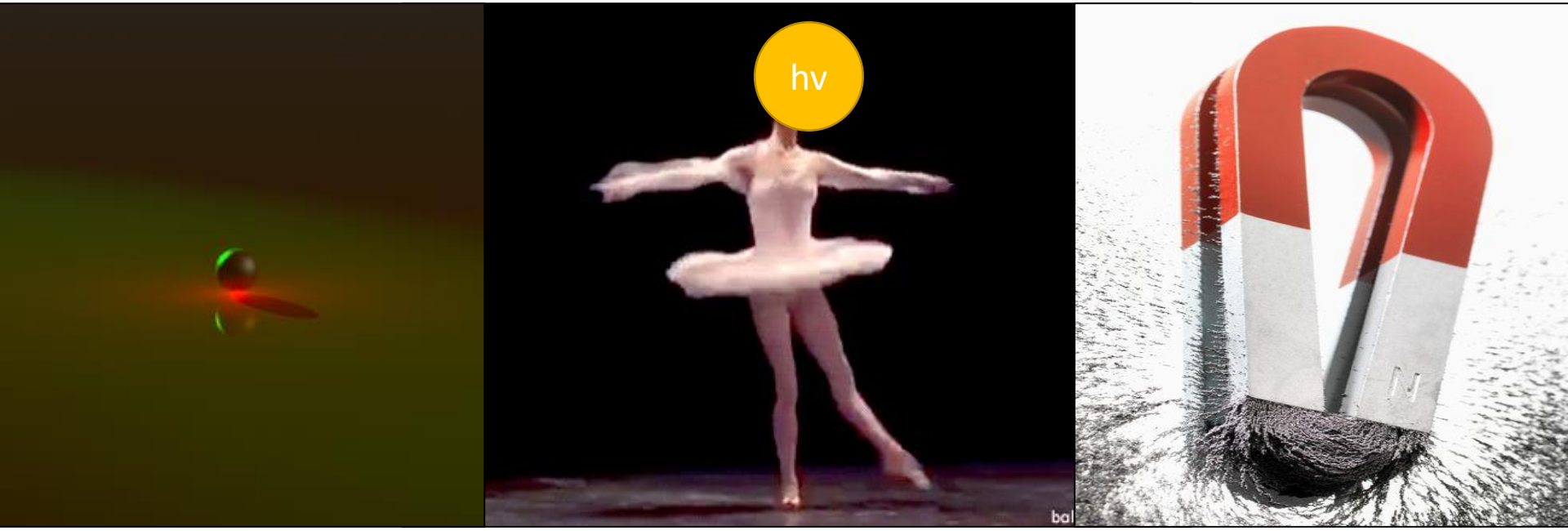
UNIVERSITY OF GOTHENBURG

Nano-optics with a spin: interplay between light and magnetism at the nanoscale



Chatdanai Lumdee (Tua, ตั๊ว)

Chulalongkorn University
February 3, 2017

Naresuan University
February 6, 2017

King Mongkut's Institute of Technology Ladkrabang
February 17, 2017

Outline

Where is Gothenburg?

Breaking down the title

Nano-optics with a spin: interplay between light and magnetism at the nanoscale

- Nano-optics and optical near-field
- Optical polarization and angular momentum
- Light and magnetism
- Why nanoscale?

Hybrid metallic-magnetic nanostructures

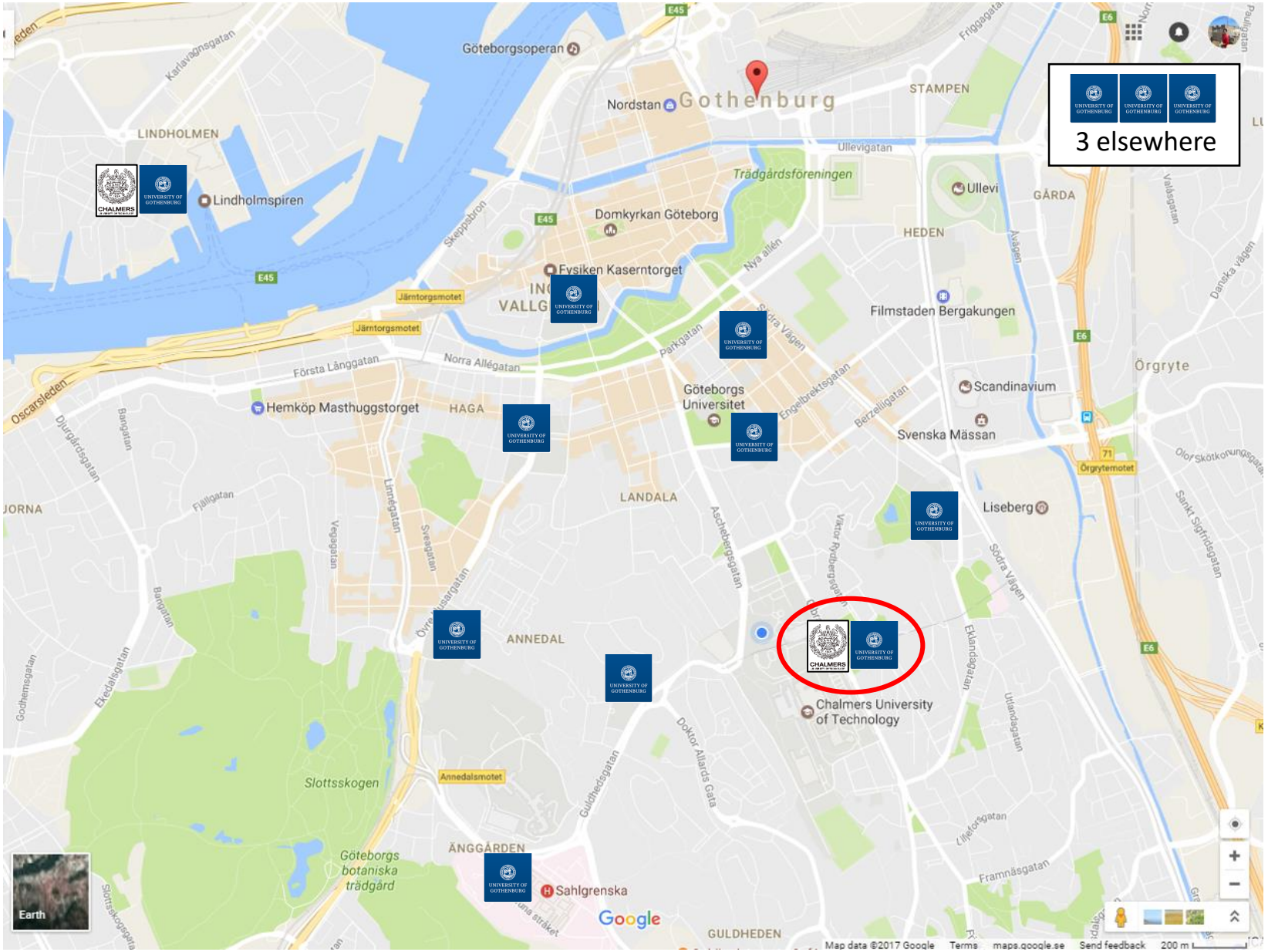
Plasmon-induced magneto-optical effects

Summary and future plan

Gothenburg (Swedish: Göteborg)

Gothenburg (Swedish: Göteborg)

Gothenburg (Swedish: Göteborg)



Education and research institutes

UNIVERSITY OF GOTHENBURG

UNIVERSITY OF GOTHENBURG

UNIVERSITY OF GOTHENBURG

CHALMERS

Gothenburg Physics Centre

AVANCEZ 1829

CHALMERS

UNIVERSITY OF TECHNOLOGY

MC2

1240 m^2 of cleanroom classified area

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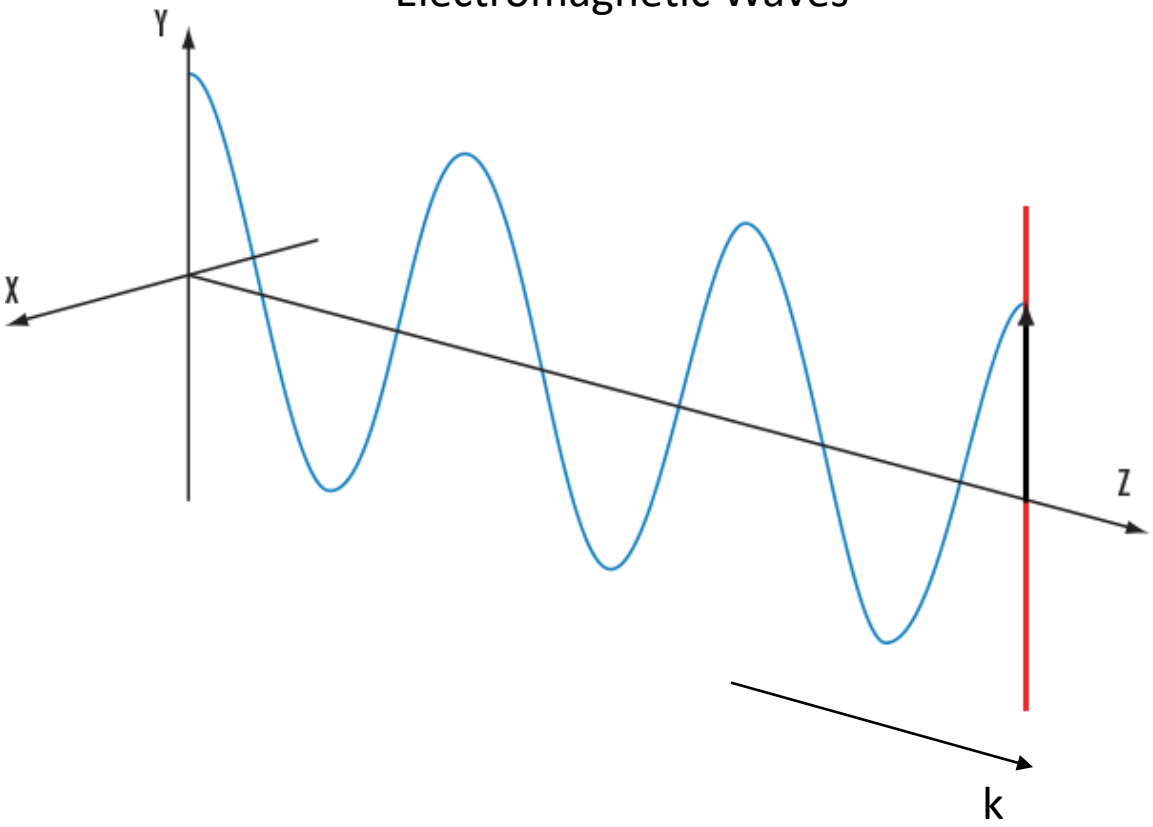
http://www.edmundoptics.com/resources/application-notes/optics/introduction-to-polarization/

Electromagnetic Waves



Nano-optics?

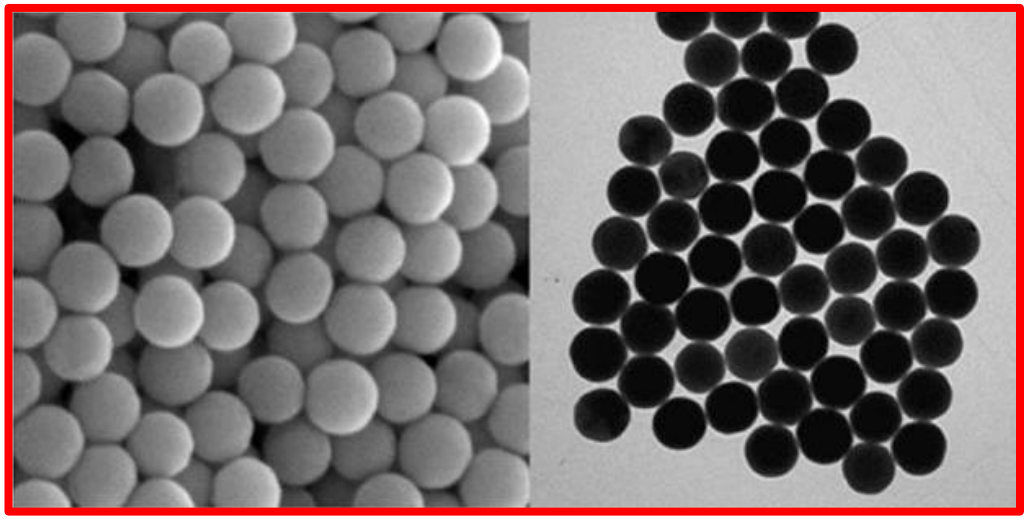
Nanophotonics

From Wikipedia, the free encyclopedia

Nanophotonics or **nano-optics** is the study of the behavior of light on the nanometer scale, and of the interaction of nanometer-scale objects with light. It is a branch of optics, optical engineering, electrical engineering, and nanotechnology. It often (but not exclusively) involves metallic components, which can transport and focus light via surface plasmon polaritons.

Optical resonances by metallic **nanostructures** (plasmons)

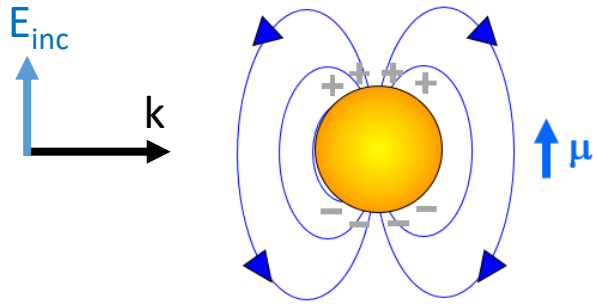
Simplest form → nanosphere



ACS Nano 7, 11064 (2013)

Optical Near-field

Single NP in free space



Electrostatic approximation

Particle << wavelength

$$\frac{E_{in}}{E_{inc}} = -3\frac{\epsilon_{out}}{\epsilon_{in} + 2\epsilon_{out}}$$ (Homogeneous)

Boundary conditions

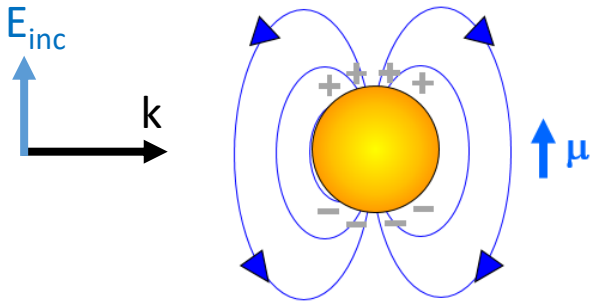
$$\frac{E_{out}}{E_{inc}} = -3\frac{\epsilon_{in}}{\epsilon_{in} + 2\epsilon_{out}}$$ (on NP surface)

Real metal: $\epsilon_{in}(\omega) = \epsilon'(\omega) + i\epsilon''(\omega)$ $\boxed{E_{in}\ and\ E_{out} \to \infty}$ $when$ $\epsilon_{in} + 2\epsilon_{out} = 0$

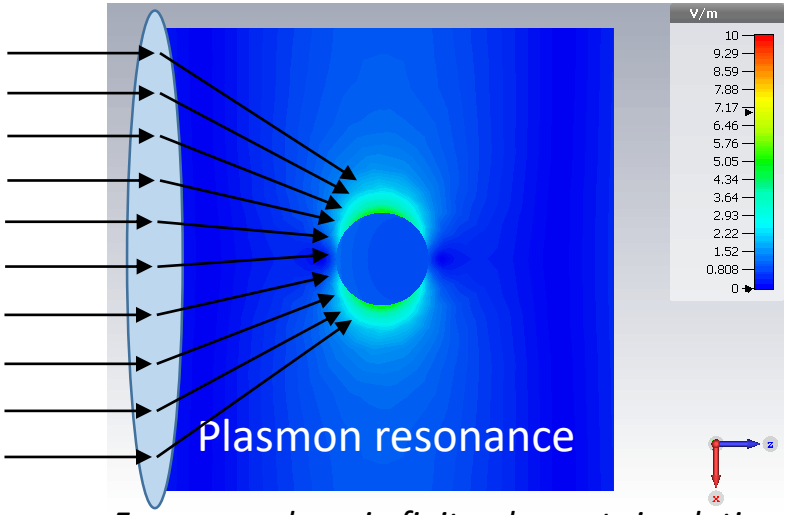
(resonance frequency)

Optical Near-field

Single NP in free space



50 nm diameter Au NP in water



Frequency domain finite-element simulation

Real metal: $\epsilon_{in}(\omega) = \epsilon'(\omega) + i\epsilon''(\omega)$ $E_{in}\ and\ E_{out} \rightarrow \infty$ $when$ $\epsilon_{in} + 2\epsilon_{out} = 0$

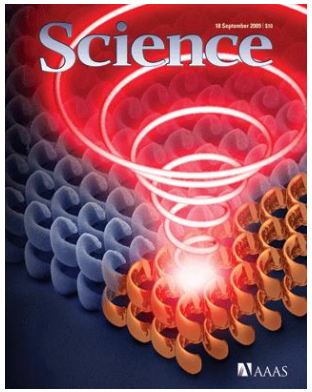
(resonance frequency)

Near-field $\propto \frac{1}{r^3}$ Decays quickly → localized in a nm^3 volume (nano-optics)

Nano-optics?

