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Magnetic vortex-antivortex dynamics on a picosecond timescale in a rectangular Permalloy pattern

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Abstract

We report our experimental finding that there exists a pair of magnetic vortex and antivortex generated during an excited motion of a magnetic vortex core. Two vortices structure in $2 \times 4\ \mu m^2$ rectangular Permalloy pattern is excited by an external field pulse of 1-ns duration, where each vortex is excited and followed by the vortex core splitting. X-ray microscopy with high spatiotemporal resolution enables us to observe a linking domain between two temporarily generated pairs of vortex-antivortex cores only surviving for several hundreds of picoseconds. The linking domain structure is found to depend on the combinational configuration of two original vortex cores, which is supported by micromagnetic simulations with a very good agreement.

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In a patterned ferromagnetic film system with a confined geometry, magnetization tends to curl around the center to meet the requirement to reduce magnetostatic energy, leading to a flux-closure magnetic state[1]. The curling magnetization configuration, however, competes with an increase of exchange energy which prefers to have spins aligned parallel to each other. The cost of having the curling magnetization particularly in the center of the pattern becomes extremely expensive due to the exchange energy. As a compromise, spins at the central region of a tiny ferromagnetic pattern form a structure with a singularity called as a magnetic vortex, where spins in the core region are not on the plane any more but standing out of the plane. The magnetization components out of the plane constitute a magnetic vortex core, whose magnetization direction is either up or down[2, 3]. Recently, the dynamics of vortex core has been attracting huge attention, since memory and logic devices based on the vortex core configuration have been proposed[4–6]. Dynamics of a magnetic vortex structure excited by an external magnetic field pulse has been observed using the photoemission electron microscopy[7], where it has been found that a magnetic vortex core in a rectangular pattern exhibits a gyrotropic motion around the equilibrium position on a nanosecond timescale after being excited by a short magnetic pulse field. Excited motion of magnetic vortex showing non-gyrotropic trajectory has been also observed[8, 9], where a clear mechanism of the non-gyrotropic mechanism is not fully presented.

From the technological point of view, a controlled switching of vortex core is essential in future application. The vortex core switching phenomenon has been experimentally explored recently by applying short burst of external field[10] or by injecting spin-polarized electrical current[5]. In these studies, vortex core trajectory with resonant gyrational motion has been compared before and after an application of the burst of an external resonant field or an electrical resonant current, based on the fact that the rotational sense of gyrational motion is depending on the vortex core handedness[5, 7, 10]. From these pioneering experimental studies, vortex core is now believed to be switchable either by the resonant field burst or by the resonant ac electrical current. The question which still needs to be answered is *how* the magnetic vortex core is switched during the reversal process.

Vortex core switching mechanisms based on numerical studies have been proposed[11–15], where all the scenarios include a generation of a vortex-antivortex pair along with excited motion of the original vortex core. Generated antivortex is a spin structure which also has a core magnetization out of the plane but has surrounding spins not simply curling around the core unlike the vortex due to a broken axial symmetry[1]. Although the theories and numerical calculations have predicted a pair creation of vortex-antivortex during the highly excited vortex motion, no clear experimental evidence for the pair creation has been reported so far. The difficulty of an experimental observation arises since the cores of vortex and antivortex are too small[16] to be clearly spatially resolved during its excited dynamic motion. Moreover, the relevant timescale of the creation and annihilation of vortex-antivortex pair is expected to be on a picosecond timescale[12, 13]. Thus, to reveal the dynamics of vortex and antivortex pair, a magnetic microscopy technique with high spatial and fast temporal resolution is needed.

In this Letter, we report our observation of dynamics of vortex and antivortex in a patterned Permalloy by means of magnetic transmission X-ray microscopy. We positioned two vortices in $2 \times 4\ \mu m^2$ permalloy rectangle whose ground state is 7-domains Landau flux closure state. By applying a fast field pulse of 1-ns duration, two vortices are excited and seem to be followed by a creation of vortex-antivortex pair. We have observed a magnetic domain structure connecting two pairs of vortex-antivortex temporarily generated from the excited motion of the original vortices. The observed connecting domain structure is observed to exist only for few hundreds of picoseconds. The connecting magnetic domain is considered to be a direct consequence of mutual interaction between the generated pairs of vortex-antivortex. Our experimental observation provides the first experimental evidence of interacting vortex-antivortex dynamics on a picosecond timescale during the excited vortex core motion, which is in a good agreement to the prediction of micromagnetic simulation.

