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Ferromagnetic resonance in exchange-coupled magnetic vortices

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The results of a study of low-frequency ferromagnetic resonance in a system of two overlapping permalloy disks by magnetic resonance force spectroscopy are presented. It is shown that the resonant frequency of the gyrotropic mode of oscillations of magnetic vortices in this system significantly depends on the vorticity of their shells. The experimental dependences of the resonant frequencies of various states on the external magnetic field are qualitatively consistent with the results of micromagnetic modeling.

Keywords: ferromagnetic resonance, magnetic resonance force spectroscopy, magnetic vortices.

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1. Introduction

The low-frequency resonance of the magnetization oscillations of the magnetic vortex is associated with the circular (gyrotropic) motion of its core around the equilibrium position [1,2]. Recently, interest in this type of magnetization oscillation has increased significantly due to the development of compact high-frequency nanogenerators based on spin-transfer vortex oscillators (STVO) [3,4]. In order to increase the generated power, it is proposed to use arrays of synchronized STVO and, in particular, the most promising are arrays of nanogenerators with an exchange coupling [5,6]. The results of study on gyrotropic modes of magnetization oscillations in a system of double overlapping disks by magnetic resonance force spectroscopy [7,8] are given in this paper.

2. Experimental methods and micromagnetic modelling

The array of ferromagnetic overlapping disks was produced by methods of electronic lithography and ion etching. The original 40 nm $Ni_{80}Fe_{20}$ (Py) permalloy layer was grown by magnetron deposition. Polished glass plates (180 μm thick) and membranes of amorphous silicon nitride (30 nm thick) were used as substrates. The Py surface was centrifuged with a 100 nm thick layer of positive electron resist (polymethyl methacrylate). The resist was exhibited in the scanning electron microscope SUPRA 50 VP with the lithographic setup ELPHY PLUS (Carl Zeiss, Germany). In the result an array of exposed areas in the form of overlapping disks with a diameter of 1 μm was formed, forming a square grid with a period of 6 μm. After that, the exposed resist removed in an organic solvent so that an array of corresponding windows formed in the resist layer. The resulting structure was covered with a layer of V (20 nm thick) and a layer of Pt (3 nm thick). The procedure „Lift-off" in acetone was then performed, leaving a metal V/Pt protective mask in the form of a double disk array on the surface of the permalloy. At the final stage, the sample was etched with Ar^+ ions until the permalloy was completely removed from the exposed areas of the film. The area of the array of received elements in the form of double disks is shown in Fig. 1, *a*.

The magnetic states of the double disks have been investigated by the Lorentz transmission electron microscopy (LTEM) [11] microscope LIBRA 200 MC (Carl Zeiss, Jena). Lorentz images were recorded at an accelerating voltage of 200 kV in the Fresnel contrast mode (defocusing method).

The resonance properties of the disks have been investigated using a magnetic resonance force microscope (MRFM), developed in IPM RAS on the basis of the vacuum probe microscope Solver HV (NT-MDT Spectrum Instruments, Zelenograd) [12] The SG-01 (ScanSens, Hamburg) probe sensors were used to record ferromagnetic resonance (FMR), with a four-sided pyramid point. The tip face of the pyramid was covered with a Co film (100 nm thick) covered with a protective layer of Cr (10 nm thick). Cantilever hardness was 0.003 N/m, resonance frequency — 6.3 kHz. The microwave pumping of the sample was produced by emitting by a generator PS 20 (Spectran, Saratov) with 100% amplitude modulation at a cantilever resonance frequency. Measurements were made at a distance of 800 nm from the surface. The sample was placed in a short-circuited coplanar line in the antinode of a radiofrequency magnetic field. The power of microwave pumping was $P = -2$ dBm. The external magnetic field was applied in the plane of the sample. The

