Design of All-Optical Reversible Logic Circuits Using Novel Optical Reversible Gates

Adapa Venkata Paramkusam
Associate Professor & HoD,
Department of ECE,
MLR Institute of
Technology.

V.Arun
Assistant Professor,
Department of ECE,
MLR Institute of
Technology.

P.Anjaneyulu
Assistant Professor,
Department of ECE,
MLR Institute of
Technology.

Md Rizwan
M.Tech Student,
Department of ECE,
MLR Institute of
Technology.

Abstract:

The development in the field of nanometer technology leads to minimize the power consumption of logic circuits. Reversible logic design has been one of the promising technologies gaining greater interest due to less dissipation of heat and low power consumption. Recently, in the literature, reversible logic gates and combinational circuits have been proposed in optical domain using Semiconductor Optical Amplifier (SOA) based Mach Zehnder interferometer (MZI) switches due to its significant advantages such as high speed, low power, fast switching and ease of fabrication. Optical reversible designs have used ad-hoc approaches and require high cost in terms of MZI switches, Beam Splitters (BS), and Beam Combiners (BC) as well as optical delay. In this work, an optical reversible MNOT gate and all-optical realization of 4×4 Toffoli Gate have been proposed which is used in all-optical realization of optimized reversible combinational circuits.

A general design approach to realize all-optical reversible circuits based on MZI switches has been proposed first time in the literature. Optimized all-optical reversible 2×1 multiplexer and full adder circuits have been designed using these proposed gates and design approach. All-optical reversible designs of 4×1 multiplexer, 1×4 Demultiplexer and 3to8 Decoder circuits have also been presented in this work first time in the literature. Our results have shown significant improvements over existing designs in terms of MZI switches, BS, BC and optical delay.

Keywords—Optical Reversible computing; Mach-ZehnderInterferometer(MZI); Full Adder; Multiplexer; Decoder; optical cost.

INTRODUCTION:

The growing technologies have increased the demand of high performance computing. According to G. Moore's low [1], number of transistor counts to be integrated per unit area in devices will almost double in one and half year. To achieve high speed computation, high packaging density in the logic circuits is required which results in more heat dissipation.

The conventional computing is found unable to deal with low power, high compaction and heat dissipation issues of the current computing environment. In 1961, R. Laundaur [2] stated that heat dissipation occurs due to energy loss in irreversible logics. Each bit of information dissipates an amount of energy equal to KTln2 joules where K is Boltzmann's Constant and T is the absolute temperature. In 1973, C. H. Bannett [3] stated that reversible logic can overcome the heat dissipation problem of VLSI circuits because the bits of information are not erased in reversible computing.

New technologies are emerging to deal with these issues. Reversible Computing is one way to overcome the problem of heat dissipation in computing chips which in turn help in increasing the packaging density.

Reversible Logic seems to be hopeful due to its wide application in emerging technologies such as quantum computing, optical computing and power efficient nanotechnologies etc. Reversible circuits do not lose information. A reversible logic gate has one to one mapping between input and output vectors i.e. number of input lines are equal to number of output lines in the reversible gate [12], [14]. Fan-out is not permitted in the reversible logic.Constant inputs and garbage output line can be added to the circuit to make it reversible[12], [13], [14].

Optical Computing is computation with photon as opposed to conventional electron based computation. Unmatched high speed and zero mass of photon have attracted the researchers towards the optical realization of reversible logic gates using Semiconductor Optical Amplifier (SOA) based Mach Zehnder Interferometer (MZI) switches. MZI Switches are preferred because of its high speed, fast switching, low power and ease in fabrication [4], [5], [6].

The authors have presented the optical realization of popular reversible logic gates such as Feynman and Toffoli Gates [4], Fredkin Gate [5], and Peres Gate [6] etc. All-optical reversible combinational circuits for instance 2×1 Multiplexer [7], Binary Ripple Carry Adder [8], NOR Gate [9], New Gate [10], Hybrid New Gate (HNG) [11] and Modified Fredkin Gate [15] etc. are proposed by the authors in the literature.

In this paper, we have proposed an optical reversible MNOT gate using one MZI switch. All-optical realization of 4×4 Toffoli Gate has been presented which is used in alloptical realization of optimized reversible combinational circuits. A general design approach to realize all-optical reversible circuits based

on MZI switches has been proposed first time in the literature.

