Dynamics of Bloch lines in yttrium iron garnet

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The behavior of Bloch lines (BL) in 180-degree domain walls (DW) in monocrystalline plates of yttrium iron garnet is investigated by a magnetooptical method, as it depends on the frequency, amplitude, and direction of the external magnetic field. The effective mass ($\sim 1\cdot 10^{-10}$ g/cm) and mobility (~ 350 cm/sec·Oe) of the BL are determined. It is shown that resonance displacement and free oscillations of the BL are excited by a field acting either normal to the direction of the magnetization in the domains or parallel to it, when motion of the DW itself, characterized by a relaxation spectrum of oscillations, occurs simultaneously. It is established that the rotation of the spins in all the BL on transition from subdomain to subdomain, in each DW, occurs, as a rule, in a single direction. In the frequency dependence of the amplitudes of oscillation of the DW, peaks are detected, which are due to resonance displacement of BL. The phenomenon of reproduction of BL in an alternating field, parallel to the direction of the magnetization in the domains, is observed and studied.

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1. INTRODUCTION

The phenomenon of dynamic reconstruction, in an external magnetic field, of the structure of a domain wall in a ferromagnet, including the generation, motion, and annihilation of Bloch lines (BL), began to be considered in the theory of magnetism comparatively recently.[1] The development and active use of ideas about these effects was stimulated by investigations of the mobility of cylindrical magnetic domains, used as carriers of information in new computer memory elements on the basis of magnetically uniaxial garnet plates. It seemed possible to explain the experimental data on mobility of domain walls in these materials only on the basis of an assumption regarding the existence in domain walls of horizontal and vertical BL, free to move, reproduce, annihilate, and accumulate during displacement of the whole Bloch wall.[2]

At present, practically nobody questions the statement that processes of dynamic transformation of the domain wall structure can exert a decisive influence on the values of their mobility and limiting velocity of motion, on the "ballistic" effects, etc.[3,4] So far, however, it has not been possible in garnet films to carry out a direct experimental study not only of the dynamic reconstruction of the Bloch wall structure, but also of its static state. Because of difficulties in principle, investigation of the fine structure of domain walls in these materials by the most used and most highly developed magnetooptic methods proves impossible.

Such possibilities open up in the investigation of single crystals of another type, multiaxial ferrimagnetic garnets,[5,6] in which the dynamics of Bloch walls likewise does not lend itself to description on the basis of a one-dimensional model of the wall, but requires for its explanation the introduction of information about the three-dimensional distribution of spins in a moving wall.[7,8] The authors[9-11] succeeded in performing a direct measurement of the displacement of BL in a domain wall in yttrium iron garnet and in obtaining the first information about their dynamic properties. We present below the results of further development of these investigations, directed toward the determination of the basic dynamic parameters of BL and the establishment of the laws governing the change of structure of a domain wall that results from generation and annihilation of BL under the action of a magnetic field.

2. EXPERIMENTAL METHOD

The investigations were made on plates of yttrium iron garnet, cut along crystallographic planes (112) and (110) from single-crystal bars of $Y_3Fe_5O_{12}$ grown from solution in the melt. After cutting and mechanical and chemical polishing, the plates had thickness 30–60 μm. They contained alternating neighboring domains of 180-degree, magnetized in the plane of the specimen.

As is well known,[5,6] 180-degree domain walls in such specimens already contain, even in the static state, "vertical" BL, normal to the surface of the plate, which arise under the action of the demagnetizing field produced by magnetic surface charges. The BL are transitional regions between subdomains— sections of a domain wall with opposite directions of rotation of the spins. The presence in a given wall of components of the magnetization **M** perpendicular to the plate surface, which at the same time are antiparallel in adjacent subdomains, creates a possibility of revealing them in linearly polarized light on the basis of the Faraday effect. In observation of such a plate in a polarizing microscope (with slightly uncrossed nicols) in the direction perpendicular to its plane, the BL reveal themselves as boundaries between light and dark subdomains[9,10] (see also Figs. 7–9).

The image of a section of such a wall, containing a single BL, was bounded by a rectangular diaphragm, as is shown in Fig. 1a (dashes), and was projected on the photocathode of a photoelectronic multiplier for measurement of the value of the change (ΔI) of intensity of the light coming along the wall during motion of the BL. The value of ΔI under the conditions of the experiment was proportional to the displacement x of the BL. Calibration of the photoelectric signal was accomplished by direct measurements of the displacements x by means of a micrometer ocular. The dimensions of the diaphragm were chosen to be the best for establishment of

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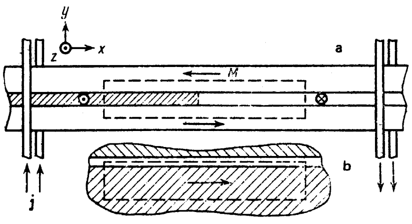

FIG. 1. Arrangement of conductors with current j in relation to a domain wall during local action on a single BL by a field H_z, and schematic representation of a section of the crystal (bounded by dashes) projected on the photocathode of the photomultiplier during measurement of displacements of BL (a) or of the domain wall (b). The darker regions are hatched.

maximum signal/noise ratio.

