Volume 3, Number 7 ACTA PHYSICA SINICA July, 1994
1004-423X/94/03070506-06 (Overseas Edition) © 1994 Science Press

A STUDY ON REAL-TIME LOW-FREQUENCY SPATIAL FILTERING PROCESS OF AN OPTICAL IMAGE USING $LiNbO_3$:Fe CRYSTAL*

LIU SI-MIN(刘思敏), LU YI(陆 漪)†, CHEN HAI-DONG(陈海东),
LIU JUN-MIN(刘军民), XU JING-JUN(许京军), ZHANG GUANG-YIN(张光寅),
YANG LI-SEN(杨立森)‡, MEN LI-QIU(门丽秋), and SUN QIAN(孙 骞)
Department of Physics, Nankai University, Tianjin 300071, China
†*Department of Physics, Branch College of Tianjin University, Tianjin 300193, China*
‡*Department of Physics, Neimenggu Normal University, Huhhot 010020, China*

(Received 2 September 1992; revised manuscript received 30 August 1993)

The optimum image processing result of low-frequency filtering was obtained when $LiNbO_3$:Fe crystal as a spatial filter was placed at a certain position behind the spatial-frequency spectral plane of an optical Fourier transform system, which corresponds to the minimum transmittance ratio in Z-scan curve. The experimental results show that self-defocusing due to photorefractive negative-lens effect is the main factor responsible for the low-frequency filtering.

PACC: 4280B; 4280C

I. INTRODUCTION

Low-frequency spatial filtering character of $LiNbO_3$:Fe crystal has been reported recently.[1] We also studied this character of $LiNbO_3$:Fe crystal, using it as a spatial filter in an optical Fourier transform system. We found that the result of low-frequency filtering of the optical image was best when the crystal was placed at a certain position behind the spatial-frequency spectral plane of the system. An object image placed at the object plane and illuminated homogeneously was transformed real-timely into an image at the image plane, whose edge was clear and bright but the inside of it was dark. This image processing can protrude the image shape and helps to observe and distinguish it clearly, the resolution and contrast of the image are increased greatly. By measuring the Z-scan curve of $LiNbO_3$:Fe crystal, we found that the optimum position of $LiNbO_3$:Fe crystal in the processing system was that at which the transmittance ratio was minimum in the Z-scan curve. This shows that self-defocusing due to photorefractive negative-lens effect was the main factor responsible for the low-frequency filtering character of $LiNbO_3$:Fe crystal.

Reference [1] has given a photograph of low-frequency filtered image. Because the observed screen was not exactly placed at the image plane, and the crystal was not placed at the optimum position behind the lens in Ref.[1], the image edge became thicker. In Ref.[1]

*Project supported by the National Natural Science Foundation of China and by the State Science and Technology Commission of China, through a grant for key research project in climbing program.

it was concluded that the self-diffraction effect and size-effect of the light-induced scattering are responsible for this low-frequency filtering.

II. EXPERIMENTAL RESULTS

The experimental setup is shown in Fig.1. After spatial filtered and collimated, a He-Ne laser beam with light power 20 mW is incident homogeneously on an input image "a" placed at the front focal plane of the lens $L(f = 134.56\,\text{mm})$. A homogeneous and clear image "a'" can be observed on the screen "s" which is placed exactly at image plane. Then a $LiNbO_3$:Fe crystal (0.9–2 mm thick) is inserted at the back focal plane of lens L. The polarization of the incident beam is along c-axis of the crystal (e-polarization). Experimental results show that the result of image process depends sensitively on the position of the crystal; the optimum position corresponds to the minimum transmittance ratio of Z-scan curve (Fig.2). The details are as follows:

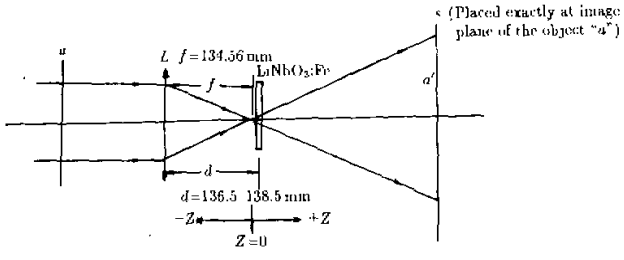

Fig. 1. The experimental setup.

