Multiport polarization-independent wavelength-interleaving bidirectional quasicirculator

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Abstract. An alternative type of multiport polarization-independent wavelength-interleaving bidirectional quasicirculator is proposed. It contains holographic spatial and polarization modules (HMs), a Lyot-Ohman filter (LOF), a quarterwave plate, and a mirror. Each HM contains a holographic spatial walk-off polarizer, a half-wave plate, and a glass plate. The LOF consists of three half-wave plates and three identical pairs of crystals. The functions of the HM and the LOF are described. Then, the operating principle and the performance of this quasicirculator are described and discussed. In this circulator, the signals in the even and odd channels can circulate with opposite handedness regardless of signal polarizations. It offers a high isolation level, polarization independence, low polarization-mode dispersion, parallel input/output ports and ease of increasing the number of ports. [DOI: 10.1117/1.2931586]

Subject terms: holographic optical elements; optical communications; multiplexing; polarization.

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1 Introduction

Circulators are necessary components in the construction of foundational network modules such as add-drop multiplexers,[1] dispersion compensation,[2] optical amplifiers,[3] and time-domain reflectometry.[4] As the design of optical communication system becomes increasingly complex, a bidirectional transmission device[5] is highly desirable because of its obvious advantages over unidirectional transmission. Although some bidirectional transmission devices have been reported,[6–8] they have complicated configurations because of the introduction of two multiport unidirectional optical circulators.[9] On the other hand, holographic gratings[10] can function as beamsplitters and beam deflectors very well. When two gratings are arranged as a substrate-mode hologram, it can function as a polarization beamsplitter[10,11] and it can be used to replace the conventional crystal spatial walk-off polarizer.[12]

To mitigate the drawbacks, an alternative type of multiport polarization-independent wavelength-interleaving bidirectional quasicirculator based on holographic spatial and polarization modules (HMs) is proposed in this paper. Besides the HMs, it also contains a Lyot-Ohman filter (LOF), a quarterwave plate, and a mirror. Each HM contains a holographic spatial walk-off polarizer (HS), a half-wave plate, and a glass plate. The LOF consists of three half-wave plates and three identical groups of crystals.

The functions of the HMs and the LOF are described. Then, the operating principle and the performance of this quasicirculator are described and discussed. In this circulator, the signals in the even and odd channels can circulate with opposite handedness regardless of the signal polarizations. This circulator has some merits, such as high isolation level, polarization independence, low polarization-mode dispersion (PMD), parallel input/output ports, and ease of increasing the number of ports.

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2 Principles

2.1 *Holographic Spatial and Polarization Module*

In this paper, we propose a spatial and polarization HM, which comprises a holographic spatial walk-off polarizer HS, a 45-deg half-wave plate H, and a transparent glass plate G, as shown in Fig. 1(a). The HS is essentially a transmission-type phase volume holographic grating[10,11] that is fabricated on a substrate. Its structure and its operating principle are described in our previous paper.[12] It can divide normally incident unpolarized light into two orthogonally polarized parallel beams with a separation d. Because of reciprocity, it can combine two orthogonally polarized parallel beams propagating in the reverse direction into one beam. For convenience, a rectangular coordinate system is imposed on the upper left part; the states of polarization (SOPs) and relative positions of the light

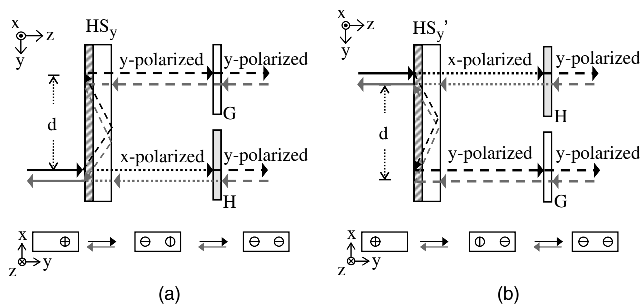

Fig. 1 Structures and operating principles of the (a) HM and (b) HM′.

