Inelastic scattering of light by a dynamic domain wall

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The inelastic light scattering by a moving domain wall has been detected for the first time by using the method of (Mandelstam-) Brillouin spectroscopy. The scattering spectra show that the velocity of the domain wall depends on the pulsed magnetic field. As the domain-wall velocity approaches the sound velocity, the intensity of the scattered light increases sharply as a result of the emission of phonons by the domain wall. Regions of time-varying motion, in which the scattering spectra are complex in nature, have been detected.

Inelastic scattering of light, including Brillouin scattering, in solids is usually found to occur at delocalized (freed) quasiparticles: phonons and magnons.[1] A localized domain wall of a ferromagnet, which is an irregularity of the magnetic structure, renders the medium optically inhomogeneous due to the magneto-optical effects. As a result, the light wave is partially reflected (scattered) from the domain wall. Because of the Doppler effect, a moving domain wall scatters light with a shift in the frequency $\Delta\nu$ given by

$$2\pi\Delta\nu = \mathbf{v}\mathbf{q}\,, \tag{1}$$

where $\mathbf{v}$ is the velocity of the domain wall, and $\hbar\mathbf{q}$ is the momentum transfer due to scattering. The inelastic light-scattering method can therefore be used to study the domain-wall dynamics. The velocity of a domain wall can be determined by measuring the frequency shift in the scattering spectra.

In the present letter we report the results of a study of a weak ferromagnet $YFeO_3$ with $T_N = 645$ K by the Brillouin-scattering method. In this material the domain-wall dynamics was studied in detail by the method of high-speed photomicrography.[2] The domain-wall dynamics of weak ferromagnets is of interest because the limiting velocity of the domain wall in these crystals is large in comparison with that of ordinary ferromagnets. Since this velocity is larger than the velocity of sound,[3] the interaction of a moving domain wall with acoustic phonons and with other quasiparticles can be studied. In such studies the Brillouin-scattering method clearly holds advantage over other methods, since it in principle allows the phonons emitted by the domain wall to be detected directly.

Our samples were cut in the form of thin ($\sim$100-μm-thick) wafers, with the plane directed perpendicular to the optic axis. These wafers were then polished mechanically and chemically. The wafers fabricated in this manner are fairly transparent: for $\lambda = 632.8$ nm the penetration depth is 50 μm. These wafers can easily form domain walls and a contrasting band structure can be optically observed in them.[2]

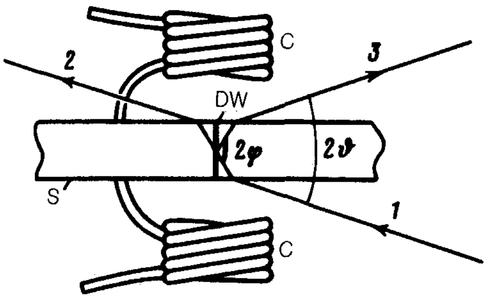

FIG. 1. Experimental layout. S—Sample; DW—domain wall; C—coil producing a pulsed magnetic field; 1, 2, and 3—incident, transmitted, and scattered rays, respectively.

The experimental layout is shown in Fig. 1. A single domain wall, which is stabilized by applying to it a small non-uniform magnetic field ($\nabla \mathbf{B} \approx 30$ mT/cm), is formed in a sample which is held at room temperature. A laser beam (from an LGN-215 He-Ne laser) incident at the Brewster angle is focused on the domain wall. The

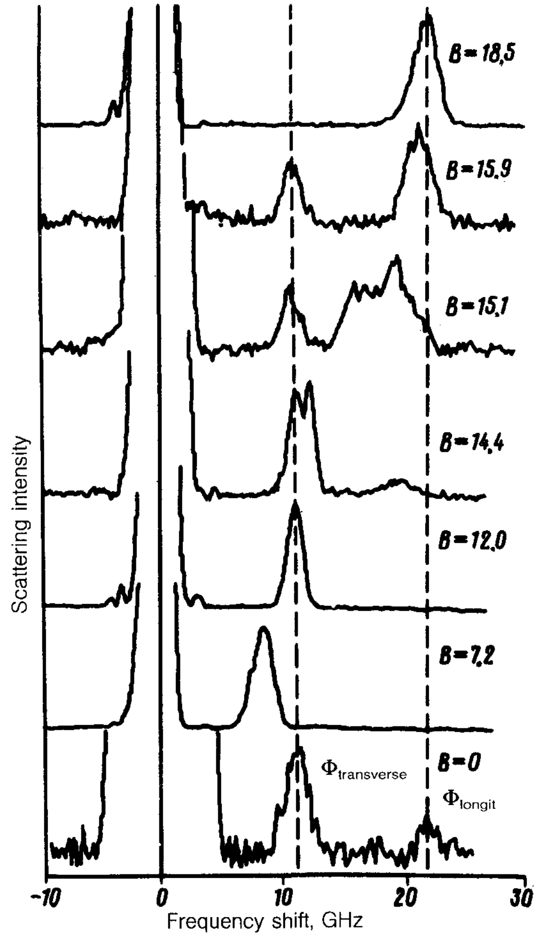

FIG. 2. Spectra of inelastic light scattering in $YFeO_3$ (only the anti-Stokes part is shown). The corresponding pulsed magnetic field B (in mT) is indicated at each spectrum. The vertical scale is different for each spectrum.

coils which produce a magnetic field **B** receive square current pulses of length $T \sim 10^{-7}$ s and repetition frequency 1–5 MHz ($I_{\max} = 30$ A, $B_{\max} = 30$ mT). As a result of application of the magnetic field, the domain wall begins to move at a certain velocity v and during the time between the pulses $\tau = 5$–$15\ T$ it returns to its equilibrium state. The scattered-light spectrum is analyzed with a high-contrast spectrometer based on a scanning, five-port, Fabry-Perot interferometer. During a single scan of the interferometer, the domain wall traverses many times ($\sim 10^6$) the spot upon which the laser beam is focused. The light is scattered only a short time, $t \sim 0.2\ T$, while the domain wall is passing through this spot.

