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Novel All-optical Flip-Flop using Dark-Bright Soliton Conversion Control

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Abstract: This study proposed a new design for all-optical S-R and D flip-flop using optical technique namely dark-bright soliton conversion control within an optical add-drop filter. In operation, all-optical data input logic '0', '1' is formed by dark soliton (D) and bright soliton (B) pulses, respectively. The conversion behavior between dark and bright soliton pulses can be obtained and formed the logic pulses by a $\pi/2$ phase shifted optical coupler device. The binary logic operation can be formed simultaneously at the through and drop ports, respectively. In application, the proposed scheme can be recognized as a simple and flexible system for forming the logic switching system. Numerical simulation results are obtained and confirmed for the useful application of an advanced logical system can be operated.

Key words: All-optical flip-flop, optical computing, digital optics, add-drop filter

INTRODUCTION

One of the most important information technologies today is to find a more efficient way to store and process digital information. All-optical technologies represent the main aim for future of computation and communication system, in which different architectures, algorithms, logical and arithmetic operations have been proposed, in which the use of the systems such as an all-optical adder/subtractor (Pahari *et al*., 2004; Phongsanam *et al*., 2011; Poustie *et al*., 1999a), systems of Semiconductor Optical Amplifier (SOA) (Berrettini *et al*., 2006; Cong *et al*., 2009; Hun *et al*., 2002; Kim *et al*., 2003, 2005), a quantum dot (Kawazoe *et al*., 2006; Ma *et al*., 2010), a Terahertz Optical Asymmetric Demultiplexer (TOAD) (Maity *et al*., 2010; Poustie *et al*., 1999b; Roy and Gayen, 2007), cascaded microring resonators (Zhang *et al*., 2010), an all-optical arithmetic unit (Gayen and Roy, 2008; Roy *et al*., 2007), an all-optical binary counter (Poustie *et al*., 2000) has been reported. However, these systems tend to be complex and most do not lend themselves to minimization. Therefore, the search of new materials and techniques has become the challenge, where the use of ring resonator system and dark-bright soliton conversion (Mitatha, 2009; Sarapat *et al*., 2009) behaviors are recognized and recommended for such applications.

An all-optical flip-flop is the packet switches for the next generation of communication networks. The flip-flop is a logic gate that maintains a stable state output even after the input is turned off. The key basic function is represented by the logic gates (NOR, NAND). To date, an all-optical flip-flop is the essential component for latching functions in ultrahigh speed all-optical processing applications (Hill *et al*., 2001, 2004; Liu *et al*., 2010; Ramos *et al*., 2005). Currently, many systems such as a Terahertz Optical Asymmetric Demultiplexer (TOAD) (Maity *et al*., 2010), semiconductor optical amplifier (Mahran *et al*., 2012; Malacarne *et al*., 2007; Song *et al*., 2007), Fabry-Perot laser diode (Jeong *et al*., 2006), ring lasers (Tangdiongga *et al*., 2005), photonic crystals (Chen *et al*., 2011; Shinya *et al*., 2006), DBR laser diode (Huybrechts *et al*., 2009; Sundararajan *et al*., 2009) have been used. In this study, we propose an all-optical flip-flop circuit for logical processing operation which can be used for an electronic circuit replacement (Mukhopadhyay *et al*., 1993; Pahari *et al*., 2004; Peyghambarian and Gibbs, 1985; Rumelhart and McClelland, 1986) based on dark-bright soliton conversion control (Mitatha, 2009; Sarapat *et al*., 2009). In this concept, the all-optical flip-flop operation of binary using dark-bright soliton conversion behaviors can be performed. The coincidence dark and bright soliton pulses can be separated after propagating into the $\pi/2$ phase

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shifted optical coupler device (Sarapat *et al*., 2009). From the obtained results, the through and drop signals are the invert signals, for instance, when the through port signal is bright soliton, the drop port signal is dark. The proposed scheme is based on a 1 bit binary for the complex logic circuits which can be compared by any 2 bits, when logic ‘0’ and ‘1’ are formed by dark and bright soliton pulses, respectively.

