Dynamics of ferromagnetic nanomagnets with vortex or single-domain configuration

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We study the dynamics of flat circular permalloy nanomagnets for 1.) magnetic vortex and 2.) single-domain configurations using micromagnetic simulation. Dynamical studies for isolated vortex structures show that both the vorticity and the polarity of the out-of-plane component can be switched fast (50-100 ps). Micromagnetic simulations of the switching process in thin cylindrical Permalloy(Py) nanoparticles with an initial stable single-domain state show nearly homogeneous single-domain behavior followed by excitation of spin waves.

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The magnetism of small ferromagnetic structures has become increasingly important e.g. for nonvolatile random access memories (MRAMs) \cite{1}. Nanostructured Permalloy is a possible candidate for such devices. As it is an essential feature in the technology of magnetic recording to read and write magnetic states as fast as possible we study the dynamics of flat circular permalloy nanomagnets with magnetic vortex or single-domain configuration using micromagnetic simulations.

There are four equivalent vortex states since the vorticity (clockwise/counterclockwise) and the central polarization (up or down) are independent. The possibility of storing and switching two bits of information instead of only one makes these vortex structures quite interesting.

It is known from \cite{3} that the vorticity of a magnetic dot can be switched in $\approx 40$ ps with strong enough and short enough perpendicular out-of-plane field pulses.

In the present work, we consider 1.) the question, whether also the polarization can be switched reproducibly and as fast as the vorticity.

Therefore the results of a micromagnetic simulation performed with OOMMF, \cite{4}, on a cylindrical Py dot with diameter 300 nm and 10 nm thickness are shown. We have used Py parameters ($M_s = 80000 \, \mu$ for the saturation magnetisation, $A = 1.3 \times 10^{-11} \, \text{J/m}$ for the exchange stiffness and $\alpha = 0.008$ for the Gilbert damping). The initial magnetisation configuration is a (relaxed) vortex state. We apply a typical out-of-plane field pulse (100 ps duration) of $B_z = 0.2 \, \text{T}$, plus $B_x = 0.002 \, \text{T}$ to induce torque at $x = y \approx 0$.

Fig. 1 shows the magnetic configurations of this dot at different times. After 100 ps the central polarization flips from "up" to "down".

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{(Color): Bistable switching of the central polarisation of a Py dot with vortex structure.}
\end{figure}
Thus it is possible to switch the central polarization of a Py dot with vortex configuration in 100 ps by applying strong out-of-plane perpendicular field pulses. So these Py dots are candidates for independent switching of both the chirality, and the central polarization of vortex configurations.

2.) In the following the switching dynamics of single-domain-states in a flat circular Py cylinder are considered (diameter 150 nm, thickness 2 nm, same material as above, with an additional small in-plane uniaxial anisotropy \( K_u = 500 \text{ J/m}^3 \) with easy axis along the magnetisation at \( t = 0 \); the initial state is a stable single-domain-state). In the simulation now an in-plane field-pulse of 0.05 T (strong enough for precessional switching) perpendicular to the magnetisation was applied instantaneously for \( t \geq 0 \) and switched off at \( t \approx 0.1 \text{ ns} \), just after the reversal of the magnetisation. Fig. 2 shows the time-dependence of the x-component of the magnetisation, compared to a numerical calculation of the same process with fictitiously homogenous magnetisation (no exchange interactions).

The main results are:

a) During the switching process (\( t \leq 0.1 \text{ ns} \)) single-domain-behaviour predominates.

b) After the reversal dipole-exchange-spinwaves are excited.

c) The energy of the spin-system decreases exponentially \( \sim \exp(-t/\tau) \) with a time constant \( \tau \approx 0.65 \text{ ns} \).

Figure 2. Dynamics of the x-component of the magnetisation

Figure 3. Frequency-spectrum of the z-component of the magnetisation

A Fourier transformation of \( M_z(t) \) leads to a 'discrete' frequency-spectrum (fig. 3) because of the edge-conditions (free spins at the edge). The lowest frequencies \( f_1 \) and \( f_2 \) can be explained by uniform precession of the spins in the anisotropy fields of the above-mentioned uniaxial anisotropy \( K_u \) and a (fictitious) fourfold anisotropy, generated by the discretization of the simulation volume; the frequencies \( f_3 \) and \( f_4 \) are eigenmodes of the spin-wave-spectrum, the corresponding eigenfunctions are shown as inset in figure 3 (the greyscale corresponds to the z-component of the magnetisation). A theory for these quantized modes is given in 2.

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