Self-organization processes in multidomain magnetic media and the formation of stable dynamical structures

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A special excited state, called by the authors an anger state, arises in iron-garnet films in an oscillating magnetic field. Characteristic for this state are the presence of self-organization processes in a system of moving domain boundaries, the formation of ordered dynamical domain structures (DDS), and the presence of quasiperiodic processes of alternating appearance and disappearance of dynamical domains with a frequency several orders of magnitude lower than the frequency of the oscillating field. A considerable number of distinctive features are found in the formation and behavior of the DDS as the frequency and amplitude of the pumping field vary, when uniform and nonuniform constant magnetic fields are applied. The frequency dependence and amplitude dependence of some of the quantitative parameters of the excited state are determined.

1. In Refs. 1 and 2 the first observation of a special excited state of a multidomain magnetically uniaxial iron-garnet crystal (film) was reported. The state arises in the presence of low-frequency (10^2–10^4 Hz) pumping and is accompanied by the formation of stable dynamical domain structures (DDS) with a definite geometry. This provides evidence of self-organization processes and disorder-$\rightleftharpoons$order transitions in the dynamical system of domain boundaries (DB). It is assumed that the state detected is analogous to known autowave states of open thermodynamic systems.[3,4] Naturally, the problem arises of the further systematic investigation of the new phenomenon, and, in particular, of the elucidation of the regular features in the formation and behavior of the DDS, the study of the properties of the dynamical domains, the determination of the characteristic parameters of the excited state, and so on. The present paper is devoted to the solution of certain aspects of this problem.

2. Epitaxial films of the iron garnet $(YSm)_3(FeGa)_5O_{12}$, characterized by perpendicular anisotropy and a small coercive force (~ 1 Oe) were investigated. Samples of diameter 5 mm were placed in a magnetizing coil with internal diameter 6 mm. The constant or oscillating magnetic field was oriented along the normal to the surface of the film, i.e., along the easy-magnetization axis. The amplitude H_i of the oscillating field, which had the form of rectangular pulses of alternating sign, varied from 0 to 200 Oe. The pulse rise time was $\Delta\tau = 0.04$ msec. The frequency f of the field could be varied from 0 to 30 kHz; however, for $f > 15$ kHz the rectangular shape of the pulses was not maintained. The domain structure was exhibited by means of the Faraday effect. The DB were photographed with an exposure time of $\Delta t_{\rm exp} = 1.2$ msec.

The results obtained are demonstrated for the example of two samples I and II, in the form of films of thickness 5.5 and 11.5 μm, respectively.

3. In the samples in the initial state the usual labyrinthine domain structure (DS) was observed (Fig. 1a). Upon magnetization in a constant field the DS also varies in the usual way (Fig. 1b). The period $2d$ of the domain structure for $H = 0$ is 11 μm and 27 μm for samples I and II, respectively; in a field H_s, of intensity 100 Oe and 70 Oe for samples I and II, respectively, saturation is reached. The behavior of the DS of the two films in an oscillating magnetic field was found to be similar in many respects, but at the same time a number of differences were also detected, so that the experi-

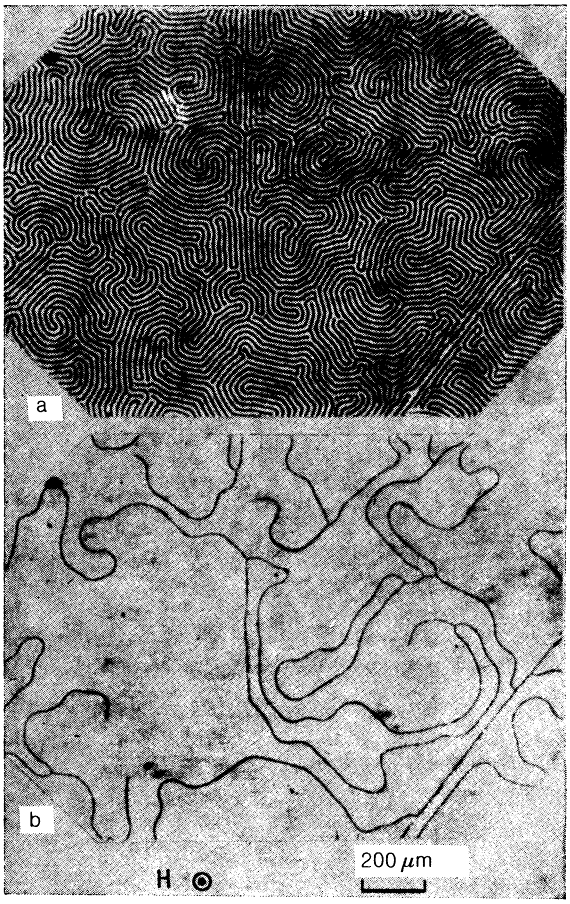

FIG. 1. Initial domain structure of sample I, (a) in the absence of a magnetic field, and (b) in a static field of 84 Oe.

