ISSN 2063-5346

ANALYSIS OF PHOTONIC CRYSTAL BASED ALL-OPTICAL 4-PORT DIRECTIONAL COUPLER DESIGN USING FDTD METHOD

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Article History: Received: 12.05.2023 **Revised:** 25.05.2023 **Accepted:** 05.06.2023

Abstract

The ever-growing demand for larger integration density, higher bandwidth, and lower power consumption in conventional electronic technology has made photonics one of the key drivers in global data communications. The success and ongoing trend of nanophotonic anticipate a photonic roadmap leading to ultra-compact, broad bandwidth, high-speed optoelectronic devices. However, there is a severe deadlock imposed on the miniaturization of nanophotonic devices as long as conventional propagating light is used. This view dramatically changed due to the emerging field of nonlinear photonic crystals. To meet these purposes all optical 4-port Directional Coupler is a potentially important components for future optical integrated circuits. This project proposes the design of a Directional Coupler where the propagation of the electromagnetic wave is simulated at the wavelength of 1.55 µm in dielectric material Silicon of refractive index 3.4757 with the hexagonal lattice of the lattice constant of 0.750 µm in 2D photonic crystal using Finite Difference Time Domain (FDTD) method. The Photonic Bandgap (PBG) of the material can be observed using Plane Wave Expansion (PWE) method and a photonic bandgaps width of 0.148 GHz and 0.152 GHz at a normalized frequency of 0.379 GHz, 0.653 GHz respectively was obtained which leads to an opportunity for a number of applications that can be used in ultrafast optical circuits and future optical networks.

Keywords: Optical Computing, Photonic Crystal, Photonic Integrated Circuits, all-optical directional coupler, FDTD, PWE, Bandgap.

I. INTRODUCTION

Recently, digital computing suffers from limited bandwidth and lower speed when the number of users increases. By 2020, the demand for digital communication bandwidth is predicted to greatly exceed all existing technology. High-speed transmission, minimized energy losses, and parallel processing capability can be achieved, if you have used photons instead electrons as carriers. So finally optical computing coming into the picture. Optoelectronic devices require optical-electronic-optical conversion. To avoid speed limitations, all-optical processing solutions are the next step. But there exists a problem of enormous size in all optical conventional devices. So, the next step of nanophotonics arises. Microstructure photonic crystals serve as a platform on which to build devices in the order of wavelengths of light for future photonic integrated circuits. By creating point defects in the photonic crystal, a triangular lattice-based directional coupler was developed for all-optical switching [1]. A ring resonator based on a four-port wavelength demultiplexer was proposed by Saraniya [2]. By varying the index differences along each port various wavelengths can be obtained for tuning the device. Photonic crystal-based directional couplers are used as a platform to realize various optical devices such as wavelength selective devices, ring resonators, and wavelength demultiplexers [2-4]. All optical switches [5-8] and all-optical Logic Gates [9-11] can be implemented using directional couplers. It was suggested and shown that directional couplers could switch at short switching lengths while maintaining a wide bandwidth [12]. Ring resonator based two dimensional photonic crystals effectively designed and demonstrated all optical half adder circuits [13, 14] and optical combined half adder/subtractor [15].

Here, in this paper, we proposed a new hexagonal lattice based 4-port directional coupler by introducing line defect in the photonic crystal. There is no mode overlapping and interference in the proposed design because of hexagonal lattices and defects. By removing the row of dielectric rods we can overcome the time delay and fabrication complexity. Finally, the simulation is performed at the wavelength of 1.55 μm and a normalized frequency of 0.4839 GHz is obtained which is very suitable for a number of applications. The bandgap structure was determined through the utilisation of the plane wave expansion (PWE) technique.

II. DEVICE CONCEPT

The schematic diagram of a 4-port directional coupler is shown in Figure 1. It shows that a directional coupler is a passive device that acts as a building block of all-optical combinational circuits. The directional coupler can be configured by combining two linear waveguides in close proximity at the center portion of a certain length in terms of wavelength (λ). In this proposed work, we have considered 4 port directional couplers. Port 1 is considered as the input port, port 2 is the received port. Most of the output is received at this port. Port 3 is the reverse side port. No signal should be present due to reflection. In port 4, forward power can be measured.

