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TEMPORAL SOLITON: GENERATION AND APPLICATIONS IN OPTICAL COMMUNICATIONS

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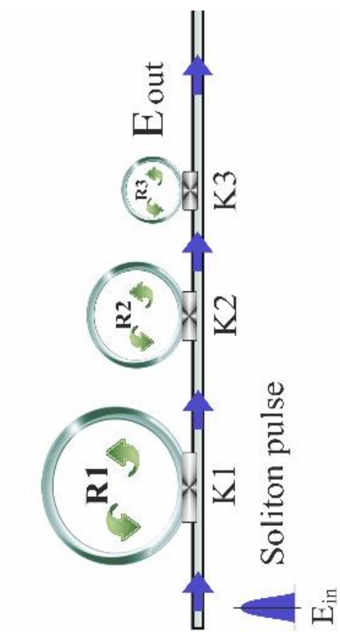
Graphical abstract



Abstract

In general, the temporal and spectral shape of a short optical soliton pulse does not change during propagation in a nonlinear medium due to the Kerr effect which balances the chromatic dispersion. Microring resonators (MRRs) can be used to generate chaotic signals. The smaller MRR is used to form the stopping and filtering system. The employed optical material was InGaAsP/InP, which is suitable for use in the practical devices and systems. The tuning and manipulation of the bandwidth of the soliton signals is recommended to control the output signals. The MRRs can be applied to produce ultra-short pulses, where the medium has a nonlinear condition, thus, using of soliton laser becomes an interesting subject. Therefore, an ultra-short pulse in the scope of pico and femtoseconds soliton pulses can be utilized for many applications in engineering communications. In order to obtain smaller bandwidth of the optical soliton pulses, we propose integrating series of MRRs. In this study, 5 fs soliton pulse could be generated using a series of five MRRs. The soliton signals experience less loss during the propagation, where they are more stable compared to normal conventional laser pulses. Using the series of MRRs connected to an add/drop system, shorter soliton bandwidth and highly multi soliton pulses can be obtained. Therefore, generation of ultra-short multi picosecond (1.2 and 1.3 ps), could be performed, where the radius of the add/drop system has been selected to 50 and 300 μm respectively.

Keywords: Microring Resonator, temporal Soliton, pico/femtosecond Soliton, kerr effects

Abstrak

Secara umum, bentuk temporal dan spektrum nadi soliton optik yang singkat tidak berubah semasa perambatan dalam medium nonlinear disebabkan oleh kesan Kerr yang mengimbangkan penyebaran kromatik. Microring resonator (MRRs) boleh digunakan untuk menjana isyarat huru-hara. MRR lebih kecil digunakan untuk membentuk perhentian dan penapisan sistem. Bahan optik yang digunakan adalah InGaAsP/InP, sesuai untuk digunakan dalam peranti praktikal dan sistem. Penalaan dan manipulasi lebar jalur isyarat soliton adalah disyorkan untuk mengawal isyarat output. MRRs boleh digunakan untuk menghasilkan denyutan ultra-short, di mana medium yang mempunyai nonlinear, dengan itu, dengan menggunakan laser soliton menjadi subjek yang menarik. Oleh itu, denyutan ultra-short dalam skop pico dan femtoseconds denyutan soliton boleh digunakan untuk banyak aplikasi dalam komunikasi kejuruteraan. Untuk mendapatkan lebar jalur yang lebih kecil daripada denyutan soliton optik, kami mencadangkan mengintegrasikan siri MRRs. Dalam usaha untuk mendapatkan lebar jalur yang lebih kecil daripada denyutan soliton optik, kami mencadangkan mengintegrasikan siri MRRs. Dalam kajian ini, 5 fs nadi soliton boleh dijana menggunakan satu siri lima MRRs. Isyarat soliton mengalami kurang kehilangan semasa pembiakan, di mana mereka lebih stabil berbanding dengan denyutan laser konvensional biasa. Menggunakan siri MRRs berhubung dengan add sistem/drop jalur lebar soliton lebih pendek dan denyutan pelbagai soliton boleh diperolehi. Oleh itu, generasi picosecond ultra-pendek pelbagai (1.2 dan 1.3 ps), boleh dilakukan, di mana jejari sistem add/drop telah dipilih untuk 50 dan 300 mikron masing-masing.

