Structure of the Inhomogeneous Magnetic State of an FeBO$_3$ : Mg Easy-Plane Weak Ferromagnet

B. Yu. Sokolov
National University of Uzbekistan, Tashkent, 700174 Uzbekistan
e-mail: optic@nuuz.uzsci.net
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Abstract—The magnetic linear birefringence of an FeBO$_3$ : Mg ferromagnetic crystal is investigated as a function of the magnetic field strength, the magnetic field orientation, and the coordinates. The structure of the inhomogeneous magnetic phase of this weak ferromagnet is determined by analyzing the experimental results obtained. It is shown that, in an inhomogeneous magnetic state, the ferromagnetic moment does not deviate from the basal plane of the crystal and the angle of its deviation from the direction of the applied magnetic field is described by a one-dimensional harmonic function of the spatial coordinate along the axis of magnetization.

1. INTRODUCTION

Previous investigations [1] have demonstrated that, upon magnetization in the basal plane, iron borate doped with diamagnetic ions of magnesium (FeBO$_3$ : Mg) undergoes a phase transition from the homogeneous magnetic state to the inhomogeneous magnetic state. The inhomogeneous magnetic state of this weak ferromagnet is observed at temperatures $T < 130$ K under the condition where the external magnetic field $H$ is aligned parallel to the hard magnetization axes of the in-plane hexagonal crystalline anisotropy (in a direction perpendicular to any of the three $C_2$ axes). In our previous work [1], we performed a magneto-optical investigation of the inhomogeneous magnetic state in FeBO$_3$ : Mg ferromagnetic crystals with the use of a light-polarizing microscope and visually observed the appearance of magnetic inhomogeneities of the crystal in the form of a quasi-periodic system of alternating bright and dark fringes with diffuse boundaries directed perpendicularly to the applied magnetic field.

When interpreting the results obtained in [1], it was assumed that, in an inhomogeneous magnetic state, the vector of the weak ferromagnetic moment $\mathbf{m}$ oscillates about the direction of the magnetic field $\mathbf{H}$ aligned parallel to the axis of magnetization but remains in the basal plane of the crystal. However, another situation can also occur. In observations of the crystal in polarized light (in the experiment, the light waves propagate along the normal to the basal plane), the appearance of a system of bright and dark fringes on the image of the crystal surface can be caused by a spatial modulation of the azimuth of the vector $\mathbf{m}$ when the magnetization vector deviates from the basal plane. This leads to a periodic variation in the magnitude of the Faraday effect along the direction of the magnetic field $\mathbf{H}$ due to the change in the projection of the ferromagnetic moment $\mathbf{m}$ onto the direction of the propagation of light waves.

In this work, the structure of the inhomogeneous magnetic state of an FeBO$_3$ : Mg ferromagnetic crystal was determined by analyzing the spatial distribution of the vector $\mathbf{m}$ in this crystal as a function of the applied magnetic field.

2. EXPERIMENTAL TECHNIQUE

It is known that the magnetic linear birefringence substantially depends on the orientation of the magnetization in the crystal (see, for example, [2]). Therefore, in order to determine the structure of the inhomogeneous magnetic state of an FeBO$_3$ : Mg crystal, it is expedient to investigate the dependence of this even magneto-optical effect on the spatial coordinates in the basal plane of the crystal. Let us elucidate how the orientation of the ferromagnetic moment in an FeBO$_3$ : Mg crystal affects the magnetic linear birefringence of this crystal. A similar problem was solved earlier by Fedorov et al. [3], who considered the structure of the photoinduced modulated magnetic state in FeBO$_3$ : Ni crystals.

According to Fedorov et al. [3], when a light wave propagates in iron borate along the optic axis (i.e., along the $C_3$ axis of the crystal), the magnetic linear birefringence...
birefringence at a point on the basal plane with the coordinates \((x, y)\) can be represented in the form
\[
\Phi = A(x, y) \sin 2[\theta - \varphi(x, y)],
\]
\[
A(x, y) = A_0 (a^2 + b^2)^{1/2},
\]
\[
A_0 = 2\pi(n^2 - n^1)l/\lambda,
\]
\[
a = l\int_0^1 \cos 2\varphi(x, y, z)dz,
\]
\[
b = l\int_0^1 \sin 2\varphi(x, y, z)dz.
\]

