Magnetic information in the light diffracted by arrays of nanostructures

P. Vavassori

-Ikerbasque, Basque Fundation for Science and CIC nanoGUNE Consolider, San Sebastian, Spain.

In collaboration with

T. Veduci
University of Ferarra, Italy

M. Grimsditch,
Materials Science Division, Argonne National Laboratory, Argonne, IL.

V. Metlushko,
Dept. of Electrical and Computer Engineering, University of Illinois at Chicago, IL.

Outline

Magneto-optics:

brief overview of the Magneto-optical Kerr effects (MOKE).

MOKE from diffracted beams:

experimental setup

simple theory of diffracted MOKE

how to use it: examples of applications

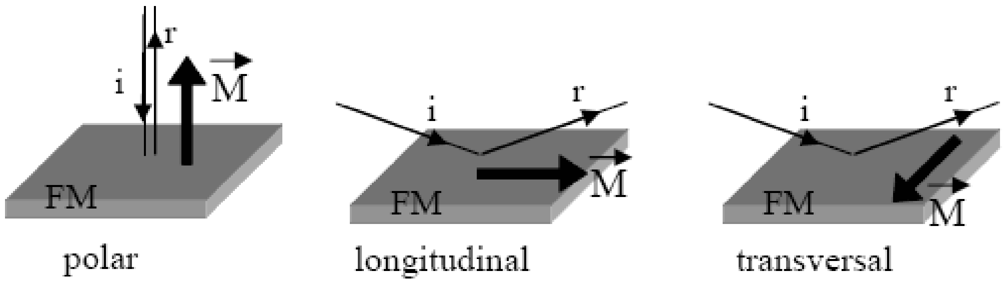
in conjunction with micromagnetics

in conjunction with MFM.

Recent developmnets:

from magnetometry to lensless far field microscopy magnetic imaging

MOKE



$$\hat{\varepsilon} = \begin{bmatrix} \varepsilon_0 & 0 & 0 \\ 0 & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{bmatrix} \Rightarrow \hat{\varepsilon} = \begin{bmatrix} \varepsilon_0 & i\varepsilon_z & -i\varepsilon_y \\ -i\varepsilon_z & \varepsilon_0 & i\varepsilon_x \\ i\varepsilon_y & -i\varepsilon_x & \varepsilon_0 \end{bmatrix}$$

$$\varepsilon_x = \varepsilon_0\, Q\, m_x;\ \varepsilon_y = \varepsilon_0\, Q\, m_y;\ \varepsilon_z = \varepsilon_0\, Q\, m_z;$$

- **Non-destructive;**
- **High sensitivity;**
- **Finite penetration depth (~ 10 nm);**
- **Fast (time resolved measurements);**
- **Laterally resolved (microscopy);**
- **Can be easily used in vacuum and cryogenic systems;**

J. Kerr, Philosophical Magazine **3** 321 (1877)
Z. Q. Qui and S. D. Bader, Rev. Sci. Instrum. **71,** 1243 (2000)

The magneto-optic Kerr effect (MOKE, discovered in 1877 by John Kerr) technique is well established for the investigation of magnetic materials. It relies on small, magnetization induced changes in the optical properties which modify the polarization or the intensity of the reflected light.

Macroscopically, magneto-optic effects arise from the antisymmetric, off-diagonal elements in the dielectric tensor.

Microscopically, the coupling between the electric field of the propagating light and the electron spin in a magnetic medium occurs through the spin-orbit interaction.

Fresnell reflection coefficients

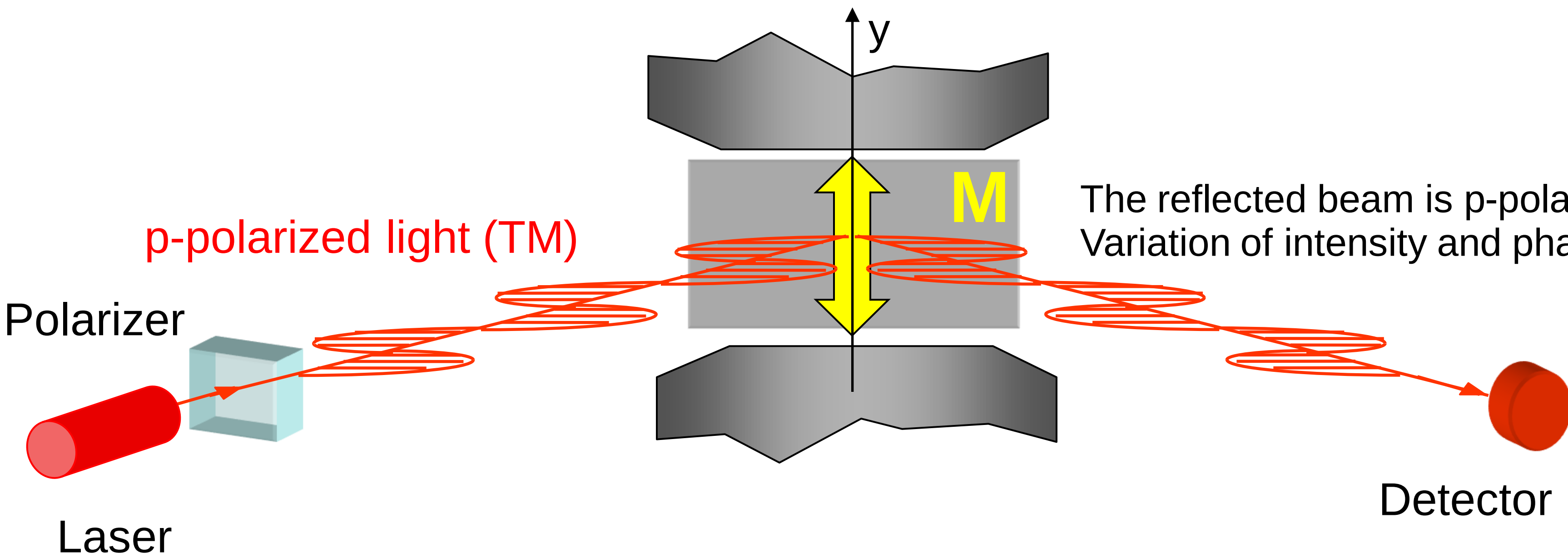
$$\text{Sample} \begin{pmatrix} r_{pp} & r_{ps} \\ r_{sp} & r_{ss} \end{pmatrix}$$

$$r_{pp} = r^0_{pp} + r_{pp}^M \propto m_y$$
$$r_{ps} = \propto -m_x - m_z$$
$$r_{sp} = \propto m_x - m_z$$

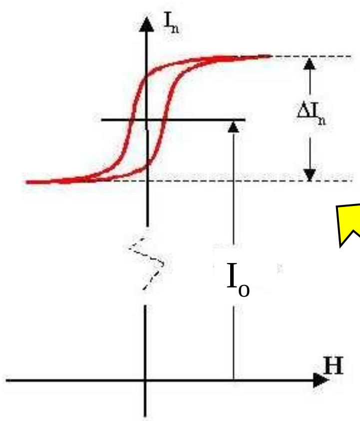
$$r_{pp} = \frac{E_{rTM}}{E_{iTM}} \quad r_{ps} = \frac{E_{rTM}}{E_{iTE}} \quad r_{sp} = \frac{E_{rTE}}{E_{iTM}} \quad r_{ss} = \frac{E_{rTE}}{E_{iTE}}$$

P. Vavassori, APL 77 1605 (2000)

Transverse Kerr effect magnetometry



The reflected beam is p-polarized.
Variation of intensity and phase.



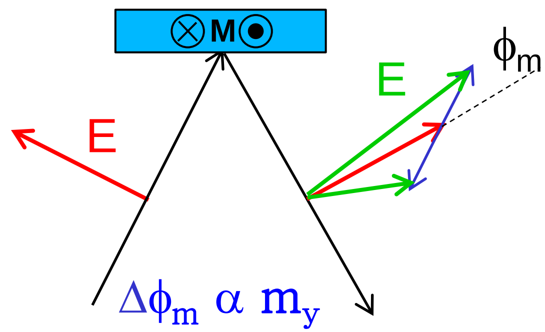
$$E_r = r_{pp} E_o$$

$$r_{pp} = r^{o}_{pp} + r^{m}_{pp} m_y$$

$$I_r = E_r (E_r)^*$$

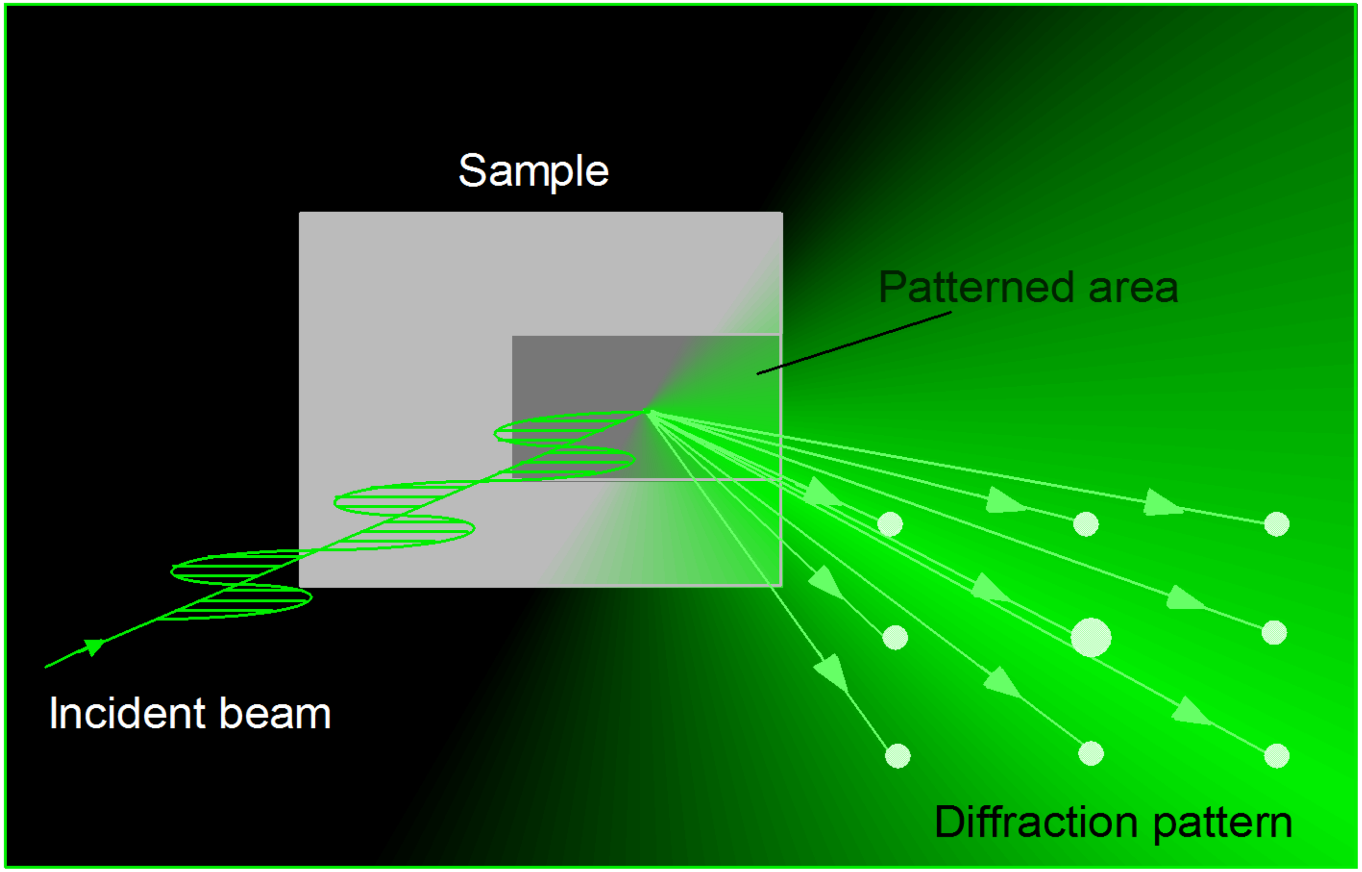
$$I_r = I_o + \Delta I_m \qquad \Delta I_m / I_o \ \alpha \ m_y$$

