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Emitter-couple logic circuit design based on the threshold-arithmetic algebraic system*

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Abstract: Based on the threshold-arithmetic algebraic system which has been proposed for current-mode circuit design, we propose a systematic methodology for emitter-couple logic (ECL) circuit design. Compared to the traditional methodologies and the theory of differential current switches, the proposed methodology uses the HE map and the characteristics of the internal current signals of ECL circuits to determine the external voltage signals. The operations of the HE map are direct and simple, and the current signals are easy to add or subtract, which make this methodology more flexible, direct, and effective, and make it possible to design arbitrary binary and multi-valued logic functions. Two example circuits are designed and simulated by HSPICE using 0.18 μm TSMC technology. Simulation results confirm the validity of the proposed methodology.

Key words: Threshold-arithmetic algebraic system, HE map, ECL circuit, Current-mode circuits
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1 Introduction

Emitter-couple logic (ECL) circuits can operate at high switching speeds because of the unsaturated transistors, which eliminate the transistor memory time and allow the power dissipation of ECL circuits to remain constant as the frequency increases. ECL circuits have often been employed in very high speed very-large-scale integration (VLSI) circuits (Gustat *et al*., 2008; Arbabian *et al*., 2010; Mavrek *et al*., 2010; Lanni *et al*., 2012). Multi-valued logic, which can reduce the number of logic cells and the interconnection among them, has been receiving more and more attention (Lin M *et al*., 2011; Moaiyeri *et al*., 2011; Arjmand *et al*., 2012; Lin S *et al*., 2012; Vudadha *et al*., 2012). Traditional ECL circuit design methods use gates as the basic component based on Boolean algebra. In the theory of differential current switches (Wu and Zhang, 1991), instead, switches (transistors) are used as the basic component; the current signals are easy to add or subtract by simply tying wires with each other, which leads to a simplified circuit design. However, in the theory of differential current switches, ECL circuits are treated as voltage-mode circuits, and the internal current signals of ECL circuits are not used, failing to achieve a direct, effective, and simple ECL circuit design.

Based upon the fact that the current signals are easy to add or subtract by simply tying wires with each other, we have proposed the threshold-arithmetic algebraic system (TAAS) in our previous work (Zhang *et al*., 2011) for current-mode circuit design. TAAS is composed of such basic operations as threshold-arithmetic operations, arithmetic operations, and nonnegative operations. The HE map in this system is expressed as a threshold-arithmetic function of a Karnaugh map for a logic function.

It is well known that the voltage signals of ECL circuits depend on the internal current signals operation (Wu *et al*., 1999). According to this

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characteristic of ECL circuits, in this paper we propose a methodology for ECL circuit design based on the TAAS. The graphic method is simple and direct for logic circuit design, and the HE map employed not only makes this new methodology more direct, simple, and effective, but also simplifies the structure of circuits using the threshold-controllable technique (Hang and Wu, 2000).

2 Threshold-arithmetic algebraic system

2.1 Threshold-arithmetic operations

Wu *et al*. (1993) proposed the transmission current-switches theory for current-mode complementary metal–oxide–semiconductor (CMOS) circuit design. With reference to this theory, the features of current-mode CMOS circuits should be described separately according to the switching state of a MOS transmission transistor and signal variables. Their connection operations are as follows:

Connection operation I: it describes the physical process in which the switching state of an element is determined by comparing the signal with the detection threshold.

Connection operation II: it describes the physical process in which the switching state of an element controls the transmission and formation of the signal.

Combining these two connection operations, the threshold-arithmetic operations can be defined as follows (Zhang *et al*., 2011):

Low-threshold-arithmetic operation:

$$\langle x \rangle_t = \begin{cases} 1, & x > t, \\ 0, & x < t. \end{cases} \tag{1}$$

High-threshold-arithmetic operation:

$$\langle x \rangle^t = \begin{cases} 1, & x < t, \\ 0, & x > t. \end{cases} \tag{2}$$

Dual-threshold-arithmetic operation:

$$\langle x \rangle_{t_1}^{t_2} = \begin{cases} 1, & t_1 < x < t_2, \\ 0, & \text{otherwise.} \end{cases} \tag{3}$$

In Eqs. (1)–(3), $x \in \{0, 1, \ldots, N\}$ (N is a positive integer) represents the signal variable, and t, t_1, $t_2 \in \{0.5, 1.5, \ldots, N-0.5\}$ are the detection thresholds.