Optimized all-optical reversible 2×1 multiplexer and full adder circuits have been designed using these proposed gates and design approach. All-optical reversible designs of 4×1 multiplexer, 1×4 D e-multiplexer and 3to8 Decoder circuits have also been presented in this work first time in the literature. Our results have shown significant improvements over existing designs in terms of MZI switches, BS, BC and optical delay.

BASICS OF ALL OPTICAL REVERS IBLE LOGIC

Reversible logics are implemented with optical technology using some building blocks such as MZI based optical switch, beam splitter and beam combiner.

SOA Based MZI Switch

An SOA based MZI switch can be de signed using two Semiconductor Optical Amplifiers (SOA-1, SOA-2) and two couplers (C -1, C-2) [8], [9]. In an MZI switch, there are two inputs ports A and B, and two output ports called bar port and cross port, respectively, as shown in Figure 1 and 2.
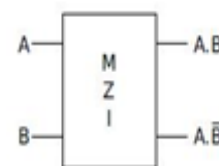

Fig. 1. Block diagram of Mach-Zehnder Interferometer switch [8]

Fig. 2. SOA based Mach-Zehnder Interferometer switch [8]

The optical signal at port B is termed as the control signal and signal at port A is termed as incoming signal. When there are signals present at port A and port B then there is a presence of light signal at the bar port an d absence of light signal at the cross port. In the absence of co ntrol signal at port B and presence of incoming signal at port A, the outputs of MZI are interchanged and results in the presence of light at the cross port and no light at the bar port. Here, absence of light is considered as the logic value 0 and p resence of light is considered as logic value 1.

This behavior of SOA based MZI switch can be written as Boolean functions having inputs to outputs mapping as $(A, B) \rightarrow (P=A.B, Q = A.\overline{B})$, where A, B are the inputs and P, Q are the outputs of MZI, respectively. The optical cost and the delay ( ) of MZI based all optical switch is considered as unity. The authors have considered the following optimization parameters for the all-optical reversible logics: optical cost i.e. number of MZI switches, number of BC and BS used in the logic circuit, and optical delay i.e. number of stages of MZI switches used in the design of logic circuit.

All-optical Feynman gate:

The Feynman gate (FG) has mapping $(A, B) \rightarrow (P=A, Q=A\oplus B)$ where A, B are the inputs and P=A, $Q=A\oplus B$ are the outputs, respectively. The Feynman gate can be realized using 2 MZI switches, 2 bea m combiners (BC) and 3 beam splitters (BS) in all optical domain as shown in figure 3 [4].
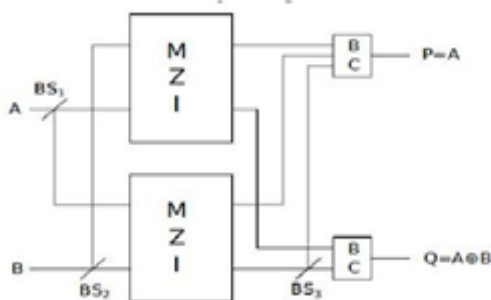

Fig. 3. Feynman gate and its all-optical implementation [4]

PROPOSED ALL-OPTIC AL REVERSIBLE LOGIC GATE

We have proposed a new M NOT gate and presented an all-optical realization of 4×4 Toffoli Gate which are efficient to design optimized optical reversible circuits.

Proposed all-optical reversible MNOT Gate:

A new 2×2 all-optical reversible MNOT gate (1, A) → (P, Q) has been proposed, where P =A and Q = Ā. Figure 4 shows the Block diagram of M NOT gate.

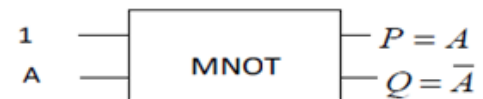This gate generates logical NOT of the input logic A. Table I shows the truth table of MNOT gate.

Fig. 4. Block diagram of Proposed 2×2 MNOT gate

TABLE I TRUTH TABLE OF THE PROPOSED REVERSIBLE GATE

Input		Output	
1	*A*	$P = A$	$Q = \overline{A}$
1	0	0	1
1	1	1	0

The all-optical reversible MNOT gate has been shown in figure 5. This gate is designed with single MZI switch. The incoming signal of MZI switch is set to 1 then output generated at cross port is inverse of the input at control signal.

