Experimental study of the inhomogeneous rotation of the magnetization vector in crystalline iron garnet films

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(Submitted 2 July 1984)
Zh. Eksp. Teor. Fiz. **88**, 260–271 (January 1985)

An experimental study is made of the inhomogeneous rotation of the magnetization vectors in crystalline epitaxial iron garnet films in pulsed magnetic fields up to 2000 Oe. An equipmental configuration employing electron-optic chronography is developed, enabling real-time study of fast processes in thin magnetic films with a time resolution of ~ 60 psec. This complex has permitted a detailed study of the features of the inhomogeneous rotation of the magnetization vectors at arbitrary points in the sample and at different orientations and strengths of the external magnetic fields. It is shown that the magnetization-reversal (or "remagnetization") time can be determined at local points in magnetic films. It is found that local regions of the sample can be remagnetized in less than 1 nsec. It is established experimentally that because of the finite intrinsic relaxation times of the magnetic moments, the system under study is unable to follow changes in the external magnetic field if the characteristic times of these changes are of the order of nanoseconds. The rate of the inhomogeneous-rotation process depends strongly on the strength of the pulsed or static magnetic fields in the plane of the sample. The features of the formation and motion of magnetic-moment flip waves (MMFWs) are studied in detail. It is established that the velocity of the MMFWs is proportional to $\partial H_{\rm pul}/\partial t$ and to the spatial gradient of $H_{\rm pul}$, i.e., to $\partial H_{\rm pul}/\partial r$. The width of the MMFWs ranges, as a rule, from tens to hundreds of microns depending on the strength and orientation of the external magnetic fields. In multilayer iron garnet films, MMFWs can form successively, with a time interval ~ 0.5–1 nsec, in the initial stage of the inhomogeneous rotation. It is found that a practically homogeneous rotation of the magnetization vectors is possible in one of the layers of a sample in a strong gradient field.

1. INTRODUCTION

Dynamical processes in magnetically ordered media have been the subject of many experimental and theoretical studies. Attention has focused primarily on the features of the domain-wall motion, particularly in highly anisotropic uniaxial ferromagnets and ferrimagnets.[1–3] Pulsed remagnetization of magnetic materials through inhomogeneous rotation of the magnetization vectors has been studied in detail only in polycrystalline thin magnetic films.[4] In recent years the first experimental papers have appeared on the subject of the inhomogeneous rotation of magnetization vectors in thin crystalline iron garnet films.[5–9] In Ref. 5 it was first shown that in a pulsed gradient magnetic field $H_{\rm pul}$ the inhomogeneous rotation of the magnetization vectors is accompanied by the formation of a magnetic-moment flip wave (MMFW), which moves into the region of weaker fields. The MMFW is initiated near the windings of the pulsed coil if the magnetic field acting on the sample,

$$\Delta H(r{\sim}R) = H_{\rm pul}(r{\sim}R) - H_b, \qquad (1)$$

(where r is the distance from the center of the coil, R is the inside radius of the coil, and H_b is a static bias field) exceeds the effective uniaxial anisotropy field H_k^*. In a first approximation H_k^* is defined as

$$H_k^* = H_a - 4\pi M_s, \qquad (2)$$

where $H_a = 2K_u/M_s$ is the uniaxial anisotropy field, K_u is the uniaxial anisotropy constant, and $4\pi M_s$ is the saturation magnetization.

The remagnetization of iron garnet films in pulsed fields $H_{\rm pul}(r=0)$ has been studied in Refs. 5–9 for the case when the effective field $\Delta H(r=0)$ is somewhat lower than H_k^*. It was shown that if the iron garnet film had been grown on a substrate with the (111) crystallographic orientation, a strictly oriented triangular region would arise in the central part of the pulsed coil; in this region the remagnetization took place through the motion of domain walls. For convenience, this region was called a triangular magnetic domain. The bisectors of the angles of the triangular magnetic domain lie in the directions of the easy axes in the plane of the sample.[6,7]

In Refs. 7 and 8 we detected a layer-by-layer remagnetization through inhomogeneous rotation in iron garnet films and visually observed layers having different properties. In weakly varying fields $\Delta H(r{\sim}0) \gtrsim H_k^*$ the inhomogeneous rotation of the magnetization vectors had a pronounced "turbulent" character.[8]

In fields $\Delta H(r=0) > H_k^*$ the remagnetization of the sample over the entire area bounded by the pulsed coil took place through the motion of MMFWs. The velocity of the MMFWs could reach several tens of km/sec.[5]

Inhomogeneous rotation in iron garnet films having extremely low damping was studied in Ref. 9. In that study "magnetic vortices" were observed and were interpreted as

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Rossby solitons. Analysis of the MMFW dynamics in Ref. 9 showed that the motion of MMFWs reflects a spatial displacement of the boundary at which the strength of the nonuniform field during the rise of the pulse reaches a critical value.

