Polarization-independent optical switch composed of holographic optical elements

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A novel 2×2 polarization-independent optical switch with holographic optical elements is proposed. The switch consists of an electro-optic half-wave plate sandwiched between two pairs of holographic polarization beam splitters. Normally incident input and output couplings of this compact and lightweight device provide better flexibility and easier alignment for system applications.

A 2×2 reversible optical switch with two inputs and two outputs is a basic unit for multistage switching networks[1,2] and for protection rings in optical communications.[3] Basically, a polarization beam splitter (PBS) in conjunction with electro-optic half-wave plates can form this type of switch. Wollaston and Rochen prism cubes are conventionally used for polarization beam splitting. Since 1990, holographic optical elements have been proposed and investigated as replacements for conventional prism cubes in switching applications.[4-6] However, these optical switches with holographic elements are used only for specified linearly polarized input beams (s polarization or p polarization with respect to the grating planes). Polarization-independent optical switches with electro-optic half-wave plates and polarization beam-splitting prisms have also been investigated.[7,8] In this Letter we present a novel structure to form a 2×2 polarization-independent optical switch with a pair of holographic PBS's and an electro-optic half-wave plate. This lightweight and compact structure with normally incident input and output couplings provides the advantages of easy alignment and integrability.

The structure of our holographic PBS is shown in Fig. 1.[5,6] Two symmetric polarization-selective grating pairs are formed on two sides of a dielectric substrate. The diffraction angle in the film medium is θ_D, and the Bragg reconstruction input angle is 0°; i.e., the input beam is normally incident upon the device. In contrast, in the output coupling, the reconstruction angle is θ_D, and the output diffracted beam is also normal to the device, as shown in Fig. 1. Based on Kogelnik's coupled-wave theory,[9] the diffraction efficiencies of the s- and the p-polarization fields for each grating, η_s and η_p, are given as

$$\eta_s = \sin^2 \nu_s = \sin^2 \frac{\pi n_1 d}{\lambda \sqrt{\cos \theta_D}}, \tag{1}$$

$$\eta_p = \sin^2 \nu_p = \sin^2 \frac{\pi n_1 d \sqrt{\cos \theta_D}}{\lambda}, \tag{2}$$

respectively, where λ is the operating wavelength, d is the thickness of the grating film, and n_1 is the index modulation of the grating.

Based on Eqs. (1) and (2), suitable values for θ_D and $n_1 d/\lambda$ can be solved to yield the following high polarization-selective properties:

$\eta_s = 0\%$ and $\eta_p = 100\%$, i.e., s transmission/p diffraction:

$$\nu_s = m\pi, \quad \nu_p = [m - (1/2)]\pi, \qquad m = 1, 2, 3, \ldots, \tag{3}$$

$\eta_s = 100\%$ and $\eta_p = 0\%$, s diffraction/p transmission:

$$\nu_s = [m + (1/2)]\pi, \qquad \nu_p = m\pi, \qquad m = 1, 2, 3 \ldots. \tag{4}$$

Several sets of solved values are shown in Table 1; these devices were designed, and some were fabricated.[5,6]

Let us use s-transmission/p-diffraction gratings in the structure shown in Fig. 1 as an example. When the input beams are s polarized, the device will perform the function of straight connections (direct transmission), as shown by the solid connection lines in Fig. 1. In contrast, when the input beams are p polarized, the device will perform the function of swap connections (diffraction), as shown by the dashed connection lines. This device is the basic unit of our polarization-independent optical switch. (For s-diffraction/p-transmission gratings, this holographic PBS will perform an s-swap/p-straight function.)

The structure that we propose for a polarization-independent holographic optical switch is shown in Fig. 2. This switch is composed of an electro-optic half-wave plate sandwiched between two
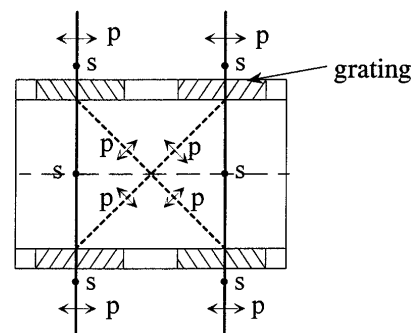

Fig. 1. The structure of a holographic PBS.

