Reorientation and transformation of the structure of domain walls in an oscillating magnetic field

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Magnetooptic and induction methods were used in a study of domain structure modification in iron garnet films with a transverse magnetic field gradient under the influence of an hf magnetic field applied in the film plane. Certain attributes of the induction signal were found, associated with the excitation of nonlinear dynamic processes in the magnetic subsystem during reorientation of domain walls. Anomalies of a secondary signal were observed at field amplitudes less than the reorientation field, attributed to the formation of Bloch lines in polarized domain walls.

1. INTRODUCTION

Unusual behavior of the domain structure of iron garnet films characterized by an easy magnetization axis perpendicular to the surface was recently observed[1] in oscillating fields in the megahertz frequency range. An hf magnetic field, which was perpendicular to the magnetization in the domains and did not shift domain walls, induced gradual reorientation of these walls: as the field amplitude was increased, the walls became oriented first perpendicular and then parallel to the field polarization. This effect was observed at external field frequencies much lower than the frequency of a natural ferromagnetic resonance and was attributed in Ref. 1 to the processes of creation and annihilation of Bloch lines in an oscillating field. Reorientation of domain walls in films containing magnetic bubble domains as well as nonlinear phenomena observed in bulk iron garnet plates (including a change in the domain structure period,[2] periodic formation of domain walls,[3] and creation of Bloch lines[4]) demonstrated that nonlinear excitations played an important role in the dynamic response of a magnetic material to an oscillating field. The interest in such excitations recently increased strongly in connection with the development of theoretical ideas on intrinsic nonlinear modes which are widespread in many (physical, chemical, etc.) dynamic systems.[5]

We carried out a detailed investigation of dynamic changes in the domain structure of iron garnet films. We determined the spectra of an induction signal and identified behavior demonstrating that wall reorientation was linked to the generation of nonlinear excitations. Moreover, at field amplitudes which were low compared with the reorientation fields, we found maxima of amplitudes of higher harmonics in the induction response of samples with initially polarized walls; we attributed these maxima to the creation of Bloch lines in the walls.

2. EXPERIMENTAL METHOD

We investigated iron garnet films with the easy magnetization axis perpendicular to the surface and grown on (111) substrates made of gadolinium gallium garnet. The samples were cut in the form of disks 2 mm in diameter in which the magnetic layer was retained on one surface and was ground off from the other surface. The film parameters were determined using standard magnetooptic methods.[6,7] In the present paper we shall report the results obtained for a film of $(YGdYb)_3(FeGa)_5O_{12}$ characterized by a magnetization of $4\pi M_s = 186.5$ G, an anisotropy field $H_a = 190$ Oe, a Q factor amounting to 1.02, a thickness $d = 25\,\mu$m, a characteristic length $l = 0.25\,\mu$m, a domain period $11.2\,\mu$m, and an exchange constant $A = 2.12\times 10^{-7}$ erg/cm.

An exciting field of $f = 0 - 15$ MHz frequency and $h_0 = 0 - 30$ Oe amplitude was applied in the plane of a film. It was created by a small solenoid coil subjected to a voltage from a high-power hf oscillator. Since there were gaps between the turns in the middle of the coil, it was possible to examine visually the state of the domain structure. This structure was analyzed using polarized light and the Faraday effect.

A secondary coil in the form of a flat spiral of several turns with an inner diameter of 200 μm was located at the center of the primary coil on a special tilted platform, which was used to compensate the induction signal induced by the field of the primary coil. The sample tested with the magnetic layer in direct contact with the secondary coil. The signal induced in the coil was due to the fringing fields resulting from fluctuations of the magnetization both in domains and in their walls.

The signal from the secondary coil was fed through a coaxial cable to a 50-Ω input of a wide-band amplifier and then to a spectrum analyzer. The analyzer recorded the induction response spectra at a fixed amplitude and frequency of the exciting field. A selective microvoltmeter was connected in parallel to the wide-band amplifier via a removable high-resistance probe sample; the signal from the output of the microvoltmeter was applied to one of the inputs of an X–Y plotter. The second input received a voltage proportional to the amplitude of the alternating current in the coil. In this way we determined the amplitude of any harmonic of the secondary signal as a function of the amplitude of the oscillating magnetic field (at a constant frequency $f = \text{const}$).