The brief review given above shows that the inhomogeneous rotation of the magnetization vectors in magnetically ordered media has been insufficiently studied. In particular, because of the lack of experimental studies with time resolutions of less than 1 nsec the features of the formation and motion of MMFW remain unclear. There have been no studies of the physical processes and characteristic times for remagnetization through inhomogeneous rotation in multilayer iron garnet films in magnetic fields of different configurations and strengths.

In the present study we use the method of electron-optical chronography to make a detailed study of the features of the inhomogeneous rotation of the magnetization vectors in crystalline iron garnet films in the region of strong gradients of the pulsed magnetic fields.

2. EXPERIMENTAL TECHNIQUES

The domain structures were visualized with the aid of the Faraday effect. Depending on the particular experiment the sample was, as a rule, initially held in a static magnetic field of the required strength and configuration. Then a pulsed magnetic field $H_{\rm pul}$ produced by a planar, single-ply coil with inside diameter ~ 1.5 mm disrupted the equilibrium of the domain structure. As in previous studies,[5-8] the axial symmetry and the nonuniform character of $H_{\rm pul}$ were taken into account in the experiments. The dynamical transition of the magnetic system from one stable state to another was studied by two methods.

1. Electron-optical high-speed photography. This method, as described in detail in Ref. 8, was used in the present experiments without substantial modification to study dynamical processes with characteristic times > 10 nsec and to obtain scanning photographs of the dynamical processes over the entire area bounded by the pulsed coil. Its limited time resolution makes this technique practically unsuitable for studying certain features of the inhomogeneous rotation of the magnetization vector. Consequently, for studying nonrepetitive fast processes with characteristic times < 10 nsec in magnetically ordered media (for example, the formation and motion of MMFWs) one must use a technique for studying the domain structures that has a resolution of 1 nsec or better. This problem can be solved in two fundamentally different ways.

The first way involves the design and construction of an illumination source which produces one or several light pulses with a duration τ_p of not over 1 nsec. This source should satisfy a number of requirements:

The energy of the light pulse should be of the order of 10^{-3} J to permit observation of low-contrast domain structures.

The light pulse should be closely synchronized with the leading edge of the magnetic-field pulse.

The wavelength of the light should give the required spatial resolution and lie in the transparency region of the samples ($\lambda \sim 0.5\ \mu$m).

With these requirements, the necessary time resolution can be realized using a Q-switched YAG:Nd^{3+} laser ($\tau_p \sim 8$ nsec, radiation power ~ 0.57 MW) in three basic ways:

1. Use an electrooptic deflector[10] to form a short light pulse ($\tau_p \sim 50$ psec).

2. Apply the principle of distributed feedback ($\tau_p \sim 90$ psec) to the laser illuminating the sample.[11]

3. Obtain a short pulse using the passive mode-locking effect[12] ($\tau_p \sim 40$ psec).

Analysis of these ways of improving the time resolution of the apparatus shows that meeting the requirements on the source would require putting together a complex radiophysical complex operating at the limits of many engineering and physical parameters. We therefore chose another way of getting the necessary time resolution.

2. Electron-optical chronography. This method has been used often in recent decades for studying fast processes in the most diverse areas of physics and technology,[13] but it has remained practically unused (with one exception[14]) for studying fast processes in magnetically ordered media.

As a rule, the method of electron-optical chronography is used to study the features of the dynamics of one-dimensional objects.[13] In our experiments the one-dimensional object of study (for example, a segment of a domain wall or MMFW) is formed by an optical slit. Under the action of $H_{\rm pul}$ the segment moves along the slit. Here the chronogram is a sweep of the motion of this object over time in the direction perpendicular to the slit.

In its overall form the experimental apparatus is analogous to that described earlier.[8] The source of illumination was a Q-switched yttrium aluminum garnet (YAG:Nd^{3+}) laser with frequency conversion of the fundamental radiation. The duration at half amplitude of the illumination pulse was $\tau_p \sim 8$ nsec, the wavelength was $\lambda \sim 0.53\ \mu$m, and the pulse energy was $W \sim 10^{-3}$ J.

The laser light was projected onto the surface of the sample with the aid of an optical system. For the analyzer and polarizer we used Glan-Thompson prisms. An image of the magnetic object was projected through a Dove prism and a slit onto the photocathode of an electron-optical converter (EOC). The image of the slit on the screen of the EOC could be oriented in the required direction with the aid of the Dove prism.

