

Polarization-selective elements with a substrate-mode grating pair structure

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A novel device with a substrate-mode grating pair structure to perform the function of polarization selection is presented. Normally incident and output coupling of this compact and lightweight component provides better flexibility and easier alignment for system applications. A highly polarization-selective substrate-mode grating pair has been designed and fabricated. Polarization-selective switching experiments with this device are demonstrated.

Polarization-selective elements have many applications, such as in switching cells of optical multistage networks^{1,2} and in the polarization-sensing device of the optical pickup head for a magneto-optic data storage system.³ For switching cells the devices consist of polarization beam splitters and electro-optic half-wave plates, and electric signals are used to control optical signal paths. For the optical head, the polarization-selective element is used to detect the rotation of the polarization of the beam reflected from the magneto-optic disk medium. Conventionally, Wallaston and Rochon prisms are used as polarization-selective elements. In 1990, compact and lightweight polarization-selective holographic elements with a high diffraction angle were designed to replace those prism devices.⁴ In this Letter we investigate, theoretically and experimentally, a novel substrate-mode grating pair structure with the features of better performance and an easier fabrication process to provide the polarization-selective function.

For a transmission-type phase volume hologram, the relation between the diffraction efficiency for an *s*-polarized field η_s and the efficiency for a *p*-polarized field η_p with the same Bragg reconstruction condition depends strongly on the diffraction angle and is expressed as⁵

$$\eta_{s,p} = \sin^2 \nu_{s,p}; \quad (1)$$

and the modulation parameters, ν_s (*s* field) and ν_p (*p* field), are given, respectively, as

$$\nu_s = \frac{\pi n_1 d}{\lambda (\cos \theta_{r1} \cos \theta_{r2})^{1/2}}, \quad (2)$$

$$\nu_p = \nu_s \cos(\theta_{r2} - \theta_{r1}), \quad (3)$$

where λ is the reconstruction wavelength, d is the medium thickness, n_1 is the index modulation, and θ_{r1} and θ_{r2} , respectively, are corresponding angles of the reconstruction and diffracted beams in the hologram medium.

From the diffraction efficiency formulas in Eqs. (1)–(3) it can be seen that when the value of ν_s is $1/2\pi$, then $\eta_s = 100\%$, and if the diffraction angle, $|\theta_{r2} -$

$\theta_{r1}|$, is also 90° , then $\nu_p = 0$ and $\eta_p = 0\%$. In this case, a highly polarization-selective element can be obtained. However, because of the high diffraction angles (90°) this element needs additional input and output couplers to form a complete device. This type of element has been investigated, and a typical structure is shown in Fig. 1.⁴ In this configuration, the polarization-selective grating is H_{PBS} ; when $\theta_{r1} = 45^\circ$, $\theta_{r2} = -45^\circ$, and $n_1 = 0.016$ with the film thickness of $17 \mu\text{m}$, we have $\eta_s = 100\%$ and $\eta_p = 0\%$. For the input polarization-independent coupling grating H_I , $\theta_{r1} = 0^\circ$, $\theta_{r2} = 45^\circ$, and $n_1 = 0.022$, we have $\eta_s = \eta_p = 93\%$; for the output *s*-field coupling grating H_{OS} , $\theta_{r1} = -45^\circ$, $\theta_{r2} = 0^\circ$, and $n_1 = 0.019$, we have $\eta_s = 100\%$; for the output coupling grating H_{OP} , $\theta_{r1} = 45^\circ$, $\theta_{r2} = 0^\circ$, and $n_1 = 0.027$, we have $\eta_p = 100\%$. Theoretically the maximum transmission efficiency for both *s* and *p* channels is only 93%. In addition, four different grating angles and index modulation values make the complete component complicated and difficult to fabricate. In this Letter we present a new structure with a smaller diffraction angle to perform a highly polarization-selective procedure that provides a higher transmission efficiency and a much simpler fabrication process. The configuration of this device is shown in Fig. 2.

