Design of electro-optic Mach–Zehnder interferometer based all-optical binary half adder and half subtractor

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Abstract
By exploiting the phenomena of optical switching, different logical and arithmetic operations can be performed. This paper presents a novel optimized design structures to perform addition and subtraction of two binary digits using electro-optic effect based Mach–Zehnder interferometer operating at 1460 nm in the S band. The proposed structures are numerically simulated and designed using beam propagation method and MATLAB software. The different performance parameters like extinction ratio, contrast ratio, insertion loss, amplitude modulation and relative eye opening have been evaluated and the optimized structure yields maximum ER of 33.22 dB and 28.76 dB for half adder and half subtractor respectively. Additionally, a comparison of the proposed structures is presented with the previously designed structures.

Keywords Optical computing · Lithium niobate · Beam propagation method · Mach–Zehnder interferometer · Electro-optic effect

1 Introduction
The expansion of optical signal processing technology is necessary for future high-speed optical systems for signal manipulation to implement all-optical signal processing functions including switching, multiplexing/demultiplexing, coding/decoding, logic gates, add/drop, multicasting, etc. without optical to electronic conversion. To achieve a speed of terabytes, electronic devices are replaced by all-optical devices. All-optical logic gates become the fundamental building block to implement optical devices for high-speed optical signal processing. Till now, several combinational logic circuits such as adder/subtractor (Kumar

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et al. 2014a, 2021), encoders and decoders (Pal et al. 2018; Rezaei and Zarifkar 2021; Srivastava et al. 2019), bit magnitude comparator (Kumar and Raghwanshi 2016), multiplexers/demultiplexers (Kumar and Chauhan 2016; Sharma and Roy 2021), code converters (Choudhary and Kumar 2017; Pal et al. 2017), etc. have been proposed. Several works on designing sequential circuits such as flip-flops (Chauhan et al. 2017; S. Kumar et al. 2015b; Pal et al. 2017), counters (Kumar et al. 2015a), shift registers (Nair et al. 2021b), etc. have been reported in the recent years. However, most of the combinational and sequential circuits are designed by integrated all-optical logic gates together. Many different techniques have been proposed in past decade in the field of design of all-optical arithmetic logic circuits such as half adder and half subtractor using semiconductor optical amplifier (SOA) (Dai et al. 2013; Nair et al. 2021a), highly non-linear fibers (HNLF) (Singh et al. 2016; Zahir et al. 2018), four-wave mixing in SOAs (Li et al. 2006), periodically-poled lithium niobate (PPLN) (Jiang et al. 2015; S. Kumar et al. 2006), a terahertz optical asymmetric demultiplexer (TOAD) (Gayen et al. 2014), quantum dot semiconductor optical amplifier (QD-SOA) MZI (Gayen et al. 2012; Nady et al. 2013), Graphene plasmonic waveguides (Rezaei and Zarifkar 2019, 2021; Xu et al. 2021), and photonic crystal (Abdollahi and Parandin 2019; Alipour-Banaei and Seif-Dargahi 2017; Ebrahimi et al. 2015; Karkhanehchi et al. 2017; Parandin et al. 2017; Parandin and Reza Malmir 2020; Sadegh-Bonab and Alipour-Banaei 2020; Seifouri et al. 2019; Serajmohammadi et al. 2018; Swarnakar et al. 2019). Several approaches have been presented to realize all-optical arithmetic computing circuits. The first technique was based on a semiconductor optical amplifier (SOA). A simultaneous half addition and half subtraction using two semiconductor optical amplifiers is demonstrated experimentally at the repetition rate of 10Gbps with an extinction ratio of larger than 14 dB (Dai et al. 2013). However, SOA-based design demonstrated great potential in terms of low power consumption but has limitations such as low-operation speed due to large response time and unwanted spontaneous emission of noise degrade the performance of devices (Rezaei and Zarifkar 2021).

The second approach utilizes four-wave mixing in a semiconductor optical amplifier (SOA). A novel scheme for an ultrahigh-speed all-optical half adder based on four-wave mixing (FWM) in semiconductor optical amplifiers (SOAs) is proposed using the non-existence of pattern effect and polarization-shift-keying (PolSK) modulation format (Li et al. 2006).

The third approach uses highly non-linear fiber (HNLF). A multifunctional combinational logic module capable of performing half-addition/subtraction, single-bit comparison, and 2-to-4 decoding simultaneously is proposed. Several logic functions are implemented by connecting some nonlinear effects, such as cross-phase modulation (XPM), cross-gain modulation (XGM), and four-wave mixing (FWM) inside only two highly nonlinear fibers (HNLF) arranged in a parallel structure. Quality-factor ≥ 7.4 and extinction ratio ≥ 12.30 dB have been achieved at repetition rates of 100 Gbps for all logic functions (Singh et al. 2016). Similarly, half adder and half subtractor was designed using highly nonlinear fiber (Zahir et al. 2018).

Another popular approach was periodically-poled lithium niobate (PPLN). An all-optical half adder was demonstrated using only two nonlinear optical elements. A PPLN waveguide is used as an AND gate and an SOA is used to perform the XOR operation required to generate the SUM output. With a power penalty of ≤ 2 dB, error-free performance was achieved (Kumar et al. 2006). By combining polarization based basic logic gates such as NOT gate, AND gate and OR gate, half adder/half subtractor was designed using MgO-doped periodically poled lithium niobate (Jiang et al. 2015). PPLN waveguide based logic devices have been implemented with various advantages such as
negligible spontaneous emission of noise, fast response time, and multifunctional but have limitations like temperature, polarization dependencies and minimum size. Along the propagation path at refracting points, polarization changes that degrade the performance of the device (Kaur 2016).

