

Controlled vortex core switching in a magnetic nanodisk by a rotating field

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The control of the vortex state magnetic nanoparticle by ultrafast magnetic fields is studied theoretically. Using the micromagnetic simulations for the Permalloy nanodisk we demonstrate that the vortex core magnetization can be irreversibly switched by the alternating field, rotating in the disk plane, with the frequency about 10 GHz and intensity about 20 mT. We propose an analytical picture of such phenomena involving the creation and annihilation of vortex-antivortex pairs and calculate the phase diagram of the fields parameters leading to the switching. © 2007 American Institute of Physics. [DOI: 10.1063/1.2770819]

I. INTRODUCTION

Artificial mesoscopic magnetic structures now provide a wide testing area for concepts of nanomagnetism and numerous prospective applications.^{1,2} A remarkable example is a vortex state nanodot. Having nontrivial topological structure on a scale of a nanomagnet, magnetic vortex is a promising candidate for a high density magnetic storage and high speed magnetic random access memory.³ The basis of the vortex statics and dynamics in Heisenberg magnets was studied in the 1980s, for a review, see Ref. 4. Typically, the vortex is considered as a rigid particle without internal degrees of freedom. Using such an approach a number of dynamical effects were studied in Heisenberg magnets⁴ and also in nanomagnets.⁵ However, the rigid approach fails when considering the vortex dynamics under the influence of a strong or fast external force. In particular, it is known that external pumping excites internal modes in vortex dynamics in Heisenberg magnets, whose role is important for understanding the switching phenomena^{6–11} and the limit cycles in the vortex dynamics.^{12,13}

In the present work we study the effect of influence of the homogeneous rotating field $\mathbf{B}(t) = (B \cos \omega t, B \sin \omega t, 0)$ on nonlinear internal dynamics of the vortex state magnetic nanodot in the framework of Landau–Lifshitz–Gilbert equations with an account of the exchange and dipolar interaction. Using micromagnetic simulations for material parameters of Permalloy (Py),³² we found that the irreversible flipping process of the vortex core polarity p is possible in a specific range of the field parameters (B, ω) , when the direction of ω is opposite to the vortex polarity, i.e., when $\omega p < 0$.

The simplest way to flip the vortex can be realized by applying a perpendicular direct current (dc) field B_{\perp} . Due to this field, the heavy vortex, which is polarized against the

field, becomes unstable^{14,15} and at some critical value ($B_s \sim 1.5\pi M_S$,¹⁶ M_S is the saturation magnetization³²) it flips to the light vortex state in which the core magnetization is parallel to the field. Note that this switching field should be strong enough, $B_s \sim 2.5$ kOe.^{16–19} Another possibility to switch the vortex is to use a weak but fast rotating field $\mathbf{B}(t)$.^{7–10} The physical idea is very simple. Let us consider our system in a moving frame, which rotates with a frequency ω together with the field. In this frame instead of the rotating field one has a static in-plane field B . According to the Larmor theorem, there also appears an effective perpendicular field $B_{\perp} = \hbar\omega / (g\mu_B)$. Thus the switching problem under the action of the alternating current (ac) field reduces to the problem with two dc fields. This idea works perfectly for the Heisenberg magnets and the dynamical picture of the switching is almost the same for both the dc and ac fields.¹⁰ However, as we show in this article, this simple picture fails for magnetic nanodots, where the dipolar interaction is decisive for the vortex structure.^{1,2}

II. MODEL AND NUMERICAL SIMULATIONS

Probably the simplest way which gives physical insight into how the dipolar interaction secures the stability of curling ground state is to use a local approach.²⁰ In this approach the dipolar interaction can be reduced approximately to an on-site anisotropy energy which in the case of a cylindrical nanodot has the form

$$\frac{E_{\text{dipolar}}}{\pi R^2 h M_S^2} \approx \int d^2x [\mathcal{A}(r) + \mathcal{B}(r) \cos 2(\phi - \chi)] \sin^2 \theta. \quad (1)$$

Here (r, χ) are the polar coordinates in the XY plane and we use the angular parametrization for the magnetization $M_x + iM_y = M_S \sin \theta \exp(i\phi)$ and $M_z = M_S \cos \theta$. For thin nanodots the easy-plane anisotropy parameter $\mathcal{A}(r)$ is negative being practically a constant. The in-plane anisotropy parameter $\mathcal{B}(r)$ is coordinate dependent: it vanishes in the disk center and it is sharply localized near the disk edge.²⁰ One