The maximum operation and minimum operation are

$$x \vee y = \begin{cases} x, & y < x, \\ y, & y > x, \end{cases} \tag{4}$$

$$x \wedge y = \begin{cases} y, & y < x, \\ x, & y > x. \end{cases} \tag{5}$$

2.2 Nonnegative operation

The results of arithmetic operations can be positive or negative, which means the current signal may be bi-directional. This makes the circuit structure complicated. To prevent this from occurring, the nonnegative operation is defined as

$$\lceil F(x) \rceil = \begin{cases} F(x), & F(x) > 0, \\ 0, & F(x) \le 0, \end{cases} \tag{6}$$

where x=0, 1, …, N and $F(x)$ is composed of the arithmetic operation and the threshold-arithmetic operation.

2.3 Threshold-arithmetic algebraic system and threshold-arithmetic functions

The basic operations of TAAS include arithmetic operations, threshold-arithmetic operations, and non-negative operations. These operations are composed of threshold-arithmetic functions in this system to express the logical relationships of current-mode circuits. The value of the threshold-arithmetic function is a natural number.

A functionally complete operation set is defined as a set of logic operations from which arbitrary combinational logic functions can be realized. According to the definition of the threshold-arithmetic operation, an arbitrary radix-R single variable threshold-arithmetic function can be expressed as

$$\begin{aligned} F(x) = {} & F(0) \cdot \langle x \rangle^{0.5} + F(1) \cdot \langle x \rangle_{0.5}^{1.5} + \ldots \\ & + F(i) \cdot \langle x \rangle_{i-0.5}^{i+0.5} + \ldots + F(R-1) \cdot \langle x \rangle_{R-1.5}. \end{aligned} \tag{7}$$

Thus, an arbitrary radix-2 single variable threshold-arithmetic function can be expressed as

$$F(x) = F(0) \cdot \langle x \rangle^{0.5} + F(1) \cdot \langle x \rangle_{0.5}, \tag{8}$$

and an arbitrary radix-3 single variable threshold-arithmetic function can be expressed as

$$F(x)=F(0)\cdot\langle x\rangle^{0.5}+F(1)\cdot\langle x\rangle_{0.5}^{1.5}+F(2)\cdot\langle x\rangle_{1.5}. \quad (9)$$

Note that in this paper 'F' represents the threshold-arithmetic function, 'f' represents the logic function, the symbol '.' denotes AND operation for logic functions or multiplication arithmetic operation for threshold-arithmetic functions, and '+' denotes OR operation for logic functions or addition arithmetic operation for threshold-arithmetic functions. Therefore, arithmetic, threshold-arithmetic, and nonnegative operations compose a complete operation set for threshold-arithmetic functions (Wu, 1994).

2.4 Properties of basic operations

The properties of the operations should be considered for transformation and simplification of the function forms.

1. Properties relative to threshold-arithmetic operation

According to the definitions of the operations in Eqs. (1)–(5), the following properties can be proved:

$$\begin{cases}\langle x\rangle^{t_1}\cdot\langle x\rangle^{t_2}=\langle x\rangle^{\min(t_1,t_2)},\\ \langle x\rangle^{t_1}\vee\langle x\rangle^{t_2}=\langle x\rangle^{\max(t_1,t_2)},\end{cases} \quad (10)$$

$$\begin{cases}\langle x\rangle_{t_1}\cdot\langle x\rangle_{t_2}=\langle x\rangle_{\max(t_1,t_2)},\\ \langle x\rangle^{t_1}\vee\langle x\rangle^{t_2}=\langle x\rangle_{\min(t_1,t_2)},\end{cases} \quad (11)$$

$$\begin{cases}\langle x\rangle_{t_1}\cdot\langle x\rangle_{t_2}=\begin{cases}1, & \text{if } x>\max(t_1,t_2),\\ 0, & \text{otherwise},\end{cases}\\ \langle x\rangle^{t_1}\vee\langle x\rangle^{t_2}=\begin{cases}0, & \text{if } x<\min(t_1,t_2),\\ 1, & \text{otherwise},\end{cases}\end{cases} \quad (12)$$

$$\begin{cases}\langle x\rangle^{t}\cdot\langle y\rangle^{t}=\langle \max(x,y)\rangle^{t},\\ \langle x\rangle^{t}\vee\langle y\rangle^{t}=\langle \min(x,y)\rangle^{t},\end{cases} \quad (13)$$

