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# A review of ultra-short soliton pulse generation using InGaAsP/InP microring resonator (MRR) system

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**Abstract:** System of microring resonators (MRRs) incorporating with an add/drop MRR system are presented to generate single and multi-temporal and spatial ultra-short soliton pulses applicable in optical soliton communications. The chaotic signals caused by the nonlinear condition could be generated and propagated within the system. The Kerr effect in the MRR system induces the nonlinearity condition. The proposed MRR systems are used to generate ultra-short soliton pulse within the system. Using the appropriate MRR parameters, ultra-short spatial and temporal signals are generated spreading over the spectrum. In this work, narrow soliton pulses could be localized within the proposed systems. Here soliton pulses of 0.7 ps, 0.83 fs and 19 pm are generated using series of MRRs connected to an add/drop MRR system. The nonlinear refractive index is  $n_2=2.2 \times 10^{-17} \text{ m}^2/\text{W}$ . Using the panda ring resonator system, the ultra-short soliton pulses with full width at half maximum (FWHM) and free spectral range (FSR) of 5 MHz and 2 GHz, were generated at the throughput port. The output signals pulses with FWHM of 10 MHz and FSR of 2 GHz could be obtained at the drop port of the system. As second results using this system, multi-carrier soliton pulses with FWHM=20 MHz are localized within this system with respect to 20,000 roundtrips of the input pulse. Localized optical tweezers could be generated using the half-Panda MRR system, where the peaks have FWHM and FSR of 8.9 nm and 50 nm respectively. The nonlinear refractive index was selected to  $n_2=2.5 \times 10^{-17} \text{ m}^2/\text{W}$ .

**Keywords:** Microring Resonator (MRR), Ultra-Short Soliton, Spatial and Temporal Soliton, Kerr Effect

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## 1. Introduction

Ultra-short soliton generation is very attractive especially when it uses quantum cryptography in an optical communication network, which is reported by Amiri [1-4]. A spectrum of light over a broad range can be generated, thus an optical soliton pulse is advised as a powerful laser pulse which can be utilized to generate chaotic filter features when spreading within microring resonators (MRRs) [5-8]. Therefore, the capacity of the transmission data can be secured and increased when the chaotic packet switching is utilized provided using this technique, [9-11]. In this study, we propose a systems of MRRs that uses ultra-short localized spatial and temporal soliton pulses to form the high capacity communication [12-16]. The device parameters are simulated associating to the practical device parameters [17-21]. Orthogonal frequency division multiplexing (OFDM) is a

combination of modulation and multiplexing [22-25]. Modulation refers to the process of changing the carrier phase, frequency, amplitude, or their combination with a modulated signal that typically contains information to be transmitted [26-29]. However, the aim of multiplexing is to share a bandwidth. Single-carrier modulation is a technology that modulates information onto only one carrier [30-33]. The main problem of this technology is satisfying the need for high bandwidth in fixed spectrum limits of one single-carrier [34-38]. High data rate in one carrier causes a high symbol rate. As the duration of one symbol or bit becomes smaller, the system becomes more susceptible to loss of information from impulse noise, signal reflections, and other impairments [39-43]. These impairments can impede the ability to recover information sent. In addition, as the bandwidth used by a single-carrier system increases, the susceptibility to interference from other continuous signal sources becomes greater. This type of interference is commonly labelled as a

carrier wave (CW) or frequency interference [44-47]. Dark-Gaussian soliton controls within a semiconductor add/drop multiplexer has numerous applications in optical communication [48-53]. Nano optical tweezers technique has become a powerful tool for manipulation of micrometer-sized particles/photons in three spatial dimensions [54-62]. It has the unique ability to trap and manipulate molecules/photons at mesoscopic scales with widespread applications in biology and physical sciences [63-69]. The output is achieved when the high optical field is set up as an optical tweezers [70-73]. For communication's application purposes, the optical tweezers can be used to generate entangled photon within the proposed network system [74-78].

