The oscillation spectrum of asymmetric domain walls in ferrite-garnet films

S. A. Burmistrov, Yu. I. Yalyshev, and V. G. Pokazan'ev

Ya. M. Sverdlov Ural Mountains Electromechanical Institute of Railway Transport Engineers

(Submitted 13 February 1992)
Zh. Eksp. Teor. Fiz. **102**, 633–639 (August 1992)

In this paper we study the domain walls (DW) of a collection of strip domains in a ferrite garnet film, specifically how an asymmetric distribution of magnetization within these DW affects their oscillation spectrum. We show theoretically and experimentally that when the central symmetry of the distribution of DW magnetization through the film thickness is broken, new modes of oscillation are excited in the DW spectrum.

1. INTRODUCTION

In this paper, our main topic of study is the nature of the magnetization distribution across the thickness of the film, which can be varied by external conditions, in particular by constant uniform fields in the plane of the film, and how this distribution influences the spectrum of oscillations of a DW. It is known that in the absence of external fields, the oscillation spectrum of a right-handed twisted domain wall (TDW) in a lattice of strip domains in a ferrite garnet film consists of a set of even and odd modes of oscillation (we will discuss only modes of oscillation corresponding to bending of the film).[1] The representation of the modes in terms of parity arises from consideration of the displacement of a domain wall from its equilibrium position. The value of the displacement q is a function of the coordinate z (the z-axis is perpendicular to the plane of the film), since the TDW has an effective mass which is distributed nonuniformly through the layer thickness. In the case where the function $q(z)$ is even, we speak of even modes of oscillation of the DW, and label them with indices $n = 0, 2, 4$, etc.; the odd functions correspond to odd (antisymmetric) modes with indices $n = 1, 3, 5$, etc.

In spectroscopic experiments a uniform small-amplitude sinusoidal magnetic field perpendicular to the film thickness is used to excite DW oscillations. This field gives rise to forces that act on adjacent walls in opposite directions. Consequently, it can only excite even modes of oscillation of the DW.

However, even if we knew some sort of method for exciting the odd modes of oscillation of the wall, it turns out to be impossible to record their magnetooptic response through the Faraday effect, because in this case the DW oscillations do not cause any relative change in volume for adjacent domains.[1]

In this paper we will show theoretically and experimentally that it is possible to observe mixed modes of oscillation, which are superpositions of even and odd DW modes. Toward this end, we use a constant uniform magnetic field H_y perpendicular to the DW plane.

2. DISCUSSION OF THE RESULTS OF THEORETICAL AND EXPERIMENTAL INVESTIGATIONS

Calculation of the structure and spectrum of oscillations of a DW analytically is extremely difficult; therefore, we use numerical methods. The experimental data we have obtained on the DW spectrum will be compared with the results of numerical calculations which make it possible for us to determine the character of the oscillation modes excited, and to monitor the DW structure.

2.1. Calculation of the structure of a domain wall

The theoretical results of this paper were obtained based on numerical solution of the equations of a truncated description of the DW dynamics.[2] In these calculations we assumed that the DW of a collection of strip domains are all completely equivalent (polarized). The structure of a twisted DW, i.e., the distribution of magnetization in the direction of the z-axis, is characterized by an angle φ. This latter angle, taking into account the external uniform magnetic lying in the plane of the layer, obeys the equation[2]

$$\Lambda^2 \frac{\partial^2 \varphi}{\partial \xi^2} = \sin\varphi \cos\varphi - [h_y(\xi) + h_y] \cos\varphi + h_x \sin\varphi,$$

where $\xi = 2z/h$ is the coordinate along the z-axis normalized by the thickness of the film h ($\xi \in [-1,1]$), $\Lambda = 2(A/2\pi M^2)^{1/2}/h$ is the nonuniform exchange parameter, A is the exchange interaction constant, $h_y(\xi) = H_y(\xi)/8M$ is the normalized stray field, $h_x = H_x/8M$, $h_y = H_y/8M$ are the normalized external magnetic fields applied along and perpendicular to the plane of the wall, respectively, and M is the saturation magnetization.