$$\begin{cases}\langle x\rangle_{t}\cdot\langle y\rangle_{t}=\langle \min(x,y)\rangle_{t},\\ \langle x\rangle_{t}\vee\langle y\rangle_{t}=\langle \max(x,y)\rangle_{t},\end{cases} \quad (14)$$

$$\begin{cases}\langle x\rangle^{t}\cdot\langle y\rangle_{t}=\begin{cases}1, & \text{if } x<t<y,\\ 0, & \text{otherwise},\end{cases}\\ \langle x\rangle_{t}\vee\langle y\rangle^{t}=\begin{cases}0, & \text{if } x<t<y,\\ 1, & \text{otherwise}.\end{cases}\end{cases} \quad (15)$$

2. Properties relative to nonnegative operation

According to the definition of the nonnegative operation in Eq. (6), the following properties can be proved:

$$\lceil x-y\rceil\cdot z=\begin{cases}x\cdot z-y\cdot z, & x>y,\\ 0, & x\le y,\end{cases} \quad (16)$$

$$\lceil x-y\rceil+z=\begin{cases}x-y+z, & x>y,\\ z, & x\le y.\end{cases} \quad (17)$$

3. Properties relative to the simplification of threshold-arithmetic operation

Properties of threshold transformation:

$$\begin{cases}\langle x\rangle_{t_1}^{t_2}=\langle x\rangle_{t_1}\cdot\langle x\rangle^{t_2}=1-\left(\langle x\rangle^{t_1}+\langle x\rangle_{t_2}\right),\\ \langle x\rangle_{t_1}^{t_2}\cdot\langle x\rangle_{t_3}^{t_4}=0,\ \ (t_1,t_2)\cap(t_3,t_4)=\varnothing,\end{cases} \quad (18)$$

where $\varnothing$ is the empty set.

From Eq. (7), the following can be proved:

$$\langle x\rangle^{0.5}+\langle x\rangle_{0.5}^{1.5}+\ldots+\langle x\rangle_{i-0.5}^{i+0.5}+\ldots+\langle x\rangle_{R-1.5}=1. \quad (19)$$

Eqs. (18) and (19) indicate that a threshold-arithmetic operation can be expressed by other threshold-arithmetic operations; therefore, the following can be proved:

$$\begin{cases}\langle x\rangle_{i-0.5}^{i+0.5}=\overline{\langle x\rangle^{0.5}\vee\ldots\vee\langle x\rangle_{i-0.5}^{i+0.5}\vee\langle x\rangle_{i+0.5}^{i+1.5}\vee\ldots\vee\langle x\rangle_{R-1.5}},\\ \langle x\rangle_{i-0.5}^{i+0.5}=\overline{\langle x\rangle^{0.5}}\cdot\ldots\cdot\overline{\langle x\rangle_{i-0.5}^{i+0.5}}\cdot\overline{\langle x\rangle_{i+0.5}^{i+1.5}}\cdot\ldots\cdot\overline{\langle x\rangle_{R-1.5}},\end{cases} \quad (20)$$

$$\begin{cases}x=\langle x\rangle_{0.5}+\langle x\rangle_{1.5}+\ldots+\langle x\rangle_{R-1.5},\\ \overline{x}=\langle x\rangle^{R-0.5}+\ldots+\langle x\rangle^{1.5}+\langle x\rangle^{0.5},\end{cases} \quad (21)$$

where '¯' is the NOT operation.

2.5 Standard expansion of threshold-arithmetic functions, and the HE map

According to Eq. (7), the expression for an arbitrary radix threshold-arithmetic function can be obtained. Taking binary logic and ternary logic as examples, an arbitrary three-variable radix-2 threshold-arithmetic function and a two-variable radix-3 threshold-arithmetic function are shown in Eqs. (22) and (23), respectively:

$$\begin{aligned} F(x,y,z) = &F(0,0,0)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle^{0.5}\cdot\langle z\rangle^{0.5} \\ &+F(0,0,1)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle^{0.5}\cdot\langle z\rangle_{0.5} \\ &+F(0,1,0)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle_{0.5}\cdot\langle z\rangle^{0.5} \\ &+F(0,1,1)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle_{0.5}\cdot\langle z\rangle_{0.5} \\ &+F(1,0,0)\cdot\langle x\rangle_{0.5}\cdot\langle y\rangle^{0.5}\cdot\langle z\rangle^{0.5} \\ &+F(1,0,1)\cdot\langle x\rangle_{0.5}\cdot\langle y\rangle^{0.5}\cdot\langle z\rangle_{0.5} \\ &+F(1,1,0)\cdot\langle x\rangle_{0.5}\cdot\langle y\rangle_{0.5}\cdot\langle z\rangle^{0.5} \\ &+F(1,1,1)\cdot\langle x\rangle_{0.5}\cdot\langle y\rangle_{0.5}\cdot\langle z\rangle_{0.5}, \end{aligned} \tag{22}$$

$$\begin{aligned} F(x,y)=&F(0,0)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle^{0.5}+F(0,1)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle_{0.5}^{1.5} \\ &+F(0,2)\cdot\langle x\rangle^{0.5}\cdot\langle y\rangle_{1.5}+F(1,0)\cdot\langle x\rangle_{0.5}^{1.5}\cdot\langle y\rangle^{0.5} \\ &+F(1,1)\cdot\langle x\rangle_{0.5}^{1.5}\cdot\langle y\rangle_{0.5}^{1.5}+F(1,2)\cdot\langle x\rangle_{0.5}^{1.5}\cdot\langle y\rangle_{1.5} \\ &+F(2,0)\cdot\langle x\rangle_{1.5}\cdot\langle y\rangle^{0.5}+F(2,1)\cdot\langle x\rangle_{1.5}\cdot\langle y\rangle_{0.5}^{1.5} \\ &+F(2,2)\cdot\langle x\rangle_{1.5}\cdot\langle y\rangle_{1.5}. \end{aligned} \tag{23}$$

Similar to a Karnaugh map in Boolean algebra, an HE map is defined and used as the graphic representation of threshold-arithmetic functions. Fig. 1a shows the HE map of an arbitrary three-variable radix-2 function $F(x_1, x_2, x_3)$. Fig. 1b shows the HE map of an arbitrary two-variable radix-3 function $F(x, y)$. It has the same axis as a Karnaugh map, and every single square is filled in with the corresponding values of the threshold-arithmetic functions. In fact, the Karnaugh map is a subset of the HE map. With the HE map expressing the threshold-arithmetic functions, the characteristics of threshold-arithmetic functions are clarified, and from input to output we can intuitively make judgments according to the arithmetic and threshold-arithmetic operations in the HE map. The HE map is the basic tool for current-mode circuit design.

x_1 \ x_2x_3	00	01	11	10
0	F(0,0,0)	F(0,0,1)	F(0,1,1)	F(0,1,0)
1	F(1,0,0)	F(1,0,1)	F(1,1,1)	F(1,1,0)

(a)

x \ y	0	1	2
0	F(0,0)	F(0,1)	F(0,2)
1	F(1,0)	F(1,1)	F(1,2)
2	F(2,0)	F(2,1)	F(2,2)

(b)

Fig. 1 HE map: (a) three-variable radix-2 function $F(x_1, x_2, x_3)$; (b) two-variable radix-3 function $F(x, y)$

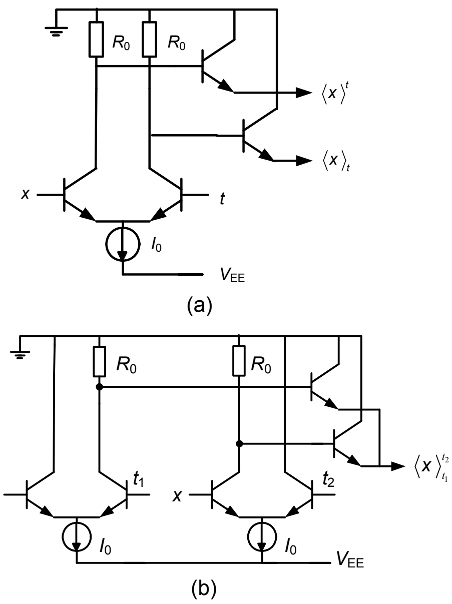

Fig. 2 ECL threshold-arithmetic operations
(a) High/Low threshold-arithmetic operation; (b) Dual-threshold-arithmetic operation

3 ECL circuit design based on the threshold-arithmetic algebraic system

In ECL circuit design, using the TAAS, the ECL threshold-arithmetic units are proposed to implement threshold-arithmetic operations (Fig. 2).