In other approaches, terahertz optical asymmetric demultiplexer (TOAD) and QD-SOA based logic devices were reported. A model to perform simultaneous addition and subtraction of two binary digits using TOAD with various performance parameters such as ER, CR, AM, Q-factor have been reported (Gayen et al. 2014). A high-speed all-optical half adder based on a single QD-SOA MZI was discussed. The simulation results show ER ratio of 14.71 dB for sum and 10.13 dB for carry (Gayen and Chattopadhyay 2013). All-optical full adder using QD-SOA based Mach–Zehnder interferometer is demonstrated. The measured values of ER and Q-factor are 11.7 dB and 12.5 dB, respectively (Nady et al. 2013).

Above mentioned techniques are different from each other in terms of ease of use, optical integration, complexity, reliability, speed of performance, and power consumption (Wang et al. 2022). To overcome the limitations of different techniques use to implement all-optical signal processing at speed of terabytes per second, researchers have focus on graphene plasmonic waveguides and photonic crystals (PCs) (Xu et al. 2021). Currently, photonic crystal is providing a lot of attractive features like optical integration, compact dimensions, flexibility in design, wide operating bandwidth, high speed of operation, and low power consumption. A simultaneous half adder/subtractor was realized by plasmonic waveguides using graphene instead of noble metal making it an efficient device due to high confinement and low losses. Maximum extinction ratios of 24.66 dB and 28.2 dB have been obtained for sum and carry bits. Similarly, difference and borrow bits give a minimum extinction ratio of 22.39 dB and 25.98 dB (Rezaei and Zarifkar 2021). A subwavelength half-adder and half-subtractor circuit is designed using graphene plasmonic waveguide with a contrast ratio of 10.60 dB and 15.75 dB for difference and borrow bits and 7.4 dB and 14.83 dB for sum and carry bits (Rezaei and Zarifkar 2019). Using a two-dimensional photonic crystal, a simple structure of all-optical half adder has been created using interference effect gives contrast ratio of 9.3 dB and 8.22 dB for sum and carry ports with the response time of 0.22 ps (Seifouri et al. 2019). The small dimensions and simple design photonic crystals based half subtractor with triangular and square lattice were designed that provided low-time delay and high bit-rate (Parandin et al. 2017, 2021). A simple structure of half adder based on 2D photonic crystals was designed and simulated using FDTD method in wavelength ranged of 1480–1500 nm and 1540–1570 nm (Karkhanechhi et al. 2017). A novel design structure of a one-bit half adder with hexagonal lattice was presented with the smallest size of 25×20 making it useful to realize all-optic logic gates (Abdollahi and Parandin 2019). For high-speed data transmission using 2D photonic crystal based optical half adder, optical XOR, and AND gate was designed and simulated (Parandin and Reza Malmir 2020). Similarly, half subtractor based on 2D photonic crystal based was presented without using an optical amplifier and non-linear materials (Swarnakar et al. 2019).

All-optical 2-bit adder/Subtractor was realized using nonlinear photonic crystal ring resonators by combining optical XOR gate with 2-bit full adder (Sadegh-Bonab and Alipour-Banaei 2020). A photonic crystal based all-optical half adder was proposed by combining power splitters, ring resonators, and optical waveguides. The design provides on–off contrast ratios for sum and carry ports 9.77 dB and 6.98 dB, respectively (Serajmohammadi et al. 2018). By using FDTD, a photonic crystal based 1-bit full adder was realized by cascading two 1-bit half adder, eight optical waveguides, and two nonlinear resonant rings (Alipour-Banaei and Seif-Dargahi 2017). A photonic crystal based nanobeam was
designed to implement an electro-optic filter with high quality factor for high-speed optical communication and detection devices (Ebrahimy et al. 2015).

Moreover, the electro-optic (EO) effect in MZI based devices have been used to design optical computational and sequential circuits for some fascinating features. In this work, a lithium niobate-based Mach–Zehnder interferometer (LN-MZI) has been used to implement the optical arithmetic circuit (half adder/subtractor) using EO effect. LN-MZI devices gaining a lot of attention because of their features like low power consumption, thermal stability, optical integration, and reconfigurability. As mentioned above, the researchers concentrate on photonic crystals because of some unique properties such as high speed and low power consumption. There are a few challenges that have been faced by PCs that affect the performance of optical logic devices. The PC allows the light to be guided or controlled for some wavelengths only. These are the man-made fabricating structures designed for a particular photonic bandgap (PBG). During fabrication in the doping process the properties of PCs can be changed. Also, the photonic crystals are complex to design on the 3D scale. The comparison between the electro-optic modulator and photonic crystals based logic gates are summarized in Table 1.

In this communication, the novel design of half adder and half subtractor using minimum number of MZI switching configurations in S-band (1.46 µm) are discussed and numerically simulated. The performance parameters such as extinction ratio, contrast ratio, insertion loss, amplitude modulation, and relative eye opening has been calculated and compared with the previously designed devices presented in literature. The proposed design of half adder and half subtractor is the improved version of the structure previously implemented in literature from the perspective of performance parameters. The article is organized as follows: Sect. 2, describes the basic concept and operation principle of MZI. Sections 3 and 4 are concerned with layout design and mathematical formulation of structure. Simulation results of the proposed half adder and half subtractor with the help of the Beam propagation method (BPM) and MATLAB are discussed in Sects. 5 and 6. Section 7 is related with results and discussion. Finally, the conclusion is drawn in Sect. 8.