Examples of applications:

Science 325, 1513 (2009)

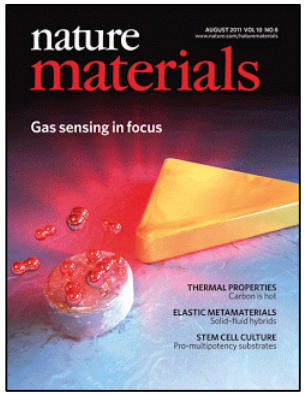


Broadband circular polarizer

Nano Letters 10, 1537 (2010)

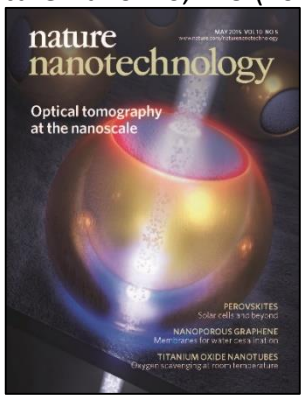
Nanodisk resonators

Nature Mat. 10, 631 (2011)



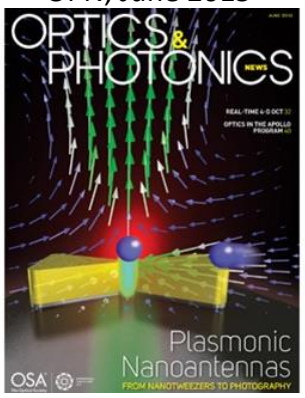
Gas sensor

Nature Nano. 10, 429 (2015)



3D imaging

OPN, June 2015



More …

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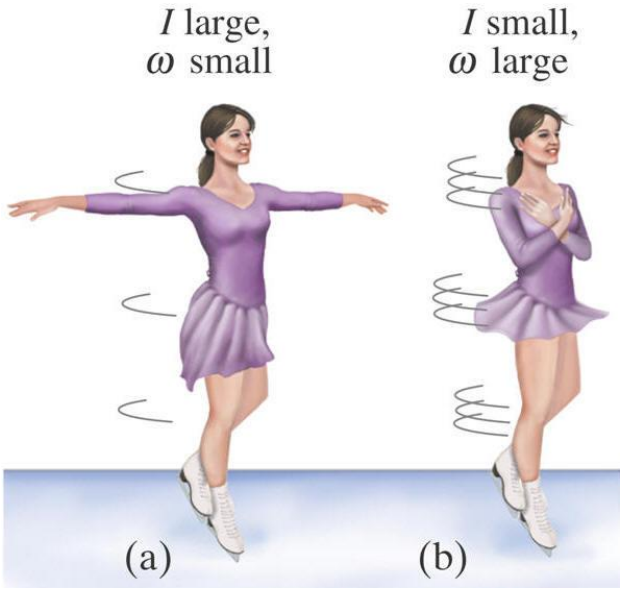
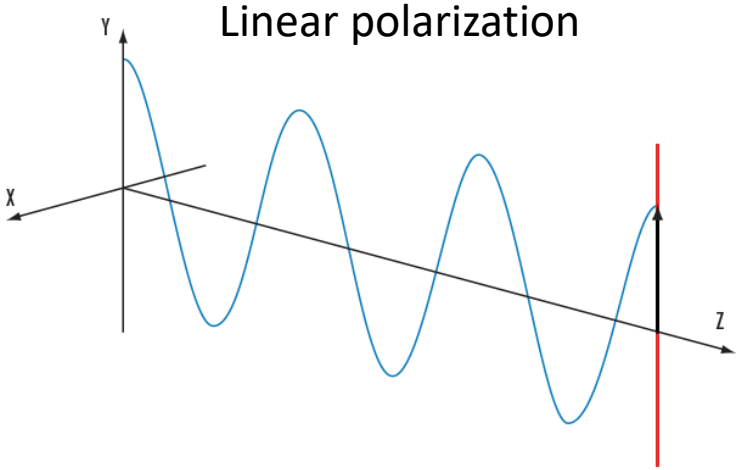


http://ffden-2.phys.uaf.edu/webproj/211_fall_2014/Ariel_Ellison/Ariel_Ellison/Angular.html

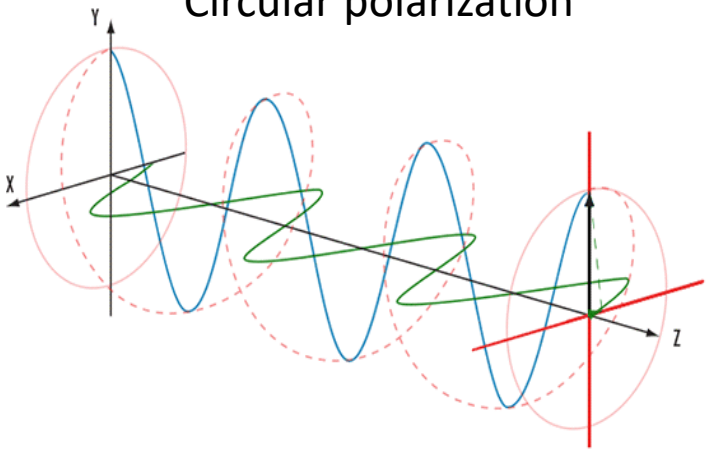
Optical polarization and angular momentum

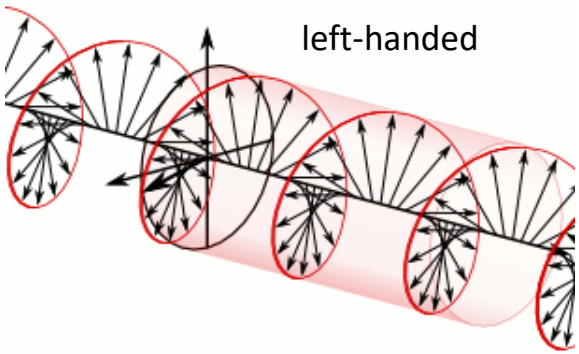
http://www.edmundoptics.com/resources/application-notes/optics/introduction-to-polarization/

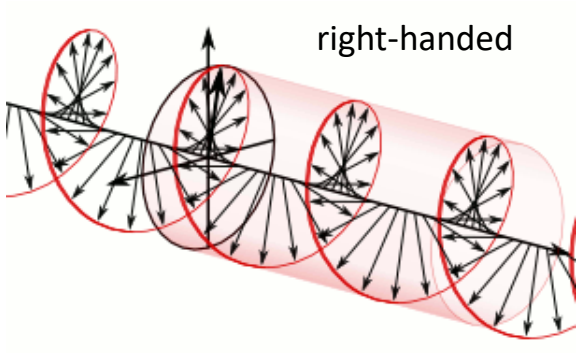
Linear polarization



Circular polarization

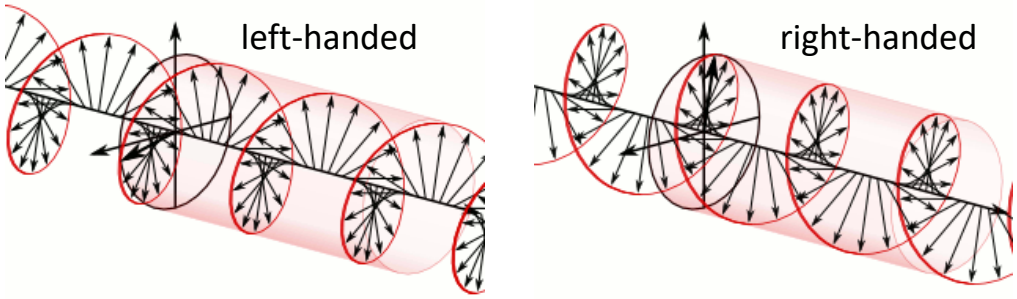




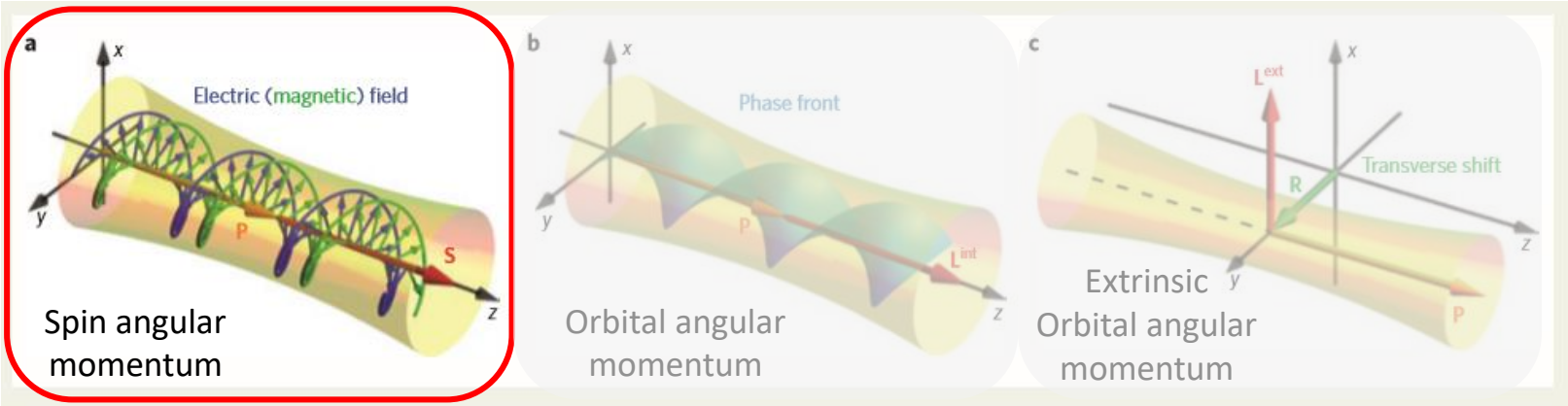


https://en.wikipedia.org/wiki/Circular_polarization

Optical polarization and angular momentum



Nature Phot. 9, 796 (2015) <review>

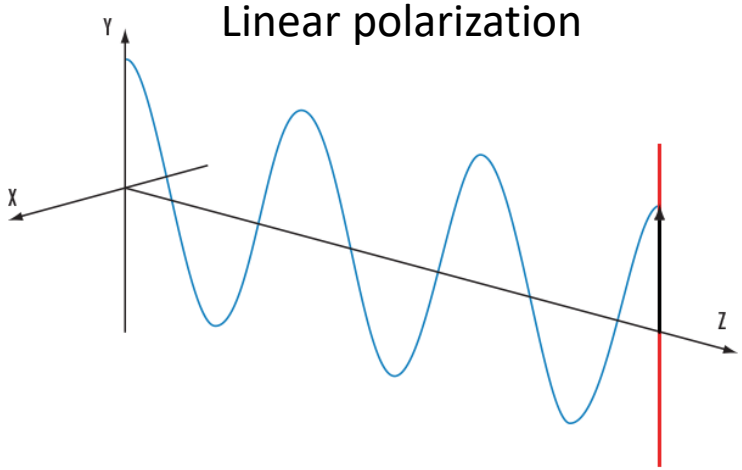


Angular momenta of paraxial optical beams. a, SAM for a right-hand circularly polarized beam with $\sigma = 1$. The instantaneous electric and magnetic field vectors are shown. **b**, IOAM in a vortex beam with $\ell = 2$. The instantaneous surface of a constant phase is shown. **c**, EOAM due to the propagation of the beam at a distance **R** from the coordinate origin.

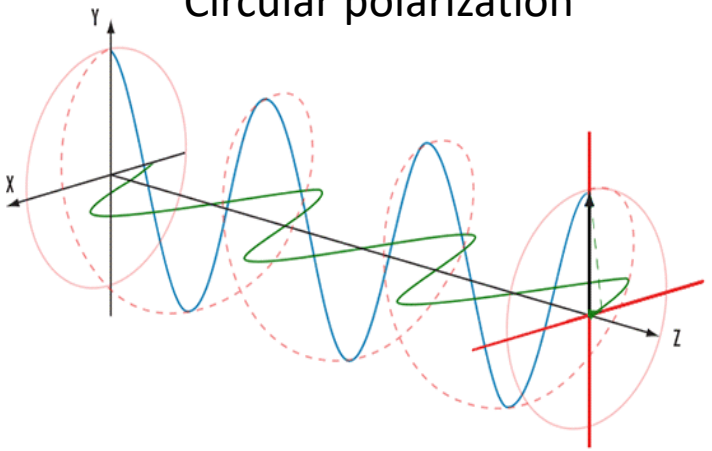
Optical polarization and angular momentum

http://www.edmundoptics.com/resources/application-notes/optics/introduction-to-polarization/

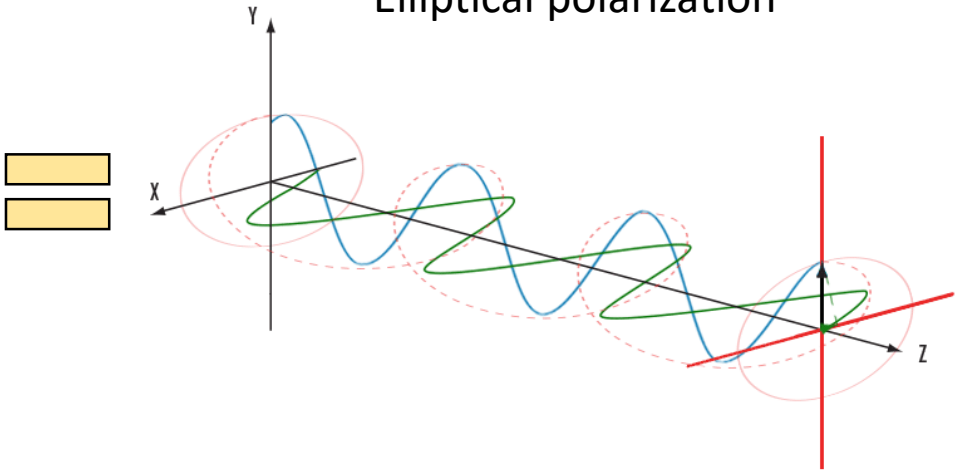
Linear polarization

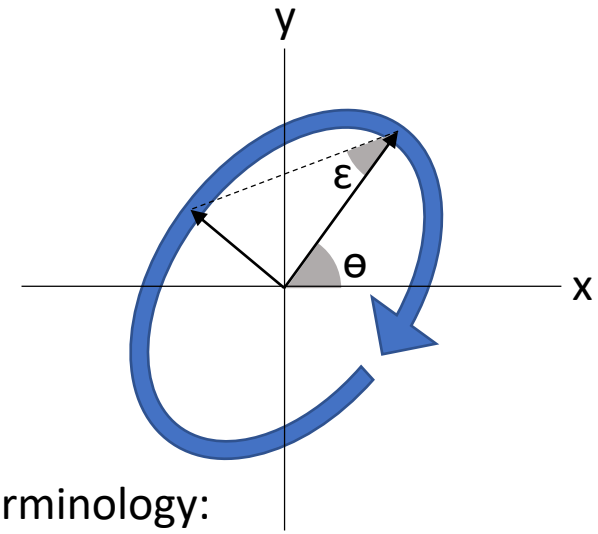


Circular polarization



Elliptical polarization





Terminology:
ϴ = rotation,
ε = ellipticity (and handedness)

