研 究

Optical Implementation of Logic Operations Using Photoinduced Anisotropy in Amorphous As_2S_3 Thin Film

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Boolean logic operations are optically implemented in a spatial light modulator (SLM) which uses photoinduced anisotropy in amorphous As_2S_3 thin films. The SLM consists of the anisotropic As_2S_3 thin films and a pair of polarizers. The analytic expressions of the output intensities of the reading beam transmitted through SLM are derived as functions of the third-order nonlinear susceptibilities of the thin film and the polarization angle of the reading beam. The experiment is carried out for two binary inputs placed between a polarizer and an analyzer. All sixteen Boolean logic operations are realized.

1. Introduction

The optical logic gate is one of the fundamental functions in the optical digital computer under exploration. A variety of optical logic gates have been reported.[1-7] In general, optical logic operation can be realized by combining fundamental image-processing techniques such as addition, subtraction, and contrast reversal.

Photoinduced anisotropy (PIA) in amorphous As_2S_3 thin film, which was discovered by Hajto and Ewen[8] and Zhdanov *et al.*[9] is one of the attractive phenomena of optical image processing. The kinetics,[10,11] the correlation with photodarkening,[12] and the application[13] of the PIA in amorphous As_2S_3 thin film have been investigated by various groups. In the previous paper,[14] we demonstrated a method of image processing-addition, subtraction, selective reconstruction, and constrast reversal-using PIA in amorphous As_2S_3 thin films which can be applied to the optical logic gate.

In this paper, we report a new application of PIA in amorphous As_2S_3 thin films in the optical implementation of Boolean logic operations. Two input images are recorded on the nonlinear media, and they are read out in series from the medium through an analyzer. Basic properties of the present spatial light modulator (SLM) are described.

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2. Spatial Light Modulator Based on Photoinduced Anisotropy

The basic construction of a SLM which employs PIA is shown in **Fig. 1** (A). The SLM consists of a nonlinear medium with PIA, and a set comprising crossed polarizer and analyzer. PIA can be produced by a linearly polarized intense laser beam, and the medium M with the induced anisotropy acts like an uniaxial crystal having an opticaxis parallel to the recording beam polarization. When the reading beam propagates through SLM, the polarization is changed due to anisotropy of the medium, and the output signal depends on transmission angle v of the polarizer and the analyzer. The output signal of SLM using PIA can be expressed in terms of third-order nonilnear susceptibilities. Since the amorpuous As_2S_3 thin film is isotropic, the nonvanishing independent elements of the third-order nonlinear susceptibilities are $\chi^{(3)}_{1221}$, $\chi^{(3)}_{1122}$, $\chi^{(3)}_{1212}$, and $\chi^{(3)}_{1111}=\chi^{(3)}_{1221}+\chi^{(3)}_{1122}+\chi^{(3)}_{1212}$. When

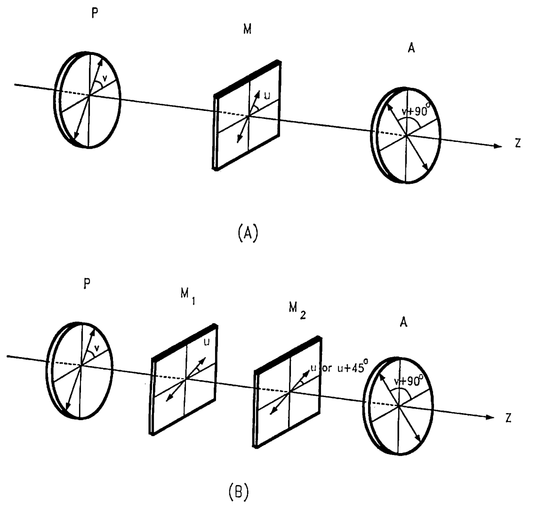

Fig. 1 The structure of spatial light modulator using photoinduced anisotropy on amorphous As_2S_3 thin film. (A) One nonlinear medium is sandwiched between crossed polarizers. (B) Two nonlinear media are sandwiched between crossed polarizers. The anisotropic axes of two medium are parallel or 45° angled with respect to each other.

