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Electro- and magnetogyration

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Abstract. A general picture of electro- and magnetogyration is presented together with the results obtained in the study of these phenomena in the crystals of linear dielectrics and ferroelectrics.

Keywords. Electrogyration; magnetogyration; crystallography; phase transition.

1. Introduction

Electrogyration and magnetogyration as new physical phenomena were predicted rather recently on the basis of general relations of tensor crystallography (Zheludev 1964, 1980, 1982). After several experiments on the observation and study of electrogyration (Vlokh 1970; Vlokh *et al* 1972, 1975) these investigations were rewarded with a diploma for a discovery (Zheludev and Vlokh 1980). The first communication on the observation of magnetogyration appeared quite recently (Vlokh 1981, 1982).

2. Electrogyration

Electrogyration, by definition, consists of the effect of electric field on the gyrotropy of crystals. Analytically, it can be represented by the power expansion of gyration tensor g_{ij} (second-rank axial tensor) in electric fields E:

$$g_{ij} = g^0_{ij} + \gamma_{ijk}E_k + \beta_{ijkl}E_kE_l + \ldots,$$

where g^0_{ij} is the gyration tensor in the absence of the field, and γ_{ijk} and β_{iikl} are third- and fourth-rank axial tensors describing linear and quadratic electrogyration effects, respectively. Linear electrogyration occurs in all crystal classes except for $m3m$, $\bar{4}3m$ and 432; with tensor γ_{ijk} being the same as those describing piezomagnetism (Zheludev 1983).

Phase transition in ferroelectrics with the appearance (or disappearance) of spontaneous polarization P_s provides a natural possibility to observe and study spontaneous electrogyration. The most simple and reliable are the cases where a centrosymmetric optically inactive crystal acquires gyrotropy. This phenomenon was observed for a number of crystals. In particular, the studies of the phase transition in triglycine sulphate (TGS) crystals near 49°C show that at temperatures less than T_c specific rotation of the polarization plane ρ is really proportional to P_s (Vlokh *et al* 1971).

For some ferroelectrics, appearance of P_s of opposite orientations results in the formation of the domains with enantiomorphism of different signs having therefore optical activity of different signs. This, particularly, enables us to observe both change in sign of optical activity and gyration hysteresis in ferroelectrics (*e.g.* in $5PbO \cdot 3GeO_2$ crystals) during domain repolarization (Iwasaki *et al* 1972). Of special interest is the possibility to obtain high-induced electrogyration in ferroelectric crystals in the phase transition region. Anomalies of induced electrogyration in the phase transition region are determined finally by dielectric anomalies (Vlokh *et al* 1977), the attainable specific rotation of the light polarization plane being as high as several degrees in the field of 1 kV.

Detection of forced electrogyration required a careful search for suitable crystals and refined experimental technique. Linear electrogyration has been observed, measured and studied in α-HIO_3, $LiIO_3$, $PbMoO_4$ and several other crystals todate. The study of electrogyration in optically biaxial α-HIO_3 crystals (class 222) was made difficult by the accompanying electrooptic and piezooptic effects. The experimental value of electrogyration coefficient γ_{52} is $(4{\cdot}33 \pm 0{\cdot}70) \cdot 10^{-13}$ m/V for $\lambda = 632{\cdot}8$ nm (Vlokh *et al* 1972).

Electrogyration in uniaxial crystals of classes 4, 6, 3, etc. is not so complicated by electrooptic and piezoeffects if the electric field applied and the wave normal are directed along the optical axis (the crystal remains uniaxial). Therefore, experiments with $LiIO_3$ crystals belonging to class 6 (Vlokh *et al* 1975) were of key importance in proving the observability of the forced electrogyration. The effect was measured at -140°C, since the crystal exhibited ionic conductivity at room temperature. The value of $(1{\cdot}57 \pm 0{\cdot}30) \cdot 10^{-13}$ m/V was obtained for electrogyration coefficient γ_{33}, the contribution of piezoelectric deformation being 17% of the value observed (figure 1).