The detection unit was based on a controllable EOC of the UMI-93 type with a multislit photocathode, giving a time resolution of $\sim 10^{-11}$ sec and a spatial resolution of ~ 10 pairs of lines per 1 mm and having a photocurrent gain of $\sim 10^5$. The electrostatic system for deflecting the electron beam could make a linear sweep of the image. In the experiments the linear part of the sweep had a duration $\tau_p \approx 12$ nsec and a length 1 on the EOC screen of 22 mm. At a projected slit width $d \approx 100\ \mu$m on the screen of the EOC, the time resolution of the apparatus was

$$N = \frac{\tau_p}{l/d} \approx 56 \text{ psec} \cdot \qquad (3)$$

The chronogram images were photographed from the output screen of the EOC.

To form pulsed magnetic fields we used a current-pulse generator made up of a TGI-100/8 thyratron. The amplitude of the square current pulses reached 50 A and the rise time τ_f was not over ~ 10 nsec. The operation of all the pulse circuits was monitored with an S1-75 oscilloscope. In the experiments H_b was varied from 0 to 400 Oe, and $H_{\rm pul}$ from 0 to 2000 Oe. The samples were iron garnet films grown by liquid-phase epitaxy on the (111) plane of $Gd_3Ga_5O_{12}$ substrates. Samples with different compositions and properties were studied (see, e.g., Refs. 5–8). Part of the results of this paper are given for a sample of composition $(BiTm)_3(FeGa)_5O_{12}$ with a thickness $h \sim 7.5\ \mu$m, a bubble collapse field $H_0 \approx 131$ Oe, a uniaxial anisotropy field $H_a \approx 600$ Oe, a saturation magnetization $4\pi M_s \approx 236$ Oe, and a stripe-domain period $P_0 \approx 12.6\ \mu$m.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In the present study we have carried out an experimental investigation of the inhomogeneous rotation of the magnetization vectors in crystalline iron garnet films. We have made a detailed study of the characteristic times for the occurrence of this process in magnetic fields of different orientations and strengths.

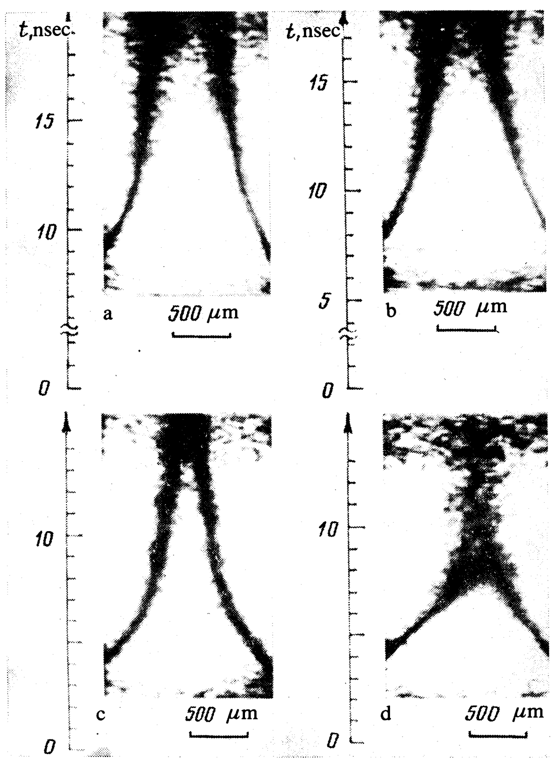

FIG. 1. Chronograms illustrating the remagnetization of iron garnet films through the motion of MMFWs in different pulsed fields $H_{\rm pul}$ ($r = 0$): a) 720 Oe, b) 800 Oe, c) 1600 Oe, d) remagnetized sample in a field $H_{\rm pul}$ ($r = 0$) ≈ 1600 Oe in the presence of a field $H_{\rm pl} = 100$ Oe in the plane ($H_{\rm pl}$ is directed along the slit from left to right). The origin of coordinates corresponds to the time at which the pulsed field is applied. The rise time of $H_{\rm pul}$ is $\tau_f \approx 10$ nsec, $H_b = 190$ Oe.

Pulsed remagnetization of iron garnet films in strong gradient magnetic fields

Let us consider the inhomogeneous rotation in magnetization vectors in strong gradient magnetic fields, i.e., near the windings of the pulsed coil. It is well known[5,8] that near the windings of a coil the inhomogeneous rotation begins with the formation of an annular MMFW, which moves at high speed toward the center of the coil. Because of the fast rates at which these processes occur, we used the method of electron-optical chronography. Since we observed no anisotropy of the speed of the MMFW in the given region, we studied the motion of two MMFW segments cut out by the optical slit, which was placed along the diameter of the pulsed coil. The chronograms represented a time sweep of the motion of the two parts of the MMFW in the direction perpendicular to the slit (Fig. 1). The experiments, as a rule, were done in completely crossed polarizing sheets to give the highest contrast for visualizing those regions of the iron garnet film in which the projection of the magnetization vectors onto the optic axis is minimum. The chronograms of the MMFWs, as a rule, were dark, bow-shaped regions which were protracted along the time axis (Fig. 1a–c) and divided the sample into regions which had been remagnetized through inhomogeneous rotation (outside the trajectories of the MMFWs) and regions which had not been remagnetized (between the trajectories). Figure 1 shows chronograms of the MMFWs for a sample that has been described in detail elsewhere.[5,8] The dimension of the chronograms along the horizontal axis is limited by the inside diameter of the pulsed coil, and the vertical dimension is limited by the duration of the EOC sweep.