the recording beam $E(\omega)$ is linearly polarized along a direction at an angle u with respect to the x-axis and the reading beam $C(\omega')$ at an angle v, the x and y components of the nonlinear polarization at frequency ω' are given by

$$P_x^{(3)}(\omega')=[\chi_{1111}^{(3)}E^2\cos u+\chi_{1122}^{(3)}E^2\sin u]C(\omega')\cos v+\frac{1}{2}[\chi_{1111}^{(3)}-\chi_{1122}^{(3)}]E^2\sin 2uC(\omega')\sin v,$$
$$P_y^{(3)}(\omega')=[\chi_{1111}^{(3)}E^2\sin u+\chi_{1122}^{(3)}E^2\cos u]C(\omega')\sin v+\frac{1}{2}[\chi_{1111}^{(3)}-\chi_{1122}^{(3)}]E^2\sin 2uC(\omega')\cos v, \quad (1)$$

where $E^2=|E(\omega)|^2$ is the recording beam intensity. Since the analyzer is crossed to reading beam polarization, the parallel component of nonlinear polarization to the transmission axis of the analyzer, $P_{\text{out}}^{(3)}(\omega')$, is

$$P_{\text{out}}^{(3)}(\omega')=P_x^{(3)}(\omega')\sin v-P_y^{(3)}(\omega')\cos v=\frac{1}{2}[\chi_{1111}^{(3)}-\chi_{1122}^{(3)}]C(\omega')E^2\sin 2(v-u), \quad (2)$$

where $\chi_{1111}^{(3)}-\chi_{1122}^{(3)}(\cong 6.4\times 10^{-4}\ \text{esu})$[13] is the PIA in isotropic As_2S_3 media.[15] The intensity of the output signal obtained after the analyzer is given by

$$I(\omega')\propto|P_{\text{out}}^{(3)}|^2\propto\frac{1}{4}[\chi_{1111}^{(3)}-\chi_{1122}^{(3)}]^2|C(\omega')|^2E^4\sin^2 2(v-u). \quad (3)$$

Another type of SLM which consists of two anisotropic media, a polarizer, and an analyzer is shown in Fig. 1 (B). The output signal of this SLM is given by a function of the angle between the anisotropic axis of each medium. We consider only two simple cases. One is that in which the anisotropic axes of the media are parallel, and the other is the case in which the anisotropic axes are at 45° angles. When the anisotropic axes of two media are parallel, the output signal observed after analyzer can be obtained using Jones calculus[16] as follows,

$$I(\omega')\propto\frac{1}{4}[\chi_{1111}^{(3)}-\chi_{1122}^{(3)}]^2|C(\omega')|^2\times(E_1{}^2+E_2{}^2)^2\sin^2 2(v-u), \quad (4)$$

where $E_1{}^2$ and $E_2{}^2$ are the intensities of the recording beam on the medium M_1 and M_2, respectively. When the anisotropic axis of the medium M_1 is set at an angle u and the anisotropic axis of the medium M_2 is $u+45°$ with respect to the x-axis, the output signal can be obtained in the same way, substituting u in Eq. (3) by $u+45°$ and using Jones calculus,

$$I(\omega')\propto\frac{1}{4}[\chi_{1111}^{(3)}-\chi_{1122}^{(3)}]^2|C(\omega')|^2\times\{E_1{}^2\sin 2(v-u)+E_2{}^2\cos 2(v-u)\}^2. \quad (5)$$

These intensity modulations of the readout beam by passing through the SLM, given by Eqs. (3), (4), and (5), are applied to logical processing of the two-dimensional image recorded in the medium.

3. Experiments

A Boolean logic consists of two binary inputs and a single output; i.e., the result of a logic operation applied to two input images is obtained as a single output image. **Table 1** shows all sixteen possible functions of two binary inputs. To demonstrate the logical operation, the binary patterns depicted in **Fig. 2** are used as inputs ***A*** and ***B***. The input ***A*** has the vertical strip (assigned by a) in which the anisotropic axis, u, is oriented parallel to the x-axis and in the rest (assigned by $\bar{a}$), the anisotropic axes form a 45° angle. The input ***B*** consists of the horizontal strip (b) and the rest ($\bar{b}$) in which the anisotropic axes are indicated with arrows.

In the experiment, two inputs are prepared by recording the patterns on two amorphous As_2S_3

Table 1 Boolean logic algebra for two binary inputs.