**Table 1. Parameter Values of
Polarization-Selective Gratings**

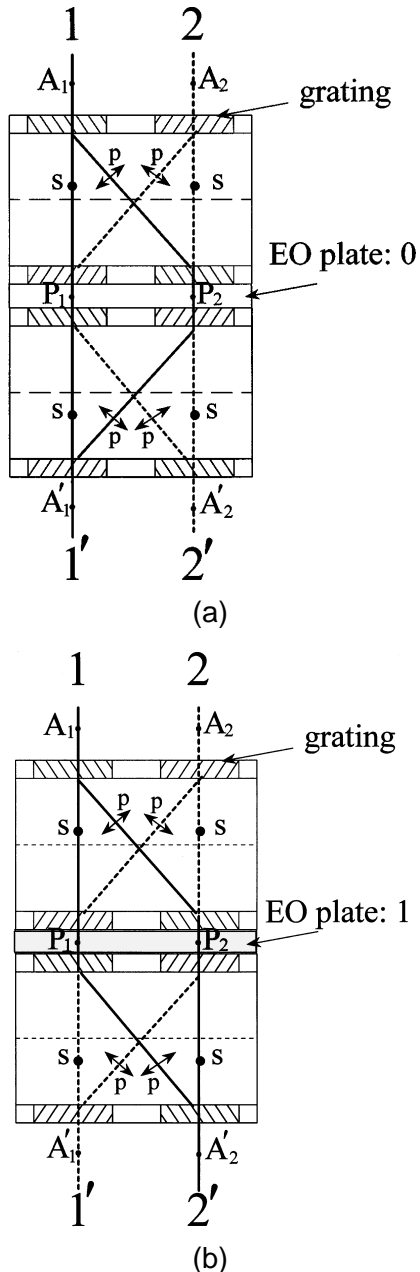| Parameter	Value		
ν_s, ν_p	$\pi, {}^{1}/_{2}\pi$	${}^{3}/_{2}\pi, \pi$	$2\pi, {}^{3}/_{2}\pi$
η_s, η_p	0%, 100%	100%, 0%	0%, 100%
θ_D	60.0°	48.2°	41.4°
$n_1 d/\lambda$	0.707	1.22	1.73

Fig. 2. The structure of a polarization-independent holographic optical switch with s-transmission/p-diffraction gratings: (a) state 0, (b) state 1.

holographic PBS's. In this example the gratings perform s-transmission/p-diffraction functions. For convenience of discussion, we denote six positions on the connection paths by points A_1, A_2 (corresponding to channels 1 and 2); P_1, P_2 (corresponding to plate positions); and A_1', A_2' (corresponding to channels $1'$ and $2'$).

Consider an optical signal coming from channel 1 to the switch as shown in Fig. 2. The signal is split into two parts, one with s polarization, which directly passes the first holographic PBS and propagates along the path from point A_1 to point P_1, and the other with p polarization, which is diffracted by the first holographic PBS, propagates along the path from point A_1 to point P_2. When the electro-optic half-wave plate is inactive [(state 0), as shown in Fig. 2(a)], the field polarizations are not changed after they pass through the plate. In this case the signal component with s polarization again directly passes the second holographic PBS, propagates along the path from P_1 to A_1', and is combined with the s-polarization component. Thus all polarization components are transmitted from channel 1 to channel $1'$. Similarly, the optical signal from channel $1'$ will follow the same paths backward with corresponding polarizations and finally reach channel 1. The connection between channel 2 and channel $2'$ is established by the same operation. Therefore the inactive state (state 0) of the electro-optic half-wave plate will make the switch perform the function of bidirectional straight connections $(1 \leftrightarrow 1', 2 \leftrightarrow 2')$, as shown in the figure.

In the other case, i.e., when the electro-optic half-wave plate is active (state 1), as shown in Fig. 2(b), the field polarizations will be changed after they pass through the plate. Also consider the optical signal coming from channel 1. The s-polarization component along path $A_1 \rightarrow P_1$ becomes p polarized after it passes through the half-wave plate and is diffracted by the second holographic PBS to follow the path from point P_1 to point A_2'. In contrast, the original p-polarization component from channel 1, which is along path $A_1 \rightarrow P_2$, becomes s polarized after it passes through the half-wave plate, directly passes the second holographic PBS to follow path $P_2 \rightarrow A_2'$, and is then combined with the other polarization component from path $P_1 \rightarrow A_2'$. Therefore all polarization components are transmitted from channel 1 to channel $2'$. Similarly the optical signal from channel $2'$ will follow the same paths backward with corresponding polarizations, and will finally reach channel 1. The connection between channel 2 and channel $1'$ is established by the same operation function. Thus the active state (state 1) of the electro-optic plate will make the switch perform the function of bidirectional swap connections $(1 \leftrightarrow 2', 2 \leftrightarrow 1')$, as shown in Fig. 2(b). All connection states are also clearly shown in Table 2.