Internet security becomes an important function in the modern internet service. However, the security technique known as quantum cryptography has been widely used and investigated in many applications, using ultra-short optical solitons [79-83]. Amiri et al, have proposed the new design of optical switching used in optical communication systems [84-89]. This method uses nonlinear behaviour of light in MRR which can be applicable for high-capacity transmission and switching [90-94]. Transmission of all-optical OFDM can be implemented by generating multiple optical subcarriers, separating these subcarriers via optical devices, and finally modulating each subcarrier separately [95-97]. Optical carrier generation thus constitutes the basic building block to implement OFDM transmission fully in the optical domain [98-101]. The MRR system provides a viable means to generate this building block that represents the generation of the necessary multi-carriers [102-104]. A soliton solution of the nonlinear wave equation is always stable over a long distance link, and this stability of soliton signals is even more remarkable than the possibility of balancing dispersion and non-linearity [105-110]. One important aspect of the MRR system is that suitable tuning of the system parameters allows for desired soliton carriers with specific key characteristics, such as full width at half maximum (FWHM) and stability, to be obtained at the drop/through ports of the system [111-116].

## 2. Picosecond Soliton Pulses Generation

The schematic diagram of the proposed system is shown in Fig. 1. A soliton pulse with 20 ns pulse width, peak power at 500 mW is input into the system. The suitable ring parameters are used, for instance, ring radii  $R_1=10 \mu\text{m}$ ,  $R_2=5\mu\text{m}$ , and  $R_3=4\mu\text{m}$ . In order to make the system associate with the practical device, the selected parameters of the system are fixed to  $\lambda_0=1.55\mu\text{m}$ ,  $n_0=3.34$  (InGaAsP/InP) [117-121],  $A_{\text{eff}}=0.50, 0.25\mu\text{m}^2$  and  $0.12\mu\text{m}^2$  for the different radii of MRRs respectively [122-124],  $\alpha=0.5\text{dBmm}^{-1}$ ,  $\gamma=0.1$  [125-127]. The coupling coefficient ( $\kappa$ ) of the MRR ranged from 0.50 to 0.975 [128-130].

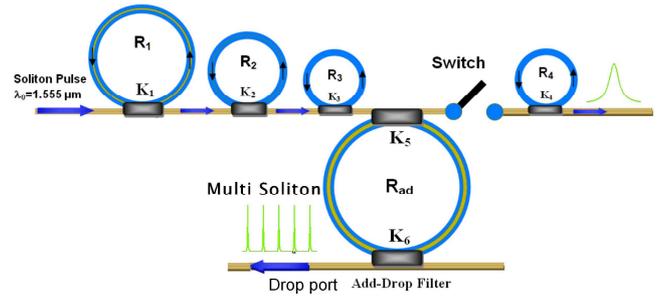


Fig. 1. Schematic diagram of soliton pulse generation,  $R_s$ , ring radii and  $\kappa_s$ , coupling coefficients

The soliton pulse is introduced into the proposed system. The input optical field ( $E_{\text{in}}$ ) can be in the form of bright soliton (equation 1), dark soliton (equation 2) and Gaussian laser beam (equation 3) [131-136]. Here, the bright soliton pulse is input into the system. The input optical field ( $E_{\text{in}}$ ) of the bright soliton, dark soliton and Gaussian laser beam are given by:

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

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

$$E_{\text{in}}(t) = A \exp \left[ \left( \frac{z}{2L_D} \right) - i\omega_0 t \right] \quad (3)$$

$A$  and  $z$  are the optical field amplitude and propagation distance, respectively [137, 138].  $T$  is a soliton pulse propagation time in a frame moving at the group velocity [139-141],  $T = t - \beta_1 \times z$ , where  $\beta_1$  and  $\beta_2$  are the coefficients of the linear and second order terms of Taylor expansion of the propagation constant [142-144].  $L_D = T_0^2 / |\beta_2|$  is the dispersion length of the soliton pulse [145, 146]. The frequency shift of the soliton is  $\omega_0$ .

This solution reports a pulse that maintains its temporal width invariance as it spreads, and thus is called a temporal soliton [147-149]. When a soliton peak intensity ( $\beta_2 / \Gamma T_0^2$ ) is established, then  $T_0$  is recognized [150-152]. For the soliton pulse in the MRR system, a balance should be accomplished between the dispersion length ( $L_D$ ) and the nonlinear length ( $L_{NL} = 1 / \Gamma \phi_{NL}$ ) [153-155], where  $\Gamma = n_2 \times k_0$ , is the length scale over which dispersive or nonlinear effects makes the beam gets wider or narrower [156, 157].

