皮秒量级的快速率可重构光混沌逻辑运算

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摘要：基于垂直腔表面发射激光器 (VCSEL) 自身的光反馈以及线性电光调制效应，设计了一种实现动态可重构的光混沌逻辑运算的技术方案。归一化注入电流被调制为逻辑输入，横向电场被调制为控制信号，逻辑输出通过读取 VCSEL 输出的 x 偏振光功率的均值与阈值微差进行解调。通过转换控制信号与逻辑输入的逻辑运算关系，系统就能在基本的逻辑运算如 NOT, AND, NAND, OR, NOR, XOR 以及 XNOR 间自由切换。当码元宽度为 600 ps 且噪声强度高达 2.75 × 10^9 情况下，逻辑运算的成功概率仍为 1，表明系统具有良好的抗噪声性能。并且噪声强度等于 2.5 × 10^9 时，当码元宽度至少达到 579 ps，逻辑运算的成功概率才为 1。本文研究对于研发快速稳定的组合逻辑运算器件等具有参考价值。

关键词：垂直腔表面发射激光器；可重构；光混沌逻辑运算；皮秒量级

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Reconfigurable Optical Chaotic Logic Operations with Fast Rate of Picoseconds Scale

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Abstract: In order to realize dynamic and reconfigurable optical chaotic logic operations, a specific technical scheme based on Vertical Cavity Surface Emitting Laser (VCSEL) feedback by its own light and linear electro-optic modulation effect has been proposed. The normalized injection current is modulated as logic input, the transverse electric field is modulated as control signal, and the logic output is demodulated by the difference between the average value and the threshold value of the x-polarized light intensity from the output of VCSEL. By transforming the logic operation relationship between control signal and logic input, the system can switch freely among basic logic operations such as NOT, AND, NAND, OR, NOR, XOR and XNOR. When the code width is 600 ps and the noise intensity is as high as 2.75 × 10^9, the success probability of the logic operation still equals 1, indicating that the system has good anti-noise performance. And when the noise intensity equals 2.5 × 10^9, the success probability always equals 1 if the code width is at least 579 ps. The above results have great reference value for the development of fast and...
stable combinational logic operation devices.

**Key words:** Vertical Cavity Surface Emitting Laser (VCSEL); Reconfigurable; Optical chaotic logic operation; Picoseconds scale

**OCIS Codes:** 060.4510; 140.1540; 140.3460; 140.3510

0 Introduction

With the rapid development of communication technology, optical communication has been widely used in the market because of its large communication capacity, low transmission loss, and large frequency bandwidth. The chaotic laser signal, which is highly sensitive to the initial conditions of the system and external interference, has strong randomness and is not easy to be deciphered. So now which it has been widely used in the field of secure optical communication. Meanwhile, the logic operations realized by chaotic signals generated by semiconductor lasers have attracted great attention currently. Compared with edge-emitting laser, Vertical Cavity Surface Emitting Laser (VCSEL) has the advantages of low production cost, small divergence angle, small size, and low threshold current \(^{[45]}\), etc. In addition, it can excite mutually orthogonal chaotic \(x\)-Polarized Light \((x\text{–PL})\) and chaotic \(y\)-Polarized Light \((y\text{–PL})\) under current or feedback injection of external light. The polarization switching and bistability can also be induced under suitable parameter conditions \(^{[22,23]}\). Based on VCSEL’s nonlinear dynamics, previous work has exploited different experimental schemes to realize optical logic gates. Based on polarization bistability, noise and tunable light injection, Masoller et al explored experimental schemes for random logic gate and all-optical logic gate \(^{[32,34]}\). For laser amplitude modulation based on coupled feedback and parallel synchronization of laser chaos, Yan realized photovoltaic composite logic gate and all-optical logic gate \(^{[2,34]}\). In 2015, our research group reported the experimental scheme of optoelectronic composite logic gate based on polarization switching in Optics Express \(^{[16]}\). In 2016, based on the generalized chaos synchronization theory and the polarization switching, we also realized the all-optical random logic gate \(^{[15]}\). In 2017, using frequency detuning to control polarization bistability, we further obtained dynamic all-optical chaotic logic operations \(^{[16]}\).

