Imaging Magnetization Dynamics

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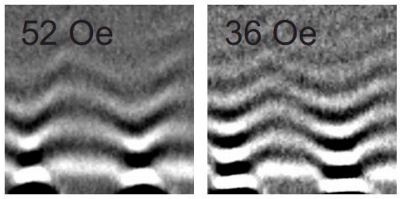
- Introduction to magnetization dynamics
- Examples:
  - Single modes excited by microwaves
  - Microwave assisted switching
  - Imaging spin wave propagation
- Conclusion



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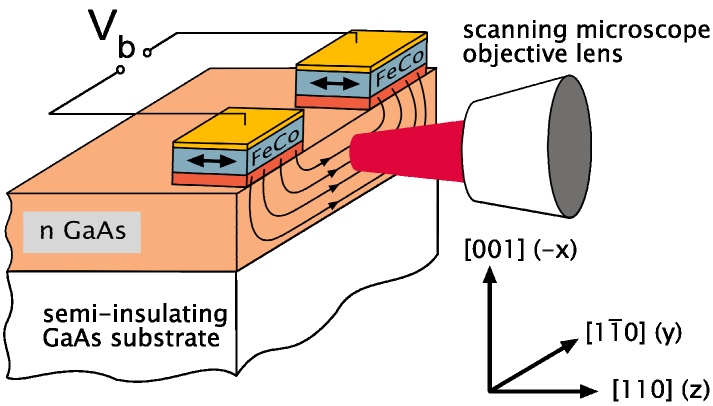
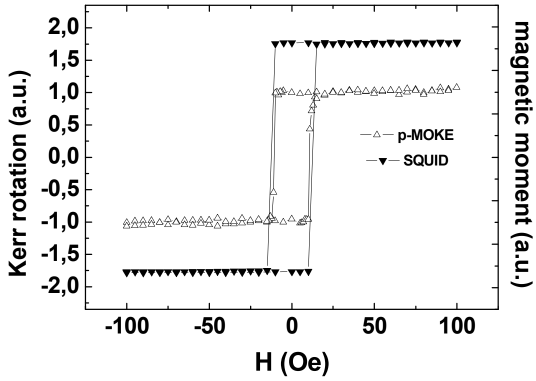
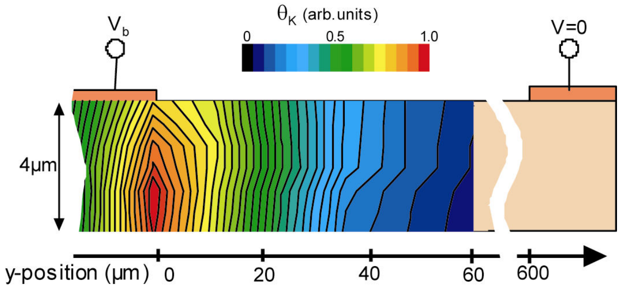
Priority Programme 1133 "Ultra Fast Magnetization Processes„
SFB 689 „Spin Phenomena in Reduced Dimensions“

Spin transport in lateral geometries: spin injection and transport



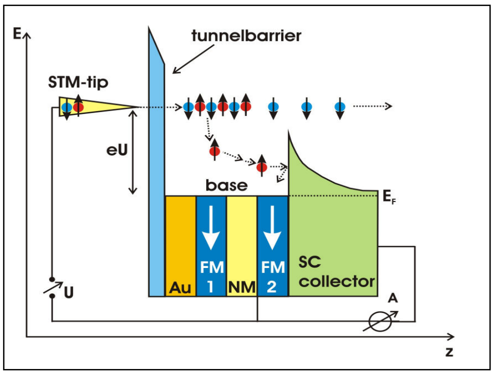


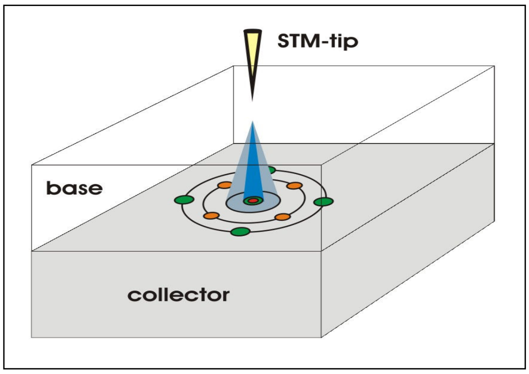


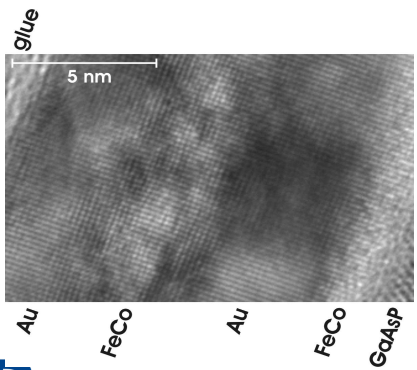
Nature Physics **3**, 872 (2007)

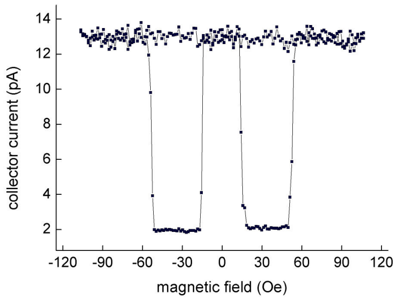
Spintransport in reduced dimensions SFB 689

Spin transport in perpendicular geometries: spin injection and scattering









Phys. Rev. B **75**, 073307 (2007)

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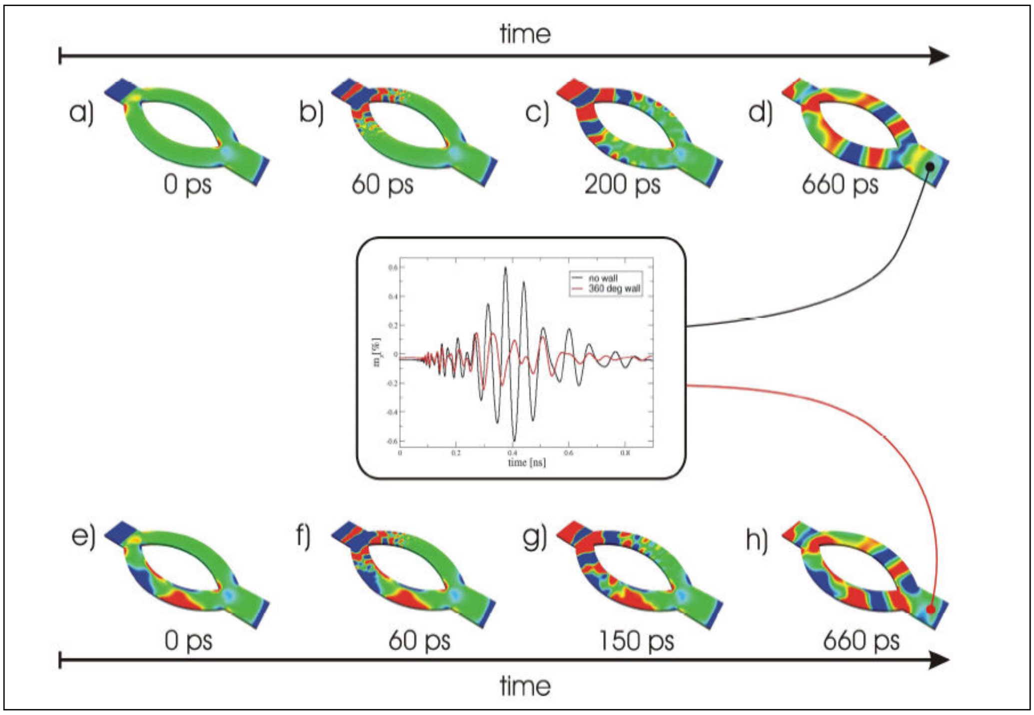
In these cases charge is needed to transport spin information !

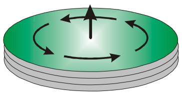
Can we use spin waves to transport information, create switches, phase shifters ...

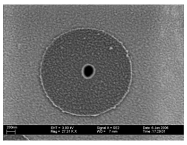


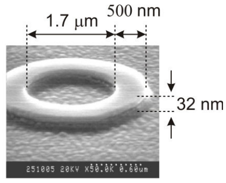
R. Hertel et al. Phys. Rev. Lett. **93**, 257202 (2005)

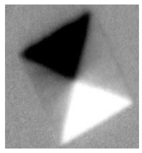
What do we need to know ?

