From magneto-optics to ultrafast manipulation of magnetism

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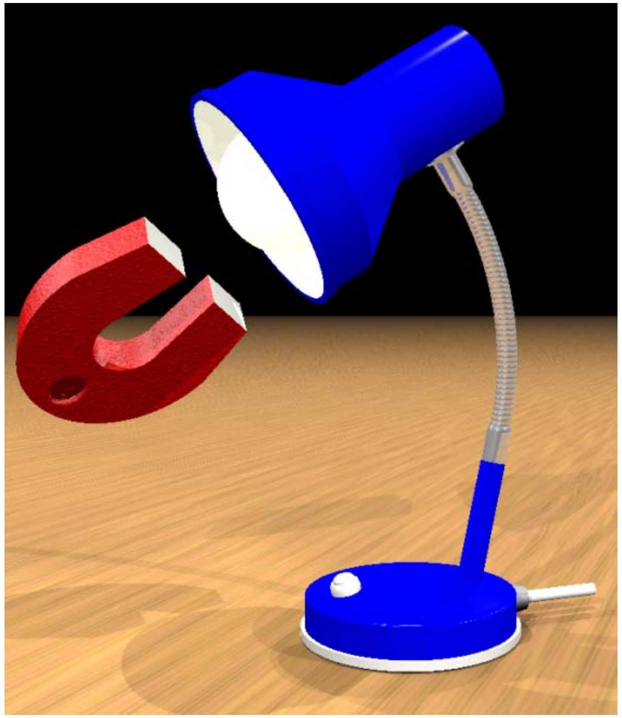

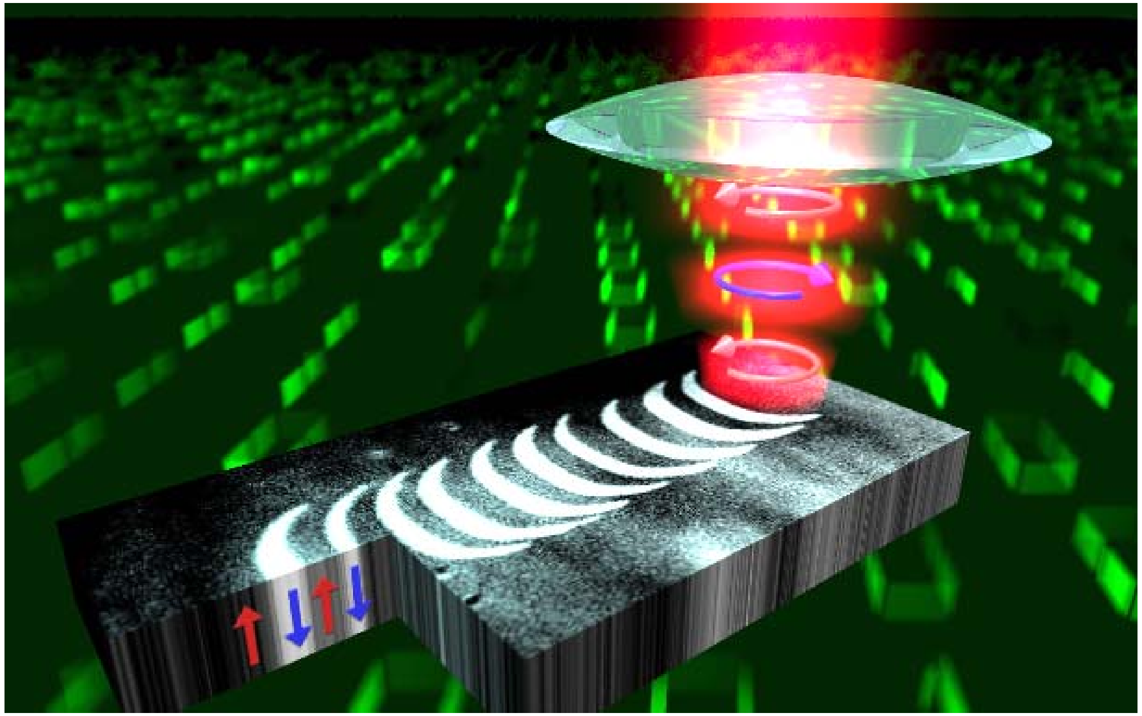

Outline of the lecture

- Light as a probe
  - linear magneto-optics
  - nonlinear (magneto-)optics
- Example: all-optical FMR
- Light as an excitation
  - classification of effects
  - basics of opto-magnetism
  - coherent control
  - local control of spins
- *can this become too-ultrafast?*

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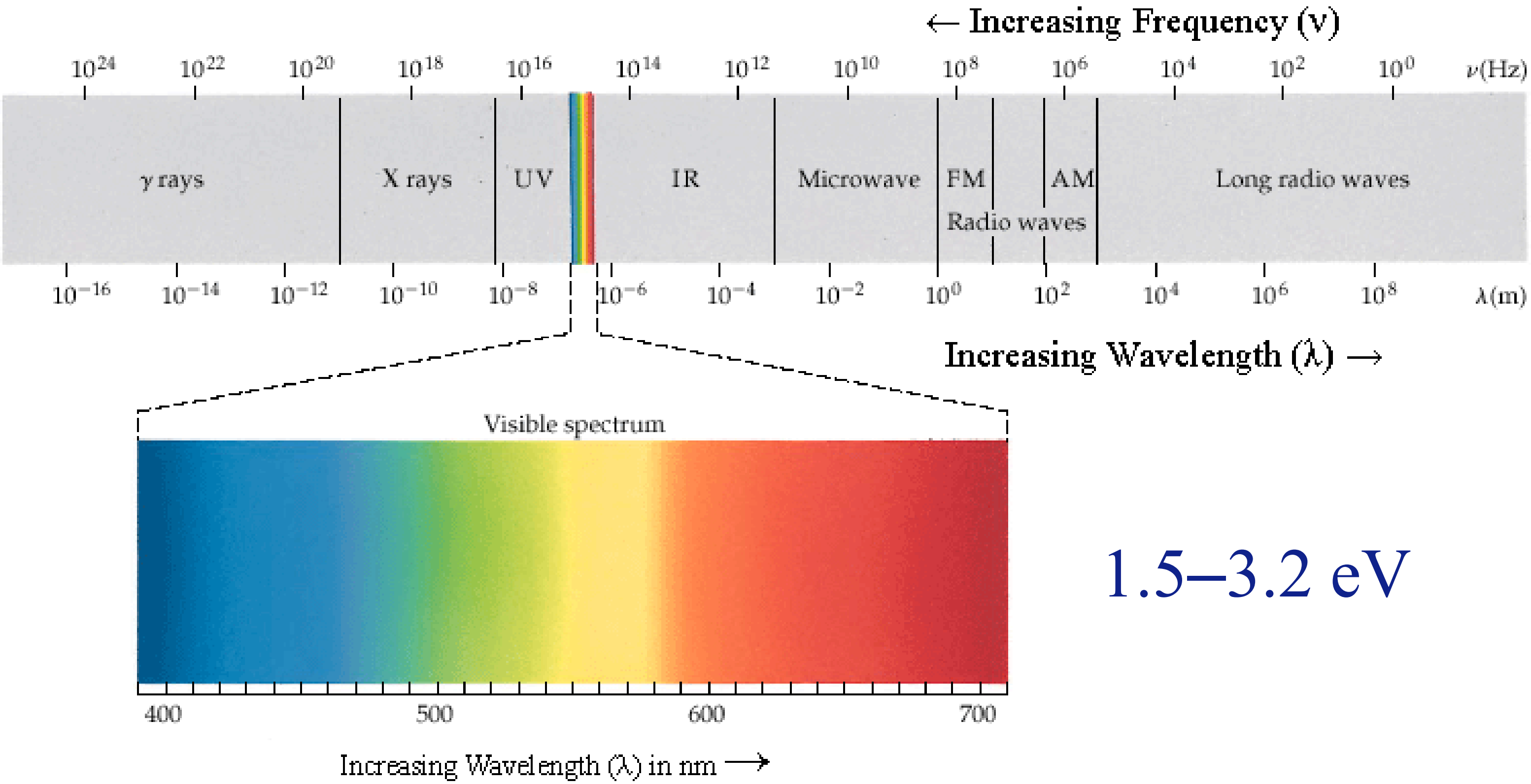
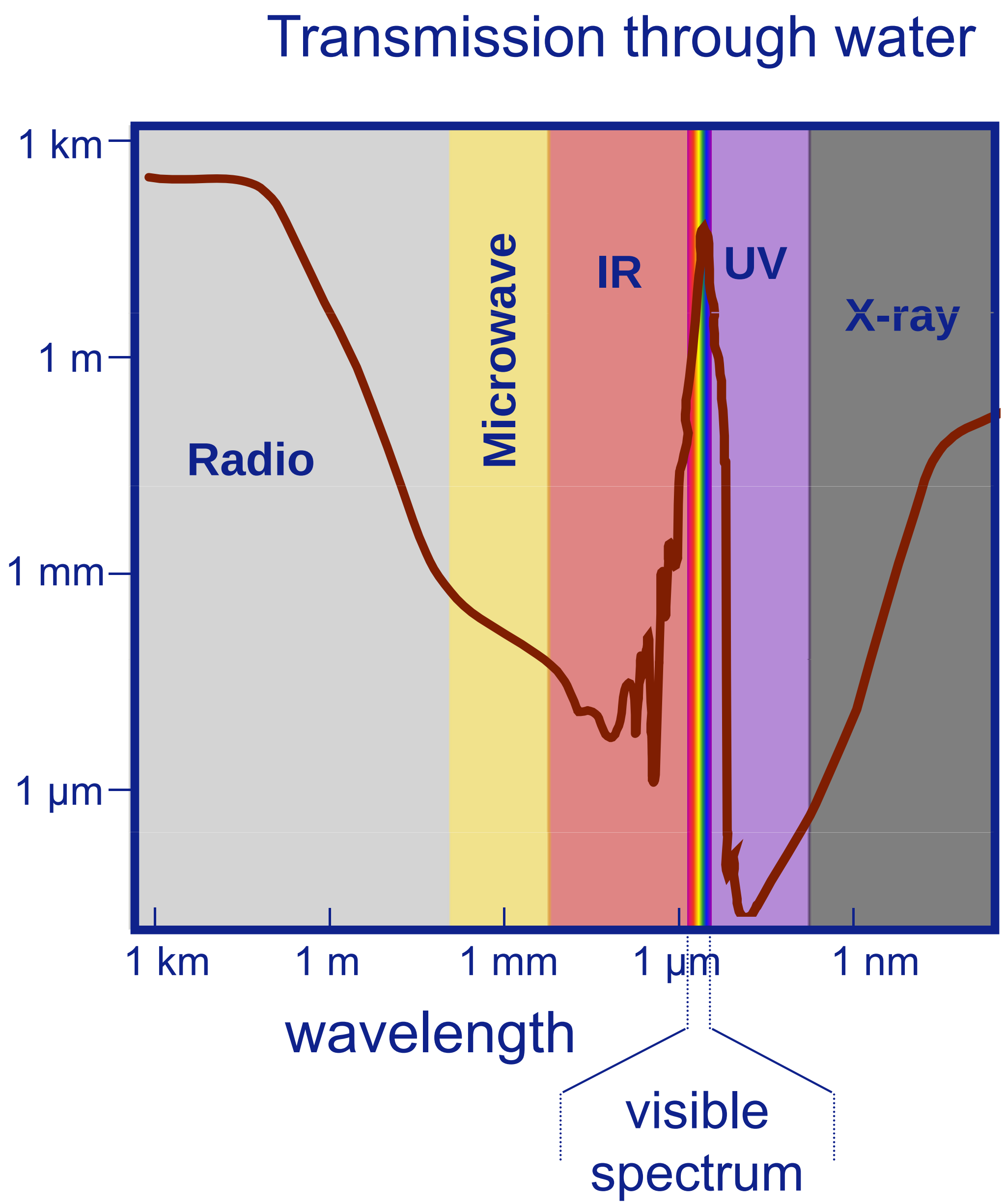
Optics

