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# Design of Excess 3 to BCD code converter using electro-optic effect of Mach-Zehnder Interferometers for efficient data transmission

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## ABSTRACT

Excess 3 code is one of the most important codes used for efficient data storage and transmission. It is a non-weighted code and also known as self complementing code. In this paper, a four bit optical Excess 3 to BCD code converter is proposed using electro-optic effect inside lithium-niobate based Mach-Zehnder interferometers (MZIs). The MZI structures have powerful capability to switching an optical input signal to a desired output port. The paper constitutes a mathematical description of the proposed device and thereafter simulation using MATLAB. The study is verified using beam propagation method (BPM).

**Keywords:** Electro-optic effect; Mach-Zehnder interferometer; Beam Propagation Method, optical computing, Excess 3 code, BCD code.

## 1. INTRODUCTION

Digital arithmetic plays an imperative role in the design of digital processors, signal processing, and communications to achieve fast computation, less processing time, high system efficiency and data speed [1]. However, as the hunger of high speed data requirement is increasing day by day hence ultra fast computation is also becomes viable. To achieve future requirements, researchers have shown great interest to implement sequential and combinational logic circuits in all optics [2-15] such as full adder [2], multiplier [3], shift registers [4], synchronous up counter [5], encoder [6], comparators [7], and code converters[8]. There are various methods to implement all optical circuits i.e. Micro-electromechanical systems (MEMS) [9], terahertz optical asymmetric de-multiplexer (TOAD) [10], non-linear material (NLM) [11], semiconductor optical amplifier based Mach-zehnder interferometers (SOA-MZI) [12], cross-gain modulation (XGM) effect [13], cross-phase modulation (XPM) effect of SOA based MZI [14], and LiNbO<sub>3</sub> based MZI [15]. Here an optical Excess 3 code to BCD converter using electro-optic effect [15] in LiNbO<sub>3</sub> based MZI is proposed. LiNbO<sub>3</sub> seems to be a promising solution, because of its characteristic features of compact size, thermal stability [16], integration potential [16], re-configurability [17], low latency [17] and low power consumption [17]. Excess 3 codes is self complimentary code and play a significant role in arithmetic operations. It is also used in efficient data storage and transmission [18].

In this paper, an Excess 3 to BCD code converter is designed using electro-optic effect of lithium niobate based MZIs. Section 2 explains the schematic diagram and working of Excess 3 to BCD code converter. Section 3 presents mathematical description of device along with MATLAB simulation results. Section 4 explains the BPM layout with its BPM simulation results. Finally Section 5 comprises the conclusion of work.

## 2. DESIGN OF EXCESS 3 TO BCD CODE CONVERTER

Conversion circuits are used between two systems if each uses different codes for the same information. A combinational circuit performs this transformation by means of logic gate. K – Map and digital circuit to make excess 3 to BCD code conversion is given in Fig 1. Schematic diagram of proposed device using MZI is shown in Fig 2. Continuous wave (CW) optical signal is launched through the first port of MZI1, MZI2, MZI4, MZI6, MZI8, MZI11, and MZI13. As Excess 3 code is 4 bit code, second output port of MZI1 is equivalent to the B<sub>0</sub> bit ( $\bar{E}_0$ ). Second bit B<sub>1</sub> is equivalent to ( $E_1 \oplus E_0$ ) and available at the second output port of MZI3. Third bit B<sub>2</sub> is equivalent to ( $\bar{E}_2 \bar{E}_1 + \bar{E}_2 \bar{E}_0 + E_2 E_1 E_0$ ) and available at the combination of first output port of MZI5, MZI7, and MZI10. Fourth bit B<sub>3</sub> is equivalent to ( $E_3 E_2 + E_3 E_1 E_0$ ) and is available at the combination of first output port of MZI12 and MZI15.