High amplitudes of the alternating field required high currents through the primary coil, but this resulted in heating. Therefore, the temperature of the coil and sample were stabilized using an automatic system which ensured cooling with nitrogen vapor or controlled heating, as required. The experiment used static magnetizing fields applied in the film plane, created by two pairs of coaxial coils. One pair of these Helmholtz coils produced weak homogeneous magnetizing fields for the control of the domain wall structure and the

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other pair magnetized the sample in its plane to saturation, which was essential for preliminary orientation of the walls relative to the direction of the oscillating magnetic field. It was established that a reduction of the static field $\mathbf{H}_s$ from the saturation value created a lattice of stripe domains which were parallel to $\mathbf{H}_s$.

3. EXPERIMENTAL RESULTS

As in the case of the samples we investigated earlier,[1] the epitaxial iron garnet films used in the present investigation exhibited a gradual reorientation of domain walls under the influence of the oscillating magnetic field. When the amplitude of this field h_0 reached a threshold H_{c1} which depended on the frequency, the initial maze domain structure (Fig. 1a) was converted into a lattice of stripe domains with walls perpendicular to the direction of the alternating field (Fig. 1b). This domain lattice was formed because of growth of the blocks of stripe domains with walls almost perpendicular to the field and because of shrinkage of the regions where the walls were oriented along the field. The stripe domain blocks with different wall orientations not only exhibited a change in their dimensions, but also moved discontinuously along the film.

When all the domain walls in the initial structure were first oriented along the field, an increase in h_0 caused abrupt bending of some of the domains, orienting some wall sections at an angle to the field direction. This was followed by the formation of domain blocks with walls which were not parallel to the field and a transition to a lattice of domains perpendicular to the field, exactly as in the case of the initial maze structure. A further increase in h_0 resulted in low-frequency random bending vibrations of domain walls, creating sections of the walls oriented along the field, which then increased so that the lattice of domains parallel to the field formed in a critical field H_{c2}. It should be pointed out that the behavior of such a lattice of domain walls parallel to the field depended on the frequency of the exciting field. For frequencies $f < 3.5$ MHz, the lattice was stable in the field H_{c2}. At frequencies in the range $f = 3.5$–15 MHz the domain walls created by H_{c2} and parallel to the field were unstable: the walls exhibited a random vibration, so that their image was smeared out when illumination was continuous. In this case the wall orientation was determined by illumination with a pulsed laser (pulse duration ~ 8 nsec). However, on increase in the field amplitude the lattice of walls parallel to the field became stablized (Fig. 1c). The field amplitude in which these walls became stable increased as a function of

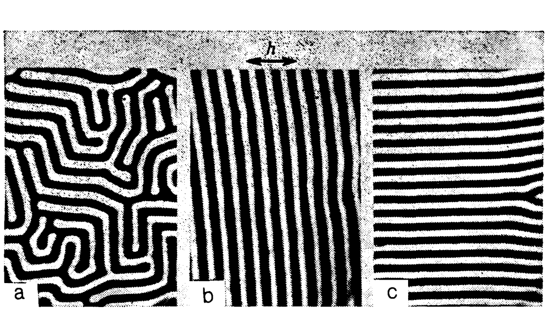

FIG. 1. Changes in the domain structure under the influence of an alternating field of $f = 5.3$ MHz frequency: a) $h_0 = 0$; b) $h_0 = 13.0$ Oe; c) $h_0 = 25.0$ Oe.

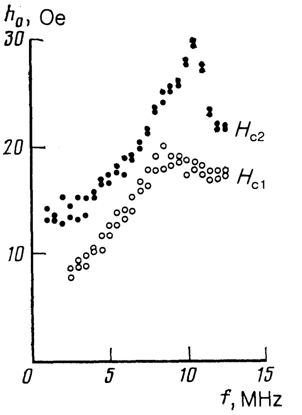

FIG. 2. Frequency dependence of the amplitudes of the field in which reorientation of domain walls takes place. In the field H_{c1} the domains become oriented perpendicular to the field and in H_{c2} they become parallel to the field.

the frequency, and in the range $f > 6$ MHz no stable domain structure was observed right up to the highest field amplitudes used in our experiments.

It was found that when a lattice of domains parallel to the field was stabilized by an oscillating field (in the range $H_0 > H_{c2}$), the domain structure period decreased as a function of the amplitude h_0, although not as rapidly as in the case of single-crystal iron garnet plates.[2] Note that the field amplitudes at which the domain wall reorientation processes took place (H_{c1}) varied nonmonotonically with the field frequency. The dependence $H_{c1}(f)$ obtained for films of other compositions was qualitatively similar to that plotted in Fig. 2 for $(YGdYb)_3(FeGa)_5O_{12}$.