The most noteworthy are the experiments on forced electrogyration in $PbMoO_4$ crystals, because, unlike the above crystals optically active even in the absence of the electric field, $PbMoO_4$ acquires gyrotropy only when the field is applied (the crystal is centrosymmetric, its symmetry group being $4/m$). Electrogyration can be observed in pure form without the usually accompanying electrooptic and piezoeffects. Specific rotation in readily obtainable fields (~ 10 kV/cm) attains quite considerable values in

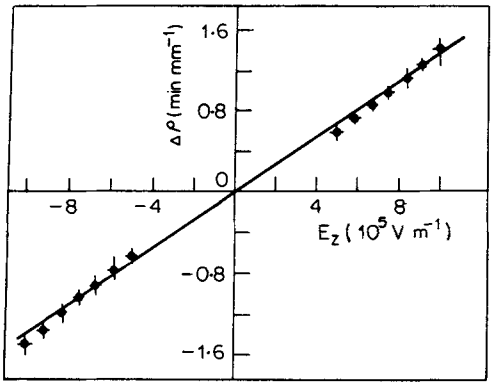

Figure 1. Dependence of the increment of the specific rotation of polarization plane on the field strength E_z for $LiIO_3$ crystals.

this crystal, being as high as several degrees. The phenomenon is characterized by the dispersion (figure 2): at $E = 10$ kV/cm $\rho = 1{\cdot}5\ \text{cm}^{-1}$ for $\lambda = 700$ nm and $\rho = 5\ \text{cm}^{-1}$ for $\lambda = 400$ nm. Coefficient γ_{33} (the field and wave normal directed along the optical axis) is $(1{\cdot}23 \pm 0{\cdot}12) \cdot 10^{-12}$ m/V for $\lambda = 517$ nm (Vlokh *et al* 1975).

Quadratic electrogyration is described by a fourth-rank axial tensor and can occur only in acentric crystals (Vlokh *et al* 1970). It was experimentally observed in quartz crystals with electric field applied along crystallographic axes and plane-polarized wave propagating along the optical axis. The value of the quadratic electrogyration coefficient observed was $\beta_{31} = (4{\cdot}5 \pm 0{\cdot}34) \cdot 10^{-20}\ m^2/V^2$ (Vlokh 1971).

3. Magnetogyration

There is a number of well-known and well-investigated magnetic phenomena (Ramaseshan 1951). Magnetogyration is a new one consisting, by definition (Zheludev 1964), of the ability of anisotropic media to acquire (or to change) their optical activity g_{ij} (g_{ij} is a symmetric second-rank tensor) in the magnetic field, H_k:

$$g_{ij} = g_{ij}^0 + \delta_{ijk}H_k + Q_{ijkl}H_kH_l + \ldots,$$

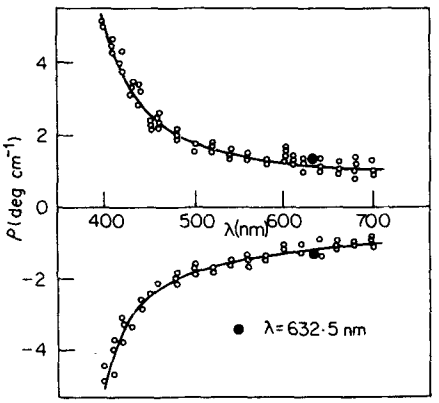

Figure 2. Dispersion of induced optical activity of $PbMoO_4$ crystals in static field $E_z = 10$ kV/cm.

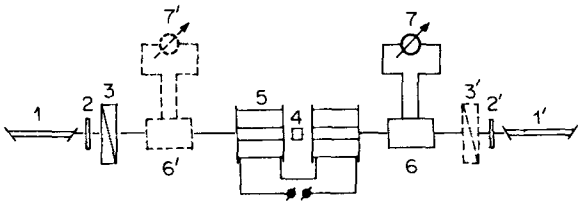

Figure 3. Block diagram of the experimental device used in studying Faraday effect and magnetogyration. 1,1'—He–Ne lasers; 2,2'—$\lambda/4$ plate in diagonal position; 3,3'—rotatable polarizer with limb; 4—sample under investigation; 5—permanent electromagnet; 6,6'—recording system; 7,7'—galvanometer.

where g_{ij}^0 is the gyration tensor in the absence of the magnetic field; and δ_{ijk} and Q_{ijkl} are third- and fourth-rank polar and axial tensors describing linear and quadratic magnetogyration, respectively. Tensor δ_{ijk} has nonvanishing components only in the case of non-centrosymmetric crystals and textures, its form being the same as that of the respective piezoeffect tensors. Magnetogyration as well as the natural optical activity can be described by a surface of the "twisted cylinder" symmetry, group $\infty 2$ (or by a set of such surfaces).

If magnetic field is applied to a non-centrosymmetric medium (particularly, to a nonmagnetic one), the rotation of the light polarization plane is determined by the two effects: Faraday effect and magnetogyration. The contributions of these effects, linear in field, can be separated due to the difference in their symmetry (Faraday effect is characterized by the symmetry of "rotating cylinder", group ∞/m). One of the methods of their separation lies in measuring the rotation of the polarization plane for the light passed in opposite directions (figure 3). If both effects occur simultaneously, they have the same sign (*i.e.* add up) for one direction, and different signs (*i.e.* subtract from each other) for the opposite direction.

