All-optical logic XOR/XNOR gate operation using microring and nanoring resonators

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Abstract

In this paper, a novel system of simultaneous optical logic AND and OR gates using dark-bright soliton conversion within the add/drop optical filter system is proposed. The input logic ‘0’ and control logic ‘0’ are formed by using the dark soliton pulse (D) trains. By using the dark-bright soliton conversion behavior within the π/2 phase shift device, we found that the simultaneous optical logic AND and OR gates at the drop and through ports can be randomly formed, respectively.

Keywords: All-optical logic gate; Dark-bright soliton conversion; Add/drop optical filter; Photonic circuits

1. Introduction

To date, many researchers have demonstrated the interesting techniques that can be used to realize the various optical logic functions (i.e. AND, NAND, OR, XOR, XNOR, NOR) by using different schemes, including thermo-optic effect in two cascaded microring resonator [1], quantum dot [2, 3], semiconductor optical amplifier (SOA) [4-11], TOAD-based interferometer device [12], nonlinear effects in SOI waveguide [13, 14], nonlinear loop mirror [15,16], DPSK format [17,18], local nonlinear in MZI [19], photonic crystal [20, 21], error correction in multipath differential demodulation [22], fiber optical parametric amplifier [23], multimode interference in SiGe/Si [24], polarization and optical processor [25], and injection-locking effect in semiconductor laser [26]. However, the search for new techniques remains and there are some rooms for new techniques that can be used to be the good candidate. Therefore, in this work, we propose the use of the simultaneous arbitrary two-input logic XOR/XNOR and all-optical logic gates based on dark-bright soliton conversion within the add/drop optical filter system. The advantage of the scheme is that the random codes can be generated simultaneously by using the dark-bright soliton conversion behavior, in which the coincidence dark and bright soliton can be separated after propagating into a π/2 phase retarder, which can be used to form the security codes. Moreover, this is a simple and flexible scheme for an arbitrary logic switching system, which can be used to form the advanced complex logic circuits. The proposed scheme is based on a 1 bit binary comparison XOR/XNOR scheme that can be compared to any 2 bits, i.e., between 0 and 0 (dark-dark solitons), 0 and 1 (dark-bright solitons), 1 and 0 (bright-dark solitons) or 1 and 1 (bright-bright solitons), which will be detailed in the next section.

2. Dark-bright soliton conversion mechanism

In operation, dark-bright soliton conversion using a ring resonator optical channel dropping filter (OCDF) is composed of two sets of coupled waveguides, as shown in Figure 1(a) and 1(b), where for convenience, Figure 1(b) is replaced by Figure 1(a). 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 acquire a phase of π with respect to the input port signal. In application, if we engineer the coupling coefficients appropriately, the field coupled into the through port on
resonance would completely extinguish the resonant wavelength, and all power would be coupled into the drop port. We will show that this is possible later in this section.

\[ E_{i_a} = -j \kappa_1 E_i + \tau_1 E_{d_a}, \]  
(1)

\[ E_{s_b} = \exp(j \omega T/2) \exp(-\alpha L/4) E_{i_a}, \]  
(2)

\[ E_{s_c} = \tau_2 E_{s_b} - j \kappa_2 E_{i_a}, \]  
(3)

\[ E_{d_d} = \exp(j \omega T/2) \exp(-\alpha L/4) E_{s_c}, \]  
(4)

\[ E_s = \tau_1 E_i - j \kappa_1 E_{d_a}, \]  
(5)

\[ E_d = \tau_2 E_i - j \kappa_2 E_{s_b}, \]  
(6)

where \( E_i \) is the input field, \( E_a \) is the add(control) field, \( E_t \) is the through field, \( E_d \) is the drop field, \( E_{a_s}, \ldots, E_{a_d} \) are the fields in the ring at points \( a_s, \ldots, d_s \), \( \kappa_1 \) is the field coupling coefficient between the input bus and ring, \( \kappa_2 \) is the field coupling coefficient between the input bus and ring, \( \alpha \) is the loss in the ring per unit length. We assume that this is the lossless coupling, i.e., \( \tau_{1,2} = \sqrt{1 - \kappa_{1,2}^2} \).