The close synchronization (to within ± 1.0 nsec) of the leading edge of the magnetic-field pulse $H_{\rm pul}$ with the start of the EOC sweep made it possible to determine the magnetic field acting on the sample at every instant after the start of $H_{\rm pul}$. The markings on the time axis in Fig. 1 begin at the time when $H_{\rm pul}$ reaches 0.1 times its maximum amplitude. Experiments have shown (Fig. 1) that the inhomogeneous rotation of the magnetization vectors and, consequently, the formation of the MMFW begin back at the leading edge of $H_{\rm pul}$. Here, as in Ref. 5, the MMFW formed at the leading edge of $H_{\rm pul}$ continues to move even after the magnetic field has reached its maximum value. This suggests that the assertion[9] that the motion of the MMFW is accomplished at the leading edge of $H_{\rm pul}$, i.e., reflects the spatial displacement of the boundary at which the strength of the nonuniform field reaches its critical value, is not general but depends on the conditions of the experiment. It can be correct only under the assumption that the intrinsic relaxation times of the magnetic moments are much shorter than the time required for the effect of the pulse to become established; we did not observe such a situation in our experiments.

It is of interest to measure the velocity V_w of the MMFW in the established magnetic field, i.e., after the leading edge of $H_{\rm pul}$ has passed. This is easily done from the data shown in the photographs in Fig. 1a–c. A calculation shows that in magnetic fields $\Delta H(0) \approx 530$ Oe, $\Delta H(0) \approx 610$ Oe, and $\Delta H(0) \approx 1400$ Oe the MMFW velocity reaches $\sim 30 \cdot 10^3$ m/

sec and remains substantially unchanged with increasing H_{pul}. These results are somewhat different from those presented in Ref. 5. This is entirely natural, since the accuracy of the measurements in Ref. 5 was considerably poorer because of the low time resolution of the apparatus and since that study did not investigate the MMFW velocity for increasing and established values of the field H_{pul}.

Thus by employing the method of electron-optical chronography one can do a high-time-resolution, real-time study of the formation and motion of MMFWs. It becomes possible to determine the time over which the inhomogeneous rotation of the magnetization vectors occurs at an arbitrary point in the sample for different orientations and strengths of the external magnetic field. For a known geometry of the pulsed coil, the magnetic field acting on the sample can be calculated very simply (see, e.g., Refs. 7 and 15). Fig. 2 shows the normalized strength of the pulsed field H_{pul} as a function of the distance r to the center of the coil used in the experiment. Also shown here is the r-dependence of the angle of deviation of the vectors H_{pul} from the normal to the plane of the film. By shifting the coil and slit relative to the sample and then changing the external magnetic field, one can study the inhomogeneous rotation at any point in the sample. To determine the remagnetization time (due to inhomogeneous rotation) of the iron garnet film at an arbitrary point with the aid of a chronogram, one must draw a line from the given point r in the direction of the image sweep (along the time axis) and determine the time interval at which the straight line intersects the trajectory of the MMFW. It is clearly seen in Figs. 1a–c that the inhomogeneous rotation occurs most rapidly near the windings of the coil. In this region local areas of the sample can be remagnetized over a time of the order of 1 nsec (Fig. 1a–c). It should be noted that in this case, as a rule, the pulsed magnetic field does not reach its full (amplitude) value. This means that the inhomogeneous rotation is affected largely by the gradient character and orientation of the external field. The determining factor is apparently the field direction, since it is seen in Fig. 2 that it is at the windings of the coil that the planar component of H_{pul} is maximum. To check this assumption

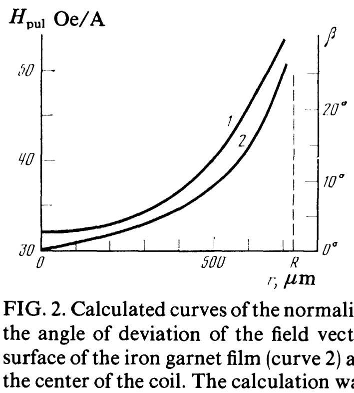

FIG. 2. Calculated curves of the normalized pulsed field H_{pul} (curve 2) and the angle of deviation of the field vector $\mathbf{H}_{pul}$ from the normal to the surface of the iron garnet film (curve 2) as functions of the distance r from the center of the coil. The calculation was done for a coil with the following parameters: inside radius $R = 730$ μm; wire diameter $d = 70$ μm; number of turns $n = 5$. The field was determined at a distance $h = 120$ μm from the central plane of the coil.

