Multi-port polarization-independent optical quasi-circulators by using a pair of holographic spatial- and polarization- modules

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Abstract: In this paper we proposed an alternative type of multi-port polarization-independent optical quasi-circulator by using a pair of holographic spatial- and polarization- modules. The prototype is fabricated and experimentally tested. In addition, the operating principles, the characteristics and the performances of this device are discussed. The merits of this design include polarization-independence, compactness, high isolation, low polarization mode dispersion, and easy fabrication. Furthermore, the number of ports can be scaled up easily.

OCIS codes: 060.4510 (Optical communications); 090.2890 (Holographic optical elements); 260.5430 (Polarization).

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1. Introduction

Optical circulators [1-5] are important nonreciprocal devices that direct a light from one port to another sequentially in only one direction. Circulators are necessary components in the construction of fundamental network modules such as optical add/drop multiplexers [6, 7], dispersion-compensation [8], optical amplifiers [7], and time-domain reflectometry [9]. As the design of optical communication systems becomes more and more complex, a device with many input and output ports has become highly desirable. Several types of circulator design had been proposed [2-5] that use conventional birefringent crystals to manipulate the polarized components of incident light. However, the conventional birefringent crystals suffer from the challenge of high optical qualities, crystal manufacturing, and hard optical fabrications. So the cost may be too high. A volume holographic grating has special functions and high efficiency, so it is always used as an alternative element, especially in the category [10, 11] of optical communications. In our previous paper [2], we had proposed an holographic spatial walk-off polarizer (HSWP) to replace the crystal type spatial walk-off polarizer (SWP), and applied this HSWP in a design of 4-port polarization-independent optical circulator with good performance. In this paper, based on the similar consideration, we propose an alternative type of multi-port polarization-independent optical quasi-circulator by using a pair of holographic spatial- and polarization- modules (HSPMs), where the HSPM is composed of a pair of HSWPs, a 45° Faraday rotator (FR), and a 45° half-wave plate (H). This optical quasi-circulator consists of a pair of HSPMs, polarization-beam splitters (PBSs), and reflection prisms (RPs). To demonstrate the feasibility of the idea, the prototype of a 6-port polarization-independent optical quasi-circulator operating at a wavelength of 1300nm was assembled. In addition, the operating principles and the performance of this device are discussed in the following sections. This design has advantages of polarization-independence, compactness, high isolation, low polarization mode dispersion, and easy fabrication. Furthermore, the number of ports can be scaled up easily.

2. Principles

In our previous paper [2], our fabricated HSWP is essentially a transmission-type phase volume holographic grating fabricated on a substrate of which the structure and the operation principle are shown in Fig. 1. When an unpolarized light is normally incident at point A, the s-polarized component is transmitted straightly through the HSWP while the p- polarized component is totally diffracted toward B and totally reflected at point B. In this way, the diffracted light hits the grating again at point C. This light is again totally reflected at point C, and the reflected light from point C satisfies the Bragg condition [12] of the grating. The diffracted light at point C will be parallel to the input light at point A. Consequently, two orthogonally polarized parallel beams with a separation of length L can be obtained.

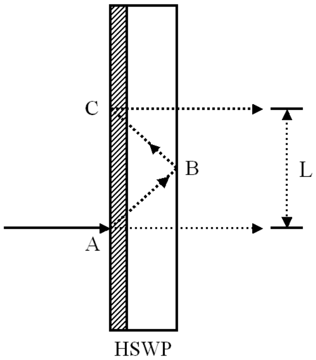

Fig. 1. Structure and operation principle of the holographic spatial walk-off polarizer.

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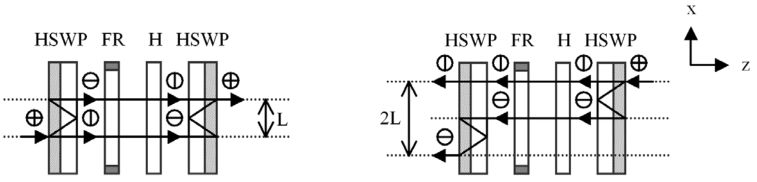
In this paper, we propose a new HSPM, which is composed of a pair of HSWPs, a 45° Faraday rotator, and a 45° half-wave plate. The operation characteristic of the HSPM is shown in Fig. 2. For easy understanding, a circle with a bisecting line is used to represent the associated states of polarization (SOP) of the light after propagating through each component. An orthogonal x-z coordinate system with an unit distance L is utilized to characterize the beam propagation direction and the associated spatial location. Symbols ⦶ and ⊖ represent the electric-field polarizations which lie in the planes perpendicular (s-polarization) and parallel (p-polarization) to the paper plane, respectively. The symbol ⊕ represents the light beam that has both s- and p- polarized components.



