Magnetic vortices: controlled dynamic switching of the curl made fast and energy-efficient

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The circulating topology of vortices is a physical phenomenon, which is found across a large range of length scales, from galaxies, hurricanes down to the nanoscale, e.g. in superconducting materials under an applied magnetic field. Magnetic vortex structures also form in thin disk shaped ferromagnetic elements where the magnetic moments, i.e. the spins in the plane of the disk try to follow the disk shape's boundary. In the center of a magnetic vortex there is a vortex core where the magnetization points perpendicular to the plane. These in-plane and out-of-plane spin configurations of a magnetic vortex define its two independent binary parameters, the polarity and circulation. Controlling those entities on a sub-nanosecond timescale is currently a hot topic both for fundamental and applied reasons.

When excited by a fast-rising magnetic field or spin-polarized current, vortices exhibit a rich variety of fundamental dynamic behaviors that are inherent to chiral structures [1–4]. Generally, the magnetization distribution of a vortex is an example of a magnetic topological soliton [5] and features low-frequency precessional modes [2] associated with the translational motion of the core. The precessional mode has been the subject of considerable interest, with applications in oscillators [3,4] and resonant amplification of gyrotropic precession for low-field [6] or low-current [7] excitations. Because of their multiple stable ground states, vortices have also been studied as potential multibit memory cells [8]. This application requires independent control of both the circulation and the polarity. The polarity can be reversed by applying a static out-of-plane magnetic field, although its magnitude needs to be quite large, on the order of 0.5–1.0 T [9]. However, fast stimuli can lead to much more efficient core polarity switching. Using a magnetic field [6], or current [7], the vortex core can be driven into gyrotropic precession and the core polarity reversed as soon as the core reaches a critical velocity [10]. The switching process typically occurs in less than 0.1 ns.

The subnanosecond character of vortex polarity switching raises the question of controlling the spin circulation on similar timescales (Fig. 1), thus opening a path to selective and independent control of the polarity and circulation. Unlike switching core polarity, controlled switching of spin circulation with magnetic fields requires displacing the vortex core out of the disk and then reforming the vortex with the opposite spin circulation. The core expulsion can be performed by using an in-plane static magnetic field that moves the core to the side of the disk and finally annihilates the vortex when $B_{\text{an-stat}}$ is reached [12]. The sense of magnetization circulation that forms as the field is removed can be controlled either by exploiting an asymmetry in the structure shape [13] or in the spatial distribution of the applied magnetic field [14].

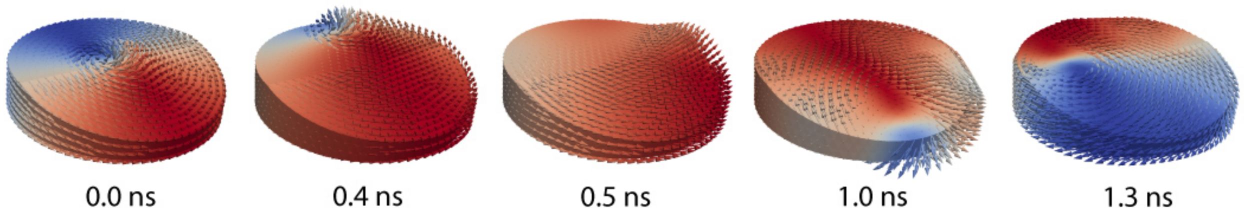


Fig. 1 Temporal evolution of the magnetization circulation switching in a 100-nm-wide nanodisk by a 0.5-ns-long magnetic field pulse applied in the disk plane (micromagnetic simulation in the finite-element FastMag code [11]). Snapshots show the instantaneous magnetization configuration at indicated time delays.

Magnetic imaging of the dynamic spin circulation switching

In our initial study [15] we showed that far-from-equilibrium gyrotropic precession enables dynamic switching of spin circulation and substantially decreases the dynamic annihilation field $B_{\text{an-dyn}}$ compared with static conditions. This annihilation field reduction is analogous to the reduction of switching fields in Stoner–Wohlfarth particles by precessional reversal using fast-rising magnetic field pulses [16]. We further showed that the lower bound of the time required for spin circulation switching is set by the gyrotropic eigenfrequency of the vortex core motion, which is defined by the disk geometry [2].

In particular, we studied permalloy ($Ni_{80}Fe_{20}$) disks of different diameters (250–1100 nm) and thicknesses (20 and 30 nm) that are excited by externally applied static magnetic fields or by applying in-plane magnetic field pulses created by current pulses in a waveguide (details of the sample and waveguide are shown in Fig. 2). Magnetization states were imaged with full-field magnetic soft X-ray transmission microscopy (MTXM) at the Advanced Light Source (ALS), BL 6.1.2 [17].