we applied a planar field H_{pl} of from 0 to 100 Oe in various directions. The presence of H_{pl} leads to a substantial increase (by several times) in the rate of inhomogeneous rotation and in the anisotropy of the MMFW velocity (see Fig. 1d). Evidence of this is the breaking of the symmetry of the MMFW chronograms with respect to the time axis and also the change in their steepness. Under certain conditions (see Ref. 15) this anisotropy of the MMFW velocity causes a displacement of the triangular magnetic domains with respect to the center of the coil.

$$d\mathbf{M}/dt = -\gamma[\mathbf{MH}],$$

The influence of the planar component of the external fields on the rate of inhomogeneous rotation can be justified qualitatively by considering the Landau-Lifshitz equation (without dissipation) where γ is the gyromagnetic ratio and $\mathbf{H}$ is the external magnetic field. It follows from (4) that the rate of motion of the magnetic moments $\mathbf{M}$ is directly proportional to the torque $\mathbf{T} = \mathbf{M} \times \mathbf{H}$. In our experiments the magnitude of this moment under otherwise equal conditions ($|\mathbf{M}|$ and $|\mathbf{H}|$) is maximum near the coil windings (see the orientation of H_{pul} in Fig. 2, since the angle between $\mathbf{M}$ and $\mathbf{H}$ is maximum). Therefore, near the pulsed coil, and also in the presence of a static field H_{pl}, we also observed a higher rate of rotation of the magnetic moments, i.e., in regions where H_{pl} is maximum the areas of the sample were remagnetized in the minimum time.

Let us ask qualitatively which external conditions have the main influence on the MMFW velocity. It has been pointed out[5,8] that the inhomogeneous rotation of the magnetization vectors begins when the external fields $\Delta H(r)$ reach the value of the effective uniaxial anisotropy field H_k^*. Because of the finite rise time τ_f of the leading edge of H_{pul} the inhomogeneous rotation begins back at the front of the pulse. However, by virtue of the finite relaxation times of processes in iron garnet films and the complex configuration of the pulsed field the sample in a real experiment is practically never remagnetized in the time τ_f. Therefore, it is useful to distinguish the MMFW velocity in a varying and constant pulsed field. Depending on the rise time and the strength of H_{pul} the path traveled by a MMFW over the time τ_f will be different. It is entirely natural that for a given rise time of H_{pul}, the higher the amplitude of the pulse the faster the critical field H_k^* is reached at every point. Consequently, in a changing field the MMFW velocity will be proportional to $\partial H_{pul}/\partial t$. This assertion is well illustrated by the chronograms shown in Figs. 1a–c. These figures show that the MMFW slows down as it moves toward the center of the coil. This means that over the entire time that H_{pul} acts, the MMFW velocity is directly proportional to the spatial gradient of H_{pul}, which is determined by the geometry of the coil, i.e., $V_w \sim \partial H_{pul}/\partial r$. This assumption is confirmed by the fact that even if the effective field ΔH $(r = 0)$ in the central region of the coil (where $\partial H_{pul}/\partial r \to 0$) is greater than H_k^*, the MMFW velocity is found to decrease in the experiments (see Fig. 1c). We therefore believe that the assertion[16] that V_w is inversely proportional to the spatial gradient of the field is clearly in error.

In considering the relationship of V_w and $\partial H_{pul}/\partial r$, it is evidently useful to consider separately the gradients of the normal ($H_{pul\perp}$) and planar ($H_{pul\|}$) components of H_{pul}. This is because, as we have shown above, it is the planar component of H_{pul} that has the important influence on the rate of rotation of the magnetic moments. However, to determine even qualitatively the relationship between the MMFW velocity and $\partial H_{pul\perp}/\partial r$ and $\partial H_{pul\|}/\partial r$ will require additional experiments.

Some features of the formation of MMFWs

Experiments have shown that upon any changes in H_{pul}, H_b, and H_{pl}, the formation of MMFWs begins at the leading edge of H_{pul}. This is due first to the finite rise time τ_f, since if the amplitude of $\Delta H(0)$ is greater than H_k^* the magnetic moments begin to turn even as H_{pul} is becoming established. Let us discuss the most interesting features of MMFW formation that emerge from our detailed study of the sample described in this paper (see Fig. 3). The MMFW, as the entire entity considered above (see Fig. 1), is generally not formed right away. In the early moments the inhomogeneous rotation is characterized by a complex and extremely rapid interaction of the magnetic moments at different points in the sample. Here one can observe in the experiment a specific "sawtooth" pattern of the MMFW trajectory, which in time transforms to the typical (without fine structure) trajectory.