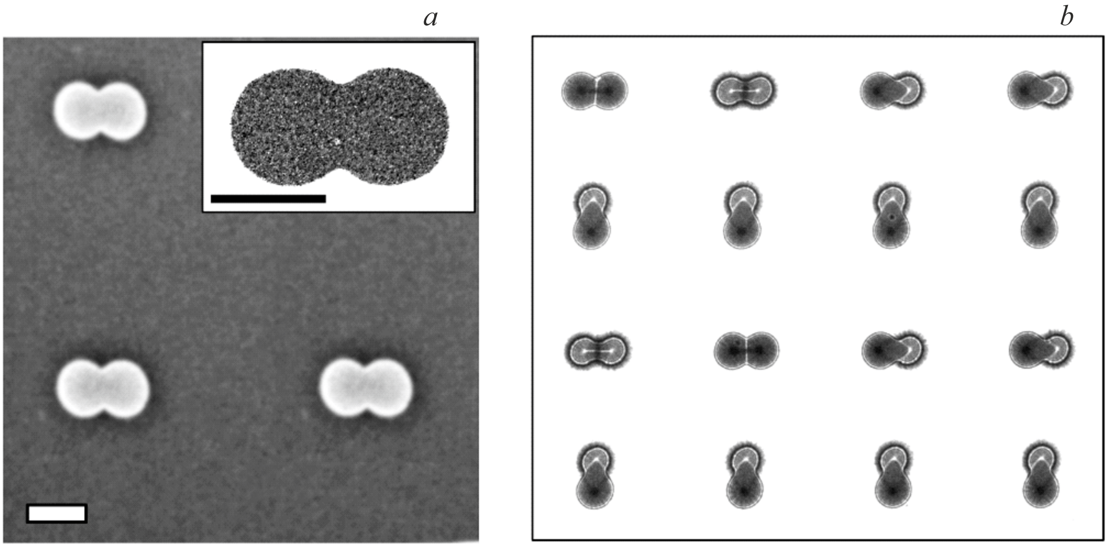

Figure 1. (*a*) Micrography of the array of overlapping disks (SEM). In the inset, a bright field image of a single permalloy particle, obtained in a transmission electron microscope (TEM). The size of scale labels is 1 μm. (*b*) — Lorentz micrography of the array of particles.

MRFM probe was positioned above the sample so that the external magnetic field was oriented in the magnetic plane of the probe and perpendicular to its magnetization. The applied fields had small values (up to ± 200 Oe), and the anisotropy of the shape of the magnetic coating ensured that the probe operated without being magnetized. The measurements were performed in a vacuum (residual gas pressure 10^{-3} Torr), with a cantilever quality factor of ~ 1000. In microwave pumping, vortex cores move in stationary closed orbits, close in shape to a circle. At the same time, areas where magnetization is directed to the opposite side of the cores are formed near the cores. It is the scattering fields from this area that are the main contributors due to the interaction of the probe with the sample [13,14].

Numerical modelling of the dynamics of the magnetization of the sample under the influence of the high-frequency magnetic field and the effects of the interaction of the magnetic vortex with the external field was carried out by solving the Landau–Lifshitz–Hilbert equation using the software package MuMax3 [15]. The following material parameters were used in calculations: magnetization in a saturation of $M = 890$ kA/m, an exchange constant of $J = 13 \cdot 10^{-12}$ J/m, an anisotropy constant of $K = 0$, a dimming parameter $\alpha = 0.01$ and a gyro-magnetic ratio $\gamma/2\pi = 2.80$ GHz/kOe. For micro-magnetic calculations, a $512 \times 256 \times 1$ grid was used. The grid step in the lateral direction was 4 nm, which is less than the exchange length, which for the selected parameters is $l_{ex} \approx 5$ nm. The frequency characteristics of the system were determined by applying a short pulse of the magnetic field in the plane of the sample with a duration of 0.1 ns and an amplitude of 1 Oe. The oscillogram (about 100 periods) of the relaxation oscillations of the mean value of magnetization was recorded, from which, by means of the rapid Fourier transformation, the range of proper frequencies of the system was calculated [16].

3. Results and discussion

Double disks with an overlap of 20%, i.e., while the distance between the centers of the disks was 80% of the diameter were experimentally examined. The array consisted of elements whose long axes were oriented perpendicular to each other (Fig. 1, *b*). Thus, at the tilting of the sample and at the change of the external magnetic field (by changing the current in the objective TEM lens) it was possible to simultaneously study the magnetization process along the long and short axis of the double disks.

Depending on pre-magnetization, different vortex states were realized in the double disks. At magnetization along the short axis of the system the states with the different direction vorticities of the shells (Fig. 2, *a, b*) were formed. Then we will denote this state as VV (vortex-vortex). When magnetizing along the long axis with a probability close to 50% it was possible to observe distributions with the same shell vorticity (Fig. 2, *c, d*). This condition is referred to as VAV (vortex-antivortex-vortex).