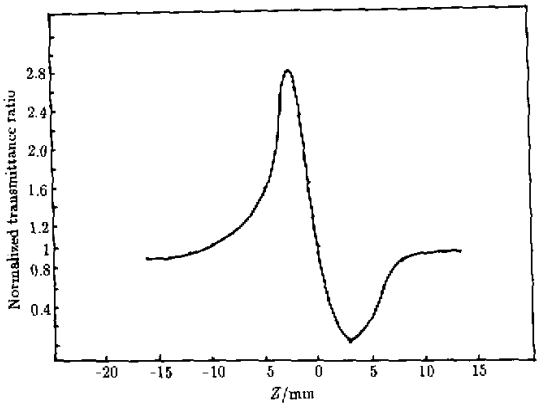

Fig. 2. The Z-scan curve of the $LiNbO_3$:Fe crystal.

A. When the crystal is exactly located at the back focal plane of lens L (the distance

between the crystal and the lens L, $d = f = 134.56$ mm), the self-diffraction fringes which expand out from the edge of the image with regular-spaced white-black streaks[2] appear on the screen "s". They correspond to different diffraction orders from lower to higher, but the scattering light fanning is hardly observed.

B. When the crystal is located at a position behind the back focal plane of the lens L, which corresponds to the minimum transmitance ratio in the Z-scan curve ($d > f, d = 136.5 - 138.5$ mm), the intensity inside image "a'" becomes weaker immediately and the dark region expands gradually, until it reaches the whole area except the edge of the image. Meantime, the self-diffraction fringes appear outside the image "a'", but its intensity is weaker than that in case A; the symmetrical scattering fanning appears along the $\pm c$ direction and becomes brighter and brighter; finally the self-diffraction fringes are suppressed by the scattering fanning. The edge of image "a'" is always bright and its intensity does not change. This edge is very thin and very clear as shown in Fig.3.

C. When the crystal is located in front of the back focal plane of lens L ($d < f, d = 110.0 - 133.5$ mm), the inside of the image "a'" becomes darker and darker from the edge to the inside, but the central region of the image "a'" becomes brighter gradually and forms a large bright spot. This phenomenon shows the energy inside image "a'" gradually concentrates upon the central region of it and at the same time the symmetrical scattering fanning appears.

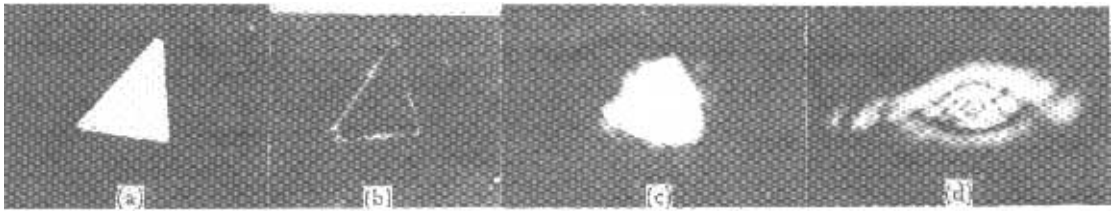

Fig. 3. The result of the low-frequency spatial filtering process using the $LiNbO_3$:Fe crystal. (a) The image of the object "a" (without crystal); (b) the case of d=136.5 mm; (c) the case of d=132 mm; (d) the case of $d = f = 134.56$ mm.

D. In the above three cases, the intensity and the size of the image edge do not change. The difference among the three cases is caused by the change of the intensity inside image "a'", which is sensitive to the position of the crystal, thus the contrast of the edge to the inside of image "a'" is changed as well. When an incident beam (signal beam) is normally incident on the crystal, the edge of the image "a'" will not be broken. However, when the incident beam deviates from the normal direction of the crystal's incident plane, the edge of image "a'" will be broken.