2 Concept and operational principle of Mach–Zehnder interferometer

Many different approaches have been proposed to design all-optical digital logic functions. Among different technologies, Mach–Zehnder interferometer working on electro-optic effect acts as powerful optical switch represents the best solution to implement all-optical logic functions using a conversion of phase modulation into intensity modulation. MZI switch consists of one 2×2 optical splitter at the input ports and one 2×2 optical combiner at the output ports. Two interferometer arms are connected between the splitter and the combiner as shown in Fig. 1.

An optical signal is injected into the input ports. Then, it is equally divided by the splitter into two arms. The divided signal has a phase difference of π/2 rad. A constructive and destructive interference at the cross and bar output ports are introduced if the two interferometer arms have the same parameters. To switch the signal from one output port to another, a phase shift π needs to be introduced into one of the interferometer arms. So the phase modulation can occur, these switches use metal electrodes over the interferometric arms to create refractive index variations by applying an electric field to the electrodes. Switching technology can be classified based on physical effect, device design and material used such as Electro-Optic, Acousto-Optic (Deng et al. 2021), Thermo-Optic,
| Parameters                | Photonic crystal                                                                 | Electro-optic waveguide                                                                 |
|--------------------------|----------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
| Principle of operation   | Photonic crystals are the microstructure (Ji et al. 2021) photonic material with a periodic distribution of dielectric constant. It operated on the principle of photonic band gap (PBG), which efficiently manipulate light in the required direction over a wide bandwidth. | The electro-optic modulators work on the electro-optic (EO) effect. It is the phenomenon that cause a change in the refractive index of material due to the application of an electric field. |
| Material used            | Boron silicate glass or boron-doped with active elements                         | This effect exhibits in a wide range of materials such as inorganic crystals (mostly ferroelectric compounds), organic and molecular crystals. These are the materials with a voltage-controlled index of refraction. Gallium arsenide (Chen et al. 2019; Li et al. 2018), barium titanate, barium niobate, and lithium niobate are available materials. Lithium niobate is the most widely used material due to its significant features and high electro-optic coefficient. |
| Structures               | Photonic crystal or photonic band gap structures. It is a periodic arrangement of structure with periodic variation of refractive index in different directions. | Interferometric mach–zehnder structures are used. |
| Operational wavelength   | The periodic structure and refractive index, photonic crystal is to block a certain range of frequencies to prevent spontaneous emission. Therefore, due to photonic band gap structures, all frequencies cannot be propagated through it. Wavelength depends upon inter hole spacing (*) and hole diameter (d). | Operational wavelength depends upon the type of the material. For example: LiNbO₃ operated at 1.3 to 1.55 µm. |
| Cost                     | These are man-made structures and more expensive than conventional devices.       | These are readily available and easy to integrate.                                      |
| Control parameters       | Control parameters are inter hole spacing and hole diameter. These are less flexible because the design parameters are decided at the manufactured stage. | Control parameters are the dimensions of the device and the external applied electric field. |
| Performance parameters   | ER and CR of not more than 30 dB is obtained.                                    | ER and CR of more than 30 dB can be achieved.                                          |
Opto-mechanical and Optical Amplifier based switching. One of the physical phenomena that can provide the required phase shift is the electro-optic (EO) effect (Singh et al. 2014). The refractive index of material change under the influence of applied electric field is called EO effect. The wide range of materials that exhibits the EO effect includes inorganic crystal, organic and molecular crystals. The parameter which characterizes the EO material is called the EO coefficient. Lithium niobate (high loss and low electro-optic coefficient) and gallium niobate (high electro-optic coefficient) are the most widely used EO materials. The change in refractive index is represented as (Raghuwanshi et al. 2013; Sharma and Roy 2021; Xu and Nieto-Vesperinas 2019)

$$\Delta n = \left(\frac{n^3}{2}\right) rE$$

(1)

where r is EO coefficient and E is the electric field. Now by using the EO effect, the variation in refractive index introduces a phase shifts in the light propagating through the material can be represented as

$$\Delta \varphi = \frac{2\pi}{\lambda} (\Delta n) L$$

(2)

According to the formula in Eq. (1), the phase change ($\Delta \varphi$) can be written as

$$\Delta \varphi = \frac{2\pi}{\lambda} \left( \left(\frac{n^3}{2}\right) rE \right) L$$

(3)

For a given material, EO coefficient r and refractive index n are constant. Similarly, $\lambda$ is also constant for a given optical signal. So, we have the product of two parameters E and L that decide the required phase difference.

In order to obtain a substantial phase change, the electric field is increased, the gap between the electrodes is reduced and the length of the device is also reduced to a few millimeters. Various simulation parameters are represented in Table 2. Now, for the voltage difference V and the separation d between two electrodes, the electric field will be defined as V/d. Therefore, the phase shift can be given as

$$\Delta \varphi = \frac{2\pi}{\lambda} \left( \left(\frac{n^3}{2}\right) r \frac{V}{d} \right) L$$

(4)

