Novel Design of All-Optical Reversible Logic Gates Using Mach-Zehnder Interferometer in the Field of Nanotechnology

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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. In this study, we have introduced reversible optical quantum Peres gate using optical Mach-Zehnder interferometer (MZI) switches with new design. The proposed optical Peres gate (OPG) will be optical logic gate and reversible. As the proposed gate is a complete one, it can implement all the MZI-based quantum circuits. All the scales are in the nanometric area.

Key words: All optical switch, Mach-Zehnder interferometer, Reversible logic gate, Peres and Optical computing, Quantum computing.

INTRODUCTION

Computers have revolutionized human life and have led to huge advances in human societies. Since their emergence up until now, computers and their functionalities have been improved significantly in that they have higher speed and accuracy, and yet are smaller in size.

Today, computers have been enhanced with respect to these parameters. However, as human mind is never convinced with any level of progress, we strive to achieve fundamental changes and use other technologies for our benefit. The use of optical and quantum technologies, instead of current technologies, is considered as a way to meet this goal.

Today, photonics obviously has many benefits in the field of electronics. If logic gates are designed optically, many problems arising in the field of electronics could be overcome and numerous advantages have been obtained, including the absence of fan-out problem, higher bandwidth that dramatically increases the speed and accuracy, noise-free signals, preventing signals’ weakening, significant reduction in size, and dozens of other benefits.

Furthermore, if these gates are designed using quantum concepts, they will be reversible and thus CMOS-based circuits can be implemented with low power consumption. However, these circuits have limitations, such as fan-out and feedback problems.

In contrast to electronic logic gates, quantum logic gates are reversible and only one mode will appear in the output for each entry. As larger and more complex set of circuits can be made, including basic gates such as NOT, AND, OR, XOR gates, the fundamental changes in the structure requires fundamental changes in the building block gates (Doran, N.J. and D. Wood, 1998; Patel, N.S., 1996; Hamilton, S.A., 2001; Senior, J.M., 1992; Collet, J.H., D. Litazie et al., 2000; Bennett, C.H. and D.P. DiVincenzo, 2000; Gerd Keiser, 2000; Masanori Konshiba, 1992).

One important idea is that optics and quantum technologies can be integrated to benefit from the advantages of both the fields. In this paper, PG and FRG gates are designed optically and two new all-optical quantum gates are introduced.

In the following sections, first, we will introduce Mach-Zehnder interferometer (MZI) optical switches structures and then will describe the performance of quantum gates, such as Peres, MIG, and Verdi. Furthermore, we will investigate their outputs by using the MZI switch with optical structure design and implement their operational analysis, as well as each simulation performed will be considered in the final episode to explain the results and future work.

In Figure 1, two input signals from Source 1 and Source 2 come to BS1. BS1 splits the input signals and sends them to two mirrors. In the next step, two signals reflected from the mirrors come to BS2, and finally, they are split by BS2 and are sent to two detectors named as Detector 1 and Detector 2.
2. Introduction to all-optical MZI Switch:

Figure 1 shows the structure of all-optical MZI switch. MZI is used to detect the optical signals and is very useful in many optical measuring instruments. MZI components include two full reflecting mirrors on the upper left and lower right, and two beam splitters, one on the upper right (BS2) and other on the lower left (BS1) (Diez, S., 1999; Hill, M.T., et al., 2005; Schreieck, R., 2001; Ueno, Y., 2001; Zhang, M., 2003; Li Junqing, 2006; Chen, H., 2002).

Fig. 1: Schematic view of the Mach-Zehnder-Interferometer.

A variation of MZI-based all-optical switch is semiconductor optical amplifier (SOA)-based MZI optical switch with two SOA in its structure, as shown in Figure 2.

Fig. 2: SOA-based MZI optical switch.

A schematic of the MZI that uses SOA in its design is shown in Figure 2.

Fig. 3: Schematic diagram of SOA-bas.
Port (2) input signal is considered as the control signal with various wavelengths. It is a stronger signal, when compared with the input signal of Port (1). The element WC provides different wavelengths and EDFA plays the role of an input signal booster for this port.

The intensity and transmission amount of the input to output signals can be calculated using the following relationships that are implicitly presented in (Agrawal, G.P., N.A. Olsson, 1989; Eiselt, M., 1995; Wang, Q., 1998; Leuthold, J., 1998):

\[
T_3(t) = \frac{1}{4} G_1 \left[ k_1 k_2 + (1-k_1)(1-k_2) R_G - 2 \sqrt{(k_1 k_2 + (1-k_1)(1-k_2) R_G)} \cos(\Delta \Phi) \right]
\]  
\[
T_4(t) = \frac{1}{4} G_1 \left[ k_1(1-k_2) + k_2(1-k_1) R_G - 2 \sqrt{(k_1 k_2 + (1-k_1)(1-k_2) R_G)} \cos(\Delta \Phi) \right]
\]

The relationship between the output signals (Ports 3 and 4) and input signals (Ports 1 and 2) can be calculated using the following expressions:

\[
P_{\text{out,3}}(t) = P_{\text{in,1}}(t) \cdot T_3(t)
\]
\[
P_{\text{out,4}}(t) = P_{\text{in,2}}(t) \cdot T_4(t)
\]

The truth table of MZI switch is given in Table 1.