E. If we put a pen point or a needle near the spatial-frequency spectral plane instead of the $LiNbO_3$:Fe crystal to block the low-frequency components of the incident beam, an image similar to the experimental result in B appears on the screen "s".

F. The measurement setup of Z-scan curve is similar to the one in Ref.[3]. Here Z indicates the distance between the crystal and the back focal plane of the lens L (when $Z = 0$, the crystal is located exactly at the back focal plane of the lens L; when $z < 0$, the crystal is getting closer to the lens L; when $Z > 0$, as Z increases, the crystal is away from the lens L). The transmittance ratio is the normalized ratio of the transmitted intensity through the central hole at the screen to the incident intensity. The Z-scan curve of the $LiNbO_3$:Fe crystal is shown in Fig.2.

III. DISCUSSION

The experimental results in B and E show clearly that the $LiNbO_3$:Fe crystal can be used as a low-frequency filter in optical Fourier transform system under certain experimental conditions. Because the energy inside the image "a'" is transferred to the outside of the image "a'", the intensity inside the image "a'" becomes weaker. However, the light energy at the edge of the image "a'", corresponding to frequency components, almost remain unchanged after passing through the crystal. Thus the image outline can be obtained on the image plane. But how is the light energy transferred from the inside to the outside of the image "a'"? And why is the light energy at the edge of the image not transferred to the outside? i.e., why is the $LiNbO_3$:Fe crystal possible to be used as a low-frequency filter? The answers will be easily found if we compare the experimental results in A-C with the Z-scan curve in Fig.2.

It is well known, a laser beam with the Gaussian distribution propagating through a photorefractive crystal will cause lens-like effect[2], which will change the propagating direction of the laser beam in the crystal and cause converging or diverging of the laser beam. This phenomenon is called self-focusing or self-defocusing. In $LiNbO_3$:Fe crystal because of photorefractivity $\Delta n < 0$, the photorefractive lens-like effect is negative, and this has been proved by the measurement of its Z-scan curve (Fig.2). The dependence of photorefractivity Δn on the coordinates of the illuminated region has been measured by Chen *et al.*[4-6]

First, we will discuss the low-frequency components inside the image:

A. When the crystal is located exactly at the spatial frequency spectral plane ($Z = d - f = 0$), the negative lens effect increases the laser beam-waist size of the incident convergent beam in front of the focal point in the crystal, at the same time it increases the divergency of the incident beam and decreases its beam-waist size behind the focal point in the crystal, so in this case its influence on the propagating direction of the incident beam

is small. However, because the gradient $d(\Delta n)/dl$ at the point with different coordinates in the illuminated region is different, so a regular self-diffraction pattern will appear on the screen "s".[2]

B. When the crystal is located behind the back focal plane of the lens L ($Z = d - f > 0$), the divergency of the incident beam and the negative lens effect of the crystal will overlap, so the output beam will be more diverging, and this will cause the deflection of the propagating direction of the low-frequency component of the beam from the inside into the outside of the image and the inside region of the image becomes dark. With the increase of the exposure time, the stronger the negative lens effect, the larger the deflection and the area of the low-frequency components inside the image, so that the dark region is extended from the center to the edge of the image gradually, until the whole region inside the image becomes dark. This is the reason why we have the experimental result in case B of sect.Ⅱ and the decreasing transmittance ratio in $Z > 0$ region of the Z-scan curve.

C. When the crystal is located in front of the back focal plane ($Z = d - f < 0$), the incident beam is a convergent beam in the crystal, and the negative lens effect reduces the convergency to a certain extent. This is equivalent to extending the focal length of the lens L, so that the beam-waist diameter becomes larger. As a result, the energy inside the image is converged to the central region in the experimental result C of sect. Ⅱ. It corresponds to the case of the maximum of the transmittance ratio in the Z-scan curve.