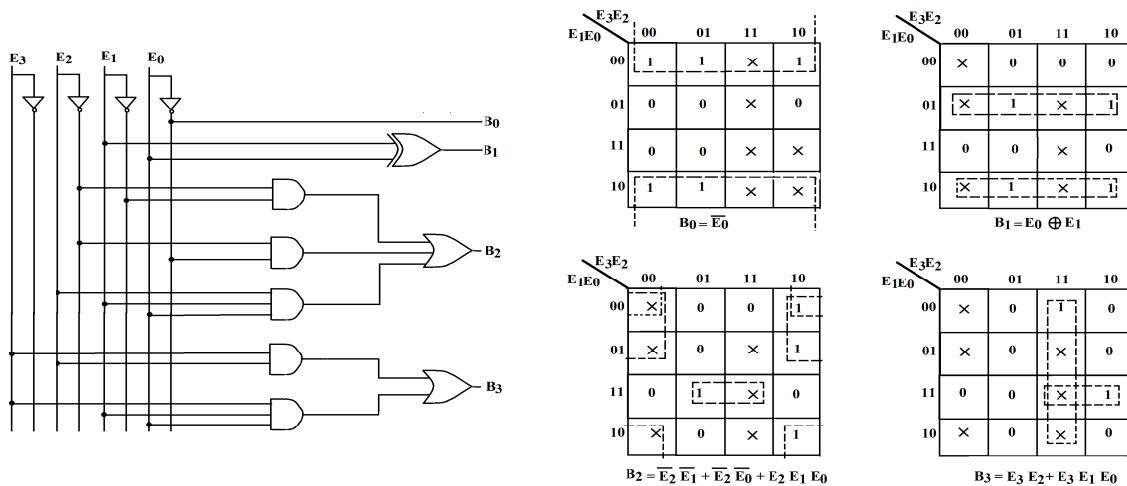


Figure 1: Digital circuit and K-map of Excess 3 to BCD code converter.

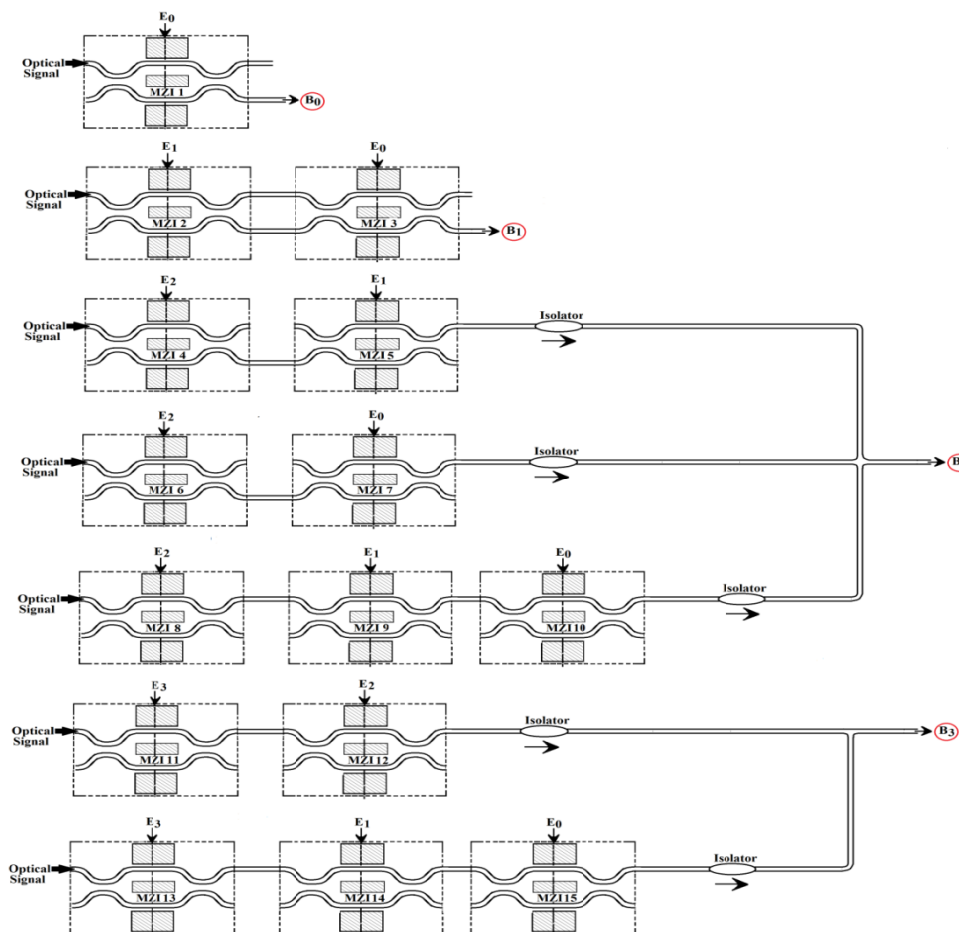


Figure 2: Schematic diagram of excess 3 to BCD code converter using MZIs

### 3. MATHEMATICAL FORMULATION OF NORMALIZED POWER AT VARIOUS OUTPUT PORTS

$P_0, P_1, P_2, P_3$  is output power calculated for  $B_0, B_1, B_2, B_3$  respectively. Here  $\Delta\phi$  is the phase difference occurs in MZI after applying the appropriate voltage  $V_\pi$ .

$$\Delta\phi = \frac{2\pi}{\lambda} (\Delta n) L \quad (1)$$

Where  $\lambda$  = wavelength of light source,  $L$  = substantial length of electrode,  $\Delta n$  is change in refractive index occurs due to electro-optic effect. Voltage  $V_\pi$  and  $\Delta n$  can be calculated as,

$$\Delta n = \left(\frac{n^3}{2}\right) rE \quad (2)$$

Here  $n$  = refractive index,  $r$  = Electro-optic (EO) coefficient of material, and  $E$  is electric field.

