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Fast and controllable switching the circulation and polarity of magnetic vortices

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ABSTRACT

We report a method to switch both the circulation and polarity of magnetic vortices in a controlled manner within a nanosecond utilizing micromagnetic simulations. The controllable switch is achieved with the combination of two different types of magnetic field pulses on submicron permalloy disks with heptagonal shape. When a magnetic field pulse of ~100 mT is applied along one of the edge directions of the heptagon, the circulation of the vortex can be manipulated according to the pulse direction. When a pair of pulses with a few tens of mT in magnitude and relative delay of about 100 ps is applied in orthogonal directions, the polarity can be further controlled without influencing the circulation. The different magnitude of switching fields allows for the combination of both types of pulses in the control of both the circulation and polarity of magnetic vortices. The switching mechanism and the controlling parameters for disks with diameters of 500 and 700 nm are discussed.

1. Introduction

Magnetic vortices have attracted much attention recently because of the fundamental interest due to their unique spin structures [1–3], as well as their strong potential applications in microwave oscillators [4,5], magnetic storage, and logic devices [6–10]. Recently, vortices are also proposed to create Skyrmion crystal in combination with perpendicular films [11]. A magnetic vortex is characterized by an in-plane clockwise (CW) or counter-clockwise (CCW) circulating magnetization (circulation, *C*) around a nm-sized central core magnetized perpendicularly up-or down (polarity, *P*), yielding 4 degenerate states. These four states allow for storing 2 bit instead of the usual 1 bit of information in one single unit. The special magnetization configuration also minimizes the stray field of each unit thus the interaction between units. These features make magnetic vortices appealing for nanomagnetism and magnetic data storage. To store the information, a fast and controllable switching among these four states is required. The switching behaviour of magnetic vortices has been studied extensively [10,12–44]. Methods include magnetic field switching [10,12–33] and current induced switching through spin transfer torques [34–41]. These studies are mainly focused on the individual switching of either the vortex core [10,12–18,24,28,29,36–40] or the circulation [19–21,31,35]. The individual control of the vortex circulation [19,27,31] and polarity [28–30] also has been experimentally demonstrated. Recently, a few studies were devoted to the switching among the four states [25–27,32,34]. Ref. [26] proposed utilizing two magnetic field pulses with different magnitude for switching the magnetic vortex polarity and circulation. Similarly, Ref. [34] proposed switching the magnetic vortex among the four-fold degenerate states with perpendicularly polarized spin currents. These two methods, however, require a pre-knowledge of the exact initial states; therefore, they are not controllable switching. Utilizing an interesting "pac-man" geometry, the simulations in Ref. [25] show that it is possible to control the circulation by saturating the sample along different directions, and the polarity with an additional magnetic field sweeping within minor loops. The discussion, however, is limited to static switching only. In contrast, a fast and controllable switching is highly desired for applications in magnetic logic devices and data storage.

In this paper, utilizing micromagnetic simulations, we report a method to switch both the circulation and polarity of vortices controllably within a nanosecond (ns). The method is different from previous findings in that it is fast and does not require pre-knowledge of the initial state. By applying a field pulse of ~100 mT in magnitude and sub-ns in width (*w*) along one of the edge directions of heptagonal permalloy (Py) submicron disks, the circulation can be manipulated according to the pulse direction. With a pair of orthogonal pulses of a few tens of mT in magnitude, sub-ns both in width and in relative delay, the polarity

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can be controlled additionally by the field sequence (either CW or CCW) without influencing the vortex circulation. The different magnitudes of the switching fields in these two pulses allow them to be combined to control both the circulation and the polarity. The mechanism for the manipulation of both the circulation and polarity and the controlling parameters for disks with diameters of 500 and 700 nm is discussed. It is found that both the circulation and polarity can be controlled in a wide region in the width-magnitude phase diagram of the field pulses, demonstrating the feasibility of the proposed method.

2. Micromagnetic simulation method

The micromagnetic simulations are performed utilizing the NIST OOMMF code [45], which is based on the Landau–Lifshitz (LL) equation. Submicron Py disks with heptagonal shape are considered. It has been demonstrated that the vortex state can be stabilized in triangular, pentagonal and heptagonal magnetic disks with appropriate aspect ratios. Moreover in a polygonal disk with odd edges, it has been experimentally demonstrated that the vortex can be controlled into either CW or CCW state according to the applied field direction [19,27]. In our simulations, heptagonal disks with the circumscribed circle diameter of 500 nm and 700 nm are discussed. The thickness of the disks is fixed to be 50 nm. The heptagonal shape is chosen because it is close to a perfect circle but yet the asymmetry in the shape is still sufficient for circulation control. Typical material parameters of Py are used: the saturation magnetization of $M_s = 7.5 \times 10^5$ A/m, the exchange constant of $A = 1.3 \times 10^{-11}$ J/m, and the damping factor of $\alpha = 0.01$. Magnetic anisotropy is neglected in the calculations. The cell size in all the simulations is $2 \times 2 \times 10$ nm^3. We also repeated the calculations with smaller cell size for a few simulations and found that the essential physics remained unchanged.