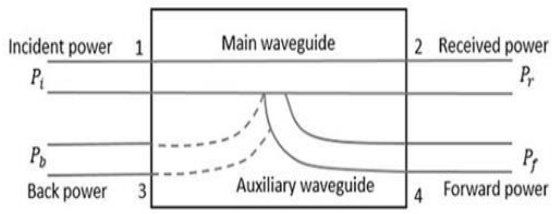

Figure 1. Schematic diagram of a 4-port directional coupler

Compared with the power at the received power port, the power at the forward power port is less. The directional coupler was constructed using dielectric rod type photonic crystal in a hexagonal lattice structure. It consists of two linear waveguides made by creating a line of defects by removing two rows of atoms. When these waveguides are parallel because of the interaction of electromagnetic fields power can be coupled between the waveguides. Here, the phenomenon involved is the Kerr effect. In the directional coupler, any port can be the input.

A linear combination of symmetric and anti-symmetric modes was exited during the power incident at one waveguide. The excitation may be of constructing the modes in one waveguide and destructing the modes in other waveguides. A phase difference was introduced in the system due to the inequality in the propagation constants. The modal addition is present in the second waveguide and deletion is present in the first waveguide, when the total phase difference is π. Further signal propagation in the resulting length of the waveguide is happen when the phase difference is 2π, which leads to power transfer back to the first waveguide. Hence, the power coupling between the two waveguides will happen periodically.

III. DESIGN METHODOLOGY

In the proposed directional coupler structure, the lattice arrangement is hexagonal with a lattice constant of 0.750 µm. It consists of rods with silicon, a high refractive index of 3.4757, and radii of 0.2 µm embedded in a background material with a low refractive index of 1 (air).

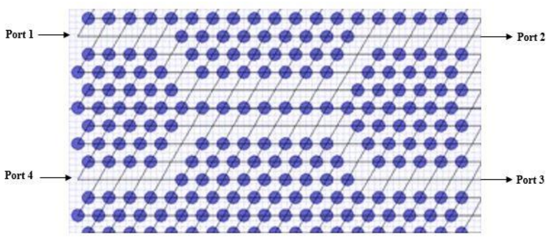

Figure 2. Design Layout of the proposed directional coupler

The directional coupler is made by removing a row of rods entirely as shown in Figure 2. So, there is no frequency overlap between the waveguides. This is an improvement over previously reported similar structures.

The bandgap structure of the same can be observed by using the plane wave expansion method which is depicted in Figure 3. This structure has two photonic bandgap in TE mode within the normalized frequency range of 0.379 GHz, 0.653 GHz respectively.

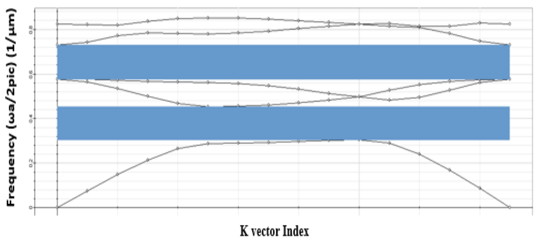

Figure 3. Bandgap structure

The frequency ranges are from 0.304484 to 0.45267 & 0.577229 to 0.729649 and the corresponding wavelength are from 3284 nm to 2209 nm & 1732 nm to 1371 nm. Between these two wavelength ranges, the low loss telecommunication wavelength 1550 nm was lies in the second bandgap range could be consider for proposed directional coupler design. The point source is the radiation source. The wave radiated from the point source propagates through the directional coupler and the responses is observed at the observation points at port 1, port 2, port 3, and port 4.

IV. RESULTS AND DISCUSSION

The 2D Finite Difference Time Domain (FDTD) approach is utilized for the simulation in order to gain an understanding of how the suggested architecture functions. The input was given at both port 1 as depicted in Figure 4 and observations were made at all four ports of the directional coupler. The input amplitude of 0.12 (a.u) was given at input port 1 and the received signal amplitude at port 2 is 0.048 (a.u) and the forward signal amplitude at port 3 is 0.052 (a.u), there will be a 0.02 (a.u) present at port 4. Similarly, The input amplitude of 0.12 (a.u) was given at input port 2 and observations were made at all the four ports as depicted in Figure 5. The time domain representation of all the four ports responses were depicted in Figure (6-9).