Most of the above solutions implemented static logic operations. In the past, our research group studied logic operations with code width of 10 ns (the operation rate is 0.1 GHz) \(^{[16]}\), the operation rate needs to be improved. Here in the paper, based on the theory of linear electro–optic modulation, reconfigurable chaotic logic operations with fast rate and good anti–noise performance are realized by the scheme of VCSEL feedback by its own light in this paper. The second part below describes the basic theory and model in detail, the third part shows the experimental results and discussion, and the fourth part is the conclusions.

1 Theory and model

The system composition and detailed light path are shown in Fig. 1. Here, the normalized injection current \(\mu\) is the sum of two square waves of \(d_{\text{a}}\) and \(d_{\text{b}}\) that encode two logic inputs \(I\) and \(I\) respectively, i.e., \(\mu = d_{\text{a}}(I) + d_{\text{b}}(I)\). The transverse electric field \(E_x\) is represented by a square wave that encode the control signal \(I\), the high level and low level of the square wave are represented by \(E_{\text{H}}\) and \(E_{\text{L}}\) respectively. When \(E_{\text{H}} = E_{\text{H}}\), \(I = 0\); and \(I = 1\) if \(E_{\text{H}} = E_{\text{L}}\). Supposing that the average value of \(x\text{–PL}\) intensity from the VCSEL defined as \(A\), its threshold is fixed at \(A\). The steps of realizing reconfigurable chaotic logic operations are as follows

1) The appropriate values for normalized injection current \(\mu(t)\) \([d_{\text{a}}(t), d_{\text{b}}(t)]\) and transverse electric field \(E_x(t)\) are selected to encode the logic inputs \([I(t), I(t)]\) and control signal \(L(t)\);

2) Add the normalized injection current and control signal, \(I(t) = I(t) + I(t)\) and \(L(t)\);

3) Use an electronic logic calculator to make \(I(t)\) and \(I(t)\) satisfying different logic operation relationships such as NOT, AND, NAND, OR, NOR, XOR and XNOR in different time periods; for the logic NOT operation, \(I(t) = I(t)\).

4) Calculate the average value \(A\) under each group of logic inputs.

5) Threshold mechanism for obtaining the logic output, i.e., with the fixed threshold \(A\), the logic out \(X = 0\) if \(A - A > 0\); \(X = 1\) if \(A - A > 0\).

Next, the working principle of the system is presented. The light emitted by VCSEL passes through the
Fiber Isolator (FI) and then is separated by the Fiber Polarization Beam Splitter (FPBS) into $x$-PL and $y$-PL. The $x$-PL is split into two beams by a Fiber Splitter (FPS). The electric signal is used to modulate the logic output through Subracter (SR). Another $x$-PL beam is directly injected into the PPLN crystal as $o$-light input. The $y$-PL converts the polarized direction to the direction of the $z$-axis of the crystal by Faraday Rotator 1 (FR 1) and Half-Wave Plate 1 (HWP 1), and then injects into crystal as $e$-light input. After linear electro-optic modulation, the $x$-PL output from the PPLN crystal passes through the Neutral Density Filter 1 (NDF 1), and the $y$-PL passes through FR 2, HWP 2, and NDF 2. Then they are feedback into the VCSEL together. The feedback delay is $\tau$, and NDF 1 and NDF 2 are used to control the feedback strength of $x$-PL and $y$-PL respectively.

