Micromagnetic calculation of the high frequency dynamics of nano-size rectangular ferromagnetic stripes

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Abstract

Nano-size ferromagnetic dots, wires and stripes are of strong interest for future high speed magnetic sensors and ultra high density magnetic storage. High frequency dynamic excitation is one way to investigate the time scale of the magnetization reversal in submicron particles with lateral nanometer dimension. Macroscopic models like the Landau-Lifshitz (LL) model are often used to describe the switching process. However, these models do not take into account the non uniformity of the magnetization structure. In this paper dynamic micromagnetic calculations are used in determining the high frequency susceptibility of a 1 μm $\times$ 50 nm $\times$ 5 nm Permalloy stripe. The studied structure exhibits two resonance modes. The higher, primary peak is around 10 GHz, and can be identified with the uniform resonance mode predicted by the macroscopic LL model. The low frequency peak is attributed to the splay of the magnetization distribution near the end of the stripe.

I. INTRODUCTION

Patterned mesoscopic magnetic structures have attracted much interest for their possible application to data storage applications and microwave devices. However, shrinking structures to submicrometer size affects the magnetic static and dynamic properties of the structures. The knowledge of the dynamic behavior of such structures is fundamental for the design of MRAM components [1,2] or microwaves devices. In the first case, [3] shows that the ring down occuring after switching takes several ns to dissipate. In the latter case, the shape of the imaginary part of the susceptibility and the frequency position of the resonances are very important for the applications of the device.

Frequently a macroscopic model (like Landau Lifshitz) is used to describe switching processes or linear response to small excitations in terms of susceptibility. In such models, the magnetization is assumed to be uniform in the sample. These models can give a good qualitative prediction of the susceptibility if associated with a good evaluation of the demagnetizing fields [4]. However, such model are unable to take into account the non-uniformity of the magnetization pattern. Except in few special cases, an analytic determination of the susceptibility is impossible. Micromagnetic calculations can take into account an arbitrary magnetization pattern and can therefore be used to obtain the susceptibility [5,6]. In this work, micromagnetic calculations are used in determining the dynamic susceptibility $\chi(\omega)$ of a Permalloy stripe.

II. MAGNETIC SUSCEPTIBILITY CALCULATIONS

A. Calculation method

In the micromagnetic framework [7,8], the magnetization distribution is obtained by the minimization of the total energy density functional:

$$\mathrm{E} = \mathrm{E}_{\mathrm{exch}} + \mathrm{E}_{\mathrm{demag}} + \mathrm{E}_{\mathrm{anis}} + \mathrm{E}_{\mathrm{zeeman}}. \tag{1}$$

The average energy density E is a function of $\mathbf{M}$ and includes exchange, demagnetization, anisotropy and applied field (Zeeman). The exchange is calculated by an 8-neighbor interpolation: $E^i_{\mathrm{exch}} = (A/3)\sum_{j=1}^{8}(1 - \mathbf{m}_i \cdot \mathbf{m}_j)$. The magnetostatic fields are calculated using FFT techniques. One can find more details about the program and the evaluation of the energy terms in [9,10]. The time evolution of the magnetization distribution is determined by solving a microscopic Landau-Lifshitz equation, in which the effective field is a function of time and position:

$$\frac{\partial \mathbf{M}(\mathbf{r},t)}{\partial t} = -|\gamma|\mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{\mathbf{eff}}(\mathbf{r},t) - \frac{\alpha|\gamma|}{|M|}\mathbf{M}(\mathbf{r},t) \times (\mathbf{M}(\mathbf{r},t) \times \mathbf{H}_{\mathbf{eff}}(\mathbf{r},t)) \tag{2}$$

$$\mathbf{H}_{\mathbf{eff}} = -\frac{1}{\mu_0}\frac{\partial E}{\partial \mathbf{M}}. \tag{3}$$

Starting in an equilibrium state, the susceptibility is obtained by exciting the system with a small external field $h(t) = 7.96 \cdot 1_{[0,\infty]}(t)\exp(-7.675t)$ A/m (t in ns). The Fourier transform of this expression leads to $h(\omega) = 7.96/(7.675 + 2\pi i\omega)$ (ω is in GHz). This form as significant response up to 20 GHz, which enable us to calculate the susceptibility up to this frequency. This field is spatially homogeneous in the volume V of the sample, and is introduced into the density functional of the Zeeman term. The amplitude of the driving field is very small to minimize non-linear behavior. We define the spatial average dynamic susceptibility χ in the direction $\mathbf{u}$ (here $\mathbf{u}$ is along the x axis) by:

$$< \mathbf{M}(t) > \cdot\mathbf{u} = \int_{-\infty}^{+\infty} \chi(t - t')[\mathbf{h}(t') \cdot \mathbf{u}]dt', \tag{4}$$

where

$$< \mathbf{M}(t) >= \frac{1}{V}\int_V \mathbf{M}(\mathbf{r},t)d\mathbf{r}. \tag{5}$$

