Appearance of Optical Vortex at Conical Refraction. Examples of $NaNO_2$ and $YFeO_3$ Crystals

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Received: 01.06.2003

Abstract

In the present paper it is shown that effect of conical refraction is accompanied by a generation of vortex due to the existing singularities on the surfaces of phase and group velocities in biaxial crystals. This fact is confirmed experimentally by the studies of conical refraction in $YFeO_3$ and interference patterns in $NaNO_2$ crystals. The angle of external conical refraction in $YFeO_3$ crystals determined by us is equal to 4.2°.

Key words: conical refraction, optical vortex, biaxial crystals

PACS: 42.15.Dp, 78.20.Fm, 65.57.Fg

Introduction

The conical refraction is a well-known phenomenon that has been theoretically predicted by V. Hamilton in 1832 on the basis of the wave surfaces constructed by Fresnel and experimentally found one year later by Lloyd [1] in aragonite crystals. The angle of the conical refraction for most materials is quite small (see, for example, [2]). This is just the reason why conical refraction has not yet been used in optical devices. Under disappearing the linear birefringence, the conical refraction disappears, too. The conical refraction appears only in optically biaxial crystals when the light propagates along an optical axis, due to the existence of unique regions on the surfaces of group and phase velocities – a "conical crater". Only directions that belong to these regions can be considered as singular directions in homogeneous crystals. From the other side, such singularities of the phase and ray velocities should produce wave front singularities (see, e.g., [3,4]) and so optical vortex generation.

The present studies have been launched in order to analyze the conditions for vortex generation in anisotropic crystals and observe them experimentally.

Optical Tornado in Biaxial Crystals

The analogy between mechanical (gas or liquid) tornado and optical vortex can be simply demonstrated on the next example. Let us consider a water stream outflowing from a tube. The water velocity near the tube wall is lower than that near the tube axis, in accordance with the difference in the friction forces. Such the velocity difference produces the elementary volumes spinning and of their movement direction change out of the tube axis, like a spinning ball. In such a case the velocity vectors of the elementary volumes that do not correspond to the tube axis possess three velocities components υ_z, υ_y, and υ_x, with the Z axis of Cartesian coordinate sys-

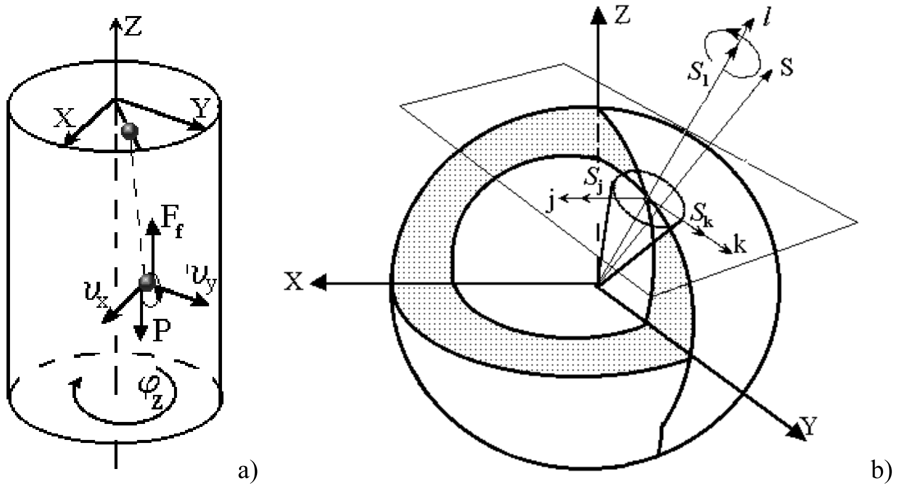

Fig.1. Vortex generation in the liquid streaming through the tube (a) and for the case of light propagation along the optical axis in biaxial crystals (b).

tem coinciding with the tube axis (see Figure 1,a). The product of υ_y υ_x polar vectors produces an axial vector φ_z of a screw-like movement of water and, as a result, the vortex generation.

