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Title: Force Detected Ferromagnetic Resonance Microscopy

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Abstract:

Force Detected Ferromagnetic Resonance Microscopy

D. V. Pelekhov and P. C. Hammel (MST-10); M. M. Midzor, P. E. Wigen, W. Chen, M. C. Cross, M. L. Roukes

Detection of ferromagnetic resonance (FMR) by means of a scanned microscale magnetic probe enables measurement of local spatial variations in the FMR response of a microscopic ferromagnet on a spatial scale finer than ever previously possible. FMR provides detailed and unique insight into the dynamic and static magnetism of ferromagnetic materials and devices. This ability to investigate microscopic structures will enable new understanding and applications. We present the development and underlying physical principles of force detected FMR allowing measurements and analysis on micron-scale samples never before possible. These reveal that the FMR dispersion relation is perturbed in the immediate vicinity of a scanned magnetic probe, thus demonstrating the ability to obtain microscopic, local scanned probe measurements of the static and dynamic ferromagnetism from a volume defined by the magnetic probe tip.

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Outline

- *General principles of MRFM operation*
  - *Experimental setup*
  - *Thermal noise characteristics*
- *Scanned probe FMR spectrometer*
- *Basic FMR theory*
- *Spatially resolved forced FMR detection in patterned YIG samples*
  - *Operation in medium/high probe field regime*
  - *Observation of "hidden" mode*
  - *Observation of mode enhancement*
- *"Square well" model of magnetostatic mode enhancement*

Force Detection of Magnetic Resonance

INGREDIENTS:

sensitive force detector

compliant mechanical element
displacement readout

miniature magnet

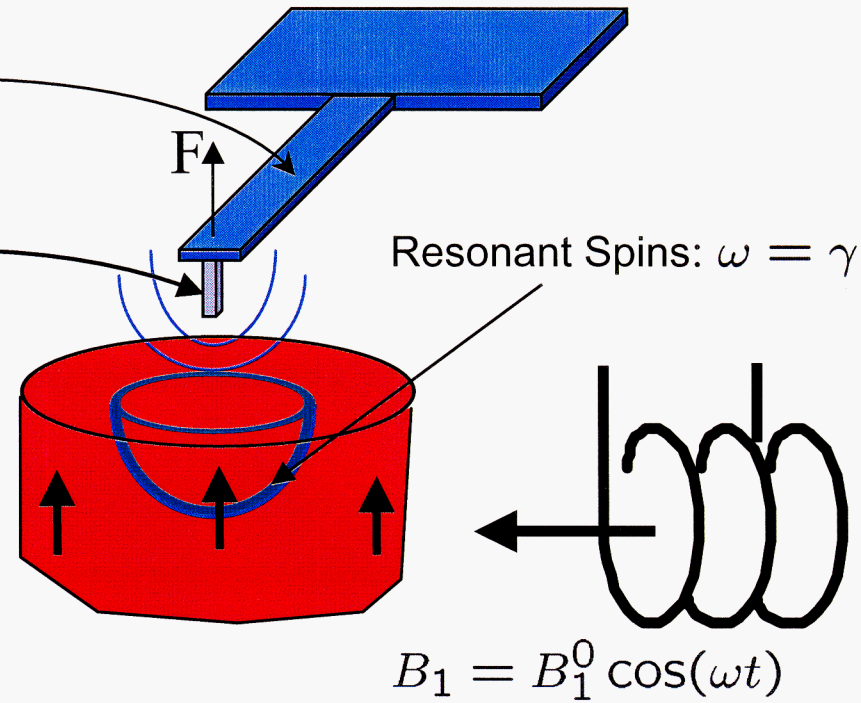
generates field gradient:

provides coupling to spins)

➔ $F = (m \bullet \nabla)B$

defines magnetic resonance imaging volume

➔ $\omega(r) = \gamma B(r)$



J. A. Sidles, Appl. Phys. Lett. ***58****, 2854 (1991)*

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Maximizing MRFM Sensitivity

Minimum Detectable Signal *(number of spins yielding S/N ~ 1)* :

$$N_{\text{mds}} = \frac{\sqrt{S_f \Delta f}}{F_{\text{spin}}} = \underbrace{\frac{1}{|\nabla B|}}_{\substack{\text{Field gradient} \\ \text{(force/moment)}}} \underbrace{\frac{3k_B T}{(h\gamma)^2 I(I+1)B}}_{\substack{\text{Spin Polarization} \\ \text{(moment/spin)}}} \underbrace{\sqrt{\frac{2kk_B T \Delta f}{Q\omega_0}}}_{\substack{\text{Force Sensitivity of} \\ \text{Mechanical Element}}}$$

- *Increase ∇B*
- *Reduce T*
- *Improve force sensitivity*

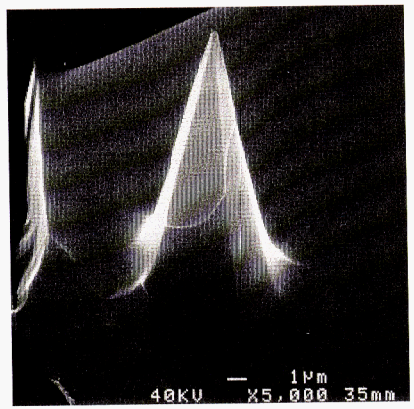
Single Electron Spin Detection is Achievable

FMRFM spectrometer

Detection Cantilever (with ∇B)

Fiber optic interferometer

$$F = (m \cdot \nabla)B$$



Sputter Coated NiFe Tip

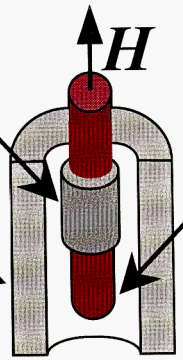
RF Microstrip Resonator (ω)