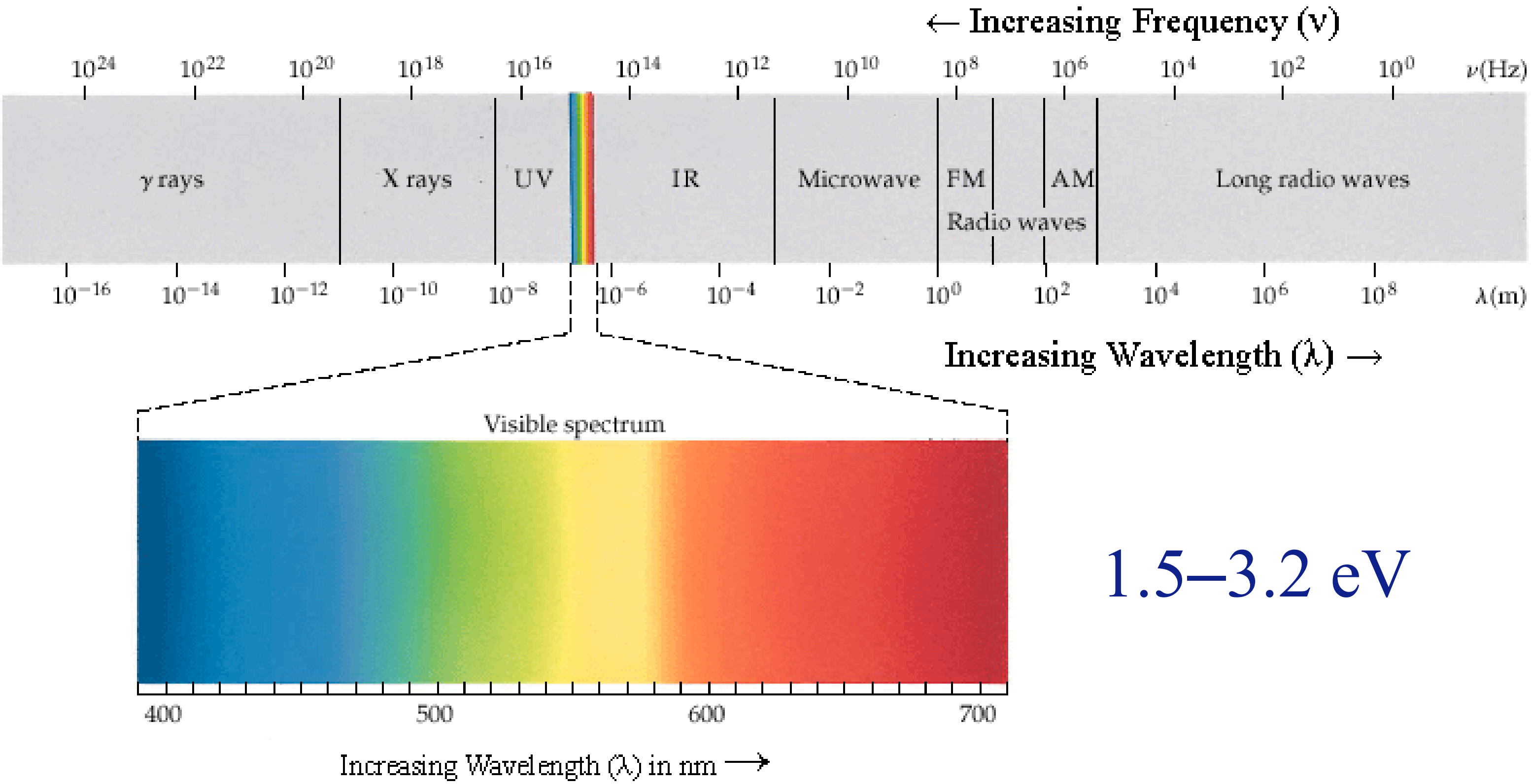


1.5–3.2 eV

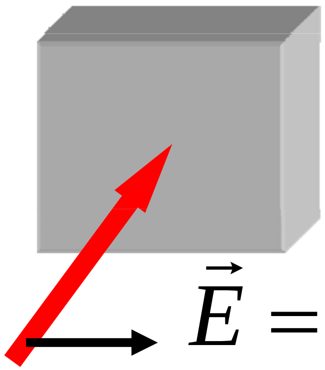
Why are certain wavelengths “visible”?



Optics



1.5–3.2 eV



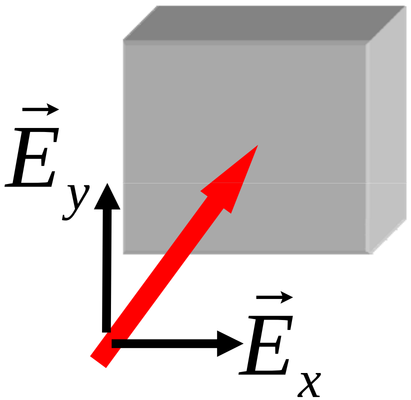
$$\vec{D} = \hat{\varepsilon}\varepsilon_0\vec{E} \quad \text{or} \quad \vec{P} = \hat{\chi}\varepsilon_0\vec{E}$$

$$\vec{E} = \vec{E}_0 e^{i(\vec{k}\vec{r}-\omega t)} \qquad \vec{D} = \varepsilon_0\vec{E} + \vec{P} \qquad \hat{\varepsilon} = 1 + \hat{\chi}$$

$$\varepsilon = n^2$$

Anisotropic media

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\ \varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\ \varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz} \end{pmatrix}$$

