Investigation of the dependence of the dynamic properties of domain walls in yttrium iron garnet on the state of their structure

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An optical polarization method was used in a direct experimental study of the change in the nature of motion of 180° domain walls and of Bloch lines in these walls, observed on increase in the amplitude H_0 of a pulsed magnetic field applied parallel to the magnetization vectors of these domains in a crystal of yttrium iron garnet. It was found that in the range of sufficiently low amplitudes ($H_0 \lesssim 20$ mOe) the magnetic field excited free vibrations of domain walls, the inertial properties of which were governed by the Bloch lines present in a wall and moving along elliptic paths under the action of gyrotropic forces. An increase in H_0 altered the nature of motion of domain walls (from vibrations to aperiodic damped motion) and also the behavior of the Bloch walls: unidirectional displacement, creation, and annihilation processes of the lines began. It is suggested that the decisive role in the dynamic transformation of the structure of domain walls is played by nonlinear magnetization waves excited in them by the applied magnetic field. The conditions for creation of one-dimensional domain walls in yttrium iron garnet were achieved for the first time and the dynamic properties of such walls were studied. Flexural vibrations of domain walls were discoverd in an inhomogeneous magnetic field: they traveled at a high velocity (~ 20 km/sec) along such walls. An experimental determination was made of the effective mass (m) and of the viscous friction coefficient (β) of a one-dimensional wall. These values were considerably smaller than m and β for a two-dimensional domain wall containing Bloch lines, but they were still much higher than those calculated from a theory of one-dimensional walls. The possible reasons for the discrepancy between the theoretical predictions and experimental results are analyzed.

It was reported in Refs. 1 and 2 that the measured values of the mobility μ and effective mass m of domain walls in yttrium iron garnet (YIG) differed considerably from those calculated by solving the Landau-Lifshitz equations for a one-dimensional domain wall[3,4]: the difference was between two and three orders of magnitude. Identification of the reasons for such a striking disagreement is essential for solving a number of fundamental problems in dynamics of magnetization of ferromagnetic insulators and their applications in technology. The observed discrepancies may be due to a variety of mechanisms.

One group of reasons originates from the fact that even in the initial static state a 180° domain wall in YIG is not one-dimensional: it contains Bloch lines. Direct experimental studies of the dynamic structure of domain walls in YIG were reported in Refs. 5–7. It was found that under the conditions used in the study of domain wall dynamics the Bloch lines present in the walls are set in motion and the nature of this motion depends strongly on the amplitude of an external magnetic field. In weak fields these Bloch lines exhibit free or forced vibrations near their original equilibrium positions in a wall. The spectrum of amplitudes of the domain wall vibrations includes peaks at the resonance frequencies of the displacement of the Bloch lines, demonstrating their direct influence on the domain wall motion. Under these conditions the Bloch lines exhibit properties typical of magnetic vortices.[8,9] Their motion involves an additional process of dissipation of the energy supplied by an external field to a wall, involving a reduction in μ. The different behavior of the magnetization in a one-dimensional domain wall and that containing Bloch lines is naturally responsible for the difference between the inertial properties of the two kinds of wall.

The other group of reasons for the discrepancy is the presence of nonlinear soliton-type excitations in a system of spins localized in a domain wall, discovered in Refs. 7 and 9. In certain ranges of the amplitudes and frequencies of an external field such excitations are essential elements of the structure of a moving domain wall. They transform the initial structure of the wall, cause unidirectional motion of the existing Bloch lines, generate new lines, etc.

We shall report a systematic study of the dynamics of a one-dimensional domain wall in a weak magnetic field that does not create Bloch lines, motion of a two-dimensional wall containing Bloch lines in similar weak fields, and dynamics of a two-dimensional domain wall in strong fields stimulating dynamic transformation of the wall structure. The aim will be to identify the contributions of the various mechanisms to the anomalies mentioned above.

EXPERIMENTAL METHOD

We investigated plates cut from a YIG single crystal parallel to the (112) plane; they were 40–80 μ thick and were subjected first to mechanical and then to chemical polishing. They were in the form of rectangular prisms strongly elongated along the $[11\bar{1}]$ axis and, therefore, they contained only one or two parallel Bloch walls separating domains with the magnetization lying in the plane of the sample. The

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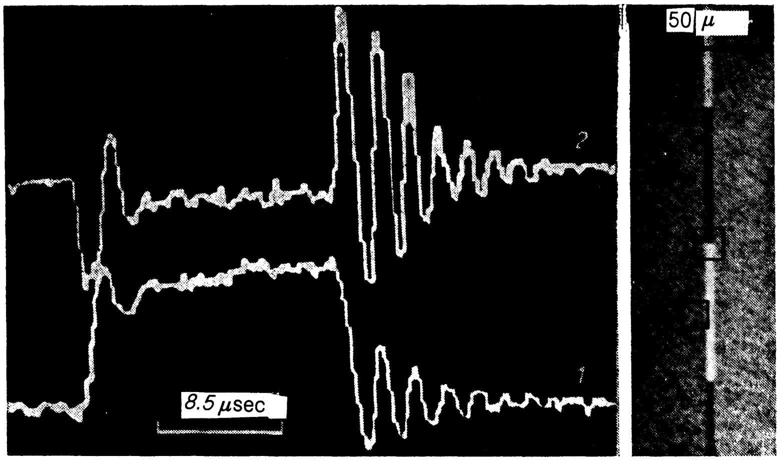

FIG. 1. Free damped vibrations of a domain wall (curve 1) and of a Bloch line (curve 2) induced by a magnetic field pulse H_x of amplitude 22.4 mOe, duration $\tau = 15$ μsec, and repetition period $T = 200$ μsec (the signals were displayed on the screen of a visual display unit after storage in a computer memory). The photograph on the right shows a domain wall with identification of the regions subjected to photometric analysis in recording curves 1 and 2.