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mental data turned out to be mutually complementary. We first discuss the results of the observation of the DS for sample I.

4. In an oscillating field ($f < 120$ Hz) the visually observable pattern of the DS spreads out into a gray background. If one photographs this background with the exposure indicated above, irregularly arranged domains similar to those which are shown for the case of a static field in Fig. 1b will be visible. Repeated photographing gives various DS patterns, in which no order of any kind is observed. This means that the DS are arranged randomly and move randomly.

For $f = 120$–200 Hz, in a certain range of amplitudes $H_i < H_s$, a contrast DDS, consisting of concentric ring domains, is formed (Fig. 2). These systems appear, disappear, and reappear; the lifetime of one system of rings is 5–10 sec.

Figure 2 shows the variation of the DDS with time on a given part of the sample. The photographs were taken with an interval of ~ 1 min. It can be seen that the pattern of the DDS varies in details, but its character remains the same: These are systems of 3–6 ring domains; the diameter of the inner ring is 200–400 μm, and that of the outer ring is 400–600 μm. The system of rings can move through the sample with a speed of ~ 10 μm/sec; extended defects serve as a barrier to such motion.

5. At frequencies $f > 200$ Hz the character of the DDS changes. Instead of the ring domains, spiral domains appear (Fig. 3). A spiral domain (SD) "lives" for a certain time and then disappears, and in this region of the sample a new domain (or new domains) is formed. The DDS pattern is continuously renewed, but the character of the DDS is preserved—it is a system of spiral domains in which the size of the core of the spirals is 20–30 μm and the pitch near the core is of the same order.

The width of the domains in the ring or spiral structures (Fig. 2, 3) is practically equal to the width d of the domains in a static field of the same magnitude (compare with Fig. 1b). As can be seen from Fig. 3, the spirals can twist clockwise and counterclockwise, i.e., can have different signs of the topological charge $\pm q$. For a symmetric rectangular pulse and in the absence of magnetizing fields, neither sign was favored over the other.

The lifetime of an SD for $f = 300$ Hz reaches ~ 10 sec; the larger the spiral, i.e., the larger the number of turns that it has, the longer it will live. From time to time the core of a spiral "pulsates", and this gives rise to unwinding (winding) of the spiral. Between two successive appearances of an SD in the part of the sample under observation there is a certain waiting time T_w when only the gray background is visible. For a part with area ~ 1 mm^2 in the center of the sample the time T_w for $f = 300$ Hz amounts, on average, to a few seconds. If the outer turns of a spiral are not pinned at defects, the spiral domain can move through the sample with a low speed ~ 5–10 μm/sec.

6. When two SD with the same or opposite signs of q collide they interact as two elastic systems. The distance between the turns decreases, and a region of bunching is formed (Fig. 3d). An analogous pattern is observed in the interaction of SD with point or extended defects. The peripheral turns of the spiral come together in the neighborhood of the defect and envelop it. At positions of bunching the shortest distance between turns is approximately twice the width of the inverse domains (black in Fig. 1b) in a static field of the same intensity. This implies that when the field H_i reverses the DB here move hardly at all.

7. As the frequency of the oscillating field increases to 6 kHz no qualitative changes occur in the dynamics of the DS. For $f > 6$ kHz, a stable, organized DDS is not displayed, either visually or by means of photography. Thus, a DDS in the form of ring and spiral domains exists in the region of frequencies 120–6000 Hz.

Figure 4 shows the frequency dependence of quantitative parameters of the excited state of sample I. The upper and lower field boundaries (H_i^{max} and H_i^{min}, respectively) of formation of the DDS are shown in Fig. 4a. It can be seen that the interval $\Delta H_i = H_i^{max} - H_i^{min}$ for ring domains (for $f = 120$–200 Hz) is shifted in the direction of higher fields in comparison with ΔH_i for spiral domains for $f = 200$–1000 Hz. For higher frequencies the values of H_i^{max} and H_i^{min} also increase with increase of f. We note that the behavior of the