Kata kunci: Microring Resonator, temporal Soliton, pico/femtosecond Soliton, kerr effects

1.0 INTRODUCTION

The nonlinear behaviors associated with light moving inside a fiber optic microring resonator (MRR) can be induced by the effects such as the Kerr effects, four-wave mixing, as well as the external nonlinear pumping electrical power. In general, the temporal and spectral shape of a short optical soliton pulse changes during propagation in a transparent medium due to the Kerr effect and chromatic dispersion [1].

Under certain circumstances, however, the effects of Kerr nonlinearity and dispersion can exactly cancel each other. Apart from a constant phase delay per unit propagation distance, so that the temporal and spectral shape of the pulses is preserved even over long propagation distances [2].

In order to obtain a range of signals throughout a wide scope, an optical soliton would be affective as a powerful laser source. The chaotic signals can be generated using soliton input propagating within the nonlinear MRR systems [3].

This system can be used to localize optical solitons with the pico/femtosecond bandwidth. MRR can be made of two or more waveguides. One of these waveguides is like a ring, and the other is a straight waveguide, separated by a very small gap that they interact with each other through it. The important aspect of the configuration is to tune the soliton pulses easily by controlling the parameter of the system. Firstly, the specified power is input into the waveguide by a bigger effective core area of the MRR. Smaller MRR is associated to form the filtering and stopping behavior [4].

The filtering features of the signal can be performed in an MRR. Appropriate MRR parameters can be operated to receive the required output power. Several parameters describe the MRR performance, such as the free spectral range (FSR), full width half maximum (FWHM) and the finesse. In a dense wavelength multiplexing (DWDM) system, channel filters with lower insertion loss, higher selectivity which can be obtained by larger FSR and high stop band rejection are demanded. The used optical material was InGaAsP/InP, which is suitable for use in the practical devices and systems [5].

Fabrication of InGaAs/InP waveguide is based on the semiconductor materials [6]. It is necessary to consider various physical constraints limiting the microwave intensity, during designing the material and device structures for waveguide modulators, output power, the modulation depth, and the bandwidth [7, 8]. This paper presents the design of the system of single and multiple soliton generation and characterization using the practical device parameters. Fiber optic sensors and microstructured fibers hold great promise for integration of multiple sensing channels MRRs can be used by new applications in a wide range of nanophotonics integrated systems.

The micro and nanostructure optical devices have promising application in science and technology. The mathematical derivation of such systems have same conceptions as ring cavities, and Fabry–Perot system. Additional information regarding these kinds of behaviors in an MRR evidently are defined by Amiri *et al.* Amiri *et al.*, have shown an add/drop system could be built by means of MRRs, where the system features have shown promising applications in optical communication systems .

The tuning and manipulation of the bandwidth of these signals is recommended to control the output signals. The chaos filtering via the add/drop device is performed by using suitable parameters of the system. The bandwidth manipulation of the generated single soliton pulse can be performed by variation of ring parameters such as coupling coefficients [9].

Optical storage devices offer significant advantages over other high-capacity storage devices, such as tape and microfilm, with faster access times and a hierarchical type file organization [10]. The promising technique of the optical quantum memory generation has been reported in both theory and experiment. Recently, the pico/femtosecond laser has become a powerful tool for many applications, especially in biological science [11].

High optical output signals can be obtained using the MRR systems. Extremely ultra-short bandwidth signal in the range of pico or femtoseconds solitons can be used for many applications in engineering communications [12]. The bandwidth manipulation of the single soliton signal can be performed using fabricated ring resonator system [13].

2.0 MODELLING AND THEORY OF INTEGRATED MRRs

Schematic diagram of the proposed MRRs system is shown in Figure 1.

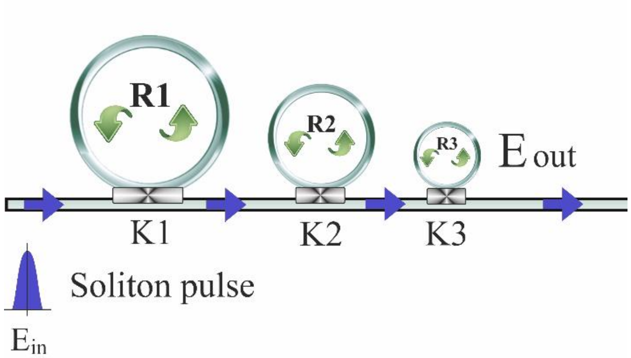


Figure 1 Schematic diagram of three integrated MRRs

The soliton is inserted into the proposed MRRs system, where the input optical field (E_{in}) can be in the type of bright soliton (equation 1) or dark soliton (equation 2). In this case, a bright soliton is input into the system [14].

