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INFLUENCE OF SHAPE IMPERFECTION ON DYNAMICS OF VORTEX SPIN-TORQUE NANO-OSCILLATOR

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The dynamics of vortex gyration under spin-polarized current in a spin-torque nano-oscillator with axial symmetry violated by shape imperfection has been studied by micromagnetic modeling. We have considered the following kinds of shape: the displacement of the nanodisks centers, the pyramidal shape and the shape with several small cutouts. The corresponding frequency spectra of the vortex oscillations are presented. We found that shape imperfection can influence not only fundamental frequency but also can genarate second and higher harmonics. The impact of different types of shape on the vortex dynamics has been analyzed qualitatively. New ideas of microwave signal arising by artificial nonidealities of structure were proposed.

Keywords: Spintronics; nanomagnetism.

High-frequency dynamics of magnetic vortices induced by the spin transfer effect[1,2] observed recently in nanopillars and nanocontacts have raised a strong interest. The oscillations of magnetization[3] lead to huge oscillations of resistance due to the GMR or TMR effects and as a consequence, to signal generation. The associated microwave emissions in vortex spin-torque nano-oscillators (STNOs)[4] can occur at low current densities, together with large powers and narrow linewidths. The frequency in these devices can be tunable over a wide range by sweeping dc current[5] and external field.

The main goal of this work was to study the influence of shape imperfection on the spin-current generated vortex dynamics in a two vortices STNO, where both layers are in a vortex state. Coupled gyrotropic mode is then excited, with vortices rotating at the same frequency, with a phase difference ruled by the relative polarity signs of the cores[6] ($\Delta\varphi = 0$ for parallel cores and $\Delta\varphi = \pi$ for antiparallel cores). Such systems based on vortex dynamics attract particular interest recently because of strongly improved features of their microwave signal compared to state of the art.[6–9]

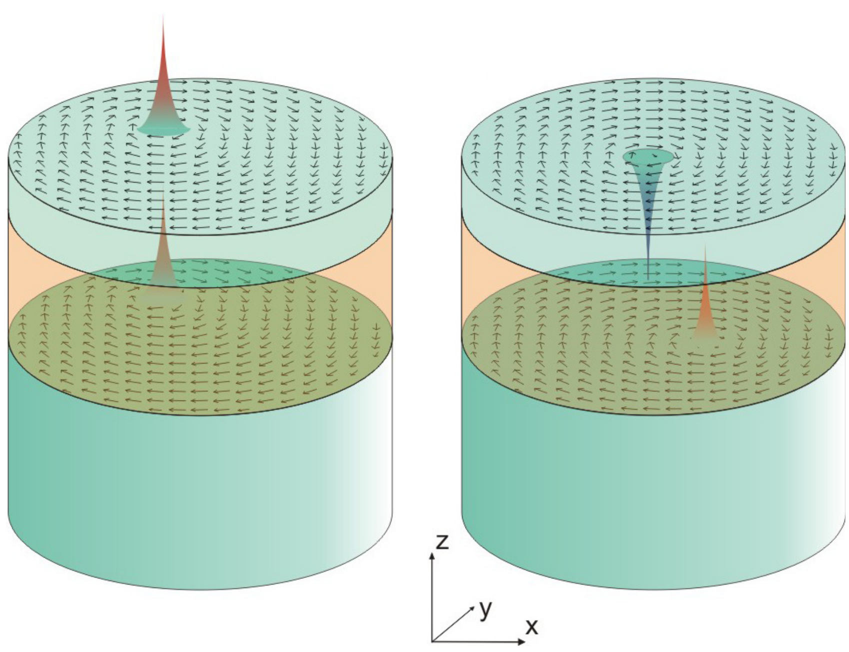
The main focus of the present work is related to the fact that for an ideal circularly symmetric system, where the vortices are rotating at the same frequency, the system does not provide any signal through the magnetoresistance effect. For this reason, the study of the influence of shape imperfection, that might disturb the coupled vortex pair dynamics, is an important objective to identify some ways to get some microwave signal and eventually to increase it.

