Design And Development of A 6-Port Optical Circulator Using Silicon Photonic Crystals

Divya Vani

VIT University

Pooja Gupta

VIT University

Sangeetha Anandan

VIT University

Prabu Krishnan (✉ nitprabu@gmail.com)

National Institute of Technology Karnataka <https://orcid.org/0000-0001-9730-7997>

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Abstract

A 6-port optical circulator using silicon photonic crystals has been designed and proposed in this paper as an essential component of an optical communication system. The proposed 6-port circulator has greater isolation loss values between the input and isolated ports and lower insertion loss values between the input and output ports. The proposed circulator achieves maximum isolation of -38.7 dB and minimum insertion loss of 0.0029dB. The proposed designs are extremely useful in the telecommunications industry, wavelength division multiplexing and photonic integrated circuits applications due to their low insertion and high isolation losses.

Introduction

The circulator, which isolates the input and output signals and thus protects the source signal from unwanted reflections, is widely used in modern radar and microwave multiplex communication systems. Optical circulators based on photonic crystals have received a lot of attention over the last decade due to their compactness and suitability for photonic integrated circuits. A multi-port optical circulator (3 port, 4 port or more) is a non-reciprocal passive component. An optical circulator directs light wave from one port to another with maximum intensity while blocking other light transmissions from other ports to the output port [1–3]. Light input at input port is transmitted out to through the other ports without much changing the characteristics of the input light signal [4, 5]. Since 1990, optical circulators have played an important role in advanced optical communication systems, particularly advanced wavelength division multiplexing systems. Optical circulators have found use not only in the telecommunications industry, but also in medical and imaging applications [6]. They are used in optical add-drop multiplexing (OADM), where they are made to behave as couplers and are used as primary filters by using fibre Bragg grating. They are also used in optical amplifiers, which amplify light beams without converting them to electrical form [7].

Optical circulators are used to route signals in optical sensors that measure stress, strain, temperature, and pressure. Because of the high isolation between input and reflected power, as well as the low insertion loss, optical circulators are an excellent choice [8]. Photonic crystals are periodic optic nanostructures that manipulate photons when they are illuminated [11]. Photonic crystals can be one-dimensional, two-dimensional, or three-dimensional. In the crystals, a photonic bandgap is formed, and electromagnetic wave propagation is forbidden for all wave vectors [12–14]. Several authors predicted and demonstrated improved Faraday rotation in photonic crystals with defects [N1-N3]. The following is how the improvement works: A periodic thin film stack with at least one magnetic component material receives linear polarised light. The stack, as a periodic system, has a photonic band gap through which light cannot flow. A transmission resonance in the band gap associated with a trapped state is created when there is a defect in the periodicity. Light near a resonance is mostly transmitted, but magnetic circular birefringence acts across a significantly longer optical path length than typical. As a result, the two equally excited circularly polarised modes are transmitted with a high phase difference, resulting in a significant Faraday rotation [N4].

To realise the tunability of the propagation channel, a hexagonal six-port circulator based on six photonic crystal defects-based waveguide junctions was designed in this work. A hexagon six-port circulator is formed by connecting six waveguide junctions. Due to the external magnetic field, the incident wave's propagation direction can be changed in the circulator. Reflection phase shifters, reflection amplifiers, add-drop multiplexers, diagnostic or detection systems, polarizers and optical band pass filters are all possible applications for the proposed circulator. OptiFDTD software was used to implement 6-port optical circulator designs based on silicon photonic crystals. The goal is to achieve higher isolation loss values between the input and isolated ports while lowering insertion loss values between the input and output ports [9, 10].

Principle Of An Optical Circulator

A periodicity structure is a photonic crystal. An external magnetic field can be used to adjust the photonic band gap in a specific frequency range. Waveguides are often made using linear defects in photonic crystals to modify a row of conventional photonic crystal elements. There are two main features to achieve optimal operation in integrated optical applications: having an operative single mode in a specific frequency interval and propagating mode inside the photonic band gap to prevent irradiation loss. To obtain a primary design, the procedure is to use a frequency domain solver. Finally, an FDTD code is used to create the final design. When a light beam is incident upon port 1, as shown in Fig. 1, it circulates the input signal to the next adjacent output port 2. This circulator is designed to realize the nonreciprocal propagation among the six ports, denoted by $P1 \rightarrow P2$, $P2 \rightarrow P3$, $P3 \rightarrow P4$, $P4 \rightarrow P5$, $P5 \rightarrow P6$ and $P6 \rightarrow P1$.

Design And Implementation

Figure 2 depicts the proposed layouts for 6-port optical circulator. Table 1 shows the optimised parameters for the proposed circulator structure. The design is made up of photonic crystals. OptiFDTD simulation software is used to model the simulation setup. The simulation was carried out in TE Mode [17–19]. The structure has been designed for a wavelength of 1900 nm. The small elliptical crystals are photonic crystals, whereas the large elliptical crystals are defects that interfere with light propagation. These defects prevent light from propagating in a specific direction [20, 21, 7]. There are two kinds of defects: Spot Defects are caused by a single defective photonic crystal placed along the port. Line Defects are caused by lining the port with multiple defective photonic crystals. This layout makes use of linear defects [22, 23]. Figures 3 and 4 show the 2D and 3D design layouts of the proposed 6-port optical circulator when input is applied to each port 1 to 6.