Mode structure of simple ferromagnetic elements in the single domain and multidomain state

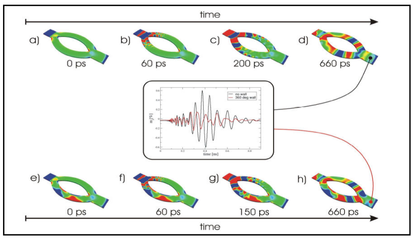




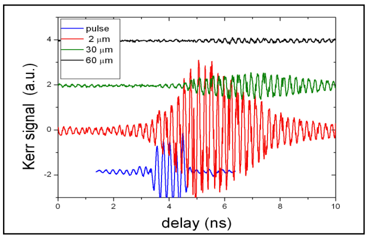




Properties of propagating (magnetostatic) spin waves

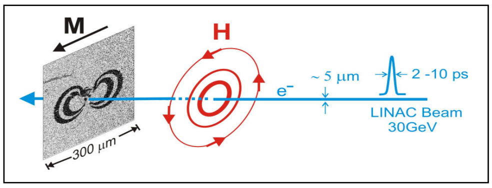


Phys. Rev. Lett. **93**, 257202 (2005)

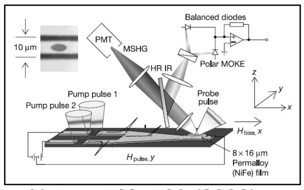


Phys. Rev. B **77**, 054425 (2008)

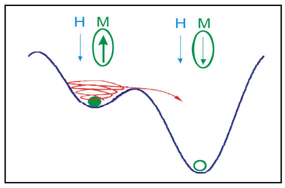
Strategies for switching on ps timescales



Science, **285** 864 (1999)



Nature **418**, 509 (2002)



Phys. Rev. Lett. **99**, 227207 (2007)

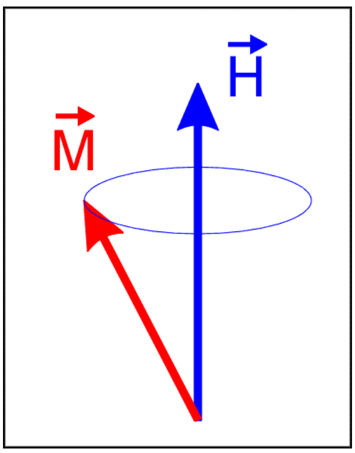
Landau-Lifshitz Equation:

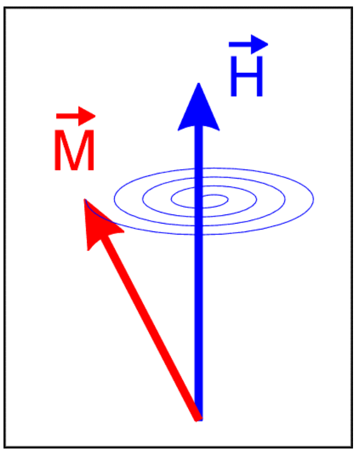
$$\frac{d\vec{M}}{dt} = \underbrace{-\gamma_0(\vec{M}\times\vec{H}_{eff})}_{} \underbrace{-\alpha\frac{\gamma_0}{M}\left[\vec{M}\times(\vec{M}\times\vec{H}_{eff})\right]}_{}$$

$$\vec{H}_{eff} = -\frac{\partial E}{\partial \vec{M}}$$

γ_0: gyromagnetic ratio

sets the time scale





The energy landscape:

Zeeman-Energy E_z

$$E_z = -J_s \int \vec{H}_{ext}(\vec{r}) \cdot \vec{m}(\vec{r})\, dV$$

Exchange-Energy E_{ex}

$$E_{ex} = A \int (grad\ \vec{m}(\vec{r}))^2\, dV$$

Anisotropy-Energy E_{an}

$$E_{an} = \int \varepsilon_{an}(\vec{m})\, dV$$

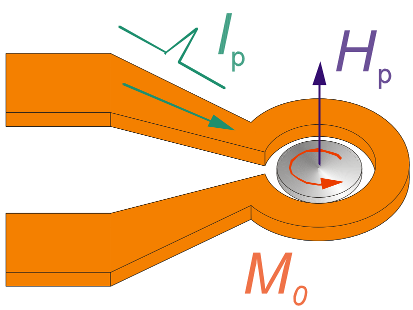
Stray field-Energy E_d

$$E_d = -\frac{1}{2} \int \vec{H}_d(\vec{r}) \cdot \vec{J}(\vec{r})\, dV$$

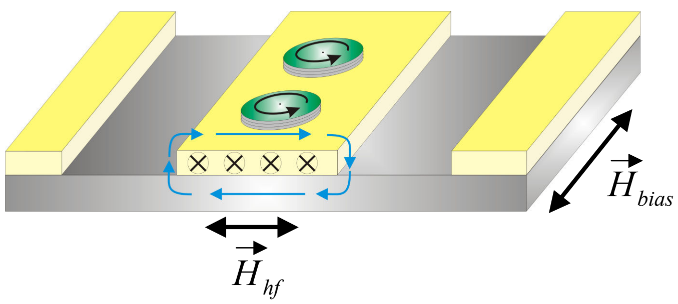
Pulsed Precessional Motion: small angle excitation of the magnetization

(via a magnetic field pulse)