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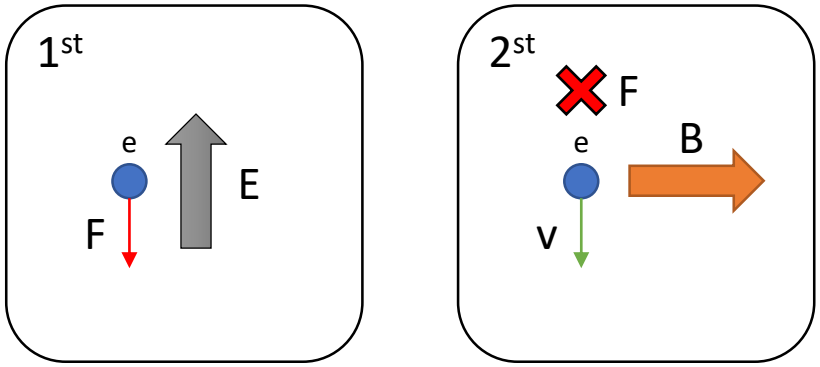
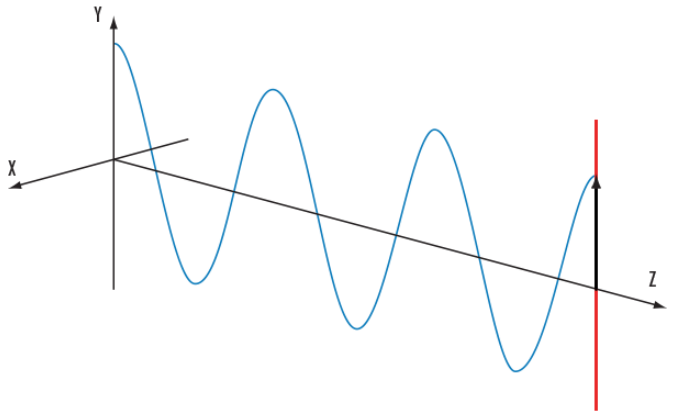
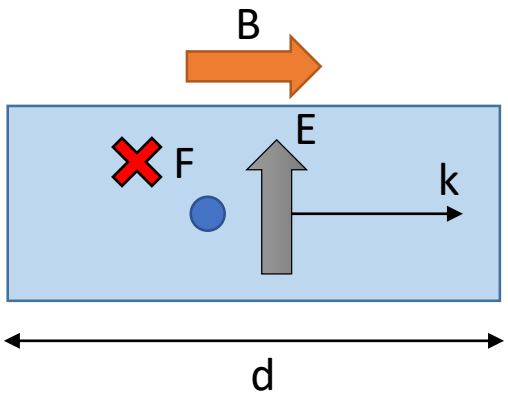
Lorentz force

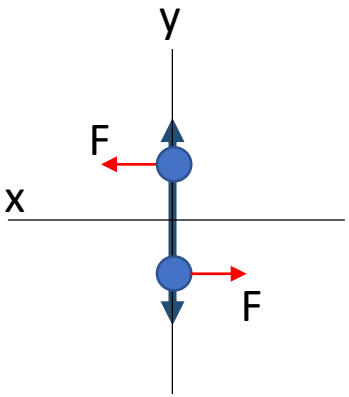
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



Faraday Effect



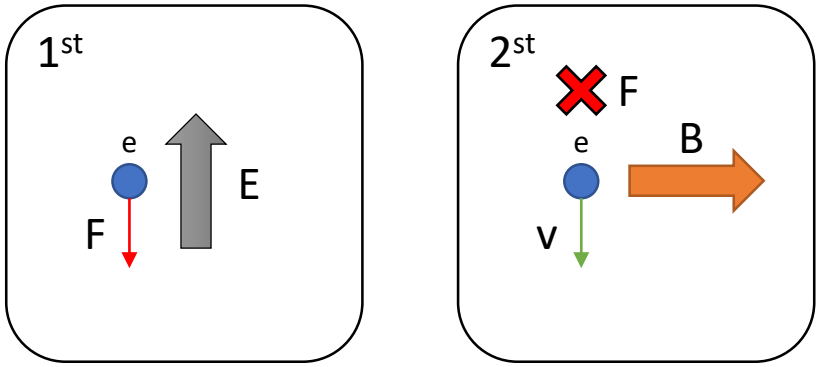




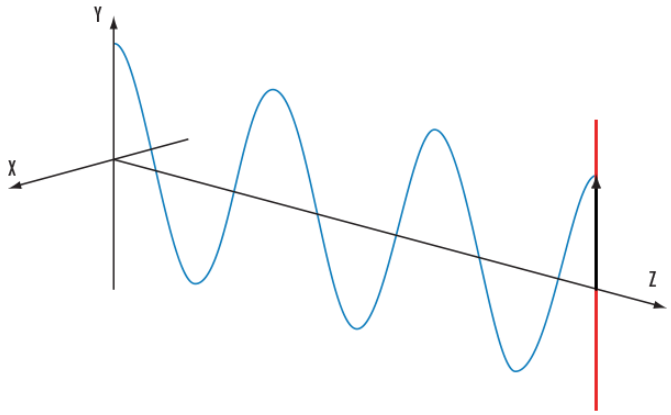
Light and magnetism

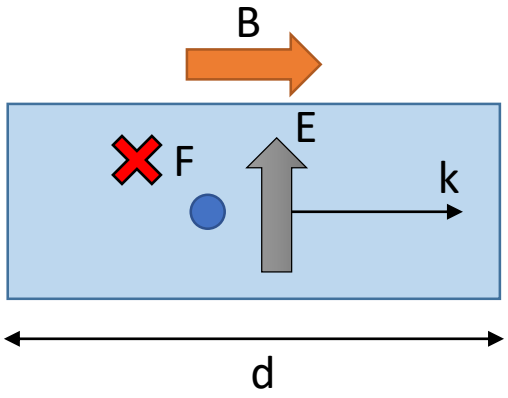
Lorentz force

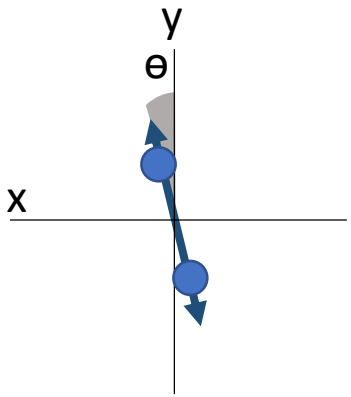
$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$



Faraday Effect





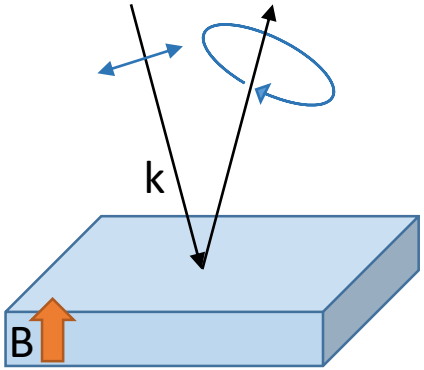


$$\theta = \Upsilon B d$$

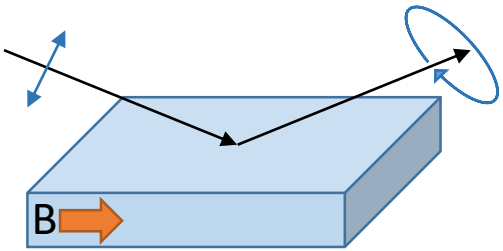
Anisotropy in absorption → elliptical polarized light (ɵ and ε)

Light and magnetism

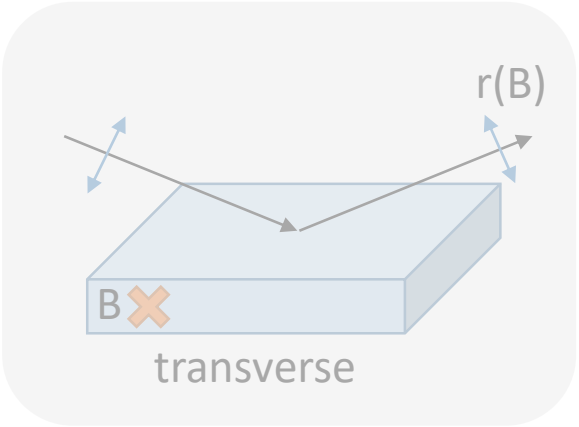
Magneto-optical Kerr effect (MOKE)



polar

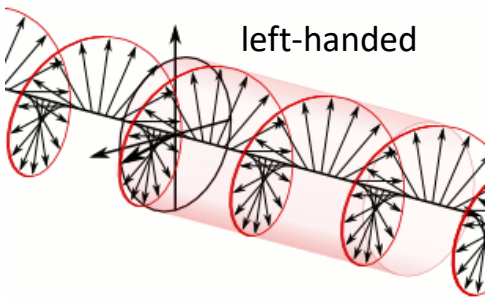


longitudinal



transverse

Inverse Faraday effect



Science 345, 1337 (2014)

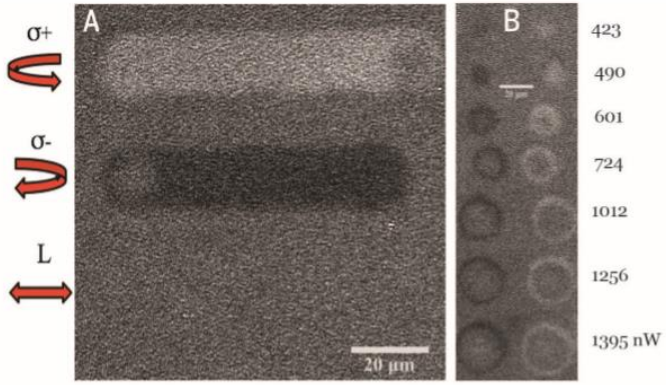


Fig. 3. Magneto-optical response in zero applied magnetic field of a 15-nm FePtAgC granular film sample starting with an initially demagnetized sample. (**A**) Line scans for σ^+, σ^-, and linear polarized light (L). The laser beam was swept over the sample, and the magnetization pattern was subsequently imaged. (**B**) Images of magnetic domains written by keeping the laser spot at a fixed position on the sample. The laser was either σ^+ polarized (left column) or σ^- polarized (right column). The laser power is given next to the image.

Quadratic magnetic rotation, Voigt effect, Zeeman effect, …

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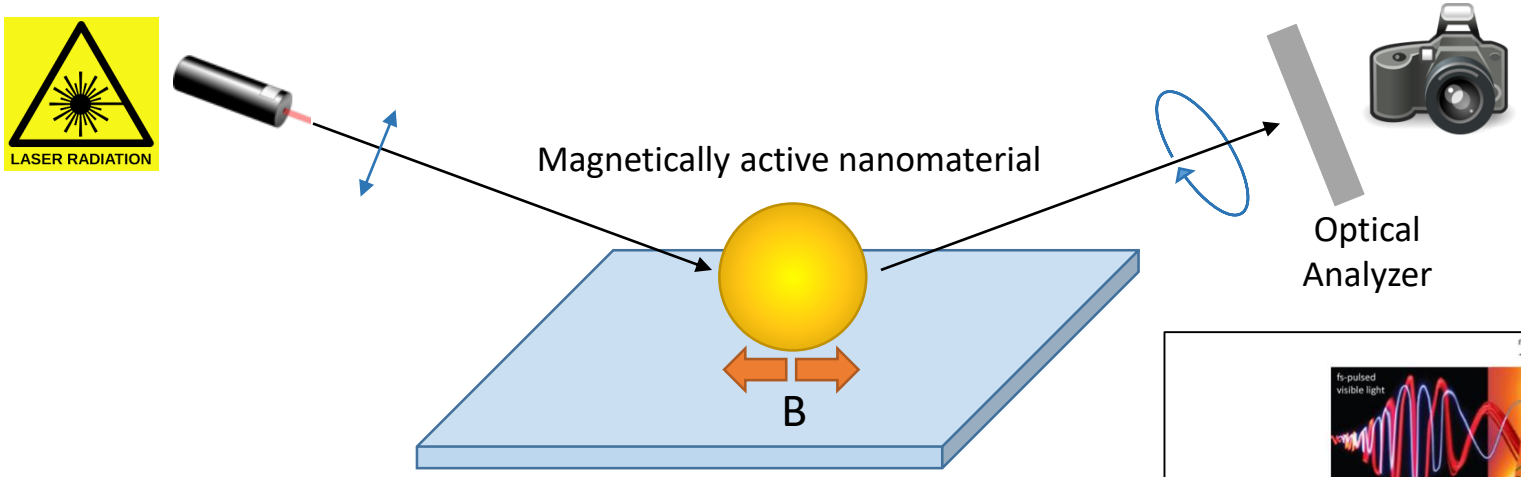
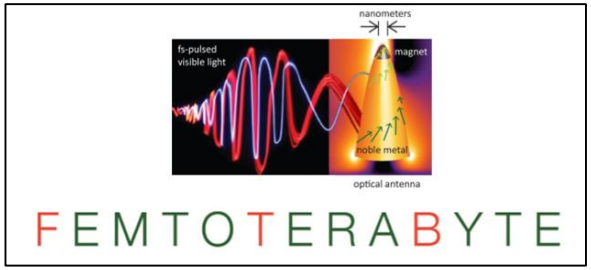
Why nanoscale?

