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Unidirectional motion of magnetic domain walls: the experiment and numerical simulation

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Abstract. The results of study of unidirectional motion of topologically different domain structures under the influence of periodic bipolar and unipolar magnetic field pulses applied perpendicular to the sample plane of (111) iron garnet single crystal plate are presented. The response of the domain structure to the field pulses was studied by direct observations utilizing the stroboscopic technique. Experimentally obtained dependences of the speed of unidirectional motion of stripe domains on the parameters of external bipolar pulsed magnetic field are compared with the results of numerical simulations.

1. Introduction
The unidirectional motion of various magnetic structures (domain walls (DWs), bubble magnetic domains (BMDs), skyrmions) is a key phenomenon necessary for creating new types of magnetic memory devices [1-4]. The motion of an array of domain walls as a whole under the influence of an alternating magnetic field is known as the drift of DWs. Up until now in most of the works the DW drift was studied in harmonic magnetic fields [5-9]. In [10] the drift was observed under the influence of magnetic field pulses.

This paper is devoted to determination of patterns and revealing of the necessary conditions for the ordered unidirectional motion of various domain structures (DSs) in single crystals of iron garnets under the influence of pulsed magnetic fields. The results of experimental studies are compared with the results of numerical simulations performed using the model of coupled harmonic oscillators [5,7,11] with the parameters of the real sample.

2. Methods
The experimental studies of the directed motion of domain walls were performed on a single crystal (111) plate of rare earth $(TbErGd)_3(FeAl)_5O_{12}$ iron garnet with thickness $L = 70\,\mu m$, saturation magnetization $M_s = 40$ Gs, uniaxial anisotropy constant $K_u = 5.5 \cdot 10^3$ erg/cm^3 and cubic anisotropy constant $K_1 = -3.4 \cdot 10^3$ erg/cm^3. Domain structures were revealed using the magneto-optical Faraday effect. The DWs drift speed measurements were performed using the stroboscopic setup [5] based on a pulsed solid-state Nd:YLF laser with a wavelength $\lambda = 527$ nm and a pulse duration $\tau_L = 30$ ns.

