A Review on MZI Based All Optical Reversible Gates

Rohit Chauhan, Jyoti Kedia

Abstract— **All optical reversible computing is one of the most promising fields for designing high speed and low power consuming future computers. Recently, many researches have been going on for the chip level implementation of the optical circuits. Reversible logic is also the popular research for reducing the power consumption of the integrated circuits. In this paper, all optical implementation of reversible gates has been presented. These gates are implement by using a semiconductor optical amplifier (SOA) based Mach Zehnder Interferometer (MZI) switch. MZIs are popularly used for all optical implementation of various digital circuits. A 2-bit all optical reversible Carry Skip Adder (CSA) have also been presented and its other previous works have also been discussed.**

Index Terms— **Reversible gates, All-optical switch, Mach-Zehnder interferometer (MZI), Carry Skip Adder (CSA).**

I. INTRODUCTION

Reversible logic has gained significant importance in recent years due to its ability to reduce power dissipation. It has found applications in fields such as low power complementary metal oxide semiconductor (CMOS) digital design, Quantum computing, Quantum dot cellular automata (QCA), optical computing and DNA computing. A circuit is said to be reversible if it has one to one correspondence between input and output. In reversible logic circuits, neither fan out nor feedback is allowed as these will make the circuit irreversible [1]. Reversible gates are do not lose any information as it moves the bits from one node to another instead of erasing them. The power dissipated is directly proportional to the number of bits lost during computation. Thus, power dissipation is one of major hurdles faced during the design of integrated circuits. In 1961, Landauer [2] proved that if a circuit performs data processing in the classical trend, $KTln2$ is the amount of heat which will be dissipated for every bit of information lost during computation. Since reversible gates are free from information loss, power dissipation during computation is theoretically zero. In 1973, Bennett [3] established that no internal power will be dissipated due to information loss if the circuit is constructed using reversible logic.

A Boolean function $f : B^n \rightarrow B^m$ over the variables $X := \{x_1, \ldots\ldots, x_n\}$ is reversible if:
(1) its number of inputs is equal to the number of outputs (i.e. $n = m$) and
(2) it maps each input pattern to a unique output pattern.
Reversible functions are realized by reversible circuits.

As per the rules to maintain the reversibility in a given logic circuit there should be equal number of inputs and outputs, which results in some Ancillary / Constant inputs(AI) whose value remains unchanged throughout the operation. There will also be some Garbage Outputs(GO) which are the unwanted outputs and only present to maintain reversibility [1]. Another parameter of a reversible gate is Delay (Δ), which is the time taken by the logic circuit to compute the output for the given input. Delay depends on the quantum cost and can be minimized by reducing the quantum cost.

Optical computing these days have been accounted as an alternative to quantum computing as a possible future technology. The current limitations imposed by conventional CMOS based designs could be removed by the optical computing. The growing need for high speed data processing with minimal power dissipation has led to the all optic implementation of reversible gates. Photons can travel at a very high speed and information could be stored at zero rest mass, are the few properties which have motivated the researchers to shift to the optical domain.

In recent times, several optical devices such as Mach-Zehnder Interferometer (MZI) [4], ultrafast nonlinear interferometers (UNI) [5], Terahertz optical asymmetric demultiplexer (TOAD) [6], Microring Resonator (MRR) [7] etc. have been used as optical switches for realizing all optic reversible gates. In this paper we will discuss about all optic reversible gates based on MZI. It is most widely used due to its low power consumption, simple structure, compact in size, compatible with already existing CMOS technology and more stable than other interferometric structures.

II. MZI AS AN ALL OPTICAL SWITCH

An all optic MZI is a basic interferometric device which consist of two semiconductor optical amplifiers(SOAs) (SOA-1 and SOA-2) and three couplers (C1, C2 and C3) as shown in Fig..1 which in most of the designs represented as two couplers, one coupler is for the output and the other one for the input [5].