Let us consider some features of the MMFW formation at a fixed bias field $H_b = 200$ Oe. We shall give the values of the field H_{pul} ($r=0$) at the center of the pulsed coil. From these values and the functional forms shown in Fig. 2 it is extremely easy to calculate the strength and orientation of the field at an arbitrary point in the sample. In fields H_{pul} $(0) \approx 300$ Oe a single MMFW forms near the coil windings, and then, after ~ 1 nsec, a second MMFW forms (see Fig. 3a). For a certain time ($t_w \sim 4$–6 nsec) these waves move independently, and then, at a distance $r_w \sim 300\,\mu$m from the edge of the coil, they flow together to form a combined MMFW. As H_{pul} is increased from 300 to 2000 Oe the trajectories of the MMFW become noticeably steeper with respect to the time axis, and the characteristic time t_w for the confluence of the separate MMFWs decreases from ~ 6 nsec to ~ 3.5 nsec (see Figs. 3a,b).

On changes in the initial conditions—the bias field H_b—the above picture of the MMFW formation remained basically the same. Experiments were done at $H_b > H_0$, since for $H_b < H_0$ the presence of domain structure substantially complicates observation of the MMFW formation. Increasing H_b all the way to 400 Oe in fields $H_{pul} \geqslant 1000$ Oe makes it possible to detect the appearance of the contours of the third, fourth, and even the fifth MMFW, which were formed, as before, with a time interval 0.5–1 nsec (see Fig. 3c). Here the time of formation of the united MMFW is somewhat longer.

It must be stressed that the formation of the combined MMFW for the actual geometry of the coil is accomplished at a distance $r_w = 300$–$350\,\mu$m from the edge of the coil. In this region (Fig. 2) H_{pul} has the largest planar component.

We note that the MMFW can be characterized by a definite width Δ_w, i.e., the minimum distance at which a 180-degree rotation of the magnetic moment occurs. From Figs. 1 and 3 it is plain that as the wave moves toward the center of the coil (i.e., into the region of weak gradients of H_{pul}), Δ_w increases from tens of microns to hundreds of microns.

Turning now to the nature of the formation of combined MMFW, we must point out that it is not due to transients in the formation of H_{pul}. In particular, an increase in the rise time of H_{pul} from 10 to 50 nsec has no substantial effect on the dynamical process in the sample. It is natural to assume that the features of the formation of the united MMFW are due to the characteristics of the sample itself, the most important of which are apparently the intrinsic relaxation times of the magnetic moments.

In the course of the experiments it was found that depending on the relative orientation of the polarizer and analyzer, the greatest visual contrast was seen at different parts of the trajectories of the MMFWs prior to their confluence. The position of the polarizing sheets determines the number of observable MMFW trajectories and also the features of the confluence of the MMFWs—the formation of the "sawtooth" pattern (Fig. 3b–d). We note that the angle α by which the polarizing sheets were uncrossed was not more than 1–2°. In particular, the photographs shown in Fig. 3 were taken at

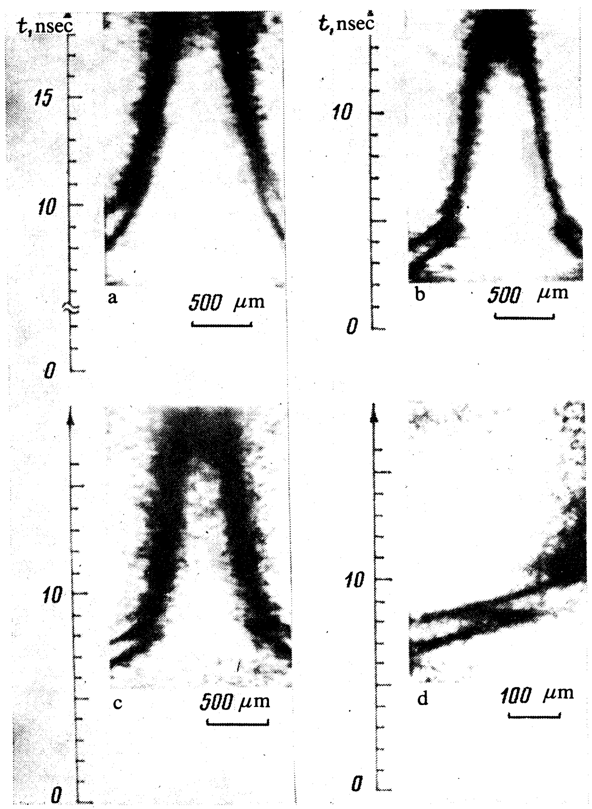

FIG. 3. Chronograms characterizing the formation of a MMFW extending through the thickness of the sample in a multilayer sample in different pulsed fields: a) $H_b = 190$ Oe, $H_{pul}(r=0) \approx 500$ Oe; b) $H_b = 190$ Oe, H_{pul} $(r=0) \approx 1600$ Oe; c, d) $H_b = 300$ Oe, $H_{pul}(r=0) \approx 850$ Oe. The polarizer and analyzer are uncrossed by an angle $\alpha \leqslant 30'$, and $\tau_f \approx 10$ nsec.

