Proc. Natl. Sci. Counc. ROC(A)
Vol. 20, No. 5, 1996. pp 532-537

(Scientific Note)

Polarization-Dependent Fanning along Negative C Axis in $BaTiO_3$

HSIN-HUA CHANG*, CHING-CHERNG SUN**,†, JENQ-YANG CHANG*, REN-HAN TSOU*, AND MING-WEN CHANG*

*Institute of Optical Sciences,
National Central University
Chung-Li, Taiwan, R.O.C.
**Electronic Engineering Department
Chine Hsin College of Technology & Commerce
Chung-Li, Taiwan, R.O.C.

(Received November 15, 1995; Accepted April 24, 1996)

ABSTRACT

A fanning structure with the incident beam along the negative optics axis of $BaTiO_3$ is demonstrated. Fanning is allowed in the plane which is constructed by the optics axis and the polarization of the incident beam. From the theoretical calculations and the experimental measurements of the fanning angles, we conclude that the fanning direction results from more than one amplification of the scattered light.

Key Words: fanning, photorefractive effect, $BaTiO_3$

I. Introduction

Fanning in a photorefractive crystal is an interesting phenomenon which has been intensively studied (Huignard and Gunter, 1988, 1989; Voronov *et al.*, 1980; Gu and Yeh, 1991; Segex *et al.*, 1993; Parshall *et al.*, 1995; Banerjee and Misra, 1993; Feinberg, 1982). In addition, fanning is useful in understanding how large the coupling gain of a crystal is and whether the crystal can be used as a self-pumped phase conjugator (Feinberg, 1982). Fanning is caused by amplification of the scattered light (Voronov *et al.*, 1980). The amplification is a function of the space charge field and the electro-optic coefficient of the crystal, and it depends on the incident conditions (Banerjee and Misra, 1993; Sun *et al.*, 1992). $BaTiO_3$ is one of the crystals which typically fans easily. From the point of view of application, fanning in $BaTiO_3$ leads to generation of a self-phase conjugate wave (Feinberg, 1982). In this paper, we demonstrate a fanning structure in which the incident light is along the negative C axis. The fanning plane is polarization-dependent. We analyze the fanning structure and find that the fanning results from more than one amplification process, i.e., the fanning light at turns least twice.

II. Polarization-Dependent Fanning Plane in $BaTiO_3$

Fanning is the result of amplification of scattered light. In other words, it is the result of two-beam coupling between scattered light and incident light, and/or between more than one source of scattered light. Two-beam coupling can be expressed as (Yeh, 1989)

$$I(l) = I(0)\frac{1+m}{1+me^{-\Gamma}}e^{-\alpha l}, \quad (1)$$

where m is the initial intensity ratio, α is the absorption coefficient, l is the interaction length and Γ is the coupling strength, which is defined as

$$\Gamma = \gamma l, \quad (2)$$

where γ is the coupling parameter. The coupling parameter is a function of the polarization of the interaction light. Here, we define γ_e as the coupling parameter for the extraordinary polarization light, and

†To whom all correspondence should be addressed

γ_o as the coupling parameter of the ordinary polarization light, and they can be expressed as (MacDonald and Feinberg, 1983)

$$\gamma_e = \frac{\pi\cos(\alpha_f-\alpha_i)}{\lambda n\cos(\frac{\alpha_f-\alpha_i}{2})}\frac{K_BT}{q}\frac{K_g}{1+(\frac{K_g}{K_o})^2}$$

$$\times n_o^4\gamma_{13}\sin\alpha_i\sin\alpha_f\cos\beta+n_o^2n_e^2\gamma_{42}\sin^2\beta$$

$$+n_e^4\gamma_{33}\cos\alpha_i\cos\alpha_f\cos\beta, \quad (3)$$

and

$$\gamma_o = \frac{\pi\cos(\alpha_f-\alpha_i)}{\lambda n\cos(\frac{\alpha_f-\alpha_i}{2})}\frac{K_BT}{q}\frac{K_g}{1+(\frac{K_g}{K_o})^2}n_o^4\gamma_{13}\cos\beta, \quad (4)$$