In the present study, the full-field X-ray microscopy (XM-1) developed in the beamline 6.1.2 at the Advanced Light Source synchrotron is adopted to investigate the spin structures of permalloy rectangles[17]. Utilizing Fresnel zone plate as an optical element, lateral spatial resolution of 15 nm or better can be achieved in observation of magnetic domains[18, 19] Magnetic contrast is provided by the X-ray magnetic circular dichroism[20] with controlling polarization of incoming X-ray. X-ray photon energy is tuned to be 854 eV to match Ni L_3 aborption edge, where the dichroic contrast becomes maximum for Permalloy[21]. The samples were prepared onto 100-nm thick Si_3N_4 membrane to allow enough transmission of X-ray for an imaging. 100-nm thick Au are deposited by sputtering and patterned by electron beam lithography to be a coplanar waveguide structure with 5 μm ground line width. Then, Permalloy rectangles of $2 \times 4\ \mu m^2$ with 50-nm thickness are patterned directly on the Au waveguide. To observe a spin dynamics on a sub-ns timescale, we integrated a stroboscopic pump-probe measurement setup into the X-ray microscope. The pump pulse is a short electronic current pulse generated by an electronic pulser with a rise time less than 100 ps and a fall time less than 200 ps. Current pulse of 1-ns duration and 2 V height is launched into the coplanar waveguide, generating about 100 Oe field parallel to the plane of the rectangle and perpendicular to the longer side of the rectangle. The probes are flashes of X-ray pulses with a 70-ps pulse width determined by the synchrotron electron bunch structure. Stroboscopic pump-probe observation has been carried out during the two-bunch operation mode, where the pump X-ray flashes are separated by 328 ns in time. The pump is controllably delayed with 100-ps time step by electronic delay line with a jitter level less than few ps. Typical accumulation time for one image at each time step is about few minutes. More experiment details have been reported elsewhere[22]. Micromagnetic simulation is carried out to understand detailed vortex and antivortex dynamics based on Landau-Liftshitz Gilbert equation[23] with cell size of $5 \times 5 \times 10$ nm^3 and damping constant α of 0.01.

Pattern is initially saturated with an external field of 1 kOe along the horizontal direction parallel to the longer axis of the rectangle. After the external field is turned off, two vortices are positioned on the left and the right side of the rectangle, forming a ground state with flux-closure 7 domains. Direct observation of 7-domains structure visualized by means of XM-1 are demonstrated in Fig. 1(a), where the magnetization direction of each domain is denoted by solid arrow. Image at each time step is smoothed and then, normalized by the image of saturated magnetization state so that we can achieve magnetically contrasted images. The magnetic field pulse of 1-ns duration is applied and the time is set to be zero ($t = 0$ ps) at this moment. Direction of the 1-ns field pulse is shown in the figure by dotted arrow, which is parallel to the shorter axis of the rectangle.

Typical domain evolution patterns are illustrated in Fig. 1(b). Gradient images corresponding to images of magnetic contrast are also depicted next to the contrast images, to help easy detection of vortex and domain wall positions. After an excitation by the field pulse, two vortices seem to be kicked to direction toward the center of pattern, followed by bulging domain walls, which might be understandable by the fact that the enlarged domains pointing upward are having magnetization parallel to the applied field. However, rather than exhibiting an expected simple gyrotropic motion, two vortex cores approach each other to the center of the rectangle. This seems quite contradictory to the simple expectation[5, 7, 10], but nongyrotropic motions have already been experimentally observed as well[8, 9]. While excited, each vortex core seems to be stretched along the applied field direction. The stretched vortex core seems to be splitted vertically, which is barely observable in gradient images between t = 800 $\sim$ 1200 ps in the figure. Vortex core becomes no longer rigid and thus, a simple gyrotropic core trajectory is not observed in the present configuration. Further experimental investigation may be needed with a magnetic microscopy having a better spatial resolution to directly spot the splitted vortex cores, which is beyond the scope of this paper.