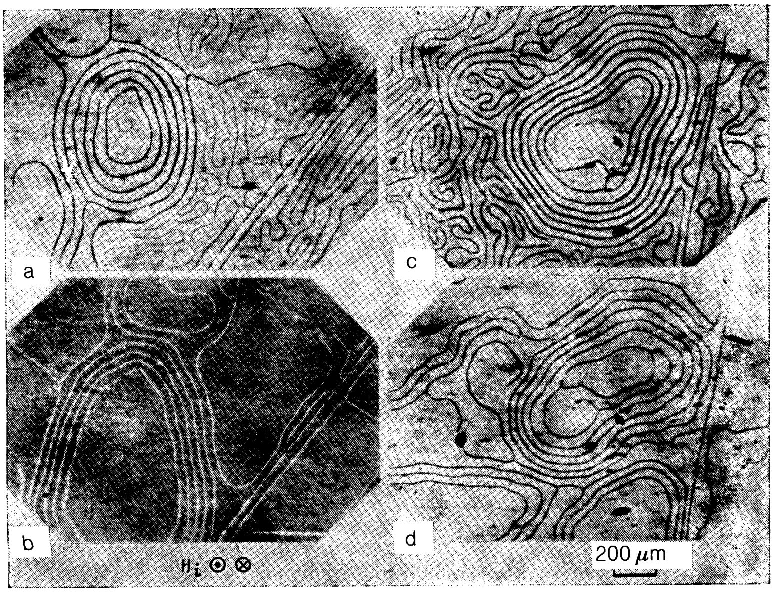

FIG. 2. Ring dynamical domains in sample I at 120 Hz, (a,b) in a field $H_i = 90$ Oe, and (c,d) in a field $H_i = 83$ Oe.

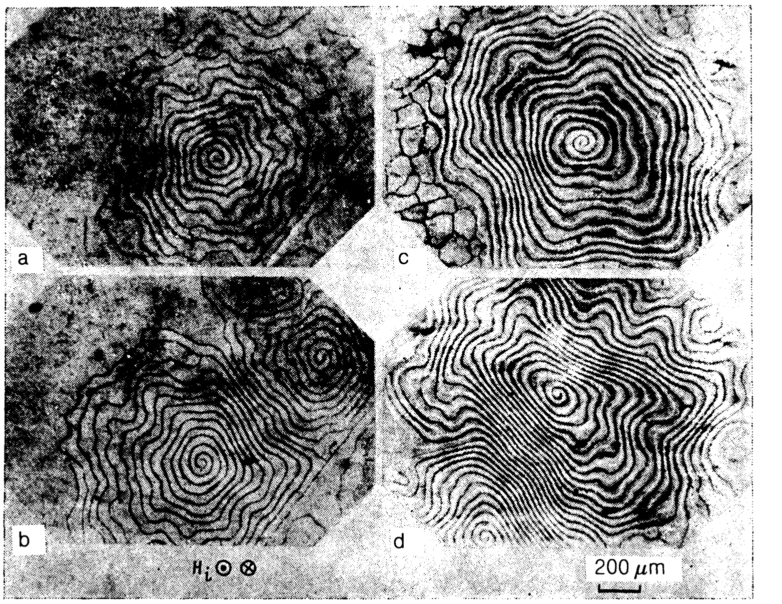

FIG. 3. Spiral dynamical domains in sample I, (a,b) for $f = 300$ Hz and $H_i = 80$ Oe, and (c,d) for $f = 400$ Hz and $H_i = 81.5$ Oe.

dependence $H_i(f)$ is substantially influenced by the temperature (compare curves 1, 1′ and 2, 2′ in Fig. 4a).

Figures 4b and 4c show how the lifetime T_g of the spiral domain and the waiting time T_w depend on the frequency of the oscillatory field H_i. The dashed curves correspond to the largest values of T_g and T_w, and the solid curves correspond to values averaged over 11 measurements. As can be seen from Fig. 4b, the curve $T_g(f)$ has a maximum at $f = 300$ Hz. At this frequency the number of spirals appearing per unit area of the crystal is still small, and so the spirals have the opportunity to grow to large sizes; large spirals, as noted above, are more stable. As f increases further the number of coexisting spiral domains increases; they do not give each other the opportunity to increase in size, and as a consequence their lifetime decreases.

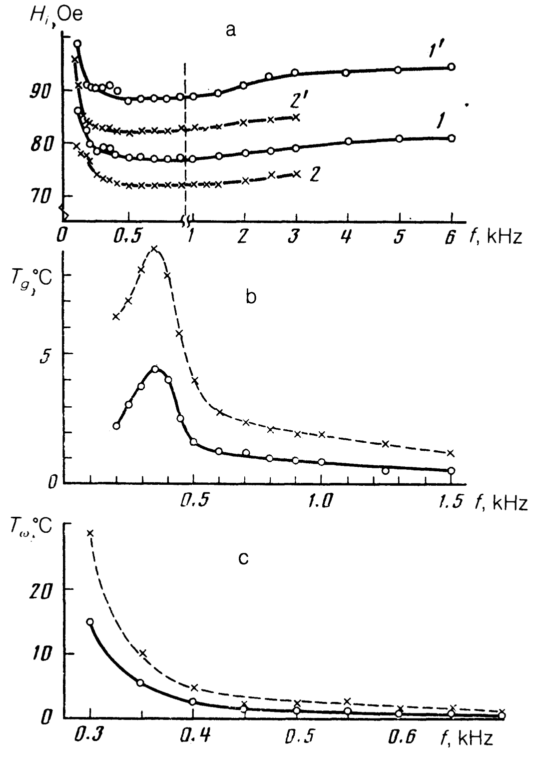

FIG. 4. Frequency dependences (for sample I) of (a) the interval of fields in which ring and spiral domains exist at temperatures $T_1 = 24$ °C (curves 1 and 1′) and $T_2 = 44$ °C (curves 2 and 2′), (b) the lifetime T_g of a spiral, and (c) the waiting time T_w at 24 °C.