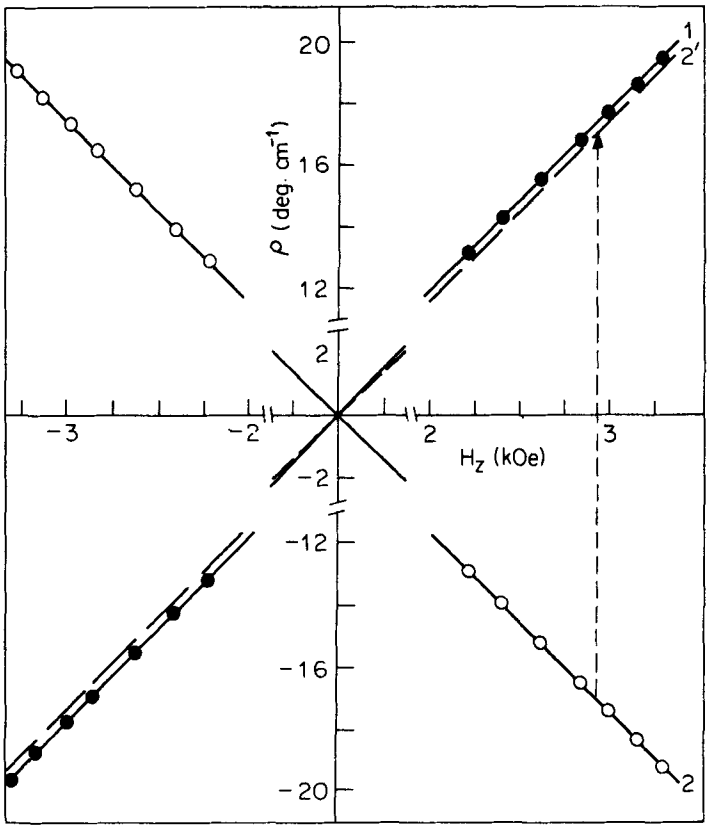

Figure 4. Dependence of the specific rotation of polarization plane on the magnetic field strength for CdS crystals. 1—wave vector is $+k$; 2—wave vector is $-k$; 2′—curve 2 reflected with respect to H_z-axis.

Magnetogyration represents a magnetic analogue of electrogyration. In the simplest cases, the former consists of the appearance of optical activity induced by a magnetic field (axial action) applied along the exclusive polar direction (crystals of $3m$, $4mm$, $6mm$ symmetry), whereas the latter lies in the appearance of the optical activity induced by an electric field (polar action) applied along the exclusive axial directions (crystals of $\bar{6}$, $4/m$, $6/m$ symmetry). In particular, by analogy with the occurrence of the spontaneous electrogyration in the phase transitions due to spontaneous polarization P_s in the crystals of this symmetry, spontaneous magnetization I_z in crystals of classes $3m$, $4mm$, $6mm$ results in the spontaneous magnetogyration. Magnetogyration is a consequence of the spatial dispersion, *i.e.* the dependence of the quantities characterizing the interaction of electromagnetic wave with medium on the wavelength (wave vector)