For automatic recording, the signal from the photomultiplier was fed to the vertical axis of an N306 xy recorder through one channel of an S7-12 stroboscopic oscillograph. Along the horizontal axis of the recorder was recorded, depending on the problem to be solved, a voltage proportional to the value of the magnetic field H, the frequency ν of its variation, or the time t. In investigation of the motion of the BL in time, $x(t)$, the quantity fed to the horizontal axis was the time sweep signal of the stroboscopic oscillograph; in measurement of the frequency dependence of the amplitude of the BL displacement, $x_0(\nu)$, it was the frequency-sweep voltage of the generator (for frequency sweeping of the G6-28 generator, a G6-15 generator was used); in the latter case, the signal from the photomultiplier entered the vertical axis of the recorder through a V3-39 amplifier. The dependence of the BL displacement on the value of a quasistatic magnetic field, $x(H^{st})$, was recorded in the pulsed mode of motion of the BL (by use of a G5-54 generator). For this purpose, the value of the magnetic field pulse was recorded along the horizontal axis of the recorder, through the second channel of the stroboscopic oscillograph, and the recording of $x(H^{st})$ was carried out by the system automatically in each period of action of the field, solely at the instant of complete stopping of the BL.

Displacement of BL along the domain wall was induced by the action of an external magnetic field, which was produced by various methods. A uniform field was formed by Helmholtz coils with a diameter exceeding by more than a factor three the maximum dimension of the plates being investigated in these coils. For magnetization of a local section of the domain wall, containing a single BL, a system of two pairs of parallel conductors was used, directly in contact with the plate from two sides (Fig. 1). Such conductors, when current passes through them in the directions shown in Fig. 1, produce a magnetic field characterized by only two nonvanishing components ($H_y = 0$).

The variation of the component H_z in the space between the conductors, on the path of motion of the BL ($|x| \leq 30\ \mu$m), does not exceed ~2%. The maximum value of the field component H_x is several times smaller than H_z. Furthermore, H_x, varying smoothly in value over the space, vanishes along two mutually perpendicular planes located midway between the conductors. On passage across them, H_x reverses its direction; it therefore produces no resultant force for motion of the domain wall as a whole. Beyond the limits of the space included between the conductors, both components of the field drop rapidly, with increasing distance from them, to negligibly small values. For production of a local field in the direction of the x axis (see Fig. 1), the same system of four conductors, rotated about the y axis through 90°, was used.

Monitoring of the displacements of the domain wall itself was accomplished with the microscope nicols completely crossed, and with location of the domain wall at the edge of the photometered section of the crystal (Fig. 1b). Under these conditions, as is seen from Fig. 1b, displacement of the BL separating two subdomains of similar tint does not lead to a change of the recorded photomultiplier intensity. The latter occurred only during oscillations of the domain wall. This method made it possible to increase the sensitivity of the apparatus to a change of displacement of the wall through small distances by an order of magnitude as compared with the previous paper.[8]

3. EXPERIMENTAL RESULTS

1. *Motion of Bloch lines.* Measurements of free and forced oscillations of a large number of BL showed that the amplitude of their oscillations and the frequency of the resonance displacement depend on the conditions of the experiment and, in particular, on the degree of perfection of the crystalline structure of the magnet, the direction and magnitude of the external magnetic field, and the dimensions of the subdomains in the domain wall. The nonuniformity of the potential-energy contours (caused by defects of the crystal lattice) for BL motion and the connectedness of the BL system, caused by the presence of magnetostatic demagnetizing fields, led to the result that under conditions of free oscillations, excited by a uniform external magnetic field, each BL often oscillated asynchronously with the other BL and moved in time according to a law dependent on the magnitude and direction of the external field and on the location of the BL in the crystal. In forced oscillations of BL, besides the nonuniformity and anharmonicity of their motion, there was observed also a displacement of the equilibrium positions near which they oscillated. Furthermore, irreversible changes of the substructure of the domain wall, occurring often at definite amplitudes of the field, were accompanied by changes in time of the character of the motion of the BL.

The most stable results, and the most repeatable from experiment to experiment, could be obtained by acting locally on only a single BL by means of the system of four conductors described above, arranged perpendicular to the only domain wall in the crystal, in such a way that only a single BL was located between them. Then effective action on the chosen BL only was insured when the distance between the two pairs of conductors was considerably smaller than the dimensions of the subdomains.