As shown in Fig. 2a, the left transistor turns on when $x<t$ ($V_x>V_t$) (negative logic); hence, current I_0 goes through the left transistor, and $\langle x\rangle^t=1$. So, the comparison between voltage signals determines the current I_0 flow; therefore, the TAAS is suitable for ECL circuit design.

Using threshold-arithmetic functions to express logical relationships of ECL circuits, the corresponding ECL circuits can be designed according to the HE map and Fig. 2. The following is the procedure of the proposed ECL circuit design:

1. Draw the Karnaugh map of the logical function to be designed, which is the target HE map.

2. According to the target HE map and logical function, construct a relatively simple threshold-arithmetic function, for which the HE map is similar to the target HE map.

3. Operating on the constructed HE map using threshold-arithmetic, arithmetic, and nonnegative operations, we can obtain the final HE map, which is the same as the target HE map.

4. According to the operating process of HE map operations, the corresponding threshold-arithmetic functions can be obtained, and the ECL circuits can be designed based on Fig. 2.

In the following we give two examples to demonstrate the design methodology.

Example 1 Design of an ECL binary three-variable XOR circuit

According to the XOR definition, the logic function f_1 is

$$f_1(x, y, z)=x\oplus y\oplus z.$$

The Karnaugh map of f_1 is as shown in Fig. 3a, being the target HE map. According to the target HE map and the logical function f_1, we construct an HE map (Fig. 3b) and the corresponding threshold-arithmetic function

$$F_1(x, y, z)=x+y+z. \quad (24)$$

Comparing Fig. 3a with Fig. 3b, we can obtain Figs. 3c and 3d using the threshold-arithmetic operation, and the corresponding F_2 and F_3 as follows:

$$F_2(x,y,z)=\langle F_1(x,y,z)\rangle_{0.5}^{1.5}=\langle x+y+z\rangle_{0.5}^{1.5}, \quad (25)$$

$$F_3(x,y,z)=\langle x+y+z\rangle_{2.5}. \quad (26)$$

Fig. 3c plus Fig. 3d is Fig. 3a. Hence, according to the process of the HE map operation, F_4 can be obtained as

$$F_4(x,y,z)=\langle x+y+z\rangle_{0.5}^{1.5}+\langle x+y+z\rangle_{2.5}. \quad (27)$$

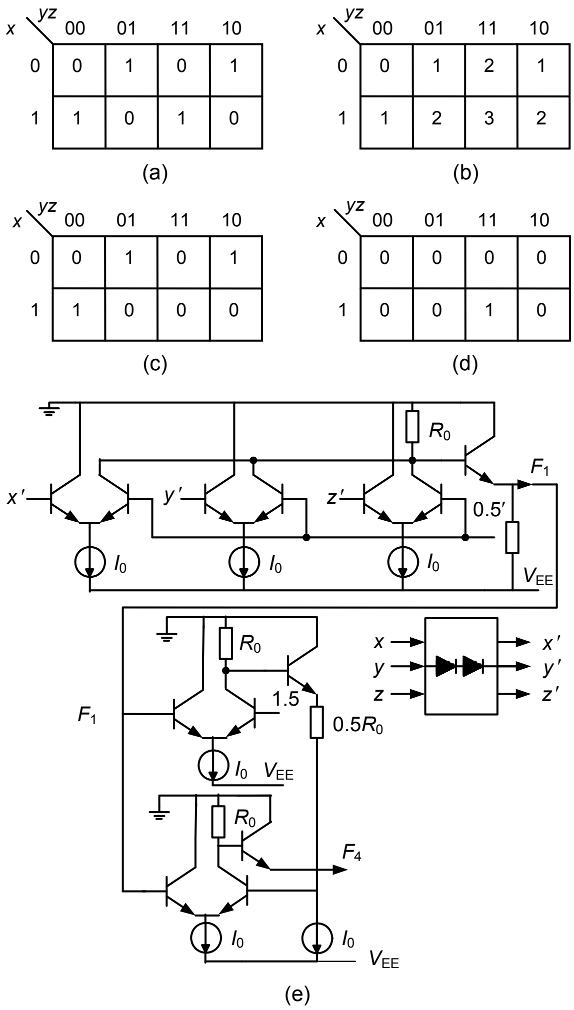

Fig. 3 ECL binary three-variable XOR circuit
(a) Karnaugh map of f_1; (b) HE map of F_1; (c) HE map of F_2; (d) HE map of F_3; (e) ECL circuit

