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**Abstract.** – The effects of additional magnetic fields on the regularity Néel lines motion along 180° Bloch walls oscillating in yttrium iron garnet single crystal plates under the action of an AC magnetic field parallel to the magnetization in domains are investigated using a magnetooptical method.

## Introduction

As is well known, the fundamental principles of the theory of the formation of domain structure in ferromagnets and of domain-wall dynamics were established in the famous paper of Landau and Lifshitz [1]. It was shown that the thermodynamic-equilibrium state should correspond to a crystal broken up into domains such that the resultant magnetic moment of the sample is equal to zero in the absence of a magnetic field. Landau and Lifshitz [1] and Néel [2] considered one-dimensional domain-wall models in which the distribution of the magnetization varies only in the direction perpendicular to the plane of the wall.

In real crystals the structure of the domain boundaries differs from the idealized scheme of such a one-dimensional planar wall. In the overwhelming majority of crystals the essential elements of the Bloch-wall structure are Bloch (Néel) lines which arise due to the demagnetizing field on the surface of the sample. They separate the subdomains in the wall with both opposite direction of the spin rotation in the wall and type of the magnetic poles on the surface, intersecting the Bloch wall [3]. Without taking these elements into account it is impossible to describe the mobility of the domain walls in ferromagnetic crystals [4].

A direct experimental study of the dynamical properties of Néel lines enabled us not only to determine for the first time their effective mass and mobility [5 to 7], characterizing the motion of a magnetic vortex, but also reveal the unknown processes of Néel-line drift, generation and disappearance [8, 9][1] which play a decisive role in the formation of the structure and properties of the Bloch wall. To have a deeper insight into the regularity of the motion of these interesting objects, we badly need information on their magnetic structure and its dynamical transformations under external action. The absent direct experimental methods for investigating the Néel-line structure predetermines the necessity of developing studies which could give extra information about the distribution of spins in the Néel lines and the character of the potential relief in which they move.

The present paper reports on the results of a magnetooptical investigation of the dynamics of Néel lines in yttrium iron garnet single crystal, aimed at solving the above problem. The spectrum of the low-amplitude Néel-line oscillations and their drift in an AC magnetic field ($H_{x_1}$) parallel to the magnetization in domains was studied successively as a function of the parameters $H_y$ and $H_{x_2}$, namely additional magnetic fields. The DC magnetic field $H_y$ was applied to the crystal in the direction normal to the 180° Bloch walls, in order to affect the distribution of spins in Néel lines. The AC magnetic field $H_{x_2}$ of a given frequency ($\nu_2$) swung the Bloch wall at a much larger distances than the simultaneously acting axial field $H_{x_1}$, which as supposed, should change the local potential relief formed as a result of the magnetic after-effect discovered in these crystals earlier [7].

## Experiment

The regularity of the Néel-lines motion in a 180° Bloch wall (see Fig. 1) was studied in a thin plate of yttrium iron garnet single crystal placed into an uniform AC field $H_{x_1}$ of an amplitude $H^0_{x_1}$ and frequency $\nu_1$. The field was produced by Helmholtz coils 6 mm in radius and was aligned along the domain magnetization lying in the sample plane. The low-amplitude oscillation of the 180° Bloch wall induced by the AC

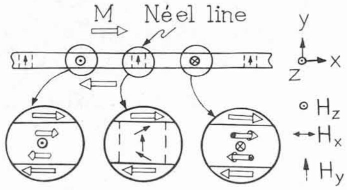


Fig. 1. – Distribution of the magnetization in a 180° Bloch wall with vertical Néel lines.

[1] In references [5-9] the transition areas between subdomains in a 180° Bloch wall have been referred to as "Bloch lines" analogous to those in uniaxial garnet films [4]. Since in the yttrium iron garnet plates in a middle layer of such a transition area the rotation of the spin direction on passing through the wall is probably such that the spin directions lie in the plane of the plate (Fig. 1), this area can be also termed the "Néel line"

magnetic field $H_{x_1}$ gave rise to gyrotropic forces, alternating with frequency $\nu_1$ and acting on the Néel lines along the moving Bloch wall. As a result, the Néel lines moved along elliptic paths revealed [6, 7] directly by recording the both mutually perpendicular components of the Néel-line motion: normal and parallel to the 180° Bloch wall. Therefore in the present work we restrict our attention to the investigation of one component of the motion of elliptically polarized oscillations of Néel lines.