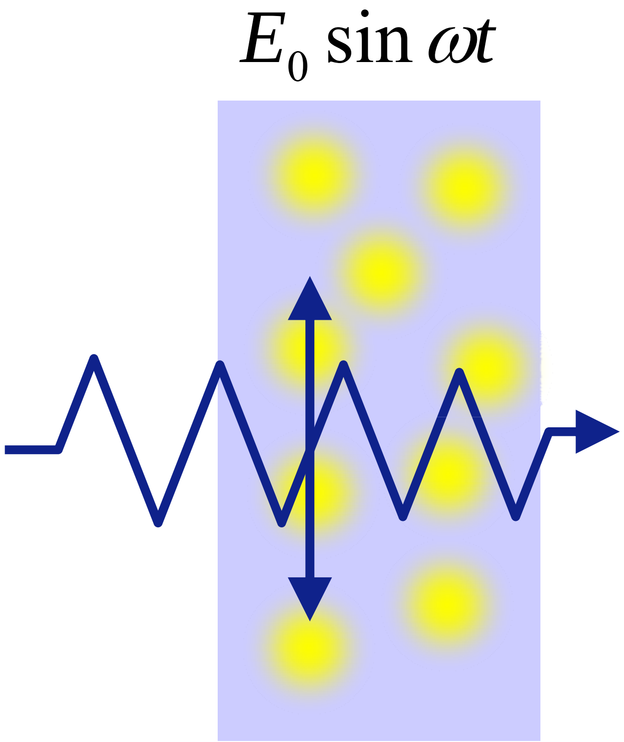


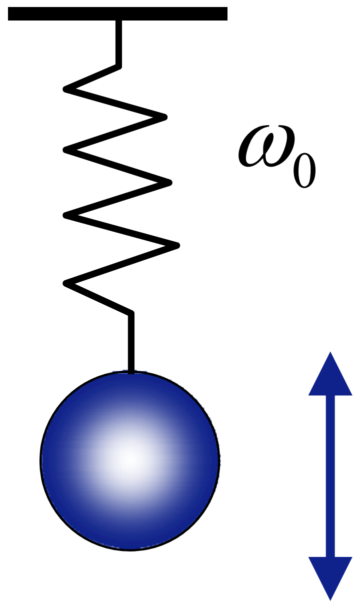
if $\mathrm{H} = 0$

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{pmatrix}$$

i.e. one could chose such a coordinate system

Driven oscillator model



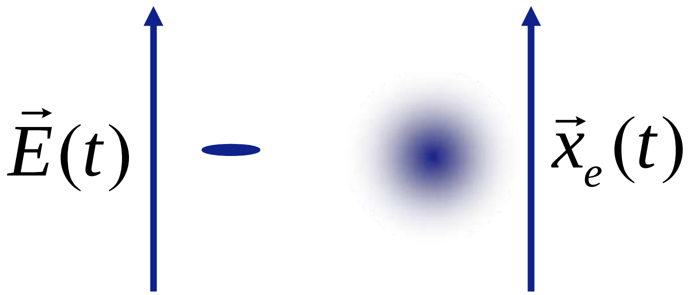


$$m\left(\frac{d^2x}{dt^2}+\omega_0^2 x\right)=F$$

$$F = eE_0 \sin \omega t$$

$$\frac{d^2x}{dt^2}+\omega_0^2 x=\frac{e}{m}E_0 \sin \omega t$$

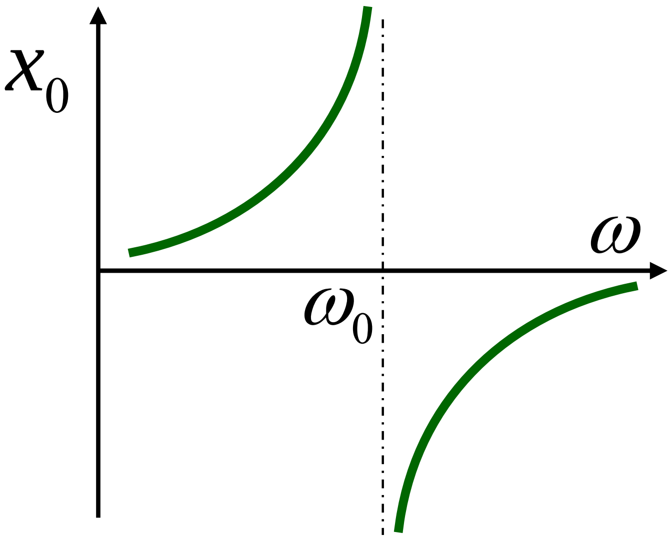
Driven oscillator model

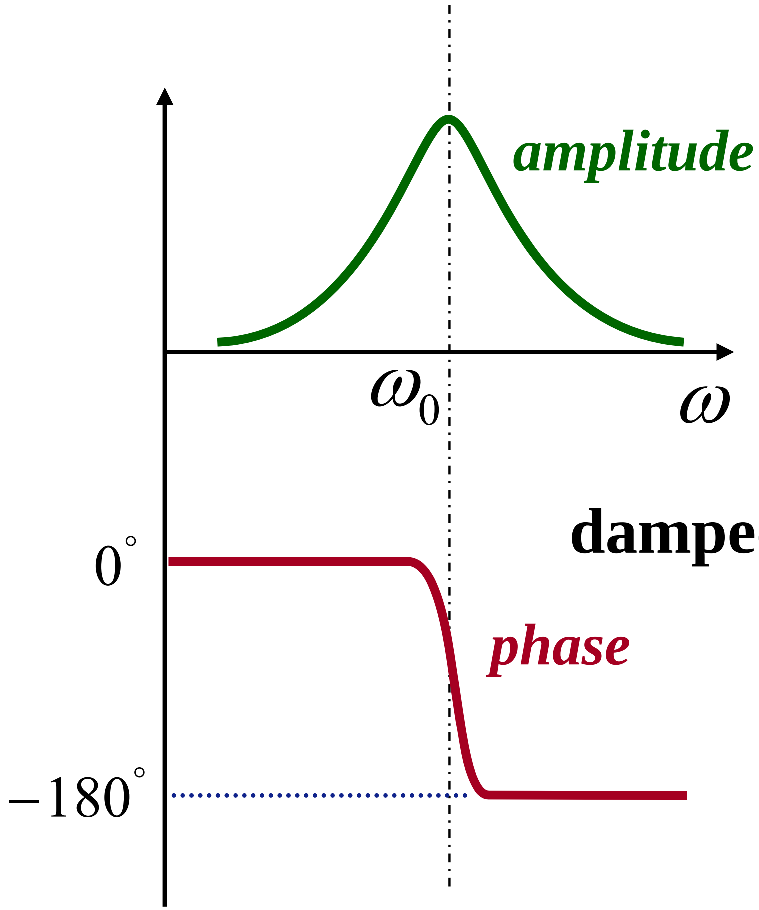


solution in the form:

$$x = x_0 \sin \omega t = \frac{eE_0}{m\left(\omega_0^2 - \omega^2\right)} \sin \omega t$$

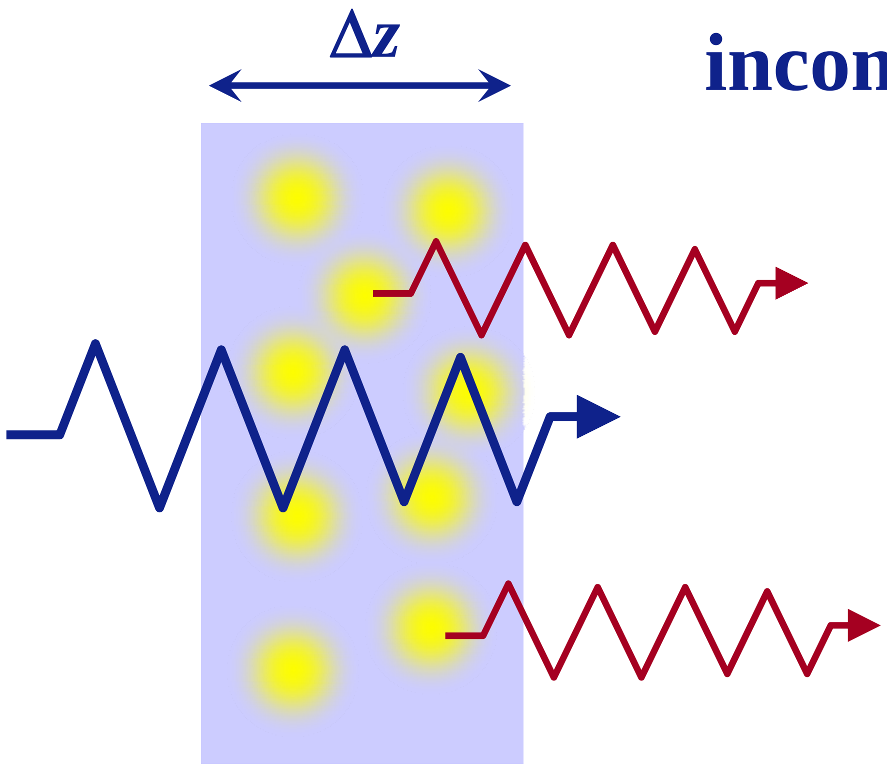
amplitude depends on ω





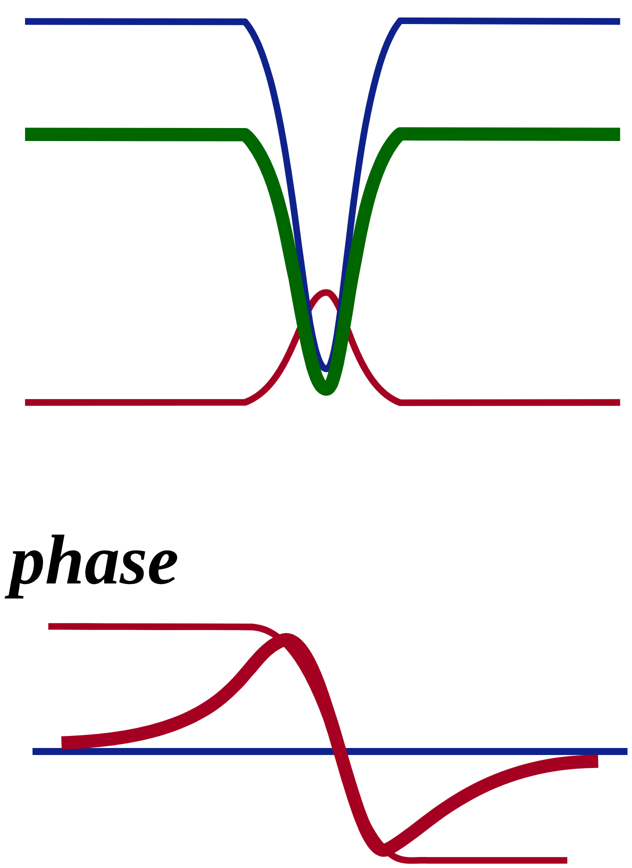
damped oscillator

Sum of the two waves:

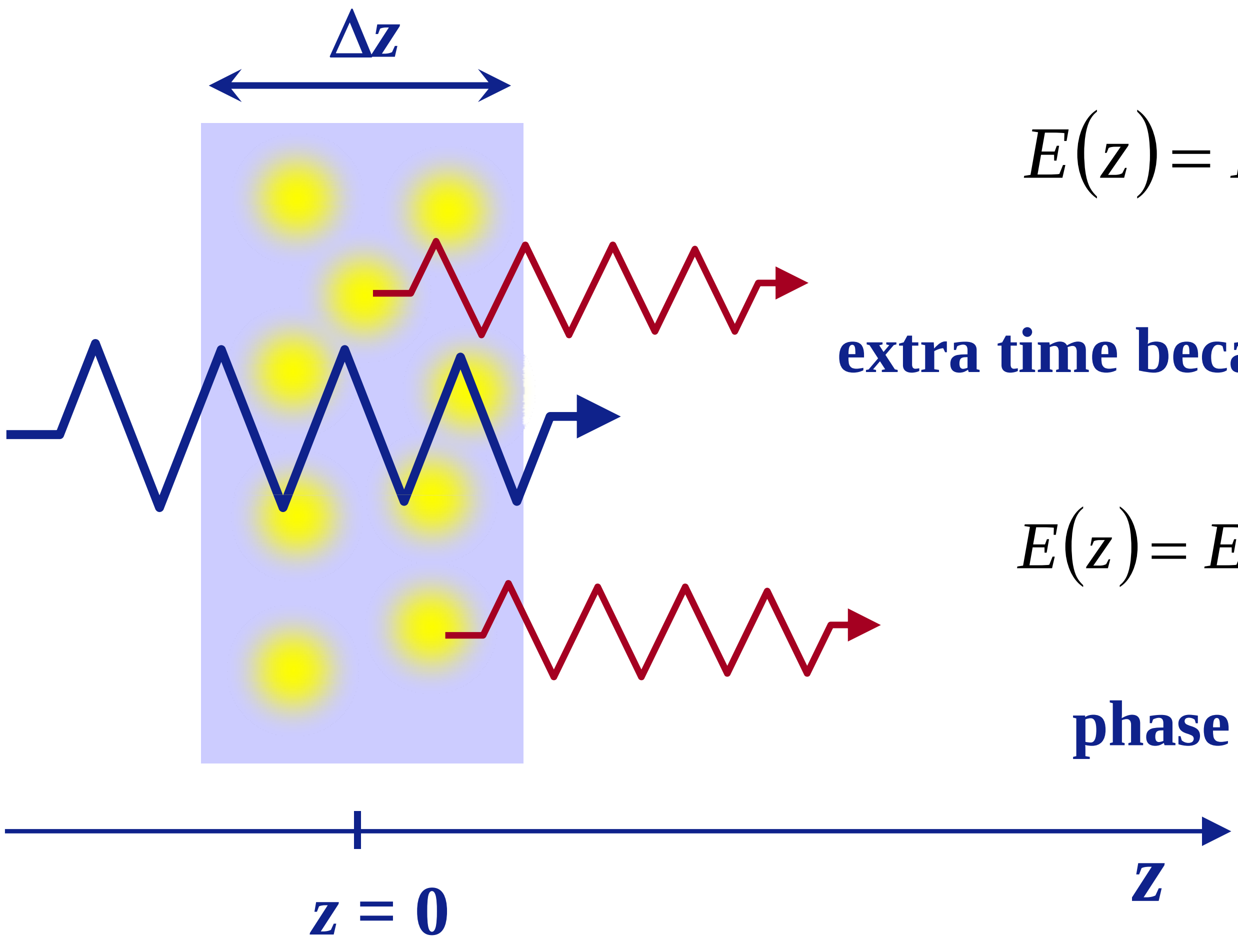


$$E(z=0) = E_0 \sin \omega t$$

incoming + outgoing



Phase of the light after transmission



$$E(z) = E_0 \sin \omega \left(t - \frac{z}{c} \right)$$

extra time because of *n*: $(n-1)\dfrac{\Delta z}{c}$

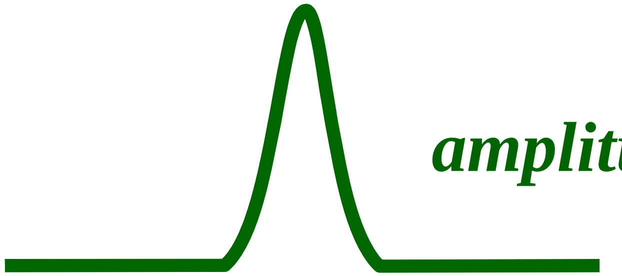
$$E(z) = E_0 \sin \omega \left(t - \frac{z}{c} - (n-1)\frac{\Delta z}{c} \right)$$