Sample on substrate

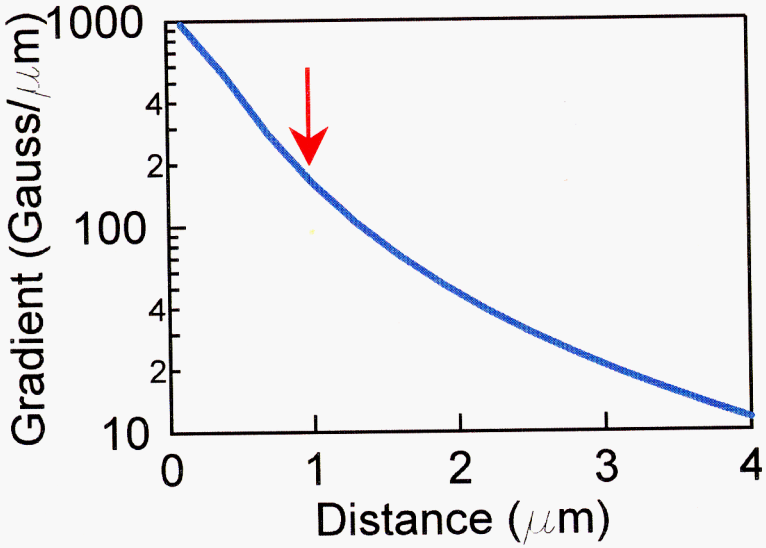
Modulation Field, B_{mod}

Bias Field Solenoid (± 300 G)

Bias Field B (permanent magnet)



Gradient > 100 Gauss/μm at 1 μm



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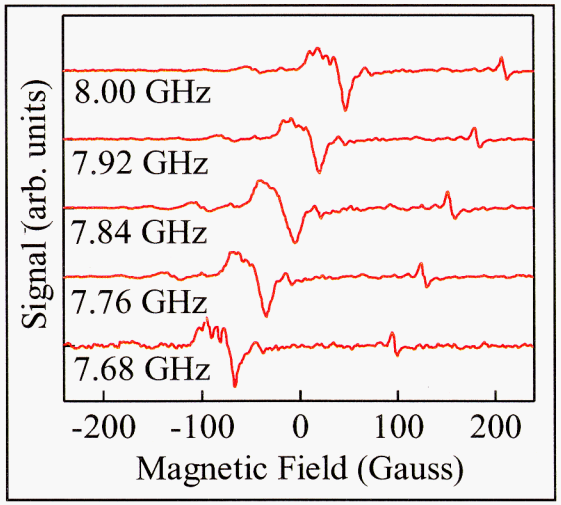
Ferromagnetic Resonance Imaging

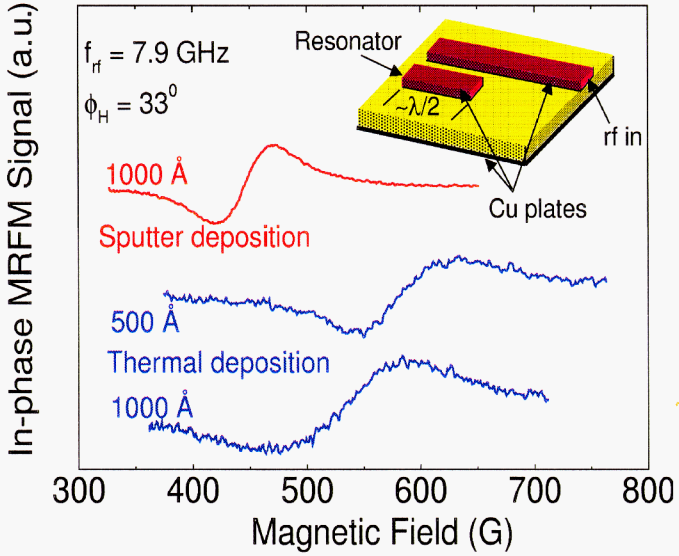
- *Strong interactions between ordered moments in ferromagnet: resonance frequency is a* ***non-local*** *function of applied field*
- *Imaging is more complex than for conventional magnetic resonance*
- *Effect of probe magnet*
  - ***Weak Probe Field:*** *Local detection, but frequency/field relationship determined by sample geometry only*
  - ***Intermediate Probe Field:*** *Perturbing field of probe alters the intensities of the ferromagnetic modes but not their resonance frequencies*
  - ***Strong Probe Field:*** *Local ferromagnetic resonance modes are entirely determined by the probe field independent of sample geometry.*

MRFM Detection of Ferromagnetic Resonance

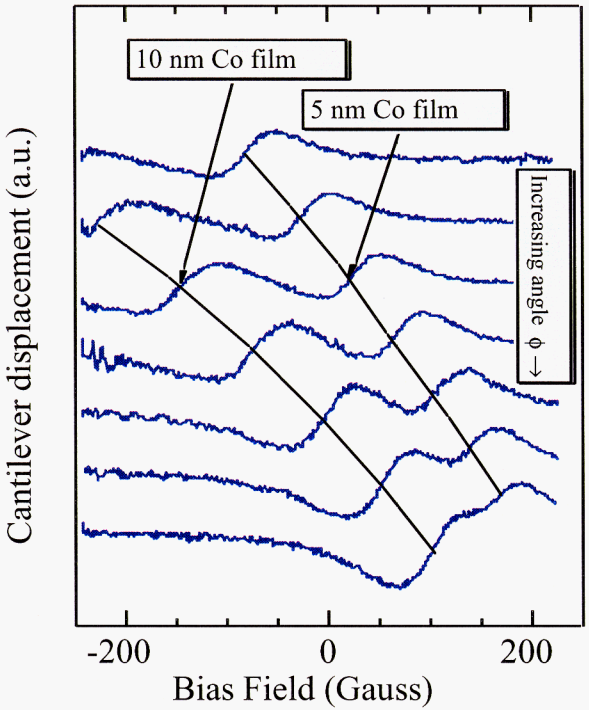
Yttrium Iron Garnet (YIG) Film



Cobalt Film



Cobalt Trilayer



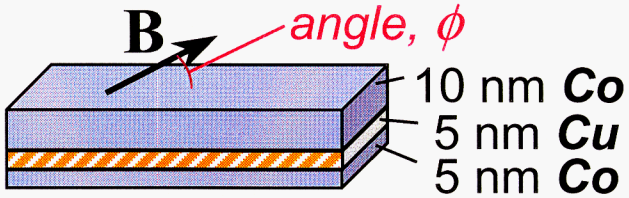
YIG FMR

Z. Zhang, P.C. Hammel and P. Wigen, *Appl. Phys. Lett.* **68**, 2005 (1995).

Co films and multilayers

Z. Zhang, P.C. Hammel, M. Midzor, M.L. Roukes and J.R. Childress, *Appl. Phys. Lett.* **73**, 2036 (1998).

B.J. Suh, P.C. Hammel, Z. Zhang, M.M. Midzor, M.L. Roukes, J. Childress, *J. Vac. Sci. Technol.* **B16**, 2275 (1998).



