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Design Of All Optical Reversible Logic Gates

Kuki Bordoloi, T. Theresal , Shanthi Prince

Abstract—**Considering the benefits of Quantum and Optics, if the logic gates in the quantum field and electronic structure are implemented using optical elements, then it will be benefited from advantages of Quantum and design, and these processing circuits can be used in optical computing and quantum computing, genetic processes, and other useful nanotechnology applications. Advantages of reversible logic systems and circuits have drawn a significant interest in recent years as a promising computing paradigm having application in low power CMOS, quantum computing, nanotechnology, and optical computing. In this study, we have introduced reversible optical Double Feynman gate using optical Mach-Zehnder interferometer (MZI) switches with new design. The proposed optical Double Feynman gate will be optical logic gate and reversible. As the proposed gate is a complete one, it can implement all the MZI-based quantum circuits.**

Index Terms— **Feynman Gate , Mach-Zehnder interferometer (MZI), Optical Double Feynman Gate, Reversible Logic.**

I. INTRODUCTION

In conventional computers, the computation carrying out is irreversible i.e. once logic block generates the output bits, the input bits are lost [1]. But it is not in the case of reversible logic circuits. The classical set of gates such as AND, OR, and EXOR are not reversible as they are all multiple input single output logic gates. A gate is reversible if the gate's inputs and outputs have a one-to-one correspondence, i.e. there is a distinct output assignment for each distinct input [2]. Therefore, a reversible gate's inputs can be uniquely determined from its outputs. Reversible logic gates must have an equal number of inputs and outputs [3]. Then the output rows of the truth table of a reversible gate can be obtained by permutation of input rows.

Reversible logic circuits have emerged as a promising technology in the field of information processing. Irreversible hardware computation results in energy dissipation due to information loss. On the other hand, the reversible logic circuits offer an alternative that allows computation with arbitrary small energy dissipation. There is number of existing reversible gates in literature like Fredkin, Feynman and Toffoli gates etc [4]. Each of these gates is universal, i.e. any logical reversible circuit can be implemented using these gates.

All-optical logic for optical network is an exciting field of research where we can expect much innovation. High capacity, low cost communication systems are needed to keep up with the increasing demand for the broad band communications. Photon being the ultimate unit of information with unmatched speed and with data package in a signal of zero mass, the techniques of computing with light may provide a way out of the limitations of computational speed and complexity inherent in electronics computing. Different optical logic gates have already been proposed to perform irreversible logic function. But, reversible computation in a system can be performed if the system is composed of reversible gates.

The all optical implementation of reversible gates can be designed based on semiconductor optical amplifier (SOA) based Mach-Zehnder interferometer (MZI) due to its significant advantages such as high speed, low power, fast switching time and ease in fabrication. Semiconductor optical amplifier (SOA) based Mach-Zehnder interferometer (MZI) can play a significant role in this field of ultra-fast all-optical signal processing. The interferometer employs bidirectional couplers and semiconductor amplifier in one of its arms. Interferometer acts as a very high speed switch since it does not need any conversation from optical to electronic and vice versa.

This paper is organized as follows. In section II, principle and operation of MZI based optical switch is discussed. In section III, all-optical circuit of Feynman gate is discussed. All-optical circuit of Fredkin gate is discussed in section IV . Simulation results using OptiSystem software confirming describe methods are also given in this paper. In section V, a new design of reversible optical Double Feynman gate is proposed. Finally, the conclusions are formulated.

II. SOA BASED MACH-ZEHNDER INTERFEROMETER (MZI) SWITCH

Mach-Zehnder Interferometer (MZI) Switch, as shown in the Fig.1 and Fig.2 is a very powerful optical device to realize ultra-fast all optical switching [5]. In this switch a semiconductor optical amplifier is inserted in each arm of MZI. The incoming signal to be switched is split between the

Kuki Bordoloi is with Department of Electronics and Communication Engineering, SRM University, Kattankulathur - 603 203, Tamil Nadu, India (e-mail: kukibordoloi622@gmail.com).

T.Theresal is a assistant professor in Department of Electronics and Communication Engineering, SRM University, Kattankulathur – 603203, Tamil Nadu, India (e-mail:theresal2004@gmail.com).