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

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

The optical field amplitude and propagation distance are shown by A and z respectively. T is a soliton pulse propagation time in a frame moving at the group velocity, $T = t-\beta_1 \times z$, where β_1 and β_2 are the coefficients of the linear and second order terms of the Taylor expansion of the propagation constant [15-18]. $L_D = T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse [19]. The carrier frequency of the soliton is ω_0. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton [20]. The soliton peak intensity is defined as $\left(|\beta_2 / \Gamma T_0^2|\right)$. For the soliton pulse propagating within the MRR system, a balance should be accomplished among the dispersion length shown by L_D and the nonlinear length shown by ($L_{NL}=1/\Gamma\phi_{NL}$). Here, $\Gamma=n_2 \times k_0$ represents the length scale over which disperse or nonlinear effects cause the beam becomes wider or narrower. In the case of soliton propagation, a balance between dispersion and nonlinear length is established, thus $L_D=L_{NL}$. Soliton propagates within the nonlinear Kerr medium, thus the refractive index (n) varies with respect to the equation 3 given by [21]

$$n = n_0 + n_2 I = n_0 + \left(\frac{n_2}{A_{eff}}\right)P \tag{3}$$

The n_0 and n_2 present the linear and nonlinear refractive indices, respectively. I and P are defined as optical intensity and power respectively. The effective mode core area of the system is shown by A_{eff} and for the MRR system, it ranges from 0.50 to 0.12 μm^2. Whenever the soliton pulse is input to the system shown in Figure 1, the resonant output signal is performed, thus, the normalized output is introduced by the ratio between the output and input fields E_{out} (t) and E_{in} (t) in each round-trip as [22]

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

κ is the coupling coefficient, and $x=\exp(-\alpha L/2)$ represents a round-trip loss coefficient, $\Phi_0=kLn_0$ and $\Phi_{NL}=kLn_2|E_{in}|^2$ are the linear and nonlinear phase shifts, $k=2\pi/\lambda$ is the wave propagation number in a vacuum. Where L and α are the waveguide length and linear absorption coefficient, respectively. In this work, the iterative method is introduced to obtain the results as shown in equation (4), similarly, when the output field is connected and input into the other ring resonators [23].

3.0 RESULTS AND DISCUSSION

The wide bandwidth signals within the MRRs system can be generated by using a soliton pulse input into the system shown in Figure 1, where the expected signals can be generated and perform. The nonlinear refractive index is n_2=2.5 x 10^{-17}m^2/W. A soliton pulse with peak power at 500 mW is input into the system. The suitable ring parameters are used, for instance, ring radii R_1=10 μm, R_2=5μm, and R_3=2μm. In order to make the system associated with the practical device, the selected parameters of the system are fixed to n_0=3.34, A_{eff}=0.50, 0.25 and 0.12μm^2, α=0.5dBmm^{-1} and γ=0.1. The coupling coefficient of the MRR ranged from 0.9 to 0.975. From Figure 2, the signal is split into the smaller signal spreading out throughout the spectrum, showing that the wide bandwidth is achieved within the first MRR. Compress bandwidth is obtained within the ring R_2. The amplified gain is obtained within the MRR (i.e. ring R_3). Temporal soliton is formed and localized by using the constant gain condition. The attenuation of the optical power within the MRR is required in order to keep the constant output gain, where the next round input power is attenuated and kept the same level with the R_2 output. The total round trip is 40000 and the central wavelength has been selected to λ=1.55 μm.

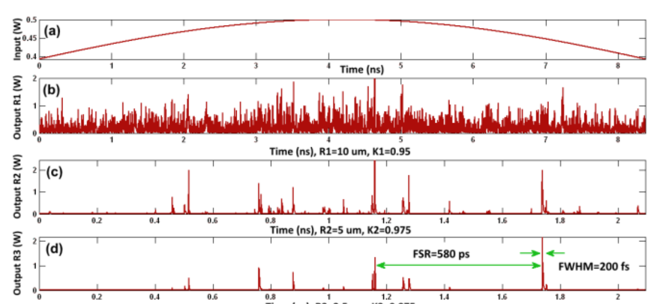


Figure 2 Results when a temporal soliton is localized within the MRR, where (a): Input bright soliton, (b): Output signal from R_1, (c): Output signal from R_2, (d): Output signal from R_3 with FWHM and FSR of 200 fs and 580 ps respectively

In order to obtain smaller bandwidth of the optical soliton pulses, we include five MRRs. The input optical bright soliton with power of 3 W and nanosecond pulse width can be used to generate femtosecond soliton pulses. Figure 3 shows the series of MRR used to generate sub-femtosecond bandwidth optical soliton.