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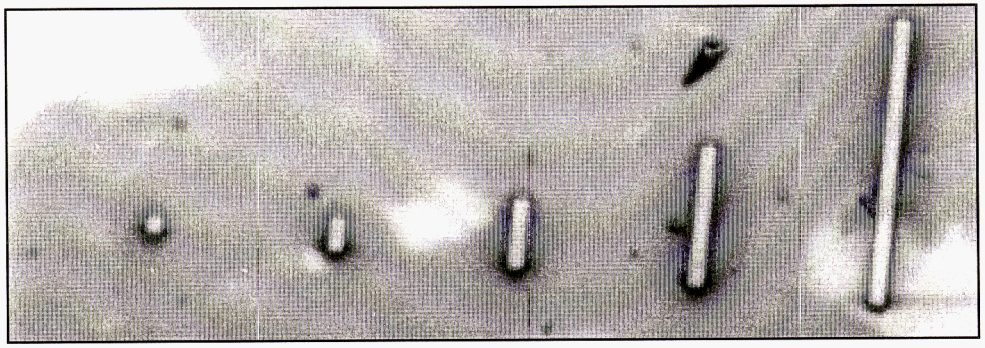
Ferromagnetic Resonance in Patterned YIG Samples

Demonstrated first high sensitivity scanned probe Ferromagnetic Resonance (FMR)



Sample parameters

Material: Yttrium Iron Garnet (YIG)

Patterning: optical lithography and ion beam milling

Substrate: gadolinium gallium garnet (GGG)substrates

Growth method: liquid phase epitaxy

Thickness: 3 μm

Width: 10 and 20 μm

Length: 20 to 320 μm

Magneto-static Mode Dispersion Relation: Theory

The dispersion relation for small geometries is given as:

$$\omega^2 = \omega_i \pi \left[\omega_i + \omega_M \left(1 - \frac{1 - \exp(-k_t d)}{k_t d} \right) \right]$$

Where, $\omega_i = \gamma(H_{res} - H_d)$ and $\omega_M = \gamma M_S$

H_d - demagnetization field

H_{res} - external fled

ω - applied RF frequency ($w=2pf_{rf}$)

d - film thickness

k_t - transverse wave number

For a typical sample: d = 3.37 μm, $4\pi M_s$ = 1760 Gauss, γ = 28 GHz/T and f_{rf} = 7.6 GHz

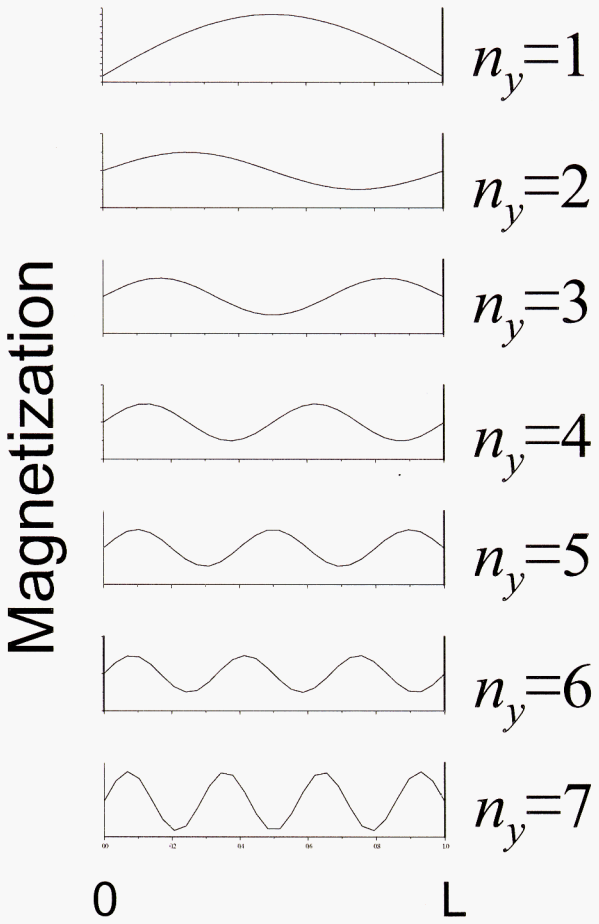
B. A. Kalinikos, IEEE Proc.,**127**(Pt H),4(1980)

Magneto-static Modes

Transverse wave number k_t

$$k_t^2 = k_x^2 + k_y^2 = \left(\frac{\pi n_x}{w}\right)^2 + \left(\frac{\pi n_y}{L}\right)^2$$

