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Synchronization of auto-oscillations of exchange-coupled magnetic vortices

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The results of micromagnetic modeling of the gyrotropic mode of magnetization auto-oscillations in overlapping ferromagnetic disks under the action of a spin-polarized current are presented. It is shown that the exchange interaction between disks significantly increases the binding energy of magnetic vortices and, as a consequence, reduces the dephasing of the vortex core gyration in neighboring disks.

Keywords: vortex nanooscillator, auto-oscillations, synchronization, exchange coupling.

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1. Introduction

Vortex spin-transfer nano-oscillators (STNO) based on nanoscale magnetic spin valves have been actively investigated in recent decades due to the prospect of creating compact electromagnetic oscillation generators [1]. These instruments are based on the phenomenon resonant gyro oscillations magnetic vortex in the ferromagnetic disk under the action polarized electric current [2–4]. This resonance has a small line width and lies in the megahertz frequency range. The use of such a vortex oscillator in generators based on multi-layered tunnel contacts with the MgO barrier allows the generation of microwave oscillations of sufficiently high power [5,6].

Currently, the main research in this area is aimed at both increasing the generated power of individual STNO and solving the problem of synchronization of large STNO arrays, in order to increase the total generated power. Both the magnetostatic [7,8] and the exchange [9–11] interactions between individual oscillators are used to synchronize the STNO. In our view, the most promising approach to solving the problem of increasing the generated power is the internal synchronization of the STNO array based on the exchange interaction of individual generators.

In the present work, phase synchronization of two interacting vortex nanooscillators, excited by spin-polarized current, has been investigated by methods of micromagnetic modelling.

2. Micromagnetic modelling

Simulation of forced magnetization oscillations under the action of spin-polarized current was carried out by numerical integration of the Landau–Lifshitz–Gilbert equation for magnetic torque taking into account the spin transfer

$$\frac{\partial \mathbf{M}}{\partial t} = -|\gamma|\left[\mathbf{M} \times \mathbf{H}_{eff}\right] + \mathbf{T}_D + \mathbf{T}_s, \tag{1}$$

where $\mathbf{M}$ ismagnetization, γ is gyromagnetic ratio. The effective magnetic field $\mathbf{H}_{eff}$ is expressed as follows:

$$\mathbf{H}_{eff} = \mathbf{H}_{ex} + \mathbf{H}_m, \tag{2}$$

where $\mathbf{H}_{ex}$ is exchange field, $\mathbf{H}_m$ is dipole magnetostatic field. Term describing the attenuation of precession

$$T_D = \frac{\alpha}{M_0}\left[\mathbf{M} \times \left[\mathbf{M} \times \mathbf{H}_{eff}\right]\right], \tag{3}$$

where M_0 is magnetization in saturation, α is a dimensionless damping parameter. The term describing the spin transfer effect [12]:

$$\mathbf{T}_s = \frac{\sigma_0 j_s}{M_0}\left[\mathbf{M} \times \left[\mathbf{M} \times \mathbf{e}_s\right]\right], \tag{4}$$

where j_s is volumetric density of spin-polarized current flowing through the sample, $\mathbf{e}_s$ is unit vector along the polarization of the spins, σ_0 ratio is determined by material parameters and geometry of the sample

$$\sigma_0 \simeq \frac{g\mu_B}{2eM_0 h}, \tag{5}$$

where g is Lande factor, μ_B is Bohr magneton, e is electron charge, h is sample thickness.

The MuMax3 simulator (version 3.10, stable release) [13] was used to solve equation (1). Circular permalloy disks with a radius of $r = 250$ nm and a thickness of $h = 20$ nm were chosen as the basic element for the modelling. The following material parameters were used in calculations: saturation magnetization $M_s = 800$ kA/m, exchange stiffness $J = 1.3 \cdot 10^{-11}$ J/m, damping parameter $\alpha = 0.01$, anisotropy constant $K = 0$. The simulation was carried out on a $256 \times 128 \times 1$ grid and the size of one cell was $4.2 \times 4.2 \times 20$ nm, which is less than the exchange length for the specified material parameters $l_{ex} \approx 5.7$ nm. The magnetization distributions we are investigating are homogeneous in the thickness of the whole sample and it is therefore acceptable to use a cell height of 20 nm.

