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Narrowing of the frequency-linewidth in structured magnetic strips: Experiment and theory

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We examine the frequency-linewidth in structured magnetic materials experimentally and theoretically and show that this linewidth can decrease as the external field (or the frequency) is increased. This decrease in the frequency-linewidth occurs in many different systems and does not indicate an increase in damping at low frequencies, as has been suggested. Further, the frequency-linewidth can be very large for extended ferromagnetic films, but becomes significantly smaller for structured films that are narrower than a few microns. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1968433]

Ferromagnetic resonance experiments have been a significant characterization tool for decades. Often the resonance is detected by imposing a small oscillating magnetic field on a sample at a fixed frequency and scanning slowly over different values of a semiconstant, external magnetic field. The resonance frequency in a magnetic sample is determined, in part, by the external field. As the external field is adjusted, the natural precession frequency eventually equals the frequency of the oscillating field and significant power absorption occurs. The absorption is typically characterized by two parameters: the resonant field and the width, in magnetic field, of the absorption curve. It is well known that the width of the absorption curve depends on the frequency of the measurement. An often quoted result[1] is

$$\Delta H = \Delta H_o + 1.16\alpha\omega/\gamma, \tag{1}$$

showing that the field-linewidth ΔH increases linearly with angular frequency ω. Here ΔH_o is a frequency-independent contribution to the linewidth caused by inhomogeneous broadening, γ is the gyromagnetic ratio, and α is the damping parameter from the Landau-Lifshitz equations.

Recently, a variation of the traditional ferromagnetic resonance technique has become popular. In this method the external field is held constant and one scans over frequency.[2–5] One then obtains a linewidth in frequency rather than a linewidth in field. Intuitively, one might expect that the frequency-linewidth ought to increase as the frequency is increased, just as is found for the field-linewidth, since both measurements represent measures of damping. In fact, one often finds that the frequency-linewidth decreases as a function of frequency rather than increases.[2–5] This decrease in frequency-linewidth occurs in many different systems and suggests, incorrectly, an increase in damping at low frequencies.

In this letter, we address the issue of the differences between frequency-linewidth and field-linewidth and apply these considerations to the behavior of linewidth measurements in ultrasmall magnetic structures. We show that the frequency-linewidth can initially decrease and then increase as the external frequency is increased. We will demonstrate, furthermore, that in planar magnetic films the frequency-linewidth can be quite large at low frequencies, but if the magnetic film is structured so as to reduce its lateral dimensions, then the frequency linewidth can be dramatically reduced. We will explain the differences between frequency-linewidth and field-linewidth using the properties of the resonance frequency for planar films and structured samples.

To illustrate this behavior, we carried out a series of measurements on microstrip waveguides operating in the transverse magnetic mode.[7–9] In our microstrip structures a thin ferromagnetic film, biased by an external magnetic field, is on the inside of the waveguide and absorbs energy significantly when the frequency of the electromagnetic wave inside the waveguide matches the ferromagnetic resonance frequency. Figure 1 shows the transmission as a function of frequency for different applied fields. It is clear that the frequency-linewidth is distinctly narrower at higher frequencies.

In Fig. 2(a) we show the behavior of the frequency-linewidth of the transmission dip as a function of field for microstrips with a Fe layer thickness of 100 nm, a length of 3 mm, and for different widths. The frequency-linewidth is measured as the width of the dip in S_{12} seen 3 dB above the minimum value of S_{12}. The 3 dB difference represents a change of half-power. It is clear that the wider microstrips have significantly larger linewidths, and that the frequency-linewidth *decreases* as a function of field. Figure 2(b) shows a similar behavior for a different set of samples. Again, the wider microstrips have larger frequency-linewidths, but now the frequency-linewidth initially decreases as the field is increased and then subsequently increases.

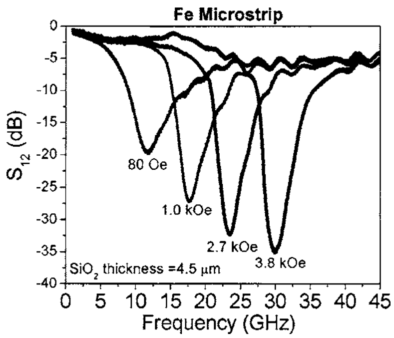

FIG. 1. Transmission as a function of frequency for different applied fields in a Fe-based microstrip geometry. The thickness of the Fe film is 350 nm, the length is 3.3 mm, and the width is 18 μm. The width of the transmission dip clearly narrows as the frequency increases.

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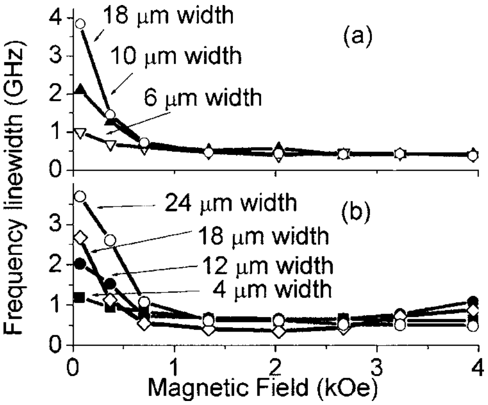

FIG. 2. Experimental results summarizing the frequency-linewidth for Fe-based microstrips with different widths. The results in (a) and (b) are from different sets samples. In (a) the length of the device is 3 mm, in (b) it is 2 mm. The thickness is 100 nm in all cases.

