Feng Chia University
Outstanding Academic Paper by Students

Title：Design of optical circulators with a small-aperture Faraday rotator by applying two pairs of confocal cylindrical lenses

Author(s): Yung Hsu

Class: 2nd year of Department of Photonics

Student ID: M0100579

Course: Master Thesis

Instructor: Dr. Jing-Heng Chen

Department: Department of Photonics

Academic Year: Semester 2, 2013-2014

Abstract

This letter proposes a new and low-cost design of four-port optical circulator. By introduction of two pairs of confocal cylindrical lenses, a small size Faraday rotator is required. To show the feasibility of the design, a prototype of four-port optical circulator was fabricated. The insertion losses are 0.69 dB, the isolations are 23.04–29.65 dB, and return losses are 27.72 dB. This design should bear merits of a simple and symmetric structure that is low cost, easily fabricated, polarization-independent, and polarization-mode dispersion resolved, and exhibits high performance.

Keyword： Confocal cylindrical lenses, Faraday rotator, optical circulator, polarization.

CONTENT

1. Introduction

Optical circulators are important nonreciprocal devices that can direct a light from one port to another in only one direction. They are essential components in the construction of fundamental network modules, such as optical add-drop multiplexers, dispersion-compensation, optical amplifiers, and time-domain reflectometry [1-7]. Consequently, the introduction of new device can provide new network solutions for improving the system performance, stability, and reliability, and can significantly reduce the network build cost. In general, an optical circulator is consisted of three main elements including Faraday rotator, half-wave plate, and spatial walk-off polarizer. Faraday rotator and half-wave plate are utilized for breaking the time-reversal symmetry. These elements combine with spatial walk-polarizers and different prisms to compose an optical circulator. Because Faraday rotator are made of powerful magnet ring and magneto-optical glass, and conventional spatial walk-off polarizer is essentially birefringent crystal. These materials all contain rare earth. Consequently, their costs directly depend on size, and are expensive. In order to reduce the cost of a device, some strategies had been proposed by using polarizing beam splitter cube or holographic spatial walk-off polarizer as spatial walk-off polarizer [8-9]. However, limited by the size demand of Faraday rotator window, the price is still hard to be reduced.

Accordingly, in this letter, a new low-cost design of four-port optical circulator is proposed. By introduction of two pairs of confocal cylindrical lenses, only a relative small Faraday rotator window is required. Therefore, the device cost can be significantly reduced. In order to show the feasibility of the design, a prototype of four-port optical circulator was assembled. Its characteristic parameters are tested and discussed. This design should bear merits of a simple and symmetric structure that is low cost, easily fabricated, polarization-independent, and polarization-mode dispersion (PMD) resolved, and exhibits high performance.

2. Principles

The structure and operation principle for the proposed four-port optical circulator are shown in Figs. 1 and 2. As shown in figure 1, the four-port device is constructed of a 45° Faraday rotator (FR), a 45° half wave-plate (H), two pairs of confocal cylindrical lenses (CLs), two polarizing beam splitter cubes (PBSs), and two reflection prisms (RPs). Due to the introduction of the pairs of confocal cylindrical lenses, small windows of Faraday rotator and half wave-plate are required.

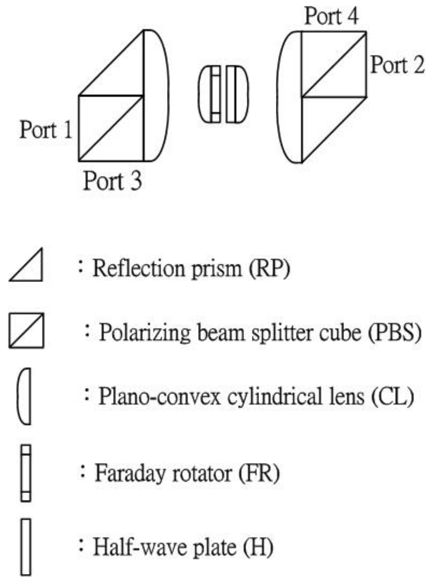

Fig. 1. Structure and composition of a four-port optical circulator.