Bloch walls were split into subdomains by vertical Bloch lines. A sample of this kind was placed in Helmholtz coils which created a homogeneous magnetic field (**H**) parallel (H_x) or perpendicular (H_z) to the domain magnetization (**M**). A local inhomogeneous field was created by a rectilinear current-carrying conductor placed on the plate at right-angles to the domain walls.[10]

When such a plate was viewed in linearly polarized light it was possible to reveal 180° domain walls because of the Faraday effect: the walls appeared as narrow bright strips between dark domains. A slight uncrossing of the Nicol prisms revealed Bloch lines as boundaries between the bright and dark subdomains (Fig. 1). The motion of Bloch lines along domain walls was studied by selecting the image of a local part of a crystal containing one Bloch line with the aid of a stop and projecting it on the cathode of a photomultiplier producing a signal, proportional to the displacement of the Bloch line, which was recorded using a sampling oscilloscope.[6] In a study of the displacements of a domain wall a rectangular stop selected a part of a crystal which contained part of a domain wall (which had to be less than its width in the middle of a subdomain) and the neighboring domain (Fig. 1). The motion of domain walls over long distances was recorded utilizing the contrast between neighboring domains, which appeared when a sample was inclined and the Nicols in the microscope were slightly uncrossed.[2] The signals representing the Bloch line and domain wall motion were recorded automatically. A MERA SM-3A computer controlled the operation of the sampling oscilloscope (it set the scanning voltage as well as it switched the oscilloscope from the signal measurement regime to the regime of measurement of the magnetic field or calibration of the signal), of the external oscillators, and of various auxiliary units. Moreover, the computer compensated for the slow drift of the output signal and fluctuations of the gain of the apparatus, and at the same time it averaged a large number of measurements (6000–10 000); the computer also carried out mathematical processing and storage of the results.

Nonperiodic displacements of Bloch lines were investigated by the method of recording the photomultiplier signal in real time and using a storage oscilloscope operating in the regime of a single scan or synchronized with a field pulse. The signal reached the oscilloscope input via an integrating RC circuit in order to improve the signal/noise ratio.

EXPERIMENTAL RESULTS

1. The motion of a domain wall to a new equilibrium position in an external magnetic field investigated in Refs. 2 and 5 was aperiodic and damped in fields $H \gtrsim 50$ mOe. It was found that in such fields it caused a considerable transformation of the structure of a domain wall[8,11] because of the directional motion and multiplication of Bloch lines. Therefore, one of our tasks was to investigate the dynamic properties of domain walls and Bloch lines in very weak fields which would not cause any significant changes in the structure of a domain wall.

Figure 1 shows examples of records taken from the screen of a visual display unit showing simultaneously the motion of a domain wall (curve 1) and one of the Bloch lines in the same wall (curve 2), when pulses of a homogeneous magnetic field of amplitude $H_0 = 22.4$ mOe were applied parallel to the magnetization in the domains. Clearly, such a weak pulsed field caused free damped vibrations both in the domain wall and in the Bloch line along it. The frequencies of these vibrations ($\nu_0 = 630$ kHz) and the decay times were practically the same for both the wall and line.

It was remarkable that the nature of the vibrations of the domain wall and Bloch line was different on switching on and off the magnetic field. A study showed that this effect depended on the magnetic field amplitude and became significant only when the off-duty factor (defined as the ratio of the pulse repetition period to the pulse duration) was sufficiently large. We observed oscillograms of free vibrations of a Bloch line initiated by field pulses of different amplitude when the off-duty factor was large (Fig. 2). We found that the nature of the Bloch line vibrations which appeared at both ends of a field pulse were practically the same in the weakest field, but an increase in H_0 resulted in a considerable difference between the vibrations produced by switching on and by switching-off the magnetic field. This difference in the vibrations of a Bloch line at the leading and trailing edges of a field pulse disappeared when the pulse repetition period became equal to twice the pulse duration. Therefore, these

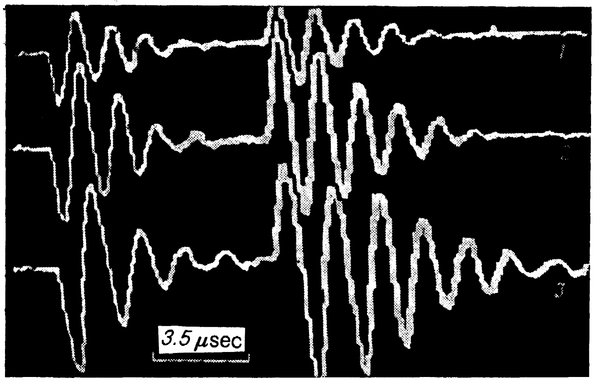

FIG. 2. Free vibrations of a Bloch line initiated by pulses of a magnetic field H_x of different amplitudes: 1) $H_0 = 6.5$ mOe; 2) 9.7; 3) 13.0; $\tau = 7$ μsec, $T = 200$ μsec.

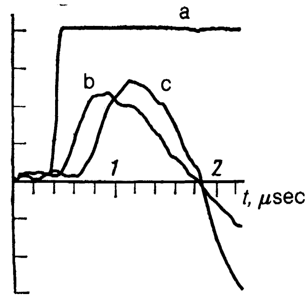

FIG. 3. Time dependences: a) magnetic field step (identifying the onset of the action of both homogeneous and inhomogeneous fields); b) motion of a Bloch line after switching on a homogeneous field; c) motion of a Bloch line after switching on an inhomogeneous field.

results showed that the behavior of both domain walls and Bloch lines depended on the ratio of the times during which they were in each of the two equilibrium positions. The states of a system of spins composing a domain wall and Bloch lines varied with time. As H_0 was reduced, this dependence disappeared because the amplitude of the domain wall or Bloch line vibrations became so small compared with the domain wall or Bloch line thickness that both the equilibrium positions were practically equivalent. This characteristic feature of the aftereffect had not been observed earlier. In the case of YIG it was manifested in the course of an investigation of macroscopic characteristics of doped crystals at sufficiently low temperatures.[12,13] This and the photomagnetic effect[14] were not exhibited by all the investigated samples. We analyzed only the free vibrations which appeared on switching-off the field and these vibrations were practically unaffected by the off-duty factor.