The pulses of current in the magnetizing device were formed using a programmable generator and power amplifier. Pulses of magnetic field had repetition frequency $f = 60\text{-}1000$ Hz and amplitudes up to $H_0 = 400$ Oe. The parameters of the pulses (shape, amplitude and frequency) were monitored using
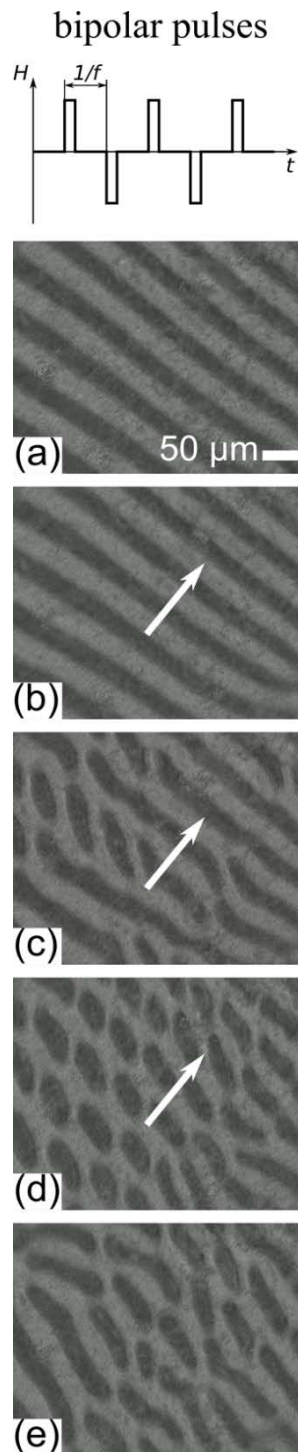
Figure 1. The dynamic domain structures observed under the influence of a pulsed magnetic field of alternating polarity with pulse repetition frequency $f = 400$ Hz at field amplitudes H_0 equal to (a) 0, (b) 248, (c) 303, (d) 315, (e) 343 Oe. The presence and direction of the drift is indicated with an arrow.
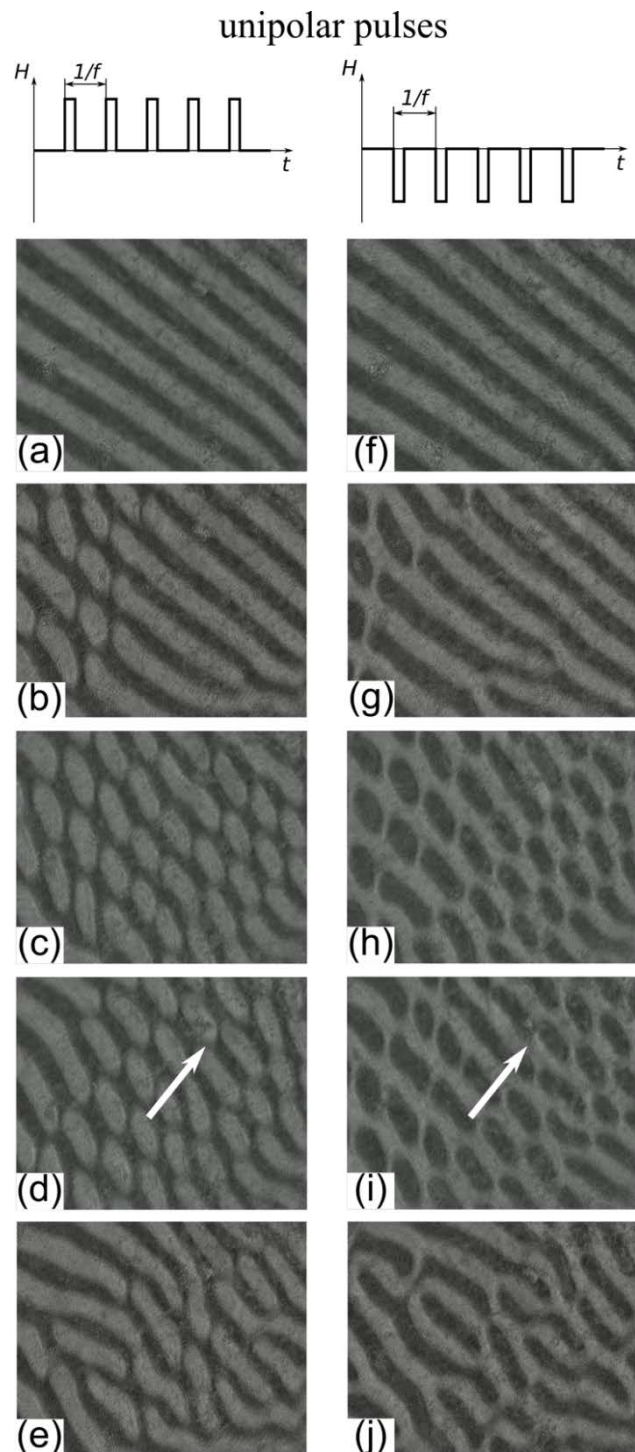
Figure 2. The dynamic domain structures observed under the influence of unipolar magnetic field pulses with pulse repetition frequency $f = 400$ Hz: (a-e) – positive field pulses, (f-j) – negative field pulses. The field amplitudes H_0 are (a) 0, (b) 301, (c) 319, (d) 339, (e) 370, (f) 0, (g) 301, (h) 328, (i) 344, (j) 370 Oe. The presence and direction of the drift is indicated with an arrow.

a Hall sensor (inset in figure 4). The duration of pulses was 0.2 ms. During the measurements the sample temperature was kept constant at 295 K.

3. Experimental results

The dynamic DSs realized in an iron garnet plate under the influence of a pulsed magnetic field with alternating pulses polarity (figure 1) and in pulses of the same polarity (figure 2) were studied. The pulse repetition frequency was 400 Hz (see the schemes in figure 1 and figure 2), the amplitude of the pulses was increasing from 0 to 400 Oe.