Since for a soliton pulse, there is a balance between dispersion and nonlinear lengths, therefore  $L_D = L_{NL}$  [158, 159]. Whenever light spreads within the nonlinear medium, the refractive index ( $n$ ) of light within the medium is contributed by [160-162].

$$n = n_0 + n_2 I = n_0 + \left( \frac{n_2}{A_{\text{eff}}} \right) P, \quad (4)$$

where  $n_0$  and  $n_2$  represent the linear and nonlinear refractive indices, respectively.  $I$  and  $P$  are the optical intensity and powers, respectively [163, 164]. The effective mode core area of the device is introduced by  $A_{\text{eff}}$ . For the MRR and NRR, the effective mode core areas range 0.50 to 0.10  $\mu\text{m}^2$ . When a soliton pulse is input and propagated within a MRR as shown in Fig. 1, the resonant output can be performed, hence, the normalized output of the light field is defined by the ratio between the output and input fields presented by  $E_{\text{out}}(t)$  and  $E_{\text{in}}(t)$  in each roundtrip, and can be expressed as [165-168]

$$\left| \frac{E_{\text{out}}(t)}{E_{\text{in}}(t)} \right|^2 = (1-\gamma) \left[ 1 - \frac{(1-(1-\gamma)x^2)\kappa}{(1-x\sqrt{1-\gamma}\sqrt{1-\kappa})^2 + 4x\sqrt{1-\gamma}\sqrt{1-\kappa}\sin^2(\frac{\phi}{2})} \right] \quad (5)$$

The equation 5 suggests that a MRR in the special case is very similar to a Fabry-Perot cavity, having an input and an

output mirrors with a field reflectivity,  $(1-\kappa)$ , and a fully reflecting mirror [169, 170].  $\kappa$  is the coupling coefficient, and  $x=\exp(-\alpha L/2)$  symbolizes a roundtrip loss coefficient,  $\Phi_0=kLn_0$  and  $\Phi_{\text{NL}}=kLn_2|E_{\text{in}}|^2$  are the linear and nonlinear phase shifts [171, 172],  $k=2\pi/\lambda$  is the wave propagation number in a vacuum. Where  $L$  and  $\alpha$  are the waveguide length and linear absorption coefficient, respectively [173, 174]. In this work, the iterative method is brought in to obtain the results as shown in equation 3, likewise, when the output field is associated and input into the other ring resonators. The nonlinear refractive index is  $n_2=2.2 \times 10^{-17} \text{ m}^2/\text{W}$ . In this case, the waveguide loss utilized is  $0.5\text{dBmm}^{-1}$ . As shown in Figure 2, the signal is chopped into a smaller signals spreading over the spectrum. The attenuation of the optical power within a MRR is necessitated in order to maintain the constant output gain.

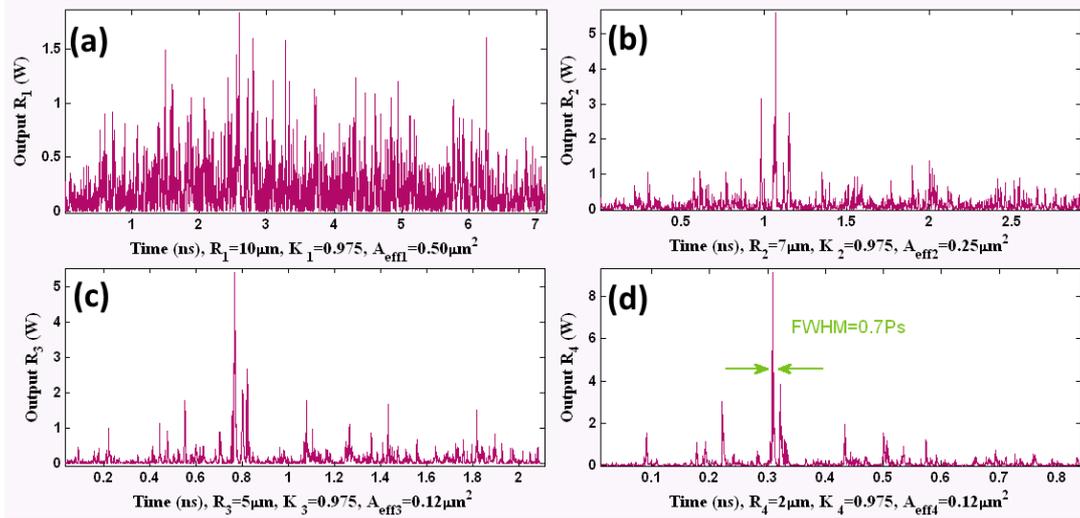


Fig. 2. Results obtained when temporal soliton is localized within a MRR, where (a): Chaotic signals from  $R_1$ , (b): Chaotic signals from  $R_2$ , (c): temporal soliton, (d): temporal soliton with FWHM of 0.7 ps.

