All-optical half adder based on non-linear triangular lattice photonic crystals with improved contrast ratio

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Abstract
An all-optical half adder based on two-dimensional photonic crystals is proposed. The proposed structure is composed of a triangular array of dielectric rods made of non-linear optical material in air. The structure consists of four waveguides and one ring resonator which are formed by removing a number of dielectric rods. The structure has been simulated and analysed by the plane wave expansion method and the finite-difference time-domain method. The size of the proposed structure is small with dimensions of 17 μm × 14.8 μm, and the material of the rods and lattice constant are uniform across the structure. The proposed half adder has a minimum contrast ratio of 13.51 dB in the steady state, with a maximum time delay of 2 ps.

1 | INTRODUCTION

All-optical logic devices play an important role in optical computing and communication systems. Compared with electrons, using photons as the information carriers can provide higher transmission rate, parallel processing, and lower energy losses. In recent years, photonic crystals have attracted a lot of attention to design photonic devices because of their interesting properties. Photonic crystals are periodic structures which are composed of materials with a spatially periodic distribution of dielectric constant in one, or two, or three dimensions [1,2]. The periodicity of dielectric material in photonic crystals produces their unique photonic band gap property, which is the basis for photonic crystal devices realization. A photonic crystal reflects incident electromagnetic waves with frequency located in the photonic band gap region. Lattice defects in the perfect periodic structures break down the periodicity and thus the photonic band gap completeness. Therefore, by introducing lattice defects in the photonic crystal structures, it is possible to confine light inside the structures and use them as light controller, which can lead to the design and realization of photonic crystal-based optical devices. To confine light inside a photonic crystal, the wavelength of light should be within the photonic band gap of the structure.

Various types of optical devices have been designed based on two-dimensional photonic crystals in recent years, such as fibres [3], switches [4], filters [5], multiplexers [6], demultiplexers [7], splitters [8], couplers [9], sensors [10], and different kinds of logic gates such as AND, NAND, OR, NOR, XOR, and NOT [11–18].

In addition to the logic gates, the half adder is one of the most important logic devices. The half adder adds two binary digits. This device has two input ports and two output ports. The input ports are A and B, and the output ports are Sum and Carry which are realized by XOR gate and AND gate, respectively. The truth table for the half adder is shown in Table 1.

An optical half adder is proposed based on two-dimensional photonic crystals. The proposed structure is composed of a triangular lattice of dielectric rods in air. The dielectric rods are made of a non-linear optical material whose dielectric constant depends on the radiation intensity. The structure consists of four waveguides and one ring resonator which are formed by the absence of some dielectric rods. The proposed structure has an improved contrast ratio with no displaced rods in the structure. The device also has a small size, low time delay, and stable output signal levels.

A number of photonic crystal-based half adders have been reported in the literature. Karkhanaehei et al. [19] proposed an optical half adder based on constructive and destructive interference at waveguides cross point in a two-dimensional hexagonal lattice photonic crystal structure with a contrast ratio of about 3 dB. Ghadrdan and Mansouri-Birjandi [20] proposed an optical half adder based on non-linear photonic crystal ring resonators in a two-dimensional square lattice of dielectric rods.
TABLE 1  Half adder truth table

| A | B | Sum | Carry |
|---|---|-----|-------|
| 0 | 0 | 0   | 0     |
| 0 | 1 | 1   | 0     |
| 1 | 0 | 1   | 0     |
| 1 | 1 | 0   | 1     |

consisting of three ring resonators made of two different materials. The contrast ratio of this structure is about 5.6 dB. Sonth et al. [21] proposed an optical half adder based on interference in a two-dimensional photonic crystal structure using four T-shaped waveguides and 180° phase shift inputs. It is composed of a square lattice of dielectric rods, in which some rods are not located at the original lattice site. The maximum contrast ratio of this structure is about 11.67 dB at an unstable state of output signals over a short period of time. Jiang et al. [22] proposed an optical half adder based on the self-collimated effect in two-dimensional photonic crystals, which consists of line defect acting as a splitter. The structure is composed of dielectric rods with two different refractive indices arranged in square lattice. The contrast ratio of this structure is about 8 dB. Neisy et al. [23] proposed an optical half adder based on resonant cavities in a two-dimensional square lattice photonic crystal. It consists of two non-linear resonant cavities, which are created by replacing ordinary silicon rods with non-linear doped glass rods. The contrast ratio of this structure is about 11.5 dB, and its time delay is about 3 ps.

