Domain wall resonant modes in nanodots with a perpendicular anisotropy

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Abstract

The dynamic susceptibility spectra of ferromagnetic nanodots with a large perpendicular anisotropy exhibiting a two-stripe domain state at remanence are investigated using 3D micromagnetic simulations. Due to the confined geometry, multiple domain wall excitations are revealed within the frequency range 0.1 - 15 GHz. The size dependence (dot thickness $L_z$ and dot diameter $D$) of the excitation spectra is reported.

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Magnetization dynamics in nanometer-sized elements attracts much attention due mainly to the promising applications in advanced storage media or spin electronic devices. One intriguing class of nanostructures corresponds to cylindrical dots with a large uniaxial perpendicular anisotropy ($Q > 1$, where $Q$ is the quality factor defined as $Q = K_u/2\pi M_s^2$, with $K_u$ the uniaxial anisotropy constant and $M_s$ the saturation magnetization). It was recently evidenced [1] both experimentally and theoretically that various magnetic states (quasi-uniform single-domain state, bidomain states consisting of either a two-stripe domain structure or a bubble state [2]) can be stabilized in such systems depending on the ratio $D_0 = D/P_0$, where $D$ is the dot diameter and $P_0$ is the zero-field period of the stripe domains [3] for the continuous film with the same magnetic parameters and the same thickness.

The purpose of this paper is to investigate the high-frequency response (0.1 - 15 GHz) of perpendicularly magnetized cylindrical nanodots in the size regime $D_0 \leq 1$ for which the two-stripe domain structure is the ground-state configuration. The zero-field dynamic susceptibility spectra were computed using two three-dimensional (3D) micromagnetic codes based on the Landau-Lifshitz equation for magnetization motion, described elsewhere [4,5] and previously used for studying the dynamic response of cylindrical dots with a vortex-type magnetic configuration [6]. The selected material parameters are representative of ferromagnetic alloys (FePt, CoPt, FePd) displaying a large perpendicular anisotropy, namely, $M_s = 1.15 \times 10^6$ $\text{A/m}$, the exchange constant $A = 1.10^{-11}$ $\text{J/m}$, $K_u = 0.95 \times 10^6$ $\text{J/m}^3$ ($Q = 1.2$), the gyromagnetic ratio $\gamma = 1.76 \times 10^1 \text{s}^{-1}$ and the damping parameter $\alpha = 0.02$. The used mesh sizes are $\Delta x = \Delta y = \Delta z = 1.5 \text{nm}$.

Figure 1 shows the two-stripe domain equilibrium magnetization configuration for a cylindrical dot with the thickness $L_z = 48 \text{nm}$ and the diameter $D = 96 \text{nm}$. This state consists of a single domain wall (DW) separating up and down magnetized domains. As reported for continuous magnetic films with a large perpendicular anisotropy [7], the DW displays a Bloch character at the dot center and a Néel character at the dot surfaces, the DW being wider in the Néel part than in the Bloch part. In addition, the lateral confinement of the DW induces the appearance of spatial distortions along both the $y$ axis at the dot surfaces and the $z$ axis for vertical planes near the dot edge. Lastly, the DW terminates perpendicularly to the dot edge leading for the investigated dot to a large magnetization component $M_y$ within the Bloch DW part at the dot edge.

The dynamic susceptibility spectra (imaginary part, $\chi_{yy}''$ and $\chi_{zz}''$) associated with this nanodot are reported in Fig. 2. For the $\chi_{zz}''$ spectrum, three intensive resonance lines, labeled (1), (2), and (3), are observed at 1.72 GHz, 2.93 GHz, and 5.14 GHz, respectively. An analysis of the spatial distribution of the dynamic magnetization (modulus of $\chi_{zz}$) at

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each resonance frequency permits us to identify these lines as DW modes characterized by different localizations of the excited spins. The low-frequency resonance can be viewed as a bulk DW mode whereas the intermediate-frequency resonance corresponds mainly to an edge DW mode. The high-frequency resonance is associated with an higher-order DW mode. It should be noted that these resonances exist also at the same frequencies but with one order of magnitude weaker for the $\chi''_{yy}$ spectrum (not presented here). For the $\chi''_{yy}$ spectrum, three resonance lines of weaker intensities, labeled (4), (5), and (6), appear at higher frequencies (10.47 GHz, 10.79 GHz, and 12.81 GHz). These lines are also assigned to DW modes arising from spins localized essentially within the Néel DW parts. These modes can also be classified according to the spatial variations along the y axis (bulk DW mode, edge DW mode, and higher-order DW mode for increasing resonance frequencies). These results can be compared with those obtained from 2D dynamic micromagnetic simulations for thin films with a perpendicular anisotropy [7,8]. In this case, one main DW resonance is revealed for each pumping configuration (a Bloch-type DW mode for the $\chi''_{yy}$ and $\chi''_{zz}$ spectra and a Néel-type DW mode for the $\chi''_{yy}$ spectrum). The lateral confinement induces a splitting of the DW modes existing in the continuous media.

It should be noted that high-frequency resonances (beyond 35 GHz) related to domain modes were also pointed out numerically for both the $\chi''_{yy}$ and $\chi''_{zz}$ spectra. The thickness dependence of the different DW resonance frequencies is reported in Fig. 3(a) for a dot diameter $D = 96$ nm. Within the thickness range 24 nm - 48 nm, a weak variation of the resonance frequencies is observed for the three low-frequency DW modes ($\chi''_{yy}$ spectrum). In contrast, the resonance frequencies of the three Néel-type DW modes ($\chi''_{yy}$ spectrum) decrease rapidly with increasing dot thickness. This last evolution is in agreement with the one observed for extended films with a perpendicular anisotropy [7] and is related to the progressive change of the internal DW structure as the film or dot thickness increases. For thinner dots, the DW structure is deeply modified (existence of Bloch lines, vanishing total $M_z$ component) leading to another dynamic behaviors.

![Fig. 1](image1.png)

**Fig. 1.** Two-stripe domain magnetization configuration for a cylindrical dot with $Q = 1.2$, $L_z = 48$ nm and $D = 96$ nm. (a) $M_z$ component. (b) $M_y$ component within the vertical plane at the position $y = 0.94 D / 2$. (positive values in red).

![Fig. 2](image2.png)

**Fig. 2.** Dynamic susceptibility spectra (imaginary part $\chi''_{yy}$ and $\chi''_{zz}$) and spatial distribution of $|\chi_{zz}|$ at each resonance frequency (isosurfaces of $|\chi_{zz}|$ in beige showing the highest excited spin regions).

![Fig. 3](image3.png)

**Fig. 3.** Size dependence of the DW excitation spectra. (a) Thickness evolution of resonance frequencies. (b) $\chi''_{yy}$ spectrum for three dot diameters.

The effect of the dot diameter on $\chi''_{yy}$ spectrum is displayed in Fig. 3(b) for a dot thickness $L_z = 24$ nm. For the investigated diameter range 48 nm - 144 nm, the number of DW resonance lines is found to be an increasing function of the dot diameter.

As a concluding remark, it should be underlined that the multiple DW excitations resulting from the reduced lateral dimensions were obtained without any pinning condition at the dot edge.

**References**