Ultrafast dynamics of a magnetic antivortex

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Within the past years, research on nanoscale magnetization dynamics has made great progress in isolating fundamental magnetization structures and investigating their individual properties. In particular, the study of magnetic vortices has recently emerged as one of the most important topics in nanomagnetism, especially following the discovery that the vortex core can easily be switched by means of short field pulses [1, 2]. The investigation of this micromagnetic reversal process has shown that it is in part mediated by the formation of an *anti*vortex – the topological counterpart of the vortex. However, not much is known to date about the dynamics of antivortices. Using micromagnetic finite-element simulations we have studied the ultrafast magnetization dynamics of an individual antivortex, which was stabilized in a specially tailored soft-magnetic thin-film element. We find that a short perturbation induced by a single in-plane field pulse can cause the reversal of the antivortex core, following a process which is perfectly complementary to the case of a vortex [3]. These findings show that the complementarity between vortices and antivortices does not only apply to their static structure, but also to their ultrafast dynamics. The new antivortex core switching process could be used for the effective generation of spin waves to drive novel logical circuits [4].

Antivortices spontaneously form alongside vortices in thin ferromagnetic films above a critical size. Both structures possess a tiny core at their center in which the magnetization points perpendicular to the plane and which has been found to decisively affect their dynamics. Only few studies exist however on antivortex dynamics and these have focussed on the antivortex response to small perturbations from equilibrium, such as in a recent experiment by Kuepper *et al.* [5]. Using fully three-dimensional micromagnetic simulations we have investigated the ultrafast dynamic response of a single magnetic antivortex to an external field pulse a few tens of ps long. This triggers a highly non-linear behavior leading to irreversible changes in the antivortex structure. In particular, we find that suitably shaped field pulses can induce a rapid series of vortex-antivortex creation and annihilation processes, complementary to the ones observed in a vortex [2], and which ultimately lead to the reversal of the antivortex core.

In contrast to vortices, it is rather difficult to isolate an antivortex, *i.e.*, to prepare a nanostructure that contains only a single antivortex. This is due to divergences in the in-plane magnetization distribution of the antivortex which tend to destabilize the structure, in contrast to the vortex which is divergence-free. The different in-plane structures of vortices and antivortices are schematically illustrated in Fig. 1a. We have successfully isolated an antivortex in a Permalloy sample constructed from four circular segments, shown in Fig 1b. The in-plane shape anisotropy of this particular geometry can sustain an antivortex due to the tendency of the magnetization to align with the sample boundaries.

The dynamic simulations have been performed with our micromagnetic finite-element code which has also been used in Ref. [2]. The magnetic volume was discretized into about 200,000 tetrahedral elements and the magnetization dynamics was calculated using the Landau-Lifshitz-Gilbert equation with damping parameter $\alpha = 0.01$. The magnetization dynamics in response to a short 60 mT in-plane Gaussian-shaped pulse of a duration of 80 ps is shown in Fig. 1c-j. Figs. c-f show the in-plane magnetic structure at the indicated times while in Figs. g-j the colors represent the out-of-plane component of the magnetization (m_z). The isosurface representation introduced in Ref. [6] has been used to highlight the precise location of the antivortex core, that is, the region where the magnetization is exaclty perpendicular to the sample plane ($m_z = \pm 1$). This situation occurs where the $m_x = 0$ and $m_y = 0$ isosurfaces intersect, as shown in Fig. 1. Following the application of the field pulse, the antivortex is displaced from its equilibrium position and the in-plane magnetization of the sample is distorted (Fig. 1d). In a region close to the core, this distortion leads to the formation of a “dip” in which the magnetization rotates out of the plane in the direction opposite to the antivortex core (Fig. 1h). Approximately 80 ps after the pulse maximum, a new antivortex is emitted from the original antivortex (Fig. 1e). However, the formation of a single antivortex would violate the conservation of a topological invariant (the winding number). A new vortex is thus also produced, which is located between the two antivortex structures. The newly formed antivortex-vortex pair is made clearly visible

