Solitons on a dynamic domain wall of a ferromagnet

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Experiments are described on head-on collisions of two vertical Bloch-line (VBL) clusters with a domain wall (DW) of an epitaxial iron-garnet film with perpendicular anisotropy. The cluster amplitudes are equal in magnitude and have topological charges of opposite sign. It is shown that at low DW velocities the clusters annihilate via a breather that relaxes during the DW bending relaxation. At higher DW velocities, but still below the Slonczewski peak, mutual penetration of the clusters is observed without change of amplitude or velocity, i.e., they behave like solitons.

1. INTRODUCTION

The experimental search for solitons[1-3] in solids and especially in ferromagnets, has recently attracted noticeable interest. Kjems and Steiner[4] have observed, in neutron scattering from the ferromagnet $CsNiF_3$, a peak interpreted as the first observation of solitons in a quasi-one-dimensional ferromagnet. These experiments as well as related ones, and their far-from-simple theoretical treatment, are described in a review by Izyumov.[5] Nikitenko and co-workers[6] investigated the dynamics of structure elements of type of vertical Bloch lines (VBL) of wide domain walls (DW) of yttrium ion garnets, which have cubic magnetic anisotropy. In their opinion, these should have the properties of solitons. The experiments described below show that VBL in vertical DW of uniaxial ferromagnets have a soliton-like dynamics.

A wall between two oppositely magnetized domains in a uniaxial ferromagnet can have a complicated inner structure. It can contain Bloch lines that separate domain-wall sections with opposite magnetization directions.[7] If the magnetization of a DW center is uniformly directed, the number N of VBL that can exist in the DW is 2π. The dynamics of Bloch lines in epitaxial films of iron garnets with uniaxial magnetic anisotropy was investigated in Ref. 8. It is of interest to investigate the interactions of Bloch lines as they are moved by a gyroscopic force. Such investigations were initiated by us in Ref. 9, and have been continued in the present study. It was shown in Ref. 8 that theory[10-12] predicts the formation of a solitary DW bending wave that accompanies the motion of the VBL. If the nondimensional damping parameter α is large, the wave shape has a strongly pronounced asymmetry that ensures reliable registration of the VBL in the domain wall.

The dynamics of a VBL can be investigated in real time by double high-speed photography. This method is particularly important for the study of interaction between moving VBL, since it makes it possible to record two VBL clusters before and after their collision. It turns out in this case that in collisions between two clusters of equal size but opposite topological charge it is possible to observe not only their annihilation via breather formation[9] but also their interpenetration without changes of amplitudes and shapes of the solitary DW bending waves before and after head-on collisions. This is evidence of the soliton-like behavior of two colliding VBL with opposite topological charges.

2. EXPERIMENT

To record in real time VBL moving in different directions we have used double high-speed photography.[13] During the action of one pulse of the magnetic field that sets the DW in motion, and also through the action of the gyroscopic force and of the VBL cluster, two light pulses separated by the required time interval are incident on the investigated two-domain sample. The angel $2\alpha_F$ between the principal planes of the polarizers in the first and second light rays is equal to double the Faraday rotation in the sample. The principal plane of the analyzer is perpendicular to the bisector of the angle between the principal axes of the polarizers. The first dynamic position of the DW with the VBL cluster is recorded on the photographic film in this case as a light-to-darkness transition, and the second dynamic position as a darkness-to-light transition.[13] At high domain-wall velocities, 10–20 m/s as a rule, it is difficult to produce the required 0.5–1 μs time delay between the two light beams. We used therefore in the experiment two LGI-21 lasers that pumped Rhodamine-6Zh (yellow) dye. Two 8-ns light pulses were then produced, separated by the required interval with electronic circuitry. The optical resolution was not worse than 0.5 μm. The objectives used for this purpose in the microscope had $60^\times$ and $100^\times$ magnification. Two conducting loops perpendicular to the DW were coated on the surface of the investigated two-domain sample. They generated the VBL and the horizongal DW. Current pulses from a G5-48 oscillator were applied to the loops and produced magnetic fields of equal strength but opposite sign, so that the topological charges of the VBL were of opposite sign. After the DW was set in motion in the sample, two VBL clusters with opposite azimuthal-angle-twist directions started to move towards each other. The experimental setup is shown in Fig. 1. In all other details, the procedure em-
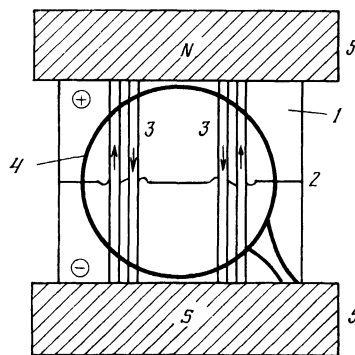

FIG. 1. Experimental setup: 1—two-domain sample; 2—domain wall; 3—conductor loops for the production of VBL; 4—current-carrying coil producing the pulsed magnetic field that propels the DW; 5—permanent magnets to stabilize the DW location.

ployed is similar to that described in Ref. 8. We used epitaxial films of $(BiLaTm)_3(FeGa)_5O_{12}$ iron garnets having domain widths 20–40 μm, $Q \sim 50$, $4\pi M_s \sim 100$ G, and a Bi content close to 1, thus ensuring high magnetooptic contrast.