An example of the variation of the amplitude x_0 of

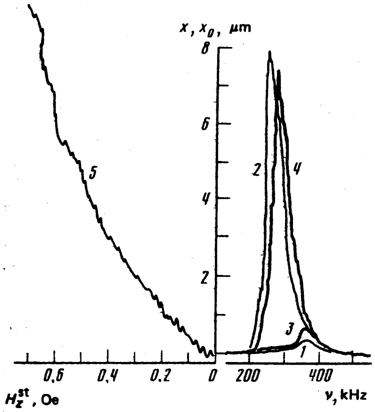

FIG. 2. Resonance of amplitude (x_0) of BL displacement in sinusoidal fields H_z (1,2) and H_x (3,4), and dependence of the displacement x of this same BL on the value of the quasistatic field H_z^{st} (5). 1) $H_z = 75$; 2) $H_z = 150$; 3) $H_x = 6$; 4) $H_x = 7.5$ mOe.

forced oscillation of a BL located between such conductors with the frequency ν of a sinusoidal field H is shown in Fig. 2. These measurements were made on a rectangular (112) plate, greatly elongated along the easy axis of magnetization $[11\bar{1}]$, so that it contained only two neighboring 180-degree domains, the wall between which was parallel to the $(1\bar{1}0)$ plane. A solitary domain wall was chosen in order to exclude interaction between BL located in neighboring walls.

As is seen from Fig. 2, resonance displacement of the BL is excited at practically the same frequencies for two different orientations of the magnetic field: perpendicular to the magnetization **M** in the domains, H_z (Curves 1 and 2), and acting along **M** in the domains, H_x (Curves 3 and 4). But the field amplitudes H_z and H_x that produce displacement of the BL over the same distances differ from each other by more than an order of magnitude. The resonance displacement of the BL appeared on attainment of a certain threshold value of the field (at $H_z \gtrsim 70$ or $H_x \gtrsim 5$ mOe) and increased sharply with increase of its amplitude; and the peak on the $x_0(\nu)$ curve shifted slightly toward the lower-frequency region. At large BL displacements, there often occurred an irreversible change of the substructure of the domain wall.

Although in local action on a single BL it was possible to obtain more symmetric $x_0(\nu)$ curves, in comparison with data from measurements with coils made of wire small in comparison with the specimen diameter[9] and with Helmholtz coils,[11] nevertheless BL motion in time, stimulated by a sinusoidal field and observed in the record of the curves of Fig. 2, was anharmonic. But the frequency of the forced oscillations of the BL was equal to the frequency ν of the field. The $x_0(\nu)$ curves recorded for forward and backward directions of change of the value of ν coincided. Measurement of the BL displacements in time showed, furthermore, that in the process of change of ν, passage through the resonance frequency, as was to be expected, was accompanied by a change of phase of the forced BL oscillation by the amount π.

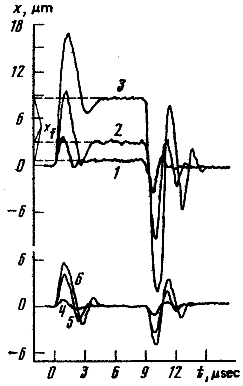

FIG. 3. Free BL oscillations excited by rectangular pulses of local fields H_z (1–3) and H_x (4–6) of duration 9 μsec. 1) $H_z = 300$; 2) $H_z = 500$; 3) $H_z = 700$; 4) $H_x = 8$; 5) $H_x = 15$; 6) $H_x = 20$ mOe.

Figure 3 shows examples of the motion of this same BL in time, when a rectangular pulse of current of duration 9 μsec passed through the conductors, producing local fields H_z (Curves 1–3) or H_x (Curves 4–6). It is seen that free oscillations of the BL, attenuating rapidly in time, occur at the instants of turning on ($t = 0$) and turning off ($t = 9$ μsec) either of the field H_z or of the field H_x. The frequencies of BL oscillations initiated by the fields H_z and H_x are found to be approximately the same; they increase slightly with decrease of the field amplitudes and are close to the value of the resonance frequency. $\nu_r \approx 375$ kHz, measured in forced motion of the BL in a sinusoidal field (H_z or H_x) of minimal amplitude.

In pulsed fields, there is observed yet another difference between the effects of H_z and H_x on the BL. It is evident that while H_z produces oscillations of the BL and in the end shifts it to a new equilibrium position $x = x = x_f$, dependent on the field amplitude, the field H_x only produces free oscillations of the BL with respect to the original position $x = 0$. Near $x = x_f$ there is a more rapid damping of the BL oscillations induced by the field H_z than near $x = 0$. When the field is turned off, the BL begins to move in the direction opposite to its displacement at the instant of application of the field.