Table 1
Optical circulator design parameters and
its values

Design Parameters	Values
Crystal Lattice Structure	17X19
Substrate Material	Silicon
Refractive Index	3.1
Radius of photonic crystals	0.3um
Major radius of defects	0.5um
Minor Radius of defects	0.4um
Relative permeability	8.9
Wavelength	1900nm

Results And Discussions

The simulation was carried out with the help of the optiFDTD analyser software. When these structures were simulated, power output through each port was achieved by changing the input Port. Power is transmitted from port 1 to port 2, port 2 to port 3, and port 3 to port 1 in a three-port circulator [24]. As a result, an optical circulator is circular and non-reciprocal [25]. 4-Port and 6-Port Circulators exhibit similar circular behaviour [8, 26, 27]. The obtained power was plotted for the input, output, and isolated ports. The obtained power was used to calculate the insertion and isolation losses for each case.

$$Insertion\ loss = 10\log\left(\frac{P_{out}}{P_{in}}\right) \quad (1)$$

$$Insertion\ loss = 10\log\left(\frac{P_{isolated}}{P_{in}}\right) \quad (2)$$

The electric field distribution analysis of the proposed 6-port optical circulator structure is shown in Fig. 5 for clockwise mode at 1900 nm wavelength. Figure 5a depicts the post-simulation view of a 6-Port Optical Circulator with port 1 as the input. Port 2 provides access to the output. Because port 3, port 4, port 5, and port 6 are all blocked, there is no transmission through those ports. When the input is at port 2, Fig. 5b shows the post-simulation view of a 6-Port Optical Circulator. Port 3 provides access to the output. Because port 1, port 4, port 5, and port 6 are all blocked, there is no transmission via port 1, port 4, port 5, or port 6.

Similarly, when the input is given to ports 3, 4, 5, and 6, the light signal is transmitted to the next adjacent ports, while the other ports are isolated, as illustrated in Figs. 5c to 5f. When input is applied to each port 1 to 6, the minimum insertion and maximum isolation losses at the output ports are 0.22 dB, 0.21 dB,

0.29 dB, 0.26 dB, 0.0029 dB, 0.29 dB and – 33.8 dB, -28.5 dB, -27.4 dB, -26 dB, -38.7 dB, -28.8 dB, respectively.

Figure 6 shows the transmission and isolation power spectrum of a 6-Port Optical Circulator with input applied to each port 1–6. When a signal is applied to port 1, the measured input and output power spectrum of all six ports is shown in Fig. 6a. According to Fig. 6a, the input and output power are at their highest (Ports 1 and 2), while the isolated port power is at its lowest (ports 3, 4, 5 and 6). At ports 1 and 2, the measured input and output powers are 0.0194 mW and 0.0184 mW, respectively. Similarly, when the input is applied to ports 2, 3, 4, 5, and 6, the corresponding power spectrum is illustrated in Figs. 6b–6f, and the measured power values are shown in Table 2.

Table 2 shows the Isolation and Insertion Losses of various Ports for the proposed 6-Port Circulator. The achieved insertion loss is 0.0029 dB, with a maximum isolation loss of -38.7 dB. The insertion loss rises from 0.0017 dB to 0.29 dB, while the isolation loss ranges from – 26dB to -38.7dB. The maximum transmission rate from input port to output port is 98.6 %.

Table 2
Isolation loss and Insertion Loss various Ports for 6-Port Circulator

Input Port	Output Port	Input Port Power (mW)	Output Port Power (mW)	Insertion loss (dB)	Isolation loss (dB)
Port 1	Port 2	0.0194	0.0184	0.22	-33.8
Port 2	Port 3	0.0144	0.0137	0.21	-28.5
Port 3	Port 4	0.0154	0.0144	0.29	-27.4
Port 4	Port 5	0.0135	0.0127	0.26	-26
Port 5	Port 6	0.0151	0.0149	0.0029	-38.7
Port 6	Port 1	0.0154	0.0142	0.29	-28.8

Conclusion

In this study, we designed a 6-port optical circulator out of Silicon and implemented it with the help of photonic crystals at $1.9\mu m$. The insertion loss and isolation loss values of a circulator decide its performance. The better the performance of the optical circulator, the greater the isolation loss and the lower the insertion loss [28]. This paper achieves lower insertion loss and higher isolation loss levels than [8], which achieves a minimum insertion loss of 0.017 dB and a maximum isolation loss of -32.7 dB. The greater the number of ports used, the greater the efficiency, as this structure provides lower insertion loss and higher isolation loss values than 3-port and 4-port optical circulators. It should also be noted that silicon-based photonic crystals can be an excellent material for the construction of optical circulators.

Declarations

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Figures

Figure 1

Internal Structure of an Optical Circulator

(a)

(b)

Figure 2

Layout of 6-Port Optical Circulator a) 2D diagram b) 3D diagram

(a)

(b)

(c)

(d)

(e)

(f)

Figure 3

Layout of 6-Port Optical Circulator 2-D diagram input at a) Port 1 b) Port 2 c) Port 3 d) Port 4 e) Port 5 f) Port 6

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4

Layout of 6-Port Optical Circulator 3-D diagram input at a) Port 1 b) Port 2 c) Port 3 d) Port 4 e) Port 5 f) Port 6

(a)

(b)

(c)

(d)

(e)

(f)

Figure 5

Electric field distribution of 6 port when input is a) Port 1 b) Port 2 c) Port 3 d) Port 4 e) Port 5 f) Port 6

(a)

(b)

(c)

(d)

(e)

(f)

Figure 6

Transmission and Isolation power spectrum of 6-Port Optical Circulator when input at a) Port 1 b) Port 2 c) Port 3 d) Port 4 e) Port 5 f) Port 6