phase delay: $\omega(n-1)\dfrac{\Delta z}{c}$

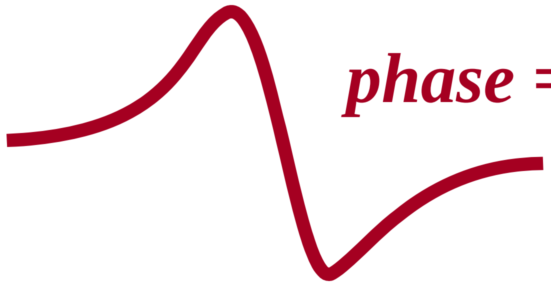
$$E(z=0) = E_0 \sin \omega t$$

thus if a phase delay occurs,
this is equivalent to the refractive index

Absorption en refractive index

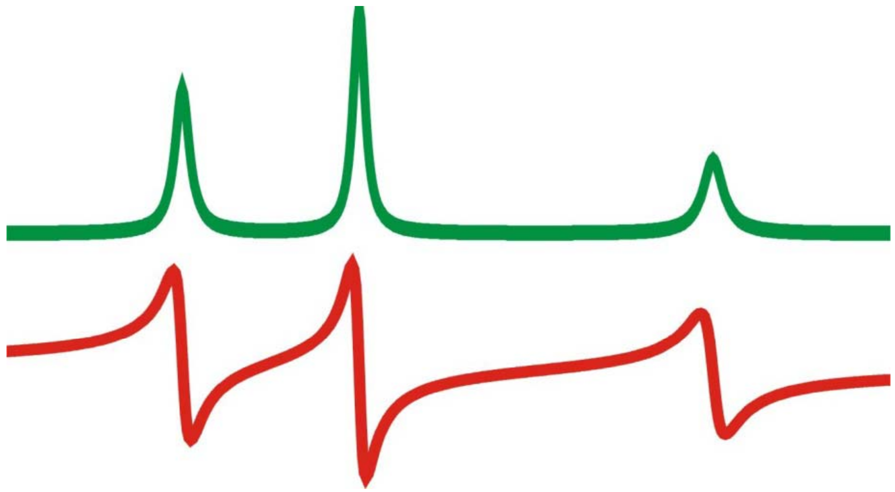


amplitude = absorption



phase = refractive index

multiple resonances:



$$\alpha = \frac{Ne^2}{2\varepsilon_0 c_0 m_e} \frac{\gamma/2}{(\omega_0-\omega)^2+(\gamma/2)^2} \qquad n-1 = \frac{Ne^2}{4\varepsilon_0 \omega m_e} \frac{\omega_0-\omega}{(\omega_0-\omega)^2+(\gamma/2)^2}$$

γ accounts for damping

Kramers-Kronig relations

$$\varepsilon = \varepsilon_1 + i\varepsilon_2$$

$$\tilde{n} = n + ik$$

$$\varepsilon_1 = n^2 - k^2$$

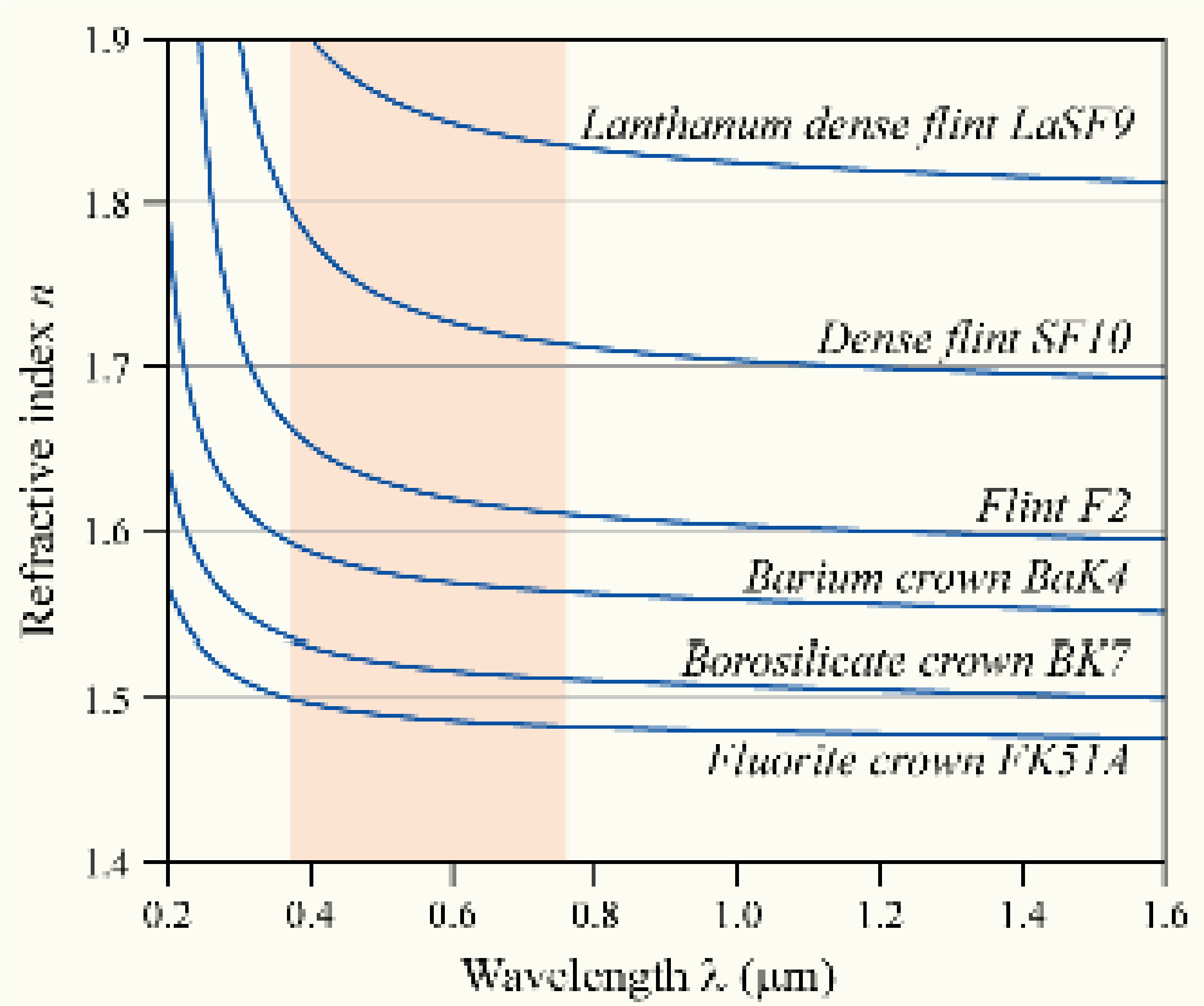
$$\varepsilon_2 = 2nk$$

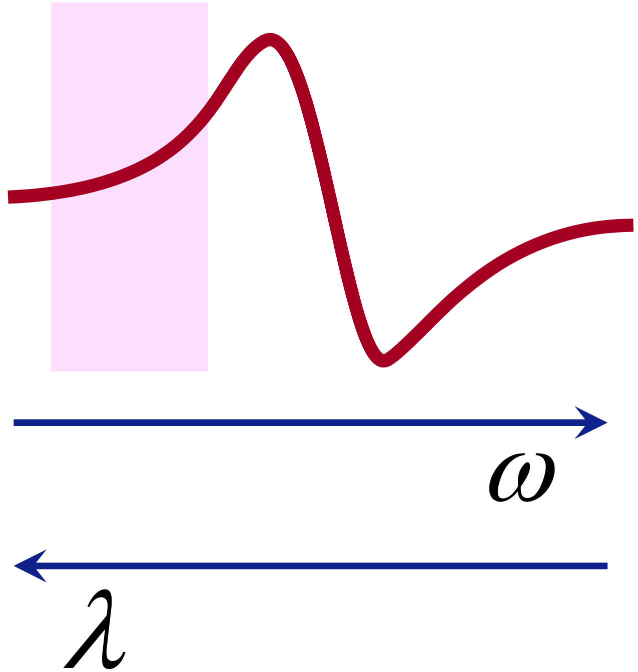
$$\varepsilon_2(\omega) = \frac{2\omega}{\pi} \int_0^\infty \frac{1 - \varepsilon_1(u)}{u^2 - \omega^2} du$$

$$\varepsilon_1(\omega) = \frac{2}{\pi} \int_0^\infty \frac{u \varepsilon_2(u)}{u^2 - \omega^2} du$$

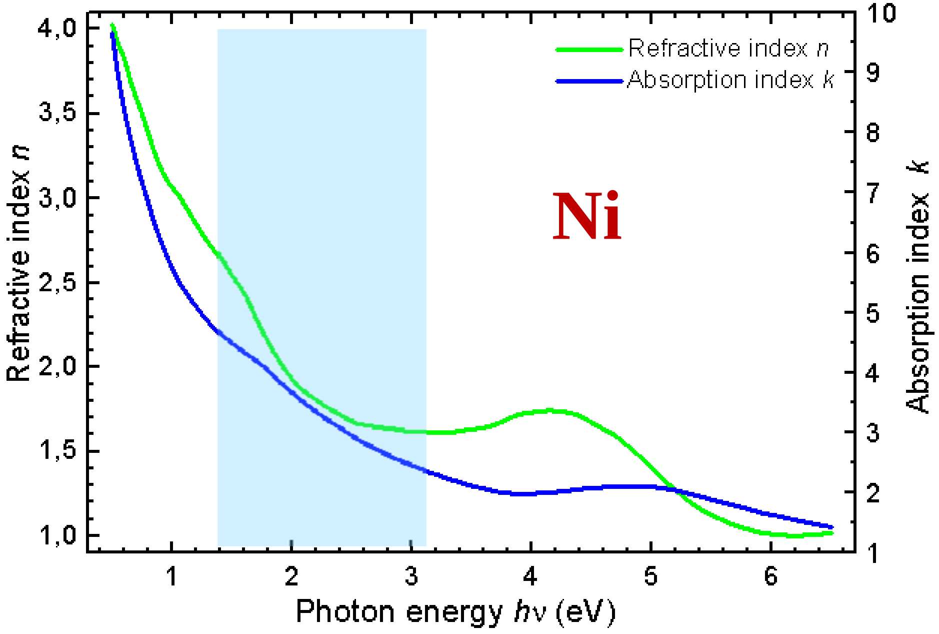
real and imaginary parts are not independent!

