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Domain structure regularization in monocrystalline barium hexaferrite

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Abstract. Conditions for regular domain structure formation in a single-crystal barium hexaferrite plate have been studied experimentally. The purpose of the work was to develop a simple and, at the same time, an effective method of regularizing the cylindrical domain structure in these plates. The cylindrical domain structure was created by the field method, and its visualization was carried out using the Faraday effect. Radiophysical method of microwave spectroscopy was used to study characteristics of the spectra of magnetostatic oscillations, which are uniquely related to the type and quality of the formed domain structure. The method of cylindrical domain structure regularization in single-crystal barium hexaferrite has been proposed, which is based on applying a constant fixed magnetic field along the easy magnetization axis. It has been ascertained that the optimal value of regularization field lies within the range 3.3...3.6 kOe. However, with the fields exceeding 3.6 kOe, the cylindrical domain structure is significantly distorted. It was found out that the proposed method allows increasing the intensity of the most high-frequency domain magnetostatic resonance by more than 4.5 dB.

Keywords: barium hexaferrite, domain structure, single-crystal, magnetostatic oscillations.

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1. Introduction

Ferrites are a known class of magnetic materials, which can be separated by three main groups: garnet, spinel, and hexagonal ferrites. M-type hexaferrites ($MFe_{12}O_{19}$, where M = Ba, Sr or Pb) have considerably higher value of crystallographic anisotropy field H_a than garnets or spinels, which allows to excite ferromagnetic resonance (FMR) in millimeter (mm) range, even in the absence of external magnetic fields H_0 [1].

Such outstanding physical and chemical properties of barium M-type hexaferrite ($BaFe_{12}O_{19}$) as comparatively large values of H_a, saturation magnetization M_s and Curie temperature, along with corrosion resistance, excellent chemical stability and low cost, make this material promising for many applications including high-frequency radiation absorbers, functional elements of the mm-range, high-capacity information recording, sensors and various military devices [2, 3]. Being based on $BaFe_{12}O_{19}$, tunable resonators [4, 5], insulators and radio absorbing coatings [6] have already been developed.

It is known [7] that the temporal application of magnetic field H_0 directed at a certain angle φ to the plane of the $BaFe_{12}O_{19}$ platelet determines the resulting type of domain structure (DS), which remains stable in the absence of this field. At the same time, as shown in [8], the type of formed DS is uniquely associated with characteristics of the spectrum of magnetostatic oscillations (MSO) in hexaferrite platelets. Thus, the study of the MSO spectra for DS generated by magnetization reversal of hexaferrite samples by the field H_0 of up to 22 kOe, in the range of angles $0° \leq \varphi \leq 90°$, showed that $\varphi = 2°$ and 2°30' correspond to the most regular cylindrical DS (CDS), provided that an easy magnetization axis (EMA) is directed along the normal to the plane of platelets. In this case, the magnetostatic resonance that corresponds to the type of DS is characterized by the highest intensity and the minimum bandwidth [8]. It is these two conditions that provide minimal losses in the propagation of magnetostatic waves in the $BaFe_{12}O_{19}$ platelets, as shown experimentally in [9]. Consequently, the issue of DS regularization becomes of particular relevance.

In a series of experiments [10], it was found that $\varphi \approx 2°22'$ is the most optimal angle for creation of CDS. However, because of spontaneous nature of the DS nucleation process, it looks differently after each phase of magnetization reversal and is accompanied by the appearance of defects. Thus, CDS domains of different diameters arise, which is often accompanied by violation of the hexagonal configuration in such a manner that one domain is surrounded by 5...8 neighbors [11].

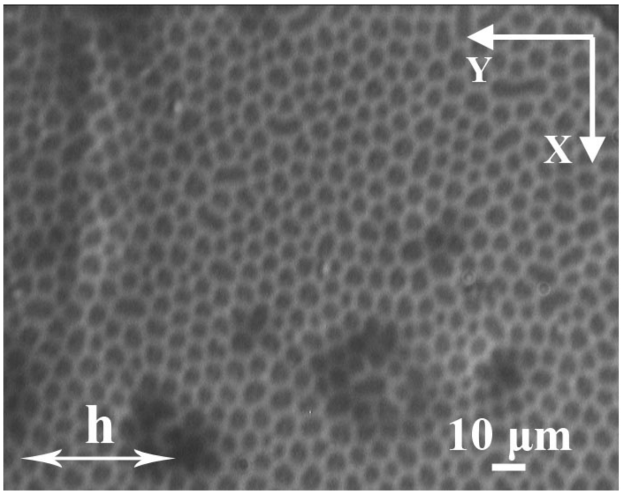

Fig. 1. Unregularized CDS in the hexaferrite platelet in the absence of field H_0.