The similarity of the behavior of the domain walls and Bloch lines demonstrated in Fig. 1 was a property of all our samples when the field amplitude was sufficiently low. It was due to the action of gyrotropic forces, first described theoretically in Ref. 15. A Bloch line exhibiting simultaneous vibrations along two mutually perpendicular directions (together with the domain wall and along it) behaves similarly to a magnetic vortex. The action of the gyrotropic force was manifested most clearly in an experiment in which the displacement of a Bloch line along a domain wall was determined also under conditions when an external inhomogeneous field had practically no direct influence on the Bloch line. Such a field was applied to a domain wall by a rectilinear current-carrying conductor located far from a Bloch line: this created local flexural vibrations of the domain wall. The part of the wall located beween the conductor and the investigated Bloch line was transformed into a unipolar state (by a method described in Ref. 10) in order to avoid the magnetostatic interactioin between the lines. Curves b and c in Fig. 3 describe the initial parts of the signals representing the motion of a single Bloch line observed on application of a homogeneous (curve b) or local (curve c) fields to a crystal. A slight apparent delay of the onset of motion of a Bloch line (and the onset of a shift of a domain wall not shown here) relative to the moment of application of a homogeneous field step (curve *a*) was governed by delay of the photomultiplier signal. A significant motion of a Bloch line under the influence of the local field experienced by the domain wall clearly began later and it practically coincided with the onset of motion of the wall near this Bloch line, because of propagation of the flexural vibrations along the wall. This was deduced from measurements, similar to those carried out on a Bloch line (Fig. 3), of local displacements of a domain wall near the conductor and the Bloch line. Therefore, this experiment demonstrated directly that the displacement of a Bloch line along a domain wall was initiated by the gyrotropic force acting on the line during the motion of the wall in the perpendicular direction at the point of location of the line, the motion being due to flexural vibrations of the wall.

A more accurate determination of the velocity of flexural vibrations of a domain wall was studied by passing a sinusoidal current of frequency ν through the conductor and determining, by Fourier analysis carried out on the computer, the phase shift ($\Delta\varphi$) of the main harmonics of the signals of the domain wall vibrations in regions separated by a distance $l = 3$ mm from one another. Figure 4 shows the $\Delta\varphi(\nu)$ dependence obtained in this way. It is clear from this figure that the velocity v_v of flexural vibrations governed by the slope of the $\Delta\varphi(\nu)$ curve was practically independent of the frequency. The value $v_v = 2\pi\nu l/\Delta\varphi \approx 20$ km/sec calculated from the results in Fig. 4 agreed with an estimate obtained

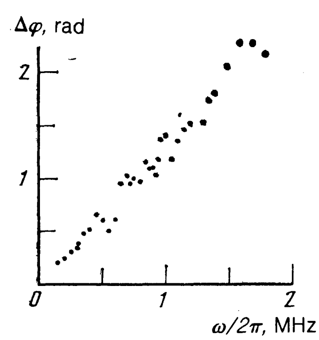

FIG. 4. Frequency dependence of the difference between the phases of harmonic vibrations of a domain wall determined near a current-carrying conductor and at a distance of 3 mm from it.

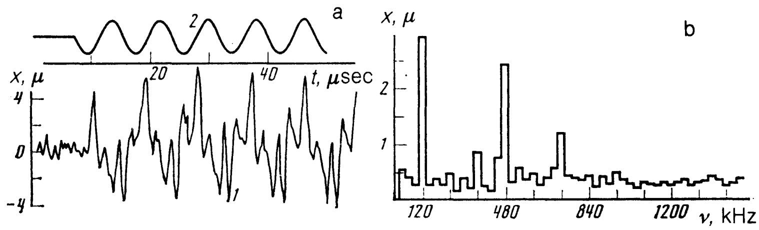

FIG. 5. a) Vibrations of a Bloch line (curve 1) in a domain wall (curve 2) induced by an rf sinusoidal field H_x of $H_x^0 = 22.4$ mOe amplitude. Only the initial parts are shown. b) Fourier analysis of curve 1.

from the delay of the onset of vibrations of a Bloch line in a local field (Fig. 3). This value was much higher than the minimum phase velocity not only of the Winter waves (~ 500 m/sec),[16] but also acoustic waves in YIG.

Flexural vibrations of a domain wall containing a Bloch line were clearly excited also by a homogeneous magnetic field because the natural frequencies of the vibrations of the various Bloch lines in the same domain wall were frequently different.

Experiments involving forced vibrations of a domain wall revealed also excitation of subharmonic resonances of the Bloch line displacement. We plotted in Fig. 5a a typical example of vibrations of a Bloch line (curve 1) along a domain wall vibrating under the action of a sinusoidal field H_x in the form of an rf pulse (curve 2) with a carrier frequency $\nu = 120$ kHz and an amplitude $H_x^0 = 22.4$ mOe. A Fourier analysis of the signal in Fig. 5a was carried out by the computer (Fig. 5b). Clearly, the Bloch line vibrations occurred not only at the frequency of the driving field, but also at multiples of this frequency (including the natural frequency of $\nu_0 = 480$ kHz). Subharmonic resonances were not observed when the ratio ν_0/ν differed strongly from an integer or in weaker fields H_x^0.

2. An increase in the field pulse amplitude enhanced the nonlinear processes of motion in a system of Bloch lines. Figure 6 shows examples of oscillations of two neighboring Bloch lines observed when a crystal was subjected to magnetic field pulses of three different amplitudes. Clearly, in a field of $H_0 = 15$ mOe the free vibrations exhibited by a Bloch line were still nearly harmonic. The vibrations of the neighboring Bloch lines were in antiphase (curves 1 and 1′). An increase in H_0 distorted the Bloch line vibrations more and more from the harmonic form and the Bloch lines began to travel in one direction common to both lines over distances greater than in the opposite direction. This asymmetry of the Bloch-line vibrations increased on increase in H_0 and was the same when the field was switched off and on. A reversal of the field pulse polarity and a change in the duration ($\Delta\tau$) in the range $\Delta\tau \gtrsim 0.3$ μsec had no influence on the direction of the preferential displacement of the Bloch lines, but reversed, naturally, the direction of motion of the domain wall.