In order to realize dynamic and reconfigurable chaotic logic operations, it is necessary for the control signal to change synchronously with the logic inputs. To solve this problem, we propose the following scheme: since the normalized injection current $\mu = -d\mu_1 + d\mu_2$, and $d\mu_1$ and $d\mu_2$ are encoded into two logic inputs $I_1$ and $I_2$ respectively. Here we use time-varying current source $S_t$ to generate two identical electrical signals $d\mu_1$ and $d\mu_2$. Similarly, the same two electrical signals $d\mu_2$ and $d\mu_3$ are generated by $S_t$. And $d\mu_1$ and $d\mu_3$, in turn, are encoded into two electric logic inputs of Electronic Logic Calculator (ELC) such as $i_1$ and $i_2$. Due to $d\mu_1 = d\mu_2$ and $d\mu_3 = d\mu_4$, the logic sets of the signals $i_1$ and $i_2$ are synchronized with those of the signals $I_1$ and $I_2$. The logic output of the ELC is defined as $R$, which can control the Transverse Electric Field (TEF) $E_x$ by Transverse Electric Field Controller (TEFC). Here, $R=0$ is encoded in the low level $E_{oa}$, $R=1$ is encoded in the high level $E_{oe}$. If $R = 0$, we obtain $E_x = E_{oa}$ and $L_0 = 0$; when $R = 1$, we have $E_x = E_{oe}$ and $L_1 = 1$. Using the ELC, $R$ and $i_1$, $i_2$ can perform different logic operations, so that $L_0$ can implement different logic operations with $I_1$ and $I_2$ indirectly. It is noted that the switching rate of the control signal is determined by ELC. At present, the reconfigurable operation rate of ELC can reach more than 10 GHz, which can satisfy the needs of reconfigurable chaotic logic operations realized in this paper.

Due to the VCSEL subject to the delay feedback of its own light, the dynamic equations of $x$-PL and $y$-PL are represented as follows:

$$
\frac{d}{dt} \begin{pmatrix} E_x(t) \\ E_y(t) \end{pmatrix} = k \begin{pmatrix} 1 & i\omega \\ -i\omega & 1 \end{pmatrix} \begin{pmatrix} N(t) \\ |E_x(t)|^2 + |E_y(t)|^2 \end{pmatrix} + k \begin{pmatrix} 1 & i\omega \\ -i\omega & 1 \end{pmatrix} \begin{pmatrix} E_x(t) \\ E_y(t) \end{pmatrix} + \begin{pmatrix} E_x \pm iE_y \end{pmatrix} \begin{pmatrix} E_x \pm iE_y \end{pmatrix}$$

(1)

$$\frac{dN(t)}{dt} = -\gamma_x \left( N(t) - \mu + N(t)(|E_x(t)|^2 + |E_y(t)|^2) + iN(t) \right) \frac{dN(t)}{dt}$$

(2)

$$\frac{dn(t)}{dt} = -\gamma_x n(t) - \gamma_y \left( n(t)(|E_x(t)|^2 + |E_y(t)|^2) + iN(t) \right) \frac{dN(t)}{dt}$$

(3)

In the above formulas, subscripts $x$ and $y$ mean $x$-PL and $y$-PL respectively; $E$ represents the complex amplitude of light; $N$ is the total carrier concentration; $n$ is the difference in concentration between carriers with
spin-up and carriers with spin-down; \( \omega_c \) is the center frequency of light; \( \beta_n \) represents the spontaneous emission factor, which is also defined as noise intensity; \( \xi \) and \( \eta \) are a pair of gaussian white noises that are independent of each other and obey the standard normal distribution. The meanings and values of other physical quantities are shown in Table 1 below.