DARK-BRIGHT SOLITON CONVERSION

The operation of dark-bright soliton conversion (Mitatha *et al*., 2009a) uses a ring resonator as shown in Fig. 1. In this case the dark-bright soliton conversion system (Juleang *et al*., 2011; Phatharaworamet *et al*., 2010) in an Optical Channel Dropping Filter (OCDF) (Absil *et al*., 2001; Grover *et al*., 2001; Mitatha *et al*., 2009b; Van *et al*., 2002; Yupapin and Pornsuwancharoen, 2008) comprises of two set of coupled waveguide, as shown in Fig. 1a and b. For convenience, Fig. 1b is replaced by Fig. 1a. The relative phase of the two output light signals after coupling into the optical coupler is π/2 before coupling into the ring and the input bus, respectively. This means that the signals coupled into the drop and through ports acquires a phase of π with respect to the input port signal. In application, if the coupling coefficients are formed appropriately, the field coupled into the through port would completely extinguish the resonant wavelength and all power would be coupled into the drop port. Then, the dark-bright conversion behaviors can be described by Eq. 1-8:

$$E_{ra} = -j\kappa_1 E_i + \tau_1 E_{rd} \tag{1}$$

$$E_{rb} = \exp(j\omega T/2)\exp(-\alpha L/4)\, E_{ra} \tag{2}$$

$$E_{rc} = \tau_2 E_{rb} - j\kappa_2 E_a \tag{3}$$

$$E_{rd} = \exp(j\omega T/2)\exp(-\alpha L/4)\, E_{rc} \tag{4}$$

$$E_t = \tau_1 E_i - j\kappa_1 E_{rd} \tag{5}$$

$$E_d = \tau_2 E_1 - j\kappa_2 E_{rb} \tag{6}$$

where, E_i is the input field, E_a is the added(control) field, E_t is the throughput field, E_d is the dropped field, $E_{ra}...E_{rd}$ are the fields in the ring at the point a...d, κ is the field coupling coefficient between the input and the ring, κ_2 is the field coupling coefficient between the ring and the output bus, L is the circumference of the ring (2πr), T is the time taken for one round trip, $T = Ln_{eff}/c$ and α is the power loss in the ring per unit length. We assume that there is a lossless coupling, i.e., $\tau_{1,2} = \sqrt{1-\kappa_{1,2}^2}$.

The output power/intensities at the drop port and through port can be written as:

$$|E_d|^2 = \left| \frac{-\kappa_1\kappa_2 A_{1/2}\Phi_{1/2}}{1-\tau_1\tau_2 A\Phi} E_i + \frac{\tau_2 - \tau_1 A\Phi}{1-\tau_1\tau_2 A\Phi} E_a \right|^2 \tag{7}$$

$$|E_t|^2 = \left| \frac{\tau_2 - \tau_1 A\Phi}{1-\tau_1\tau_2 A\Phi} E_i + \frac{-\kappa_1\kappa_2 A_{1/2}\Phi_{1/2}}{1-\tau_1\tau_2 A\Phi} E_a \right|^2 \tag{8}$$

where, $A_{1/2} = \exp(-\alpha L/4)$ (the half-round-trip amplitude), $A = A_{1/2}^2$, $\Phi_{1/2} = \exp(j\omega T/2)$ (the half-round-trip phase contribution) and $\Phi = \Phi_{1/2}^2$.

The input and control fields at the input and add ports are formed by the dark and bright optical soliton pulses as shown in Eq. 9-10 (Sarapat *et al*., 2009):

$$E_{in}(t) = A_0 \tanh\left[\frac{T}{T_0}\right] \exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right] \tag{9}$$

$$E_{in}(t) = A_0 \operatorname{sech}\left[\frac{T}{T_0}\right] \exp\left[\left(\frac{z}{2L_D}\right) - i\omega_0 t\right] \tag{10}$$

where, A and Z are optical field amplitude and propagation distance, respectively. T is soliton pulse propagation time in a frame moving at the group velocity $T = t-\beta_1 z$, where β_1 and β_2 are the coefficients of the linear and 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. T_0 in Eq. 9 and 10 are the initial soliton pulse width, where 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