The optical cost of MNOT gate is one. NO Beam Splitter (BS) or Beam Combiner (BC) is used in this gate. As only one MZI switch is used, so the delay is 1Δ.
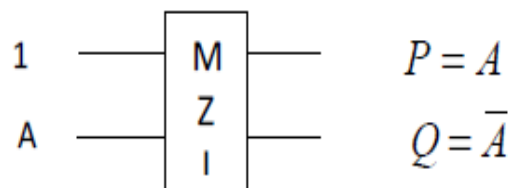

Fig. 5. Proposed 2×2 Optical Reversible MNOT gate

The optical MNOT gate is a useful logic gate in all-optical reversible circuit realization. Earlier the authors has used Feynman gate to generate inverse of logic with optical cost 2 MZI switches. Using this gate cost has been reduced to one MZI switch.

Optical Realization of 4×4 Toffoli Gate

The 4×4 Toffoli Gate (4×4 TG) is mapped from input vector (A, B, C, D) to output vector (P, Q, R, S), where P=A, Q=B, R=C, and S=D $\oplus$ ABC, respectively. Basically, 4×4 Toffoli gate is Multiple Controlled Toffoli gate (MCT) with 3
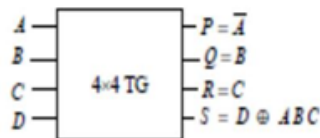

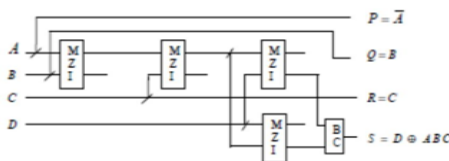**Fig. 6. Block diagram of 4×4 Toffoli gate**

Fig. 7. All-optical Realization of 4×4 Toffoli gate control lines.

Figure 6 shows the Block dia gram and Figure 7 Shows th.e all -optical realization of 4×4 Toffoli gate. This gate has been realized with 4 MZI Switches, Five Beam splitters (BS) and one Beam Combiners (BC). The optical delay of this gate is considered as 3∆.

PROPOSED GENERAL DESIGN A PPROACH

We have realized optical reversible circuits using MZI switches in different ways. No specified approach is followed in the synthesis of the all -optical reversible circuits. In this work, we have proposed a general design approach to realize all-optical reversible circuits. The approach is described as follows:

Algorithm 1: Design approach to realize optical reversiblecircuits

Step1. Consider the desired combinational logic circuit
Step2.IF the desired logic function is complex then
Step3.Apply Replacement Method

Step4. ELSE apply Truth Table based Method with desiredoutput logic function
Step5. Realize the optical reversible logic circuit

Algorithm 2: Replacement Method

Step1. Repeat step 2 to 6 WHILE all the gates in theconventional logic circuit are replaced
Step2. Choose a logic gate from conventional circuit
Step3. IF equivalent optical reversible gate is alreadyexisted then
Step4. Replace the chosen gate with equivalent gate
Step5. ELSE design the required optical reversible logicgate with truth table based method
Step6. Replace the chosen gate with this designed gate

Algorithm 3: Truth table Based method

Step1. Derive the desired output logic function from thetruth table of the circuit
Step2. Add constant inputs and garbage output lines tomake it reversible if needed
Step3. Design the all-optical reversible circuit using MZIswitches, Beam Splitters and Beam Combiners realizing the logic functions at output lines

PROPOSED ALL-OPTICA L REVERSIBLE LOGIC CIRCUITDESIGNS

Proposed All-optical Reversible 2×1 Multiplexer

This section describes the design and realization of the reversible 2×1 Multiplexer in all-optical domain using the proposed MNOT gate and optical Toffoli Gate (TG) [4]. It has two data inputs (D_0 and D_1), a single output O and a select line S_0 to select one of the two input data lines. The outputfunction of 2×1 Multiplexer is given by O = $S_0D_0+S_0D_1$.

