Controlling spin vortex states in magnetic nanodisks by magnetic field pulses

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Abstract. We present the principles of the switching of the polarity and chirality of a magnetic nanodisk by external in-plane field pulses. We show that to switch the polarity requires a field pulse of a sufficient amplitude. On the other hand, to switch the chirality requires a pulse with a smaller amplitude and with a precisely chosen duration. Both phenomena together form the full control of the vortex state.

1. Introduction

The magnetic vortex is one of spin distributions occurring in equilibrium of patterned magnetic nanodisks and analogous elements [1, 2, 3, 4, 5], and is promising for high-density data storage [6], signal sensing [7] and manipulation [8]. The two binary characteristics of vortices, the chirality $c = \pm 1$ (counterclockwise (CCW) or clockwise (CW) vortex’s flow) and the polarity $p = \pm 1$ (up or down orientation of the vortex’s out-of-plane polarized core [9, 10]), determine the dynamic response to ultrafast magnetic field pulses and are important candidates for nonvolatile magnetic memory. For this purpose, the nearly zero stray field of the closed flux spin distribution offers high density arrangements of non-interacting nanodisks. In addition, an in-plane field pulse initiates movement along the direction determined by the vortex “handedness” $h = cp$ (chirality relative to polarity) [11], whereas the relaxation motion traces a spiral whose orientation depends on the polarity but is independent of the chirality, the whole process lasting a few nanoseconds. Both phenomena suggest high-speed vortex state monitoring via the dynamic response.

A major issue is the external manipulation of the polarity and chirality of vortices. While they are very stable against slowly varying fields [12], using short pulses enables high-speed switching [13], requires small amplitudes of switching fields [14], and gives new scopes for research and applications based on nonsteady spin dynamics [15, 16]. Polarity switching has recently been demonstrated by field pulses [14, 13, 17] and electrical currents [18, 19, 20, 21, 22], yielding considerable advantages over the traditional manipulation. On the other hand, it has been frequently claimed that to switch the chirality requires a geometric asymmetry [23, 24, 25]; it has thus been performed by a spin transfer torque [26] and by a field pulse whose symmetry

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was broken by a mask [27]. In this paper we show, using micromagnetic simulations, that the switching of both polarity and chirality of a perfectly symmetric disk can be achieved by a uniform in-plane field pulse, while the only asymmetry required is the polarity and chirality themselves, which is a result of the highest interest for experiments involving magnetic vortices with defined states.

2. Theory and numerical procedures

We carry out the time integration of the Landau-Lifshitz-Gilbert (LLG) equation, \( \frac{d\mathbf{m}}{dt} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \alpha \mathbf{m} \times \frac{\partial \mathbf{m}}{\partial t} \), where \( \mathbf{m} \) denotes the unit magnetization vector, \( \gamma \) the gyromagnetic ratio, \( \alpha \) the Gilbert damping parameter, \( t \) the time, and \( \mathbf{H}_{\text{eff}} = -(\mu_0 M_s)^{-1} \partial E/\partial \mathbf{m} \) the effective magnetic field, determined from the energy density \( E \) (with \( \mu_0 \) being the magnetic permeability of vacuum and \( M_s \) the saturation constant) and being the sum of the externally applied field term \( \mathbf{H}_{\text{ext}} \), exchange term \( \mathbf{H}_{\text{exch}} = (2A/\mu_0 M_s)\nabla^2 \mathbf{m} \) (with \( A \) denoting the exchange stiffness constant), and demagnetization term \( \mathbf{H}_{\text{dem}} \). The LLG equation and all the field terms are numerically treated via regular discretization. The cylindrical nanodisk of the diameter \( 2R \) and thickness \( L \) uses the splitting of the rectangular area \( 2R \times 2R \times L \), containing the nanodisk, into a regular grid of \( N \times N \) rectangular cells of the sizes \( d_x \times d_y \times d \), where \( d_x = d_y = d = 2R/N \). We assume \( R = 100 \text{ nm}, L = 20 \text{ nm}, N = 100, \) and \( d = 2 \text{ nm} \). Magnetic material fills each jth cell whose central lateral coordinates \( x_j, y_j \) satisfy the condition \( x_j^2 + y_j^2 \leq R \); all the other cells contain air. In the discretized LLG equation the unit magnetization \( \mathbf{m}^{(j)} \) is assumed uniform within each cell. Thus the exchange field is calculated as \( \mathbf{H}_{\text{exch}} = (2A/3\mu_0 M_s d^2) \sum_j \mathbf{m}^{(j)} \), with the summation over all eight neighbours in the grid [28]. The demagnetizing field is generated by surface magnetic charges present on each cell, with help of analytical formulæ used for surface integrations as described by Hubert and Schafer [29]. The method is numerically compatible with the Object Oriented Micromagnetic Framework [30]. All numerical experiments were carried out on a Py nanodisk of the diameter of 200 nm, thickness of 20 nm, with \( c = p = 1 \), using material parameters \( M_s = 860 \text{ kAm}^{-1}, A = 1.3 \times 10^{-11} \text{ Jm}^{-1} \), and \( \alpha = 0.01 \).