\[ T = L n_{gs} / c. \]  

The output power/intensities at the drop and through ports are given by

\[ |E_d|^2 = \frac{-\kappa_1 \kappa_2 A_{1/2} \Phi_{1/2}}{1 - \tau_1 \tau_2 A \Phi} E_i + \frac{\tau_2 - \tau_1 A \Phi}{1 - \tau_1 \tau_2 A \Phi} E_a. \]  
(7)

\[ |E_t|^2 = \frac{\tau_1 - \tau_2 A \Phi}{1 - \tau_1 \tau_2 A \Phi} E_i + \frac{-\kappa_1 \kappa_2 A_{1/2} \Phi_{1/2}}{1 - \tau_1 \tau_2 A \Phi} E_a. \]  
(8)

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

The input and control fields at the input and add ports are formed by the dark-bright optical soliton as shown in Equations (9) – (10),

\[ E_{in}(t) = A_0 \tanh \left( \frac{T}{T_0} \right) \exp \left( \frac{z}{2L_0} - i \omega t \right) \]  
(9)

\[ E_{in}(t) = A_0 \sech \left( \frac{T}{T_0} \right) \exp \left( \frac{z}{2L_0} - i \omega t \right) \]  
(10)

**Figure 1.** A schematic diagram of a simultaneous optical logic XOR and XNOR gate.
where $A_0$ and $z$ are the optical field amplitude and propagation distance, respectively. $T = t - \beta_1 z$, where $\beta_1$ and $\beta_2$ 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 equation is a soliton pulse propagation time at initial input (or soliton pulse width), where $t$ is the soliton phase shift time, and the frequency shift of the soliton is $\omega_0$. When the optical field is entered into the nanoring resonator as shown in Figure 2, where the coupling coefficient ratio $\kappa_1: \kappa_2$ are 50:50, 90:10, 10: 90. By using (a) dark soliton is input into input and control ports, (b) dark and bright soliton are used for input and control signals, (c) bright and dark soliton are used for input and control signals, and (d) bright soliton is used for input and control signals. The ring radii $R_{ad} = 300\text{nm}$, $A_{eff} = 0.25\mu\text{m}^2$, $n_{eff} = 3.14$ (for InGaAsP/InP), $\alpha = 0.1\text{dB/mm}$, $\gamma = 0.01$, $\lambda_0 = 1.55\mu\text{m}$.

### 3. Optical XOR/XNOR logic gate operation

The proposed architecture is schematically shown in Figure 1(c). A continuous optical wave with a wavelength of $\lambda$ is formed by an optical dark-bright soliton pulse train $X$ using MRR 1, in which the optical pulse trains that appear at the through and drop ports of MRR 1 are $\bar{X}$ and $X$, respectively ( $\bar{X}$ is the inverse of $X$ or dark-bright conversion). It is assumed that the input optical dark-bright soliton wave is directed to the drop port when the optical signal is 1 (dark soliton pulse). In other words, the MRR 1 resonates at $\lambda$ when the input dark soliton pulse is applied.

If the optical pulse train $X$ is fed into MRR 2 from its input port solely and is formed by an optical pulse train $Y$ bit by bit using MRR 2, where we assume that no signal is fed into MRR 2 from its add port, in which the optical pulse trains that appear at the through and drop ports of MRR 2 will be $\bar{X} \cdot \bar{Y}$ and $X \cdot Y$, respectively, whereas the aforementioned assumption is provided. The symbol represents the logical operation AND here.

If the optical pulse train $\bar{X}$ is fed into MRR 3 from its input port solely and is formed by an optical pulse train $Y$ bit by bit using MRR 3, where we assume that no signal is fed into MRR 3 from its input port, in which the optical pulse trains that appear at the through and drop ports of MRR 3 will be $\bar{X} \cdot Y$ and $\bar{X} \cdot \bar{Y}$, respectively, whereas the aforementioned assumption is provided. The symbol represents the logical operation OR here.