Shanthi Prince is a professor in Department of Electronics and Communication Engineering, SRM University, Kattankulathur - 603 203, Tamil Nadu, India (e-mail: shanthi.p@ktr.srmuniv.ac.in).

arms of the interferometer. The interferometer is balanced so that, in the absence of a control signal, the incoming signal emerges from one output port. The presence of a strong control pulse changes the refractive index of the medium. A change in the index adds a phase shift between the two arms of the interferometer, so that the incoming signal is switched over to another output port. This method of switching is based on cross-phase modulation (XPM).

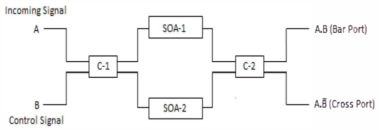


Fig. 1. Semiconductor optical amplifier based Mach-Zehnder interferometer.

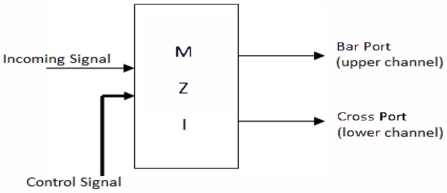


Fig. 2. Mach-Zehnder interferometer based all optical switch.

There two input ports A and B called as incoming signal port and control signal port respectively and two output ports called as bar port and cross port respectively in a MZI switch [6]. We consider no light or absence of light as the logic value 0. When there is an incoming signal at port A and control signal at port B then there is a light present at the output bar port and there is no light at the output cross port. In the absence of control signal at the input control port B and when there is an incoming signal at input port A then the outputs of MZI are switched and result in the presence of light at the output cross port and no light at the bar port. In the absence of incoming signal at the input port A there is no light at both the output ports. The above behavior of MZI can be written as Boolean functions having inputs to outputs mapping as (A,B) to ($X = AB$, $Y = A\overline{B}$), given in Table I.

Table I
Truth Table of MZI based switch

Input		Output	
Incoming Signal	Control Signal	Bar Port	Cross Port
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	0

The simulation setup of MZI based switch using OptiSystem software is shown in Fig. 3. OptiSystem is a comprehensive design suite that enables users to plan, test, and simulate optical links in the transmission layer of modern optical networks [7].

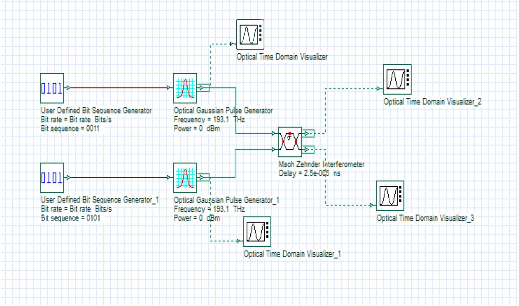
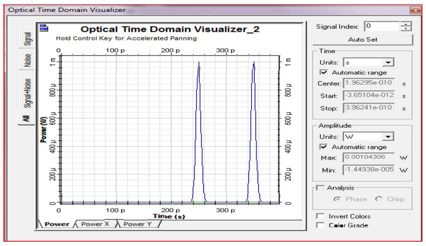
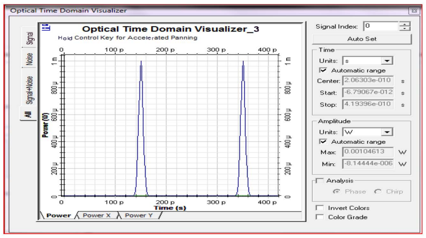


Fig. 3. Simulation Setup of MZI switch in OptiSystem.

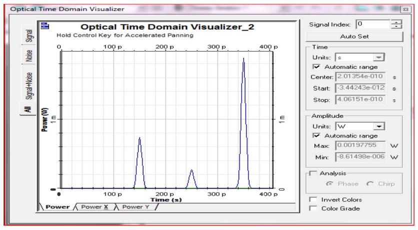
The simulated results of MZI based switch using OptiSystem as obtained in the optical time domain visualizer is given in Fig. 4.



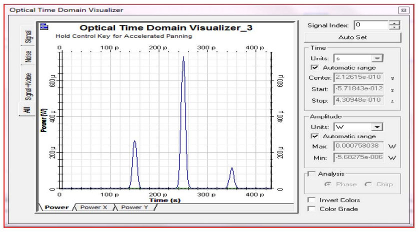
Input (0011)



Input (0101)



Output (0001)



Output (0010)
Fig. 4. Simulated inputs and outputs of MZI switch.