n_x, n_y – mode numbers
n_x, n_y = 1,2,3…
w – sample width
L – sample length



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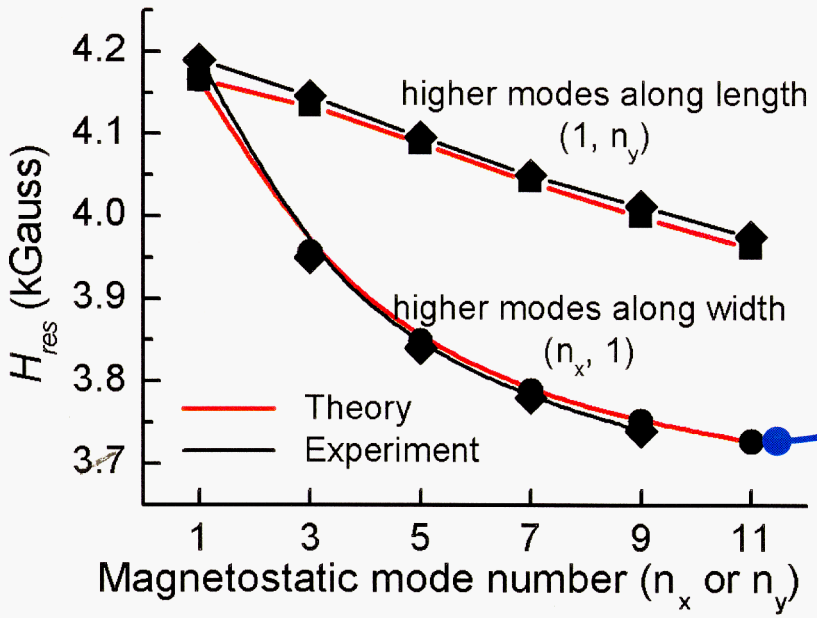
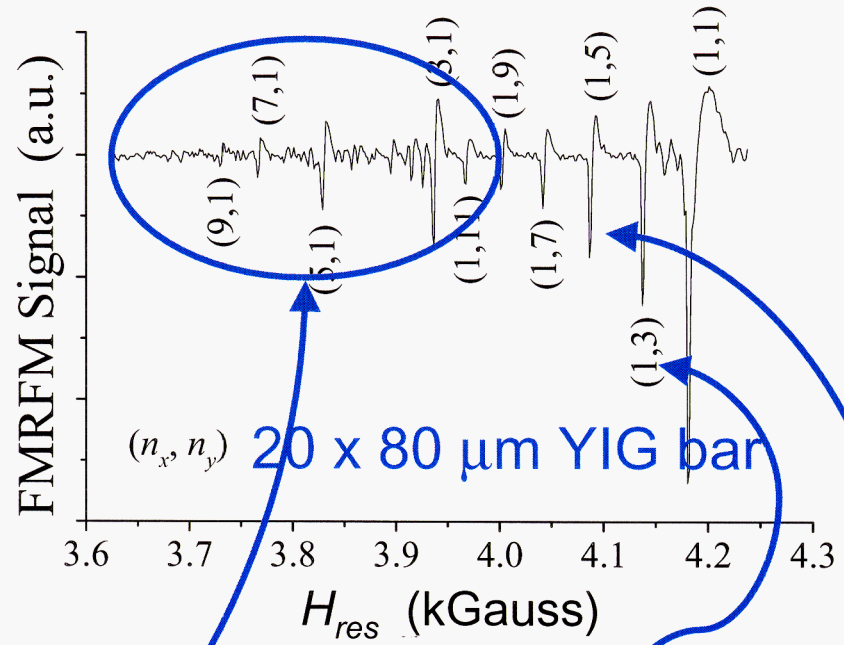
Magnetostatic Modes in Patterned YIG Samples

Clear observation of magnetostatic modes in microscopic sample ***Transverse*** *(n_x=3,5,…) and* ***longitudinal*** *(n_y=3,5,…) magnetostatic modes are well described by theory*

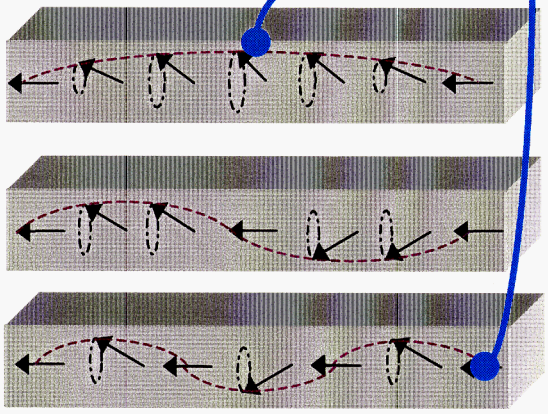




n_y=1

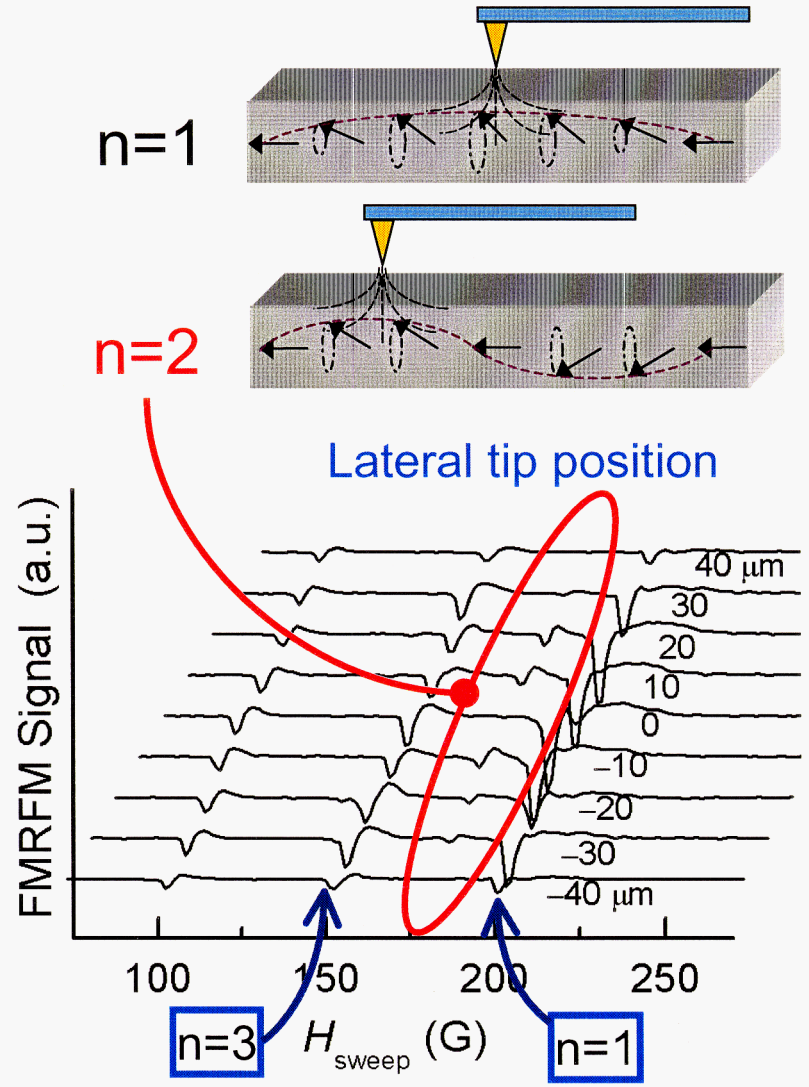
n_y=2 ("hidden")

n_y=3



FMR Imaging: Lateral Scanning I

- *Lateral scan: local **detection** of magnetization associated with various magnetostatic modes*
- *Suppression of all modes toward edge of sample*
- *Non-monotonic dependence of n=3 mode*
- *Hidden n=2 mode revealed by probe tip*
  - *Probe breaks symmetry allowing coupling to uniform rf field*
  - *Non-monotonic variation with position*