Input		Output															
A	B	F	AND	$A \cdot \bar{B}$	A	$\bar{A} \cdot B$	B	XOR	OR	NOR	XNOR	$\bar{B}$	$A+\bar{B}$	$\bar{A}$	$\bar{A}+B$	NAND	T
0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
0	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
1	0	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
1	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

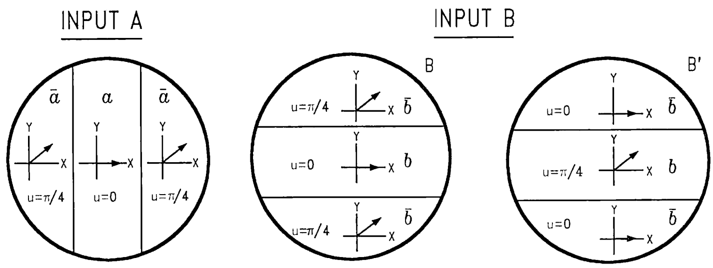

Fig. 2 Input ***A*** and ***B*** recorded on amorphous As_2S_3 thin film and the recording state. Arrows represent the anisotropic axes.

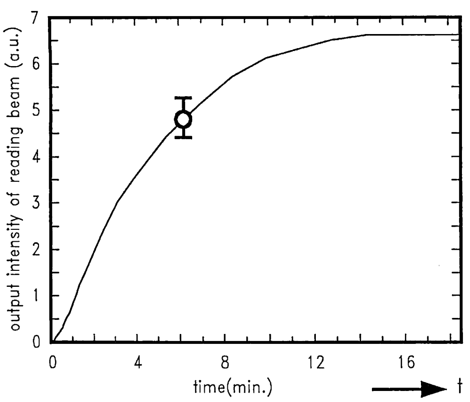

Fig. 3 Asymptotically increasing behavior of photoinduced anisotropy in As_2S_3 thin film under illumination of the linearly polarized Ar^+ ion laser beam with 200 mW/cm^2 power density.

thin films which have the same thickness (3 μm). The amorphous As_2S_3 thin films are prepared by the vacuum evaporation method and annealed in vacuum for 30 minutes near the glass transition temperature (450 K) for uniform composition. The anisotropy is induced by linearly polarized Ar^+ ion laser beam ($\lambda=514.5$ nm). **Figure 3** shows the recording behavior of PIA in As_2S_3 thin film with 200 mW/cm^2 power density.[9] The output signal is monitored by using a polarized probe beam (He-Ne laser beam, $\lambda=632.8$ nm and $v=45°$).

Figure 4 shows the experimental setup for logic operations. Two inputs, ***A*** and ***B***, encoded by PIA as shown in Fig. 2 and a polarizer (P) and an analyzer (An) are arranged along the z-axis. Note that An is always crossed to P. Imaging lenses are used for the reduction of Fresnel diffraction noise.

In optical implementation, the sixteen logic operations can be classified into three categories as follows.

Group (i): The operations ***A***, $\bar{\boldsymbol{A}}$, ***B***, $\bar{\boldsymbol{B}}$ and ***F*** shown in Table 1 are included in this group in which we use a single input ***A*** or ***B***. When one of the two inputs is removed from the experimental setup shown in Fig. 4, the remaining system can be treated as the SLM containing one nonlinear medium described in section 2. If input ***A*** remains, the output signal I_a of the area a and $I_{\bar{a}}$ of the area $\bar{a}$ are obtained by introducing $u=0$ and 45° into Eq. (3), respectively. They are given by

$$I_a \sim E^4 \cos^2 2v,$$
$$I_{\bar{a}} \sim \bar{E}^4 \sin^2 2v, \qquad (6)$$

where E^2 and $\bar{E}^2$ are respective recording beam intensities of the areas a and $\bar{a}$. In the experiment, we choose to let the recording beams of the two areas have equal intensities. From Eq. (6), the logic operations ***A*** and $\bar{\boldsymbol{A}}$ are obtained by setting the transmission angle of the polarizer P at $v=0$ (where $I_a \sim E^4$ and $I_{\bar{a}} \sim 0$) and $v=45°$ (where $I_a \sim 0$ and $I_{\bar{a}} \sim \bar{E}^4$). If the transmission angle of the polarizer P is set at $v=22.5°$, the output signal is given by $I_a \sim E^4/2$ and $I_{\bar{a}} \sim \bar{E}^4/2$. It represents the uniform dark level and indicates operation ***F***. In the same way, we can obtain the