TABLE II TRUTH TABLE OF 2×1 MULTIPLEXER

Input			Output
D_0	D_1	S_0	O
0	0	0	0
0	0	1	0
0	1	0	0
0	1	1	1
1	0	0	1
1	0	1	0
1	1	0	1
1	1	1	1

The truth table of 2×1 Multiplexer is shown in table II. The optical realization of 2×1 Reversible Multiplexer is shown in figure 8. It is designed with one MNOT and two TG gates. Here, MNOT gate behaves as NOT gate. When the third input line of TG is set to Constant 0 (Zero), the TG behaves as AND gate.
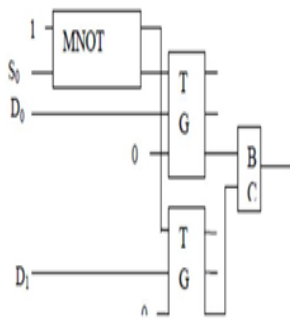

Fig. 8. Optical Realization of 2×1 Reversible Multiplexer

The MNOT gate is made of 1 MZI Switch. No BS and BC are used in the design of MNOT gate. The TG is made of 3 MZI Switches, 4 BS and one BC [4]. The delay of MNOT gate is 1Δ and that of TG is 2Δ. Thus, total optical cost of Optical Reversible 2×1 Multiplexer is 7 MZI Switches; total Beam splitters used are 8; beam Combiners used are 3 and Delay of the multiplexer circuit is calculate d as 3Δ as the two TG are working in parallel. It can be observed that optical cost of the Optical Reversible 2×1 Multiplexer h as been improved significantly in compare to existing one [7] which was implemented using 8 MZI switches, 12 Beam splitters, 5 Beam combiners, and optical delay 3Δ.

Proposed All-optical Reversible Full Adder Circuit

This section describes a design of all-Optical reversible full Adder circuit using two existing all-Optical Reversible Logic gates with improved Optical cost. The truth table of the full adder circuit is shown in the table III. The output functions of Full Adder circuit are given as follows:

$S = A \oplus B \oplus C$; $C_{out} = AB + (A \oplus B) C$

TABLE III TRUTH TABLE OF THE FULL ADDER CIRCUIT

Input			Output	
A	B	C	S	C_{out}
0	0	0	0	0
0	0	1	1	0
0	1	0	1	0
0	1	1	0	1
1	0	0	1	0
1	0	1	0	1
1	1	0	0	1
1	1	1	1	1

The new improved Optical Reversible F ull Adder circuit is designed using two existing all-optical reversible logic gates; One is Optical Feynman Gate which is mapped as (A, B) → (P,Q) where P=A and Q=A⊕B, and another is ORG-I [8] which is mapped as (A, B, C) → (P, Q, R) where P=AB+(A⊕B)C,Q=A⊕B and $R = A\bar{B} + \overline{(A \oplus B)}C$.

The ORG-I gate is shown in the Figure 9. T he improved all-optical reversible full adder is shown in the figure 10. Input bit A, B and C are passed at three inputs of the ORG -I gate. The output P of ORG-I implements the output carry function of Full adder; Output Q of ORG-I and input C are passed to input lines of Feynman gate which produces output Sum Function of Full Adder.
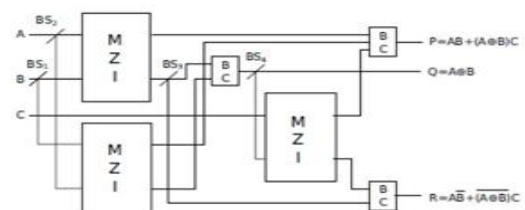

Fig. 9. Optical Reversible Gate (ORG)-I [8]

The ORG-I has 3 MZI switches, 4 BS and 3 BC with optical delay as 2Δ. The Feyn man Gate is realized with 2MZI switches, 3 BS, 2 BC and optical delay is 1Δ . Thus, it can be observed from the figure that All-Optical Reversible Full Adder is realized with 5 MZI switches, 8 Beam Splitters and 5
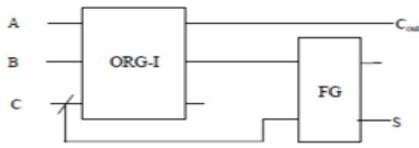
Fig. 10.The improved All- Optical Reversible Full Adder

Beam Combiners. The optical delay is considered as 3Δ. It can be seen that the optical cost of the All-Optical Reversible Full Adder Circuit is improved significantly compared to the existing design of Full adder circuit [8] in terms of MZI switches and Beam Combiners.