Using the threshold-controllable technique (Hang and Wu, 2000), F_4 can be expressed as

$$F_4(x,y,z)=\begin{cases}\langle x+y+z\rangle_{0.5}, & x+y+z<1.5,\\ \langle x+y+z\rangle_{2.5}, & x+y+z>1.5,\end{cases} \quad (28)$$
$$=\langle x+y+z\rangle_{0.5+\langle x+y+z\rangle_{1.5}}.$$

The threshold-arithmetic function F_4 is the expression of the logical function f_1, and according to Eq. (28), we can obtain the ECL circuit of f_1 as illustrated in Fig. 3e.

Example 2 Design of an ECL ternary two-variable modulo multiplication circuit

The logical function of ternary two-variable modulo multiplication f_2 is $f_2(x, y)=x\otimes y$. The

Karnaugh map of f_2 is as shown in Fig. 4a. According to the target HE map, when x=0 or y=0, the value of the threshold-arithmetic function is 0. This means that we can express the threshold-arithmetic function F_5 corresponding to f_2 as

$$F_5(x,y)=F_6(x,y)\cdot\langle x\rangle_{0.5}\cdot\langle y\rangle_{0.5}. \quad (29)$$

In accordance with Eq. (29), we can cut the target HE map and then construct an HE map.

Operating on the HE map with the arithmetic operation and threshold arithmetic operation, we can obtain the target HE map. From the process of the operation of Fig. 4b, F_6 is

$$F_6(x,y)=\langle x+y\rangle_{2.5}^{3.5}+1. \quad (30)$$

F_5, which is the threshold-arithmetic function of logical function f_2, can then be expressed as

$$F_5(x,y)=\left(\langle x+y\rangle_{2.5}^{3.5}+1\right)\cdot\langle x\rangle_{0.5}\cdot\langle y\rangle_{0.5}. \quad (31)$$

From Eq. (31), the ECL circuit can be obtained, as shown in Fig. 4c.

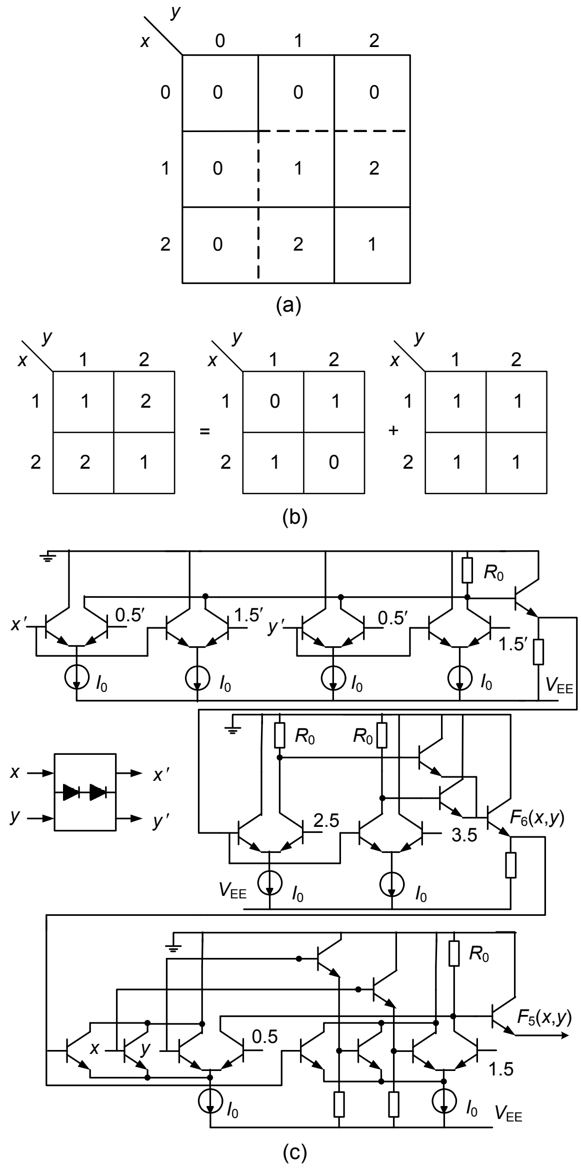

Fig. 4 ECL ternary two-variable modulo multiplication circuit
(a) The target HE map; (b) Process of HE map operation; (c) ECL circuit

4 Simulation results and discussion

The designed circuits in Figs. 3e and 4c were simulated using 0.18 μm TSMC technology with HSPICE. The HE map in Fig. 1a is used as a load. The transient waveforms of simulation results for Figs. 3e and 4c are shown in Fig. 5.