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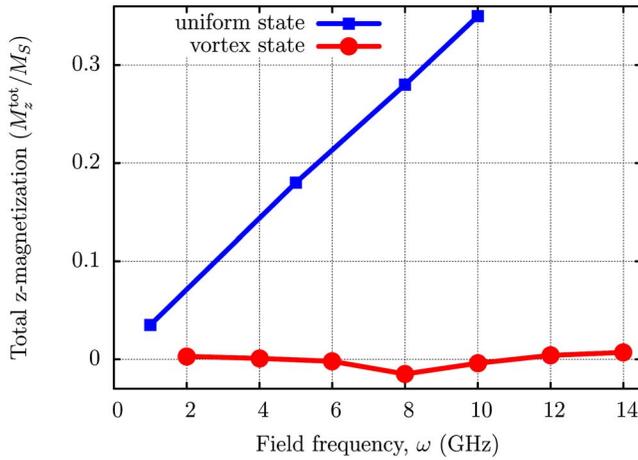


FIG. 1. (Color online) The ground state magnetization of the nanodot as a function of the ac field frequency: blue squares correspond to the uniform state nanodot (80 nm diameter, 2 nm thickness), and red circles to the vortex state nanodot (132 nm diameter, 20 nm thickness). For both cases the field strength $B=0.05$ T.

can see that for the easy-plane uniform state nanodot with $\phi=\text{const}$, $\theta=\pi/2$, the second (in-plane) energy term in Eq. (1) vanishes after integration and makes no important contribution. However, for the vortex state

$$\cos \theta = pf\left(\frac{r}{\ell}\right), \quad \phi = q\chi + \aleph \frac{\pi}{2}, \quad (2)$$

with $q=1$ being the vorticity and $\aleph=\pm 1$ being the chirality, $\cos 2(\phi-\chi)=-1$ and the dipolar interaction (1) is of crucial importance. In Eq. (2) an exponentially localized function $f(r/\ell)$ describes the vortex core structure. For thin disks one can neglect the z dependence of the magnetization.¹⁶ The topological properties of the magnetization distribution are characterized by the Pontryagin index

$$Q = \frac{1}{4\pi} \int d^2x Q, \quad Q = \epsilon_{ij} \sin \theta \partial_i \theta \partial_j \phi. \quad (3)$$

For the vortex configuration (2) the Pontryagin index is $Q=pq/2$.

To study the vortex core dynamics in a nanoparticle we performed detailed simulations, using the micromagnetic simulator for Landau–Lifshitz–Gilbert equations.²¹ We simulated the vortex state Py nanodisk³² with the diameter $2L=132$ nm and the thickness $h=20$ nm.

First we decided to validate the analogy between the rotating ac field and effective dc field for the nanodot. Since the visual effect of the dc field is the change of the ground state magnetization, we calculated the dependence of M_z^{tot} on the frequency of the ac field ω , see Fig. 1. For the uniform state nanodot, the dependence is linear, $M_z^{\text{tot}}=\hbar\omega/(4\pi g\mu_B)$, hence, the analogy with the effective static field B_{\perp} works correctly for this case. However, it fails for the vortex state nanodot, where $M_z^{\text{tot}}\approx 0$, see Fig. 1. The reason for this is the following. While in infinite systems the transformation to the rotating frame of reference in the space of spin variables ($\phi\rightarrow\tilde{\phi}=\phi+\omega t$) makes the Hamiltonian of the system time independent, this is not the case in finite-size systems. As is seen from Eq. (1) (and also takes place for the total dipole-

dipole interaction) to produce a time independent Hamiltonian in addition to the spin transformation one should transfer to the rotating frame of reference in real space: $\chi\rightarrow\tilde{\chi}=\chi+\omega t$. Thus in the rotating frame one has a static magnetic field \mathbf{B} along one axis in a disk plane. Besides that, taking into account that the Lagrangian of the system contains a gyroscopical term of the form $\int d^2x(p-\cos\theta)\partial_t\phi$,²² the Larmor and gyroscopical terms provide an additional energy contribution

$$\Delta E = \frac{M_S h \omega}{\gamma} \int d^2\tilde{x} (p - \cos \theta) \left(1 - \frac{\partial \tilde{\phi}}{\partial \tilde{\chi}} \right). \quad (4)$$

Without a vortex, the additional energy term (4) is equivalent to the action of an effective perpendicular magnetic field, $\Delta E=-B_{\perp}M_z^{\text{tot}}$, which results in a nonvanishing M_z^{tot} , in accordance with the earlier results, see Fig. 1. If the vortex is present, the situation drastically changes. In particular, $\Delta E=0$ for the vortex which is situated exactly in a disk center. This explains why we do not have an essential field influence on a centered vortex.