$$V_\pi = \frac{\lambda}{n^3} \frac{1}{r} \frac{d}{L} \quad (3)$$

Here  $r$  = EO coefficient of material,  $d$  = separation between the electrodes. After applying the appropriate voltage at MZI we can get the desired phase difference at the output. Output power can be calculated by given Eqs. (4-7):

$$P_0 = \cos^2 \left( \frac{\Delta\phi_{MZI1}}{2} \right) \quad (4)$$

$$P_1 = \sin^2 \left( \frac{\Delta\phi_{MZI2}}{2} \right) \cos^2 \left( \frac{\Delta\phi_{MZI3}}{2} \right) + \cos^2 \left( \frac{\Delta\phi_{MZI2}}{2} \right) \sin^2 \left( \frac{\Delta\phi_{MZI3}}{2} \right) \quad (5)$$

$$P_2 = \cos^2 \left( \frac{\Delta\phi_{MZI4}}{2} \right) \cos^2 \left( \frac{\Delta\phi_{MZI5}}{2} \right) + \cos^2 \left( \frac{\Delta\phi_{MZI6}}{2} \right) \cos^2 \left( \frac{\Delta\phi_{MZI7}}{2} \right) + \sin^2 \left( \frac{\Delta\phi_{MZI8}}{2} \right) \sin^2 \left( \frac{\Delta\phi_{MZI9}}{2} \right) \sin^2 \left( \frac{\Delta\phi_{MZI10}}{2} \right) \quad (6)$$

$$P_3 = \sin^2 \left( \frac{\Delta\phi_{MZI11}}{2} \right) \sin^2 \left( \frac{\Delta\phi_{MZI12}}{2} \right) + \sin^2 \left( \frac{\Delta\phi_{MZI13}}{2} \right) \sin^2 \left( \frac{\Delta\phi_{MZI14}}{2} \right) \sin^2 \left( \frac{\Delta\phi_{MZI15}}{2} \right) \quad (7)$$

Phase difference in MZI can be calculated as:

$$\left. \begin{aligned} \Delta\phi_{MZI1} &= \phi_{11} - \phi_{12} \\ \Delta\phi_{MZI2} &= \phi_{21} - \phi_{22} \\ \Delta\phi_{MZI3} &= \phi_{31} - \phi_{32} \\ \Delta\phi_{MZI4} &= \phi_{41} - \phi_{42} \\ \Delta\phi_{MZI5} &= \phi_{51} - \phi_{52} \\ \Delta\phi_{MZI6} &= \phi_{61} - \phi_{62} \\ \Delta\phi_{MZI7} &= \phi_{71} - \phi_{72} \\ \Delta\phi_{MZI8} &= \phi_{81} - \phi_{82} \\ \Delta\phi_{MZI9} &= \phi_{91} - \phi_{92} \\ \Delta\phi_{MZI10} &= \phi_{101} - \phi_{102} \\ \Delta\phi_{MZI11} &= \phi_{111} - \phi_{112} \\ \Delta\phi_{MZI12} &= \phi_{121} - \phi_{122} \\ \Delta\phi_{MZI13} &= \phi_{131} - \phi_{132} \\ \Delta\phi_{MZI14} &= \phi_{141} - \phi_{142} \\ \Delta\phi_{MZI15} &= \phi_{151} - \phi_{152} \end{aligned} \right\} \quad (8)$$

Figure 3(a) to 3(c) shows MATLAB simulation results of excess 3 to BCD code converter for different combinations of  $E_3E_2E_1E_0$  as this converter makes 10 input condition starts from 0011 to 1111.