III. MZI BASED FEYNMAN GATE

Feynman gate is a 2×2 reversible gate having A and B as input vector and X and Y as output vector, where X=A, Y=A⊕B [8], given in Table II.

Table II
Truth Table of Feynman Gate

Input		Output	
A	B	X	Y
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

The circuit of all- optical MZI based Feynman gate is shown in Fig. 5. and the simulation setup Feynman gate using OptiSystem software is shown in Fig. 6.

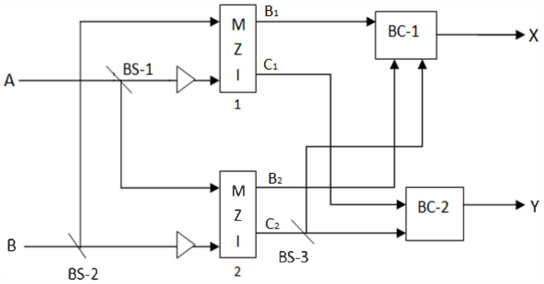


Fig. 5. All-optical circuit of Feynman gate. BC: beam combiner, ▷: EDFA, BS: 50:50 beam splitter.

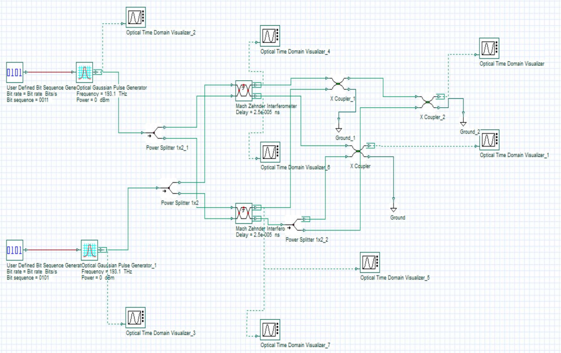
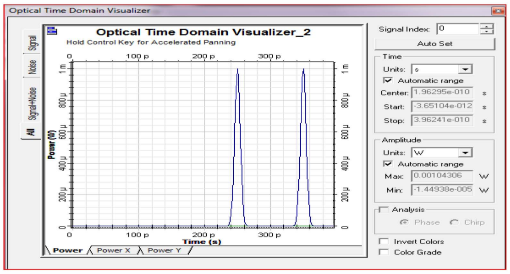


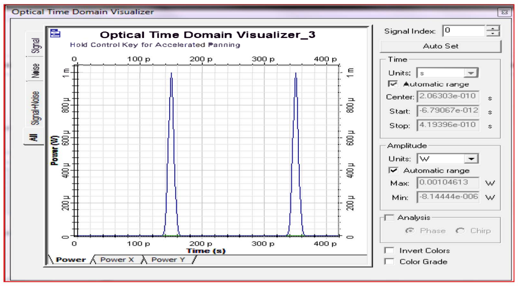
Fig. 6. Simulation Setup of Feynman gate.

The simulated results of optical Feynman gate using OptiSystem is given in Fig. 7.



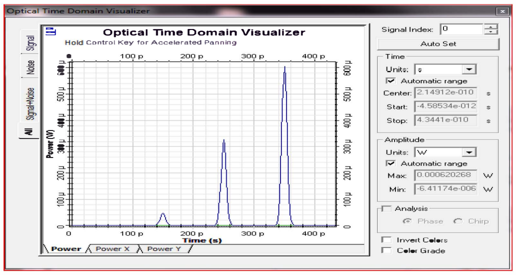
Signal Index: 0
Units: s
☑ Automatic range
Center: 1.96295e-010 s
Start: -3.65104e-012 s
Stop: 3.96241e-010 s
Units: W
☑ Automatic range
Max: 0.00104306 W
Min: -1.44938e-005 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Input (0011)



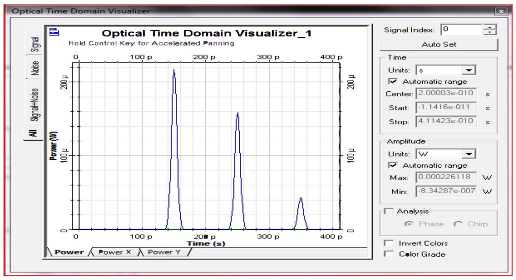
Signal Index: 0
Units: s
☑ Automatic range
Center: 2.06303e-010 s
Start: -6.79067e-012 s
Stop: 4.19396e-010 s
Units: W
☑ Automatic range
Max: 0.00104613 W
Min: -8.14444e-006 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Input (0101)