For easy understanding, an *x*-*z* coordinate system is introduced. Symbol ⊕ represents unpolarized light and symbols ⊖ and ⦶ respectively represent *p*- and *s*-polarized lights. As shown in figure 2(a), when an unpolarized light from port 1 is incident into the left PBS in +*z* direction, the *p*- polarized light transmits the PBS directly; the *s*-polarized light is reflected by the PBS and by the first RP, respectively. These two orthogonally polarized lights are separated a distance *D* then pass through the first pair of confocal cylindrical lenses, the 45° FR and the 45° H. Therefore, their separated distance *D* concentrates to *d*, and their states of polarization (SOPs) are rotated 90° in total. Continuing their journey, they pass through the second pair of confocal cylindrical lenses, respectively enter the second pair of RP and PBS and are recombined. Finally, the transmitted unpolarized light enters port 2. In Fig. 2(b), when an unpolarized light from port 2 is incident into the second PBS in −*z* direction, the *p*-polarized light transmits the PBS directly; the *s*-polarized light is reflected by the PBS and by the RP, respectively. These two orthogonally polarized lights then sequentially pass through the second pair of confocal cylindrical lenses, the 45° H and the 45° FR. Their separated distance concentrates from *D* to *d*; their SOPs are rotated −45° by the H and +45° by the FR. Because Faraday rotator is a nonreciprocal element, their SOPs are rotated 0° in total. Therefore, the transmitted *s*- and *p*-polarized lights pass through the first pair of confocal cylindrical lenses. With the similar principle described, they finally join together by the first pair of PBS and RP and enter port 3. Again, based on the same principle, the routes of port 3→port 4 and port 4→port 1 are respectively shown in Figs. 2(c) and 2(d). Accordingly, a low-cost four-port optical circulator with a small size Faraday rotator can be obtained.

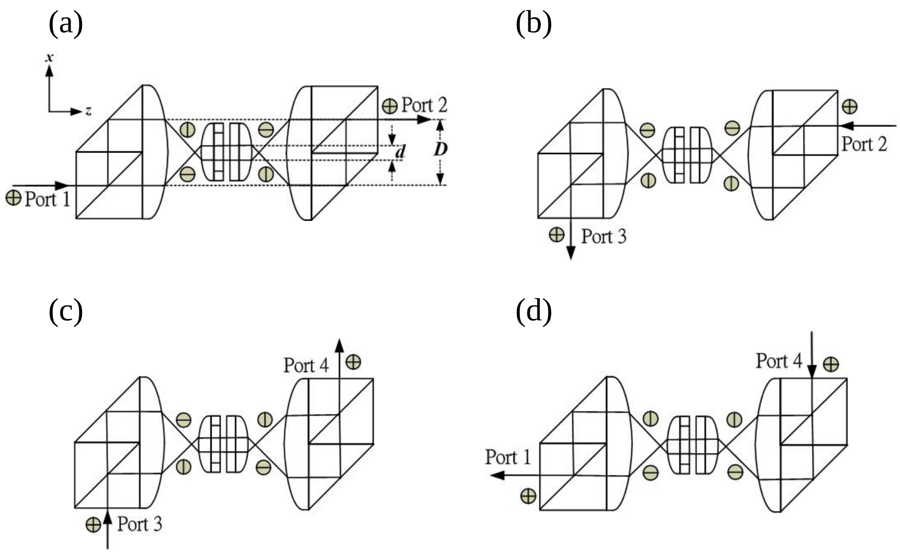

Fig. 2. Structure and operation principle of a four-port optical circulator for routes of (a) port 1→port 2, (b) port 2 →port 3, (c) port 3→port 4, and (d) port 4→port 1.

3. Experimental Results and Discussions

In order to show the feasibility of the proposed design, a prototype of four-port optical circulator was assembled with one Faraday rotator (4R650, Electro-Optics Technology), one quartz half wave-plate (WPH05M-633, THORLABS), two pairs of BK7 confocal cylindrical lenses (LJ1960L1-A and LJ1310L1-A, THORLABS), two BK7 polarizing beam splitter cubes, and two BK7 reflection prisms. The dimensions of the device, including all the elements, are 132×30×30 mm. He-Ne laser with a wavelength of 632.8 nm was used as test light source. As listed in Table I, the insertion losses are 0.69 dB, the isolations are 23.04–29.65 dB, and return losses are 27.72 dB. These results successfully demonstrate the function of the device.

Because the introduction of two pairs of confocal cylindrical lenses, a small window Faraday rotator is required. The dimensions of PBS and RP are 5×5×5 mm; the focal lengths of the cylindrical lenses are separately 20 and 4 mm. Consequently, the distance *D* and *d* are 5 and 1 mm, respectively. The actually window size (diameter) of the Faraday rotator is 4 mm which is sufficient for the demand of 1 mm. Therefore, the cost of the device could be reduced.