Y. Souche et al.
JMMM 226-230, 1686 (2001);
JMMM 242-245, 964 (2002).



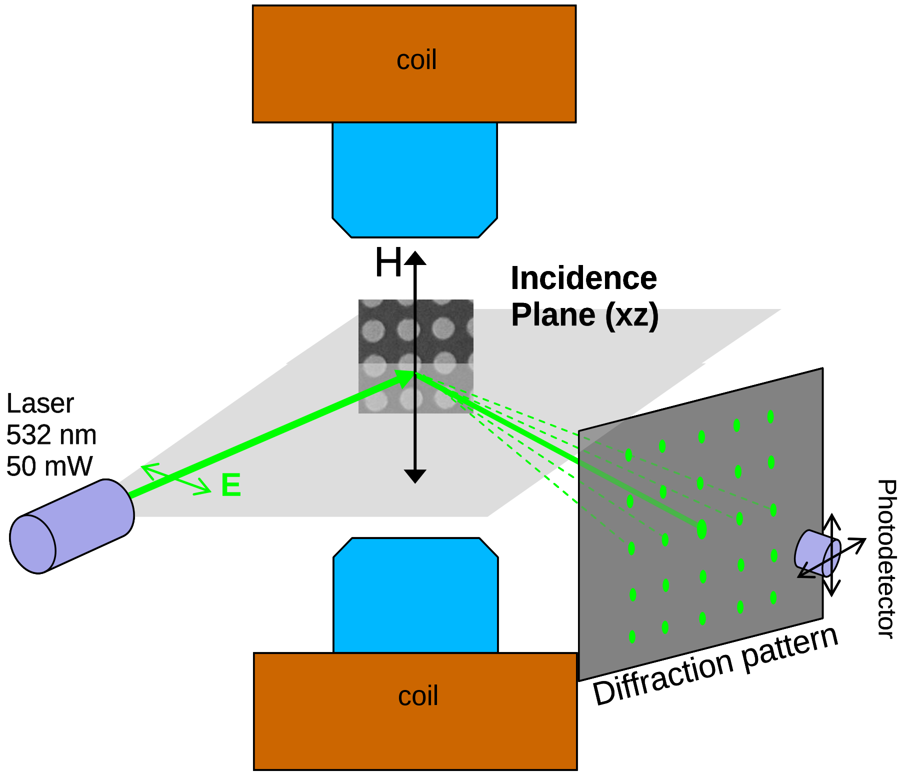
Diffraction of light by an array

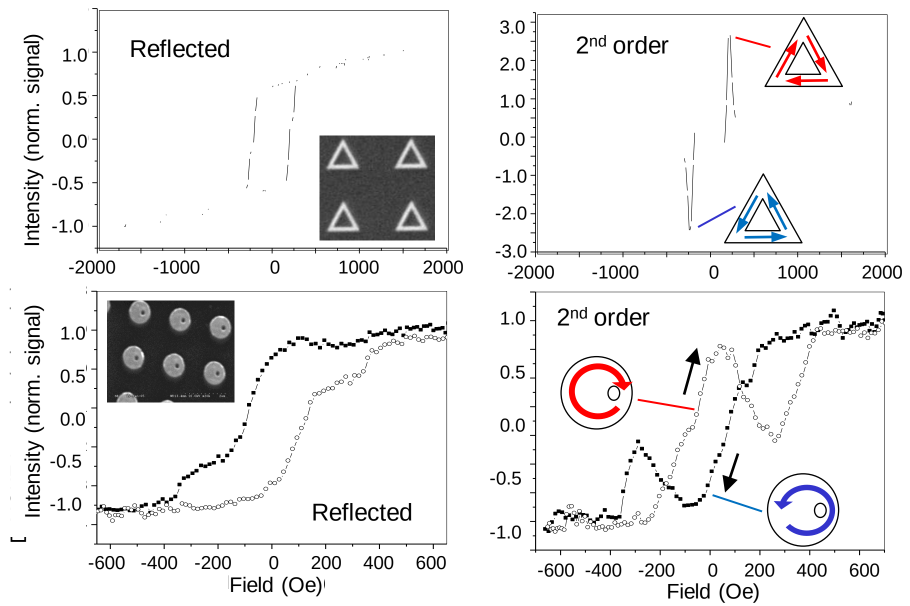
As is well known for optical gratings, when a beam of light is incident upon a sample that has a structure comparable to the wavelength of radiation, the beam is not only reflected but is also diffracted. If the material is magnetic, one may ask whether the diffracted beams also carry information about the magnetic structure.



"Diffracted-MOKE: What does it tell you?",
M. Grimsditch and P. Vavassori J. Phys.: Condensed Matter **16**, R275 - R294 (2004).

Examples of D-MOKE loops



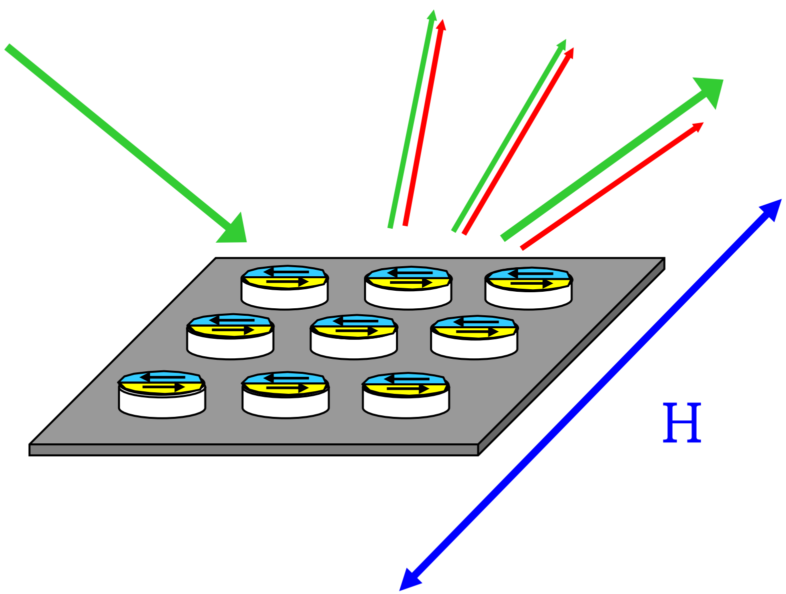


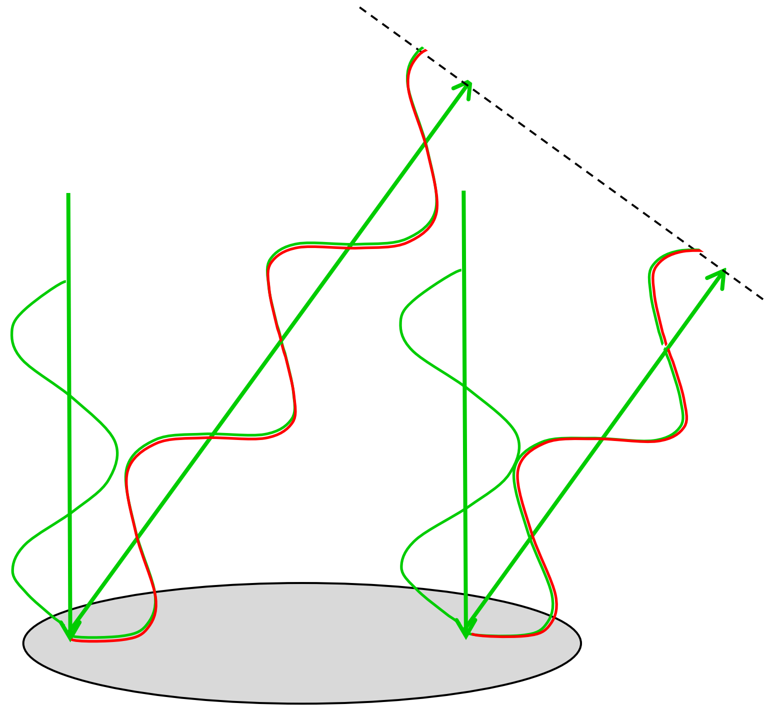
Peculiar structures due to
- Collective properties
- Interference effects

P. Vavassori, et al.,Phys. Rev. B **59** 6337 (1999)
M. Grimsditch, P. Vavassori, et al., Phys. Rev. B **65**, 172419 (2002)
P. Vavassori, et al., Phys. Rev. B **67**, 134429 (2003)
P. Vavassori, et al., Phys. Rev. B **69**, 214404 (2004)
P. Vavassori, et al., J Appl. Phys. **99**, 053902 (2006)
P. Vavassori, et al., J. Appl. Phys. **101**, 023902 (2007)
P. Vavassori, et al., Phys. Rev. B **78**, 174403 (2008)

Intuitive explanation of D-MOKE loops

$$r_{pp} = r^{o}_{pp} + r^{m}_{pp} m_y(x,y)$$





Peculiar structures due to
- Interference effects
- Collective properties

O. Geoffroy et al., J. Magn. Magn. Mat. **121** (1993) 516
Y. Souche et al., J. Magn. Magn. Mat., **140-144** (1995) 2179

Simple theory of diffracted-MOKE

Physical-optics approximation provides a very simple and physically transparent description.

The electric field in the n^{th} order diffracted beam, due to the periodic modulation of the "effective" reflectivity r'_{pp} is:

$$E^n_d = E_o f_n$$

$$f_n = \int_S r'_{pp} \exp\{i\, n\, \mathbf{G} \cdot \mathbf{r}\}\, dS$$

where n integer, G reciprocal lattice vector and S is the unit cell.

$$r'_{pp} = r^o_{pp} + r^m_{pp}\, m_y(x,y,H)$$

$$E_n^d = E_o \left(r^o_{pp} f_n^{nm} + r^m_{pp} f_n^m\right)$$ with $r^o_{pp}(\theta_i, \theta_n, \varepsilon_{dots}, \varepsilon_{subst})$, $r^m_{pp}(\theta_i, \theta_n, \varepsilon_{dots}, Q)$

$$f_n^{nm} = \int_S \exp\{i\, n\, \mathbf{G} \cdot \mathbf{r}\}\, dxdy$$ ← **non-magnetic form factor**

$$f_n^m(H) = \int_{Dot} m_y(x,y,H) \exp\{i\, n\, \mathbf{G} \cdot \mathbf{r}\}\, dxdy$$ ← **magnetic form factor**

$$I_n^d = E_n^d (E_n^d)^* \qquad \Delta I_n^m(m_y) = A_n \mathrm{Re}[f_n^m] + B_n \mathrm{Im}[f_n^m]$$

What are the differences due to?

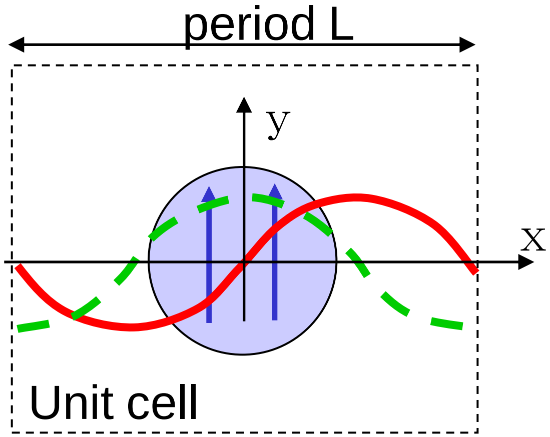
Diffracted spots in the scattering plane

$G_x = 2\pi/L$ reciprocal lattice vector

$$\Delta I_n^m \ \alpha \ A_n \, Re[f_n^m] + B_n \, Im[f_n^m]$$

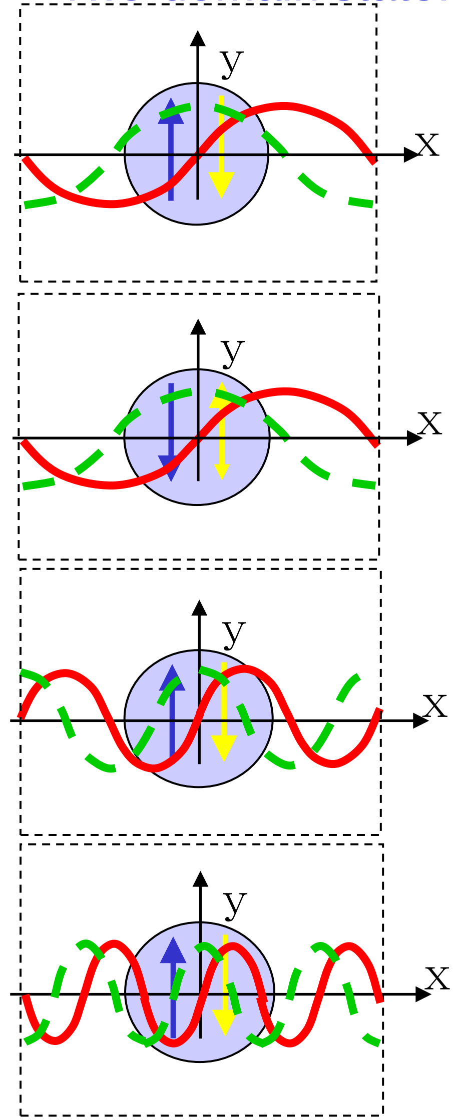
$$Re[f_n^m] = \int_{Dot} m_y \cos(n \, G_x \, x) \, dS$$