(a) (b)

Fig. 2. Structure and operation characteristics of the holographic spatial- and polarization-module.

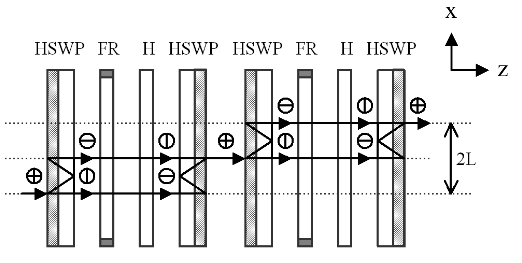
In Fig. 2(a), when an unpolarized light is incident along the +z direction on the HSPM, the s- component passes through the first HSWP directly. On the other hand, the p-component passes through this HSWP after two diffractions and two total-reflections. Next, these two orthogonally polarized components pass through FR and H. Their SOPs are rotated a total of 90°, +45° by FR and +45° by H. These two components finally enter the second HSWP and then recombine together at the output with the similar diffraction and total-reflection effects in the first HSWP. Therefore, the outgoing unpolarized light of this HSPM is shifted spatially with a distance L along +x direction. In Fig. 2(b), when an unpolarized light is incident along the -z direction on the HSPM, the s- component passes through the first HSWP directly and the p- component also passes through this HSWP after two diffractions and two total-reflections. Next, these two orthogonally polarized components pass through H and FR. Their SOPs are rotated a total of 0°, -45° by H and +45° by FR. Finally, the s-component passes through the second HSWP straightly; the p- component passes through the second HSWP after two diffractions and two total-reflections more. Therefore, the s-component is transmitted straightly of this HSPM while the p- component is shifted spatially with a distance 2L along -x direction and then transmitted.

Based on the same principles, we connect a pair of HSPMs sequentially, their operation characteristic is shown in Fig. 3(a) and (b). In Fig. 3(a), when an unpolarized light is incident along the +z direction on these HSPMs, the outgoing unpolarized light is shifted spatially with a distance 2L along +x direction and then transmitted. In Fig. 3(b), when an unpolarized light is incident along the -z direction on these HSPMs, the s- component is transmitted straightly while the p- component is shifted spatially with a distance 4L along the -x direction and then transmitted.

According to the previous described operation characteristics, the spatial positions of the input and output of the s- and p- polarized components of each channel are shown in Fig. 4, when a pair of series connected HSPMs is applied to the design of an optical quasi-circulator. In this figure, the numbers after the character s and p mean the port number, n is a positive integer; and the arrows indicate the propagation direction of the light. When an unpolarized light is shuttled between the two sides of the HSPMs, the s- and p- components are separated toward upside and downside gradually with a Z shape, respectively. For easy understanding, we assume that the thickness of HSPM is 4L and they are located in the range of z=L~5L and z=-L~-5L, respectively. The odd (2n-1) ports are at the –z region and the even (2n) ports are at the +z region. Therefore, the positions of the s- and p- components at a j-th port can be expressed as (x_{sj}, z_{sj}) and (x_{pj}, z_{pj}). Suppose the initial positions of the s- and p- components are at $x_{s1}=x_{p1}=0$, then the corresponding x- positions of each polarized components at the two sides of HSPMs can be expressed as

$$\begin{bmatrix} x_{s(2n-1)} \\ x_{p(2n-1)} \end{bmatrix} = \begin{bmatrix} 2(n-1)L \\ 2(1-n)L \end{bmatrix}, \quad \text{(for an odd port)} \tag{1}$$

$$\begin{bmatrix} x_{s(2n)} \\ x_{p(2n)} \end{bmatrix} = \begin{bmatrix} 2nL \\ 2(2-n)L \end{bmatrix}. \quad \text{(for an even port)} \tag{2}$$



(a) (b)

Fig. 3. Structure and operation characteristics of the series connected holographic spatial- and polarization- modules.