From the expression of phase shift (Eq. 4), it has been seen that the phase change remains zero when no voltage is applied and phase change will be $\pi$ when some particular voltage ($V_\pi$) is applied. This particular voltage can be given as (Raghuwanshi et al. 2013)
By applying the EO effect, MZI exhibits stable performance parameters for a wide range of optical power. The expression of normalized power at different output ports of Mach–Zehnder interferometer can be obtained by electro-optic effect as follows (Kumar et al. 2014b; Srivastava et al. 2019)

\[ P_{OUT1} = \left| \frac{OUT_1}{E_{in}} \right|^2 = \left| e^{-j(\phi_0)} \sin \frac{\Delta \varphi}{2} \right|^2 = \sin^2 \left( \frac{\Delta \varphi}{2} \right) \]  

\[ P_{OUT2} = \left| \frac{OUT_2}{E_{in}} \right|^2 = \left| e^{-j(\phi_0)} \cos \frac{\Delta \varphi}{2} \right|^2 = \cos^2 \left( \frac{\Delta \varphi}{2} \right) \]  

where, \( \phi_0 = \frac{\varphi_1 - \varphi_2}{2} \) and \( \Delta \varphi = \varphi_1 - \varphi_2 \). Due to the application of a voltage across the electrodes on the MZI, phase difference arise are represented by \( \varphi_1 \) and \( \varphi_2 \). Here, \( \varphi_1 = \left( \frac{\pi}{V_x} \right)V_1 \) and \( \varphi_2 = \left( \frac{\pi}{V_x} \right)V_2 \). \( V_x \) is the voltage at which phase difference across two interferometer arms is \( \pi \). Depending upon the phase difference, signal shift from one output port to another output port.

### Table 2 Specifications for simulation parameters to obtain particular voltage \( V_x \)

| Parameters                  | Values of parameters  |
|-----------------------------|------------------------|
| Wavelength (\( \lambda \))  | 1.46 \( \mu \)m        |
| Separation between the electrodes (d) | 6 \( \mu \)m          |
| Refractive index            | 1.47                   |
| Electro-optic coefficient   | \( 3.66 \times 10^{-10} \) m/V |
| Substantial length (L)      | 10,000 \( \mu \)m       |

\[ V_x = \frac{\lambda}{n^2} \frac{1}{rL} \]  

3 Design and mathematical formulation of half adder

A half adder is a combinational logic circuit that can perform the addition of two binary numbers (X and Y) and gives two single-bit binary outputs Sum and Carry. To develop a half adder, a basic Mach–Zehnder interferometer based electro-optic switch has been used at a wavelength of 1.46 \( \mu \)m in Opti-BPM software (Kaur et al. 2019). The schematic layout design of the optical half adder is shown in Fig. 2. A continuous optical input signal is provided at the input of MZI1. Three MZIs are being used in designing half adder. The output port 1 of MZI1 is connected to the first input port of MZI2. The second output port of MZI1 is connected to the second input port of MZI3. Similarly, the second output port of MZI2 is connected to the first input port of MZI3. Two inputs X and Y are provided as control signals to the second electrode of three MZIs. Controls Signal X is provided to the second electrode of MZI1 by keeping the other two electrodes at the ground potential. Similarly, control signal Y is given to the second electrode of MZI2 and MZI3. Table 3 represents all possible combinations of the control signal and the output optical signal obtained at the different output ports of the designed structure as shown in Fig. 2.
3.1 Normalized output power at different output ports of half adder

By using the output power relationship of the single-stage Mach–Zehnder interferometer in Eqs. (2) and (3), the normalized output power for different combinations of control signals X and Y is obtained at output ports. When the control signals X and Y are 00 (i.e. X = 0 and Y = 0), the output power comes out at output port 1 of MZI3 and can be represented as

$$ \frac{OUT_{1_{MZI3}}}{E_{in}} = \left\{ -je^{-j(\phi_{MZI1})} \cos\left( \frac{\Delta \phi_{MZI1}}{2} \right) \right\} \left\{ -je^{-j(\phi_{MZI3})} \cos\left( \frac{\Delta \phi_{MZI3}}{2} \right) \right\} $$

$$ m_0 = \left| \frac{OUT_{1_{MZI3}}}{E_{in}} \right|^2 = \cos^2\left( \frac{\Delta \phi_{MZI1}}{2} \right) \cos^2\left( \frac{\Delta \phi_{MZI3}}{2} \right) \tag{8} $$

Similarly, the normalized output power for control signal 01 (i.e., X = 0 and Y = 1) using Eqs. (6) and (7) for single stage MZI are given as

$$ \frac{OUT_{2_{MZI3}}}{E_{in}} = \left\{ -je^{-j(\phi_{MZI1})} \cos\left( \frac{\Delta \phi_{MZI1}}{2} \right) \right\} \left\{ -je^{-j(\phi_{MZI3})} \sin\left( \frac{\Delta \phi_{MZI3}}{2} \right) \right\} $$

$$ m_1 = \left| \frac{OUT_{2_{MZI3}}}{E_{in}} \right|^2 = \cos^2\left( \frac{\Delta \phi_{MZI1}}{2} \right) \sin^2\left( \frac{\Delta \phi_{MZI3}}{2} \right) \tag{9} $$

Again, by analyzing the single-stage MZI response, the normalized output power at output port 2 of MZI3 for control signal 10 (i.e., X = 1 and Y = 0) can be written as
Finally, for the control signals 11 (i.e., X = 1 and Y = 1), the normalized output power can be written as

\[
\frac{OUT_{MZI3}}{E_{in}} = \left\{ -je^{-\phi(0MZI1)} \sin \left( \frac{\Delta \phi_{MZI1}}{2} \right) \right\} \left\{ -je^{-\phi(0MZI2)} \cos \left( \frac{\Delta \phi_{MZI2}}{2} \right) \right\} \left\{ -je^{-\phi(0MZI3)} \cos \left( \frac{\Delta \phi_{MZI3}}{2} \right) \right\}
\]

\[
m_2 = \left| \frac{OUT_{MZI3}}{E_{in}} \right|^2 = \sin^2 \left( \frac{\Delta \phi_{MZI1}}{2} \right) \cos^2 \left( \frac{\Delta \phi_{MZI2}}{2} \right) \cos^2 \left( \frac{\Delta \phi_{MZI3}}{2} \right)
\]

(10)

Thus, the overall output power expression for Sum can be obtained by combining the power at output ports \( m_1 \) and \( m_2 \).