$$Im[f_n^m] = \int_{Dot} m_y \sin(n \, G_x \, x) \, dS$$



Saturated state $\Rightarrow$ $Im[f_1^m] = 0$, $Re[f_1^m] > 0$

Two-domain state: asymmetric M distribution



1st order

$\Rightarrow$ $Im[f_1^m] < 0$, $Re[f_1^m] = 0$

$\Rightarrow$ $Im[f_1^m] > 0$, $Re[f_1^m] = 0$

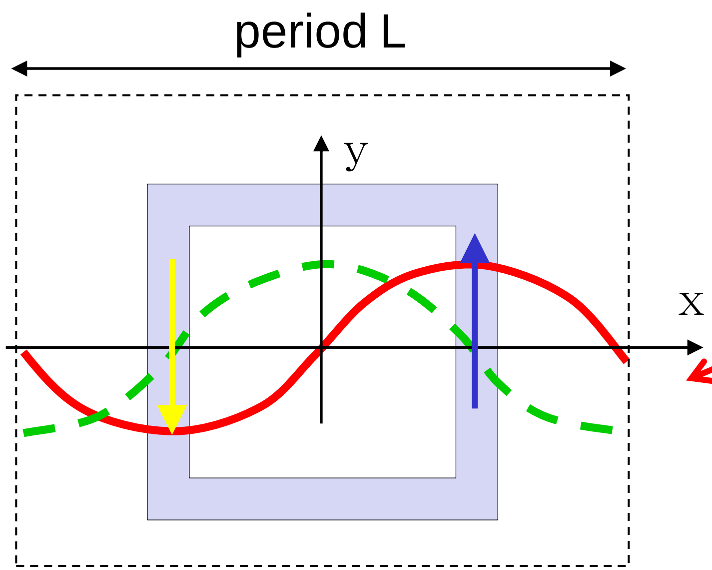
2nd order

$\Rightarrow$ $Im[f_2^m] < 0$ large, $Re[f_2^m] = 0$

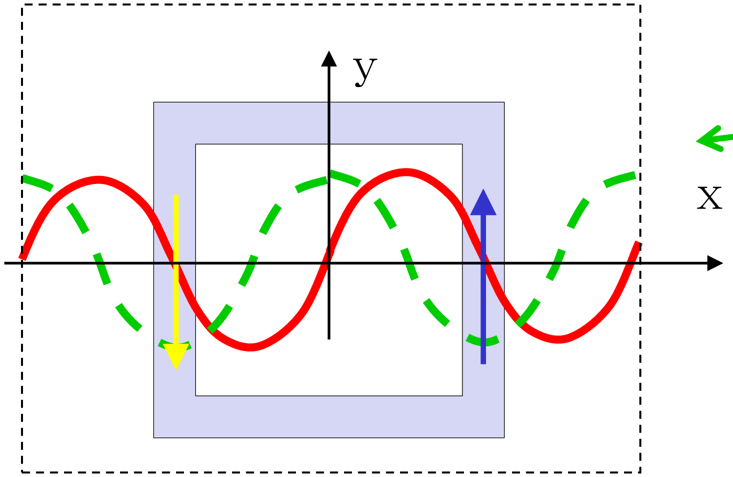
3rd order

$\Rightarrow$ $Im[f_2^m] < 0$ very large, $Re[f_2^m] = 0$

Tuning the sensitivity to selected portions of the dot!



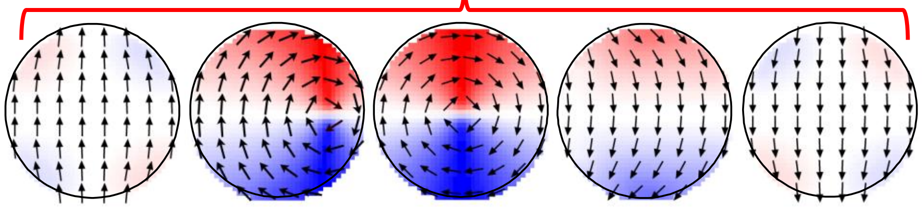
Immaginary contribution:
highlight any asymmetric
(y-mirror symmetry breaking)
magnetic (m_y) behaviour



Real contribution:
horizontal segments
y-mirror symmetry m_y

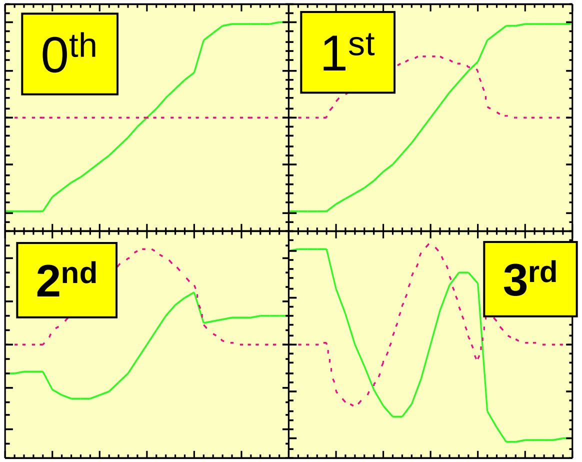
Calculated form factors and D-MOKE loops

- Micromagnetic simulations (OOMMF platform)
- Mathematica



$\mathrm{Re}[f_n^m]$

$\mathrm{Im}[f_n^m]$



$$\Delta I_n^m (m_y) = 2 f_n^{nm} \{ A_n \mathrm{Re}[f_n^m] + B_n \mathrm{Im}[f_n^m] \}$$

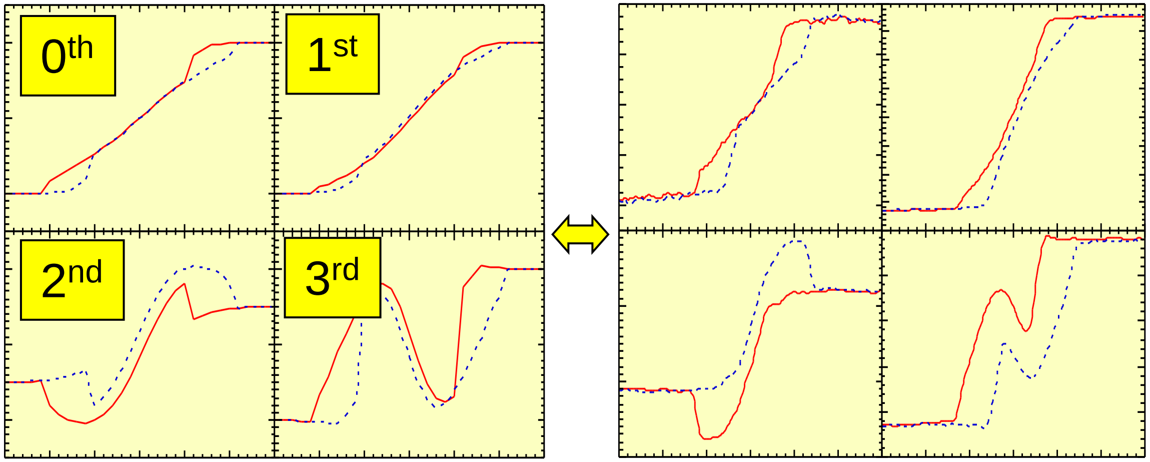
$$(\Delta I_n^m)_{norm} = \mathrm{Re}[f_n^m] + C_n \mathrm{Im}[f_n^m] \qquad C_n = B_n/A_n$$

C_n ?

$C_n (\theta_i, \theta_n, \varepsilon_{dots}, \varepsilon_{sub}, Q)$

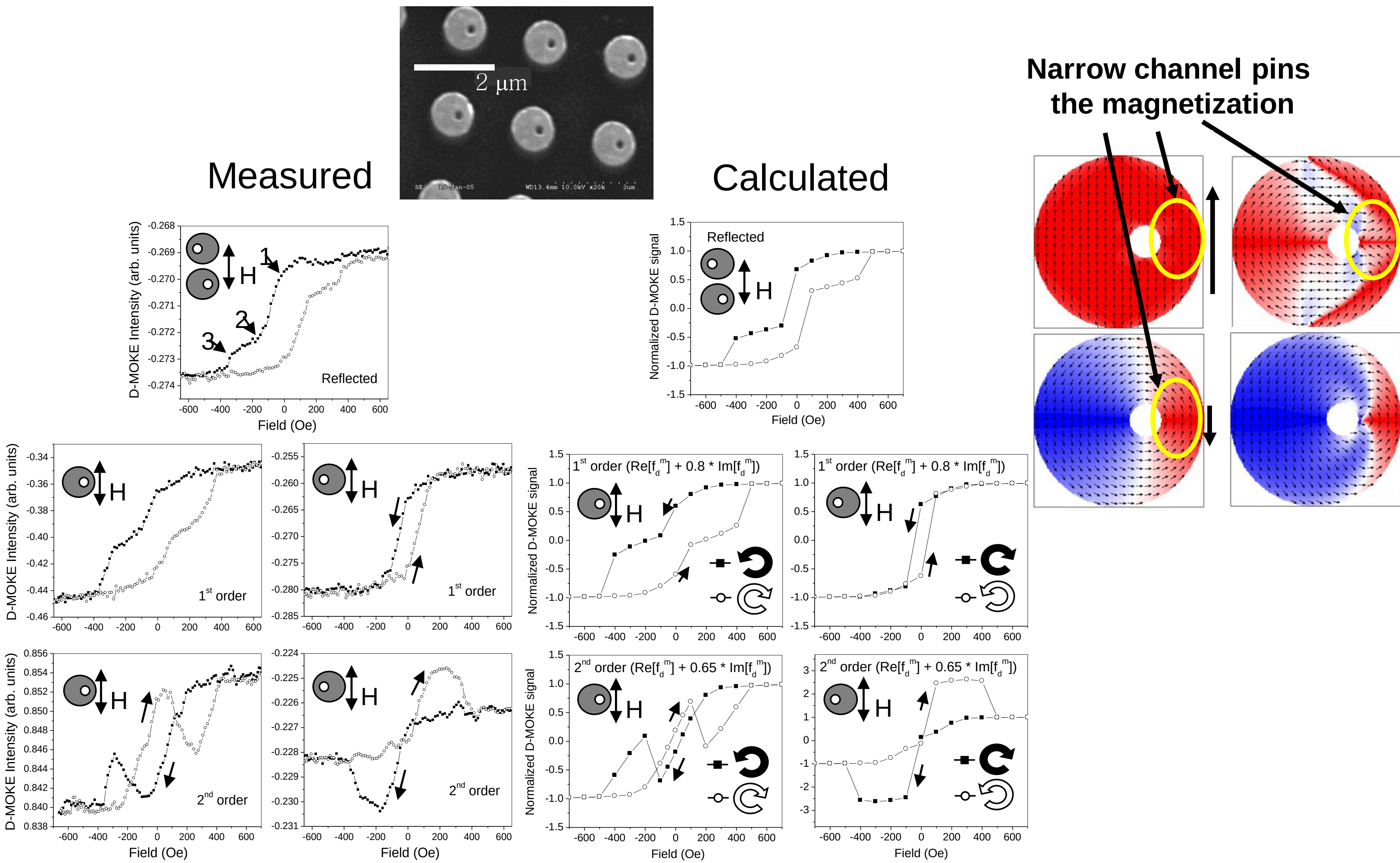
- It can be that not all the dots behave the same.

- Treated as an adjustable parameter.



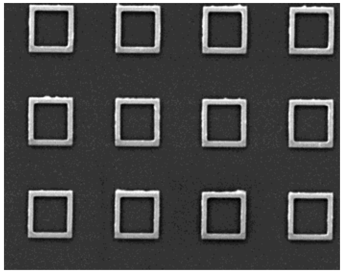
M. Grimsditch, P. Vavassori, V. Novosad, V. Metlushko, H. Shima, Y. Otani, and K. Fukamichi, Phys. Rev. B **65**, 172419 (2002)