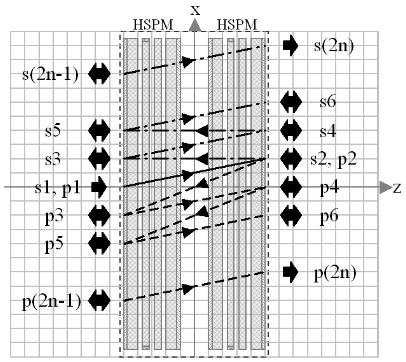


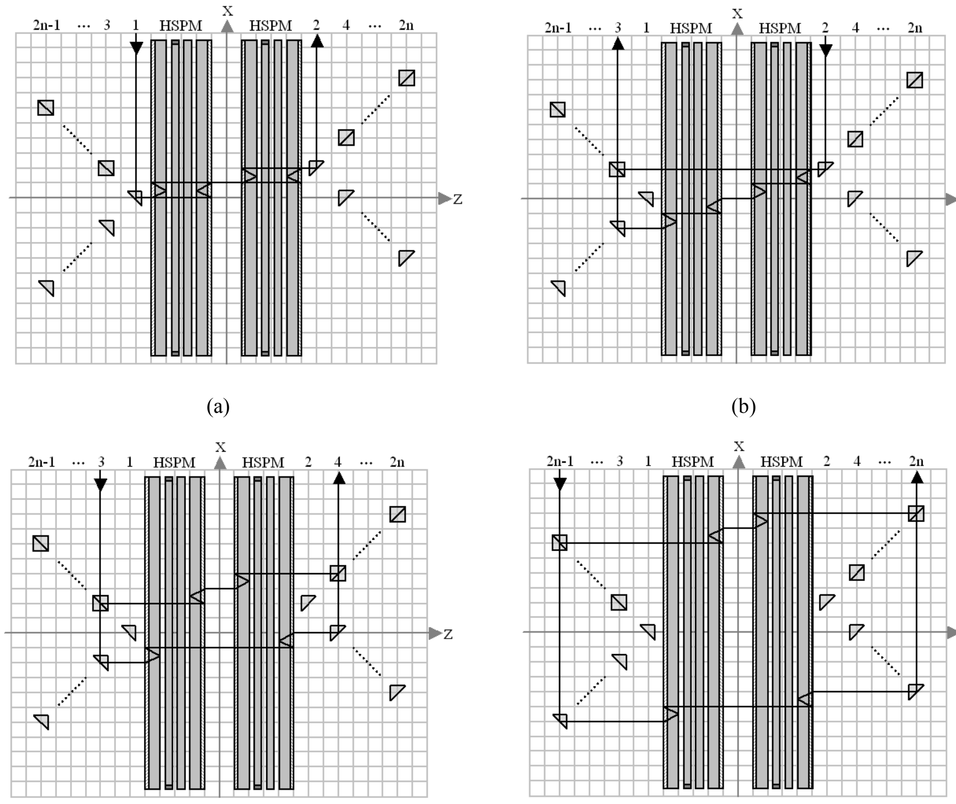
Fig. 4. Operation characteristics of the series connected holographic spatial- and polarization- modules when an unpolarized light is shuttled between its two sides.

It is obvious that if some polarization-beam splitters (PBSs), and reflection prisms (RPs) are introduced appropriately at the corresponding positions of the s- and p- components, we can obtain a multi-port optical quasi-circulator. Shown in Fig. 5 is an optical quasi-circulator with 2n-ports consisting of a pair of HSPMs, PBSs, and RPs. According to equations (1) and (2), the introduced PBSs and RPs at the j-th port are located at (x_{PBSj}, z_{PBSj}) and (x_{RPj}, z_{RPj}), which can be expressed as

$$\begin{bmatrix} x_{PBS(2n-1)} & z_{PBS(2n-1)} \\ x_{RP(2n-1)} & z_{RP(2n-1)} \end{bmatrix} = \begin{bmatrix} 2(n-1)L & (-2n-4)L \\ 2(1-n)L & (-2n-4)L \end{bmatrix}, \quad \text{(for an odd port)} \tag{3}$$

$$\begin{bmatrix} x_{PBS(2n)} & z_{PBS(2n)} \\ x_{RP(2n)} & z_{RP(2n)} \end{bmatrix} = \begin{bmatrix} 2nL & (2n+4)L \\ 2(2-n)L & (2n+4)L \end{bmatrix}, \quad \text{(for an even port)} \tag{4}$$

where n is a positive integer. Figure 5(a), (b), (c), and (d) show the routes of port 1→port 2, port 2→port 3, port 3→port 4, and port (2n-1)→port 2n, respectively. In these figures, symbols ⧄ and ⊿ represent a PBS and a RP. Other propagation routes can be obtained based on the similar principle.



(a)

(b)

(c)

(d)

Fig. 5 Structure and operation principles of the proposed multi-port optical quasi-circulator.