\[
\frac{OUT_{MZI2}}{E_{in}} = \left\{ -je^{-\phi(0MZI1)} \sin \left( \frac{\Delta \phi_{MZI1}}{2} \right) \right\} \left\{ -je^{-\phi(0MZI2)} \sin \left( \frac{\Delta \phi_{MZI2}}{2} \right) \right\}
\]

\[
m_3 = \left| \frac{OUT_{MZI2}}{E_{in}} \right|^2 = \sin^2 \left( \frac{\Delta \phi_{MZI1}}{2} \right) \sin^2 \left( \frac{\Delta \phi_{MZI2}}{2} \right)
\]

(11)

\[
OUT_{Sum} = m_1 + m_2 = \cos^2 \left( \frac{\Delta \phi_{MZI1}}{2} \right) \sin^2 \left( \frac{\Delta \phi_{MZI3}}{2} \right) + \sin^2 \left( \frac{\Delta \phi_{MZI1}}{2} \right) \cos^2 \left( \frac{\Delta \phi_{MZI2}}{2} \right) \cos^2 \left( \frac{\Delta \phi_{MZI3}}{2} \right)
\]

(12)

Similarly, the expression for normalized output power for Carry can be written as

\[
OUT_{Carry} = m_3 = \sin^2 \left( \frac{\Delta \phi_{MZI1}}{2} \right) \sin^2 \left( \frac{\Delta \phi_{MZI2}}{2} \right)
\]

(13)

### 4 Design and mathematical formulation of half subtractor

A half subtractor is a combinational logic circuit performing subtraction of two binary bits. It has two inputs X and Y, and generates two binary outputs difference and borrow. Figure 3 represents the schematic design of a 2-bit half subtractor that performs subtraction of two single-bit numbers using MZI. The proposed design consists of three MZIs with two control signals X and Y acting as inputs. A continuous input signal is given to the input port of MZI1. The output port 1 of MZI1 is connected to the input port 1 of MZI2. Similarly, the output port 2 of MZI1 is connected to the input port 2 of MZI2 and to the input port of MZI3. The MZI1 is controlled by signal X (voltage applied at the second electrode, by keeping the other two electrodes at ground potential). The control signal Y is provided to the second electrode of MZI2 and MZI3. The values of the control signal are 0 (0 V) and 1 (8 V) at the second electrode of each MZI. Table 4 shows the different combinations of the control signal provided at the second electrode of each MZI and their corresponding output power generated at different output ports shown in Fig. 3.
4.1 Normalized output power at output ports of half subtractor

To perform half subtraction, the expression of normalized output power for all possible combinations of control signals can be calculated using the expression of single-stage MZI in Eqs. (6) and (7).

For control signal 00 (i.e. X=0, Y=0)

\[
\frac{OUT_{MZI1}}{E_{in}} = \left\{ -je^{-(\phi_{MZI1})} \cos\left(\frac{\Delta \phi_{MZI1}}{2}\right) \right\} \left\{ -je^{-(\phi_{MZI2})} \cos\left(\frac{\Delta \phi_{MZI2}}{2}\right) \right\}
\]

\[m_0 = \left| \frac{OUT_{MZI1}}{E_{in}} \right|^2 = \cos^2\left(\frac{\Delta \phi_{MZI1}}{2}\right) \cos^2\left(\frac{\Delta \phi_{MZI2}}{2}\right)\] (14)

For control signal 01 (i.e., X=0, Y=1)

\[
\frac{OUT_{MZI2}}{E_{in}} = \left\{ -je^{-(\phi_{MZI1})} \cos\left(\frac{\Delta \phi_{MZI1}}{2}\right) \right\} \left\{ -je^{-(\phi_{MZI3})} \cos\left(\frac{\Delta \phi_{MZI3}}{2}\right) \right\}
\]

\[m_1 = \left| \frac{OUT_{MZI2}}{E_{in}} \right|^2 = \cos^2\left(\frac{\Delta \phi_{MZI1}}{2}\right) \cos^2\left(\frac{\Delta \phi_{MZI3}}{2}\right)\] (15)

In similar manner, for control signal 10 (i.e., X=1, Y=0) and control signal 11 (i.e., X=1, Y=1), the output powers can be calculated using similar expressions.

### Table 4  Truth table of half subtractor using different combinations of control signals

| Inputs | Output of half subtractor |
|--------|----------------------------|
| X Y    | Difference (Port 2) Power (mW) | Borrow (Port 3) Power (mW) |
| 0 0    | 0.00057                     | 0.00140                    |
| 0 1    | 0.87250                     | 0.98147                    |
| 1 0    | 0.97476                     | 0.000                      |
| 1 1    | 0.00115                     | 0.00010                    |

![Schematic diagram of half subtractor](image-url)
\[
\frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} = \left\{ -je^{-j(\phi_{\text{MZI1}})} \cos\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \right\} \left\{ -je^{-j(\phi_{\text{MZI2}})} \sin\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right) \right\}
\]
\[
m_2 = \left| \frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} \right|^2 = \cos^2\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \sin^2\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right)
\]
\[
\frac{\text{OUT}_{\text{MZI3}}}{E_{\text{in}}} = \left\{ -je^{-j(\phi_{\text{MZI1}})} \cos\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \right\} \left\{ -je^{-j(\phi_{\text{MZI3}})} \sin\left(\frac{\Delta\phi_{\text{MZI3}}}{2}\right) \right\}
\]
\[
m_3 = \left| \frac{\text{OUT}_{\text{MZI3}}}{E_{\text{in}}} \right|^2 = \cos^2\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \sin^2\left(\frac{\Delta\phi_{\text{MZI3}}}{2}\right)
\]