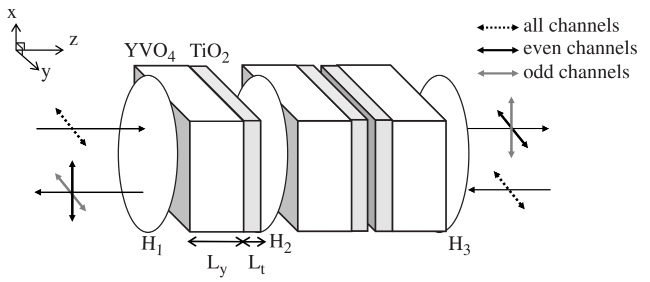

Fig. 2 Structure and operation principle of the Lyot-Ohman filter.

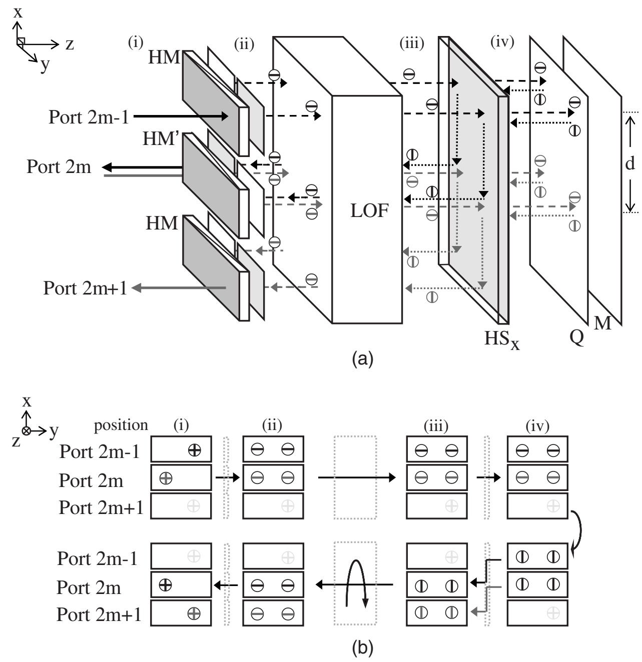

Fig. 3 (a) Operation principle for signals in even channels on the routes (port $2m-1$)→(port $2m$) and (port $2m$)→(port $2m+1$); (b) the signals' SOPs and their relative positions.

beams after propagating through each component are also shown in the lower part in Fig. 1(a). The path of the light from left to right is shown in black, and the reverse propagation is in gray; the symbols ⊖, ⦶, and ⊕ represent y polarization, x polarization, and no polarization respectively. In addition, when the light beam is incident on the HS along the $+z$ direction, and the two polarization components are separated in the $-y$ direction, the $+y$ direction, and the $-x$ direction, for clearness the associated HSs are called HS_y, HS'_y, and HS_x,respectively.

The design in Fig. 1(a) employs an HS_y. Accordingly, the x-polarization component of the incident light beam passes through the HS_y directly and is rotated to be the y-polarized light after passing through H. The y-polarization component is diffracted and propagates out perpendicularly to the HS_y, and passes through G. To avoid PMD, the optical thickness of G should be the same as that of H. Also since pairs of holograms are used, chromatic compensation can be automatically built into the HS.[13–15] Hence, the HM can divide a normally incident unpolarized light beam into two y-polarized beams with a separation d in the $-y$ direction. If the HM is rotated 180 deg around the z axis, its configuration is changed to that shown in Fig. 1(b) and called the HM′ for clarity. Similarly, the HM′ can also divide an incident unpolarized light beam into two y-polarized beams with the separation d in the $+y$ direction.