The studied system is the nanopillar with diameter $D = 200\,\text{nm}$ composed of two ferromagnetic $Ni_{80}Fe_{20}$ layers separated by a nonmagnetic spacer (see Fig. 1). Both magnetic layers have a magnetic vortex as ground state.[10] The thicknesses of top and bottom layers are 4 nm and 15 nm, respectively. We considered two possible relative orientations of vortices cores: parallel (later called "up-up", see Fig. 1(a)) and antiparallel (later called "down-up", see Fig. 1(b)). The magnetic parameters that we use are: $M_S = 800\,\text{emu/cm}^3$, the exchange energy $A = 1.3 \times 10^{-6}\,\text{erg/cm}$ and the damping parameter $\alpha = 0.01$. In all simulations we used a current density $J = 25 \times 10^6\,\text{A/cm}^2$ and a spin polarization $P = 0.3$. The current-induced Oersted field defines the chiralities in both cases. The micromagnetic simulations are performed by numerical integration of the generalized Landau–Lifshitz–Gilbert equation of magnetization motion[11] using our micromagnetic finite-difference code SpinPM based on the fourth-order Runge–Kutta method with an adaptive timestep control for the time integration and a mesh size $3 \times 3\,\text{nm}$. The main difference between this equation and the standard LLG is the addition of term corresponding to spin torque:

$$\mathbf{T}_{\text{s.t.}} = -\frac{\gamma a_J}{M_S}\mathbf{M} \times (\mathbf{M} \times \mathbf{m}_{\text{ref}}) + \gamma b_J \mathbf{M} \times \mathbf{m}_{\text{ref}}, \quad (1)$$

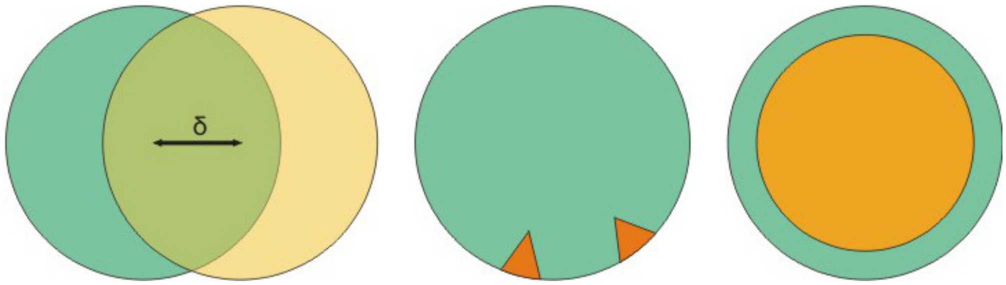
where $a_J = PJ/M_S h$ with P the spin polarization, J the current density, h the thickness of the layer, M_S the saturation magnetization and γ the gyromagnetic ratio and $\mathbf{m}_{\text{ref}}$ is the unit vector of magnetization of the reference layer. It should be noted that in this investigated system b_J has almost no influence on the behavior of the system.

It is known that for the system consisting of cylindrical dots two gyrotropic vortex modes can be excited in the layered nanopillar for the given vortex cores orientation.[12] However, this result obtained in case of ideal circularly symmetric system. As for the system with broken symmetry, analytical solution of this problem is quite difficult. At the same time



(a) (b)

Fig. 1. Schematic representation of vortex-based oscillator: (a) parallel and (b) anti-parallel orientations of vortex's cores. During their spin transfer exited dynamics, the vortices are rotating at the same frequency with phase difference $\Delta\varphi = 0$ for parallel cores (a), and $\Delta\varphi = \pi$ for antiparallel cores (b).



(a) (b) (c)

Fig. 2. Schematic representation of different cases: (a) displacement of the centers, (b) shape with several small cutouts and (c) pyramidal shape.

numerical modeling allows us to explore such systems, while taking into account the effects of spin transfer.

Different types of shape imperfection that we have studied in this work are represented in Fig. 2. For each case, we compare the magnetization oscillations spectra with the spectra of the magnetoresistance signal. Signal in this work is defined as the normalized integral over the whole volume of the interlayer of the scalar product of elementary magnetizations of both layers (in each cell). It is proportional to real GMR signal.

The first type of shape imperfection that has been considered is the displacement of the centers of ferromagnetic disks. The obtained results for the signal for three different displacements δ (5, 10 and 20 nm) in "down-up" configuration are shown in Fig. 3.