3. Results and discussion

3.1. General scheme of the approach

In the absence of external field, the disks are in the vortex state. Their polarities and circulations, however, are randomly distributed. Fig. 1 presents the proposed two-step approach to control both the circulation and polarity within 1 ns. To control the circulation, a pulse field of ~100 mT and sub-ns width is applied along one of the heptagonal edge directions, which is defined as the x-axis shown in Fig. 1(a). As will be demonstrated below, the pulse field brings the disks close to saturation and after a few ns, the remanent state relaxes to a vortex. Remarkably, the circulation of the re-formed vortex is absolutely determined according to the field direction. When the field is along the $+x/-x$ direction, a CW ($C = -1$)/CCW ($C = +1$) vortex is obtained, respectively [shown in Fig. 1(a)]. We note that a similar method has been used to control the vortex circulation statically [19]. Here, we use a stronger field pulse to achieve the fast switching. Control of vortex polarity has also been experimentally demonstrated with a rotating *ac* magnetic field [28–30]. In our case, a combination of two slightly weaker field pulses along the x-axis and y-axis with a certain delay as shown in Fig. 1(b) is used. With the pulse fields applied along the $+x$ and $+y$ directions, the vortex core can be formatted to pointing down ($P = -1$), independent of its initial configuration. On the contrary, the resulting vortex core is always pointing up ($P = +1$) when the pulsed fields are applied in the $+x$ and $-y$ directions. In short, the field sequence and the end polarity form a left-handed geometry. In our simulations, the field strength used for polarity control is chosen to be only a tenth to a quarter of that used for the circulation setting and the already initialized vortex circulation therefore remains unchanged. So, with this designed two-step approach, the circulation and polarity can be controlled according to the directions of the type I and type II pulses without pre-knowledge of the initial state.

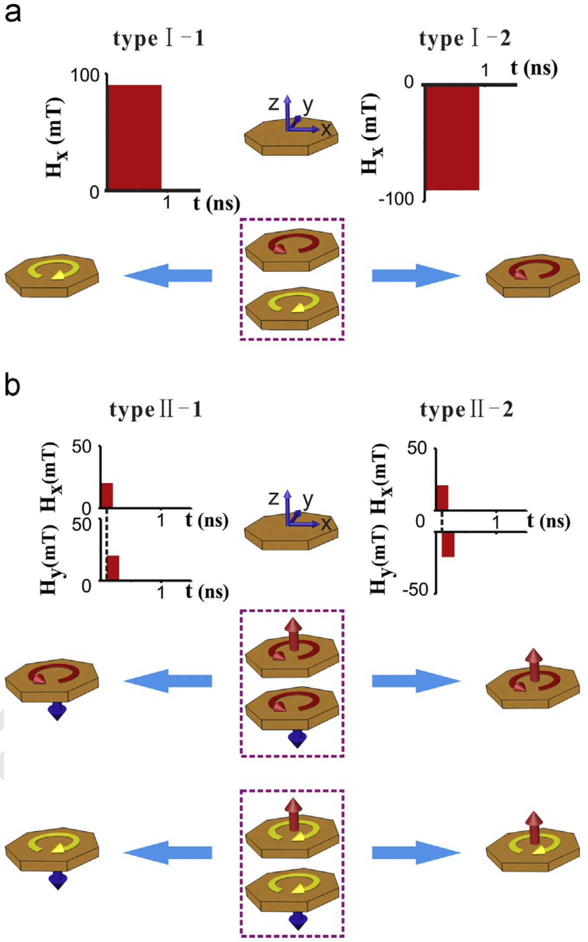

Fig. 1. Schematic picture of the proposed two-step process for the control of the vortex circulation and polarity in heptagonal disks. (a) Utilizing a high amplitude magnetic field pulse along the edge direction of the heptagon, the circulation can be configured into CW or CCW according to the sign of the field direction. (b) With a pair of magnetic field pulses applied along the x- and y-axes, the polarity of the vortex will be determined according to the direction of the field along the y-axis.

3.2. Controllable switching of circulation

Fig. 2(a) shows the calculated temporal evolution of the in-plane magnetization of vortex with CCW and CW (not shown due to the similarity) initial configurations after applying a pulsed field of 100 mT in magnitude, and 900 ps in width along the $+x$ direction. The diameter of the circle circumscribed around the disk is 500 nm. With the strong field pulse, the core is pushed out of the disk. At $t = 900$ ps when the magnetic field is switched off, the magnetization is almost parallel to the $+x$ direction, forming a single domain state [panel II in Fig. 2(a)] independent of the initial configuration. With the given geommetry, the single domain state is however unstable and the system needs to relax into the vortex state. To reduce the demagnetizing energy, the moments near each edge of the heptagonal disk will rotate towards the directions parallel to the edges. Since there is a high energy barrier when the moments are perpendicular to edge directions, the local moments prefer to rotate with acute angles. In such a case, the local moments near the four edges A, B, F and G shown in Fig. 2(b) form a CW

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