Polarization-selective volume holograms: general design

Yang-Tung Huang

General design of polarization-selective volume holograms is discussed in detail. The required diffraction angles for these highly polarization-selective elements are calculated. An effective index-modulation parameter is defined and used to calculate the required index-modulation value at any specified operating wavelength. Design examples of operating wavelengths at 780, 830, 1050, 1300, and 1550 nm are given. Highly polarization-selective substrate-mode grating pairs for 780-nm operation were fabricated to verify the idea. These elements are suitable for applications in optical switching networks and magneto-optic data storage systems.

1. Introduction

The polarization-selective element is one of the key components in many system applications. In an optical multistage interconnection network the polarization-selective element in conjunction with electro-optic half-wave plates can form a basic optical switching cell.[1,2] Optical connection paths through this cell can be controlled by electric signals that drive the electro-optic half-wave plates. Using these switching cells with designed fixed connections between stages, one can build a programmable optical interconnection network. In an optical pickup head used for a magneto-optic data storage system the polarization-selective element is used to detect the rotation of the polarization of the beam reflected from the magneto-optic disk medium.[3]

Conventionally, Wallaston and Rochon prisms are used as polarization-selective elements. However, these bulky optical elements limit the system integration density and present alignment problems. In 1990, compact and lightweight polarization-selective holographic elements with a high diffraction angle (90°) were presented to replace these prism devices.[4] In 1992 a polarization-selective holographic element with a smaller angle (<90°) was also suggested for a multichannel optical switch suitable for integration.[5] In this paper the general design of a volume holographic element with a diffraction angle smaller than 90° to perform the polarization-selective function is discussed in detail. Based on the derived formulas, the required values of the grating angle and the index modulation for a polarization-selective element at a specified operating wavelength can be obtained. With available index-modulation values from conventional holographic recording materials, achievable conditions for these polarization-selective elements are also discussed in detail. In addition, the substrate-mode grating-pair structure is presented. Required parameter values for several examples of operating wavelengths at 780, 830, 1050, 1300, and 1550 nm are designed. Experimental results for polarization-selective elements are given, and the polarization-selective switching functions of these devices are demonstrated.

2. Design Formulas

For a transmission type of phase volume hologram, shown in Fig. 1, the relation between the diffraction efficiencies of s- and p-polarization fields, η_s and η_p, strongly depends on the diffraction angle, and is given as[6]

$$\eta_{s,p} = \sin^2 \nu_{s,p}, \tag{1}$$

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

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

$$\nu_p = \nu_s \cos(\theta_{r2} - \theta_{r1}). \tag{3}$$

λ is the reconstruction wavelength, d is the medium

The author is with the Department of Electronics Engineering and Institute of Electronics, National Chiao Tung University, Hsinchu 300, Taiwan, China.

Received 16 March 1993.
0003-6935/94/112115-06$06.00/0.

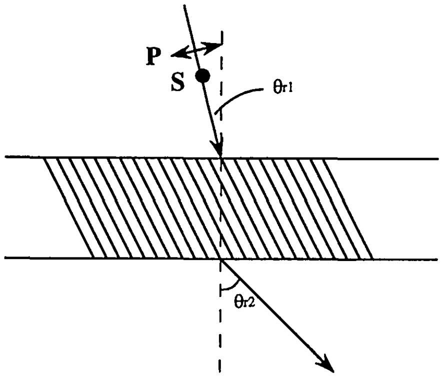

Fig. 1. Reconstruction geometry of a volume phase hologram: S, s-polarization field; P, p-polarization field.

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

From the diffraction efficiency formulas in Eqs. (1)–(3) it can be seen that when the diffraction angle, $|\theta_{r2} - \theta_{r1}|$, is 90° and ν_s is $[m - (1/2)]\pi$ (m is a positive integer), then $\eta_s = 100\%$ and $\eta_p = 0\%$, and a highly polarization-selective element can be obtained. This type of element has been investigated before, and a typical structure of a complete device is shown in Fig. 2.[4] With this type of polarization-selective element [polarization beam splitter hologram (H_{PBS})] the complete device requires additional input (H_I) and output (H_{OS}, H_{OP}) grating couplers, which result in additional fabrication processes and limit the total propagation efficiency.[7] In this paper we investigate another structure with a smaller diffraction angle (< 90°) to perform a highly polarization-selective property.