4-bit Optical Reversible Full Adder Circuit

A 4 -bit optical reversible full adder circuit is designed using 4 ORFA (optical reversible full adder). The diagram of the 4-bit optical reversible full adder is shown in the Figure 11. The carry output of first ORFA is passed to carry input of second ORFA, carry output of second ORFA is passed to carry input of third ORFA and so on.
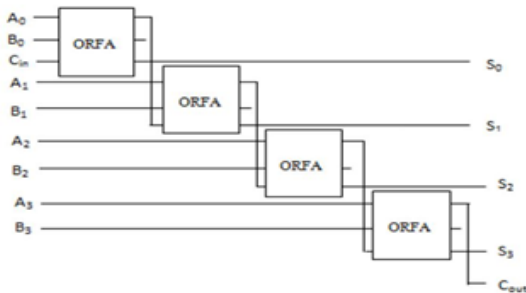

Fig. 11. 4-bit Optical Reversible Full Adder Circuit

Finally the carry output line of the fourth ORFA produces output carry of addition of two 4-bit numbers. The sum output line of all he ORFA collectively produces 4-bit sum of two 4-bit numbers. Optical cost of the circuit is 20 MZI switches as each ORFA is designed with 5 MZI switches, 8 Beam Splitters and 5 Beam Combiners. Thus, total 32 BS and 20 BC are used in the design of 4-bit optical reversible full adder. The optical delay of the circuit is 12Δ.

Design of Optical Reversible 4×1 Multiplexer

This is first attempt in the literature for designing all-Optical Reversible 4×1 multiplexer circuit. The all-optical Reversible 4×1 Multiplexer circuit has been realized with proposed Optical Reversible MNOT gate and Optical 4×4 Toffoli Gate (4×4 TG). It has four data input lines (D_0-D_3), two selection lines S_0 and S_1 to select one of the four inputs and a single output line O. the expression for data output O is given as

$$O = D_0 \bar{S_1} \bar{S_0} + D_1 \bar{S_1} S_0 + D_2 S_1 \bar{S_0} + D_3 S_1 S_0$$

The truth table of 4×1 Multiplexer is shown in table IV .The optical realization of the 4×1 Reversible Multiplexer is shown in the figure 12. It is designed using two MNOT gates and four optical 4×4 TG gates. The fourth input lines of all the 4×4 TG are set to constant 0, which results in Logical AND of the remaining three inputs at fourth output line of 4×4 TG. The fourth output lines of all the 4×4 TG are combined using Beam Combiner (BC) at the final output.

The MNOT gate is designed with 1 MZI Switch. No BS and BC are used in the design of MNOT gate.The 4×4 TG is realized with four M ZI Switches, Five Beam splitters (BS) and one Beam Combiners (BC). The delay of this gate is considered as 3Δ. Thus, the optical cost of the all -optical 4×1 Reversible Multiplexer circuit comes out to be 18 MZI Switches, 24 BS, 5 BC. The delay is calculated 4Δ as two MNOT gates as well as four 4×4 T G are working in parallel.

TABLE IV   THE TRUTH TABLE OF 4×1 MULTIPLEXER

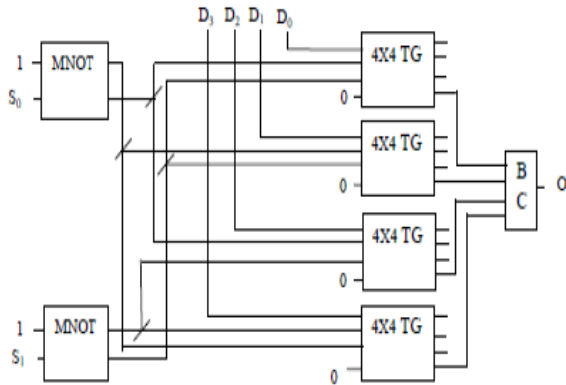| Input		Output
S_1	S_0	O
0	0	D_0
0	1	D_1
1	0	D_2
1	1	D_3