<table>
<thead>
<tr>
<th>Table 1: Truth table of MZI switch.</th>
<th>Input</th>
<th>Port (2)</th>
<th>Port (3)</th>
<th>Port (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port (1)</td>
<td>Input</td>
<td>Control signal</td>
<td>Bar Port</td>
<td>Cross Port</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

With a little comparison and reflection that can be downloaded, the functions of an MZI optical switch can be observed to be almost similar to a DeMux 2:1.

The schematic of a DeMux 2:1 is shown in Figure 4 and its truth table is provided in Table 2.

<table>
<thead>
<tr>
<th>Table 2: Truth table of DeMux 2:1.</th>
<th>Input</th>
<th>Port (2)</th>
<th>Port (3)</th>
<th>Port (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Port (1)</td>
<td>In</td>
<td>Selector</td>
<td>Out-1</td>
<td>Out-2</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

3. Introduction to Peres Quantum Gate:

The schematic of a 3×3 Peres gate is shown in Figure 5. Pins A, B, and C are the input ports, while pins P, Q, and R are the output ports. Pin A is connected to the output pin P directly. Output pin Q is XOR base A and base B (Fredkin, E. and T. Toffoli, 1982; Perkowski, M., 2003; Hung, W.N.N., 2004; Fateme Naderpour, Abbas Vafaei, 2008; Shams, M., 2008; Haghparast, M. and K. Navi, 2008).
Table 3: Truth table of Peres gate

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

4. Design of MZI-based Peres Gate and Introduction to Optical Peres Gate:

Schematic diagrams of Peres gate and the circuit of all-optical Peres gate are shown in Figures 6 and 7, respectively. In this schematic, BS, BC, MZI, and CP represent 50:50 Beam Splitter, Beam Combiner, Mach–Zehnder Interferometer, and Control Pulse, respectively.

Fig. 6: Schematic diagram of OPG.

4.1. State Diagram of Peres Gate:

The state diagram of Peres gate is given in Figure 8. In this diagram,

(1) When A=B=C=0, inputs A, B, and C do not receive any light, and the final outputs P, Q, and R receive no light from any port of MZI. Thus, P=Q=R=0, which satisfies the first row of the truth table presented in Table 3.

(2) When A=B=0 and C=1, only incoming signal is present at MZI-3 and control signal is present at MZI-4. Thus, only the cross port of MZI-3 receives light and other cross ports and bar ports do not receive any light. Thus, P=Q=0 and R=1 satisfy the second row of the truth table presented in Table 3.

(3) When A=C=0 and B=1, the incoming signal is present at MZI-1 and control signal is present at MZI-2. Thus, only cross port of MZI-1 receives light and other output ports do not receive any light. Therefore, P=R=0 and Q=1 satisfies the third row of the truth table given in Table 3.

(4) When A=0 and B=C=1, the incoming signals are present at MZI-1 and MZI-3 and control signals are present at MZI-2 and MZI-4. Thus, cross ports of MZI-1 and MZI-3 receive light. Therefore, P=0, Q=R=1 satisfies the fourth row of the truth table given in Table 3.

(5) When A=1 and B=C=0, the incoming signal is present at MZI-2 and control signal is present at MZI-1, and no incoming or control signals are present at other MZIs. Thus, only cross port of MZI-2 receives light and other ports do not receive any light. Therefore, P=Q=1 and R=0 satisfies the fifth row of the truth table presented in Table 3.

(6) When A=C=1 and B=0, the incoming signals are present at MZI-2 and MZI-3, and control signals are present at MZI-1 and MZI-4. Thus, cross ports of MZI-2 and MZI-3 receive light. Therefore, P=Q=R=1 satisfies the sixth row of the truth table presented in Table 3.
When \( A=B=1 \) and \( C=0 \), the incoming signals are present at MZI-1, MZI-2, and MZI-4, and control signal is present at MZI-3. Thus, cross ports of MZI-1 and MZI-2 do not receive any light, and \( Q=0 \) and cross port of MZI-4 receives light. Therefore, \( P=R=1 \) satisfies the seventh row of the truth table given in Table 3.

When \( A=B=C=1 \), the incoming signals and control signals are present at all MZIs. Thus, \( P=1 \) and cross ports of all MZIs do not receive any light. Therefore, \( Q=R=1 \) satisfies the eighth row of the truth table given in Table 3.