3. EXPERIMENTAL RESULTS AND THEIR DISCUSSION

The procedure described was used to investigate the interactions of colliding VBL clusters. Figures 2 and 3 show a number of double high-speed photographs of a dynamic domain wall with two VBL clusters of equal amplitude, but with opposite sign of the topological charge. As the DW moves downward, the clusters move towards each other. The velocities of the DW and of the VBL clusters can be easily determined from the data of the figure and from the delay time Δt of the light pulses, a time close to 0.5 μs under the conditions of our experiment. From the DW and cluster velocities one can estimate the number of Bloch 2π lines in the cluster. It follows from the data of Fig. 3 that the VBL cluster velocities are double the DW velocities. Therefore, using the results of Ref. 8 and recognizing that the DW velocity is of the order of 17–22 m/s, we can estimate the number of Bloch 2π lines at $N = 4$–6.

The DW velocities were chosen to be lower than the peak Slonczewski velocity.[7] In this case there is no spontaneous generation of VBL on the dynamic DW, and the only source of VBL are current loops that intersect the DW and twist the magnetization azimuthal angle ψ in the DW.

At DW velocities 15–17 m/s two VBL clusters approaching each other from opposite sides and having topological charges of equal size and opposite sign annihilate within a time of the order of 10^{-6} s (Fig. 2). This time is close to the DW bending relaxation time given by

$$\tau^{-1} = \mu \frac{dH}{dx}, \tag{1}$$

where μ is the DW mobility and dH/dx is the gradient of the magnetic field that stabilizes a single Dw in the investigated sample. This sample had $\mu = 120$ cm/s·Oe, $dH/dx = 4000$ Oe/cm, and, according to (1), $\tau \sim 2 \cdot 10^{-6}$ s. The result described is similar to fluxon–antifluxon annihilation in a distributed Josephson line.[14] The kink–antikink annihilation in the DW of a uniaxial ferromagnet is described in Ref. 9. The results of kink–antikink collisions on a DW, at high DW velocities reaching 20–22 m/s but still slower than the Slonczewski peak velocity, are shown in Figs. 3a–3c. Interpenetration of the kink and antikink is observed. At the instant t_1,
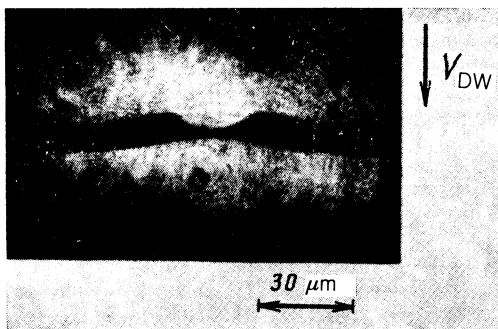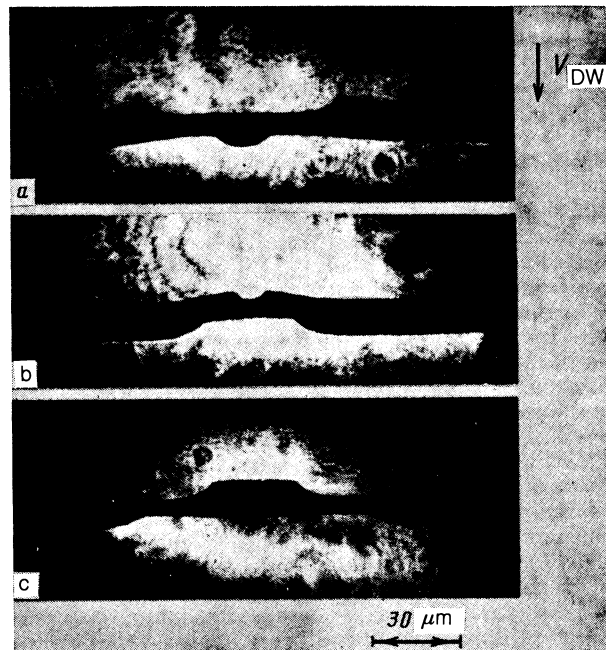