Since the hologram medium thickness d depends on the material and the processing, and since the reconstruction wavelength λ depends on the system requirement, a generalized parameter called the effective index modulation N_1 is defined as

$$N_1 = \frac{n_1 d}{\lambda}. \quad (4)$$

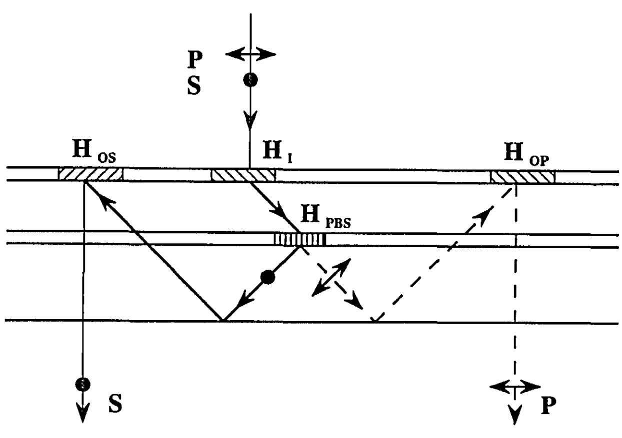

Fig. 2. Complete polarization-selective element with a substrate-mode hologram of the diffraction angle of 90°.

Then ν_s in Eq. (2) can be rewritten as a general form,

$$\nu_s = \frac{\pi N_1}{(\cos\theta_{r1}\cos\theta_{r2})^{1/2}}, \quad (5)$$

and ν_p is still given as Eq. (3). For a specified operating wavelength λ and a film thickness d, each N_1 value corresponds to one n_1 value, which is determined by the recording condition.

For a diffraction angle smaller than 90° there are two cases in which the hologram can perform a highly polarization-selective property:

(1) $\eta_s = 100\%$ and $\eta_p = 0\%$; i.e.,

$$\nu_s = [m + (1/2)]\pi, \quad (6a)$$

$$\nu_p = m\pi, \quad (6b)$$

where m is a positive integer.

(2) $\eta_s = 0\%$ and $\eta_p = 100\%$; i.e.,

$$\nu_s = m\pi, \quad (7a)$$

$$\nu_p = [m - (1/2)]\pi. \quad (7b)$$

With a suitable grating structure and index modulation in Eqs. (2) and (3), conditions in Eqs. (6a) and (6b) or (7a) and (7b) can be achieved, and a highly polarization-selective element can be obtained. The case of $\nu_s = 3\pi/2$ and $\nu_p = \pi$ has been briefly studied.[5] In this paper we discuss the general design in detail.

3. Polarization-Selective Substrate-Mode Grating Pairs

The basic structure of a substrate-mode grating pair is shown in Fig. 3. The reconstruction beam is normally incident upon the input coupling grating H_I and diffracted at an angle beyond the critical angle in the substrate, then propagates through the substrate with the total internal reflection to the output coupling grating H_O, and then it is normally coupled out with a conjugate diffraction. Compared with a conventional polarization beam splitting cube, normally incident and output coupling of this compact and

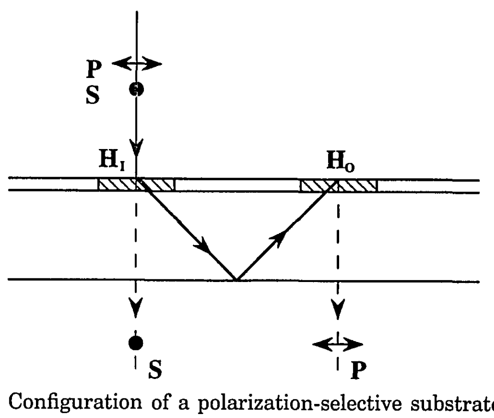

Fig. 3. Configuration of a polarization-selective substrate-mode grating pair.