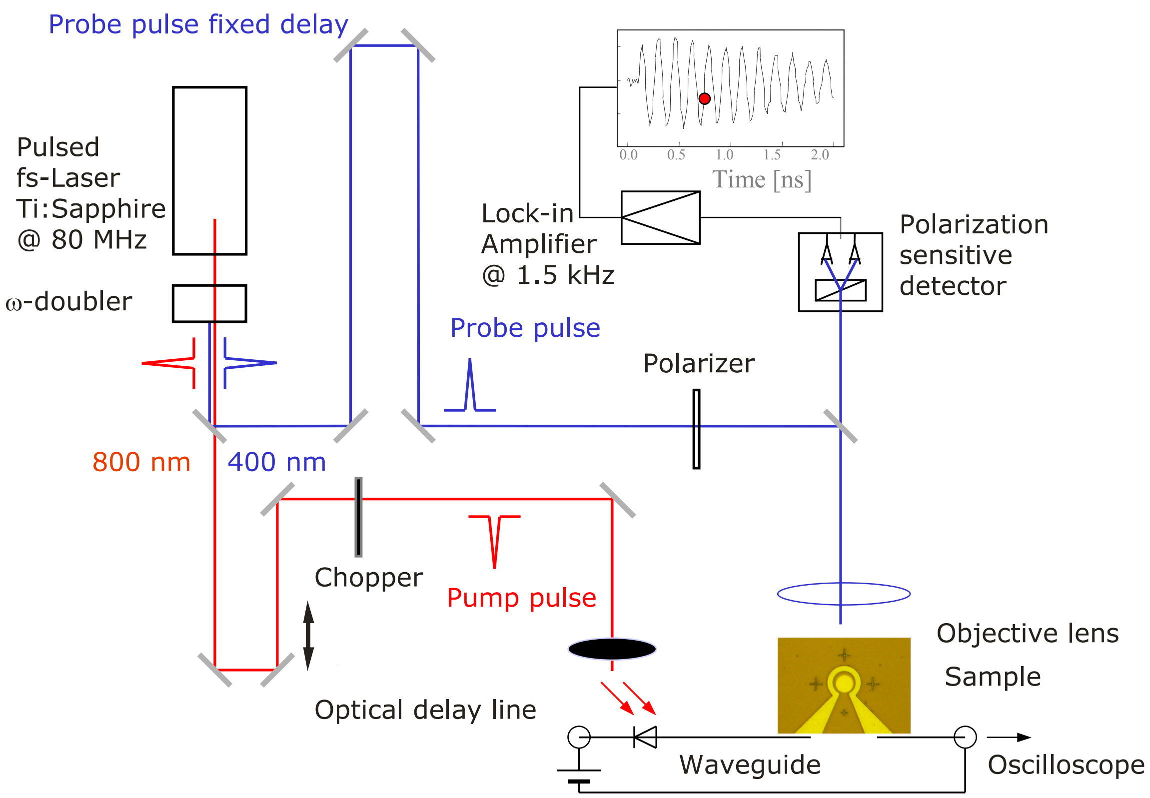
(a) Perpendicular field pulse



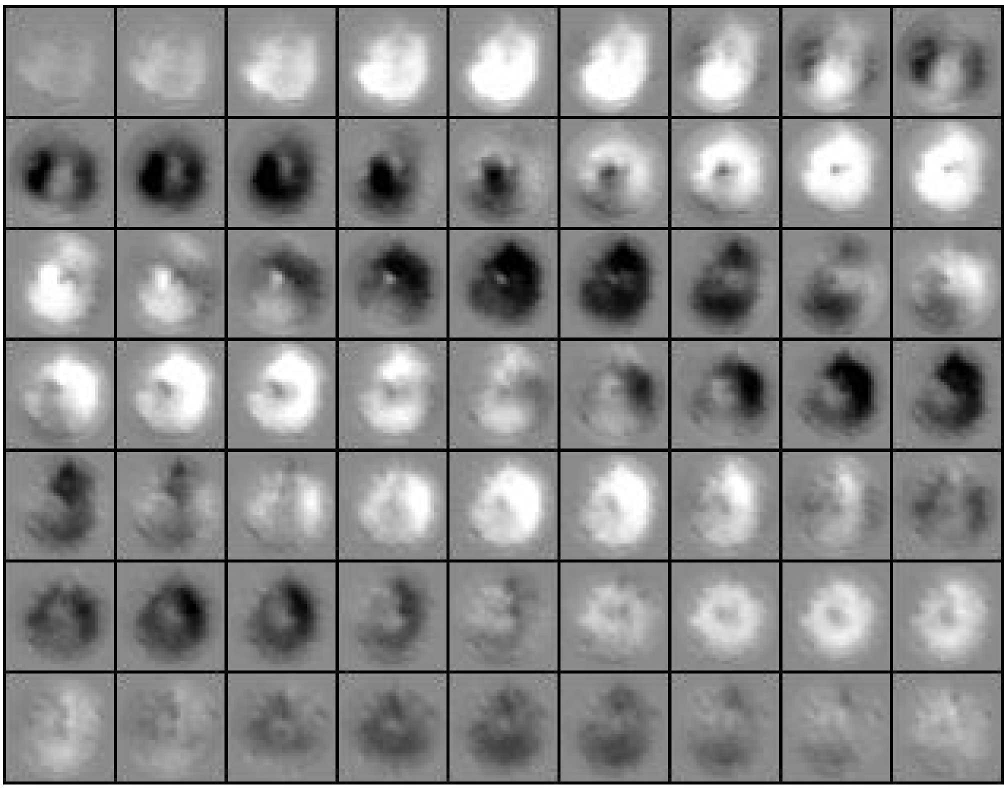
(b) Excitation in the plane



Time resolved (< 1ps) scanning (~ 300nm) Kerr microscopy

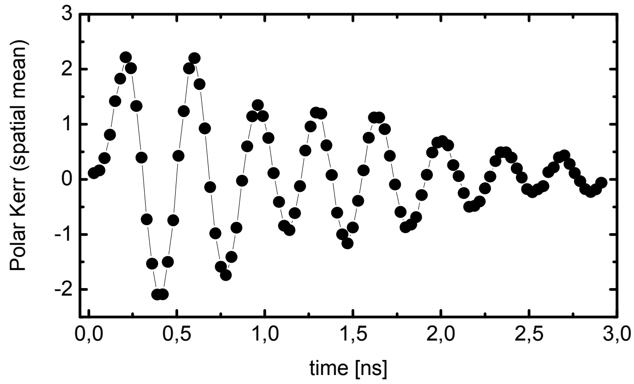


Time domain movie: polar MOKE



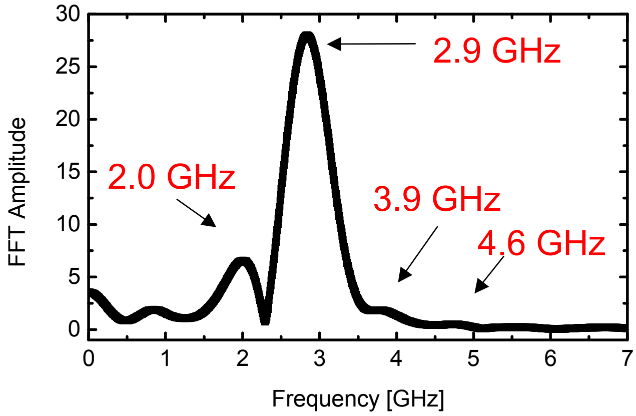
6 micron Permalloy disk, d = 15 nm, perpendicular field pulse, 30 ps frame rate

Polar Kerr data averaged over the whole movie



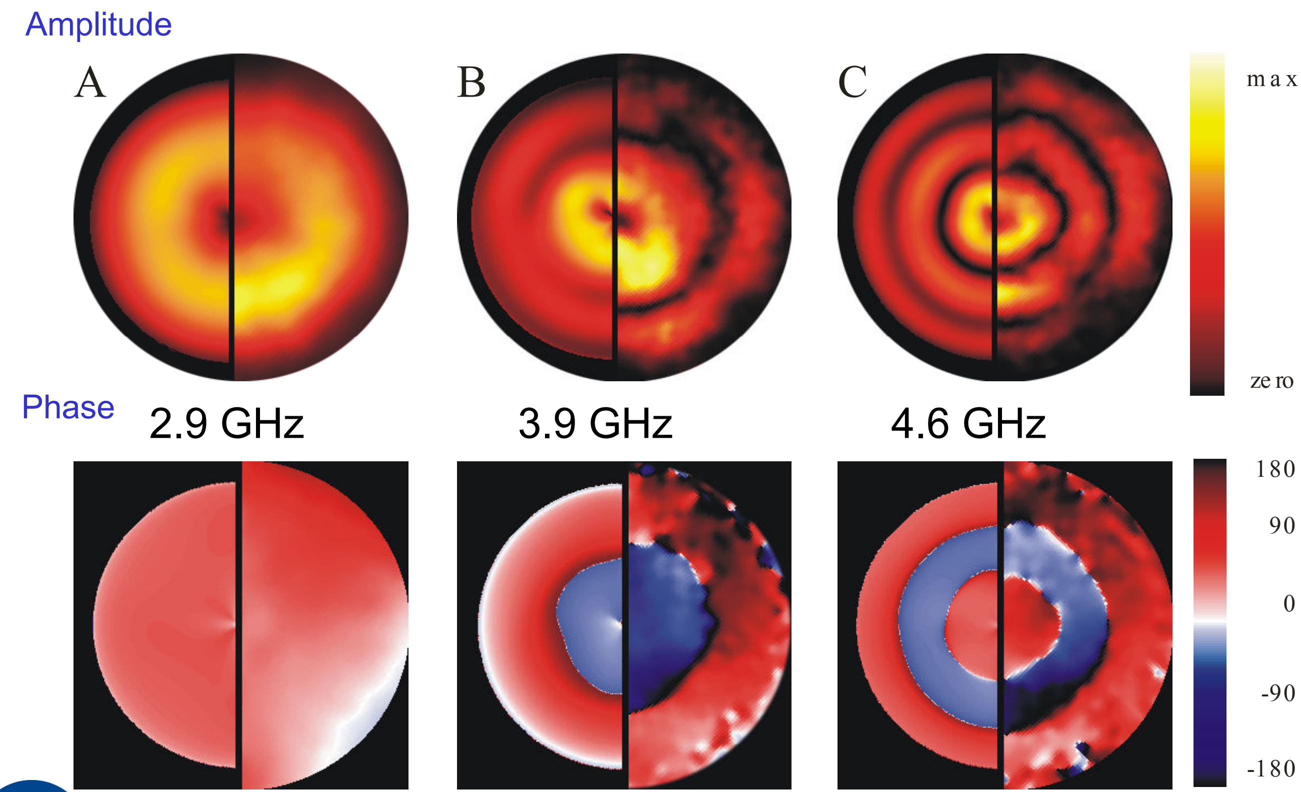
Time domain

NiFe disks:
6µm diameter
d = 15 nm, $\mu_0 M_s$ = 1 T

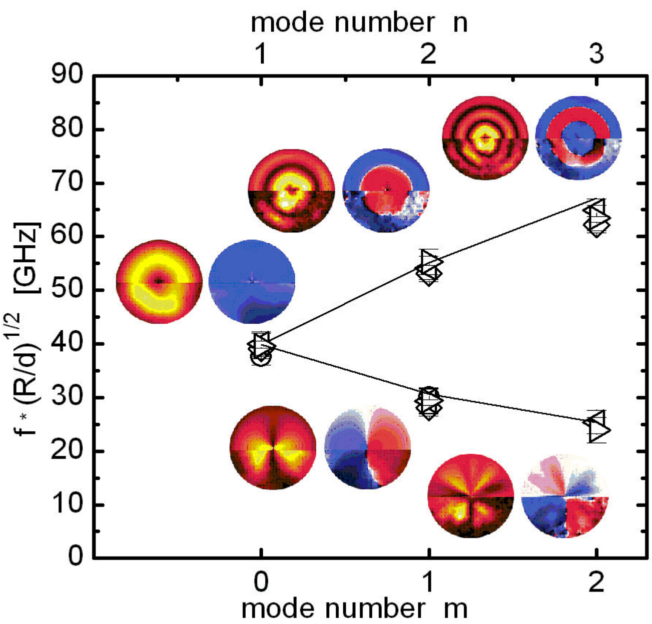


Frequency domain
Global FFT

Extraction of the axial modes from the FFT movie



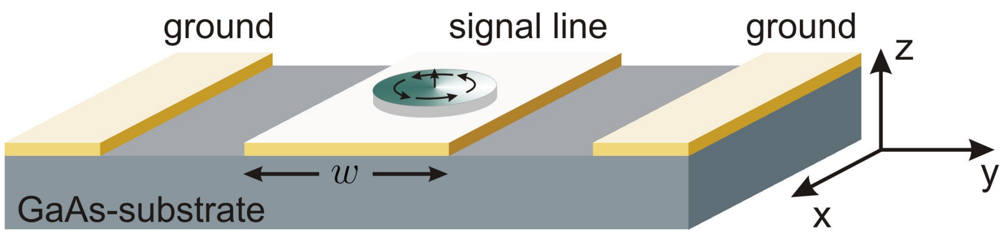
Summary of the normal modes of micron sized disks



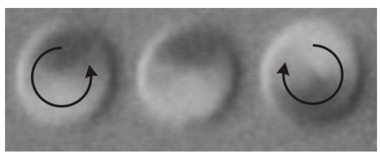
Y. Acremann et al., Science **290**, 492 (2000)
M. Buess et al., Phys. Rev. Lett. **93**, 077207 (2004)
M. Buess et al., Phys. Rev. B **71**, 104415 (2005)
M. Buess et al., Phys. Rev. Lett. **94**, 127205 (2005)
I. Neudecker et al., Phys. Rev. B **73**, 134426 (2006)
F. Hoffmann et al., Phys. Rev. B **76**, 014416 (2007)