This component characterizes the Néel-line motion along the 180° Bloch wall and was studied by measured the intensity of the polarized light (at slightly uncrossed polarizers of the microscope) transmitted through a local 180° Bloch wall area that comprised a single Néel line. For measurements we used a photomultiplier tube (PMT). The PMT-signal whose variation was proportional to the value of the Néel-line displacement along the Bloch wall was applied either to a sampling and storage oscilloscopes or to a spectrum analyser, depending on the problem in hand. While studying the amplitude-frequency characteristics of Néel lines oscillating near the equilibrium positions, the gyrotropic force amplitude (which was proportional to the product $H^0_{x_1}\nu_1$ [7]) was held automatically constant at the cost of an appropriate variation of $H^0_{x_1}$ with changing $\nu_1$. The characteristics of the nonperiodic motion of Néel lines under drift conditions were studied using the storage oscilloscope and by a technique of short exposure of the crystal to the AC magnetic field $H_x$ [8].

The additional AC magnetic field $H_{x_2}$ was induced by the same coils that the field $H_{x_1}$, whereas the additional DC magnetic field $H_y$ perpendicular to them was produced by Helmholtz coils 8 mm in radius.

## Results and discussion

Figure 2 (curve 1) illustrates dependence of the magnetooptical signal proportional to the amplitude of forced Néel-line oscillations along the 180° Bloch wall on frequency of the AC magnetic field $H_{x_1}$. A weakly

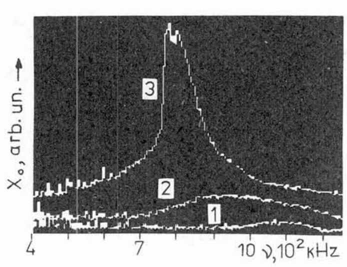


Fig. 2. – Amplitude $X_0$ of the Néel-line oscillations as a function of the frequency $\nu_1$ of the ac field $H_{x_1}$, measured for a constant value $H^0_{x_1}\nu_1 = 800$ OeHz and various values $H_y$ (Oe) : 1) 0; 2) 1.25; 3) 2.2.

pronounced peak seen in the curve reflects the resonance motion of the Néel line. It should be noted that here and below we deal with the simplest dependence involving only the translational motion of Néel line as a whole. In the experiment we often had to do with more complicated dependences of the amplitude of forced Néel-line oscillations on the magnetic field frequency. These dependences were associated, in particular, with the excitation of "flexural" modes of Néel-line motion [10].

The Néel-line oscillations induced by the AC magnetic field $H_{x_1}$ were changed substantially on applying a DC magnetic field $H_y$ to the crystal (curves 2 and 3 in Fig. 2). In this case the Néel-line oscillation amplitude not only increased as in figure 2, but also fell down to zero and then grew at a gradual increase of $H_y$. The phase analysis of magnetooptical signal has shown that in passing through the zero amplitude the phase of Néel-line oscillations was inverted. A DC maggnetic field $H_y$ affected in the same manner the amplitude and phase of free damping Néel-line oscillations initiated by a step of magnetic field $H_x$.

To explain these data, one has to take into account the dependence of the magnitude and direction of the gyrotropic forces on the distribution of spins in the Néel line, in particular, on the sense of rotation of the spins in the transition area between subdomains. It is expected that the DC magnetic field $H_y$ changed the polarization of spins in the Néel line, for example, at the cost of a displacement of Bloch points [4], and thus determined the magnitude and direction of the action of gyrotropic forces on the Néel line.

Using Thiele's model [11, 12] for yttrium iron garnet single crystal, we obtained the expressions for the effective mass ($m_x$) and viscous-friction coefficient ($\beta_x$) of Néel line [7]:

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

$$\beta_x = \alpha\frac{2ML}{\gamma\Delta}\left[\frac{\kappa_x}{\kappa_y} + \frac{2\Delta^2}{\Lambda L}\right],$$

where $\alpha$ is the dissipation parameters in the Landau-Lifshitz-Gilbert equation [4]; $\gamma$ is the gyromagnetic ratio; $M$ is the saturation magnetization; $L$ is the average distance between neighboring Néel lines;

$$\Lambda = \left(A/2\pi M^2\right)^{1/2};$$

$A$ is the exchange-interaction constant; $\Delta$ is the width of a Bloch wall; $\kappa_x$ and $\kappa_y$ are the coefficients characterizing the elastic forces which return the Néel line to the original position as a result of its displacement, respectively, along and with the wall.