The solution to these equations is found for the free boundary condition

$$\left.\frac{\partial \varphi}{\partial \xi}\right|_{\pm 1} = 0.$$

A similar method of calculating the distribution $\varphi(z)$ and the DW oscillation spectrum was discussed in Ref. 3.

2.2. Sample characteristics and experimental conditions

The experimental results were obtained using a magnetooptic spectrometer with high spatial resolution. Irising of a polarization microscope in the plane of observation allowed us to achieve a resolution of $\sim 2\ \mu$m. The sample under study was an epitaxial ferrite garnet film with the following parameters: thickness $h = 6.1\ \mu$m; normalized DW surface energy density $l = 4(AK)^{1/2}/4\pi M^2 = 0.36\ \mu$m where K is the anisotropy constant; normalized anisotropy constant $Q = K/2\pi M^2 = 5$ ($4\pi M = 225$ G); equilibrium domain width $W = 4.2\ \mu$m; dimensionless attenuation constant $\alpha = 0.02$, which characterizes dissipative effects in the magnetization dynamics described by the Landau–Lifshits equations; and gyromagnetic ratio $\gamma = 20.9$ MHz/G. The attenuation constant and gyromagnetic ratio were chosen to obtain agreement between the calculated and experimental widths of the oscillation signal at the fundamental frequency. The amplitude of the RF field came to ~ 0.05 to 0.1 Oe.

 0038-5646/92/080338-04$05.00

The spectrometer recorded the DW oscillation signal in the frequency range 1 to 100 MHz.

The strip domain structure was created by demagnetizing a sample from a state of saturation in the presence of a constant planar field $H_x = 180$ Oe. A section of the sample was chosen in which the strip domain structure was without defects within the region of observation. The experimental equivalence of the domain walls was verified after creating the strip domain structure by the unchanging shape of the oscillation signal as we passed from one boundary to another.

2.3. The effect of the field H_x on the DW oscillation spectrum

It is known that the oscillation spectrum of a polarized DW is a set of even oscillation modes that can be excited by an RF field H_{RF}. The results of investigating the zero- and second-order oscillation modes of the DW, along with the dependence of their frequencies on the field H_x directed along the DW ($H_x > 0$), were presented in Refs. 3 and 4.

We note that the field H_x leads to a decrease in the torsion of the DW, causing its structure to approach a Bloch wall and thereby decreasing the inverse effective mass of the DW. This also explains the dependence of the frequencies of the zero-order (ν_0) and second-order (ν_2) modes of the TDW on the field H_x (see Fig. 1, $H_x > 0$).

In this work, we studied the field dependence of the frequencies of these modes in the range of fields H_x from 0 to -5 Oe (in a direction opposite to the initial polarization of the DW. In this range of fields H_x, we observed splitting of the oscillation signal ($H_x = -5$ Oe), which turned into broadening of the signal as the field H_x was increased up to 0 Oe and then to positive values.

We associated this effect with the existence of an asymmetric distribution of magnetization parallel to the z axis with respect to the midpoint of the film. In order to prove this assumption, we used a constant field H_y which was capable of creating a strong asymmetry in the distribution of magnetization if there was no such asymmetry to begin with.

2.4. "Mixed" modes of oscillation of DW

The field H_x can change the structure of the DW, but in this case the distribution of magnetization across the film preserves its central symmetry [the function $\varphi(z)$ is centrally symmetric with respect to the point $z = h/2$; see Fig. 2]. This field does not change the DW spectrum, which consists of even DW oscillation modes (Fig. 3a).

A completely different situation arises if we apply a field H_y to the DW, which is perpendicular to the DW plane. In this case the central symmetry of the distribution $\varphi(z)$ is broken: the field H_y shifts the central region of the DW ($\varphi = 0$) from the midpoint of the film ($z = h/2$) to one of its surfaces (see Fig. 2). Then the two parts of the DW with respect to a region where $\varphi = 0$ become inequivalent in the sense of a distribution of effective mass, which of course is inevitably reflected in the DW spectrum.

