Ferromagnetic resonance of localized nonuniform states in magnetic nanostructures

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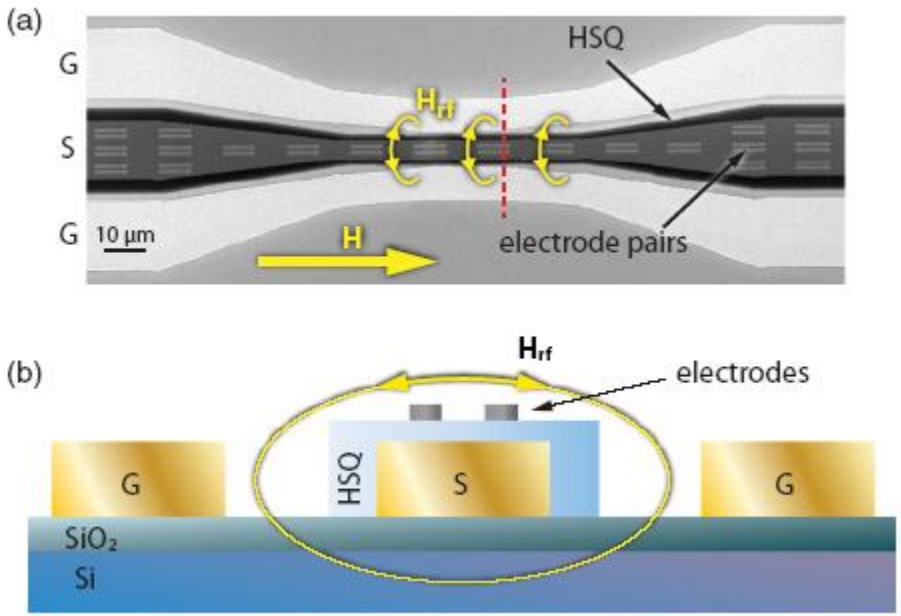
Plan

1. Motivation
2. Micromagnetic modeling of FMR
3. Domain walls in nanowires
4. Spatially modified CoPt films
5. Conclusion

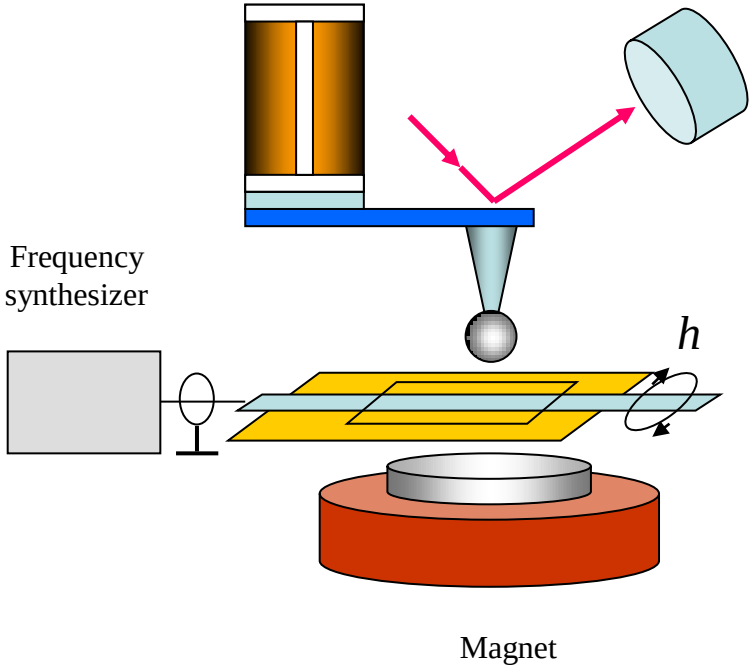
Motivation

Microwave nanoelectronics
based on coplanar microwaveguides



N.Kuhlmann et al., PRB, **85**, 014410, (2012)

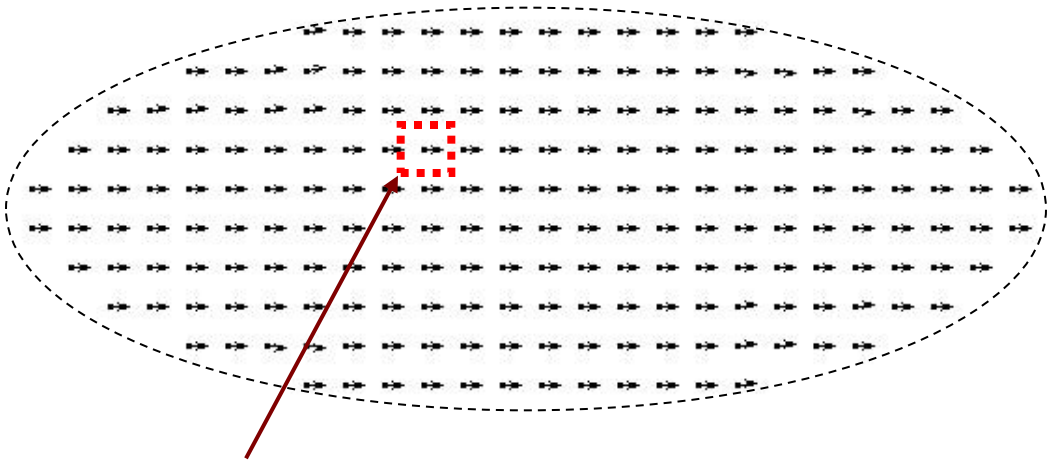
Magnetic resonance
force microscopy



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

Micromagnetic modeling

Modeling of magnetic dynamics



$$\frac{d\vec{m}^j}{dt} = -\gamma\,[\vec{m}^j \times \vec{H}^j_{eff}] - \frac{\lambda}{\left|\vec{m}^j\right|^2}[\vec{m}^j \times [\vec{m}^j \times \vec{H}^j_{eff}]]$$

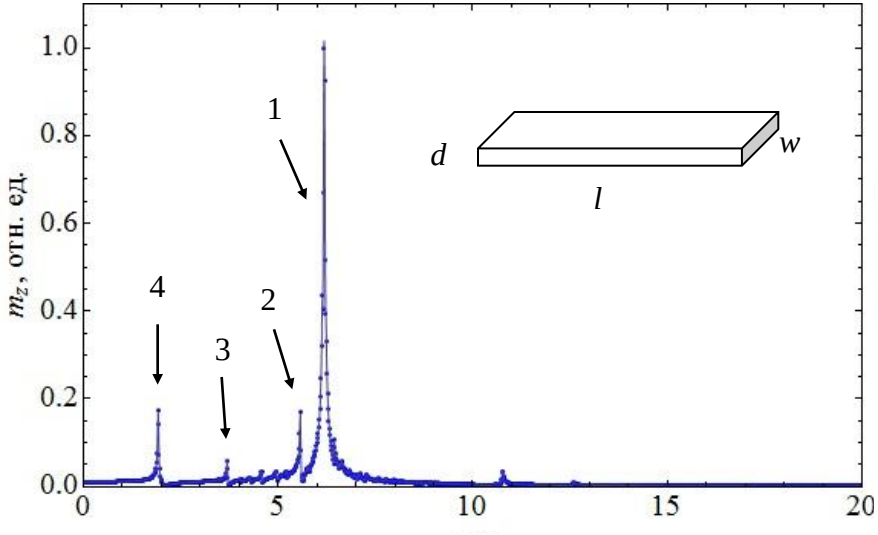
$$\vec{H}_{eff} = -\delta E / \delta \vec{M}$$