For control signal 10 (i.e., X = 1 and Y = 0), the normalized output power can be calculated as
\[
\frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} = \left\{ -je^{-j(\phi_{\text{MZI1}})} \sin\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \right\} \left\{ -je^{-j(\phi_{\text{MZI2}})} \cos\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right) \right\}
\]
\[
m_4 = \left| \frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} \right|^2 = \sin^2\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \cos^2\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right)
\]

Similarly, for control signal 11 (i.e., X = 1 and Y = 1) the output power at output port 1 of MZI2 can be derived as
\[
\frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} = \left\{ -je^{-j(\phi_{\text{MZI1}})} \sin\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \right\} \left\{ -je^{-j(\phi_{\text{MZI2}})} \sin\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right) \right\}
\]
\[
m_5 = \left| \frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} \right|^2 = \sin^2\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \sin^2\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right)
\]

The expression for normalized output power for Difference and Borrow can be written as
\[
\text{OUT}_{\text{Difference}} = m_2 + m_4 = \left| \frac{\text{OUT}_{\text{MZI2}}}{E_{\text{in}}} \right|^2 = \cos^2\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \sin^2\left(\frac{\Delta\phi_{\text{MZI2}}}{2}\right)
\]
\[
\text{OUT}_{\text{Borrow}} = m_3 = \left| \frac{\text{OUT}_{\text{MZI3}}}{E_{\text{in}}} \right|^2 = \cos^2\left(\frac{\Delta\phi_{\text{MZI1}}}{2}\right) \sin^2\left(\frac{\Delta\phi_{\text{MZI3}}}{2}\right)
\]

For the calculation of Eqs. (8)–(21) we have assumed that
\[
\phi_{\text{0MZI1}} = \frac{\phi_{1\text{MZI1}} + \phi_{2\text{MZI1}}}{2}, \quad \Delta\phi_{\text{MZI1}} = \phi_{1\text{MZI1}} - \phi_{2\text{MZI1}} = \frac{\pi}{V_{\pi}}X
\]
where $\phi_{1MZI1}$, $\phi_{2MZI1}$, and $\phi_{3MZI1}$ are the phase angles at the upper arm of MZI1, MZI2, and MZI3 respectively. $\phi_{2MZI1}$, $\phi_{2MZI2}$, and $\phi_{2MZI3}$ are the phase angles at the lower arm of MZI1, MZI2, and MZI3 respectively. The control signal X is the voltage applied at the second electrode of MZI1 keeping the other two electrodes at the ground potential. Similarly, MZI2 and MZI3 are controlled by control signal Y.

5 Implementation of half adder using opti-BPM

The Opti-BPM layout of the optical half adder is shown in Fig. 4. A continuous optical input signal is provided at the input port of MZI1. Two inputs X and Y are provided as control signals to the second electrode of three MZIs. A detailed combination of control signals X and Y applied to the designed structure and their corresponding response at the output ports is discussed as follows.

5.1 Case 1: $X = 0$, $Y = 0$

Here, the continuous optical input signal is incident on the first input port of MZI1. The control signal X applied to the second electrode of MZI1 is low (0 V), so optical power reaches the output port 2 of MZI1. The output power at output port 2 of MZI1 represents the input to MZI3. Now, if the control signal Y is applied to the second electrode of MZI3 is also low, then the signal reaches at the output port 1 of MZI3. Hence, no optical signal appears at output port 1 and output port 3 of the designed structure.
5.2 Case 2: $X = 0$, $Y = 1$

In this case, a continuous optical input signal is provided at input port 1 of MZI1. As a low control signal ($X = 0$) is provided at the second electrode of MZI1, it allows the optical signal to appear at the output port 2 of MZI1. The output signal that appears at output port 2 of the MZI1 again becomes the input of MZI3. If the control signal $Y$ applied to the second electrode of MZI3 is high ($Y = 1$), then the optical signal that appears at output port 3 of the MZI3 represents the sum of two bits. Hence, for $X = 0$ and $Y = 1$, the optical power appears only at output port 2 of the MZI3.

5.3 Case 3: $X = 1$, $Y = 0$

In this case, the control signal applied to the second electrode of MZI1 is high ($X = 1$), the optical signal appears at the output port 1 of MZI1 that acts as the input of MZI2. Since control signal $Y$ applied to the second electrode of MZI2 is low ($Y = 0$), the output signal appears at output port 2 of MZI2. Now, the output signal at port 2 of MZI2 becomes the input of MZI3. Again, the control signal $Y = 0$ is applied to the second electrode of MZI3, then the optical signal appears at output port 2 of MZI3 representing again the sum of two bits.

5.4 Case 4: $X = 1$, $Y = 1$

Similarly, for the combination of control signals $X = 1$ and $Y = 1$, the optical signal is observed at the output port 1 of MZI1. The signal that appears at output port 1 of MZI1 becomes the input of MZI2. As the control signal $Y$ applied to the second electrode of MZI2 is high, the output power appears at output port 1 of MZI2. Therefore, due to the presence of each control signal the optical power appears at output port 1 of MZI2.

