Realization of All-Optical Sequential circuit using Mach Zehnder Interferometer

Umesh Kumar, Ashish Mishra

Abstract— **In this paper, realization of inverter latch is proposed through an all-optical cascadable tri-state buffer as a sequential circuit which is designed with Mach-Zehnder Interferometer (MZI). This sequential circuit is assembled based on electro-optic effect and is verified by simulation. The applications of tri-state buffer for optical data transfer and the advantage of using this circuit as an octal tri state buffer over the currently existing ICs has been explained.**

Index Terms— **Latch, All-optical devices, Electro-Optic Effect, Mach Zehnder Interferometer, Sequential circuit, Tri-state buffer, Optical Data Transmission.**

I. INTRODUCTION

The communication systems and data transmission in today's era is most commonly done in the optical domain (Ref. [1-5]) using optical fibres etc. But there arises a situation where the optical signal is to be converted into electrical signal for its passage through certain systems like sequential or combinational logic circuits, tri-state buffer, multiplexer etc., which consume some time for conversion.

To avoid such delays and to enhance the speed of data transmission, researches are carried in large numbers using Mach-Zehnder Interferometer (MZI). Optical logic gates, multiplexers etc. have been already designed (Ref. [6]) but another vital element of data transmission systems, which is all optical tri-state buffers, has not been designed yet. Given that tri-state buffer has a wide range of applications, there is a necessity for its design for optical communication which can be best achieved using MZI.

II. ELECTRO-OPTIC EFFECT

An electro-optic effect is a change in the optical properties of a material in response to an electric field that varies slowly compared with the frequency of light. It is a second order nonlinear optical effect that results in attaining a refractive index which is a function of E: applied electric field (voltage).

$$n(E) = n + a_1 \mathrm{E} + \frac{1}{2} a_2 E^2 + \cdots \qquad (1)$$

here, $a_1 = \frac{dn}{dE} | E = 0$; $a_2 = \frac{d^2 n}{dE^2} | E = 0$

where,

$$n = \frac{Speed\ of\ light\ in\ vaccum}{Speed\ of\ light\ in\ material}$$

This shows that increase in the applied electric field increases its refractive index and hence slows down the speed of signal (light) propagating through it.

When an optical signal is given as input to a 3dB coupler then it is first split based on power, into two equal waves. An electrical signal is applied to one of the wave, which modifies the properties of the material in that particular branch, and slows down the signal. Based on the applied voltage on that branch, a phase difference is created between the waves in the upper branch and the wave in the lower branch. As we increase the voltage to a point where the phase difference between the waves in the upper and lower branch is π, then, addition will result to zero. This stage is considered to be logic LOW. To obtain an optical logic HIGH, we have to obtain a phase difference of zero between the two waves.

III. MACH ZEHNDER INTERFEROMETER

Fig. 1 shows the construction diagram of MZI on the Lithium-niobate substrate (Ref. [7]). The device contains two input and two output ports associated with the electrodes. The refractive index of one of the arms of the MZI can be changed with the application of a particular voltage across it. The input signal is applied in the form of continuous optical signal. MZI has two channels to provide input and the output can be taken across two other channels. The optical signal is to be processed in between the output and input ports by applying electric field using electrodes.

There are two 3-db couplers in the construction of MZI. The applied input signal is first split using the input 3-db coupler before the application of electric field and then, the signals which are received after passing through the electrode arrangement, again passes through output 3-db coupler. With the application of electric field, the signal lags in phase with respect to the signal which did not experience any electric field. When such signals are combined, destructive interference takes place. The phase lag in the signal takes place depending on the strength of the applied electric field. This provides the phase modulation functionality.

The integrated switch is created on a wafer of lithium niobate and is surrounded by the air cladding. We have selected the crystal as lithium niobate with the cladding dielectric material with refractive index 1. For the Ti-diffused profile, we have taken the lateral diffusion length and diffusion length in depth as 3.5 µm and 4.2 µm, respectively. The length of the device is taken to be 33 mm and width as 100 µm. The width of the wafer is 8 µm. For the 3D wafer properties, the cladding material is air with the cladding thickness 2 µm. The substrate material is taken as Lithium Nioabate with the thickness

10 µm. In order to achieve perfect switching phenomena, we are required to define the electrode region in the proper manner. For this particular optical switching device the electrode region starts from 11500 µm and ends at 21500 µm.