At the tilting of the sample and at the same time a small excitation of the objective lens (an increase in the external magnetic field applied to the structure) the magnetization distribution changed. In case of VV state, the application field changed the size of the central rhombic domain (Fig. 3). Whereas when applying the field to magnetized particles VAV, one of the vortices gradually shifted to the particle edge, while the other vortex approached the antivortex, the position of which was almost unchanged with the field application (Fig. 4, *a, b*). At the magnitude of the

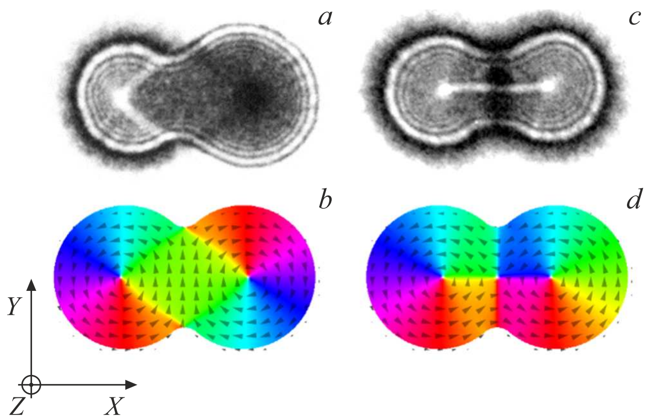

Figure 2. Micrographs of double disks with the Fresnel contrast and corresponding model magnetization distributions. (*a, b*) Condition VV with different vortex shells. (*c, d*) Condition VAV with the same vorticity of the shells.

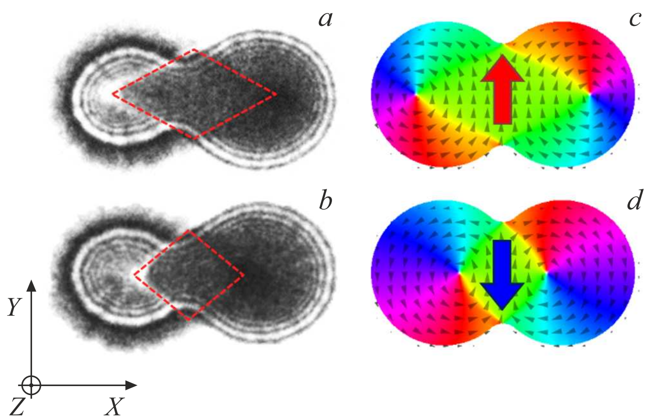

Figure 3. VV states change in double disks under the action of an external field applied along the axis Y and corresponding Lorentz micrography. The direction of the field application is shown by arrows. The red dotted lines represent the boundaries of the rhombic domain.

field of the order 220 Oe the vortex and antivortex merged and the particle formed a state with a vortex in one half and quasi-uniform in the other (Fig. 4, *c, d*).

In MRFM measurements the probe was exposed above the center of the two-disk system and the dependence of amplitude of forced oscillations of the cantilever on the sample pumping frequency for different values of external magnetic field was recorded. The electromagnet field was applied in the plane of the sample along the axis Y (Fig. 2). The high-frequency field was applied along the axis X.

The field relationships of the resonance frequencies of both states are significantly different. Thus, when applying an external permanent magnetic field to the state VV (Fig. 3), depending on the direction of the field relative to the central rhombic domain, the frequency either increases or decreases. In other words, frequency is a monotonic function of the external field [17–19]. In this case, there is no frequency splitting, as the cores of both vortices are in a mirror but identical environment of magnetostatic charges, which determine the partial frequency of gyromovement of each of the vortices [20]. The experimental and model dependence of the resonance frequency of vortices from the external magnetic field is given in Fig. 5.

In the VAV state, the field dependences of the resonant frequencies are significantly more complex. It should be noted that the evolution of the VAV states in the outer field is symmetric and depends on the quantity, but not the direction of the field (Fig. 4, *a, b*). In this case, in

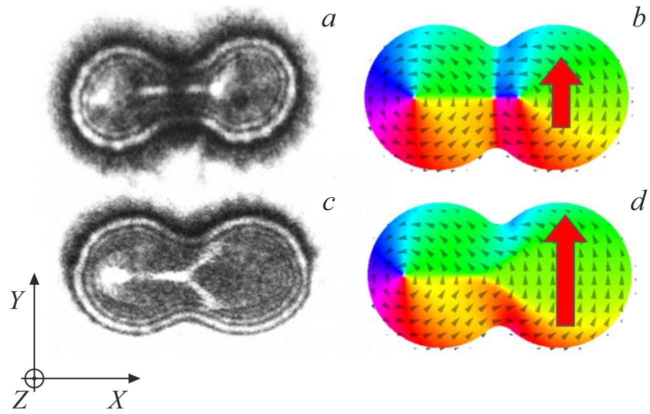

Figure 4. Change of VAV states in double disks under the action of an external field applied along the axis Y and their corresponding images with Fresnel contrast. The direction of the field application is shown by arrows.

