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Resonant Magnetoelastic Coupling Between Magnetic Vortex and Lattice Breathing Modes

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Optical photons are ideal carriers for long-distance transmission, while state-of-the-art quantum processors, such as superconducting qubits, operate at microwave frequencies. An important requirement for networked quantum computation is therefore the ability to coherently convert the quantum information from microwave to optical frequencies and vice-versa. We theoretically address a scheme to achieve this via an intermediate conversion to magnons that enhances the weak direct magneto-optical coupling. We wish to demonstrate the feasibility of such a scheme by employing the magnetoelastic coupling between the modes of a magnetic vortex (vortex breathing mode, VBM) and that of the lattice (elastic breathing mode, EBM), which requires no additional external bias field. In our setup all but the opto-mechanical coupling can be made resonant. We propose an alternative Mumax3 simulation post-processing procedure for semi-classical normalization, where we use regression analysis of the the internal energy dependency on excitation amplitude in a limit cycle motion. We provide estimates for direct resonant coupling between the VBM and the EBM.

***Index Terms*—magnetostriction, magnetic vortex, breathing mode, nanomagnetism**

ALL of the intermediate coupling steps, such as electromagnonic, magnetoelastic, etc., have already been demonstrated separately in macroscopic systems, see for example [1]–[3]. However, despite achieving strong cooperativities, i.e., the measure of the ratio between how efficiently information is exchanged to the rate of dissipative decay in the interacting subsystems, it remains difficult to integrate them all in one setup.

We argue that nanoscopic systems possess unique advantages allowing for the conversion steps to be combined. In particular we investigate free-standing Yttrium Iron Garnet (YIG) thin-film structures [4]. Suspended structures confine the mechanical vibrations and don't allow them to leak out into the substrate, which reduces the mechanical losses. Importantly, at the nanoscale we get into intrinsic, i.e. not requiring external biases, high frequency oscillatory regimes: mechanically, a decrease in particle size raises the frequencies of the standing acoustical waves, and in the magnetic system magnetic vortices can provide access to high-order gyromodes [5] and whispering gallery modes [6] among others.

Here we consider free-standing magnetic discs. Breathing modes are a generic mode type characterized by having $m = 0$ azimuthal nodes, and $l = 0$ radial nodes. In the mechanical sub-system, the Elastic Breathing Mode describes a periodic shrinking and expansion of the cylindrical nanoparticle radius. In the center of a magnetic vortex that we call a core, the curl of the magnetization does not vanish, and magnetic momenta are oriented out of the plane to minimize the exchange interaction. It is the core which changes its size in analogy to EBM forming a Vortex Breathing Mode [7]. We find the VBM spatial distribution to be quite complex, with the oscillations propagating through the entire particle volume. The non-local distribution of the VBM plays in our favour, because it has a bigger overlap with the EBM distribution than one could imagine when only seeing the dynamics of the vortex core.

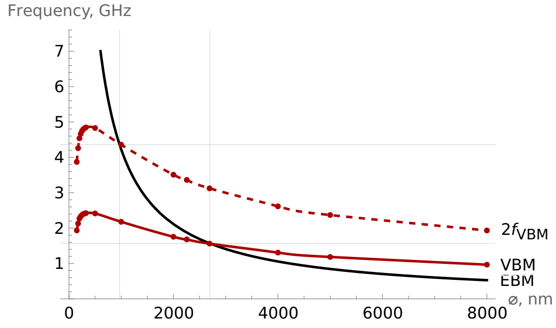

Fig. 1. Frequencies of the EBM, obtained analytically [8], and the VBM, obtained numerically, versus the diameter of a magnetic nanodisk. Grid lines point to the crossing points, a simple linear resonance at 2691 nm; and the nonlinear resonance at $f_{EBM} = 2f_{VBM}$ at double frequency for 969 nm. The disk has a thickness of 100 nm, and is made of YIG with $M_s = 139$ kA/m, $A = 3.7$ pJ/m, and longitudinal sound wave speed of 7.2 km/s.

As Fig. 1 shows, the two mode frequencies cross. The crossing point can be tuned with bias fields and is adjustable at the design stage with geometry. A non-monotonous radius dependence of the VBM is reported in [7], which ensures that a crossing with the EBM is always possible.

We will show how for this specific coupling, the interaction between the two can be described by the Hamiltonian [9],

$$\mathcal{H} = \hbar g_{me}^{(0)}(\hat{m} + \hat{m}^{\dagger})(\hat{b} + \hat{b}^{\dagger}) + \hbar g_{me}^{(1)}\hat{m}^{\dagger}\hat{m}(\hat{b} + \hat{b}^{\dagger}) - \hbar g_{me}^{(2)}(\hat{m}^{\dagger}\hat{m}^{\dagger} + \hat{m}\hat{m})(\hat{b} + \hat{b}^{\dagger}), \tag{1}$$

where $\hat{m}^{(\dagger)}$, $\hat{b}^{(\dagger)}$ are bosonic creation (annihilation) operators of magnons and phonons, respectively, and $g_{me}^{(n)}$ describe the phenomenological magneto-elastic coupling rates. The first and last terms provide strong resonant coupling at the VBM frequency and its double correspondingly.

To calculate the coupling coefficients we use the Mumax3 [10] micromagnetics solver. We expand on the ideas presented previously [11], [12] to do a simple regression analysis of the internal system energy at various VBM amplitudes and receive magnon population in a single post-processing step. In this way we explicitly check if we are within the linear magnonic regime, and we are able to achieve high precision by using more accurate distributions and energies from the high amplitude, but still within linear regime. The coupling coefficients turn out to be large $g_{me}^{(0)}/2\pi \approx 0.2$ MHz, smaller than those observed for gyrational vortex mode coupling [13], but with much higher operating frequency, and no external bias required to shift a vortex into optimal position. These values for nanosystems, both the gyrational and breathing modes of the magnetic vortex, beat results for non-resonant interaction in macroscopic system which yield only ~ 1 mHz couplings.

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