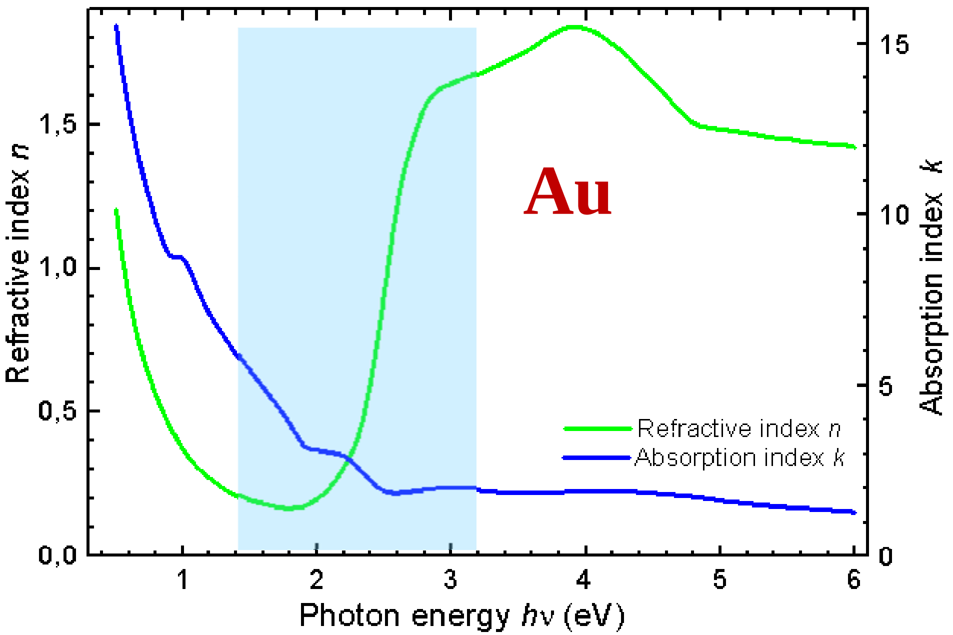
Dispersion of glass





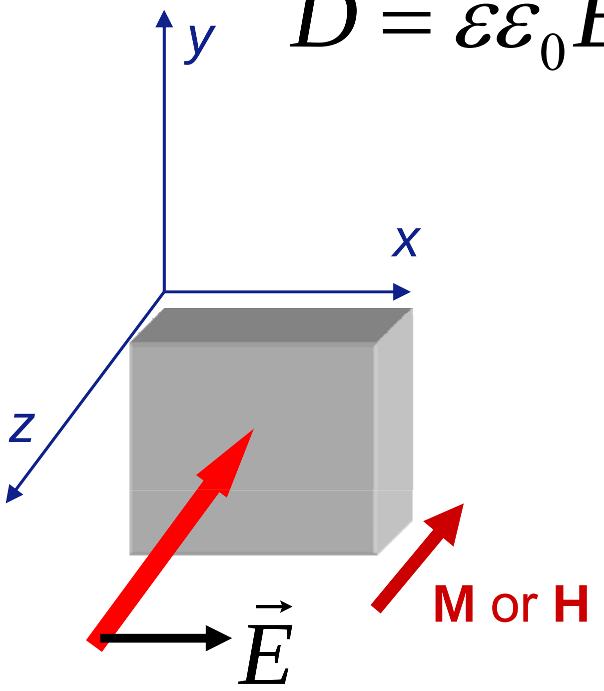
Optical constants of metals





Interaction of light with magnetic solids

How does magnetic field (magnetization) modify dielectric tensor?

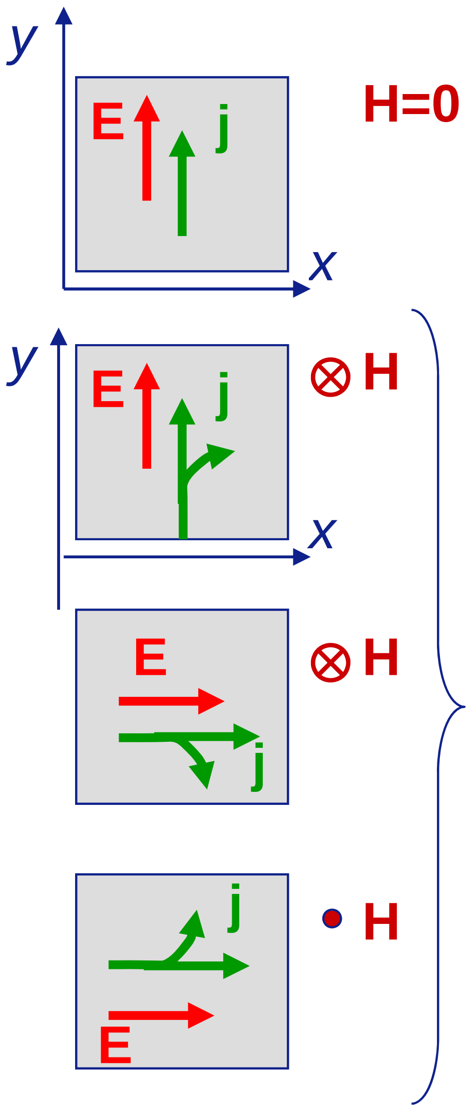


$$\vec{D} = \varepsilon\varepsilon_0\vec{E}$$

H=0 $$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} = n^2$$ **if isotropic**

H≠0 $$\varepsilon = \begin{bmatrix} ? & ? & ? \\ ? & ? & ? \\ ? & ? & ? \end{bmatrix}$$

How does magnetic field modify conductivity?



$$\sigma = \begin{bmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{bmatrix}$$

$$\vec{j} = \sigma \vec{E}$$

$F_L = e[V \times H]$ Lorentz force

$$E_y \rightarrow j_x$$
$$E_x \rightarrow j_y$$

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ \sigma_{yx} & \sigma_{yy} & 0 \\ 0 & 0 & \sigma_{zz} \end{bmatrix}$$

Onsager principle: symmetry of kinetic coefficients

H=0

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}$$

H≠0

$$\varepsilon = \begin{bmatrix} \varepsilon_{xx} & \varepsilon_{xy} & 0 \\ \varepsilon_{yx} & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix}$$

$$X_i = S_{ij} f_j \qquad \frac{\partial W}{\partial t} = f \frac{\partial X}{\partial t} \quad \Rightarrow \quad S_{ij} = S_{ji}$$

X - response
f - stimulus
W - energy

If S is a function of magnetic field

$$S_{ij}(H) = -S_{ji}(H) = S_{ji}(-H)$$

$$D_i = \varepsilon_{ij} E_j \qquad \frac{\partial W}{\partial t} = E \frac{\partial D}{\partial t} \quad \Rightarrow$$

Onsager principle is applicable to ε

$$\varepsilon_{ij}(H) = -\varepsilon_{ji}(H) = \varepsilon_{ji}(-H)$$

in non-absorbing media $\varepsilon_{ij} = \varepsilon_{ji}^*$

Landau & Lifshitz, Theoretical Physics, vv. 5 and 8.

Faraday effect – 1

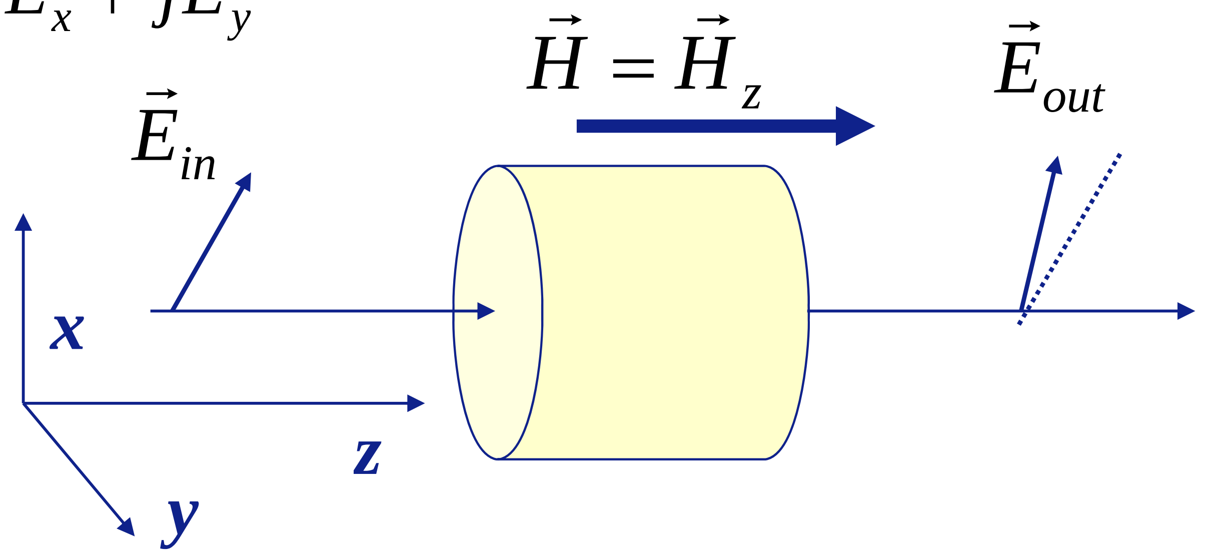
Isotropic medium in a magnetic field:

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_0 & -i\varepsilon_{xy} & 0 \\ i\varepsilon_{xy} & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 + \varepsilon_{zz} \end{pmatrix}$$

$$\varepsilon_{xy} \propto M_z$$

$$\varepsilon_{zz} \propto M_z^2$$

$$\vec{E}_{in} = \vec{i}E_x + \vec{j}E_y$$



$$\vec{E}_{out} = ???$$

Faraday effect – 2

To find the eigenvalues of the problem:

$$\vec{D} = \hat{\varepsilon}\vec{E} = \begin{pmatrix} \varepsilon_0 & -i\varepsilon_{xy} & 0 \\ i\varepsilon_{xy} & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ 0 \end{pmatrix} = n^2 \vec{E} \qquad \begin{pmatrix} \varepsilon_0 & -i\varepsilon_{xy} \\ i\varepsilon_{xy} & \varepsilon_0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = n^2 \begin{pmatrix} E_x \\ E_y \end{pmatrix}$$

$$\begin{vmatrix} \varepsilon_0 - n^2 & -i\varepsilon_{xy} \\ i\varepsilon_{xy} & \varepsilon_0 - n^2 \end{vmatrix} = 0 \quad \Rightarrow \quad n^2 = \varepsilon_0 \pm \varepsilon_{xy}$$

$$n \cong \sqrt{\varepsilon_0} \pm \frac{1}{2}\frac{\varepsilon_{xy}}{\varepsilon_0} \qquad \varepsilon_{xy} \sim 10^{-3} - 10^{-4}$$

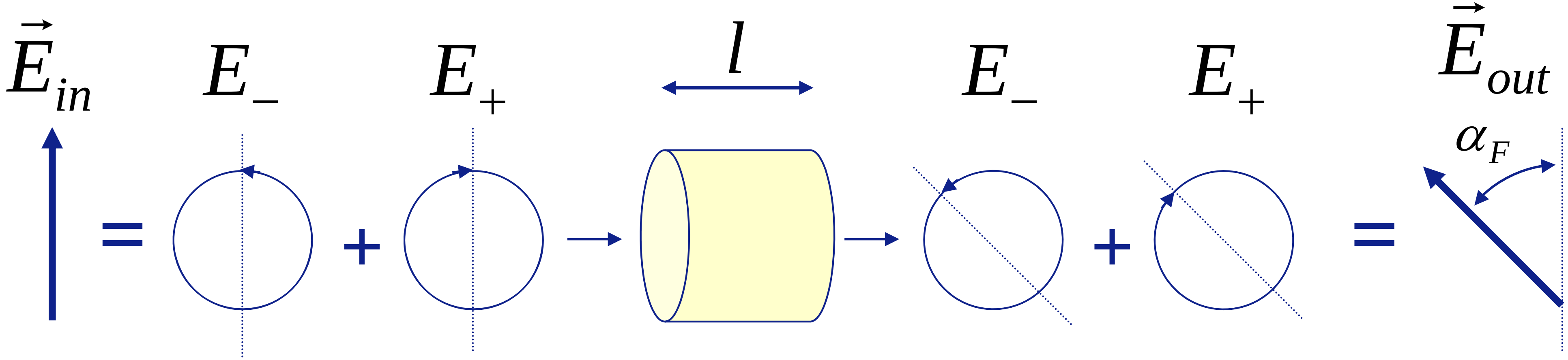
eigenmodes $E_x = \pm i E_y$, or $\begin{pmatrix} 1 \\ i \end{pmatrix}$ and $\begin{pmatrix} 1 \\ -i \end{pmatrix}$