<table>
<thead>
<tr>
<th>Parameter and symbol</th>
<th>Value</th>
<th>Parameter and symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line—width enhancement factor ( a )</td>
<td>3</td>
<td>Duty ratio ( R )</td>
<td>0.5</td>
</tr>
<tr>
<td>Field decay rate ( k )</td>
<td>300</td>
<td>Polar angle ( \theta/\pi )</td>
<td>1/2</td>
</tr>
<tr>
<td>Spin relaxation rate ( \gamma_s/\text{ns}^{-1} )</td>
<td>50</td>
<td>Azimuth ( \phi )</td>
<td>0</td>
</tr>
<tr>
<td>Nonradiative carrier relaxation ( \gamma_c/\text{ns}^{-1} )</td>
<td>1</td>
<td>Crystal temperature ( T_c/\text{K} )</td>
<td>293</td>
</tr>
<tr>
<td>Dichroism ( \gamma_d/\text{ns}^{-1} )</td>
<td>-0.1</td>
<td>Poled period of crystal ( \Lambda/\text{m} )</td>
<td>( 5.8 \times 10^3 )</td>
</tr>
<tr>
<td>Birefringence ( \gamma_b/\text{ns}^{-1} )</td>
<td>2</td>
<td>Crystal length ( L/\text{mm} )</td>
<td>15</td>
</tr>
<tr>
<td>Delay time ( \tau/\text{ns} )</td>
<td>2</td>
<td>Refractive index of ( \sigma-)light ( n_\sigma )</td>
<td>2.24</td>
</tr>
<tr>
<td>Effective refractive index of active layer ( n_a )</td>
<td>3.6</td>
<td>Refractive index of ( e-)light ( n_e )</td>
<td>2.17</td>
</tr>
<tr>
<td>Effective area of light spot ( S_a/\mu \text{m}^2 )</td>
<td>( 38.485 )</td>
<td>Differential material gain ( g/\text{m}^2\text{s}^{-1} )</td>
<td>( 2.9 \times 10^{-12} )</td>
</tr>
<tr>
<td>Length of the laser cavity ( L_c/\mu \text{m} )</td>
<td>10</td>
<td>Field confinement factor to the active region ( \Gamma )</td>
<td>0.05</td>
</tr>
<tr>
<td>Optical feedback strength ( R )</td>
<td>0.05</td>
<td>Volume of the active layer ( V/\mu \text{m}^3 )</td>
<td>384.85</td>
</tr>
<tr>
<td>Code width ( T/\text{ps} )</td>
<td>600</td>
<td>The noise intensity ( \beta_n )</td>
<td>( 2.5 \times 10^6 )</td>
</tr>
</tbody>
</table>

The \( x-\)PL and \( y-\)PL from VCSEL are injected into the PPLN crystal and converted into \( \sigma-\)light and \( e-\)light respectively, and their amplitudes satisfy the following relationship

\[
U_{x,y}(0, t - \tau) = \frac{\hbar \omega_V}{S_a T_i c_n^2} E_{x,y}(t - \tau)
\]  

(4)

The linear EO modulation effect occurs in the PPLN crystal, and coupled wave equation of \( \sigma-\)light and \( e-\)light can be expressed as follows

\[
U_{x,y}(L, t - \tau) = \rho_{x,y}(L, t - \tau) \exp(i \beta_0 L) \exp \left[i \phi_{x,y}(L, t - \tau) \right]
\]  

(5)

where

\[
\rho_{x,y}(L, t - \tau) = \left\{ U_{x,y}^2(0, t - \tau) \cos^2(vL) + \frac{\gamma U_{x,y}(0, t - \tau) + d_{11} U_{x,y}(0, t - \tau)}{v} \right\}^{1/2}
\]  

(6)

and

\[
\phi_{x,y}(L, t - \tau) = \arctan \left[ \pm \frac{\gamma U_{x,y}(0, t - \tau) - d_{11} U_{x,y}(0, t - \tau)}{v U_{x,y}(0, t - \tau)} \right]
\]  

(7)

\[
\beta_0 = \frac{\Delta k - d_3 - d_4}{2}
\]  

(8)

\[
v = \sqrt{\frac{(\Delta k + d_3 - d_4)^2 + 4d_3 d_4}{2}}
\]  

(9)

\[
\gamma = \frac{d_4 - d_3 - \Delta k}{2}
\]  

(10)

