UDC 538.1; 548

THE TEMPERATURE DEPENDENCE OF THE FARADAY EFFECT IN TERBIUM GARNET FERRITE IS INVESTIGATED NEAR ITS MAGNETIC-COMPENSATION TEMPERATURE

Sharipov M. Z.

Bukhara Engineering - Technologies Institute, 200100, Bukhara, Uzbekistan, m.z.sharipov@rambler.ru

The temperature dependence of the Faraday Effect in terbium garnet ferrite, $Tb_3Fe_5O_{12}$, is investigated near its magnetic-compensation temperature, T_c = 249 K. A non-monotonous variation in the value of the Faraday rotation angle Φ is observed in a weak magnetic field as the temperature approaches T_c: the temperature plot of the Faraday rotation angle has two local maxima observed left and right of the magnetic compensation point. A theoretical model is proposed, which follows from the phenomenological theory of domain-boundary displacement under the action of a magnetic field, offering an unambiguous description of the principles of domain-structure influence on the Faraday Effect in $Tb_3Fe_5O_{12}$ near T_c.

Keywords: magnetic compensation temperature, domain structure, Faraday effect.

Introduction

It is well known that many properties (thermal capacity, Faraday rotation, Young modulus, etc.) of rare-earth garnet ferrites (REGFs) undergo an abrupt change. By far the majority of experimental studies dealing with this problem report the results of their investigation performed under conditions of uniform magnetization of the crystal (in a single-domain state of the specimen) [1].In a weak magnetic field, however, where there is a certain domain structure (DS) in the crystal, variation of the physical properties of REGFs at $T \to T_c$ can be much more complex. Within recent years, an interest in the investigation of variations in DS and the related magnetic characteristics of REGFs near T_c is prompted by the prospects of developing promising materials, based on these ferrimagnetics, for the elemental base of devices of the new-generation magnetic microelectronics, whose operating principle relies on the flexomagnetoelectric effect [2].

To this end, we performed an experimental investigation of the influence of DS on the Faraday Effect (FE) in garnet ferrite, $Tb_3Fe_5O_{12}$, in the temperature interval close to the point of its magnetic compensation, T_c = 249 K [3], and present its results in what follows.

1. Samples and experimental procedure

It is well known that in $Tb_3Fe_5O_{12}$ the easy-magnetization axes are the crystallographic directions of the □111□type [1], i.e., the crystal has four easy magnetization axes along which we could orient vector $\boldsymbol{M_s}$, which significantly complicates the resulting DS pattern. In order to simplify the problem, in our experiments we used a single crystal $Tb_3Fe_5O_{12}$ specimen shaped as a parallel plate (measuring ≈100 μm in thickness) cut so as to let its [111] axis make an angle of ≈10° with the normal to its plane, and one of the □111□axes was directed to have a smaller tilt to the plane compared to the two others. This crystal orientation gave us a specimen with the simplest (from the point of interpretation of the experimental results) banded 180° DS of the Cotton type [4]. For the sake of illustration, Fig. 1 presents a number of photos of the specimen taken in its demagnetized state during heating from the lowest temperature attainable in the experiment T= 85 K (heating rate ~0.2 K/s), which shows the general trend of its DS variation as a function of temperature. Figure 1 suggests that during transition through the point of magnetic compensation there is a stable DS in the specimen (in contrast to the theoretically predicted DS of a thin

ferrimagnetic plate [5, 6]). The variation of DS with temperature occurs as a process of domain-boundary (DBs) hopping from one metastable position into another, the average width of the resulting domains remaining practically unvaried from case to case. Note that the positions of DBs on the specimen's surface are somewhat different. In addition, we observe a marked irreversibility of DS in the course of heating-cooling of the specimen (more detail in [4]).