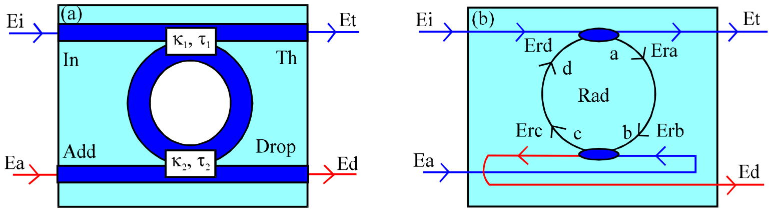

Fig. 1(a-b): A schematic diagram of the dark-bright soliton conversion control as it propagates and thus is called a temporal soliton. When the soliton peak intensity $(\beta/\Gamma T_0^2)$ is given, then T_0 is known. For the soliton pulse in the nanoring device, a balance should be achieved between the dispersion length (L_D) and nonlinear length, $L_{NL} = (1/\Gamma\phi_{NL})$ where, $\Gamma = n_2k_0$, is the length scale over which dispersive or nonlinear effects make the beam become wider or narrower. For a soliton pulse, there is a balance between dispersion and nonlinear lengths, hence, $L_D = L_{NL}$.

When light propagates within the nonlinear material (medium), the refractive index (n) of light within the medium is given by Eq. 11:

$$n = n_0 + n_2 I = n_0 + \frac{n_2}{A_{eff}} P \tag{11}$$

where, n_0 and n_2 are the linear and nonlinear refractive indexes, respectively. 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/nanoring resonator, the effective mode core areas range from 0.10-0.50 μm². The resonant output of the light field is the ratio between the output and input fields [$E_{out}(t)$ and $E_{in}(t)$] in each round-trip which is given by references (Juleang *et al*., 2011; Mitatha *et al*., 2009a; Phatharaworamet *et al*., 2010; Yupapin *et al*., 2008).

All-optical flip-flop operation: In principle, a soliton is very narrow pulse width which works well for ultrafast switching. It can be used to manipulate the wave form and amplitude. A dark-bright soliton pair is a coincident match pare and it is better to represent logic '0' and '1', respectively. A flip-flop circuit can maintain a binary state with two stable states. The electronic circuit flip-flop is formed by two different gates (NOR, NAND). In this paper, the basic flip-flop (S-R flip-flop, D flip-flop) using dark-bright soliton conversion control as NOT gate is designed and proposed.

All-optical S-R flip-flop: S-R flip-flop is the cross-coupled NOR or two cross-coupled NAND gates which is shown in Fig. 2a and b, respectively. It has two input signals, where one is S, the other is R for setting, resetting the outputs Q_{n+1} and $\bar{Q}_{n+1}$, respectively. The S-R flip-flop outputs are the feedback signals. There are three status logic output signals called "Hold" when there is no input signal (S = 0, R = 0), "Set" when S = 1 and R = 0, "Reset" when S = 0, R = 1, respectively. The proposed scheme for all-optical S-R flip-flop using Beam Splitter (BS) and Beam Combiner (BC) is as shown in Fig. 2c. The input logic '1' is formed by bright soliton and logic '0' is formed by the absence of the input signal. The other technique that can be used to form a similar operation (Maity *et al*., 2010), in which the optical power signal is manipulated by Erbium Doped Fiber Amplifier (EDFA) (Malacarne *et al*., 2008).

In simulation, the add/drop optical filter (Mookherjea and Schneider, 2008; Wang *et al*., 2009; Xu *et al*., 2008) fixed parameters used are $\kappa_S = 0.5$, $R_{ad} = 1.5$ μm, $A_{eff} = 0.25$ μm², $\alpha = 0.5$ dB mm^{-1}, $\gamma = 0.01$, $n_{eff} = 3.14$ (for InGaAsP/InP) for all add/drop optical filters in the system. Results of the all-optical flip-flop are generated by the dark-bright soliton conversion behaviors, with wavelength center at $\lambda_0 = 1.50$ μm pulse width of 35 fs, the input data logic "0" and "1" are