Surprisingly, there appears a black striped domain pattern connecting left and right vortices. The connecting domain appears around when t = 400 ps and lasts until about t = 1400 ps, thus the lifetime of the domain is only about 1 ns or less. After the connecting domain pattern disappears, it doesn't reappear for 8 ns which is the present stroboscopy time window. This implies that the connecting domain only exists in the very energetic initial state generated by the excitation field pulse. One might consider that the connecting pattern is not a magnetic domain but an interference pattern of excited spin wave. The 1-ns time scale of the connecting pattern lifetime corresponds to $\sim$ 0.5 GHz spin wave mode, if we approximate 1-ns as a half-wave period, which is too slow for spin waves in the present geometry[24].

We have repeated our stroboscopic observation after resetting the 7-domains state by fully saturating the pattern by applying an external field of 1 kOe. XM-1 has a slight tilt of the sample from the direction of the X-ray incidence to realize a magnetic contrast[19, 22]. In the tilted geometry, the saturating field direction is almost parallel to the sample plane but there exists an angle of few degree between the saturating field and the sample plane. Thus, by controlling the polarity of the saturating field, we can have a small but controllable net field along the direction out of the sample plane, as illustrated on the bottom in Fig. 2. After saturation of the same rectangle sample, new 7-domains Landau state is found to be formed at each time. After an excitation by the pulse field, connecting domain is observed again. However, very interestingly, the connecting domain becomes bright rather than black in some cases. It has been found that the contrast of connecting domains depends on the saturating field history whether the saturating field has a tiny positive out-of-the-plane component (bright) or negative component (dark), as demonstrated in Fig. 2. This implies that the saturation along the longer axis of rectangle with positive (negative) out-of-the-plane field may result in two vortex cores having positive (negative) out-of-the-plane component, since the Zeeman energy prefers to have the core magnetization parallel to the out-of-the-plane component of the saturating field. Several examples of connecting domains with bright or dark contrast are demonstrated in Fig. 2(a) and (b), respectively. For comparisons, 7-domains states having initial magnetization identical with magnetization configuration of the Fig. 1(a) are selected. Thus, all the cases shown in Fig. 2 have the same initial magnetization of domains irrespective of the connecting domain contrast. Wall type is expected to be the same as well for all the cases in the figure, since we have simply repeated our observation for the same sample.

All the images in Fig. 2 are taken at t = 800 ps for comparisons. It should be noted that the shape of connecting domains are different according to the contrast. Dark connecting domains span from the upper left to the bottom right, while bright domains span from the bottom left to the upper right, leading to an exact left-right symmetry in the shape only with a reversed contrast. All repeated observations exhibit the nongyrotropic motion of excited vortices. Left vortex is kicked to the right and right vortex is kicked to the left after the pulsed excitation, then vortex cores are stretched vertically followed by a sudden appearance of connecting domains. The contrast of connecting domains are found to be either bright or dark compared to the contrast of diamond-shaped center domains. Initially, there are 3 contrast levels in the 7-domains ground state of the rectangle due to the contrast mechanism of the XM-1[19]. The black and white represents the left and right magnetization, respectively, while the intermediate grey could be either up or down magnetization, as shown in Fig. 1(a). The diamond-shaped center domain pointing downward in the figure then has a mid-level contrast. Bright or dark connecting stripes appearing on the diamond-shaped center domain implies that the magnetization direction of the connecting domain is having a magnetization component parallel either to the right (bright) or the left (dark).