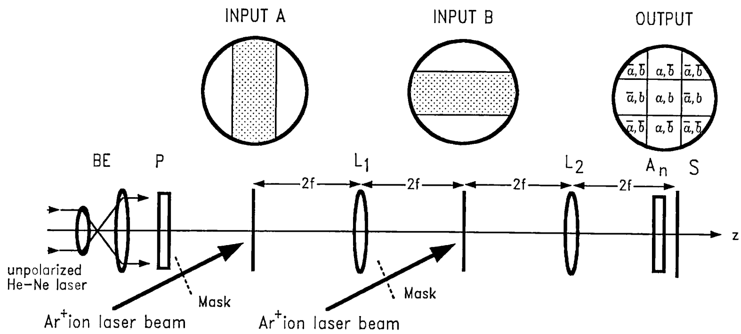

Fig. 4 Experimental setup for implementing the logic operations. Two inputs are arranged in tandem. BE; beam expander, L_1, L_2; lenses, S; photographic film, P; polarizer, An; analyzer. P and An are always crossed by 90°.

Table 2 Output intensities of Boolean logic functions.

Group (i)

Input A	Input B	Output (relative intensity) A	$\bar{A}$	B	$\bar{B}$	F
D	D	D (0)	B (1)	D (0)	B (1)	D (0.5)
D	B	D (0)	B (1)	B (1)	D (0)	D (0.5)
B	D	B (1)	D (0)	D (0)	B (1)	D (0.5)
B	B	B (1)	D (0)	B (1)	D (0)	D (0.5)
Angle (deg.)		0	45	0	45	22.5

D; dark level, B; bright level

Group (ii)

Input A	Input B	Output (relative intensity) OR	AND	XNOR	NOR	NAND	T
D	D	D (0)	D (0.4)	B (2)	D (0)	B (4)	B (2)
D	B	B (1)	D (0.4)	D (0)	B (2)	B (1)	B (2)
B	D	B (1)	D (0.4)	D (0)	B (2)	B (1)	B (2)
B	B	B (4)	B (3.6)	B (2)	D (0)	D (0)	B (2)
Angle (deg.)		0	v_1	22.5	v_2	45	67.5

$v_1=\frac{1}{2}\sin^{-1}\left(\sqrt{\frac{1}{10}}\right)$, $v_2=\frac{1}{2}\cos^{-1}\left(\sqrt{\frac{1}{10}}\right)$

Group (iii)

Input A	Input B	Output (relative intensity) $A+\bar{B}$	$A\cdot\bar{B}$	XOR	$\bar{A}\cdot B$	$\bar{A}+B$
D	D	B (4)	D (0)	B (2)	D (0)	D (0.4)
D	B	B (1)	B (2)	D (0)	B (1)	D (0.4)
B	D	B (1)	B (2)	D (0)	B (1)	D (0.4)
B	B	D (0)	D (0)	B (2)	B (4)	B (3.6)
Angle (deg.)		0	v_1	22.5	v_2	45

$v_1=\frac{1}{2}\sin^{-1}\left(\sqrt{\frac{1}{10}}\right)$, $v_2=\frac{1}{2}\cos^{-1}\left(\sqrt{\frac{1}{10}}\right)$

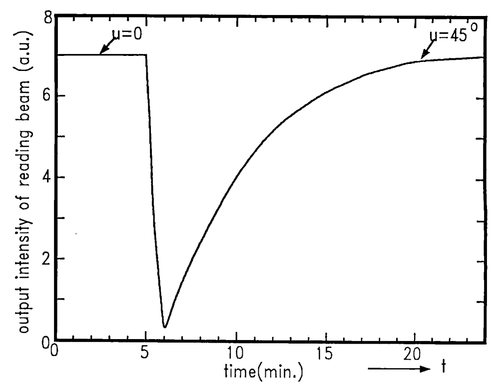

Fig. 5 Temporal behavior of reorientation of anisotropic axis in As_2S_3 thin film by changing recording beam polarization. The anisotropic axis is changed at $t=5$ (min.) from $u=0$ to $u=45°$, and the reading beam polarization is fixed as $v=22.5°$.

operations ***B*** and $\bar{\boldsymbol{B}}$ using input ***B***. The output intensities and the corresponding logic operations are listed in **Table 2**.