**Table 2. Connection States of Holographic Optical
Switch with s-Transmission/p-Diffraction Gratings**

Plate State	Field Polarization on the Signal Path	Connection State	Switch Function
0 (Inactive)	$A_1 \overset{s}{\leftrightarrow} P_1 \overset{s}{\leftrightarrow} A_1'$ $A_1 \overset{p}{\leftrightarrow} P_2 \overset{p}{\leftrightarrow} A_1'$	$1 \leftrightarrow 1'$	Straight connections
	$A_2 \overset{s}{\leftrightarrow} P_2 \overset{s}{\leftrightarrow} A_2'$ $A_2 \overset{p}{\leftrightarrow} P_1 \overset{p}{\leftrightarrow} A_2'$	$2 \leftrightarrow 2'$	
1 (Active)	$A_1 \overset{s}{\leftrightarrow} P_1 \overset{p}{\leftrightarrow} A_2'$ $A_1 \overset{p}{\leftrightarrow} P_2 \overset{s}{\leftrightarrow} A_2'$	$1 \leftrightarrow 2'$	Swap connections
	$A_2 \overset{s}{\leftrightarrow} P_2 \overset{p}{\leftrightarrow} A_1'$ $A_2 \overset{p}{\leftrightarrow} P_1 \overset{s}{\leftrightarrow} A_1'$	$2 \leftrightarrow 1'$	

Table 3. Connection States of Holographic Optical Switch with _s_-Diffraction/_p_-Transmission Gratings

Plate State	Field Polarization on the Signal Path	Connection State	Switch Function
0 (Inactive)	$A_1 \overset{s}{\leftrightarrow} P_2 \overset{s}{\leftrightarrow} A_1{'}$ $A_1 \overset{p}{\leftrightarrow} P_1 \overset{p}{\leftrightarrow} A_1{'}$ $A_2 \overset{s}{\leftrightarrow} P_1 \overset{s}{\leftrightarrow} A_2{'}$ $A_2 \overset{p}{\leftrightarrow} P_2 \overset{p}{\leftrightarrow} A_2{'}$	$1 \leftrightarrow 1{'}$ $2 \leftrightarrow 2{'}$	Straight connections
1 (Active)	$A_1 \overset{s}{\leftrightarrow} P_2 \overset{p}{\leftrightarrow} A_2{'}$ $A_1 \overset{p}{\leftrightarrow} P_1 \overset{s}{\leftrightarrow} A_2{'}$ $A_2 \overset{s}{\leftrightarrow} P_1 \overset{p}{\leftrightarrow} A_1{'}$ $A_2 \overset{p}{\leftrightarrow} P_2 \overset{s}{\leftrightarrow} A_1{'}$	$1 \leftrightarrow 2{'}$ $2 \leftrightarrow 1{'}$	Swap connections

For _s_-diffraction/_p_-transmission gratings, the holographic PBS shown in Fig. 1 will perform _s_-swap and _p_-straight beam-splitting functions. However, the structure presented in Fig. 2, with _s_-diffraction/_p_-transmission holographic PBS's, can provide the same 2×2 bidirectional polarization-independent switching functions as can that with _s_-transmission/_p_-diffraction holographic PBS's. The only difference is that the propagation paths of _s_- and _p_-polarization fields are interchanged within this switching device, as shown in Table 3.

We also calculate the cross talk of the switch shown in Fig. 2. Assume that X is the extinction ratio, defined as the ratio of the output power of the desired polarization to the output power of the other, undesired polarization of each element. With a power summation model, the cross talk can be evaluated as follows:

$$\text{Cross talk} = X_{\text{PBS}}{}^{-1} + X_{\text{Plate}}{}^{-1} + X_{\text{PBS}}{}^{-1}, \quad (5)$$

where the subscripts PBS and Plate represent the holographic polarization beam splitter and the electro-optic half-wave plate, respectively. For a grating with a contrast of 30:1, we obtain $X_{\text{PBS}} = 900 = 29.5$ dB because of the effect of a grating pair.[6] If $X_{\text{Plate}} = 500 = 27.0$ dB,[10] we have a cross talk of -23.7 dB. For an 85% transmission efficiency of each holographic PBS and half-wave plate,[6,10] the insertion loss is approximately 2.1 dB.

Finally, we evaluate the delay time between two polarization fields that is due to the optical path difference and the maximum bit rate (BR) of signals that can be transmitted by the switch without losing the correct information. If the distance between the centers of the pair of holograms on the same plane D, and the diffraction angle in the substrate is θ_s, then the optical path difference ΔL is

$$\Delta L = 2D\left(\frac{1}{\sin \theta_s} - \frac{1}{\tan \theta_s}\right), \quad (6)$$

the delay time $\Delta \tau$ is

$$\Delta \tau = \frac{\Delta L}{c/n_s}, \quad (7)$$

and the maximum BR is given as

$$\text{BR} = \frac{1}{2\Delta \tau}, \quad (8)$$

where c is the speed of light in free space and n_s is the refractive index of the dielectric substrate. Using $D = 3$ mm (i.e., 2-mm beam diameter and 1-mm separation between beams), $\theta_s = 41.4°$, and $n_s = 1.56$, we obtain BR $\cong 48$ GHz, which is suitable for most optical communication systems. When D is increased, the maximum BR is reduced.

In summary, a polarization-independent optical switch composed of holographic optical elements has been presented. The switch consists of an electro-optic half-wave plate sandwiched between two pairs of holographic polarization beam splitters. The operation principle has been discussed in detail, and the device characteristics have been evaluated. Normally incident input and output coupling with this compact and lightweight device provides better flexibility and easier alignment for system applications.

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