3. Autooscillations of magnetic vortices in the system of two disks

In the magnetic vortex two areas can be conventionally identified. The central region of the vortex (core) has a magnetization directed perpendicular to the plane of the ferromagnetic disk. The core may have a different polarity of $p = \pm 1$ depending on the direction of magnetization. The peripheral vortex area (shell) lies in the plane of the disk and can have a different vorticity of $c = \pm 1$ (either clockwise or counterclockwise). The lowest frequency mode of vortex magnetization oscillation is gyrotropic mode. In this case, the vortex core moves in a circular orbit around the equilibrium position with typical frequencies in the range of $0.1-1.0$ GHz depending on the material and geometric parameters of the disk.

We studied gyrotropic auto-oscillations of magnetic vortices in the overlapping disk system using micromagnetic modelling methods. It was considered a configuration in which vortices had the same polarity of the cores and different vorticity of the shells (Fig. 1). The pumping of the system was carried out by a direct current, flowing perpendicular to the plane of the disks and polarized along the axis Z. The dependence of resonance characteristics of the system on the distance between the centers of disks was investigated. The size of the overlap was chosen as the parameter characterizing the disk spacing

$$\Delta = \frac{2r - d}{2r} \times 100\%, \tag{6}$$

where d is the distance between disk centers (Fig. 1).

When the disks are located at large distances from each other ($\Delta < 0$) between vortices only magnetodipole interaction is carried out. When the disks overlap ($\Delta > 0$) the exchange interaction is added to the magnetodipole. We have modelled the overlap from -10% to 28%. Depending on the monotony and steepness of the calculated characteristic, the step of 2% or 4% was chosen. The upper limit is due to the fact that when we switch from a double disk to a two-dimensional grid of disks, we get a solid film at an overlap of 30%. To demonstrate the contribution of the exchange link, we also simulated the overlap of 1%, which corresponds to the distance between the edges of the disks 5 nm, i.e., larger than the size of one cell. At 0% overlap, a guaranteed exchange is already provided through at least one cell. For this reason, all calculated dependencies may have a gap and a nonmonotonicity near 0%.

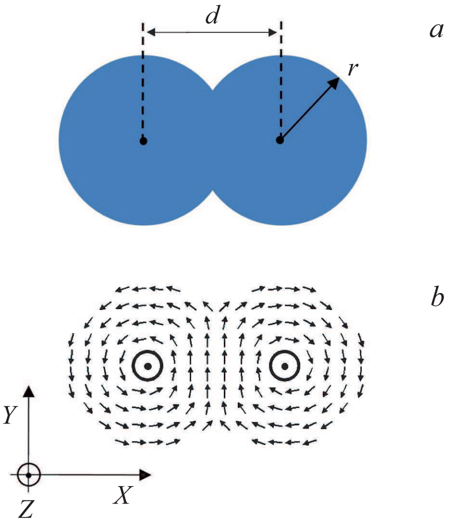

Figure 1. (*a*) System of two overlapping disks. (*b*) Magnetization distribution in two disks.

When a homogeneous spin-polarized current is flowing, the disks are excited by an uncommitted auto-oscillation corresponding to the gyro motion of the vortices cores around the equilibrium state. In this mode of oscillation the cores of both vortices are moving counterclockwise. In this case, the induced magnetic moments of the shells of vortices are parallel and rotate synchronously [14,15]. With the increase of pumping current the frequency and radius of gyration are increased. At the critical current, when the gyration radius also reaches a critical value, the polarity of the core of one of the vortices (or both) changes and generation stops [16,17]. In the numerical experiment we regestered the current density values of j_{Start}, at which stable auto-oscillations were realized, and the critical current density of j_{Stop}, at which the oscillations ceased. In Fig. 2 the dependence of critical currents for the system is also given depending on the degree of overlap between the disks. It is seen, that the overlapping of the disks leads to a reduction in current j_{Start} and j_{Stop}.

We have investigated the efficiency of synchronizing the gyro movement to the vortices cores depending on the distance between the disk centers. The pumping of the system was made by homogeneous direct current, polarized on the spin along the axis Z. The pumping current density was $j_0 = 1.2 \cdot 10^{11}$ A/m^2. At the initial moment of time, magnetic vortices in adjacent disks were unbalanced by applying local magnetic fields. The $H_1(10;\,1;\,0)$ Oe field was applied to the first disk, and for the second one the field was $H_2(1;\,10;\,0)$ Oe. This established the initial phase difference of the gyro movement of vortices in adjacent disks. Then the spin-polarized current was turned on and the magnetic fields were turned off. The oscillating induced magnetic moment in each disk was characterized by a complex value

$$m_n = m_{nx} + i m_{ny}, \tag{7}$$

where the index n takes the value of $n = 1, 2$. For each set of current and distance parameters, a steady phase

