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The effects of Dzyaloshinskii-Moriya interactions on the ferromagnetic resonance response in nanosized devices

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The effects of Dzyaloshinskii-Moriya interaction (DMI) on the ferromagnetic resonance response are investigated in nanometer-sized disks using 3D micromagnetics with the inclusion of DMI energy. A rich complexity is found in the effects on the spinwave eigenmodes and their behavior when varying parameters. Two distinct results are demonstrated: first, unique DMI modes are found to form, instead of the expected modes forming in the absence of DMI and they can be uniquely accessed using field rotation; and second, modal evolution with the DMI parameter involves distinct modal twisting and rotations. © 2014 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4870138>]

A precise understanding of unique thin-film magnetic systems, anticipated for use in novel memory and sensor device technologies, is important for a number of reasons, and it is often enabled by measurement of system parameters. In magnetic systems like magnetic tunnel junctions (MTJs) and spin-Hall/Rashba-type systems, forms of spin-orbit coupling (SOC) are already known to play an important role via mechanisms such as crystalline anisotropy (acting on local spins) and spin-flip scattering (acting on itinerant spins), as examples. Recently, there is growing evidence of another distinct form of SOC known as Dzyaloshinskii-Moriya interaction (DMI)¹ having been observed in an increasing number of thin-film heterostructures including systems such as W/Fe, W/Mn, Pt/CoNi, and even Ta/CoFe/MgO, which is particularly interesting, given the wide existing interest for applications in STT-MRAM devices.^{2–6} The discrete Hamiltonian expressing the energy of what is now known as DMI was first proposed as a phenomenological construct to understand weak ferromagnetism, given by¹⁰

$$E_D = \vec{D} \cdot \vec{S}_i \times \vec{S}_j. \quad (1)$$

$\vec{D}$ is the so-called Dzyaloshinskii-Moriya vector. The energy in (1) was later derived rigorously from spin-orbit coupling.¹¹ DMI was found to have two distinct forms, one arising when the Dzyaloshinskii-Moriya vector $\vec{D}$ points along the displacement vector direction between two nearest-neighbor spins $\vec{S}_i$ and $\vec{S}_j$, illustrated in Fig. 1(a), labelled as form 1.

The second form of DMI, form 2, arises when $\vec{D}$ is orthogonal to the displacement vector between the two neighboring spins (but still within the plane of spins), as illustrated in Fig. 1(b). A general result is that the spins tend to rotate around $\vec{D}$ vector to lower the energy. DMI has been shown to lead to various effects including stabilizing Neel

walls, delaying Walker breakdown in domain wall motion, and in the proper magnetic conditions, DMI leads to a unique state of quasi-particles known as skyrmions.^{1,7} The rich complexity being uncovered in recent years in thin films owing to DMI is rather remarkable. The results presented here deal exclusively with form 2, which is expected to be the form most relevant to spintronics applications.¹

In such systems, typically assumed without DMI, ferromagnetic resonance (FMR) has been a widely used experimental approach to extract magnetic parameters such as magnetic damping α , effective magnetization M_{eff} , g -factor, and exchange stiffness A_x . The recent findings relating to DMI suggest that feasible quantitative measurement techniques of the DMI parameter $|\vec{D}| = D$ will be useful. Owing to the already wide use of FMR in many magnetic systems, this work uses full micromagnetics simulations with DMI added to investigate its effects on the FMR response in nanometer sized (diameter = 100 nm, thickness = 1 nm) disks to probe the

FIG. 1. Illustration of the Dzyaloshinskii-Moriya interaction in the two distinct cases when (a) $\vec{D}$ is parallel to the displacement vector between spins i and j and (b) $\vec{D}$ is perpendicular to the displacement vector between spins i and j , and in the plane of the spins.

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FIG. 2. The spectral response and peak-associated eigenmode pairs for (left) a system without DMI and (right) a system with DMI, where $D = 3.3$ mJ/m². The two modes below the spectral response show the eigenmodes for the respective peaks in the spectral response.

potential for detecting DMI as well as investigate how the FMR response changes in the presence of DMI.