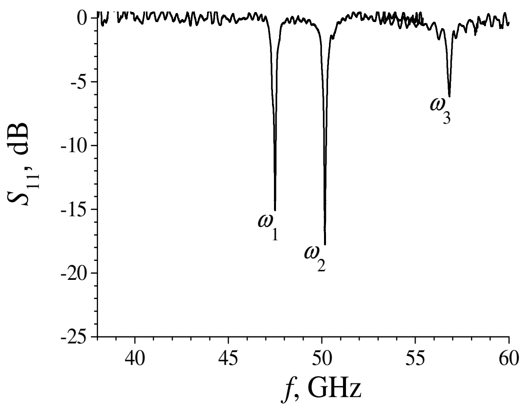

Fig. 2. MSO spectra in $BaFe_{12}O_{19}$ platelet with sizes 2.3×4.9×0.04 mm and formed CDS in the initial state, measured in absence of magnetic field H_0.

The possibility of CDS regularization, that is, bringing it to such a state, which is determined only by the parameters of a particular sample, and not by random processes of domains origination, is demonstrated in the work [12]. A constant magnetic field H_0 directed along EMA ($H_0 = (0.8...0.9)\times H_s$, where H_s is a saturation field) and a changeable modulating field $H_{mod} =$ 100 Oe was additionally applied to $BaFe_{12}O_{19}$ platelet with already formed CDS.

This work is aimed to development of CDS regularization method in $BaFe_{12}O_{19}$ platelets and comparison of visualized DS with the resulting MSO spectrum.

2. Method of CDS regularization and details of experimental researches

The domain structure in $BaFe_{12}O_{19}$ platelet was created using the field method by applying the electromagnet and magnetic induction meter Ш1-8. The magnetic field $H_0 \approx 21$ kOe was directed at the angle $\varphi = 2°22'$ to the surface of hexaferrite platelet, which corresponds to the optimal conditions for CDS formation. The investigated sample was a platelet of $BaFe_{12}O_{19}$ with the sizes 2.3×4.9 mm and thickness of the ferrite layer close to 40 μm; EMA is directed along the normal to the plane of platelet. To ensure mechanical strength, the ferrite was glued to a silica substrate of 100-μm thickness. DS visualization was carried out using a computerized infrared polarization microscope МИК-4, which is based on the Faraday effect that takes place in the conditions of passing infrared radiation through ferrite.

The proposed method of CDS regularization is as follows. H_0 of a value, which is less than the saturation one H_s (that is close to 4.6 kOe for the configuration under study), was directed along EMA of the hexaferrite platelet with an already formed CDS. The increase of applied field occurred gradually to a certain fixed value H_{reg} – field of regularization, after which it again decreased to zero; several similar cycles were repeated. The increase in the value of this field results in a decrease of the domain sizes, since magnetization of domains occur in the opposite direction to this field. It leads to a gradual “wiping” of domains that are abnormally small. As a result, domains are located in the most advantageous energy position, and the hexagonal configuration is improved. The experiment was to find such a value of the H_{reg} field, which corresponds to the most effective CDS regularization.

Along with the visual observation, the quality of the received CDS was also controlled by the method of ultrahigh-frequency (microwave) spectroscopy using a scalar network analyzer Я2Р-67 and the generators Р2-68 and Р2-69. The frequency dependence of the reflection coefficient module S_{11} for $BaFe_{12}O_{19}$ samples was measured on the shorted end of the rectangular waveguide section. This dependence characterizes the spectrum of MSO that arise in a platelet of hexaferrite under the action of an alternating magnetic field H of an electromagnetic wave, which propagates in a waveguide section.

3. Results of the study and their discussion

Fig. 1 shows visualized CDS in the hexaferrite sample under investigation in the initial state in the absence of an external field H_0. It is seen from this figure that there are inhomogeneities in CDS, the most typical of which is different diameters of cylindrical domains.