lightweight component can provide better flexibility and easier alignment for system applications. Two identical gratings formed on a single film provide a much simpler fabrication process compared with the configuration in Fig. 2. A similar structure with different design requirements has been suggested for optical interconnect[8–10] and wavelength-division-multiplexing applications.[11]

In this substrate-mode structure, we have

$$\theta_{r1} = 0°, \quad \text{i.e.,} \quad \cos\theta_{r1} = 1. \tag{8}$$

Therefore the modulation parameters become

$$\nu_s = \frac{\pi N_1}{(\cos\theta_{r2})^{1/2}}, \tag{9a}$$

$$\nu_p = \pi N_1 (\cos\theta_{r2})^{1/2}. \tag{9b}$$

When two values of ν_s and ν_p in Eqs. (9a) and (9b) are specified as Eqs. (6a) and (6b) or (7a) and (7b) for a highly polarization-selective property, two simultaneous equations can be solved to obtain the two required values for $\cos\theta_{r2}$ and N_1, and the grating structure and the recording condition can be determined:

(1) $\eta_s = 100\%$ and $\eta_p = 0\%$ $\{\nu_s = [m + (1/2)]\pi$ and $\nu_p = m\pi\}$.

Substituting the values of ν_s in Eq. (6a) and ν_p in Eq. (6b) into Eqs. (9a) and (9b) gives

$$\frac{N_1}{(\cos\theta_{r2})^{1/2}} = m + (1/2), \tag{10a}$$

$$N_1(\cos\theta_{r2})^{1/2} = m. \tag{10b}$$

Solving Eqs. (10a) and (10b) yields

$$\cos\theta_{r2} = \frac{m}{m + (1/2)}, \quad \text{i.e.,} \ \theta_{r2} = \cos^{-1}\frac{m}{m + (1/2)}, \tag{11a}$$

$$N_1 = \{m[m + (1/2)]\}^{1/2}. \tag{11b}$$

Corresponding values of θ_{r2} and N_1 for different m values are listed in Table 1.

(2) $\eta_s = 0\%$ and $\eta_p = 100\%$ $\{\nu_s = m\pi$ and $\nu_p = [m - (1/2)]\pi\}$.

Using similar algebraic manipulations as in Subsection 3.A., solutions for θ_{r2} and N_1 can also be solved as

$$\cos\theta_{r2} = \frac{m - (1/2)}{m}, \quad \text{i.e.,} \ \theta_{r2} = \cos^{-1}\frac{m - (1/2)}{m}, \tag{12a}$$

$$N_1 = \{[m - (1/2)]m\}^{1/2}. \tag{12b}$$

Corresponding values of θ_{r2} and N_1 for different m values are listed in Table 2.

For conventional holographic recording materials the maximum achievable index modulation is ~ 0.1. Figure 4 shows curves of the N_1 value versus the n_1 value for λ equal to 780, 830, 1050, 1300, and 1550 nm, respectively, and with a typical film thickness of $d = 17$ μm. These curves provide useful design information. For a maximum n_1 of 0.1, the corresponding value of N_1 is 2.18, 2.05, 1.62, 1.31, and 1.10 for λ equal to 780, 830, 1050, 1300, and 1550 nm, respectively. With this film thickness of 17 μm the condition of $m = 1$ ($N_1 = 1.22$) in Table 1 can be achieved for λ equal to 780, 830, 1050, and 1330 nm but not for 1550 nm; for $m \geq 2$ in Table 1 the required N_1 values (≥ 2.24) cannot be achieved unless d/λ can be significantly increased since the N_1 value is proportional to d/λ, as shown in Eq. (4). Similarly in Table 2 the condition of $m = 1$ ($N_1 = 0.707$) can be achieved for all five wavelengths, but the condition of $m = 2$ ($N_1 = 1.73$) can be achieved only for 780 and 830 nm; for $m \geq 3$ in Table 2 the required N_1 values (≥ 2.74) cannot be achieved unless d/λ can be significantly increased.