To obtain the FMR response, simulations are carried using Object-Oriented Micro-Magnetics Framework (OOMMF), where we have added DMI. FMR spectra information is determined as follows: first, a dynamic simulation is done using a modulated sinusoidal input $g(t) * h_{ac}$ and a dc field H_{dc} along the x-direction (horizontal) is applied. The function $g(t)$ is chosen to be a Gaussian, to enable a broadband, rather than a single frequency response. After the dynamic simulations, the average volume magnetization dynamic response is then resolved, followed by application of a FFT to obtain the spectral response. Executing this locally on $M(x,y,z)$ within the magnetic structure, also allows us to construct the eigenmodes. Fig. 2 shows two sets of spectral responses for two specific cases: (a) a system with no DMI $D = 0$, under conditions that can lead to more than one eigenmode, which for in-plane anisotropy follows from sufficiently high saturation magnetization M_s .^{8,9}

Fig. 2(a) also shows that in the case of a system without DMI, the two modes that form are quite different from those that form in the presence of DMI, shown in Fig. 2(b), particularly the second mode. The modes shown in the left column are the typical edge and edge-to-center modes in nanometer-sized magnetic disks with in-plane anisotropy, which have even been observed experimentally.^{8,12,13} In nearly the same system, with lower M_s , which is expected to weaken the

higher order second eigenmode, but with DMI ($D = 3.3$ mJ/m²), the first mode (edge-mode) does become more uniform, as expected, however, the second mode is fundamentally different. M_s is different between the two cases so that conditions can be reached where only two distinct eigenmodes form. Without DMI, the second mode formation is due largely to magnetostatic energy of the structure, which is strong, however, with DMI, the energy minimization process will be affected by the additional energy term. The observed mode with DMI is neither an

FIG. 3. Spectra for 100 nm disk with a rotation of the dc field H_{dc} from in-plane = 0° to out-of-plane = 90°.

FIG. 4. Evolution of the DMI-mode with the DMI-parameter = 3.3, 6.0, and 6.7 mJ/m^2 . The dashed line serves as a guide to see the modal twisting as D increases.

edge-mode nor a center mode, as typically observed. Precession amplitudes persist from edge-to-edge, across the center parallel to the direction of H_{dc} . Indeed, the 2nd mode can be seen to be more stable with respect to DMI. When DMI is present, it turns out that H_{dc} is pointed along the same axis as $\vec{D}$ (x -axis). Therefore, to lower energy, it is favorable for the spins to find angles rotated about H_{dc} , thus in the y - z plane.

The resulting spins precess predominantly in the y - z plane (however, much more towards y , than z , due to demagnetization energy which will limit out-of-plane motion), anti-symmetrically about $\vec{D}$, to lower E_D . For the case of spins along x , it is more favorable for the spins to rotate in the x - z plane. The combined result, then, favors the mode illustrated in Fig. 2. DMI is seen to lead to very distinct eigenmodes which should be more favorable than the expected modes that form in the absence of DMI.

Field rotation is another common method used in FMR to measure magnetic parameters, for example, in cavity-type systems, which cannot use frequency as a varying parameter. Field rotations from 0 to 90 degrees have been simulated and results are shown in Fig. 3.

As shown in Fig. 3, we have also found that by doing a 90° field rotation of H_{dc} in the x - z plane, the number of modes (or peaks observed) can change. Note that this is in stark contrast to the cases without DMI, where we find that if the system has a single or double mode in a given field, i.e., one or two peaks, field rotations do not alter the number of peaks. However, with DMI, the second peak can be made to vanish via the field rotation. Recent work on the influence of DM on the spinwave spectra finds consistent results in an infinite film. Specifically, Ortuno and Landeros find that DM is perceived mostly when the spins are in the plane. Moreover, the general reduction in the resonance frequency observed as the field is rotated out of the film plane is also consistent with the recent theoretical results, owing to the fact that the resonance frequency for a film with DMI is proportional to $\cos\phi_M$, where ϕ_M is the angle between the magnetization and the film plane. Rotating the magnetic field out-of-plane, which will rotate $\vec{M}$ out-of-plane, will consequently reduce the resonance frequency.

We also investigate how the DMI-mode evolves with the DMI parameter. Simulations were done, extracting the 2nd eigenmode, varying the DMI parameter. Results are shown in Fig. 4. Varying the D -parameter leads to changes in the eigenmode structure.

In particular, we find that there is an evolution of the mode that involves modal-twisting. It is seen that for relatively lower D , the modal centerline is more aligned with the x -axis. However, as the D -parameter increases, the mode undergoes twisting about the z -axis. Note that the twisting observed is not linear in D . This behavior is quite distinct and represents a unique feature of the FMR response in the presence of DMI.

In conclusion, the effects of DMI have been investigated in nanometer-sized disks using micromagnetics. DMI has been found to significantly change the FMR response in distinct ways. First, unique eigenmodes have been observed, that we find are associated only with DMI. Additionally, the particular mode associated with DMI was found to be capable of being suppressed through 90° field rotation. Such conditions are consistent with many FMR experimental configurations, and thus, can be explored in various FMR setups. Finally, the DMI-mode was also shown to evolve with the $\vec{D}$ parameter, demonstrating modal-twisting about the z -axis. Such distinct features in the FMR response with DMI suggest a good probability that FMR may be a useful tool to detect and measure DMI, even in nanometer sized structures.

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