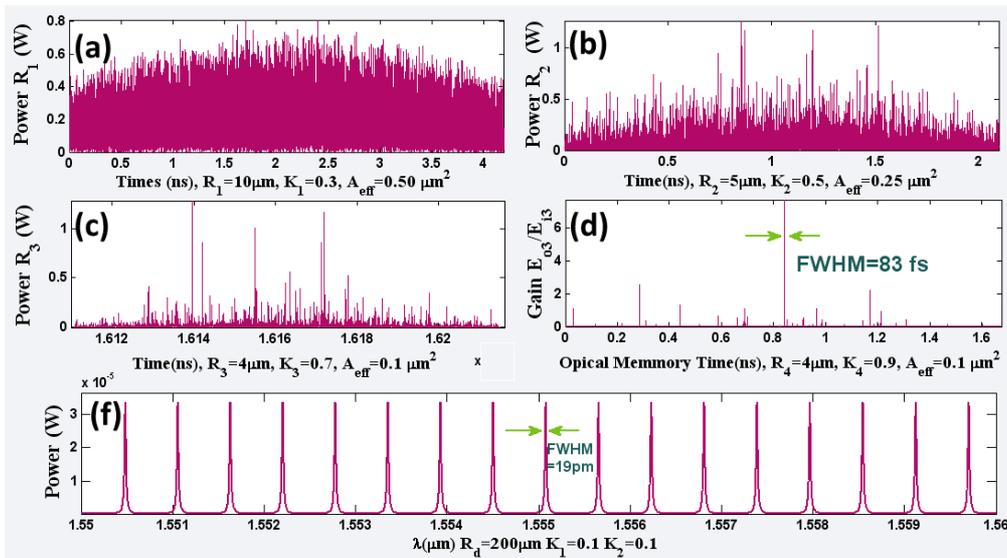


Fig. 3. Results of temporal and spatial soliton generation, where (a): Chaotic signals from  $R_1$ , (b): Chaotic signals from  $R_2$ , (c): filtering signals, (d): Temporal soliton with FWHM of 83 fs, (e): Spatial soliton with FWHM=19 pm

Figure 3 demonstrates the results while temporal and spatial optical soliton pulses are localized within a MRR and add/drop MRR systems with 20,000 roundtrips, thus the optical pulse of 83 fs can be generated. Here, the ring radii are  $R_1=10\ \mu\text{m}$ ,  $R_2=5\ \mu\text{m}$ ,  $R_3=4\ \mu\text{m}$ ,  $R_4=4\ \mu\text{m}$  and  $R_{\text{ad}}=200\ \mu\text{m}$  with coupling coefficient of  $\kappa_1=0.3$ ,  $\kappa_2=0.5$ ,  $\kappa_3=0.7$ ,  $\kappa_4=0.9$ ,  $\kappa_5=0.1$  and  $\kappa_6=0.1$ .

### 3. Soliton Generation in Frequency domain for Communication Application

The system of soliton frequency band generation is shown in Figure 4. Here, series of ring resonators are connected to a panda ring resonator system. The filtering process of the input soliton pulses is performed via the ring resonators, where frequency band ranges 40–60 GHz can be obtained via the output signals of the panda ring resonator system. The soliton pulse shown by equation 1 is introduced into the nonlinear system.