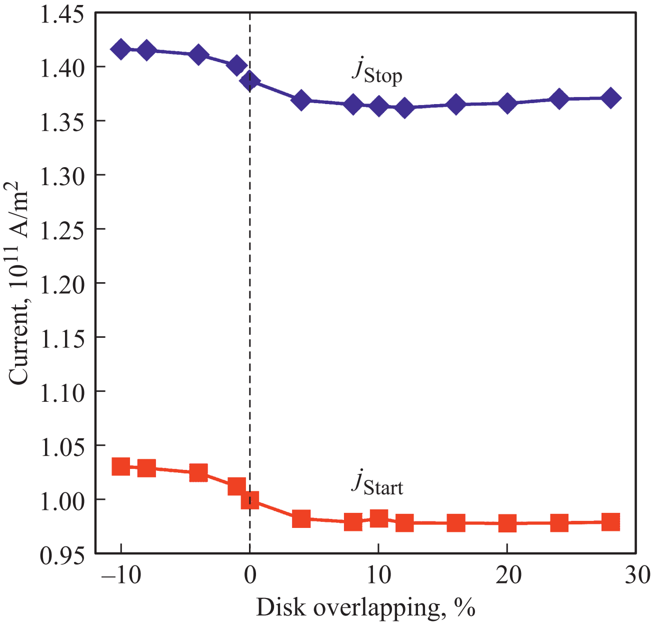

Figure 2. Dependence of density of current of beginning generation (squares) and cessation of generation (diamonds) on the degree of overlap between the disks. The point of 10% is the maximum point for the curve j_{Start}.

difference of induced magnetic moments was recorded $\Delta\varphi_{12} = \text{Arg}(m_1) - \text{Arg}(m_2)$.

In Fig. 3 the dependence of vortex interaction energy on the distance between the disks at uniform pumping current density $j_0 = 1.2 \cdot 10^{11}$ A/m^2 is shown. The coupling energy was defined as the value of the variable component of the total magnetic energy in the overlapping disk, from which the double value of the variable component of the total magnetic energy in the stand-alone disk was subtracted [9].

As can be seen from the figure, the overlapping of the disks leads to a significant increase in the bond energy of vortices. As a result, it reduces its own gyro frequency of oscillation and reduces synchronization time. Dependence of resonance frequency of gyrotropic mode and and synchronization time of vortex oscillations on the distance between the centers of disks are given in Fig. 4. Both have a gap in the point about of 0% due to the emergence of an exchange contribution to vortex energy. It is seen that when overlap the disks, the synchronization time is significantly reduced and reaches the minimum at $\Delta = 12\%$.

An important practical issue is the stability of phase synchronization in such a system, depending on the spread of pumping currents in adjacent disks. With this purpose we have investigated the steady-state difference of phases of gyration of vortices at different pumping currents in neighboring disks and at different distances between the centers of disks. Initially, the same currents were set in both disks $j_0 = \frac{j_{Stop}+j_{Start}}{2}$. Then the current in one disk decreased, and in the other simultaneously increased by the amount of $j_{Step} = \frac{j_{Stop}-j_{Start}}{10}$ at each step. Thus, currents in disks on the n-th step

$$j_1 = j_0 - nj_{Step},$$

$$j_2 = j_0 + nj_{Step}.$$

Fig. 5 shows the dependencies of the phase difference $\Delta\varphi$ on the current difference in the adjacent disks for covering $\Delta = -10\%$ and $\Delta = 10\%$. The endpoints on the graphs

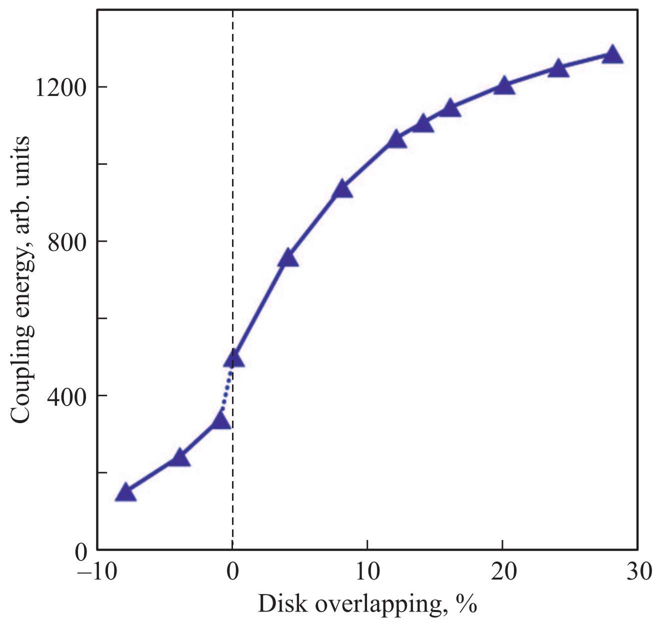

Figure 3. Interaction energy dependence on distance between disk centers. The energy is normalized to the oscillation energy of a single disk.