In addition, two y-polarized light beams are incident on the HM or HM′ along the $-z$ direction, as shown in gray in Figs. 1(a) and 1(b); they will travel along the original paths in the reverse direction. Then they will be merged into a single beam and propagate out perpendicularly to the HM or HM′.

2.2 *Lyot-Ohman Filter*

The LOF[16,17] consists of three 45-deg half-wave plates (H_1 to H_3) and three identical pairs of crystals as shown in Fig. 2. Each pair of crystals consists of a YVO_4 crystal and a TiO_2 crystal, whose thicknesses are L_y and L_t, respectively. One pair is located between H_1 and H_2; the other two groups of crystals face in the opposite direction and are located between H_2 and H_3. If Δn_y and Δn_t are the differences between the ordinary and extraordinary refractive indices of the YVO_4 and the TiO_2, respectively, then the free spectral range (FSR) of the LOF is given as[17]

$$\mathrm{FSR} = \frac{c}{\Delta n_y L_y + \Delta n_t L_t}, \tag{1}$$

where c is the speed of light. Consequently, when an x-polarized or a y-polarized light beam with central frequency f_c passes through the LOF along the $+z$ direction, the SOP is rotated by 90 deg if the frequency equals $f_c \pm (2m+1)\cdot \mathrm{FSR}$ (odd channels), where m is an integer; and the SOP remains unchanged if the frequency equals $f_c \pm 2m \cdot \mathrm{FSR}$ (even channels). The upper path in Fig. 2 displays the operation, and the dotted, solid, and gray arrows represent the signals in all channels, even channels, and odd channels, respectively. If the light beam passes through the LOF along the $-z$ direction, the SOPs of signals in odd channels remain unchanged, and the SOPs of signals in even channels are rotated by 90 deg. The operation of the lower path is also depicted in Fig. 2. Hence the LOF can rotate the SOPs of signals with wavelength interleaving. For simplicity only the conditions where the y-polarized light beams are incident on the LOF along the $+z$ direction are designed and discussed in this study.

2.3 *Multiport Polarization-Independent Wavelength-Interleaving Bidirectional Quasicirculator Module*

The optical configuration of this quasicirculator module is shown in Fig. 3(a) and Fig. 4(a) for even and odd channels, respectively. It consists of a series of the HMs and the HM′s, an LOF, an HS_x, a quarterwave plate Q with the fast axis at 45 deg to the x axis, and a mirror M. Here the HMs and the HM′s are interlaced for the odd and even ports An unpolarized light beam is incident on the HM or HM′ along the $+z$ axis, and two y-polarized light beams with a separation d in the $-y$ or $+y$ direction are obtained. They enter the LOF; the signals in even channels are still y-polarized

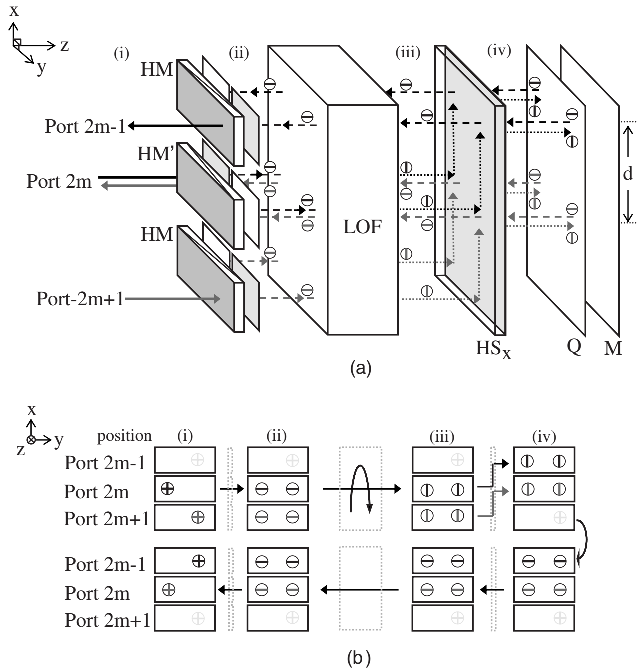

Fig. 4 (a) Operation principle for signals in odd channels on the routes (port $2m+1$)→(port $2m$) and (port $2m$)→(port $2m-1$); (b) the signals' SOPs and their relative positions.

