Anisotropic Self-Defocusing in Knbo3: Fe Crystal

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Abstract. All the characteristics of the self-defocusing and “position dispersion” in KNbO3:Fe crystal are experimentally investigated. The results show that the scattering from KNbO3:Fe crystal is mainly due to the photo-induced lensing.

1. Introduction
Photo-induced scattering in photorefractive crystals has been investigated widely by many researchers because it has important application on photorefractive holography, phase conjugation, etc. The scattering features of it depend on the properties of the crystals, wavelength and intensity of irradiating beam as well as its polarization and orientation relative to the crystallographic axis of the crystal [1-3]. In this paper, neglecting the conical ring scattering [4], we study the main scattered pattern. For this kind of photo-induced scattering, some researchers proposed that it was caused by the surface and bulk imperfection of the crystals, and the crystals used in the study were LiNbO3: Fe, LiTaO3 and BaTiO3, and the fixed crystal sample and the spacing of the focusing lens were used. KNbO3 is an important crystal material, which can be used in two-wave mixing, phase conjugation and dynamic holography [5,6]. In this paper, the photo-induced scattering in KNbO3: Fe crystal and the dependence of the size of the scattering beam relative to the crystal position are presented. The results show that the photo-induced anisotropic light scattering in KNbO3: Fe crystal is mainly dominated by photo-induced lensing.

2. Experiment
The schematic diagram of the experimental setup is shown in Figure1. The incident laser is perpendicular to the c axis of a KNbO3: Fe crystal of 5 mm thickness. A He-Ne laser beam (633nm) is focused on the surface of the KNbO3: Fe crystal by a lens with focal length of 10cm. A polaroid behind the crystal is used to separate the scattering in two mutually perpendicular directions. The far-field scattered patterns are observed on the screen. A linear array detector is employed to measure the intensity distribution of these scattered patterns. Alternatively, a detector with a small aperture is used to measure the central transmitted light.
**Figure 1.** Schematic diagram for measuring anisotropic light scattering of KNbO$_3$: Fe crystal

Figure 2 shows the photographs of the far field distributions of the photo-induced scattering by the crystal under different conditions. Here, $P$ represents the polarization direction of the incident laser, $C$ is the direction of the C axis of the crystal, and $I$ indicates the direction of polarization of the polaroid. KNbO$_3$ is a biaxial crystal, so we use parallel and vertical scattering light to represent the scattering components perpendicular to each other in the two polarization directions. And the polarization directions of the parallel and vertical scattered light are parallel and perpendicular to the C axis of the crystal, respectively.

Figures 2(a), (b) and (c) represent the far-field scattered patterns with the polarization direction of the incident light perpendicular to the c axis of the crystal, where figure 2(a) and (c) are the scattered spots when the crystal is placed on the left and right side of the focal plane of the lens respectively, however, figure 2(b) shows the scattered pattern when the crystal is located on the focal plane of the lens, where the spot is relatively small and the size of scattered light spot is centered. It can be seen that the size of the scattered spot in figure 2(a) is the smallest, while the size of the scattered spot in figure 2(c) is the largest. Moreover, the scattered light spot in figure 2(c) is not axially symmetric, but expands along the c axis of the crystal, which is similar to the effect of a negative cylindrical lens. According to the propagation characteristics of the focused Gaussian beam through the lens, when the thin negative lens is located in front of the focal plane of the beam (left), the beam is convergent and the radius of subsequent beam becomes smaller, while when the thin negative lens is located behind the focal plane of the beam (right), the beam is diverged and the spot becomes larger. When a thin negative lens is located on the focal plane of the Gaussian beam, the spot size and propagation of it will not be affected. Therefore, when the crystal is located on the focal plane of the lens, the spot size is centered. It can be seen that the size of the scattered spot in figure 2 reflects the characteristics of the photo-induced lensing in the crystal.