Displacement of the BL from the equilibrium position under the action of any external force obviously leads to an increase of the demagnetizing field H_z^d of the domain wall by the amount $\Delta H_z^d = kx/2M\Delta_0$ (k is a coefficient of proportionality, Δ_0 is the wall-width parameter), which at each instant of motion of the BL determines an elastic force $F = kx$, restoring it toward the original position, and in the static state compensates the external H_z. The measured dependence of the displacement x of this BL on the value of the external quasistatic field H_z^{st}, shown in Fig. 2 (Curve 5), shows that under the conditions of the experiment, the value of k was not constant. Near $x = 0$ the values of k and therefore also of F exceeded the values corresponding to $x = x_f$ and, apparently, thereby caused the difference of behavior noted of the BL near the original and the displaced equilibrium positions. With sharply expressed nonlinearity of the $x(H_z^{st})$ relation, free oscillations of

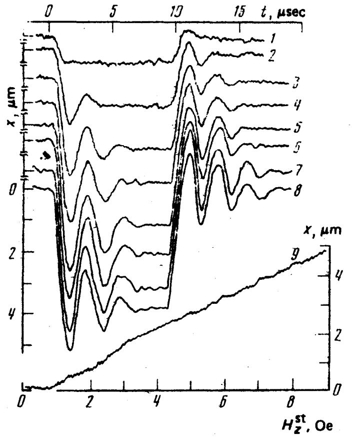

FIG 4. Free BL oscillations, excited by a pulsed local field, H_z (in Oe) of duration 9 μsec (1) $H_z = 1.9$; 2) 2.85; 3) 3.8; 4) 4.75; 5) 5.7; 6) 6.85; 7) 7.6; 8) 8.55, and variation of the displacement of this BL with the value of a quasistatic field H_z^{st} (9).

the BL about $x = x_f$ did not occur.

Also notable is the large (exceeding $|x_f|$) value of the BL oscillations after turning off of the field step H_z (Fig. 3), which is not characteristic of known free, attenuating oscillations. As experiments showed, such oscillations occurred for a field direction not strictly along the z axis, leading to the appearance of a component H_x. Depending on the field direction, H_x enhances or weakens the initial BL pulse induced by the field H_z.

With stricter orientation of the direction of the pulsed field along the z axis, we observed normal, exponentially damped free oscillations of the BL. A series of such $x(t)$ curves, measured on another specimen and characterizing the motion of a BL in time under the action upon it of a local pulsed field H_z of various amplitudes, is shown in Fig. 4. Here, with increase of H_z there are clearly observed only an increase of the amplitude of the BL oscillations and a consequent increase of the distance to the new equilibrium position $x = x_f$. The $x(H_z^{st})$ relation for this BL (Fig. 4, Curve 9) is linear over a quite large field interval.

As is seen from Fig. 3, a BL ultimately, after application to the crystal of a field H_x of small amplitude, remained in the original position. The process of magnetization of a crystal by such an external field, parallel to the magnetization in one of the domains, should occur principally by motion of the whole domain wall. But it was not possible to resolve the displacement of a small section of the wall under local action upon it of a field H_x, in the experiments described above. Therefore such measurements were made in Helmholtz coils. It was then possible to follow simultaneously the behavior of the domain wall and of the BL in it. Figure 5 shows examples of the displacements of a domain wall (y) and of a BL (x) with time, after turning on ($t = 0$) of a pulsed field H_x of amplitude of 10 mOe. It is seen that the motion of the domain wall, under the action of H_x, to a new equilibrium position has the character of aperiodic damping and is accompanied by oscillations of the BL. An estimate of the mobility μ_0 of the wall from the initial section of the $y(t)$ curve gives a value 28–30 m/sec·Oe, which, although it exceeds μ_0 as measured in larger fields, nevertheless remains considerably smaller than the value calculated on the basis of ferromagnetic resonance data.[8]

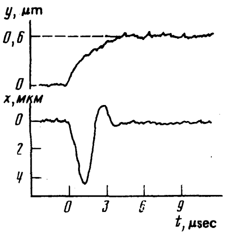

FIG. 5. Variation of displacements of domain wall (y) and of BL (x) with time, after turning on of a pulsed uniform field H_x of amplitude 10 mOe.

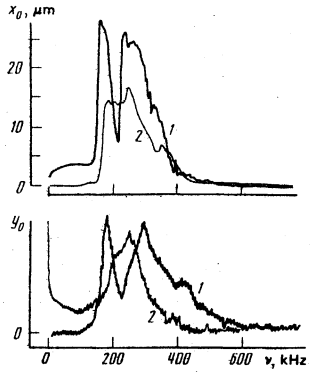

FIG. 6. Forced oscillations of BL (x_0) and of domain wall (y_0) in sinusoidal fields H_z of amplitude 1.35 Oe (1) and H_x of amplitude 10 mOe (2).