Additional information on the processes responsible for domain structure modification was obtained by investigating the induction response of a crystal. It was found that such domain structure modification was accompanied by changes in the spectrum of the secondary signal. They were observed clearly in the field-amplitude dependence of the amplitudes of higher harmonics of the signal. We shall illustrate the main relationships found by quoting the results of specific measurements.

At low field amplitudes the induction response rose linearly with the field and the spectrum consisted of just the fundamental (first-harmonic) frequency. However, an increase in h_0 gave rise to higher harmonics in the signal. In Fig. 3 we have plotted the secondary signal spectra for several amplitudes of the oscillating field of frequency 5.3 MHz. The higher harmonics appeared and grew on increase in the exciting field (Figs. 3b and 3c; only the fundamental can be seen in Fig. 3a). They reached the highest amplitudes just before reorientation of the domains to the direction perpendicular to the field and then, after reorientation, the amplitudes fell (Fig. 3d). A further increase in the exciting field increased the amplitude of the harmonics and broadened the spectrum of the signal (Fig. 3e). However, immediately after alignment of the domains along the field, the amplitudes of the harmonic again decreased somewhat (Fig. 3f) and then rose again.

In fields $h_0 < H_{c2}$ the greatest change occurred in the amplitude of the second harmonic A_2. In Fig. 4, we have plotted the field-amplitude dependence of the amplitude of this harmonic (when the initial structure was maze-like).

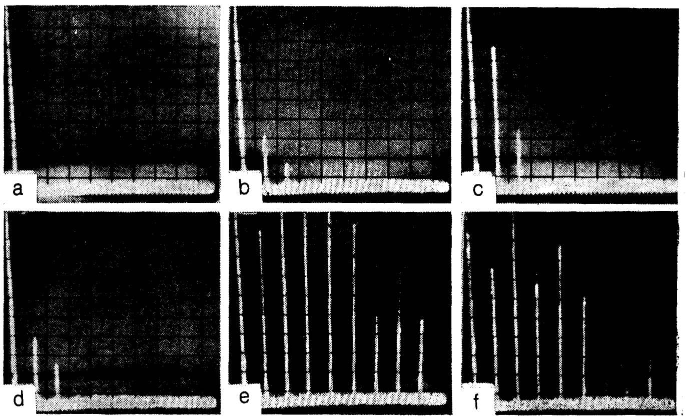

FIG. 3. Changes in the spectra of the secondary signal with increasing amplitude of the exciting ($f = 5.3$ MHz) field h_0 (Oe): a) 1.6; b) 10.4; c) 11.9; d) 13.2; e) 15.5; f) 17.0.

The arrows identify the instants of time corresponding to domain reorientation: 1) a considerable increase in the parts of the domains almost perpendicular to the field (where the amplitude A_2 fell); 2) domains aligned at right-angles to the field (where A_2 was a minimum); 3) domains aligned along the field (another minimum of A_2). The dependence $A_2(h_0)$ had irregular peaks (which were amplified when the domains began their reorientation toward the direction of the field, i.e., for $h_0 > H_{c1}$), corresponding to abrupt bending of domains, displacements of domain blocks and random vibrations of the walls.

When the domain walls were initially perpendicular to the field, the harmonics were absent from the signal right up to fields H_{c1} and then the changes were the same as in the case when the initial domain structure was maze-like.

The characteristic features of the response of the magnetic subsystem associated with wall reorientation were determined also at the fundamental frequency (i.e., the frequency of the external field), but the relative changes in the amplitude of the fundamental during the domain structure modification processes were slight. The absolute value of the amplitude of the fundamental in fields $h_0 < H_{c2}$ was several dozen times higher than the amplitude of the second harmonic.

Additional features of the induction signal were observed when the walls in the initial domain structure were subjected to a preliminary polarization procedure. Polarized walls were observed after the application of a high (up to saturation) static magnetic field H_s in the plane of the film. The subsequent reduction of this field produced a lattice of stripe domains parallel to the field. When the static field was switched off, the magnetization in the middle of the walls remained oriented along H_s. When the oscillating field was parallel to the walls oriented in this way, then at field amplitudes considerably less than the critical fields for domain structure modification a maximum appeared in the dependence of the amplitude of the second harmonic on the field amplitude (curve *a* in Fig. 5) but subsequently A_2 decreased practically to zero. This maximum did not appear when the initial domain structure was maze-like. Moreover, it did not appear when the initial domain orientation was along the field if the sample was already subject to an oscillating field of amplitude exceeding h_0^* corresponding to the maximum. The maximum reappeared only when the walls were polarized by a static field.