In comparison with the structures mentioned above, our proposed structure exhibits higher contrast ratio with a minimum contrast ratio of 13.51 dB in the steady state. The structure is also smaller, and its input/output ports are located at better positions, compared to most of them. The overall size of the proposed structure is small with dimensions of 17 μm × 14.8 μm. Moreover, all dielectric rods are made of the same material and are located at their original position across the structure, making it easier to fabricate with less fabrication errors. In the proposed structure, the input ports are located on the left side and the output ports are located on the right side, which will increase its integration capability. Another important advantage of the proposed structure is that it is possible to design a full adder by cascading two of them. In addition to higher contrast ratio, the structure has a very stable output in the steady state, which results in the elimination of detection errors at the output ports.

2  | STRUCTURE DESIGN

The proposed structure for optical half adder is depicted in Figure 1. The structure is composed of a two-dimensional 29a × 27a triangular lattice array of circular dielectric rods in air. The rods are made of aluminium gallium arsenide (AlGaN), which is a material with a large optical non-linearity. The lattice constant a is 600 nm, and the radius of the dielectric rods is 0.2a.

AlGaN is an ideal candidate for the non-linear optical designs because of its high non-linear refractive index, high linear refractive index, and large transparency window. Moreover, its well-developed fabrication technology allows complex structures and integrated circuits to be fabricated.

Another advantage of AlGaN/GaAs is that its band gap can be tuned by changing the composition x. The real part of the refractive index in the zincblende materials below the direct band gap edge can be expressed as [24]

$$n(\lambda) = \sqrt{A_0 \left[ f(\chi) + \frac{1}{2} \left( \frac{E_0}{E_0 + \Delta_0} \right)^{\frac{3}{2}} f(\chi_{so}) \right] + B_0}$$

with

$$f(\chi) = \frac{2 - (1 + \chi)^{1/2} - (1 - \chi)^{1/2}}{\chi^2}$$

$$\chi = \frac{\hbar c}{\lambda E_0}$$

$$\chi_{so} = \frac{\hbar c}{\lambda(E_0 + \Delta_0)}$$

where $A_0$ and $B_0$ are constants, $\hbar$ is Planck’s constant, $c$ is speed of light in vacuum, $E_0$ is lowest direct gap energy, and $\Delta_0$ is spin-orbit splitting energy.

For AlGaN/GaAs alloy, the quantities $A_0$, $B_0$, $E_0$, and $E_0 + \Delta_0$ as a function of composition $x$ are written as

$$A_0(x) = 6.3 + 19.0x$$

$$B_0(x) = 9.4 - 10.2x$$

$$E_0(x) = 1.425 + 1.155x + 0.37x^2$$
\[ E_0(x) + \Delta_0(x) = 1.765 + 1.115x + 0.37x^2 \quad (8) \]

Introducing these numerical values into Equation (1), the refractive index of Al\(_x\)Ga\(_{1-x}\)As with a composition \(x\) can be calculated. The refractive index of AlGaAs at \(\lambda = 1550\) nm is considered as \(n = 3.3\) [25].

The refractive index of a non-linear material changes in proportion to the light intensity. The intensity-dependent refractive index can be represented as [26]

\[ n = n_0 + n_2 I \quad (9) \]

where \(n_0\) is the linear refractive index, \(n_2\) is the non-linear refractive index, and \(I\) is the time-averaged intensity of the incident light.

In the non-linear case, the polarization is described by

\[ P(\omega) = \varepsilon_0 \left( \chi^{(1)} + 3\chi^{(3)} |E(\omega)|^2 \right) E(\omega) \quad (10) \]

where \(\chi^{(1)}\) and \(\chi^{(3)}\) are the linear and third-order non-linear susceptibilities, respectively.

