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We employed time- and space-resolved full-field magnetic transmission soft x-ray microscopy to observe vortex-core gyrations in a pair of dipolar-coupled vortex-state Permalloy (Ni$_{80}$Fe$_{20}$) disks. The 70 ps temporal and 20 nm spatial resolution of the microscope enabled us to simultaneously measure vortex gyrations in both disks and to resolve the phases and amplitudes of both vortex-core positions. We observed their correlation for a specific vortex-state configuration. This work provides a robust and direct method of studying vortex gyrations in dipolar-coupled vortex oscillators.


Recently, vortex-core oscillations in micrometer-size (or less) magnetic elements have been intensively studied for their promising application as microwave emission sources.\(^1\)\(^{-12}\) Vortex-core oscillators provide high-power output and narrow linewidths. Most studies have focused on electrical measurements using isolated single disks.\(^4\)\(^{10}\)\(^{-12}\) However, the need for high-power signals and high packing density have spurred further studies, not only on coupled vortex-state disks but also on multiple-disk arrays. In cases of sufficiently short distances between nearest neighboring disks, dipolar interaction alters their dynamics.\(^13\)\(^{-15}\) Thus, the examination of the influence of dipolar interaction on vortex oscillations is important. To characterize the interaction between individual elements a time- and space-resolving measurement technique is mandatory.

Recent advances in time-resolved microscopy enable imaging of the spin dynamics of nanoscale magnetic elements at a time resolution of less than 100 ps.\(^16\)\(^,\)\(^17\) Time-resolved full field imaging is required for simultaneous measurement of different local areas. In this letter, we chose a pair of physically separated disks in order to resolve vortex gyrations in both disks, along with their amplitude and phase relations. We report on an experimental observation of coupled vortex gyrations in Permalloy (Py:Ni$_{80}$Fe$_{20}$) disks and the effect of dipolar interaction on each disk’s gyration.

The two-disk system studied was prepared on a 100-nm-thick silicon nitride membrane by electron-beam lithography, thermal evaporation, and lift-off processing. Each Py disk has a diameter of $2R=2.4$ $\mu$m and a thickness of $L=50$ nm. The disks are arranged in a pair with a center-to-center distance of $d_{mc}=2.52$ $\mu$m (see Fig. 1). In order to locally excite one vortex, a 1.5-$\mu$m-wide and 75-nm-thick Cu strip covers the top of the right Py disk, as can be seen in Fig. 1. The vortex eigenfrequency of around $157 \pm 3$ MHz in the isolated Py disks was measured on an array of Py disk pairs of identical dimensions\(^18\) using a broadband-ferromagnetic resonance setup.\(^15\)

Measurements of the dynamic evolution of vortex-core gyrations were carried out by full-field magnetic transmission soft x-ray microscopy (MTXM) at beamline 6.1.2, Advanced Light Source (ALS), Berkeley, CA, utilizing a stroboscopic pump-and-probe technique. The optical setup of the x-ray microscope,\(^19\) shown in Fig. 2, consists of the bending magnet source providing elliptically polarized soft x rays, a monochromator and illuminating assembly (comprising the first Fresnel zone plate, the condenser zone plate, and a pin-hole close to the sample), a high resolution imaging objective lens, the microzone plate, and a two-dimensional charge coupled device (CCD) detector. The spatial resolution is mainly determined by the outermost zone width of the microzone plate. The temporal resolution is set by the inherent pulsed time structure of the x-ray source, and is typically about 70 ps in two-bunch mode operation of the ALS, where two electron bunches of 70 ps length are separated by 328 ns.\(^20\)\(^,\)\(^21\) The magnetization contrasts of the Py disks in the present study were measured by monitoring the spatial distribution of the local magnetizations through x-ray magnetic

![FIG. 1. (Color online) Schematic illustration of two-disk system and its structural transmission soft x-ray image.](image-url)
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downward core in disk 2 gyrates clockwise, corresponding to
tion of the cores after excitation.1,5 The upward core in disk
core polarization can be determined from the sense of rota-
area are resolved in both disks. Correlations of the ampli-
1 gyrates counterclockwise, indicating
clockwise in-plane curling magnetization,
Both disks’ initial configuration shows the same chirality of
relatively bright region in the disks represents magnetizations
point in the +x direction, whereas the relatively
dark area corresponds to opposite-direction magnetizations.
Both disks’ initial configuration shows the same chirality of
clockwise in-plane curling magnetization, \( C_1 = C_2 = -1 \).
The core polarization can be determined from the sense of rota-
tion of the cores after excitation.1,5 The upward core in disk
1 gyrates counterclockwise, indicating \( p_1 = +1 \), whereas the
downward core in disk 2 gyrates clockwise, corresponding to
\( p_2 = -1 \) (see the top of each column in Fig. 3).
In the serial images, the core positions of both disks can be
determined by the variations of the in-plane curling mag-
netizations. The vortex-core oscillation around its center po-
sition in disk 1 (right disk) is excited by the local field of the
strip line at the beginning of perturbation. The vortex gyra-
tion in disk 2, also shown in Fig. 3, is not excited by the local
field, but is induced by the dipolar interaction with its neigh-
boring disk. Local fields produced through the Cu strip did
not excite the neighboring disk, which is proven by exper-
imental confirmation with a reference sample that contained
only the disk beside the strip. Calculations also confirm that
the local fields emanating from the strip line can be ne-
glected at the position of the left disk.22 The core positions
varying in time and in in-plane space over a relatively large
area are resolved in both disks. Correlations of the ampli-
tudes and phases of both vortex-core positions can be easily
identified with reference to the serial images.