The dynamic domain structures formed under the influence of bipolar magnetic pulses are shown in figure 1. The sample was subjected to demagnetization in an alternating magnetic field with an amplitude decreasing to zero, as a result a stripe domain structure with DWs oriented along the axis $[\bar{2}11]$ was formed in the sample (figure 1(a)). At low amplitudes of pulses ($H_0 < 250$ Oe), the oscillations of the DWs occur in the sample, while the equilibrium positions of the DWs do not change over time. At the pulses amplitude $H_0 = 250$ Oe the DWs drift begins and the DS remains a stripe DS with the same orientation of the DWs (figure 1(b)). In the range of amplitudes of the magnetic field $H_0 = 285$–310 Oe, a transition from stripe DS to hexagonal BMDs lattice occurs through the appearance of gaps in stripe domains and the formation of BMDs out of torn stripes. Figure 1(c) shows the DS during the transition process: it is visible that the BMDs being formed have an elongated shape (average ratio of sizes along axes is 2.6), the axis of the BMDs is on the average tilted by an angle of 25° to the initial orientation of stripe DS. In the process of forming the BMDs lattice, the drift of the DWs continues, the direction of the drift coincides on the average with the direction of the drift of the stripe DS. The formed BMD lattice is shown in figure 1(d) for the amplitude $H_0 = 315$ Oe. After the formation of the BMDs lattice, the DS drift continues up to the field amplitude $H_0 = 345$ Oe, above which the ordered drift motion of the DS changes to an unordered where DS is a stripe DS with a large number of magnetic defects.

The main difference in the behavior of the sample DS under the influence of unipolar magnetic field pulses is the absence of a drift of the stripe domain structure until the transition to the BMDs lattice, which occurs when the field amplitude H_0 is in the range 285–315 Oe (figure 2(b),(g)). The formed BMDs lattice, similar to the one formed in a bipolar field, is shown in figure 2(c),(h), the polarity of the BMDs is opposite to the polarity of the pulses. The directed motion of the BMDs begins at field amplitudes $H_0 = 339$ and 344 Oe, respectively, for positive and negative polarity (figure 2(d),(i)), its direction coincides with the direction of the drift of DS in the case of bipolar pulses. The directed motion stops with the transition to unordered motion at $H_0 = 360$ and 364 Oe (figure 2(e),(j)).

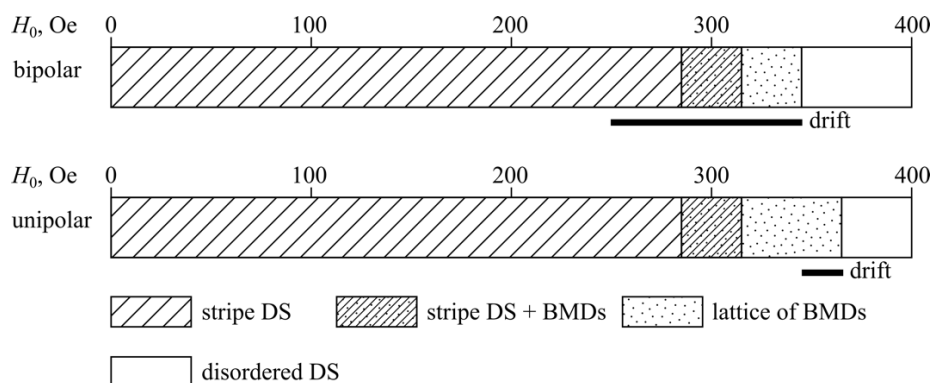The dynamic DSs observed in the sample are shown in the scheme in figure 3.

Figure 3. Scheme of domain structures existing in bipolar and unipolar pulsed magnetic fields.

At the magnetic field amplitudes $H_0 = 240$–300 Oe, in which the drift of the stripe DS was observed, the dependences of the drift speed V_{dr} on the amplitude of the magnetic field H_0 were