The expression for $m_x$ differs from those obtained in references [13 and 14], derived ignoring energy dissipation, only by an additional factor in the square brackets. The coefficients $\kappa_x = 34.6$ g.cm$^{-1}$.sec$^{-2}$ and $\kappa_y = 2.9 \times 10^3$ g.cm$^{-1}$.sec$^{-2}$ were determined experimentally from static dependences of the coordinates of a Néel line $(x)$ or a Bloch wall $(y)$, respectively, on the field $H_z$ (which is normal to the magnetization in domains) or $H_x$ [15]. The values of the $m_x = 0.85 \times 10^{-12}$ g.cm$^{-1}$ and $\beta_x = 0.2 \times 10^{-6}$ g.sec$^{-1}$.cm$^{-1}$ were calculated [15] using the above expressions and the parameters $\alpha = 10^{-4}$ (deduced from FMR measurements [16]), $M = 139$ G, $A = 4.2 \times 10^{-7}$ erg/cm, $\gamma = 1.8 \times 10^7$ Oe$^{-1}$.sec$^{-1}$, $L = 60$ $\mu$, and $\Delta = 1$ $\mu$ (close to the experimental value given in Ref. [17]).

The values of $m_x$ and $\beta_x$ obtained from an analysis of the experimental results using the familiar expressions for the resonant frequency of Néel-line oscillations and of the width of the resonance line $X(\nu)$ of such oscillations are $0.9 \times 10^{-12}$ g.cm$^{-1}$ and $0.7 \times 10^{-6}$ g.cm$^{-1}$.sec$^{-1}$, respectively [15]. The Néel-line mass and viscous-friction coefficients determined in the experiment, made in the presence of a DC magnetic field $H_y$, are in rather good agreement with those calculated. This provides evidence that Néel lines do move in accordance with the law of the magnetic-vortex motion, under the action of gyrotropic forces. Moreover, the Néel lines in yttrium iron garnet single crystal can involve peculiarities such as Bloch points predicted for uniaxial magnetic films [4]. On the other hand, small discrepancies between experimental data and calculated ones may be partly due to the fact that the calculations do not take into account some unknown features, in particular, magnetic after-effect.

The frequency dependences of the amplitude of Néel-line oscillations under the action of $H_{x1}$ shown in figure 3 were measured at various amplitudes $\left(H^0_{x_2}\right)$ of the additional field $H_{x2}$ with frequency $\nu_2 = 850$ kHz. It is seen that at increasing $H^0_{x_2}$ the frequency of the resonance motion of Néel line decreases, while the amplitude of Néel-line oscillation increases. With varying $\nu_2$ the situation did not change in principle.

The frequency of the resonance motion of Néel line is proportional to $\left(\gamma/4\pi^2 M\right)\left(\kappa_x\kappa_y\right)^{1/2}$ [7]. The coefficients $\kappa_x$ and $\kappa_y$ characterizing the elastic restoring forces should depend partly on the relief which can be formed due to the redistribution of point defects, whose energy state depends on the magnetization direction and which are responsible for the "magnetic after-effect" [18]. Then the potential well produced by the Néel line will be the deeper the smaller the amplitude of Néel-line oscillations. Therefore the additional AC magnetic field $H_{x_2}$ acting on the crystal makes the Néel line oscillating with frequency $\nu_1$ simultaneously oscillate at the frequency $\nu_2$. And the larger the distance at which the Néel line displaces from the equilibrium position under the action of the additional AC field $H_{x_2}$, the shallower apparently the relief that the "Néel line + Bloch wall" system forms in the AC magnetic field $H_{x_1}$.

As evidenced by the data of figure 4, the 180° Bloch wall makes its own potential well without any Néel line. This figure shows how the oscillation amplitude of a 180° monopolar Bloch wall depends on the frequency $\nu_1$ of AC magnetic field $H_{x_1}$ at various values of oscillation amplitudes $H^0_{x_2}$ of an additional AC magnetic field $H_{x_2}$. These dependences were measured in conditions when the photometered light passed through the local crystal area comprising half the width of the 180° Bloch-wall image and a part of the domain [6, 7]. The peaks on these dependences are related to the resonant excitations of flexural waves in the Bloch wall [19]. The wave vector is directed along the normal to the plate. With applying $H_{x_2}$ (curve 2 in Fig. 4) the resonant frequencies of the peaks decrease in the same manner as in figure 3.