The experimentally observed light-scattering spectra for different values of the applied magnetic field **B** are shown in Fig. 2. The intense line with a zero frequency shift (the principal line) is associated with the elastic scattering of light by the crystal defects. In the case of a domain wall at rest (the $B = 0$ spectrum) we have detected Brillouin scattering by thermal phonons. The presence of intense satellites in the spectra with $B \neq 0$ suggests that we have detected inelastic light scattering due to the motion of the domain wall. The corresponding frequency shifts are determined by the velocity of the domain wall or the phonons:

$$\Delta\nu = \frac{2v\,n}{\lambda} \cos\varphi = \frac{2v}{\lambda} \cos\theta\ , \tag{2}$$

Where n is the refractive index of the medium, λ is the wavelength of light in a vacuum, and φ and θ are denoted in Fig. 1. In our experiments we have $\lambda = 632.8$ nm and $\theta = 20°$. The value of the wave vector of the detected phonons is $q = 2\cos\theta / \lambda = 3 \times 10^5$ cm^{-1} ($cq \sim 10$ GHz). We wish to emphasize that the intensity of the Brillouin scattering by thermal phonons (the $B = 0$ spectrum) is two to three orders of magnitude lower than that of the scattering associated with a moving domain wall.

In the case of scattering of light by a domain wall, which moves in the direction opposite to the incident light beam (to the right in Fig. 1), with the pulsed field **B** oriented in a certain direction, the spectrum exhibits anti-Stokes satellites, which are attributable to the fast motion of the domain wall, and Stokes satellites, which arise as a result of a slow return of the domain wall to the equilibrium state. A change in the direction of the magnetic field reverses the signs of the frequency shifts of the satellites. In our experiments we have detected only a satellite which corresponds to a fast motion of the domain wall and which has a large frequency shift.

A spectrum of Brillouin scattering by thermal phonons (Fig. 2, $B = 0$) has both a Stokes satellite and an anti-Stokes satellite.

Figure 3a is a plot of the velocity of the domain wall, obtained from the scattering spectra, as a function of the pulsed magnetic field B. This plot basically agrees with the curves given in Refs. 3 and 4. In small fields this dependence is linear, $v = \mu B$, and in the given crystal it corresponds to the mobility $\mu = 4 \times 10^7$ cm/(s·T). At domain wall velocities 4.1×10^5 cm/s and 7.0×10^5 cm/s, which correspond to the velocities of transverse and longitudinal sound in YFeO$_3$ (Fig. 2), the $v(B)$ curve has plateaus. Directly behind these plateaus are the regions in which the scattering spectrum has several satellites (the spectra in Fig. 2 with $B = 14.4$, 15.1, and 15.9 mT). This effect is

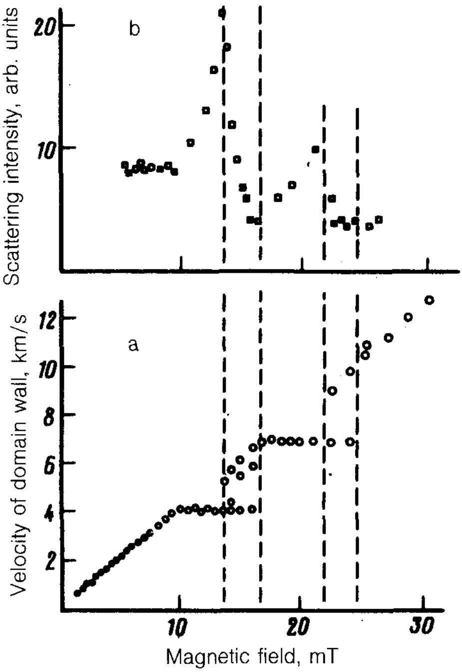

FIG. 3. The velocity of the domain wall (a) and the intensity of inelastic light scattering (b) versus the pulsed magnetic field *B*. Dashed line—Region of time-varying motion of the domain wall.

apparently attributable to the fact that the domain wall moves in an irregular manner during the pulse.

In Refs. 5 and 6 the plateaus on the $v(B)$ curve were attributed to magnetoelastic retardation of the domain wall or to the emission of phonons by the domain wall.[5] To verify this assumption, we measured the scattering intensity I as a function of the pulsed magnetic field B. This plot is shown in Fig. 3b. A comparison of Fig. 3a and Fig. 3b shows that the scattering intensity does not depend on B in the linear part of the $v(B)$ curve. As the $v(B)$ curve approaches a plateau, $I(B)$ rapidly increases and reaches a maximum at the end of the plateau. At this point I is ~ 2.5 times the intensity of the Doppler line and $\sim 10^3$ times the intensity of the thermal phonons. In the region of time-varying motion of the domain wall the scattering intensity decreases and then increases again at the second plateau. The sharp increase of I at the plateaus suggests that the domain wall and the phonons emitted by it both contribute to the scattering intensity. As the velocity of the domain wall approaches the velocity of sound (transverse or longitudinal), the amplitude of the elastic strain accompanying it increases and the symmetry of the elastic strain changes (see Ref. 6). A decrease in the intensity of the scattering of light and hence in the amplitude of the elastic strain in the transient region apparently stems from the fact that the motion of the domain wall in this case is nonuniform (see Refs. 3 and 7) and/or irregular.

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