Properties of the "thin" structure domain walls in rare-earth ortho-ferrites

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Dynamics of thin-structure domain walls (DW) has been studied taking into account of the g-factor anisotropy. The line speed has been found as a function of the DW motion speed different from that known before. A 180-deg DW of the Neel type with a zero-deg Bloch line localized thereon has been considered using numerical methods. The law of the magnetization vector turning, effective widths of the DW and line, and energy per unit line length have been determined for such a DW. The more precise taking of the DW bidimensionality into account has been shown to result in significant differences as compared to the approximate analytical methods.

Исследована динамика доменных границ (ДГ) с тонкой структурой с учетом анизотропии g-фактора. Найдена скорость движения линии в зависимости от скорости движения ДГ, отличающаяся от ранее известной. С помощью численных методов, рассмотрена 180-градусная ДГ неелевского типа с локализованной на ней ноль-градусной линией Блоха. Определены закон разворота вектора намагниченности такой ДГ, эффективные ширины ДГ и линии, энергия, приходящаяся на единицу длины линии. Показано, что более точный учет двумерности ДГ приводит к существенным отличиям по сравнению с приближенными аналитическими методами.

To date, the dynamics of homogeneous domain walls (DW) in rare-earth ortho-ferrites (REO) being non-collinear antiferromagnetics with weak ferromagnetism (WFM) is studied in experiment in detail enough and explained theoretically in main features [1, 2]. In contrast to ferromagnets, the situation with the "thin" structure investigation is quite different. Theoretically, the existence possibility for two "thin" structure types of DW in REO was predicted rather long ago for the case when $Q = k_{ab}/k_{cb} >> 1$ (k_{ab} and k_{cb} being the effective anisotropy constants in the ab and cb planes, respectively) [3]. The dynamic characteristics of such DWs must differ significantly from those of DWs with lines in ferromagnets [4, 5]. For example, the gyrotropic term of the dynamic force acting on the REO line appears in an external field perpendicular to the rotation plane of the antiferromagnetism vector **l** and it may be comparable to the inertia and viscosity terms in absolute value. There are also experimental results [6–8] which can be interpreted as observation of dynamic lines on a DW in REO moving at a supersonic speed.

In those experiments, however, conditions were used that were not considered theoretically (e.g., a Neel DW, high speeds of the DW and line), so that, generally speaking, it is unclear what a specific type of the DW "thin" structure is realized in practice. In [8], a doubt has been expressed that the experimental results obtained, e.g., the line speed dependence on the DW speed, can be explained well enough using the field gyroscopic force. In principle, three further types of possible gyroscopic forces are known for two-sublattice magnetics [9]. In the case of $YFeO_3$ used in experiments [6–8], however, the first of those forces (resulting from a purely relativistic invariant in the Dzialoszynski interaction) is absent, as well as the second one associated with the difference between the magneto-mechanical ratios of the sublattices. To obtain the third force, similar to that in ferromagnets and proportional to the effective magnetization of sublattices, M_s, it is necessary to turn down the use of one of the integrals $\mathbf{ml} = 0$ in the motion equations for magnetization. To date, this is realized for homogeneous magnetics only [10]. Therefore, to derive a new kind of gyroscopic force, it is of interest to take into account the anisotropy of the g-factor that may be of great importance in the antiferromagnet dynamics [11].

In general case, the Vlasov-Ishmukhametov equation for spin planes should be used to that end. It has been shown [11] that the Landau-Lifshits equations can be applied to a magnetic with anisotropic g-factor if the latter is taken into account in thermodynamic potential through the Zeeman energy. In this work, first, the dynamics of a thin-structure DW is studied taking into account the g-factor anisotropy. Second, a 180-deg Neel DW with a zero-deg line is considered using numerical methods for arbitrary values of the material quality factor Q.

Let an infinite REO plate be considered in the two-sublattice model. The obiect state is described by two sublattice magnetization vectors $\mathbf{M}_1$ and $\mathbf{M}_2$ with the same modules ($|\mathbf{M}_1| = |\mathbf{M}_2| = M_0$). Then, the ferromagnetism vector $\mathbf{m}$ and the antiferromagnetism one, $\mathbf{l}$, can be determined as $\mathbf{m} = (\mathbf{M}_1 + \mathbf{M}_2)/2M_0$, $\mathbf{l} = (\mathbf{M}_1 - \mathbf{M}_2)/2M_0$, respectively. The Cartesian coordinate axes x, y, z are believed to be oriented along the crystallographic ones a, b, c, respectively. The energy density of the REO can be presented [10, 11] as