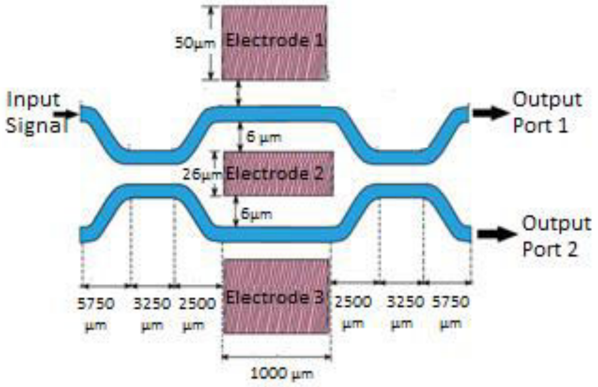

Fig. 1. Mach-Zehnder Interferometer construction with dimensions

Basically, we want to build the electrodes on the buffer layer. The refractive index of the buffer layer material is 1.47 with horizontal and vertical permittivity as 4. The thickness of the buffer layer is taken as 0.3 µm. On the buffer layer the electrode section is developed with the thickness of 4 µm. The device consists of a set of three electrodes. The width of the first, second, and third electrode is taken as 50 µm, 26 µm and 50 µm, respectively. The gap between electrodes 1–2 and 2–3 is maintained at 6 µm. We have selected the center position of the electrode as 5.5 µm. It is required that the precise input plane with the starting field mode and offset position should be zero. It is assumed that the other simulation parameters such as refractive index as modal, wavelength as 1.3 µm, polarization TE, and BPM solver as Paraxial, scheme parameter as 0.5 and boundary condition as TBC. Hence the obtained optical switching device behaves as the basic building blocks for the simulation of logic circuits. The expression of the normalized output power at output port1 and output port2 can be written as

$$P_{out1} = \left|\frac{OUT_1}{E_{in}}\right|^2 = \left|je^{-j(\varphi_0)}\sin\left(\frac{\Delta\varphi}{2}\right)\right|^2 = \sin\left(\frac{\Delta\varphi}{2}\right)^2$$
(2)

$$P_{out2} = \left|\frac{OUT_2}{E_{in}}\right|^2 = \left|je^{-j(\varphi_0)}\cos\left(\frac{\Delta\varphi}{2}\right)\right|^2 = \cos\left(\frac{\Delta\varphi}{2}\right)^2$$
(3)

Where $\Delta\varphi = \varphi_1 - \varphi_2$ And $\varphi_1 = (V_1/V_\pi)\pi$ *and* $\varphi_2 = (V_2/V_\pi)\pi$ and φ_1 *and* φ_2 are the phase differences developed due to application of the voltage across the electrodes.

In accordance to the control signal which is used as a phase modulator in this case, a phase difference is created based on electro-optic effect, which can be used as a switch from one port to another in the design of logic circuits (Ref. [8]).//////

IV. Implementation of Active-Low Tri-State Buffer using MZI

The tri-state buffer is available in IC forms. In Fig. 2 is an Octal Tristate Buffer IC (74LS244). This IC takes the input signal in the form of electrical signal and the output is also in electrical domain. But, by using the design by MZI shown in Fig. 3, a very novel octal tri-state buffer can be realized for enhanced action in optical domain.

In Fig. 3, the tri-state buffer shown in Fig. 2 has been implemented in optical domain. (The dimensions and structure of MZI used in Fig. 3 is same as that shown in Fig.1). The continuous optical signal is given through the first input port of MZI 1. This optical signal undergoes phase modulation depending on the applied electrical signal. The enable signal is given to the Electrode 2 of MZI 1//////////.