In investigation of BL oscillations in a uniform field H_z, perpendicular to the magnetization in the domains, it was also possible to observe displacements of the domain wall itself, initiated by the BL motion. Curves 1 in Fig. 6 show the dependences of the amplitudes of oscillation of the domain wall (y_0) and of the BL (x_0) on the frequency of an external sinusoidal field H_z. Measurement of $y_0(\nu)$ was done by the method described above, immediately after the recording of the oscillations of several BL. It is evident that motion of the domain wall is observed only when the BL are displaced over considerable distances, so that the $x_0(\nu)$ and $y_0(\nu)$ graphs are to a large degree similar. Proofs of the fact that the measured magnetooptic signals corresponded to translation of the wall as a whole, and not to change of its width or rotation about the x axis, were obtained in experiments in which the image of the section of a domain wall between BL was located exactly at the center of the aperture or on opposite edges of it (see Fig. 1b). It was found that in the first case, application of an alternating field to the crystal did not lead to the appearance of a magnetooptic signal. It appeared only when the image of the wall was located on the edge of the aperture; the phases of the signals corresponding to positions on opposite edges of the aperture differed by π.

The peaks on the curves of amplitude of domain-wall oscillation vs field frequency, which are directly related to resonance of BL, were observed also under action of an external field along the direction of magnetization in the domains, for which, in accordance with the results of Fig. 5, the $y_0(\nu)$ relation would be of relaxational type. A field H_x acting on all the BL in a domain wall produced resonance displacement of each BL [$x_0(\nu)$, Curve 2, Fig. 6]; then the amplitude of oscillation of the wall also increased [$y_0(\nu)$, Curve 2]. It is furthermore evident from Fig. 6 that the resonance curves for BL during remagnetization of a whole domain wall have a more complicated character as compared with those measured in local fields (see Fig. 2); and the resonance frequencies in fields H_z and H_x coincide.

2. *Transformation of domain-wall structure in an alternating magnetic field.* An earlier paper[10] has already reported observation of the phenomenon of generation of BL in a domain wall of yttrium iron garnet under the influence of an alternating magnetic field, at certain values of ν exceeding the frequency of resonance displacement of BL. Since in Ref. 10 the field, produced by coils of wire small in comparison with the specimen size, was nonuniform in magnitude and direction over the crystal, in the present work, in order to explain more completely the conditions for generation of BL, Helmholtz coils were used, whose axis could be oriented at an arbitrary angle with respect to the plate; this made it possible to study this phenomenon in its dependence on the direction of a uniform field with respect to **M** in the domains.

It was found that the maximal effect of generation and accumulation of BL in a domain wall is observed in the presence of a component of the sinusoidal field H_x, parallel to the magnetization in the domains. In the case $\mathbf{H} \perp \mathbf{M}$, although reconstruction of the wall substructure still occurred in individual sections of the walls (as a rule, ones located close to defects of the crystalline lattice) as a result of generation and annihilation of BL, their density did not increase substantially. In relatively low fields, $H_z \leq 5$ Oe, at frequencies exceeding ν_r and up to the end of the range studied in the experiment (12.5 MHz), forced oscillations of BL did not appear. But a slight departure of the field from the direction of the z axis, leading to the occurrence of a component H_x, at once strongly stimulated the processes of transformation of the wall structure. They proceeded actively also in a uniform field parallel to the magnetization in the domains.

It is possible to pick out the following characteristic features of the behavior of BL in a uniform field H_x during a process of smooth variation of its frequency, at constant amplitude H_x^0, in various ranges of its values. At values of H_x^0 slightly exceeding the coercive force (equal to ~5 mOe), the BL oscillations occurred only in a small frequency interval near the resonance frequency ν_r. They occurred about equilibrium positions corresponding to $H_x^0=0$ and were observed visually on the basis of the smeared-out boundaries of the subdomains in the wall (Fig. 7b). In different domain walls, and even in different sections of the same wall, appreciable oscillations began at different ν. The wide range of resonance frequencies of Bloch lines (from several tens to hundreds of kHz) was apparently caused by defects of the crystalline lattice. Even in the initial state, they determined a large spread of the dimensions of the subdomains in the walls, which by itself caused a difference in the values of the elastic forces restoring the BL to equilibrium positions, and hence also in the values of ν_r.

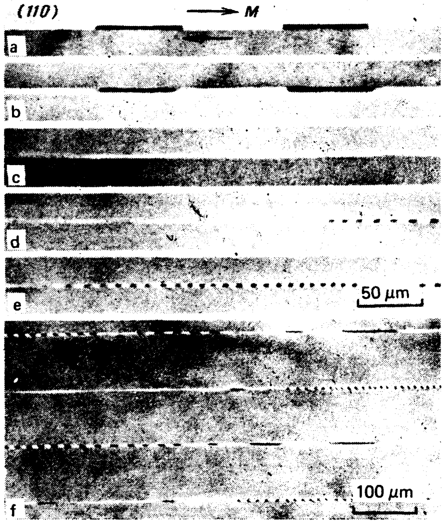

FIG. 7. Various states of a domain wall, realized for: a) $H_x^0=0$; b) $H_x^0=20$, $\nu=0.25$; c) $H_x^0=45$, $\nu=0.8$; d) $H_x^0=45$, $\nu=1.5$; e) $H_x^0=45$ mOe, $\nu=1.9$ MHz; f) general form of a section of the domain structure for $H_x^0=45$ mOe, $\nu=1.9$ MHz.