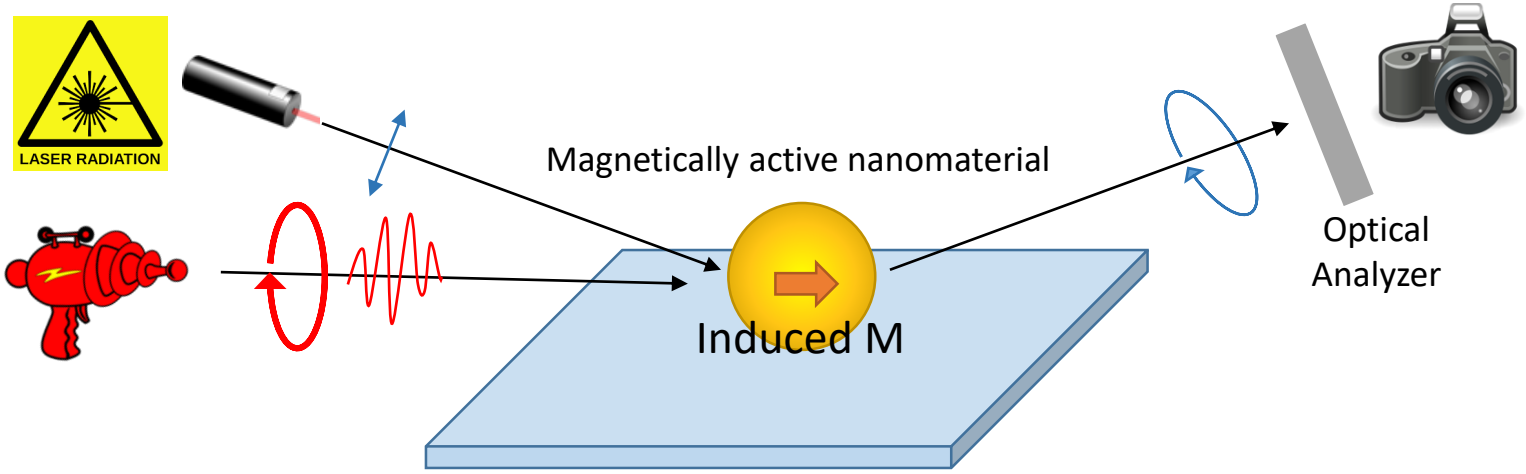
Magneto-optical effects at the nanoscale

→ Active control nanophotonic circuits (nano Faraday/MOKE)





→ High density data storage units (inverse-nano Faraday)



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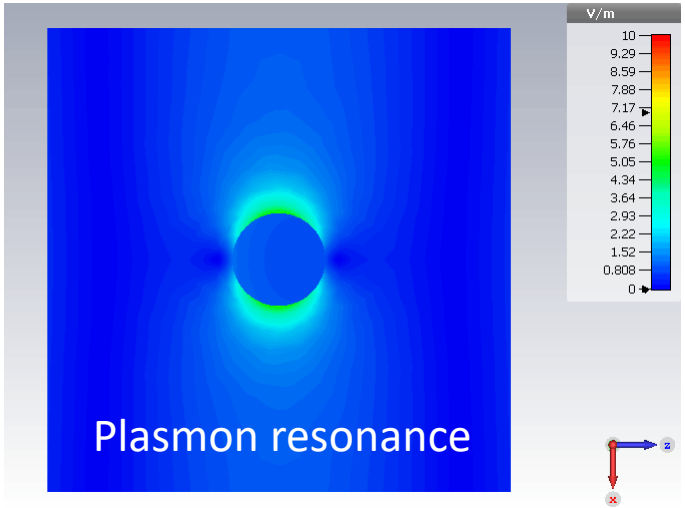
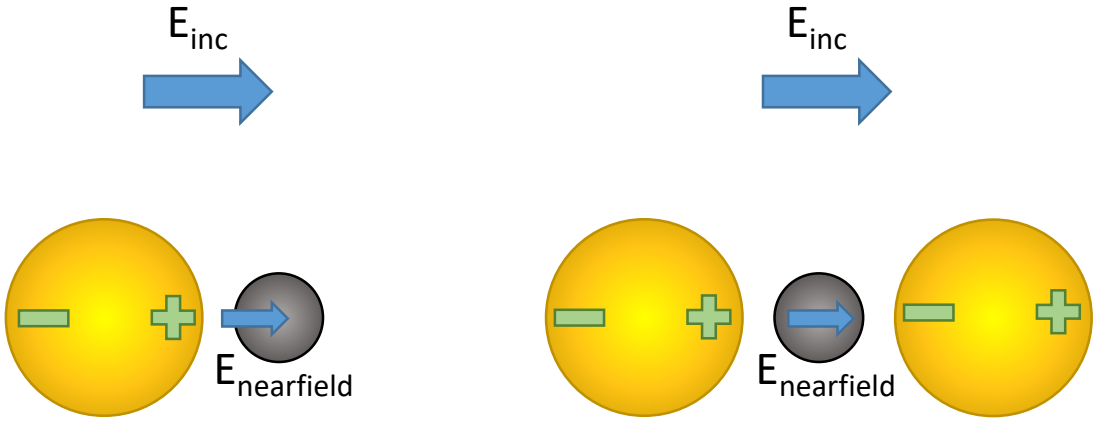
Why hybrid?

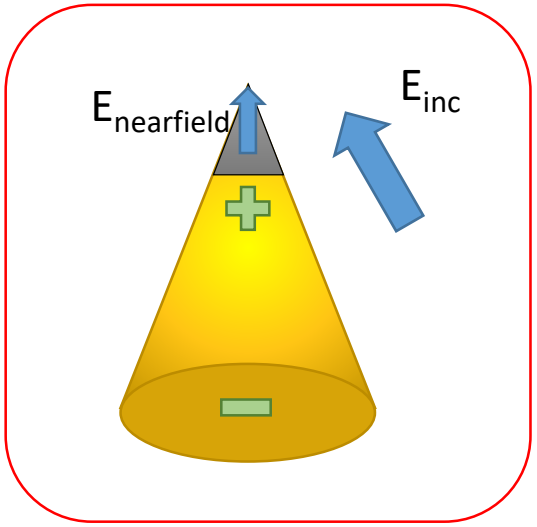
Au = plasmonics' favorite, but not magnetically active
Ferromagnetic = lossy → low field enhancement

Au-Ferromagnetic nanocones

50 nm diameter Au NP in water



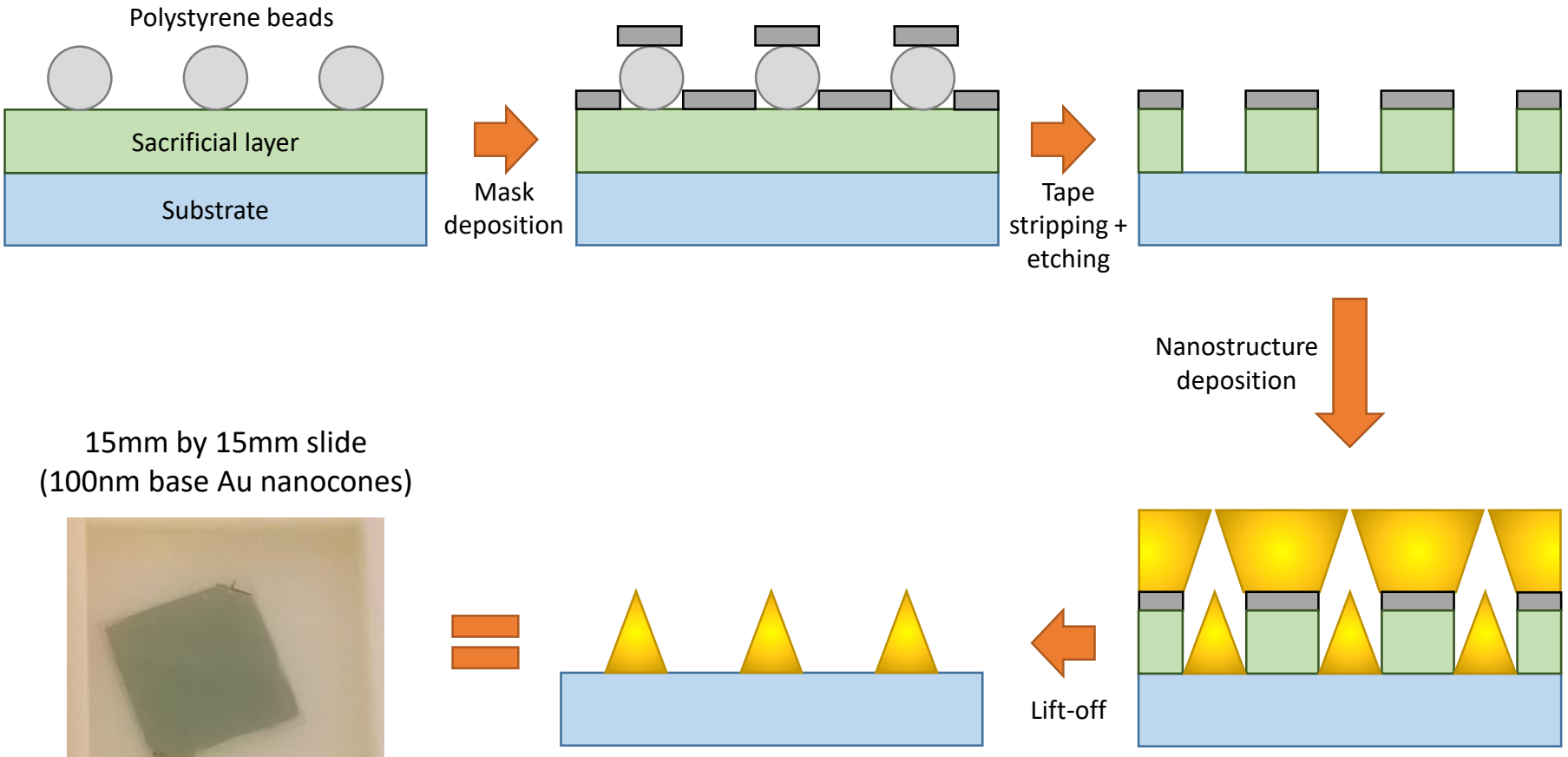




Hybrid metallic-magnetic nanostructures

Fabrication process: Hole-Mask Colloidal Lithography

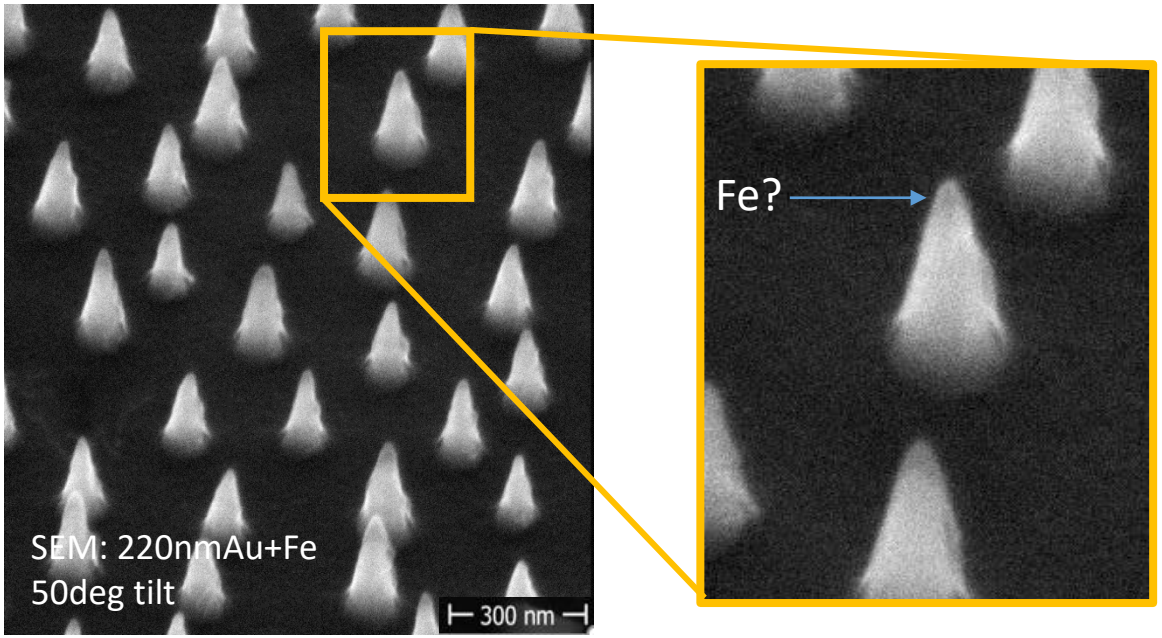
Adv. Mat. 19, 4297 (2007)

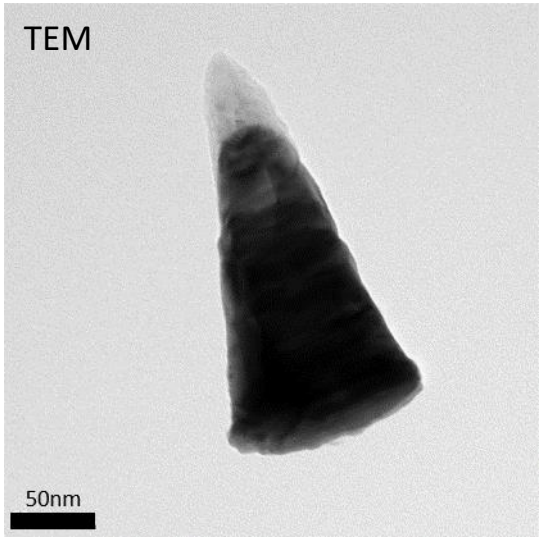


15mm by 15mm slide
(100nm base Au nanocones)

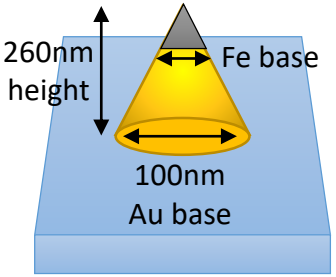
Hybrid metallic-magnetic nanostructures

Sample characterization





Further statistical and chemical analysis needed.
Preliminary (from AFM): 260nm total height



Deduce Fe base and equivalent Fe thickness from geometry and density (AFM+SEM)

Outline

Where is Gothenburg?

Breaking down the title

Nano-optics with a spin: interplay between light and magnetism at the nanoscale

- Nano-optics and optical near-field
- Optical polarization and angular momentum
- Light and magnetism
- Why nanoscale?

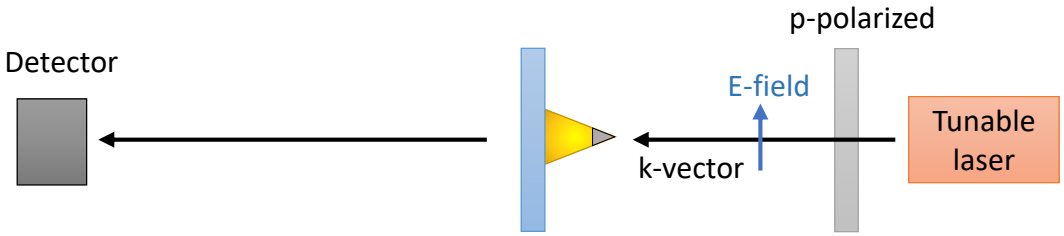
Hybrid metallic-magnetic nanostructures

Plasmon-induced magneto-optical effects

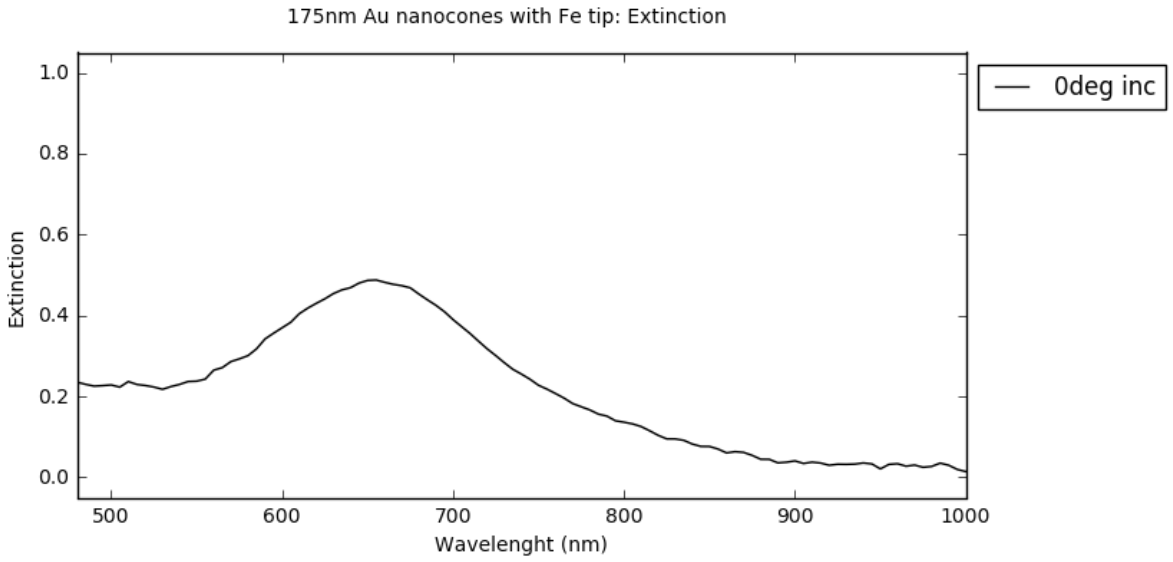
Summary and future plan

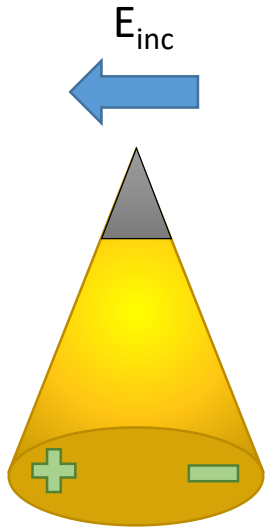
Plasmon-induced magneto-optical effects

Resonance modes of nanocones



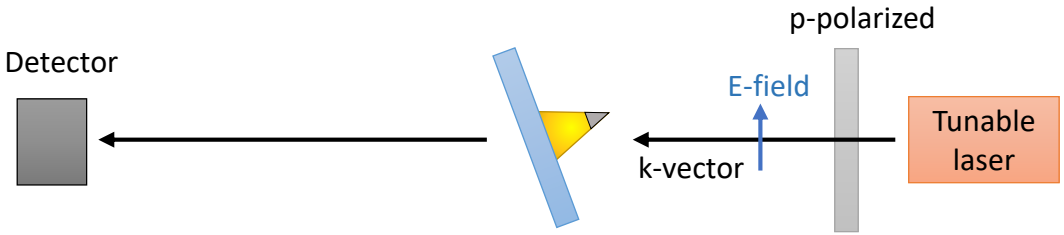
Transmission measurement → extinction (1-Trans) spectra at different angles of incidence
Horizontal mode and vertical mode