In figure 5 the amplitude of forced oscillations of a monopolar 180° Bloch wall $(Y_{01})$ in AC magnetic field $H_{x_1}$ ($H^0_{x_1} = 2.5$ mOe, $\nu_1 = 0.4$ MHz) is depicted as a function of the amplitude of a simultaneously acting AC magnetic field $H^0_{x_2}$ ($\nu_2 = 850$ kHz). For a rather weak and growing field $H_{x_2}$ the value of $Y_{01}$ and conse-

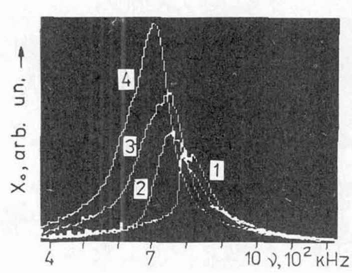


Fig. 3. – Amplitude $X_0$ of the Néel-line oscillations as a function of the ac field $H_{x_1}$ $\left(H^0_{x_1}\nu_1 = 800 \text{ Oe Hz}\right)$, measured for a simultaneous action of an additional DC field $H_y = 2.2$ Oe and AC field $H_{x_2}$ of different amplitudes $H^0_{x_2}$ (mOe) : 1) 0; 2) 0.8; 3) 2.5; 4) 4.5 and frequency $\nu_2 = 850$ kHz.

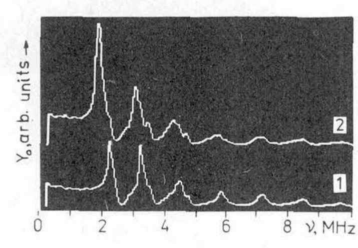


Fig. 4. – Frequency dependences of the amplitude of the forced oscillations of the monopolar Bloch wall in an AC field $H_{x_1}$ of amplitude $H^0_{x_1} = 2.5$ mOe, measured for $H^0_{x_2} = 0$ (1) and $H^0_{x_2} = 11$ mOe $\nu_2 = 850$ khz (2). An additional DC field $H_z = 18.5$ Oe, normal to the plate plane, was applied to the crystal in order to stabilize the monopolar Bloch wall state.

quently of the monopolar Bloch-wall velocity increase. This also points to a decrease of the relief height under the action of the additional magnetic field $H_{x_2}$. Moreover, since the value of the gyrotropic force displacing the Néel line along the 180° Bloch wall is proportional to the Bloch-wall velocity [7], the growth of the latter seems to be the main reason why the amplitude of Néel-line oscillations increases in an additional magnetic field $H_{x_2}$ (Fig. 3). To some extent this effect undoubtedly depends on the relief produced by the Néel line itself.

As seen from figure 5, the amplitude of Bloch-wall oscillation, driven by an AC magnetic field $H_{x_1}$, grows with an increase of the additional AC magnetic field $H_{x_2}$ only when its amplitude does not exceed a certain critical value. Upon reaching the critical one the Bloch-wall oscillation amplitude begins to decrease (the resonance oscillations of Néel line (Fig. 3) measured in this range of $H_{x_2}$ amplitude also got weaker with increasing $H^0_{x_2}$). This occurs due to the action of new mechanisms of energy losses that come into play in high drive fields. The mechanisms are associated with strongly non-linear processes of the Bloch-wall structure transformations leading in the end to the excitation of solitary non-linear waves [20], the generation of Néel lines and their unidirectional propagation (drift) [8, 9].

The solitary non-linear spin waves in 180° Bloch walls were revealed for $H^0_{x_2} \gtrsim 40$ mOe (in the presence of an AC magnetic field $H_{x_1}$) using a storage oscilloscope [9, 20]. The two single-sweep oscillograms shown in the insets to figure 5 are recorded at $H^0_{x_2} = 46$ and 119 mOe. Each peak on the oscillograms reflects the passage of a solitary excitation through the photometered Bloch-wall section. It is seen that with increasing $H^0_{x_2}$, an increase took place in the density of the solitary excitations. The high density of the solitary excitations at $H^0_{x_2} = 119$ mOe seems to be the main reason for the fact that the amplitude of Bloch-wall oscillation, under this condition, is found to be very small compared to the initial one.

