MAR15-2014-020074

Abstract for an Invited Paper
for the MAR15 Meeting of
the American Physical Society

Mode- and Size-Dependent Landau-Lifshitz Damping in Magnetic Nanostructures

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At nanometer dimensions, magnetic excitation bands transform into discrete eigenmodes with nontrivial shape and size dependence. The eigenmode spectral peak positions are well-understood in terms of conventional micromagnetics [R. D. McMichael and M. D. Stiles, J. Appl. Phys. 97, 10J901 (2005)][H. T. Nembach, et al., Phys. Rev. B 83, 094427 (2011)]. However, the effect of finite size on the damping process is not yet settled. Conventional micromagnetics does not predict any effect, insofar as numerical formulations of magnetization dynamics are usually predicated on the assumption of local damping. However, nonlocal damping has been predicted for metals via nontrivial scattering between coherent excitations and uncorrelated spin-flip electron-hole pairs [Y. Tserkovnyak, et al., Phys. Rev. B 79, 094415 (2009)] [I. V. Baryakhtar and V. Baryakhtar, Ukr. Phys. Journ. 43, 1433 (1998)]. In particular, theory predicts a dependence of damping on the eigenmode curvature. We developed a novel Kerr microscope to measure ferromagnetic resonance in deep-sub-wavelength structures. We use heterodyne mixing for phase-sensitive detection of the magnetization dynamics with a signal-to-noise ratio proportional to the square-root of the scattered optical power. The heterodyne magneto-optic microwave microscope (H-MOMM) is optimized for cw measurements to extract the damping parameter. We measured damping in e-beam-patterned 10-nm-thick Permalloy nanomagnets ranging in size from 100 to 400 nm. We observe two eigenmodes; the end-mode, with an exponentially decaying amplitude for increasing distance from the ends along the applied field direction, and the center mode, with relatively uniform amplitude throughout much of the nanomagnet volume, though with two nodes near the ends. The center-mode damping increases with decreasing nanomagnet size, but the end-mode damping exhibits the opposite trend [H. T. Nembach, et al., Phys. Rev. Lett. 110, 117201 (2013)]. We quantitatively fit the data with the Barakhtar/Tserkovnyak theory, but obtain a much larger dependence on sample size than expected from microscopic considerations. Subsequent measurements by us of perpendicular standing spin waves in thick Permalloy films, as well as additional H-MOMM investigations of variable thickness Permalloy nanomagnets, strongly suggest that the observed non-local damping is enhanced with decreasing film thickness. Such thickness dependence is not theoretically predicted, and indicates that surface/interface scattering is important.