If we apply the field, which rotates clockwise ($\omega<0$), the vortex with $p=+1$ starts to move counterclockwise. This vortex motion has a gyroscopic nature: the vortex trajectory $\mathbf{R}(t)$ results mainly from the balance between the field interaction and the internal gyroscopic force $\mathbf{G}\times d\mathbf{R}/dt$, where $\mathbf{G}=-4\pi M_S h \gamma^{-1} Q \mathbf{e}_z$ is the gyrovectore.

During its motion, the vortex excites a number of spin waves,²³ the vortex trajectory becomes complicated, and sometimes it is tricky to identify the exact vortex position. We used the spatial distribution (3) of the topological density Q , to determine the vortex center position $\mathbf{R}(t)$. This distribution of Q is shown in the left panel of Fig. 2. Typical vortex trajectories are shown in Fig. 3. Mainly magnon modes of two kinds are excited in this system: symmetrical and azimuthal ones.^{7,10} The azimuthal mode is caused by the influence of the in-plane field and the symmetrical one by the effective out-of-plane field B_{\perp} . Due to the continuous pumping the system goes to the nonlinear regime: the amplitude of the azimuthal mode increases and there appears an out-of-plane dip nearby the vortex, similar to the vortex structure distortion by the in-plane field pulse^{24–26} or an ac oscillating field²⁷; this dip is shown in the right panel of Fig. 2 by the dark gray color and it is surrounded by the white isosurface. To highlight the vortex core position on the XY plane (right panel of Fig. 2), we plot the isosurfaces $M_x=0$ and $M_y=0$: each intersection of these isosurfaces determines the position of the vortex ($q=+1$) or the antivortex ($q=-1$).²⁴ All isosurfaces are closed inside the disk, or goes the disk edge, hence, the number of crossing points can be changed during the system dynamics only by 2, reflecting the processes of the vortex-antivortex pair creation and annihilation.

When the amplitude of the out-of-plane dip reaches the minimum ($M_z=-M_S$) a pair of a new vortex ($p=-1, q=+1$) and antivortex ($p=-1, q=-1$) is created, see Figs. 2(c) and 2(d). Since the total topological charge of the pair $Q=0$, this process does not cost a lot of energy.²⁸ In Fig. 2(c) one can see three peaks in the Q distribution. Two positive peaks correspond to the initial vortex and the new antivortex.

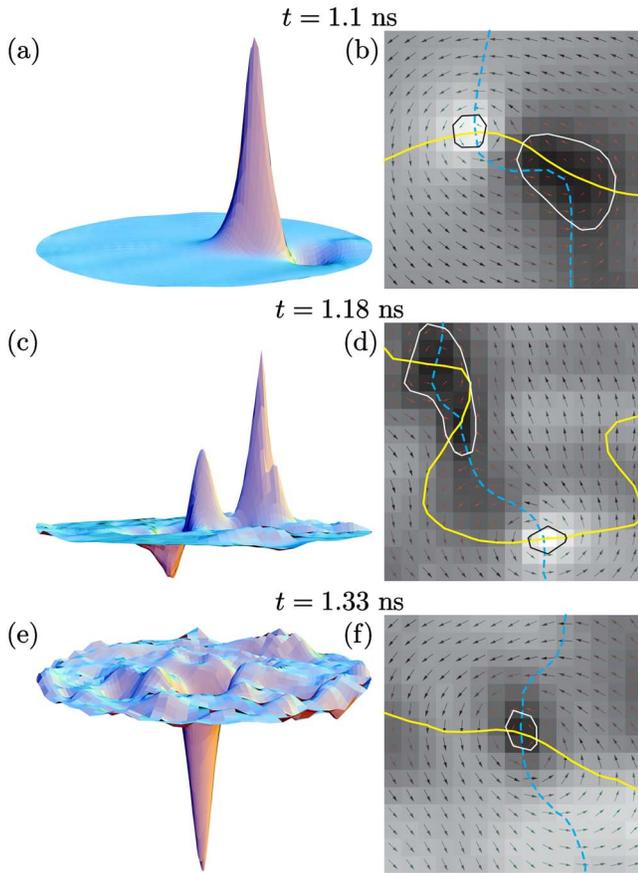


FIG. 2. (Color online) The temporal picture of the vortex switching process for the 132 nm diameter and 20 nm thickness Py disk: the left panel [(a), (c), (e)] corresponds to the 3D distribution of the topological density Q , see Eq. (3), and the right panel [(b), (d), (f)] represents the in-plane magnetization distribution. The dashed blue and the solid yellow curves represent $M_y=0$ and $M_x=0$ isosurfaces, respectively; the black and the white curves correspond to $M_z/M_s=0.75$ and $M_z/M_s=-0.75$ isosurfaces, respectively. The field parameters: $\omega=4$ GHz and $B=0.06$ T.