$$H_{ex} = H_0 + h_0 \exp(i\omega t)$$

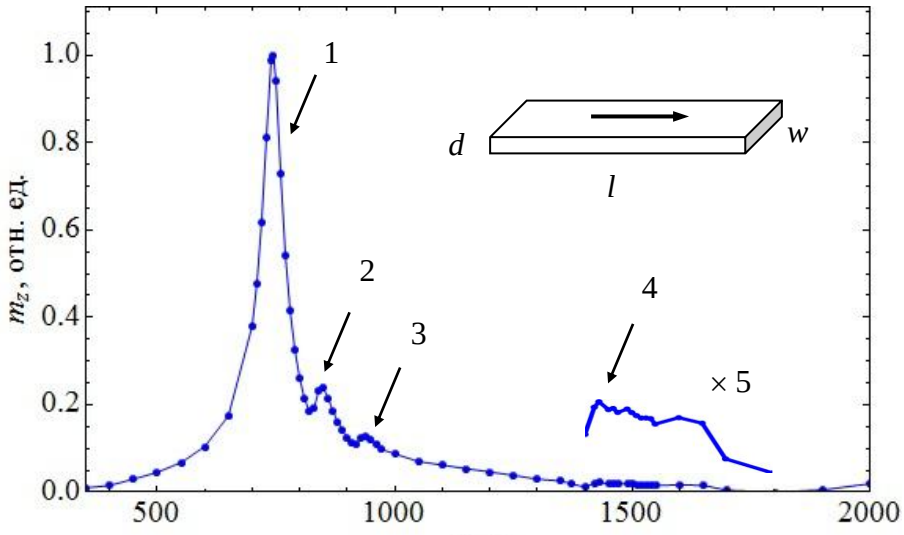
Modified OOMMF Code

http//math.nist.gov/oommf

Model FMR spectra



ν, GHz

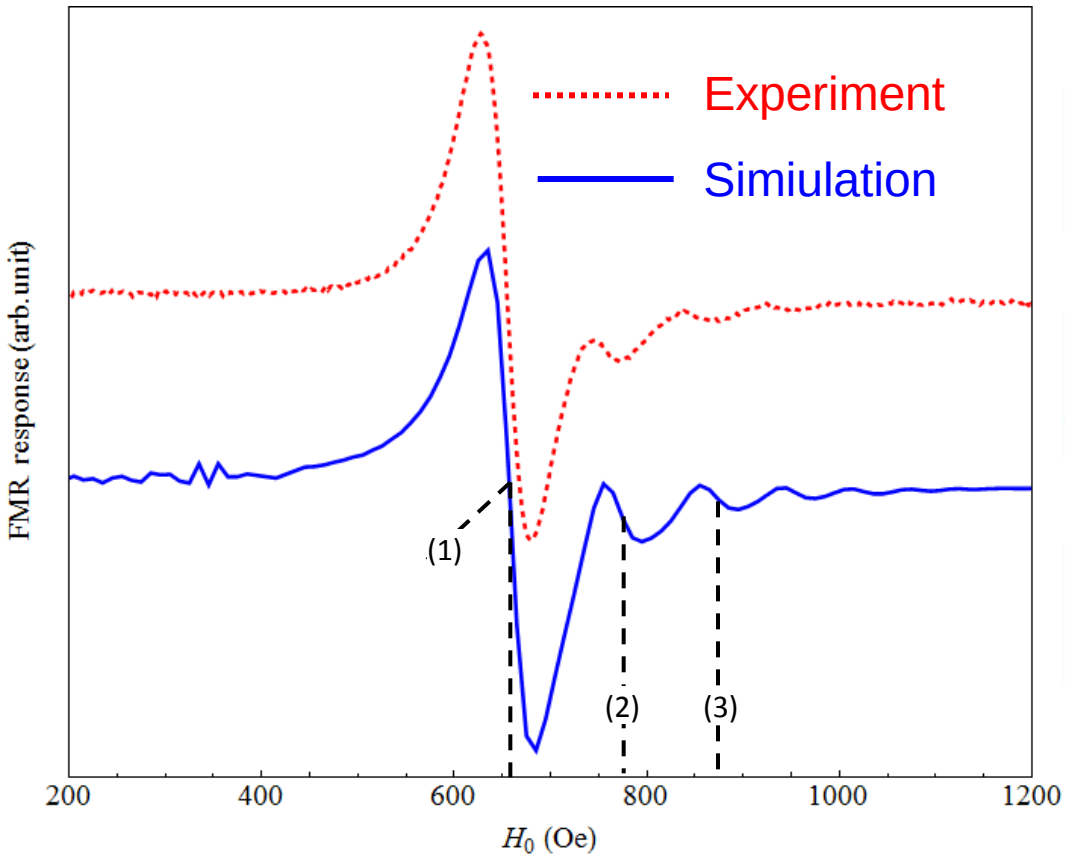


H, Oe

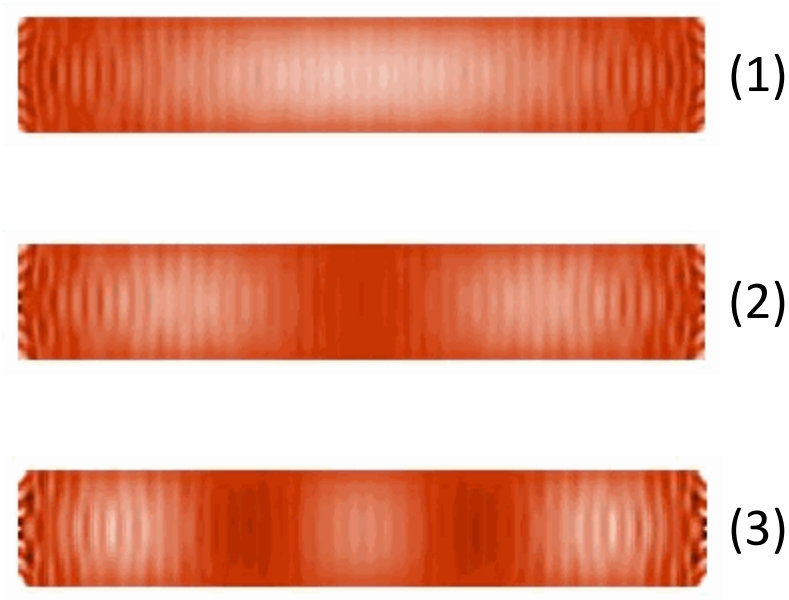
Р.В. Горев, В.Л. Миронов, Е.В. Скороходов - Поверхность, №3, 37-40, (2016).

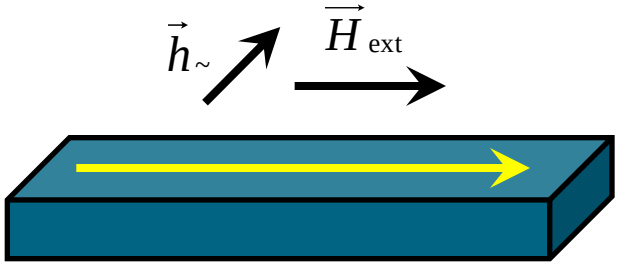
E. V. Skorohodov, et al. Journal off Magnetism and Magnetic Materials, **424**, 118-121 (2017)

Resonance in Permalloy stripes



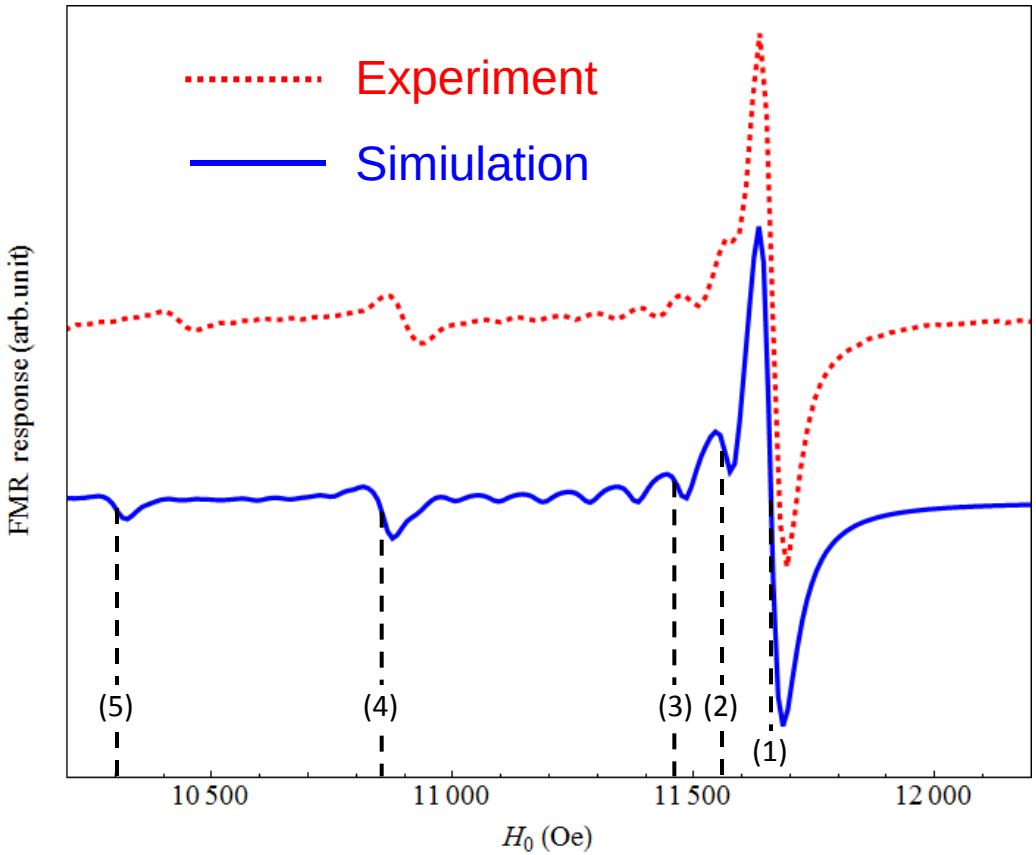
EPR Spectrometer "Bruker EMX"