where

$$\beta = \frac{\alpha_f+\alpha_i}{2}, \quad (5)$$

and

$$K_o = (\frac{Nq^2}{\varepsilon\varepsilon_o K_BT})^{1/2}. \quad (6)$$

n_o, n_e are the refractive indices of ordinary and extraordinary waves inside the crystal; α_i, α_f are the angles of the *incident and fanning light* with respect to the C axis; γ_{13}, γ_{33} and γ_{42} are the nonzero electro-optic coefficients of $BaTiO_3$, with values 8, 28, 820 pm/V, respectively (Yariv and Yeh, 1984); K_B is Boltzmann's constant; T is the temperature; q=1.6× 10^{-19}C; N is the effective trap density; ε is the dielectric constant in the direction of grating vector; and K_g is the amplitude of the grating vector.

From Eqs. (1)-(4), we can find that the coupling of the extraordinary light is stronger than that of the ordinary light. This is why the extraordinary light has large gain, which causes fanning and can be used to generate a self-pumped phase conjugate wave.

When a plane wave is incident along the negative C axis, the incident light is always ordinary light regardless of what polarization the light is, but it is different for the scattered light because the polarizations may or may not be normal to the C axis. As shown in Fig. 1(a), the fanning light can be divided into two orthogonal fanning planes. The polarizations of the fanning light in one plane are always normal to the C axis, but in the other plane they will not be. The former case is called ordinary fanning, and the latter case is called extraordinary fanning. According to the Eqs. (1)-(4), the coupling parameter of the extraordinary scattered light is always larger than that of the ordinary scattered light. Thus, the former will be amplified to a much larger degree than will the latter. Therefore, fanning happens only on the plane which is constructed by the polarization of the incident light and the c axis as shown in Fig. 1(b) and (c). Hence, fanning is polarization-dependent. In contrast, we can judge the polarization of the incident light by observing the fanning plane.

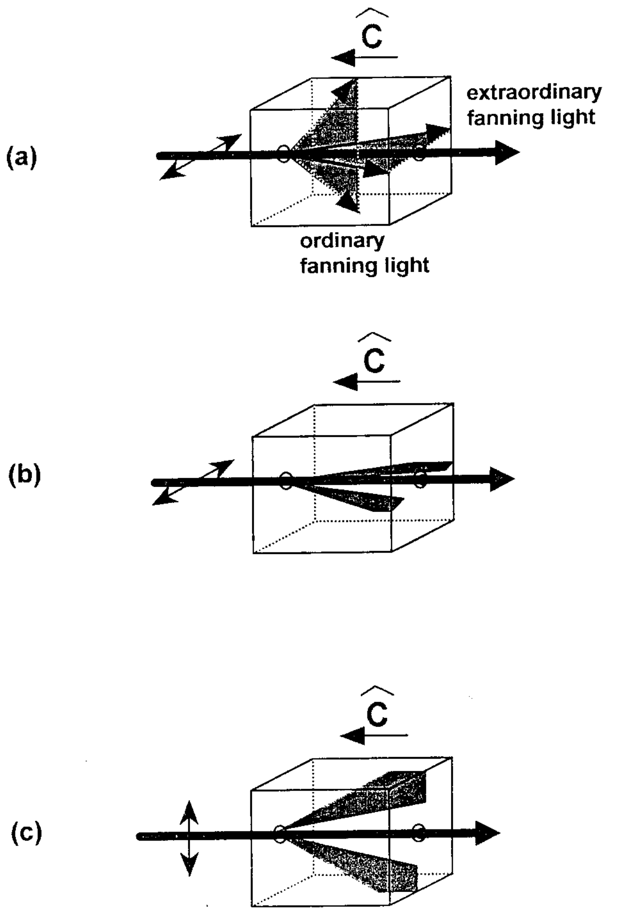


Fig. 1. The schematic diagram of the polarization-dependent fanning. (a) The types of fanning light on the plane parallel and perpendicular to the polarization of the incident light are extraordinary and ordinary, respectively. (b) and (c) show the polarization-dependent fanning.