Plasmon-induced magneto-optical effects

Resonance modes of nanocones



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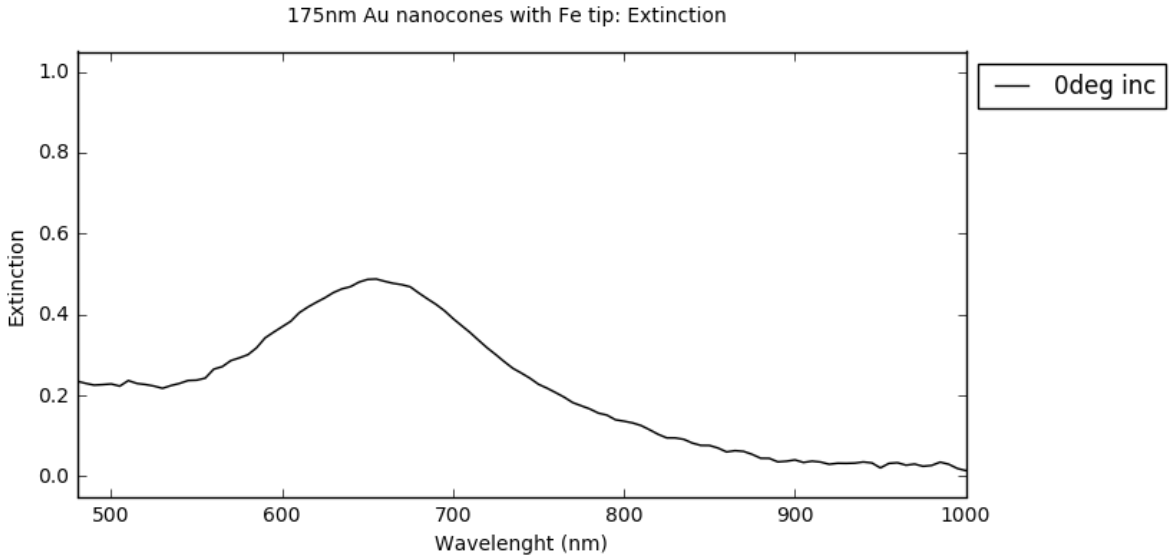

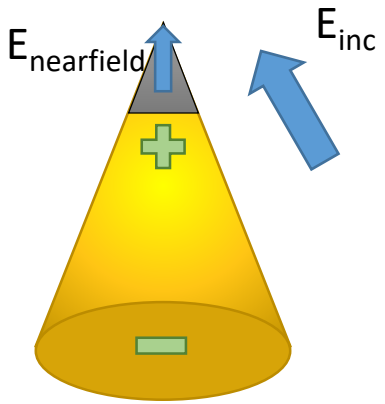

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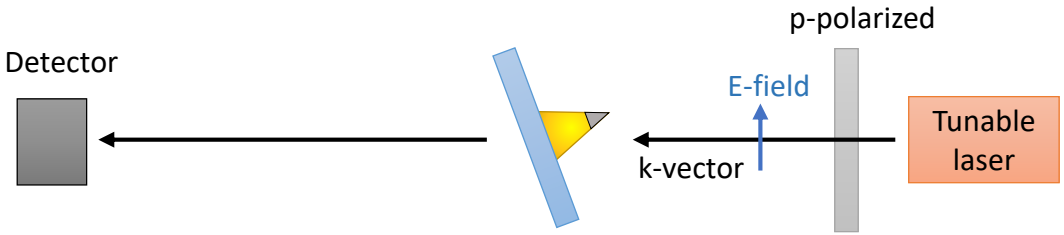

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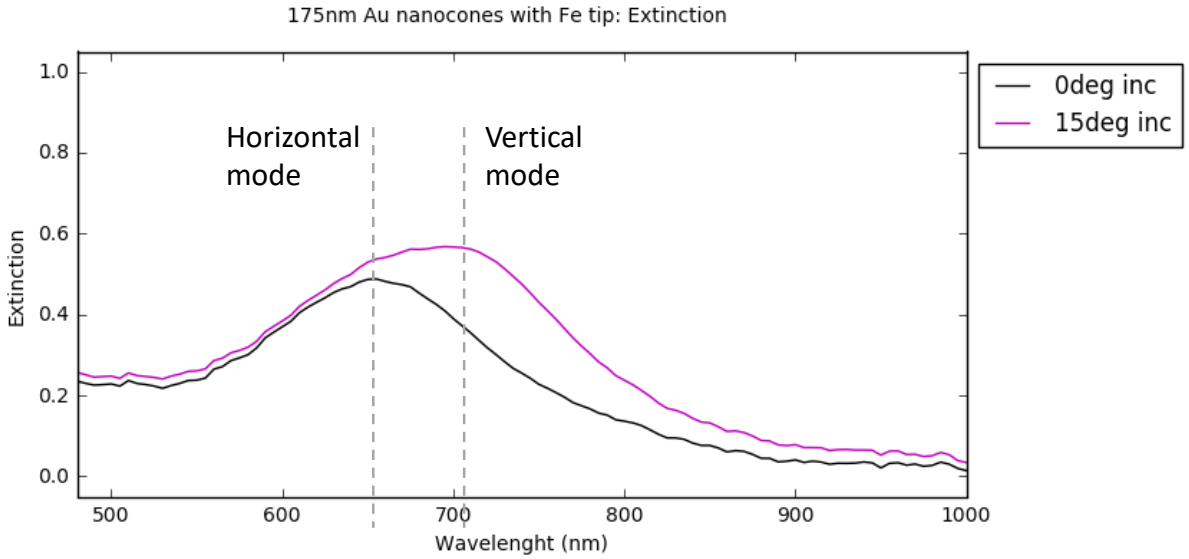
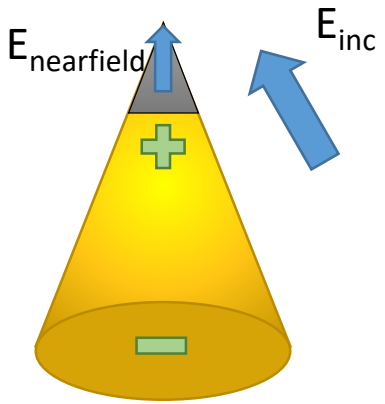
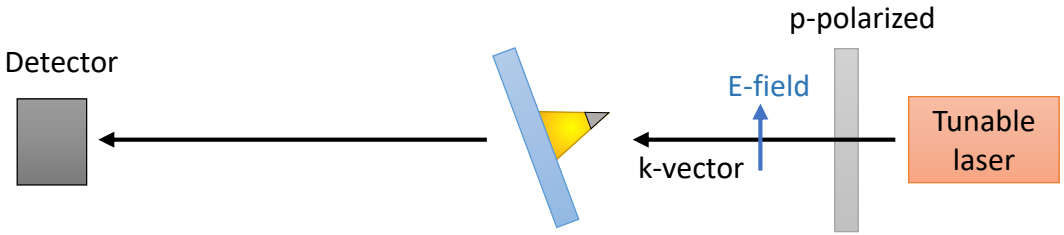




Plasmon-induced magneto-optical effects

Resonance modes of nanocones



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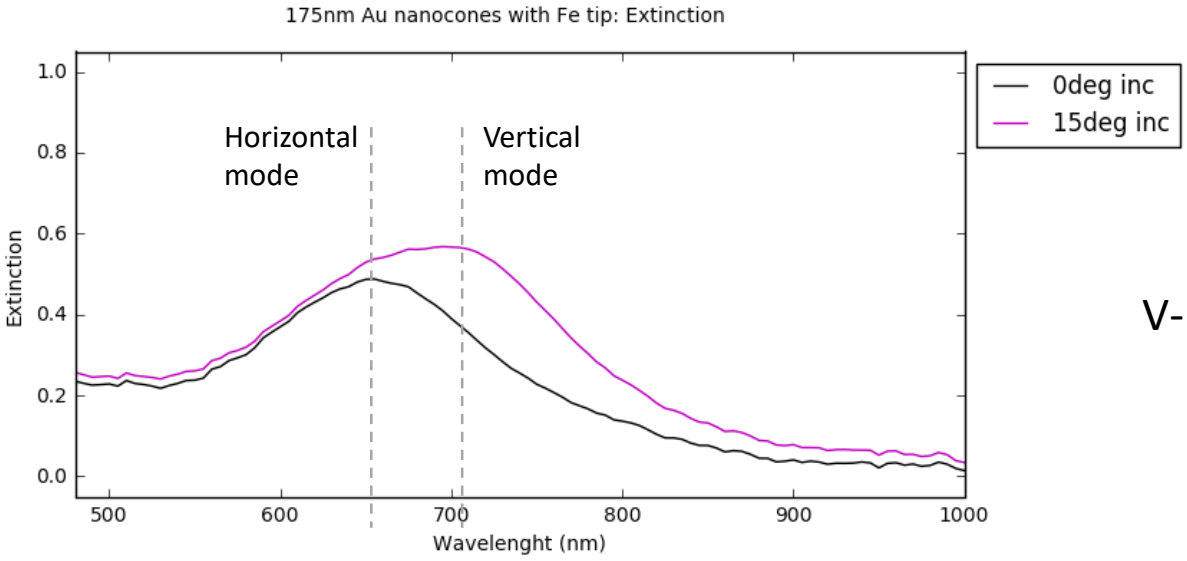
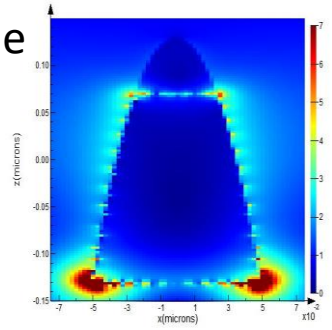
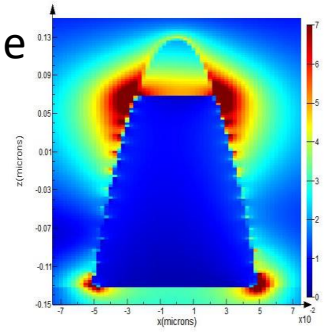


H-mode

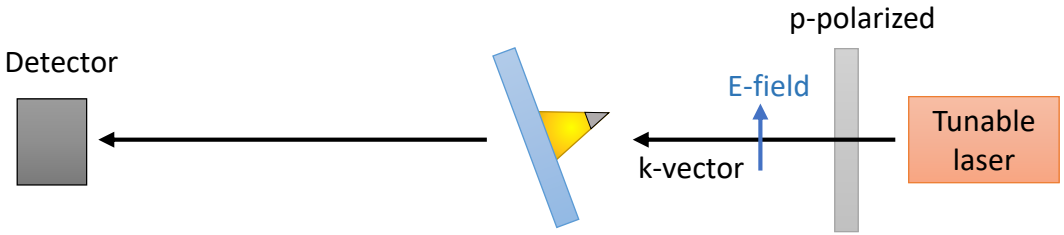


V-mode



Plasmon-induced magneto-optical effects

Resonance modes of nanocones



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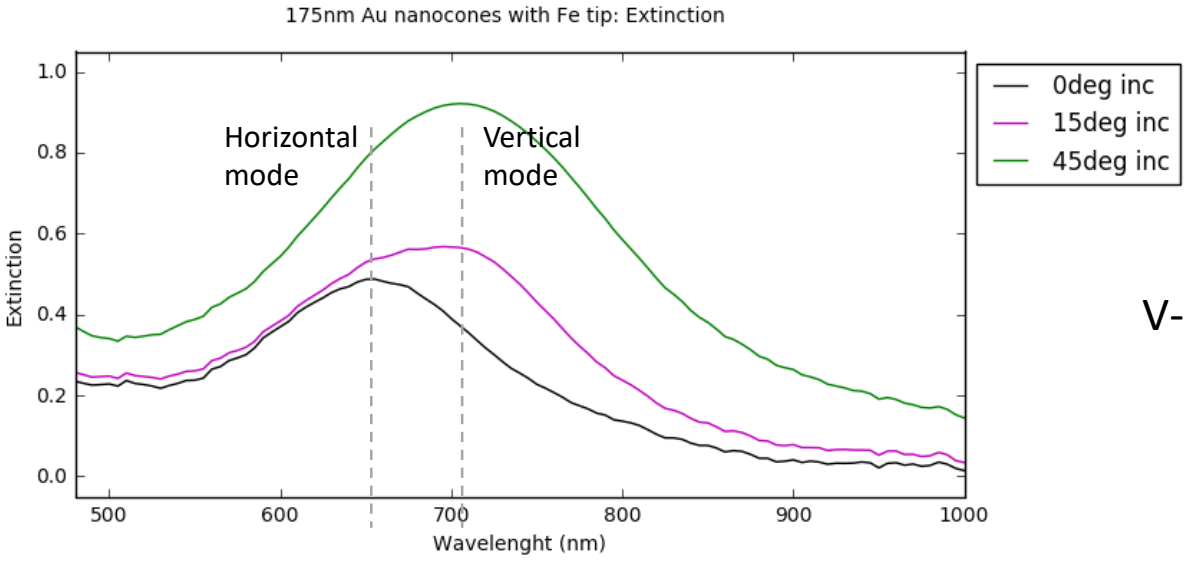

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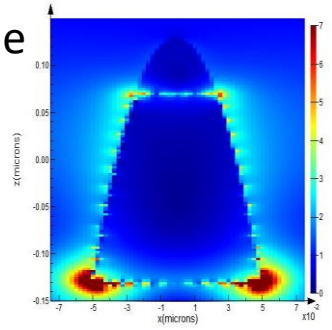
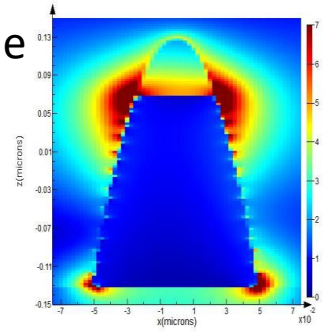
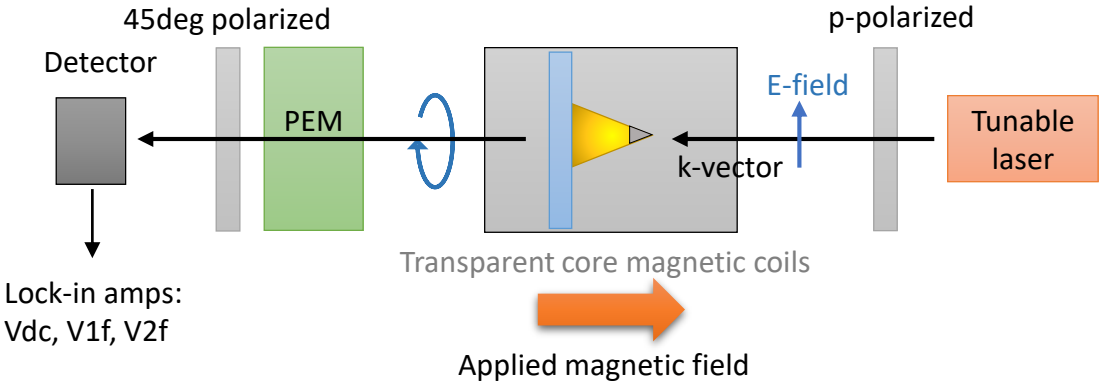


