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Magnetic vortex dynamics on a picoseconds timescale in a hexagonal Permalloy pattern

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Abstract

We have observed a motion of magnetic vortex core in a hexagonal Permalloy pattern by means of Soft X-ray microscopy. Pump-probe stroboscopic observation on a picosecond timescale has been carried out after exciting a ground state vortex structure by an external field pulse of 1 ns duration. Vortex core is excited off from the center position of the hexagonal pattern but the analysis of the core trajectory reveals that the motion is non-gyrotropic.

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Magnetic configuration in patterned ferromagnetic elements has been attracting a great interest due to the future spintronic applications on a sub-micrometer scale. Spin structure of the patterned ferromagnetic elements becomes sensitive to the shape of the pattern to minimize a magnetostatic energy as well as an exchange energy. As a result, magnetic vortex structure is found in various kinds of ferromagnetic patterns[1,2]. Several memory devices based on the magnetic vortex structures are proposed as well[3,4].

Numerous studies have been devoted to understand the magnetic vortex behavior mostly in square[5,6] and circular patterns[7,8]. Recently, magnetic vortex structure in a hexagonal ferromagnetic element has been studied[9,10], where the 6-domain state with a magnetic vortex at the center has been imaged by a magnetic force microscopy. In these studies, it has been reported that a chirality of the curling spin around the vortex core is controllable by applying an oblique external field to a ring network of the hexagonal elements, which is thought to be possible due to the stray field from the 6-domain states of the hexagonal element. In this way, the vortex structure in hexagonal patterns is considered to be a building block for a network structure of combinational chiralities. So far, however, no study has been devoted to investigation on the dynamics of magnetic vortex structure in a hexagonal ferromagnetic element. In this work, we report our observation of a magnetic vortex dynamics in a hexagonal Permalloy pattern on a picosecond timescale by means of Soft X-ray microscopy.

Permalloy hexagon is prepared on Au coplanar waveguide structure. First, the 50-nm Permalloy film is deposited by sputtering and then patterned by electron beam lithography to be a hexagon with each side of 1-μm length. To observe a picoseconds dynamics, we adopted an electronic pump-probe stroboscopy to the soft X-ray microscopy (XM-1) at the beamline 6.1.2 in Advanced Light Source[11,12]. The 1-ns pump pulse generated by an electronic pulser. The pulse height is about 3 V, which is estimated to generate about 100 Oe field on the surface of the Au waveguide when it is launched. X-ray pulse with 70 ps pulse duration is used to probe the vortex dynamics, forming a stroboscopic image with a delay time step of 100 ps. Magnetic contrast has been achieved using the X-ray magnetic circular dichroism at the X-ray energy of 854 eV to match the Ni L_3 absorption edge[13].

Time-dependent dynamic vortex structures in a hexagonal Permalloy pattern are illustrated in Fig. 1. Vortex structures during 2.6 ns are shown together with gradient images and guiding points for the core location. Gradient images are processed from raw digitized images to spot the core position. At t = -100 ps, it is clearly seen that the vortex core is located at the center of the pattern. Then the vortex structure is excited by the 1-ns field pulse so that the core is kicked out of the center position. The chirality of the curling spins around the vortex core is clockwise, which is determined from the contrast of the Soft X-ray microscopy. The polarity whether the core is upward or downward cannot be determined experimentally due to the spatial resolution limit (40 nm) of the microscopy setup in the present study. Since the initial kicking direction of the core is downward in the figure with the clockwise chirality, we can estimate that the core magnetization stands up out of the figure[5].

Interestingly, the core is not simply gyrating around the center of the pattern. Instead, it is kicked downward for the first 1-ns duration when the field pulse is on. Then it simply comes back to the original center position rather slowly. The total period of the core excursion from center to center is about 2.5 ns, which is comparable to the other eigenmode gyration frequencies in similar ferromagnetic patterns reported so far[14]. However, obviously there is almost no change of the core position along the horizontal direction during the excursion but a change of the core position is clearly observed along the vertical direction. The non-gyrotropic motion has been reported as well in other experiments without a clear physical explanation[15,16]. We consider a possibility of the vortex core structure change for understanding of the non-gyrotropic core motion. Recently, there have been intensive theoretical studies on how the vortex core is excited by an external magnetic field or a spin current. It has been predicted that the core can be split with a pair generation of vortex and antivortex. We believe that the split core might be possible in the present work considering about the field pulse strength (~ 100 Oe) which we applied to the pattern. Further investigation using micromagnetic simulation may be needed to fully understand the behavior.