Asymmetry to induce the desired vortex rotation

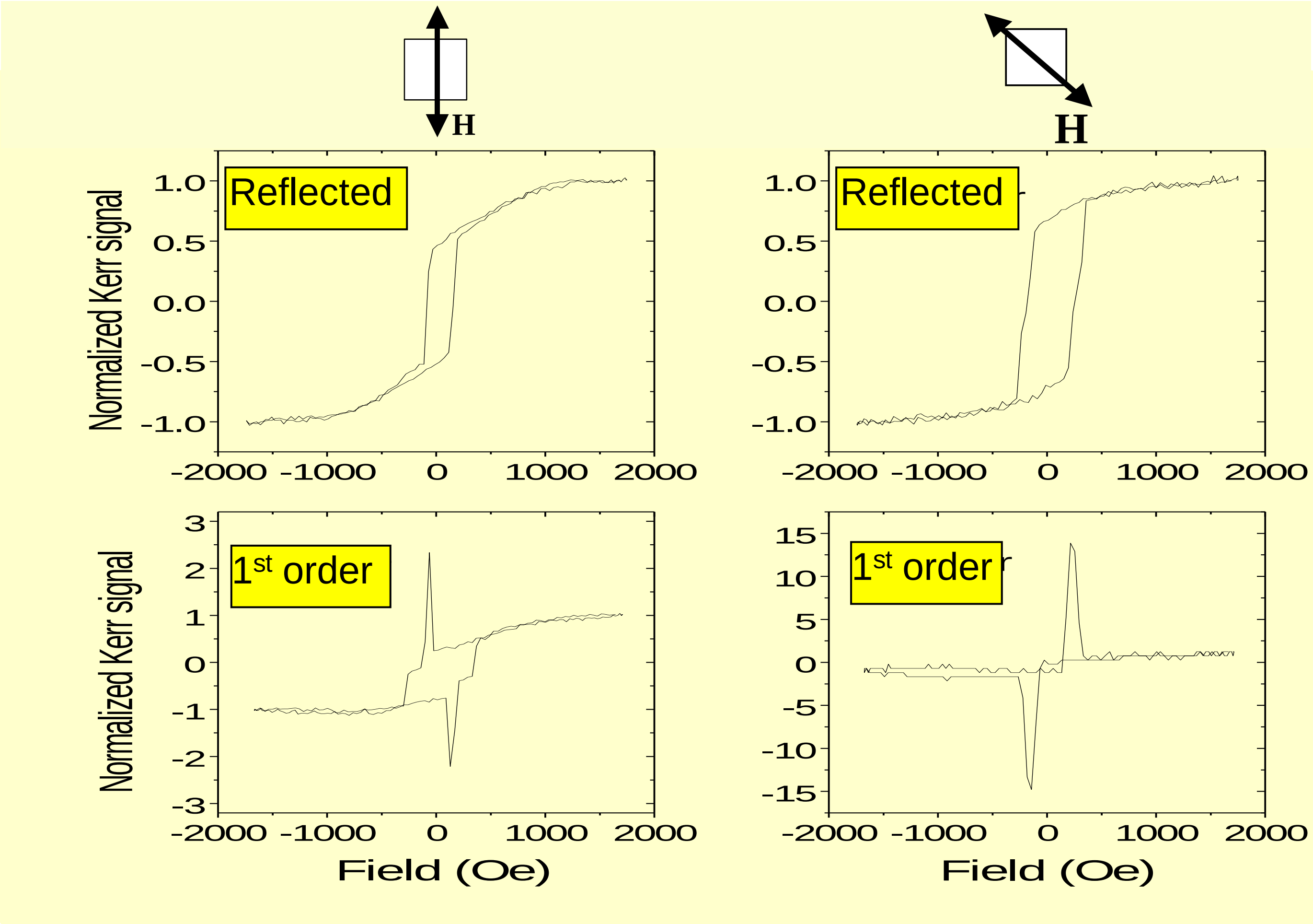


P. Vavassori, R. Bovolenta, V. Metlushko, and B. Ilic, J Appl. Phys. **99**, 053902 (2006)

Measured D-MOKE loops from square rings



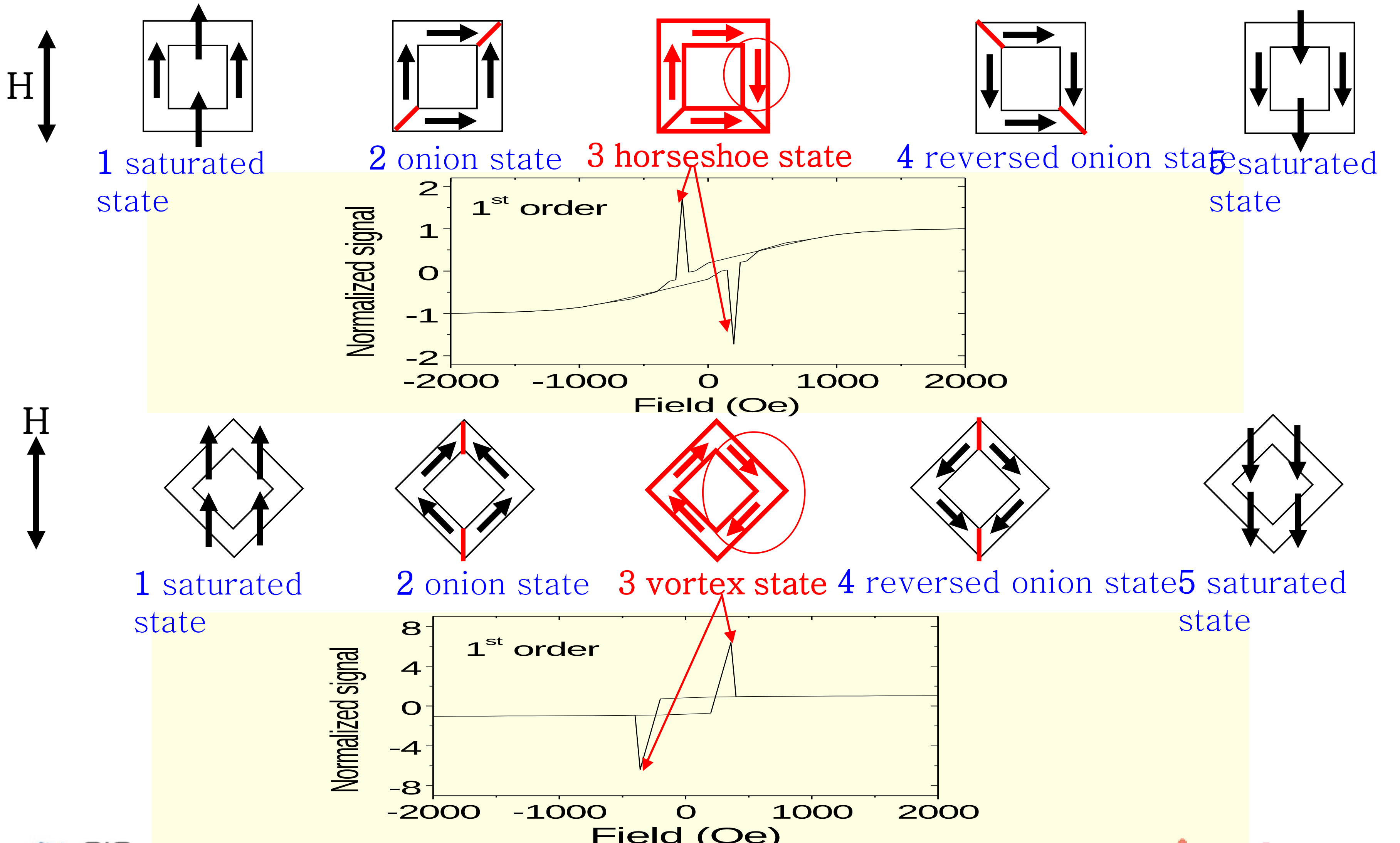
Square lattice (4.1x4.1 μm²) of Permalloy square rings (2.1 μm side). Nominal width 250 nm. Thickness 30 nm.



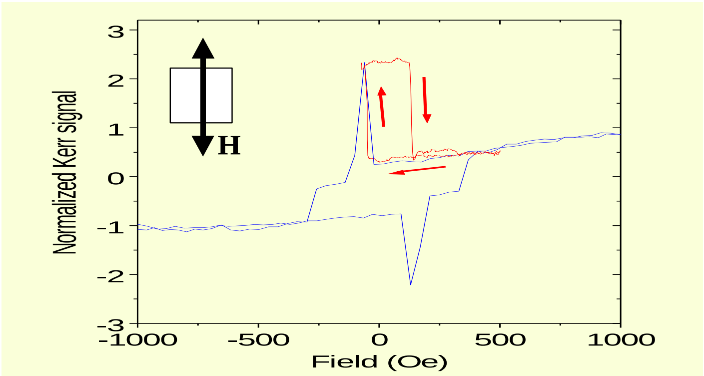
P. Vavassori, et al., Phys. Rev. B **67**, 134429 (2003)

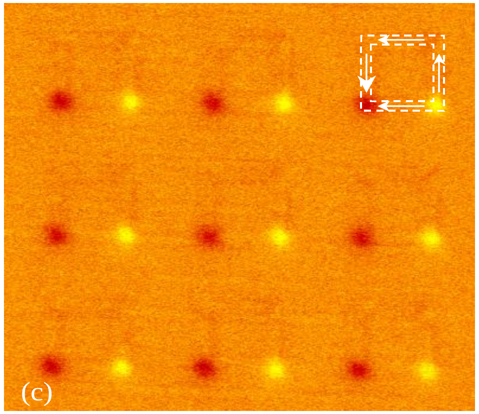
Note intense peaks in the diffracted loops

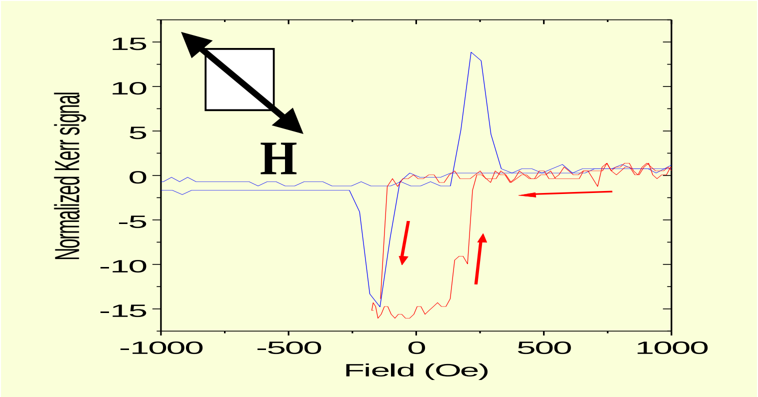
Square ring structures

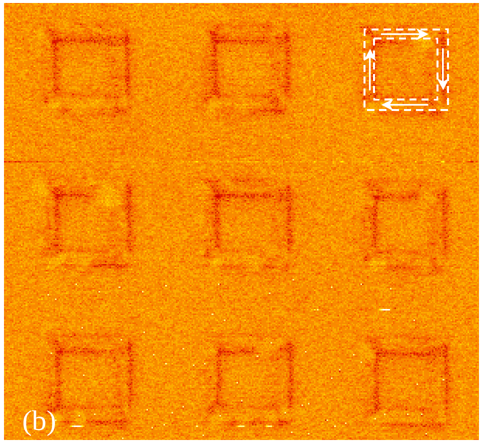


Quenching structures in intermediate states and image them with MFM









P. Vavassori, M. Grimsditch, V. Novosad, V. Metlushko, B. Ilic, P. Neuzil, and R. Kumar, Phys. Rev. B **67**, 134429 (2003)

Summary of theory of diffracted-MOKE

- Diffracted-MOKE (D-MOKE) loops are proportional to the magnetic form factor, or equivalently, to the Fourier component of the magnetization corresponding to the reciprocal lattice vector of the diffracted beam.

- D-MOKE can examine the collective properties of an array of magnetic nanoelements (requires an array ($\lambda/2$ < period < ≈10λ).

- In the examples shown so far it seems that D-MOKE data can only be used as a test of a proposed magnetic configuration: in cases where the micromagnetic simulations do not predict the observed D-MOKE loops, it is necessary to re-evaluate the assumptions.

- This is the exact equivalent to being able to calculate the intensity of any x-ray Bragg peak if the unit cell is known.

- What about the converse problem, i.e. extracting the magnetic configuration from the D-MOKE loops?

About A_n and B_n

$$\Delta I_n^m (m_y) = 2\, f_n^{nm} \{ A_n \mathrm{Re}[f_n^m] + B_n \,\mathrm{Im}[f_n^m] \}$$

A_n and B_n $(\theta_i, \theta_n, \varepsilon_{dots}, \varepsilon_{sub}, Q)$

$$A_n = \mathrm{Re}[r^o_{pp}{*}\, r^m_{pp}]$$

$$B_n = \mathrm{Im}[r^o_{pp}{*}\, r^m_{pp}]$$

$r'_{pp} = r^o_{pp} + r^m_{pp}$ "effective" reflectivity

Y. Suzuki, C. Chappert, P. Bruno, and P. Veillet, *J. Magn. Magn. Mater.* ***165*** 516 (1997) only for size >> λ

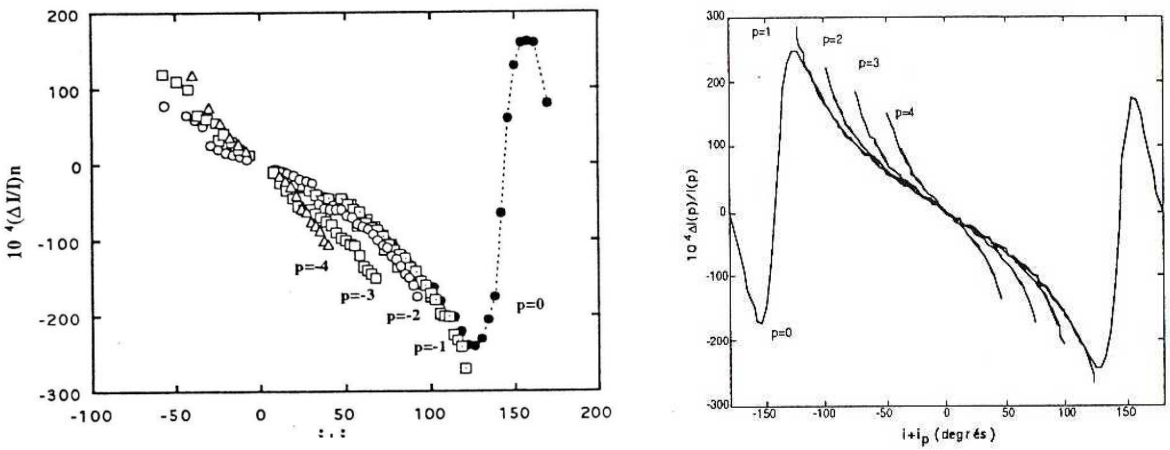
For inhomogeneous gratings $r^o_{pp} = r^o_{pp,\, dot} + r^o_{pp,\, sub}$

An interesting characteristic of D-MOKE related to this : the absolute value of $(\Delta I/I_o)_n$ is increased up to several times the specular value. Effect due to the compensation of the non-magnetic component of the light diffracted by the magnetic dots and the light diffracted by the (non-magnetic) complementary part of the substrate.

$$I_{o,n} = |r^o_{pp,\, dot}|^2 f_n^{nm} + |\, r^o_{pp,\, sub}\,|^2 f'^{nm}_n = (\,|r^o_{pp,\, dot}|^2 - |\, r^o_{pp,\, sub}\,|^2\,) f_n^{nm}$$

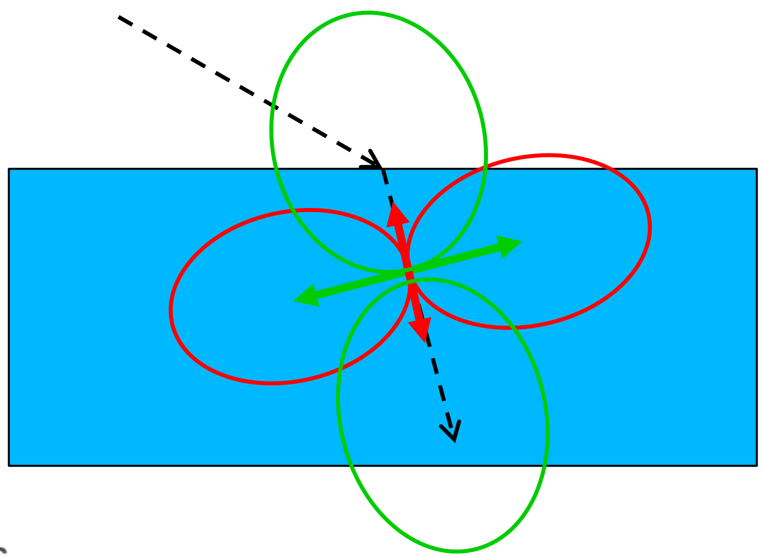
Theoretical approaches

Perturbative approach of the Rayleigh theory.