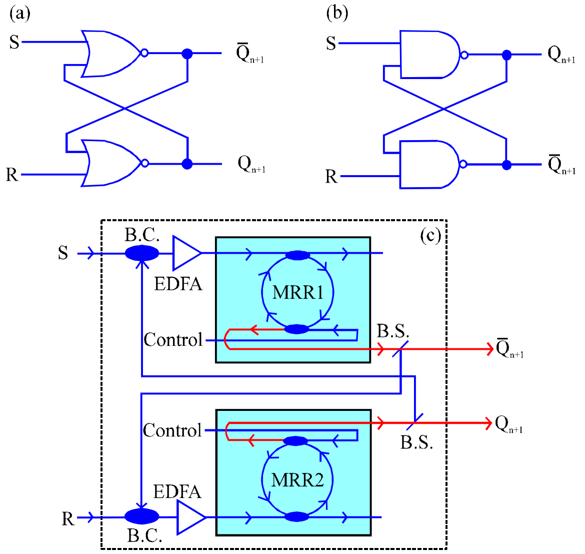

Fig. 2(a-c): Cross coupled gates of (a) NOR, (b) NAND and (c) Scheme of R-S flip-flop represented by the dark and bright soliton pulses, respectively. However, in practice, the time domain results can be obtained by using the term T = 1/f, where, T and f are a period and frequency of the signal. In Fig. 3, the simultaneous output optical logic is seen which can be configured as follows.

- **Case 1:** When there is no input signal, S = R = 0, in which Q_{n+1} and $\bar{Q}_{n+1}$ are not interchangeable. This is the "Hold" state
- **Case 2:** By using the dark-bright soliton conversion behavior, when S = 0 and R = 1, the input logic '0' and '1' formed by the dark-bright soliton, where both input signals are converted to dark-bright soliton pulses with a π phase shift. The detector D2 receives the logic '0' (dark soliton), i.e., $Q_{n+1} = 0$ which is connected to the input 'S', then allowing the dark-bright soliton conversion with π phase shift to be operated again. When the detector D1 receives the logic '1' (bright soliton), then $\bar{Q}_{n+1} = 1$ (Fig. 4), in which Q_{n+1} and $\bar{Q}_{n+1}$ are connected to the input 'S' and 'R', respectively. Therefore, if both 'S' and 'R' have no input signals, i.e., S = R = 0, then Q_{n+1} and $\bar{Q}_{n+1}$ acts as the feedback signals known as the "Reset" state

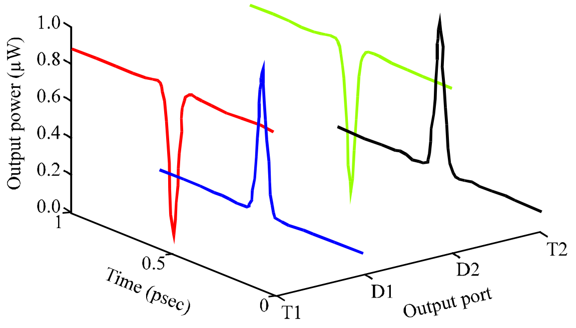

Fig. 3: The optical output when "Reset" state

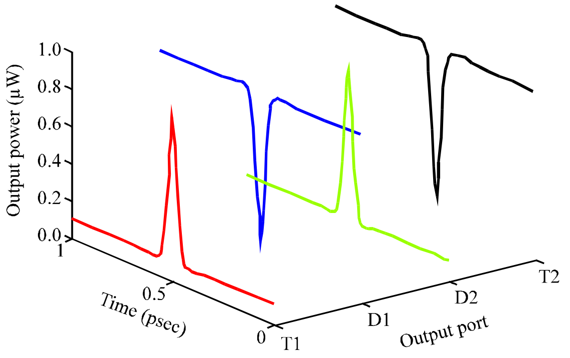

Fig. 4: The optical output when "Set" state

- **Case 3:** If S = 1 and R = 0, the logic '0' and '1' is formed by dark-bright soliton, where in which both input signals are converted to dark-bright soliton with π phase shift. When D1 receives the logic '0' (dark soliton) i.e., $\bar{Q}_{n+1} = 0$ and is connected to the input 'R', then the dark-bright soliton conversion with π phase shift is formed. When the detector D2 receives the logic '1' (bright soliton), hence, $Q_{n+1} = 1$ (Fig. 4), where Q_{n+1} and $\bar{Q}_{n+1}$ are connected to the input 'S' and 'R', respectively. Therefore, if both 'S' and 'R' are without any input signals, i.e., S = R = 0, then Q_{n+1} and $\bar{Q}_{n+1}$ becomes the feedback signals which is called the "Set" state
- **Case 4:** When S = R = 1 then both MRR1 and MRR2 receive both the incoming bright soliton signals, i.e., $Q_{n+1} = \bar{Q}_{n+1} = 1$ (Fig. 5). This is called the "Forbidden" state

The truth table for output of the one bit binary R-S flip-flop is summarized in Table 1. The hold state, there is no signal in the other state, the dark soliton is used for a logic '0', the bright soliton is used for a logic '1'.