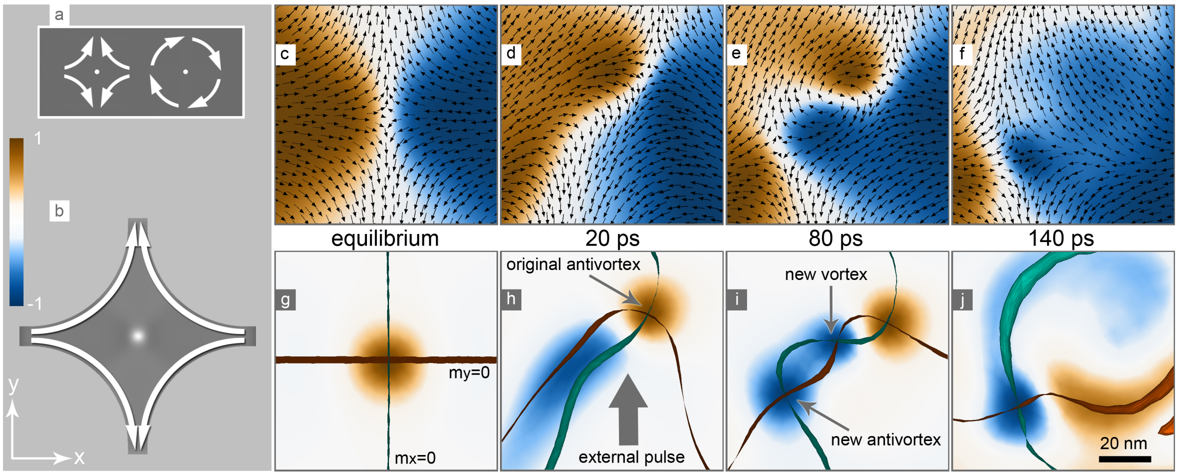

FIG. 1: Ultrafast dynamic response of an isolated magnetic antivortex. ***a***, *Schematic respresentation of the in-plane structure of an antivortex as compared to a vortex. The two structures are related by underlying topological properties: In both cases, the local magnetization rotates by 360° on a closed loop around the core.* ***b***, *Modeled sample: the circular segments have a 200 nm radius and are 20 nm thick. The arrows indicate the direction of the magnetization, which aligns with the sample boundary. The frames* ***c-j*** *show the distortion of the antivortex structure induced by an in-plane field pulse. The frames are snapshots of the magnetic structure around the core at different times relative to the maximum of the applied pulse. The arrows in the top row (****c-f****) represent the in-plane magnetization while the colors represent the x component of the magnetization. In the bottom row (****g-j****) the colors represent m_z while the green and red "ribbons" are the $m_x = 0$ and $m_y = 0$ isosurfaces, respectively.*

by the two additional isosurface crossings in Fig. 1i. This strongly inhomogeneous structure is eventually resolved through the annihilation of the initial antivortex with the newly created vortex, whose cores have opposite orientations [6]. This results in a sudden reduction of the local exchange energy density and leaves behind the newly formed antivortex with oppositely magnetized core as shown in Fig. 1f,j.

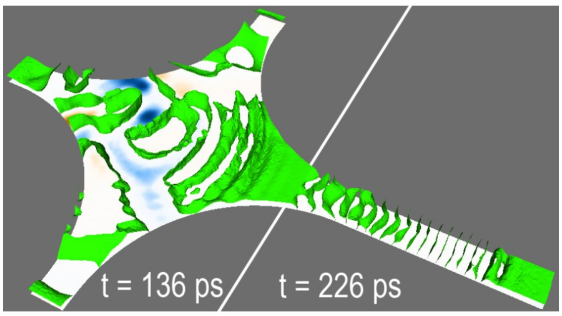

FIG. 2: Spin wave propagation in an extended branch of the sample at two different times following the field pulse maximum. The $m_z = 0$ isosurfaces shown in green allow to visualize the wave fronts. The blue spot represents the switched core.

The annihilation of a vortex-antivortex pairs with opposite core magnetization has been shown to be connected with the emission of spin-wave bursts in the GHz range [6, 7]. The core reversal of the antivortex structure could therefore be used for the generation of spin-waves. By extending the branches of the sample, the spin waves produced in the antivortex can smoothly be injected into a strip acting as a waveguide as simulated in Fig. 2. Such spin waves would then be processed in logical circuits where their phase can be manipulated to perform logical operations [4].

We have presented a new fundamental process in magnetism on the nanoscale which consists in the reversal of the antivortex core. This is the result of complex and ultrafast modifications which can be triggered by applying a short field pulse. It is remarkable that, in spite of the very different magnetic in-plane structure of vortices and antivortices, their ultrafast dynamics are analogous, involving the creation of new magnetic structures followed by a destruction process.

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