Fig. 12. Design of 4×1 Optical Reversible Multiplexer

Design of Optical Reversible 1×4 De-Multiplexer

Authors, in the literature, have not yet designed any single Reversible 1×4 De-Multiplexer in optical domain. This is first time, an All -optical Reversible 1×4 De-Multiplexer has been proposed. It has one input data line D, 2 select input lines (S_0 and S_1) and four output lines (O_0- O_3).The truth table of 1×4 De-Multiplexer is shown in table V. The expression for output lines are given as follows:

$$O_0 = D\overline{S_1}\overline{S_0} , O_1 = D\overline{S_1}S_0 , O_2 = DS_1\overline{S_0} \text{ and } O_3 = DS_1S_0$$

For optical realization of Reversible 1×4 De-Multiplexer, transformation based approach is used. The Optical Reversible 1×4 De-Multiplexer is designed with optical MNOT gate and optical 4×4 TG gates. The logical NOT Gate and the logical AND are replaced with proposed optical reversible MNOT gate and 4×4 TG, respectively. Optical realization is shown in Figure 13.

TABLE V TRUTH TABLE OF 1×4 DE-MULTIPLEXER

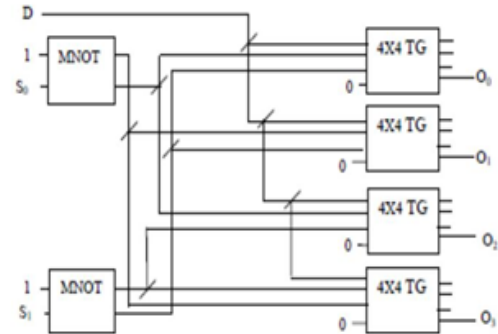| Input		Output			
S_1	S_0	O_3	O_2	O_1	O_0
0	0	0	0	0	D
0	1	0	0	D	0
1	0	0	D	0	0
1	1	D	0	0	0

Fig. 13. Optical realization of reversible 1×4 De-Multiplexer

It can be observed that 2 optical MNOT gates and four 4×4 TG gates have been used in optical realization of 1×4 De-Multiplexer. This circuit is designed using 18 MZI Switches, 27 Beam Splitters and 4 Beam Combiners. Two MNOT Gates as well as four 4×4 TG are connected in parallel. Thus, Delay is calculated as 4Δ.

Design of Optical Reversible 3to8 Decoder

A Decoder circuit is similar to the De- Multiplexer circuit but there is no data input line. This is also first time attempt in the literature to design an all- Optical Reversible 3to8 Decoder circuit. A 3to8 Decoder has three input li nes (P, Q, R) and eight output lines (O_0 - O_7). The truth table of 3to8 decoder has been given in table VI. The output function of the 3to8 Decoder is expressed as follows:

$$O_0 = \overline{P}\overline{Q}\overline{R} ; \quad O_1 = \overline{P}\overline{Q}R ; \quad O_2 = \overline{P}Q\overline{R} ; \quad O_3 = \overline{P}QR$$

$$O_4 = P\overline{Q}\overline{R} ; \quad O_5 = P\overline{Q}R ; \quad O_6 = PQ\overline{R} ; \quad O_7 = PQR$$

Optical reversible 3to8 decoder design using proposed MNOT gate and Optical 4×4 T G. To realize this circuit, three MNOT gates and eight 4×4 TG gates are needed. The all-Optical realization of the reversible 3to8 Decoder is shown in the figure 14. The circuit is designed with 35 MZI switches, 58 Beam Splitters and 8 Beam Combiners. Delay of the circuit is 4Δ.