and the signals in odd channels are changed to be x-polarized. Consequently, the signals in even channels pass through the HS_x directly, and the signals in odd channels are displaced a distance d along the $+x$ direction after the HS_x. Then, all of them pass through Q and are reflected by M. They propagate reversely along the original paths and pass through Q again. Their SOPs are rotated 90 deg here due to two passages through Q and one reflection at M. Next, they enter the LOF again along the $-z$ direction, and their SOPs are again changed to be y-polarized regardless of the channel number. The signals in the even (odd) channels are displaced by d along the $-y$ $(+y)$ directions. Finally, two corresponding beams are merged into one output beam at the associated output port.

Therefore, we can see that the signals in even (odd) channels propagate clockwise (counterclockwise) in this quasicirculator in the order $1 \rightarrow 2 \rightarrow 3 \rightarrow \cdots \rightarrow N-1 \rightarrow N$ $(N \rightarrow N-1 \rightarrow \cdots \rightarrow 2 \rightarrow 1)$. For clarity, the operating principles for the signals in even [odd] channels along the routes (port $2m-1$)→(port $2m$) and (port $2m$)→(port $2m+1$) [(port $2m+1$)→(port $2m$) and (Port $2m$)→(port $2m-1$)] are shown in Fig. 3(a) [4(a)]. The signals' SOPs and their relative positions in regions (i) to (iv) are shown in Figs. 3(b) [4(b)]. If port 1 is located at the position (0,0), then another port can be found at

$$[x_{2m-1}, y_{2m-1}] = [d - d(2m-1), 0] \quad \text{for odd ports,} \tag{2}$$

$$[x_{2m}, y_{2m}] = [-d(2m-1), -d] \quad \text{for even ports.} \tag{3}$$

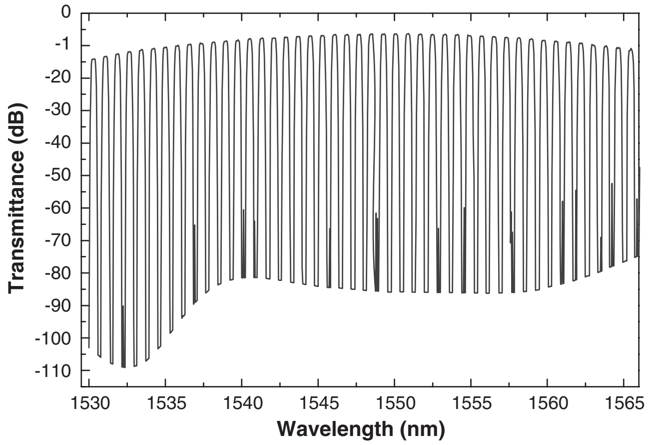

Fig. 5 The experimental transmittance spectrum of the route from port 1 to port 2.

3 Experiments and Discussions

Fabricated HSs were used together with a customer-designed LOF to assemble a prototype of a five-port bidirectional quasicirculator for the C band. Those HSs were fabricated with a He-Cd laser at $\lambda = 441.6$ nm with the dichromated gelatin (DCG) as the recording material, as reported in our previous work.[18] Their diffraction efficiencies were measured at 1550 nm to be $\eta_s = 3\%$ and $\eta_p = 90\%$ with $d = 3.2$ mm. The signals in each clockwise propagation route have the same transmittance spectrum, and the signals in each counterclockwise propagation route also have the same transmittance spectrum. The two transmittance spectra have similar curves, except there is a 50-GHz ($\approx$0.4-nm) shift in frequency (wavelength) between them. So, only the transmittance spectrum of the route from port 1 to port 2 of this prototype in the C band was measured with an optical spectrum analyzer (Advantest Q8384) to demonstrate its performance. The result is shown in Fig. 5, and it has a clear channel spacing of 50 GHz ($\approx$0.4 nm). The even channels have losses from -6.5 to -13.5 dB, and the odd channels have losses more than -76.5 dB. Consequently, the signals of the even channels can propagate from port 1 to port 2, and the signals in the odd channels are blocked.