Quantitative agreement
Complicated
Requires ε_{dots}, ε_{sub}, Q

D. van Labeke, A. Vial, V. Novosad, Y. Souche, M. Schlenker, A.D. Santos, Optics Communications, **124** (1996) 519



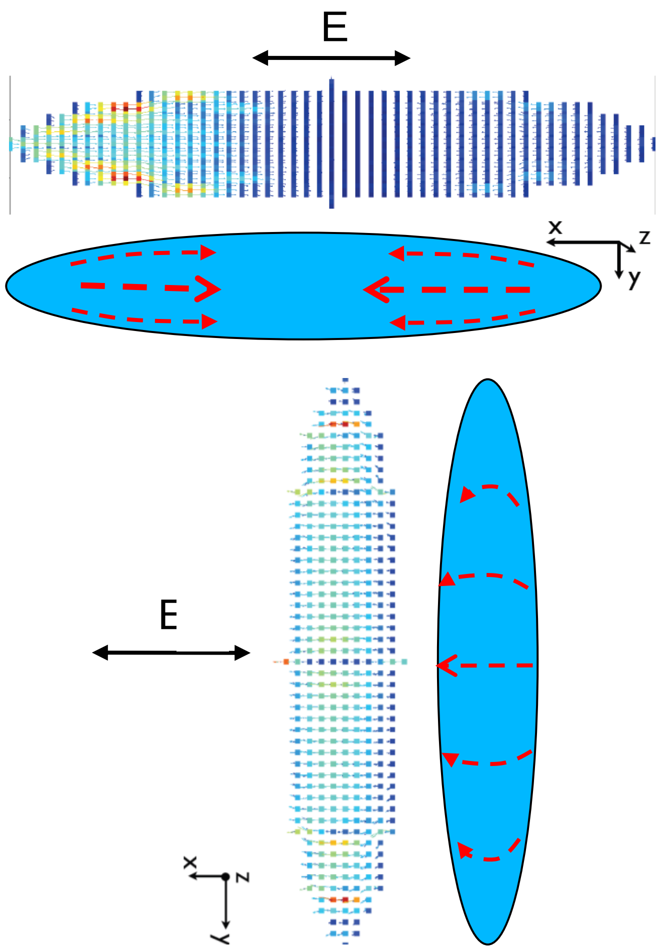
Induced dipole $\mathbf{p} = ([\varepsilon] - \varepsilon_o I)\mathbf{E}_o$

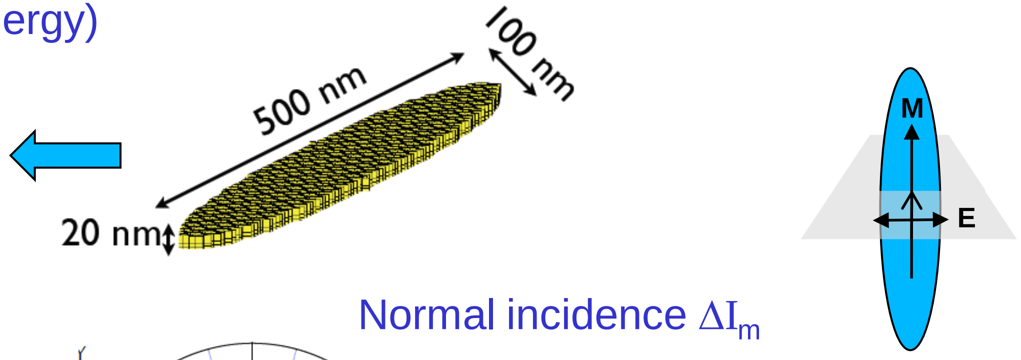
Quantitative agreement only for I_o
Simple
Requires ε_{dots}, ε_{sub}, Q

Finite size effects

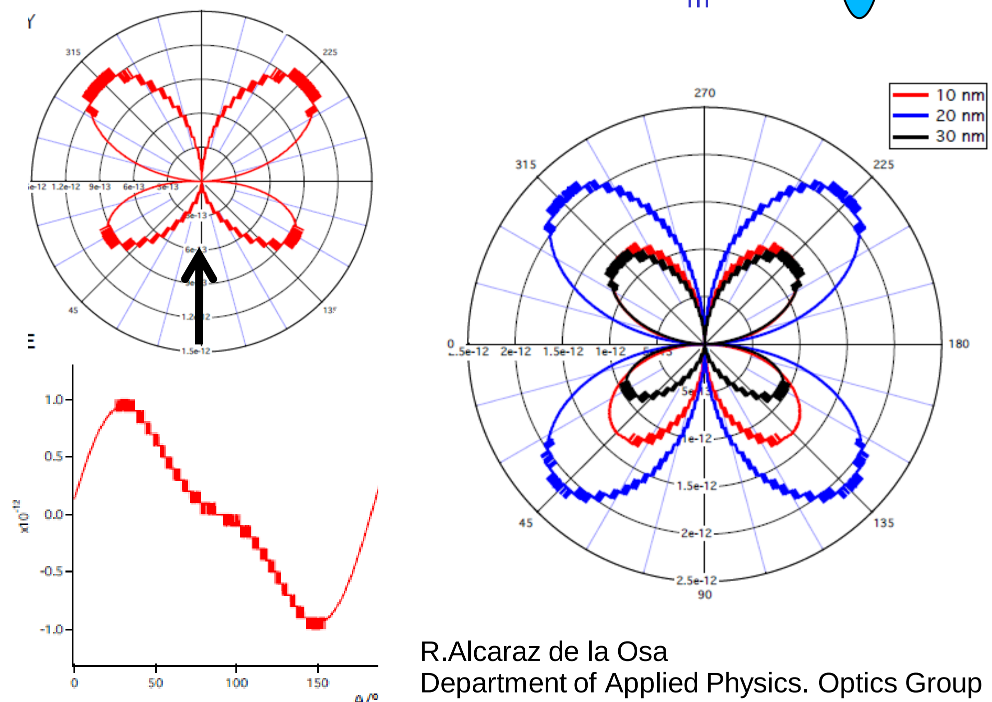
Numerical simulations based on the discrete dipole approximation for magneto-optical scattering

E field maps (S is important: flux energy)





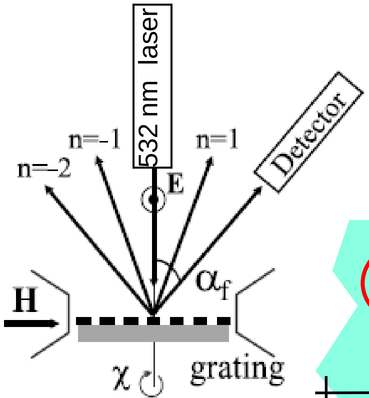
Normal incidence ΔI_m

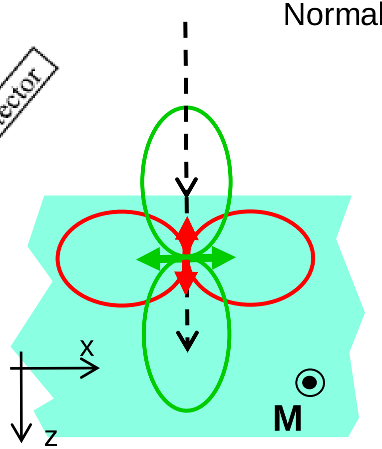


D. A. Smith and K. L. Stokes, Opt. Express **14**, 5746 (2006)

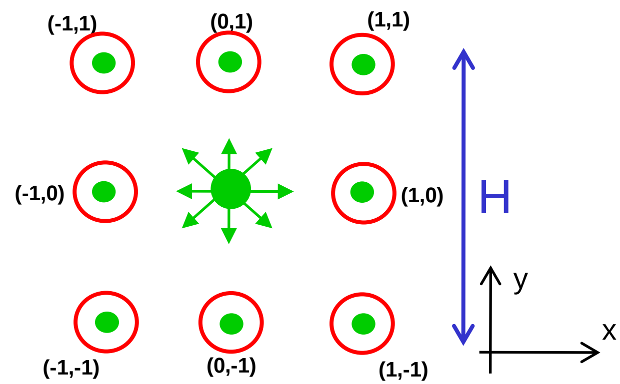
R.Alcaraz de la Osa
Department of Applied Physics. Optics Group
Faculty of Sciences. University of Cantabria

Different approach: towards Fourier imaging? 1st step





Normal incidence: the scattering plane is defined by the selected spot

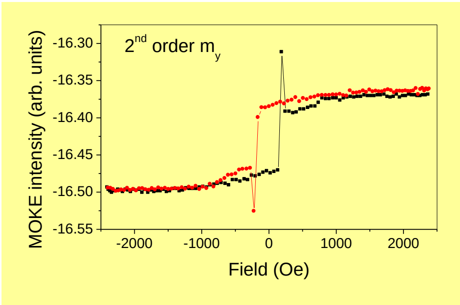


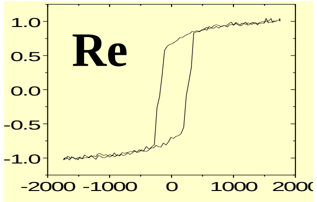
Sensitivity to (m_x , m_y)

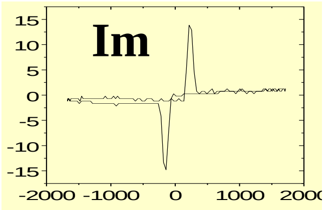
Sensitivity to m_y

$$(\Delta I_n^{\,m})_{norm} = A_n\,\mathrm{Re}[f_n^{\,m}] - B_n\,\mathrm{Im}[f_n^{\,m}]$$

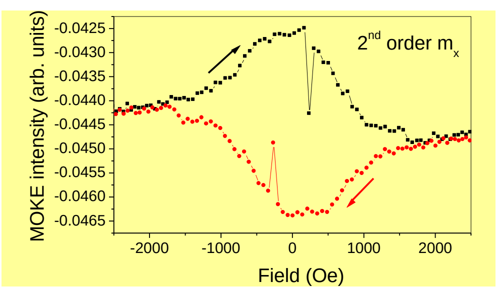
$$(\Delta I_{-n}^{\,m})_{norm} = -A_n\,\mathrm{Re}[f_n^{\,m}] - B_n\,\mathrm{Im}[f_n^{\,m}]$$