The waiting time determined during observation of the DS on a region with area ~ 1 mm^2 and for $H_i = 82$–83 Oe, as can be seen from Fig. 4c, decreases montonically with frequency, and especially sharply in the range 200–400 Hz. Up to $f = 300$ Hz the conditions for the appearance of spirals are evidently not optimal, and therefore the waiting time T_w is long. At frequencies $f > 700$ Hz the time T_w falls practically to zero—as soon as one spiral disappears, another appears in the region being monitored.

It must be noted that all the regular features described above were found to be extremely sensitive to the form of the dependence $H(t)$. For example, changing from rectangular pulses of alternating signs to a sinusoidal field in this particular sample caused the excited state together with all its characteristic features to disappear completely. At the same time, on the other hand, in other films only the sinusoidal pumping field induced the formation of stable ordered dynamical domain structures.[5]

8. In the second sample, even for small amplitudes of the alternating magnetic field and frequencies f of tens of Hertz, as well as the "flickering" of the DS certain displacements of the systems of strip domains occur. As a result, those elements of the spiral structure that are contained in the original labyrinthine DS are manifested ever more sharply. This is the stage of "magnetic shaking." Next, with increase of H_i up to H_s, the dynamical DS becomes disordered.

For $f \geqslant 120$ Hz and $H_i > 30$ Oe self-organization processes intensify in the system of randomly moving domain boundaries, and the film goes over into an excited state similar to that which was observed in sample I (see above), with, however, the important difference that in sample II ring dynamical domains similar to those shown in Fig. 2 are not formed. Spiral domains appear, disappear, reappear, and so on, and are much less distorted in shape than those in sample I.

As an example, Fig. 5 shows one such spiral domain. It can be seen that the spiral is double—it is composed of a "black" and a "white" strip domain, which have magnetizations pointing "toward us" and "away from us" and are separated by gray regions. This three-contrast phenomenon is due to the fact that the photographs in Fig. 5 (like those in Figs. 2 and 3) were obtained for an exposure time $\Delta t_{\rm exp}$ slightly shorter than the half-period of the oscillating field $H_i(t)$. Hence, three cases are possible:

a) $\Delta t_{\rm exp}$ overlaps only a positive half-period of the field $H_i(t)$; then a black spiral or ring domain (or domains) will be visible on the photograph, as in Fig. 2a;

b) $\Delta t_{\rm exp}$ belongs to a negative half-period of $H_i(t)$; then there will be a white domain on the photograph, as in Fig. 2b;

c) $\Delta t_{\rm exp}$ falls on both positive and negative values of $H_i(t)$; then both black and white domains are fixed, as in Fig. 5.

In Fig. 6 we give sketches clarifying the cases described. Those regions (gray on the photograph of Fig. 5) through which the domain boundaries in the turns of the spiral pass, moving toward each other as the field $H_i(t)$ changes during the exposure time, are shaded on the sketch. For $\Delta t_{\rm exp} \ll \Delta\tau$, e.g., when high-speed photography is used, a two-contrast DDS should be observed.

Thus, the presence of "gray domains" on the photographs of the DDS in no way indicates rotation of the magnetization or broadening of the domain boundaries. It is a purely methodological effect. A positive aspect here is the fact that, simultaneously on one photograph, we can see the limiting DB positions, corresponding to the amplitude values $+H_i$ and $-H_i$. Of course, this pertains not only to the ordered but also to the disordered structure (see, e.g., Fig. 7b). We again draw attention to the fact that in some of the spiral domains the distance between the first two or three turns near the core is slightly shorter than that between the peripheral turns. This compression can reach 40%.

9. The conditions for visual observation of the DDS for $f = 300$–500 Hz were more favorable in sample II than in sample I. This was due to the fact that, in comparison with sample I, in sample II the contrast of the DS pattern was higher, the width of the strip domains from which the spiral domains were formed was greater, and, finally, the lifetimes of the spiral domains were considerably greater.

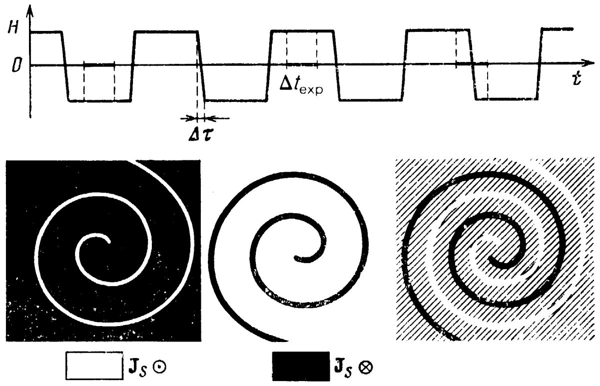

FIG. 6. Sketch clarifying the behavior of white, black, or double spirals on the photographs of the DS.

