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Fast spin-wave-mediated magnetic vortex core reversal

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Spin-wave-mediated vortex core reversal is investigated using x-ray magnetic circular dichroism in a time-resolved scanning transmission x-ray microscope in combination with micromagnetic simulations. The evolution of magnetization dynamics in Permalloy disks is imaged after excitation with one-period rotating rf-field bursts. Selective unidirectional switching of the vortex polarity is achieved due to different switching thresholds for clockwise and counterclockwise excitations. A lower limit of about 200 ps for the unidirectional switching time after the onset of a one-period burst is found for the geometry of our disks (1.6 μm in diameter and 50 nm in thickness).

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I. INTRODUCTION

The magnetic ground state in micro- and nanosized circular magnetic platelets (disks) is the vortex structure[1] with an in-plane curling magnetization and a perpendicularly magnetized core with a size of about 10 nm at the center of the platelet. The direction of the out-of-plane component of the magnetization is defined as the polarization p of the vortex core (up, $p = +1$; down, $p = -1$). The sense C of the in-plane flux closure (circularity) can be clockwise (CW), $C = -1$, or counterclockwise (CCW), $C = +1$. The pair (p,C) defines the ground-state configuration and all possible combinations are energetically degenerate. Since a bit of information can be assigned to the vortex polarization state, arrays of circular platelets may be used[2,3] as nonvolatile magnetic random access memories (MRAMs), if it is possible to switch p in a well-defined manner with low power. These MRAMs then may be called vortex magnetic random access memories (VMRAMs). Vortex core switching can be achieved by addressing different dynamic modes of the platelet with vortex structure. Different types of excitations can be distinguished. The low-frequency gyrotropic motion of the vortex (with a frequency of 100 MHz to 1 GHz) is characterized by a gyration of the vortex core around the equilibrium.[4] In addition, magnetostatic radial and azimuthal spin-wave excitations of the flux closed magnetization occur in the multi-GHz-frequency range.[5,6] These two types of excitations interact[6] leading to a splitting of the azimuthal modes of the order of the frequency of the low-lying gyrotropic mode.

The switching of the vortex core by dynamical excitations has been investigated experimentally and theoretically,[3,7–17] as has been the switching of an antivortex core.[18,19] Dynamic vortex core switching was first demonstrated using linear rf fields and has been shown to be caused by the vortex-antivortex pair formation mechanism.[8,17] The application of linear rf fields has the disadvantage that the vortex polarization is only toggled from its up to its down state and vice versa; i.e., there is no well-defined switching of the core into the desired polarization state. This problem can be avoided by using rotating in-plane rf fields[12,13,16,20] and rotating spin-polarized currents[2,18] at low frequencies which excite the gyrotropic vortex motion. Since the gyration sense of the vortex is determined only by p there is a high asymmetry in the gyrotropic resonance excited by rotating fields with different rotation senses.[21] Selective unidirectional switching only occurs when the rotation senses of the exciting field and of the freely gyrating vortex are the same.[12,13] This type of switching leads to switching times larger than 1 ns. Recently, it has been theoretically predicted[20] and experimentally shown[16] that the vortex polarization can be selectively switched also by applying low rotating in-plane fields in the multi-GHz-frequency range which excite azimuthal spin waves. Here we demonstrate that it is possible to selectively switch the polarization of vortex cores by the excitation of rotating spin waves in the GHz range with very short (e.g., one period) rotating magnetic-field bursts.

The out-of-plane component Δm_z of the magnetization of the magnetostatic excitations can be described in polar coordinates (r,ϕ) as[5] $\Delta m_z^{n,m}(r,\phi,t) = R_{z,n}(r)\, e^{im\phi} e^{-i\omega_p^{n,m} t}$, where n ($n \geqslant 1$) is the number of radial nodes. The azimuthal mode number m can have negative and positive integer values with $|m| \geqslant 0$, and $|2m|$ is the number of azimuthal nodes. The positive (negative) sign of m denotes the CCW (CW) rotation sense of Δm_z. For given n,m the frequency $\omega_p^{n,m}$ depends also on the vortex polarization p. The symmetry in the frequency splitting can be written as $\omega_{-p}^{n,m} = \omega_p^{n,-m}$.