\( U, U_x, U_y \) and \( U_{x,y} \) in Eqs. (4)−(10) represent the amplitudes of \( \sigma-\)light and \( e-\)light respectively; \( T_i \) represents the time it takes for light to travel back and forth in the laser cavity once; \( \hbar \) is the Planck constant; \( \Delta k = k_1 - k_0 + K_0 \), \( k_1 \) and \( k_0 \) denote the wave vectors of \( \sigma-\)light and \( e-\)light at \( \omega_c \) and \( k_2 = 2\pi n_c / \omega_c, k_3 = 2\pi n_e / \omega_c, K_0 = 2\pi / \Lambda \), \( \Lambda \) is the poled period, where the coefficients \( d_1, d_2, d_3, \) and \( d_4 \) are presented in Ref. [17]. The meanings and values of other physical quantities are presented in Table 1. The \( \sigma-\)light and \( e-\)light are converted into \( x-\)PL and \( y-\)PL respectively after being output from the crystal, and the conversion relationship can be expressed as follows

\[
E_{x,y}(t - \tau) = \frac{S_a T_i c_n^2}{\hbar \omega_V} U_{x,y}(L, t - \tau)
\]  

(11)
2 Results and discussions

The Eqs. (1)～(3) can be solved according to the fourth-order Runge–Kutta method and the system parameters in Table 1. Because \( \mu = d_{\mu} + d_{\mu} \), \( \eta_{\mu} \) and \( \eta_{\mu} \) are used to modulate binary logic inputs \( I_x \) and \( I_y \), respectively. The logic input sequence \((I_x, I_y)\) has four combinations as \((0, 0), (0, 1), (1, 0) \) and \((1, 1)\), and the specific modulation rules are: when \( d_{\mu} = 0.74 \), \( I_x = 0 \), and when \( d_{\mu} = 0.75 \), \( I_x = 1 \). Similarly, when \( d_{\mu} = 0.74 \), \( I_y = 0 \); when \( d_{\mu} = 0.75 \), \( I_y = 1 \). Therefore, when logic input \((I_x, I_y) = (0, 0)\), \( \mu = d_{\mu} + d_{\mu} = 1.48 \); while \((I_x, I_y) = (0, 1) \) or \((1, 0)\), \( \mu = d_{\mu} + d_{\mu} = 1.49 \); and \( \mu = d_{\mu} + d_{\mu} = 1.50 \) if logic input \((I_x, I_y) = (1, 1)\). The control signal \( L_x \) is modulated by the transverse electric field \( E_x \), it means that, if \( E_x = E_{\mu} = 0.75 \) kV/mm, \( L_x = 1 \); else if \( E_x = E_{\mu} = 0.589 \) IV/mm, \( L_x = 0 \). Moreover, the logic output \( X \), can be demodulated by performing difference processing between \( A \) and the threshold \( A^* \) under each logic input, namely, if \( A \leq A^* \), \( X = 0 \), else if \( A^* > A^* \), \( X = 1 \).

The threshold value \( A^* \) determines the reliability of the logic operations. In order to obtain a suitable threshold, we adopt the following technical solutions; since \( L_x \) and \( (I_x, I_y) \) can form the basic logic operation relationships such as NOT, AND, OR, XOR, etc., for each of the above-mentioned logic operation relations, we have calculated the maximum average \( A_{\mu} \) of \( x \)-PL intensity when \( L_x = 0 \), and the minimum average \( A_{\mu} \) under \( L_x = 1 \), as shown in Table 2. It can be found from the table that in all the logic relationships that \( L_x \) and \( (I_x, I_y) \) satisfy, the maximum value of \( A \) when \( L_x = 0 \) is \( A_{\mu} = 0.003 \), and that’s minimum value when \( L_x = 1 \) is \( A_{\mu} = 0.021 \). Therefore, the threshold \( A^* \) must meet \( 0.003 < A^* < 0.021 \). Here we take \( A^* = 0.013 \), that is, if \( A < 0.013 \), \( X = 0 \); otherwise \( X = 1 \).

### Table 2: For the different logic operations relationship between \( L_x \) and \( (I_x, I_y) \), the maximum average \( A_{\mu} \) of the \( x \)-PL intensity under \( L_x = 0 \) and its minimum average \( A_{\mu} \) under \( L_x = 1 \).