We can verify that a new feature appears in the DW spectrum when we turn on the field H_y by comparing Figs. 3a and 3b, in which we present our experimental and theoretical results for the spectrum of oscillations in zero and nonzero fields H_y. In place of two peaks at frequencies $\nu_0 = 50$ MHz and $\nu_2 = 84$ MHz (Fig. 3a, $H_y = 0$) we observe three peaks at frequencies $\nu_0' = 44.5$ MHz, $\nu_1' = 60$ MHz, and $\nu_2' = 79$ MHz (Fig. 3b, $H_y = 60$ Oe). The dependence of the frequencies of these three new modes on the field H_y is shown in Fig. 4. In small fields H_y, the signal from the primary frequency broadens, and as the field increases it proceeds to split. In order to clarify what is causing the appearance of the new peak, we turn to the results of numerical calculations. In Figs. 5a and 5c, we present calculated results for the amplitude q_0 and phase η of the DW oscillations at frequencies $\nu_0 = 50$ MHz and $\nu_2 = 84$ MHz of the spectrum (the zero and second-order even modes) for the case where the field satisfies $H_y = 0$ (the dashed curves).

In this case the first odd mode ($n = 1$) is not excited, and we do not calculate it. However, the functions $q_0(z)$ and $\eta(z)$ for this mode are shown in Fig. 5b, based on results taken from Ref. 1.

The functions $q_0(z)$ and $\eta(z)$ for the corresponding frequencies of the DW spectrum in the presence of the field $H_y = 60$ Oe are shown in Fig. 5 by the solid curves. It is clear that these functions will not be even or odd functions of z, although the form they have is similar to that of the function shown in Fig. 5 for zero field H_y.

If this problem were to be solved analytically, since the DW in the field H_y changes from a symmetric structure to one that is asymmetric, we would have to use a new set of oscillation modes to describe the DW spectrum, which are

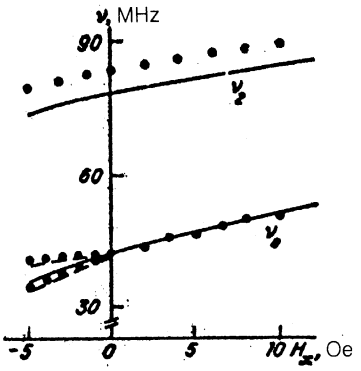

FIG. 1. Experimental (dots) and calculated (solid curve) frequencies of the zero and first order even modes of oscillation of a DW as functions of the field H_x. The dashed curve shows the results of calculations in a field $H_y = 10$ Oe.

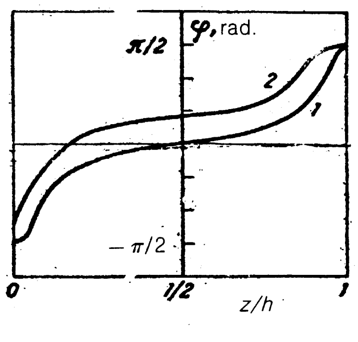

FIG. 2. Distribution of azimuthal angle φ of the deviation of magnetization from the plane of the wall throughout the film thickness: *1*—a DW located in a field $H_x = 10$ Oe ($H_y = 0$); *2*—a DW located in fields $H_x = 10$ Oe and $H_y = 60$ Oe.

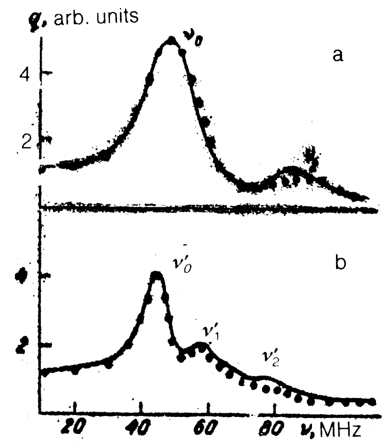

FIG. 3. DW oscillation spectrum in a field $H_x = 10$ Oe: a—$H_y = 0$ Oe; b—$H_y = 60$ Oe. Dots—experiment, solid curve—theory.