After applying both the static and pulsed magnetic fields, the final circulation is the same in all the disks and depends solely on the sign of the applied magnetic field. This is a result of a controlled symmetry-breaking in the disks arising from a wedge-like variation in the disk thickness at the disk boundary (Fig. 2b). Figure 3 shows the remanent magnetic state in 250/20 disks in response to pulsed magnetic fields. From the left: the initial state set by a static field, followed by magnetic states after applying 1 ns and 1.5 ns pulsed fields, respectively, to initiate dynamic switching. Although we see a significant reduction in the switching field with pulsed current, there is a lower limit to the pulse duration where switching is not observed or could only be achieved at higher applied fields. In 250/20 disks, the onset of switching was observed for pulses of 1 ns or longer.

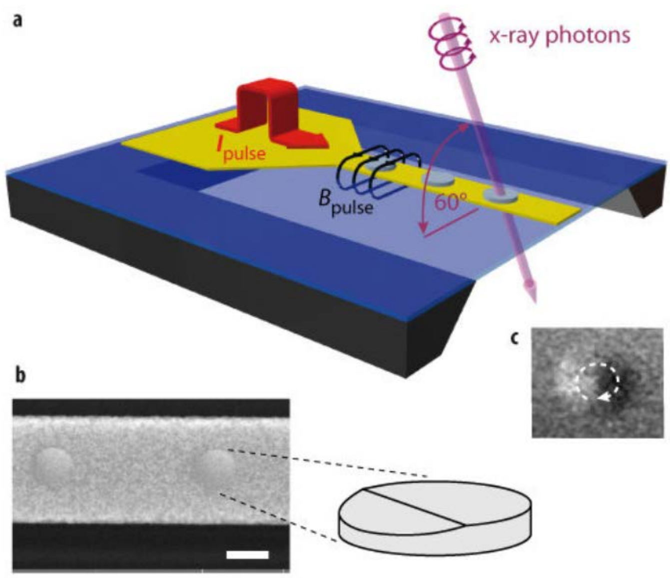


Fig. 2 Schematic of the sample: ***a*** *nanodisk chain fabricated on top of a 50-nm-thick gold waveguide. An applied positive current I_{pulse} produces an in-plane field B_{pulse} transverse to the stripline. The stripline is fabricated on a 200-nm-thick Si_3N_4 membrane window, which is transparent to the incoming soft X-rays, allowing magnetic imaging in transmission geometry.* ***b****, A scanning electron microscopy (SEM) image showing the detail of a 500-nm-wide and 20-nm-thick disk. The thickness asymmetry at the bottom-left part of the disks is highlighted by the schematic close-up. Scale bar, 500 nm.* ***c****, Magnetic contrast in the image of a 1,000-nm-wide nanodisk after dividing it with a reference image containing a vortex with the opposite spin circulation. The curl of the magnetization is indicated. The black and white domains represent parallel and antiparallel orientation of the magnetization projected on the incident soft X-ray beam.*

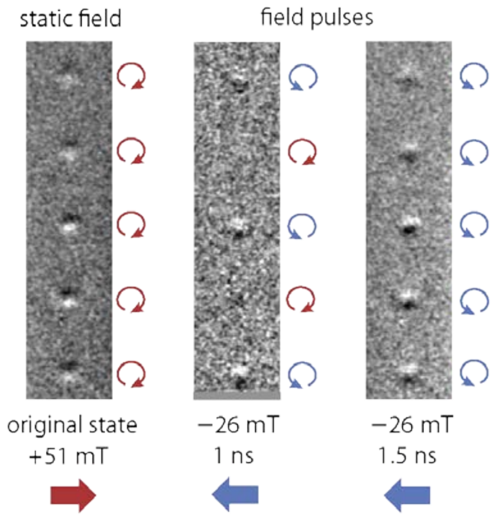


Fig. 3 The MTXM images of vortices in 250-nm-wide and 20-nm-thick disks were taken after application of in-plane magnetic fields. The arrows on the right of each image indicate spin circulation. Arrows and labels below the images show the polarity and magnitude of the applied field, as well as pulse duration where applicable.