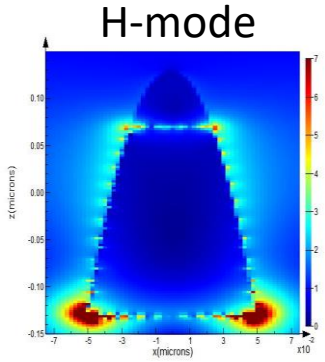
V-mode

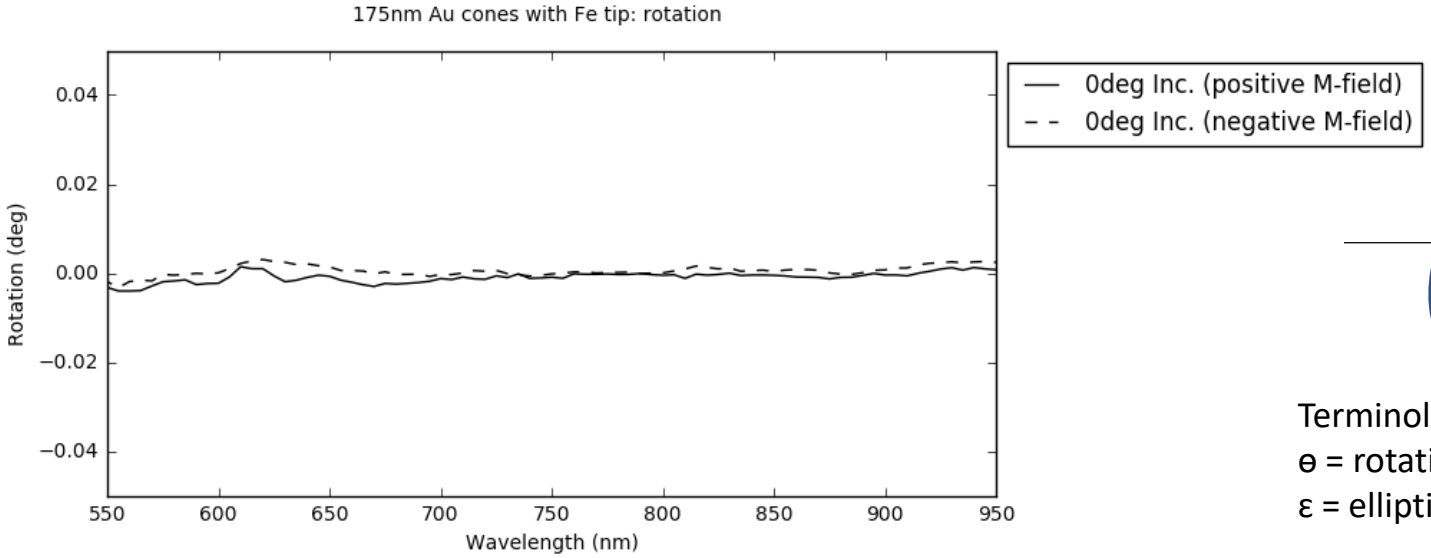


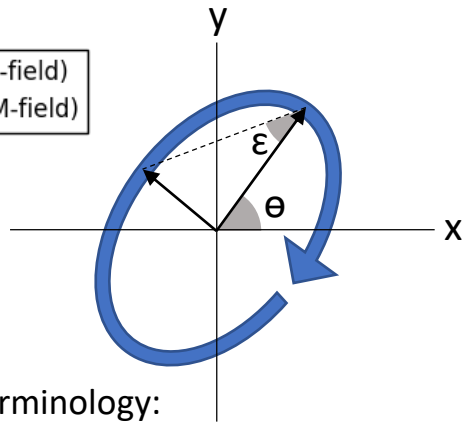
Plasmon-induced magneto-optical effects

Faraday rotation/ellipticity measurement





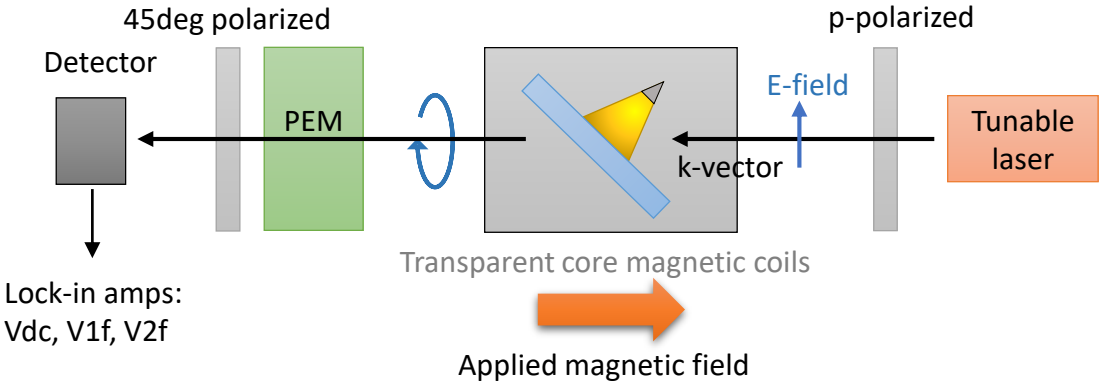


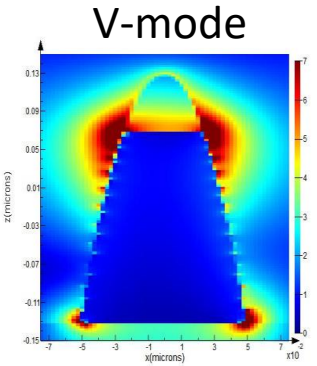


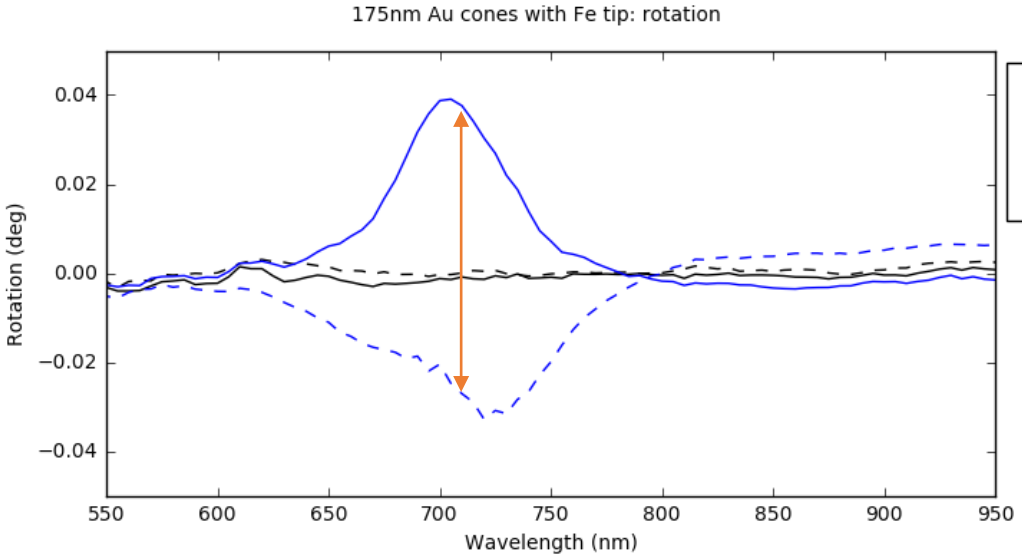
Terminology:
ϴ = rotation,
ε = ellipticity (and handedness)

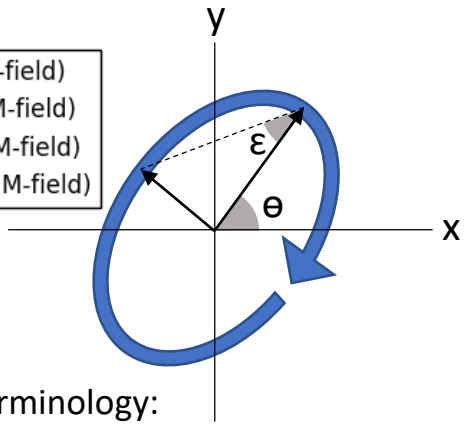
Plasmon-induced magneto-optical effects

Faraday rotation/ellipticity measurement









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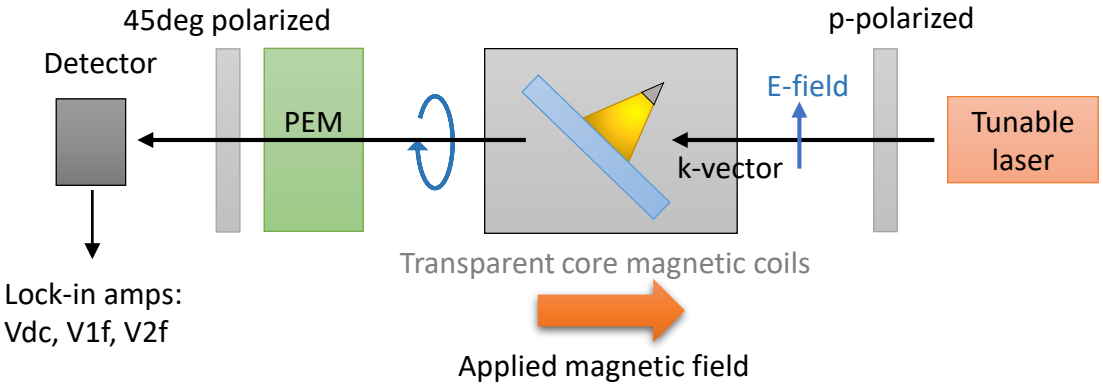

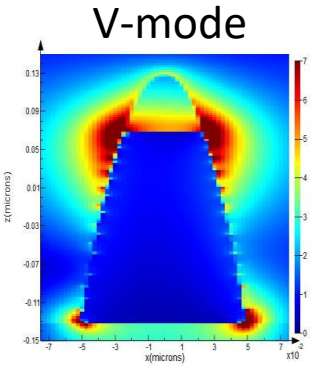

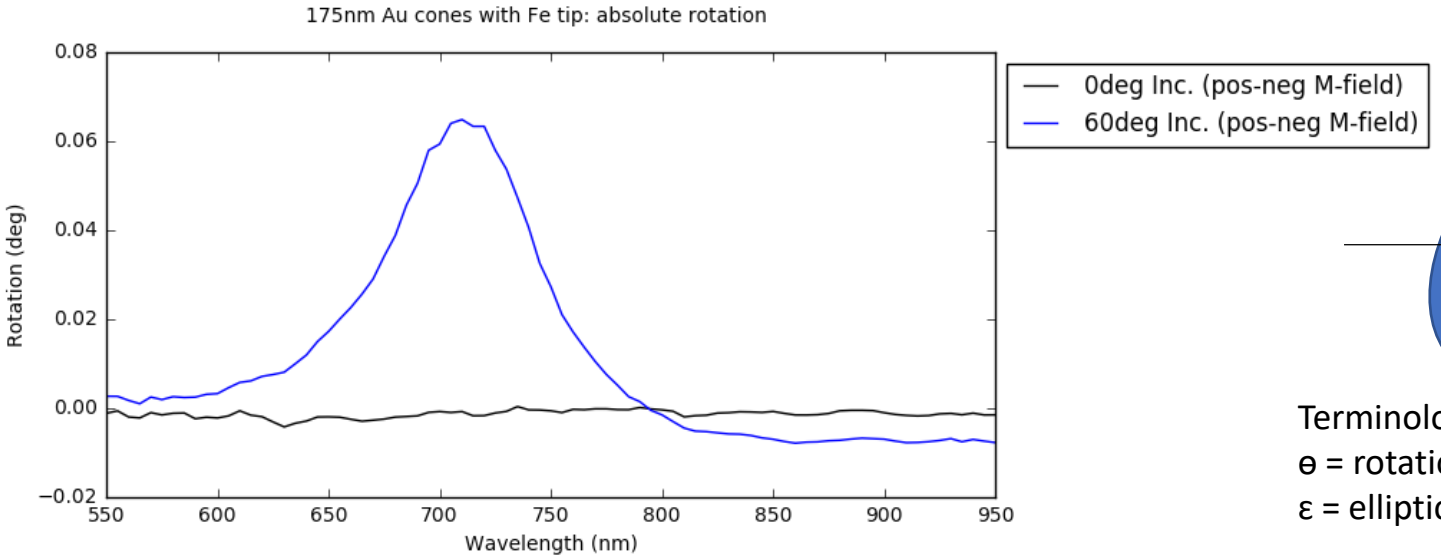

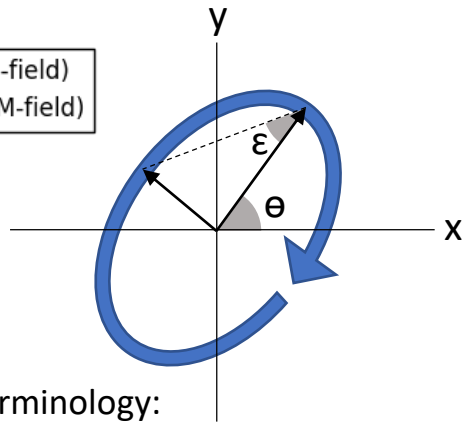

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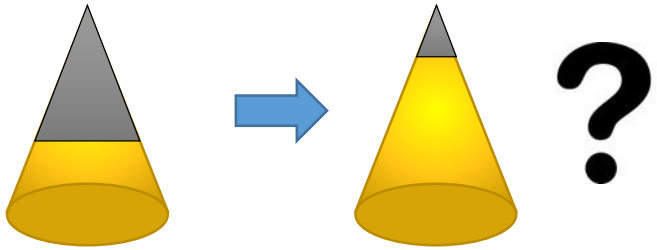
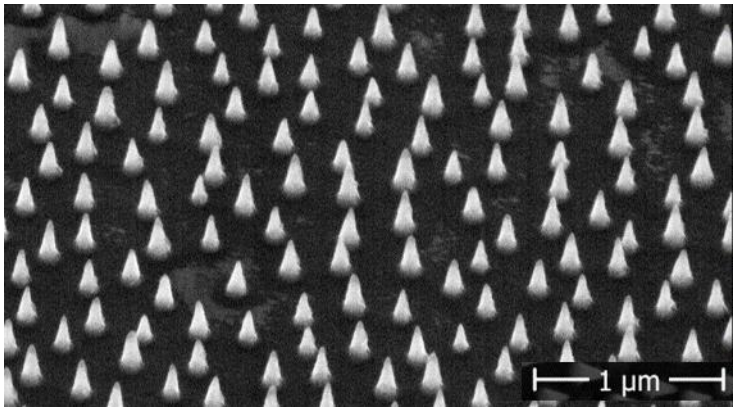
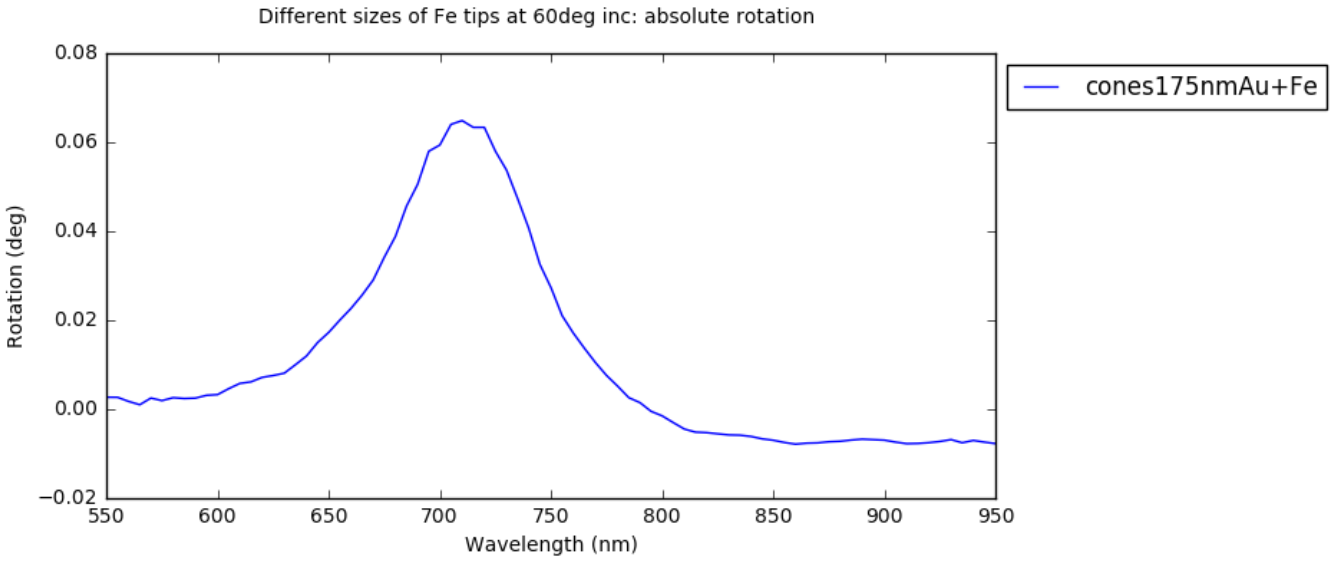
Plasmon-induced magneto-optical effects

Smaller Fe?