We found that when the scanning of the amplitude was stopped on reaching a value corresponding to the left-hand wing of the maximum, the signal was established at a certain value, but if h_0 was in the right-hand wing of the maximum,

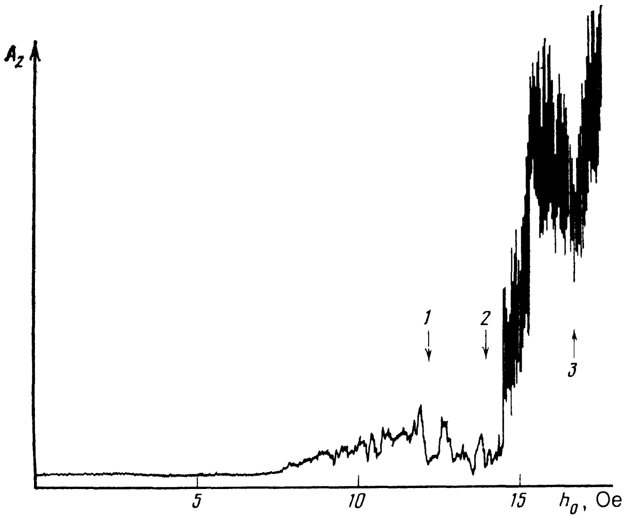

FIG. 4. Amplitude of the second harmonic of the induction signal vs the amplitude of the oscillating field in the case when the initial domain structure is maze-like ($f = 5.3$ MHz).

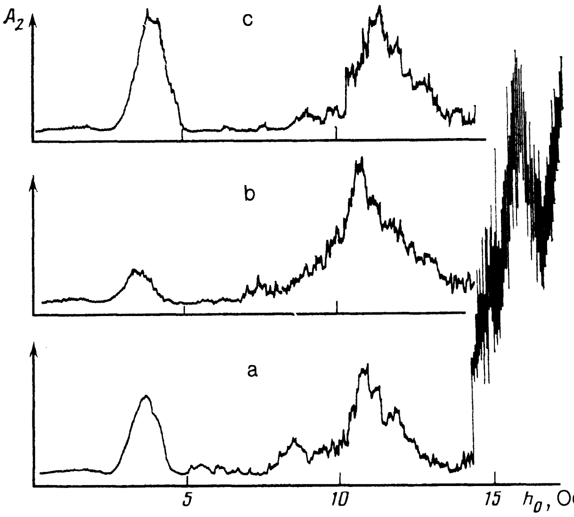

FIG. 5. Dependence of the amplitude of the second harmonic of the induction signal on the amplitude of the oscillating field applied to samples with initially polarized domain walls, subjected to various static magnetizing fields H_s (Oe): a) 0; b) -0.14; c) 0.14.

the induction response decreased with time. This drift of the signal indicated that irreversible changes in the magnetic structure occurred after reaching the amplitude corresponding to the peak of the maximum. No changes in the domain structure were then observed. Therefore, it was natural to conclude that these changes were due to creation of Bloch lines in unipolar walls under the action of an oscillating field and that these walls then vibrated linearly along the walls at the frequency of the applied field.

To check this hypothesis a sample was subjected to a weak static field parallel to the stripe domains with polarized walls, either parallel to the polarization of these walls ($+H_s$, which increased the barrier hindering Bloch line creation) or in the antiparallel direction ($-H_s$, which facilitated Bloch line creation); this was followed by scanning of the oscillating field and determination of the changes in the second harmonic of the induction signal. When the maximum was associated with Bloch line creation, then in the case when the static field was applied along the wall polarization, the maximum should shift toward higher field amplitudes, whereas in the antiparallel magnetizing field, it should shift toward lower values of h_0. Our measurements indicated that when the field was parallel to the wall polarization, the first peak did indeed shift toward higher amplitudes and its amplitude increased (curve c in Fig. 5). The antiparallel field reduced the peak amplitude and shifted it slightly to the left (curve b in Fig. 4). At some value of the magnetizing field $-H_s$ the maximum disappeared completely.