Because the crystal is located near the spatial frequency spectral plane, the low- and the high-frequency components are spatially separated in the crystal. Because the intensity of the high-frequency components is much weaker than that of the low-frequency components, the photorefractivity caused by the high-frequency components can be neglected, as compared with that of the low-frequency components. Hence the light wave of the image edge propagates along its initial incident direction through the crystal, and the intensity and the size of the image edge will not change.

The transient energy transfer[7,8] which causes light scattering amplification (scattering fanning) also plays a role in the energy transfer from the inside to the outside of the image (i.e., energy is transferred to the scattering light via the noise grating). The experimental results B and C in sect.Ⅱ show that the scattering fanning will appear when $d > f$ and $d < f$, but the result of the low-frequency filtering is different obviously. This shows that the scattering light amplification is not important for the low-frequency filtering effect, in which the self-defocusing of the photorefractive negative lens effect should be a decisive factor.

Over one hundred years ago, since Abbe-Porter experiment was reported[9], the optical information processing has been performed by using a method of changing the spatial

frequency spectrum. A new image whose spatial frequency spectrum is different from its initial image can be obtained by using a spatial filter which is located at the back focal plane of the lens. Experimental results of this paper show that a new image of protruding edge is obtained by using $LiNbO_3$:Fe crystal as real-time low-frequency filter in optical Fourier transform system, because it possesses the low-frequency filtering character under certain conditions. This is different from the general edge-enhancement[10] and the differentiation effect of image.[11] The former is obtained mainly by using a weaker reference beam I_R and a stronger signal beam I_S to record hologram and I_R is also used as a reading beam. The latter is the result of a spatial or temporal differential operation for the object function. In our experiment a new image of protruding edge is obtained directly by a single beam.

IV. CONCLUSION

We have for the first time, so far as we know, obtained a clear image of protruding edge by using $LiNbO_3$:Fe crystal as a spatial low-frequency filter in optical Fourier transform system. This can greatly increase the resolution and the contrast of the image. By measuring the Z-scan curve and comparing it with the results of low-frequency filtering at different positions of the crystal near the spatial frequency spectral plane, we concluded that the self-defocusing due to photorefractive negative-lens effect is the main factor responsible for the low-frequency filtering character of $LiNbO_3$:Fe crystal.

REFERENCES

[1] Y. Q. Wu, J. J. Xu, S. M. Liu, G. Y. Zhang, *Appl. Opt.*, **31**(1992), 3210.
[2] Liu Si-min, Zhang Guang-yin and Wu Yuan-qing, *Acta Physica Sinica*, **37**(1988), 268 (in Chinese).
[3] Liu Si-min, Kang Min-jian, Zhang Guang-yin, Wu Yuan-qing and Xu Jing-jun, *Acta Physica Sinica*, **40**(1991), 923 (in Chinese).
[4] F. S. Chen, *J. Appl. Phys.*, **40**(1969), 3389.
[5] Y. V. Vladimirtsev, V. A. Golenishchev-Kutuzov, S. A. Migachev and N. A. Shamukov, *Ferroelectrics*, **22**(1978), 653.
[6] P. A. Augustov and K. K. Shvarts, *Appl. Phys.*, **18**(1979), 399.
[7] N. Kukhtarev, V. Markov and S. Odulov, *Opt. Commun.*, **23**(1977), 338.
[8] V. L. Vineskii, N. V. Kukhtarev, S. G. Odulov and M. S. Soskin, *Sov. Phys. USP*, **22**(1979), 742.
[9] X. H. Zhong, Light Diffraction and Transformation Optics (Advanced Education Press, 1985), P.72 (in Chinese).
[10] E. Ochoa, J. W. Coodman and L. Hesselink, *Opt. Lett.*, **10**(1985), 430.
[11] Y. H. Ja, *Appl. Phys.*, **B36**(1985), 21.