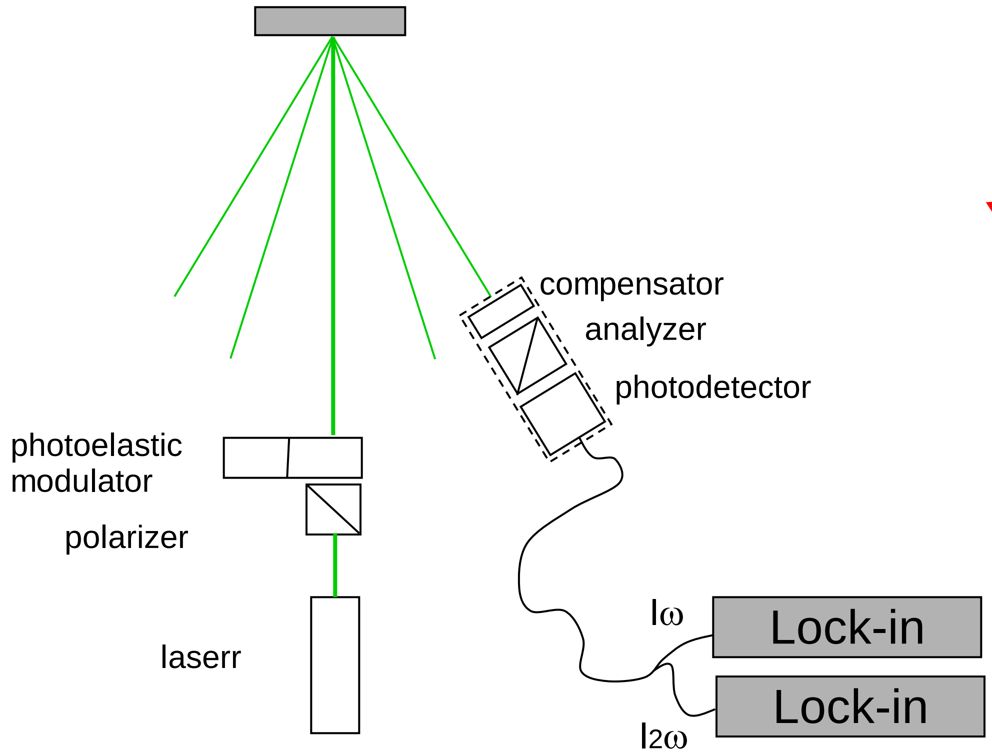


Sensitivity to m_x



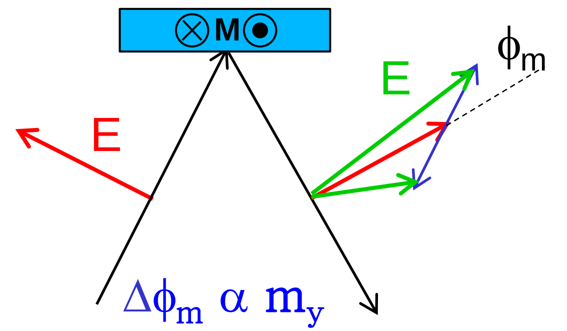
Vectorial D-MOKE

D-MOKE problem fully solved



$Im[\Delta r_m/r_0] = \Delta\phi_m/\phi_0$

$Re[\Delta r_m/r_0] = \Delta I_m/I_0$



$\Delta I^n{}_m/I^n{}_o = A_n\, Re[f_n{}^m] - B_n\, Im[f_n{}^m]$ $\Delta I^{-n}{}_m/I^{-n}{}_o = -A_n\, Re[f_n{}^m] - B_n\, Im[f_n{}^m]$

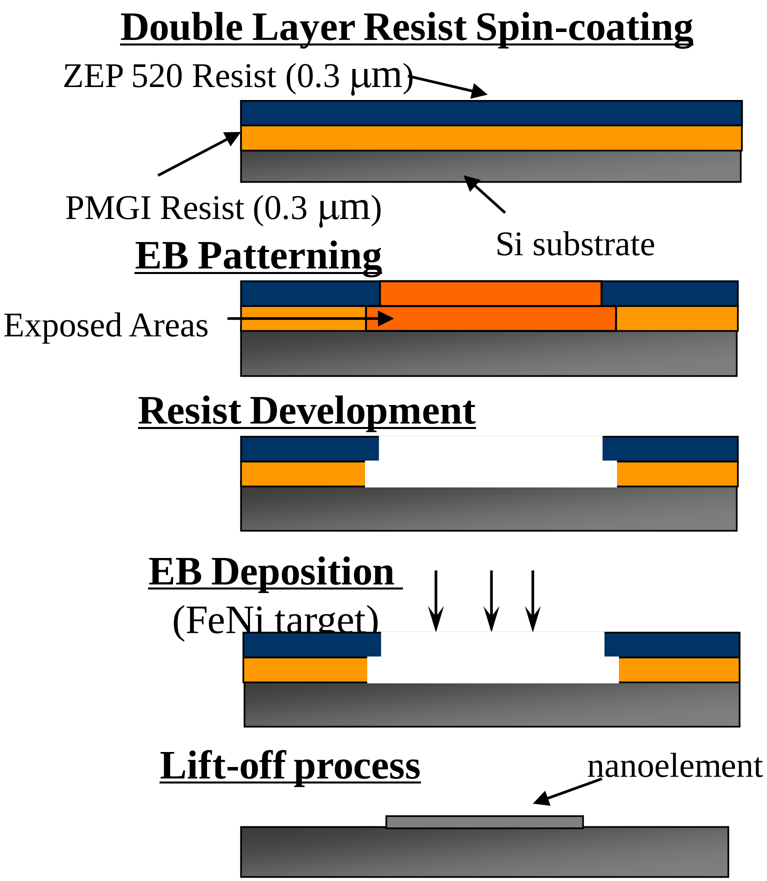
$\Delta\phi^n{}_m/\phi^n{}_o = B_n\, Re[f_n{}^m] - A_n\, Im[f_n{}^m]$ $\Delta\phi^{-n}{}_m/\phi^{-n}{}_o = -B_n\, Re[f_n{}^m] - A_n\, Im[f_n{}^m]$

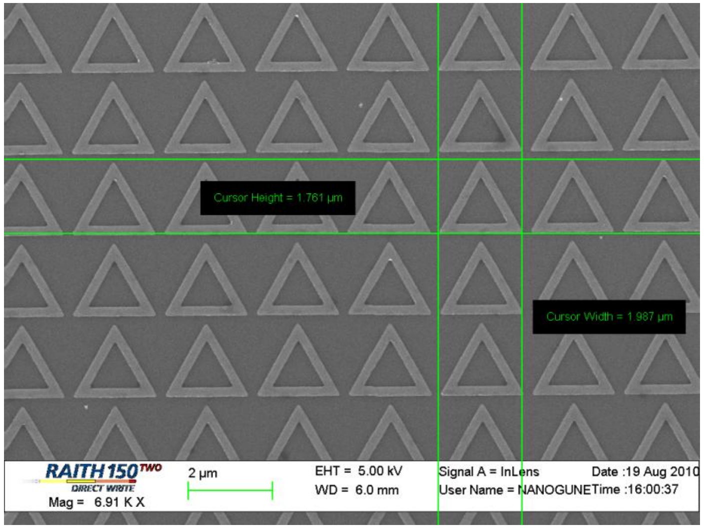
$\Rightarrow$ $Re[f_n{}^m]$, $Im[f_n{}^m]$

K. Postava et al. “Null ellipsometer with phase modulation,” Opt. Express **12**, 6040 (2004)

Samples: arrays of NiFe triangular rings

Electron beam lithography

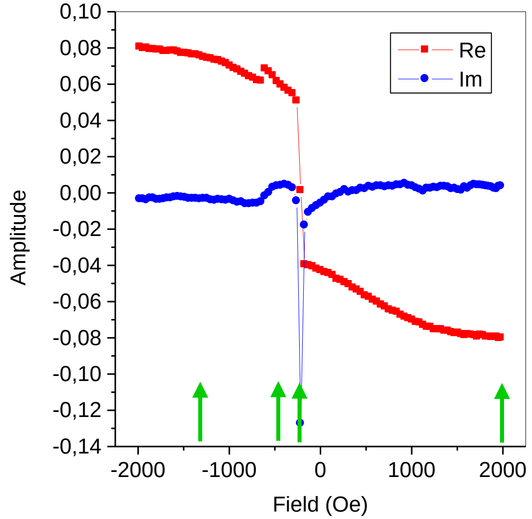




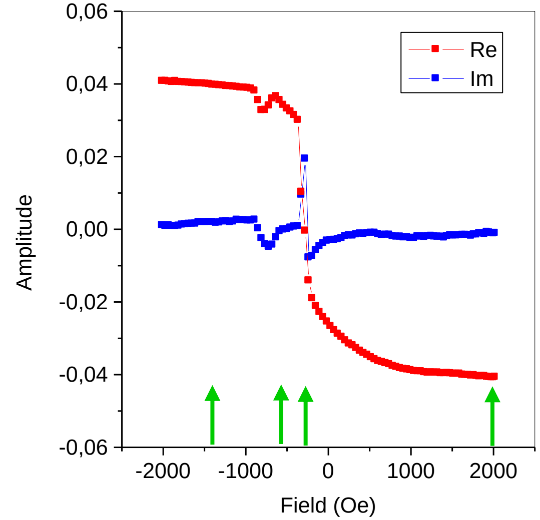
Triangular rings (2.1 μm side).
Nominal width 250 nm.
Nominal thickness 30 nm.