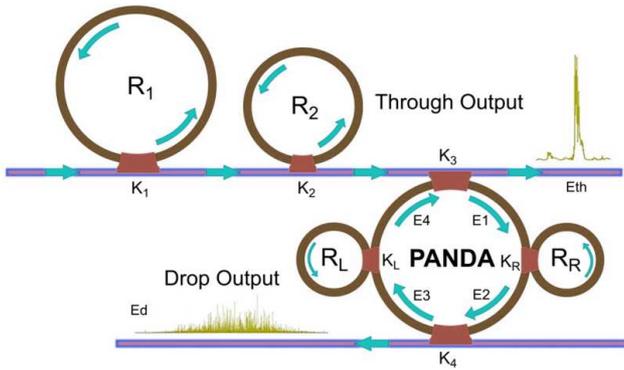


Fig. 4. Optical frequency band generation system using a panda ring resonator connected to a series of MRRs

A frequency soliton pulse can be formed and trapped within the panda ring resonator system with suitable ring parameters. The centred ring of the panda ring resonator system has a radius of  $100\ \mu\text{m}$  and coupling coefficients of  $\kappa_3=0.35$  and  $\kappa_4=0.30$ , where the right and left rings have radii of  $18\ \mu\text{m}$  and  $8\ \mu\text{m}$ , respectively. The effective core areas of the right and left rings are  $A_{\text{eff}1}=A_{\text{eff}2}=0.25\ \mu\text{m}^2$ , where the coupling coefficients have been selected to  $\kappa_R=0.22$  and  $\kappa_L=0.10$ . Filtering of the interior soliton signals can be performed when the pulses pass through the couplers,  $\kappa_3$  and  $\kappa_4$ . The output signals from the throughput and drop ports of the system can be seen in Figure 5, where soliton range of 40–60 GHz are generated and used in many optical communication applications, such as wireless personal area networks (WPANs) and wireless local area networks (WLANs). The throughput output ( $E_{\text{th}}$ ) shows localized ultra-short soliton pulses with an FWHM and free spectral range (FSR) of 5 MHz and 2 GHz, respectively, where soliton pulses at frequencies of 50 GHz and 52 GHz are generated. The drop output signals expressed by  $E_{\text{d}}$  are shown in Figure

5(b-c), where, pulses with FWHM of 10 MHz and FSR of 2 GHz are obtained.

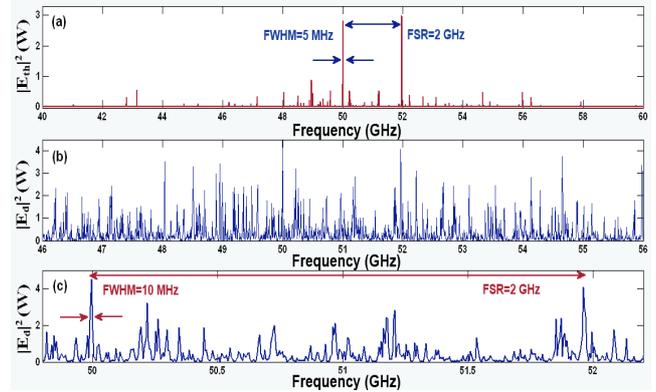
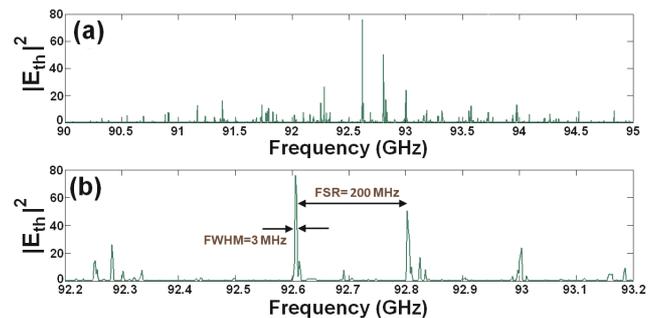


Fig. 5. Results of localized solitons: (a): throughput output signal with FWHM=5 MHz and FSR=2 GHz, (b): chaotic soliton pulses, (c): expansion of the soliton pulses ranges 50–52 GHz with FWHM=10 MHz and FSR=2 GHz