TABLE I

Associated losses and isolations (in Decibels)

Input	Output 1	2	3	4
1	27.72[a]	0.69[b]	29.65	23.04
2	24.05	27.72[a]	0.69[b]	28.10
3	29.50	24.56	27.72[a]	0.69[b]
4	0.69[b]	28.96	24.40	27.72[a]

[a]Return losses; [b]Insertion losses, [c]All values without a superscript are isolations

Furthermore, due to the symmetrical and regular structure, this device can be assembled easily and compactly. In Figs. 2(a)-2(d), for all the routes of port 1→port 2, port 2→port 3, port 3→port 4, and port 4→port 1, the orthogonally *s*- and *p*-polarized lights experience the same optical path length (OPL). Accordingly, the device is polarization-independent and the PMD problem can be resolved. When the device assembling tolerance is accurately controlled to be less than 20 μm, the PMD can be made lower than 0.1 ps. For easy alignment and measurement, He-Ne laser of 632.8 nm was applied as test light source. As a consequence, the operation wavelength can be designed at 830, 1300, or 1550 nm for optical communications.

4. Conclusions

A new low-cost design of four-port optical circulator was proposed. By introducing two pairs of confocal cylindrical lenses, a Faraday rotator with a small window is required. Due to the simple and symmetric structure, the design is polarization-independent and polarization mode dispersion resolved. To show the feasibility of the design, a prototype of four-port optical circulator was fabricated and tested. The design has advantages of low cost, compact, and high performance.

Acknowledgment

The authors would like to thank the National Science Council of the Republic of China, Taiwan for financially supporting this research under Contracts No. NSC101-2221-E-035-053 and No. NSC100-2632-E-035-001-MY3.

References

[1] D. K. Mynbaev, and L. L. Scheiner, *Fiber-optic communications technology.* New Jersey: Prentice Hall, 2001, ch. 6.

[2] Y. K. Chen, C. J. Hu, C. C. Lee, K. M. Feng, M. K. Lu, C. H. Chang, Y. K. Tu, and S. L. Tzeng, "Low-crosstalk and compact optical add-drop multiplexer using a multiport circulator and fiber Bragg gratings," *IEEE Photon. Technol. Lett.*, vol. 12, no. 10, pp. 1394–1396 (2000).

[3] A. V. Tran, C. J. Chae, and R. S. Tucker, "A bidirectional optical add-drop multiplexer with gain using multiport circulators, fiber Bragg gratings, and a single unidirectional optical amplifier," *IEEE Photon. Technol. Lett.*, vol. 15, no. 7, pp. 975–977 (2003).

[4] T. Komukai, Y. Miyajima, and M. Nakazawa, "An in-line optical bandpass filter with fiber gratings and an optical circulator and its application to pulse-compression," *Jpn. J. Appl. Phys.*, vol. 34, pp. L230–L232 (1995).

[5] H. Lin and C. H. Chang, "High power C+L-band Erbium ASE source using optical circulator with double-pass and bi-directional pumping configuration," *Opt. Express,* vol. 12, no. 25, pp. 6135–6140 (2004).

[6] M. Yamada, M. Shimizu, Y. Ohishi, J. Temmyo, T. Kanamori, and S. Sudo, "Highly efficient configuration of a pr3+-doped fluoride fiber amplifier module with an optical circulator," *IEEE Photon. Technol. Lett.*, vol. 5, no. 9, pp. 1011–1013 (1993).

[7] Y. Sato and K. Aoyama, "OTDR in optical transmission systems using Er-doped fiber amplifiers containing optical circulators," *IEEE Photon. Technol. Lett.*, vol. 3, no. 11, pp. 1001–1003 (1991).

[8] J. H. Chen, K. H. Chen, C. H. Yeh, and W. P. Huang, "Simplified Design of Multiport Optical Circulator with Parallel Connection of Mirror-image Arranged Spatial- and Polarization-modules," *IEEE Photon. Technol. Lett.,* vol. 23, no. 23, 1766–1768 (2011).

[9] J. H. Chen, P. J. Hsieh, D. C. Su, and J. C. Su, "Multi-port polarization-independent optical quasi-circulators by using a pair of holographic spatial- and polarization- modules," *Opt. Express*, vol. 12, no. 4, 601–608 (2004).