Signal Index: 0
Units: s
☑ Automatic range
Center: 2.14912e-010 s
Start: -4.58534e-012 s
Stop: 4.3441e-010 s
Units: W
☑ Automatic range
Max: 0.000620268 W
Min: -6.41174e-006 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Output (0011)



Signal Index: 0
Units: s
☑ Automatic range
Center: 2.00003e-010 s
Start: -1.1416e-011 s
Stop: 4.11423e-010 s
Units: W
☑ Automatic range
Max: 0.000226118 W
Min: -8.34287e-007 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Output (0110)

Fig. 7. Simulated inputs and outputs of Optical Feynman gate.

IV. MZI BASED FREDKIN GATE

Fredkin gate is a 3×3 reversible logic gate having A,B,C as input vector and X,Y,Z as output vector, where X=A, $Y = \overline{A}B \oplus AC$, $Z = \overline{A}C \oplus AB$ [9], given in Table III.

Table III
Truth Table of Fredkin Gate

Input			Output		
A	B	C	X	Y	Z
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	1	0
1	1	0	1	0	1
1	1	1	1	1	1

The all-optical circuit of Fredkin gate is shown in Fig. 8. and the simulation setup of the same using OptiSystem software is shown in Fig. 9.

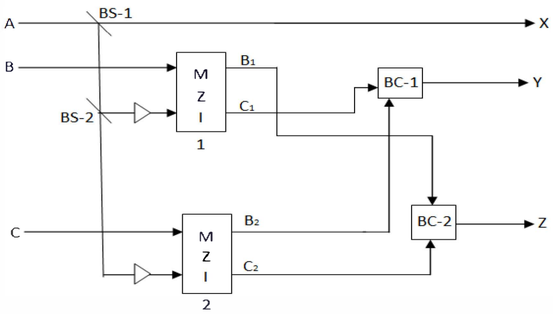


Fig. 8. All-optical circuit of Fredkin gate.

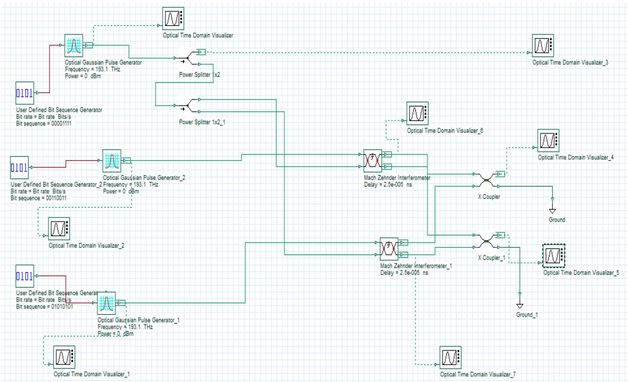
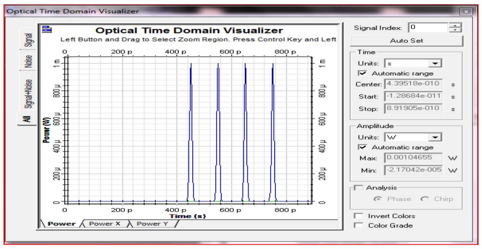


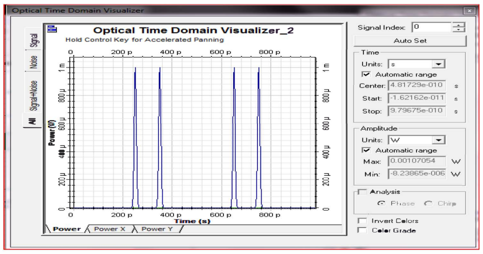
Fig. 9. Simulation Setup of Fredkin gate.

The simulated results of optical Fredkin gate using OptiSystem is given in Fig. 10.