III. Experimental Results

The experimental setup is shown in Fig. 2. The dimensions of the crystal dimension were 5×5×5 mm^3. The incident light was derived from an Argon-ion laser with wavelength 514.5 nm. A half-wave plate and polarized beamsplitter-cube were used to control the incident intensity. Another half-wave plate was used to control the polarization of the incident light. As shown in Fig. 3, fanning was symmetric to the incident light, which was exactly along the negative C axis. We found that the fanning plane was always parallel to the polarization of the incident light. As the beam width of the incident light was changed, we find the fanning angle is changed as shown in Fig. 4. The fanning angle is defined as the angle deviation between the fanning light and incident light. In addition, the changes of the incident beam width induce the change of the fanning strength and finally the intensity of the transmission light is changed. The measurement of the ratio of transmission intensity to the incident intensity is shown as Fig. 5.

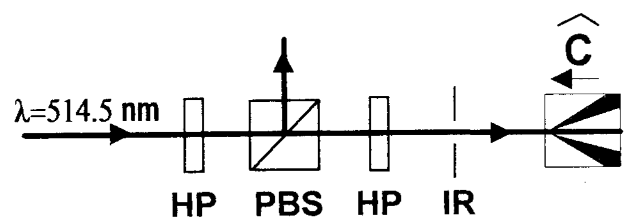
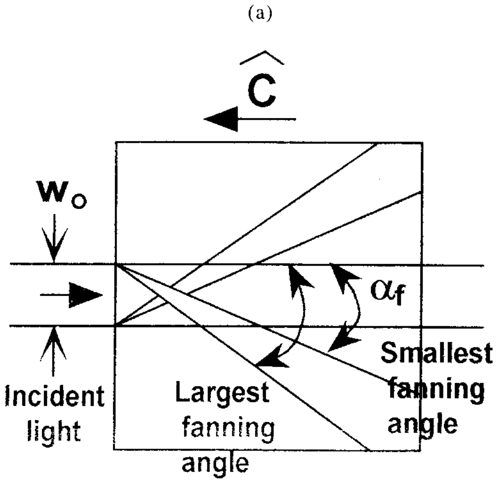


Fig. 2. The experimental setup. HP, half-wave plate; PBS, polarized beamsplitter cube; IR, iris.

(a)



(b)

Fig. 3. The photograph (a) and the corresponding geometry (b) of the fanning structure.

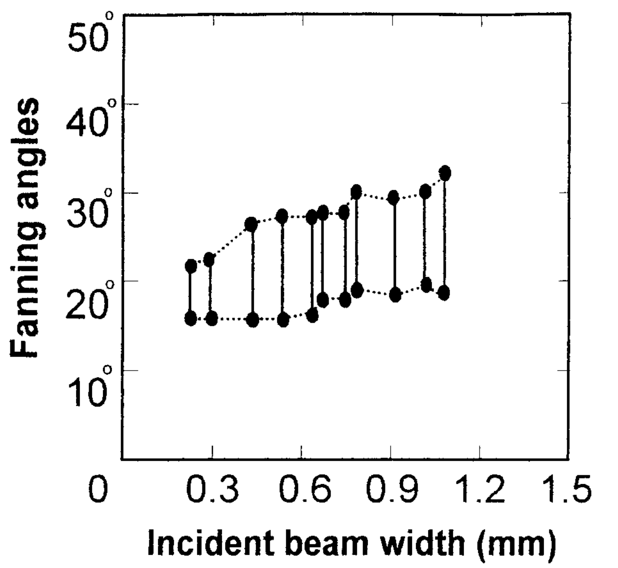


Fig. 4. Experimental measurement of the fanning angles vs. the incident beam width.