Faraday effect – 3

Two circularly polarized waves
with different refractive indices:

$$E_x = \pm i E_y$$

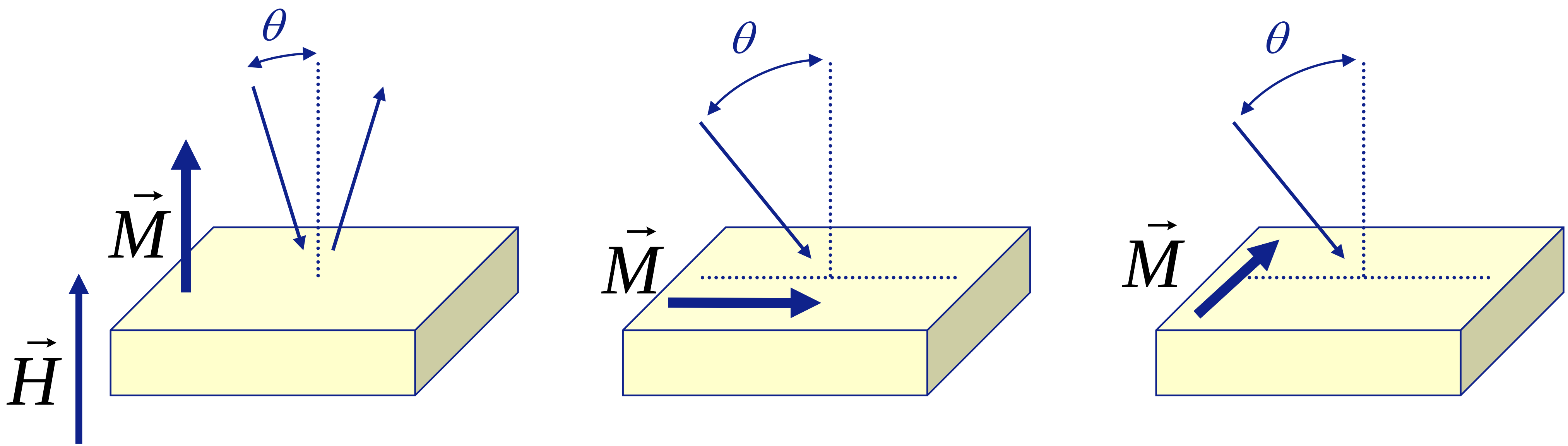
$$n_{\pm} \cong \sqrt{\varepsilon_0} \pm \frac{1}{2}\frac{\varepsilon_{xy}}{\varepsilon_0}$$



Faraday rotation: $\alpha_F = \frac{2\pi l}{\lambda}\frac{\varepsilon_{xy}}{\varepsilon_0}$

M. Faraday, *On the magnetization of light and the illumination of magnetic lines of force*, Phil. Trans. R. Soc. Lond. **136**, 104 (1846).

Kerr effect: various geometries



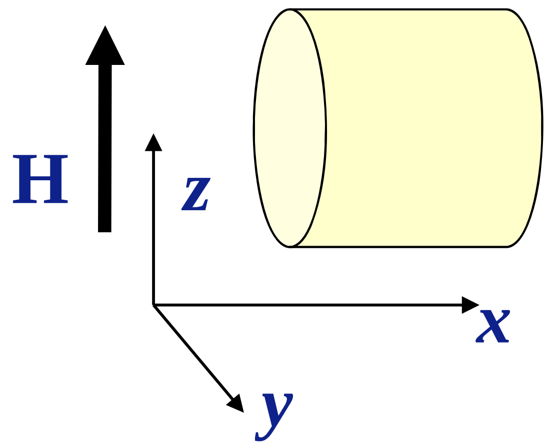
$\theta \approx 0^\circ$ | $\theta >> 0^\circ$ | $\theta >> 0^\circ$

polar | **longitudinal** | **transverse**

Magnetic linear birefringence

light propagates along x axis, so that

$$\vec{E}_{in} = \vec{j}E_y + \vec{k}E_z$$



$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_0 & -i\varepsilon_{xy} & 0 \\ i\varepsilon_{xy} & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 + \varepsilon_{zz} \end{pmatrix}$$

Eigenvalues $\varepsilon_0, \ \varepsilon_0 + \varepsilon_{zz}$ $\quad \varepsilon_{zz} \propto M^2$

Eigenmodes $\vec{E}_y, \vec{E}_z$

PHYSICAL REVIEW VOLUME 97, NUMBER 2 JANUARY 15, 1955

Theory of the Faraday and Kerr Effects in Ferromagnetics*

PETROS N. ARGYRES†
Department of Physics, University of California, Berkeley, California

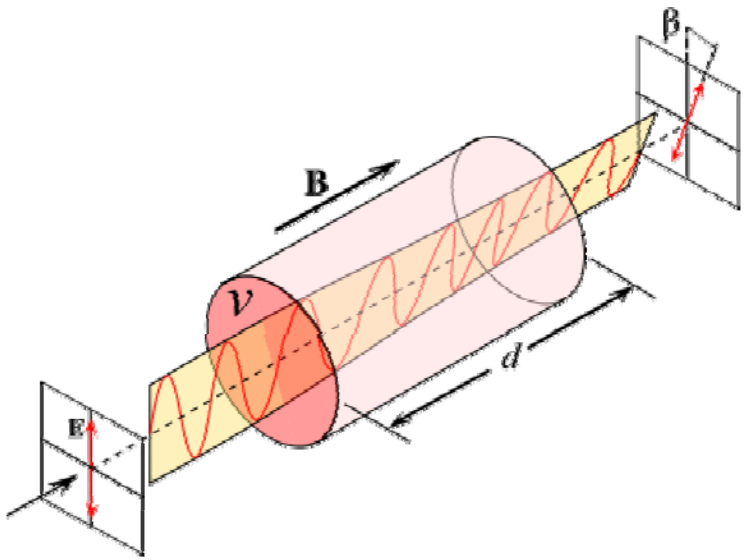
(Received August 20, 1954)

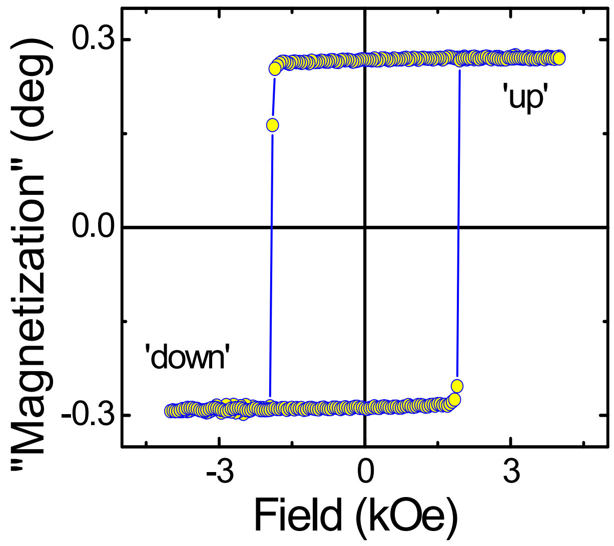
Both the Faraday and (magneto-optic, polar) Kerr effects in ferromagnetics are treated on the basis of the band theory of metals. The spin-orbit interaction gives the electron wave functions such left-right asymmetry that the "magnetic" electrons, under the action of a plane polarized light wave, produce an average current perpendicular to the plane of polarization.

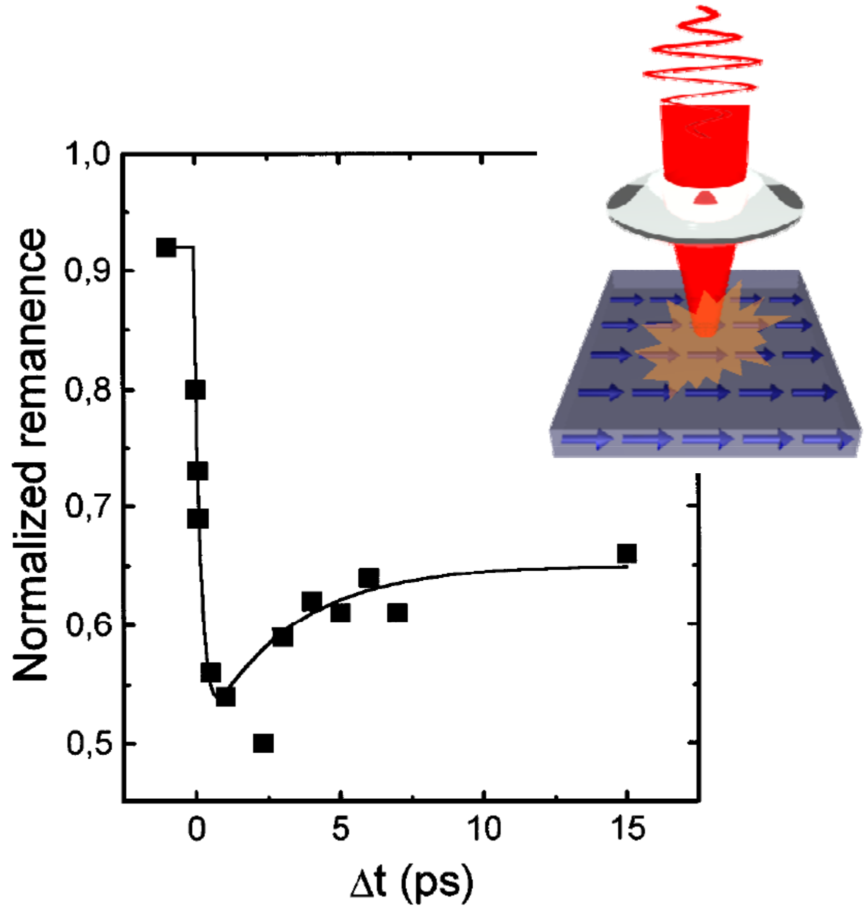
spins → orbits → light wave

exchange + spin-orbit

What could be measured?