For a detailed investigation, we have carried out a micromagnetic simulation. After preparing the 7-domains initial state of a Permalloy rectangle with the same area dimension, 1-ns pulse field of 100 Oe field strength has been applied. Two cases of core polarities (p) are chosen to be either p = +1 (Fig. 3(a)) or p = -1 (Fig. 3(b)) to compare with the observation in Fig. 2. Micromagnetic simulation reveals the splitting behavior of vortex cores more clearly. Simulated trajectories of the two original cores and bulging domain walls are found to well match our experimental observations. Here, it should be noted that the connecting domains having the contrast as observed are regenerated, as demonstrated in the figure. For direct comparisons, simulated snapshots are taken at the same time (t = 800 ps) as in the case of Fig. 2. The connecting shape and the time-evolution of the link domain are in good agreement to the experimental observation. In the simulation, it has been observed that the two original cores experience a splitting with a pair generation of vortex-antivortex. The vortex-antivortex pair generated during the excited motion of the original vortex core seems to preferentially stay for the domain wall region since the cores located on the wall costs a less exchange energy than the cores in the middle of domain. This temporarily stabilize the existence of the newly generated vortex-antivortex pair. At this moment, due to the high exchange energy accumulated between the vortex-antivortex pair and the excess energy distributed over the diamond shaped central domain, a stripe domain starts to grow simultaneously from the left and the right vortex-antivortex pairs, leading to the link domain connecting the left and the right vortex-antivortex pairs. For example, as in Fig. 3(a), a stripe domain with magnetization to the bottom right direction grows from each side and merges, forming the connecting domain with the uniform magnetization to the bottom right. A stripe domain with magnetization to the bottom left direction (Fig. 3(b)) is explainable in a similar way. The detailed spin configuration for each vortex-antivortex pair is zoomed in the middle row of Fig. 2, where cores are spotted with circles as a guide. A schematic diagram describing the processes are illustrated as well on the bottom row of the figure.

We like to stress that our experimental finding has been successfully reproduced by the micromagnetic simulation. In particular, the shape, the contrast, and the timescale of the temporarily surviving connecting domain is understood as a result of mutual interaction between the two pairs of vortex-antivortex generated due to the excitation of the original vortex structures. Thus, we believe that the present work provides a meaningful evidence of the vortex-antivortex pair generation process which is predicted to play a key role in the excited vortex core motion and the core switching.

In conclusion, dynamics of the vortex and the antivortex in a rectangularly patterned Permalloy element has been explored on a picosecond timescale using high-resolution X-ray microscopy. Prediction of the pair creation of vortex-antivortex during the excited motion of the original vortex core is experimentally evidenced by observing the very fast link domain spanned between the two newly generated antivortex cores. The shape and contrast of the link domain is well matching with the micromagnetic simulation.

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[1] A. Hubert and R. Schafer, *Magnetic Domains* (Springer, 1998).

[2] T. Shinjo *et al.*, Science **289**, 930 (2000).

[3] A. Wachowiak *et al.*, Science **298**, 577 (2002).

[4] S. Bohlens *et al.*, Appl. Phys. Lett. **93**, 142508 (2008).

[5] K. Yamada *et al.*, Nat. Mat. **6**, 269 (2007).

[6] H.-G. Piao *et al.*, Appl. Phys. Lett. **94**, 052051 (2009).

[7] S.-B. Choe, *et al.*, Science **304**, 420 (2004).

[8] J. Raabe *et al.*, Phys. Rev. Lett. **94**, 217204 (2005).

[9] K. Yu. Guslienko *et al.*, Phys. Rev. Lett. **96**, 067205 (2007).

[10] B. Van Waeyenberge *et al.*, Nature **444**, 461 (2006).

[11] R. Hertel and C. M. Schneider, Phys. Rev. Lett. **97**, 177202 (2006).

[12] R. Hertel *et al.*, Phys. Rev. Lett. **98**, 117201 (2007).

[13] K.-S. Lee *et al.*, Phys. Rev. B **76**, 174410 (2007).

[14] S. Choi *et al.*, Phys. Rev. Lett. **98**, 087205 (2007).

[15] K. Guslienko *et al.*, Phys. Rev. Lett. **100**, 027203 (2008).

[16] J. Miltat and A. Thiaville, Science **298**, 555 (2002).

[17] W. Chao *et al.*, Nature **435**, 1210 (2005).

[18] D.-H. Kim *et al.*, J. Appl. Phys. **99**, 08H303 (2006).

[19] P. Fischer *et al.*, Mater. Today **9**, 26 (2006).

[20] J. Stöhr and H. C. Siegmann, *Magnetism* (Springer, 2006).

[21] Center for X-ray Optics and Advanced Light Source, *X-Ray Data Booklet* (Lawrence Berkeley National Laboratory, 2001).

[22] B. L. Mesler *et al.*, J. Vac. Sci. Technol. B **25**, 2598 (2007).

[23] K.-J. Lee *et al.*, Nature Mat. **3**, 877 (2004).