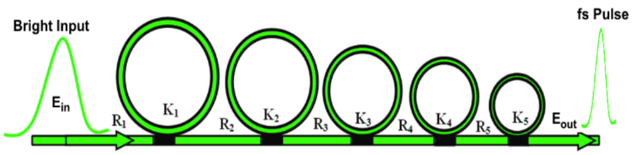


Figure 3 Integrated MRRs to generate ultra-short bandwidth soliton pulse

Figure 4 shows the output soliton signals from the ring resonators. The compression of the soliton happens during the round-trip of the input pulse within the MRR system. Each MRR uses the output signals from the previous MRR as input pulse. The resonant condition occurs during the propagation, where signals with constructive interferences passes the MRR and can be detected [24]. Signals with destructive interferences will vanish and disappear after some times. As a result, a generation of ultra-short femtosecond soliton pulse can be obtained shown by Figure 4(g). Here, the five fs soliton pulse could be generated.

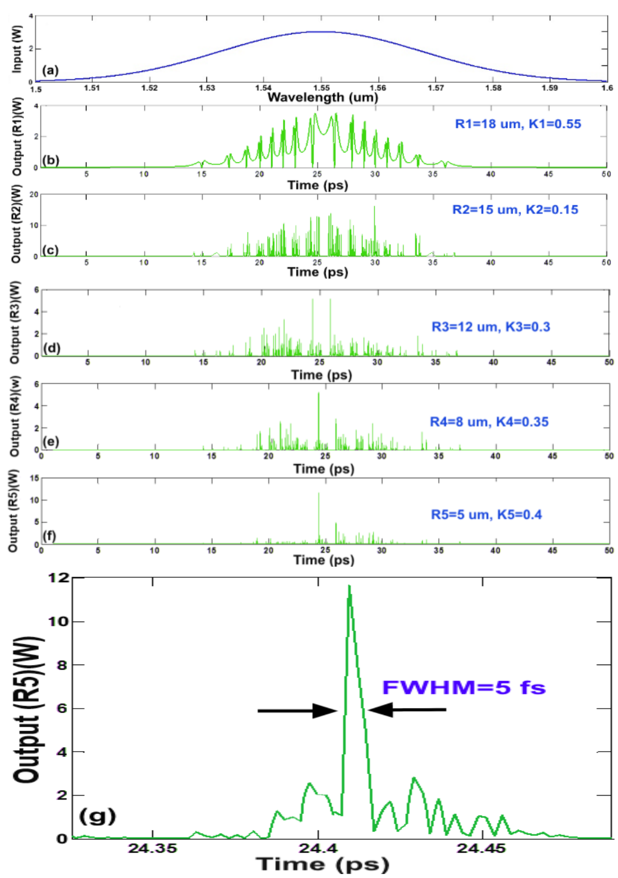


Figure 4 Results of localized temporal soliton within the MRR, (a): Input soliton, (b): Output signal from R_1, (c): Output signal from R_2, (d): Output signal from R_3, (e): Output signal from R_4, (f): Output signal from R_5 with FWHM of 5 fs shown in (g)

Due to nonlinear conditions of the system, the temporal and the spatial shape of the soliton signals would be unchanged during the propagations [25]. The soliton signals experience less loss during the transmission, where they are more stable compared to normal conventional laser pulses. Considering the MRR system shown in Figure 1, the temporal and spatial profile of the input dark soliton pulse can be seen from Figure 5, where it has a 350 mW power with central wavelength of 1.3 µm. The ring radii of the rings are selected to R_1=30µm, R_2=12µm and R_3=5µm, where κ_1=0.7, κ_2=0.9 and κ_3=0.93.