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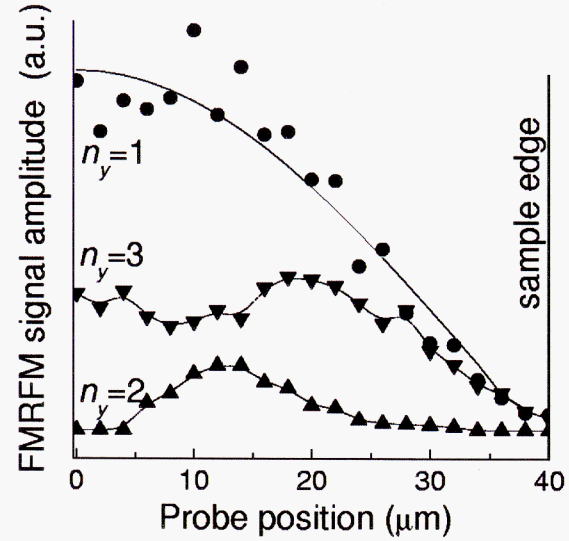
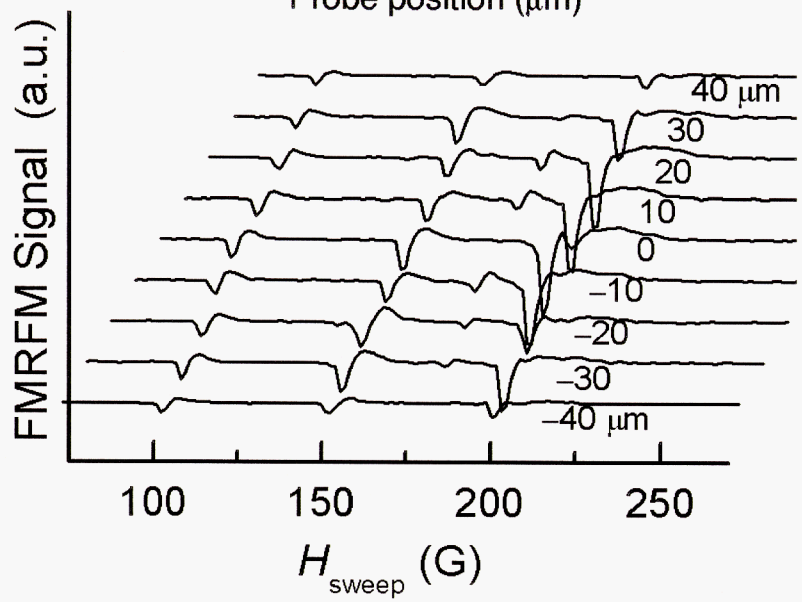
FMR Imaging: Lateral Scanning II

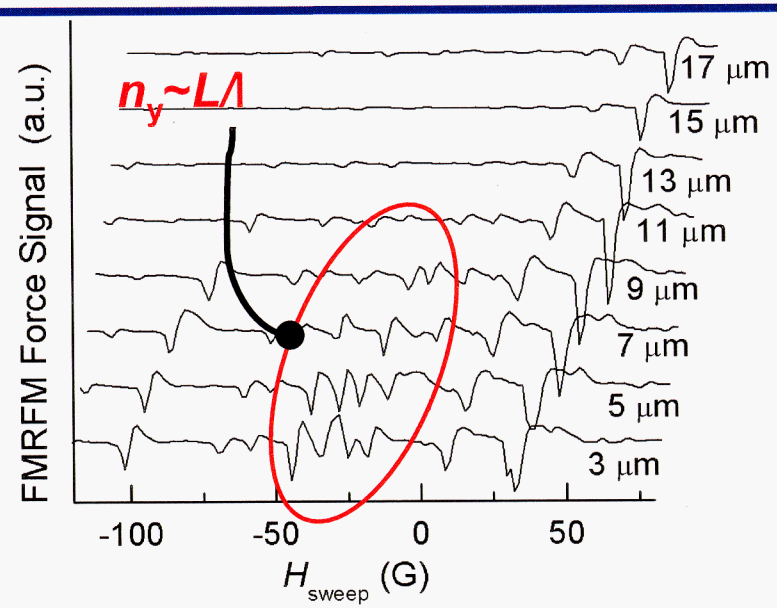
- *Lateral scan: local **detection** of magnetization associated with various magnetostatic modes*
- *Suppression of all modes toward edge of sample*
- *Non-monotonic dependence of n=3 mode*
- *Hidden n=2 mode revealed by probe tip*
  - *Probe breaks symmetry allowing coupling to uniform rf field*
  - *Non-monotonic variation with position*