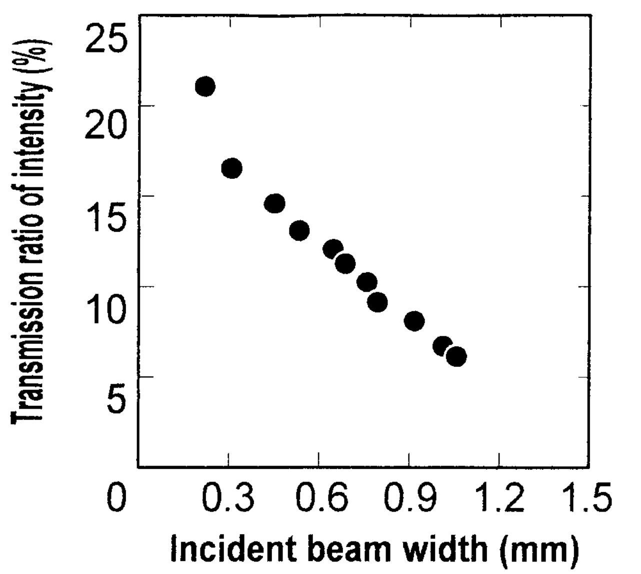


Fig. 5. Experimental measurement of the transmission ratio of the intensity vs. the incident beam width.

IV. Discussions

The experiments show that both the fanning angles and transmission intensity ratio are the functions of the incident beam width as in Figs. 4 and 5. This is because that the interaction length is also a function of the incident beam width. As shown in Fig. 6, if the beam width is ϖ_o, the interaction length can be expressed as (Sun *et al.*, 1992)

$$l=\varpi_o/\sin\alpha_f. \tag{7}$$

Therefore, from Eqs. (1), (2) and (7), not only the fanning angle but also the coupling energy are the functions of the incident beam width.

Figure 7 shows the theoretical calculations of the transmission light intensity as a function of the beam width by using Eqs. (1)-(3) and (7). We assume that the number photons are 1000. The photon numbers of the scattered light are 10, 40, 70 and 100, respectively with 20° departed from the incident light. The parameters are $N=2\times10^{16}$ cm^{-3}, $T=300°$ K, $n_o=2.488$ and $n_e=2.424$ at 514.5 nm, $\alpha=1$ cm^{-1}, and the dielectric values of 106, 4300 are parallel and perpendicular to C axis, respectively (MacDonald and Feinberg, 1983; Yariv and Yeh, 1984; Wemple *et al.*, 1968). It shows that the increase of the beam width will increase the energy transfer from the incident lights to the fanning lights. It means that the increase of the incident width will enhance the fanning.

Now, we will consider the possibility of multiple fanning. As shown in Fig. 8, the second-order fanning light had the highest gain from the first-order fanning light, and so did the third one from the second one. Figure 9 is the theoretical calculations of the fanning angles of the highest coupling strength with different incident beam widths using Eqs. (2)-(7). Curve A is the first-order fanning angle from the incident light while Curves B and C are the second-order and third-order fanning angles from the first and second fanning lights. By comparing Fig. 4 and Fig. 9, we can obtain that the final fanning angles resulted from two or three fanning processes; i.e., before each fanning light pointed to its final direction, it turned twice or three times. Now, the question is what factor the fanning lights to stop turning. The possible answers are as follows. Once there existed multiple strong sources of fanning light, the contrast of the gratings was reduced, which then caused the coupling strength of the fanning light to be reduced. Thus, the reduced coupling strength caused the amplification of the fanning light to be less than the absorption by the crystal. Therefore, high-order fanning was prevented, and the fanning angles