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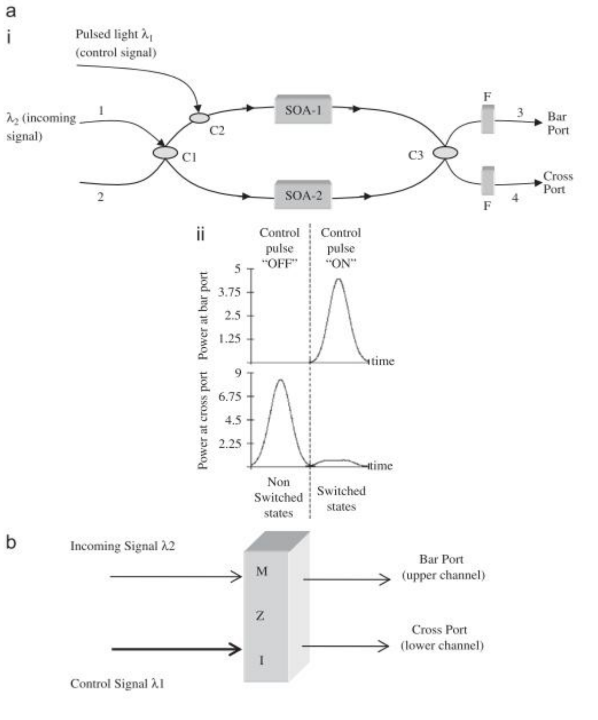


Fig. 1. (a) (i) SOA based All optical MZI switch, (ii) Output characteristics, (b) Schematic diagram of SOA-based MZI optical switch.[8]

The incoming signal is divided by the first coupler and was sent to two SOAs. In the absence of any control signal the MZI is balanced so the output is present at only one port i.e. the cross port. When control signal is applied to one of SOAs then it results in change of refractive index of that particular SOA. This change in refractive index is given by $\Delta n = nI$, where Δn is the change in refractive index, n is the nonlinear refractive coefficient, I is the intensity of the incident light. This change is refractive index will cause the phase shift in the signal passing through the first SOA. As a result, the incoming signal will be switched to the other port which is the bar port. It is based on cross-phase modulation (XPM) which is a nonlinear optic effect.

An all optic MZI switch is shown in Fig. 1(a)(i) and its schematic is shown in Fig. 1(b). It will act as a switch in which the incoming signal (λ_2) is controlled by the control signal (λ_1). The incoming signal of wavelength λ_2 is divided by coupler C1 (50:50) and propagates through two SOAs inserted separately in two arms of the MZI. Port is kept open; no signal is applied on it. So, both the SOAs were providing unsaturated gains resulting in the incoming signal at the cross port (Port 4) and no signal at bar port (Port 3). When a pulsed signal of wavelength λ_1 is applied to the MZI through coupler C2 providing most of the signal to SOA-1 which is placed in the upper arm. This will cause the SOA-1 to get saturated resulting differential phase shift between the signals passing through the two arms. SOA-2 is still providing unsaturated gain. This cause the output signal at Port 4 to switch to Port 3 which is the bar port. It is known as the 'switched state'. Optical filters (F) are used to block the control signal λ_1 at the output. Output characteristics of MZI are shown in Fig..1(a)(ii) showing the output in two states which are 'switched state' and 'non-switched state'. The truth table for MZI based optical switch is shown in Table 1.

Table 1. Truth Table of Fig..1

Input		Output	
Incoming signal (λ_2)	Control signal (λ_1)	Port-3 (bar port)	Port-4 (cross port)
0	0	0	0
0	1	0	0
1	0	0	1
1	1	1	0

III. ALL OPTICAL IMPLEMENTATION OF REVERSIBLE GATES USING MZI SWITCH

MZI switch is a very high speed all optical switch which makes it most suitable for designing all optical reversible gates. The above given characteristic of MZI switch have been used by researchers to design popular reversible gates. Some these gates have been discussed in this section. The performance of an all-optic gate or circuit was compared by the calculation of its optical cost and delay. The total number of MZIs used in any realization will be its optical cost. The number of MZIs which comes in between the longest route between inputs and outputs multiplied by unit Δ is the optical delay of that circuit. Optical delay is also defined as highest number of MZI stage the signal have to pass before reaching the output.