A further increase in H_0 made the displacements of Bloch lines irreversible. This was detected using a storage oscilloscope. Figure 7 shows two single oscillograms demonstrating the change in the magnetooptic signal in the course of a short time interval (120 msec) when a crystal was subjected to periodically repeated (every 5 msec) magnetic field pulses. The almost vertical lines in the oscillograms corresponded to the motion of Bloch lines at the moment of application of the field. When the signal intensity decreased with time, a part of a domain wall subjected to a photometric

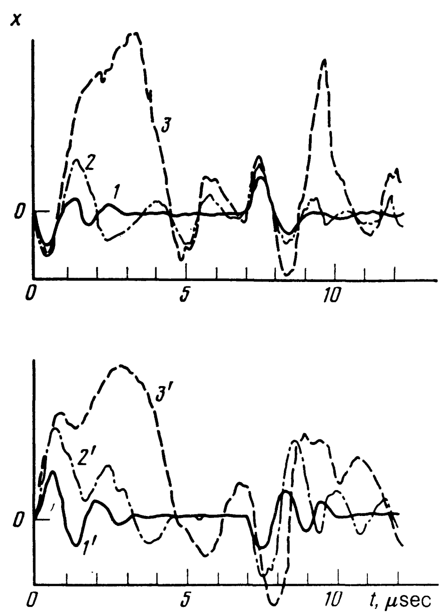

FIG. 6. Free vibrations of neighboring Bloch lines under the action of magnetic field pulses of the following amplitudes H_0 (mOe): 1) 15; 2) 25; 3) 30; $\tau = 7$ μsec, $\nu = 200$ Hz.

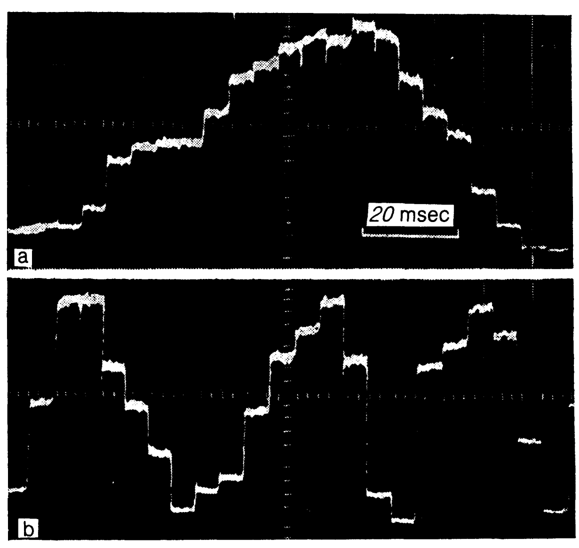

FIG. 7. Single oscillograms obtained using a storage oscilloscope for $H_0 = 0.4$ Oe (a) and 0.5 Oe (b); $\tau = 7$ μsec, $\nu = 200$ Hz.

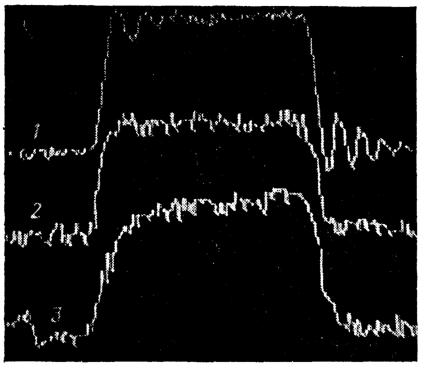

FIG. 8. Motion of a domain wall (containing Bloch lines) under the action of magnetic field pulses of different amplitudes H_0 (mOe): 1) 28; 2) 50; 3) 100; $\tau = 15\,\mu$sec, $T = 200\,\mu$sec.

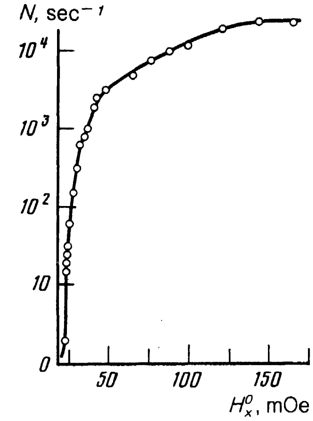

FIG. 10. Number N of nonlinear excitations crossing in 1 sec a region of a unipolar domain wall subjected to a photometric analysis, plotted as a function of the amplitude (H_x^0) of an exciting sinusoidal field of frequency $\nu = 1$ MHz; $H_z = 15$ Oe.

analysis exhibited gradual penetration of a "black" subdomain, whereas an increase in the field with time resulted in penetration of a "white" subdomain. A comparison of these oscillograms showed that an increase in H_0 increased the irreversible displacements of subdomains and of the Bloch lines separating them.

The velocity of the directional motion of a Bloch line during one field pulse reached ~ 5 m/sec, as readily estimated from the second oscillogram (in which the extrema corresponded to the moments of coincidence of the middle of the photometrically measured part of a domain wall with the center of gravity of a white or black subdomain of $\sim 50\,\mu$ size).

Successive photography of a domain wall between the applications of single field pulses showed that Bloch lines in neighboring domain walls shifted irreversibly in opposite directions. The fact that the directional motion of the Bloch lines occurred throughout the action of periodic field pulses was evidence of a simultaneous occurrence of the processes of creation and annihilation of Bloch lines. This unidirectional motion of Bloch lines was similar to the motion induced by a sinusoidal magnetic field in the same crystals.[7,11]

Figure 8 shows examples of the motion of a domain wall when the field pulse amplitudes were close to those in which directional motion began in a system of Bloch lines. The application of a sufficiently weak field in which Bloch lines still vibrated freely about their equilibrium positions, generated also vibrations of domain walls (curve 1) at the same frequency. An increase in H_0 to 100 mOe resulted in a change from free vibrations of a domain wall to aperiodic damped motion (curve 3). Under these conditions the system of Bloch lines already exhibited processes of unidirectional motion, creation, and annihilation.