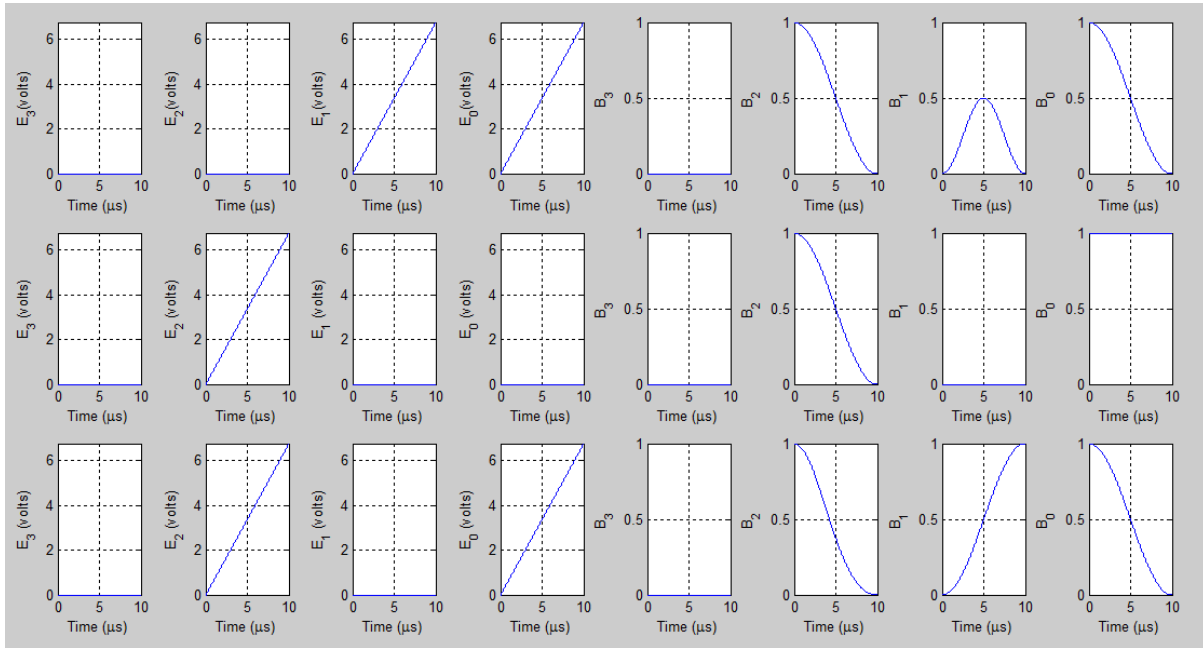


Figure 3(a): MATLAB simulation result of Excess 3 to BCD code converter where  $E_3 E_2 E_1 E_0$  varies from 0011 to 0101.

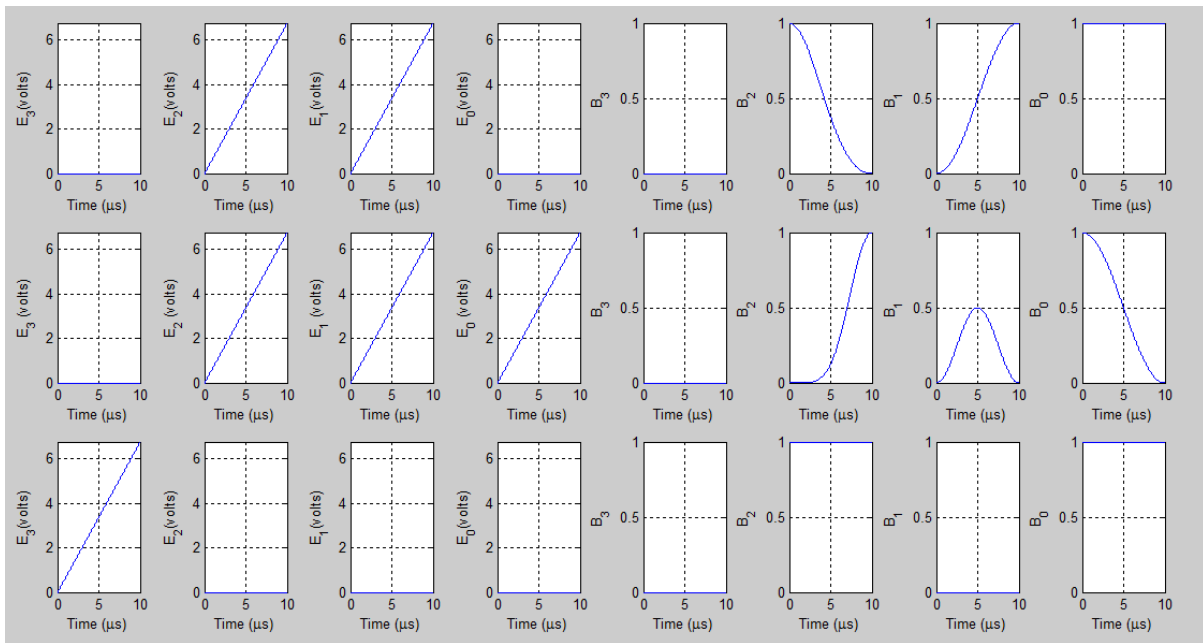


Figure 3(b): MATLAB simulation result of Excess 3 to BCD code converter where  $E_3 E_2 E_1 E_0$  varies from 0110 to 1000