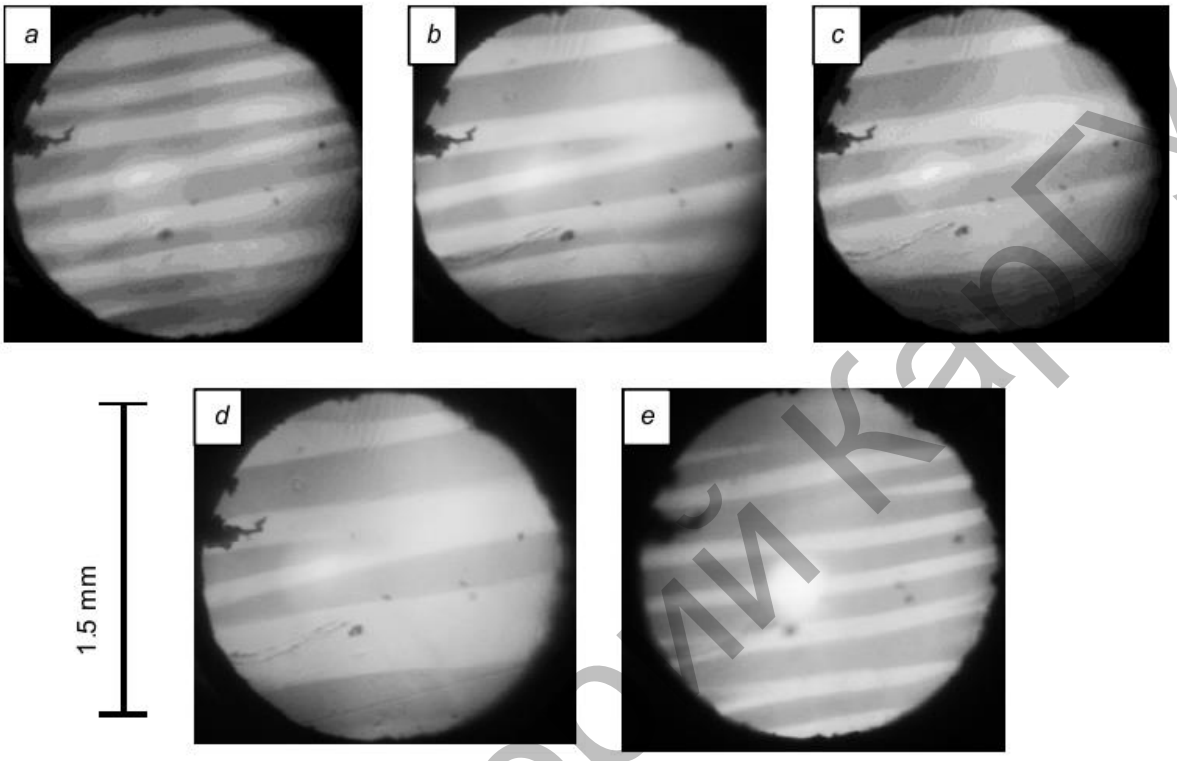

Fig. 1. Photographs of domain structure of the specimen taken at different temperatures: 224(a), 245(b), 250 (c), 254 (d) and 295 K (e).

In the experiment we investigated the evolution of DS of the specimen during variations in the temperature and magnetization of the external magnetic field and the resulting FE changes caused by these variations. Within the framework of a two-sublattice model of REGF[1] for the case of nomal incidence of light on the specimen's surface the spontaneous Faraday effect can be given by the following [7]:

$$\varphi = \pm (a M_{Fe} \cos\theta_1 + b M_R \cos\theta_2) l, \quad (1)$$

where a and b are the magnetooptical coefficients depending on the light frequency, θ_1, θ_2 are the angles formed by vectors $\boldsymbol{M}_{Fe}$ and $\mathbf{M}_R$ with the normal to the specimen's plane (in our case θ_1, $\theta_2 \approx 80^0$), l is the specimen's thickness; the positive sign before the brackets refers to the temperatures higher than T_c and the negative sign – to those lower than this temperature.