FIG. 3. Set of double high-speed photographs illustrating the passage of two VBL clusters to each other without change of velocity and amplitude of the solitary wave in head-on collision. The DW velocity is 22 m/s.

the distance between two VBL clusters moving counter to each other is of the order of 60 μm (Fig. 3a). After 0.5 μs they are already substantially closer. The cluster velocities are nearly 40 m/s but opposite. The first position of the colliding VBL clusters on Fig. 3b was chosen to be one close (with a small delay time ~ 100 ns) to the second position (Fig. 3a). After 0.5 μs the colliding VBL clusters turn out to be interpenetrating over an approximate distance 25 μm. The amplitudes of the DW kinks do not change. Nor is the velocity changed, as is particularly clearly seen from Fig. 3c, where the cluster interpenetration reaches already 70 μm, so that there is no longer any talk of their interaction, since the localization of the topological charges of the VBL takes place near the maxima of the DW bend and does not extend to the tails of the bend. Of course, one would like to record the kink–antikink passage over appreciably larger distances than noted above, but this requires a substantial increase of the light-pulse intensity, to be able to illuminate much larger sample areas. This entails also a loss in the microscope magnification.

FIG. 2. Double high-speed photography of the annihilation of two VBL clusters colliding head-on. The domain wall velocity is 15 m/s.
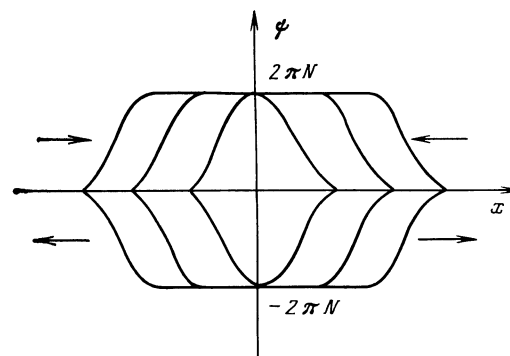

FIG. 4. Schematic illustration of the change of the azimuthal angle between kinks before and after a collision.
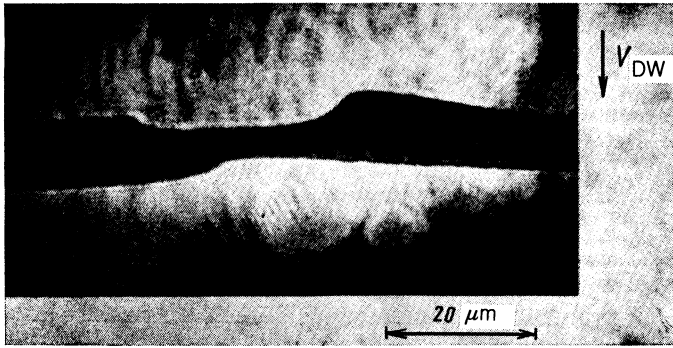
FIG. 5. Double photograph of head-on collision of the VBL clusters with different amplitude of the solitary wave. The DW velocity is 16 m/s.

The obtained photographs of the interpenetrating kinks and antikinks on a dynamic DW correspond to a change of the azimuthal angle between the kinks from $2\pi N$ to $-2\pi N$, as shown schematically in Fig. 4. This result is similar to theoretical result of Perring and Skyrme for the sine-Gordon equation.[2,3]

That the Slonczewski equations describing VBL clusters under the assumption that the DW bending is small at the location of a dynamic VBL cluster are equivalent to the sine-Gorden equation for the azimuthal angle ψ was theoretically demonstrated by Zvezdin.[9] A more adequate theoretical description of the experimental situation calls apparently for numerical computations.

From the experimental standpoint it is of interest to investigate a head-on collision of two kinks having different amplitudes, and topological charges of opposite sign. Such a collision leaves only one cluster having an amplitude equal to the difference between the amplitudes and moving in the direction of the cluster that was larger prior to the collision (see Fig. 5), but the details of the collisions have not yet been investigated.

We have shown thus that when two VBL clusters of equal amplitude but opposite topological-charge sign collide head-on they behave like solitons if the domain-wall velocity is high enough. It is apparently possible to compensate here for the losses in the magnetic subsystem by pumping energy from the external magnetic field to the domain wall and through the gyroscopic force to the VBL clusters. A transition from kink annihilation to penetration is apparently similar to a system of colliding fluxons and antifluxons with account taken of the losses in the system.[2] The greatest difficulties of the theoretical analysis are due here to the substantial bending of the DW at the location of the VBL cluster, so that the wall can only approximately be regarded as one-dimensional.

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