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Bright and Dark Soliton Stopping using Nonlinear Waveguide

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Abstract

In this study we propose an interesting system in which a bright and dark soliton pulse can be stopped within a nonlinear nano-waveguide. The system consists of micro and nano ring resonators, in which soliton pulse is input into the system and stopped pulse can be achieved within the nonlinear waveguide. A soliton input is chopped by the nonlinear effects into smaller pulses (chaos). The required pulse is filtered and amplified, which can be controlled and localized within the nonlinear waveguide. The localized bright and dark solitons are stopped by controlling the input power, which means that the photons stopping is controlled by light.

Keywords: Dark soliton; Bright soliton, Nonlinear nano waveguide, Stopped light,

1. Introduction

Recent work of stopping light was proposed, where the general analysis for the criteria to stop and store light coherently using the micro-cavity array was proposed by Yanik and Fan [1,2]. However, the system is complicated, which makes it difficult to implement the realistic work. Yupapin and Pornsuwancharoen [3] proved that the large bandwidth light pulses can be achieved, compressed and stored coherently within a nonlinear waveguide, whereas the use of such a proposed device in many applications has been reported [4,5]. Bright and dark solitary waves are commonly induced by the nonlinear effects and the external soliton pumping power [6]. The study of dark and bright soliton behaviors in different forms in both theories and experiment [7] has been presented. The use of soliton such as bright in long-distance communication link, has been implemented for nearly two decades; however, the interesting works use bright soliton in communication remain, whereas the use of a soliton pulse within a nonlinear waveguide for communication security has been investigated [8]. The interesting results are performed when the

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technique is used within a tiny device such as micro and nano ring resonators. In fact soliton penalty in nonlinear waveguide can be used as benefit. Yupapin and his group [7,9] have reported the interesting results of light pulse propagating within a nonlinear micro-ring device, where the transfer function of the output at resonant condition is derived and used. They found that the broad spectrum of light pulse can be transformed to the discrete pulses.

In this paper, we design a system using the nonlinear behaviors for bright and dark solitons trapping within a micro and nano ring resonators, where the bright and dark solitons can be controlled and slowed within the waveguide, which can be used as an optical memory. Bright and dark soliton behaviors within a micro and nano ring resonator are also investigated and described.

2. Principle Operation

Optical soliton is a powerful laser pulse that is used to enlarge the optical bandwidth when propagating within the nonlinear waveguide. Moreover, the superposition of self-phase modulation (SPM) soliton pulses can keep the large output power [10]. First the optimum energy is split into the waveguide by a lager effective core area device, i.e. ring resonator. The smaller ring is connected to the system to form the stopping behaviour of soliton. To maintain the soliton pulse propagating within the ring resonator, suitable coupling power into the device is required, whereas the interference signal is a minor effect compared to the loss associated with the direct passing through. Bright and dark soliton pulses are introduced into the multi-stage nano-ring resonators as shown in Fig. 1. The input optical field (E_{in}) of the bright and dark soliton pulses input is given by Equations. (1) and (2) [11].

$$E_{in} \quad A\,\mathrm{sec}h\left[\frac{T}{T_0}\right]\exp\left[\left(\frac{z}{2L_D}\right) \quad i\omega_0 t\right] \tag{1}$$

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

where A and z are the optical field amplitude and propagation distance, respectively. T is a soliton pulse propagation time in a frame moving at the group velocity $T=t-\beta_1 z$, where β_1 and β_2 are, respectively, the coefficients of the linear and the second order terms of Taylor expansion of the propagation constant. $L_D=T_0^2/|\beta_2|$ is the dispersion length of the soliton pulse, where T_0 is the soliton pulse propagation time at initial input. t is the soliton phase shift time, and the frequency shift of the soliton is ω_0. This solution describes a pulse that keeps its temporal width invariance as it propagates, and thus is called a temporal soliton. When a soliton peak intensity ($|\beta_2/\Gamma T_0^2|$) is given, then T_0 is known. For the soliton pulse in the micro-ring device, a balance should be achieved between the dispersion length (L_D) and the nonlinear length ($L_{NL}=1/\Gamma\varphi_{NL}$), where $\Gamma=n_2k_0$ is the length scale over which dispersive or nonlinear effects make the beam wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear lengths; hence $L_D=L_{NL}$.

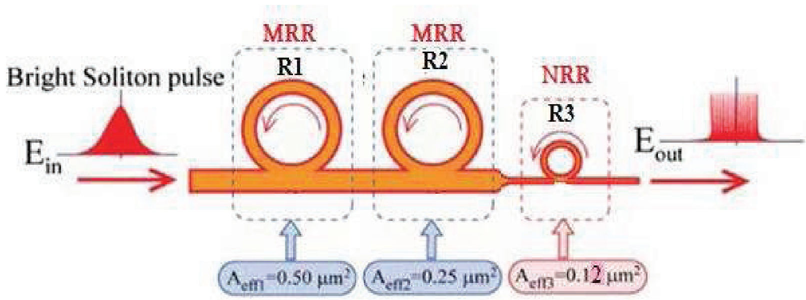

Fig. 1. A schematic of optical bright soliton pulse systems, R_s: ring radii, κ_s: coupling coefficients, MRR: micro-ring resonator and NRR: nano-ring resonator.