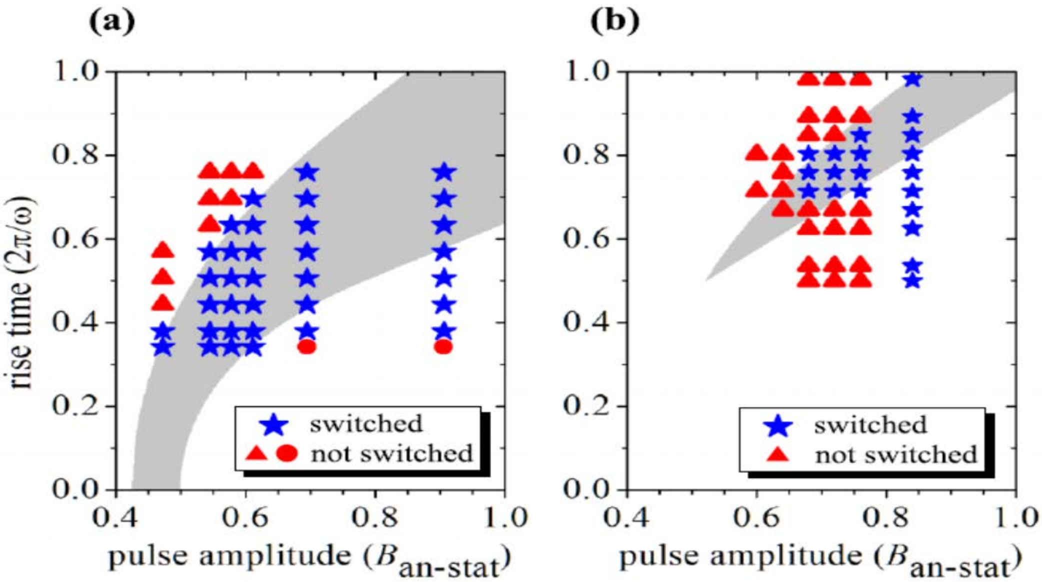
The results are supported by both analytical models and micromagnetic simulations, showing that both the time and field switching scales strongly depend on the disk geometry. Importantly, scaling down the disks accelerates circulation switching. The analytical model and micromagnetic simulations predict that switching times shorter than 0.5 ns are possible for 100/20 disks. The limit is set by the transition of the vortex state to a monodomain state for permalloy disks smaller than 100 nm [18]. In our experiments we observed nucleation of a random core polarity upon circulation reversal, preventing full control of vortex chirality by in-plane field pulses. However, currently we are testing ways how the core polarity could potentially be controlled by an additional out-of-plane bias field and temporal shape of the in-plane field pulse. Alternatively, the core polarity can be subsequently adjusted by an additional pulse with parameters leading to toggle-switching or selective polarity switching [19].

Exploring the limitations and efficiency of circulation switching

Can we switch the vortex circulation for a given disk geometry even faster than in the threshold-field limit? Although this might be less energetically favorable, by increasing the field amplitude the core follows a shorter trajectory, so the time it needs to reach the disk boundary is lower. On top of that, increasing the field also increases the velocity of the core. However, this eventually leads to reaching the critical core velocity for polarity switching. This substantially complicates the situation – for instance when the amplitude of the pulse is only slightly above the threshold, the polarity switching might even prevent the core from reaching the disk boundary, even if the field strength should initially be enough to expel the core. This aspect becomes an issue for disks thicker than approximately 20 nm, where the eigenfrequency of the core gyrotropic motion leads to velocities reaching the polarity switching threshold.

However, in our experiments the circulation is switched by threshold-amplitude pulses in disks up to 30 nm thick and 1,100 nm in diameter. This is not expected based on the analytical model or simulations and can be explained by the positive effect of finite pulse rise time. If the rise time is comparable to the period of the core eigen-oscillation, the core moves together with the equilibrium point (set by the instantaneous value of the magnetic field during the pulse). The core follows a cycloidal trajectory, and the instantaneous distance between the core and the equilibrium point is decreased, maintaining the core velocity below the critical velocity for core polarity switching. Consequently, the amplitude of the pulse has to be increased above $B_{an\text{-}stat}/2$ to expel the core, but the polarity is not flipped.

The experimentally determined pulse rise time–pulse amplitude phase diagram showing the regions of successful circulation switching was reproduced with an analytical model based on Thiele's equation [20] describing vortex core motion in a parabolic potential. We found that the analytical model is in good agreement with experimental data for a wide range of disk geometries. From both the analytical model and the experimental findings we have determined the geometrical condition for dynamic vortex core annihilation and the pulse parameters giving the most efficient and fastest circulation switching [21]. We have also determined the maximum thickness (37 nm) of the disk above which the model does not predict a possibility of dynamic annihilation of the core with a pulse amplitude lower than $B_{an-stat}$. Pulses with an amplitude approaching or exceeding $B_{an-stat}$ and a sufficient duration will annihilate the vortex no matter what the exact dynamic behavior is, with no



benefit for the energy cost associated with the circulation switching.

Fig. 4 (a) Pulse rise time–pulse amplitude phase diagram experimentally determined for a 1600-nm-wide, 20-nm-thick permalloy disk with an estimated eigenperiod $2\pi/\omega$ = 7.9 ns and experimentally determined static annihilation field $Ban-stat$ =19 mT. The pulse rise times and pulse amplitudes are given in units of the gyrotropic oscillation period ($2\pi/\omega$) and vortex static annihilation field ($B_{an-stat}$), respectively. Red triangles represent a case of unsuccessful switching. Blue stars represent a case where successful core annihilation led to a circulation switching. Red *dots represent a case where the circulation switching was not achieved in spite of using shorter rise time and larger pulse amplitudes (limit of the core polarity switching). (b) Phase diagram for a 1600-nm-wide, 30-nm-thick permalloy disk. The region of successful circulation switching moved towards top right of the normalized phase diagram. The gray areas in the phase diagrams define boundary of the region of successful circulation switching predicted by the analytical model.*

These studies set an important milestone towards fast and energy-efficient control of magnetic vortex structures in novel magnetic devices.

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