[24] M. Buess *et al.*, Phys. Rev. Lett. **93**, 077207 (2004).

[25] K. S. Buchanan *et al.*, Nature Phys. **1**, 172 (2005).

FIGURES

Figure 1. (a) Typical domain configuration of 2 x 4 μm^2 permalloy rectangle with 7-domains Landau state including 2 vortices. Solid arrow represents magnetization direction at each domain. Vertically upward dotted arrow denotes the direction of external pulse field. (b) Time-resolved observation of magnetic configurations and corresponding gradient images after the pulse field is switched on at t = 0 ps.

Figure 2. Repeated observations of connecting magnetic domains at t = 800 ps. All figures are from the same single pattern after resetting vortices configuration by applying a saturating external field. In dotted circles, connecting domains are found. (a) Connecting domains between the upper left and the bottom right with a dark contrast and (b) connecting domains between bottom left and upper right with bright contrast.

Figure 3. Simulated spin configurations of the Permalloy rectangle at t = 800 ps after an excitation with (a) the same core polarities with p = +1 (up/up) and (b) with p = -1 (down/down). Color code represents the M_x component as denoted in the color bar. Detailed spin configurations for the area with vortex cores are zoomed in the middle row. Schematic diagram is described in the bottom row, where V and AV represent vortex and antivortex, respectively.

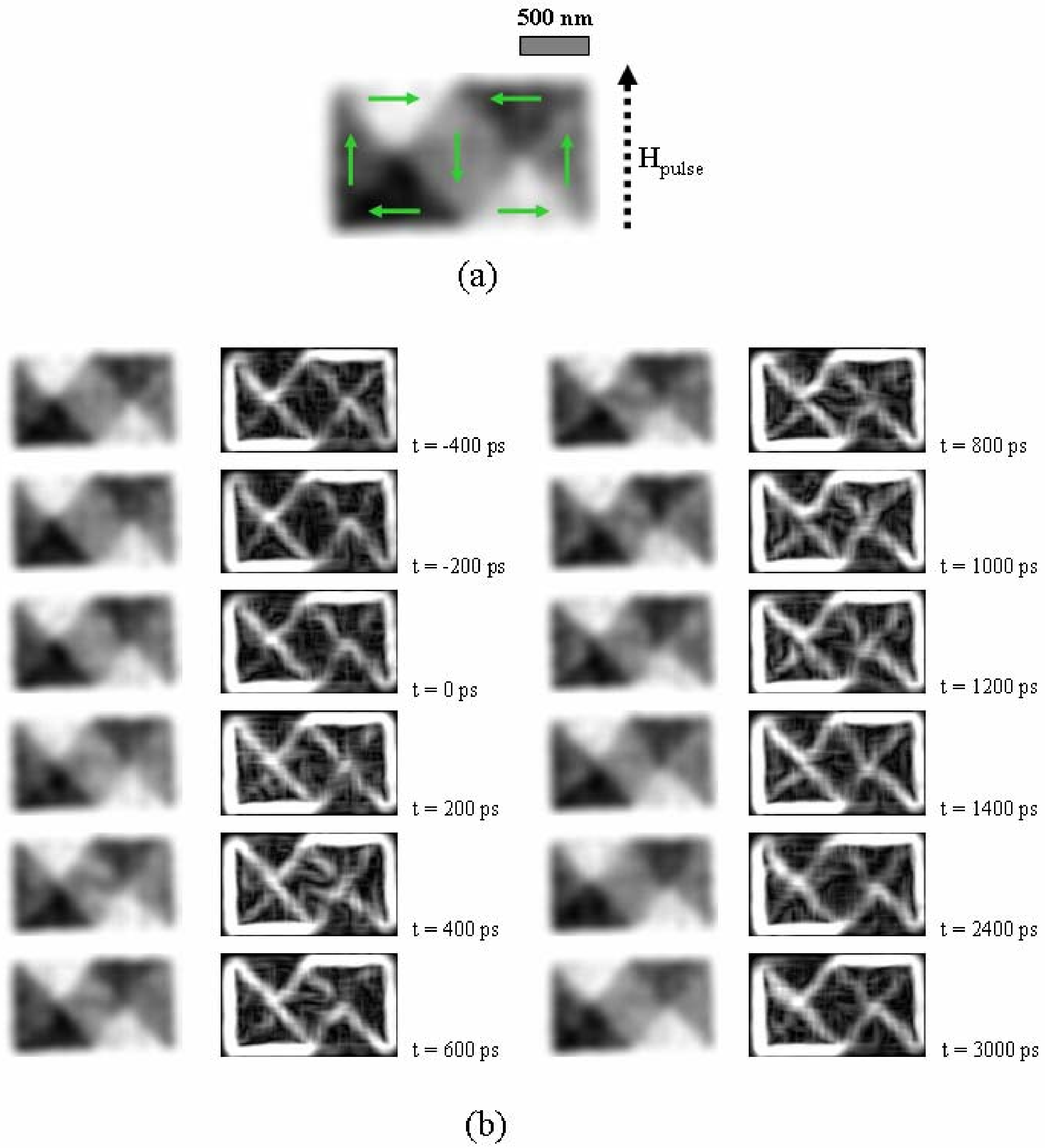
500 nm
H pulse
(a)
t = -400 ps
t = -200 ps
t = 0 ps
t = 200 ps
t = 400 ps
t = 600 ps
t = 800 ps
t = 1000 ps
t = 1200 ps
t = 1400 ps
t = 2400 ps
t = 3000 ps
(b)