3. As already reported,[10] a quasi-one-dimensional structure of a domain wall in YIG can be created by the simultaneous application of a sinusoidal field parallel to the magnetization in a domain and a static field H_z applied perpendicular to the plane of the plate, which suppressed creation of new Bloch lines under conditions of undirectional motion of the existing lines. The resultant unipolar domain-wall state was found to be stable also in weak pulsed fields, which made it possible to study for the first time the dynamic properties of such a "one-dimensional" domain wall in YIG. Figure 9 shows examples of free damped vibrations of a domain wall, recorded from the screen of a remote visual display unit, which were initiated by pulses of a homogeneous magnetic field of three different amplitudes. These measure-

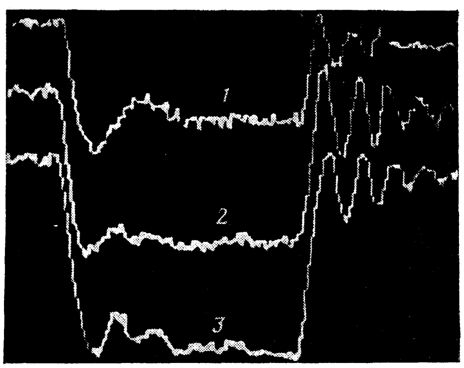

FIG. 9. Motion of a one-dimensional domain wall under the action of magnetic field pulses of different amplitudes H_0 (mOe): 1) 20.2; 2) 22.4; 3) 24.6; $\tau = 4\,\mu$sec, $T = 200\,\mu$sec; $H_z = 18$ Oe.

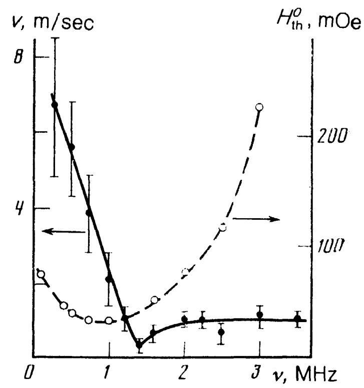

FIG. 11. Frequency dependences of the threshold amplitude (H_{th}^0) of a sinusoidal field above which excitations of soliton waves begin and the velocities (v) of their motion, measured for $H_x^0 = H_{th}^0$; $H_z = 15$ Oe.

ments revealed also a difference between the domain wall vibrations at the moments of switching the field on and off. The frequency of free vibrations of a domain wall at the trailing edge of a pulse was ~ 1.8 MHz, whereas the amplitude increased first on increase in H_0 and then fell. Our investigation indicated that the fall could be due to the onset of excitation of nonlinear perturbations of the magnetic dynamic soliton type in domain walls, as found already experimentally in higher fields H_0 (Refs. 7 and 10).

Figure 10 shows the dependence of the number of such nonlinear excitations per second, in a part of a quasiunipolar domain wall subjected to a photometric analysis, on the amplitude of a sinusoidal field H_x^0. It indicated that only a fivefold change in H_x^0 increased the rate of formation of such nonlinear excitations by four orders of magnitude. These measurements were carried out using not a pulsed but a sinusoidal field, because the perturbations created in the latter case exhibited a continuous unidirectional motion through the part of the domain wall subjected to photometric analysis and could therefore be recorded with the aid of a storage oscilloscope.[7] When the field amplitudes were sufficiently high, such excitations resulted in splitting of domain walls into subdomains, which was accompanied by a change in the nature of the domain wall motion. Figure 11 shows the frequency dependences of the velocity v of nonlinear waves determined at the threshold value of the amplitude of a sinusoidal field (H_{th}^0) in which they began to be excited, obtained under the conditions of consecutive passage of each wave across two light beams.[10] An important point was the absence of a correlation between v and H_{th}^0, although an increase in the field amplitude above H_{th}^0 at a constant frequency increaseed v.

DISCUSSION OF RESULTS

1. The characteristics of dynamic properties of domain walls and Bloch lines performing free vibrations can be determined using the harmonic-oscillator equation

$$m\ddot{\mathbf{r}}+\beta\dot{\mathbf{r}}+\varkappa\mathbf{r}=\mathbf{F}. \qquad (1)$$

The effective mass (m), the viscous friction coefficient (β), and the restoring force coefficient ($\varkappa$), and the external force ($\mathbf{F}$) refer to a unit length of a Bloch line (when the index x will be used), to a unit area of a domain wall (index y), or a whole subdomain (index L). The coefficients $\varkappa_x = 100 \pm 30$ g·cm^{-1}·sec^{-2} and $\varkappa_y = (7.5 \pm 0.5) \times 10^4$ g·cm^{-1}·sec^{-2} ($\varkappa_{yL} = L\varkappa_y \approx 450$ g·cm^{-1}·sec^{-2}) were determined experimentally from static dependences of the coordinates of a Bloch line (x) or a domain wall (y), respectively, on the field H_z or H_x. All the values of m and β for domain walls and Bloch lines obtained in the present study from an analysis of the experimental results using the familiar expression for the frequencies of free vibrations and of the damping decrement of such vibrations are listed in the third, fourth, and seventh lines of Table I. For comparison, the first and second lines give the values of m_y and β_y determined in Ref. 2 from measurements in higher fields.

The third and fourth lines of Table I list the experimental values and show that the presence of a Bloch line in the domain wall increases the wall mass by an order of magnitude and the coefficient β_y by a factor of about 3 compared with the corresponding values for a one-dimensional domain wall. It should be pointed out that the values of m and β of domain walls and Bloch lines determined for different samples can differ considerably (within one order of magni-

TABLE I. Measured and calculated dynamic parameters of Bloch lines and of 180° domain walls containing Bloch lines or free of such lines.

	$m_y = m_{yL}/L$, g/cm^2	$\beta_y = \beta_{yL}/L$, g·sec^{-1}·cm^{-2}	$\mu_y = 2M/\beta_y$, cm·sec^{-1}·Oe^{-1}
Domain wall with Bloch line (two-dimensional domain wall)			
1 $H_x^0 = 1$ Oe (Ref. 2)	$6\cdot10^{-8}$	0.2	$1.4\cdot10^3$
2 $H_x^0 = 50$ mOe (Ref. 2)	$2\cdot10^{-8}$	0.1	$2.8\cdot10^3$
3 $H_x^0 = 20$ mOe	$4.2\cdot10^{-9}$	$4.4\cdot10^{-3}$	$6.3\cdot10^4$
Domain wall without Bloch line (one-dimensional domain wall)			
4 $H_x^0 = 20$ mOe	$6.6\cdot10^{-10}$	$1.2\cdot10^{-2}$	$2.3\cdot10^5$
Two-dimensional domain wall			
5 Calculated from Eqs. (8) and (9)	$4.1\cdot10^{-9}$	$1.6\cdot10^{-4}$ *	$1.5\cdot10^6$
One-dimensional domain wall			
6 Calculated from Refs. (3) and (4)	$6\cdot10^{-11}$	$1.9\cdot10^{-4}$	$1.5\cdot10^6$
	m_x, g/cm	β_x, g·sec^{-1}·cm^{-1}	$\mu_x = 2M\delta/\beta_x$, cm·sec^{-1}·Oe^{-1}
7 Bloch line (exper.), $H_0 = 20$ mOe	$6\cdot10^{-12}$	$3.6\cdot10^{-6}$	$0.8\cdot10^4$
8 Bloch line [calc. from Eqs. (8) and (9)]	$5.5\cdot10^{-12}$	$2\cdot10^{-7}$	$1.4\cdot10^5$