In Ref. 16 switching of p by multi-GHz rotating in-plane fields was investigated using magnetic-field bursts with 24 periods in the GHz range. A rotating field excites spin waves with negative or positive m. For a given p, high-frequency modes with both signs of m can switch p.

For excitations where the product $pm = -1$ the out-of-plane magnetization component $m_z(\mathbf{r})$ is opposite in sign to the out-of-plane magnetization of the vortex core in just one region close to the core, whereas for $pm = +1$ there are two such regions.[16] This asymmetry can be explained in the following way: The rotating field generates an azimuthal spin wave, and the interaction of this mode with the vortex results in a gyrating motion of the vortex core with the same sense of rotation and the same frequency, albeit with a small gyration radius. The corresponding gyrofield[11] leads to an out-of-plane magnetization. Since a well-defined phase relation between the spin-wave rotation and the gyrofield[22] exists, the superposition of the out-of-plane magnetization of the spin wave with the gyrofield-induced magnetization is different for $pm = +1$ and -1.[16]

For small field amplitudes, long excitation bursts (24 periods) are required for switching. Consequently, a straightforward idea to reduce the switching time is to use larger fields. However at large field amplitudes, even after the first switching event, the excitation field still transfers a sufficient amount of energy to the magnetic system. A second vortex-antivortex pair is formed and hence multiple vortex switching events occur until the excitation field is turned off after 24 periods. This means that single unidirectional switching is not possible at large field amplitudes. In order to overcome the problem of multiple switching at higher-field amplitudes and to achieve a single selective switching event, a possible solution is to use rotating field bursts of shorter (e.g., one period) duration suppressing the formation of subsequent vortex-antivortex pairs. Note that the Fourier transform of a one-period burst yields a broad frequency spectrum which includes the frequencies $\omega_p^{n,m}$ for different n,m,p. Therefore it is not possible to generate unidirectional switching by simply tuning the excitation frequency to a specific $\omega_p^{n,m}$, as in the case of a low-field 24-period burst excitation. However, by combining frequency and field amplitude tuning, a one-period excitation can lead to unidirectional switching. The reason for this is an asymmetry in the switching threshold between CW and CCW for a vortex of given polarization which will be discussed below. As a consequence, the field amplitude can be chosen in such a way that a vortex core of given p is switched with one sense of rotation only.

II. METHODS

The experiments are carried out at the MAXYMUS scanning transmission x-ray microscope (STXM) at BESSY II, Berlin, in standard multibunch mode, combining a lateral resolution of typically 25 nm (given by the Fresnel zone plate) with a temporal resolution of about 35 ps (determined by the time structure of the storage ring) and using x-ray magnetic circular dichroism at the Ni L3 edge. Time-resolved imaging is achieved by the stroboscopic pump and probe technique where the samples are excited periodically, and the time delay between the excitation (pump) and the imaging x-ray flashes (probe) is varied. The pump excitation has been a rotating magnetic in-plane field. To produce these fields, a sample stack was prepared (on a 100-nm-thick Si_3N_4 membrane) which consists of a 170-nm-thick crosslike copper stripline suitable for linear and rotating field generation. CCW and CW field rotation senses have been achieved by superimposing x and y magnetic-field components with a phase shift of plus and minus 90 deg. On top of the copper stripline a Permalloy disk with a diameter of 1.6μm and a thickness of 50 nm has been prepared by electron-beam lithography and liftoff patterning.

In addition to the experiments we have performed micromagnetic simulations using Gilbert's equation[23] and the OOMMF code.[24] The simulations are for a Permalloy disk with the same size as the sample investigated experimentally. The following parameters were used: exchange parameter $A = 13 \times 10^{-12}$ J/m, a damping constant of $\alpha = 0.006$, and a saturation magnetization of $M_s = 750 \times 10^3$ A/m.