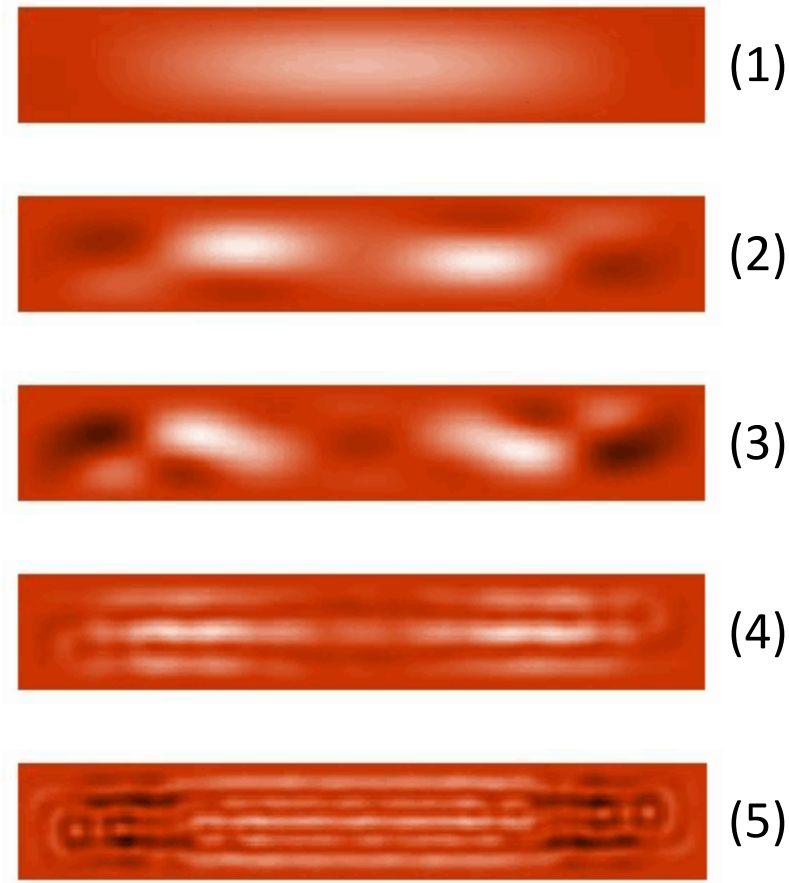




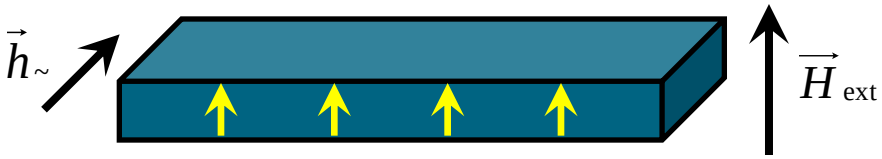
E. V. Skorohodov, et al. **JMMM**, **424**, 118-121 (2017)

Resonance in Permalloy stripes





E. V. Skorohodov, et al. **JMMM**, **424**, 118-121 (2017)



Domain walls in nanowires

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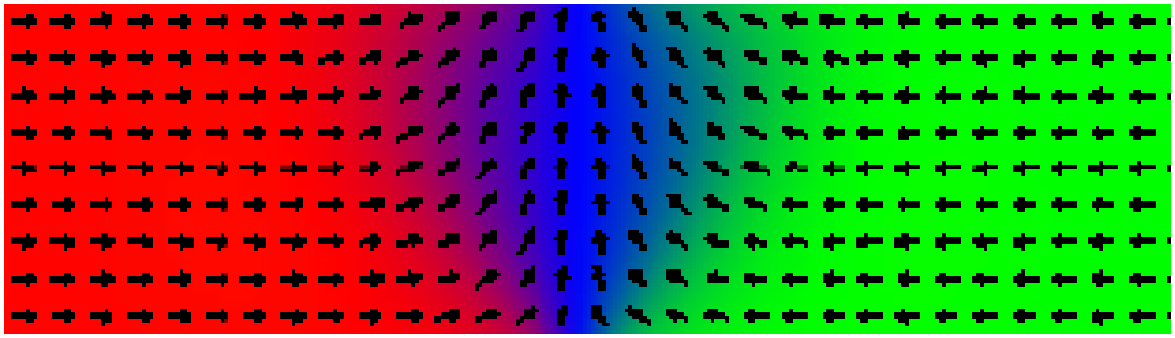
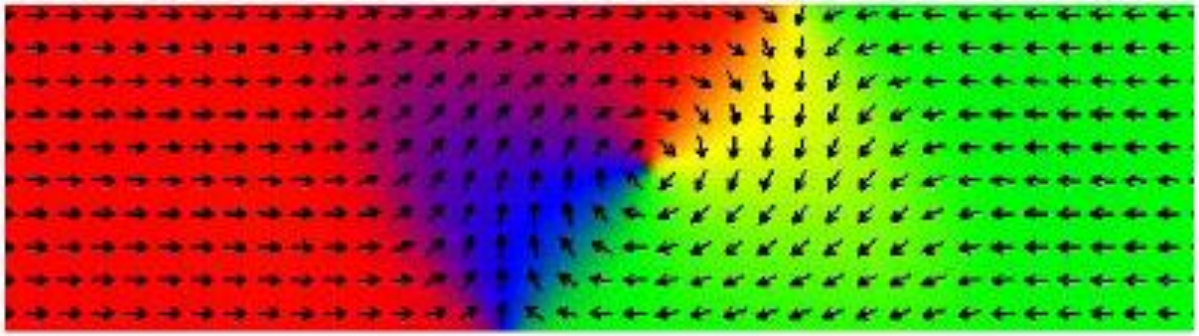
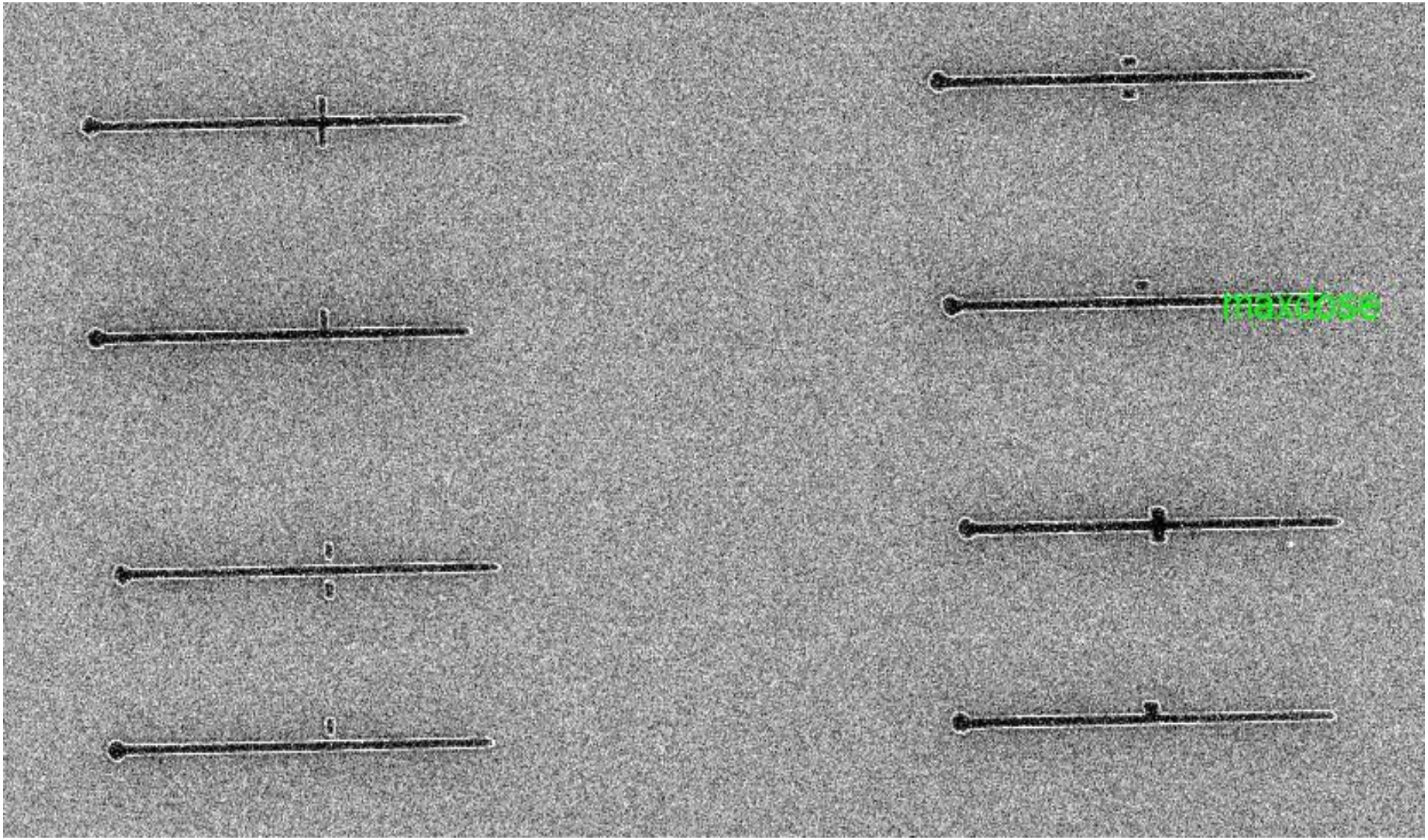