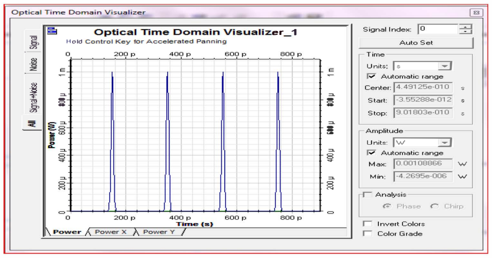
Signal Index: 0
Units: s
☑ Automatic range
Center: 4.39518e-010
Start: -1.28684e-011
Stop: 8.91905e-010
Units: W
☑ Automatic range
Max: 0.00104655 W
Min: -2.17042e-005 W
☐ Analysis
☐ Invert Colors
☐ Color Grade

Input (00001111)



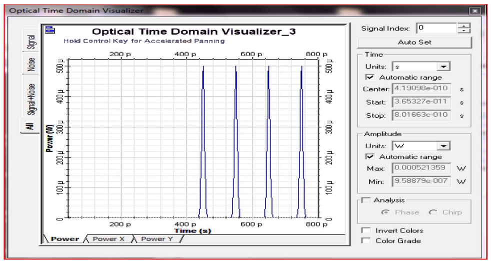
Signal Index: 0
Units: s
☑ Automatic range
Center: 4.81729e-010
Start: -1.62162e-011
Stop: 9.79675e-010
Units: W
☑ Automatic range
Max: 0.00107054 W
Min: -8.23865e-006 W
☐ Analysis
☐ Invert Colors
☐ Color Grade

Input (00110011)



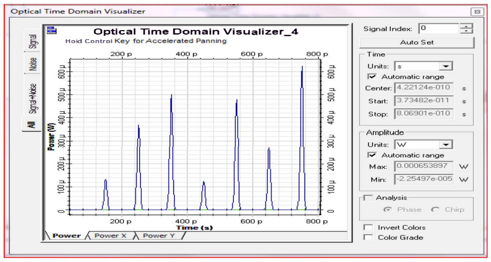
Signal Index: 0
Units: s
☑ Automatic range
Center: 4.49125e-010
Start: -3.55288e-012
Stop: 9.01803e-010
Units: W
☑ Automatic range
Max: 0.00108866 W
Min: -4.2695e-006 W
☐ Analysis
☐ Invert Colors
☐ Color Grade

Input (01010101)



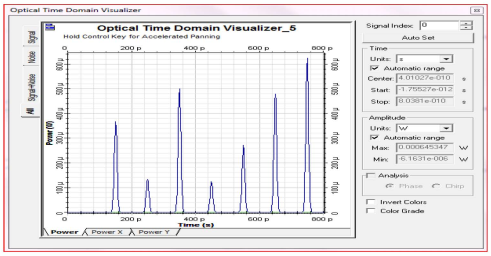
Signal Index: 0
Units: s
☑ Automatic range
Center: 4.19098e-010
Start: 3.65327e-011
Stop: 8.01663e-010
Units: W
☑ Automatic range
Max: 0.000521359 W
Min: 9.58879e-007 W
☐ Analysis
☐ Invert Colors
☐ Color Grade

Output (00001111)



Signal Index: 0
Units: s
☑ Automatic range
Center: 4.22124e-010
Start: 3.73482e-011
Stop: 8.06901e-010
Units: W
☑ Automatic range
Max: 0.000653897 W
Min: -2.25497e-005 W
☐ Analysis
☐ Invert Colors
☐ Color Grade

Output (00110101)



Signal Index: 0
Units: s
☑ Automatic range
Center: 4.01027e-010
Start: -1.75527e-012
Stop: 8.0381e-010
Units: W
☑ Automatic range
Max: 0.000645347 W
Min: -6.1631e-006 W
☐ Analysis
☐ Invert Colors
☐ Color Grade

Output (01010011)

Fig. 10. Simulated inputs and outputs of Optical Fredkin gate.

V. PROPOSED MZI BASED ALL-OPTICAL DOUBLE FEYNMAN GATE

Double Feynman gate is 3×3 reversible logic gate having A, B, C as input vector and X,Y,Z as output vector, where X=A, Y=A⨁B and Z=A⨁C [10]. The schematic block diagram is shown in Fig. 11 and truth table is given in Table IV.

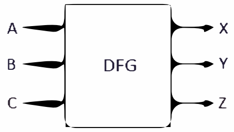


Fig. 11. Schematic diagram of Double Feynman gate.