The OptiBPM simulation results of the proposed half adder can be represented in Fig. 5. Similarly, Fig. 6 shows MATLAB simulation results of half adder for different combinations of control signals ‘$X$ $Y$’ (i.e., 00, 01, 10, and 11). The first row represents the control signal $X$ provided to the second electrode of MZI1. The second row represents the control signal $Y$ provided to the second electrode of MZI2 and MZI3. The last two rows represent the response of optical propagation on various output ports of half adder for given combinations of control signals. So, the third and fourth row of Fig. 5 represents the SUM and CARRY bits of the half adder. From OptiBPM results in Fig. 5 and MATLAB results in Fig. 6, it is shown that the results obtained from Opti-BPM are perfectly matched with the simulation results obtained in MATLAB for the proposed structure. Also, the results obtained with MATLAB and OptiBPM can be verified from Table 3.
6 Design of half subtractor using electro-optic effect based MZI structure

Figure 7 represents the layout design of a 2-bit half subtractor using beam propagation method. The proposed design consists of three MZIs with two control signals X and Y. The continuous optical input signal is given to the first input port of MZI1.

Depending upon the combination of the different control signals provided at the second electrode of MZIs, the output power generated at the output ports of MZIs represents the difference and borrow bit and are discussed as:

6.1 Case 1: \(X = 0, Y = 0\)

Figure 7 represents the optical signal incident on input port 1 of MZI1. As the control signal X provided to the second electrode of MZI1 is low (0 V), the optical signal appears at output port 2 of MZI1. This port is further connected to input port 2 and input port 1 of MZI2 and MZI3. Since the control signal Y provided to the second electrode of MZI2 and MZI3 is also low, the output appears at output port 1 and output port 2 of MZI2 and MZI3.
6.2 Case 2: $X = 0$, $Y = 1$

In this case, the control signal X provided to MZI1 is low again. Due to this, the optical signal again appears at output port 2 of MZI1. As the control signal Y applied to the second electrode of MZI2 and MZI3 is high (1 V), the output signal appears at output port 2 and output port 1 of MZI2 and MZI3 which represents difference and borrow.
6.3 Case 3: $X = 1$, $Y = 0$

In this case, the control signal $X$ provided to the second electrode of MZI1 is high (1 V), the output signal emerges from output port 1 of MZI1. This output signal is the input provided to input port 1 of MZI2. Finally, due to the absence of control signal $Y$ (0 V) provided to MZI2, the output signal comes out at output port 2 of MZI2 representing the difference of 2 bits.

6.4 Case 4: $X = 1$ and $Y = 1$

Similarly, in this case, the combination of control signals provided to MZI1, MZI2, and MZI3 is high. The output signal appears at output port 1 of MZI1. The optical signal that appears at output port 1 of MZI1 will go to input port 1 of MZI2. Due to the presence of control signal $Y$ (1 V), the output signal will go straight and appears at output port 1 of MZI2.

Figure 8 shows OptiBPM results of half subtractor for different combinations of control signal $X$ and $Y$. Similarly, MATLAB simulation results of half subtractor are represented in Fig. 9. From Fig. 9, it has been seen that the first and second row represents control signal $X$ and $Y$ provided to the second electrode of MZIs, and the last two rows represent the

![Fig. 8 Opti-BPM simulation results of half subtractor by applying a different combination of control signals](image_url)
difference and borrow outputs of the proposed structure. The simulation results obtained from MATLAB and OptiBPM can be verified from the results provided in Table 4.

7 Results and discussion

To validate the performance of half adder and half subtractor, some important performance parameters such as extinction ratio (ER), contrast ratio (CR), amplitude modulation (AM), insertion loss (IL), and eye opening have been calculated from the simulation results. The extinction ratio (ER) is defined as the ratio of minimum output peak power for logic 1 to maximum output peak power for logic 0 and is given as (Rezaei and Zarifkar 2021; Singh et al. 2014)

\[
ER (dB) = 10 \log \frac{P_{1 \text{min}}}{P_{0 \text{max}}}
\]  

(22)

where \(P_{1 \text{min}}\) and \(P_{0 \text{max}}\) are the minimum and maximum power at the output for logic 1 and logic 0 respectively. For better operation, the higher the value of ER, the easier for the device to differentiate between high and low logic states. It should be larger than 10 dB. For the proposed design of a half adder, the minimum and maximum value of ER is 27.33 dB and 33.22 dB respectively for sum and carry bits. Similarly, for half subtractor, ER is 28.76 dB and 28.45 dB respectively for difference and borrow bits. The second parameter used to evaluate the performance of the proposed structures is the contrast ratio (CR). The contrast ratio is the ratio of average optical power for logic 1 state to the average optical power for logic 0 state (Chattopadhyay 2011; Sharma and Roy 2021)
where $P_{\text{mean}}^1$ and $P_{\text{mean}}^0$ are the mean value of output peak power for logic 1 and logic 0 respectively. For optimum performance, the CR must be high so that the main fraction of input can exist at the output. The maximum and minimum value of CR ratio is obtained as 36.32 dB and 29.58 dB for carry and sum bits respectively. The CR ratio for difference and borrow bits is 30.29 dB and 32.90 dB respectively. The third important parameter that affects the performance of the device is insertion loss. Mathematically, the insertion loss is defined as (Srivastava et al. 2019)

$$IL (dB) = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}$$

(24)

It is the ratio of output optical power to given optical power. The insertion loss should be less than 1 dB. For sum and carry bits, IL is calculated as 0.05 dB. The proposed structure of half subtractor gives the IL of 0.08 dB and 0.11 dB for borrow and difference bits respectively. At last, other performance parameters, the amplitude modulation (AM) and relative eye opening (O) are measured. The amplitude modulation is defined as the ratio of maximum to the minimum value of power intensity for logic 1 (Chattopadhyay 2011).

$$AM (dB) = 10 \log \frac{P_{\text{max}}^1}{P_{\text{min}}^1}$$

(25)

where $P_{\text{max}}^1$ and $P_{\text{min}}^1$ are the maximum power intensity for logic 1 and minimum power intensity for logic 1. Similarly, the relative eye opening (O) is given as (Gayen et al. 2014; Nady et al. 2013)

$$O = \left( \frac{P_{\text{min}}^1 - P_{\text{max}}^0}{P_{\text{min}}^1} \right) \times 100\%$$

(26)

The value of AM and relative eye opening for the proposed half adder design is calculated as 0.019 dB and 99.95% and for the half subtractor, the corresponding values are 0.480 dB and 99.85% respectively. In addition, Tables 5 and 6 show the comparison of the performance parameters of the proposed work with the previously reported devices in the literature.