**Figure 2.** Anisotropic scattering of KNbO$_3$: Fe crystal
For the case that the polarization direction of irradiated light is parallel to the C axis, figure 2(d) and (f) are the scattered spot when the crystal is placed on the left and right side of the focal plane of the lens respectively, and figure 2(e) is the scattered light spots when the crystal is placed on the focal plane of the lens. The scattered light spot in figure 2(d) is slightly larger than that in figure 2(a), while the scattered light spot in figure 2(f) is slightly smaller than that in figure 2(c). This indicates that the lensing produced by the polarization direction of irradiated light parallel to the C axis is slightly smaller than that produced by perpendicular one. Figure 3 shows the far-field scattered spot when the crystal is located on the right of the focal plane of the lens and the polarization direction of the polaroid is 45° from the crystal C axis. Here, the spot still spreads along the C axis. When the polarization direction of the scattered light is parallel to one of the incident lights, the scattering intensity (figure 3(a)) is greater than the vertical (figure 3(b)). So, the photo-induced vertical light scattering in KNbO₃: Fe is similar to that in LiNbO₃: Fe [5].

![Figure 3. Far-field scattered spots when the direction of polarization of the irradiated light is 45° from C axis of the crystal.](image)

The effects of the intensity of the illumination beam and the crystal position with respect to the focal plane on the photo-induced scattering are investigated by technique similar to Z-scan [7,8]. Z-scan method has been used for determining both the sign and magnitude of effective nonlinearity n² in cubically nonlinear materials. The schematic diagram of experimental setup we used is shown in Fig.1. Here we use the aperture with a detector to measure the central transmitted power of the far field. For a fixed illumination beam power, the size (1/e² intensity) of the scattered beam in the far field is measured as a function of the crystal position with respect to the focal plane. Due to the photorefractive effect, the refractive index change will lead to an induced-lensing in the irradiated area. When the negative induced-lensing is on the left side of the focal plane, it tends to collimate the far field beam which in turn causes a decrease in the size of the scattered beam resulting an increase of the detected power. When an induced-lensing (either positive or negative) is at the focal planes of the focusing lens, the size of the far field pattern will be roughly the same as the size of the illumination beam without induced lensing inside the crystal. When the negative induced-lensing is on the right side of the focal plane, the far field tends to be more divergent, which results in an increase of the size of the scattered beam causing a decrease of detected power. The transmittance of the crystal which is inversely proportional to the size of the scattered beam, as a function of the distance of the crystal position from the focal plane of the focusing lens, is similar to a dispersion-shaped curve which we call “position dispersion” [9]. A pre-focal minimum (size maximum) corresponds to a negative change in the refractive index induced by light.

Figure 4 is the normalized transmittance of the crystal as a function of its relative position to the focal plane for three illumination powers’. The transmittance is normalized to the respective values obtained when the crystal on the focal plane. The polarization of the illumination beam is parallel to the c axis of KNbO₃: Fe crystal.
The aperture’s linear transmittance is $s=0.54$. The curves in Figure 4 show a negative position dispersion, which means the change of the refractive index induced by focused Gaussian illumination beam is negative. Thus, the induced-lensing is similar to a negative cylindrical lens. It can be seen that the normalized transmittance minimum or the maximum is proportional to the proportional to the illumination intensity.

**Figure 4.** Position dispersions of KNbO3 crystal for the different power Pin of the illumination beam under the fixed focal length of 10cm. (a) pin=27mw, (b) pin=17mw, and (c) pin=9mw.

The curves in Fig.5 are the normalized transmittances as a function of the position of the KNbO₃: Fe crystal, for different focusing lenses at a fixed illumination power of 25mw with polarization direction of scattered light parallel to the c axis of KNbO₃: Fe crystal and $s=0.28$. For shorter focal length, the intensity inside the crystal is stronger, resulting a stronger lensing effect as shown by curves (a). This result is consisted with, and can be explained by the results of Figure 5. In addition, the separation between peak (maximum) and valley (minimum) of the normalized transmittance in the z direction, $\Delta z_{p-v}$, is proportional to focal length of the focusing lens. This phenomenon can be explained by the theory that $\Delta z_{p-v}$ is proportional to the diffraction length [7] which is proportional to the waist of the focused beam.

**Figure 5.** Position dispersions of KNbO₃ crystal for the different focal length under the fixed power 25mw of the illumination beam. (a) f=10cm, (b) f=15cm, and (c) f=20cm.