Transverse domain wall *d* < 20 nm



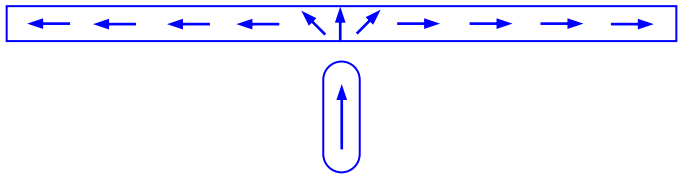
Vortex domain wall *d* > 20 nm

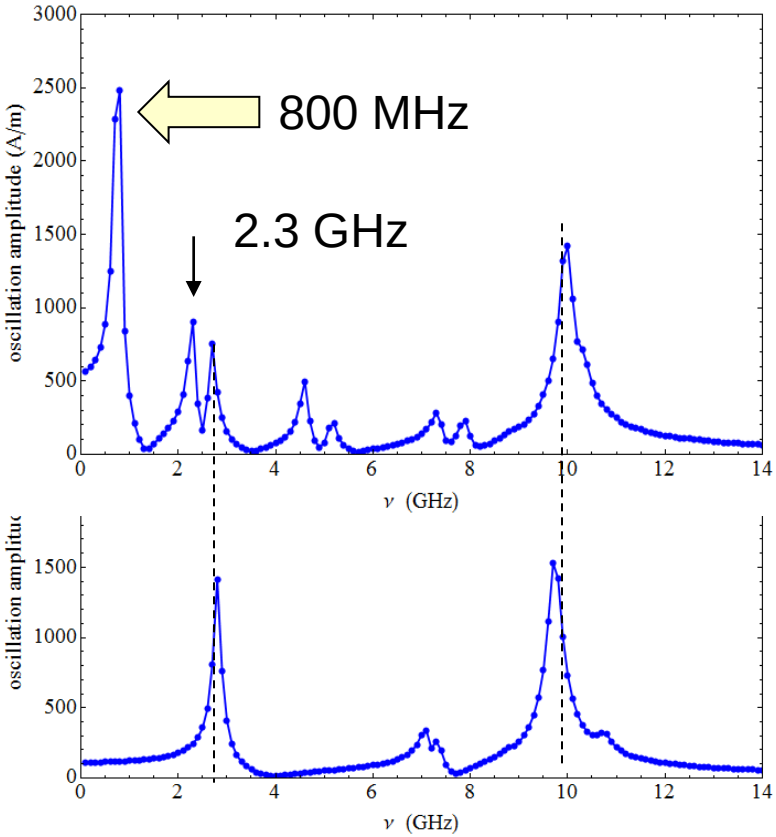
Ferromagnetic nanowires

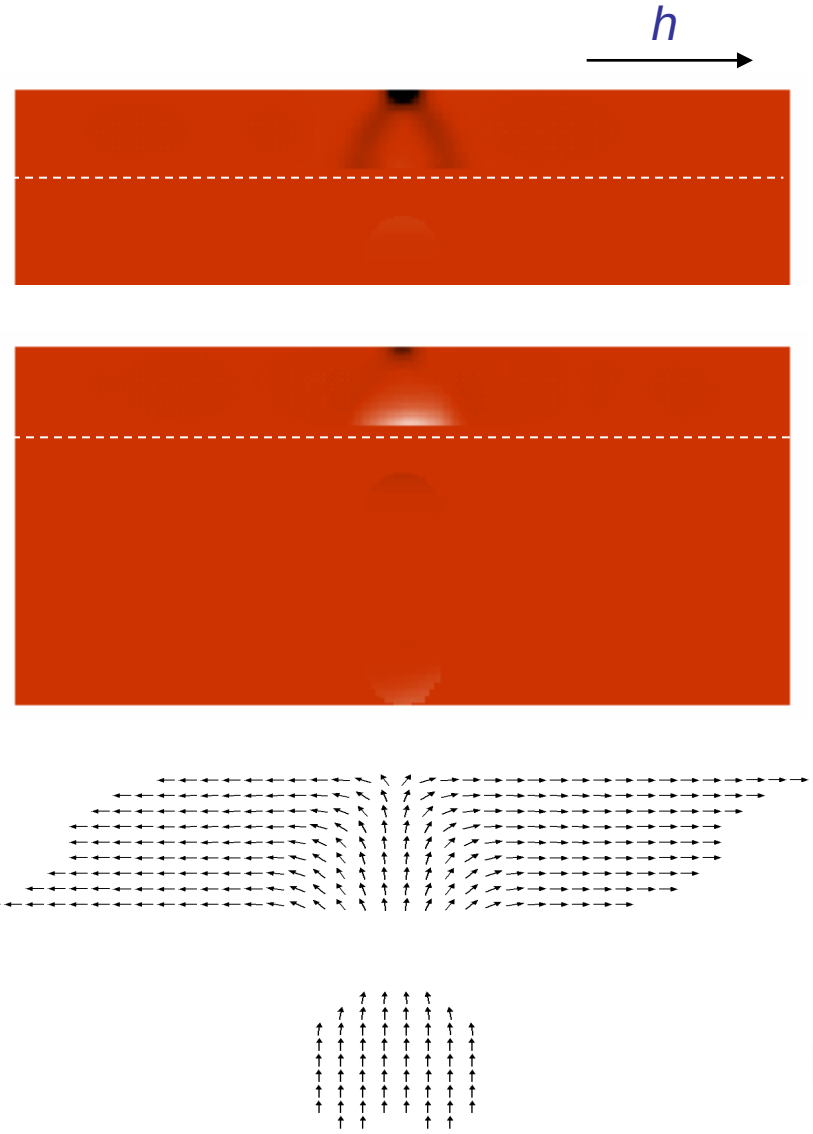


FMR of transverse domain wall

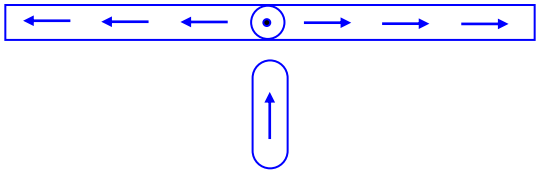
1000×100×20 nm



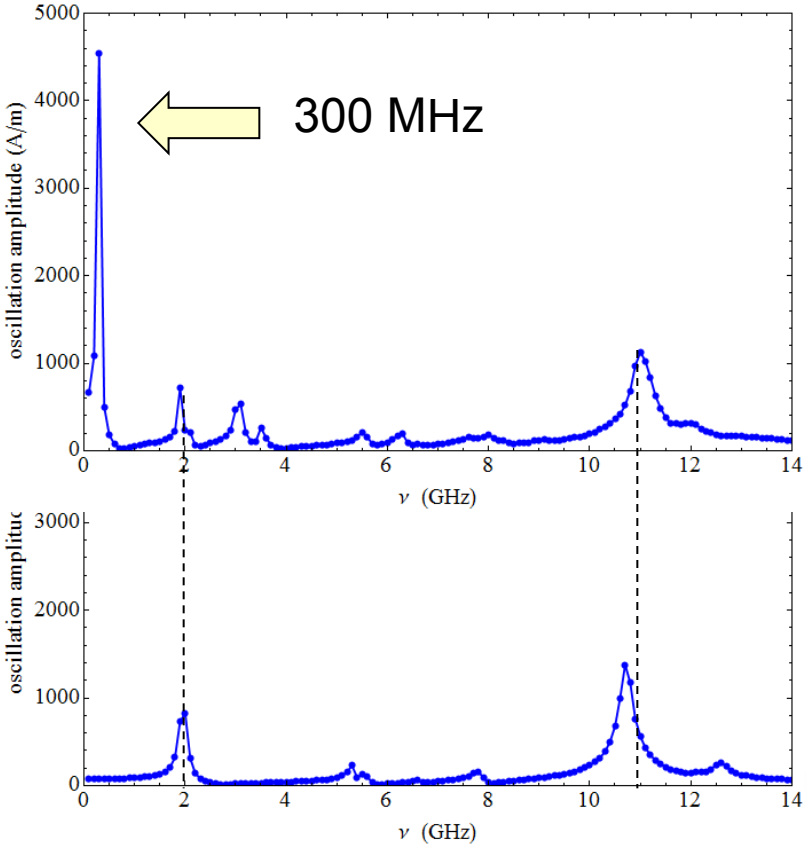


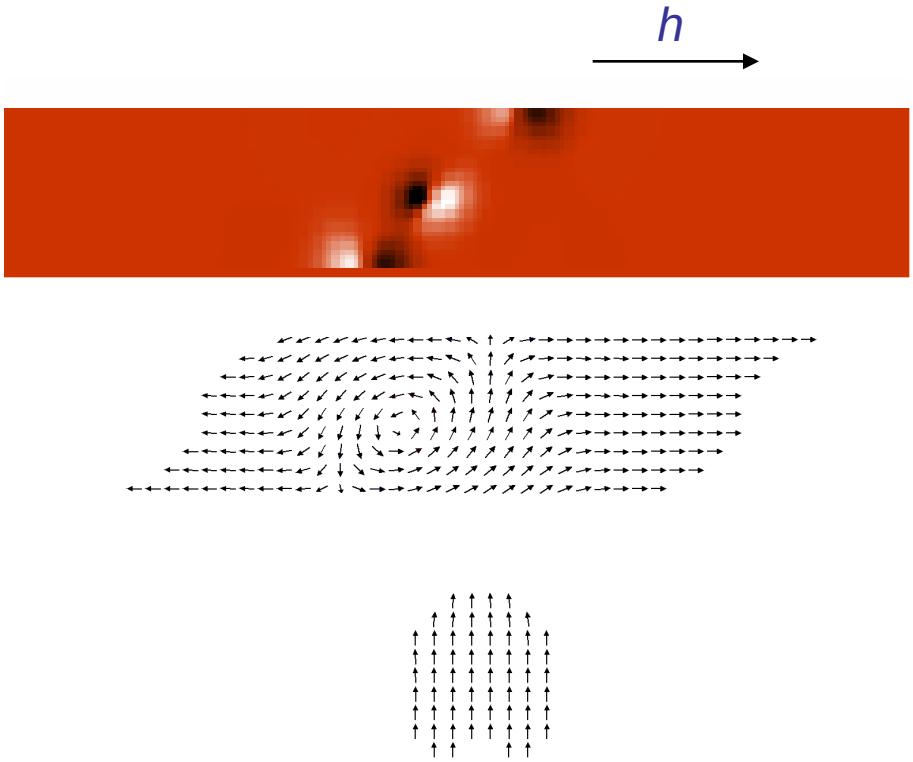


FMR of vortex domain wall