<table>
<thead>
<tr>
<th>Logic operations</th>
<th>((I_x, I_y) = (0, 0))</th>
<th>((I_x, I_y) = (0, 1) / (1, 0))</th>
<th>((I_x, I_y) = (1, 1))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_x = I_x \cdot I_y )</td>
<td>( A_{\mu} = 0 )</td>
<td>( A_{\mu} = 0 )</td>
<td>( A_{\mu} = 0.021 )</td>
</tr>
<tr>
<td>( L_x = I_x / I_y )</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( L_x = I_x + I_y )</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>( L_x = I_x \cdot I_y )</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( L_x = I_x \oplus I_y )</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( L_x = I_x \odot I_y )</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>( L_x = I_x \oslash I_y )</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

When \( L_x \) and logic input satisfy different logic operation relationships, the system can implement different logic operations. In order to obtain logic AND operation, \( L_x \) needs to satisfy the AND operation relationship with \( I_x \) and \( I_y \) as shown in Fig. 2(a). The solid green line represents \( E_x \), the red dotted line represents the \( \mu \), and the blue solid line in Fig. 2(b) denotes \( x \)-PL intensity \( I_x \). When \((I_x, I_y) = (0, 0)\), \( (0, 1), (1, 0) \), respectively, \( x \)-PL intensity \( I_x \) is very small, and \( A_{\mu} = 0 < A^* \) (see Table 2), then \( X = 0 \); when \((I_x, I_y) = (1, 1)\), \( x \)-PL intensity \( I_x \) gets large, and \( A_{\mu} = 0.021 > A^* \) (see Table 2), thus \( X = 1 \), so the logic output is produced by demodulation as shown in Fig. 2(c). In summary, the system has performed logic AND operation, namely \( X = I_x \cdot I_y \). In the same way, \( L_x = I_x / I_y \) is satisfied in Fig. 2(a), and the system realizes logic NAND operation as shown in Fig. 2(b), (c). Table 3 is the truth table of AND and NAND.

Similarly, we further obtain OR, NOR, XNOR, XOR and NOT operations, as shown in Fig. 3. 4 and 5. Table 4, 5 and 6 are the truth tables for the above five logic operations.

The above-mentioned logic operations are performed under the condition that the control signal \( L_x \) and the logic input \((I_x, I_y)\) form the static logic operation relationship. In order to show the reconfigurable ability of the system, relying on ELC to convert the logic relationship between \( L_x \) and \((I_x, I_y)\) as shown in Fig. 5(a), during the time of \( 3 \) ns~4.8 ns, 4.8 ns~7.2 ns, 7.2 ns~9.6 ns, 9.6 ns~12 ns, 12 ns~14.4 ns, 14.4 ns~16.8 ns, 16.8 ns~17.4 ns, \( L_x \), and \((I_x, I_y)\) in turn form logic OR, XOR, XNOR, AND, OR, NAND and NOT relationship, the reconfigurable logic operations are obtained as shown in Fig. 5(b), (c).

0306008-5
Fig. 2  The implementation of chaotic logic AND (left column) and NAND (right column) operations

<table>
<thead>
<tr>
<th>Logic input</th>
<th>AND</th>
<th>NAND</th>
</tr>
</thead>
<tbody>
<tr>
<td>((I_1, I_2))</td>
<td>(L_c)</td>
<td>(X_o)</td>
</tr>
<tr>
<td>((0,0))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>((0,1))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>((1,0))</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>((1,1))</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 3  The truth table of logic AND and NAND
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Fig. 3  The implementation of chaotic logic OR (left column) and NOR (right column) operations

(c) The logic output

Fig. 4  The implementation of chaotic logic XNOR (left column) and XOR (right column) operations

(a) The transverse electric field and normalized injection current
(b) The normalized injection current and the intensity of x-PL
(c) The logic output