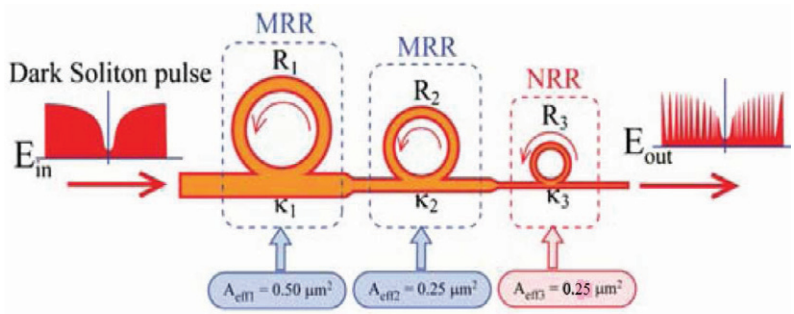

Fig. 2. A schematic of optical dark soliton pulse systems, R_s: ring radii, κ_s: coupling coefficients, MRR: micro-ring resonator and NRR: nano-ring resonator.

When light propagates within the nonlinear material (medium), the refractive index (n) of light within the medium is given by

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

where n_0 and n_2 are the linear and nonlinear refractive indices, respectively and I and P are the optical intensity and optical power, respectively. The effective mode core area of the device is given by A_{eff}. For the micro-ring and the nano-ring resonators, the effective mode core areas range from 0.12 to 0.50 μm^2 [4].

Soliton pulse is input and propagated within a micro-ring resonator as shown in Figs. 1 and 2. The system consists of a series of micro and nano ring resonators. The normalized output of the light field is the ratio between the output and the input fields ($E_{\mathrm{out}}(t)$ and $E_{\mathrm{in}}(t)$) in each roundtrip, which can be expressed as

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

The close form of Eq. (4) indicates that a ring resonator in the particular case is very similar to a Fabry–Perot cavity, which has an input and output mirror with a field reflectivity ($1-\kappa$), and a fully reflecting mirror. κ is the coupling coefficient, and $x=\exp(-\alpha L/2)$ represents a roundtrip loss coefficient, $\varphi_0=kLn_0$ and $\varphi_{\mathrm{NL}}=kLn_2|E_{\mathrm{in}}|^2$ are the linear and the nonlinear phase shifts, respectively, $k=2\pi/\lambda$ is the wave propagation number in vacuum and L and α are the waveguide length and linear absorption coefficient, respectively [12,13].

The results obtained use dark and bright solitons [7]. The bright soliton with pulse with of 20 ns and peak power of 500 mW is input into the system. Suitable ring parameters are used, for instance, ring radii R_1=16.0 μm, R_2=16.5 μm and R_3=4 μm. In order to make the system associate with the practical device [3], the selected parameters of the system are fixed to λ_0=1555 nm, n_0=3.34 (InGaAsP/InP), A_{eff}=0.50 μm^2, 0.25 μm^2 and 0.12 μm^2 for a micro-ring and nano-ring resonator, α=0.5 dB mm^{-1} and γ=0.1. The coupling coefficient (kappa, κ) of the micro-ring resonator ranged from 0.3 to 0.975. The nonlinear refractive index is $n_2=2.2\times10^{-17}$ m^2/W. In this case, the wave-guided loss used is 0.5 dB mm^{-1}.

The input soliton pulse is chopped (sliced) into smaller signal spreading over the spectrum as shown in Figs. 3(b) and 4(b). Here the large bandwidth signals are generated within the first ring device. The large bandwidth signals do not occur when the Gaussian pulse are input into the same system. Figs. 3(c) and (d) and 4(c) and (d) show the decrease in the spectral width of the output signals.