The high static field in the plane of the film influenced also the modification of the domain structure. An increase in the magnetizing field shifted the transition to the domain orientation perpendicular to the field toward higher values of h_0 and then suppressed such orientation. It should be pointed out that the maximum of the second harmonic preceding the orientation of the domains perpendicular to the field was higher when the initial domain structure was not maze-like, but consisted of stripes with walls parallel to the field.

4. DISCUSSION

The existing theories[8,9] of domain wall reorientation (which had been observed earlier in iron garnet films at the natural ferromagnetic resonance frequencies[10,11]) in terms of a change in the effective energy of domains and their walls in an oscillating magnetic field **h** failed to account for the modification of the domain structure observed in our study. Firstly, rigorous calculations[9] have been carried out only for frequencies in excess of the ferromagnetic resonance frequency $f_{\rm FMR}$. Secondly, these calculations account for the alignment of the walls only along the field (for $f \approx \gamma H_A$) or only across the field [for $f \approx \gamma (H_A(H_A + 4\pi M_s))^{1/2}$], whereas in our experiments the walls were reoriented twice along mutually perpendicular directions when the field amplitude **h** was increased.

It was suggested in Ref. 1 that the observed reorientation of domain walls at frequencies in the range $f \ll f_{\rm FMR}$ is related to Bloch line creation processes. We shall now explain the reason for this hypothesis. A field perpendicular to the easy axis does not displace walls,[1)] but acts directly on their structure. Essentially, walls parallel to the field should experience remagnetization in the same way as long thin plates with the "easy axis" parallel to the long side by creation and growth of subdomains (sections of a wall with magnetization rotated in opposite directions), i.e., by creation and movement of Bloch lines. In turn, creation and collapse of the lines should increase the effective energy $\sigma_{\rm eff}$ of the walls and the dissipation in the walls. Creation and movement of lines should give rise to a correction to $\sigma_{\rm eff}$, similar to the dynamic contribution to the energy of the walls due to precession of the magnetization in the walls considered in Ref. 9. Moreover, the additional dissipation in the walls[13] is related to the motion of lines and directly to their creation. Domain walls become aligned perpendicular to an alternating field and in this position there is no creation or motion of Bloch lines, so that the effective energy and the losses become less than when domain walls are oriented parallel to the field. If we consider reorientation thermodynamically,[9] then the alignment of domains normal to the field is due to a reduction in $\sigma_{\rm eff}$. On the other hand, it follows from the theory of nonequilibrium processes[14] that such a reorientation corresponds to the tendency of the system to assume a state in which the entropy production rate is minimal, i.e., the losses are minimal. Both approaches justify the orientation of domain walls at right-angles to the oscillating field.

The subsequent reorientation of the walls parallel to the field, which occurs at high field amplitudes, is clearly governed by a reduction in the effective energy of the walls because of the Zeeman contribution, since the domain walls parallel to the field are "conveniently" polarized for a large part of the period (after remagnetization involving creation and rapid motion of Bloch lines).

The characteristic features of the induction response which we observed at field amplitudes causing domain wall reorientation confirm indirectly the proposed model. The appearance and growth of the amplitudes of the higher harmonics of the secondary signal in the case when the domain walls begin to align themselves perpendicular to the field is evidence of the appearance of nonlinear vibrations in the magnetic subsystem. Bearing in mind that when the walls become oriented normally to the field, the amplitudes of the higher harmonics again increase strongly, we can attribute this nonlinearity primarily to changes in the domain structures which take place easily in walls parallel to the field but are hindered in walls perpendicular to the field. The most probable changes are creation, displacement, and collapse of Bloch lines, which alter the polarity of the walls in each half-period of the alternating field. Favorable conditions for the creation and motion of the lines obtain in walls oriented along the field and, by the same token, these processes should not occur in walls normal to the field (if the wall structure is not of the Néel type, which is true of the films investigated here).

This model accounts readily for the absence of harmonics in the signal right up to fields $h_0 \sim H_{c1}$ if the walls in the initial domain structure are already oriented normal to the field, so that line creation is difficult. We can also see why when the initial domain structure has walls parallel to the field, the amplitude of the second harmonic rises before reorientation of the walls to the direction perpendicular to the field ($h_0 \lesssim H_{c1}$), reaching higher values than in the case when the initial structure is maze-like (compare Figs. 4 and 5). Such a change can be ascribed to an increase in the total area of the walls oriented along the field in which the conditions are favorable for line creation processes.