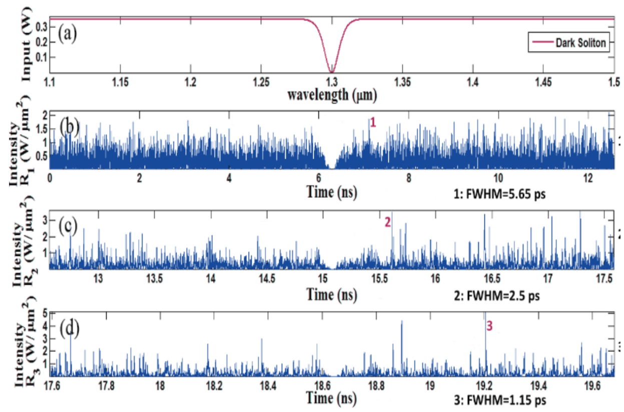


Figure 5 Simulation results of temporal chaotic signal generation within a series of MRR with dark soliton input

Using the system of MRRs shown in Figure 6, a soliton pulse with power at 800 mW is input into the system.

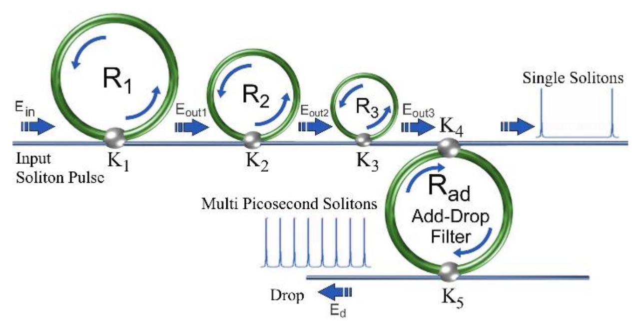


Figure 6 Series of MRRs connected to an add/drop filter system

Here, a series of MRRs are connected to an add/drop system. The selected parameters of the system are fixed to λ_0=1.55 µm, n_0=3.34 (InGaAsP/InP), A_{eff}=0.50, 0.25 and 0.12 µm^2 for different radii of MRRs respectively, α=0.5dBmm^{-1}, γ=0.1. The coupling coefficient (κ) ranges from 0.1 to 0.7. By increasing the radius of the add/drop system, the shorter soliton bandwidth and highly multi picosecond soliton pulses can be generated. Figure 7(d) shows the generation of 16 ps soliton pulses. Figure 5(e-f) shows the generation of ultra-short multi picosecond (1.3 and 1.2 ps), where the radius of the add/drop system has been selected to 50 and 300 µm respectively.

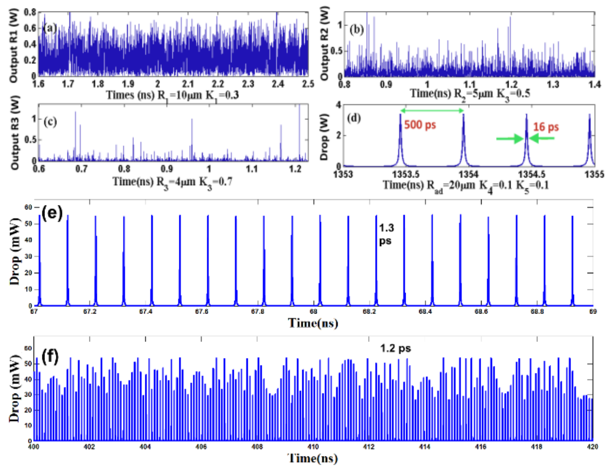


Figure 7 Picosecond soliton generation, where (a): Output from ring resonator (R_1), (b): Output from ring resonator (R_2), (c): Output from ring resonator (R_3), (d): Generation of 16 ps bandwidth soliton pulse, (e): Generation of 1.3 ps bandwidth soliton pulse, where R_{ad}=50 µm, (f): Generation of 1.2 ps bandwidth soliton pulse, where R_{ad}=300 µm

4.0 CONCLUSION

Integrated photonics MRRs have already been proposed for various interesting applications, including ultrafast pulse shaping and all-optical quantum memories. We have shown that the localized optical soliton can be generated and detected via MRR systems made of semiconductor waveguides. The required channels can be obtained by inserting the bright/dark soliton pulses into the series of MRRs. An add/drop system can be connected to the MRRs in order to generate highly ultra-short picosecond soliton pulses. The results obtained have shown that the optical solitons can be localized and stopped within the system to form the ultra-short pico and femtosecond soliton pulses. Here the temporal soliton of 200, 5 fs and 16, 5.65, 2.5, 1.3, 1.2, 1.15 ps could be generated. The results of the pico/femtosecond optical soliton are generated based on the iterative method theory, in which a number of experimental and practical parameters are employed.

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