Re and Im parts of the magnetic form factors

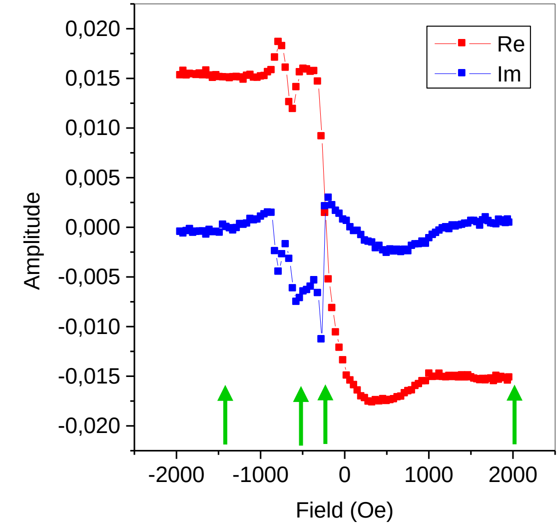
1st - h



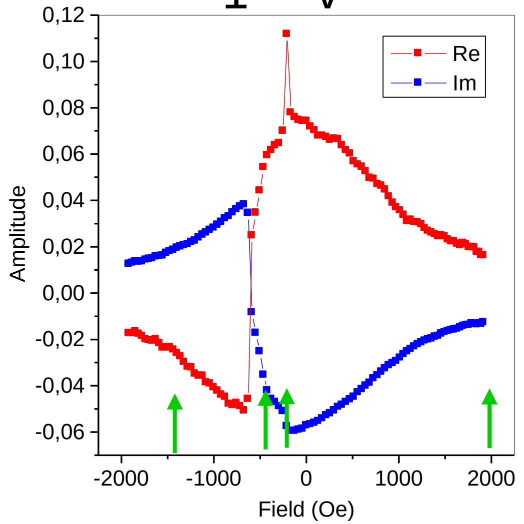
2nd - h



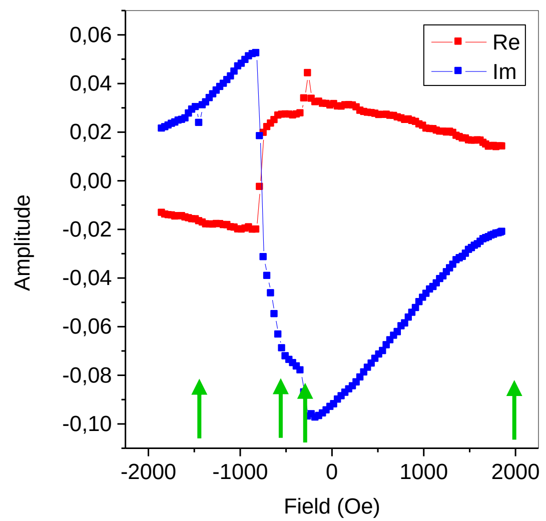
3rd - h



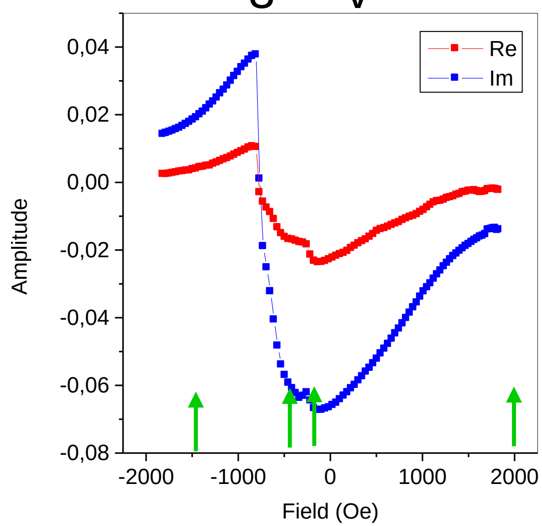
1st - v



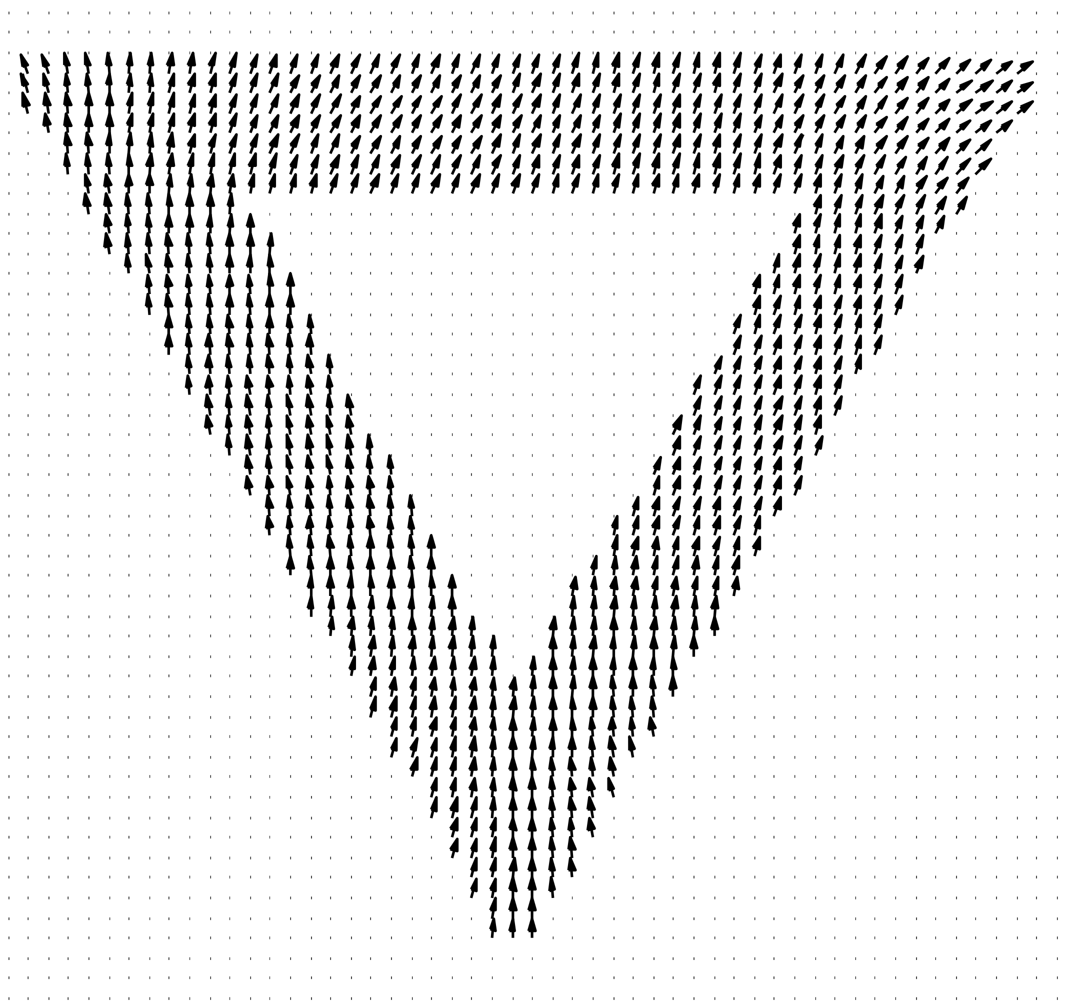
2nd - v



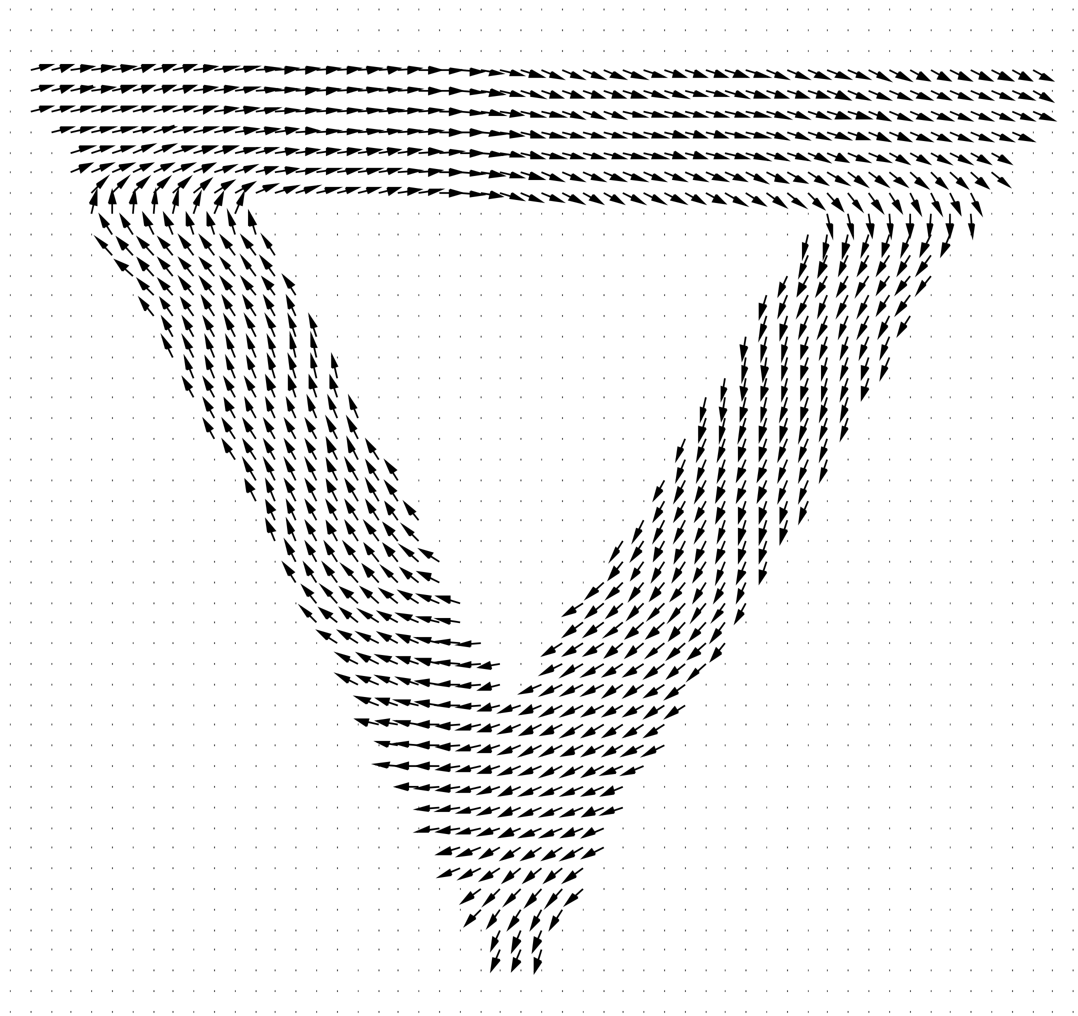
3rd - v



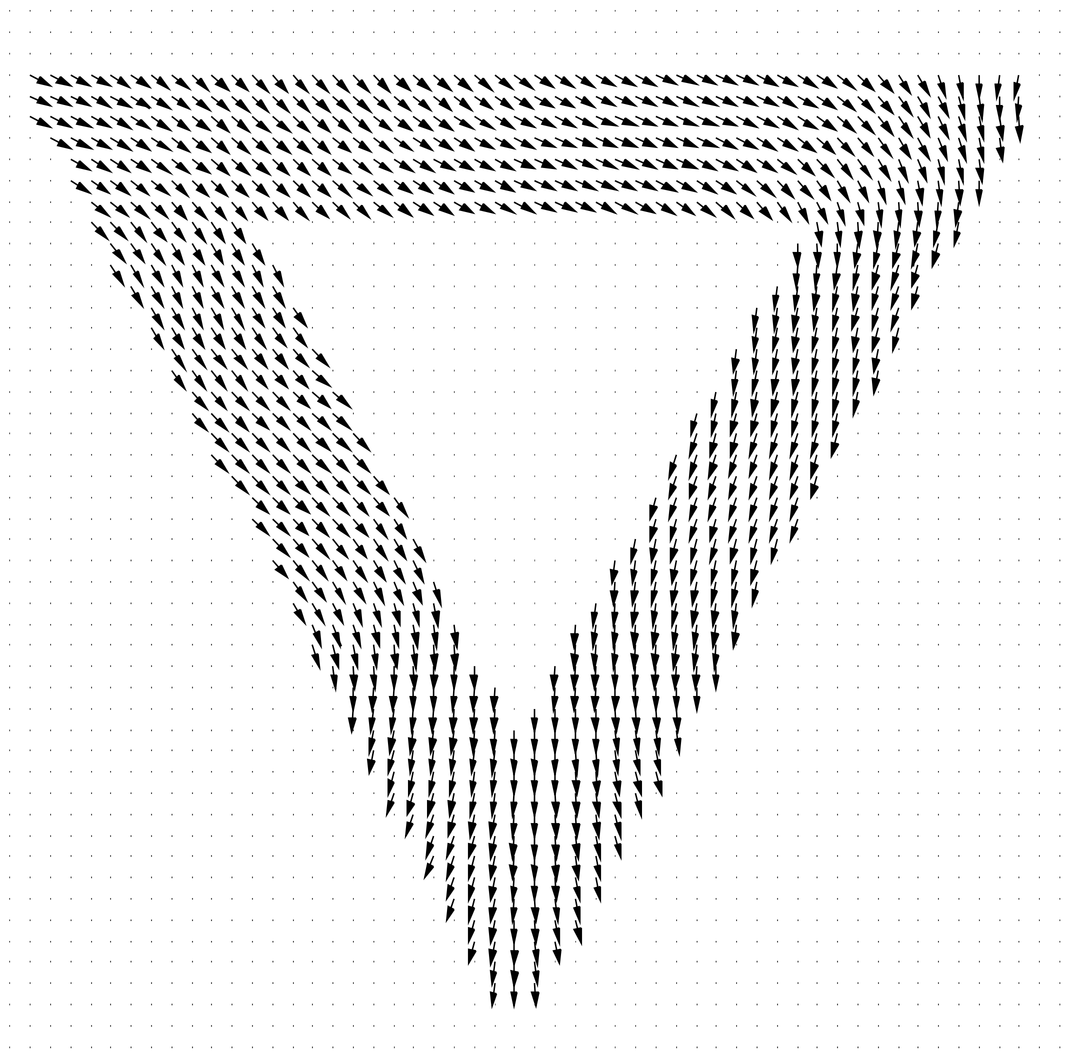
Saturated state



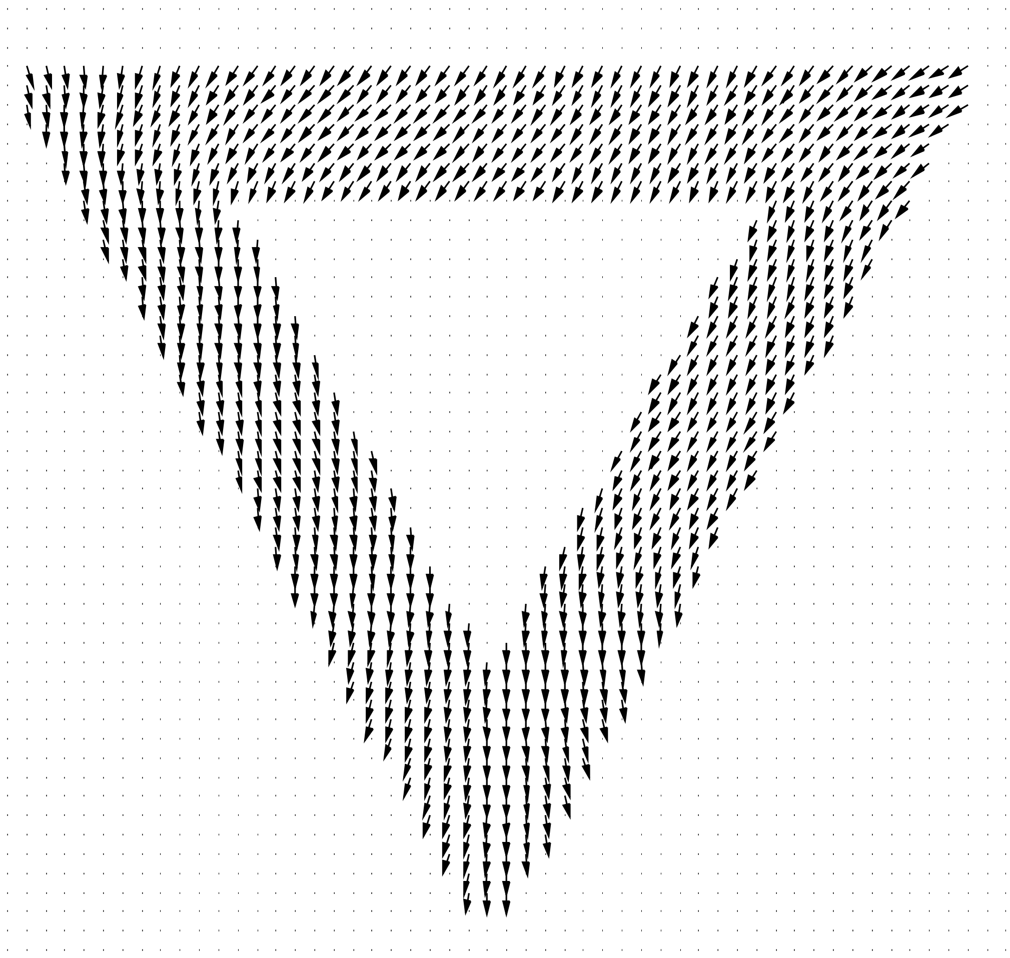
“Peak” state



After “peak”