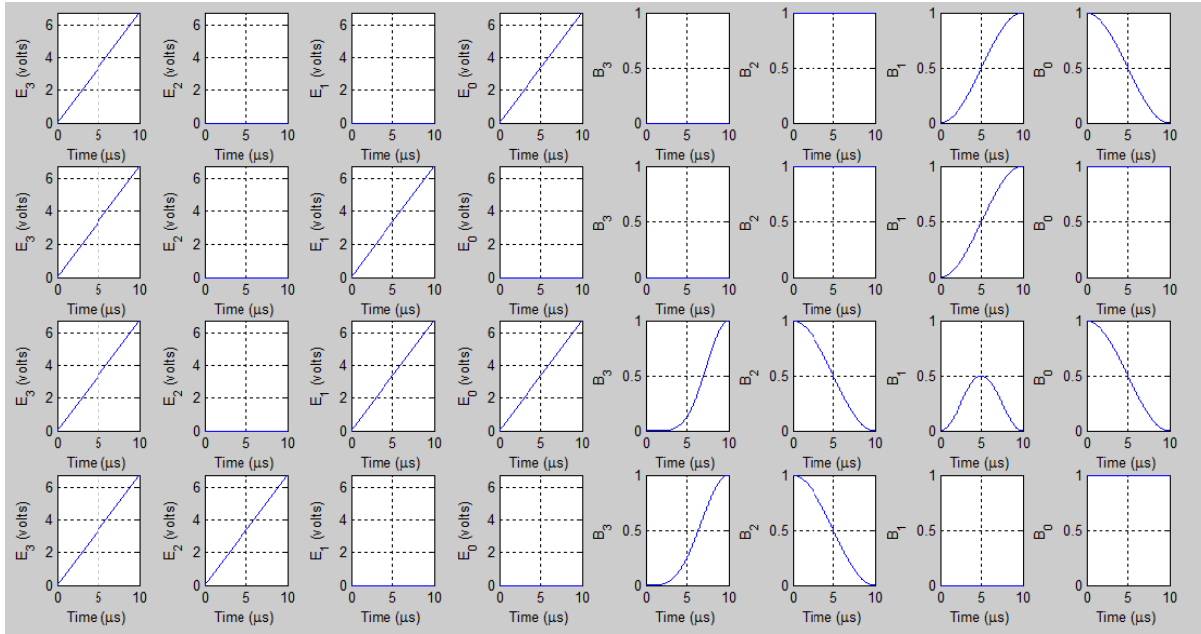


Figure 3(c): MATLAB simulation result of Excess 3 to BCD code converter where  $E_3 E_2 E_1 E_0$  varies from 1001 to 1111

#### 4. DESIGN OF EXCESS 3 TO BCD CODE CONVERTER USING BPM

MZI layout using BPM is shown in Fig. 4. The working principle of code converter is explained in Section 2. Simulation results using BPM is shown in Fig 5. Truth table of Excess 3 to BCD code converter is given in Table 1.

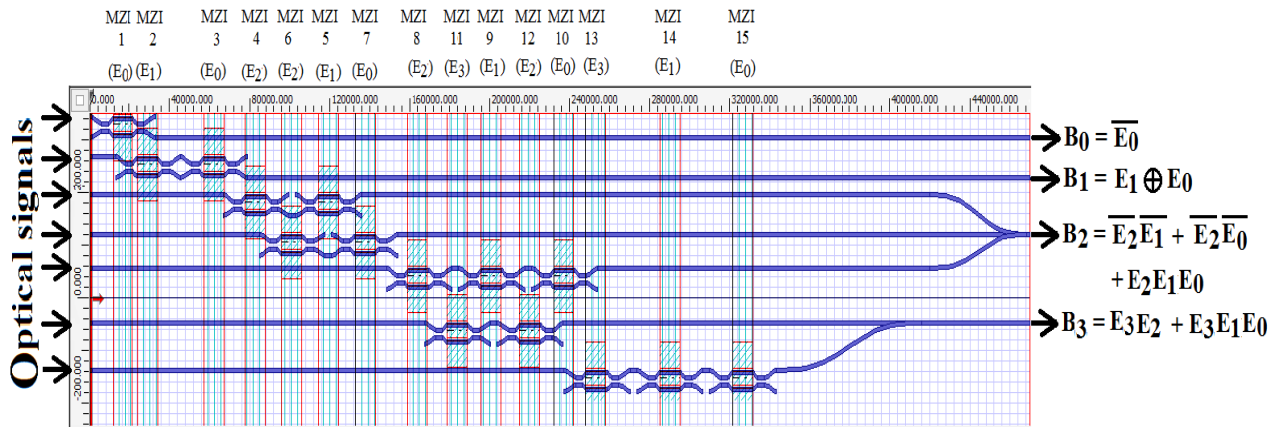


Figure 4: BPM layout of Excess 3 to BCD code converter

Case 1:  $E_3 = 0, E_2 = 0, E_1 = 1, E_0 = 1$

The continuous wave (CW) optical signal is incident on the first input port of the MZI1, MZI2, MZI4, MZI6, MZI8, MZI11, and MZI13. As  $E_0$  bit (the control signal of MZI1) is 1, no light emerges from second output port of MZI1 which means  $B_0 = 0$  and is equivalent to  $\bar{E}_0$ . For  $B_1$  bit,  $E_1$  and  $E_0$  work as the control signal of MZI2 and MZI3 respectively. For  $E_1 = 1$  output signal appears at the first output port of MZI2 and goes in to the first input port of MZI3, while  $E_0 = 1$  then no signal appears at second output port of MZI3. Which means  $B_1 = 0$  and equivalent