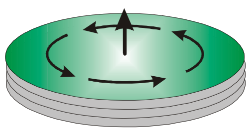
mode spectrum of a thin film platelet

rf-excitation via a coplanar waveguide



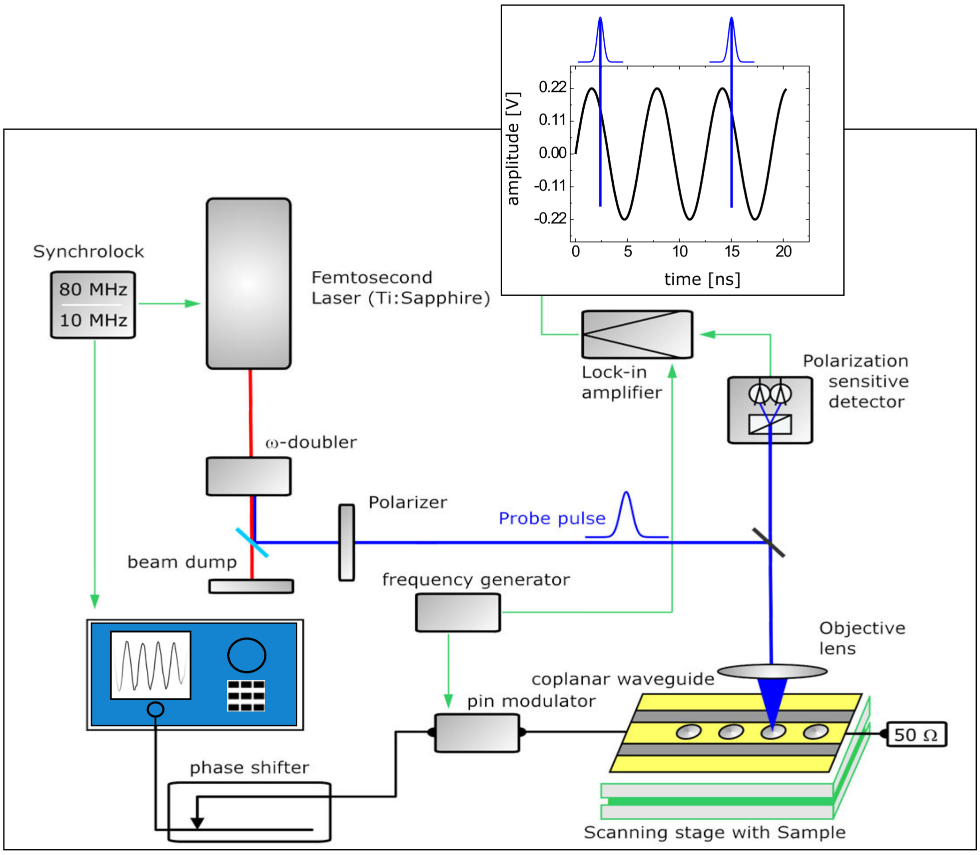
NiFe disks:
15 nm thickness
$\mu_0 M_s = 1$ T
size: 4 μm
in-plane excitation



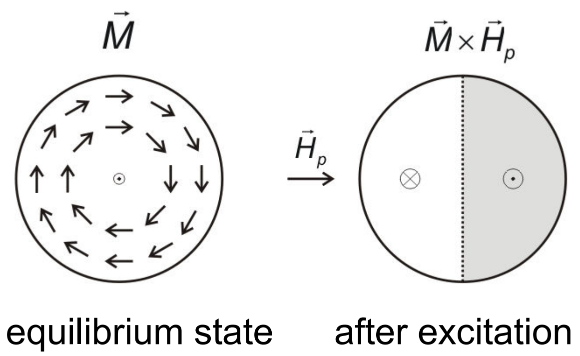


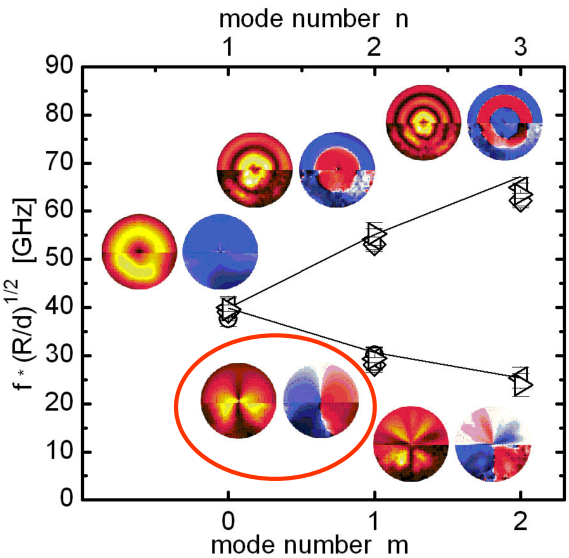
the disks are in a vortex state (flux closure)

experimental setup



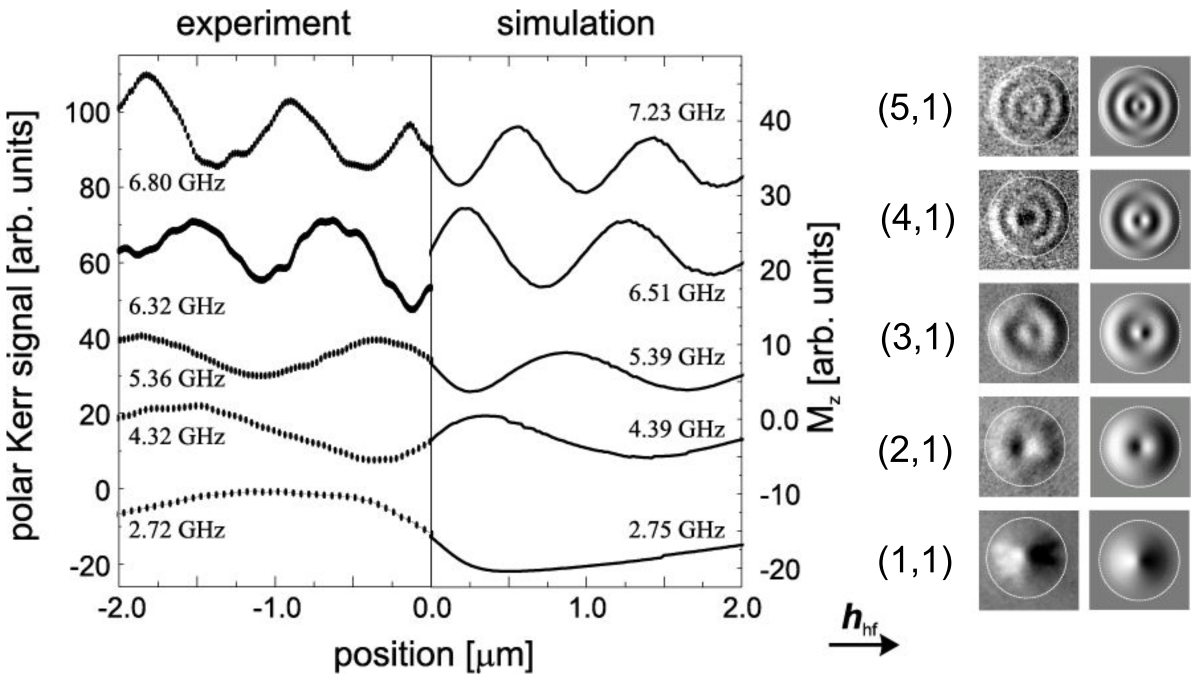
symmetry of the excitation





Y. Acremann et al., Science **290**, 492 (2000)
M. Buess et al., Phys. Rev. Lett. **93**, 077207 (2004)
M. Buess et al., Phys. Rev. B **71**, 104415 (2005)
M. Buess et al., Phys. Rev. Lett. **94**, 127205 (2005)
I. Neudecker et al., Phys. Rev. B **73**, 134426 (2006)
F. Hoffmann et al., Phys. Rev. B **76**, 014416 (2007)

Vortex state: normal modes in zero bias field



The rf-field in the plane breaks the symmetry → all modes show 1 azimuthal nodal line

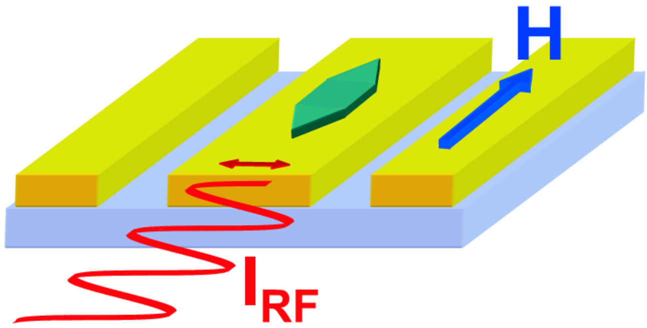
I. Neudecker et al., Phys. Rev. B **73**, 134426 (2006)

Example II: microwave assisted switching

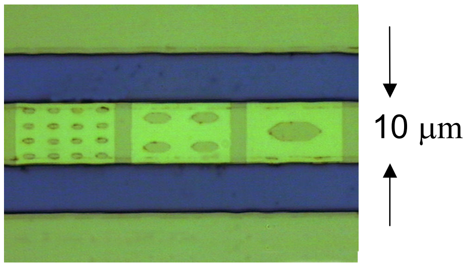
Microwave assisted switching

microwave assisted switching

What happens if you increase the power ?