To explain this behavior we first note that the frequency of the transmission dip is given accurately by the ferromagnetic resonance condition for a ribbon-shaped magnetic element:[8]

$$\omega = \gamma\sqrt{(H + H_a + (N_y - N_z)4\pi M_s)(H + H_a + (N_x - N_z)4\pi M_S)}, \tag{2}$$

where M_s is the saturation magnetization, the anisotropy field is H_a, and H is the applied field, where H is assumed to be along a uniaxial anisotropy axis. The demagnetizing factors N_x, N_y, and N_z may be approximated for a rectangular parallelepiped using an analytical approach developed by Aharoni.[10] Here N_x, N_y, and N_z govern the demagnetizing fields perpendicular to the surface of the microstrip, along the width of the microstrip, and along the length of the microstrip, respectively. As we will see, this equation plays a fundamental role in governing the frequency-linewidth.

The frequency as a function of field for microstrips of different widths is shown in Fig. 3. One finds a significant increase in frequency at zero applied magnetic field as the width of the microstrip is reduced. In addition, there is a distinct change in slope, especially at low fields. As we will see, these features will play an important role in understanding the frequency-linewidth.

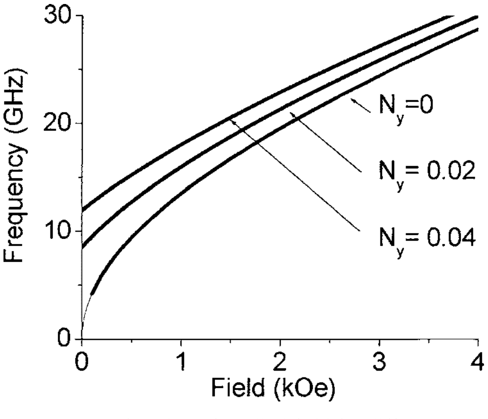

FIG. 3. Frequency as a function of applied field for different demagnetizing factors, which correspond to different widths of the magnetic element in the microstrip. N_y=0 corresponds to an infinite film. N_y=0.04 is the demagnetizing factor for a microstrip with a width of 4.2 μm and N_y=0.02 is the demagnetizing factor for a microstrip with a width of 9.6 μm, assuming a thickness of 100 nm for the magnetic film.

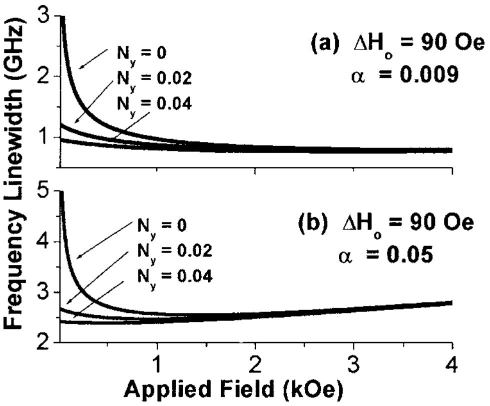

FIG. 4. Theoretical curves for frequency-linewidth as a function of field for different demagnetizing factors, and therefore different widths of the magnetic element in the microstrip. In (a) α=0.009 and the frequency-linewidth decreases as the field is increased and then becomes flat at high fields. In (b) α=0.05 and the frequency-linewidth initially decreases, and eventually increases at high fields.

The connection between the frequency-linewidth $\Delta\omega$ and the field-linewidth ΔH is now found simply by[11]

$$\Delta\omega = \frac{\partial\omega}{\partial H}\Delta H. \tag{3}$$

Thus, two factors play an important role in determining the frequency-linewidth: the slope $\partial\omega/\partial H$ and the precise form of ΔH. From Fig. 3 one can see that the slope of the ω versus H curve changes substantially depending on the width of the microstrip. For example, for N_y=0 (the infinitely extended film) the slope is large near H=0, and one would thus expect a large $\Delta\omega$. This is the fundamental reason that the frequency-linewidth should be large at low fields (or low frequencies) and become smaller at higher fields. As the width of the microstrip is narrowed, the slope near H=0 becomes smaller and $\Delta\omega$ should also be smaller, in agreement with the experimental results.

As pointed out earlier, the ΔH term also plays an important role in the frequency-linewidth. If, for example, the inhomogeneous contribution to the field linewidth is zero [ΔH_o=0 in Eq. (1)], then the frequency-linewidth increases as the external field is increased, contrary to the experimental results presented earlier. In Fig. 4 we show the theoretical results for different α values. The parameters ΔH_o=90 Oe and α=0.009 produce the results seen in Fig. 4(a), which agree reasonably well with the experimental data found in Fig. 2(a). In particular, the dependence of the frequency-linewidth on the width of the Fe film and the field dependence are well represented. In Fig. 4(b), the value of ΔH_o is unchanged, but the damping parameter is increased α=0.05. In this case, the frequency linewidth initially decreases and then slowly increases as the field is increased, in reasonable agreement with the experimental results of Fig. 2(b).

In conclusion, one finds a surprising feature in the frequency-linewidth: the frequency-linewidth decreases as the frequency (or field) is increased.[12] Further, the linewidth is very large for unstructured ferromagnetic films, but becomes significantly narrower for structured films. This behavior can be explained by an understanding of the ω versus H curve and the behavior of the field-linewidth. This effect originates from the nonlinear dependence of the resonance frequency as a function of the applied magnetic field and the presence, in the studied samples, of the inhomogeneous broadening of the field linewidth (zero frequency offset). Finally, we note that one should not expect a complete quantitative agreement between experiment and theory. The calculation presented here neglects eddy current damping in metallic samples, which can be important for samples thicker than about 30 nm.

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