TABLE VI TRUTH TABLE OF 3TO8 DEC ODER

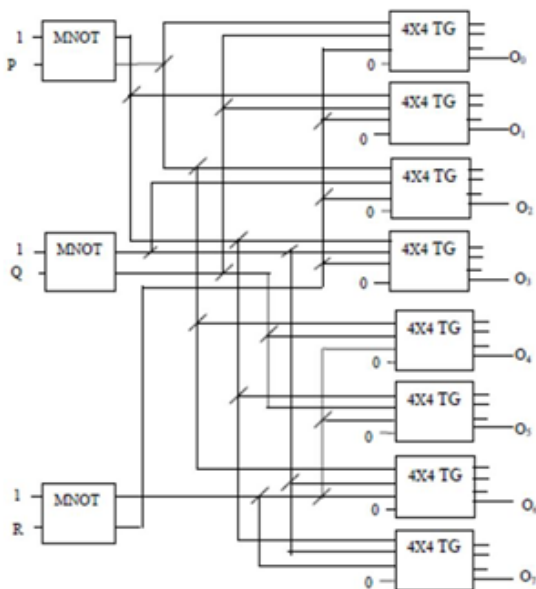| Input			Output							
P	Q	R	O_0	O_1	O_2	O_3	O_4	O_5	O_6	O_7
0	0	0	1	0	0	0	0	0	0	0
0	0	1	0	1	0	0	0	0	0	0
0	1	0	0	0	1	0	0	0	0	0
0	1	1	0	0	0	1	0	0	0	0
1	0	0	0	0	0	0	1	0	0	0
1	0	1	0	0	0	0	0	1	0	0
1	1	0	0	0	0	0	0	0	1	0
1	1	1	0	0	0	0	0	0	0	1

Fig. 14. All-Optical realization of the reversible 3to8 Decoder

COMPARISION RESULTS

The optical cost and optical propagation delay of the proposed all-optical reversib le logic circuits have been calculated in the previous section. Here the same have been analyzed and a summery has been presented in the following tables.Comparative studies of proposed designs of all-optical reversible 2×1 multiplexer and full adder circuits with the existing designs are presented in table VII and VIII respectively. This comparison is based on the optimization parameters such as optical cost, beam splitters, beam combiners, and optical delay of the circuits.The improvement percentage (IP) is calculated using the formulae: (1-proposed design cost/existing design cost) ×100. It can be observed that the proposed designs have been optimized in terms of MZI switch BS and BC.

TABLE VII COMPARATIVE STUDY OF ALL OPTICAL REVERSIBLE 2×1

Proposed Design	MZI Switch {IP in %}	BS {IP in %}	BC {IP in %}	Optical delay {IP in %}
Our proposed design	7 {12.5%}	8 {33.33%}	3 {40%}	3Δ {No IP }
G. K. Maity et al.	8	12	5	3Δ

TABLE VIII   COMPARATIVE STUDY OF ALL-OPTICAL REVERSIBLE FULL ADDER CIRCUIT

Proposed Design	MZI Switch {IP in %}	BS {IP in %}	BC {IP in %}	Optical delay {IP in %}
Our proposed design	5 {16.66%}	8 { No IP }	5 {16.66%}	3Δ {No IP }
S. Kotiyal et al.	6	8	6	3Δ

All-optical reversible designs of 4×1 multiplexer, 1×4 De-multiplexer and 3to8 Decoder circuits are proposed first time, therefore, optical cost and optical delay of the these circuits have been presented in table IX.

TABLE IX OPTICAL COST AND DELAY OF ALL-OPTICAL REVERSIBLE 4×1 MULTIPLEXER, 1×4 DE-MULTIPLEXER AND 3TO8 DECODER

Proposed Design	MZI Switch	BS	BC	Optical delay
4×1 multiplexer	18	24	5	4Δ
1×4 De-multiplexer	18	27	4	4Δ
3to8 Decoder	35	58	8	4Δ

SIMULATION RESULTS

All the synthesis and simulation results are performed using Verilog HDL. The synthesis and simulation are performed on Xilinx ISE 14.4. The simulation results are shown below figures.
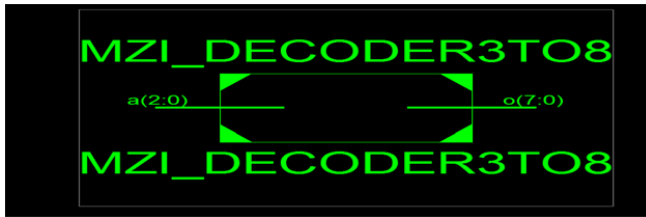
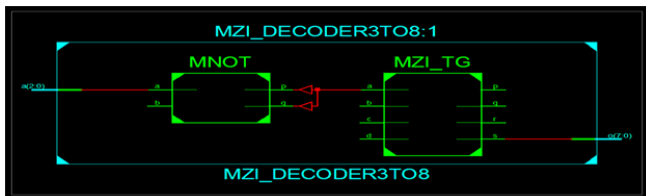**Fig.15: RTL schematic of All-Optical realization of the reversible 3to8 Decoder**