For these three achievable values of $N_1 = 1.22$ (Table 1), $N_1 = 0.707$ (Table 2), and $N_1 = 1.73$ (Table 2) the corresponding values of θ_{r2} are 48.2°, 60.0°, and 41.4°, respectively, which are greater than the critical angle of $\sim 40°$. In these three cases a polarization-selective substrate-mode grating pair can be formed. With these required values of N_1 equal to 0.707, 1.22, and 1.73 the corresponding n_1 values for various operating wavelengths with a typical film thickness of $d = 17$ μm are shown in Fig. 5, which also provides useful design information. With $\lambda = 780$ nm (GaAlAs laser diode) as the design example, the index modulation n_1 is 0.032, 0.056, and 0.080 for N_1 equal to 0.707, 1.22, and 1.73, respectively, and can be achieved with dichromated gelatin material. The required index modulation values for other operating wavelengths can also be obtained from Fig. 5. With the corresponding designed diffraction angle of 60.0°, 48.2°, and 41.4°, respectively, the polarization-

Table 1. Grating Parameters for $\eta_s = 100\%$ and $\eta_p = 0\%$

	m				
	1	2	3	4	5
$\cos\theta_{r2}$	2/3	4/5	6/7	8/9	10/11
θ_{r2}	48.2°	36.9°	31.0°	27.3°	24.6°
N_1	1.22	2.24	3.24	4.24	5.24

Table 2. Grating Parameters for $\eta_s = 0\%$ and $\eta_p = 100\%$

	m				
	1	2	3	4	5
$\cos\theta_{r2}$	1/2	3/4	5/6	7/8	9/10
θ_{r2}	60.0°	41.4°	33.5°	29.0°	25.8°
N_1	0.707	1.73	2.74	3.74	4.74

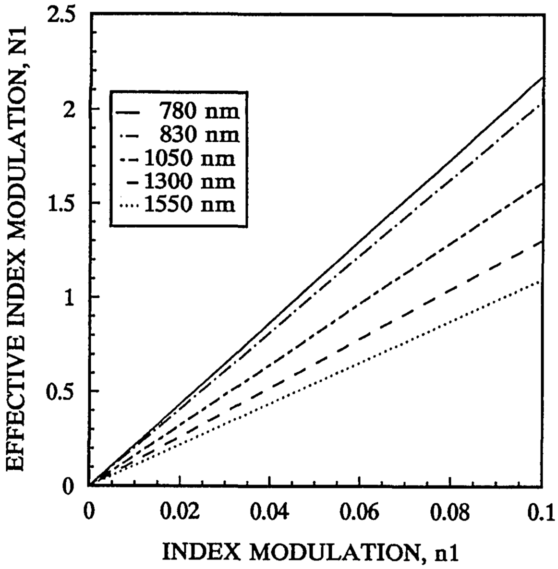

Fig. 4. Effective index modulation value N_1 versus index modulation value n_1 for film thickness 17 μm and operating wavelengths of 780, 830, 1050, 1300, and 1550 nm.

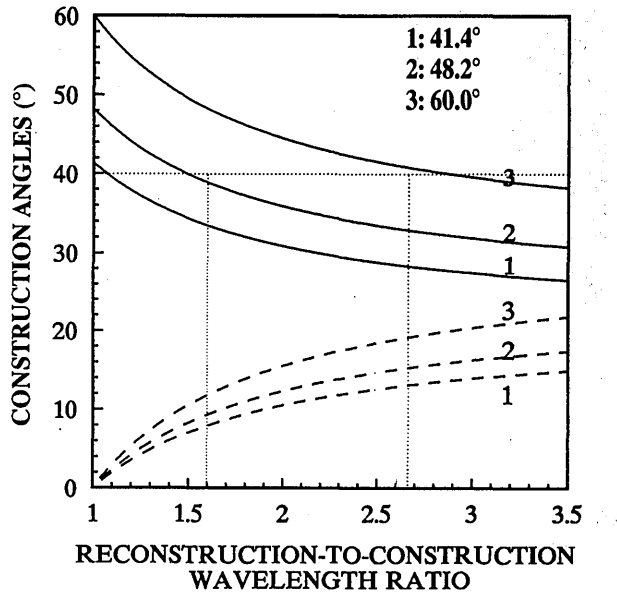

Fig. 6. Required angles of the recording reference and object beams in the emulsion as the functions of the reconstruction-to-construction wavelength ratio with designed diffraction angles of 41.4°, 48.2°, and 60.0°: dashed curves, reference beams; solid curves, object beams.