to  $(E_1 \oplus E_0)$ .  $B_2$  bit is sum of three outputs and will be equivalent to  $\bar{E}_2\bar{E}_1 + \bar{E}_2\bar{E}_0 + E_2E_1E_0$ . For  $\bar{E}_2\bar{E}_1$ , output appears at the first output port of MZI5.  $E_2, E_1$  works as control signal of MZI4 and MZI5 respectively. If  $E_2, E_1 = 0,1$ , then output will be 0 at first output port of MZI5. For  $\bar{E}_2\bar{E}_0$ , output appears at the first output port of MZI7.  $E_2, E_0$  works as control signal of MZI6 and MZI7 respectively. As  $E_2, E_0 = 0,1$ , output will be 0 at first output port of MZI7. For  $E_2E_1E_0$ , output appears at the first output port of MZI10.  $E_2, E_1, E_0$  works as control signal of MZI8, MZI9 and MZI10. As  $E_2, E_1, E_0$  are 0, 1, 1 respectively, output will appear 0 at first output port of MZI10. Sum of all these three outputs represent  $B_2$  bit and will be equivalent to 0. Bit  $B_3$  is also combination of two outputs as  $E_3E_2 + E_3E_1E_0$ . For  $E_3E_2$ , output appears at the first output port of MZI12.  $E_3$  works as control signal of MZI11 and  $E_2$  works as control signal of MZI12. While  $E_3, E_2 = 0,0$ , output will be 0 at first output port of MZI12. For  $E_3E_1E_0$  output appears at the first output port of MZI15.  $E_3, E_1, E_0$  works as control signal of MZI13, MZI14 and MZI15. In this case  $E_3, E_1$  and  $E_0$  is 0,1,1 respectively, output will appear 0 at first port of MZI15. Sum of these two outputs represent  $B_3$  bit and will be equivalent to 0.

Table 1: Truth table of Excess 3 to BCD code converter

Case	4 Bit Excess 3 information				4 Bit BCD information			
	$E_3$	$E_2$	$E_1$	$E_0$	$B_3$	$B_2$	$B_1$	$B_0$
1	0	0	1	1	0	0	0	0
2	0	1	0	0	0	0	0	1
3	0	1	0	1	0	0	1	0
4	0	1	1	0	0	0	1	1
5	0	1	1	1	0	1	0	0
6	1	0	0	0	0	1	0	1
7	1	0	0	1	0	1	1	0
8	1	0	1	0	0	1	1	1
9	1	0	1	1	1	0	0	0
10	1	1	0	0	1	0	0	1

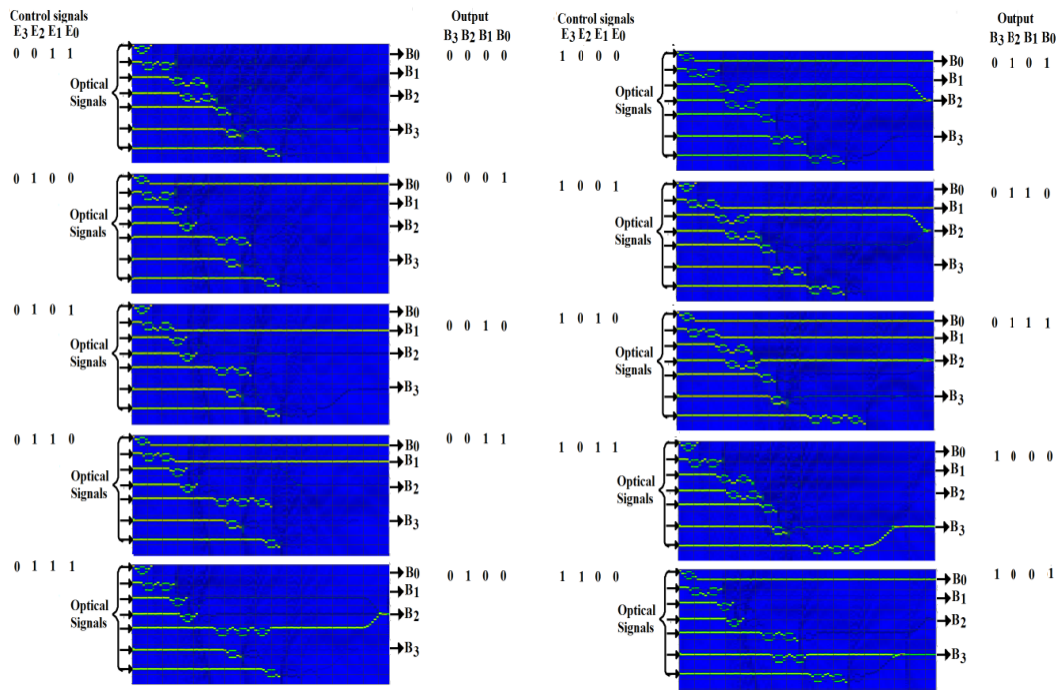


Figure 5: BPM Result of Excess 3 to BCD code converter where  $E_3E_2E_1E_0$  varies from 0011 to 1100.