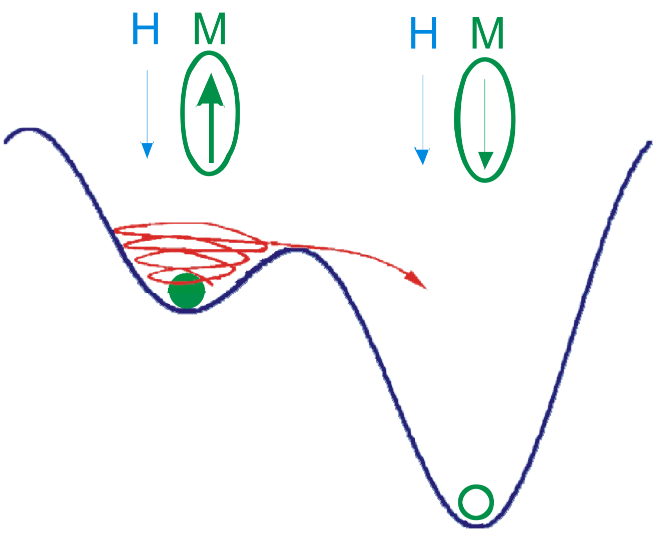


NiFe hexagons:
2 nm thickness
$\mu_0 M_s$ = 0.9 T
size: 0.7 x 1.4 μm^2, 1.5 x 3.0 μm^2
in-plane excitation



the elements are in a single domain state

microwave assisted switching



use ferromagnetic resonance to overcome the energy barrier !

C. Thirion et al. Nature Materials **2**, 524(2003)

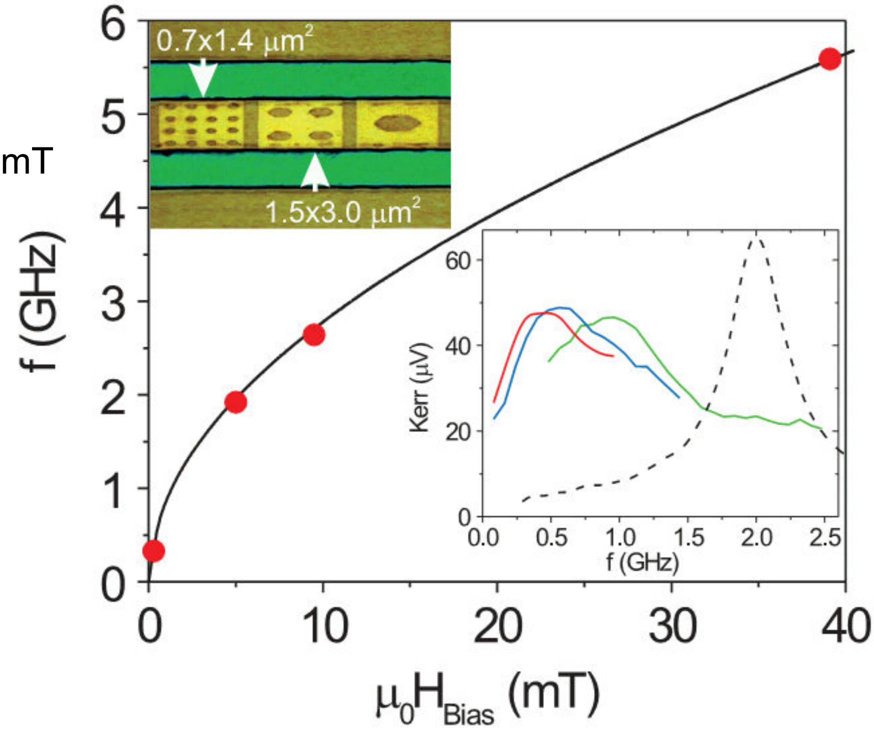
measurement technique / Kittel plot

sweep the frequency at constant field

Inset:

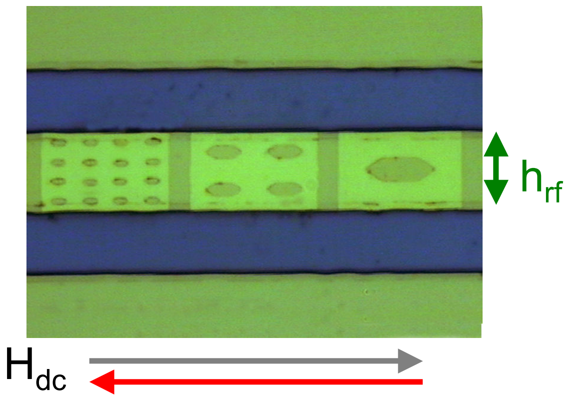
0.7 x 1.4 μm² }
1.5 x 3.0 μm² } @ 0 mT
unpatterned }

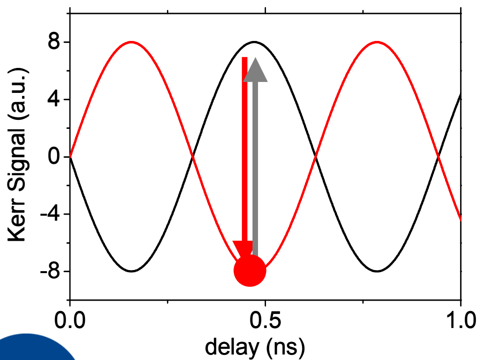
dashed line:
1.5 x 3.0 μm² @ 5 mT



Properties of the NiFe film: $\mu_0 H_A$=0.1 mT, g=2.13, α=0.008, $\mu_0 M_{eff}$=0.92 T

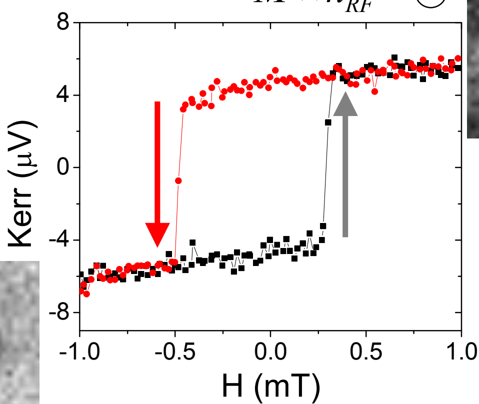
Hysteresis loops of single 1.5 x 3.0 μm² elements @ 2 GHz