The measured spectrum of MSO for CDS depicted in Fig. 1, in the absence of the field H_0, is shown in Fig. 2. The low-frequency matrix MSO mode ω_1 is observed in the samples of $BaFe_{12}O_{19}$ irrespectively of the formed DS type, but the high-frequency domain modes ω_2 and ω_3 uniquely characterize the type of DS [13].

After several cycles of magnetization by using the field $H_{reg} = 3.4$ kOe directed perpendicularly to the platelet surface, the previously created DS depicted in Fig. 1 is regularized. The resulting regularized DS is presented in Fig. 3. It is easy to see that the unevenness of the cylindrical domain diameters decreases significantly, at the same time, the number of defects in the hexagonal configuration decreases as well.

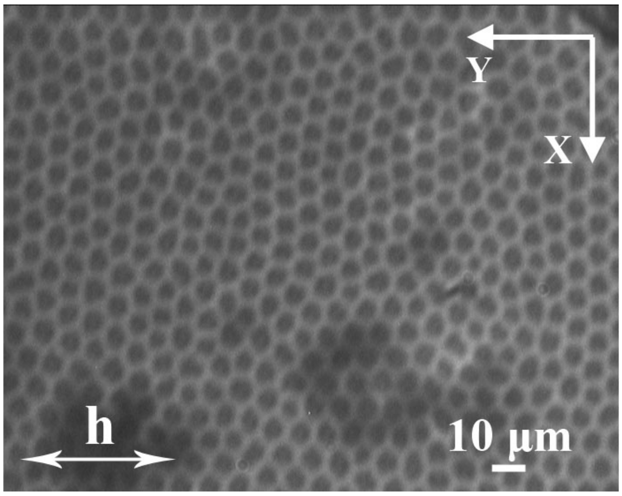

Fig. 3. Regularized using the field H_{reg} = 3.4 kOe CDS in hexaferrite in the absence of field H_0.

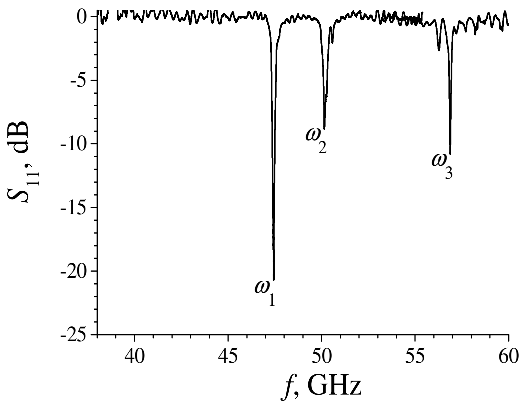

Fig. 4. MSO spectra in $BaFe_{12}O_{19}$ platelet with sizes 2.3×4.9×0.04 mm and regularized CDS using the field H_{reg} = 3.4 kOe, measured in the absence of magnetic field H_0.

The resulting MSO spectrum in a platelet with regularized DS depicted in Fig. 3 is shown in Fig. 4.

Comparing the spectra for CDS in the initial state (Fig. 2) and the regularized one (Fig. 4), one can see that the frequencies of MSO modes remain unchanged. So, for a regularized CDS (Fig. 4) we have $f_{\omega 1}$ = 47.45 GHz, $f_{\omega 2}$ = 50.15 GHz and $f_{\omega 3}$ = 56.86 GHz.

The full spectrum of MSO modes frequencies in a uniaxial plate of arbitrary thickness with CDS is determined by the system of characteristic equations [13]:

$$a_0\omega^3 + a_1\omega^2 + a_2\omega + a_3 = 0\,, \tag{1}$$

$$b_0\omega^5 + b_1\omega^4 + b_2\omega^3 + b_3\omega^2 + b_4\omega + b_5 = 0\,. \tag{2}$$

The positive solutions of the system of equations (1) and (2) allows to obtain the frequencies of MSO modes ω_1, ω_2 and ω_3, which for $H_0 = 0$ in our case (H_a = 17 kOe, M_s = 375 G) are $f_{\omega 1}^{teor}$ = 47.46 GHz, $f_{\omega 2}^{teor}$ = 50.48 GHz and $f_{\omega 3}^{\mathrm{teor}}$ = 57.04 GHz. The insignificant difference between the experimental frequencies of these two high-frequency modes ω_2 and ω_3 with the calculations performed indicates well-formed DS, which, however, is not ideally cylindrical.