$$w_m = \frac{1}{2}am^2 + \frac{1}{2}A(\nabla\mathbf{l})^2 + \mathbf{d}[\mathbf{ml}] + \frac{a_1}{2}l_x^2 + \frac{a_3}{2}l_z^2 - - 2M_0\mathbf{mH} + \frac{1}{2}D(\mathbf{ml})^2 + \frac{1}{2}D'\mathbf{m}^2\mathbf{l}^2 - - 2M_0\tau_1 H_x l_z - 2M_0\tau_2 H_z l_x, \quad (1)$$

where a, A are the homogeneous and inhomogeneous exchange constants, respectively; D, D', the symmetric exchange interaction constants; a_1, a_3, the second order anisotropy constants; $\mathbf{H}$, the external magnetic field. The quantities τ_1, τ_2 take into account the non-diagonal components of anisotropic g-factor for REO in a high-temperature magnetic phase. $\tau_1 = g_{xz}/g_{xx}$, $\tau_2 = g_{zx}/g_{xx}$, g_{ik} are the anisotropic tensor components. The vector $\mathbf{d} = d\mathbf{e}_y$, where d is the exchange-relativistic Dzialoshynski interaction. The motion equations for $\mathbf{m}$ and $\mathbf{l}$ are taken within the exchange approximation [12].

For the case $\mathbf{m} << \mathbf{l}$, similar to the pure antiferromagnets [10] (provided that the condition $\lambda_1 H/2M_0H_E << 1$, $H_E = (a + D')/4M_0$ is met), the vector $\mathbf{m}$ is related to $\mathbf{l}$ one by the relationship

$$\mathbf{m} = \left\{\frac{\chi_\perp}{2\gamma M_0}\left\{[\dot{\mathbf{l}},\mathbf{l}] + \frac{\lambda_1\chi_\perp}{2\gamma M_0^2}[\ddot{\mathbf{l}},\mathbf{l}]\right\} + + \frac{1}{a}\{[\mathbf{l},\mathbf{d}] - 2M_0[\mathbf{l}(\mathbf{lH}) - \mathbf{H}]\}\right\}(1 + \varepsilon_1 l_x + \varepsilon_2 l_z)^{-1}, \quad (2)$$

where γ is the gyromagnetic ratio; α, λ_1, λ_2, the relativistic relaxation constant and the exchange ones; $\chi_\perp = M_0/H_E$, the magnetic susceptibility component perpendicular to the equilibrium $\mathbf{l}$ direction; $\varepsilon_1 = \tau_1 H_x/2H_E$, $\varepsilon_2 = \tau_2 H_z/2H_E$.

Using (2), it is easy to obtain (provided that conditios $\lambda_1 H_d/2M_0H_E$; $2\lambda_2 H/A << 1$, $H_d = d/2M_0$ are met and taking into account that τ_i terms are small) the equation

$$[\ddot{\mathbf{l}},\mathbf{l}] - c^2[\Delta\mathbf{l},\mathbf{l}] + \frac{\gamma}{4M_0^2}[\mathbf{d},\mathbf{l}](\mathbf{dl}) + \frac{\gamma^2 a}{4M_0^2}\left[\frac{\partial w_a}{\partial l},\mathbf{l}\right] = - \frac{c^2}{A}\left[H_l^e,\mathbf{l}\right] - \frac{2\gamma M_0}{\chi_\perp}\left(\alpha - \frac{\lambda_2}{M_0}\Delta\right)[\dot{\mathbf{l}},\mathbf{l}] - \quad (3)$$
$$- \frac{\lambda_1\chi_\perp}{2\gamma M_0^2}\{[\dddot{\mathbf{l}}] + [\ddot{\mathbf{l}},\mathbf{l}]\} + \gamma\{2[[\mathbf{H},\dot{\mathbf{l}}]\mathbf{l}] + [[\dot{\mathbf{H}},\mathbf{l}]\mathbf{l}]\} - - \frac{\gamma^2}{2M_0}[[\mathbf{H},\mathbf{d}]\mathbf{l}] + \gamma(H_x\tau_1\dot{l}_z + H_z\tau_2\dot{l}_x) \times$$
$$\times \left\{\frac{\chi_\perp}{2M_0\gamma}\mathbf{l}[\dot{\mathbf{l}}\mathbf{l}] + \frac{\chi_\perp}{4M_0^2}[\mathbf{ld}] + \frac{2M_0}{a}[\mathbf{H} - \mathbf{l}(\mathbf{lH})]\right\} - - \frac{\gamma}{\chi_\perp}m_s\dot{\mathbf{l}}.$$

Note that when $m_s = \tau_1 = \tau_2 = 0$, the Eq.(3) coincides with the known equation for $\mathbf{l}$ in [2]. The account for m_s and τ_i results in new terms in that equation, including the gyroscopic kind ones.