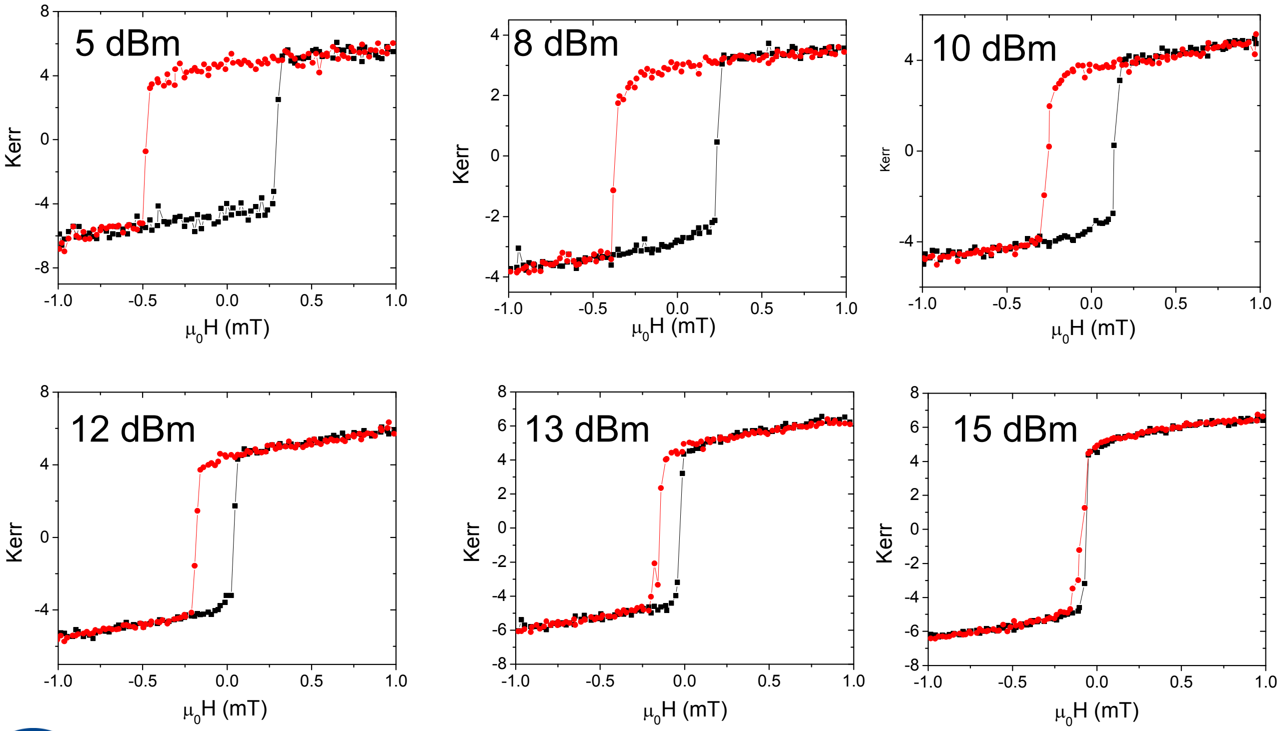
$\vec{M} \times \vec{h}_{RF} = \otimes$

$\vec{M} \times \vec{h}_{RF} = \odot$

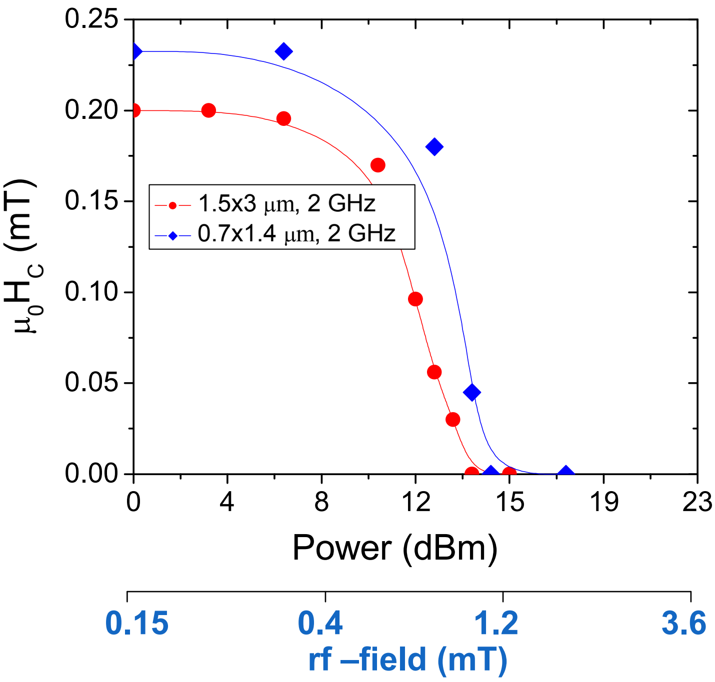


Measurements are performed far away from resonance

H_c versus power @ 2 GHz for 1.5 x 3.0 μm^2 elements

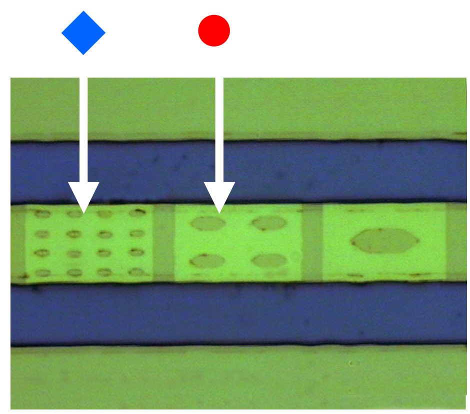


H_c versus power for two element dimensions



excitation at 2 GHz

0.7x1.4 μm^2 1.5x3 μm^2



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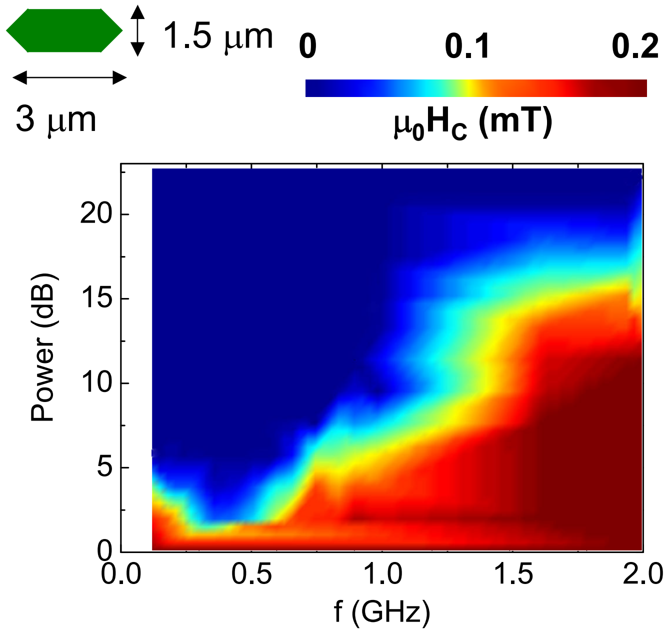
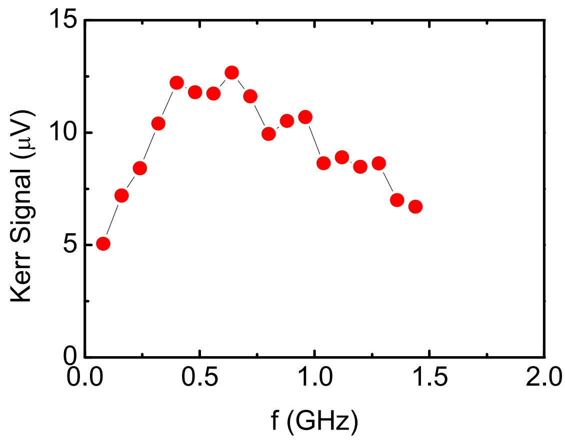
H_c as a function of power and frequency



Frequency scan H_B=0, P=0 dBm



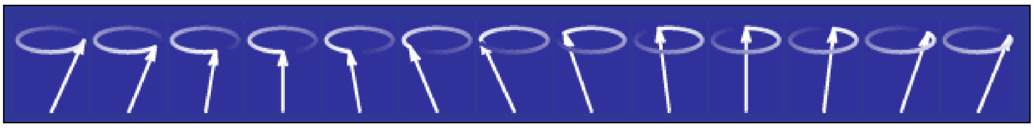
minimum H_c at the resonance frequency of the element!

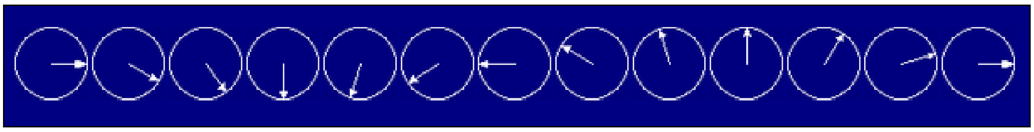
Phys. Rev. Lett. **99**, 227207 (2007)

Spin wave interference

Imaging spin wave propagation

What makes spin waves in thin films special ?



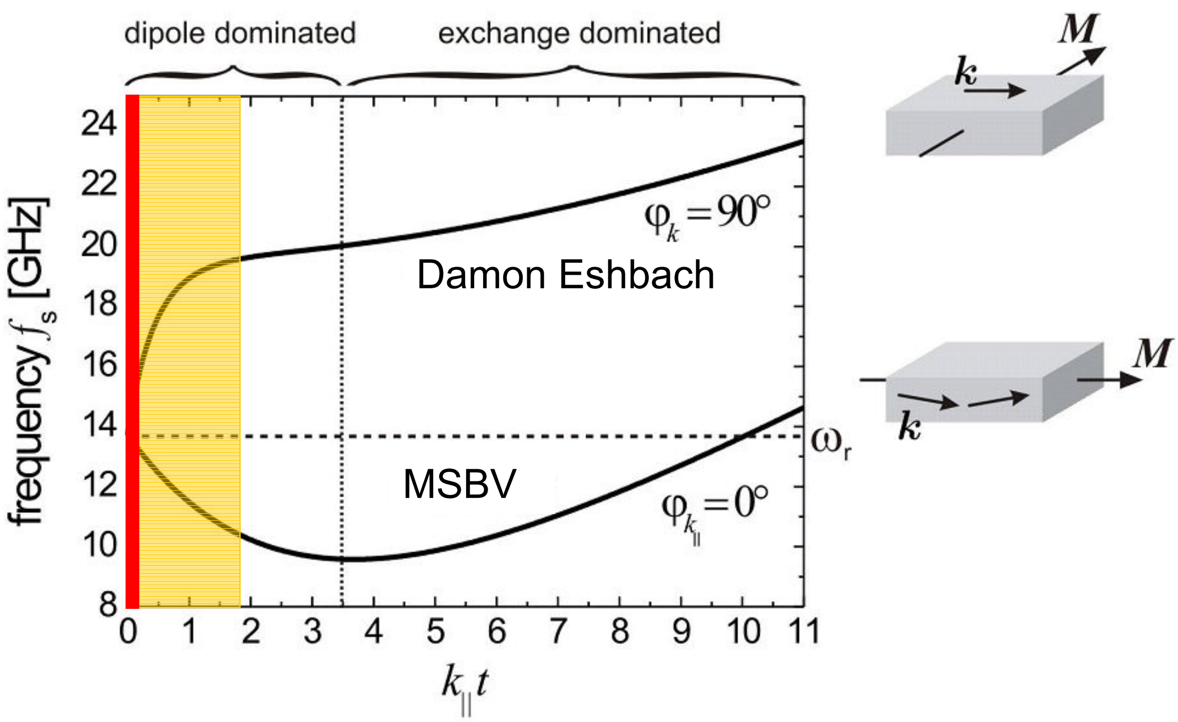


non-uniform Eigenmodes of the magnetic system, described by the LLG equation

Two types of energy contributions

- exchange energy:
  generated by twist of neighbored spins
- dipolar energy:
  generated by magnetic poles in long-wavelength spin waves

spin wave spectrum of a thin film



properties of propagating spin waves

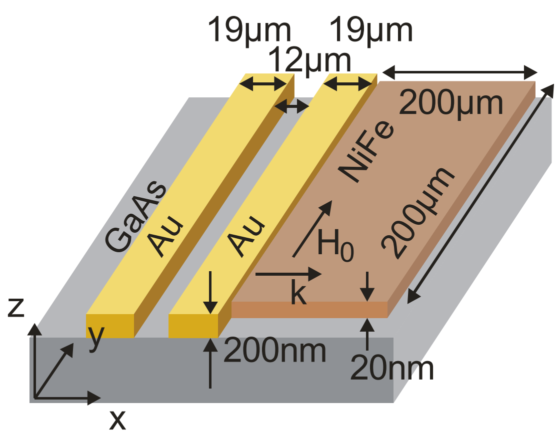
Group velocity $$v_g = \frac{d\omega}{dk}$$