The similar behaviour can be observed under illumination, with a convergent light beam, of optically biaxial crystalline plate oriented perpendicular to one of the optical axes. The same way as the surface of the group velocities possesses a crater-like singularity, the Poynting's vectors (Figure 1,b) of the emergent light would possess the s_j and s_k components (the coordinate axis l is here parallel to the ray axis), Resulting f from the product of them the axial vector φ_l appears. Thus, the conical refraction is accompanied by a generation of optical vortex. One of the properties of optical vortex is vanishing energy at the vortex axis [5]. It is interesting to note that the conical refraction produces the optical energy to be concentrated within the shell of hollow cylinder or cone, while the optical axis region remains dark (see, e.g., [3]). The other peculiarity of the optical vortex consists in the fact that the interference pattern appearing in the case of superposition of the paraxial beam bearing vortex and the conical (divergent or convergent) Gaussian beam has a shape of a spiral [5].

Experimental Results and Discussion

A scheme of the optical set-up is shown in Figure 2. The He-Ne laser (1) radiation (λ=632.8 nm) is focused with the lens (2) on the coherence scrambler (3), then it is collimated with the lens (4) and propagates through the polarizer (5), the quarter-wave plate (6), the focusing lens (7), the crystal (8), the analyser (9) and falls at the screen (10). The light emerging out of the quarter-wave plate is circularly polarized.

In our experiment we choose $YFeO_3$ crystals that possess a large value of birefringence 0.03~0.04 [6] and belong to the point symmetry group *mmm* [7]. The faces of the specimen with

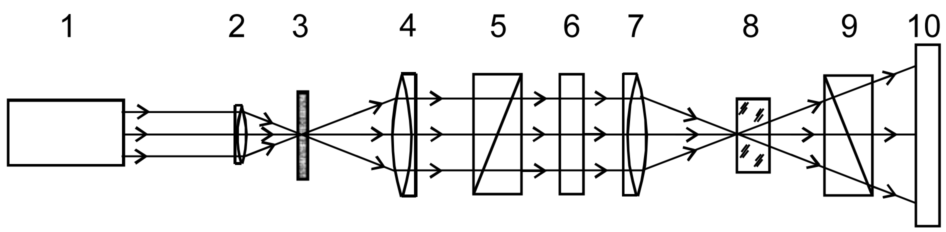

Fig. 2. Optical set-up used for observation of the conical refraction.

the thickness of d=10 μm were perpendicular to the ray axis (i.e., a biradial). For the observation of light interference we used the analyser (9).

The external conical refraction is shown in Figure 3,a. The measured value of the angle of external conical refraction behind the crystal is about 10^o. The recalculated value of this angle, with taking into account the average refractive index $n \approx 2.35$ [8], is about 4.2^o. The flash exposure in the central part of the ring is formed by a parasite light that is not completely eliminated, due to a small thickness of the sample. Unfortunately, we did not observe the interference pattern in the $YFeO_3$ crystal, because the optical retardation in the sample was too small, while thicker samples were not transparent. To confirm the vortex appearing at the conical refraction, we used $NaNO_2$ crystals. They are optically biaxial, belong to point symmetry group *mm2* and possess the optical birefringence $\Delta n_{gm}=0.188$, $\Delta n_{gp}=0.294$, $\Delta n_{mp}=0.106$ (see, e.g., [9]). The central part of the interference pattern shown in Figure 3,b is similar to the picture of singular beam bearing optical vortices with a topological charge of ±1 [5]. This fact confirms that the light propagation along the optical axis in biaxial crystals, i.e. the conical refraction, is accompanied by the optical vortex generation. It is interesting to notice that the obtained pattern is not a conoscopic one, because we do not use the analyser in this observation. The interference pattern appears in the $NaNO_2$ crystals under the circumstance of focused light propagation along the optical axis, due to a superposition of the beam that takes part in the conical refraction (i.e., containing the vortex) and the so-called reference beam that does not take part in the conical refraction. With the crossed polarizers, one can also observe the conoscopic pattern ordinary for optically biaxial crystals (Figure 3,c).