Group (ii): The operations **AND, OR, XNOR, NOR, NAND,** and **T** are included in this group. They belong to the two media cases discussed in section 2. These operations are by the same two inputs. When two inputs are superposed, there are four areas, (a, b), $(a, \bar{b})$, $(\bar{a}, b)$, and $(\bar{a}, \bar{b})$, on the output plane as shown in Fig. 4. The output signal is obtained by substituting $u=0$ (a or b) and $u=45°$ ($\bar{a}$ or $\bar{b}$) into Eqs. (4) and (5). They are given by

$$I_{ab} \sim (E_1^2+E_2^2)^2\cos^2 2v$$
$$I_{a\bar{b}} \sim (E_1^2\cos 2v-\bar{E}_2^2\sin 2v)^2$$
$$I_{\bar{a}b} \sim (\bar{E}_1^2\sin 2v-E_2^2\cos 2v)^2$$
$$I_{\bar{a}\bar{b}} \sim (\bar{E}_1^2+\bar{E}_2^2)^2\sin^2 2v. \quad (7)$$

From Eq. (7), we obtain the output intensities of each area as a function of the polarization angle of

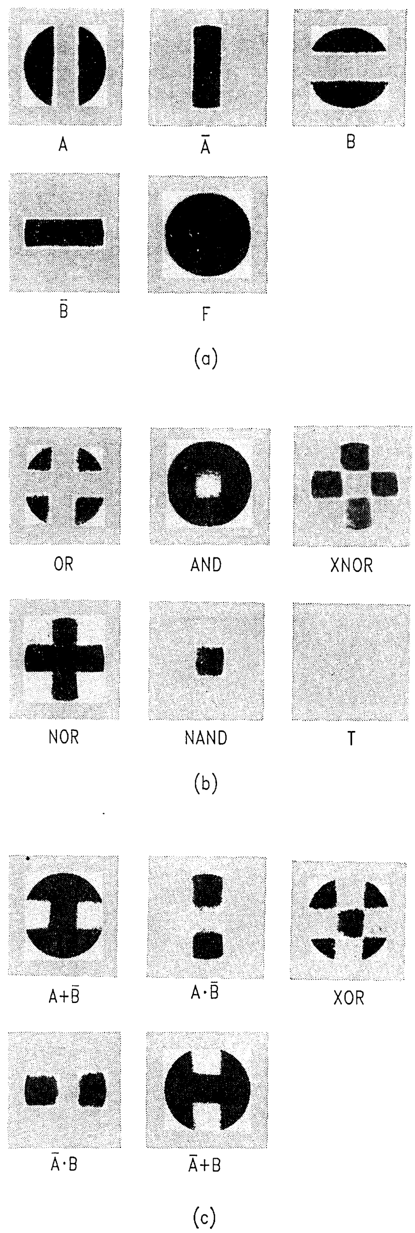

Fig. 6 Experimental results of the sixteen logic operations for two binary inputs. The results of (a); group (ⅰ), (b); group (ⅱ), and (c); group (ⅲ).

the reading beam. The output intensities and the corresponding logic operations are listed in Table 2.

Group (ⅲ): $\boldsymbol{A+\bar{B}}$, $\boldsymbol{A\cdot\bar{B}}$, ***XOR***, $\boldsymbol{\bar{A}+B}$, and $\boldsymbol{\bar{A}\cdot B}$ operations are included in this group. To implement these operations, we should change the coding state of input $\boldsymbol{B}$ to $\boldsymbol{B'}$. Since the PIA of amorphous As_2S_3 thin film has reversibility, the anisotropic axis can be changed to a new direction by a recording beam with different polarization. **Figure 5** shows the temporal behavior of the anisotropic axis change from $u=0$ to 45°. The signal is monitored by the reading beam with polarization angle $v=22.5°$, and the recording beam polarization is changed at $t=5$ (min) from $u=0$ to 45° with respect to the x-axis. Then the output intensity can be obtained from Eqs. (4) and (5):

$$I_{ab} \sim (E_1^2 \cos 2v - E_2^2 \sin 2v)^2$$
$$I_{a\bar{b}} \sim (E_1^2 + \bar{E}_2^2)^2 \cos^2 2v$$
$$I_{\bar{a}b} \sim (\bar{E}_1^2 + E_2^2)^2 \sin^2 2v$$
$$I_{\bar{a}\bar{b}} \sim (\bar{E}_1^2 \sin 2v - \bar{E}_2^2 \cos 2v)^2. \qquad (8)$$

The resultant output intensities and the corresponding logic operations are given in Table 2.