### 3. Discussion

Now, we briefly describe the underlying physics of the above phenomena. When a Gaussian illumination beam propagates perpendicularly to the c axis of KNbO₃: Fe crystal, the symmetry of the crystal demands the photo-induced B-field, $E_{sc}$, be mainly along the c axis [10]. So, the refractive index variations due to the e-o effect are mainly along the c axis, which are expressed as

$$\Delta n_{s} (c) = E_{s} (c) \frac{n_{s}^l}{z} r_{ss}$$

(1)
And
\[ \Delta n_s(c) = -E_s(c) \frac{n^1_{so}}{z} r_{33} \]  \hspace{1cm} (2)

where \( n_s \) and \( n_e \) are the linear refractive indices for waves whose polarization direction of scattered light is parallel and perpendicular to the c axis of KNbO\(_3\):Fe crystal, respectively, and \( r_{33} \) and \( r_{ss} \) are the electro-optic coefficients. Since \( E_s(c) \) due to photovoltaic effect is proportional to the intensity of the Gaussian illumination beam, the expressions indicate that the photo-induced lensing is similar to a negative cylindrical lens which affects light mainly along the c axis of the crystal. The values of the electro-optic coefficients in KNbO\(_3\) are \( r_{33} = 2 B \) (10-12 m/V) and \( r_{ss} = 64 \) (10-12 m/V). Thus \( \Delta n_s(c) \) is about 2 times larger than \( \Delta n_e(c) \). Hence the optical phase change for the wave with polarization parallel to the c axis of KNbO\(_3\): Fe crystal is larger than that of the wave with polarization perpendicular to the c axis. Therefore, the size of the scattered pattern for the former wave is larger than that of the latter wave. Figure 2 clearly shows this characteristic.

The scattered wave with orthogonal polarization component with respect to the illumination beam appears in the scattered patterns. This phenomenon is due to the following reason. The orientation of the index ellipsoid will be changed by the space charge field. Hence there is always a small component of the illumination beam in the direction of the orthogonal eigen polarization. In general, the intensity of the scattered wave with polarization perpendicular to that of the illumination beam is much weaker than the scattered wave with the same polarization as the illumination wave.

P. Günter [11] presented the distributions of the space charge field for diffusion and drift in KNbO\(_3\): Fe. The space charge field in KNbO\(_3\): Fe is dominated by the drift which is induced by the photovoltaic effect. In the case of pure diffusion, the phase shift is 90° which induces the light fanning. Feinberg [10] predicted that self-focusing or self-defocusing of the illumination beam in photorefractive crystals should be observable when there exists an either externally applied or the intrinsic electric field. Base on their theories and results, the distribution of space charge field in KNbO\(_3\): Fe will induce a change in the refractive index with in-phase spatial distribution mainly along the c-axis of the crystal. The resultant phase profile is like a negative cylindrical lens, which in turn leads to self-focusing (crystal on the left side of focal plane) or self-defocusing (crystal on the right side of focal plane) of the illumination beam passing through the crystal. The dispersion shaped change in the size of scattered pattern is a character of self-focusing or self-defocusing that is due to the photo-induced lensing [7,8]. We further performed interference measurement of the change in refractive index in the illuminated area in KNbO\(_3\): Fe crystal. The result also shows that the index profile is indeed cylindrical lens-like which is similar to the results in Ref. [11]. Our experimental results provide direct support for the theory that the photo-induced scattering is due to the self-focusing or self-defocusing by the induced-lensing. In Ref. [12], the measurement and analysis, based on the wave scattering theory, of the size of the speckle of the photo-induced scattering in LiNbO\(_3\): Fe were given. When the crystal is located on the waist of the illumination beam the size of the scattered spot size has a relative smaller value. This can be explained by the negative lensing and thus is consistent with our result.

4. Conclusions
The details of the photo-induced scattering and “position dispersion” of the normalized transmittance for the photo-induced scattering beam in KNbO\(_3\): Fe have been given. Some features of the photo-induced scattering in KNbO\(_3\): Fe are similar to that in LiNbO\(_3\), and LiTaO\(_3\), [5,6,12,13] in which the photo-induced light scattering has been reported as amplification of weak beams scattered by bulk and surface inhomogeneities. However, based on our experimental results and analysis, the photo-induced scattering in KNbO\(_3\): Fe is dominated by the photo-induced lensing rather than the imperfections in the crystal. The dispersion shaped change in the sizes of the far field pattern, as a function of the crystal position from the focal point of the illumination beam, shows clearly that the focal point of the
illumination beam, shows clearly that the pattern of the photo-induced scattering is dominated by the induced-lensing. This fact provides direct support for the theory that the origin of photo-induced scattering is due to self-focusing or self-defocusing effect in the crystals.

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