Eq.(2) is very complex and cumbersome, so it is difficult to solve it even in the simplest case of bidimensional DW with a single line. That is why in what follows, we will make use of a simplified description in the frame of collective variable method. Since the exchange ralaxation effect is studied in detail in [5], we will believe $\lambda_1 = \lambda_2 = 0$. The sole line presence influences only slightly the dynamics of DW itself. So it can be believed that the appearance of new terms in (2) does not affect very considerably the expression for the DW speed that is studied quite comprehensively (see, e.g., [5]). Therefore, we will restrict ourselves by consideration of the line motion speed in a DW of a REO.

For definiteness sake, let the high-temperature magnetic phase G_xF_z be considered where in a domain **m**||OZ and **l**||OX, and a Neel type DW with a rotation of **m** (the DW plane being parallel to YZ) containing a 180-deg vertical line without an **m** rotation. At $K_{ab} >> K_{cb} > 0$ where $K_{ab} = d^2/a - a_1$, $K_{cb} = d^2/a - a_3$, using the method described before [4, 5], we can derive an equation for the speed of the center of a sole line v_{DW}, v_L that described the line dynamic in REO:

$$(a_0 - a_0^*)v_{DW} + a_1\frac{v_{DW}^2}{\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}} + a_2\frac{v_{DW}^2 v_L}{\left(1-\frac{v_L^2}{c^2}\right)^{1/2}\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}} + a_3\frac{v_L\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}}{\left(1-\frac{v_L^2}{c^2}\right)^{1/2}} - a_4\frac{v_L^2\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}}{\left(1-\frac{v_L^2}{c^2}\right)} + \frac{v_L\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}}{\left(1-\frac{v_L^2}{c^2}\right)^{1/2}} = a_5\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}, \quad (3)$$

where

$$a_0 = \frac{\pi H_y \Lambda_0}{\alpha H_E \delta_0}, \quad a_1 = \frac{\pi\tau_2\Lambda_0}{6\ \delta_0^2}\frac{H_x}{\gamma H_d H_E}, \quad a_4 = \frac{\pi}{12}\frac{\tau_1 H_x}{\alpha\Lambda_0 H_E^2\gamma}, \quad a_0^* = \frac{\pi}{\alpha H_E}\frac{\Lambda_0}{\delta_0}2m_s H_E, \quad a_3 = \frac{\pi^2\tau_1 H_x^2}{16\,\alpha H_E^2}, \quad a_2 = \frac{\tau_2}{3\gamma^2 H_d H_E\delta_0^2}, \quad a_5 = \mu_L^0 H_x, \quad \mu_L^0 = \frac{\pi\gamma H_d\Lambda_0}{8\ \alpha H_E}. \quad (4)$$

When deriving Eq.(3), the speed of DW itself (weakly depending on the presence of a sole line) is believed to be the same as for homogeneous DW [4].

Note that in Eq.(3), new terms (with coefficients a_0, a_5, and 1) appear along with the known ones. Those are, first, the gyroscopic type term proportional to m_s and increased as compared to that proportional to a_0 because of exchange. Second, the terms in proportion to $v^2{}_{DW}$ and $v^2{}_L$. Third, it is a term mixed with respect to v_{DW} and v_L. Eq.(3) can be reduced to one quadratic with respect to variables $v_{DW}/(1 - v_{DW}^2/c^2)^{\{1/2\}}$ and $v_L/(1 - v_L^2/c^2)^{\{1/2\}}$ having the solution of the form

$$v_L = \frac{f(v_{DW})}{\left(1+\frac{f(v_{DW})}{c^2}\right)^{1/2}}, \quad (5)$$

where

$$f(v_{DW}) = \frac{b \pm \sqrt{b^2 + 4a_4 q}}{2a_4} \quad (6)$$

$$b = 1 + a_2\frac{v_{DW}^2}{\left(1-\frac{v_{DW}^2}{c^2}\right)} + a_3$$

$$q = (a_0 - a_0^*)\frac{v_{DW}}{\left(1-\frac{v_{DW}^2}{c^2}\right)^{1/2}} + a_1\frac{v_{DW}^2}{(1-v_{DW}^2/c^2)} - a_5.$$