selective substrate-mode grating pair can be designed.

4. Preliminary Experimental Results

Our polarization-selective elements were formed in dichromated gelatin prepared from Kodak 649F photographic plate and by use of the simplified procedure presented by Georgekutty and Liu.[12] With the shorter-wavelength recording technique a substrate-mode holographic element can be recorded with two free-space input beams at a visible wavelength and designed for infrared operation.[13,14] For our polarization-selective elements with normally incident reconstruction the required diffraction angle is 41.4°, 48.2°, or 60.0° in the emulsion. For these three conditions the required angles of the recording reference and object beams in the film with various reconstruction-to-construction wavelength ratios are shown in Fig. 6.[13,14] Since the critical angle in the emulsion is ~40°, the recording angles of the reference and the object beams must be less than this critical angle. In our experiments the components were recorded at 488-nm wavelength and designed for substrate-mode operation at 780 nm. In this case the reconstruction-to-construction wavelength ratio is 1.60; the conditions of the diffraction angle of 48.2° or 60.0° in the emulsion cannot be achieved by recording with two free-space input beams because of their high diffraction angles, as shown in Fig. 6. Therefore we used

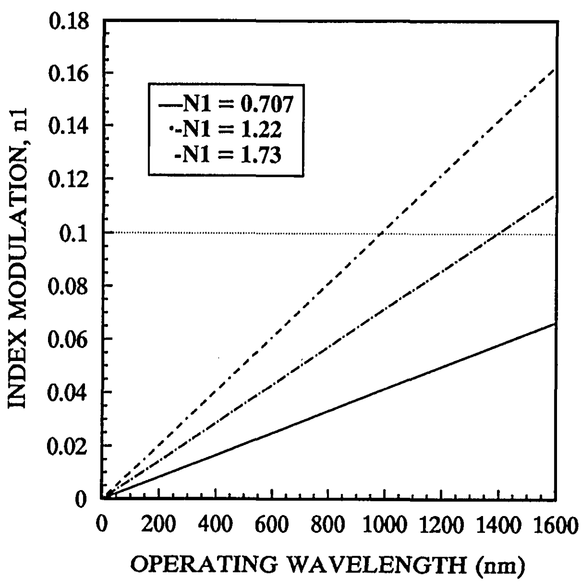

Fig. 5. Required index modulation value n_1 for various operating wavelengths with film thickness of 17 μm and designed effective index modulations N_1 of 0.707, 1.22, and 1.73.

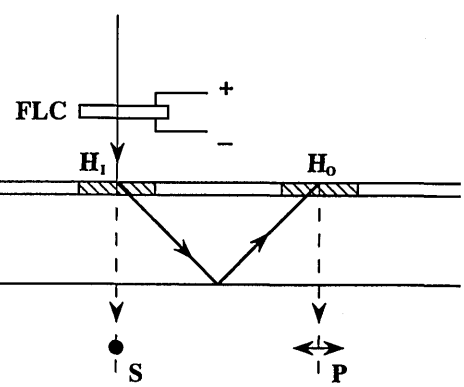

Fig. 7. Experimental configuration of polarization-selective switching.