The linear refractive index is related to the linear susceptibility by

\[ n_0 = \left(1 + \chi^{(1)}\right)^{1/2} \quad (11) \]

The non-linear refractive index is related to the non-linear susceptibility by

\[ n_2 = \frac{3}{4n_0^2\varepsilon_0 c} \chi^{(3)} \quad (12) \]

or

\[ n_2 \left(\frac{m^2}{W}\right) = \frac{282.5}{n_0^2\varepsilon_0 c} \chi^{(3)} \left(\frac{m^2}{V}\right) \quad (13) \]

The non-linear Kerr coefficient of AlGaAs at \(\lambda = 1550\) nm is \(n_2 = 1.5 \times 10^{-17}\) m\(^2\)/W [27], corresponding to the third-order non-linear susceptibility of \(\chi^{(3)} = 5.78 \times 10^{-19}\) m\(^2\)/V\(^2\) which is required for the simulation.

Propagation of electromagnetic waves in the photonic crystals can be calculated by using the Maxwell's equations [28]

\[ \nabla \times E = -\frac{\partial B}{\partial t} \quad (14) \]

\[ \nabla \times H = \frac{\partial D}{\partial t} \quad (15) \]

The Maxwell's equations can be solved by using the finite-difference time-domain (FDTD) method by first discretizing the equations in time and space and then solving them numerically. The non-linear FDTD set of equations can be written as [29]

\[ D_x^{n+1} \left( i + \frac{1}{2}j, k \right) = D_x^n \left( i + \frac{1}{2}j, k \right) - \Delta t \left[ \frac{H_y^n \left( i + \frac{1}{2}j, k + \frac{1}{2} \right) - H_y^n \left( i + \frac{1}{2}j, k - \frac{1}{2} \right)}{\Delta z} \right. \]

\[ \left. - \frac{H_z^n \left( i + \frac{1}{2}j, k + \frac{1}{2} \right) - H_z^n \left( i + \frac{1}{2}j, k - \frac{1}{2} \right)}{\Delta y} \right] \quad (16) \]

where \(D_x^n\) is the electric displacement along the \(x\) direction that is known from the non-linear constitutive relation \(D^n = f(E^n)\) \(E^n\).

\[ D = \varepsilon_0 \begin{bmatrix} \varepsilon_r + \chi^{(3)} |E|^2 & 0 & 0 \\ 0 & \varepsilon_r + \chi^{(3)} |E|^2 & 0 \\ 0 & 0 & \varepsilon_r + \chi^{(3)} |E|^2 \end{bmatrix} E \quad (17) \]

The electric field is then determined by the inverse constitutive relation \(E^{n+1} = f^{-1}(D^{n+1})D^{n+1}\).

The band diagram of the proposed structure, which has been calculated by the plane wave expansion (PWE) method, is depicted in Figure 2. According to the band diagram, the structure has a wide transverse electric (TE) mode photonic band gap in the normalized frequency range of

![FIGURE 2 Band diagram of the proposed structure](image-url)
0.282 < \frac{a}{\lambda} < 0.453, whose corresponding wavelength ranges from 1320 to 2120 nm. Therefore, light with wavelengths in the range from 1320 to 2120 nm for TE modes cannot pass through the perfect photonic crystal structure and will be reflected completely. The wavelength of the incident light at the input ports is 1550 nm, which locates in the central region of the main photonic band gap for the TE polarization.

The proposed structure consists of two input waveguides marked with W1 and W2, two output waveguides marked with W3 and W4, and a ring resonator which acts as a coupling element. The waveguides and ring resonator are formed by removing a number of dielectric rods in the structure. The input ports are marked with A and B. The output ports are marked with S and C, which are \textit{Sum} and \textit{Carry}, respectively. Several fabrication methods can be used to fabricate such a two-dimensional photonic crystal structure, including the electron beam lithography [30,31], the focused ion beam etching [32,33], the nanoimprint lithography [34,35], and the holographic lithography [36].

A continuous wave at a wavelength of 1550 nm is used as the input signal for each input port. The two input beams have the same field amplitude and phase. The structure is surrounded by a perfectly matched layer to absorb the waves at the boundaries and avoid the reflections. The length of the input waveguides is also optimized to minimize back reflections from cross point into the input waveguides.