Fig.16: RTL sub schematic of All-Optical realization of the reversible 3to8 Decoder
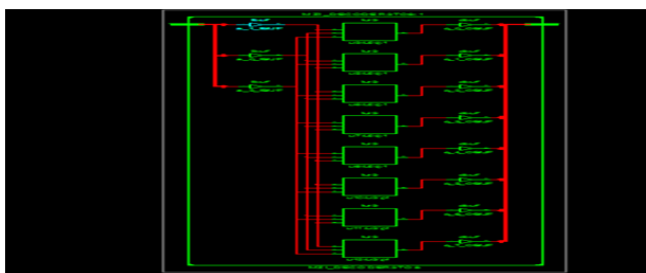

Fig.17: Technology schematic of All-Optical realization of the reversible 3to8 Decoder
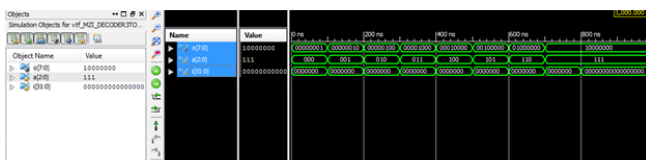

Fig.18: Simulation of All-Optical realization of the reversible 3to8 Decoder

CONCLUSION AND FUTURE SCOPE

Optical computing is emerging as a feasible technology to implement reversible logic. We have proposed a new general design approach to realize all-optical reversible logic circuits using SOA based MZI switches. An all-optical reversible MNOT gate has been proposed. The optical costs of the all opticalreversible 2×1 multiplexer and full adder circuits have been minimized in the proposed designs. A 4-bit full adder circuit has been also designed using this full adder circuit. New designs of All-optical reversible designs of 4×1 multiplexer, 1×4 De-

multiplexer and 3to8 Decoder circuits are proposed first time. An optimization algorithm may be proposed to minimize the optical cost of the all optical reversible circuits and the existing designs may be optimized. All –optical reversible sequential circuits may be designed.

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Author Details

Md.Rizwan, has completed his B.Tech in Electronics and Communication Engineering. He is pursuing M.Tech in DSCE from MLR Institute of Technology, Hyderabad.

P.Anjaneyulu, is Assistant Professor of Electronics and communication Engineering at the MLR Institute of Technology, Autonomous, Hyderabad.He has 4 years of teaching experience in various reputed Engneering Colleges.He is a life time member of ISTE. He received B.Tech in Electronics and communication and M.Tech in ECE with Systems and Signal processing Specialization from JNTU Hyderabad.He has 6 publications in National and International journals. His research interests include Signal processing, Embedded Systems.

V.Arun is Assistant Professor of Electronics and communication Engineering at the MLR Institute of Technology, Autonomous, Hyderabad. He has 7yearsofteachingexperienceinvariousreputedEngneerin gColleges.HeisalifetimememberofISTE.HereceivedB. TechinElectronicsandcommunicationandM.TechinEm beddedSystemsfromJNTUHyderabadi2007and2010res pectively.Hehas7publicationsinNationalandInternation aljournals.HisresearchinterestsincludeVideoCoding,E mbeddedSystems.

Adapa Venkata Paramkusam is a Professor of Electronics and communication Engineering at the MLR Institute of Technology, Autonomous, Hyderabad. He is a self-directed, action-oriented professional with over 16 years teaching experience at various reputed Engineering Colleges. He qualified in GATE-2000 and 2001 with percentiles 93.48 and 94 respectively. He is a member of ISTE. He received his B.E and M.E, degrees in Electronics and communication from AndhraUniversity, Visakhapatnam, India, in1996 and 2004, respectively, he completed Ph.D in the area of video coding at the JNTUH, Hyderabad. He has outstanding contribution with 18 Publication sin the National, IEEE International Conferences and International Journals. He is currently bounded as an Associate Professor and is being chaired as Head of the Department for Electronics and Communication Engineering discipline at MLR Institute of Technology, Hyderabad.