To avoid a saturation of transistors, level-shifting is necessary. When the voltage of the PN junction is Δv=0.8 V, each input voltage signal should be level-shifted down $2\Delta v$=1.6 V, and I_0R_0=0.8 V.

As shown in Fig. 3, the voltages corresponding to the logical value (0, 1) of x, y, z and x', y', z' are (−0.8, −1.6) V and (−2.4, −3.2) V, respectively. The threshold voltage corresponding to threshold 0.5′ is −2.8 V. In Fig. 4, the voltages corresponding to the logical values (0, 1, 2) of x, y and x', y' are (−0.8, −1.6, −2.4) V and (−2.4, −3.2, −4.0) V, respectively. The threshold voltages corresponding to thresholds (0.5′, 1.5′) are (−2.8, −3.6) V. In Figs. 3 and 4, the voltages corresponding to the value of threshold-arithmetic function levels (0, 1, 2, 3, 4) are (−0.8, −1.6, −2.4, −3.2, −4.0) V, and the threshold voltages corresponding to thresholds (0.5, 1.5, 2.5, 3.5) V are (−1.2, −2.0, −2.8, −3.6) V.

The waveforms show that the designed ECL circuits have the correct logical functions. The designed examples indicate that using the intuitive features of HE maps and threshold-arithmetic functions, the process of designing ECL circuits is direct, effective, and simple. Example 1 shows that the TAAS can conveniently use the threshold-controllable technique to further simplify the structure of circuits.

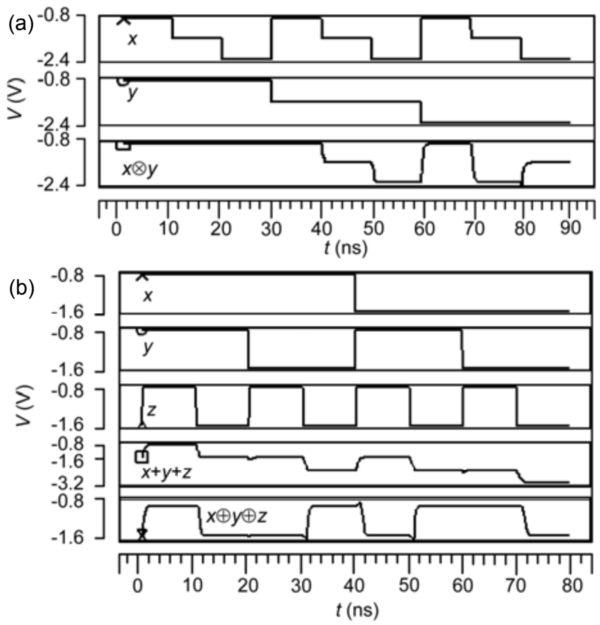

Fig. 5 The transient waveforms of simulation results
(a) The ECL binary three-variable XOR circuit; (b) The ECL ternary two-variable modulo multiplication circuit

5 Conclusions

In this paper we investigate the characteristics of ECL circuits and point out that though the input and output are voltage signals in ECL circuits, the voltage signals of ECL circuits depend on the internal current signals operations. The threshold-arithmetic algebraic system is suitable for current-mode circuit design according to the characteristics of the current signals that are easy to add or subtract, thus simplifying the circuit design. The HE map in this system is expressed for a threshold-arithmetic function as a Karnaugh map for a logic function. Based on the threshold-arithmetic algebraic system and the HE map, a new design procedure is proposed to systematically design ECL circuits. This methodology uses the internal current signals of ECL circuits and obtains the threshold-arithmetic functions according to the process of operations of the HE map, which makes the design method direct, simple, and effective, and also simplifies the structure of the designed circuits and reduces the number of transistors used. The design examples and the results of simulation show that the proposed methodology is a systematic and efficient methodology for ECL circuit design.

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