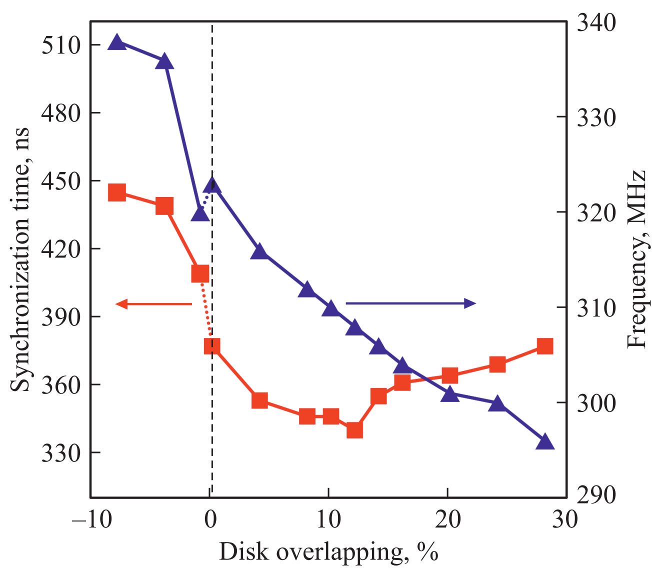

Figure 4. Dependence of resonance frequency of gyrotropic mode and and synchronization time of vortex oscillations on the distance between the centers of disks. Both dependences have a gap of about 0% in the point.

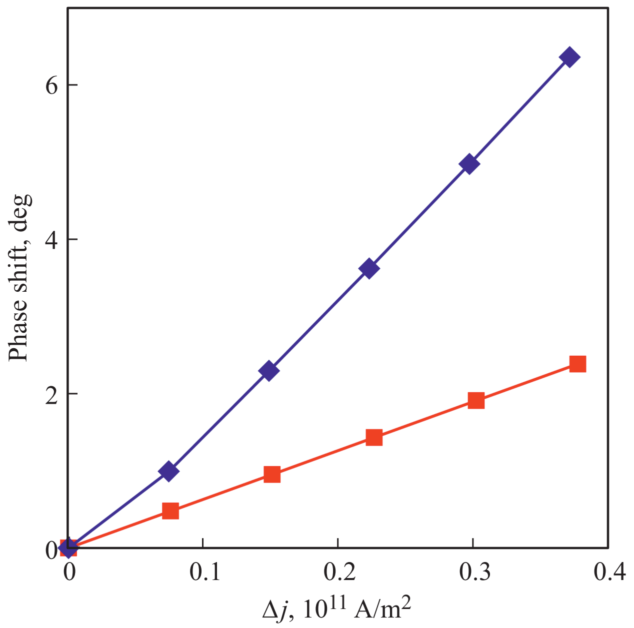

Figure 5. Dependence of phase difference between gyropic oscillations of vortices on difference of pumping currents. The curve for the $\Delta = -10\%$ overlap is indicated by diamonds, for the $\Delta = 10\%$ overlap by squares.

correspond to the case when the current in one disk is j_{Stop}, and in the other j_{Start}.

The figure shows that the exchange at disk overlap ($\Delta = 10\%$) leads to a decrease in the difference of the phases of the gyration to the cores versus the dipole coupling ($\Delta = -10\%$).

4. Conclusion

Thus, by micromagnetic simulation methods, auto-oscillations of interacting magnetic vortices in ferromagnetic disks caused by the action of spin-polarized current were investigated. It is shown, that the reduction of distance between centers of overlapping disks significantly increases the energy of interaction of vortices and as a result leads to a decrease of resonance frequency of gyrotropic mode of oscillations and a decrease of time of synchronization of oscillations. As the calculations showed, the optimum is to overlap the drives $\Delta = 12\%$, at which the minimum time of synchronization of oscillations is realized. At the same time, it is shown that the exchange coupling between vortices leads to a significant decrease in the phase difference of gyration of cores as compared to the dipole interaction. This effect can be used to synchronize STNO.

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