$\alpha \leqslant 30'$.

A qualitative analysis of the Faraday effect shows that the greatest contrast for domain walls and MMFWs which extend all the way through the film and separate regions of the sample which are magnetized in opposite directions can be obtained in completely crossed polarizing sheets. If the sample is layered, on the other hand, to obtain the greatest visual contrast for a MMFW propagating in one of the layers the polarizer and analyzer should be slightly uncrossed.

The experiments described above give direct proof that in iron garnet films the inhomogeneous rotation in layers having different properties can begin at different times after the application of $H_{\rm pul}$. The presence of layers in the sample was established by the method described in Ref. 7.

The data in Fig. 3 imply that local points in a particular layer of the sample can be remagnetized in substantially less than 1 nsec. An interesting feature of the inhomogeneous rotation in the layered sample is captured in Fig. 3d. It is plainly seen that the trajectory of the MMFW propagating in one of the layers is practically perpendicular to the time axis. This means that in the strong gradient field near the coil windings in one of the layers of the sample the magnetic moments can flip practically instantaneously, as is characteristic of inhomogeneous rotation. The observed effect is apparently directly related to the presence of the adjacent layer, which is already remagnetized through the motion of the MMFW. It can be assumed that the development of a process similar to inhomogeneous rotation in a bounded area of the sample is due to the absolute instability of the magnetic moments in the given layer and to the presence of end domain walls separating it from a remagnetized layer.

An important feature of the inhomogeneous rotation is the presence of a critical configuration of the pulsed field such that the interaction of the flip waves propagating in an individual layer in the sample gives rise to a united MMFW which extends through the entire thickness of the film. Here the planar component of $H_{\rm pul}$ plays an important role. Of course, the critical conditions for the formation of a MMFW extending through the thickness of the sample can vary depending on the properties of the sample, its position with respect to the coil, the coil geometry, etc.

These experiments suggest that the independent formation of MMFWs in layers with different properties is possible when the interaction between layers is small and the characteristic relaxation times in them are less than 1 nsec. In fact, in a first sample which was known to be layered we were unable to observe MMFWs in individual layers (Fig. 1). At the same time, the existence of such MMFWs was clearly evident in a study of the dynamical behavior of another sample (Fig. 3a,b). The reason for this difference may be a shorter relaxation time of the magnetic moments in the second sample. It is not ruled out that the observed differences are due to a weaker interaction of the magnetic moments in different layers in the second sample in comparison with the first. However, in experiments analogous to those described in Ref. 7, both samples had equally visible layers. It can therefore be assumed that the governing influence on the inhomogeneous rotation in layered samples is the characteristic relaxation time of the magnetic moments.

It follows from Fig. 3 that the width Δ_w of the wave in each of the layers of the sample is substantially narrower than Δ_w for a MMFW that extends through the thickness of the film. On the other hand, if the combined MMFW in an iron garnet film of thickness h is formed from several waves, then by virtue of the different relaxation times in the layers and, consequently, the complicated interaction between the magnetic moments of different layers the combined MMFW extending through the thickness of the sample should be wider than the analogous wave in a single-layer sample of the same thickness. This confirms the results of the experiments described above.

4. CONCLUSION

The main results of this study boil down to the following:

An experimental setup employing electron-optical chronography was assembled, permitting real-time study of fast dynamical processes in thin magnetic films with a time resolution ~ 60 psec. The use of this arrangement permitted detailed study of a number of fundamentally new physical phenomena associated with the inhomogeneous rotation of the magnetization vectors in crystalline iron garnet films.

It was found that the magnetic moments have intrinsic relaxation times on the order of a few nanoseconds (the values can differ substantially even for samples of the same composition). Because of this, the magnetic system cannot instantaneously follow changes in the external magnetic fields if these changes occur over characteristic times of the order of nanoseconds.

Experimental studies of the inhomogeneous rotation of the magnetization vectors at arbitrary points in the sample were carried out for different orientations and strengths of the external magnetic fields. It was found that local regions of the sample can be remagnetized in less than 1 nsec. It was shown that the rate of the inhomogeneous-rotation process depends strongly on the strengths of the pulsed or static magnetic fields in the plane of the sample. For example, at a static field $H_{\rm pl} \approx 100$ Oe the entire region of the sample inside the pulsed coil could be remagnetized in several nanoseconds.

