



All optical design of binary adders using semiconductor optical amplifier assisted Mach–Zehnder interferometer

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ABSTRACT

With the progress in research in the field of optical computing, architectural designs of various digital components and systems using all-optical technology are being explored. Implementations of basic gates like AND, OR, XOR, etc. and arithmetic components like adder, subtractor, etc. have already been investigated in the all-optical domain. Among the various alternatives, interferometric devices have shown great promise due to their high-speed photonic activity and ease of manufacturing. Many of these works consider semiconductor optical amplifier (SOA) assisted Mach–Zehnder Interferometer (MZI) for the implementation. In this paper we present all-optical implementations of binary adders using MZI switches, which have been validated through numerical simulation of the switch models. Some performance parameters of the design have also been evaluated. Three designs have been explored – a ripple-carry adder, an extension with faster carry propagation, and a carry save adder. The design complexities have been compared with some recently published works, both in terms of optical cost and delay.

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1. Introduction

To address the ever increasing demands of higher speeds in processing and lower power consumption, researchers have started looking at all-optical realizations as a feasible alternative [1]. There have been many works [2,3] where optical technology is used to provide ultra-fast (of the order of terabits per second) interconnects in an otherwise electronic digital system. However, to fully exploit this potential it is necessary to have a solution where repeated conversions of signals from optical domain to electronic domain and vice versa can be avoided. This necessitates the realizations of signal processing computations like wavelength conversion, arithmetic processing, etc. in the all-optical domain. This forms the basic motivation of the work reported in this paper.

Several works have been reported in recent years [4–9] where various photonic devices are used for realizations of simple combinational logic blocks. There also have been works [10–15] that try to implement reversible logic gates and sub-functions using optical technologies. The various optical technologies that have been explored in this context include semiconductor optical

amplifier (SOA) based Mach–Zehnder Interferometer (MZI) [7,8], non-linear interferometer [16], micro-ring resonator [17], semiconductor laser amplifier loop mirror [18], etc.

Regarding the implementations of arithmetic circuits using optical technologies, some preliminary works have been reported. All-optical realizations of half-adder and full-adder circuits have been discussed in [19–23]. In [21] an all-optical design of binary reversible adder is presented using MZI switches. In [23] a half-adder design is proposed where the all-optical module can generate four operations simultaneously at 10 Gbps. In [24] the Sagnac interferometer is used to construct a half-adder, while in [25] four-way mixing in SOAs has been used which uses polarization-shift-keying (PolSK) modulation format, that makes it free of pattern effect. In [7] two digital blocks are presented, one is comparator and another is full-adder. These blocks are implemented using a cascade of unique basic gates that take into consideration cross-gain modulation and cross-polarization rotation in a single SOA. Some optical implementations of binary adder has also been reported, like in [19] where terahertz optical asymmetric demultiplexers (TOAD) have been used. In [26,27], MZI based implementation for multiplexers and optimization techniques have been reported.

Although many designs of various logic gates and circuits exist using optical devices, there is a drawback with respect to weak nonlinearities [8]. Interferometric switches are based on change of

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refractive index with incident control beam intensity (I). Refractive index of nonlinear materials can be expressed as $n = n_1 + n_2 I$, where n_1 is the linear refractive index and n_2 is the nonlinear refractive index. Typically, $n_1 \gg n_2$, and hence to change the refractive index of a nonlinear material by a significant amount, very high beam intensity I is required. For example, fused silica glass has $n_1 = 1.47$ and $n_2 = 3.2 \times 10^{-20} \text{ m}^2/\text{W}$. For changing n by 0.0032, we require $I = 1.0 \times 10^{17} \text{ W/m}^2$ light intensity. In contrast, to change n by the same amount in SOAs we require $I = 1.0 \times 10^9 \text{ W/m}^2$ light intensity (as n_2 of SOA is 10^8 times higher than fused silica glass). Specifically, SOA-based MZI switch is considered to be a favorable candidate for the implementation of optical interconnects, communication, multiplexing and signal processing due to its high speed, compact size, thermal stability, low switching energy and all-optical integration compatibility.

Considering these advantages of SOA based MZI switch, in this paper we present all-optical implementations of ripple-carry binary adder, a fast carry propagation enhancement, and also carry save adder. Comparisons have been made with recent works in terms of optical cost and delays with respect to the implementation. Using mathematical models representing the optical properties of MZI switches, MATLAB simulation has been performed to evaluate the performance of the proposed implementation. Rest of the paper is organized as follows. Section 2 discusses the principle of operation of MZI switch. Section 3 provides the details of the proposed adder designs, followed by concluding remarks in Section 4.