The negative peak corresponds to the new vortex. After that the scenario of the vortex-vortex-antivortex dynamics is similar to the one discussed by Waeyenberge *et al.*²⁵ The original vortex and the new antivortex interact with each other. In the exchange limit (neglecting the dipolar interaction) the vortex-antivortex pair is topologically equivalent to the Belavin–Polyakov soliton²⁹ with the topological charge $Q=1$. This soliton is scale invariant in the continuum system.

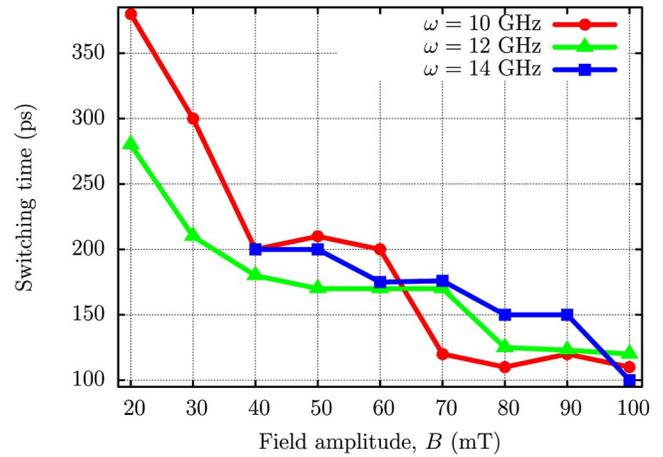


FIG. 4. (Color online) The switching time for different field parameters. The size parameters of the dots are the same as in Fig. 2.

However, in the discrete system the radius of this soliton, i.e., the distance between the vortex and antivortex, rapidly decreases almost without energy lost, since this soliton is not stable. When the soliton radius is about the lattice constant, it vanishes. After annihilation of the vortex-antivortex pair only the new vortex ($p=-1$) survives, see Figs. 2(e) and 2(f). After the flipping the vortex changes the direction of motion because it now has the opposite polarity. The interaction with the rotating field is not so strong now and the vortex rapidly goes to the disk center on a spiral trajectory. Thus, using the rotating field we obtain an irreversible switching of the vortex polarity. The supplementary video illustrates the whole evolution of the magnetization distribution during the switching process.³³ Typically the switching time is in the hundreds of picoseconds range; it can be decreased by more intensive fields, see Fig. 4.³⁴

III. CONCLUDING REMARKS

The switching occurs in a well defined range of the field parameters (ω, B) with the minimum frequency about 10 GHz and the field strength about 20 mT, see Fig. 5. This switching diagram differs from the one in Heisenberg magnets, i.e., models, where the nonlocal effects of the dipolar interaction were ignored. In Heisenberg magnets the action of the ac field is reduced to the effective dc field B_{\perp} , hence,