III. STXM IMAGING OF VORTEX DYNAMICS AND SIMULATIONS

As discussed above an asymmetry in the dynamics of the vortex core switching process by azimuthal spin waves of opposite sense of rotation exists. Here for the first time this asymmetry was observed experimentally by the scanning transmission x-ray microscope (STXM). In doing so, we have exposed the magnetic disk with vortex polarization $p = +1$ to a continuous rotating CW field with a frequency of 5.0 GHz to excite the spin-wave mode ($n = 1, m = -1$), and to a CCW field of 5.5 GHz to excite the mode ($n = 1, m = +1$). The excitation amplitudes, 0.3 mT for CW and 0.9 mT for CCW, have been chosen just below the threshold values for core reversal at these specific frequencies.[16] This allows imaging of the asymmetric magnetization configurations with high statistical accuracy in a stroboscopic experiment. The resulting images are shown in Fig. 1(a) and compared in Fig. 1(b) to the corresponding images obtained from simulations, convolved with the experimental resolution (lateral 25 nm, temporal 35 ps). For CW excitation, in the experiment and in the simulations the vortex core (indicated by the black circle) as well as the negatively polarized dip (white circle) cannot be observed due to the limited experimental resolution. The circles indicate the positions for which the nonconvolved simulations show the vortex core and the dip. The interpretation of the experimental data thus is based on a comparison with results from simulations. However, for CCW excitation, the vortex core and the dip on its left-hand side are clearly visible

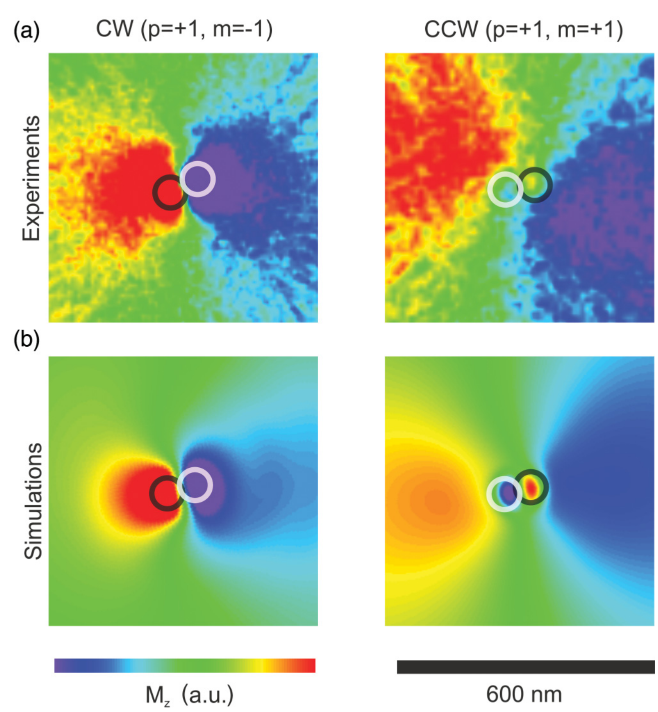

FIG. 1. (Color) Out-of-plane component of the magnetization during continuous excitation just below the switching threshold for vortex core reversal. (a) Experiment. (b) Micromagnetic simulations. Left column: CW excitation of the azimuthal spin-wave mode ($n = 1, m = -1$). Right column: CCW excitation of the mode ($n = 1, m = +1$).