*If β_y is calculated using the value $\delta \approx (A/K)^{1/2} \sim 0.08\,\mu$ (as in the case of a one-dimensional domain wall), then the value 3.3×10^{-4} g·sec^{-1}·cm^{-2} is obtained.

tude). Smaller differences are sometimes observed between the parameters of different parts of the same domain wall. However, in all cases the values of m_y and β_y for a domain wall decreased considerably when a Bloch line is removed.

We shall allow for this influence of a Bloch line on the dynamic properties of a domain wall by considering a two-dimensional wall moving under the action of gyrotropic forces. We shall use an approach developed in Refs. 17 and 9, but in the general balance of the forces we shall include energy dissipation and simultaneous action of time-dependent fields $H_x(t)$ and $H_z(t)$ affecting the positions of equilibrium of a domain wall and a Bloch line. We shall consider a plate of thickness h and a region of a rigid domain wall of length equal to the average size L of subdomains containing one Bloch line. The equation for the balance of the forces governing the motion is[15]

$$\mathbf{F}_G+\mathbf{F}_D+\mathbf{F}_S=0. \tag{2}$$

The gyrotropic force is

$$\mathbf{F}_G=\frac{1}{h}\int[\dot{\mathbf{g}}\mathbf{r}]d^3\mathbf{r}=\frac{2\pi M}{\gamma}[\mathbf{k}\dot{\mathbf{r}}], \tag{3}$$

where $\mathbf{g}=(M/\gamma)[\sin\theta\nabla\psi\nabla\theta]$; γ is the gyromagnetic ratio; $\mathbf{k}$ is a unit vector along the z axis; θ and ψ are the polar and azimuthal angles representing the direction of the vector $\mathbf{M}$ in a domain wall and a Bloch line. The force due to the dissipative effects is

$$\mathbf{F}_D=\frac{1}{h}\int\hat{\mathbf{d}}\dot{\mathbf{r}}\,d^3\mathbf{r}, \tag{4}$$

where

$$\hat{\mathbf{d}}=-\alpha(M/\gamma)[(\nabla\theta)(\nabla\theta)+\sin^2\theta(\nabla\psi)(\nabla\psi)];$$

α is the dissipation parameter in the Landau-Lifshitz-Gilbert equation.[3] The conservative force is

$$\mathbf{F}_S=(2MH_z\delta-\varkappa_x x)\mathbf{i}+(2MH_xL-\varkappa_{yL}y)\mathbf{j}, \tag{5}$$

where $\mathbf{i}$ and $\mathbf{j}$ are unit vectors along the x and y axes, respectively. The first set of parentheses in Eq. (5) describes the forces acting directly on a Bloch line along the x axis, whereas the second set of parentheses contains similar forces acting along the y axis on a selected part of a domain wall with a Bloch line.

We shall calculate the integral in Eq. (4) using the domain-wall structure described by the expressions[18]

$$\frac{d\theta}{dy}=\frac{\sin\theta}{\delta}\quad \text{и}\quad \frac{d\psi}{dx}=\frac{\sin\psi}{\Lambda} \tag{6}$$

[where $\Lambda=(A/2\pi M^2)^{1/2}$ and A is the exchange-interaction constant], and we shall make use of the following boundary conditions:

$$\theta(-\infty)=0,\quad \theta(+\infty)=\pi,$$
$$\psi(-\infty)=-\pi,\quad \psi(+\infty)=0. \tag{7}$$

Using Eqs. (2), assuming the distribution of the magnetization to be plane (i.e., $\partial\theta/\partial z=\partial\psi/\partial z=0$), and applying Eqs. (3)–(7), we obtain two equations of second order for the motion along x and y:

$$m_x\ddot{x}+\beta_x\dot{x}+\varkappa_x x=F_x, \tag{8}$$

$$m_{yL}\ddot{y}+\beta_{yL}\dot{y}+\varkappa_{yL}y=F_{yL}, \tag{9}$$

where

$$m_x=\frac{1}{\varkappa_{yL}}\left(\frac{2\pi M}{\gamma}\right)^2\left[1+\frac{2L\alpha^2}{\Lambda\pi^2}\right],$$

$$\beta_x=\alpha\frac{2ML}{\gamma\delta}\left(1+\frac{\varkappa_{yL}}{\varkappa_x}\frac{2\delta^2}{\Lambda L}\right)\frac{\varkappa_x}{\varkappa_{yL}}, \tag{8a}$$

$$F_x=2MH_z\delta+\alpha\frac{4M^2\dot{H}_zL}{\gamma\varkappa_{yL}}-\frac{4\pi M^2\dot{H}_xL}{\gamma\varkappa_{yL}},$$

$$m_{yL}=\frac{1}{\varkappa_x}\left(\frac{2\pi M}{\gamma}\right)^2\left[1+\frac{2L\alpha^2}{\Lambda\pi^2}\right],$$

$$\beta_{yL}=\alpha\frac{2ML}{\gamma\delta}\left(1+\frac{\varkappa_{yL}}{\varkappa_x}\frac{2\delta^2}{\Lambda L}\right), \tag{9a}$$

$$F_{yL}=2MH_xL+\alpha\frac{8M^2\dot{H}_x\delta L}{\gamma\Lambda\varkappa_x}-\frac{4\pi M^2\dot{H}_z\delta}{\gamma\varkappa_x}.$$

These expressions for m_x and m_y differ from those obtained in Refs. 9 and 17, derived ignoring energy dissipation, only by an additional factor in the square brackets. The effective viscosity of a two-dimensional domain wall is $[1+(\varkappa_{yL}/\varkappa_x)(2\delta^2/\Lambda L)]$ times greater than the viscosity of a one-dimensional wall.[18] The values of the coefficients in Eqs. (8) and (9) calculated using the parameters $\alpha=10^{-4}$ (deduced from FMR measurements[2]), $M=139$ G, $A=4.2\times10^{-7}$ erg/cm, $\gamma=1.8\times10^7\,\text{Oe}^{-1}\cdot\text{sec}^{-1}$, $L=60\,\mu$ (deduced from a photograph of a domain wall in Fig. 1), and $\delta=1\,\mu$ (close to the experimental value given in Ref. 19), are listed in Table I (fifth and eighth lines).