Case 2:  $E_3 = 0, E_2 = 1, E_1 = 0, E_0 = 0$

As  $E_0$  bit is 0, the light emerges from the second output port of MZI1 which means  $B_0$  bit is equivalent to 1 ( $\bar{E}_0$ ). For  $B_1$  bit, if  $E_1, E_0$  is 0, 0 then the no output signal appears at second output port of MZI3, which means  $B_1 = 0$ . For  $B_2$  bit, as  $E_2, E_1$  is 1, 0 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 1, 0 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 1, 0, 0$ , output appears 0 at first output port of MZI10. So no signal will reach at the port3 for  $B_2$  bit and it is equivalent to 0. For  $B_3$  bit, as  $E_3, E_2 = 0, 1$ , no output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 0, 0, 0$ , no output appears at the first output port of MZI15, means no signal will reach at the port4 for  $B_3$  bit and it is equivalent to 0.

Case 3:  $E_3 = 0, E_2 = 1, E_1 = 0, E_0 = 1$

As  $E_0$  bit is 1, no light emerges from the second output port of MZI1 which means  $B_0$  bit is 0. For  $B_1$  bit, if  $E_1$  is 0, then output signal appears at second output port of MZI2 and goes in to second input port of MZI3. As  $E_0 = 1$  then output signal appears at second output port of MZI3, which means  $B_1 = 1$ . For  $B_2$  bit, as  $E_2, E_1$  is 1, 0 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 1, 1 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 1, 0, 1$ , output appears 0 at first output port of MZI10. So no signal will reach at the port3 for  $B_2$  bit and it is equivalent to 0. For  $B_3$  bit, as  $E_3, E_2 = 0, 1$ , no output will be at first output port of MZI12. Again as  $E_3, E_1, E_0 = 0, 0, 1$ , no output appears at the first output port of MZI15, means no signal will reach at the port4 for  $B_3$  bit and it is equivalent to 0.

Case 4:  $E_3 = 0, E_2 = 1, E_1 = 1, E_0 = 0$

As  $E_0$  bit is 0, light emerges from the second output port of MZI1 which means  $B_0$  is 1. For  $E_1 = 1$ , the output signal appears at the first output port of MZI2 and goes in to the first input port of MZI3 and while  $E_0 = 0$ , then signal appears at the second output port of MZI3, which means  $B_1 = 1$ . For  $B_2$  bit, as  $E_2, E_1$  is 1, 1 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 1, 0 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 1, 1, 0$  output appears 0 at first output port of MZI10 and no output signal will reach at the port3 for  $B_2$ . For  $B_3$  bit, as  $E_3 = 0$  and  $E_2 = 1$ , no output will be at first output port of MZI12. For  $E_3, E_1, E_0 = 0, 1, 0$ , no output appears at the first output port of MZI15, means no signal will reach at the port4 for  $B_3 = 0$ .

Case 5:  $E_3 = 0, E_2 = 1, E_1 = 1, E_0 = 1$

As  $E_0$  bit is 1, no light emerges from the second output port of MZI1 which means  $B_0$  is 0. For  $E_1 = 1$ , the output signal appears at the first output port of MZI2 and goes in to the first input port of MZI3 and while  $E_0 = 1$ , then no signal appears at the second output port of MZI3, which means  $B_1 = 0$ . For  $B_2$  bit, as  $E_2, E_1$  is 1, 1 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 1, 1 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 1, 1, 1$ , output appears 1 at first output port of MZI10. So output signal will reach at the port3 for  $B_2 = 1$ . For  $B_3$  bit, as  $E_3 = 0$  and  $E_2 = 1$ , no output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 0, 1, 1$ , no output appears at the first output port of MZI15, means no signal will reach at the port4 and  $B_3 = 0$ .

Case 6:  $E_3 = 1, E_2 = 0, E_1 = 0, E_0 = 0$

As  $E_0$  bit is 0, light emerges from the second output port of MZI1 which means  $B_0$  is 1. For  $E_1 = 0$ , the output signal appears at the second output port of MZI2 and goes in to the second input port of MZI3 and while  $E_0 = 0$ , then no signal appears at the second output port of MZI3, which means  $B_1 = 0$ . For  $B_2$  bit, as  $E_2, E_1$  is 0, 0 then output ( $\bar{E}_2\bar{E}_1$ ) will be 1 at first output port of MZI5. Again as  $E_2, E_0$  is 0, 0 then output ( $\bar{E}_2\bar{E}_0$ ) will be 1 at first output port of MZI7. For  $E_2, E_1, E_0 = 0, 0, 0$ , output appears 0 at first output port of MZI10. So output signal will reach at the port3 from ( $\bar{E}_2\bar{E}_1$ ) path and from ( $\bar{E}_2\bar{E}_0$ ) path for  $B_2 = 1$ . For  $B_3$  bit, as  $E_2, E_1 = 1, 0$ , no output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 1, 0, 0$ , no output appears at the first output port of MZI15, means no signal will reach at the port4 for  $B_3 = 0$ .