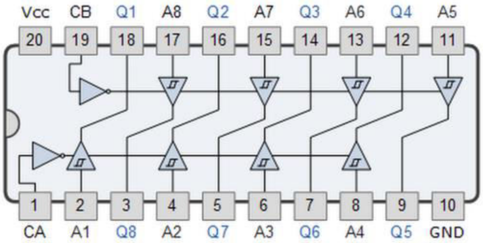

Fig. 2. IC 74LS244, Octal Tri-state Buffer

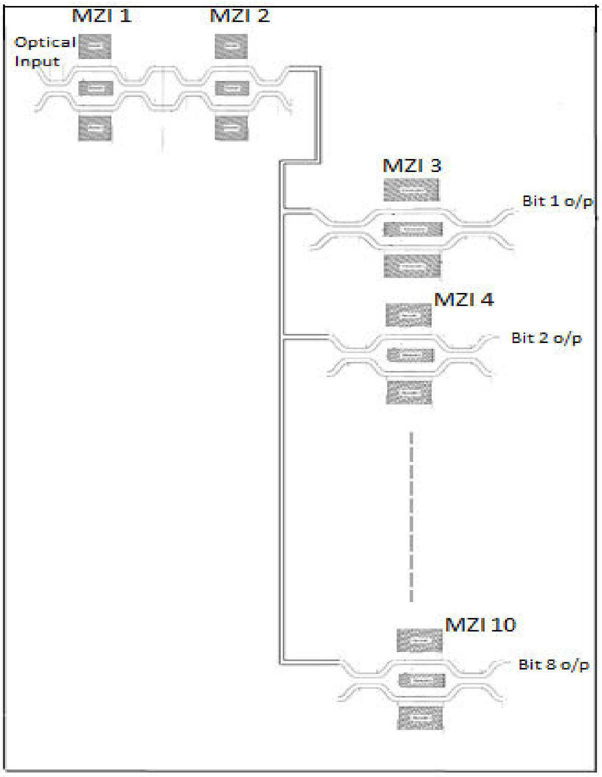

Fig. 3. Octal Tri-state buffer design using MZI for the Active LOW Enable Tri-State.

The MZIs 2 has been used to implement a NOT GATE, with its electrode 2 at always HIGH, so that it acts as a XOR Gate with one input HIGH, which results in an inverter. If the electrical signal (enable signal) is LOW, then the optical signal will pass through rest of the MZIs (MZI 3 to 10). Otherwise, destructive interference takes place and hence there will be no input optical signal to MZIs 3 to 10. This results in zero output from the output ports of MZIs 3 to 10. This implies that the circuit is in High Impedance state, i.e., irrespective of the input signal given to the device, the output is zero. In this way, the flow of Optical signal through the output channels represents an ‘Optical HIGH’ output and the condition in which there is no flow of optical signal represents an ‘Optical LOW’ output. Hence the optical signal is transmitted directly through this all-optical buffer without the requirement to convert the signal domain from optical to electrical in situations or systems which require the signal to pass through a buffer (like multiplexing, data-bus etc.), thus improving the speed of optical systems by saving the time consumed for conversion of signal domains. The simulations of this device design have been shown in Fig. [5,6,7,8] for various possibilities of tri-state buffer with active LOW Enable.

The following simulation results verify the design shown in Fig. 3 by showing appropriate results. These simulations demonstrate results for a single MZI output line in the buffer and the results can be further extended to other MZI output signal lines of the tri-state buffer.

