Microelectronics Journal 45 (2014) 825–834

Contents lists available at ScienceDirect

Microelectronics Journal

journal homepage: www.elsevier.com/locate/mejo

Efficient reversible NOR gates and their mapping in optical computing domain ☆

Saurabh Kotiyal, Himanshu Thapliyal, Nagarajan Ranganathan

Department of Computer Science and Engineering, University of South Florida, Tampa, FL, United States

ARTICLE INFO

Article history:
Received 21 April 2013
Received in revised form
1 March 2014
Accepted 3 March 2014
Available online 18 April 2014

Keywords:
Reversible logic
Optical computing
Reversible NOR logic
Toffoli gate

ABSTRACT

Reversible logic is a computing paradigm in which there is a one to one mapping between the input and the output vectors. Reversible logic gates are implemented in an optical domain as it provides high speed and low energy computations. In the existing literature there are two types of optical mapping of reversible logic gates: (i) based on a semiconductor optical amplifier (SOA) using a Mach–Zehnder interferometer (MZI) switch; (ii) based on linear optical quantum computation (LOQC) using linear optical quantum logic gates. In reversible computing, the NAND logic based reversible gates and design methodologies based on them are widely popular. The NOR logic based reversible gates and design methodologies based on them are still unexplored. In this work, we propose two NOR logic based *n*-input and *n*-output reversible gates one of which can be efficiently mapped in optical computing using the Mach–Zehnder interferometer (MZI) while the other one can be mapped efficiently in optical computing using the linear optical quantum gates. The proposed reversible NOR gates work as a corresponding NOR counterpart of NAND logic based Toffoli gates. The proposed optical reversible NOR logic gates can implement the reversible boolean logic functions with a reduced number of linear optical quantum logic gates or reduced optical cost and propagation delay compared to their implementation using existing optical reversible NAND gates. It is illustrated that an optical reversible gate library having both optical Toffoli gate and the proposed optical reversible NOR gate is superior compared to the library containing only the optical Toffoli gate: (i) in terms of number of linear optical quantum gates when implemented using linear optical quantum computing (LOQC), (ii) in terms of optical cost and delay when implemented using the Mach–Zehnder interferometer.

1. Introduction

Reversible logic is emerging as a promising computing paradigm among the emerging technologies. Reversible logic has applications in quantum computing, quantum dot cellular automata, optical computing, etc. [1–11]. Reversible logic also has applications in power-efficient nanocomputing [12–14]. In reversible logic there exists a unique one to one mapping between the input and output vectors. The unused outputs are used to maintain the reversibility of reversible circuits and are referred to as the garbage outputs. The inputs that are regenerated at the outputs are not considered as the garbage outputs [15]. The constant inputs in the reversible circuits are called the ancilla inputs.

A photon can provide unmatched high speed and can store the information in a signal of zero mass. These properties of photon have attracted the attention of researchers to implement the reversible logic gates in all optical domain. The optical implementation of reversible logic gates could be useful to overcome the limits imposed by conventional computing, and is also considered as an implementation platform for quantum computing [16–19,6–11]. In the existing literature there are two types of optical mapping of reversible logic gates: (i) based on the semiconductor optical amplifier (SOA) using the Mach–Zehnder interferometer (MZI) switch [20,3,21]; (ii) based on linear optical quantum computation (LOQC) using linear optical quantum logic gates [6–11].

In the existing literature the most widely used implementation of reversible logic gates and the reversible boolean functions are the implementations using NAND logic. This is due to the lack of research in the direction of NOR logic based reversible logic gates and functions. In this work, we propose two NOR logic based *n*-input and *n*-output reversible gates one of which can be efficiently mapped in optical computing using the Mach–Zehnder interferometer (MZI) while the other one can be mapped efficiently in optical computing using the linear optical quantum gates. The first reversible NOR gate is called as a Mach–Zehnder interferometer based reversible NOR gate (MZI-RNOR), and the second reversible NOR gate is called as a linear optical quantum computing based reversible NOR gate (LOQC-RNOR). The proposed

☆The preliminary version of this work has been published in ISVLSI 2012 (Mach–Zehnder interferometer based all optical reversible NOR gates)

http://dx.doi.org/10.1016/j.mejo.2014.03.001
0026-2692/

optical reversible NOR gates are useful for NOR logic based implementation of reversible boolean functions. The proposed MZI-RNOR gate can implement the reversible boolean functions with reduced optical cost and propagation delay compared to the implementation of reversible boolean functions using optical reversible NAND gates (NAND logic based reversible gates is all optical Toffoli gate) implemented using the MZI switch. The proposed LOQC-RNOR can implement the reversible boolean functions with a reduced number of linear optical quantum logic gates compared to the implementation of reversible boolean functions implemented using linear optical quantum reversible NAND gates (NAND logic based reversible gates is linear optical quantum Toffoli gate). As the proposed optical reversible NOR gates are n-input and n-output optical reversible NOR based counterpart of NAND logic based n-input and n-output Toffoli gate, thus we have also illustrated the optical design of the n-input and n-output Toffoli gate. In this work, the optical cost of a reversible logic gate is defined as the number of MZI switches used in its all optical implementation [22]. We illustrated the advantages of proposed optical reversible NOR gates in terms of optical cost and delay by implementing the 13 standard boolean functions [23]. The 13 standard boolean functions proposed in [23] can represent all possible 256 combinations of three variable boolean functions. It is illustrated that an optical reversible gate library having both optical Toffoli gate and the proposed optical reversible NOR gate is superior compared to the library containing only the optical Toffoli gate: (i) in terms of number of linear optical quantum gates when implemented using linear optical quantum computing (LOQC) and (ii) in terms of optical cost and delay when implemented using the Mach–Zehnder interferometer.

