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MATERIALS RESEARCH HIGHLIGHT

# Submicron resolution ferromagnetic resonance microscopy using scanned probe MRFM

E. Nazaretski and R. Movshovich[1]

Magnetic resonance force microscopy (MRFM) attracted intense interest in the last few years due to its high force sensitivity and excellent spatial resolution of magnetic properties. MRFM has successfully been used in studies of electron and nuclear spin systems culminating in a detection of a force signal originating from a single electron spin[1]. Recent experiments on nuclear spins of $^{19}F$ in $CaF_2$ samples demonstrated the spatial resolution of 90 nm, orders of magnitude better than conventional magnetic resonance imaging techniques. Experiments on strongly interacting systems, e.g. ferromagnets, showed the potential for spatially resolved ferromagnetic resonance (FMR) in continuous samples[3]. In general, ferromagnetically coupled systems pose a challenge for locally resolved FMR due to the strong interaction between the spins. In conventional experiments, the observed resonance modes typically involve precession of spins in the entire sample. The ability to perform spatially resolved FMR would allow researchers to characterize buried ferromagnetic interfaces, study locally functional materials, conduct local studies of the exchange bias phenomenon and many others.

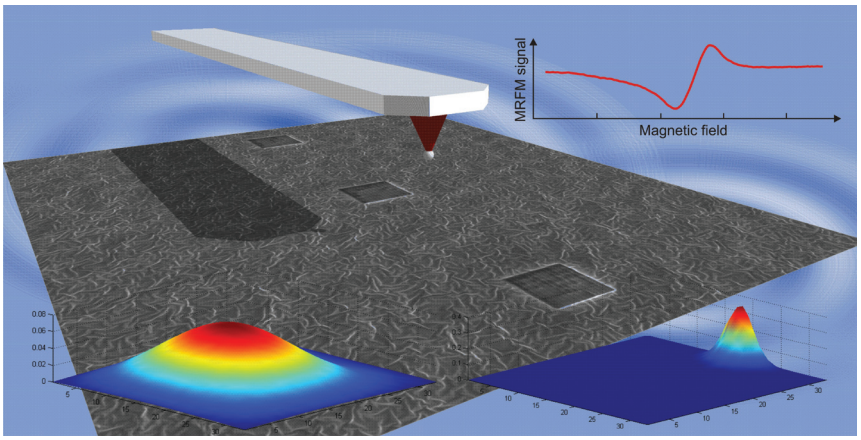


**Figure 1. Schematic of the MRFM experiment. Simulations on the front of the figure represent locally excited resonance modes in a continuous ferromagnet.**

In our work we consider an approach to spatial resolution, which relies on the unique properties of the strong-coupled MRFM and allows for sub-micron resolution even in homogeneous ferromagnetic samples. The method is based on the formation of local FMR modes caused by the strong local field inhomogeneity in the vicinity of the probe tip. The existence of such modes has been discussed previously[4], however, local modes in uniform samples have not been observed experimentally yet.

As an example of locally excited FMR, we demonstrate a direct observation of discrete resonance modes excited in a continuous permalloy film. We study the dependence of the modes' frequency on the orientation of the film relative to the external magnetic field, and on the probe-sample separation.

To understand the nature of these modes and their behavior, we performed micromagnetic simulations based on the Landau-Lifshitz-Gilbert (LLG) equation and accounting for the presence of the probe tip. The simulations indicate that the discrete modes correspond to the FMR modes highly localized in the vicinity of the MRFM tip. These modes originate from the regions of the film where the tip's magnetic field reduces the magnitude of the external uniform magnetic field. For the external magnetic field perpendicular to the film plane, the modes have a characteristic ring-like structure with the size comparable to the sample-tip distance. Even higher spatial localization of the modes is achieved by tilting the film relative to the external field. The modes acquire a crescent shape, and their coupling to the tip

[1]Condensed Matter and Thermal Physics, Materials Physics and Applications Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

is greatly enhanced, which leads to further improvement of the spatial and force resolution. The locally excited magnetic modes provide the unique opportunity to study and characterize both static and dynamic magnetic properties of extended and localized defects in a continuous ferromagnetic media.