4. Results and Conclusions

Figure 6 shows the experimental results photographed at the observation screen. Figures 6 (a), (b) and (c) show the results of groups (ⅰ), (ⅱ) and (ⅲ), respectively. From Table 2, we know that some operations have intermediate intensity levels between zero and maximum intensities. They may be hardclipped or thresholded to obtain a binary output such that intensity levels higher than or equal to 1 are bright levels and those lower than 1 are dark levels.

In conclusion, we have demonstrated the sixteen logic operations using PIA in As_2S_3 thin film. The operation principle of SLM using PIA is analyzed in terms of third-order nonlinear susceptibilities and the polarization angle of the probe beam. Implementation of the five operations in group (ⅲ) necessitates changing the direction of the anisotropic axis, which requires too long a reorientation time in this material. We are looking for new material which has faster time response in reorienting of the anisotropic axis for practical applications.

References

1) J. Tanida and Y. Ichioka: "Optical logic array processor using shadowgram," J. Opt. Soc. Am., **73** (1983) 800–806.
2) J. Weigelt: "Binary logic by spatial filtering," Opt. Eng., **26** (1987) 28–34.
3) T. Minemoto, K. Okamoto and K. Miyamoto: "Optical parallel logic gate using spatial light modulator with the Pokels effect," Appl. Opt., **24** (1985) 2055–2063.
4) K. Takizawa, H. Kikuchi, T. Aida and M. Okada: "Optical parallel logic gate using a Pokels readout optical modulator and twisted nematic liquid-crystal cells," Opt. Lett., **14** (1989) 208–210.
5) M. T. Fatehi, K. C. Wasmundt and S. A. Collins, Jr.: "Optical logic gates using liquid crystal light valve: implementation and application example," Appl. Opt

20 (1981) 2250–2256.

6) F. T. S. Yu, Q. W. Song and X. J. Lu: "Implementation of Boolean logic using a michrochannel spatial light modulator with liquid-crystal televisions," Opt. Lett., **12** (1987) 962–964.

7) F. T. S. Yu, S. Jutamulia and D. A. Gregory: "Real time liquid crystal TV XOR- and XNOR-gate binary image subtraction technique," Appl. Opt., **26** (1987) 2738–2745.

8) J. Hajto and P. J. S. Ewen: "Natural optical activity and related phenomena in As_2S_3 glasses," Phys. Status Solidi (a), **54**, (1979) 385–390.

9) V. G. Zhdanov, B. T. Kolomiets, V. M. Lyubin and V. K. Malinovskii: "Photoinduced optical anisotropy in chalcogenide viterious semiconducting films," Phys. Status Solidi (a), **52** (1979) 621–626.

10) J. M. Lee, G. Pfeiffer, M. A. Paesler, D. E. Sayers and A. Fontaine: "Photon intensity-dependent darkening kinetics in optical and structural anisotropy in a—As_2S_3: a study of X-ray absorption spectroscopy," J. Non-Cryst. Solids, **114** (1989) 52–54.

11) J. M. Lee and M. A. Paesler: "Kinetics of laser-induced phenomena in glassy As_2S_3," J. Non-Cryst. Solids, **97** & **98** (1987) 1235–1238.

12) K. Kimura, K. Murayama and T. Ninomiya: "Change in optical anisotropy of localized states associated with reversible photostructural change in a-As_2S_3 films," J. Non-Cryst. Solids, **77** & **78** (1985) 1203–1206.

13) C. H. Kwak, J. T. Kim and S. S. Lee: "Scalar and vector holographic grating recorded in a photoanisotropic amorphous As_2S_3 thin film," Opt. Lett., **13** (1988) 437–439.

14) C. H. Kwak, J. T. Kim and S. S. Lee: "Optical image processing in photoanisotropic amorphous As_2S_3 thin film," Appl. Opt., **28** (1989) 734–744.

15) S. Saikan: "Angular momentum dependence of laser-induced birefringence and dichroism in atomic resonance lines," J. Opt. Soc. Am. **68** (1978) 1184–1187.

16) A. Yariv and P. Yeh: *Optical Waves in Crystals* (John Wiley & Sons, New York, 1985).