With increase of H_x^0, the amplitude of the BL oscillations increased, and the frequency range within which they were observed broadened. Then in certain domain walls, there occurred a discontinuous reconstruction of the structure, and a slight increase or decrease of the density of BL in them. At higher H_x^0, in a number of regions of the crystal there appeared quite extended sections of domain walls of uniform tint, whose fine structure could no longer be distinguished visually (Fig. 7c). With increase of H_x^0, they widened along the whole wall. At certain frequencies, almost motionless BL began to appear on one of the edges of such a section (Fig. 7d). Their density considerably exceeded the initial density (Fig. 7a). In the process of further increase of ν, accumulation of quasistatic BL occurred by the appearance of new ones from the side of the uniformly tinted section of the wall (Fig. 7e). As a rule, this was accompanied by a gradual displacement of quasistatic subdomains in the same direction. The length of the wall section, with increased, H_x^0-dependent BL density, reached a maximum value at certain resonance frequencies ν_{rr}. With subsequent increase of ν, the formation of subdomains was again washed out.

In adjacent domain walls, the gradual displacement of quasistatic subdomains, with reproduction of BL, occurred in opposite directions, and accumulation of BL in them was often observed near opposite edges of the plate. In consequence of this, walls with equivalent structural states occurred in alternation in any section of the crystal, as is shown in Fig. 7f.

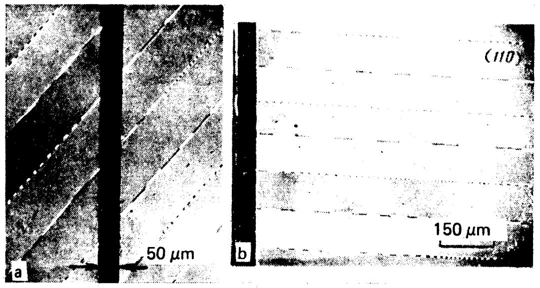

FIG. 8. a) Domain walls near two rectilinear current-carrying conductors ($\nu=2.2$ MHz, $j_0=0.1$ A), located one below the other, above and below the plate (their projection is the black band). The blurred BL are moving. b) Structure of domain walls far from the current-carrying conductors (their image is at the left): $\nu=2.5$ MHz, $j_0=25$ mA.

When the crystal was subjected to a nonuniform field H_x, produced by two current-carrying conductors located above and below the plate at an arbitrary angle to the walls (other than angle zero, for which there was no component H_x and formation of BL was not observed), generation of quasistatic BL was observed at a definite distance from the conductors (corresponding, probably, to the optimal value of the amplitude H_x^0). Then in neighboring walls the BL originated from opposite sides of the conductors (Fig. 8a) and, by gradual displacement of the subdomains, propagated along the crystal over a considerable distance (Fig. 8b). When the crystal was acted upon by a system of two pairs of such conductors (see Fig. 1), not parallel to the walls, accumulation of BL between the pairs of conductors occurred by appearance of new subdomains from the two sides of such a section (in alternate walls).

This process of reproduction of BL could be observed only during smooth variation of the frequency of a field of constant amplitude. With abrupt changes of ν or of H_x^0 (for example, with switching between ranges of the generator), reproduction of BL could occur almost instantaneously. Defects of the crystalline lattice exerted a strong influence on the characteristics of the process of generation of BL in the walls. Near them, sections of accumulation or disappearance of BL were often observed.

Effective accumulation of quasistatic BL occurred for optimal values $H_x^0=20-60$ mOe. At higher H_x^0, over the larger part of the frequency range studied there was observed intense motion of the BL, during which the wall structure was not resolved visually. An exception was the lowest frequencies, at which displacements of the domain wall also began to be observed (Fig. 9). The amplitude of its oscillations, in accordance with the relaxational character of the force oscillations, decreased with increase of ν. The BL displacements meanwhile increased; this made it possible to observe the phase relations of the oscillations. It was found that in a single domain wall the BL oscillations were, as a rule, in phase (Fig. 9a). The occasionally observed disturbances of the in-phase character of the BL oscillations (Fig. 9b) might be due to peculiarities, related to inhomogeneity of the specimen, in the potential-energy contours in which the motion of each of the BL occurred, or to a change of sign of the rotation of the spins in a BL, or to the presence of Bloch points in the BL.[2] BL oscillations of opposite phases were often observed in neighboring domain walls; this indicated that on breaking up of a series of distributed walls into subdomains, the rotation of the spins in them occurs, as a rule, in opposite directions.