As can be seen from Figs. 2 and 4, in the case of CDS regularization, there is redistribution of the intensities of the domain modes ω_2 and ω_3, and the intensity of the matrix mode ω_1 increases. The intensity of the most high-frequency domain MSO mode ω_3 increased from S_{11} = –6.13 dB down to –10.81 dB and became close to the intensity of the domain mode ω_2, which is –8.86 dB, that is a sign of the CDS regularization. At the same time, the bandwidth of ω_3 mode measured at 3 dB decreased from Δf = 235.4 MHz down to 58.7 MHz. Consequently, the visual observation of the fact of DS regularization is confirmed by the spectral characteristics of the MSO modes.

The result of measuring the MSO mode ω_3 intensity at $H_0 = 0$ after CDS regularization by using different values of H_{reg} fields is presented in Fig. 5. From the obtained experimental dependence, it is seen that, with an increase in the field of regularization up to 3.6 kOe, it is possible to increase the intensity of the mode ω_3.

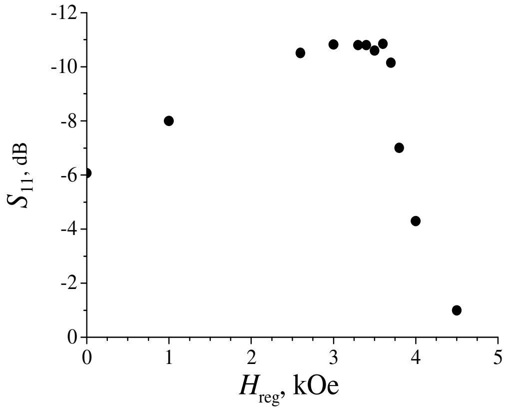

Fig. 5. Dependence of the most high-frequency domain MSO mode ω_3 intensity on the magnitude of the regularization field measured in the absence of H_0.

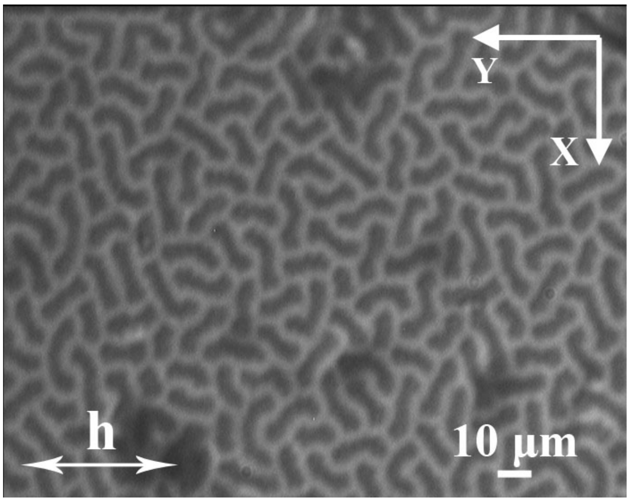

Fig. 6. DS formed in the hexaferrite platelet after application of H_{reg} = 4 kOe in the absence of the field H_0.

With approximation of the regularization field to the value H_s, a gradual remagnetization of the hexaferrite plate at the angle $\varphi = 90°$ occurs, which results in destruction of CDS and, consequently, in the decrease of the mode ω_3 intensity (Fig. 5). Depicted in Fig. 6 visualized DS after applying the field of regularization H_{reg} = 4 kOe demonstrates the aforementioned considerations. The domain structure was significantly altered, adjacent cylindrical domains actually merged to form strips. As a result, the frequencies of the high-frequency modes have changed to $f_{\omega 2}$ = 51.24 GHz and $f_{\omega 3}$ = 55.57 GHz, and the intensity of ω_3 mode decreased to $S_{11} = -4.23$ dB.

4. Conclusions

The method of CDS regularization in a single-crystal barium hexaferrite using application of a constant magnetic field along EMA has been proposed.

It has been shown that, in the fields of regularization within the limits H_{reg} = 3...3.6 kOe, it is possible to increase the intensity of the most high-frequency MSO mode ω_3 not less than by $\Delta S_{11} \approx 4.5$ dB. The optimal regularization field is H_{reg} = 3.3...3.4 kOe. The critical field, after which CDS begins to turn into strips, is H_{reg} = 3.6 kOe.

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