The good agreement between the calculated and measured values of the effective mass in the case of Bloch lines and domain walls justifies the use of the quasisteady approximation[18] for the description of free vibrations of both lines and walls and shows that the inertial properties of two-dimensional domain walls and Bloch lines are indeed governed by a specific manifestation of the gyrotropic forces. A contribution made by the Döring mass[4] to m_y is approximately two orders of magnitude less than the "gyrotropic" contribution, as shown in Table I (sixth line). The inertial effect of a domain wall is therefore practically entirely determined by the Bloch lines that it contains and the anisotropy of the Bloch line mass for the motion along two mutually perpendicular directions is governed, as demonstrated by Eqs. (8) and (9), by the ratio of the coefficients $\varkappa_{yL}/\varkappa_x=m_x/m_{yL}$. It also follows from Eqs. (8) and (9) that the Bloch line moves along an elliptic path and the natural frequency of such vibrations,

$$\omega_0=(\varkappa_x/m_x)^{1/2}=(\varkappa_{yL}/m_{yL})^{1/2}\approx(\gamma/2\pi M)(\varkappa_x\varkappa_{yL})^{1/2}=4.2\text{ MHz},$$

is in good agreement with the measured value ($2\pi\nu_0\approx4.1$ MHz).

Equations (8) and (9) also make it possible to derive expressions for the amplitudes of initial vibrations of Bloch lines and domain walls in pulsed fields H_x:

$$x^0=2MH_xL/(\varkappa_x\varkappa_{yL})^{1/2}, \quad y^0=2MH_xL/\varkappa_{yL} \tag{10}$$

and in fields H_z:

$$x^0=2MH_z\delta/\varkappa_x, \quad y^0=2MH_z\delta/(\varkappa_x\varkappa_{yL})^{1/2}. \tag{11}$$

It follows from these expressions that the amplitude of vibrations of a Bloch line along a domain wall in a field H_x is governed by the potential relief for the simultaneous motion along two mutually perpendicular directions. Similarly, the motion of a Bloch line along a domain wall in a field H_z affects in turn, because of the action of a gyrotropic force, the value of y^0. The ratio

$$H_z/H_x=(L/\delta)(\varkappa_x/\varkappa_{yL})^{1/2},$$

of the amplitudes deduced from Eqs. (10) and (11) and causing displacements of a Bloch line or a domain wall by equal distances, is much greater than 1 (≈ 30). This makes it possible to explain the greater effect of a field H_x than of H_z on Bloch lines, discovered and reported in Ref. 6. It should be pointed out that the potential relief for the motion of domain walls and Bloch lines, which depends on the crystal lattice defects, affects also the characteristic features of the dynamic properties of domain walls and Bloch lines [see Eqs. (8) and (9)], which may be the main reason for the scatter of the measured values of m and β mentioned above.

The calculated values of the viscosity coefficients of domain walls and Bloch lines agrees less well with the experimental values. One of the reasons is that the integral (4) depends strongly on the actual distribution of spins in a domain wall with Bloch lines. This distribution is not known for crystals with $Q < 1$ and, therefore, in these calculations we used a model of the domain wall structure and assumed $\delta = 1\ \mu$ from the experimental data. This circumstance should also be borne in mind in a comparison of these calculated results with theoretical predictions for a one-dimensional domain wall, when the domain wall width δ_0 is assumed to be $(A/K)^{1/2} \approx 0.08\,\mu$, in accordance with Ref. 3. The contribution of the integral (4) to the expression for the mass of a domain wall and a Bloch line is negligible [it is governed by the value of the terms in the square brackets in Eqs. (8) and (9), which is of the order of unity], and the integral (3) dominating the value of m depends mainly on the known and finite angle of rotation of spins in a domain wall.

These calculations also ignore the anharmonic effects which are known to occur in a nonlinear system of spins localized in a domain wall. They can be detected experimentally from resonances prior to the dynamic transformation of the domain wall structure. Moreover, both moving Bloch lines and inhomogeneities of the potential relief may stimulate flexural vibrations and these in turn can alter the viscosity because of an additional energy dissipation channel of a moving domain wall.

2. As the amplitude of the external field is increased, the intensities of nonlinear processes become stronger. Under these conditions the essential elements of the domain wall structure are nonlinear soliton-type waves which play in particular a decisive role in the processes of their transformation.[7,10] Their formation may occur because of the transfer of energy from a domain wall to a magnon subsystem, giving rise to coupled magnon states in the form of magnon drops or magnetic dynamic solitons,[20] the eventual transformation of which into subdomains alters the density of Bloch lines[7] and, consequently, of the values of m_y and β_y. The processes of Bloch line creation and annihilation accompanying their unidirectional motion also require additional energy losses[21] and consequently may be responsible for the observed rise of β and m on increase in H.

3. These investigations of a quasi-one-dimensional domain wall have made it possible to determine the dynamic parameters m and β, which are about an order of magnitude greater than the corresponding values calculated from a theory of a one-dimensional wall using the dissipation parameter α deduced from FMR measurements. One of the reasons for this discrepancy may be the difference between the structure of an investigated domain wall from one which is strictly one-dimensional and this may be partly due to the influence of the surface of a sample on the distribution of the magnetization in domain walls.[22] An additional contribution to the energy losses in a moving domain wall, ignored in the theory of Ref. 3, is an inhomogeneous exchange interaction[23] which occurs in the system of spins forming a wall. However, estimates of Bar'yakhtar[23] indicate that this can alter the parameter α only by a factor of 2, which is insufficient to account for the observed discrepancy.

It seems to us that the relatively high value of β for a quasi-one-dimensional domain wall obtained in our experiments is mainly due to the loss of energy as a result of nonlinear excitations in the system of spins localized in a domain wall, which in the case of a slight increase in the field amplitude are already manifested experimentally and result in a dynamic transformation of the domain wall structure.