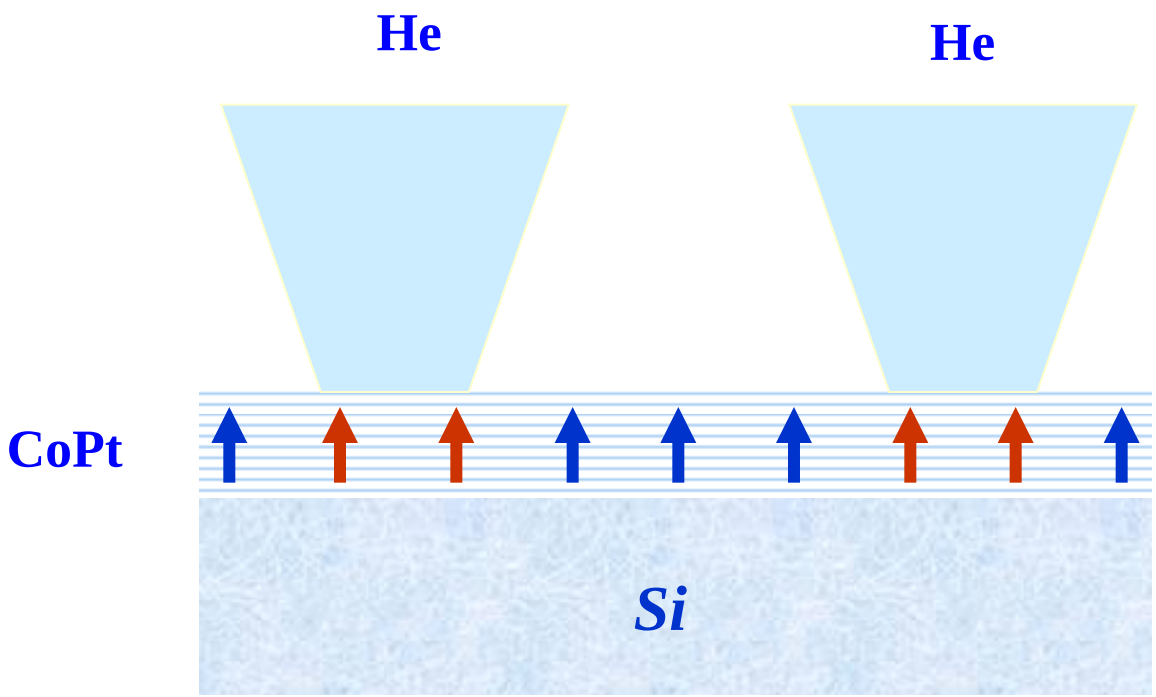
1000×100×40 nm

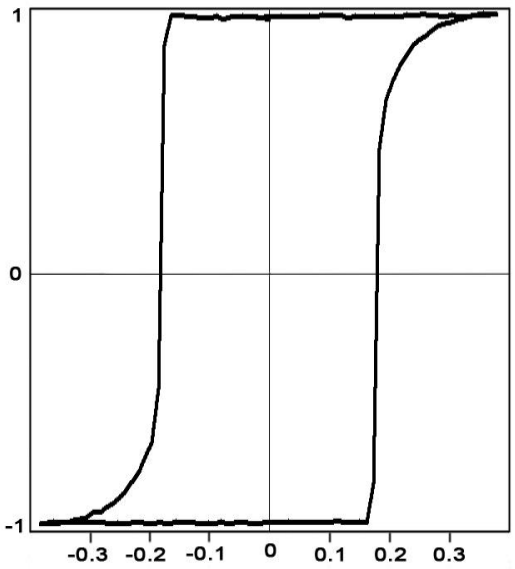




Ferromagnetic resonance in modified CoPt films with perpendicular anisotropy

CoPt multilayers modified by focused He ion beams



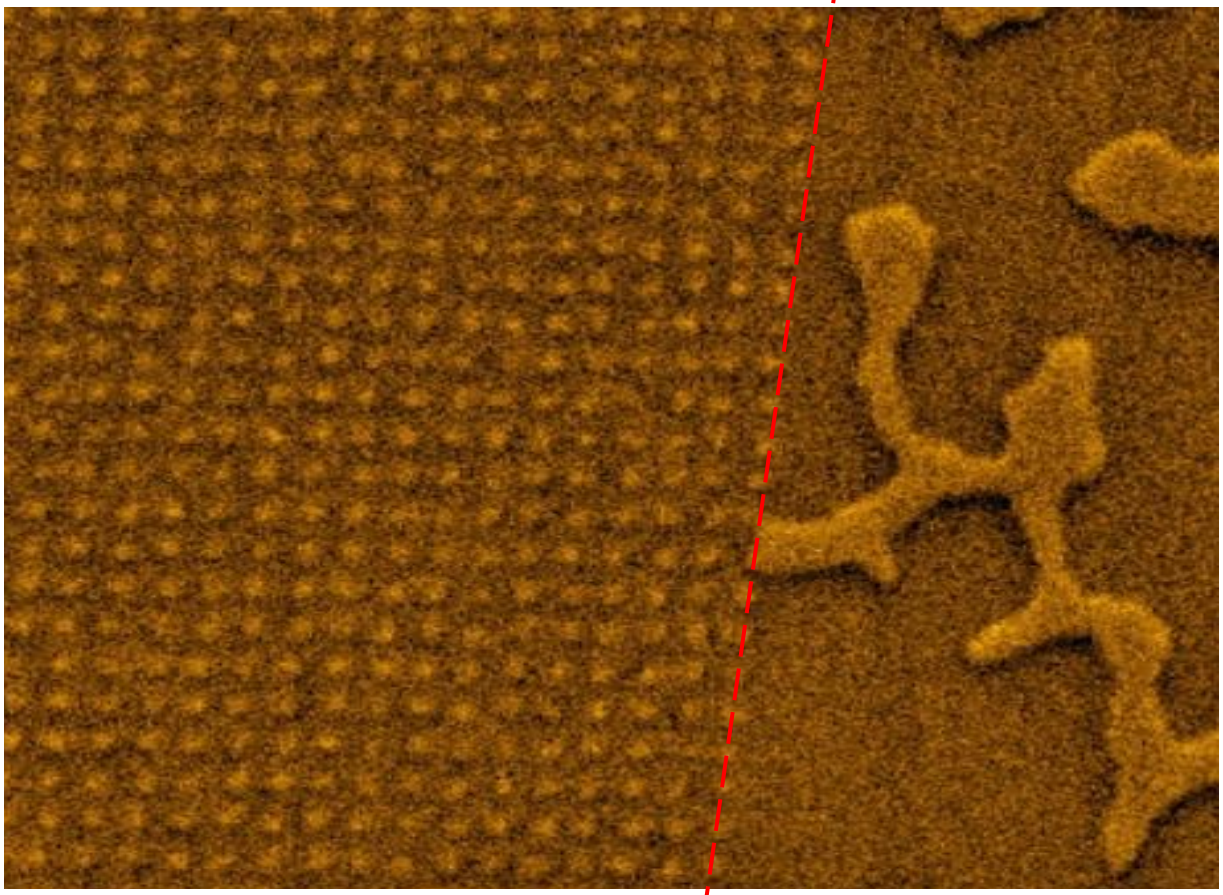


Multilayer structures

Si / [Co(0,5)Pt(1)]$_x$ ***x = 5 - 10***

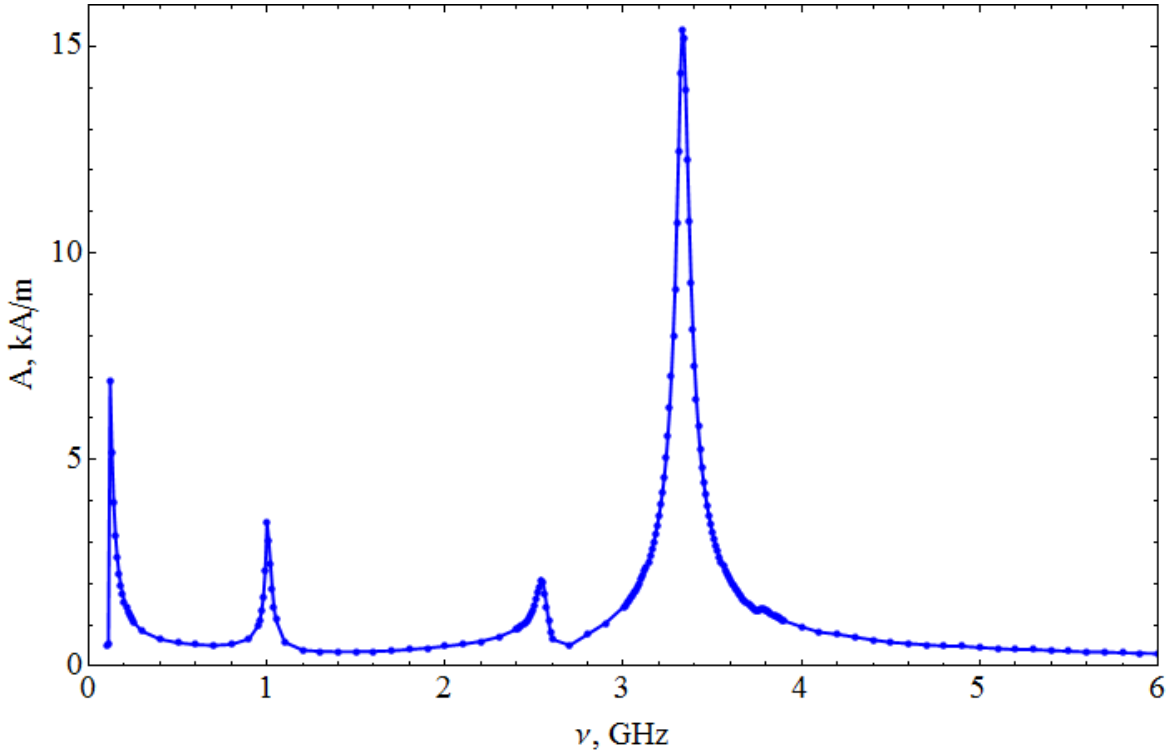
M. V. Sapozhnikov et al., Applied Physics Letters, **109**, 042406 (2016).