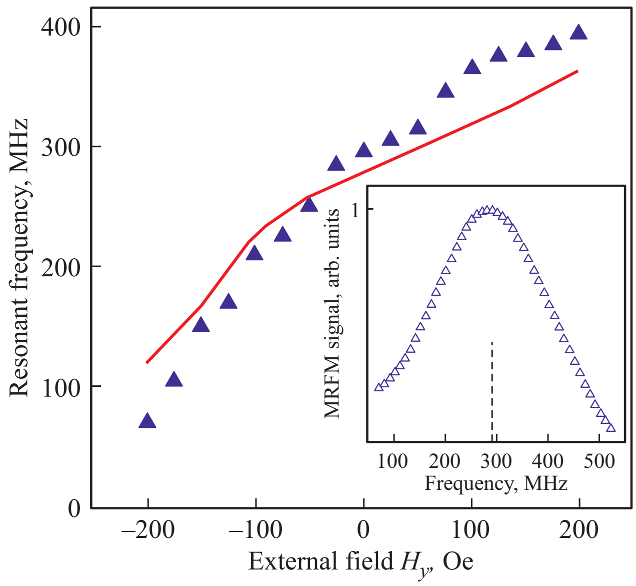

Figure 5. Dependence of resonance frequency of gyro oscillations of vortices in the VV state. The experimental relationship is shown by triangles. The simulation results are shown with a solid curve. On the inset there is an example of an experimental spectrum.

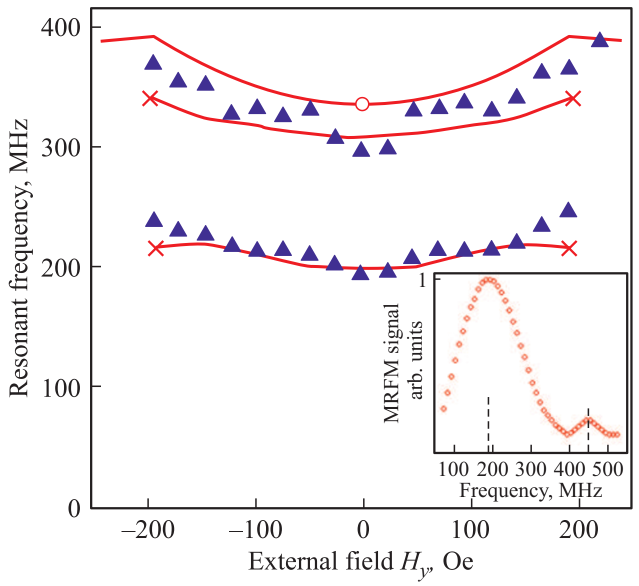

Figure 6. Dependence of resonance frequency of gyro oscillations of vortices in the VV state. The experimental relationship is shown by triangles. The simulation results are shown with solid curves. On the inset there is an example of an experimental spectrum.

the initial state in the zero field, both vortices are in the same magnetostatic environment and the presence of two frequencies in the spectrum of natural vibrations is due to the low-frequency mode of gyrotropic oscillations of the antivortex and the high-frequency mode associated with the gyrotropic motion of the vortex cores. When a field is applied, one of the vortices shifts closer to the antivortex, while the other shifts closer to the particle edge. Therefore, field spectra are, on the one hand, even relative to the external magnetic field. On the other hand, there is a splitting of the high-frequency branch when applying even small fields. At a field size of about 220 Oe vortex and antivortex merge, and only one vortex remains in the particle (Fig. 4 *c, d*) and only one resonant branch.

4. Conclusion

Thus, we have carried out MRFM studies of gyro oscillations of magnetic vortices in overlapping disks, located in VV and VAV states. It is shown that in the VV state there is a unique resonant mode of oscillation, the frequency of which can be rearranged within a sufficiently wide range under the action of the external magnetic field. On the other hand in VAV state there are several resonant modes of frequency oscillation which are slightly (compared to the VV state) changed under the action of a weighted field. The effects of switching the magnetization distributions between the VV and VAV states are well consistent with the Lorentz translucent electron microscopy. The strong dependence of the resonance frequency on the external field in the VV state can be used to control the frequency of spin-transfer vortex nanogenerators and high-frequency radiation detectors.

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Conflict of interest

The authors declare that they have no conflict of interest.

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