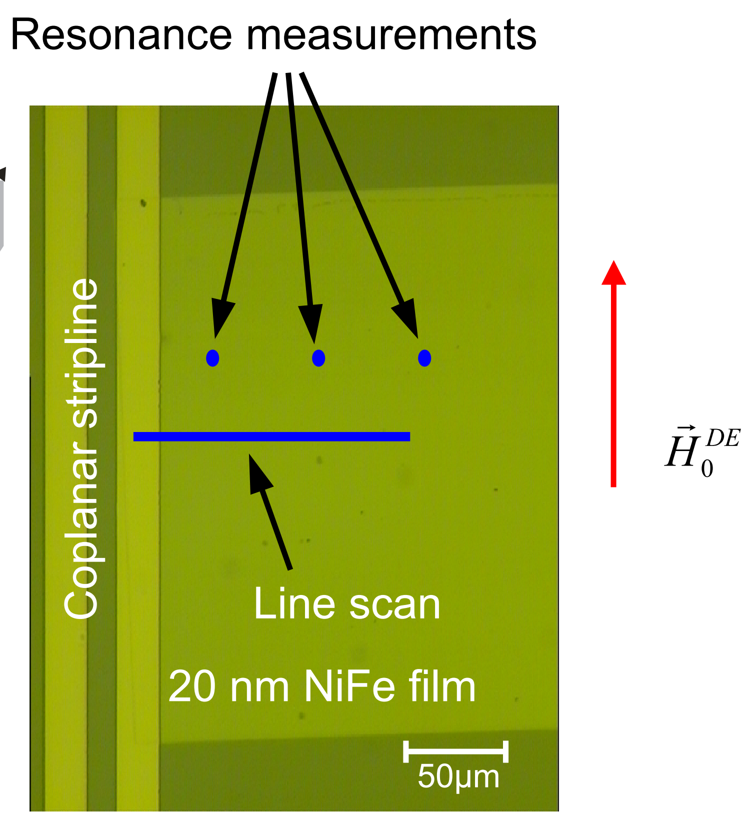
very different for DE and MSBV modes at low k-vectors