Table IV
Truth Table of Double Feynman Gate

Input			Output		
A	B	C	X	Y	Z
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	1	1
1	0	1	1	1	0
1	1	0	1	0	1
1	1	1	1	0	0

The all optical circuit of Double Feynman gate using OptiSystem is shown in Fig. 12.

(1) When A=B=C=0, i.e. when no inputs are given(absence of light), then there is no output X=Y=Z=0.

(2) When A=B=0 and C=1, incoming signal is absent at MZI-1, MZI-2 and MZI-4,then no light comes out through cross or bar port of MZI-1, MZI-2 and MZI-4. Incoming signal is present at MZI-3 but control signal is absent. Hence, the light beam emerging out through C_3 gives the output Z=1.Therefore, when A=B=0 and C=1 then X=0, Y=0, Z=1. It satisfies the second row of the truth table given in Table IV.

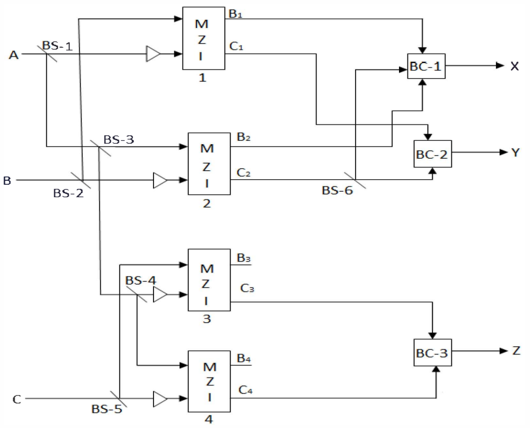


Fig. 12. All-optical circuit of Double Feynman gate. BC: beam combiner, ▷ EDFA, BS: 50:50 beam splitter.

(3) When A=C=0 and B=1 then incoming signal is absent at MZI-2, MZI-3 and MZI-4. So no light comes out through cross or bar port of MZI-2, MZI-3 and MZI-4.For MZI-1 since incoming signal B=1 and control signal A=0 thus bar port receives no light i.e. B_1=0 and cross port receives light so C_1=1 which gives the output Y=1. Therefore, when A=C=0 and B=1 then X=0, Y=1, Z=0. It satisfies the third row of the truth table given in Table IV.

(4) When A=0 and B=C=1, then the MZI-2 and MZI-4 receives no light in the incoming port, so B_2=C_2=B_4=C_4=0. MZI-1 and MZI-3 receives the incoming signal and no control signal thus B_1=B_3=0 and C_1=C_3=1 which gives X=0 and Y=Z=1. Therefore, when A=0 and B=C=1 then X=0, Y=1, Z=1. It satisfies the fourth row of the truth table given in Table IV.

(5) When A=1 and B=C=0, then the MZI-1 and MZI-3 receives no light in the incoming port, so B_1=C_1=B_3=C_3=0. MZI-2 and MZI-4 receives the incoming signal and no control signal thus B_2=B_4=0 and C_2=C_4=1, which gives X=Y=Z=1. Therefore, when A=1 and B=C=0 then X=Y=Z=1. It satisfies the fifth row of the truth table given in Table IV.

(6) When A=C=1 and B=0, then the MZI-1 receives no light in the incoming port, so B_1=C_1=0. MZI-2, MZI-3 and MZI-4 receives the incoming signal. But since B=0 there is no control signal in MZI-2 thus B_2=0 and C_2=1, which gives X=1 and Y=1. Both the MZI-3 and MZI-4 receives both the incoming and the control signal thus B_2=B_4=1 and C_2=C_4=0, which gives Z=0.Therefore, when A=1 and B=0 and C=1 then X=Y=1 and Z=0. It satisfies the sixth row of the truth table given in Table IV.

(7) When A=B=1 and C=0, then the MZI-3 receives no light in the incoming port, so B_3=C_3=0. MZI-1, MZI-2 and MZI-4 receives the incoming signal. Since C=0 there is no control signal in MZI-4 thus B_4=0 and C_4=1, which gives Z=1. Both the MZI-1 and MZI-2 receives both the incoming and the control signal thus B_1=B_2=1 and C_1=C_2=0, which gives X=1 and Y=0.Therefore, when A=1 and B=1 and C=0 then X=Z=1 and Y=0. It satisfies the seventh row of the truth table given in Table IV.