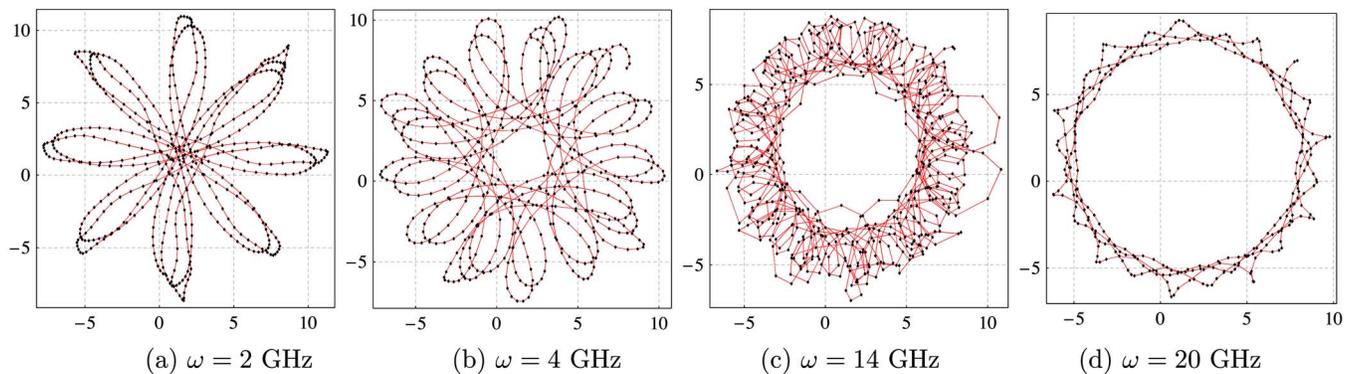


FIG. 3. (Color online) Vortex trajectories (measured in nanometers) for different frequencies. The field amplitude always is the same (0.02 T).

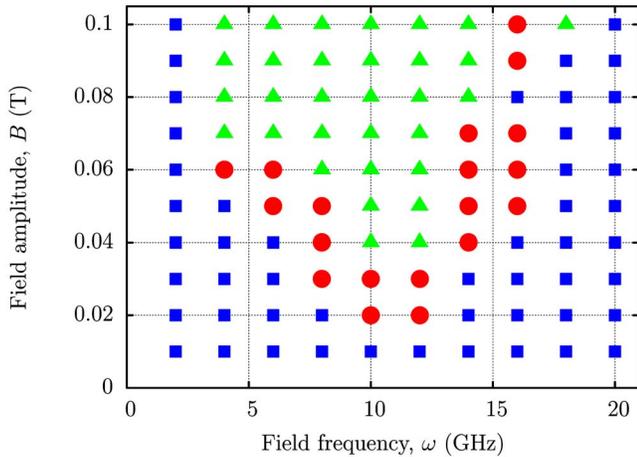


FIG. 5. (Color online) Switching diagram for the ac field parameters (amplitude and frequency): red circles correspond to parameters, when the switching occurs, blue squares describe the vortex dynamics without switching, and green triangles represent multiple switching processes.

the vortex flipping is characterized mainly by a threshold curve $B_{cr}(\omega)$ and can occur, in principle, for any frequencies ω if the field amplitude exceeds the threshold value.^{7,10} The vortex switching in the nanodot occurs only in a quite narrow range of field frequencies and amplitudes. When the field intensity is not strong enough, the vortex moves without switching. In the opposite case of strong fields, multiple switching occurs, similar to Refs. 24 and 27. When the frequency is too large or too small the switching also does not happen. Thus, the controlled switching process can be realized experimentally only for a relatively narrow range of parameters (red disks in the switching diagram, Fig. 5).

Note that in the range of the high frequency pumping, when the switching does not occur (the right side of Fig. 5), the vortex always reaches some limit cycle, which is almost a circular trajectory, see Fig. 3(d). An important feature of this limit cycle is that the frequency of the vortex orbital motion $\Omega \sim 1$ GHz is much less than the pumping frequency ω and almost does not depend on the field frequency and its amplitude. We expect that this low frequency response results from the coupling between the vortex motion and internal modes dynamics in analog with the Heisenberg magnets.^{12,13} The detailed analysis of this vortex dynamics is under construction.

In conclusion, we have described the vortex core dynamics in the nanodisk under periodic driving. The irreversible switching of the vortex polarity can be excited by a high-frequency (10 GHz) and intensity (20 mT) ac field. The mechanism of the switching involving the creation and annihilation of a vortex-antivortex pair is quite general. It appears for different kinds of vortex excitation and is induced in particular by a field pulse,^{24–26} by an ac oscillating field,²⁷ and even by an electrical current.^{30,31} We also reported about the limit cycle in the vortex dynamics for the higher frequency pumping. Both effects are caused by the strong coupling with excited internal magnon modes.

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- ³²In all simulations we used material parameters adopted for the Py particle: the exchange constant $A = 2.6 \times 10^{-6}$ erg/cm, the saturation magnetization $M_S = 8.6 \times 10^2$ G, the damping coefficient $\alpha = 0.006$, and the anisotropy was neglected. This corresponds to the exchange length $\ell = \sqrt{A/4\pi M_S^2} \approx 5.3$ nm, which determines the typical radius of the vortex core. The mesh cells have sizes of $3 \times 3 \times 20$ nm.
- ³³Supplement video, <http://www.phy.uni-bayreuth.de/~btp315/publ/Kravchuk.arXiv.0705.2046.html>.
- ³⁴In our simulations the vortex was initially shifted from the disk center on a distance about its core radius. The switching time slightly increases when we place the vortex exactly into the disk center.