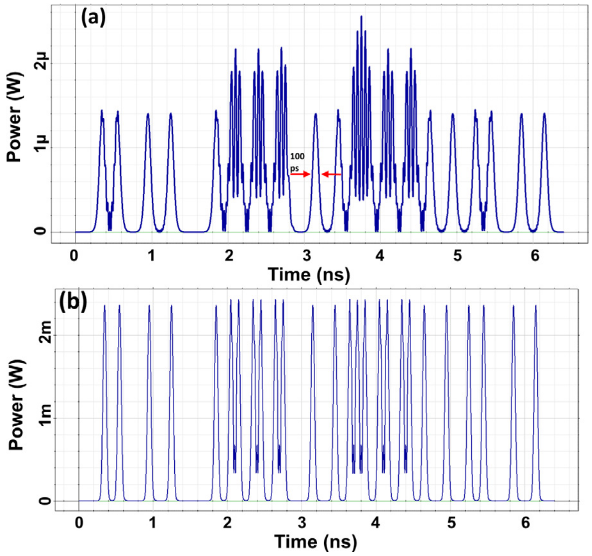

Figure 8 Temporal multi soliton pulses with FWHM of 100 ps, (a) before filtering and amplification, after filtering and amplification.

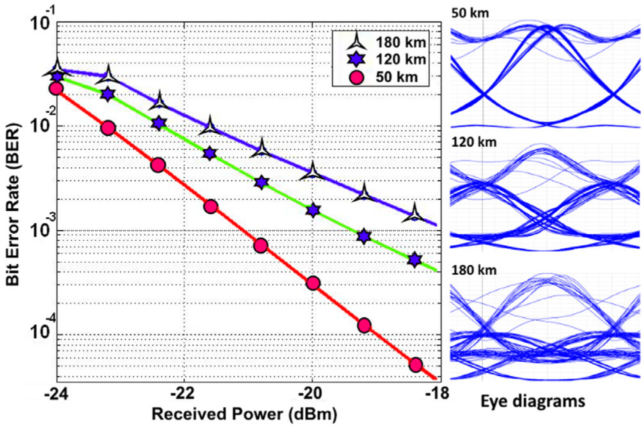

Figure 9 System performance under 50, 120 and 180 km fiber lengths.

The chaos can be generated in MRRs due to the nonlinearities [82], where soliton signals are generated due to balancing both nonlinear (Kerr effect) and linear (dispersion) effects [83]. In the proposed system the results of throughput port show more chaos behavior, where the results from drop port show generation of stable signals as solitons. In this study we used the chaotic signals to generate arbitrary code to be used in a communication system. The function of the proposed microring resonators (MRRs) is to combine and filter the inputs as Gaussians with spectral profile. The filtering process was performed during round-trip of the inputs within the MRRs on the right and left sides of the centered MRR, therefore, slicing the spectrums obtained.

4. Conclusion

In conclusion, the MRRs are presented to show an application of soliton generation and transmission. The high capacity of chaotic signals can be generated using the MRR system. In order to compress the noisy chaotic signals, we transmit them as codes via an optical fiber optic transmission link with the length of 180 km. Clear and filtered signals of spatial and temporal solitons can be generated and used for many applications in optical communications. Here the spatial and temporal signals with FWHM of 1.34 pm and 100 ps could be generated respectively.

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