FIG 1.

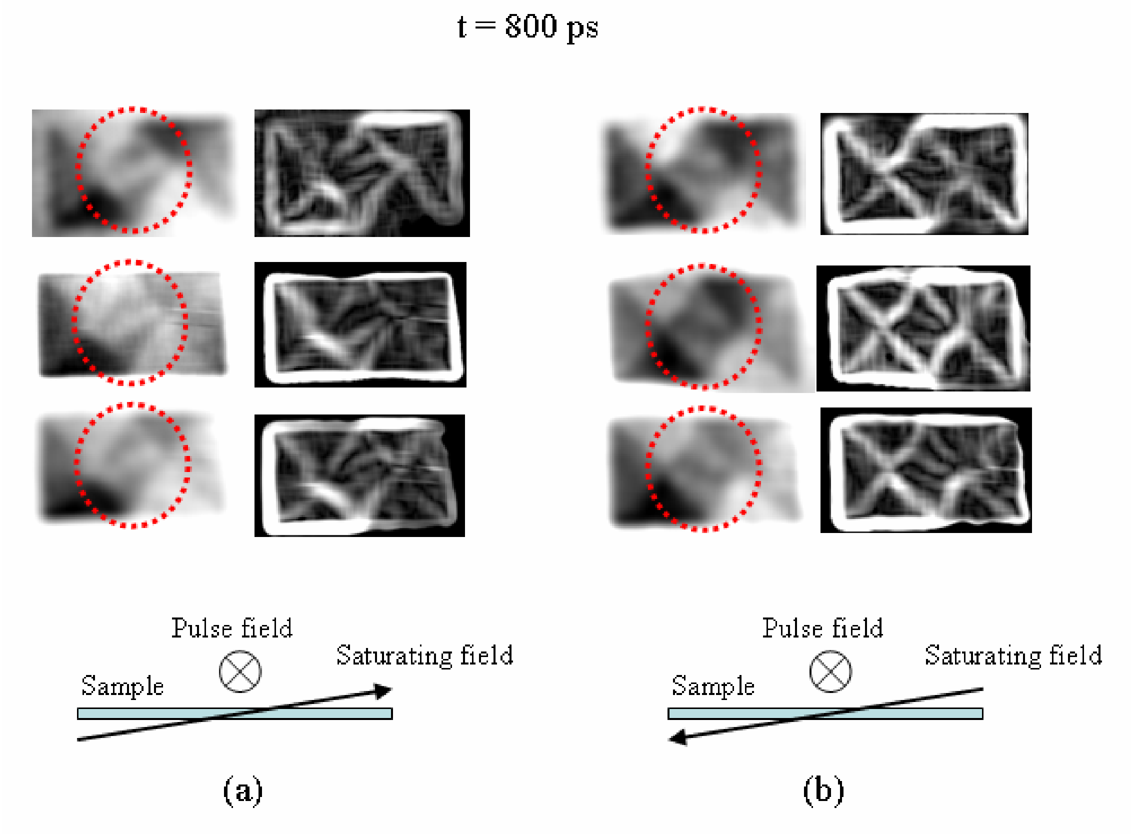
t = 800 ps
Pulse field
Saturating field
Sample
(a)
Pulse field
Saturating field
Sample
(b)