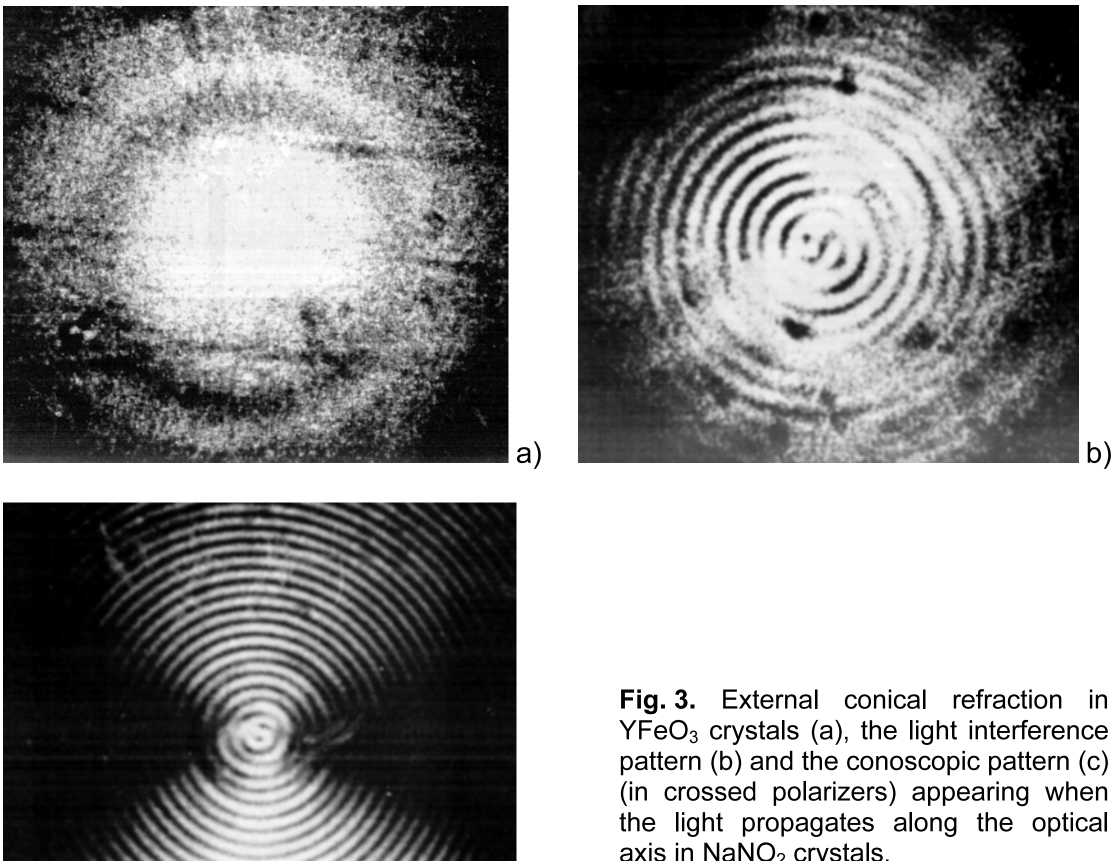

Fig. 3. External conical refraction in $YFeO_3$ crystals (a), the light interference pattern (b) and the conoscopic pattern (c) (in crossed polarizers) appearing when the light propagates along the optical axis in $NaNO_2$ crystals.

Conclusion

It is shown in the present paper that the effect of conical refraction is accompanied by the vortex generation due to availability of singularities on the surfaces of the phase and group velocities in biaxial crystals. This fact is demonstrated experimentally by studies of the conical refraction in $YFeO_3$ crystals and the interference patterns in $NaNO_2$ crystals. The determined angle of external conical refraction for the $YFeO_3$ crystals is about 4.2^o.

Acknowledgments

The authors wish to thank Dr. V. Adamiv and I. Teslyuk for supplying $YFeO_3$ and $NaNO_2$ crystals.

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