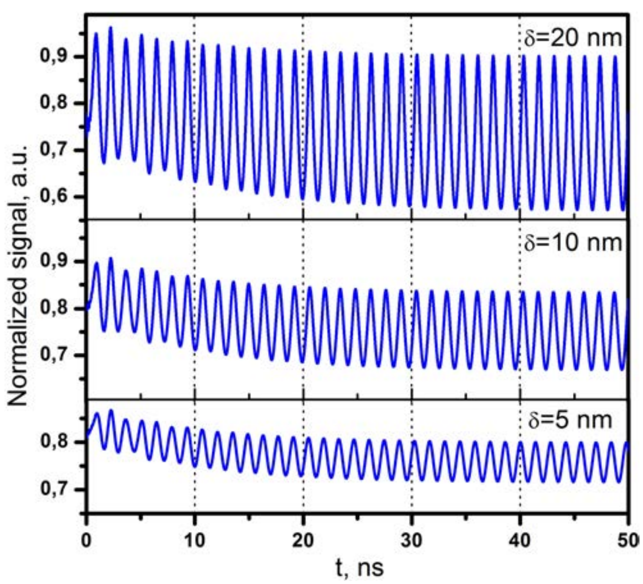


Fig. 3. Normalized magnetoresistance signal. For all three displacements δ modeling has been done in "down-up" configuration.

The calculation shows that the amplitude of the signal depends linearly on the magnitude of the displacement. For the "up-up" configuration, the vortex state in the upper layer appears to be no longer sustainable. The micromagnetic simulation showed that, after a certain time, this vortex switches,[13,14] hence the system goes into the "down-up" configuration. This can be qualitatively explained by the fact that, for the "up-up" configuration, only the situation in which one core of the vortex is exactly under the core of another vortex is energetically favorable. But this situation cannot be achieved if the discs are displaced relative to each other. As for the "down-up" configuration, the situation, when the vortex cores are separated, is already energetically favorable (cf. π phase shift). Therefore, this configuration can be sustained in the case of displaced centers.

As seen from Fig. 4, this shape imperfection leads not only to the appearance of the signal at the fundamental frequency (frequency of rotation of the vortex core), but also to the appearance of the subsequent harmonics. It is important that there is only one peak in the magnetization excitation spectra of the nanopillar but additional peaks in the magnetoresistance spectra. However, the magnitude of these subsequent harmonics decreases with increasing serial number of them, and already for the second harmonic it is much smaller than for the first one.

The second type of shape imperfection that has been considered is the presents of several small cutouts. These cutouts have a triangular shape and the characteristic size of 7 nm. In terms of the magnetization dynamics, this assumption is equivalent to the case of the nonmagnetic inclusions. Consequently, this type of shape imperfection is possible to appear in real nanostructures. The signal

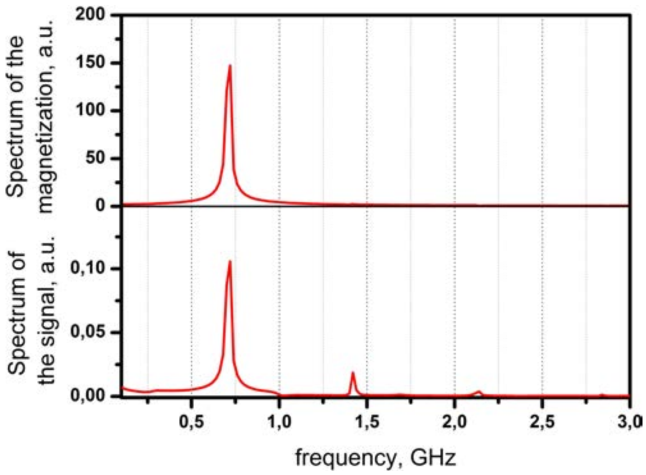


Fig. 4. Spectrum of the signal in comparison with the spectrum of magnetization oscillations in case of centers displacement.