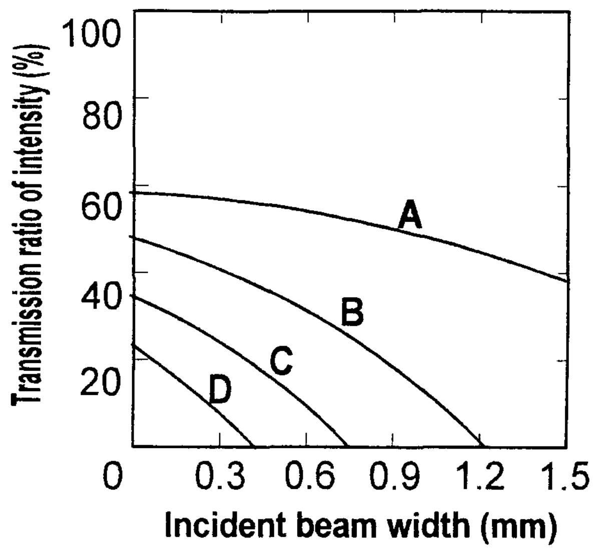


Fig. 7. Theoretical calculations of the transmission intensity ratio as a function of the incident beam width. Curves A, B, C and D are based on 10, 40, 70 and 100, respectively, as the photon number of the initial scattered light while the incident photon number is 1000.

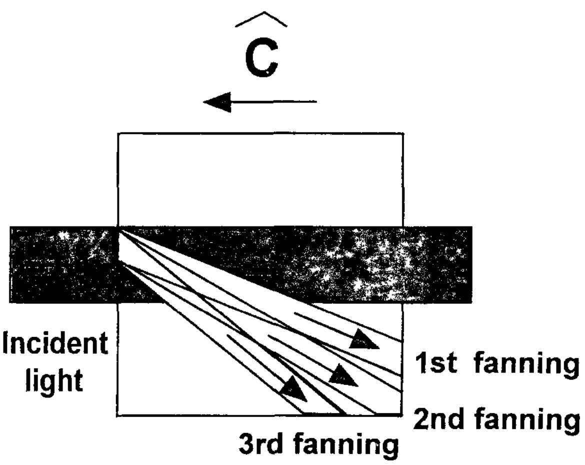


Fig. 8. The schematic diagram of the first three orders of fanning.

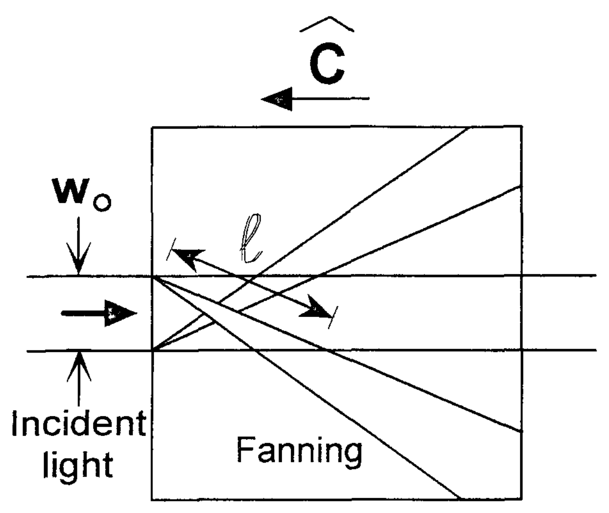


Fig. 6. The schematic diagram for determining the fanning length.

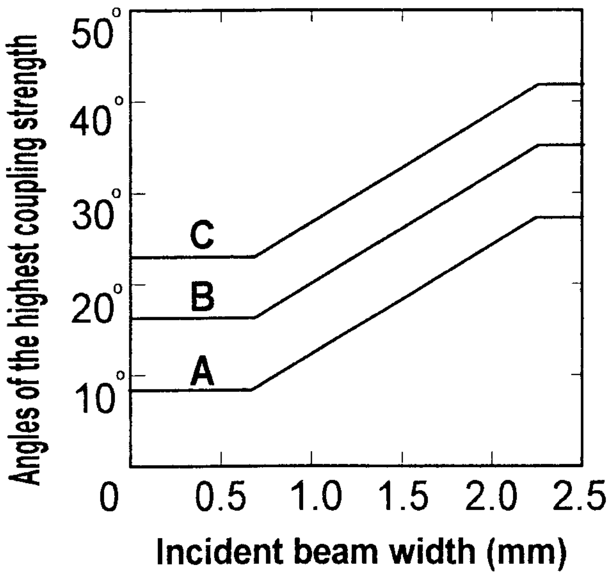


Fig. 9. Theoretical calculation of the fanning angles of the highest coupling strength with respect to the incident beam width. Curves A, B and C are the fanning angles of the first order, second order and third order fanning, respectively.