It is clear that in the case of a 180-degree DS, when we expose to light a specimen's surface, whose area exceeds that of an individual domain, the FE will be given by

$$\Phi = \varphi (S_+ - S_-) / S \propto \varphi x, \quad (2)$$

[1] In this approximation $\boldsymbol{M}_s = \boldsymbol{M}_{Fe} + \boldsymbol{M}_R$, where $\boldsymbol{M}_{Fe}$, $\boldsymbol{M}_R$ are the spontaneous magnetic moments of the iron and RE - sublattices, respectively (in a co-linear magnetic phase of the crystal vectors $\boldsymbol{M}_{Fe}$ and $\boldsymbol{M}_R$ are antiparallel); in the external magnetic field for $T = T_c$ vectors $\mathbf{M}_{Fe}$ and $\mathbf{M}_R$ turn through an angle of 180^0 [1].

where S is the exposed area of the specimen, S_+ and S_- are the areas of domains with opposite orientations of vectors $\boldsymbol{M}_s$, and x is the average DB displacement under the action of H with respect to the equilibrium position.

The DS of a specimen was visually examined using a 'peek-a-boo' method in a polarization microscope by a conventional Faraday rotation technique [4]. The Faraday angle Φ was measured by the method of a continuously spinning analyzer [8]. In order to increase the projection of vector $\boldsymbol{M}_s$ on the direction of light propagation (i.e., increasing φ), the specimen was rotated around the axis perpendicular to the average direction of DBs, to make the angle of light incidence onto its plane measure ≈ 15°. Magnetization of the specimen was performed by the H ≤ 60 Oe magnetic field oriented in its plane along the DB. A light source used was a halogen glow lamp. The main focus of the investigations was on the temperature interval (200–295) K, including T_c of the crystal.

2. Experimental results

Figure 2 presents the temperature dependence of the field strength H_c, for which the specimen transits into a single-domain (uniformly magnetized) state. Every point in Fig. 2 was obtained by direct visual observation of the disappearance of DBs from the image in the course of varying H and T: in our experiment the specimen was cooled down to a certain temperature, following which we applied a magnetic field (vector $\boldsymbol{H}$ was oriented along the middle direction of DBs in the specimen's plane) and its strength was gradually increased from zero to a value at which no DBs were left in the image; further the specimen was warmed up to room temperature, demagnetized in the alternating-sign magnetic field with an amplitude decreasing down to zero, and then magnetized again at a different value of T[1]. The $H_c(T)$ plot suggests that within the entire temperature range of interest $200 \le T \le 295$ K, except for a short ($T_c \pm 1.5$) K (in this temperature range we failed to maintain uniform magnetization state of the specimen up to the field strength H = 60 Oe used in this experiment) a single-domain state of the specimen is formed at $H > 15$ Oe, with the field H_c non-monotonously changing with temperature both on the right and left of T_c: for $T \to T_c$ the value of H_c first reaches its minimum and then sharply increases.

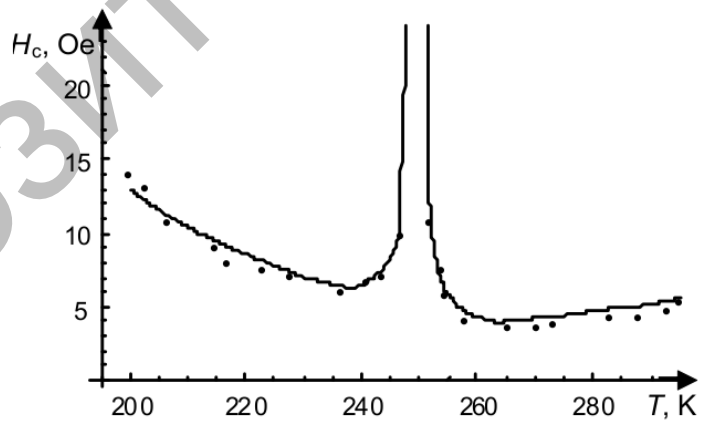

Fig. 2. Temperature dependence of the strength of an external magnetic field under which the specimen transits into a single-domain (uniformly magnetized) state: calculation via Eq. (4) (solid line) and experiment (filled circles).