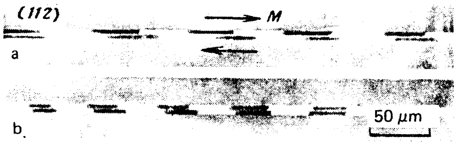

FIG. 9. Image in polarized light of two sections, oscillating in a uniform sinusoidal field H_x, of a 180-degree wall: $\nu=5$ kHz, $H_x^0=0.5$ Oe.

4. DISCUSSION OF RESULTS

It is well known[12] that in the case of a spatially nonuniform distribution of magnetization, forming a one-dimensional domain wall, in a ferromagnet, the Landau-Lifshitz equation, which describes the response of the magnetic subsystem to an external influence at relatively small H ($H \ll 2\beta M$, where β is the magnetic anisotropy constant), can be reduced to an equation of motion of a domain wall regarded as a material point, with a certain mass m_0, in a medium characterized by some viscosity r_0. Within the framework of this approximation, it was found possible to describe the free and forced oscillations of domain walls in a number of crystals, and to develop the most effective examples of measurement of the most important characteristics of the dynamic properties of domain walls.

A theoretical analysis of the dynamics of a two-dimensional domain wall, containing BL, in a multiaxial bulk crystal with $\beta \ll 2\pi$, corresponding to the experimental situation described above, is unfortunately lacking. This has begun to be accomplished only in application to magnetically uniaxial crystals. Most of the papers have considered[2] materials with $\beta \gg 2\pi$, used in the new magnetic memory elements for computers on the basis of cylindrical magnetic domains (bubbles), when the surface of the plate is perpendicular to the axis of easy magnetization. Under such conditions, vertical BL are not an indispensable element of the fine structure of a domain wall. Demagnetizing fields at the surface, at places where the domains emerge on it, can lead to twisting of the domain wall and to the appearance of horizontal BL under the action of the external magnetic field that moves the domain wall.

If the magnetization in the domains is parallel to the plate surface, then the ground state of a crystal with $\beta \ll 2\pi$, as in the experiment discussed, corresponds to a specimen which not only is divided into domains but also contains almost "demagnetized" domain walls, split into subdomains of right and left rotation of the magnetization in the wall, separated by vertical BL. From general considerations, which have received direct experimental confirmation in the results presented, it is evident that the equation of motion of a BL in a field H_z magnetizing the domain wall can also be written in the form

$$m\ddot{x}+r\dot{x}+kx=F=2MH\Delta_0, \qquad (1)$$

where m is the mass of the BL, and where r is an effective viscosity that describes the frictional forces opposing motion of BL and that determines their mobility $\mu=2M\Delta_0/r$.

In the present work, an experimental situation was successfully realized in which the frequency ν_f of free oscillations of BL was practically independent of the amplitude of the external pulsed magnetic field H_z, for variations of it over the range from ~3 to 8 Oe, where $k=\text{const}$ (see Fig. 4). This gives a basis for using, for estimation of the dynamic characteristics of BL (m and μ), data on ν_f and on the logarithmic decrement δ of the damping; the relation between these, in the linear approximation, is given by the expressions

$$2\pi\nu_f=(k/m-r^2/4m^2)^{1/2}, \quad \delta=r/2m\nu_f. \qquad (2)$$

For the case shown in Fig. 4, $\nu_f=390\pm 50$ kHz and $\delta=1.1\pm 0.3$; with use of data on the value of $k\approx 520$ g/sec·cm (Curve 9), the following values are obtained: $m=(9\pm 2)\cdot 10^{-11}$ g/cm, $r=(8\pm 4)\cdot 10^{-5}$ g/sec·cm, $\mu\approx 350$ cm/sec·Oe (Δ_0 was taken equal to 1 μm).

The mass m thus found from data on free oscillations of BL agrees in order of magnitude with that determined earlier[9] from the characteristics of the resonance of BL displacement. But the values of the effective viscosity r obtained by the two methods differ substantially (by about two orders of magnitude). This can apparently be due to several causes. First, the system of BL is in principle nonlinear: the presence of a coercive force for displacement of BL known to cause k is not constant. Second, in the experiment, along with the field H_z, there is always present a nonvanishing component H_x, which determines a gyroscopic force effectively acting on the BL. In the case of resonance of BL motion in a system for which $2km>r^2$, the errors in the determination of the true values of the force and of the resonance amplitude, produced by the causes mentioned, lead to more significant errors in the estimates (in the linear approximation) of the value of r than in that of m.

As has already been mentioned,[9] the total sum of the experimentally determined masses of the BL located in a single domain wall, in yttrium iron garnet, is found to be comparable with the measured mass of the wall itself,[8] which exceeds by several orders of magnitude that calculated according to Döring. The mobility of a BL, however, is about an order of magnitude smaller than the mobility of a domain wall.[8] It may therefore be assumed that one of the reasons for the discrepancy between experimental and theoretical data on the dynamic characteristics of Bloch walls in yttrium iron garnet[8] is the inapplicability of the one-dimensional wall model for description of their properties.