A. All optical NOT gate

Optical NOT gate is also a reversible gate in itself. Optical NOT gate can be formed by a single MZI switch. It is called as MNOT gate [9] as shown in Fig. 2. MNOT is a 2x2 gate whose two outputs simultaneously represents a buffer and a NOT gate.

An MNOT gate is made by keeping the first input of MZI always high and giving the input to the second port. This will result in the outputs $P = A$, $Q = \bar{A}$. So, the output Q will be the NOT output of the input signal. The truth table for the given gate is shown in Table 2. The optical cost of this gate is 1.

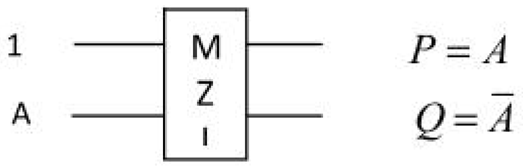


Fig. 2. All optical 2x2 MNOT gate[9]

Other circuits are also there which also realizes the NOT gate, but MNOT gate is the only one which have the minimum optical delay of 1Δ.

Table 2. Truth Table of MNOT gate

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

B. *All optical Feynman Gate*

A Feynman Gate also known as Controlled NOT (CNOT) gate is a 2x2 reversible gate, having two inputs (A, B) and two outputs (X, Y) [10]. The relation between input and output is as follows:

$X = A$ and $Y = A \oplus B$;

Table 3. Truth Table of Feynman Gate

Input		**Output**	
A	B	C	D
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0

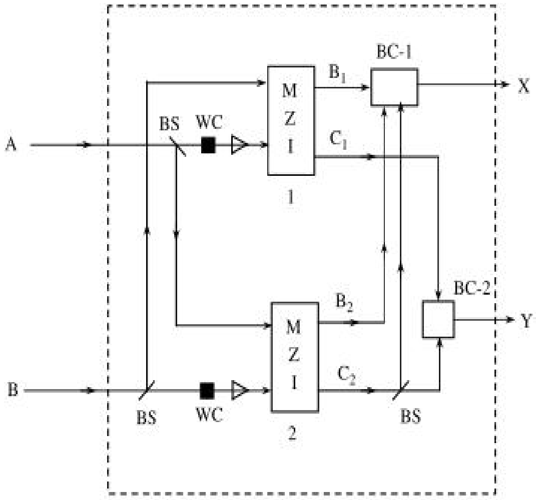


Fig. 3. All-optical circuit of Feynman gate (FyG). BC: beam combiner, WC: wavelength converter, BS: beam splitter, ▷: EDFA [8].

Truth table is provided in Table 3. The circuit for all optical Feynman gate using MZI switch is shown in Fig. 3.

C. *All optical Toffoli gate*

Toffoli Gate is 3x3 reversible gate, having three inputs (A, B, C) and three outputs (X, Y, Z) [11]. The relation between input and output is as follows:

$X = A$,

$Y = B$, and

$Z = AB \oplus C$;

The truth table of Toffoli gate is shown in Table 4. The circuit for all optical Toffoli gate using MZI switch is shown in Fig. 4.

Table 4. Truth table of Toffoli 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	0	1
1	1	0	1	1	1
1	1	1	1	1	0

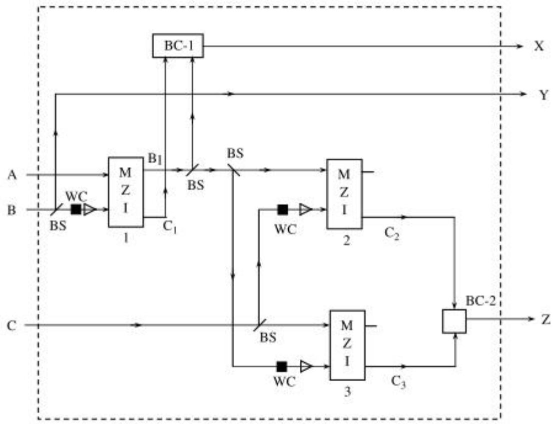


Fig. 4. All optical circuit of Toffoli gate [8]

D. *All optical Fredkin Gate*

Fredkin Gate is 3x3 reversible gate, having three inputs (A, B, C) and three outputs (X, Y, Z) [12]. The relation between input and output is as follows:

$X = A$,

$Y = \bar{A}B + AC$, and

$Z = AB + \bar{A}C$;

The truth table of Fredkin gate is shown in Table 5. The circuit for all optical Fredkin gate using MZI switch is shown in Fig. 5.