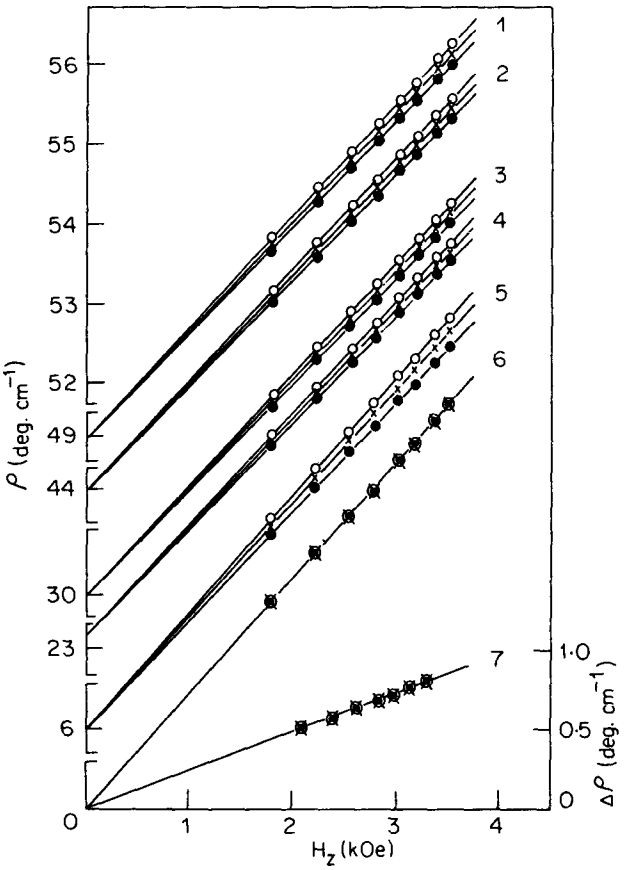

Figure 5. Dependence of the specific rotation of polarization plane on the magnetic field strength for $Pb_5Ge_3O_{11}$: Eu^{3+} crystals in different states of spontaneous electrogyration. 1, 2, 3, 4, 5 —at 20, 50, 120, 140 and 160°C, respectively; x—in polydomain crystals (plots are matched to the initial points of monodomain crystals, because in polydomain crystals $\rho = 0$ at $H = 0$); O, ●—in monodomain crystals at opposite directions of spontaneous polarization; 6—at 180°C (paraphase); 7—for quartz crystals at opposite directions of the wave vector (O, ●) and from the results of double propagation measurements (x).

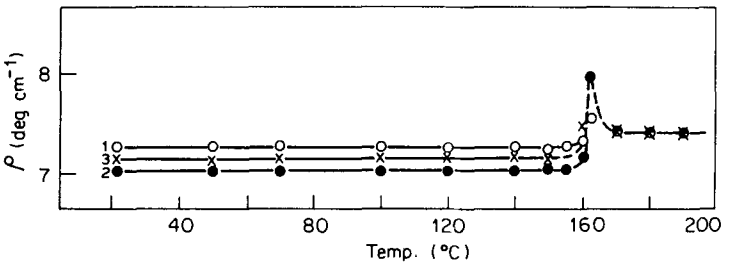

Figure 6. Temperature dependence of the increments of the specific rotation of polarization plane for $Pb_5Ge_3O_{11}$: Eu^{3+} crystals at $H_z = 3{\cdot}5$ kE. 1—in polydomain crystals (Faraday effect); 2,3—in monodomain crystals at the opposite signs of enantiomorphism (superposition of Faraday effect and magnetogyration). The curie point of the crystal is 161°C.

(Agranovich and Ginzburg 1979). Magnetogyration is determined by the part of this dependence that appears due to or is changed by magnetic field.

Linear magnetogyration was first studied in the crystals of linear dielectrics $LiIO_3$ and SiO_2 (Vlokh 1981, 1982). For $LiIO_3$ crystals (symmetry class 6) the obtained values of coefficients α_{33} (for Faraday effect) and δ_{33} (for magnetogyration) were $(111{\cdot}15 \pm 0{\cdot}04) \cdot 10^{-11}$ and $(0{\cdot}51 \pm 0{\cdot}06) \cdot 10^{-11}$ rad/Oe, respectively. Quartz crystals were studied mainly to ascertain whether Faraday effect is not accompanied with magnetogyration if field H is directed along z-axis (in third-rank polar tensor $\delta_{33} = 0$ for the crystals of class 32). In CdS crystals magnetogyration should appear in pure form if magnetic field applied is directed along the optical axis. In this crystal $\alpha_{33} = (501{\cdot}8 \pm 0{\cdot}3) \cdot 10^{-11}$ rad/Oe and $\delta_{33} = (4{\cdot}4 \pm 0.5) \cdot 10^{-11}$ rad/Oe (figure 4).

In polydomain ferroelectrics with spontaneous polarization in centrosymmetric phase, induced linear magnetogyration does not occur (TGS, $BaTiO_3$, etc.). If original modification is optically active (*e.g.* in Rochelle salt), then polydomain crystal displays magnetogyration. In the cases where domain of opposite orientation is characterized by enantiomorphism of different signs (transitions with the change in symmetry) e.g. $2/m \rightarrow 2$ (TGS), $\bar{6} \rightarrow 3$ (lead germanate, $Pb_5Ge_3O_{11}$, etc.), crystals monodomainized by electric fields of opposite directions, being affected by magnetic field, show magnetogyration of opposite signs. Studies of magnetogyration in lead germanate crystals gave $\alpha_{33} = (151{\cdot}5 \pm 0{\cdot}2) \cdot 10^{-11}$ rad/Oe and $\delta_{33} = (2{\cdot}5 \pm 0{\cdot}3) \cdot 10^{-11}$ rad/Oe (figure 5). In the phase transition temperature region (near 162°C) magnetogyration in lead germanate demonstrates an anomalous behaviour and at higher temperatures vanishes (figure 6).

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