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Damping of Confined Modes in a Ferromagnetic Thin Insulating Film: Angular Momentum Transfer Across a Nanoscale Field-defined Interface

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We observe a dependence of the damping of a confined mode of precessing ferromagnetic magnetization on the size of the mode. The micron-scale mode is created within an extended, unpatterned YIG film by means of the intense local dipolar field of a micromagnetic tip. We find that damping of the confined mode scales like the surface-to-volume ratio of the mode, indicating an interfacial damping effect (similar to spin pumping) due to the transfer of angular momentum from the confined mode to the spin sink of ferromagnetic material in the surrounding film. Though unexpected for insulating systems, the measured intralayer spin-mixing conductance $g_{\uparrow\downarrow} = 5.3 \times 10^{19} \text{ m}^{-2}$ demonstrates efficient intralayer angular momentum transfer.

Spin pumping driven by ferromagnetic resonance (FMR) is a powerful and well-established technique for generating pure spin currents in magnetic multilayers [1–4]. Understanding the mechanism that couples precessing magnetization to spin transport is an important step in utilizing this phenomenon. In addition, probing the effect of spin pumping on the damping of individual nanostructures is vital for the development of practical spintronic devices, such as spin-torque oscillators [5, 6]. Conventional FMR studies at these sub-micron length scales become difficult due to the confounding effects arising from interfaces in multilayer materials and from sensitivity limitations in detecting lateral transport in single component systems at these length scales. Recent studies have shown that individual nanoscale elements exhibit size-dependent effects, such as nonlocal damping from edge modes [7] and wavevector-dependent damping in perpendicular standing spin wave modes [8]. These experiments have revealed the effect of damping due to intralayer spin pumping, which is the transfer of angular momentum in systems with spatially-inhomogeneous dynamic magnetization.

A primary challenge in these measurements is distinguishing intralayer spin pumping from other mechanisms that cause variations in linewidth from sample to sample, such as surface and edge damage [9, 10]. In this paper we measure size-dependent angular momentum transport across a clean interface without growth-defined defects or lithography-induced edge damage. This is achieved non-invasively in a single sample by confining the magnetization precession to a mode within an area defined by the controllable dipolar field from a nearby micron-sized magnetic particle [11]. This enables a unique investigation of changes in relaxation due to angular momentum transfer across the field-defined interface between precessing magnetization within a mode to the spin sink provided by the surrounding quiescent material.

We investigate the size dependence of interfacial damping using the technique of localized mode ferromagnetic resonance force microscopy (FMRFM) [11]. By adjusting the magnitude of the dipolar field from the probe we can control the confinement radius. Localized modes have previously been observed in permalloy when the probe field is out-of-plane [11], in-plane [12] and at intermediate angles [13]. The azimuthal symmetry of the out-of-plane geometry permits simple numerical analysis based on cylindrically symmetric Bessel function modes with a well-defined localization radius [11], similar to those seen in perpendicularly magnetized dots [14]. In addition, this geometry eliminates the effect of eigenmode splitting, which can cause additional broadening [15].

We demonstrate the control of confinement radius by

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**FIG. 1.** Localized mode FMRFM spectra for thin film YIG at several probe-sample separations. The dashed line indicates the position of the uniform mode peak that does not shift with probe-sample separation. As probe-sample separation is reduced the localized modes shift to higher field relative to the uniform mode peak. Inset: transverse magnetization of the first two spin wave modes confined by the magnetic field well of the probe magnet. The energy of the confined modes is dictated by the depth of the field well.
Due to cylindrical symmetry the magnetization profile of shape and mode radius \( R \) over the sample surface probe particle that the dipole field is constant across the sample, while the uniform mode stays at constant decrease, thus increasing the (negative) probe field at higher applied field as the probe-sample separation increases. As expected, several discrete peaks emerge and shift towards higher field as the probe-sample separation increases. This modeling procedure provides both the resonance field and the radius of the mode, and these are given in Fig. 2. We see that the resonance fields of the experimental peaks are well described by the model, confirming the accuracy of the calculated mode radius.

To measure damping of a confined mode we obtain FMRFM spectra for a fixed mode radius \( R \) at multiple frequencies, one example of which can be seen in Fig. 3. The field shift of the localized modes, relative to the uniform mode \( H_{\text{uniform}} \) is constant for a fixed wavevector \( k = k_n = \chi_n / R \), independent of frequency \( \omega \), as predicted by Equation (1).

By fitting a Lorentzian lineshape to the \( n = 1 \) and \( n = 2 \) peaks we obtain the full-width at half-maximum linewidth of the localized modes and plot this as a function of microwave frequency to separate intrinsic and extrinsic linewidth broadening mechanisms [19]. Following from the Landau-Lifshitz-Gilbert equation, the linewidth \( \Delta H \) is given by

\[
\Delta H = \Delta H_0 + \frac{2\alpha\omega}{\gamma}
\]
where the slope and intercept of the frequency-dependent linewidth measure, respectively, the Gilbert damping parameter $\alpha$ and inhomogeneous broadening $\Delta H_0$ due to spatial variation of magnetic properties. We measure this frequency dependence at several probe-sample separations corresponding to several mode radii $R$.