Table 5. 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

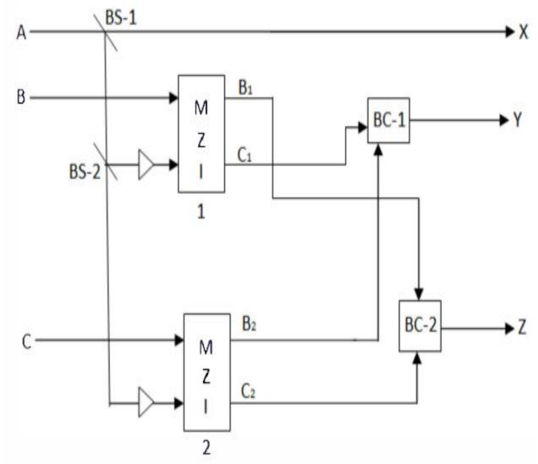


Fig. 5. All optical circuit for Fredkin Gate [13]

E. *All optical Peres gate*

Peres Gate is 3x3 reversible gate, having three inputs (A, B, C) and three outputs (X, Y, Z) [12]. The relation between input and output is as follows:

X = A,
Y = A ⊕ B, and
Z = AB ⊕ C;

The truth table of Peres gate is shown in Table 6. The circuit for all optical Peres gate using MZI switch is shown in Fig. 6 [14].

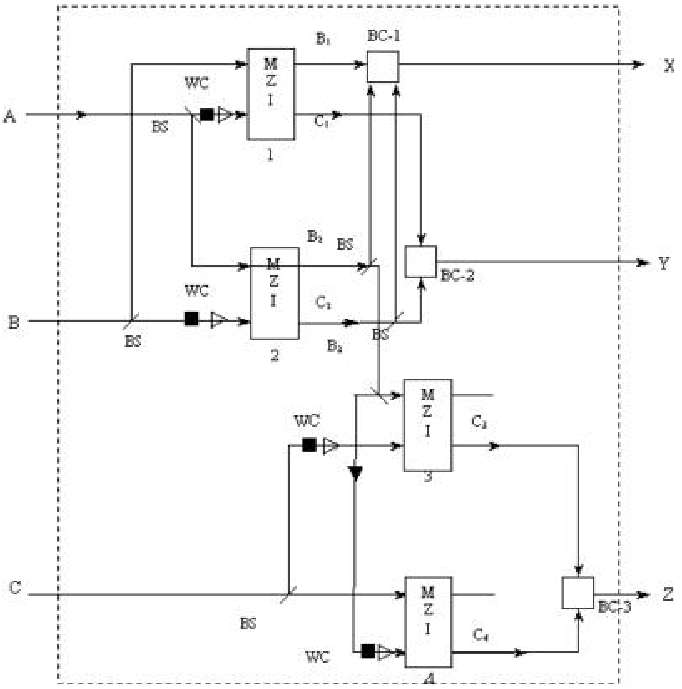


Fig. 6. All optical circuit for Peres gate [14]

Table 6. Truth table for the Peres 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	0	1
1	1	0	1	1	1
1	1	1	1	1	0

F. *All optical HNG gate*

HNG Gate is 4x4 reversible gate, having four inputs (A, B, C, D) and four outputs (P, Q, R, S) [15]. The relation between input and output is as follows:

P = A,
Q = B,
R = A ⊕ B ⊕ C, and
S = (A ⊕ B).C ⊕ AB ⊕ D;

Table 7. Truth Table of HNG gate

Inputs				Outputs			
A	B	C	D	P	Q	R	S
0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	1
0	0	1	0	0	0	1	0
0	0	1	1	0	0	1	1
0	1	0	0	0	1	1	0
0	1	0	1	0	1	1	1
0	1	1	0	0	1	0	1
0	1	1	1	0	1	0	0
1	0	0	0	1	0	1	0
1	0	0	1	1	0	1	1
1	0	1	0	1	0	0	1
1	0	1	1	1	0	0	0
1	1	0	0	1	1	0	1
1	1	0	1	1	1	0	0
1	1	1	0	1	1	1	1
1	1	1	1	1	1	1	0

The truth table of the HNG gate is shown in Table 7. The all optical implementation of HNG gate is shown in Fig. 7. HNG gate is the first reversible gate which can singly act as full adder, which is very useful in decreasing the circuit complexity of n-bit arithmetic units.