Figure 6a shows a single-sweep oscillogram obtained at the AC magnetic field amplitude sufficient to initiate a drift of the entire system of Néel lines in a demagnetized 180° Bloch wall [21]. The magnetooptical signal manifests successive passing of "dark" and "bridght" subdomains in the same direction through the photometered Bloch-wall section. Using such oscillograms, the velocity of the unidirectional Néel-line motion as well as the rates of the Néel-line generation and annihilation (that were also observed) can be estimated [7, 22]. Dynamic subdomain sizes can be observed using a polarization microscope with pulsed laser illumination [21, 23]. The Néel-line drift velocity is found to be several meters in second and the rate of Néel-line generation (or annihilation) is about $10^4$ Néel lines/sec. These processes are dependant on the real structure of the crystal and on the amplitude and frequency of the drive field [7, 21-23].

On applying a weak additional DC magnetic field $H_y$, as seen from figure 6b, the single-sweep magnetooptical signal took a form approximating a periodic one and the duration of the averaged period of its vibrations became shorter. The reason for this is that the Néel-line drift velocity increased and got stabilized. One can see also that the magnetooptical signal in figure 6b oscillates between its maximum and minimum values at a frequency equal to that of the AC magnetic field $H_x$. This means that all the Néel lines, moving in the same direction, simultaneously vibrate at this frequency. On reversing the polarity of DC magnetic field $H_y$ the direction of the Néel-line drift was also inverted. The above fact has been revealed using a direct observation of a Bloch wall between the short

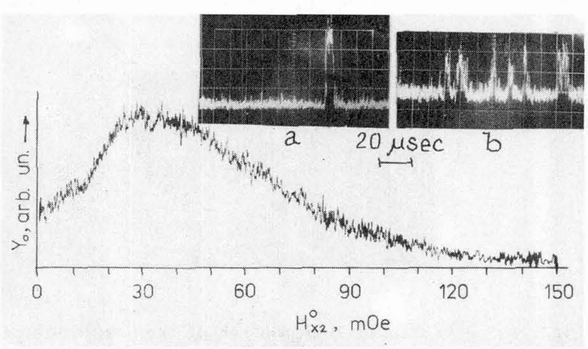


Fig. 5. – The amplitude of the forced oscillations of a monopolar Bloch wall in AC field $H_{x_1}$ ($H^0_{x_1} = 2.5$ mOe, $\nu_1 = 400$ kHz) as a function of the amplitude of the additional AC field $H_{x_2}$ ($\nu_2 = 850$ kHz). $H_z = 18.5$ Oe. Insets – a single oscillograms obtained using a storage oscilloscope for $H^0_{x_2} = 46$ (a) 119 (b) mOe.

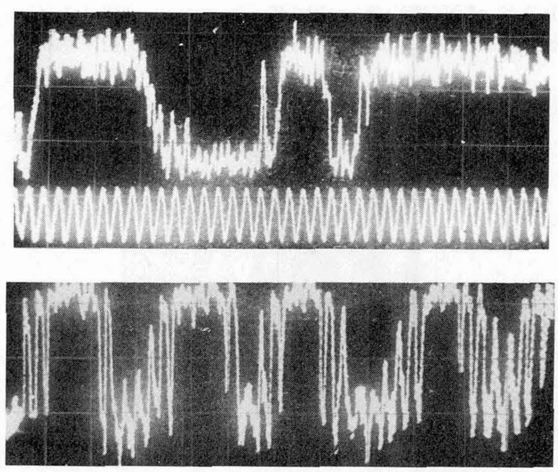

Fig. 6. – Single oscillograms (bottom) obtained for $H^0_x = 0.1$ Oe ($\nu = 350$ kHz) and $H_y = 0$ (a) and 8.4 Oe (b). Top oscillogram is the AC field signal.

exposure applications of AC magnetic field $H_x$ to the crystal [8].

It has been shown in reference [24] that under conditions of non-linear oscillations of Néel lines the latter can experience the action of some constant force responsible for their drift. A sign of the constant force according to [24] should depend on the direction of the spin rotation in the Néel line. Therefore the above experimental data may be an indication of the change in the distribution of spins in the Néel line due to the application of the field $H_y$.

## Conclusion

The data presented give a reason to believe that the distribution of spins along the Néel line in yttrium iron garnet can be nonuniform and have opposite rotations of Néel-line spins in neighboring regions. The external DC magnetic field $H_y$ magnetizing the Néel line in one (or the opposite) direction varies the magnitude and direction of the effective force acting on the Néel lines during their oscillations near the equilibrium positions as well as in the course of their drift. To describe all the processes one should take into account the mechanisms responsible for the magnetic after-effect. Their evidence seems to be the most interesting problem in our opinion, since such effects, the more so at room temperatures, had not been observed before in yttrium iron garnet single crystals grown without deliberate doping.


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