However, in the design of Fig. 5, the optical path of the p- component is larger than that of the s- component. This optical path difference might cause polarization mode dispersion (PMD) to blur the transmission signal. Therefore, in order to solve the PMD problem, we change the original optical guiding paths in Fig. 5, and introduce two different guiding modules composed of PBSs and RPs for the odd and even ports, respectively, as shown in Fig. 6. The designs of these two guiding modules with specifications $(Length \times Width)$ of $(4n-3)L \times 0.31(n-1)L$ and $(4n-4)L \times 0.31(n-1)L$ for an odd and an even port are shown in Fig. 7(a) and (b), respectively. These guiding modules are located at (x_{Mj}, z_{Mj}) which can be expressed as

$$[x_{M(2n-1)} \quad z_{M(2n-1)}] = [2(1-n)L \quad (-2n-4)L], \quad \text{(for an odd port)} \tag{5}$$

$$[x_{M(2n)} \quad z_{M(2n)}] = [2nL \quad (2n+4)L], \quad \text{(for an even port)} \tag{6}$$

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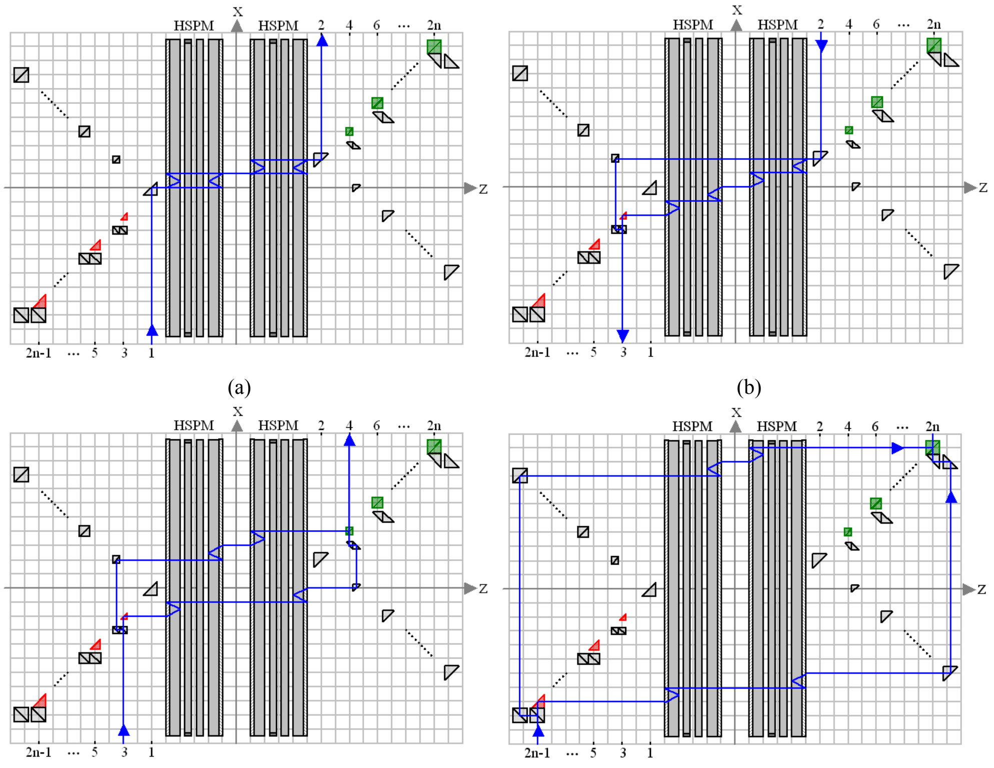
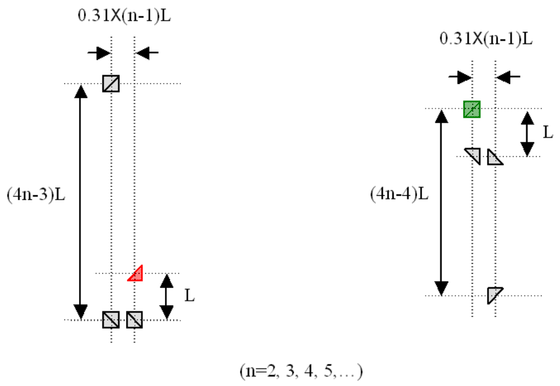


(a) (b)

(c) (d)

Fig. 6. Structure and operation principles of the proposed multi-port optical quasi-circulator without polarization mode dispersion.