All-optical D flip-flop: In this study, the S-R flip-flop is the basic flip-flop for other constructed flip-flop, for examples, D, J-K and T. In this study, the D flip-flop is constructed by using the S-R flip-flop, in which the other type of flip-flop can be formed by using the other module. All-optical D flip-flop using dark-bright soliton conversion control can be constructed by S-R flip-flop as shown in Fig. 6. When the incoming signal logic '0' and '1' are formed by dark soliton (D) and bright soliton (B) pulses, respectively, the logic status can be described in the following manner:

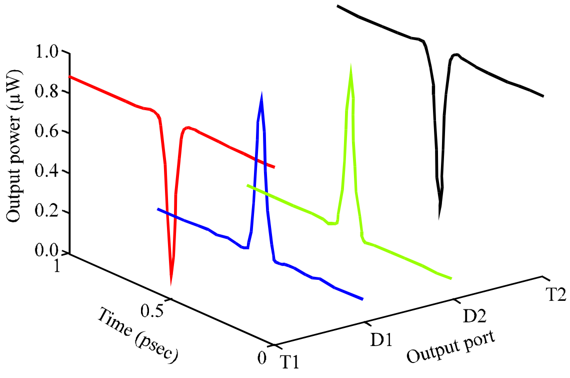

Fig. 5: The optical output when "Forbidden" state

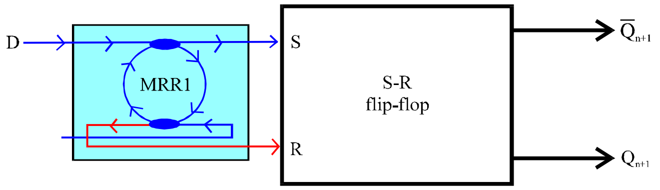

Fig. 6: All-optical D flip-flop

Table 1: Conclusion output of binary R-S flip-flop

Input		Output		
S	R	Q_{n+1}	$\overline{Q}_{n+1}$	State
0	0	Q_n	$\overline{Q}_n$	Hold
0	1	0	1	Reset
1	0	1	0	Set
1	1	1	1	Forbidden

Logic 0: Dark soliton, absence input signal, logic 1: Bright soliton

Table 2: Conclusion output of All-optical D flip-flop

Input	Output		
D	Q_{n+1}	$\overline{Q}_{n+1}$	State
0	0	1	Reset
1	1	0	Set

Logic 0: Dark soliton, logic 1: Bright soliton

- **Case 1:** When the input D = 0 (dark soliton), the soliton input logic is converted to dark and bright soliton with π phase shift at D1, T1, respectively. From the properties of S-R flip-flop discussed in Sect.3, i.e., Q_{n+1} =1 and $\overline{Q}_{n+1}$ = 0, respectively. This state is called the "Reset"
- **Case 2:** If the input D = 1 (bright soliton), the soliton input logic is converted to dark and bright soliton with π phase shift at D1, T1, respectively. The properties of S-R flip-flop gives Q_{n+1} = 0 and $\overline{Q}_{n+1}$ = 1, respectively. This state is called the "Set"

The truth table for output of the one bit binary D flip-flop is summarized in Table 2.

CONCLUSION

We proposed new design for basic all-optical flip-flop operations based on dark-bright soliton conversion control system via the modified add/drop filters for ultrahigh speed memory or signal processing application. Based on the dark-bright soliton conversion control concept, the data logic '0' (dark soliton) and '1' (bright soliton) based on all-optical in nature can be used to form the flip-flop operations. The logic status results can be obtained simultaneously at the drop and through ports, respectively. From Fig. 2, D1 is $\overline{Q}_{n+1}$, D2 is Q_{n+1}, where T1, T2 are unused. Therefore, the proposed design can be used for logical circuit. This is a simple and flexible system for performing the logic switching operators. Moreover, such device can be extended and implemented for any flip-flop such as S-R, D, T and J-K flip-flop by proper incorporation of dark-bright soliton conversion control based optical switches for more advanced applications.

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