4.2. Output Power Calculation and Results of OPG:

According to the schematic diagram of OPG:

\[
\text{MZI-1: } C_1 = \frac{1}{4} PA(t) \cdot T_4(t) \quad (5)
\]

\[
\text{MZI-2: } C_2 = \frac{1}{4} PB(t) \cdot T_4(t) \quad (7)
\]

\[
\text{MZI-3: } C_3 = \frac{1}{2} B_2 T_4 = \frac{1}{4} PA(t) \cdot T_3(t) T_4(t) \quad (8)
\]

\[
\text{MZI-4: } C_4 = \frac{1}{2} P_c(t) \cdot T_4(t) \quad (9)
\]

\[
P = PA(t) \quad (10)
\]

\[
Q = C_1 + C_2 = \frac{1}{2} T_4(t) [PA(t) + PB(t)] \quad (11)
\]

\[
R = C_3 + C_4 = \frac{1}{4} PA(t) T_3(t) T_4(t) + \frac{1}{2} P_c(t) T_4(t) \quad (12)
\]

According to the MZI structure and with reference to (Agrawal, G.P., N.A. Olsson, 1989; Eiselt, M., 1995; Wang, Q., 1998; Leuthold, J., 1998) and formulas (13) and (14), it can be concluded that:

\[
\text{EX.R(dB)}_{\text{off}} = 10 \log(p_4/p_3)_{\text{Control=off}} = \infty \quad \text{(Because } p_3 \text{ is zero)} \quad (13)
\]

\[
\text{EX.R(dB)}_{\text{on}} = 10 \log(p_3/p_4)_{\text{Control=on}} \approx 8.374 \text{ dB} \quad (14)
\]

If the incoming signal is zero, the two output ports, bar port, and cross port will be zero. However, if the incoming signal is not zero and the control signal is zero, then the bar port value will be zero and cross port value will be 0.83 times the amount of the incoming signal.
According to the specifications of input and output values presented in Table 4, when the control signal is present at MZI, the bar port output value will be 0.45 times the amount of the incoming signal and cross port value will be 0.05 times the amount of the incoming signal.

Table 4: OPG Analysis Table.

<table>
<thead>
<tr>
<th>MZI - 1</th>
<th>MZI - 2</th>
<th>MZI - 3</th>
<th>MZI - 4</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>B₁, C₁</td>
<td>B₂, C₂</td>
<td>B₃, C₃</td>
<td>B₄, C₄</td>
<td>P, Q, R</td>
</tr>
<tr>
<td>0, 0</td>
<td>0, 0</td>
<td>0, 0</td>
<td>0, 0</td>
<td>A, C₁+C₂, C₃+C₄</td>
</tr>
<tr>
<td>0, 0.83 In₁, 0, 0</td>
<td>0, 0.83 In₁, 0, 0</td>
<td>0, 0.83 In₁, 0, 0</td>
<td>0, 0.83B, 0.83C</td>
<td></td>
</tr>
<tr>
<td>0, 0.83 In₁, 0, 0</td>
<td>0, 0.83 In₁, 0, 0</td>
<td>0, 0.83 In₁, 0, 0</td>
<td>0, 0.83B, 0.83C</td>
<td></td>
</tr>
<tr>
<td>0, 0, 0, 0.83 In₁</td>
<td>0, 0, 0, 0.83 In₁</td>
<td>0, 0, 0, 0.83 In₁</td>
<td>0, 0.83A, 0.83C</td>
<td></td>
</tr>
<tr>
<td>0.45 In₁, 0.05 In₁, 0.45 In₁, 0.05 In₁</td>
<td>0.45 In₁, 0.05 In₁, 0.45 In₁, 0.05 In₁</td>
<td>0.45 In₁, 0.05 In₁, 0.45 In₁, 0.05 In₁</td>
<td>A, 0.05(A+B), 0.83AB</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8: Results obtained from the simulation of OPG outputs.

6. Conclusions and Future Work:

In this study, two quantum gates, Peres and MIG, were designed and implemented using MZI optical switches. The Peres gate has been designed with a new property, is reversible, and has been implemented optically. The gate can be considered as a basic gate and all the logical gates, such as NOT, OR, AND, etc., can be implemented by using this gate. As a result, all these gates will also have reversible properties and benefit from the advantages of the optical design.

Simulation results and analysis tables show that the design of Peres gate reflects the true optical performance. However, it is important to mention that with the developments in the field of optical elements and emergence of nonlinear super-fast switches, such as TOAD and UNI, one should go toward the design of structure gates that can use these switches (Li, W., 2005; Sokoloff, J.P., 1993; Nakamura, S., 1994; Wang, B.C., 2002; Gayen, D.K., J.N. Roy, 2008). The speed of these optical switches is in the limit of T-HTZ, and they can be used in the laboratory and subsequently can be implemented in real-world applications. In addition, they can also be utilized in enforcement phases.
REFERENCES