(a) (b)

Fig. 7. PBSs and RPs guiding modules for (a) the odd ports; (b) the even ports.

where n is a positive integer larger than 1. The coordinate in equation (5) corresponds to the center of the RP (in red color) in the odd-port guiding module; the coordinate in equation (6) corresponds to the center of the PBS (in green color) in the even-port guiding module. When the guiding modules are appropriately introduced, the optical path differences between the s- and p- components can be reduced to zero. Therefore, the PMD problem can be solved. Fig. 6(a), (b), (c), and (d) show the routes of port 1→port 2, port 2→port 3, port 3→port 4, and port (2n-1)→port 2n, respectively. Other propagation routes can be obtained based on the similar principle.

3. Experimental results and discussions

In order to demonstrate the validity of our design, we used our fabricated HSWPs to assemble a prototype of 6-port polarization-independent optical quasi-circulator for 1300nm. Those HSWPs were fabricated with an He-Cd laser of λ =441.6nm and with the dichromated gelatin (DCG) as the recording material, as reported in our previous paper. Their diffraction efficiencies were measured to be η_s=3% and η_p=90% with a diffraction angle of 60° [2]. In addition to a pair of HSPMs, it needs another eight polarization-beam splitters and ten reflection prisms to complete the function of this 6-port optical quasi-circulator.

The characteristic parameters of this prototype device can be estimated from that of each component. The diffraction efficiencies of HSWPs, as mentioned above, are measured to be η_s=3% and η_p=90%. The transmittances of FR and H, which are commercial devices, are listed to be 0.95 and 0.97, respectively. Thus, the associated losses and isolation values of this optical quasi-circulator can be estimated, as shown in Table 1(a). In order to confirm the validity of this estimation, we have measured the insertion losses of the device. The measured values are correspondent well with the estimated values. If our fabricated HSWPs are anti-reflection coated and are under accurate fabrication processes, the reflection losses should be decreased to 0.1%, and the diffraction efficiencies may reach theoretical values [13], i.e., $\eta_s \fallingdotseq$ 0% and $\eta_p \fallingdotseq$ 100%. Under these two improved conditions, the performance of this 6-port optical quasi-circulator can be enhanced greatly, and the associated parameters are calculated and listed in Table 1(b) with η_s<1% and η_p>99%. In addition, the bandwidth of the HSWP at 1300nm central wavelength is 20nm. It should also be possible to design the central wavelength to be at 1550 nm wavelength range.

Table 1. Associated losses and isolation values^a (in Decibels) of a 6-port quasi-circulator with wavelength 1300nm by using (a) our fabricated HSWPs; and (b) ideal HSWPs with anti-reflection coatings and diffraction efficiencies of η_s<1% and η_p>99%.

(a)

	Out Port					
In Port	**1**	**2**	**3**	**4**	**5**	**6**
1	14.26^b	4.18^c	>25.36	>25.36	>25.36	>25.36
2	>26.92	14.26^b	3.90^c	>26.92	>26.92	>26.92
3	>25.36	>25.36	14.26^b	4.18^c	>25.36	>25.36
4	>26.92	>26.92	>26.92	14.26^b	3.90^c	>26.92
5	>25.36	>25.36	>25.36	>25.36	14.26^b	4.18^c

(b)

	Out Port					
In Port	**1**	**2**	**3**	**4**	**5**	**6**
1	>30^b	<1^c	>43.84	>43.84	>43.84	>43.84
2	>43.93	>30^b	<1.01^c	>43.93	>43.93	>43.93
3	>43.84	>43.84	>30^b	<1.01^c	>43.84	>43.84
4	>43.93	>43.93	>43.93	>30^b	<1.01^c	>43.93
5	>43.84	>43.84	>43.84	>43.84	>30^b	<1.01^c

^{a}All values without a superscript are isolation values; ^{b}Return losses; ^{c}Insertion losses.

In order to solve the PMD problem, we appropriately introduce two different guiding modules composed of PBSs and RPs for the odd and even ports, respectively. However, if we want to fabricate more compact modules, these guiding devices should become smaller simultaneously. The result will increase the difficulty of device assembling. Expediently, we can increase the beam splitting distance L ($L = 2t\tan\theta_d$) [2] by increasing the thickness of the substrate to reduce the assembling difficulty. Another reliable method is to operate this device beginning with a high number port.

4. Conclusions

An alternative type of multi-port polarization-independent optical quasi-circulator by using a pair of holographic spatial- and polarization- modules (HSPMs) has been proposed. In order to demonstrate the feasibility, the prototype of a 6-port optical quasi-circulator operating at a wavelength of 1300nm was assembled. In addition, the operating principles and the performance of the proposed optical quasi-circulator have been described. This design has advantages of polarization-independence, compactness, high isolation, low polarization mode dispersion, and easy fabrication. Furthermore, the number of ports can be scaled up easily.

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