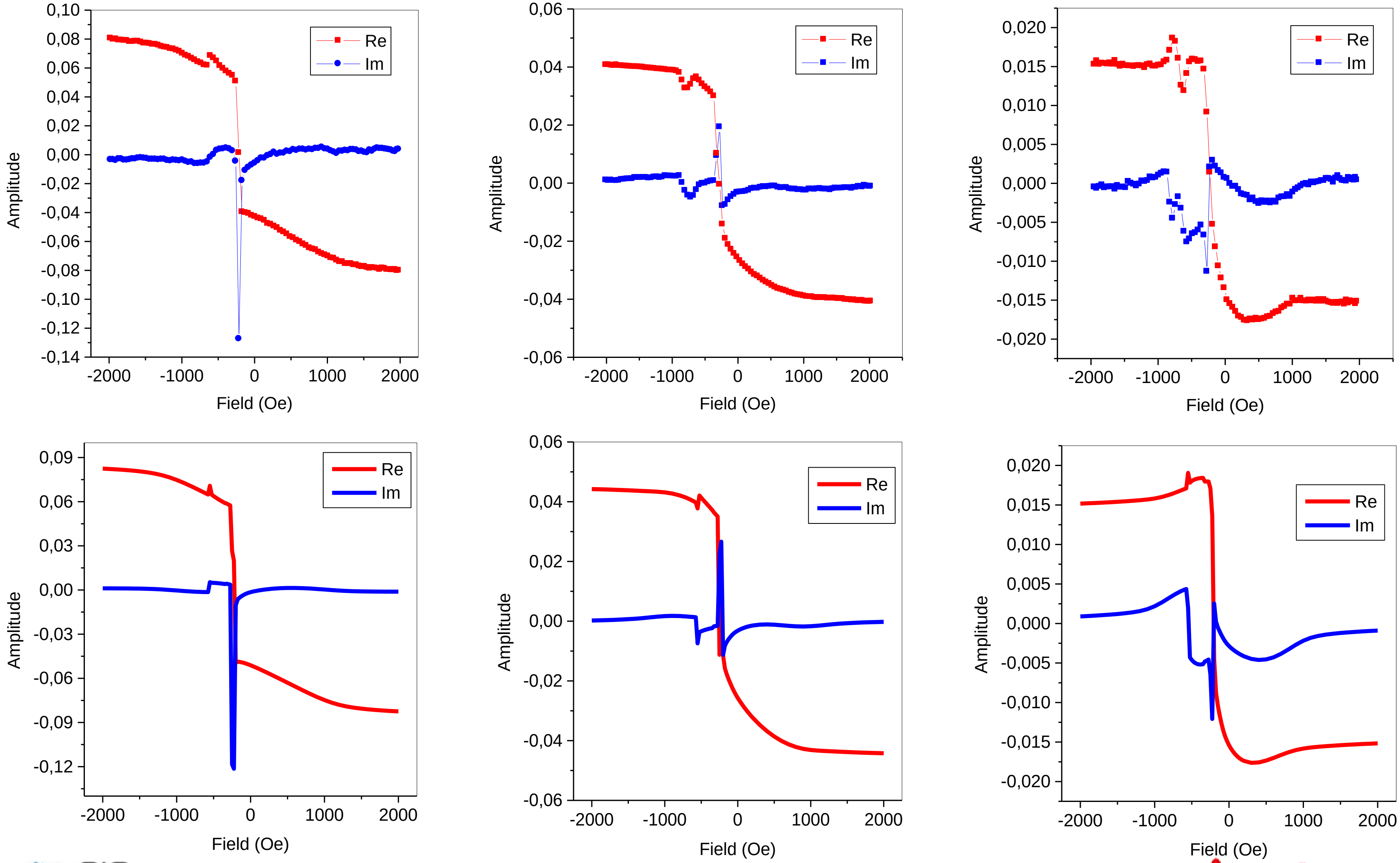


Towards negative saturation

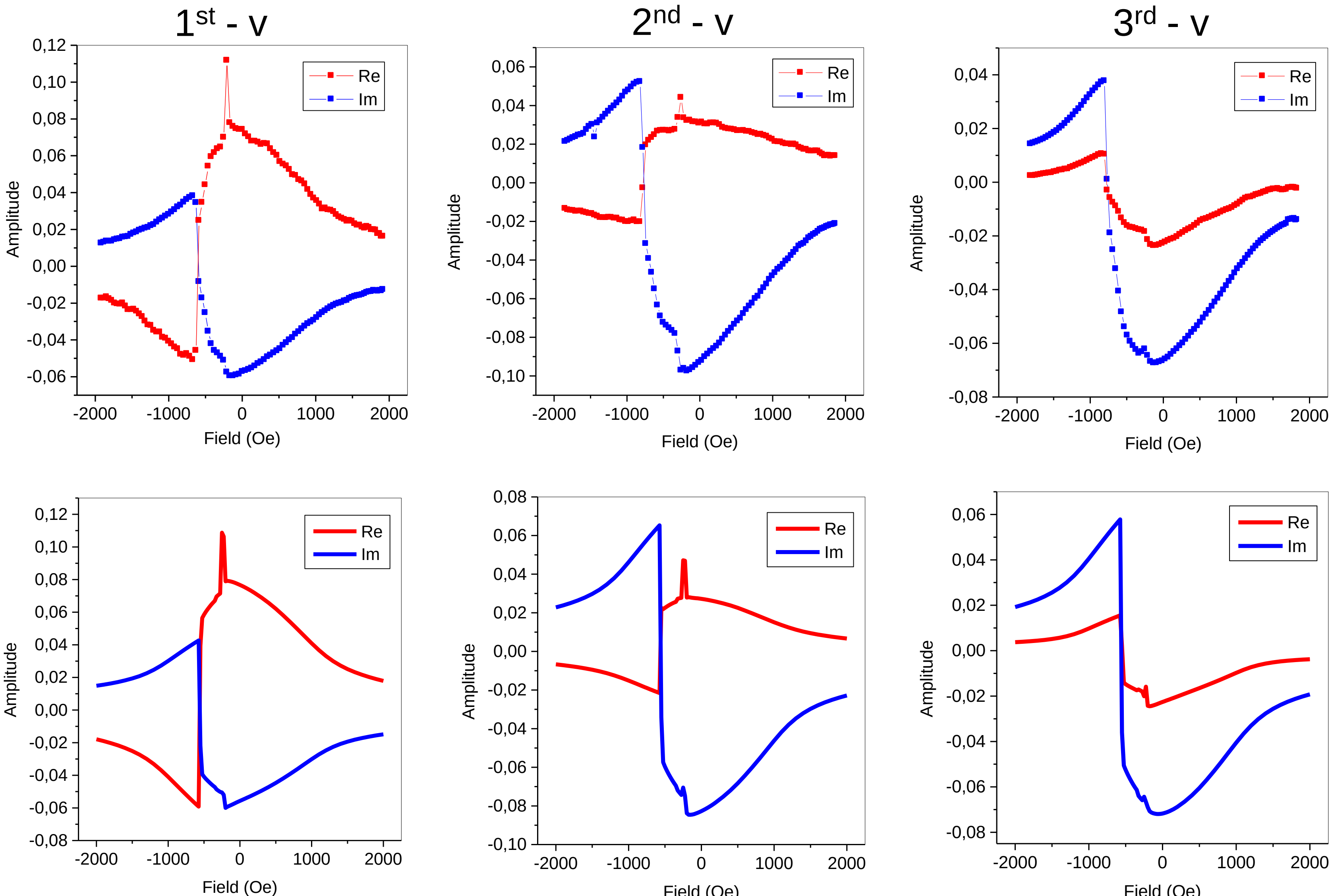


Exp and calculated Re[f_m] and Im[f_m] – horizontal plane

1^{st} - h | 2^{nd} - h | 3^{rd} - h

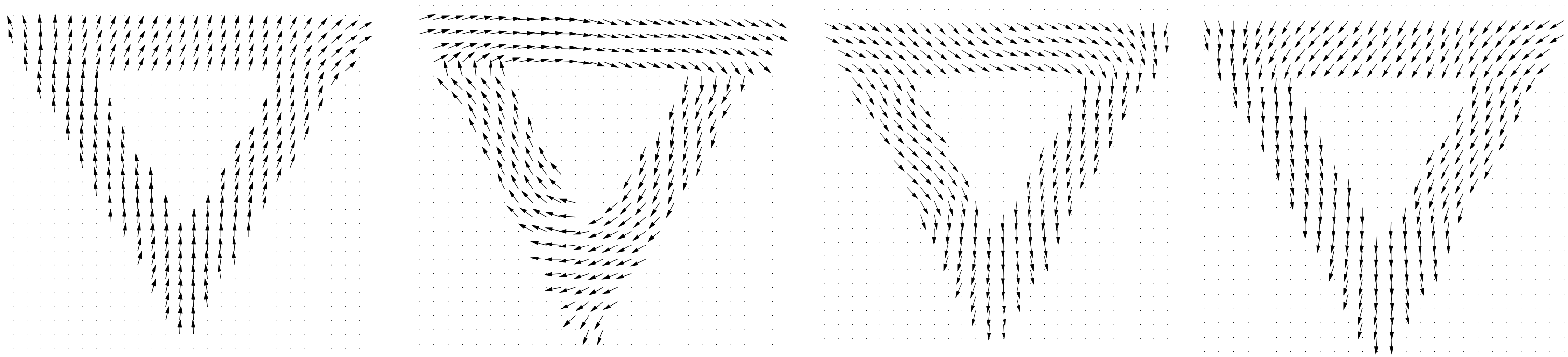


Exp and calculated Re[f_m] and Im[f_m] – vertical plane

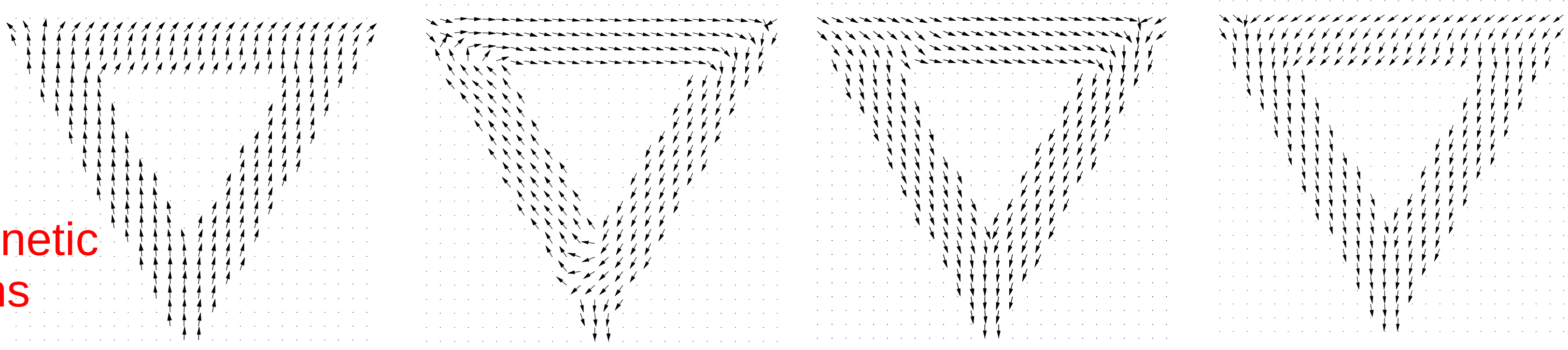


Magnetic imaging proved

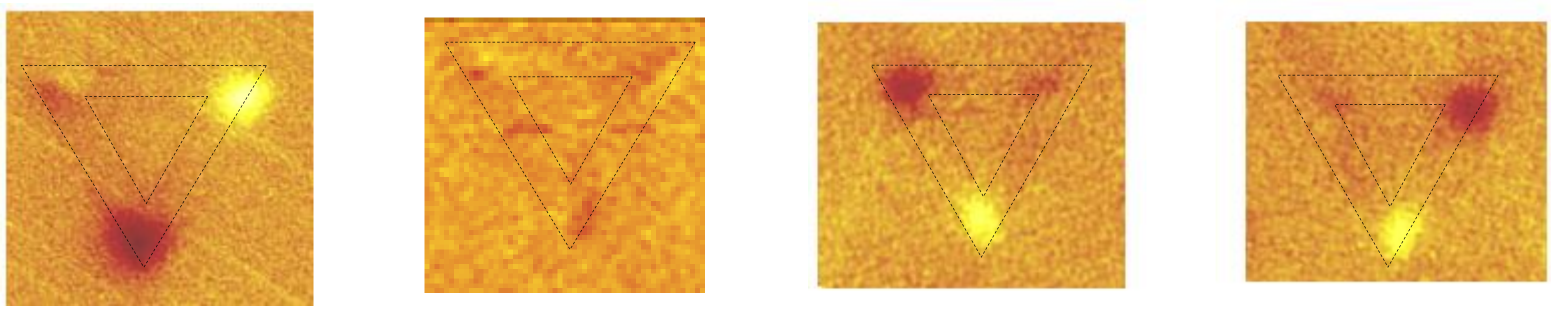
D-MOKE



Micromagnetic simulations



MFM (quenched To 0 field)



Concluding remarks

The examples presented in this talk are only a few of the many different cases investigated and reported in the literature. For example D-MOKE has been utilized to obtain the hysteresis loops of the two constituents of a superlattice array, the formation of domains in an array of antidots.

D-MOKE is a powerful technique to investigate the collective behavior of magnetic nano-arrays.

The 'Magnetic form factor' formalism provides a simple and transparent theoretical framework to interpret D-MOKE loops.

D-MOKE measurements using varying incidence polarization, at normal incidence, allows for the combination of "vector" MOKE with D-MOKE, providing a wealth of information about the magnetization process.

Extraction of the magnetic configuration from the D-MOKE loops.

Funding from the ETORTEK Program, Project No. IE06-172, the Basque Government under Program No. PI2009-17, the Spanish Ministry of Science and Education under Projects No. CSD2006-53 and No. MAT2009-07980