In order to ensure convergence in two-dimensional simulations, the grid size along the x and z axes must be less than \frac{\lambda}{10} (\Delta x < \frac{\lambda}{10} and \Delta z < \frac{\lambda}{10}). For a stable simulation, the following Courant condition must be satisfied:

\[
c \Delta t < \frac{1}{\sqrt{1/\Delta x^2 + 1/\Delta z^2}}
\]

where \(c\) is the light velocity. For two-dimensional simulation of the proposed structure, the grid sizes are chosen as \(\Delta x = \Delta z = 0.02 \text{ \mu m}\) and \(c \Delta t = 0.01 \text{ \mu m}\).

The operation mechanism of the proposed structure is based on the shift in resonant wavelength of the ring resonator caused by the change in light intensity inside the structure. The refractive index of the materials with non-linear Kerr effect changes by light intensity. The rods in the proposed structure are made of a non-linear optical material whose dielectric constant increases with light intensity. The resonant wavelength of the ring resonator depends on the refractive index of the rods and, therefore, will change by light intensity. The structure is properly designed so that at low light intensity, that is one input source is ON, the ring resonator does not affect the beam propagation along W3 towards the output port S. But at high light intensity, that is both input sources are ON, due to the change in the refractive index of the medium, and consequently the change in the resonant wavelength of the ring resonator, the light beam propagating in W3 is coupled into W4 which leads to the output port C. The resonant wavelength of the ring resonator in the proposed structure is tuned by changing the radius of the rods located at the last ring of the

![](image)

**FIGURE 3** Field distributions for (a) \(A = 1, B = 0\), (b) \(A = 0, B = 1\), and (c) \(A = 1, B = 1\)

inner rings. According to the above concept, the optical power level at the output ports of the structure depends on the state of the inputs. The optical intensity of the incident beams at the input ports is represented by \(P_{in}\). When both input signals are
OFF, the optical power at the output ports is zero. When only one input signal is ON, the optical intensity entering the structure is $P_{in}$, so that there is no matching between the wavelength of the input light beam and the resonant wavelength of the ring resonator, so the incident light beam goes to the output port S directly. In this case, the optical power at the output S is much higher than the optical power at the output C. Therefore, the power level at the output S can be considered as logic ‘1’, and the power level at the output C can be considered as logic ‘0’. When both input signals are ON, the optical intensity entering the structure is $2P_{in}$. At high input intensity, the refractive index of the rods increases due to the non-linear optical Kerr effect, and as a result, the resonant wavelength of the ring resonator shifts towards longer wavelengths. In this condition, the resonant wavelength of the ring resonator matches the wavelength of the light beam. At resonance, the light beam is transferred from W3 to W4 by the ring resonator and exits through the output port C. In this case, the optical power at the output C is much higher than the optical power at the output S. Therefore, the power level at the outputs S and C can be considered as logic ‘0’ and logic ‘1’, respectively.

### 3 | SIMULATION AND RESULTS

The electric field distributions inside the structure for different input states using two-dimensional FDTD simulation are shown in Figure 3. The normalized optical power at the output ports as a function of time for different input states is depicted in Figure 4. The optical intensity of the input beams is $P_{in} = 0.5kW/μm^2$. To

| Input a | Input B | Output S (Logic state) | Output C (Logic state) |
|---------|---------|------------------------|------------------------|
| 0       | 0       | 0 (0)                  | 0 (0)                  |
| 0       | 1       | 0.73 (1)               | 0.045 (0)              |
| 1       | 0       | 0.73 (1)               | 0.045 (0)              |
| 1       | 1       | 0.03 (0)               | 1.01 (1)               |