A bright soliton with a central frequency of 92.5 GHz and power of 2 W is introduced into the first MRR. The results of the chaotic signal generation are shown in Figure 6. The rings' radii and coupling coefficients are  $R_1=6\ \mu\text{m}$ ,  $\kappa_1=0.3$ ,  $R_2=4\ \mu\text{m}$  and  $\kappa_2=0.3$ . The ring of the Panda ring resonator system has a radius of  $120\ \mu\text{m}$  and coupling coefficients of  $\kappa_3=0.3$  and  $\kappa_4=0.5$ , where the right and left rings have the same radii of  $R_R=3\ \mu\text{m}$  and  $R_L=3\ \mu\text{m}$ . The effective core areas of the rings are  $A_{\text{eff}R}=A_{\text{eff}L}=0.10\ \mu\text{m}^2$ , where the coupling coefficients have been selected to  $\kappa_R=0.2$  and  $\kappa_L=0.1$ . The wave-guided and fractional coupler intensity losses are  $\alpha=0.5\ \text{dBmm}^{-1}$ , and  $\gamma=0.1$  respectively. The through put output shows localized narrow bandwidth soliton pulses with FWHM and FSR of 3 MHz and 200 MHz, respectively, where soliton pulses at frequencies of 92.6, 92.8 and 93 GHz are generated. The drop port output signals are shown in Figure 6(c-d), where multi-soliton pulses with FWHM of 11 MHz and FSR of 188 MHz could be generated.

As it can be concluded from the results, the efficiency of this system can be evaluated by the output solitonic carrier signal generated by the MRRs. Long distance fiber communication link is implemented using this method and can be integrated to short distance indoor wireless link for ultra-high data rate transmission.



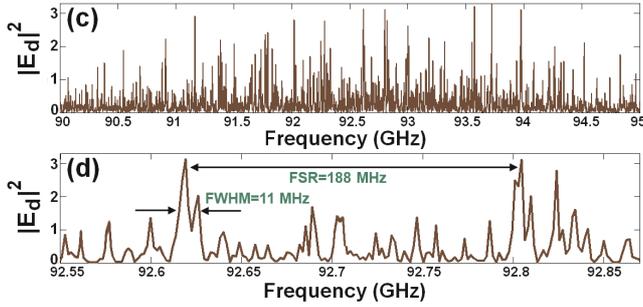


Fig. 6. (a-b) throughput output signal ( $W/\mu m^2$ ) with  $FWHM=3$  MHz and  $FSR=200$  MHz, (c-d) drop port multi-solitons output signal ( $W/\mu m^2$ ) with  $FWHM=11$  MHz and  $FSR=188$  MHz

### 4. Ultra-Short Soliton Tweezers Generation

The array of dark soliton pulses expressed by equation 2 are introduced into the input port half-Panda MRR system shown in Figure (7). This system consists of an add/drop MRR system connected to a smaller ring resonator on the right side.

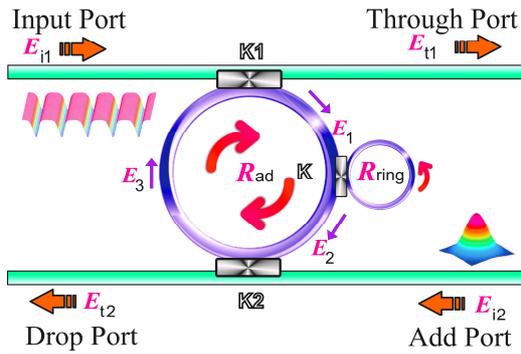


Fig. 7. A schematic diagram of Half-Panda MRR system

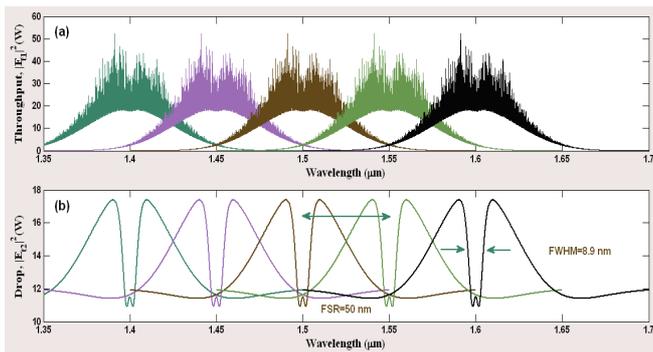


Fig. 8. (a): Through port chaotic output signals (b): drop port output with  $FWHM=8.9$  and  $FSR=50$  nm

Input optical dark solitons and Gaussian laser beam (input into the add port) with powers 2W and 1W respectively are inserted into the half-Panda MRR system. The add/drop MRR system has radius of  $R_{ad}=15 \mu m$  where the coupling coefficients are  $\kappa_1 = 0.35$  and  $\kappa_2 = 0.25$ . The dark solitons are propagating inside the half-Panda MRR system with central wavelengths of  $\lambda_0 = 1.4 \mu m, 1.45 \mu m, 1.5 \mu m, 1.55$