As the amplitude H_i increases it can be seen how rotation of the core of the spiral gives rise to untwisting (twisting) of the spiral and motion of turns of the SD from the center (toward the center). As $H_i^{\rm max}$ is approached the lifetime of the SD falls sharply and the size of a spiral and the number of turns in it decrease (Figs. 7a,b).

Besides the spiral domains described, which are formed by twisting the tip of a strip domain, two-branched spirals are observed, albeit appreciably more rarely. In such spiral domains the core is most probably formed by twisting the middle of a "white" (Fig. 7d) or a "black" (Fig. 7e) strip domain. Two-branched spiral domains can also have different numbers of turns, they can be twisted clockwise and counterclockwise, and on them a small degree of compression of the inner turns is also noticeable. Their dynamical behavior is similar to that of one-branched spiral domains. We have succeeded in observing the shortening of one of the branches and the transformation of a two-branched spiral domain into a one-branch.

10. As can be seen from Fig. 8a, raising the temperature changes the region of existence of the excited state, this change being opposite in character to that which was ob-

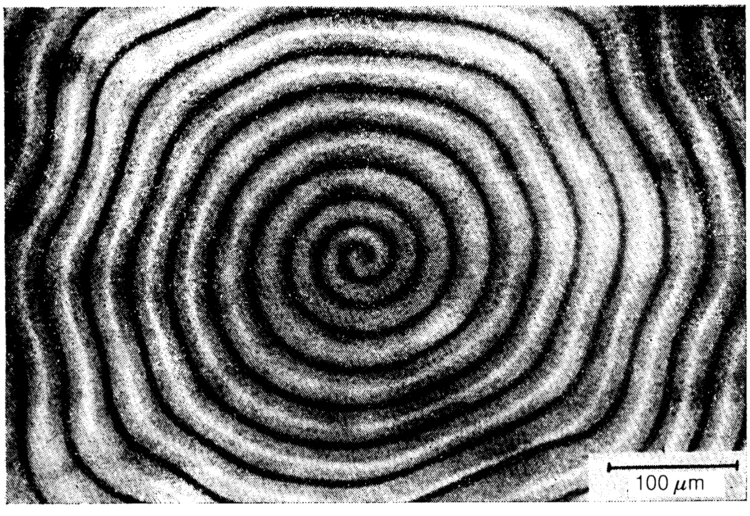

FIG. 5. Double spiral (sample II).