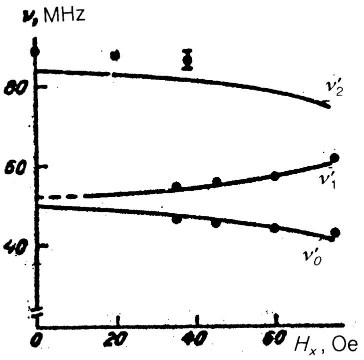

FIG. 4. Dependence of the frequencies of zero, first, and second order "mixed" modes of DW oscillation on the field H_y ($H_x = 10$ Oe). Dots—experiment, solid curve—theory.

linear combinations of the eigenmodes of the DW (even and odd). The coefficients of the linear expansion in this case should depend on the value of the fields H_x and H_y.

In the numerical calculations we obtain at once the result that the "pure" modes are superimposed to give "mixed" modes, labeled $n' = 0,1,2$, etc. Although we could not determine the exact coefficients of a mode expansion, we nevertheless may assume from an analysis of the function $q_0(z)$ and $\eta(z)$ in Fig. 5 that the primary contribution to the mixed modes $n' = 0$ and $n' = 1$ is given by modes $n = 0$ and 1, while the contribution of the other pure modes is negligibly small.

In particular, we should emphasize that by using the field H_y we created necessary and sufficient conditions for excitation of the mode $n' = 1$ by the uniform RF field; since this mode is not a pure odd mode, its presence can be recorded magnetooptically using the Faraday effect. We draw attention to the fact that as the field H_y decreases (see Fig. 4), the frequencies ν_0' and ν_1' of the mixed modes $n' = 0$ and $n' = 1$ approach each other (in the limit $H_y \to 0$ they reduce to the value $\nu_0 = 50$ MHz and $\nu_1 \approx 53$ MHz, the frequencies of the pure modes $n = 0$ and $n = 1$). In this way, we confirm experimentally the closeness of the zero and first-order oscillation modes (in Ref. 1, for the sample described there numerical calculations gave the results $\nu_0 = 41.1$ MHz and $\nu_1 = 45.3$ MHz in the absence of planar fields). The small difference in frequencies of the zero- and first-order modes for $H_y = 0$ and the character of the dependence of their frequencies on the field H_y apparently indicates that they are strongly coupled.

2.5. Asymmetry of the stray field of a DW

Now we can make an attempt to explain the experimental dependence of the frequency ν_0 on the field H_x shown in Fig. 1. To start with we turn to Fig. 6, in which we show the dependence of the frequency of the mixed oscillation mode on the field H_x ($H_y = 75$ Oe). It is clear that for small fields H_x the modes $n' = 0$ and $n' = 1$ in the DW oscillation spectrum are very well resolved. As the field H_x increases, the frequencies of these modes come together, and when a field H_x is reached on the order of 40 Oe the difference in frequencies becomes so small that the signal for these modes merges