Note that for the case $a_4 << 1$ and $v << c$, Erq.(5) has two possible solutions:

$$v_1 \approx -q/b, \quad (7)$$

$$v_2 \approx b/a_4 + q/b. \quad (8)$$

When $H_x = 0$, the expression for f can be simplified significantly:

$$f^* = \frac{(a_0 - a_0^*)v_{DW}(1 - v_{DW}^2/c^2)^{1/2}}{(1 - v_{DW}^2/c^2 + a_2 v_{DW}^2)}. \quad (9)$$

The solution obtained before without account for the g-factor anisotropy, $v_1 \approx -a_0 v_{DG}$ [4], differs from (7) in that now the numerator and denominator of (7) contain new terms proportional to $v^2{}_{DW}$. Although no values for τ_i parameters have been found in literature, it is seen from (4) that the new terms (in proportion to τ_i) are considerably smaller than the former ones. Beginning from high speeds, however, the g-factor anisotropy can influence significantly the line dynamics. It is also of interest to consider the case $H_y = 0$ when there is no usual gyroscopic force. It is seen from (5) that in this case, the form of $v_L(v_{DW})$

depends substantially on a_2. While at small a_2 the function $v_L(v_{DW})$ is almost a straight line parallel to abscissa axis, it tends to a parabola at large a_2.

Let now the $m_s \neq 0$ appearance mechanism be discussed. One possible mechanism consists in that the nonzero component of magnetic susceptibility longitudinal with respect to the equilibrium $\mathbf{l}$ direction, $\chi_{\|}$, is taken into account [10]. For simplicity, we can restrict ourselves to the case when $m_s \approx H_x\chi_{\|}/2M_0$ both in statics and in dynamics. Then the coefficient a_0 in (4) can be renormalized to $a_0{}' = \frac{\pi}{\alpha H_E}\frac{\Lambda_0}{\delta_0}\left(H_y - \chi_{\|}\frac{H_x}{\chi_\perp}\right)$. It is seen therefrom that a new gyroscopic force is appeared. It is, however, in proportion to the external magnetic field as it was before, but this time, to its H_x component.

As the theory of DW with 180-deg lines is unable now explain completely the experimental results [8], it is of interest to study the static and dynamic DW with zero-deg lines at arbitrary values of the material quality factor Q. In what follows, let the features of the static structure be considered for a 180-deg Neel DW (similar to that considered above) but this time containing a zero-deg line. Numerical methods will be used to that end. By analogy with [13], it is assumed that in general case, $\theta(x,y)$, $\varphi(x,y)$. But now a system of equations describing the bidimensional DW structure using angular variables $\mathbf{l} = \mathbf{l}(\cos\theta,\sin\theta\sin\varphi,\sin\theta\cos\varphi)$:

$$\Delta\theta - \left(K_{cb} - K_{ab}\cos^2\varphi + A(\nabla\varphi)^2 \right) \sin\theta\cos\theta = 0, \quad (10)$$

$$A\sin\theta\Delta\varphi - K_{cb}\sin^2\theta\sin\varphi\cos\varphi + 2\sin\theta\cos\theta\nabla\theta\nabla\varphi = 0, \quad (11)$$

has in the initial approximation the form

$$\theta_0 = \mathrm{arctg}(\exp(x/\delta)),$$

$$\varphi_0 = \mathrm{arctg}\left(\frac{2S}{\exp(y/Q^{1/2}\delta_0) + \exp(-y/Q^{1/2}\delta_0)}\right), \quad (12)$$

where $\theta_0(\pm\infty) = 0, \pi$, $\varphi_0(\pm\infty) = 0$, $\delta = \delta_0(1 + Q^{-1}\sin^2\varphi_0)^{-1/2}$ is the DW width; S, amplitude (maximum deviation of the vector $\mathbf{l}$ in the DW center from the turn plane of a homogeneous Neel type DW); θ_0 describes the 180-deg DW while φ_0, the "thin" structure of the DW with a zero-deg vertical Bloch line. The cases where Q = 1, 3, 5, 10 and S = 0.5, 0.75, 1, 3, 10 were considered.