CONCLUSIONS

It therefore follows that direct experimental investigations of the behavior of Bloch lines in a moving domain wall can account for the large discrepancy between the dynamic characteristics of domain walls in YIG and those calculated on the basis of a one-dimensional model, which ignores the presence of Bloch lines.[1,2] At least in sufficiently weak magnetic fields the inertial effect of such a two-dimensional domain wall, which is responsible in particular for its free damped vibrations, is almost entirely due to Bloch lines moving in accordance with the laws derived for magnetic vortices. However, the measured mobility and mass of a domain wall in higher fields are not described by the linear approximation even when an allowance is made for Bloch lines. The reason for this is the existence, observed experimentally, of strongly nonlinear excitations of the spin system which becomes stronger on increase in the field and alter radically the nature of motion of both Bloch lines and domain walls.

Some of the effects described here relating to the change in the nature of motion of domain walls on increase in the amplitude of an external magnetic field (change from free vibrations to aperiodic damping,[21,24] disappearance of a resonance of domain wall displacements[25]) have already been observed in uniaxial garnet films. They are explained on the basis of a hypothesis that the motion of a domain wall becomes unsteady when a certain critical value of the field (Walker field) is exceeded or because of the appearance and motion of Bloch lines in a domain wall in accordance with the Slonczewski mechanism. In the cited papers the conclusion about the presence or absence of Bloch lines in a domain wall has been made only on the basis of an analysis of the behavior of the walls themselves.

However, direct observations reported above show that even when a Bloch line is present right from the beginning the nature of the motion of a domain wall may change on increase in the field amplitude. This occurs because of nonlinear excitations in the spin system, responsible for a dynamic transformation of the structure of a domain wall and for the energy dissipation in the course of its motion. Therefore, a systematic description of the motion of a domain wall, both one-dimensional or containing Bloch lines, should allow for the mechanisms that determine the loss of energy by a moving domain wall due to the excitation of its spin system, formation of nonlinear solitary waves (solitons), and influence of such waves on the dynamic transformation of the domain wall structure.

[1]F. B. Hagedorn and E. M. Gyorgy, J. Appl. Phys. **32**, 282S (1961).
[2]L. M. Dedukh, V. I. Nikitenko, and A. A. Polyanskiĭ, Zh. Eksp. Teor. Fiz. **79**, 605 (1980) [Sov. Phys. JETP **52**, 306 (1980)].
[3]L. D. Landau and E. M. Lifshitz, Phys. Z. Sowjetunion **8**, 153 (1935).
[4]W. Döring, Z. Naturforsch. Teil A **3**, 373 (1948).
[5]L. M. Dedukh. V. I. Nikitenko, A. A. Polyanskiĭ, and L. S. Uspenskaya, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 452 (1977) [JETP Lett. **26**, 324 (1977)].
[6]V. S. Gornakov, L. M. Dedukh. Yu. P. Kabanov, and V. I. Nikitenko, Zh. Eksp. Teor. Fiz. **82**, 2007 (1982) [Sov. Phys. JETP **55**, 1154 (1982)].
[7]V. S. Gornakov, L. M. Dedukh, and V. I. Nikitenko, Zh. Eksp. Teor. Fiz. **86**, 1505 (1984) [Sov. Phys. JETP **59**, 881 (1984)].
[8]L. M. Dedukh. V. I. Nikitenko, and É. B. Sonin, Usp. Fiz. Nauk **145**, 158 (1985) [Sov. Phys. Usp. **28**, 100 (1985)].
[9]A. V. Nikiforov and É. B. Sonin, Pis'ma Zh. Eksp. Teor. Fiz. **40**, 325 (1984) [JETP Lett. **40**, 1119 (1984)].
[10]V. S. Gornakov, L. M. Dedukh, and V.I. Nikitenko, Pis'ma Zh. Eksp. Teor. Fiz. **39**, 199 (1984) [JETP Lett. **39**, 236 (1984)].
[11]L. M. Dedukh, V. I. Nikitenko, and V. T. Synogach, Fiz. Tverd. Tela (Leningrad) **26**, 3463 (1984) [Sov. Phys. Solid State **26**, 2083 (1984)].
[12]R. P. Hunt, J. Appl. Phys. **38**, 2826 (1967).
[13]A. Broese van Groenou, J. L. Page, and R. F. Pearson, J. Phys. Chem. Solids **28**, 1017 (1967).
[14]L. M. Dedukh and V. V. Ustinov, Fiz. Tverd. Tela (Leningrad) **17**, 2594 (1975) [Sov. Phys. Solid State **17**, 1727 (1975)].
[15]A. A. Thiele, Phys. Rev. Lett. **30**, 230 (1973); J. Appl. Phys. **45**, 377 (1974).
[16]J. M. Winter, Phys. Rev. **124**, 452 (1961).
[17]W. Jantz, J. C. Slonczewski, and B. E. Argyle, J. Magn. Magn. Mater. **23**, 8 (1981).
[18]A. P. Malozemoff and J. C. Slonczewski, Magnetic Domain Walls in Bubble Materials, Suppl. No. 1 to Appl. Solid State. Sci., Academic Press, New York, 1979 (Russ. Transl., Mir, M., 1982).
[19]V. K. Vlasko-Vlasov, L. M. Dedukh, and V. I. Nikitenko, Zh. Eksp. Teor. Fiz. **71**, 2291 (1976) [Sov. Phys. JETP **44**, 1208 (1976)].
[20]A. M. Kosevich, Fiz. Met. Metalloved. **53**, 420 (1982).
[21]B. E. MacNeal and F. B. Humphrey, J. Appl. Phys. **50**, 1020 (1979).
[22]A. Hubert, Z. Angew Phys. **32**, 58 (1971).
[23]V. G. Bar'yakhtar, Zh. Eksp. Teor. Fiz. **87**, 1501 (1984) [Sov. Phys. JETP **60** 863 (1984)].
[24]F. H. de Leeuw and J. M. Robertson, J. Appl. Phys. **46**, 3182 (1975).
[25]B. E. Argyle, W. Jantz, and J. C. Slonczewski, J. Appl. Phys. **54**, 3370 (1983).

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