The key result of our study is the observation of enhanced damping that is unambiguously dependent on the radius of the mode, as seen from the change in slope of the first localized mode linewidth with mode radius as seen in Fig. 4. The Gilbert damping parameter $\alpha$, for both the first and second localized modes, shows a surprising linear behavior when plotted against $R^{-1}$, the reciprocal of the mode radius, as seen in Fig. 5. From Equation (5) and the linear fit (solid black line) to the enhanced damping versus mode the reciprocal of the mode radius, as shown in Fig. 5, we obtain $g_{\uparrow\downarrow} = (5.3 \pm 0.2) \times 10^{19} \text{m}^{-2}$ for this system.

It is interesting and somewhat remarkable that we observe angular momentum transport in this insulating system and that its efficiency, characterized by $g_{\uparrow\downarrow}$, is larger than the spin-mixing conductance measured in YIG-metal bilayers [16, 22, 23]. We suggest that $g_{\uparrow\downarrow}$ measured in this study is an intralayer spin-mixing conductance that describes a generalization of spin pumping as the transport of energy and angular momentum from an on-resonance spin source to an off-resonance spin sink, even in the absence of both a material interface [7] and conduction electrons [24, 25]. We describe this effect as YIG-YIG intralayer spin pumping: the energy and angular momentum from the precessing confined mode can be absorbed by the surrounding ferromagnetic material of the unpatterned film, as depicted in the inset of Fig. 5. The relatively large value of

\[
\alpha_{\text{sp}} = \frac{\gamma \hbar g_{\uparrow\downarrow}}{4\pi M_s R}
\]
We consider the possible role of transverse spin diffusion [21] used previously to describe enhanced damping due to the interaction between itinerant electrons and spatially-inhomogeneous dynamic magnetization [7, 8]. While this theory applies only to ferromagnetic metals we feel that it is illuminating to compare our observations with this previously established formalism for intralayer spin transport. These previous results argue for a quadratic wavevector dependence to the enhanced damping:

$$\alpha_{\text{sp}} = \frac{\sigma_T \gamma}{M_s} k^2 \tag{6}$$

where $\sigma_T$ is the transverse spin conductivity and for our case the wavevector $k = \chi_n/R$ is given by the radius of the mode $R$ and the Bessel zeros $\chi_1 = 2.405, \chi_2 = 5.520$. We find, however, that the damping enhancement in our system (involving insulator-insulator spin transport) is independent of wavevector, as clearly demonstrated by the equivalent behavior of the 1st and 2nd localized mode, shown as the red and blue solid circles respectively in Fig 5. To quantify the comparison we allow the spin conductivity to be a free parameter and fit to the first localized mode linewidth; this fit to the wavevector-dependent intralayer spin pumping theory is shown as the red dashed line in Fig. 5. We find that the spin conductivity that describes this fit, $\sigma_T = 1.5 \times 10^{-22}$ kg m/s, is two orders of magnitude larger than that measured in a metallic ferromagnet [7]. In addition, using the same spin conductivity to estimate the linewidth of the second localized mode (blue dashed line) results in a prediction that does not accurately describe the measured second mode linewidth (blue solid circles), while confined-mode intralayer spin pumping that scales as the surface-volume ratio of the mode (black solid line) described by Eq. (5) accurately describes both sets of data. Clearly, the phenomenon we observe in a ferromagnetic insulator is qualitatively different than that observed in a ferromagnetic metal[7, 8]. More specifically, our observed effect is described by a surface-volume intralayer relaxation specific to spatially-confined precession within an extended film, previously predicted for nanocontact spin-torque oscillators [27].

Other mechanisms for linewidth broadening are ruled out by analysis of the phenomenology of our result. The dipolar field from the micromagnetic tip is a potential source of linewidth broadening as it is produces an inhomogeneous field in the sample of several hundred gauss that would dominate inhomogeneous spectral broadening in a paramagnetic sample [28, 29]. Inhomogeneous broadening from the tip can be ruled out as the source of increased damping in this study for two reasons. First, any inhomogeneous broadening would be frequency independent, and hence would lead to a change in the intercept of the frequency-dependence of linewidth shown in Fig. 4, while the change in slope alone is a clear indication of a Gilbert damping enhancement. Second, the ferromagnetic resonance excitations of a ferromagnet are eigenmodes [11, 28], in which the inhomogeneous field from the tip is cancelled by the dynamic field from the precession. This allows the effective field to be equal at every position inside the mode, and hence it can be described as an eigenmode with a single well-defined eigenfrequency. While mode splitting can con-
tribute to the measured effective damping[15], the perpendicular geometry used in our study eliminates this possibility. Other well-established mechanisms for size- or wavevector-dependent relaxation can also be eliminated due to their insufficient magnitude and differing phenomenology: 3-magnon confluence [30, 31] manifests as a linewidth broadening that is linear in k but independent of frequency, while 4-magnon scattering [32] scales as k^2.

To conclude, we observe robust intralayer spin pumping within an insulating ferromagnet, which manifests as enhanced damping of micrometer-scale confined spin wave modes. This result has consequences for devices that induce spin precession in confined regions, such as spin-torque oscillators in the nanocontact geometry [33, 34]. In addition, our study highlights the power of localized mode FMRFM for illuminating local spin dynamics and in particular for spectroscopic studies of the impact of mode relaxation across a controllable, field-defined interface.

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