It is evident from Fig. 3, which presents the FE temperature plots constructed for different magnetization field strengths, that under conditions of technological magnetization saturation the

[1] The magnetization process used differs from that followed in [4], therefore the $H_c(T)$ dependence presented in Fig. 2 is somewhat different from the one reported in [4].

$\Phi(T)$ curve has a classical form in accordance with Eq. (1), where the FE sign changes near T_c[1]. The investigations performed demonstrated that the behavior of the $\Phi(T)$ curves in the region of $H < 20$ Oe is most complicated: the observed dependences $\Phi(T)$ are asymmetrical with respect to T_c; for $T \rightarrow T_c$ the value of FE changes in a non-monotonous manner; the amplitude of the $\Phi(T)$ curve increases with H, with the maximum angle Φ approximating the value corresponding to the magnetic saturation condition; in contrast to the $\Phi(T)$ curve constructed at H= 35 Oe, from which follows that that inversion (reorientation) of vectors $\boldsymbol{M}_{Fe}$ and $\boldsymbol{M}_R$ at $T = T_c$ occurs abruptly, while in weaker magnetic fields the process of reorientation of vectors $\boldsymbol{M}_{Fe}$ and $\boldsymbol{M}_R$ proceeds in a certain temperature interval and is accompanied by a significant temperature hysteresis.

It is evident that at H< 20 Oe the shape of the $\Phi(T)$ curve is controlled by the DS realized in the specimen. In particular, a decrease in the FE at the ends of the temperature interval is due to the division of the specimen into domains of different areas with an inversely oriented projection of vector $\boldsymbol{M}_s$ in the adjacent domains onto the direction of propagating light; the stepwise character of the behavior of parameter Φ is controlled by the Barkhausen jumps; straight-line portions of the $\Phi(T)$ curve, observed at H> 4 Oe in some temperature intervals right and left of T_c, indicate single-domain states of the specimen formed in these temperature intervals.

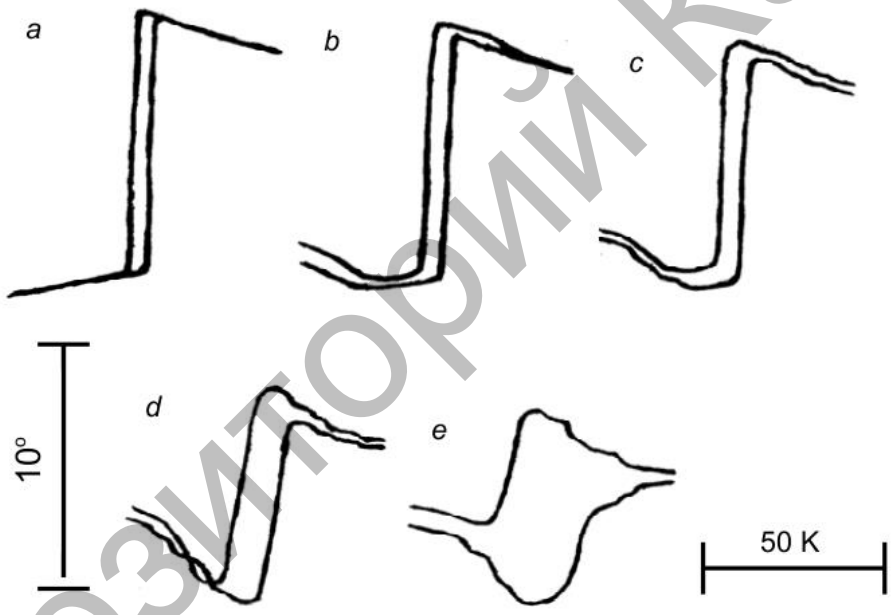

Fig. 3. Temperature dependences of the Faraday effect in the specimen under study, obtained at different field strength values, H: 35(a), 15 (b), 10 (c), 3 (d) and 2 Oe (e). Arrows show the direction of temperature variation. Horizontal axis corresponds to the zero Faraday rotation angle; the bar on the horizontal axis marks the temperature T= 295 K.