	Cone height	Cone basewidth	Au height	Fe height	Fe basewidth	Area coverage	Fe equi. thickness	Fe equi. monolayer
0	260	100	0	260	100.000000	0.1	8.666667	34.391534
1	260	100	150	110	42.307692	0.1	0.656312	2.604411
2	260	100	175	85	32.692308	0.1	0.302823	1.201678
3	260	100	200	60	23.076923	0.1	0.106509	0.422654
4	260	100	220	40	15.384615	0.1	0.031558	0.125231
5	260	100	230	30	11.538462	0.1	0.013314	0.052832



Plasmon-induced magneto-optical effects

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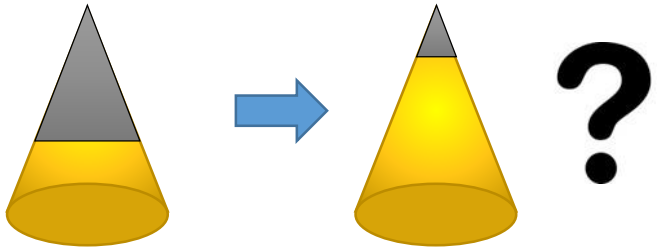

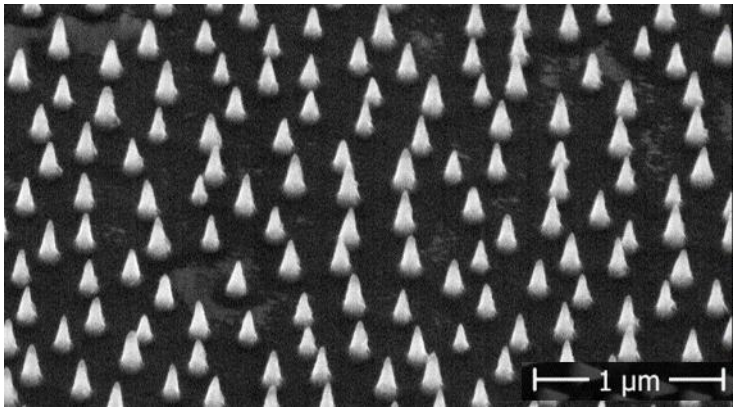

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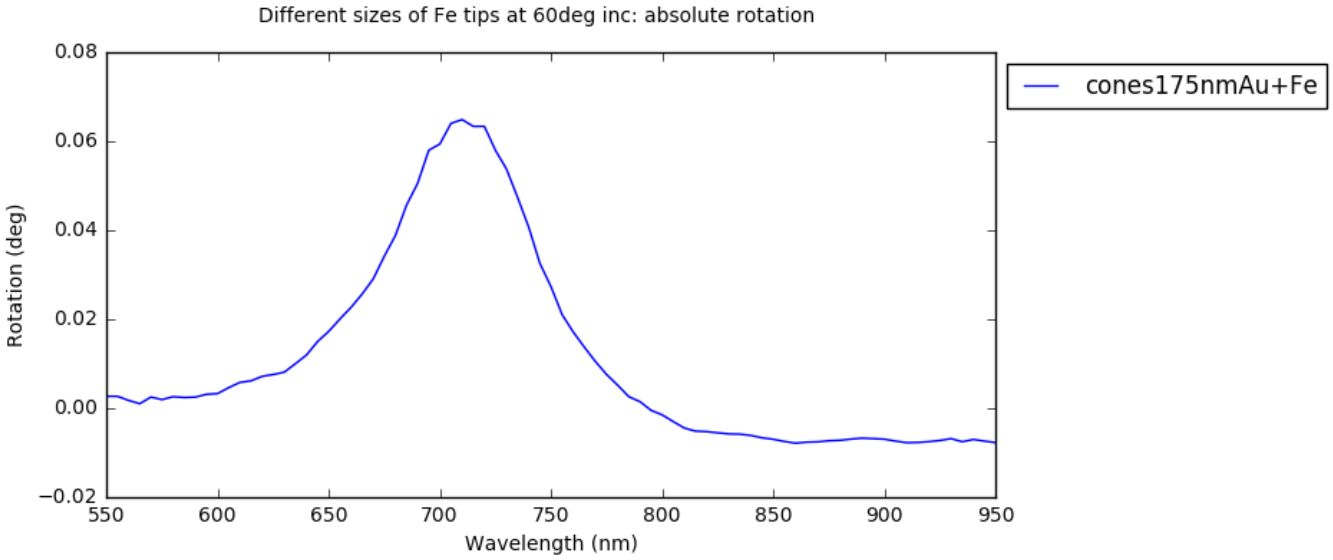

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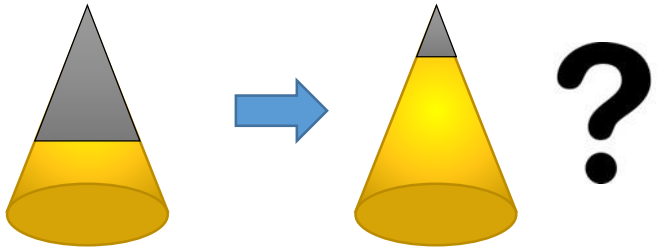

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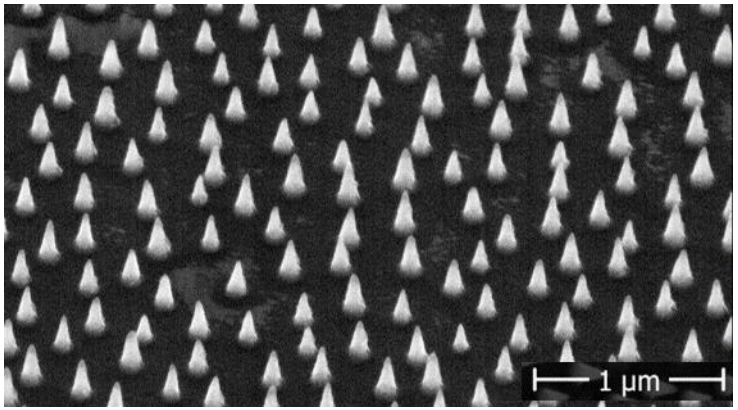

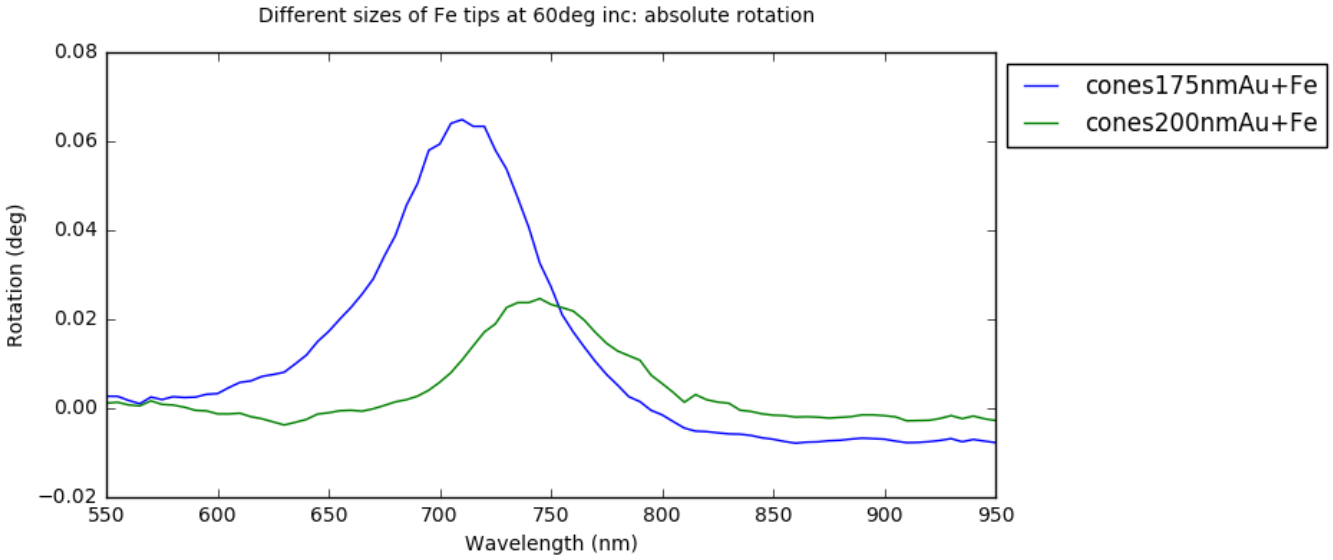

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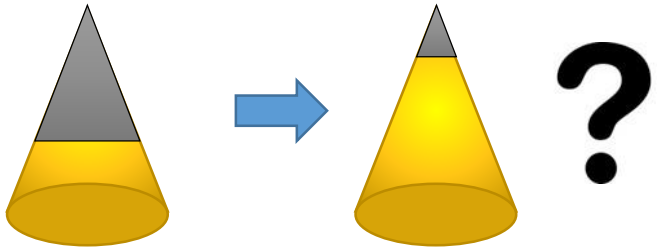

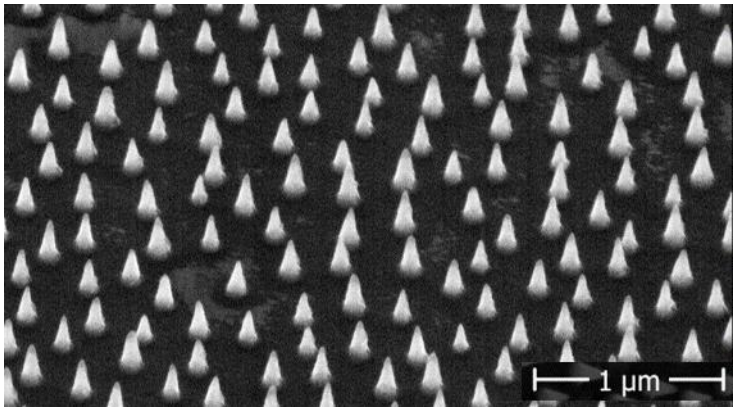

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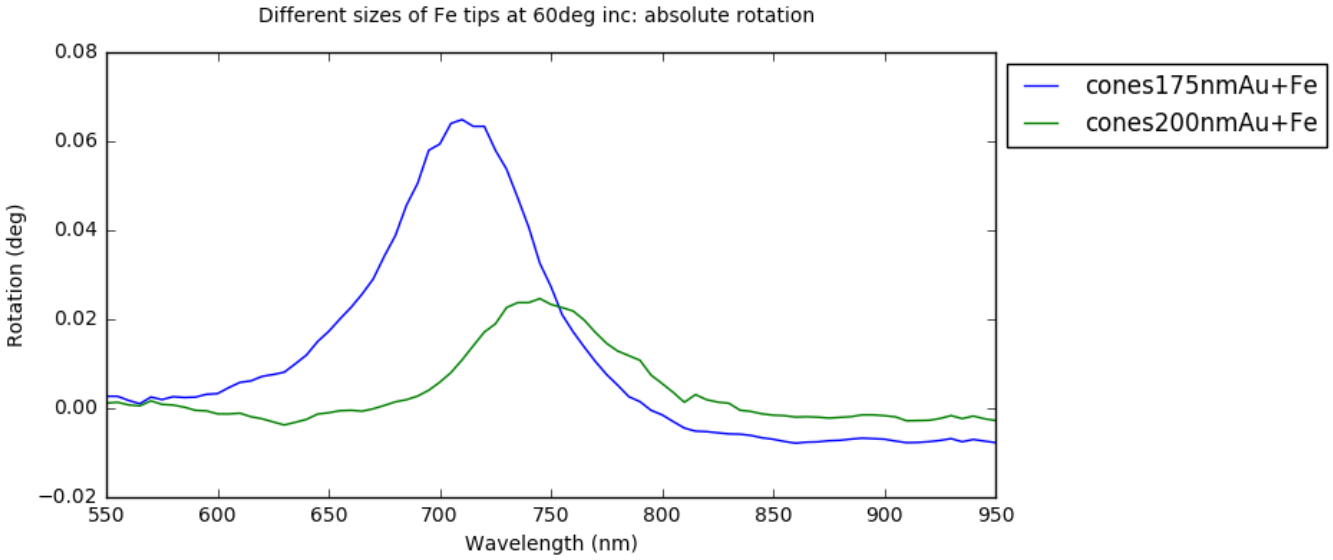

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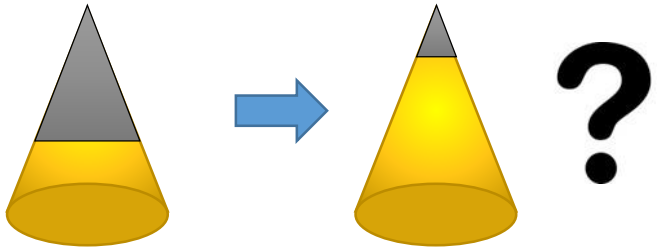

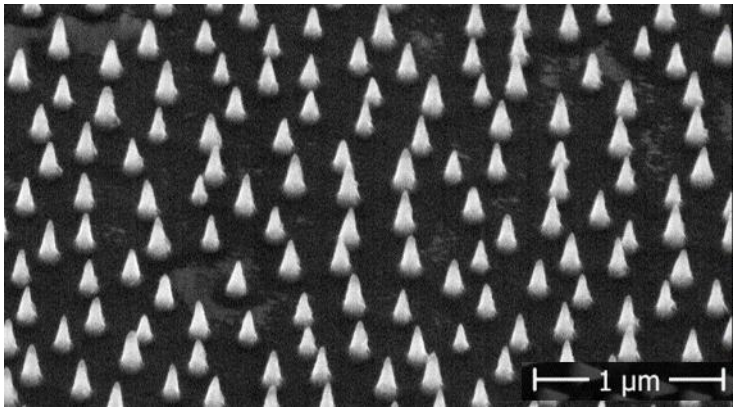

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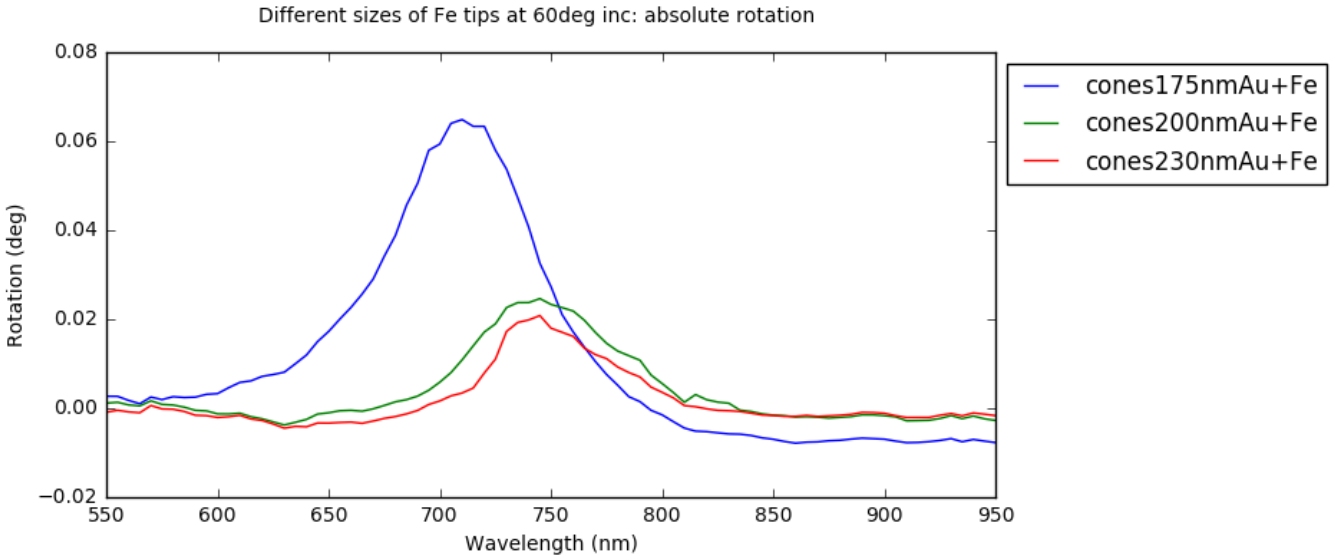