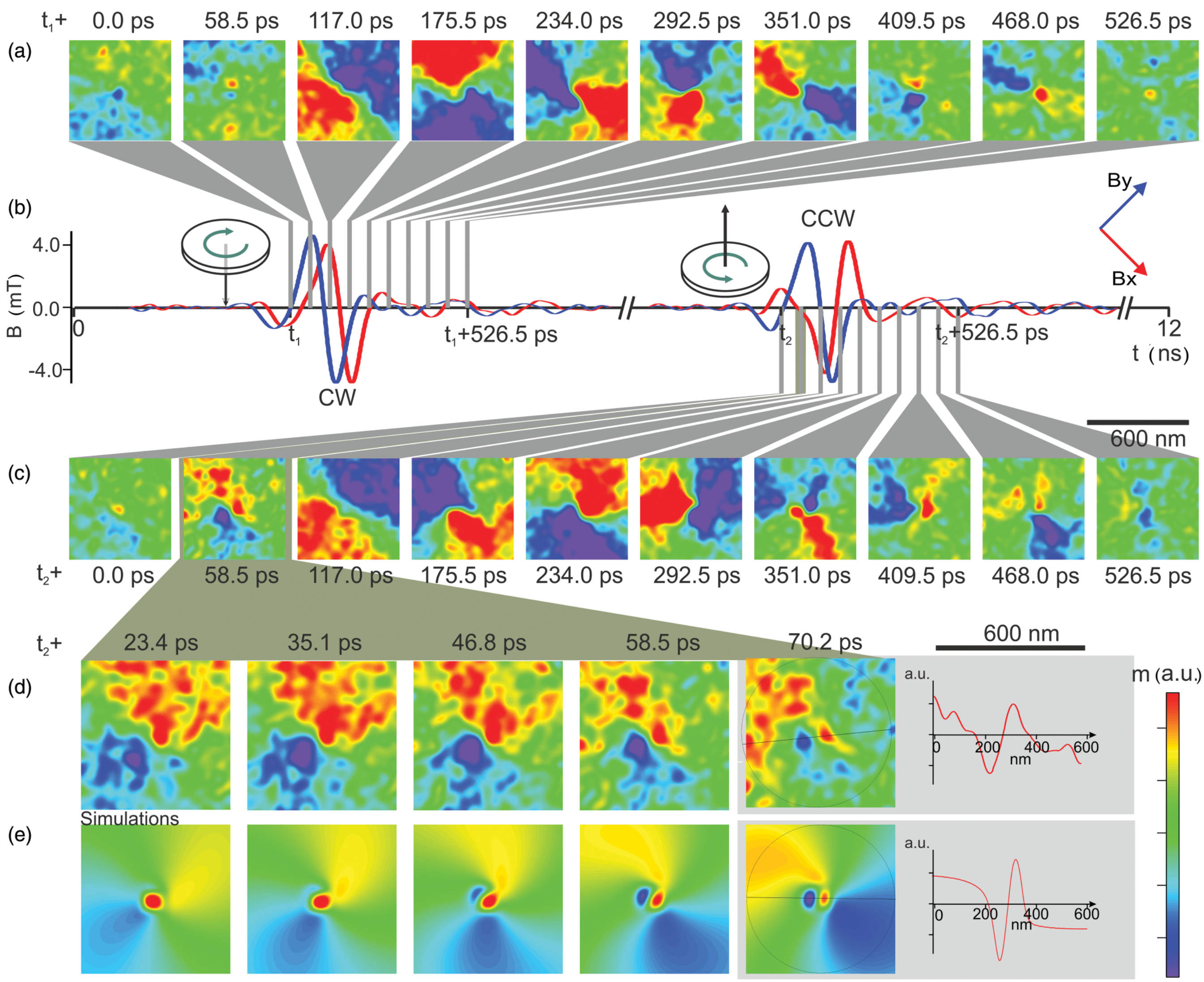

FIG. 2. (Color) Time-resolved imaging of the spin-wave mediated vortex core reversal by one-period bursts shown in Fig. 1(b). (a and c) Snapshots in steps of 55.8 ps showing the out-of-plane component of the magnetization. (d and e) Experiment and simulations, respectively: highly temporally resolved evolution of the out-of-plane component in steps of 11.7 ps. The graphs to the right show cuts along the horizontal lines through the images taken at 70.2 ps (for details see text).

due to their opposite out-of-plane magnetization with respect to the spin-wave profile. This dip (which we marked) leads to the formation of the vortex-antivortex pair. Again, the circles indicate the positions for which the original simulations show the vortex core and the dip.