FIG. 2

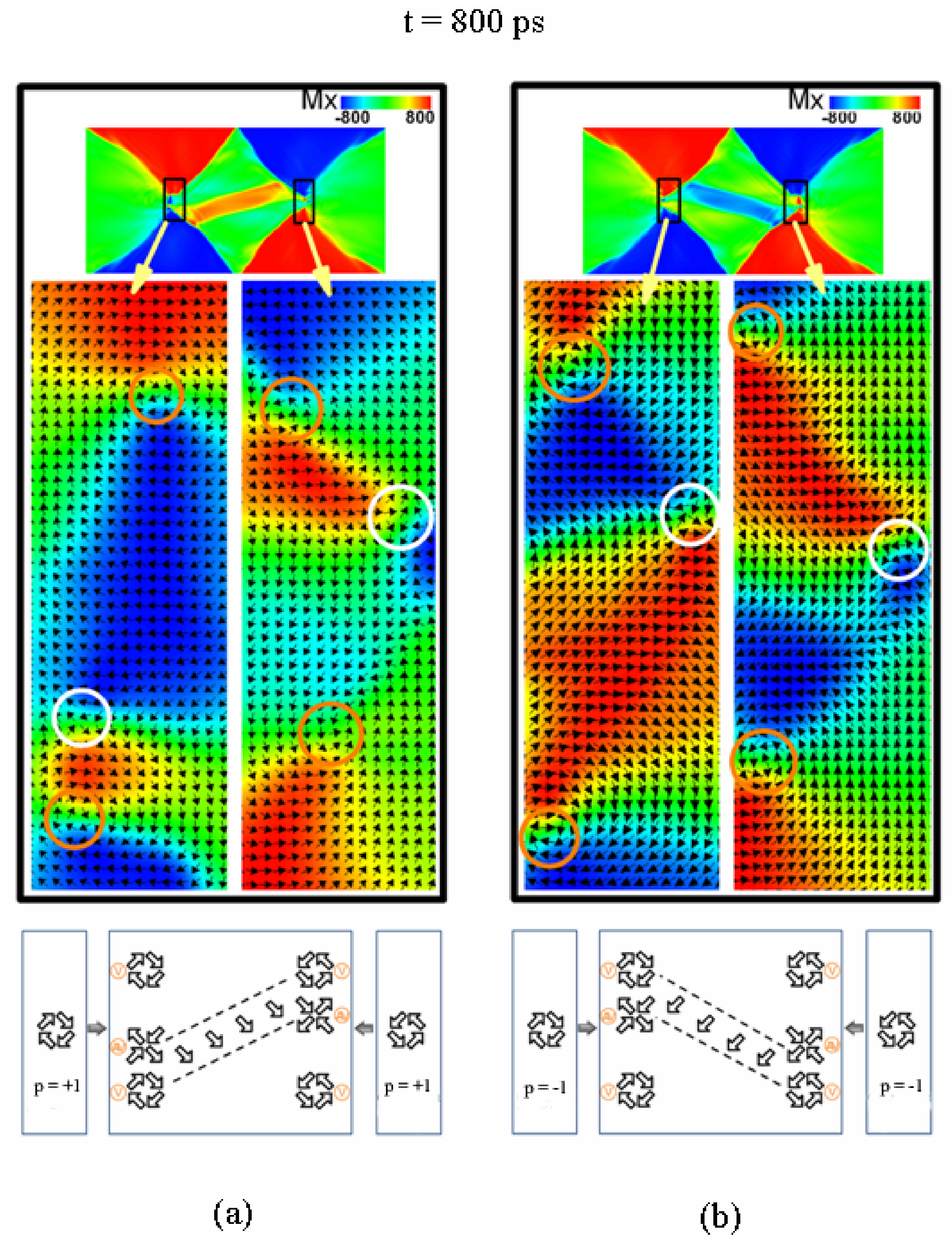

FIG. 3