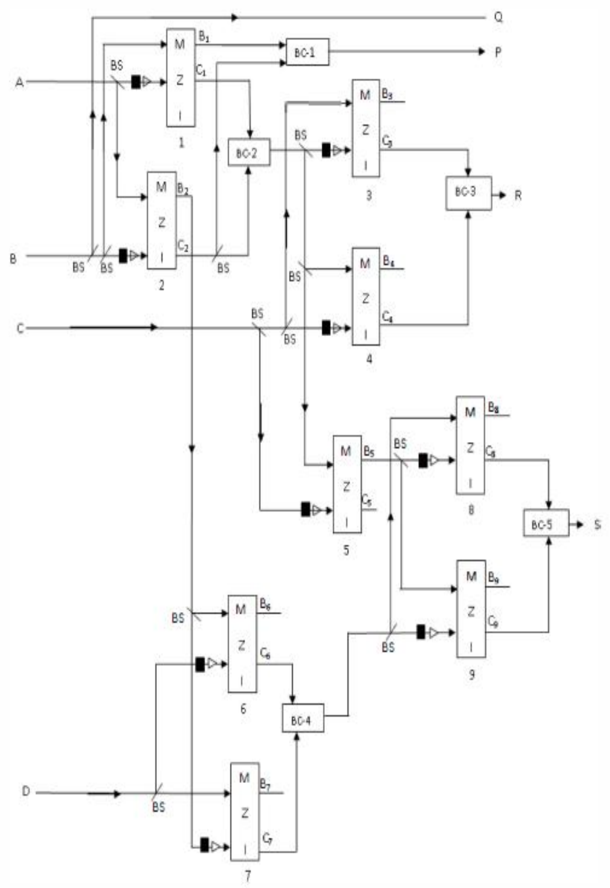
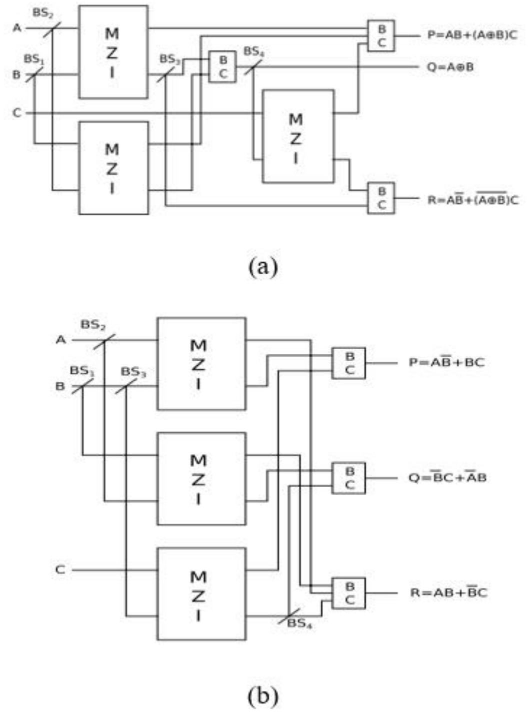


Fig. 7. All optical circuit for HNG gate [16]



(a)

(b)

Fig. 8. (a) All optical implementation of ORG-I gate, (b) All optical implementation of ORG-II gate

IV. ALL OPTICAL REVERSIBLE RIPPLE CARRY ADDER

Various non optical n-bit reversible adders have been reported such as given in [17][18][19]. Here, in Table 9 the summary of their optical cost and delay have been given by calculating the equivalent cost of the reversible gates used in their design. In [20] an all optical binary adder have been proposed using two newly proposed all optical reversible gates, which are ORG-I and ORG-II. The optical circuit of these gates have been shown in Fig. 8(a) and Fig. 8(b).