For our new structure the beam normally incident upon the input coupling grating H_I is diffracted at an

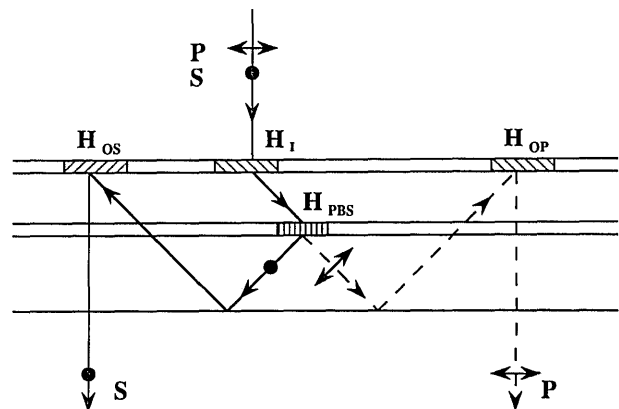


Fig. 1. Original polarization-selective substrate-mode hologram structure.

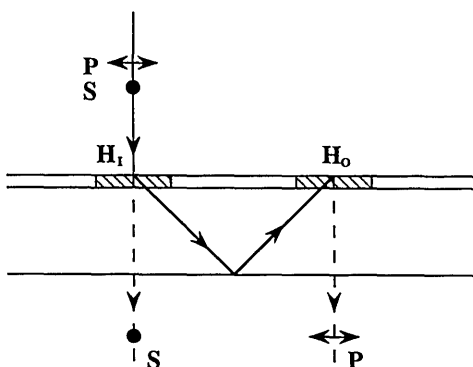


Fig. 2. New polarization-selective substrate-mode hologram structure.

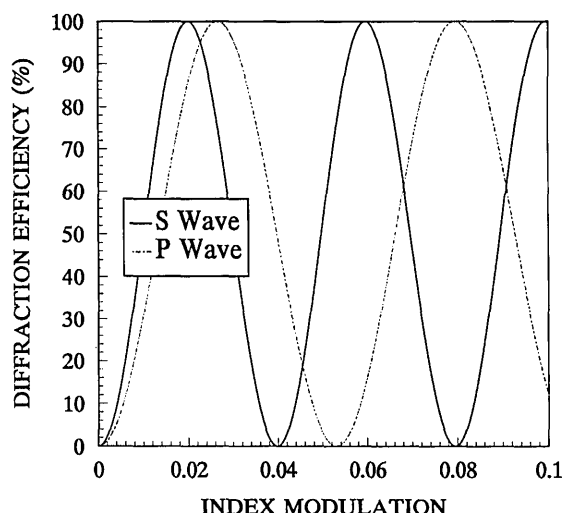


Fig. 3. Calculated diffraction efficiencies for *s*- and *p*-polarization fields, η_s and η_p , versus the index modulation n_1 .

angle beyond the critical angle in the substrate, then propagates through the substrate with total internal reflection to the output coupling grating H_0 , and then is normally coupled out with conjugate diffraction. Compared with a conventional polarization beam-splitting cube, the normally incident output coupling of this compact and lightweight component can provide better flexibility and easier alignment for system applications. Two similar gratings formed on a single film need a much simpler fabrication process than the configuration in Fig. 1. A similar structure with different design requirements has been suggested for optical-interconnect⁶⁻⁸ and wavelength-division-multiplexing applications.⁹ With this configuration, when a suitable grating angle and index modulation are designed the values of $\nu_s = 2\pi$ and $\nu_p = 3/2\pi$ can be reached, and a highly polarization-selective element, i.e., $\eta_s = 0\%$ and $\eta_p = 100\%$, is obtained. In our design the operating wavelength is 780 nm (GaAlAs laser diode). For input coupler H_1 the reconstruction beam angle θ_{r1} is 0° , and the diffraction beam angle θ_{r2} can be found to be

$$\theta_{r2} = \cos^{-1} \frac{\nu_p}{\nu_s} = \cos^{-1} \frac{3/2\pi}{2\pi} = 41.4^\circ. \quad (4)$$