were confined within a specific range, which may have depended on the parameters of the crystal.

V. Conclusions

We have demonstrated the polarization-dependent fanning along the negative *C* axis in $BaTiO_3$. The coupling strength of the fanning lights under different polarizations and different fanning directions has been calculated. By comparing the experimental results, we conclude that the final fanning direction results from the second-order or third-order fanning.

Acknowledgments

This research was supported by the National Science Council of the Republic of China through contract NSC 85-2215-E008-015.

References

Banerjee, P. P. and R. M. Misra (1993) Dependence of photorefractive beam fanning on beam parameters. *Opt. Comm.*, **100**, 166-172.

Feinberg, J. (1982) Self-pumped, continuous-wave phase-conjugator using internal reflection. *Opt. Lett.*, **7**, 486-488.

Gu, C. and P. Yeh (1991) Scattering due to randomly distributed charge particles in photorefractive crystals. *Opt. Lett.*, **16**, 1572-1574.

Huignard, J. P. and P. Gunter (1988) *Photorefractive Materials and Their Applications: I. Fundamental Phenomena*. Springer-Verlag, New York, NY, U.S.A.

Huignard, J. P. and P. Gunter (1989) *Photorefractive Materials and Their Applications: II. Applications*. Springer-Verlag, New York, NY U.S.A.

MacDonald, K. R. and J. Feinberg (1983) Theory of a self-pumped phase-conjugate emission from $BaTiO_3$ crystal. *J. Opt. Soc. Am.*, **73**, 548-553.

Parshall, E., M. Cronin-Golomb, and R. Barakat (1995) Model of amplified scattering in photorefractive media: comparison of numerical results and experiment. *Opt. Lett.*, **20**, 432-434.

Segex, M., D. Engin, A. Yariv, and G. Valley (1993) Temporal evolution of fanning in photorefractive materials. *Opt. Lett.*, **18**, 956-958.

Sun, C.C., S. Yeh, M. W. Chang, and K. Y. Hsu (1992) Optimal incident condition for a Cat-type self-pumped phase conjugate mirror. *Applied Optics*, **31**, 5769-5772.

Voronov, V. V., I. R. Dorosh, Y. S. Kuzminov, and N. V. Tkachenko (1980) Photoinduced light scattering in cerium-doped barium strontium niobate crystal. *Sov. J. Quantum Electron.*, **10**, 1346-1349.

Wemple, S. H., D. Didomenico, Jr., and I. Comlibel (1968) Dielectric and optical properties of melt-grown $BaTiO_3$. *J. Phys. Chem. Solids*, **29**, 1791-1806.

Yariv, A. and P. Yeh (1984) *Optical Waves in Crystals*. Wiley, New York, NY, U.S.A.

Yeh, P. (1989) Two-wave mixing in nonlinear media. *IEEE J. Quan. Electron.*, **25**, 484-519.

光偏極化相關之鈦酸鋇晶體負光軸扇射

張興華* 孫慶成**,† 張正陽* 鄒仁翰* 張明文*

*中央大學光電科學研究所

**健行工商專校電子工程科

摘　　要

本文驗證了沿著鈦酸鋇晶體負光軸扇射光之方向與偏極化方向有關。扇射光之方向被侷限於其偏極化方向與光軸所構成之平面上。經過理論之計算與實驗上對扇射光角度之量測，我們可推論入射光在扇射到最後的方向前，不止改變過一次放大的方向。