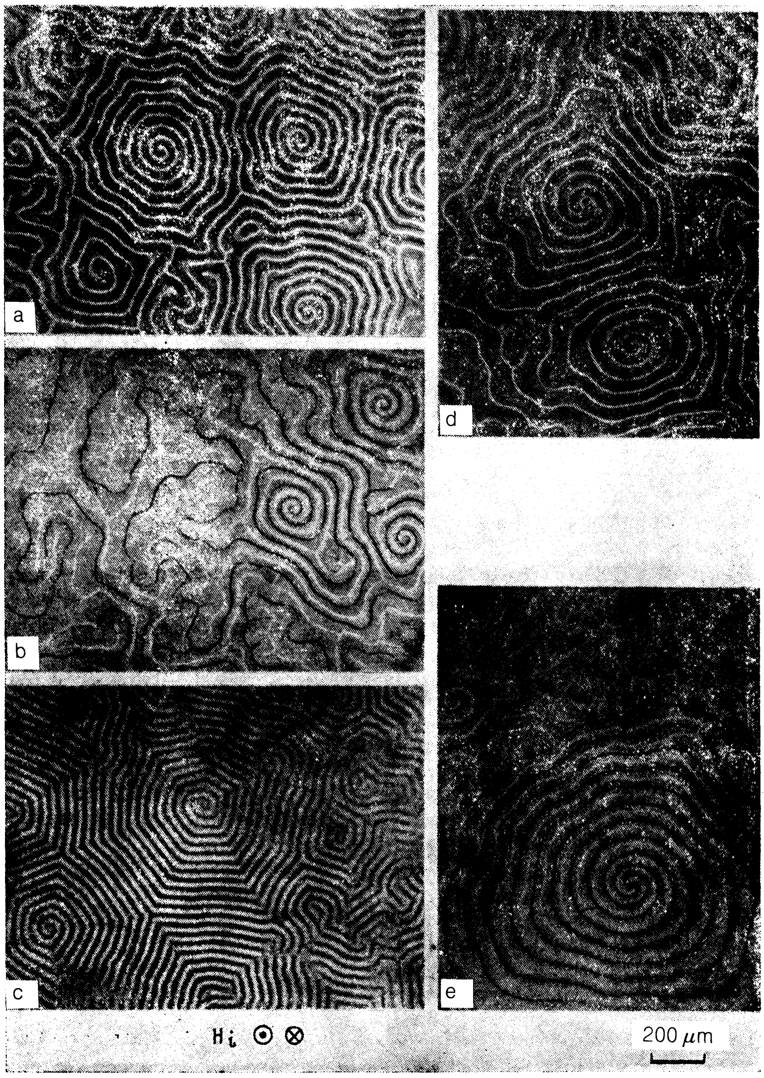

FIG. 7. Dynamical domain structures in sample II. Spiral domains are found for (a) $f = 0.5$ kHz and $H_i = 41.5$ Oe, (b) $f = 0.5$ kHz and $H_i = 46.5$ Oe, and (c) $f = 20$ kHz and $H_i = 64$ Oe. Two-branched spirals (d,e) are found for $f = 300$ Hz and $H_i = 40$ Oe; in the case of (d) a constant displacement field $H_d = 6$ Oe is applied.

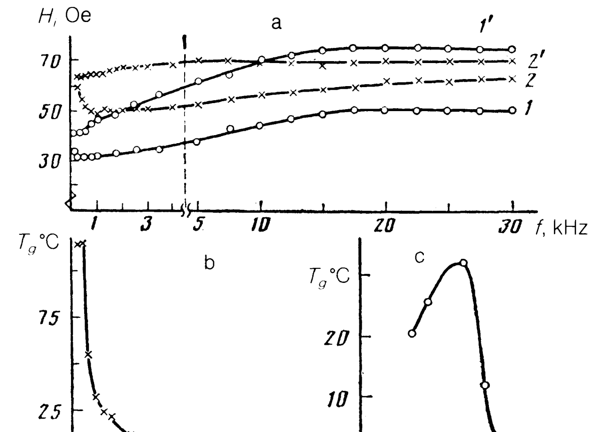

FIG. 8. Frequency dependences (for sample II) of (a) the interval of fields in which spiral domains exist at temperatures 25 °C (curves 1 and 1') and 50 °C (curves 2 and 2'), and (b) the lifetime T_g of spirals at 25°C; (c) dependence of the lifetime T_g on the amplitude H_i of the field at frequency 500 Hz and temperature 35 °C.

served for sample I (compare Figs. 8a and 4a). Evidently, this is connected with the different temperature dependence of the magnetic constants of the materials of the first and second samples.

The lifetime T_g of the spiral domains, measured for the middle of the range of H_i (Fig. 8b), falls sharply as the frequency f increases to 5 kHz. The waiting time T_w, defined as for sample I, was equal to zero, i.e., the monitored part of film II, of area ~ 1 mm^2, did not remain free of spiral domains. For a given frequency the time T_g depends on the amplitude H_i of the field. For $f = 500$ Hz, as can be seen from Fig. 8c, this dependence is nonmonotonic. In the frequency range 300–1000 Hz, both at room and higher temperatures, a general tendency is noticeable—the value of T_g decreases sharply as $H_i^{\max}$ is approached.

11. Interesting and unexpected results were obtained in the investigation of the influence of uniform (H_d) and nonuniform constant magnetizing fields on the form of the DDS and some of its quantitative parameters.

Figure 9 shows the change of the DDS in a given part of sample II as the displacement field H_d increases. It can be seen that with increasing H_d the number of turns in the SD and the size of the SD decrease; what were multiturn spiral domains (Figs. 9a,b) become two- or three-turn SD (Fig.