The proposed design of half adder/half subtractor has shown better performance than the existing structures in terms of high ER, CR, and low AM and IL. Further, the operational speed of the device is calculated which depends upon bit rate and time delay. The bit rate is the inverse of response time. For the proposed length of the designed device, the bit rate and time delay are calculated as 2 Tbps and 0.5 ps respectively. Low dimensions and low response time are considered for the practical realization of complex optical signal processing devices for high-speed operation.

8 Conclusion

In this paper, MZI based logical operations such as half adder and half subtractor are designed using beam propagation method. The optimized structure yields maximum ER of 33.22 dB, CR of 36.32 dB, IL of 0.05 dB, AM of 0.019, and relative eye opening of
| Structure                                        | Extinction ratio (dB) | Contrast ratio (dB) | Insertion loss (dB) | Amplitude modulation (dB) | Relative Eye opening (%) | Reference                      |
|-------------------------------------------------|-----------------------|---------------------|---------------------|--------------------------|-------------------------|--------------------------------|
| Two SOAs                                        | 16.70                 | –                   | –                   | –                        | –                       | Dai et al. (2013)              |
| Terahertz optical asymmetric demultiplexer      | 11.51                 | 15.62               | –                   | 0.05                     | 98.60                   | Gayen et al. (2014)            |
| Graphene plasmonic waveguide                    | –                     | 14.83               | –                   | –                        | –                       | Rezaei and Zarifkar (2019)     |
| Graphene plasmonic waveguide                    | 28.20                 | –                   | –                   | –                        | –                       | Rezaei and Zarifkar (2021)     |
| Nonlinear Plasmonic Nanocavities                | –                     | 27                  | –                   | –                        | –                       | Xie et al. (2017)              |
| IMI Plasmonic waveguides                        | 16.53                 | –                   | 0.338               | –                        | 74                      | Swarnakar et al. (2021)        |
| Silicon Microring Resonators                     | 7.16                  | 10.71               | –                   | 1.26                     | –                       | Rakshit and Roy (2016)         |
| 2D Photonic Crystals                            | –                     | 9.3                 | –                   | –                        | –                       | Seifouri et al. (2019)         |
| 2D Photonic Crystals                            | –                     | 9.29                | –                   | –                        | –                       | Abdollahi and Parandin (2019)  |
| 2D Photonic Crystals                            | –                     | 9.77                | –                   | –                        | –                       | Serajmohammadi et al. (2018)   |
| 2D Photonic Crystals                            | 6.15                  | 5.63                | 0.45                | –                        | –                       | Karkhanehchi et al. (2017)     |
| SOA-MZI                                         | 16.91                 | 19.73               | –                   | 0.09                     | 97                      | Datta et al. (2015)            |
| SOA-MZI                                         | 23.65                 | 25.75               | 0.03                | 0.03                     | –                       | Nair et al. (2021a)            |
| Electro-optic (EO) effect                       | 28.68                 | –                   | 0.024               | –                        | –                       | Prajapat et al. (2020)         |
| Electro-optic (EO) effect                       | 33.22                 | 36.32               | 0.050               | 0.01                     | 99.81                   | Proposed work                  |
Table 6  Performance comparison of the proposed half subtractor with the existing design

| Structure                                    | Extinction ratio (dB) | Contrast ratio (dB) | Insertion loss (dB) | Amplitude modulation (dB) | Eye opening (%) | Reference                           |
|---------------------------------------------|-----------------------|---------------------|---------------------|----------------------------|-----------------|-------------------------------------|
| Two SOAs                                    | 14.90                 | –                   | –                   | –                          | –               | Dai et al. (2013)                   |
| Terahertz optical asymmetric demultiplexer  | 11.11                 | 14.02               | –                   | 0.08                       | 92.27           | Gayen et al. (2014)                 |
| Graphene plasmonic waveguide                | –                     | 15.75               | –                   | –                          | –               | Rezaei and Zarifkar (2019)          |
| Graphene plasmonic waveguide                | 25.98                 | –                   | –                   | –                          | –               | Rezaei and Zarifkar (2021)          |
| Highly nonlinear fiber                      | 12.30                 | 27                  | –                   | –                          | –               | Singh et al. (2016)                 |
| Silicon Microring Resonators                | 7.16                  | 10.71               | –                   | 1.26                       | –               | Rakshit and Roy (2016)              |
| 2D Photonic Crystals                        | –                     | 8.2                 | –                   | –                          | –               | Parandin et al. (2017)             |
| 2D Photonic Crystals                        | –                     | 12                  | –                   | –                          | –               | Askarian et al. (2019)             |
| Electro-optic (EO) effect                   | 28.76                 | 32.90               | 0.081               | 0.48                       | 99.86           | Proposed work                      |
99.81% for half adder, whereas for half subtractor ER of 28.76 dB, CR of 32.90 dB, IL of 0.081 dB, AM of 0.48 dB and relative eye opening of 99.86% is achieved. The performance comparison of the proposed modules is also compared with the contemporary literature and significant improved performance has been observed. Further, the proposed module can be utilized to design complex logic circuits which paves the useful direction in the area of optical computing and telecommunication.

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