In [21] a new design for n-bit reversible Carry Skip Adder (CSA) has been proposed. In this design an optimal 2-bit all optical CSA has been designed which is further extended for n-bits. The comparison of this design with all previous designs have been shown in Table 9.

V. COMPARITIVE STUDY

Various all optical gates and circuits presented in the literature using MZI have been analyzed and compared.

A. COMPARISON OF VARIOUS ALL OPTICAL REVERSIBLE GATE

A comparison table of several all optic reversible gates implement using MZI which were reported in the literature is shown in Table 8. The performance of these gates has been compared by their optical cost and optical delay (⊿). The total number of MZIs used in optical implementation in any design is known as its optical cost. The n-controlled Toffoli gate is same as the 2-controlled Toffoli gate with n+1 inputs and outputs.

Table 8. Comparison of MZI based all optical reversible gate

Cost Metrics / Reversible gates	Number of MZI	Number of BS	Number of BC	Optical cost	Delay (⊿)
Feynman Gate[10]	2	3	2	2	⊿
Fredkin Gate) [12].	2	1	2	2	⊿
Toffoli Gate[11]	3	4	1	3	2 ⊿
n-controlled Toffoli gate[11]	n+1	n+2	1	n+1	$([\frac{n(n-1)x^2}{2n}]+1)$ ⊿
Peres gate[12].	4	6	3	4	2 ⊿
HNG gate[15]	9	12	5	9	3 ⊿

The number of MZIs which comes in between the longest route between inputs and outputs multiplied by unit Δ is the optical delay of that circuit. It can be noticed from the table that the complexity and the number of MZI will increases as number of inputs increases. But the advantage is that lesser number of gates will be used in a particular design which will

Table 9.Comparison table of MZI based carry skip adders

Designs / Parameters	Thomson et al. [17]	Cuccaro et al. design-1 [18]	Cuccaro et al. design-2 [18]	Thapliyal et al. [19]	Kotiyal et al. [20]	Das et al. [21]	
						Design-1 (Using 2-bit as basic building block)	Design-2 (Using 4-bit as basic building block)
Ancilla input	0	0	0	0	0	0	0
Garbage output	0	0	0	0	0	0	0
Optical cost	$8n$-8	$18n$-8	$18n$-19	$19n$-5	$6n$+2	$\left(\frac{11n}{2}-5\right) \approx 5.5n-5$	$\left(\frac{29n}{4}-9\right) \approx 7.25n-9$
Delay	3n+2	$4n$+1	$4n$+5	$3n$+1	$3n$+1	$\left(\frac{n}{2}+5\right) \approx 0.5n+2$	$\left(\frac{n}{4}+3\right) \approx 0.25n+3$

improve the overall efficiency. For example, HNG gate can alone act as a full adder.

B. *COMPARISON OF MZI BASED ADDERS*

Comparison Table of various MZI based all optical adder is shown in Table 9. There are several carry skip adders given in literature. Comparing these designs, we can conclude that the design-1 of Das et al. is the most efficient. It has minimum optical cost and minimum optical delay among all the previous designs. The design-2 given in [21] on comparison with design-1 in [21] have more optical cost but is approximately 50% more efficient in delay than the first design.

VI. CONCLUSION

In this paper, basic all optical reversible gates have been reviewed which are implemented by using MZI as a switch. These basic reversible gates have been compared on the basis of their optical cost and optical delay. All optical implementation of reversible gates is very important as it form the basis for the future optical computing systems. The logic circuits which will be used in optical computers for performing basic arithmetic and logic calculations will be designed by the cascade of these basic reversible gates. The working of MZI switch is also described with its function as a switch in optical circuits. An optimized design of 2-bit all optical reversible CSA has also been presented in this paper. This design can be cascaded to implement a n-bit all optical reversible CSA. On comparison with other early known adders proposed in the literature we observed that the n-bit 1 CSA adder using 2-bit CSA as the fundamental building block is the most efficient in terms of optical delay and optical cost. In future, several other reversible arithmetic and logic digital circuits could be implemented optically using MZI switch to perform various functions. These circuits should be optimized to give minimum optical cost and delay.

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