(8) When A=B=C=1, then MZI-1, MZI-2, MZI-3 and MZI-4 receives both the control and the incoming signal. Thus B_1=B_2=B_3=B_4=1 and C_1=C_2=C_3=C_4=0, which gives X=1, Y=0 and Z=0. Therefore, when A=1 and B=1 and C=1 then X=1 and Y=Z=0. It satisfies the eight row of the truth table given in Table IV.

The truth table for the proposed optical Double Feynman gate is verified theoretically. The proposed model of optical Double Feynman gate is being simulated using OptiSystem.

The simulation setup of the proposed optical Double Feynman using OptiSystem software is shown in Fig. 13.

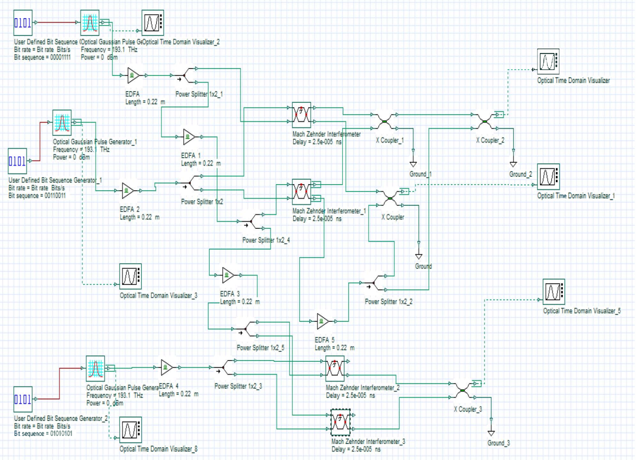
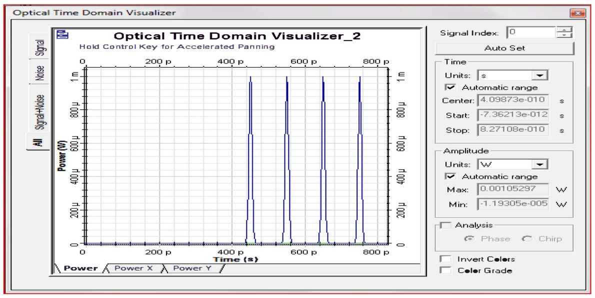


Fig. 13. Simulation Setup of optical Double Feynman gate.

The simulated results of proposed optical Double Feynman gate using OptiSystem is given in Fig. 14.


Optical Time Domain Visualizer

Optical Time Domain Visualizer_2

Hold Control Key for Accelerated Panning

Signal Index: 0

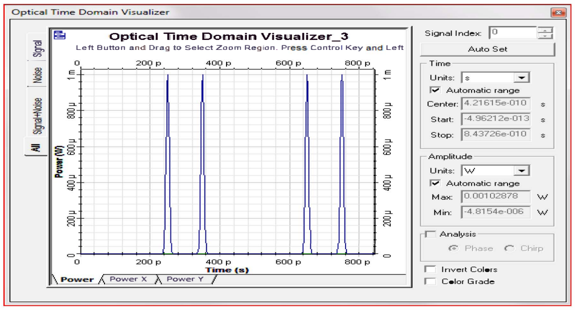
Time
Units: s
☑ Automatic range
Center: 4.09873e-010 s
Start: -7.36213e-012 s
Stop: 8.27108e-010 s

Amplitude
Units: W
☑ Automatic range
Max: 0.00105297 W
Min: -1.19305e-005 W

☐ Analysis
● Phase ○ Chirp

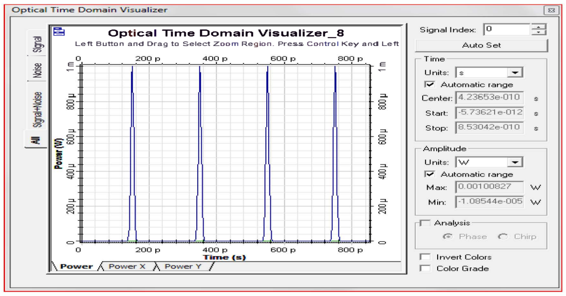
☐ Invert Colors
☐ Color Grade

Input (00001111)