The presence of local maxima in the $\Phi(T)$ curve at H< 20 Oe left and right of T_c and the non-monotonous variation of the field H_c (Fig. 2) in the temperature range in question appears somewhat unexpected, since the spontaneous magnetic moment in $Tb_3Fe_5O_{12}$ will be approximately linearly decreasing down to zero as a function of T [3], as the temperature approaches the point of compensation, and hence the pressure P= $2M_sH$ acting on the DB will gradually decrease for $T \rightarrow T_c$.

[1] In the temperature interval in question, to a good approximation we can assume that quantities M_{Fe} and M_R depend on T in a linear fashion [3], which controls the linear temperature dependence of angle $|\Phi|$ observed at H = 35 Oe (in the state of technological magnetization saturation of the specimen).

3. Discussion of experimental results

In order to interpret our results, let us turn to the thermodynamic theory of a banded 180-degree DS, since today there is no complete microscopic theory of DB mobility in REGFs [9]. It should be noted at this point that the presence of DS at $T \approx T_c$ in [4] was attributed to the transition of a crystal from a collinear magnetic phase into an angular one, in which the angle between vectors $\boldsymbol{M}_{Fe}$ and $\boldsymbol{M}_R$ is different from 180^{01}. In particular, the latter fact results in a more complicated domain configuration of the specimen in the immediate vicinity to T_c: against a background of "light" ("dark") domains there are "dark" ("light") wedge-like domains (see Fig. 1), whose length and width is varied with variation in T. Thus, the model proposed below, which describes the effect of DS on FE in $Tb_3Fe_5O_{12}$, wholly corresponds to the situation developing in the temperature range where a banded 180-degree domain structure is realized.

It is well known that the position of DB in the external field H in a perfect (defect-free) crystal is determined by the balance between its Zeeman and magnetostatic energies and depends on the geometry of the specimen under study [10]. In this case, the mean displacement of a DB from its equilibrium position at H, which is directed along the easy magnetization axis (along the DB), could be derived from the following condition [10]:

$$2M_sH = kx, \tag{3}$$

where k is the constant of a restoring force (elastic coefficient) generated in a finite-size specimen due to the demagnetization fields.

On the other hand, in a real specimen of a considerably large size the main reason controlling the position of DBs is the spatial distribution of the pinning centers (dislocations, non-magnetic impurity inclusions, etc.) in its crystal lattice: in terms of energy it is favorable for the DB plane to contain pinning centers [10]. It is evident that pinning of DBs plays a critical role in the processes of technological magnetization: specifically, the stepwise variation in the value of FE with temperature (see Fig. 3*c*-*e*) in weak magnetic fields is associated with the DB pinning on crystal-lattice defects. Thus, in order to initiate the motion of DBs as a single whole the external magnetic field has to exceed a certain threshold value determined by that of the pinning field H_p. Taking into account the latter consideration and relying on Eq. (3), the field of technological magnetization saturation can be given by

$$H_c = H_p + kd/4M_s, \tag{4}$$

where d is the width of the domain ($x = d/2$ is the maximum DB displacement possible), and Eq. (2) can be rewritten as follows: where A is the proportionality factor.

$$F = \Phi/\varphi = 2AM_s\,(H - H_p)/k, \tag{5}$$

If we assume the microscopic collections of non-magnetic impurities present in the crystal to be the DB pinning centers, then $H_p = \gamma M_s$, where γ is a coefficient depending on the number, shape and size of defects [10]. The temperature dependence of M_s for $Tb_3Fe_5O_{12}$ is well known (see, e.g., [3]), which allows us to compare Eqs. (4) and (5) with the experimental $H_c(T)$ and $\Phi(T)$ plots, respectively.