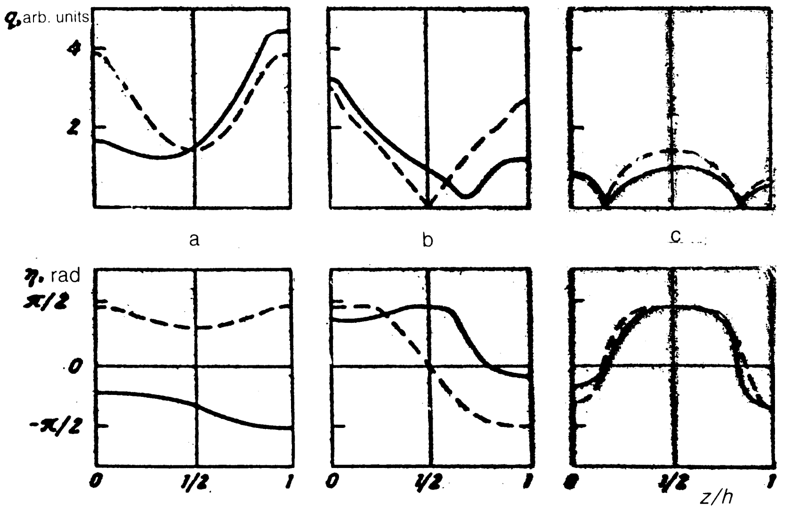

FIG. 5. Calculated dependence of the amplitude q_0 and phase η of DW oscillations on the coordinate z. The field $H_y = 0$ Oe ($H_x = 10$ Oe) is the dashed curve; a—$\nu_0 = 50$ MHz ($n = 0$); b—$\nu_1 = 53$ MHz ($n = 1$, postulated dependence); c—$\nu_2 = 84$ MHz ($n = 2$). The field $H_y = 60$ Oe ($H_x = 10$ Oe) is the solid curve; a—$\nu_0' = 44.5$ MHz ($n' = 0$); b—$\nu_1' = 60$ MHz ($n' = 1$); c—$\nu_2' = 79$ MHz ($n' = 2$).

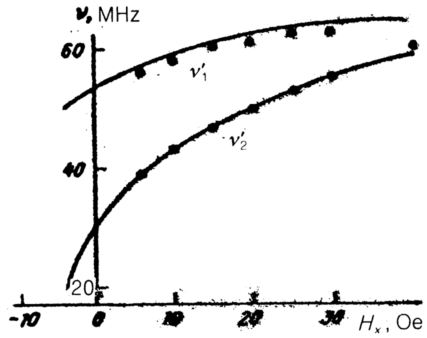

FIG. 6. Dependence of the frequencies of zero and first order mixed modes on the field H_x ($H_y = 75$ Oe). Solid curve—theory, dots—experiment.

into a single broadened signal at a frequency ~62 MHz.

Thus, we have found a way to model experimentally the function $\nu_0(H_x)$ in Fig. 1. Inclusion of a field $H_y = 10$ Oe in the calculation lets us obtain good agreement between the experimental and calculated curves (the latter is shown in Fig. 1 by a dashed curve). However, since no field H_y was included, we are forced to assume that the structure of the DW is asymmetric to begin with, without the action of any external field. We associate this feature with the asymmetry in the distribution of stray fields of the domain wall. Many authors have mentioned the possibility that such an asymmetry could exist, in particular in connection with the problem of ion implantation.

3. CONCLUSION

Thus, in this paper we have shown that when a constant uniform magnetic field is applied perpendicular to the plane of the domain walls of a lattice of strip domains in a ferrite-garnet film, there occurs a change in the distribution of magnetization described by the angle φ across the film, and as a consequence, modes are excited in the DW spectrum that are superpositions of modes of DW oscillation in the absence of this field. We may argue that this is essentially the first experimental proof of the existence of odd (antisymmetric) modes of oscillations of a right-handed TDW involving deflection across the film thickness, and the first time that the frequency of the first odd mode has been determined.

We have proposed a spectroscopic monitoring method to determine the symmetry of the stray field distribution in the film.

[1] B. E. Argyle, W. Jantz, and J. C. Slonczewski, J. Appl. Phys. **54**, 3370 (1983).
[2] A. Malozemoff and D. Slonczewski, *Magnetic Domain Walls in Bubble Materials*, Academic, New York, 1979.
[3] S. Burmistrov, J. Jalishev, and V. Pokazan'ev, J. Magn. Magn. Mater. **96**, 349 (1991).
[4] Yu. I. Yalyshev, I. F. Zheberlyaev, and V. G. Pokazan'ev, Fiz. Tverd. Tela (Leningrad) **30**, 32 (1988) [Sov. Phys. Solid State **30**, 17 (1988)].

Translated by Frank J. Crowne