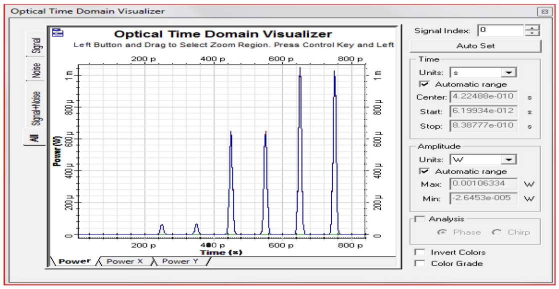
Optical Time Domain Visualizer_3
Left Button and Drag to Select Zoom Region. Press Control Key and Left
Signal Index: 0
Time
Units: s
☑ Automatic range
Center: 4.21615e-010 s
Start: -4.96212e-013 s
Stop: 8.43726e-010 s
Amplitude
Units: W
☑ Automatic range
Max: 0.00102878 W
Min: -4.8154e-006 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Input (00110011)



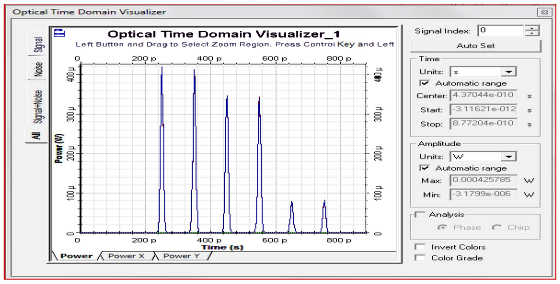
Optical Time Domain Visualizer_8
Left Button and Drag to Select Zoom Region. Press Control Key and Left
Signal Index: 0
Time
Units: s
☑ Automatic range
Center: 4.23653e-010 s
Start: -5.73621e-012 s
Stop: 8.53042e-010 s
Amplitude
Units: W
☑ Automatic range
Max: 0.00100827 W
Min: -1.08544e-005 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Input (01010101)



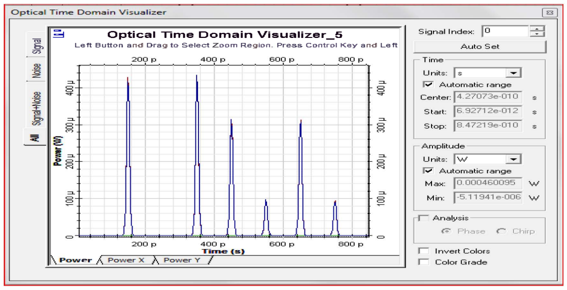
Optical Time Domain Visualizer
Left Button and Drag to Select Zoom Region. Press Control Key and Left
Signal Index: 0
Time
Units: s
☑ Automatic range
Center: 4.22488e-010 s
Start: 6.19934e-012 s
Stop: 8.38777e-010 s
Amplitude
Units: W
☑ Automatic range
Max: 0.00106334 W
Min: -2.6453e-005 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Output (00001111)



Optical Time Domain Visualizer_1
Left Button and Drag to Select Zoom Region. Press Control Key and Left
Signal Index: 0
Time
Units: s
☑ Automatic range
Center: 4.37044e-010 s
Start: -3.11621e-012 s
Stop: 8.77204e-010 s
Amplitude
Units: W
☑ Automatic range
Max: 0.000425785 W
Min: -3.1799e-006 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Output (00111100)



Optical Time Domain Visualizer_5
Left Button and Drag to Select Zoom Region. Press Control Key and Left
Signal Index: 0
Time
Units: s
☑ Automatic range
Center: 4.27073e-010 s
Start: 6.92712e-012 s
Stop: 8.47219e-010 s
Amplitude
Units: W
☑ Automatic range
Max: 0.000460095 W
Min: -5.11941e-006 W
☐ Analysis
● Phase ○ Chirp
☐ Invert Colors
☐ Color Grade

Output (01011010)

Fig. 14. Simulated inputs and outputs of optical double Feynman gate.

VI. CONCLUSION

In this paper, the all-optical design of reversible Double Feynman gate is proposed and described. The simulation of existing all-optical Feynman and Fredkin gates using OptiSystem software are also done. All these gates can be considered as basic gates and the arithmetic and logic operations in reversible systems can be performed.

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