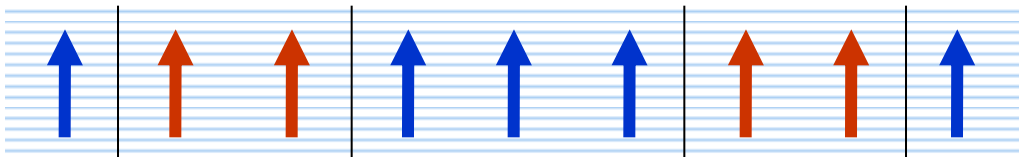
Modified CoPt film



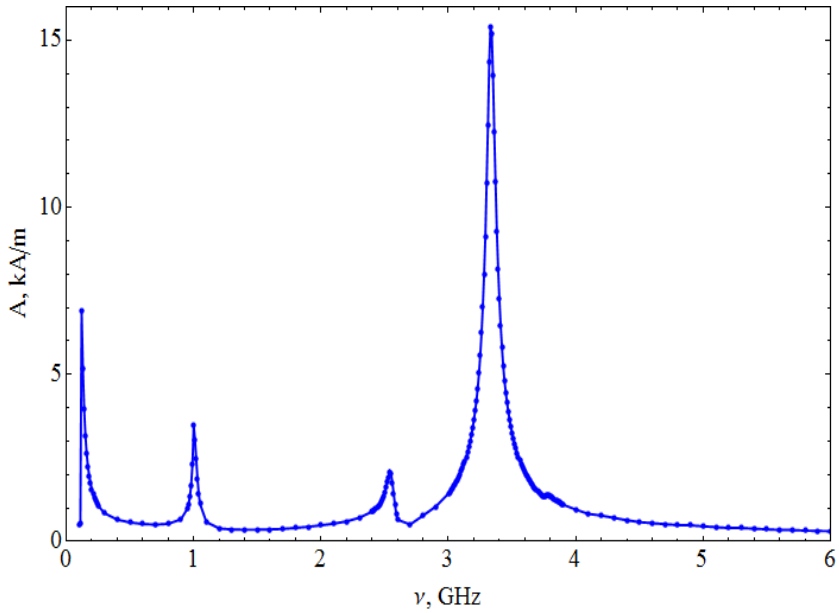
MFM image

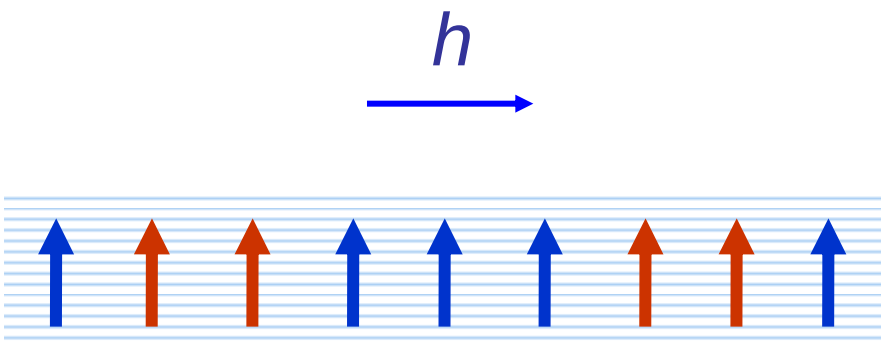
FMR spectrum of modified CoPt

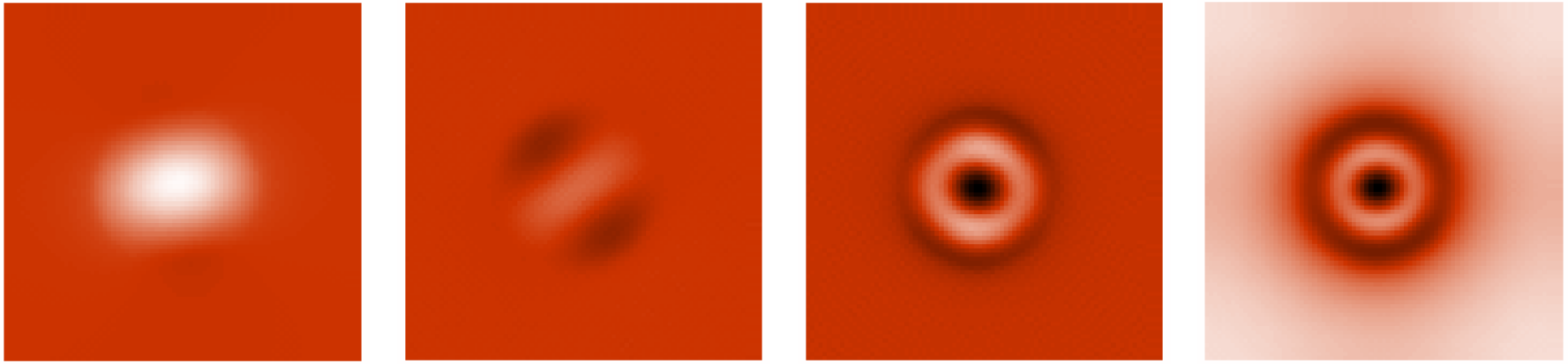




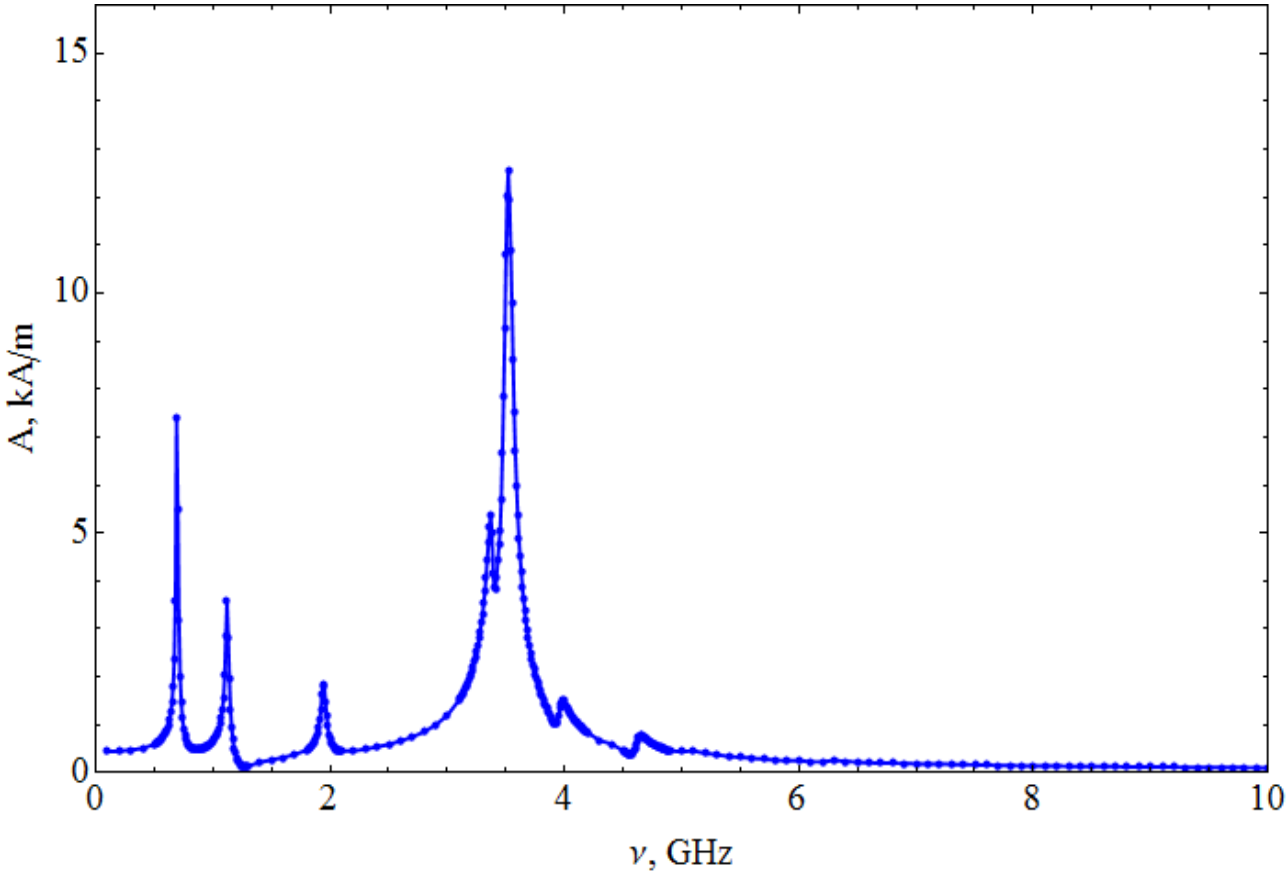
Oscillation modes

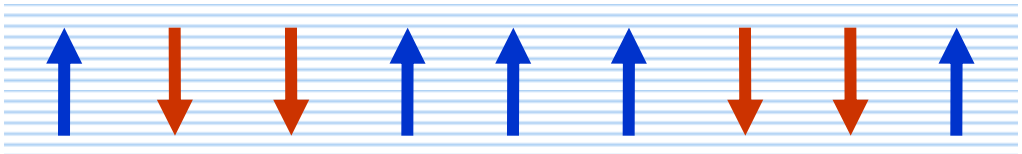




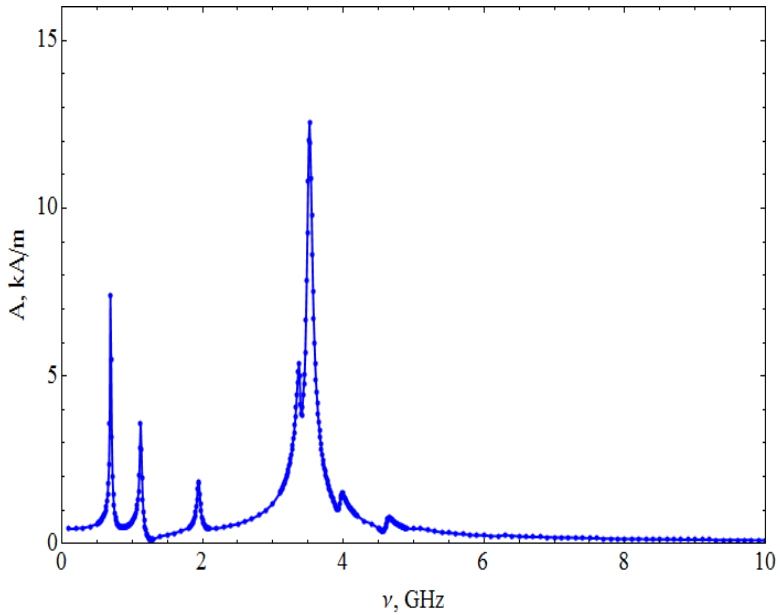


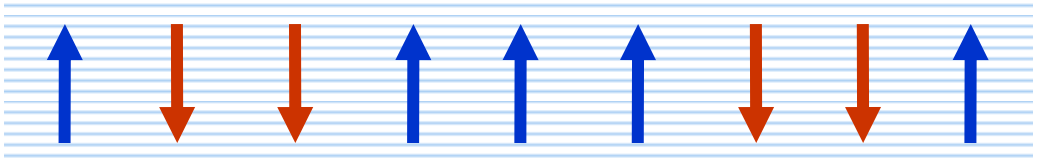
FMR spectrum of skyrmion state