The form of the equation in the time domain enables us to use Fourier transform techniques to obtain the susceptibility in the frequency domain:

$$M(t) = (\chi \star h)(t) \leftrightarrow M(\omega) = \chi(\omega) \cdot h(\omega) \tag{6}$$

B. Studied system

The dynamic properties of a Permalloy stripe of dimensions 1μm $\times$ 50 nm $\times$ 5 nm were investigated. The magnetic parameters M_s, H_k and α taken for the calculation are the parameters usually taken for Permalloy (M_s=800 kA$\cdot$m^{-1}, H_k=500 A$\cdot$m^{-1}, $\alpha = 0.015$). The mesh size is 5 nm in the plane of the layer, and along the thickness. A 2D grid was used for the calculation. The calculations were carried out with no external applied field other than the small excitation field, and the susceptibility was determined along the Ox axis (perpendicular to the length and in the plane of the stripe).

III. RESULTS AND DISCUSSION

Due to the aspect ratio of the structure, the equilibrium magnetization pattern is a nearly uniform magnetized state, with some spreading near the ends of the stripe. The imaginary part of the susceptibility ($\chi = \chi' - j \cdot \chi''$) of this structure is plotted in Fig. 1. The studied structure exhibits two resonance modes. The higher, primary peak can be identified with the uniform resonance mode predicted by the macroscopic LL model. In Fig. 1, the imaginary part of the susceptibility of a uniformly magnetized stripe of Permalloy is plotted using the macroscopic LL model. This enable us to identify the primary peak obtained by micromagnetic calculations as the uniform resonance part of the spin system. The low frequency mode, located around 4 GHz, can be attributed to the splay of the magnetization near the end of the stripe. Increasing or decreasing the width changes the shape of the magnetization near the ends of the stripe (Fig. 2(a) and 2(b)): the spreading of $\mathbf{M}$ is more important in the case of larger stripes. The imaginary part of the susceptibility is plotted in Fig. 3 for varying stripe widths. One can see that both resonance modes are strongly dependent on the width. Next, the effect of the stripe length is investigated. Since the demagnetizing field depends little on the stripe length, the equilibrium pattern is not affected. However, the relative size of the end zones will decrease with increasing length.

This is the reason why the amplitude of the low frequency mode decreases as the length is increased, and the frequency doesn't shift (Fig. 4).

Up to this section only the susceptibility, which is an average quantity, has been studied. An investigation of the local magnetization $\mathbf{M}(\mathbf{r},t)$ (more exactly the difference $M_x(\mathbf{r},t)$-$M_x(\mathbf{r},t{=}0)$), or it's Fourier transform $\mathbf{M}(\mathbf{r},\omega)$, will enable us to prove the localized nature of the low frequency mode. In Fig. 5, we have plotted the temporal response of the magnetization, for different values of $\mathbf{r}$. Fig. 5 (a) illustrates the temporal response of one spin, located in the core of the stripe. Fig. 5(c) is the resonance of one cell near end of the stripe (located in the middle of the width). Fig. 5(b) is an intermediate case. The localization of the second mode near the end of the stripe is now clear, and its existence is related to the spatial inhomogeneity of the demagnetizing fields at the boundaries.

IV. CONCLUSION

In this paper, micromagnetic calculations are applied to the determination of the susceptibility for a nano-sized magnetic stripe. Due to the non-uniformity of the magnetization pattern, two resonance modes are found: the primary mode, predicted by macroscopic resonances models like LL, is identified with the resonance of the magnetization located in the core of the stripe. The strong non-uniformity of the demagnetizing fields near the boundaries yields a second, separate resonance mode.

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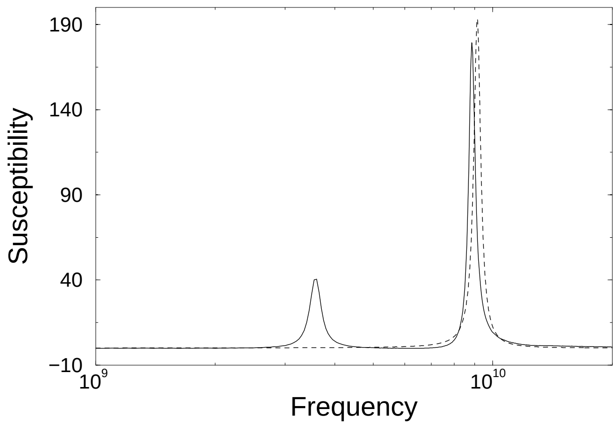
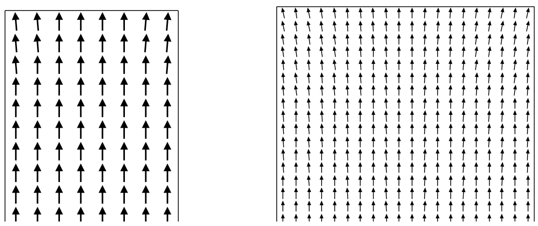