Here, \(\varphi\) is the angle between the direction of projection of the vector \(m\) onto the basal plane and the \(X\) axis of the laboratory system of coordinates (for definiteness, it is assumed that \(X \perp C_2\)); \(\theta\) is the azimuthal angle between the plane of polarization of the light incident on the crystal and the \(X\) axis; \(n^2\) and \(n^1\) are the refractive indices for the light linearly polarized parallel and perpendicular to the direction of the two-dimensional component of the vector \(m\), respectively; \(\lambda\) is the emission wavelength; and \(l\) is the thickness of the crystal along the \(Z\) axis \((Z \parallel C_3)\).

It follows from relationships (1) that, in the case when the coordinates \(x\) and \(y\) are taken to be fixed, the dependence \(\Phi(\theta)\) can be described by a harmonic function with an initial phase \(\varphi\) and an amplitude \(A\) that specify the direction and magnitude of the ferromagnetic moment at a given point on the basal plane of the crystal, respectively. Therefore, the spatial orientation of the vector \(m\) in the crystal can be judged from the results of analyzing the coordinate dependence of the magnetic linear birefringence in terms of relationships (1).

Our experiments were performed with the same ferromagnetic crystal of magnesium-doped iron borate \(\text{FeBO}_3 : \text{Mg}\) \((~0.1\ \text{wt} \% \text{Mg})\) that was studied earlier in [1]. The sample had the form of a plane-parallel plate \(\approx 3\text{-}mm\) wide and \(\approx 60\ \mu\text{m}\) thick. The developed surface of the plate coincided with the basal plane. The magnetic linear birefringence was measured using emission from a He–Ne laser at a wavelength \(\lambda = 0.63\ \mu\text{m}\) in a constant magnetic field \(H \leq 30\ \text{Oe}\) at temperature \(T = 80\ \text{K}\). The vector \(H\) was oriented in the plane of the sample, whereas the direction of light propagation was perpendicular to the plane of the sample. The magnetic linear birefringence was measured with the use of a phase compensator (plates \(\lambda/4\)) according to the traditional technique with modulation of the azimuth of the plane of light polarization [4]. The instrument sensitivity to variations in the angle \(\Phi\) was \(\approx 0.001^\circ\), and the relative measurement error was \(\approx 5\%\).

In order to investigate the coordinate dependence of the magnetic linear birefringence, laser radiation was focused onto a spot \(\approx 15\ \mu\text{m}\) in diameter on the surface of the sample with the use of a microscope. Taking into account that the spatial period of the magnetic inhomogeneity in the \(\text{FeBO}_3 : \text{Mg}\) ferromagnetic crystal is approximately equal to \(100\ \mu\text{m}\) [1] and assuming that, within the light spot, \(\varphi(x, y) \approx \text{const}\), the surface under examination can be considered a point. In our experiments, the cryostat with a sample could be displaced along two coordinates in the focal plane of the microscope. This made it possible to measure the magnetic linear birefringence at a specified point on the basal plane of the crystal and to visually observe the magnetic state of the crystal under the microscope (with an additional source of white light).

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figure 1 shows the integral field dependences (i.e., the dependences measured under illumination of the whole surface of the sample) of the magnetic linear birefringence observed under conditions where the vector \(H\) in the basal plane of the \(\text{FeBO}_3 : \text{Mg}\) ferromagnetic crystal was oriented parallel and perpendicular to one of the \(C_2\) axes and the azimuthal angle of the polarizer was \(\theta = 45^\circ\). (Since the effect has different signs for these two directions of the magnetization, Fig. 1 presents the field dependences of the magnetic linear birefringence in the form of \(|\Phi(H)|\) for convenience of comparison.) It can be seen from Fig. 1 that, under conditions of technical saturation of the magnetization, the values of \(|\Phi|\) along the above two directions coincide in accordance with relationships (1) but the curves \(|\Phi(H)|\) differ significantly in the range of magnetic fields \(3 \leq H \leq 17\ \text{Oe}\) for \(H \perp C_2\) [1] corresponding to the inhomogeneous magnetic state of the crystal. In particular, the quantity \(|\Phi|\) for the orientation \(H \parallel C_2\) reaches its maximum in a magnetic field \(H = 3\ \text{Oe}\), whereas the