The paper is organized as follows: the basics of optical computing and reversible logic in optical domain is presented in Section 2; Section 3 illustrates the proposed NOR logic based reversible gates and their mapping in the optical domain; Section 4 provides the comparison of proposed NOR logic based reversible gates with NAND logic based reversible gates mapped in the optical domain, while the conclusions are provided in Section 5.

2. Basics of optical computing and reversible logic in the optical domain

This section provides the background of optical computing, basic reversible gates and their optical mapping using MZI switch and linear optical quantum computing.

2.1. Mach–Zehnder interferometer

The Mach–Zehnder interferometer (MZI) based optical switch can be used to implement reversible logic gates [3,20,21,24]. The design of all optical MZI switch is shown in Fig. 1(a). The all optical MZI switch can be designed using two semiconductor optical amplifier (SOA-1, SOA-2) and two couplers (C-1, C-2). The operating principle of MZI based all optical switch can be explained as follows:

In a MZI switch, there are two input ports (A and B) and two output ports (called as bar port and cross port), respectively as shown in Fig. 1(a). At the input ports, the optical signal coming at port B is considered as the control signal (λ_2), and the optical signal coming at port A is considered as the incoming signal (λ_1). The working of a MZI can be explained as follows: (i) when there is an incoming signal at port A and the control signal at port B then it results in the presence of light at the output bar port and no light or the absence of light at the output cross port, (ii) in the absence of control signal at input port B and 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. We have considered no light or the absence of light as the logic value 0. The above behavior of MZI based all optical switch can be written as boolean functions having inputs to outputs mapping as (A, B) to ($P{=}AB$, $Q=A\overline{B}$), where A (incoming signal), B (control signal) are the inputs of MZI and P (Bar Port), Q (Cross Port) are the outputs of MZI, respectively. The block diagram of MZI based all optical switch is shown in Fig. 1(b). *The optical cost and the delay (Δ) of MZI based all optical switch is considered as unity*.

2.2. Linear optical quantum computing

The linear optical quantum computing uses the photons to encode the information. The information stored in a linear optical quantum computer are in the form of qubits and qutrits. A qubit has two possible logical states referred to as $|0\rangle$ and $|1\rangle$, while a qutrit has three logical states represented as $|0\rangle$, $|1\rangle$, $|2\rangle$. The representation of a qubit and qutrit in linear optical quantum computing is shown in Fig. 2. The basic linear optical quantum logic gates that perform the logical operation on the qubits and qutrits are NOT gate, Hadamard gate, X_a gate, Controlled-NOT (CNOT) gate and Controlled-Z gate. Fig. 3 shows the linear optical quantum logic gates and their unitary matrix representation.

2.3. MZI based implementation of Feynman gate

The Feynman gate (FG) is a 2-input and 2-output reversible gate. It has the mapping (A, B) to ($P{=}A$, $Q{=}A \oplus B$) where A, B are

a

$$|0\rangle = |0,1\rangle => \begin{pmatrix} 0 \\ 1 \end{pmatrix} \qquad |1\rangle = |1,0\rangle => \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

b

$$\text{Qutrit states} => |0\rangle, |1\rangle, |2\rangle => \begin{pmatrix} \alpha \\ \beta \\ \gamma \end{pmatrix}$$

Fig. 2. Qubit and qutrit in linear optical quantum computing.

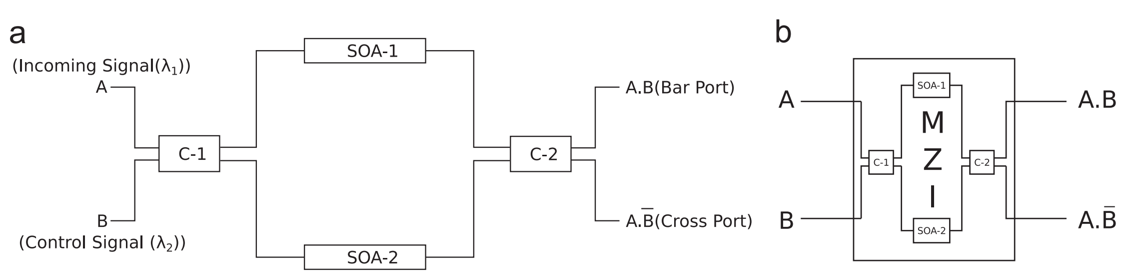

Fig. 1. Mach–Zehnder interferometer (MZI) based all optical switch. (a) Semiconductor optical amplifier based Mach–Zehnder interferometer (SOA: Semiconductor Optical Amplifier, C: Coupler). (b) Mach–Zehnder interferometer.