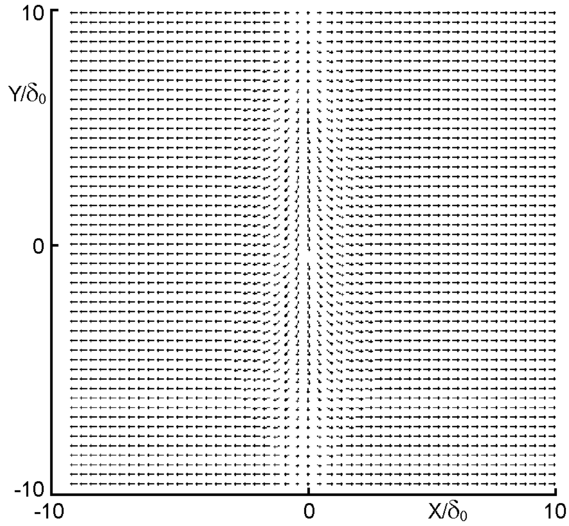

Fig. 1. Distribution structure of antiferromagnetism vector in a 180-deg Neel type DW with a zero-deg Bloch line localized at the (0,0) point. Q = 3, S = 10.

The system of equations (10)–(11) was solved using the iterative method [13–15]. Note that the method mentioned realizes automatically the minimum energy per unit line length. Using angular variables, this energy is expressed as

$$W_L = \frac{1}{2}\int\limits_S\int\left((\nabla\theta)^2 + \sin^2\theta(\nabla\varphi)^2 + \sin^2\theta(1 + Q^{-1}\sin^2\varphi)\right)dxdy - W_0\lambda, \quad (13)$$

where W_0 is the homogeneous DW energy; S, the integration region; λ, the integration region dimension along the y axis. By numerical calculations, the $\theta(x,y)$, $\varphi(x,y)$ dependences were found; proceeding from those, classical parameters defining the "thin" DW structure (the magnetization turn law, DW and line widths, energy of the structure obtained, etc.) were determined for different Q and S values. Fig. 1 presents the obtained distribution of antiferromagnetism vector in a 180-deg Neel type DW with a vertical zero-deg line localized at the point (0,0) for Q = 3, S = 10.

Schematically, the $\mathbf{l}$ turn in such DW can be described as follows. First, along the x axis, the vector $\mathbf{l}$ goes out of the ac plane (what is its turn plane in homogeneous DW) at a maximum deviation in the DW center. Second, in the DW center, the vector $\mathbf{l}$ deviation from the ac plane is increased addi-

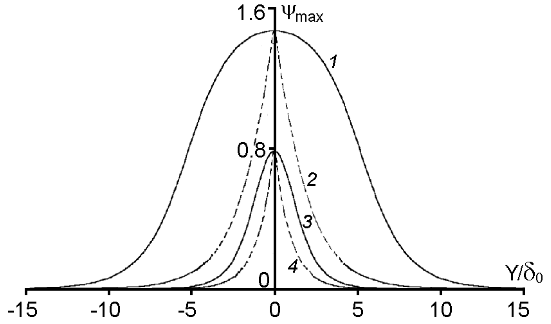

Fig. 2. Dependence of the **l** maximum deviation angle ψ_{max} from the ac plane on y coordinate at different Q and S values: $Q = 3$, $S = 10$, analytical (*1*); $Q = 3$, $S = 10$, calculated (*2*); $Q = 3$, $S = 1$, analytical (3); $Q = 3$, $S = 1$, calculated (*4*).

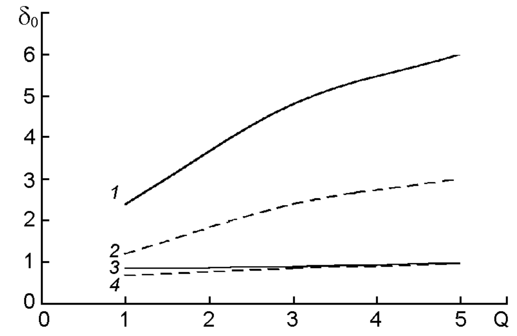

Fig. 3. DW and line width dependence on Q at $S = 0.5$: line width, analytical (*1*) and calculated (*2*); DW width, analytical (*3*) and calculated (*4*).

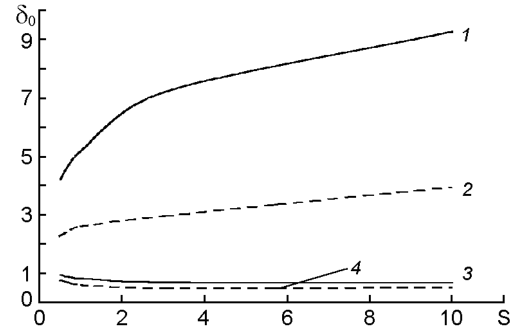

Fig. 4. DW and line width dependence on S at $Q = 3$: line width, analytical (*1*) and calculated (*2*); DW width, analytical (*3*) and calculated (*4*).

tionally as it approaches the line center where the maximum deviation is attained defined by the amplitude S and then the vector **l** returns to its initial position. The dependence of the maximum deviation angle ψ_{max} on the y coordinate for different Q and S values is shown in Fig. 2.