The clock signal of the synchrotron triggers an arbitrary
function generator (Agilent, 81150A), which launches par-
ticular pulses into a strip line. These pump pulses create local
Oersted fields. Field pulses of 5 mT strength, 30 ns length,
and 2.5 ns rise and fall time were stroboscopically applied
along the x axis on which the two disks were placed [see Fig.
1(a)]. The driving pulses were synchronized with x-ray probe
pulses to a frequency of ~3 MHz. To measure the temporal
evolution of the vortex excitations, the pulses were delayed
with respect to the x-ray probe pulse. The arrival time of the
x-ray pulses at the sample was monitored by a fast avalanche
photodiode.21 In order to obtain sufficient XMCD contrasts,
ten individual images of several million accumulated x-ray
flashes measured at the identical time delay, were integrated.
The x-ray images were recorded at every 1.67 ns step.

Figure 3 shows the resultant plane-view data for both
disks as measured after a perturbation of the right disk by the
pulse field. In the images, the structural contrast is normal-
ized by an image obtained under a static saturation field. The
relatively bright region in the disks represents magnetizations
that point in the +x direction, whereas the relatively
dark area corresponds to opposite-direction magnetizations.
Both disks’ initial configuration shows the same chirality of
clockwise in-plane curling magnetization, \( C_1 = C_2 = -1 \).
The core polarization can be determined from the sense of rota-
tion along the \( x \) axis reflect the core polarizations and the chiralities of both
disks. The initial motion of the vortex core under the strip
line is caused by the field pulse, and depending on the chiral-
ity the vortex core moves in the positive or negative \( y \) direc-
tion. The sense of core rotation is determined by the polar-
ization \( p \). The relative core positions change the effective
stray field of each disk. The experimental results were con-
firmed to be in quantitative agreement with the simulation.

FIG. 2. (Color online) Schematic of the full-field magnetic transmission soft
x-ray microscope at beamline 6.1.2, and an illustration of the stroboscopic
pump-and-probe technique including the arbitrary function generator (AFG)
and the soft x-ray sensitive CCD camera.

FIG. 3. (Color online) XMCD images of the dynamic evolution of vortex
gyrotrropic motions in both disks, and corresponding vortex states repre-
sented by color and height of the surface: \( p_1 = +1, p_2 = -1 \), and \( C_1 = C_2 = -1 \).
The dotted vertical and horizontal lines indicate the center position of each
disk.
results for the same geometry and pulse parameters [shown in Fig. 4(b)]. The estimated eigenfrequency from the vortex-core oscillations shown in Fig. 4(a) is about $143 \pm 14$ MHz, which equals to the value obtained from the simulation. The uncertainty of the core position in Fig. 4(a) was about 33 nm, considering both the spatial and time resolutions of the measurement.

We want to emphasize, that the vortex-core gyration in disk 2 was stimulated by the stray field of the neighboring disk 1 that varies with the position of the vortex core. Energy transfer between separate disks by dipolar-induced gyration is possible. It would be interesting for the purposes of a future study to examine gyratings for different disk separations and to directly study their interaction. We investigated coupled vortex-state disks of the same clockwise in-plane curling magnetization and antiparallel core orientations. For this configuration, we observed out-of-phase (in-phase) oscillations of the vortex-core positions along the x axis (y axis). This work provides a robust and direct method of studying the dynamics of vortex excitations and dipolar interaction in spatially separated disks.

Note added in proof. During its review process, we became aware of a recent publication on gyration mode splitting in magnetostatically coupled magnetic vortices studied by time-resolved magneto-optical Kerr effect (Ref. 24).

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18For the ferromagnetic resonance measurement, an array of Py disk pairs was placed under a $7\mu m$-wide stripe. The disk width of the same dimensions ($2R=2.4\mu m$ and $L=50\mu m$), but a larger value of $d_{int}=3.74\mu m$ was used to prevent interaction.
21P. Fischer, AAPPS Bull. 18(6), 12 (2008).
22The in-plane component of the local fields is effective only in the one disk on which the Cu electrode is placed; the out-of-plane field component is too weak to affect vortex excitations.
23We used the OOMMF code. See http://math.nist.gov/oommf. The material parameters of the Py disks were as follows: the exchange stiffness $A_x=13\text{ pJ/m}$ and the saturation magnetization $M_s=7.2\times10^5\text{ A/m}$ with a zero magnetic anisotropy constant. The cell size was $4\times4\times50\text{ nm}^3$ with the damping constant $\alpha=0.01$.