**Figure 4** Normalized output powers for (a) $A = 0, B = 1$ and $A = 1, B = 0$, (b) $A = 1, B = 1$

**Figure 5** Normalized output power versus $r_1$ for (a) $A = 0, B = 1$ and $A = 1, B = 0$, (b) $A = 1, B = 1$
tune the resonant wavelength of the ring resonator, the radius of
the rods in the last inner ring is set to \( r_1 = 97 \) nm. ON and OFF
input signals are defined as logic ‘1’ and logic ‘0’, respectively.
When both inputs are ‘0’, the optical power at the output ports is
zero, so \( \text{Sum} \) and \( \text{Carry} \) are ‘0’. As shown in Figure 4a, when one
input is ‘1’ and the other input is ‘0’, the incident beam continues
its propagation along W3 to the end of the waveguide and exits
through the output port S. In this case, the stable value of the
normalized optical power at the output port S is 0.03, which
is defined as logic ‘1’, and the stable value of the normalized optical
power at the output port C is 0.73, which is defined as logic ‘0’.
Therefore, \( \text{Sum} \) is ‘1’ and \( \text{Carry} \) is ‘0’. The time delay in this case
is about 1 ps. As shown in Figure 4b, when both inputs are ‘1’, the
light beam is transferred from W3 to W4 through the ring
resonator and reaches the output port C. In this case, the stable
value of the normalized optical power at the output port C is 0.045, which corresponds to logic ‘0’, and the stable value of the
normalized optical power at the output port C is 1.01, which
corresponds to logic ‘1’. Therefore, \( \text{Sum} \) is ‘0’ and \( \text{Carry} \) is ‘1’.
The maximum time delay in this case is about 2 ps.

The simulation results for all input states are summarized in Table 2. As can be seen in Table 2, when two inputs are at
different logic states, the output S is at high level and the
output C is at low level. On the other hand, when both inputs
are at high level, the output S is at low level and the output C is
at high level. Thus, the simulation results demonstrate that the
operation of the proposed structure at a wavelength of
1550 nm corresponds to the half adder operation. The contrast
ratio between the high and low logic levels is calculated using
\( CR = 10 \log(P_1/P_0) \), where \( P_1 \) is the optical power of logic ‘1’
and \( P_0 \) is the optical power of logic ‘0’ at the output ports.
From the simulation results in Table 2, the achieved contrast
ratio between logic levels at the output ports for \( \text{Sum} \) and
\( \text{Carry} \) is 13.86 dB and 13.51 dB, respectively.

To investigate the effect of small variations in \( r_1 \) on the
device performance, the simulation has been carried out with a
very small step value for \( r_1 \). The results of this simulation are
plotted in Figure 5. The plots display the variations of the
normalized output power as a function of \( r_1 \) for small
variations around 97 nm. Figure 5 shows that the proposed
structure operates as a half adder at \( r_1 = 97 \) nm with a
tolerance of about 1 nm.

The comparison between the proposed structure and
existing photonic crystal-based half adders, in terms of the
operating wavelength, contrast ratio, transient time, and
structure size is presented in Table 3. As can be seen in Table
3, the contrast ratio of the proposed half adder has been
improved compared to previous works, while the structure size
is smaller than most of them.

### Table 3: Comparison of the proposed structure with previous works

| Operating wavelength (nm) | Contrast ratio (dB) | Transient time (ps) | Structure size (μm²) |
|---------------------------|--------------------|---------------------|---------------------|
| Karkhanenchi et al. [19]  | 1550               | 3                   | -                   |
| Ghadrdan and Mansouri-Birjandi [20] | 1550     | 5.6                 | -                   |
| Sonth et al. [21]        | 1550               | ≤11.6               | -                   |
| Jiang et al. [22]        | 1863               | 8                   | -                   |
| Neisy et al. [23]        | 1551               | 11.5                | 3                   |
| Abdollahi and Parandin [37] | 1550         | 8                   | ≥1                  |
| Parandin and Malmir [38] | 1553               | 4.9                 | ≥1                  |
| This work                | 1550               | 13.5                | 2                   |

4 | CONCLUSIONS

An all-optical half adder has been proposed based on two-
dimensional photonic crystals. The proposed structure is
composed of a triangular lattice of non-linear dielectric rods in
air. The structure consists of four waveguides and one ring
resonator, which guide light from the input ports to the output
ports, depending on the light intensity entering the structure.
The simulation results demonstrate that the structure can work
as a half adder at a wavelength of 1550 nm. The proposed
structure has an improved contrast ratio of 13.86 dB and
13.51 dB between logic levels at the output ports in the steady
state, and it has a maximum time delay of 2 ps. In addition to
improved contrast ratio, the proposed structure has a very
stable output in the steady state, which helps to eliminate
detection errors at the output ports. The structure is compact
with dimensions of 17 × 14.8 μm. The input and output ports
of the structure are conveniently located on the left and right
sides, which will increase its integration capability. Further-
more, all dielectric rods in the proposed structure are made of
the same material and are located at their original position
throughout the structure, making it easier to fabricate with less
fabrication errors.

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