It follows from the numerical calculations that in the case $Q > 10$ (i.e. in the region where the analytical method $Q >> 1$ works well) the structure determined numerically coincides with the analytical one at a high accuracy. As Q decreases, the difference between those results increases in parallel with the amplitude S. But, unlike the DW with a 180-deg Bloch line [13], a maximum difference between analytically and numerically determined angle $(\varphi_0(y) - \varphi(x,y))$ is observed in the region near $Q = 3$ and this difference increases with the amplitude S. A weaker dependence on the amplitude value is found for the angle difference $(\theta_0(x) - \theta(x,y))$ that shows no pronounced maximum for the considered Q values. It is also to note that while the found $\theta(x,y)$ values depend only slightly on the y coordinate for all the Q and S values considered, the $\varphi(x,y)$ depend on x heavily enough.

The dependences of the effective DW width (as determined by the "classic" way after Lilly) and the line one on the coordinate along the DW (y) for different Q and S values are shown in Figs. 3 and 4. The DW width is seen to be substantially independent of Q and S and to differ only slightly from the analytical one, $\delta = \delta_0(1 + Q^{-1}\sin^2\varphi)^{-1/2}$. In contrast, the calculated line width differs significantly enough from the analytical one. The dependence of energy per unit line length at $Q = 3$ (normalized to the energy of a DW with a 180-deg line, ($W_L^0 = 4AQ^{-1/2}$), at $Q = 10$) on the amplitude S is shown in Fig. 5. It is to note that in our case, as S decreases at a constant Q, the calculated and analytical energy values become closer to one another while as S increases, the energy increases and the energy difference $\Delta W(Q,S)$ increases, too. As Q increases, that difference decreases, because the DW structure becomes close to the analytical one. This dependence correlates well with the calculated $\varphi(S)$ dependence. It is seen from Fig. 5 that in our case, the calculated state energy at $S < 5$ is lower than that of a 180-deg line [13], so that the zero-deg line is more energy favorable.

To conclude, it can be stated that the found $\theta(x,y)$ and $\varphi(x,y)$ values are substantially bidimensional in the line localization region and this bidimensionality increases

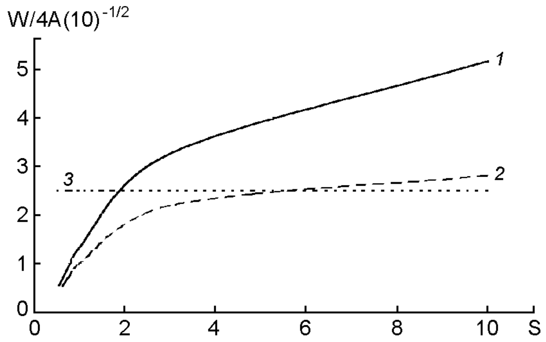

Fig. 5. Dependence of analytical (*1*) and calculated (*2*) energy per unit length of zero-deg line normalized to that of DW with a 180-deg line ($W_L^0 = 4AQ^{-1/2}$) on S at $Q = 10$. Energy per unit length of 180-deg line [13] at $Q = 3$ (*3*).

as Q decreases and as S increases, thus resulting in a considerable changes in the DW structure as compared to the solution (12). Thus, to describe adequately the zero-deg line dynamics in REO, the bidimensionality of θ and φ angle values should be taken into account in a more precise manner.

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Властивості "тонкої" структури доменних меж у рідкісноземельних ортоферитах

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Досліджено динаміку доменної межі (ДМ) з тонкою структурою з урахуванням анізотропії *g*-фактора. Знайдено залежність швидкості руху лінії від швидкості руху ДМ, яка відрізняється від відомої раніше. За допомогою числових методів розглянуто 180-градусну ДМ неєлівського типу з локалізованою на ній нуль-градусною лінією. Визначено закон повороту вектора намагніченості такої ДМ, ефективні значення ширини ДГ та лінії, енергію на одиницю довжини лінії. Показано, що більш точне урахування двовимірності ДМ приводить до істотних відмінностей порівняно з наближеними аналітичними методами.