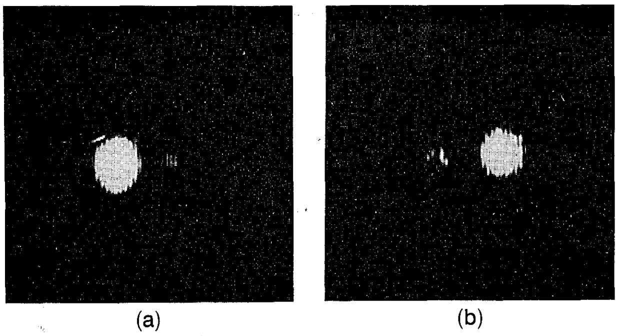

Fig. 8. Transmission images for polarization-selective switching experiments: (a) s field, (b) p field.

the case $\theta_{r2} = 41.4°$ and $n_1 = 0.08$ as the design parameter for our preliminary experiments. (For operation at a longer wavelength of 1300 nm with a higher reconstruction-to-construction wavelength ratio of 2.66, the diffraction angle of 48.2° can be achieved with this technique.) The device with $\eta_s = 1.2\%$ and $\eta_p = 90.2\%$ was fabricated, which verified the property of high polarization selectivity. Switching experiments shown in Fig. 7 were also performed by use of our polarization-selective substrate-mode element with a ferroelectric liquid crystal (FLC) at the input, which was used to control the state of the field polarization. Figures 8(a) and 8(b) show the transmission images of the s and the p fields, respectively, from the configuration shown in Fig. 7. The FLC device was a PV050-780 from Display, Inc. This FLC was controlled by the state of the electric input voltage to determine the output-beam polarization state. The results demonstrate the polarization-selective switching function obtained with our device.

To enhance the selection contrast, one must control more precisely the construction setup and the fabrication process. However, this grating-pair structure automatically provides a good way to meet the high-contrast requirement. If (η_s, η_p) and (τ_s, τ_p) are the diffraction and the transmission efficiencies, respectively, of each grating for s and p fields, then the contrast for the diffraction channel (p channel in our case) is given as $(\eta_p/\eta_s)^2$. With one more symmetric grating on the transmission output side, as shown in Fig. 9, the output contrast for the transmission channel (s channel in our case) is given as $(\tau_s/\tau_p)^2$. The propagation efficiencies for the two channels are $\eta_p{}^2$ (p channel) and $\tau_s{}^2$ (s channel). With the contrast of a value greater than 30 for each grating (for example, $\eta_p \geq 90\%$, $\eta_s \leq 3\%$, $\tau_s \geq 90\%$, and $\tau_p \leq 3\%$) the output contrast for the combined channels of the grating pair is higher than 900. The contrast of 30 for each grating is not difficult to achieve. Therefore the process control requirement is highly reduced with this structure.

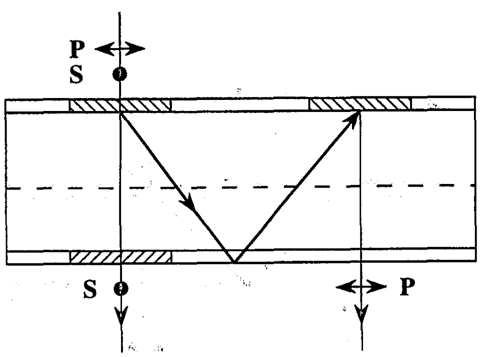

Fig. 9. Typical structure of a substrate-mode grating pair to enhance the polarization-selective contrast for both output channels.

5. Summary

The general design of a volume holographic element to perform the polarization-selective function is discussed in detail. A generalized device parameter, the effective index modulation, is introduced for general design consideration. With this parameter the required values of the grating angle and the index modulation for a polarization-selective element at a specified operating wavelength are obtained. With available index-modulation values from conventional holographic recording materials, achievable conditions for these polarization-selective elements are discussed in detail. In addition, the substrate-mode grating-pair structure is presented. Normally incident and output coupling with this compact and lightweight device provides better flexibility and easier alignment for a system setup. Required parameter values for several examples of operating wavelengths at 780, 830, 1050, 1300, and 1550 nm are designed. Highly polarization-selective elements for 780-nm operation have been fabricated. Polarization-selective switching experiments with this device have also been demonstrated.

This work was supported by the National Science Council of China under contract NSC81-0417-E-009-623.

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