We have carried out a detailed analysis of the core trajectory as illustrated in Fig. 2, where the core x-y trajectory with respect to the time is plotted in a 3-D way. In the figure, the core position is plotted with gradual contrast to denote an elapsed time. To clearly visualize the core trajectory, we separated two plots of core trajectory projected onto the horizontal and vertical axis of the hexagonal pattern. The core motion on the horizontal axis is again found to be not as big as in the case of the vertical motion. Although the amount of the horizontal displacement of the core is small, it is still slightly greater than the spatial resolution of the microscopy. Thus, the fluctuating amount of the horizontal core motion is not simply considered to be from the measurement error. If there is a split of votex core and a pair generation of the vortex and antivortex, it is expected that there exists a substantial spin wave excitation corresponding to the complex core dynamics. This could be the reason for the fluctuating horizontal core displacement.

The vertical trajectory doesn’t exhibit a monotonic displacement from the center for the initial 1 ns duration. As seen in the figure, it reaches to the maximal displacement before the pulse field is switched off, which implies that effective downward kicking force to the core from the field torque is balanced before t = 1.0 ns with a restoring force from the displaced core. Reminding that the vortex core seems to be split from the fact that the horizontal displacement of the core is just fractional compared to the vertical displacement, there should be corresponding complex spin wave excitation. The spin wave excitation could provide an extra channel for dissipation, leading to the slow and monotonic decrease of the vertical displacement after switching off the field pulse as in Fig. 2.

In summary, we have found that there exists a non-gyrotropic motion of the magnetic vortex core in a Permalloy hexagon under 1-ns pulse field by stroboscopic pump-probe observation using Soft X-ray microscopy, which might be coming from a complex spin wave behavior related to the vortex core split dynamics. For the vortex structure in a hexagonal Permalloy pattern with clockwise chirality and out-of-the-plane core polarity, the core is found to be displaced mostly vertically rather than horizontally opposite to the direction of the field pulse.

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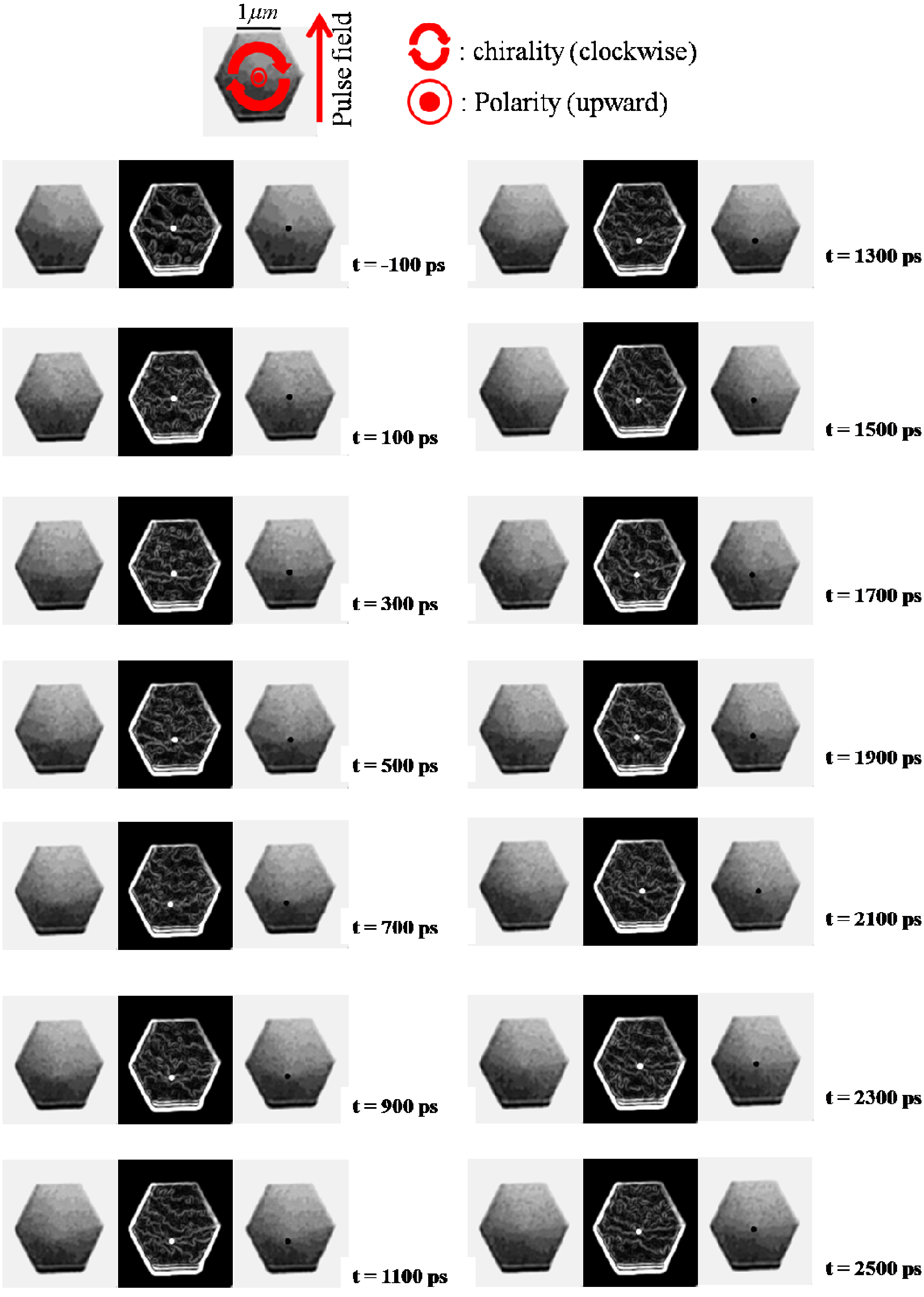
Figures