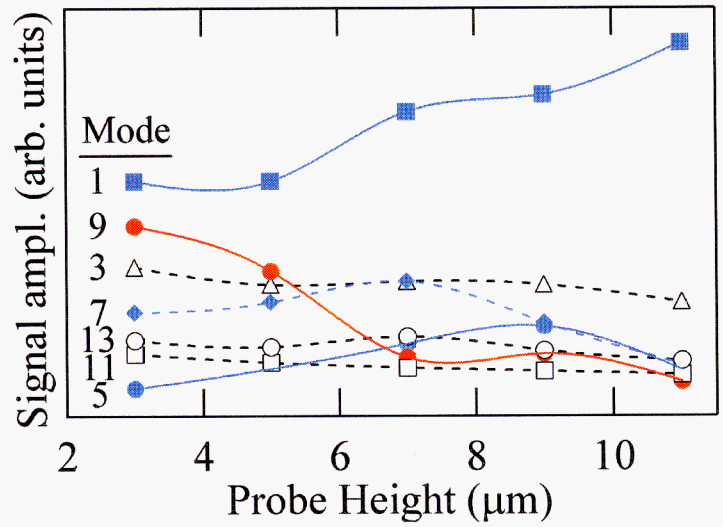




Vertical Scanning: Perturbation by Probe Field

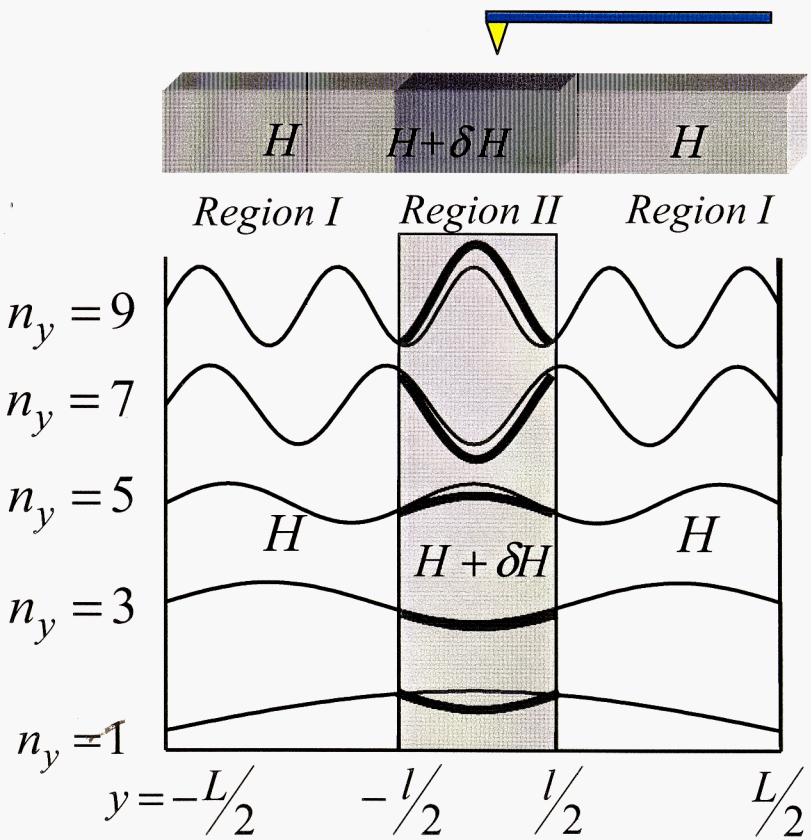
- ***Non-local*** *dependence of mode energy on applied field complicates imaging*
- *Vertical Scan of probe (over center of bar) illuminates effect of magnetic field from probe*
- *At closest approach, field of probe is ~ 20 Gauss*
- **Modes having $n_y \sim L/\ell$ are enhanced**
  - *ℓ size of region perturbed by probe field (~20 μm)*
  - *L: length of bar (160 μm)*
- *Model: Probe field modifies wavevector locally*