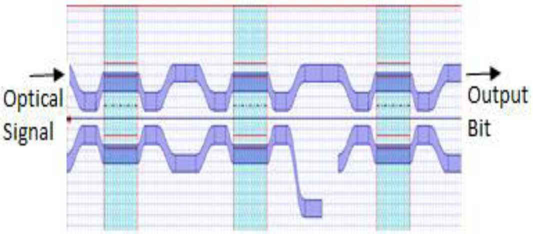

Fig. 4. Layout diagram of Tri-State Buffer with Active LOW Enable

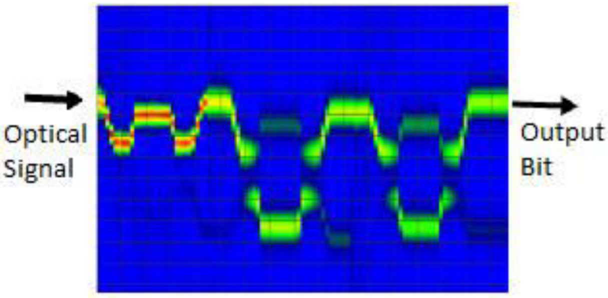

Fig. 5. Inputs: Enable=0 ; Bit I/P=1; Output: Bit O/P=1

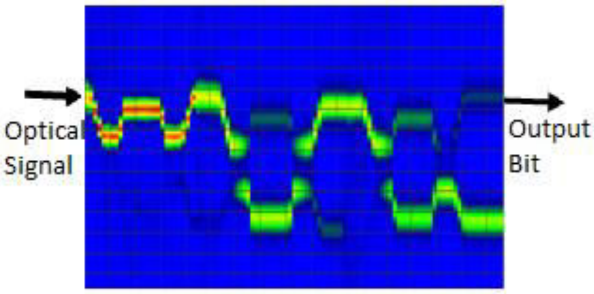

Fig. 6. Inputs: Enable=0 ; Bit I/P=0; Output: Bit O/P=0

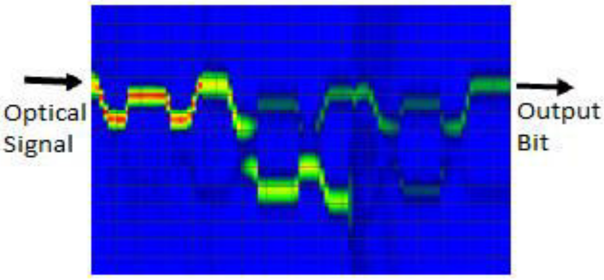

Fig. 7. Inputs: Enable=1 ; Bit I/P=1; Output: Bit O/P=0

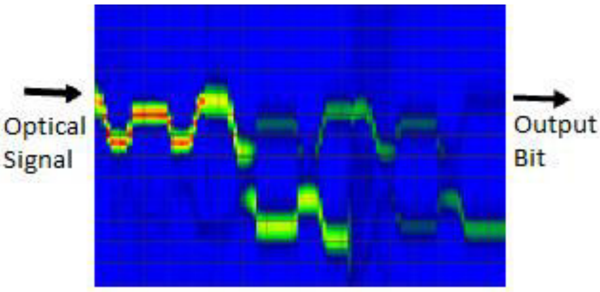

Fig. 8. Inputs: Enable=1 ; Bit I/P=0; Output: Bit O/P=0

V. Implementation of Active-High Tri-State Buffer using MZI

The same all-optical tri-state buffer can be designed with Active HIGH Enable also. This design is shown in Fig.9 and works in the fashion similar to the previous device description.

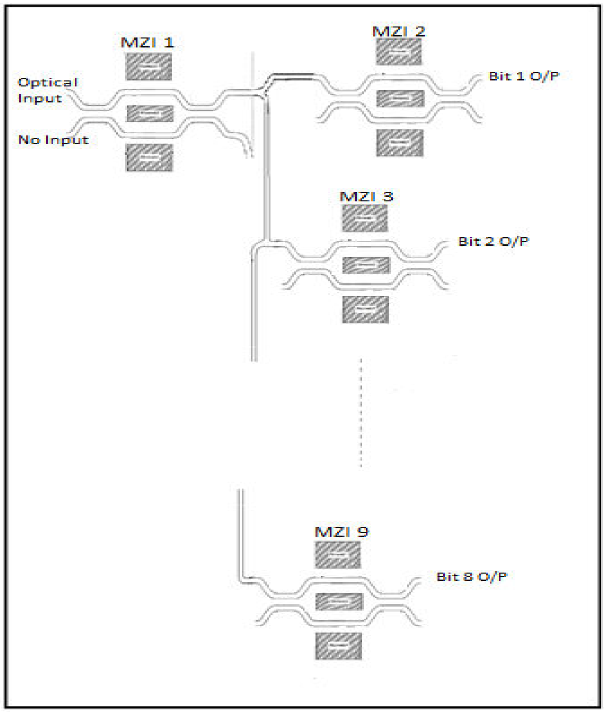

Fig. 9. Octal Tri-state buffer design using MZI with Active HIGH Enable.

The continuous input optical signal is given through the first input port of MZI 1. This optical signal gives the required optical output signal after undergoing phase modulation depending on the applied electrical signal (enable signal). Thus, with the electrical enable signal, the optical data flow takes place without domain conversion.

The enable signal is given to the Electrode 2 of MZI 1. If the electrical signal is HIGH, then the optical signal will pass through rest of the MZIs 2 to 9. Otherwise, destructive interference takes place and hence there will be no input optical signal to MZIs 2 to 9. This results in zero output from the output ports of MZIs 2 to 9. This implies that the circuit is in High Impedance state thereby resulting in zero output, irrespective of the input signals given to the MZIs. In this way, the flow of Optical signal through the output channels represents an 'Optical HIGH' output and the condition in which there is no flow of optical signal represents an 'Optical LOW' output. The simulated results of this design for all the possibilities have been shown in Fig. [11,12,13,14].