![Figure 2. Dark-bright soliton conversion results.](image-url)
pulse trains that appear at the through and drop ports of MRR 3 will be \( \overline{X} \cdot Y \) and \( \overline{X} \cdot \overline{Y} \), respectively. If the optical pulse trains \( X \) and \( \overline{X} \) are fed into MRR 2 and MRR 3 from its input ports simultaneously [see Figure 1(c)], in which the optical pulse trains \( X \cdot Y + \overline{X} \cdot Y \) and \( X \cdot Y + \overline{X} \cdot \overline{Y} \) are achieved at the through and drop ports of MRR 2 and MRR 3, respectively [see Figure 1(c)]. The symbol + represents the logical operation OR, which is implemented through the multiplexing function of MRR 2 and MRR 3. It is well known that the XOR and XNOR operations can be calculated by using the formulas

\[
\begin{align*}
X \oplus Y &= X \cdot Y + \overline{X} \cdot \overline{Y} \\
X \otimes Y &= X \cdot Y + \overline{X} \cdot \overline{Y}
\end{align*}
\]

where the capital letters represent logical variables and the symbols \( \oplus \) and \( \otimes \) represent the XOR and XNOR operators, respectively. Therefore, the proposed architecture can be used as an XOR and XNOR calculator.

By using the dynamic performance of the device as shown in Figure 3, two pseudo-random binary sequence \( 2^{n-1} \) signals at 100 Gbit/s are converted into two optical signals bit by bit according to the rule presented above and then applied to the corresponding MRRs. Clearly, a logic 1 is obtained when the applied optical bright soliton pulse signals, and a logic 0 is obtained when the applied optical dark soliton pulse signals are generated. Therefore, the device performs the XOR and XNOR operation correctly.

The proposed simultaneous all-optical logic XOR and XNOR gates device is as shown in Figure 1(c). The input and control light pulse trains are input into the first add/drop optical filter (MRR 1) using the dark solitons (logic ‘0’) or the bright solitons (logic ‘1’). Firstly, the dark soliton is converted into dark and bright soliton via the add/drop optical filter, which they can be seen at the through and drop ports with \( \pi \) phase shift [27], respectively. By using the add/drop optical filters (MRR 2 and MRR 3), both input signals are generated by the first stage add/drop optical filter. Next, the input data “Y” with logic “0” (dark soliton) and logic “1” (bright soliton) are added into both add ports, the dark-bright soliton conversion with \( \pi \) phase shift is operated again. For large scale (Figure 1(c)), results obtained are simultaneously seen by \( D_1, D_2, T_1, \) and \( T_2 \) at the drop and through ports for optical logic XNOR and XOR gates, respectively.

In simulation, the add/drop optical filter parameters are fixed for all coupling coefficients to be \( \kappa_l = 0.05 \), \( R_{ad} = 300 \text{nm} \), \( A_{eff} = 0.25 \mu \text{m}^2 \) [28], \( \alpha = 0.05 \text{dBmm}^{-1} \) for all add/drop optical filters in the system. Results of the simultaneous optical logic XOR and XNOR gates are generated by using dark-bright soliton conversion with wavelength center at \( \lambda_0 = 1.50 \mu \text{m} \), pulse width 35 fs. In Figure 4, simulation result of the simultaneous output optical logic gate is seen when the input data logic “00” is added, whereas the obtained output optical logic is “0011” [see Figure 4(a)]. Similarly, when the simultaneous output optical logic gate input data logic “01” is added, the output optical logic “0010” is formed [see Figure 4(b)]. Next, when the output optical logic gate input data logic “10” is added, the output optical logic “1000” is formed [see Figure 4(c)]. Finally, when the output optical logic input data logic

\[
\text{Figure 3. Output results dynamic performance of the device, when (a) data ‘X’, (b) data ‘Y’, (c) all-optical XOR and (d) XNOR logic gates.}
\]
“11” is added, we found that the output optical logic “0100” is obtained [see Figure 4(d)]. The simultaneous optical logic gate output is concluded in Table 1. We found that the output data logic in the drop ports, D₁, D₂ are optical logic XNOR gates, whereas the output data logic in the through ports, T₁ and T₂ are optical logic XOR gates, the switching time of 35.1 fs is noted.