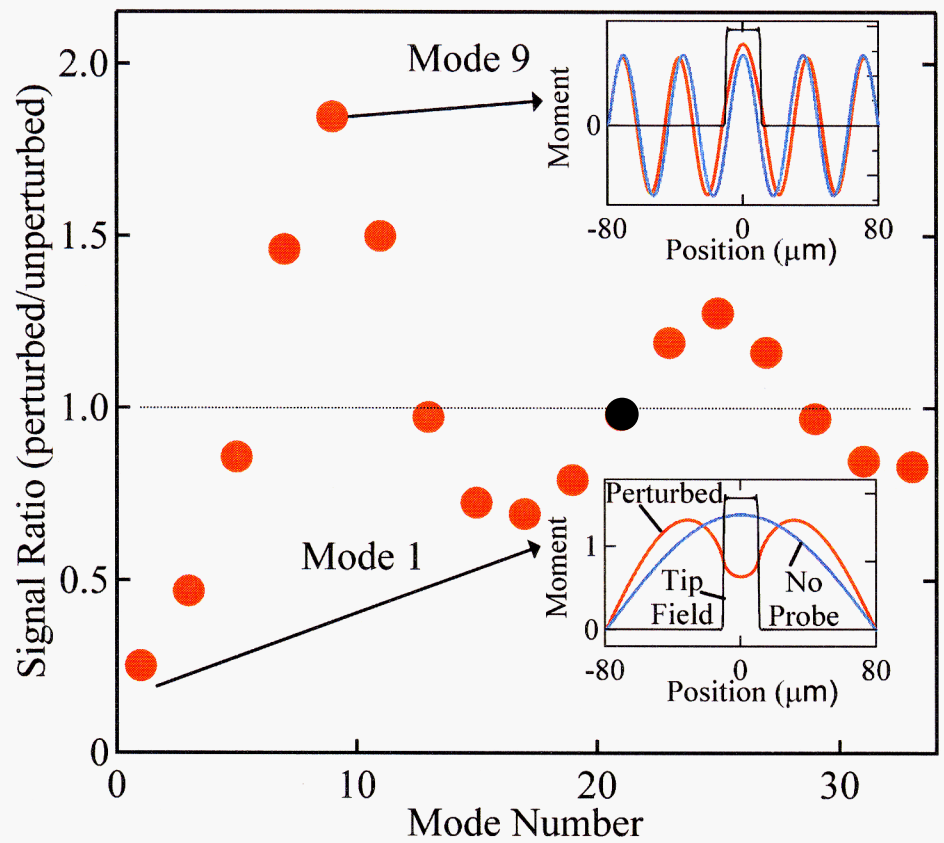


"Square wave" model

Probe magnet introduces
δH = 50 G over 20 μm region



YIG sample 20 μm x 80 μm



Model reproduces mode enhancement

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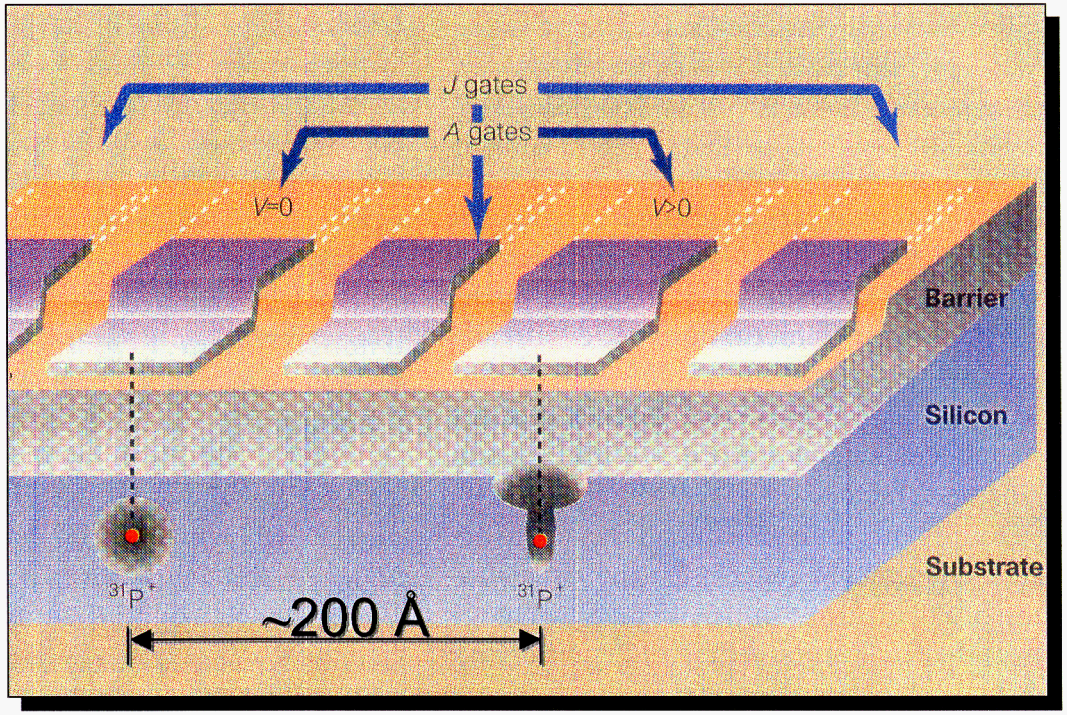
Conclusions

- *Demonstrated, **for the first time**, true spatially resolved scanning probe detection of FMR*
- *Studied influence of the local field perturbation introduced by the probe magnet on detected FMR signals*
- *Introduced a "square well" model that explains observed local perturbation effects and indicates clear route to improved spatial resolution in strong-probe field regime*
- *This work demonstrates the power of the MRFM as a tool for the study of magnetic systems*

Solid State Quantum Computer (SSQC)



"A silicon-based nuclear spin quantum computer"

B. E. Kane, *Nature* ***393***, *133* (1998).

qubits: individual ^{31}P nuclear moments

qubit initialization: via NMR and Stark shifted hyperfine interaction (via "A-gate" voltage)

2 qubit logic: control electron exchange interaction via electric field from "J-gates"

MRFM for quantum computing:

- *Direct magnetic resonance readout*
- *Characterization of SSQC during fabrication*

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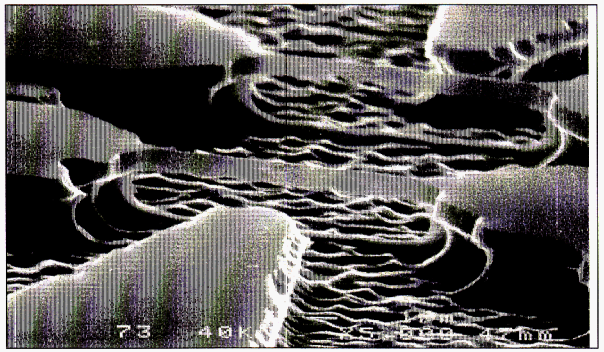
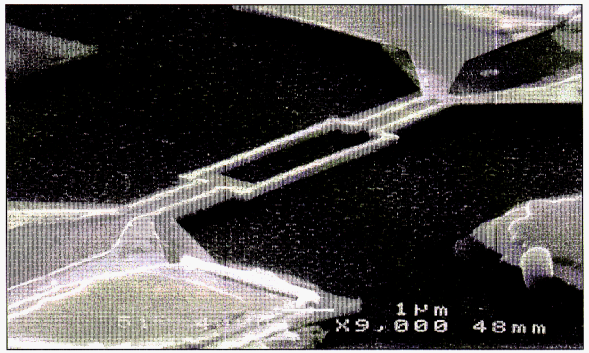
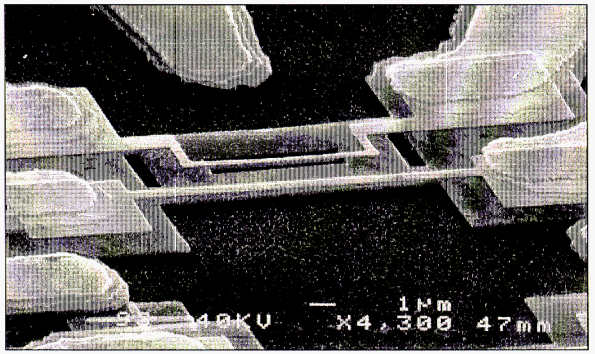
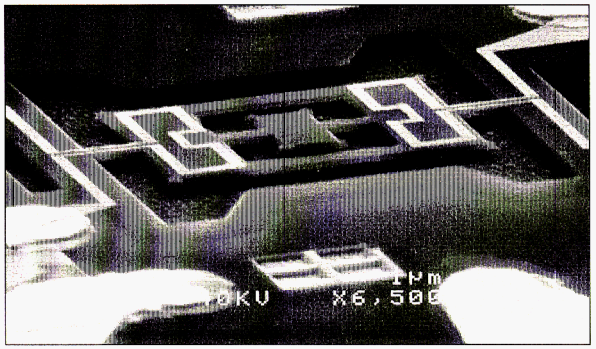
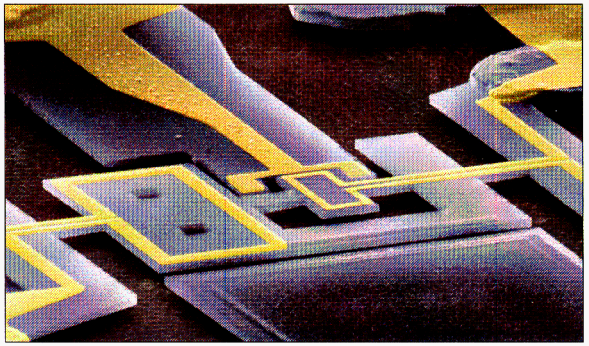
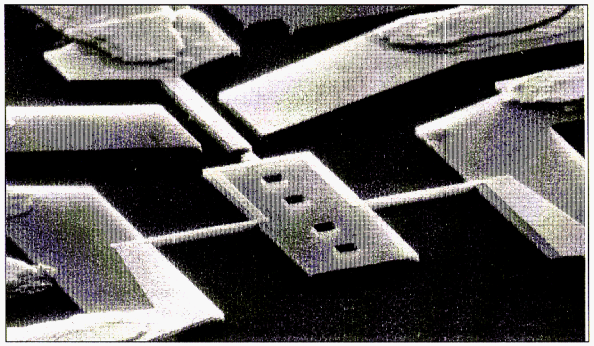
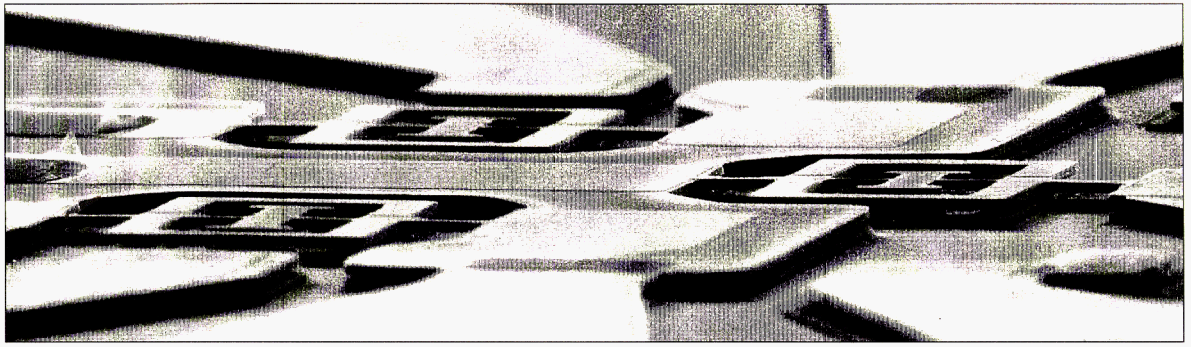
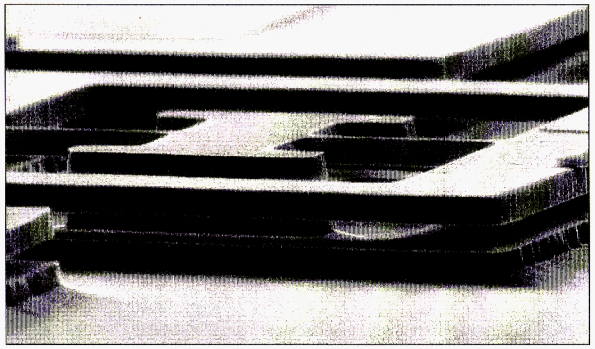
Nano Electro Mechanical Devices (Caltech '94-'99)