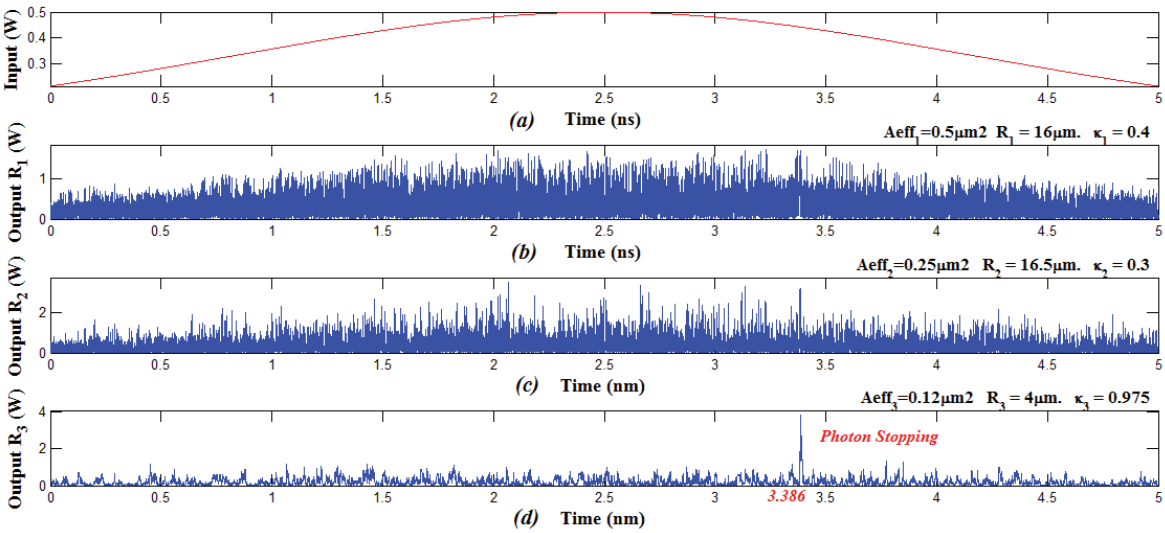

Fig. 3. Simulation signals, with (a) an input bright soliton pulse, (b) large bandwidth signals, (c) decreased spectral width signals and (d) stopping of photon at 3.386 ns

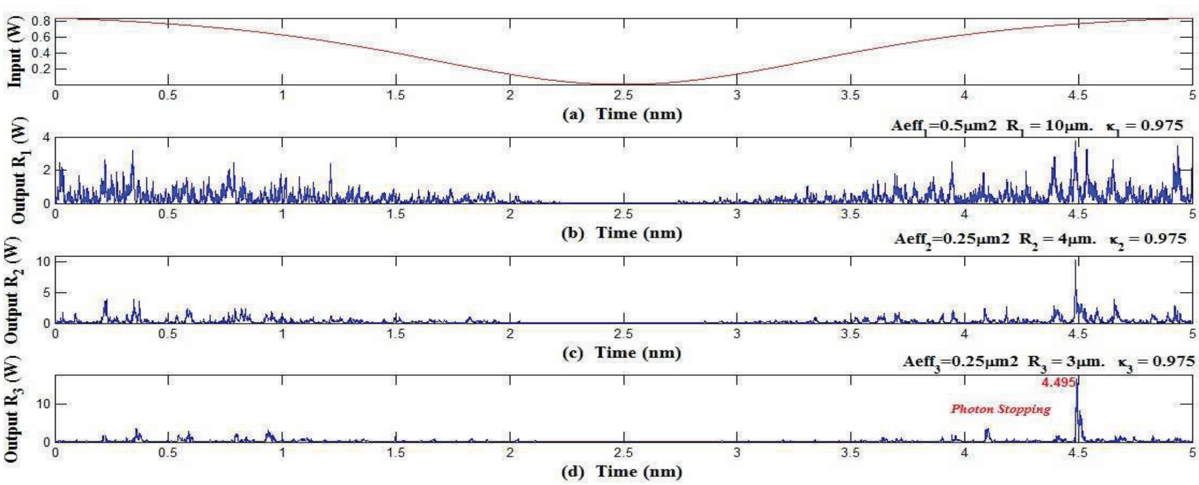

Fig. 4. Simulation signals, with (a) an input dark soliton pulse, (b) large bandwidth signals, and (c) decreased spectral width signals and (d) stopping of photon at 4.495 ns

Fig. 3 and Fig. 4 show the results obtained when bright and dark soliton pulses are input into a micro and nano ring resonator systems. The radii of the rings in proposed system shown in Fig. 2 are R_1=10 μm, R_2=4 μm, R_3=3 where the center wavelength at 1555 nm is input to the system. The dark soliton with pulse with of 20 ns and peak power of 800 mW is input into the system. The coupling coefficient is kept to constant value as $\kappa_1=\kappa_2=\kappa_3=0.975$.

The coupling loss is introduced due to the different core effective areas between micro and nano ring devices. The localized photon at 3.386ns and 4.495ns are achieved for the bright and dark solitons respectively. However, the other ring parameters are also very important to occurrence of the stopping light pulse behavior. In principle, the soliton behavior known as self-phase modulation (SPM) is performed when the balance between the dispersion and the nonlinear length phase shift occurs. Finally, light pulse is slowed down and stopped within a ring $R_{3.}$ The output energy of ring R_3 can be attenuated and made to reach the value that can be used for the next storing input power, which is applicable in the optical memory. In principle, the amplification within a nano ring device can be obtained and used for many application in optical communication network.

3. Conclusion

As conclusion, we have shown that the large bandwidth of the arbitrary wavelength of a soliton pulse can be compressed and stopped within a nano-waveguide, which is available for storing either bright or dark soliton pulses. The optical soliton can be slowed down and stopped coherently within the nonlinear nano-waveguide when the balancing between dispersion and nonlinear length is exhibited. Here the results obtained show that a bright and dark solitons are slowed down inside the nonlinear waveguide where the stopped soliton pulse at 3.386 ns and 4.495 ns are achieved respectively. The obtained results can be used for furthermore applications in communication network as optical memory.

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