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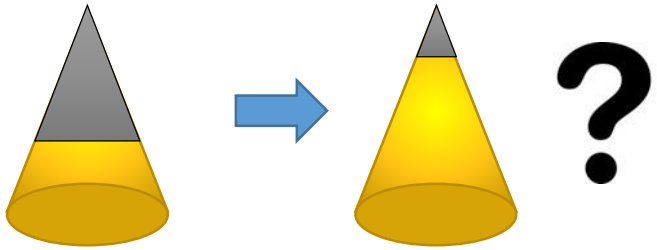

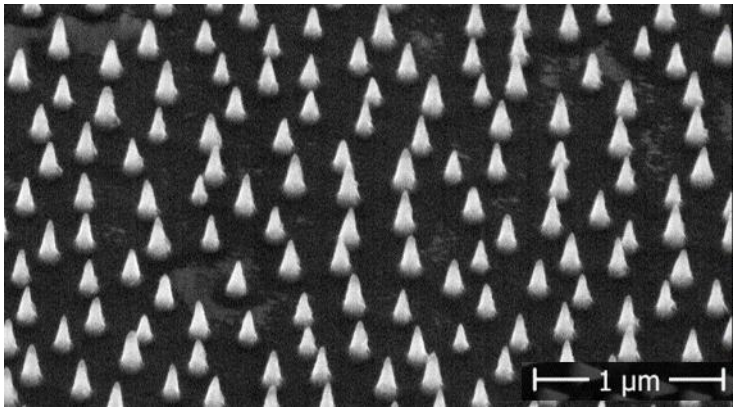

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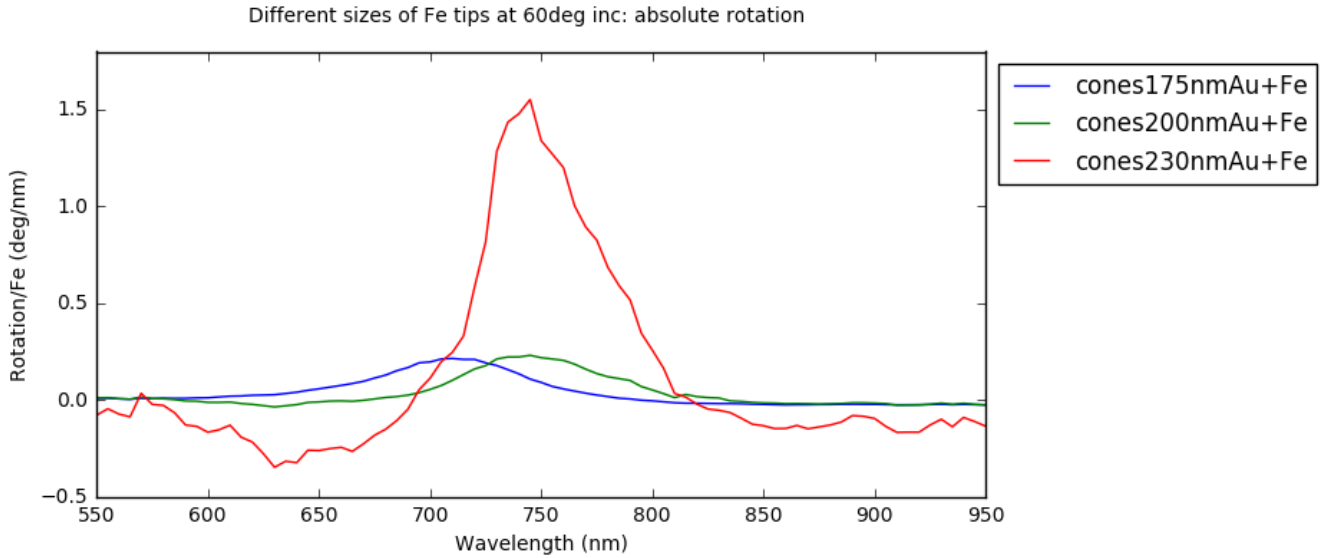
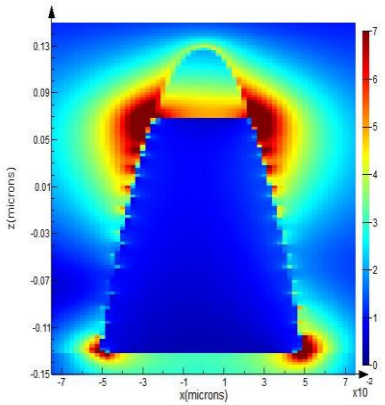
5	260	100	230	30	11.538462	0.1	0.013314	0.052832



V-mode



Smaller Fe → higher %Fe interacts with plasmon induced near-field

Outline

Where is Gothenburg?

Breaking down the title

Nano-optics with a spin: interplay between light and magnetism at the nanoscale

- Nano-optics and optical near-field
- Optical polarization and angular momentum
- Light and magnetism
- Why nanoscale?

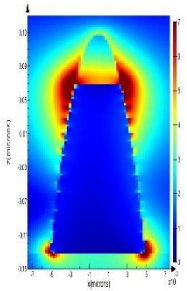
Hybrid metallic-magnetic nanostructures

Plasmon-induced magneto-optical effects

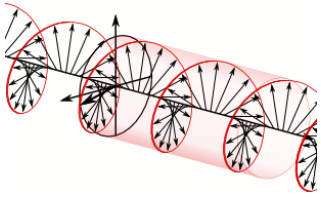
Summary and future plan

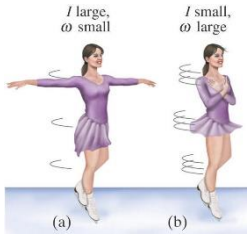
Summary

Localized surface plasmon resonances → nanoscale light focusing → nano-optics

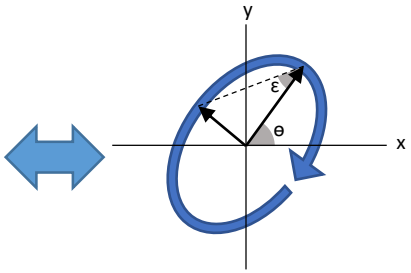


Light's polarization → spin angular momentum

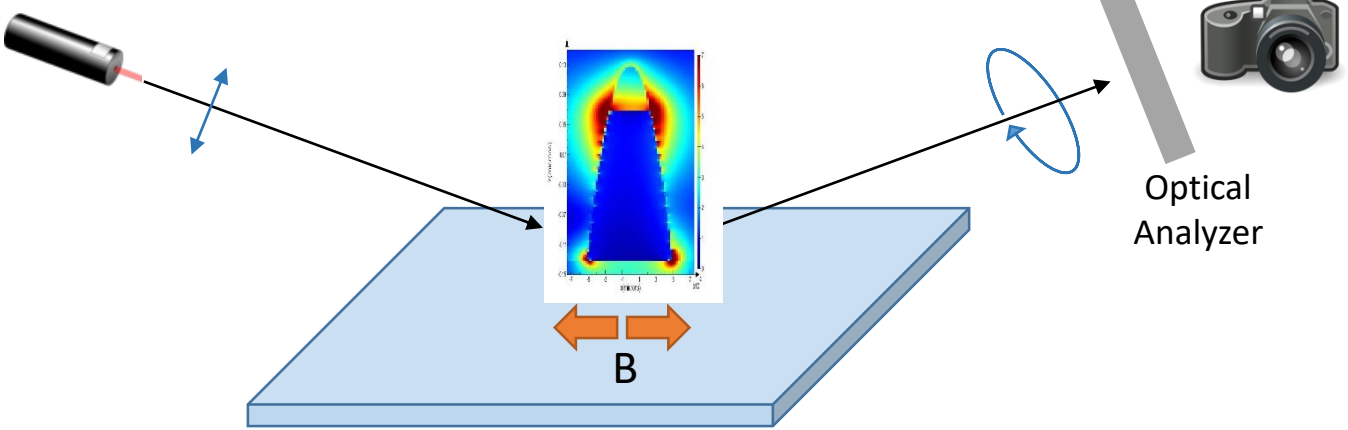




Light + magnetism → polarization rotation, induced ellipticity
e.g. Faraday, MOKE, inverse Faraday



Metallic-ferromagnetic hybrid nanostructure → focusing light to interact with magnetic material

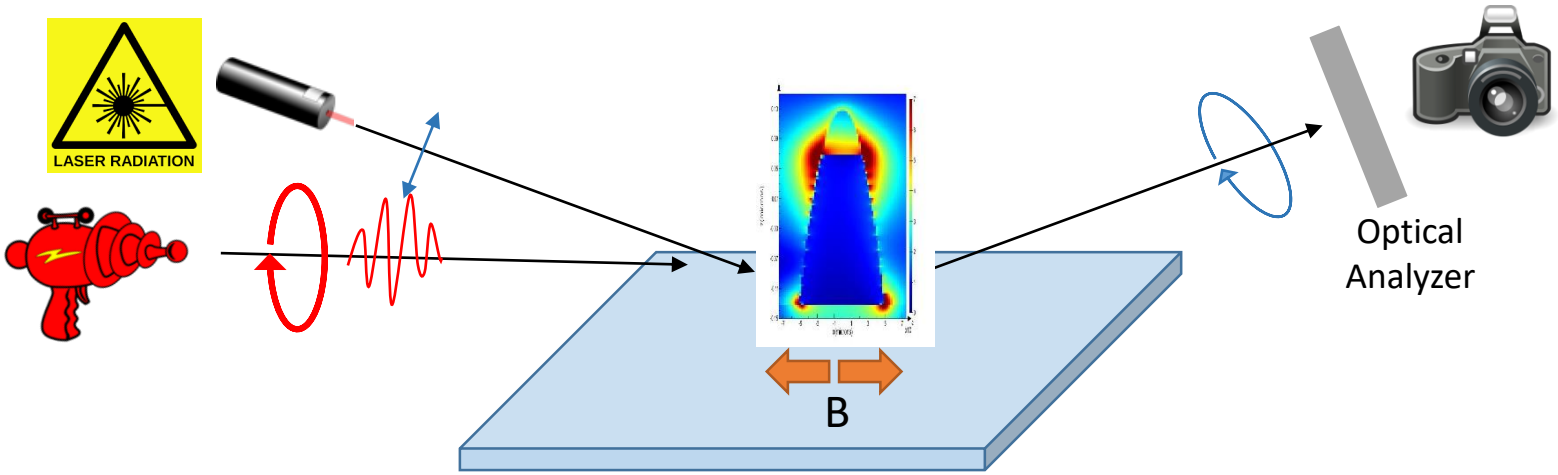


Future plan (my part)

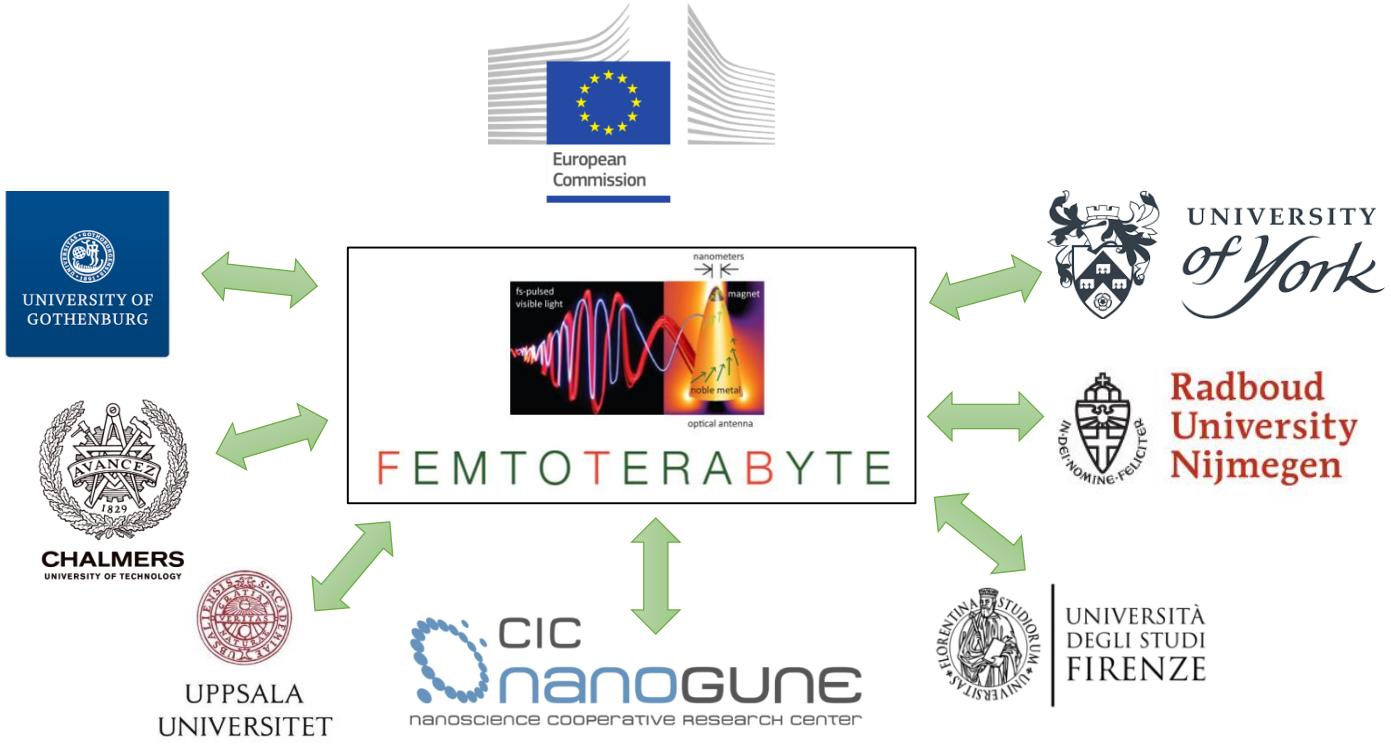
Push the limit of the smallest amount of Fe (currently 12nm basewidth)

Alternative materials (more stable, retain magnetic moment)

Low power inverse Faraday at the nanoscale



Acknowledgments



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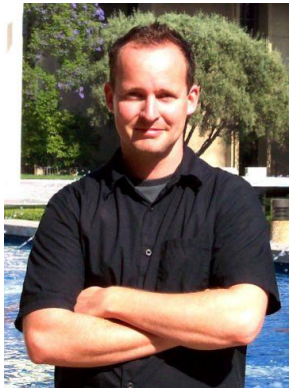

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