The transmittances of G and H, which are commercial devices, were measured to be 0.96 and 0.97, respectively. The fabricated HSs also have about 4% reflection loss at every boundary. If they are antireflection-coated, then the reflection losses should be decreased to 0.1%. In addition, if the holographic exposure and the postprocessing procedure are controlled more accurately, then the HSs may have the theoretical diffraction efficiencies[19]: $\eta_s < 1\%$ and $\eta_p > 99\%$ at 1550 nm.

Moreover, Fig. 6 plots the theoretical curves of diffraction efficiencies versus wavelengths for our HS, based on coupled-wave theory.[20] Under these optimizations, the performance of this circulator can be enhanced greatly, and the associated theoretical transmittance spectrum can be modified as shown in Fig. 7.

The experimental and theoretical characteristic parameters of this prototype for every channel for the route from port 1 to port 2 can be calculated with the data in Figs. 5

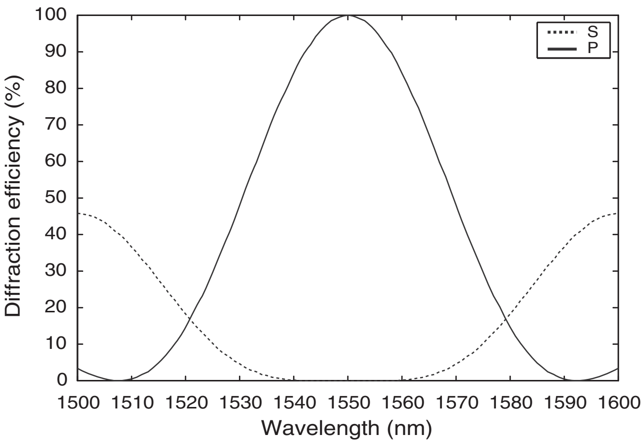

Fig. 6 Diffraction efficiencies of the HS versus wavelength at 1550-nm central wavelength.

and 7. Because the two routes have similar experimental and theoretical transmittance spectra, as shown in these two figures, the experimental and theoretical associated losses and isolation values for each route at 1550 nm can be calculated and are summarized in Table 1. For easy understanding, the experimental and theoretical transmittance spectra from 1549 to 1551 nm are redepicted and shown in Fig. 8. It is clear that this prototype has good performance.

All of the component beams have four diffractions and four total internal reflections, and their paths are parallel. Therefore, this quasicirculator has low PMD theoretically under the condition that the optical thickness of G is the same as that of H. In addition, if the positions of G and H are interchanged, then the signals in the even (odd) channels propagate counterclockwise (clockwise). Although they propagate in reverse directions, they have the same functions.

4 Conclusion

This study develops an alternative type of multiport polarization-independent wavelength interleaving bidirectional quasicirculator. It contains holographic spatial and polarization modules (HMs), Lyot-Ohman filter (LOF), a

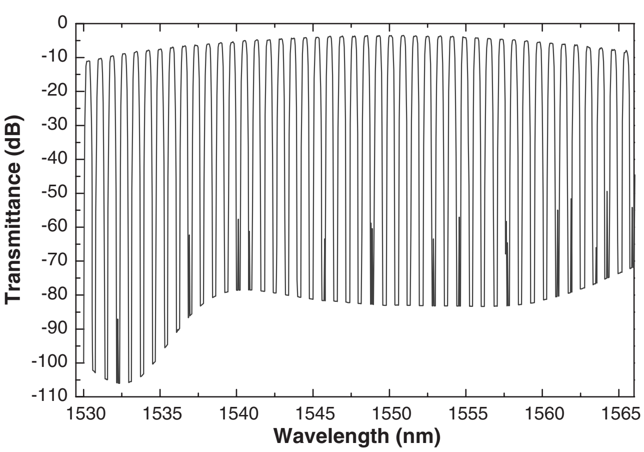

Fig. 7 The theoretical transmittance spectrum of the same route as in Fig. 5.