In a second experiment we have explored the switching behavior by applying one-period field bursts with a center frequency of 4.5 GHz as sketched in Fig. 2(b). Using the field amplitude shown here (4 mT), a CW sense of field rotation has to be applied for selective unidirectional switching of the core polarity from down to up, and then a CCW field pulse is used to switch the vortex from up to down again. The images of the out-of-plane magnetization have been recorded in time steps as short as 12 ps. The fact that we observe a clear contrast in all stroboscopic images proves that for the parameters used (i.e., one-period burst of 4.5 GHz at 4 mT) reliable unidirectional selective switching is achieved from down to up (up to down) using a CW (CCW) burst excitation. Figures 2(a) and 2(c) show the time evolution of the out-of-plane component of the magnetization induced by the two CW and CCW field pulses. The contrast in the images is dominated by the magnetostatic modes in most parts of the disk, whereas the vortex core at the center of the disk is clearly seen only at 0 and 526.5 ps: At $t = 0$ ps the down vortex core is seen as a blue dot, and at 526.5 ps a red dot represents the up vortex state. The dot is blue 526.5 ps after the second burst, showing that the polarity has been reversed again. Between 117 and 234 ps the CW rotating magnetization profile is similar to $\Delta m_z^{1,-1}$ of the azimuthal spin wave ($n = 1, m = -1$) for $p = -1$ which couples most strongly to the CW rotating homogeneous in-plane field. Figure 2(d) shows details of the time evolution of the vortex magnetization shortly after the onset of the CCW excitation (in the time window between 20 and 70 ps after the excitation has started). We observe after a CCW single-period excitation of the vortex up state the magnetic structure with two regions with m_z opposite in sign to the out-of-plane magnetization of the vortex core. This is shown in the right-most figure of Fig. 2(d) for the experiment and of Fig. 2(e) for the simulations. These figures show cuts through the images at 70.2 ps along the indicated horizontal lines which are lines along the high-symmetry axis of the system connecting the centers of the dip and of the vortex core. Along this direction the profiles of the dip and the vortex core are seen most clearly. In contrast, for all single-period excitations with $pm = -1$ we observed only one region.

IV. PHASE DIAGRAM FOR ONE-PERIOD BURST SWITCHING

We have performed micromagnetic simulations for a Permalloy disk according to the sample size used in the experiments in order to investigate vortex core switching for a one-period excitation as a function of excitation frequency and field amplitude. The initial state of the vortex is up ($p = +1$) in all simulations. The resulting phase diagrams are shown in Fig. 3. The left column addresses CW, the right column CCW excitations. For starting with $p = -1$, simply interchange CW and CCW. In Fig. 3(a) the number of switches during and after one burst is shown as a function of excitation frequency and amplitude. For reliable technological applications only the red marked regions in the phase diagram, indicating only one switching event, are relevant. Unidirectional switching is achieved at those frequencies and amplitudes where the core polarity can be reversed with one sense of rotation only—dependent on the initial polarity. The conditions for unidirectional switching are fulfilled for CCW excitations with amplitudes and frequencies below the black line. Suppose, e.g., that we start with $p = 1$ (vortex up) and perform a single switching event with a CCW rotating one-period field burst

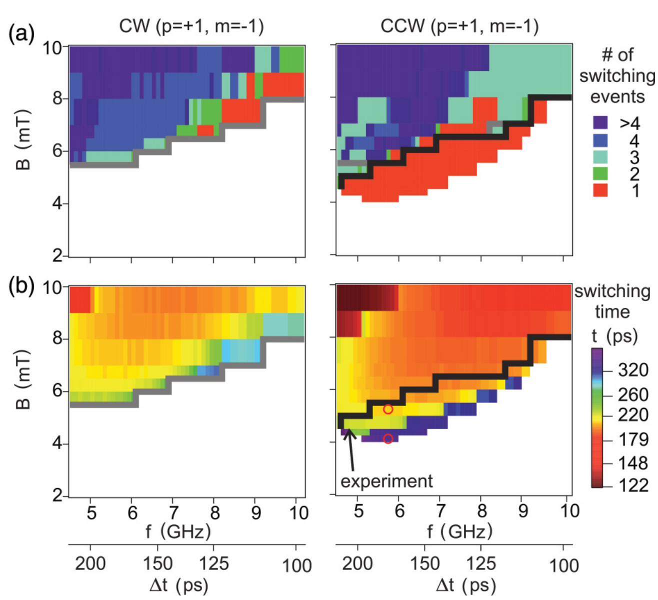

FIG. 3. (Color) Calculated phase diagrams (amplitude vs switching) for vortex core switching by one-period bursts of a rotating excitation field, starting with vortex core up. Left column: CW. Right column: CCW. (a) Number of switching events. (b) Switching times. The two circles in Fig. 3(b) represent the field amplitude and the frequency used in the simulations shown in Fig. 4. The point marked by the arrow "experiment" gives the corresponding values used in the experiment shown in Fig. 2.