For the output conjugate coupler H_0 , $\theta_{r1} = 41.4^\circ$ and $\theta_{r2} = 0^\circ$. The calculated diffraction efficiencies for *s*-

and *p*-polarized fields versus the index modulation n_1 for a film thickness of $17 \mu\text{m}$ are illustrated in Fig. 3. It is shown that $\eta_s = 0\%$ and $\eta_p = 100\%$ when $n_1 = 0.080$, which gives the desired polarization-selective property. The index modulation value can be achieved by use of dichromated gelatin. In addition to the much simpler fabrication process, the ideal transmission efficiency of 100% for this new device is also greater than the 93% for the configuration shown in Fig. 1.

Our polarization-selective device was formed in dichromated gelatin prepared from a Kodak 649F photographic plate by the simplified procedure described by Georgekutty and Liu.¹⁰ With a shorter-wavelength recording technique, this component was recorded at 488-nm wavelength with two free-space input beams for substrate-mode operation at 780 nm.¹¹ The device was fabricated with $\eta_2 = 1.2\%$ and $\eta_p = 90.2\%$, which verified the property of a high degree of polarization selection. (Theoretically, with $\theta_{r2} = 48.2^\circ$ and $n_1 = 0.056$ we have $\eta_s = 100\%$ and $\eta_p = 0\%$, also highly polarization selective. However, this high diffraction angle of 48° causes much greater difficulty in device construction.¹¹) We also performed switching experiments, using our polarization-selective substrate-mode element in conjunction with a ferroelectric liquid crystal (FLC) at the input to control the state of the field polarization, as shown in Fig. 4. Figures 5(a) and 5(b) show the transmission images of *s* and *p* fields, respectively, from the configuration in Fig. 4. The FLC device was PV050-780 from Display, Inc. We controlled

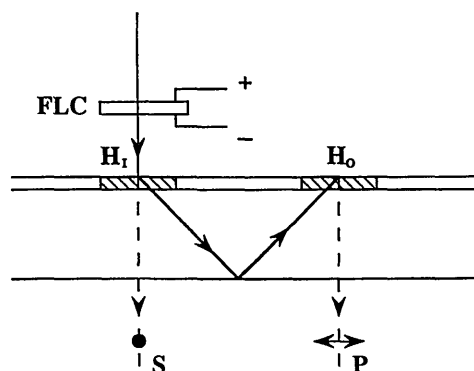


Fig. 4. Experimental configuration of polarization-selective switching.

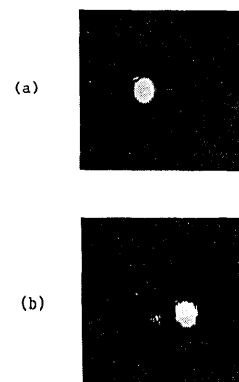


Fig. 5. Transmission images for polarization-selective switching experiments: (a) *s* field, (b) *p* field.

this FLC by the state of the electric input voltage to determine the output beam polarization state. The result demonstrates polarization-selective switching with our device. To enhance the selection contrast, the construction setup and the fabrication process must be more precisely controlled. However, this grating pair structure automatically provides a good way to meet the high-contrast requirement. With contrast of a value greater than 30 for one grating (for example, $\eta_p \geq 90\%$, $\eta_s \leq 3\%$, and $\tau_s \geq 90\%$ transmission, $\tau_p \leq 3\%$), the output contrast of the coupled channel (p field) from the pair is higher than 900. With one more grating on the transmission output side, the output contrast for the s field is also higher than 900. Therefore the process control requirement is greatly reduced.

In summary, a novel structure of a substrate-mode hologram has been presented, and the design has been discussed for highly polarization-selective applications. Normally incident and output coupling with this compact and lightweight device provides better flexibility and easier alignment for a system setup. The device has been fabricated for 780-nm operation. Polarization-selective switching experiments with this device have also been demonstrated.

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