Table 1 Associated isolation values, return losses (in parentheses), and insertion losses [in brackets] of the prototype five-port quasicirculator with a wavelength of 1550 nm under (a) experimental and (b) theoretical conditions.

(a) Experimental

Even channel

Input port	Isolation or loss (dB) Output port: 1	2	3	4	5
1	(14.26)	[6.47]	29.09	26.94	49.09
2	19.77	(14.26)	[6.47]	29.09	26.94
3	56.35	19.77	(14.26)	[6.47]	29.09
4	39.77	56.35	19.77	(14.26)	[6.47]

Odd channel

Input port	Isolation or loss (dB) Output port: None	1	2	3	4
1	[6.345]	(14.26)	19.77	56.35	39.77
2	29.09	[6.345]	(14.26)	19.77	56.35
3	26.94	29.09	[6.345]	(14.26)	19.77
4	49.09	26.94	29.09	[6.345]	(14.26)

(b) Theoretical

Even channel

Input port	Isolation or loss (dB) Output port: 1	2	3	4	5
1	(30)	[3.34]	46.22	43.34	86.22
2	26.34	(30)	[3.34]	46.22	43.34
3	66.34	26.34	(30)	[3.34]	46.22
4	66.30	66.34	26.34	(30)	[3.34]

Odd channel

Input port	Isolation or loss (dB) Output port: None	1	2	3	4
1	[3.34]	(30)	26.34	66.34	66.30
2	46.22	[3.34]	(30)	26.34	66.34
3	43.34	46.22	[3.34]	(30)	26.34
4	86.22	43.34	46.22	[3.34]	(30)

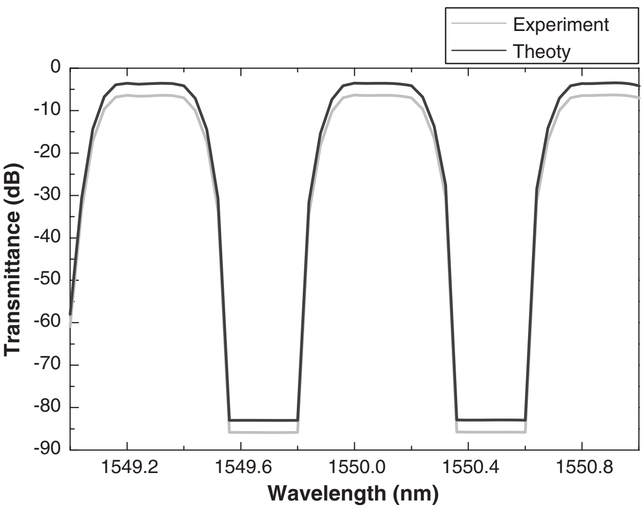

Fig. 8 The experimental and theoretical transmittance spectra from 1549 to 1551 nm.

quarterwave plate, and a mirror. Each HM contains a holographic spatial walk-off polarizer, a half-wave plate, and a glass plate. The LOF comprises three half-wave plates and three identical pairs of crystals. The functions of the HM and the LOF have been described.

The operating principles and the performance of this quasicirculator have been described and discussed. The signals in even and odd channels can circulate with opposite handedness regardless of their SOPs. This module has such advantages as high isolation level, polarization independence, low PMD, parallel input/output ports, and ease of increasing the number of ports.

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