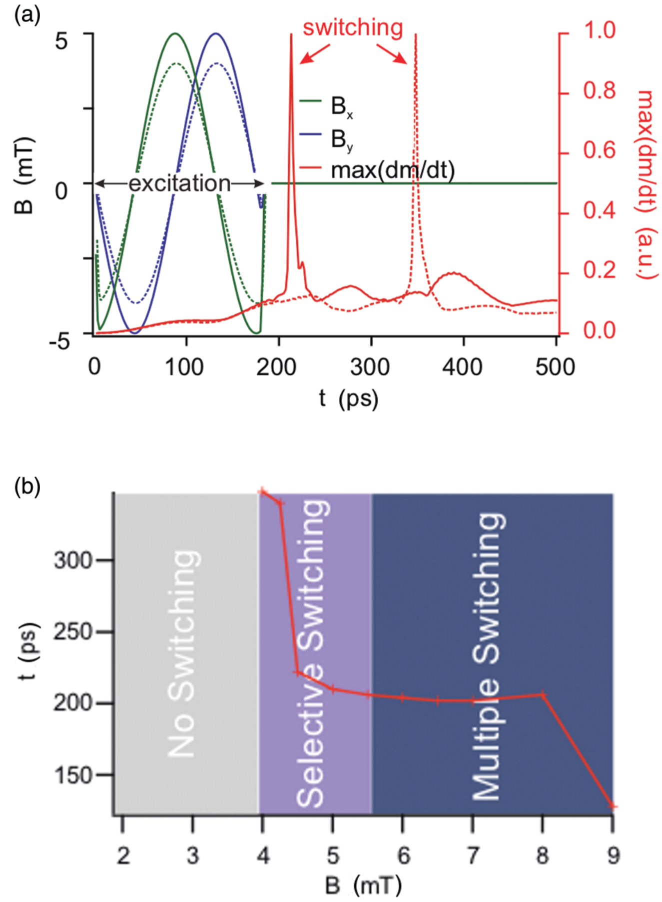

FIG. 4. (Color) (a) Micromagnetic simulations demonstrating the delayed vortex core switching for two different field amplitudes, 4.5 mT (dashed lines) and 5.0 mT (full lines) with switching times 342 and 210 ps. (b) Vertical line cut through Fig. 3(b), CCW, at 5.5 GHz.

of amplitude 4 mT and frequency 6 GHz. To see whether the core with reversed polarity, $p = -1$, can be switched back by the same CCW excitation we examine the left part of Fig. 3(a) which represents also the phase diagram for CCW excitations and $p = -1$, and we see that for 4 mT and 6 GHz no switching back occurs. The simulations also allow us to determine the time required for switching after the onset of the field burst, as shown in Fig. 4. To determine this time we evaluate the time derivatives of the out-of-plane magnetization, $dm_z(\mathbf{r},t)/dt$, for all cells at positions $\mathbf{r}$ in the simulation and plot for each time this quantity for the cell for which it is maximum. The vortex switching time is given by the time delay between excitation and the sharp peak. Figure 3(b) summarizes the simulated switching times as a function of excitation amplitude and frequency. Figure 4(b) shows that at 5.5 GHz a selective switching with switching times from 342 to 200 ps can be achieved. In the experiment shown in Fig. 2 unidirectional switching by the one-period excitation at 4.5 GHz and 4.5 mT is demonstrated. At the corresponding point the calculated phase diagram (Fig. 3) indeed predicts unidirectional switching.

Next we investigate by micromagnetic simulations whether the 200-ps limit for the switching time can be reduced further by using shorter excitation times. For that purpose simulations of the switching process with a reduced excitation time of half a period have been performed. Comparison to the one-period excitation (Fig. 3) shows that also for a half-period excitation low-field unidirectional switching of the vortex core can be achieved by CCW excitation. Compared to the one-period excitation, slightly higher switching thresholds increased by a factor of about $\sqrt{2}$ are observed. The most important finding is that for a half-period excitation the switching time still remains at 200–300 ps. Thus the limitation of the switching time of about 200 ps (for the disk geometry used) seems to be fundamental and cannot be reduced by using shorter excitation times. In addition the switching time exceeds the duration of the excitation; i.e., a delay occurs between the end of the excitation and the actual switching event.

V. CONCLUSION

In conclusion, the combination of experiments and micromagnetic simulations demonstrates that selective unidirectional switching of the vortex core is possible after excitation with one-period rotating field bursts at GHz frequencies.

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