The calculations via Eqs. (4) and (5) were performed using a standard likelihood-function-search routine, which ensured the least deviation of the curve from the experimental points, and the data obtained using the $M_s(T)$ plot from [3]. The fitting parameters used were the γ, kd and A/k, γ

[1] It was the formation of a non-collinear magnetic phase of the crystal, which in [4] interpreted the cause for the temperature hysteresis of the DS rearrangement in the $\Phi(T)$ plot near T_c.

pairs, respectively. It was assumed that coefficients γ and *k* do not depend on *T*, and the relatively weak (compared to the $1/M_s(T)$ plot) variation in the value of *d* within the range $200 \le T \le 295$ K (see Fig. 1) was neglected. Since it is difficult to analytically describe the variations in M_s of the garnet under study within the entire temperature range of interest (see [3]), we calculated the $H_c(T)$ and $F(T)$ curves in two stages. First, we fitted the functions (4) and (5) to the experimental plots $H_c(M_s)$ and $\Phi/\varphi(M_s)$, respectively, then digitized the calculated $H_c(M_s)$ and $\Phi/\varphi(M_s)$ curves, and then automatically ascribed the respective temperature to every value M_s, following which and using an additional routine, we transformed (via interpolation) the digitized $H_c(M_s)$ and $\Phi/\varphi(M_s)$ plots without any scaling along the ordinate axis into smooth $H_c(T)$ and $F(T)$ curves.

The results of fitting the $H_c(T)$ and $F(T)$ functions to the experimental data are shown in Figs. 2 and 4. The experimental points in Fig. 4 were obtained using the $\Phi(T)$ curves (Fig. 3*d* and *e*) corresponding to specimen's cooling in a state far from that of magnetization saturation (we assumed the point of crossing between the $\Phi(T)$ curves and the x-axis to be T_c) and the temperature dependence of the spontaneous FE (Fig. 3*a*). It is important to mention that the values of the respective fitting parameters used for constructing the theoretical curves *1* and 2 differ by about 10%, which in the order of magnitude corresponds to the uncertainty of the measurement results. The same refers to the values of γ, obtained via fitting the curves calculated by (4) and (5) to the experimental data, which indicates an inherent consistency of the theoretical model used.

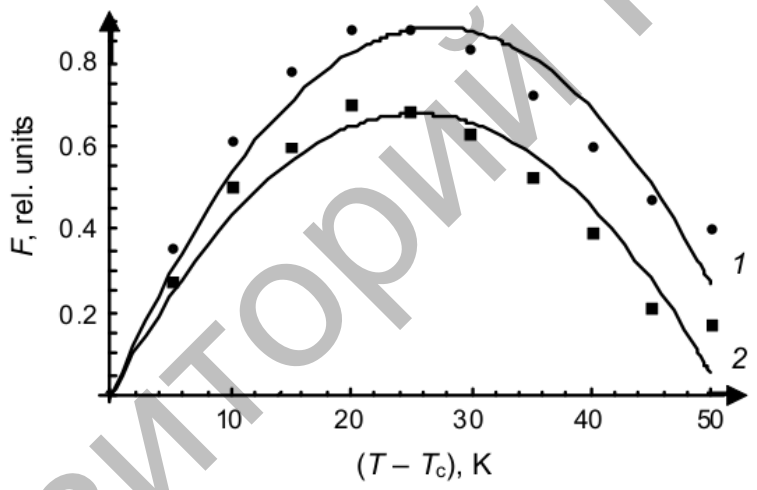

Fig. 4. Temperature plots of the Φ/φ ratio obtained for different field strengths, *H*: 3 (curve *1*) and 2 Oe (curve *2*). Solid lines – calculations via Eq. (5), filled circles and boxes – experiment.

From a comparison of the plots presented in Figs. 2 and 4 it is evident that formulas (4) and (5) provide a quite good description of the results of two independent experiments: the visual examination of variations in DS of the specimen in the course of its magnetization and the FE temperature dependence. A quite conspicuous systematic deviation of the experimental points to the left of the calculated $F(T)$ curves (Fig. 4) might be accounted for by the pinning effect resulting in the slow response of the above-mentioned stepwise variation in the DB position with lowering the temperature. Concerning the linear quasi-horizontal portions of the $\Phi(T)$ plot, which are observed at $H > 4$ Oe (Fig. 3*b* and *c*), it is evident that upon reaching the magnetization saturation field H_c, typical of a certain temperature interval, the DB displacement $x = d/2$ and hence the value of FE in this temperature range level off as well.