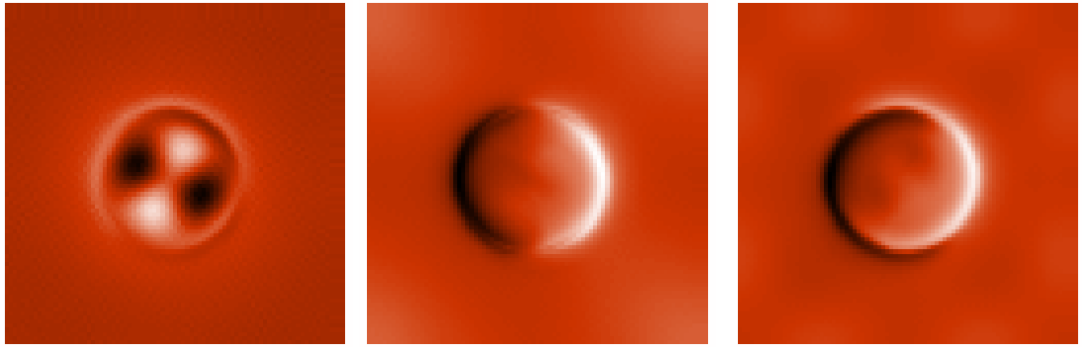


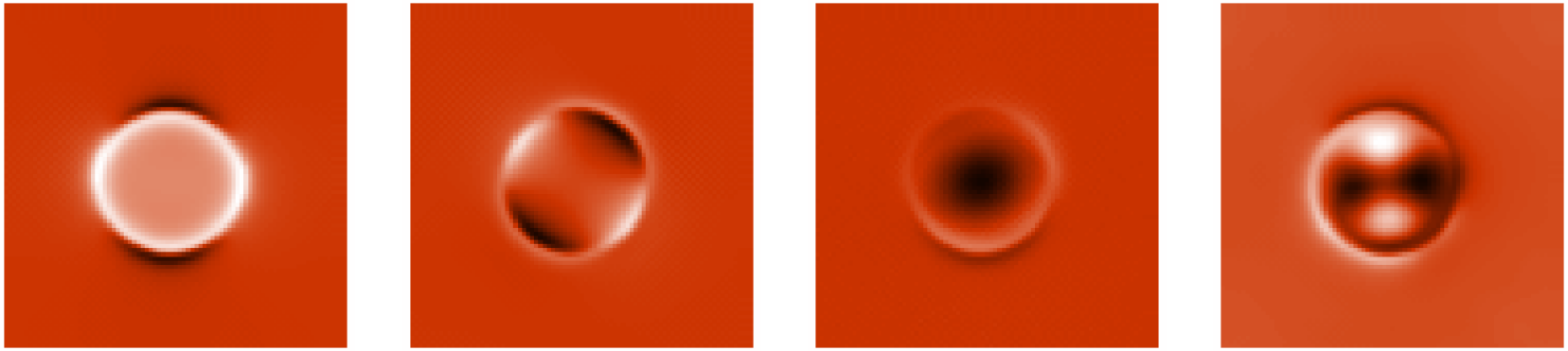


Oscillations in skyrmion state

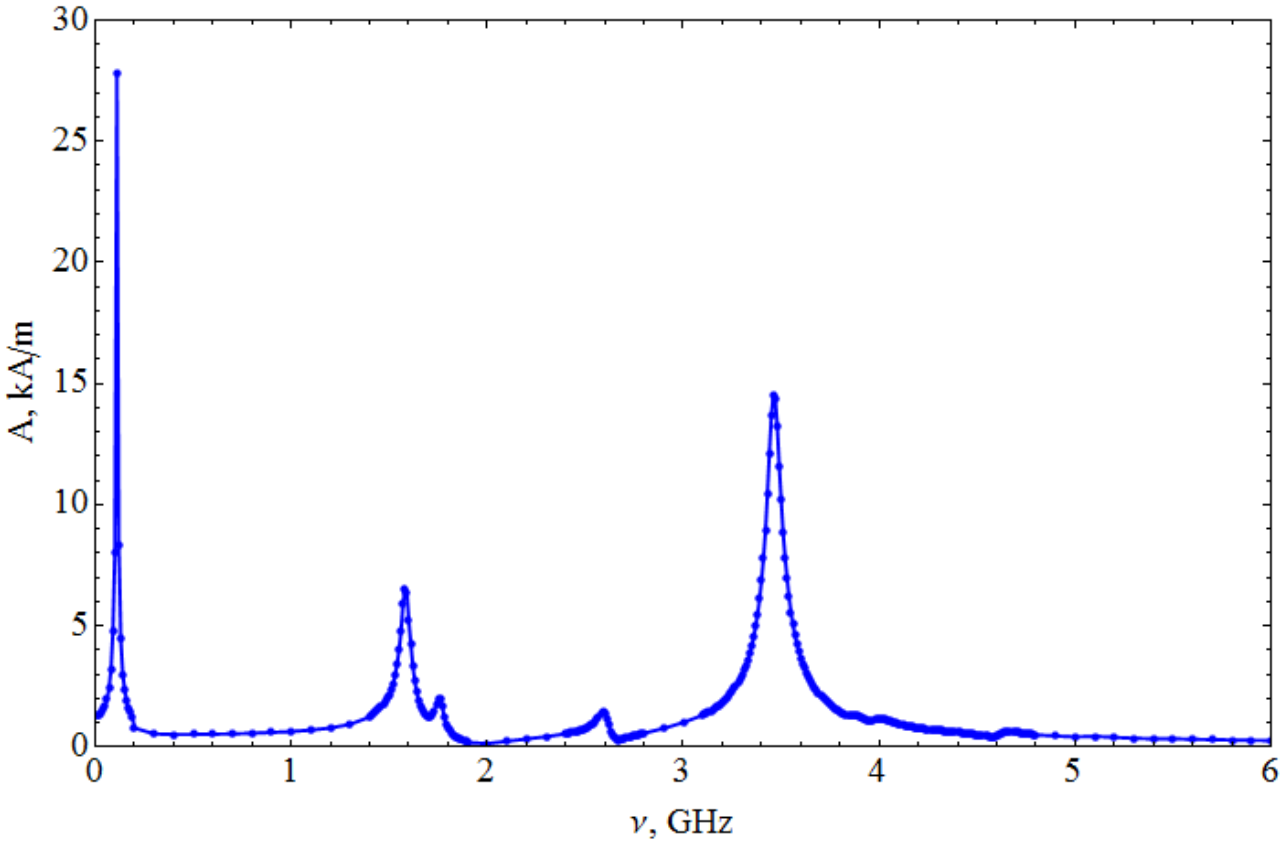


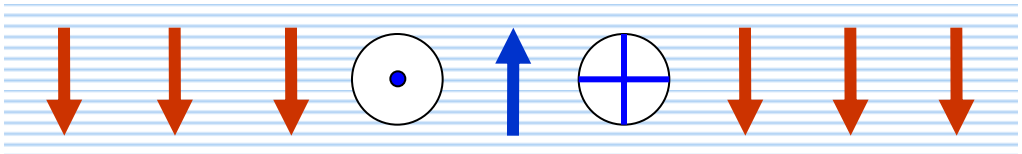




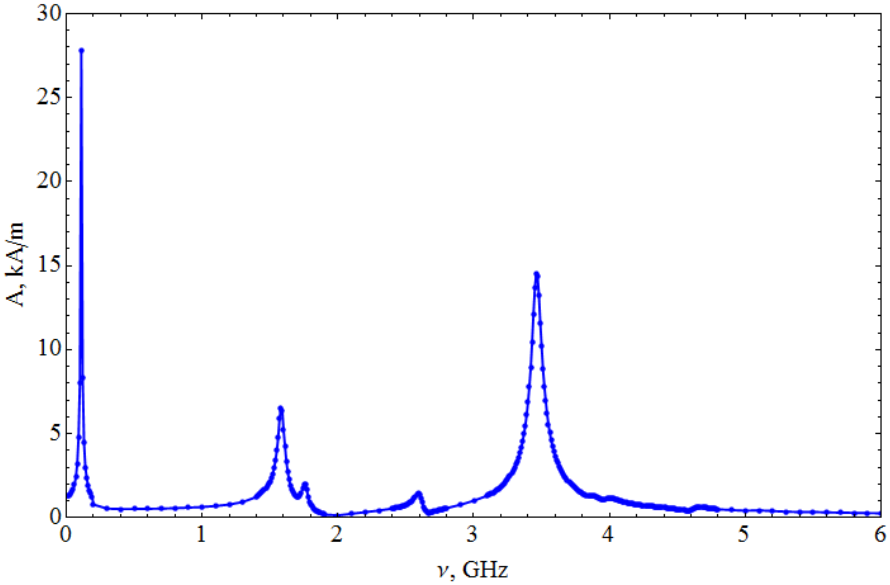


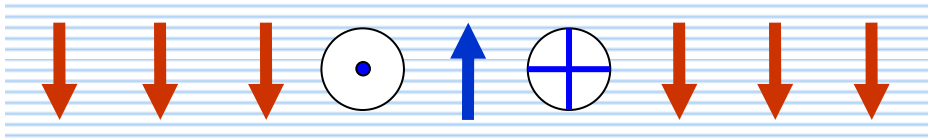
FMR spectrum of vortex state

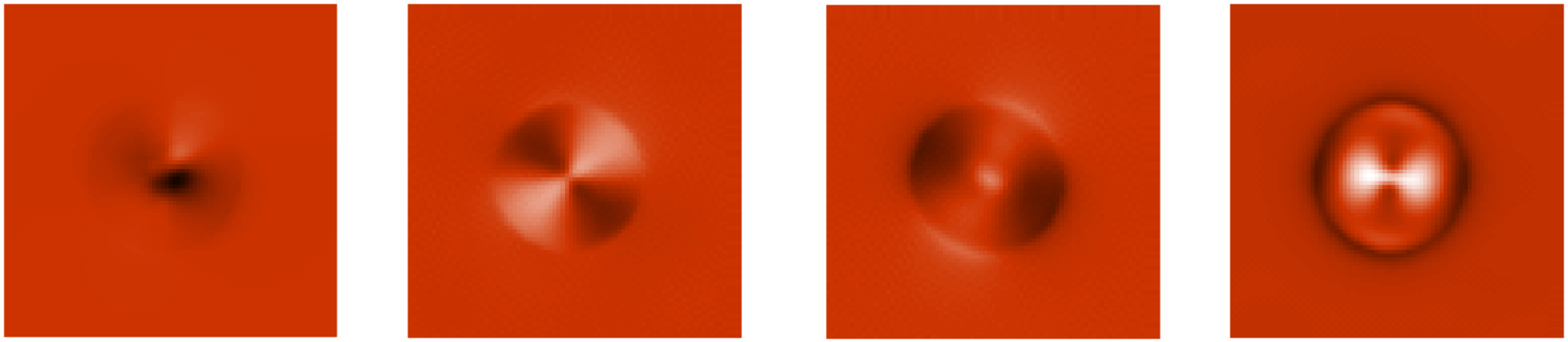




Oscillations in vortex state







Conclusion

In zero external field the magnetic resonance spectrum of ferromagnetic nanostructures substantially depends on the structure of the magnetization and can be easy rebuilt by means of external fields.

Acknowledgements

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RSF № 16-12-10254

«Magnetic resonance force microscopy of ferromagnetic nanostructures»

Official web site: http://mrfm.ipmras.ru/

Acknowledgements

1. Gorev R.V.
2. Sapozhnikov M.V.
3. Skorohodov E.V.

Thanks for your attention !