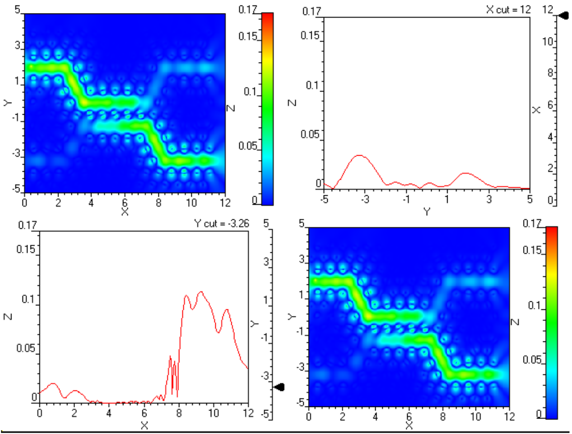

Figure 4. Directional coupler output for input at port 1

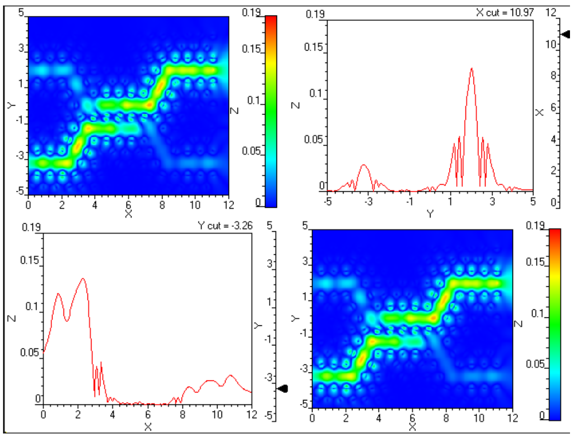

Figure 5. Output of directional coupler for input at port 2

In this proposed design of directional coupler, received power and forward power was partial present at port 3 & 4 and very less propagation was present at port 4. Figure 6 shows the incident power in the time domain at port 1 having the peak to peak amplitude of 0.12 (a.u) to -0.12 (a.u), and Figure 7 shows the received power in the time domain at port 2. The frequency DFT of all the four ports powers were depicted in Figure 9.

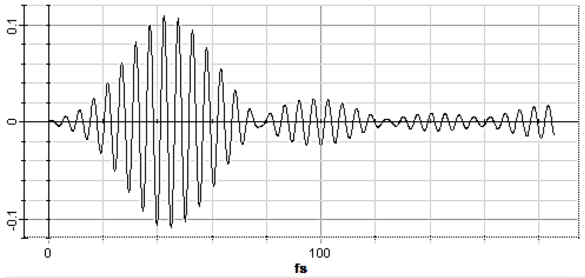

Figure 6. Incident power at port 1

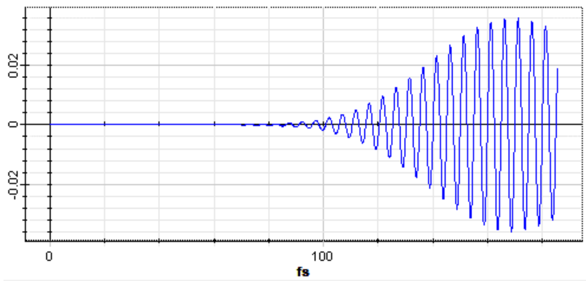

Figure 7. Received power at Port 2

Figure 8 shows the forward power in the time domain at port 3, and the reflected power which is very less as shown in figure 8. The response time of the proposed directional coupler is 100fs.