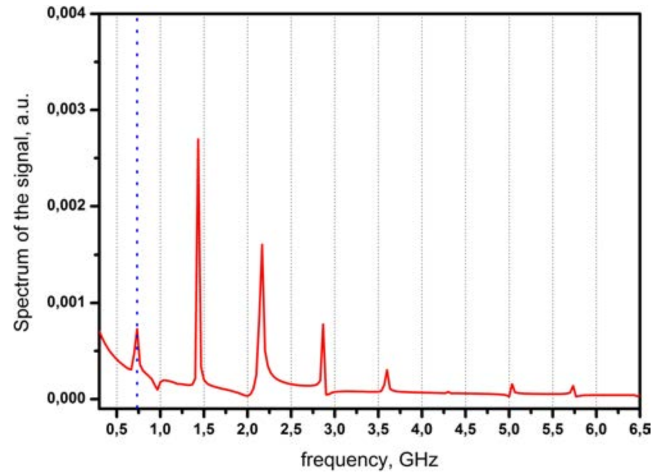


Fig. 5. The spectrum of the signal in case of the presents of several small cutouts. Dotted blue line shows the fundamental frequency of the ideal round shape (color online).

appearing from the modeling is not as big as the one in case of the centers displacement (approximately 10 times less). Indeed, in this case the cores of the vortices experience a certain effect only in a small region near the small cutout. The spectrum of the signal for "down-up" configuration is displayed in Fig. 5 (the spectrum of the signal for "up-up" configuration is almost the same).

The most crucial result of the influence of the presents of several small cutouts is the appearance of the second and higher harmonics in the spectra of magnetoresistance signal. It should be noted that addition of more cutouts or increasing their size, increases the number of nonzero harmonics, but their amplitudes decrease. This behavior is in good agreement with the symmetry of this shape, and can be understood with the simple argument that the signal during the two-vortex dynamics is at first order related to the oscillation of the core−core distance. Since for the case with a large number of cutouts distance between the vortices undergoes more complex oscillations, the signal must also has a more complex spectral structure and include harmonics with larger numbers. Decrease in the amplitude probably can be caused by the averaging in case of a large number of cutouts.

The last type of shape imperfection that has been considered is the pyramidal shape. In this case the layers are concentric circles with different radii. The radius of the top layer is 85 nm and of bottom is 100 nm. The signal appearing from the modeling is almost negligible. This confirms the idea that to increase the signal it need to break the circular symmetry. The spectrum of the signal for "down-up" configuration is displayed in Fig. 6 (the spectrum of the signal for "up-up" configuration is almost the same). In this case the first harmonic is the main one.

In conclusion, we demonstrate the influence of different types of shape imperfection. It was found that the displacement of the centers of the disks gives the most intensive signal, and in this case the signal is proportional to the displacement. The presents of small cutouts leads to the appearance of

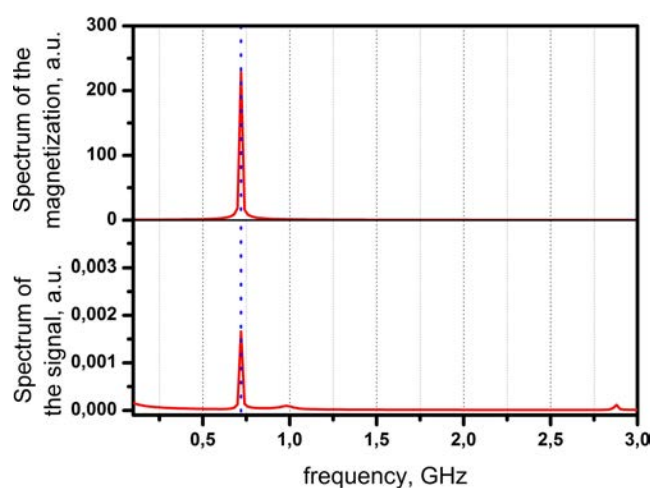


Fig. 6. Spectrum of the signal in comparison with the spectrum of magnetization oscillations for "down-up" case in case of pyramidal shape. Dotted blue line shows the fundamental frequency of the ideal round shape (color online).

the second and higher harmonic and provides a signal 10 times smaller than in the above-mentioned case. Negligible signal in case of pyramidal shape gives proof of the important role of system symmetry. All these results provide an opportunity to increase the signal through the addition of artificial imperfections of the structure. Our work has shown the possibility of creating special shapes with a predetermined spectrum of the signal.

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