3. Results and discussion

The process of dynamic switching of the vortex polarity is demonstrated in Fig. 1. An external field pulse of the strength \( B_x = 70 \text{ mT} \) and duration of 30 ps is applied to the vortex at \( t = 0 \). Shortly after turning the field off (\( t = 39 \text{ ps} \) in Fig. 1) the vortex distribution becomes slightly deviated, at \( t = 66 \text{ ps} \) a pair of a new vortex and an antivortex is created, at \( t = 73 \text{ ps} \) the antivortex annihilates together with the old vortex which creates a point source of spin waves which are scattered by the new vortex (\( t = 75 \text{ and } 80 \text{ ps} \)). Finally, the last subfigure shows a later distribution (\( t = 1 \text{ ns} \)) of the new vortex with the opposite polarity. Each arrow for \( t \) between 39 and 80 ps represents the in-plane component of the magnetization vector in a grid of \( 2 \times 2 \text{ nm} \), whereas the shades of the red–blue color correspond to the out-of-plane component.

On the other hand, to switch the chirality of the nanodisk under interest requires field above 50.6 mT (in order to expel the original vortex out of the disk) but below 57.7 mT (to avoid the

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**Figure 1.** Process of dynamic switching of the vortex polarity.
switching of the vortex polarity before the vortex annihilation), as determined by a systematic set of numerical experiments with the excitation field varying with the step of 0.1 mT. For our demonstration we have chosen the amplitude of the external field 51 mT. The whole process is demonstrated in Fig. 2, with two examples of pulse durations of 836 and 988 ps (this time with the $M_y$ dependent color range in contrast to Fig. 1). The original CCW vortex follows a curve towards the annihilation point at 584 ps, after which a CCW C-like curved state (C-state) appears, which is later transformed into an opposite (CW) C-state, both of which oscillate between each other. According to the displayed snapshots, the oscillation can be described as alternation between the CCW and CW C-states, the first of which turns into the second via domain wall motion from the north pole to the south pole of the nanodisk. The curvatures of the two C-states continuously decrease, both finally converging into a stable, saturated state. If we turn the field off at $t_{\text{off}} = 836$ ps, where the most distinct CW orientation of the C-state is present, then this CW spin curvature further evolves until a new vortex nucleates with the CW chirality, so that the chirality of the original vortex is switched (blue pulse and arrows in Fig. 2). On the other hand, if we turn the field off at $t_{\text{off}} = 988$ ps, at which the C-state possesses the CCW orientation, then this CCW spin curvature evolves into a CCW vortex, so that the original chirality is preserved (red pulse and arrows). In other words, the orientation of the C-state at which the field is turned off determines the chirality of the nucleated vortex. More detailed investigation of this process will be provided in a later paper.

4. Conclusion
In summary, we have demonstrated the principles of the fully controllable switching of the polarity and chirality based on optimizing the strength and duration of the excitation pulse. The method does not require any artificial asymmetry of the nanodisk or any particular field distribution, because the original vortex state determines the entire processes. The weakest point of the chirality switching is the fact that the information about the original polarity is lost (due to enormous release of energy during nucleating the new vortex, accompanied with one or two occurrences of the polarity switching), which can be prevented by memorizing the polarity before the vortex is excited and (eventually) by switching it after the new vortex relaxes.
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