M.L. Roukes, A.N. Cleland, D.A. Harrington, E.A. Henriksen, M.J. Murphy, and L.M. Schiavone.

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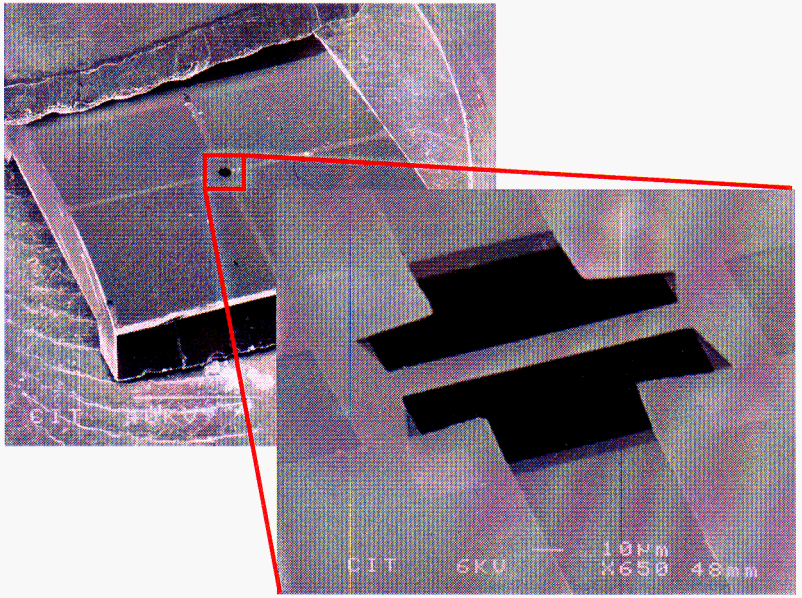
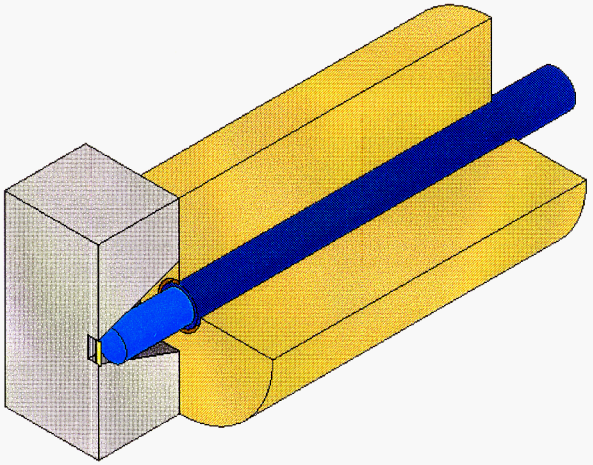
Implementation of High Frequency Resonators

- *High frequency at low spring constant requires minimizing mass: small lateral dimensions*
- *Cantilevers with a free end are not feasible at such dimensions*
- *Need access to both sides of resonator for displacement readout → suspended membrane*
- *Resonators etched from suspended membranes*
- *High accuracy registration of optical fiber to beam is required*





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