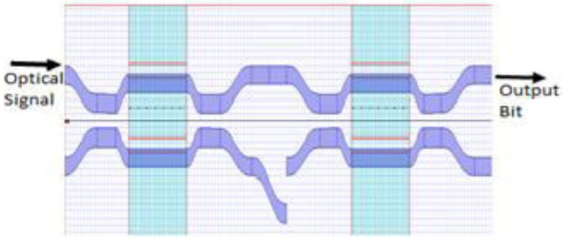

Fig. 10. Layout design of Tri-State Buffer with Active HIGH Enable

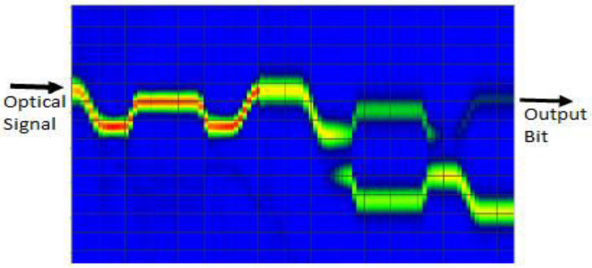

Fig. 11. Inputs: Enable=1 ; Bit I/P=0; Output: Bit O/P=0

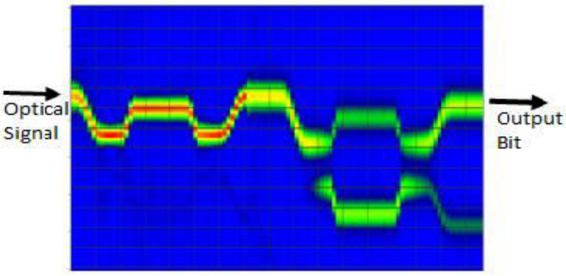

Fig. 12. Inputs: Enable=1 ; Bit I/P= 1; Output: Bit O/P=1

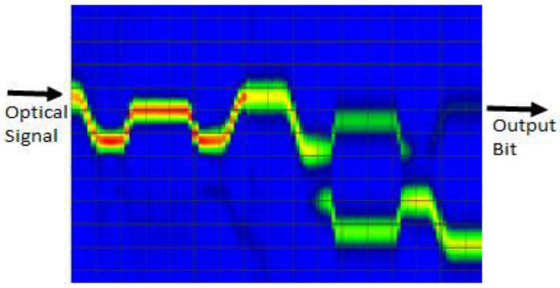

Fig. 13. Inputs: Enable=0 ; Bit I/P=1; Output: Bit O/P=0

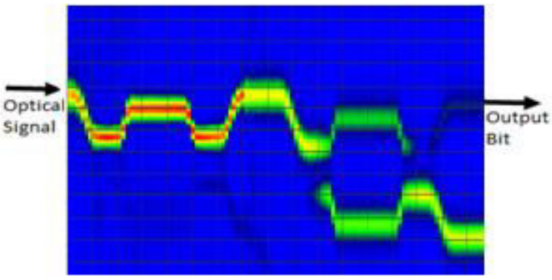

Fig. 14. Inputs: Enable=0 ; Bit I/P=0; Output: Bit O/P=0

Truth Table : Latch using tri-state buffer[9]

Active High Tri state buffer		
E	X	Z
0	0	1
1	1	Z

Active Low Tri state buffer		
E	X	Z
0	0	Z
1	1	X

E : Enable
X : Input
Z : output

VI. CONCLUSION

The use of this all-optical tri-state buffer helps in designing universal gates, multiplexer and latches consequently any of combinational and sequential circuit in optical domain for data transmission involving higher speed requirements. Moreover, additional circuitry for signal domain conversion is not required when this device is used, thus making it a cost-effective method. The octal tri-state buffer which has varied uses is designed in an innovative way for data transmission in optical domain which serves as a better technique for faster communication as the time that will be consumed for domain conversion is saved. Hence the above design is very promising for its application and use in optical data transmission systems, sequential and combinational logic circuits, optical data-bus systems, etc.

Based on the simulation results, it can be concluded that these designs are feasible and can be implemented practically.

VII. REFERENCES

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