Figure 1: Spin configuration of the hexagonal Permalloy pattern. Chirality and polarity of the vortex structure is shown on the top of the figure. Raw and gradient image of the spin structure together with a guiding point of the core position is plotted with a time step of 200 ps.

Figure 2: Core trajectory with respect to the time. Core trajectory projected vertically and horizontally are plotted. Red dotted line denotes the time direction and the blue dotted line indicates the time when t = 1.0 ns. Time dependent core trajectory built in 3-D way from an oblique angle view point is plotted on the bottom of the figure.



1 μm
Pulse field
: chirality (clockwise)
: Polarity (upward)
t = -100 ps
t = 100 ps
t = 300 ps
t = 500 ps
t = 700 ps
t = 900 ps
t = 1100 ps
t = 1300 ps
t = 1500 ps
t = 1700 ps
t = 1900 ps
t = 2100 ps
t = 2300 ps
t = 2500 ps

FIG. 1

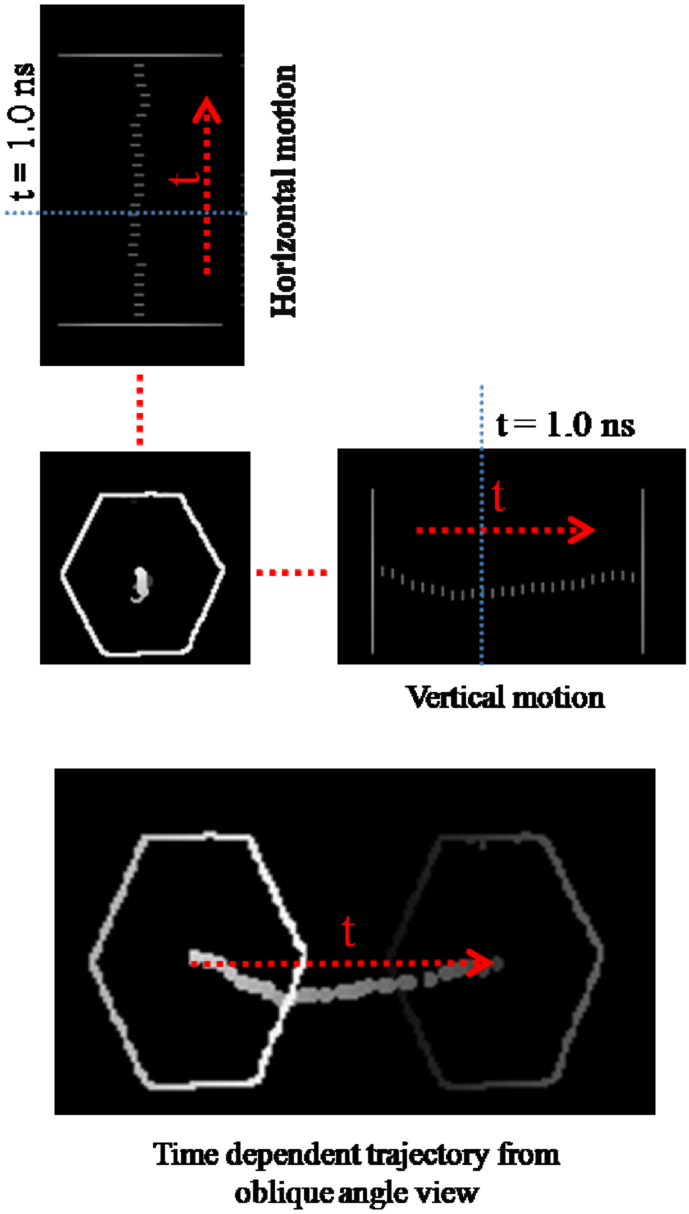

t = 1.0 ns
t
Horizontal motion
t = 1.0 ns
t
Vertical motion
t
Time dependent trajectory from oblique angle view

FIG. 2