We shall carry out a comparison of the results obtained with the predictions of theory.[13,14] In these papers, with allowance for magnetostatic stray fields in the demagnetizing-factor approximation, the static and dynamic characteristics of domain walls and BL were calculated for a plate of a uniaxial ferromagnet with $\beta\ll 2\pi$, containing, as did also the crystals of yttrium iron garnet studied by us, domains magnetized in the plane of the specimen. In Refs. 13 and 14 the following expressions were obtained for the period $2L$ of the wall substructure and for the characteristic frequency ν_0 of BL oscillations:

$$2L\approx 0.16d\left(\frac{4\pi\beta}{1+(4\pi/\beta)^{1/2}}\right)^{1/2}, \qquad (3)$$

$$\nu_0\approx\gamma M\Delta_0^{4/3}[8(\beta+2\pi)]^{1/6}/d(5\alpha^{1/2})^{1/3}\pi^{1/2}, \qquad (4)$$

where α is the exchange constant, γ is the gyromagnetic ratio, and d is the plate thickness. Substitution in these expressions of the values $\beta=0.3$, $M=139$ G, $\gamma=1.76\times 10^7\ \text{sec}^{-1}\text{Oe}^{-1}$, $\Delta_0=1\ \mu$m, and $d=35\ \mu$m, corresponding to the crystal investigated by us, gives $2L\approx 20\ \mu$m (which is about 10 times smaller than the experimentally observed period of the subdomains in the original demagnetized state) and $\nu_0\approx 130$ MHz, exceeding the measured value by several orders of magnitude. These discrepancies may be partly due to the fact that experimental results obtained on a multiaxial crystal have been compared with predictions of the theory for a uniaxial material. But it seems to us that these discrepancies indicate principally that the treatment[13,14] of BL as sections of a domain wall is an inadequate approximation to the real situation, and that what is needed is a rigorous calculation of the magnetization distribution in a BL and of its change under the action of an external field.

A spatially uniform field H_z, varying sinusoidally in time, determines a more complicated spectrum of resonance forced oscillations of the magnetic moments localized in a domain wall (see Fig. 6). It has been found to produce not only remagnetization of the wall by motion of BL, but also resonance oscillation of the domain wall itself. The spectrum of BL oscillations in a uniform field may be characterized by several peaks and is observed over a wider range of frequencies than in the case of excitation of oscillations by local action of a field H_z on only a single BL (see Fig. 2). This is a natural consequence of the coupling of a system of BL oscillating in nonuniform potential-energy contours. Resonance oscillations of a domain wall show up in the same frequency range as do resonance displacements of BL. We know of only one paper[14] in which, on the basis of a theoretical analysis of the resonance properties of a domain wall in thin magnetic films, it was shown, in particular, that in a field H_z biasing the wall, bending oscillations of the whole wall may be excited at the frequency of oscillation of the BL. The possibility is not excluded that the domain-wall oscillations observed by us in a field H_z are bending oscillations, although this question requires additional investigations.

A still richer set of types of excitation of the spin system, localized in a domain wall, is observed in a uniform alternating field H_x acting along the magnetization in the domains. It causes not only the known forced oscillations of domain walls, insured by the biasing of the specimen, whose spectrum in yttrium iron garnet is of relaxational character [Fig. 6, $y_0(\nu)$, Curve 2] under the inequality $2k_0m_0 < r_0^2$, but also oscillations of the BL under the action of a gyroscopic force [Fig. 6, $x_0(\nu)$, Curve 2]. In the experiments described, there was detected still another resonance spectrum of oscillations of the domain wall at the frequencies of resonance displacement of the BL [Fig. 6, Curve 2, $y_0(\nu)$], not previously considered theoretically. At H_x exceeding a certain critical value, there occur in the domain wall peculiar processes of transformation of its structure, leading to a substantial increase of the density of BL.

The mechanism of reproduction of BL in a field H_x may consist in the following. As investigations have shown, the motion of BL in each domain wall occurs, as a rule, in a single direction; this indicates that in an overwhelming majority of cases, the rotation of spins in the BL occurs in the same direction. Defects of the crystalline lattice, including the specimen surface, cause pinning of certain BL. As a result, the displacement of the remaining BL under the action of gyroscopic forces in the field H_x causes an increase of the size of the subdomain bordering with the barrier for BL, above the equilibrium value, and the appearance of a demagnetizing field H_z^d. In this field, at certain frequencies, there may occur a resonance broadening of the nonlinear excitation of the spin system localized in the wall—dynamic solitons—and subsequent breaking up of them into two topological solitons, two vertical BL.

In conclusion, it should be emphasized that the development of a theory of the observed resonance phenomena may make it possible to solve a number of important fundamental and applied problems; in particular, the experimental determination of the characteristics of nonlinear excitations in the magnetic subsystem, and the development of methods of purposefully changing the dynamic characteristics of domain walls by changing their fine structure.

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