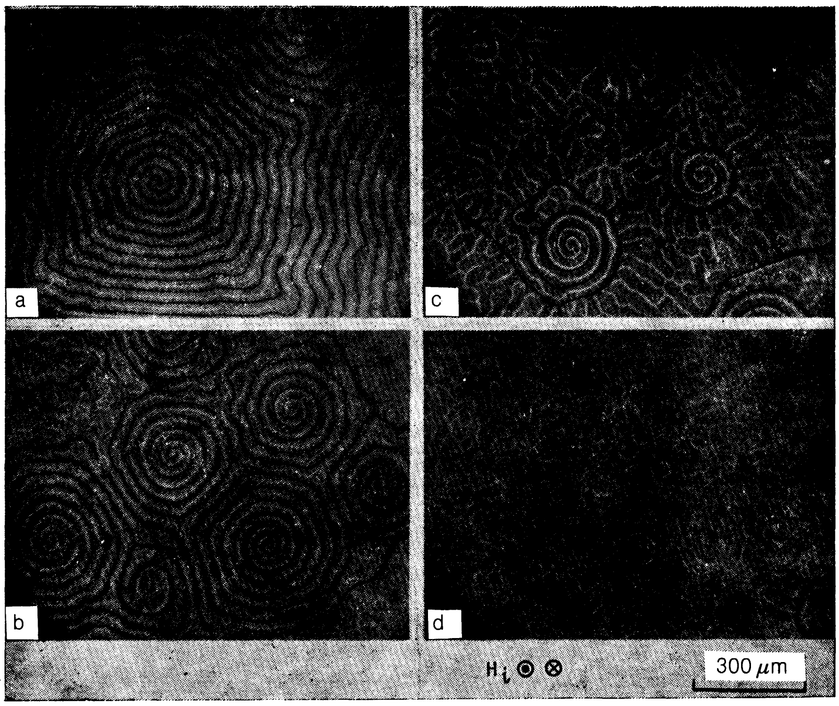

FIG. 9. Form of the spiral dynamical domains in sample II at frequency 300 Hz and for fields (a) $H_i = 38$ Oe and $H_d = 0$ Oe, (b) $H_i = 38$ Oe and $H_d = 6$ Oe, (c) $H_i = 38$ Oe and $H_d = 8.7$ Oe, and (d) $H_i = 40$ Oe and $H_d = 8.7$ Oe.

9c) or single-turn SD (Fig. 9d). Moreover, dynamical domains in the form of "brackets" and "commas" are observed (Fig. 9d). Their lifetime is much longer than the pumping period. The cores of the SD in Figs. 9a,b,c are of approximately the same size, while the cores of single-turn SD (Fig. 9d) are appreciably larger. It can also be seen that, instead of a system of mutually connected SD with opposite signs of q, isolated SD with the same direction of twist are formed (compare Fig. 9b with Figs. 9c,d). When the sign of the field H_d changes, spiral domains of the opposite twist become preferred. Thus, the displacement field H_d lifts the degeneracy with respect to the direction of the twist of the spirals. The analogous behavior is also observed for sample I.

The results of processing several tens of photographs of SD, taken for different magnitudes and signs of H_d, are given in Fig. 10. It can be seen that for sample II the experimental points are located in the first and third quadrants, while for sample I they are in the second and fourth. This implies that in film II a field $+H_d$ leaves spiral domains twisted clockwise (q^+), whereas in film I, on the contrary, this field "selects" spiral domains twisted counterclockwise. It is apparent that the direction of twist is related to the structure of the DB at the tip of the strip domain that becomes the center of the SD. It is not excluded that the left- or right-handed twist is determined by the presence here of either one or two vertical Bloch lines (or, respectively, of an odd and even number of vertical Bloch lines in the cluster).

As noted above, the SD in the DDS continuously appear, disappear, move slowly, pulsate, and rotate. The characteristic times for these processes for $f = 300$ Hz are ~ 1–10 sec. When a magnetizing field H_d is applied, the behavior of the spirals with few turns displays the following distinctive feature: At the "end of their life" some of them are transformed into rapidly rotating "tops," with a rate of rotation exceeding 10 revolutions per second. The direction of rotation is opposite to the direction of twist of the spiral. For example, the one-turn spirals of Fig. 9b, when set into rapid rotation, rotate counterclockwise. However, like the spiral domains, they can disappear without going into the "top" state. The largest rates of rotation were observed for dynamical domains in the shape of "brackets" and "commas" (Fig. 9d).

A large variety of shapes and behavior of dynamical domains was observed in uniform and nonuniform magnetizing fields. For example, a system of two few-turn spirals that have topological charges q of the same sign and are joined by an S-shaped link can arise, as can a system of two few-turn spirals that have opposite charges $\pm q$ and form a configuration with a "ram's horns" shape. During the lifetime of these DDS a quasiperiodic process of unwinding of

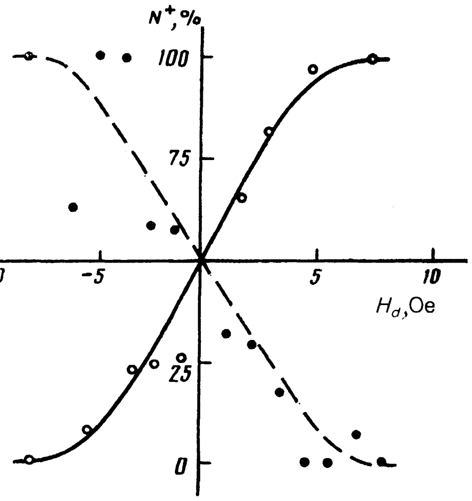

FIG. 10. Dependence of the relative number (N^+) of spiral domains with charge $+q$ on the direction and magnitude of the displacement field. The dashed curve is for sample I for $f = 100$ Hz, $H_i = 86$ Oe, and temperature 25 °C; the solid curve is for sample II for $f = 500$ Hz, $H_i = 45$ Oe, and temperature 35 °C.