In Figure 2 we show experimentally observed MRFM modes as a function of the probe-sample distance and the angle between the film plane and the direction of the externally applied magnetic field. At larger angles multiple modes are observed which merge into a single resonance mode at probe-sample distances greater than a few micrometers. In Figure 3 panel d, we show the LLG simulation of the lowest frequency mode (highest field in Figure 1). This mode is confined to the area of the sample on the order of 1 $\mu m^2$. Spatial confinement has been verified in a separate set of experiments. By scanning the MRFM cantilever across the sample and tracking the lowest frequency mode information about local magnetic properties in a continuous sample can be acquired.

*This work has been done in collaboration with I. Martin (T-11), E. A. Akhadov (MPA-CINT) and the group of Prof. P. C. Hammel at Ohio State University.*

## References

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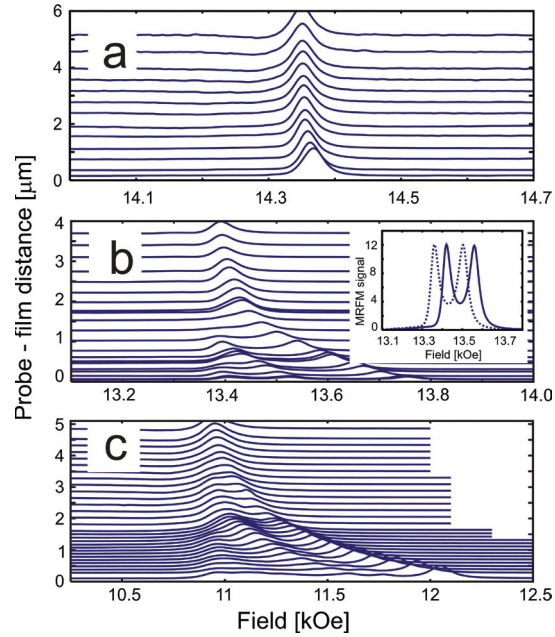


**Figure 2. 1 MRFM spectra as a function of the probe-sample distance at different angles Θ between the normal to the film plane and the direction of the external magnetic field $H_{ext}$. a) Θ=1.0 ±0.5$^0$, b) Θ=3.4 ±0.5$^0$ and c) Θ=5.4 ±0.5$^0$, $f_{RF}$=9.75 GHz, T = 11 K. Spectra are scaled for clarity. Inset in panel b) shows the shift of the entire resonance structure with the change of the microwave field from 9.75 to 9.65 GHz; probe-film distance ≈ 760 nm.**

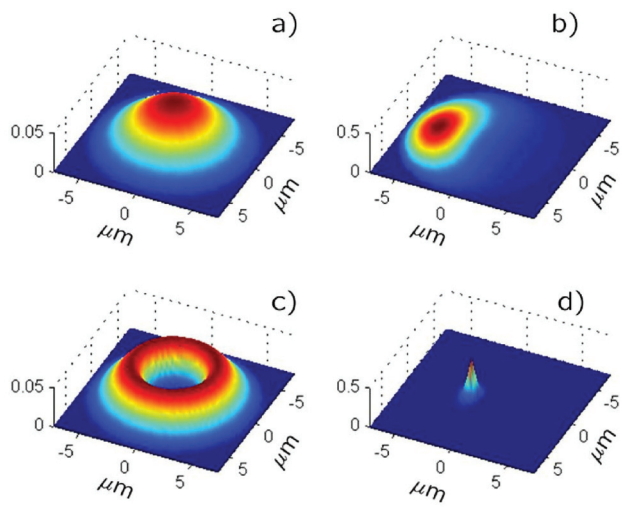


**Figure 3. Numerically calculated spatial profile of the excited transverse magnetization of the fundamental FMR mode in a 15 μm diameter, 50 nm thick permalloy disk tilted at an angle Θ with respect to the direction of the applied magnetic field in the presence of a 2.3 μm diameter probe magnet placed at distance d over the center of the disk: a) Θ=0$^0$, no probe magnet b) Θ=6$^0$, d=4 μm c) Θ=0$^0$, d = 150 nm d) Θ=6$^0$, d=150 nm.**

*Evgueni Nazaretski received his PhD in physics from the University of Bayreuth, Germany, where he studied nuclear magnetic resonance properties of solid and liquid $^3$He at low temperatures. He is a Director's Postdoctoral Fellow in the Condensed Matter and Thermal Physics Group at Los Alamos National Laboratory.*

*Roman Movshovich received his PhD from Cornell University, where he studied collective modes and order parameter in superfluid $^3$He using ultrasound. His primary interests are correlated electron phenomena and unconventional superconductivity. He is a Fellow of the American Physical Society and became a Los Alamos National Laboratory Fellow in 2007.*



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