measured at pulse repetition frequencies of 200, 600, 1000 Hz (figure 4(a)). It can be seen that for all pulse repetition frequencies the speed of the DWs drift increases monotonically with increase of the amplitude of magnetic pulses, while at $H_0 > 290$ Oe a sharp increase in the speed of drift is observed. An increase in the pulse repetition frequency f leads to an increase of the drift speed. In figure 4(b) the dependence of the average number N of dark domains in the observed region of the sample (area $S = 0.1$ mm^2) on the amplitude of the pulses H_0 is shown. It shows the process of destruction of the stripe DS and the transition to the BMDs lattice. It can be seen that a sharp increase in the number of domains N begins at $H_0 > 285$ Oe, which correlates with an increase in the drift speed V_{dr} of the remaining stripe domains.
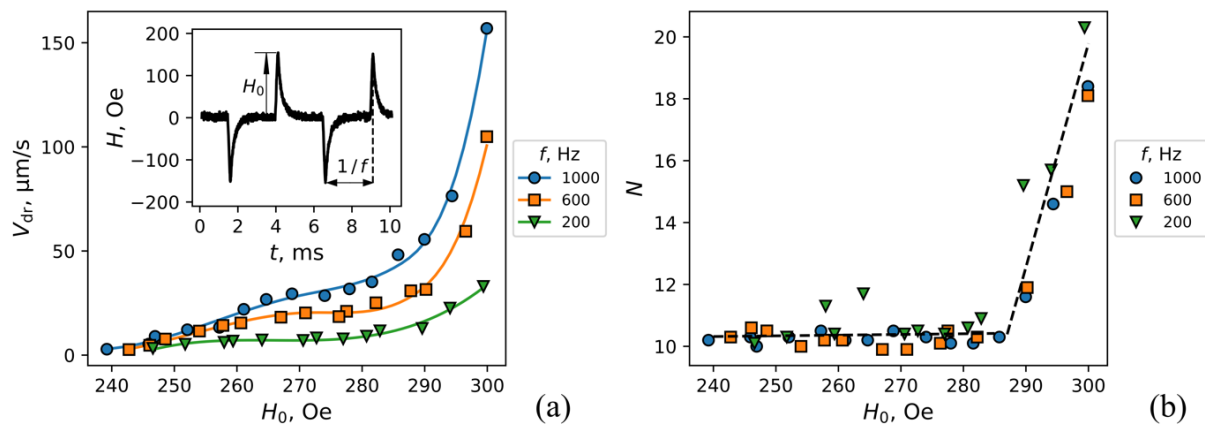

Figure 4. (a) The dependences of the drift speed V_{dr} of the stripe domain structure on the amplitude H_0 of the magnetic field pulses with alternating polarity for different pulse repetition frequencies f. The inset shows the shape of the field pulses at pulse repetition frequency $f = 400$ Hz. (b) Dependences of the average number of dark domains in the observed region of the sample on the amplitude of bipolar pulsed magnetic field.

4. Results of numerical simulation

Numerical simulations of DW motion in uniaxial crystal plate in bipolar pulsed magnetic fields were performed using the model of coupled harmonic oscillators [5,7,11-13] with the parameters of real sample. It is assumed that internal structure of DW does not change during the motion, DW has effective mass and moves due to pressure forces acting on its surface.

External periodic pulsed magnetic field is applied perpendicular to the sample plane. In this case the following forces are acting on the DW: external pulsed magnetic field force that shifts the DW from equilibrium, "restoring" force associated with magnetostatic energy of stripe domain structure and dynamic friction force associated with attenuation of magnetization precession in magnetic field. Coercivity of domain walls is not considered in the current work.

In [5] it is assumed that in a sample located in a spatially uniform harmonic magnetic field directed perpendicular to the sample plane, there is an anisotropy of the attenuation parameter: the values of the attenuation parameter are different when the DW moves in different directions along the axis that is perpendicular to the plane of the DWs. It's possible to make such an assumption since there is experimentally observed difference in the displacements of DWs under magnetic field pulses of different polarity applied perpendicular to the sample plane. The arising asymmetry leads to the drift of the DWs in the model of coupled oscillators under the influence of external harmonic magnetic field [5].

In this paper, we consider a model of stripe DS motion in a bipolar pulsed magnetic field in the preposition of the presence of anisotropy of the attenuation parameter with respect to direction. Cubic anisotropy is not taken into account in the model, because the domain structure observed experimentally is determined mainly by the uniaxial anisotropy of the sample. Taking the symmetry of

the problem into account, we can write the motion equations for two neighboring DWs, which is sufficient to describe the motion of all DWs in the considered model of the domain structure.

In dimensionless variables, the DWs motion equations in a bipolar pulsed magnetic field will have the following form [5,7]:

$$\begin{cases} \dfrac{\partial^2 a}{\partial \tau^2} + \eta(\mathrm{sgn}(\dfrac{\partial a}{\partial \tau}))\dfrac{\partial a}{\partial \tau} + g(a,b) - \pi h_0 \tilde{h}(\nu\tau) = 0 \\ \dfrac{\partial^2 b}{\partial \tau^2} + \eta(-\mathrm{sgn}(\dfrac{\partial b}{\partial \tau}))\dfrac{\partial b}{\partial \tau} + g(a,b) - \pi h_0 \tilde{h}(\nu\tau) = 0 \end{cases}. \tag{1}$$