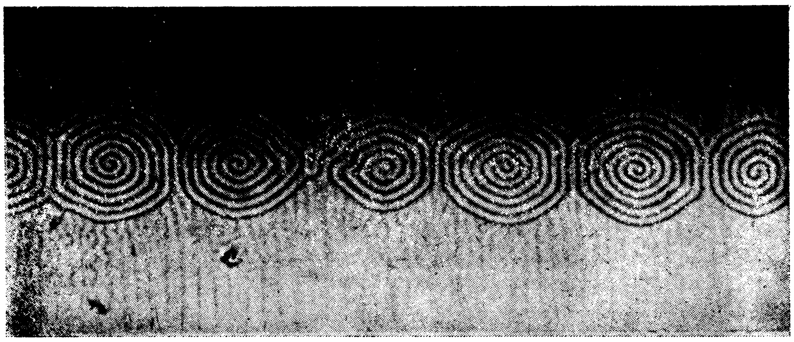

FIG. 11. Chain of spirals in a nonuniform constant field for $f = 4$ kHz and $H_i = 25$ Oe.

one spiral and winding of the other can occur. We observed single spirals with a long free end, along which (as along a directrix) the spiral "rocks," periodically winding and unwinding, during the time T_g.

In a nonuniform field, between two parts of the film that were magnetized "toward us" and "away from us," we observed the formation of a chain of spiral domains, as shown in Fig. 11. The general form, length, and width of this chain, and also the number of turns in the spiral domains and their twist (and hence the form of the linkage between the spiral domains), change with variation of the parameters characterizing the nonuniform field. Note that in the regions of film adjacent to the chain of SD on both sides (on Fig. 11) there is a planar component of the field; this component induces a rearrangement of the DS from a labyrinthine DS to a strip DS and impedes the formation of dynamical spiral domains.

We emphasize that in by no means all of the films investigated did we succeed in observing an excited state with processes of self-organization of DS in oscillating fields. For the present, we are unable to formulate clearly the necessary and sufficient conditions for the realization of such a state.

CONCLUSION

The full set of experimental data show that under suitable conditions of external pumping in a multidomain magnetically uniaxial crystal (film) a special excited state is realized, for which the following features are characteristic:

a) the presence of a self-organization process in a system of randomly moving domain boundaries, leading to the formation of rather stable ring or spiral dynamical domain structures;

b) the presence of a quasiperiodic process, consisting in the alternating appearance and disappearance of ordered systems of dynamical domains;

c) the existence of a waiting time necessary for the formation of a macroscopic ordered configuration from a random system of domain boundaries;

d) the propagation of wavelike disturbances within the dynamical domains, rotation of the domains, and mobility of the whole system of such domains in the sample;

e) low frequencies of the quasiperiodic processes in the organized dynamical system of domains in comparison with the frequency of the exciting oscillatory field (the characteristic times are several orders of magnitude longer than the pumping period).

All of this makes it possible to classify the observed excited state of a multidomain magnetic medium as being of the autowave type. To a certain extent it is similar to the state that is observed in nonequilibrium thermodynamic systems in conditions of external energy pumping.[4] It is known that, as a result of self-organization, in active distributed (autowave) media stable dissipative structures in the form of spirals (vortices) or rings can be formed. They are regarded as autowaves of the corresponding geometry.[6]

However, we cannot directly associate, e.g., spiral autowaves in a chemically active medium with spiral magnetic domains. Their properties are different: For instance, autowaves annihilate when they collide, while spiral domains interact as elastic systems. To make such an association is not justified if only because, from a macroscopic point of view, a chemically active medium is continuous whereas a multidomain magnetic medium is discrete, and so the excited state in the latter should have its own characteristic distinctive features.

Taking this into account, we propose to give a special name (e.g., anger state) to the state which arises in a multidomain medium pumped by an oscillating magnetic field, which is accompanied by self-organization processes in the system of moving domain boundaries and by the formation of ordered stable dynamical domain structure. To resolve questions concerning the nature of this state, the mechanism of the formation of the ring and spiral domains, and the reasons for the specific behavior of the dynamical structures under different physical influences, and to understand those regular features that are described in the present paper, further experimental and theoretical investigations are needed.

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[1] G. S. Kandaurova and A. É. Sviderskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **47**, 410 (1988) [JETP Lett. **47**, 490 (1988)].

[2] G. S. Kandaurova and A. É. Sviderskiĭ, Pis'ma Zh. Tekh. Fiz. **14**, 777 (1988) [Sov. Tech. Phys. Lett. **14**, 346 (1988)].

[3] G. Nicolis and I. Prigogine, *Self-Organization in Nonequilibrium Systems* (Wiley, New York, 1977) [Russ. transl., Mir, Moscow, 1979].

[4] Yu. I. Balkareĭ, L. L. Golik, and M. I. Elinson, *Autowave Media* (*Use in Electronics*) [in Russian] (Znanie, Moscow, 1985).

[5] G. S. Kandaurova, A. Ya. Chervonenkis, and A. E. Sviderskiĭ, Fiz. Tverd. Tela **31**, No. 6, 238 (1989) [Sov. Phys. Solid State **31**, 1049 (1989)].

[6] V. A. Vasil'ev, Yu. M. Romanovskiĭ, and V. G. Yakhno, *Autowave Processes* (Nauka, Moscow, 1987).

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