To sum up, we can draw a conclusion that despite a number of provisos and assumptions made here to simplify the real situation, the model of the crystal DS variation with varying *H* and *T* allows us to correctly describe (at least qualitatively) all of the identified regular features of the FE behavior in $Tb_3Fe_5O_{12}$ in the course of temperature transition via the magnetic compensation point.

Note that the FE temperature dependences similar to the plots depicted in Fig. 3 were also observed elsewhere [11] in $Dy_3Fe_5O_{12}$ in weak magnetic fields in the vicinity of T_c. The authors of [11], however, in order to interpret the results obtained made use of the DS theory from [5], i.e., they assumed that independent of the value of H in a certain temperature interval, including T_c, the crystal transits into a single-domain state. It is clear that within the framework of the latter approach it is hard to interpret the increase in the height of the $\Phi(T)$ curve and the linear quasi-horizontal portions appearing on it left and right of T_c with increasing H (unfortunately, no discussion of these effects was made in [11]).

Acknowledgments

This work was supported in part by a grant ЁФ2-1, Uzbekistan

REFERENCES

1 Belov K.P., Zvezdin A.K., Kadomtseva A., Levitin R.Z., *Orientational Transitions in Rare-Earth Magnetics*, Moscow, Nauka, 1979, 317 p. [in Russian]

2 Zvezdin A.K., Pyatakov A.P. Neodnorodnoe magnitoelektricheskoe vzaimodeystvie v multiferroikax i vizvanniy im novie fizicheskie effekti. *Usp. Fiz*. Nauk, 2009, Vol. 179, No. 8, pp. 897 - 904. [in Russian]

3 Guilot M., Le Gall H. Magnetic study of the terbium iron garnet, TbIG, along the easy (111) direction: molecular field parameters. *Journal de phys.*, 1977, Vol. 38, No. 7, pp. 871 - 875.

4 Sokolov B.Yu., Talabov M.D., Sharipov M.Z. Domain structure of a thin single-crystal plate of terbium iron garnet near the magnetic compensation point. *Physics of the Solid State*, 2013, Vol.55, No. 2, pp. 314-320.

5 Baryakhtar V.G., Yablonskii D.A. Domennaya struktura ferritov v okresnosti tochki kompensasii. *Soviet Phys. Solid State*, 1974, Vol. 16, No. II, pp. 3511-3513.

6 Bogdanov A.N., Yablonskii D.A. K teorii domennoy strukturi ferrimagnetikov. *Soviet Phys. Solid State*, 1980, Vol. 22, No. 3, pp. 680 - 687.

7 Kharchenko N.F., Eremenko V.V., Gnatchenko S.L. et al. Magnitoopticheskoe issledovanie nekollinearnoy magnitnoy strukturi gadolinievogo ferrite-granata. *Soviet Exp. Theor. Phys.*, 1975, Vol. 68, No. 3, pp. 1073 – 1090.

8 Goldstein S.Sh., Mukimov K.M., Sigal G.P., Sokolov B.Yu. Nizkochastotniy fazometr. *Instr. Exper. Tech*., 1992, Vol. 6, pp. 113 - 117.

9 Volkov V.V., Bokov V.A. Domain wall dynamics in ferromagnets. *Physics of the Solid State*, 2008, Vol. 50, No. 2, pp. 193 - 221.

10 Tikadzumi S. *Physics of Magnetism*. Moscow, Mir, 1987, 420 p.

11 Lisovskii F., Shapovalov V.I. Vliyanie domennoy strukturi na povedenie redkozemelnix ferritov-granatov v okresnosti tochki kompensasii. *Soviet Phys. Solid State*, 1975, Vol. 17, No. 10, pp. 3042 - 3045.

Article accepted for publication 02.03.2017