It should be pointed out that the appearance of bends in the walls as they are becoming oriented perpendicular to the field ($h_0 < H_{c1}$) may also be associated with lines whose motion along a wall creates local gyrotropic forces normal to the domain walls.

In fields $h_0 > H_{c1}$ when the walls become reoriented toward the field direction, random bending of the walls and abrupt displacements of domain blocks with different orientations again takes place. The abrupt changes in the induction signal due to these changes in the domain structure are superimposed on the average values of the amplitudes of the higher harmonics (Fig. 4). The increase in the amplitudes of the harmonics is evidence of a new increase in the nonlinearity in the dynamic response of the magnetic subsystem. Since in the case of the walls oriented along the field (for $h_0 \sim H_{c2}$) the amplitudes of the higher harmonics in the signal decrease significantly, we can assume that nonlinear processes are enhanced in the walls normal to the field before reorientation. These processes may be associated with the development of a flexural instability and changes in the structure of the walls from the Bloch to the Néel type, which are known to occur in walls perpendicular to a static field.[15] It should be noted that when the walls are parallel to the field, then strong random vibrations occur in fields $h_0 > H_{c2}$, but the domain structure becomes stabilized as h_0 increases. This behavior is typical of nonlinear systems subjected to strong excitation.[5]

We shall finally consider the reasons for the formation of a peak of the second harmonic at low values of h_0 (Fig. 5) when the walls in the initial domain structure are polarized and oriented along the field. We recall that this peak is observed when domain walls are immobile and the field amplitudes are much less than the anisotropy field, so that the changes in the induction signal are most probably due to changes in the walls. Since in the case of walls perpendicular to the field or parallel to the field but unpolarized, such a peak is not observed, it is natural to attribute this peak (like the one in the preceding section) to creation of Bloch lines in polarized walls. The appearance of these lines, whose creation requires overcoming of a potential barrier, is preceded by nonlinear rotation of the spins in the surface parts of the domain walls, which corresponds to the observed increase in the amplitudes of the higher harmonics. The subsequent growth of Bloch line loops toward the opposite surface of a crystal clearly creates pairs of vertical lines, which now oscillate linearly along the walls under the action of the oscillating field. The linearity of this process is responsible for the fall of the amplitudes of the higher harmonics after passing through their maxima and also for the absence of a peak in the case when a sample is already subjected to a field of amplitude greater than h_0^* corresponding to the peak (i.e., when the walls are already split into subdomains with opposite polarities). These conclusions are supported also by the decrease in the amplitudes of the higher harmonics with time observed when the field amplitude corresponds to the right-hand wing of the peak (whereas at lower values of h_0 the signal is not affected), and also by the shifts of the peak when magnetizing fields are applied in directions that differ relative to the initial polarization of the walls. Moreover, the value of the field amplitude corresponding to the tip of the peak is in good agreement with an estimate of the static field which is directed antiparallel to the wall polarization and is necessary for the creation of a Bloch line[16]:

$$H_{\rm Bl} \approx \frac{\pi\rho}{\tanh \pi\rho} \frac{1}{\pi\alpha} \frac{\Delta H_A}{dQ^{1/2}},$$

where $\rho = d/W$; W is the domain width; $0.21 \leqslant \alpha \leqslant 0.5$; $\Delta = (A/K)^{1/2}$. If $\alpha \sim 0.5$, we obtain $H_{\rm Bl} \sim 3.5$ Oe, which is practically identical with h_0^*. In general, we can expect the conditions for the creation of lines in an oscillating field to differ from the static situation, so that our selection of α needed to fit the observations is in excess of the required precision.

We shall conclude by noting that the experimentally observed width of the maxima of A_2 as well as a certain scatter of the field causing reorientation of domain walls (H_{c1} and H_{c2}) can be attributed to the presence of defects which are known to influence[17] the domain formation fields and, evidently, the processes of line creation.

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[1)]In general, an oscillating field h_y normal to a domain wall exerts a pressure on this wall.[12] However, the pressure $h_y/4\gamma$ is comparable with the pressure created by fields of the same amplitude and parallel to the easy axis ($2Mh$) only when the frequency is $f \gtrsim 4\gamma M/\pi$ (in our case, this happens in the range $f \gtrsim 330$ MHz).

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