$\mu m, 1.6 \mu m$ . In order to make the system associate with the practical device (InGaAsP/InP), the selected parameters of the system are fixed to  $n_0 = 3.34$  and  $n_2 = 2.5 \times 10^{-17} m^2/W$ . Filtered and clear optical tweezers are seen in figure 8 where the peaks have FWHM and FSR of 8.9 nm and 50 nm respectively. In the case of communication networks, generation of narrower signals is recommended to compensate the fiber loss and system's attenuation.

By using suitable dark-Gaussian soliton input powers, tunable optical tweezers can be controlled. This provides the entangled photon as the dynamic optical tweezers probe. The required data can be retrieved via the through and drop ports of the add/drop MRR. High capacity data transmission can be obtained by using more wavelength carriers. The advantage of this study is that ultra-short nano optical tweezers can be generated and transmitted via a network system thus improving the sensitivity and capacity.

### 5. Multi-Carries Soliton Generation for Wired/Wireless Optical Communication Systems

Using the system shown by Figure 1, the optical soliton carrier can be generated. Figure 9 shows the results when soliton pulses are localized within the MRR and add/drop MRR systems with 20,000 roundtrips, where the soliton pulses with  $FWHM=20$  MHz could be generated as result of the fourth ring resonator shown in Figure 9(d). The output results from the drop port of the system can be seen in the Figure 9(e-f). Here, the ring radii are  $R_1=15 \mu m, R_2=9 \mu m, R_3=6 \mu m, R_4=6 \mu m$  and  $R_{ad}=100 \mu m$  having coupling coefficients of  $\kappa_1 = 0.98, \kappa_2 = 0.98, \kappa_3 = 0.96, \kappa_4 = 0.92, \kappa_5 = 0.1$  and  $\kappa_6 = 0.1$ . The nonlinear refractive index is  $2.4 \times 10^{-17}$ .  $A_{eff1} (\mu m^2)=0.50, A_{eff2} (\mu m^2)=0.25$  and  $A_{eff3-4} (\mu m^2)=0.10$ .

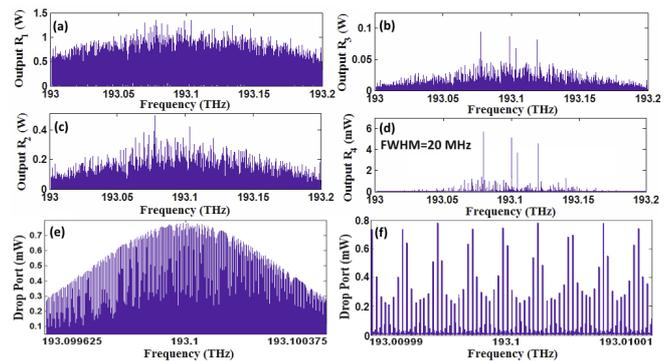


Fig. 9. (a): output from first ring resonator, (b): output from second ring resonator, (c): output from third ring resonator, (d): multi-solitons output from the drop port, (e): multi-carriers generation

Thus, filtering of the input pulse within the system allowed for generation of single- and multi-soliton pulses to be used in a multiple-input and multiple-output (MIMO)-OFDM communication systems.

## 6. Conclusion

We have proposed an interesting concept of the ultra-short soliton pulse generation using microring resonators (MRRs), in which the single and multiple temporal and spatial soliton pulses could be achieved. The balance established between the dispersion and nonlinear lengths of the soliton pulse presents the soliton behavior known as self-phase modulation, which introduces the optical output constant, meaning that the light pulse can be localized coherently within the nano-waveguide. We have demonstrated that a large bandwidth of the arbitrary soliton pulses can be generated and compressed within a microring waveguide. The chaotic signal generation by means of a soliton pulse in the nonlinear MRRs has been presented. Selected light pulse can be localized and used to perform the high capacity of optical communication due to generate ultra-short bandwidth of the pulses. Localized spatial and temporal soliton pulse are useful to generate optical communication signals applicable for wired/wireless networks. As an application, the classical information and security codes can be formed by using the temporal and spatial soliton pulses, respectively.

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