Case 7:  $E_3 = 1, E_2 = 0, E_1 = 0, E_0 = 1$

As  $E_0$  bit is 1, which means  $B_0$  bit is equivalent to 0 ( $\bar{E}_0$ ). For  $B_1$  bit, as  $E_1, E_0$  is 0, 1 then the output signal appears at second output port of MZI3, which means  $B_1 = 1$ . For  $B_2$  bit, as  $E_2, E_1$  is 0, 0 then output ( $\bar{E}_2\bar{E}_1$ ) will be 1 at first output port of MZI5. Again as  $E_2, E_0$  is 0, 1 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 0, 0, 1$ , output appears 0 at first output port of MZI10. So signal will reach at the port3 through ( $\bar{E}_2\bar{E}_1$ ) path and  $B_2$  bit is equivalent to 1. For  $B_3$  bit, as  $E_3, E_2$  is 1, 0, no output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 1, 0, 1$ , no

output appears at the first output port of MZI15, means no signal will reach at the port4 for  $B_3$  bit and it is equivalent to 0.

Case 8:  $E_3 = 1, E_2 = 0, E_1 = 1, E_0 = 0$

As  $E_0$  bit is 0, which means  $B_0$  bit is equivalent to 1 ( $\bar{E}_0$ ). For  $B_1$  bit, as  $E_1, E_0$  is 1, 0 then the output signal appears at second output port of MZI3, which means  $B_1=1$ . For  $B_2$  bit, as  $E_2, E_1$  is 0, 1 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 0, 0 then output ( $\bar{E}_2\bar{E}_0$ ) will be 1 at first output port of MZI7. For  $E_2, E_1, E_0 = 0, 1, 0$ , output appears 0 at first output port of MZI10. So signal will reach at the port3 through ( $\bar{E}_2\bar{E}_0$ ) path and  $B_2$  bit is equivalent to 1. For  $B_3$  bit, as  $E_3=1$  and  $E_2=0$ , no output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 1, 1, 0$ , no output appears at the first output port of MZI15, means no signal will reach at the port4 for  $B_3$  bit and it is equivalent to 0.

Case 9:  $E_3 = 1, E_2 = 0, E_1 = 1, E_0 = 1$

As  $E_0$  bit is 1, which means  $B_0$  bit is equivalent to 0 ( $\bar{E}_0$ ). For  $B_1$  bit, as  $E_1, E_0$  is 1, 1 then no output signal appears at second output port of MZI3, which means  $B_1=0$ . For  $B_2$  bit, as  $E_2, E_1$  is 0, 1 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 0, 1 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 0, 1, 1$ , output appears 0 at first output port of MZI10. So no signal will reach at the port3 and  $B_2$  bit is equivalent to 0. For  $B_3$  bit, as  $E_3 = 1$  and  $E_2 = 0$ , no output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 1, 1, 1$ , output appears at the first output port of MZI15, means signal will reach at the port4 for  $B_3$  bit and it is equivalent to 1.

Case 10:  $E_3 = 1, E_2 = 1, E_1 = 0, E_0 = 0$

As  $E_0$  bit is 0, which means  $B_0$  bit is equivalent to 1 ( $\bar{E}_0$ ). For  $B_1$  bit, as  $E_1, E_0$  is 0, 0 then no output signal appears at second output port of MZI3, which means  $B_1=0$ . For  $B_2$  bit, as  $E_2, E_1$  is 1, 0 then output ( $\bar{E}_2\bar{E}_1$ ) will be 0 at first output port of MZI5. Again as  $E_2, E_0$  is 1, 0 then output ( $\bar{E}_2\bar{E}_0$ ) will be 0 at first output port of MZI7. For  $E_2, E_1, E_0 = 1, 0, 0$ , output appears 0 at first output port of MZI10. So no signal will reach at the port3 and  $B_2$  bit is equivalent to 0. For  $B_3$  bit, as  $E_3 = 1$  and  $E_2 = 1$ , output will be at first output port of MZI12. As  $E_3, E_1, E_0 = 1, 1, 0$ , no output appears at the first output port of MZI15, means signal will reach at the port4 through  $E_3E_2$  path for  $B_3$  bit and it is equivalent to 1.

#### 4. CONCLUSION

Excess 3 to BCD conversion is a prominent code conversion technique and it is very useful for arithmetic operations. This paper explains successful design of Excess 3 to BCD code converter circuit using electro-optic effect of LiNbO<sub>3</sub> MZI in BPM along with mathematical description. These results are verified using MATLAB simulations.

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