FIG. 1. Imaginary part of the susceptibility. Dashed lines are from the macroscopic LL calculation, solid lines the micromagnetic simulation.



(a) width 20 nm (b) width 50 nm

FIG. 2. Equilibrium magnetization for different width of the stripe (length=1 μm, thickness=5 nm)

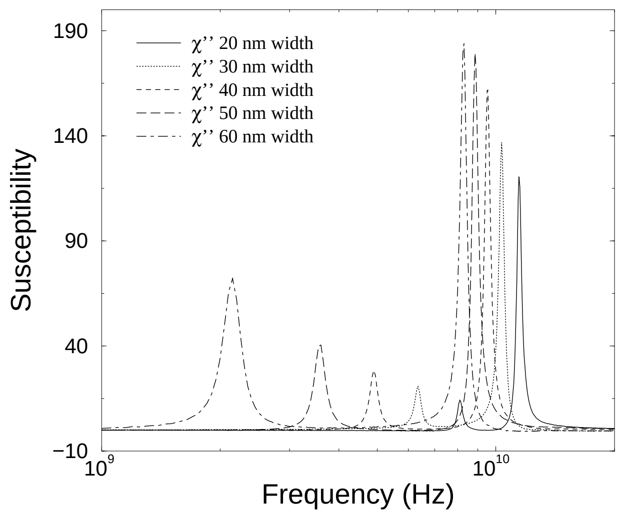


FIG. 3. Imaginary part of the susceptibility for different width of the stripe (1μm length).

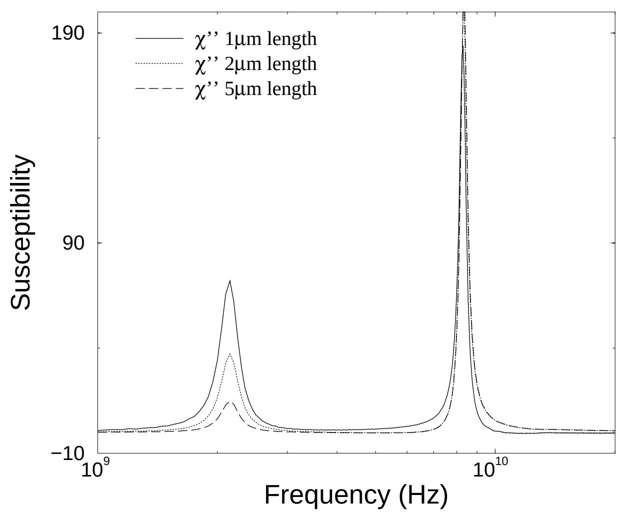


FIG. 4. Imaginary part of the susceptibility for different length of the stripe (50 nm width).

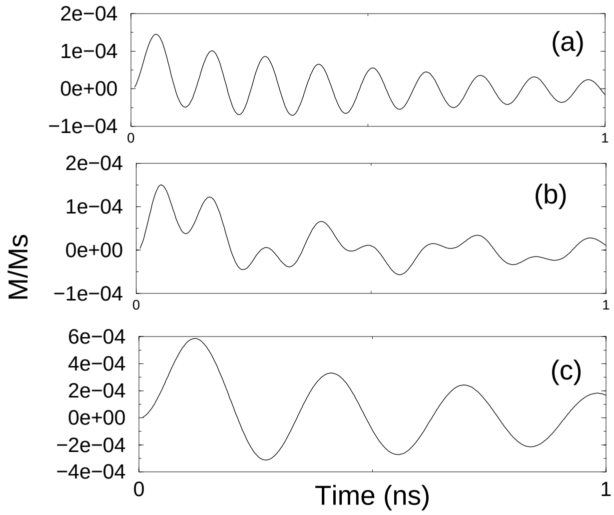


FIG. 5. Temporal response of the magnetization for an isolated cell of calculation, for a 1μm $\times$ 50 nm $\times$ 5 nm stripe. (a) is a spin located in the middle of the stripe, (c) a spin near the ends, and (b) the intermediate case.