Here a and b are dimensionless variables corresponding to the displacements of two neighboring DWs from equilibrium under the influence of external magnetic field,

$$g(a,b) = \frac{a+b}{2} + \frac{2}{\ell}\sum_{n=1}^{\infty}\left[\frac{(-1)^n}{n^2}[1-\exp(-n\ell)]\sin\frac{n(a+b)}{2} \right], \tag{2}$$

$\ell = 2\pi L / D$, L is the sample plate thickness, D is the width of a single domain in the absence of external magnetic field, $m \approx 10^{-10} g/cm^2$ is the effective mass of the DW [14], $\Omega^2 = 8\pi M_s^2 / mD$, $\tau = t\Omega$, $\nu = 1/\Omega$, h_0 is normalized amplitude of the external field pulses, $\tilde{h}$ is a pulsed field profile function.

Attenuation function $\eta(q)$ sets attenuation based on the direction of DW motion:

$$\eta(q) = \begin{cases} \eta_1, & if\ q > 0 \\ \eta_2, & if\ q < 0 \end{cases}, \tag{3}$$

where $\eta_i = \alpha_i \cdot (D / (\tilde{A}/K_u)^{1/2})^{1/2}$ are normalized attenuation parameters, α_i are Hilbert attenuation parameters typical for the given materials [15] ($\alpha_1 = 0.45$ and $\alpha_2 = \alpha_1 + \Delta$, where Δ is the difference in attenuation parameter values), $\tilde{A} \approx 10^{-7}$ erg/cm is the exchange interaction parameter, K_u is the uniaxial anisotropy constant.

System (1) was solved using Wolfram Mathematica © (LSODA Solver [16]) with homogeneous initial conditions.

Simulations show that even a small difference in attenuation parameter values for opposite directions of DW motion causes the DS drift in the model. About 4% difference in the attenuation parameter values is sufficient to reach maximum speeds of drift observed experimentally in section 3.
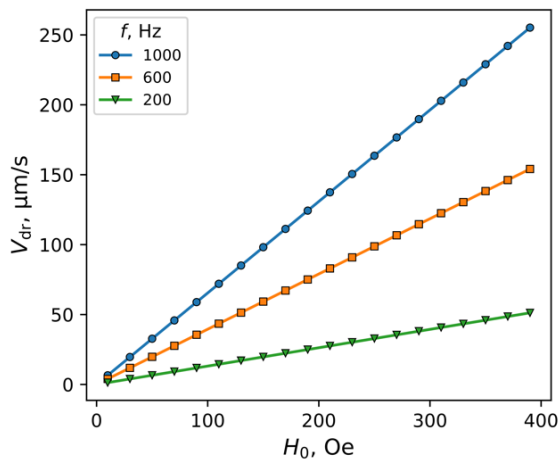

Figure 5. Dependences of stripe DS drift speed on amplitude H_0 of external bipolar pulsed magnetic field for different pulse repetition frequencies f (results of numerical simulations).

The assumption of presence of anisotropy of attenuation parameter in the sample allows to obtain the dependences of the drift speed V_{dr} on amplitude for various repetition frequencies of pulses of

external bipolar pulsed magnetic field (figure 5). The DS drift speed increases with increase of amplitude and pulse repetition frequency which is in agreement with experimental results. The quantitative discrepancy between the results of numerical simulations and experimentally obtained dependences of the drift speed V_{dr} on the external field amplitude H_0 is due to the fact that the model does not take into account a number of factors, such as coercivity of domain walls, cubic anisotropy and material defects.

5. Conclusions

Thus, the conditions for the directional motion of various types of dynamic domain structures (stripe domains, bubble magnetic domains and their lattices) under the influence of pulsed magnetic fields are established in iron garnet single-crystal plate. Intervals of amplitudes of pulsed magnetic fields in which such structures exist are determined. The dependences of the speed of directional motion of stripe domains on amplitude of bipolar pulsed magnetic field for a number of pulse repetition frequencies are established. It is shown that the direction of the drift of topologically different DSs in bipolar and unipolar pulsed magnetic fields remains the same: the drift of the DWs is directed perpendicular to the plane of the DWs in the demagnetized state.

Numerical simulations of DW motion in bipolar pulsed magnetic fields in the assumption of presence of anisotropy of attenuation parameter in the sample allowed to obtain the dependences of stripe DS drift speed on amplitude for various pulse repetition frequencies. Simulations show that the DS drift speed increases with increase of amplitude and pulse repetition frequency which is in agreement with experimental results.

Acknowledgments

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