Phase velocity $$v_{Ph} = \frac{\omega}{k}$$

similar for DE and MSBV modes at low k-vector

spin wave propagation in a thin film

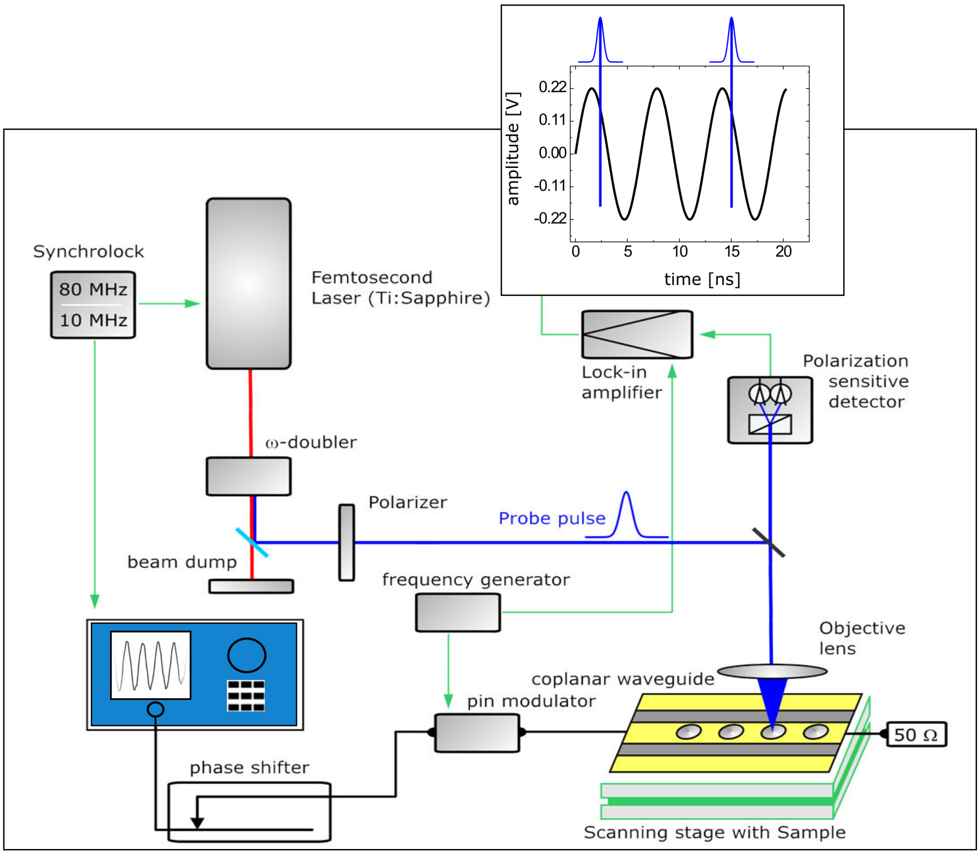




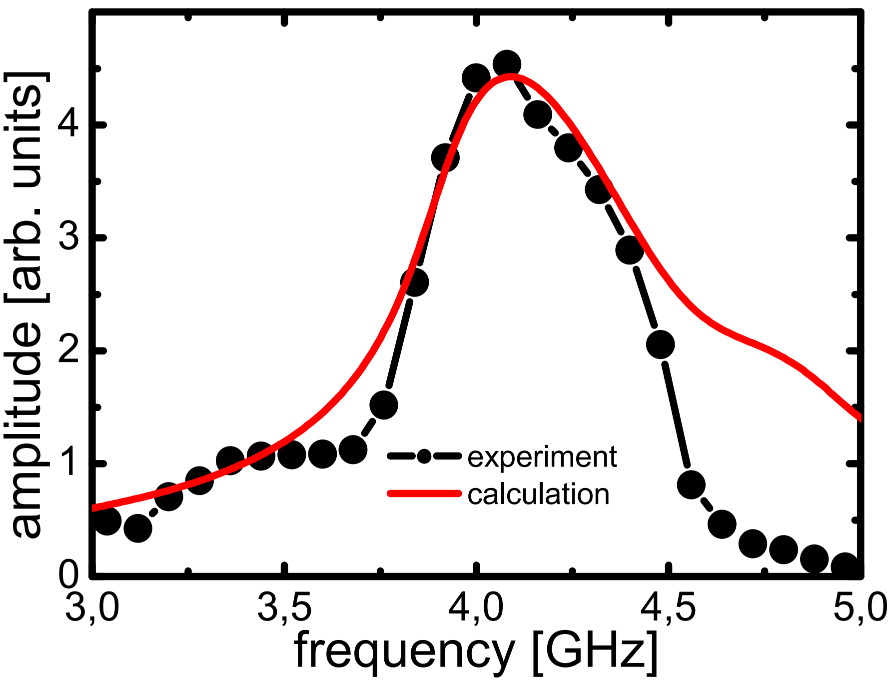
Resonance Scans: Scan in Time

Linescan: Scan in Time and Position

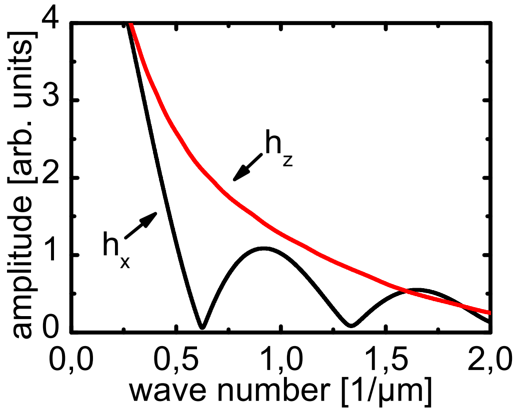
experimental setup



measurement of the excited wave vector



realistic calculation of the magnetic response

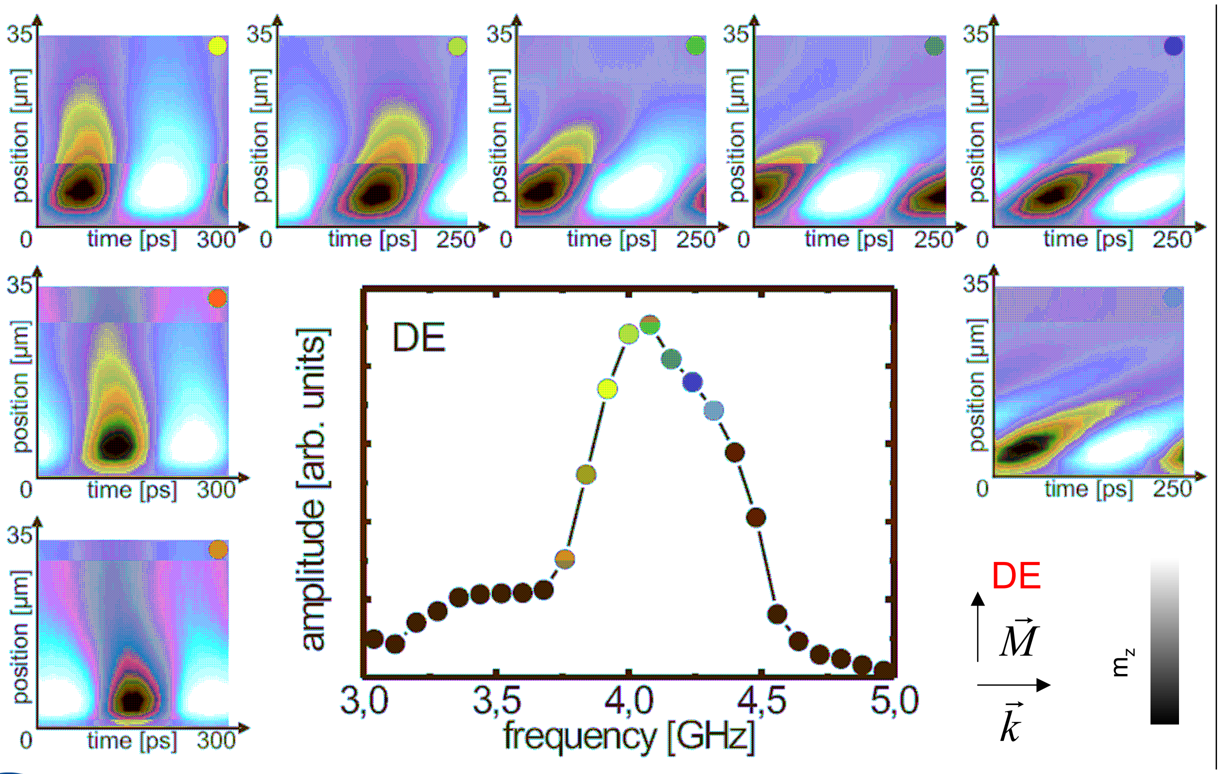


$$m_z^0\left(f_0\right) = \int_k h_j\left(k\right)\chi_{zj}\left(f_0,k\right)$$

$$\chi_{zx}^{\mathrm{DE}} = \frac{-i\frac{\omega}{\mu_0\gamma}M_s}{\left(\frac{2Ak^2}{\mu_0 M_s}+M_s\frac{1-e^{-kd}}{kd}+H_0-i\alpha\frac{\omega}{\mu_0\gamma}\right)\left(\frac{2Ak^2}{\mu_0 M_s}+M_s\frac{kd-1+e^{-kd}}{kd}+H_0-i\alpha\frac{\omega}{\mu_0\gamma}\right)-\frac{\omega^2}{(\mu_0\gamma)^2}}e^{-i\left(kx-\frac{\pi}{2}\right)}$$

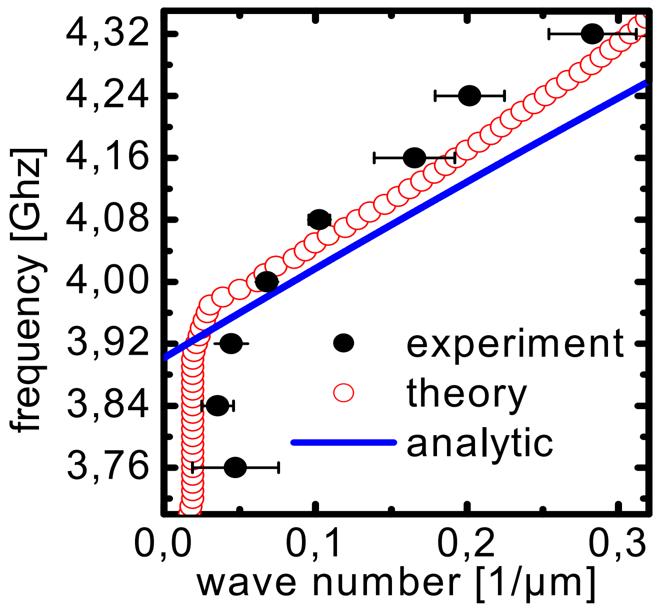
$$\chi_{zz}^{\mathrm{MSBV}} = \frac{M_s\left(\frac{2Ak^2}{\mu_0 M_s}+H_0-i\alpha\frac{\omega}{\mu_0\gamma}\right)}{\left(\frac{2Ak^2}{\mu_0 M_s}+M_s\frac{1-e^{-kd}}{kd}+H_0-i\alpha\frac{\omega}{\mu_0\gamma}\right)\left(\frac{2Ak^2}{\mu_0 M_s}+H_0-i\alpha\frac{\omega}{\mu_0\gamma}\right)-\frac{\omega^2}{(\mu_0\gamma)^2}}e^{-i\left(kx+\frac{\pi}{2}\right)},$$

line scans



phase velocity and dispersion relation

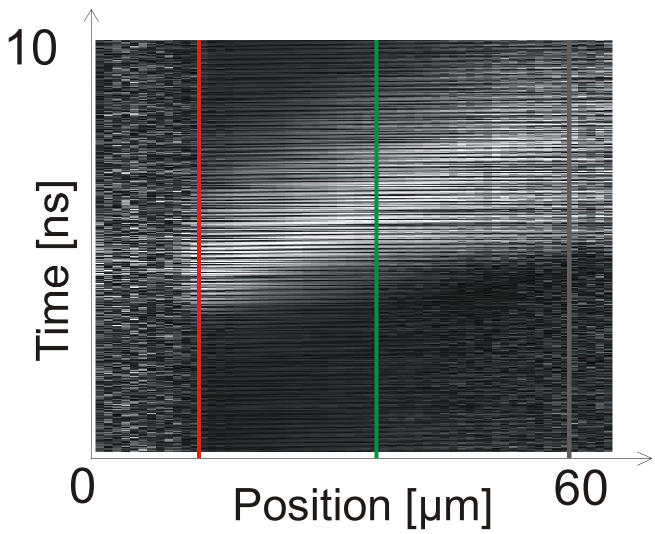
DE geometry, H = 190 Oe

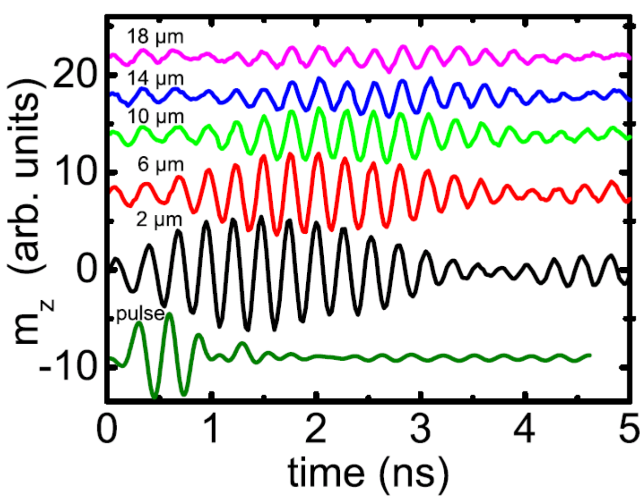


- phase velocity obtained from line scan data
- wave vectors calculated from phase velocities
- dispersion relation is reproduced by the calculation

$$k = \frac{2\pi f}{v_{\mathrm{Ph}}}$$

pulsed excitation (microwave pulses)





- group velocity as large as 10 micron/ns:
- highest values for DE geometry
- close to zero for BWVM geometry

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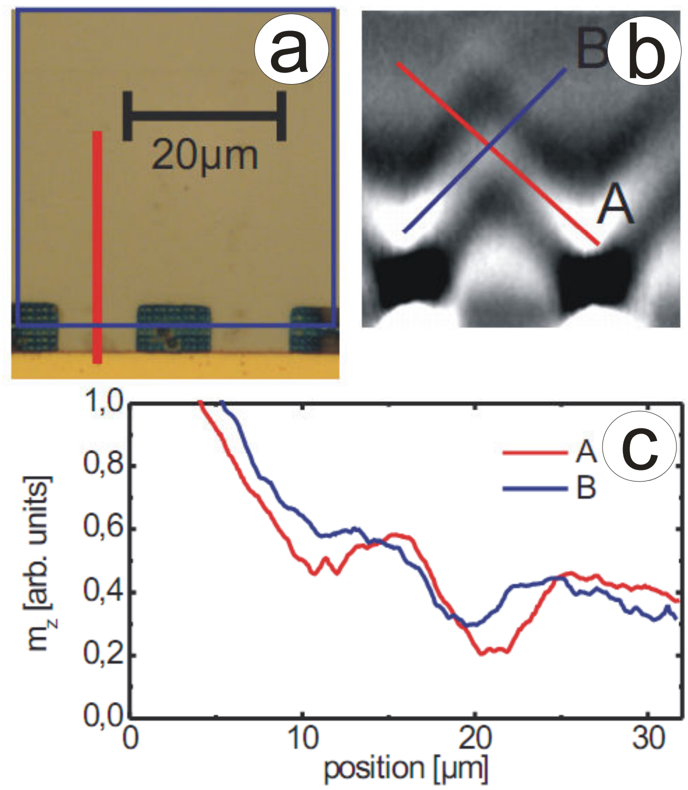
interference experiment



Conclusions

- TR-MOKE allows easy classification of normal modes in confined magnetic structures
- Microwave assisted switching demonstrated

- By observing propagation of spin waves and spin wave packets, phase and group velocities can be „imaged“
- Spin wave interference demonstrated