The features of the formation and motion of MMFWs were studied in detail. It was found that the MMFW velocity is proportional to $\partial H_{\rm pul}/\partial t$ and to the spatial gradient of $H_{\rm pul}$, i.e., $\partial H_{\rm pul}/\partial r$. Therefore, it is useful to distinguish the MMFW velocity in changing and static magnetic fields. In an established external field the MMFW susceptibilities can reach tens of km/sec. It was shown that the width of the MMFW could can appreciably depending on the strengths and orientations of the external magnetic fields and, as a rule, ranges from tens to hundreds of microns.

We studied the features of the formation of MMFWs in multilayer iron garnet films. It was found that in the initial stage of the process the inhomogeneous rotation, MMFWs can form successively with time intervals ~ 0.5–1 nsec in different layers of the sample. It was shown that regardless of the strengths of the external magnetic fields there exists a definite field configuration for which several MMFWs in different layers combine to form a united MMFW which extends through the entire thickness of the sample. It was shown that in one of the layers of the sample in a strong field gradient the magnetization vectors in a large area (0.9 mm^2) can execute a practically homogeneous rotation characterized by a rapid (~ 1 nsec) flip of the magnetic moments over the entire area.

In conclusion, it should be noted that the investigated features of the inhomogeneous rotation of magnetization vectors can find wide application in a number of fast magnetooptic devices, such as light modulators, for example.

[1]F. V. Lisovskiĭ, Fizika Tsilindricheskikh Magnitnykh Domenov [Physics of Magnetic Bubbles], Sov. Radio, Moscow (1979) Chs. 1–4.

[2]T. H. O'Dell, Ferromagnetodynamics. The dynamics of magnetic bubbles, domains, and domain walls, MacMillan, New York (1981), Chs. 1–5 [Russian translation Mir, Moscow (1983)].

[3]A. P. Malozemoff and J. C. Clonczewski, Magnetic Domain Walls in Bubble Materials, Academic Press, New York (1979), Chs. 4–8 [Russian translation Mir, Moscow (1982)].

[4]O. S. Kolotov, V. A. Pogozhev, and R. V. Telesnin, Usp. Fiz. Nauk **113**, 569 (1974) [Sov. Phys. Usp. **17**, 528 (1975)].

[5]A. S. Logginov and G. A. Nepokoĭchitskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **35**, 22 (1982) [JETP Lett. **35**, 27 (1982)].

[6]L. P. Ivanov, A. S. Logginov, A. T. Morchenko, and G. A. Nepokoĭchitskiĭ, Pis'ma Zh. Tekh. Fiz. **8**, 337 (1982) [Sov. Tech. Phys. Lett. **8**, 145 (1982)].

[7]L. P. Ivanov, A. S. Logginov, A. T. Morchenko, and G. A. Nepokoĭchitskiĭ, Pis'ma Zh. Tekh. Fiz. **8**, 708 (1982) [Sov. Tech. Phys. Lett. **8**, 306 (1982)].

[8]L. P. Ivanov, A. S. Logginov, and G. A. Nepokoĭchitskiĭ, Zh. Eksp. Teor. Fiz. **84**, 1006 (1983) [Sov. Phys. JETP **57**, 583 (1983)].

[9]N. N. Kudel'kin and V. V. Randoshkin, Pis'ma Zh. Eksp. Teor. Fiz. **38**, 481 (1983) [JETP Lett. **38**, 581 (1983)].

[10]V. I. Krzhizhanovskiĭ, V. A. Serebryakov, V. R. Startsev, and A. A. Chertkov, Kvantovaya Elektron. (Moscow) **9**, 76 (1982) [Sov. J. Quantum Electron. **12**, 48 (1982)].

[11]Z. Bor, IEEE J. Quantum Electron. **QE-16**, 517 (1980).

[12]F. Kachmarek, Vvedenie v Fiziky Lazerov [Introduction to Laser Physics], Mir, Moscow (1981), p. 381.

[13]M. M. Butslov, B. M. Stepanov, and S. D. Fanchenko, Élektronno-Opticheskie Preobrazovateli i Ikh Primenenie v Nauchnykh Issledovaniyakh [Electron-Optical Converters and Their Application to Scientific Research], Nauka, Moscow (1978), Chs. 10–16.

[14]L. P. Ivanov, A. S. Logginov, V. V. Randoshkin, and R. V. Telesnin, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 627 (1976) [JETP Lett. **23**, 575 (1976)].

[15]L. P. Ivanov, A. S. Logginov, G. A. Nepokoĭchitskiĭ, and N. I. Nikitin, Fiz. Tverd. Tela (Leningrad) **25**, 839 (1983) [Sov. Phys. Solid State **25**, 480 (1983)].

[16]N. N. Kudel'kin, A. M. Prokhorov, V. V. Randoshkin, V. B. Sigachev, R. V. Telesnin, and M. I. Timoshechkin, Proc. All-Union Conference on Topical Problems in Physics and Applications [in Russian], Moscow (1984), p. 8.

Translated by Steve Torstveit