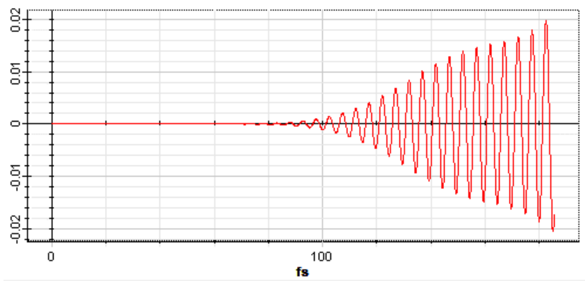

Figure 8. Forward power at port 3

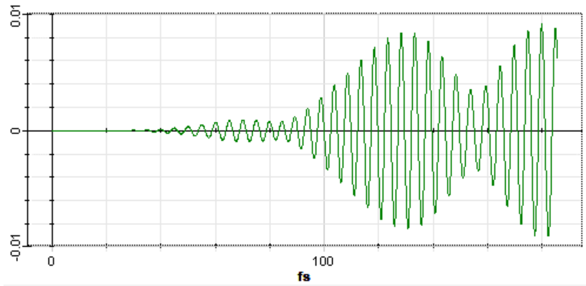

Figure 9. Backward power at port 4

The theoretical concepts of the 4 port bidirectional directional coupler were achieved effectively. The normalized frequency calculations were made both theoretically and practically depicted through Equations (1-5). The photonic bandgaps were calculated using the equations (6-7).

A. Calculation of normalized frequency

1) *Theoretical calculation*

Normalized frequency,

$$f_n = \frac{\omega a}{2\pi c} = \frac{a}{\lambda} \qquad (1)$$

Where, a= lattice constant, c= velocity of light in meter/sec, ω= angular frequency in Hz.

$$f_n = \frac{0.750\ \mu m}{1.55\ \mu m}$$

$$f_n = 0.484\ GHz \qquad (2)$$

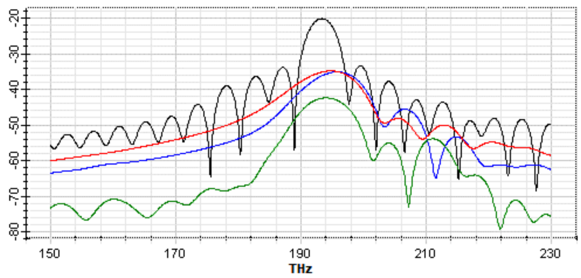

Figure 9. Frequency DFT in dB

2) *Experimental calculation*

The two Bandgaps are obtained using PWE method of simulation. The observed bandgaps are 0.304484 GHz to 0.45267 GHz and 304484 GHz 0.45267 GHz. The normalized frequency of the corresponding bandgaps are calculated based on the PWE methods are as follows.

So the normalized frequency f_{n1} & f_{n2} are,

$$f_{n1} = \frac{(0.304484\ + 0.45267)}{2}\ GHz$$

$$f_{n1} = 0.379\ GHz \qquad (3)$$

$$f_{n2} = \frac{(0.577229 + 0.729649)}{2}\ GHz$$

$$f_{n2} = 0.653\ GHz \qquad (4)$$

The average normalized frequency is,

$$f_n = 0.516\ GHz \qquad (5)$$

The Photonic Bandgap width PBG_1 is,

$$PBG_1 = (0.45267 - 0.304484\ )\ GHz$$

$$PBG_1 = 0.148 \qquad (6)$$

The Photonic Bandgap width PBG_2 is,

$$PBG_2 = (0.729649 - 0.577229)\ GHz$$

$$PBG_2 = 0.152 \qquad (7)$$

Among these two bandgaps the second gap lies between 0.577229 and 0.729649 was consider for the design of the proposed directional coupler.

V. CONCLUSION AND FUTURE SCOPE

To overcome the limitations of conventional digital computing, nanophotonic computing is performed through ultrafast optical components such as a directional coupler using nonlinear 2D Photonic Crystal (NPC). The optical directional coupler is designed by the dielectric rod type method with hexagonal lattices. The light wave propagation was observed using the FDTD method and the bandgap structures were analyzed using the Plane Wave Expansion (PWE) method. The performance of the photonic crystal based directional coupler was observed in terms of transmission and reflection. Due to the miniaturized design of the nanostructured bidirectional directional coupler, it will be used as a basic block of all-optical logic gates, all-optical combinational and all-optical sequential circuit designs.

Hence, the proposed optical component is very useful for ultrafast optical operations and future photonic integrated circuits. By using the proposed directional coupler optical switching can be performed and a number of applications can be developed for optical networks which are kept for future work.

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