4. Operation principle of simultaneous all-optical logic gates

The configuration of the proposed simultaneous all-optical logic gates is shown in Figure 5. The input and control light (“A”) pulse trains in the first add/drop optical filter (No. “01”) are the dark soliton (logic ‘0’). In the first stage of the add/drop filter, the dark-bright soliton conversion is seen at the through and drop ports with π phase shift, respectively. In the second stage (No.”11” and “12”), both inputs are generated by the first stage of the add/drop optical filter, in which the input data “B” with logic “0”(dark soliton) and logic “1”(bright soliton) are added into both add ports. The outputs of second stage are dark-bright soliton conversion with π phase shift again. In the third stage of the add/drop optical filter (No. “21” to “24”), the input data “C” with logic “0”(dark soliton) and logic “1”(bright soliton) are inserted into all final stage add ports. In the final stage of the add/drop optical filter (No. “31” to “38”), the input data “D” with logic “0”(dark soliton) and logic “1”(bright soliton) are inserted into all final stage add ports and outputs numbers 1 to 16 and shown simultaneously all-optical logic gate.

The simulation parameters of the add/drop optical filters are fixed for all coupling coefficients to be $\kappa_i = 0.05$, $R_{off} = 300nm$, $A_{eff} = 0.25 \mu m^2$ [27], and $\alpha = 0.05dB/mm^{-1}$ for all add/drop optical filter system. Simulation results of the simultaneous all-optical logic gates are generated by using the dark-bright soliton conversion at wavelength center $\lambda_0 = 1.50\mu m$, pulse width 35 fs. In Figure 6, the simulation result of simultaneous output optical logic gate when the input and control signals (‘A’) are dark solitons. Input data ‘BCD’ are (a) ‘DDD’, (b) ‘DBD’, (c) ‘DBD’, (d) ‘DBB’, (e) ‘BDD’, (f) ‘BDD’, (g) ‘BBD’ and (h) ‘BBB’, respectively. Results of all outputs are concluded as shown in Table 2 for all-optical logic gates.

| Table 1. Conclusion output optical logic XOR and XNOR gates. |
|---|---|---|---|---|---|---|
| Input data | Output logic |
| X | Y | (T₁)X·Y | D₁ | X·Y | T₂ | X·Y | D₂ | X·Y | XOR | X·Y + X·Y | XNOR | X·Y + X·Y |
| D | D | D | D | D | B | D | B | D | D |
| D | B | D | D | D | B | D | B | D | D |
| B | D | D | D | D | B | D | B | D | D |
| B | B | D | D | D | B | D | B | D | D |

‘D (Dark soliton)” = logic ‘0’, ‘B (Bright soliton)” = logic ‘1’.
Figure 5. A schematic of the proposed all-optical logic gate.

Figure 6. Simulation results of all-optical logic gate when the input and control signals (‘A’) is dark soliton. Input data ‘BCD’ are (a) ‘DDD’, (b) ‘DDB’, (c) ‘DBD’, (d) ‘DBB’, (e) ‘BDD’, (f) ‘BDB’, (g) ‘BBD’ and (h) ‘BBB’, respectively.
Figure 7. Simulation results of all-optical logic gate when the dark soliton input and control signal (‘A’) is bright soliton. The inputs ‘BCD’ are (a) ‘DDD’, (b) ‘DDB’, (c) ‘DBD’, (d) ‘DBB’, (e) ‘BDD’, (f) ‘BDB’, (g) ‘BBD’ and (h) ‘BBB’, respectively.

Table 2. Conclusion output results of all-optical logic gates.

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<th>“A”</th>
<th>Output Port No.</th>
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Colors: AND, NOR, XNOR, XOR, NAND, OR
5. Conclusions

We have proposed the novel technique that can be used to simultaneously generate the optical logic AND and OR gates using dark-bright soliton conversion within the add/drop optical filter system. By using the dark-bright soliton conversion concept, results obtained have shown that the input logic ‘0’ and control logic ‘0’ can be formed by using the dark soliton (D) pulse trains. We also found that the simultaneous optical logic AND and OR gates can be seen randomly at the drop and through ports, respectively, which has shown the potential of application for large scale use, especially, for security code application requirement.

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