2. MZI-based all-optical switch

In this section we briefly discuss some relevant background about MZI-based optical switch. Semiconductor Optical Amplifier (SOA) based MZI switch is a technologically advanced optical device which can be utilized for various operations on amplitude as well as phase modulated signals. It is one of the essential configurable components in optical computing [15]. One of the major areas where SOA based framework has shown its applicability is amplifying signals in high capacity optical networks. In addition to conventional logic functional blocks, researchers have also explored implementations of reversible gates using MZI switches [10,21,28]. The major advantage of using MZI switches in circuit design is their high quality, small size, thermal stability, fast switching time, and ease of fabrication.

An all-optical MZI switch can be constructed using two SOAs and two couplers. In SOA variation of carrier density occurs due to optical pumping which creates a change in refractive index, resulting in cross-phase modulation. A coupler is a passive optical component which can either combine or split a signal based on application requirement. Fig. 1(a) shows the schematic diagram of

a MZI switch. It consists of two input ports and two output ports. At the input side, the optical signal entering at port A is called the *incoming signal* (λ_1) and the optical signal at port B is termed as *control signal* (λ_2). The two output ports are termed as *bar port* and *cross port* respectively. C-1 and C-2 are two 3 dB couplers, that are used as beam splitter and beam combiner respectively. Control signal is applied to the lower SOA-2 via another coupler C-3. A band pass filter (BPF) at the output rejects the control signal and passes the wavelength λ_1 . The output power on the bar and cross ports can be respectively expressed as [15,20]

$$P_{\parallel}(t) = \frac{P_{in}}{4} \left\{ G_1(t) + G_2(t) - 2\sqrt{G_1(t)G_2(t)} \cos(\Delta\phi) \right\} \quad (1)$$

$$P_{\times}(t) = \frac{P_{in}}{4} \left\{ G_1(t) + G_2(t) + 2\sqrt{G_1(t)G_2(t)} \cos(\Delta\phi) \right\} \quad (2)$$

where $G_1(t)$ and $G_2(t)$ are the gains of SOA-1 and SOA-2 at time t respectively, and $\Delta\phi = -\frac{\alpha}{2} \ln \left[\frac{G_2(t)}{G_1(t)} \right]$ with α being the line width enhancement factor. The switch works as follows:

- When there is a presence of *incoming signal* (λ_1) at input port A and *control signal* (λ_2) at port B, then control signal saturates the gain of SOA-2 to saturation gain (G_s) at time t_s . On the other hand the gain of SOA-1 is constant. Hence $\Delta\phi \approx \pi$. Hence $P_{\times}(t) \approx 0$, i.e. we get the presence of light at the output *bar port* and no light at the output *cross port*.
- When the *control signal* (λ_2) is absent at port B and *incoming signal* (λ_1) is present at port A, then the gain of SOA-2 tries to recover from G_s to G_0 (unsaturated single-pass amplifier gain) in recovery time t_r . Hence after time t_r , G_1 approaches G_2 and $\Delta\phi \approx 0$, and so $P_{\parallel}(t) \approx 0$. That is, we observe the presence of light at output *cross port* and no light at output *bar port*.

If we denote the presence and absence of light by binary 1 and 0 respectively, the working behavior of the MZI switch can be expressed in terms of Boolean equations as (see Fig. 1(b))

$$\text{Bar port} = A \cdot B \quad (3)$$

$$\text{Cross port} = A \cdot \bar{B} \quad (4)$$

3. Proposed all-optical binary adder

In this section, we present the all-optical implementation of a binary adder using MZI switches. The schematic diagram of the binary adder is shown in Fig. 2, where A and B are the two n -bit numbers to be added, C_{in} is the input carry, S is the n -bit sum, and C_{out} is the output carry.

To design the n -bit binary adder we require full adders as the basic building block. In the following subsections, we show the design of all-optical SOA assisted MZI based full adder (FA), and then that of ripple-carry adder with an enhancement for faster carry propagation, along with their respective optical cost and delay analysis. We finally look at the all-optical implementation of carry save adder.

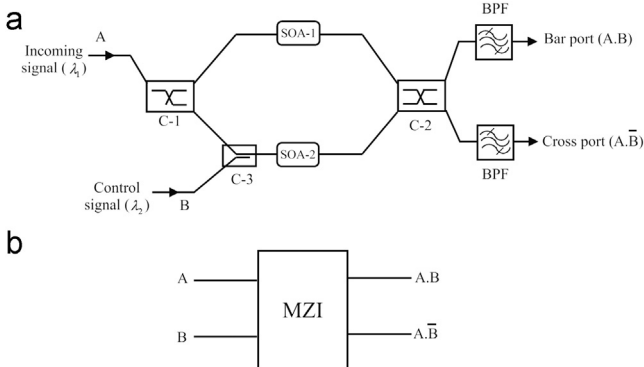


Fig. 1. (a) SOA based MZI switch. (b) Functional behavior of MZI switch.

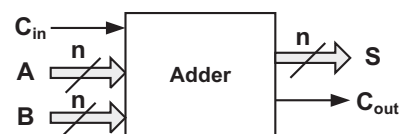


Fig. 2. Schematic diagram of binary adder.

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