(a) The transverse electric field and normalized injection current
The noise in the system has a significant impact on the reliability of logic operations \([18]\). Here, we introduce the success probability \(P\) to describe the reliability of the reconfigurable chaotic logic operations in Fig. 5(b). \(P\) is defined as the ratio between the number of the correct bits and that of total bits of the chaotic logic output. We calculate the dependence of the success probability \(P\) on the noise intensity \(\beta_{sp}\) as shown in Fig. 6. We can find that the value of \(P\) equals 1 when \(\beta_{sp} < 2.75 \times 10^9\). The value of \(P\) is greater than or equal to 0.92 even \(2.75 \times 10^9 < \beta_{sp} < 4 \times 10^9\). These show that the reconfigurable optical chaotic logic operations have good anti-noise performance.

In order to explore the influence of code width \(T\) on the reliability of logic operations, we further calculate

Table 4 The truth table of logic OR and NOR

<table>
<thead>
<tr>
<th>Logic input ((I_1, I_2))</th>
<th>OR</th>
<th>(L_c)</th>
<th>(X_o)</th>
<th>NOR</th>
<th>(L_c)</th>
<th>(X_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((0,0))</td>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>((0,1))</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>((1,0))</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>((1,1))</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 5 The truth table of logic XNOR and XOR

<table>
<thead>
<tr>
<th>Logic input ((I_1, I_2))</th>
<th>XNOR</th>
<th>(L_c)</th>
<th>(X_o)</th>
<th>XOR</th>
<th>(L_c)</th>
<th>(X_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((0,0))</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>((0,1))</td>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>((1,0))</td>
<td></td>
<td>0</td>
<td>0</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>((1,1))</td>
<td></td>
<td>1</td>
<td>1</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 6 The truth table of logic NOT

<table>
<thead>
<tr>
<th>Logic input ((I_1, I_2))</th>
<th>NOT</th>
<th>(L_c)</th>
<th>(X_o)</th>
</tr>
</thead>
<tbody>
<tr>
<td>((0,0))</td>
<td></td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>((1,1))</td>
<td></td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
the dependence of the success probability $P$ on the $T$ as shown in Fig. 7. From the picture we can find that with the gradual increase of the $T$, the curve changes from violent oscillation to smaller fluctuation, and finally becomes a stable straight line with $P$ always equals 1, which indicates that the larger the $T$, the better the reliability of the logic operations. We also discover the value of $P$ equals 1 when $T$ takes some values within 579 ps, such as $T=104.5$ ps, or $T=107.9$ ps, or $T=124.8$ ps, etc., but the value of $P$ is unstable because a slight change in the value of $T$ will cause the $P$ to oscillate. And $P$ always equals 1 when $T\geq 579$ ps. Therefore, reliable and stable logic operations can be obtained as long as the value of $T$ is at least 579 ps.

3 Conclusions

Based on chaotic system of the VCSEL feedback by its own light and the linear electro-optic modulation effect, we have realized chaotic AND, OR, NOT, XOR, NAND, NOR and XNOR logic operations. The system can also perform reconfigurable logic operations by transforming the logic operation relationship between control signal and logic inputs. The further research shows that under code width $T=600$ ps, the success probability $P$ always equals 1 when $\beta_p < 2.75 \times 10^9$. The value of $P$ is also greater than 0.92 even though $2.75 \times 10^9 < \beta_p < 4 \times 10^9$. These results indicate that the reconfigurable chaotic logic operations have good anti-noise performance. Moreover, under $\beta_p = 2.5 \times 10^9$, the value of $P$ is unstable when $T$ takes values within 579 ps. And the logic operations become reliable and stable as long as the value of $T$ is at least 579 ps. The above research results have great application and reference value for the development of faster and safer combinatorial logic devices, such as optical full adders, optical data selectors, etc., as well as for the construction of reconfigurable optical networks.

References

ZHONG Dongzhou, JI Yongqiang, LUO Wei. Controllable optoelectric composite logic gates based on the polarization switching in an optically injected VCSEL[J]. Optics Express, 2015, 23(23):29823–29833.