Beaurepaire et al, PRL **76**, 4250 (1996).

hysteresis

dynamics

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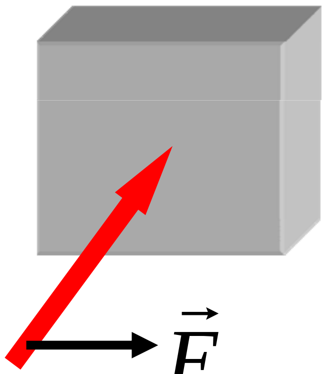
Electromagnetic wave equation and source term

$$\frac{\partial^2 \vec{E}}{\partial t^2} - c^2 \cdot \nabla^2 \vec{E} = \vec{S} \qquad \vec{S} = \frac{\partial^2 \vec{P}}{\partial t^2} + \nabla \times \frac{\partial \vec{M}}{\partial t} - \nabla \frac{\partial^2 \hat{Q}}{\partial t^2}$$



$\vec{E}$

$$\Phi = -\left(\underline{\chi^{(1,d)} E^{\omega} E^{\omega}} + \underline{\chi^{(1,m)} E^{\omega} H^{\omega}} + \underline{\chi^{(1,d)} E^{\omega} \nabla E^{\omega}}\right) \times \left(1 + \alpha E^{\omega} + \beta H^{\omega} + \gamma \nabla E^{\omega} + \ldots\right),$$

or

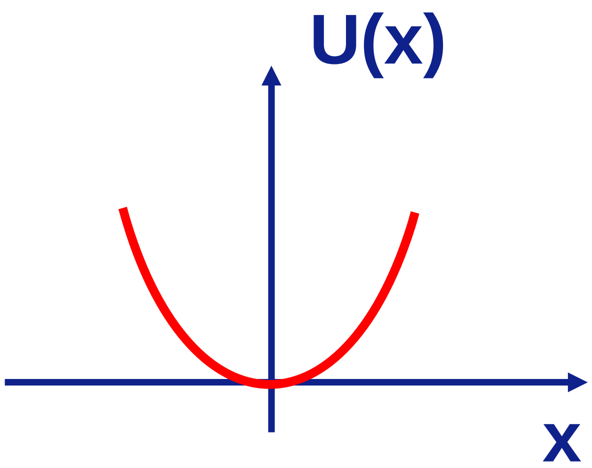
$$P^{\omega\ldots} = \underline{\chi^{(1,d)} E^{\omega}} + \underline{\chi^{(1,m)} H^{\omega}} + \underline{\chi^{(1,q)} \nabla E^{\omega}} + + \underline{\chi^{(2,d)} E^{\omega} E^{\omega}} + \underline{\chi^{(2,m)} E^{\omega} H^{\omega}} + \underline{\chi^{(2,q)} E^{\omega} \nabla E^{\omega}} \ldots$$

electric dipole approximation

magnetic dipole **electric quadrupole**

Harmonic oscillator

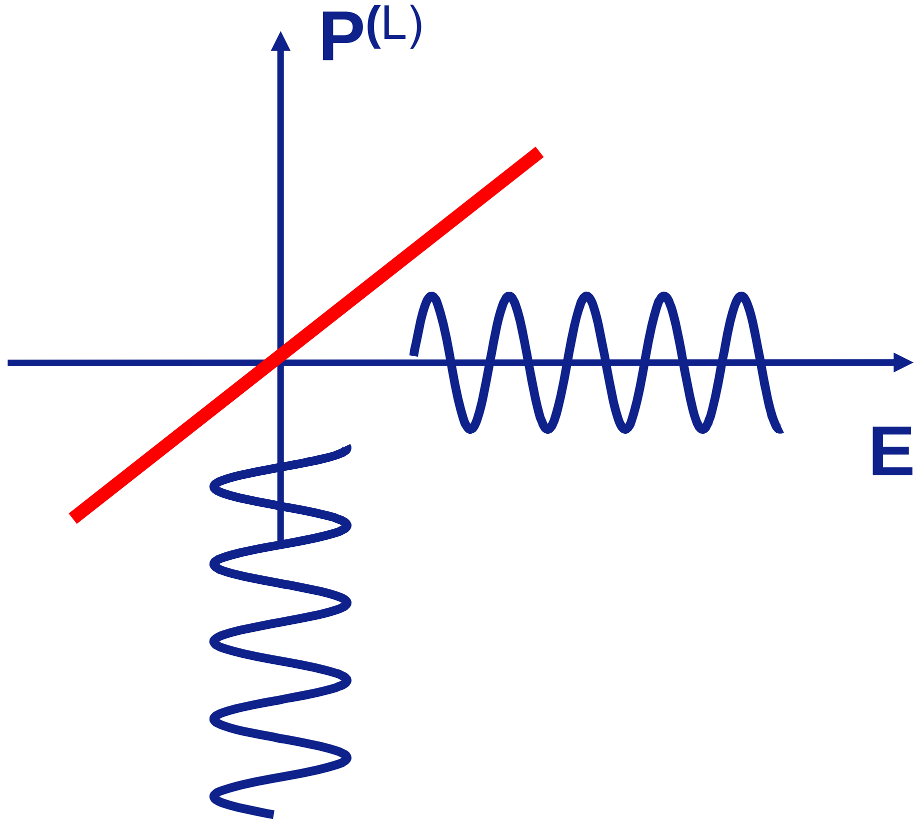
Linear response



$$U(x) = k_1 x^2$$

$$F_{el} = \frac{dU(x)}{dx} = kx$$

$$m\frac{d^2\mathbf{x}}{dt^2} + \mathbf{F}_{el} = e\mathbf{E}$$



$$P_i^{(L)}(\omega) = \chi_{ij}(\omega) E_j(\omega)$$

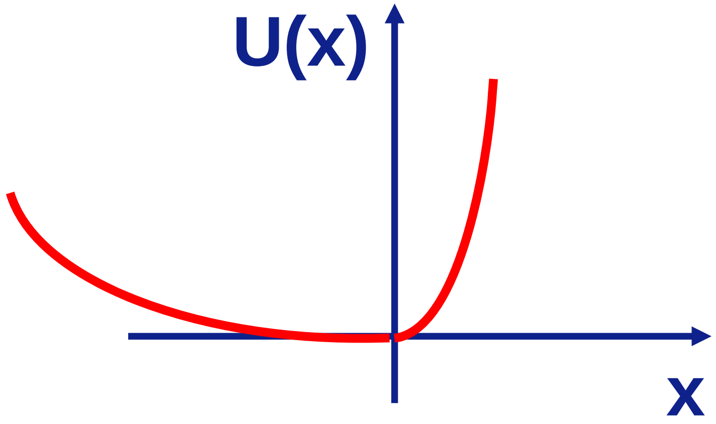
Linear vs nonlinear optics?

Linearity in optics:

- Properties of a medium ***do not depend*** on light intensity
- Principle of superposition ***holds***
- Frequency of light ***is not*** altered by its passage through the medium
- Light ***does not interact*** with light. A control of light by light is impossible.

Nonlinear oscillator

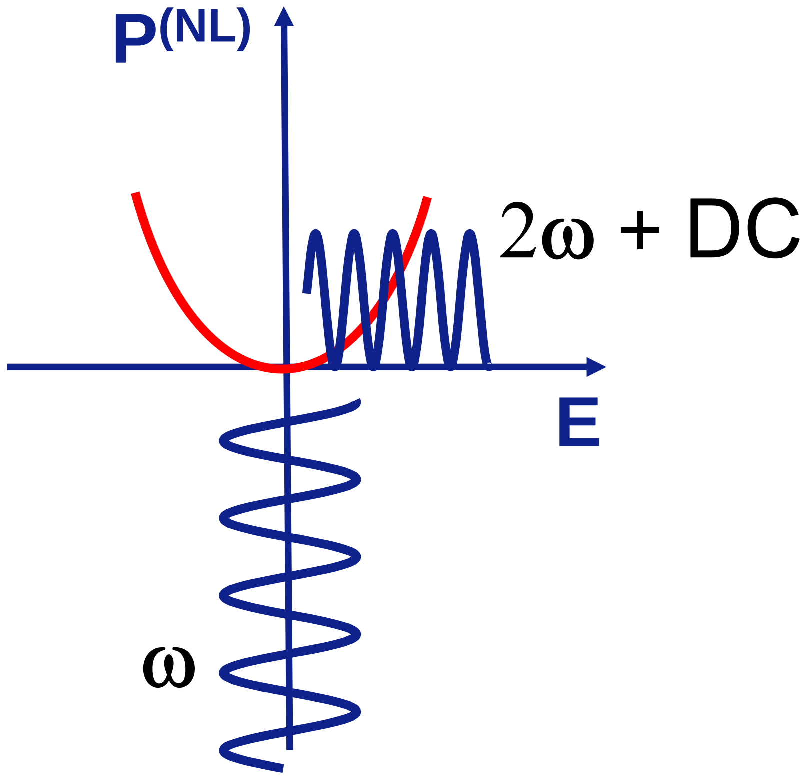
Anharmonism



$$U(x) = k_1 x^2 + k_2 x^3$$

$$F_{el} = \frac{dU(x)}{dx} = 2k_1 x + 3k_2 x^2$$

$$P = P^{(L)} + P^{(NL)}$$



$$P_i^{(NL)}(2\omega) = \chi_{ijk}(2\omega) E_j(\omega) E_k(\omega)$$

$$P_i^{(NL)}(0) = \chi_{ijk}(0) E_j(\omega) E_k(\omega)$$

Nonlinear polarization and symmetry

$$P(\omega) \propto \chi^{(1)} \cdot E^{\omega} + \chi^{(2)} \cdot E^{\omega} E^{\omega} + \ldots$$

(electric dipole approximation)

$$e^{i\omega t} \qquad e^{i\omega t} \cdot e^{i\omega t} = e^{i2\omega t}$$

second-harmonic generation

$$e^{i\omega t} \cdot e^{-i\omega t} = e^{i \cdot 0 t}$$

optical rectification

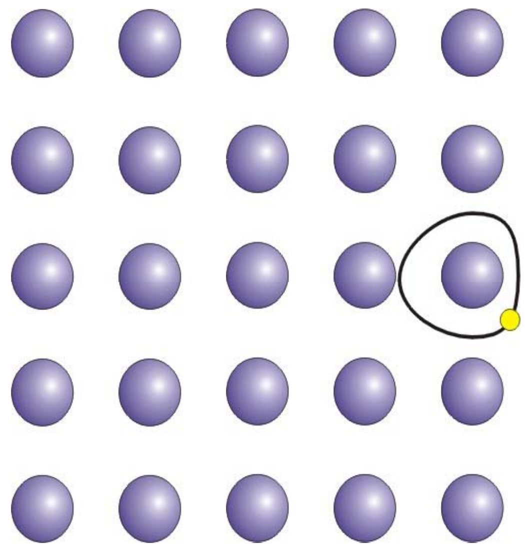
inversion symmetry:

$$P(2\omega) \propto \chi^{(2)} \cdot E^{\omega} E^{\omega}$$

$$-1 \qquad\qquad -1 \quad -1$$

$$P(2\omega) \equiv 0$$

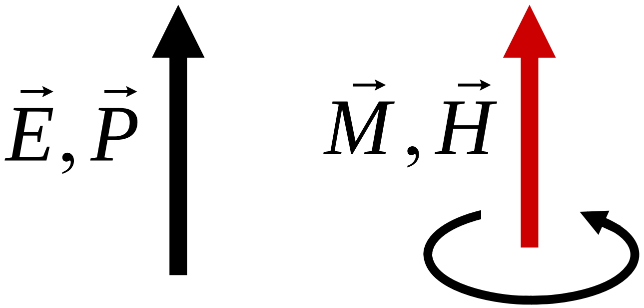
except at surface/interface



Magnetization-sensitive SHG

$$P_i^{(2\omega)} = \chi_{ijk} E_j^{(\omega)} E_k^{(\omega)} = \left(\chi_{ijk}^{(cr)} \pm \chi_{ijk}^{(m)}\right) E_j^{(\omega)} E_k^{(\omega)}$$

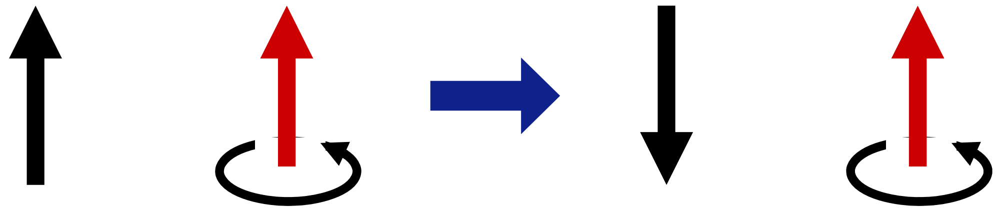
crystallographic
±
magnetic



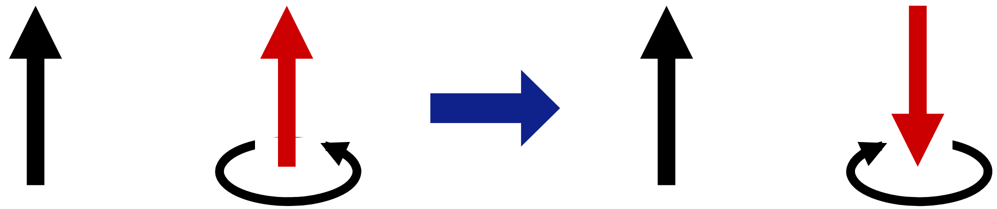
polar vector

axial vector

space inversion:



time reversal:

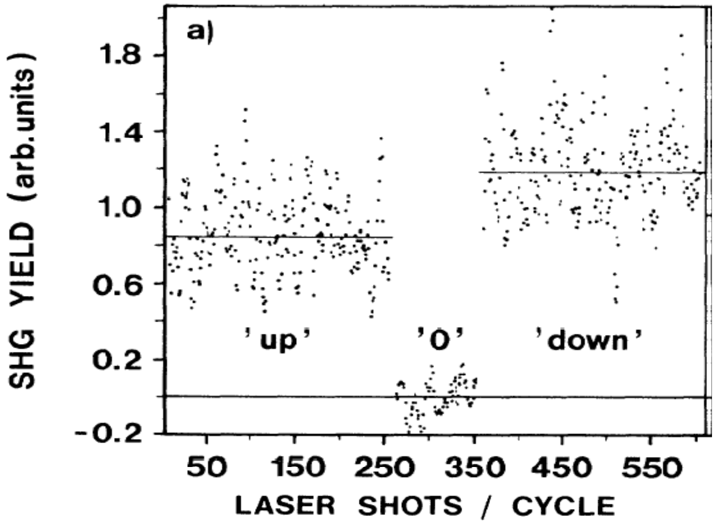


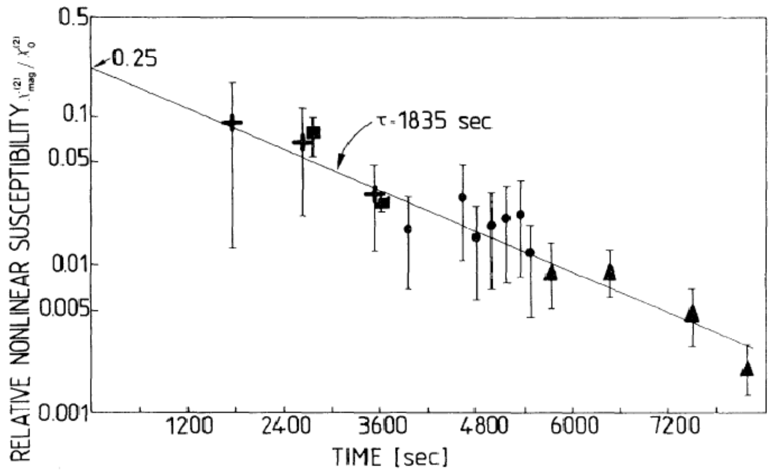
R.R. Birss, *Symmetry and Magnetism* (North-Holland, Amsterdam, 1966).

A. Kirilyuk and Th. Rasing, J. Opt. Soc. Am. B **22**, 148 (2005)

Example: surface/interface sensitivity

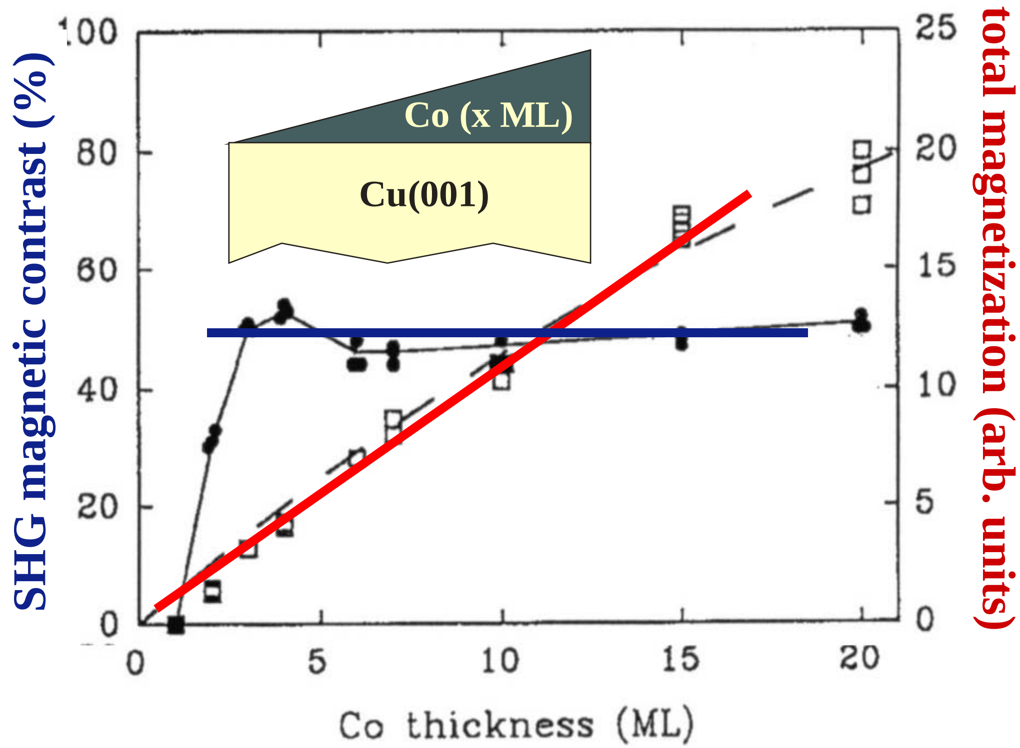
Fe(110) surface





Reif *et al*, Phys. Rev. Lett. **67**, 2878 (1991)

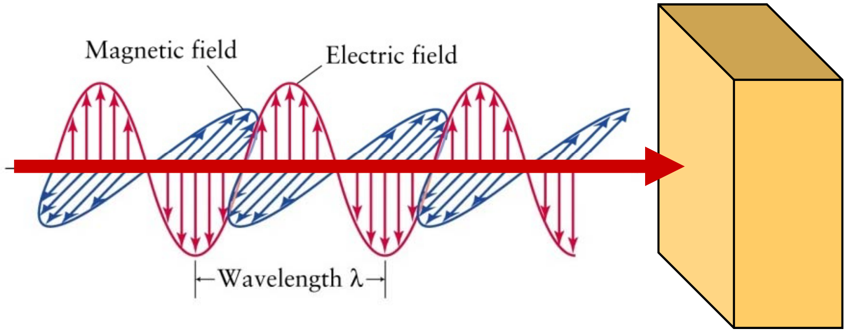
ultrathin Co/Cu(001) films



at 4 ML, both interfaces are formed

Phys. Rev. Lett. **74**, 1462 (1995);
J. Phys. D – Appl. Phys. **35**, R189 (2002)

General phenomenology



$$\vec{P} \propto \chi^{(1)} \cdot \vec{E} + \underline{\chi^{(2)} : \vec{E}\vec{E}} + \chi^{(3)} : \vec{E}\vec{E}\vec{E} + \ldots$$

$$\vec{P}^{(nl)} \propto \chi^{eee} : \vec{E}\vec{E} + \chi^{eem} : \vec{E}\vec{H} + \chi^{emm} : \vec{H}\vec{H} + o\left[\left(\vec{E},\vec{H}\right)^3\right]$$

$$\vec{M}^{(nl)} \propto \chi^{mee} : \vec{E}\vec{E} + \chi^{mem} : \vec{E}\vec{H} + \chi^{mmm} : \vec{H}\vec{H} + o\left[\left(\vec{E},\vec{H}\right)^3\right]$$

$$\hat{Q}^{(nl)} \propto \chi^{qee} : \vec{E}\vec{E} + \chi^{qem} : \vec{E}\vec{H} + \chi^{qmm} : \vec{H}\vec{H} + o\left[\left(\vec{E},\vec{H}\right)^3\right]$$

Source term:

$$\mathbf{S} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2} + \mu_0 \left(\nabla \times \frac{\partial \mathbf{M}}{\partial t} \right) - \mu_0 \left(\nabla \frac{\partial^2 \hat{Q}}{\partial t^2} \right)$$

sum- and difference frequency generation, including SHG and optical rectification

Outline of the lecture

- Light as a probe ✓
  - linear magneto-optics ✓
  - nonlinear (magneto-)optics ✓
- Example: all-optical FMR
- Light as an excitation
  - classification of effects
  - basics of opto-magnetism
  - coherent control
  - local control of spins
- *can this become too-ultrafast?*

Outline of the lecture

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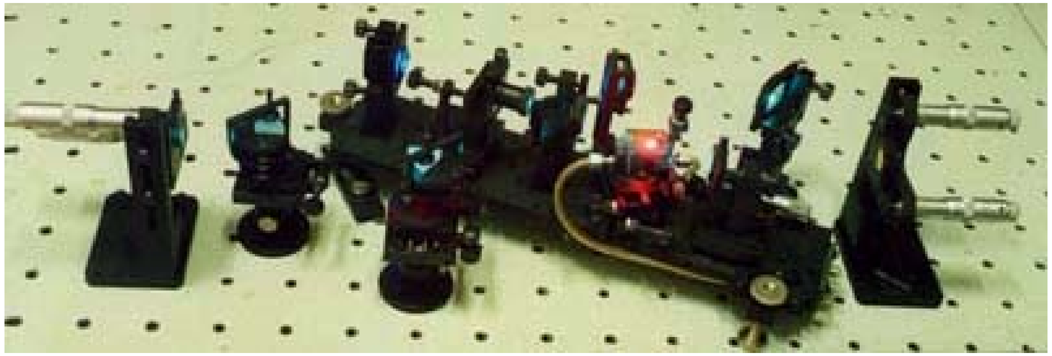
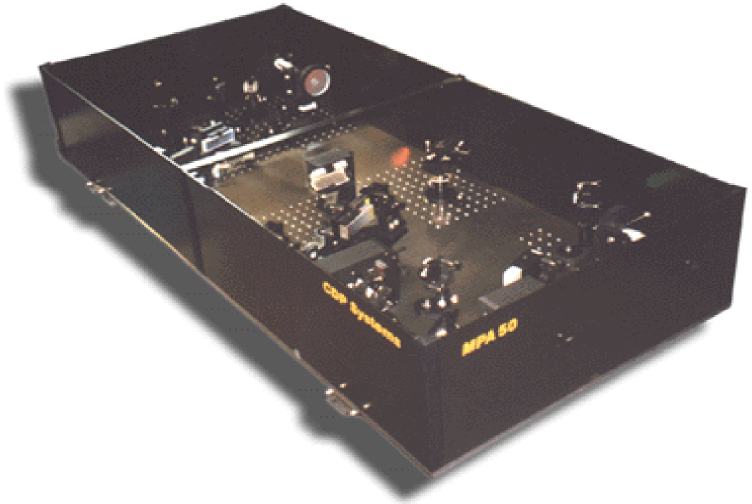
  - local control of spins
- *can this become too-ultrafast?*

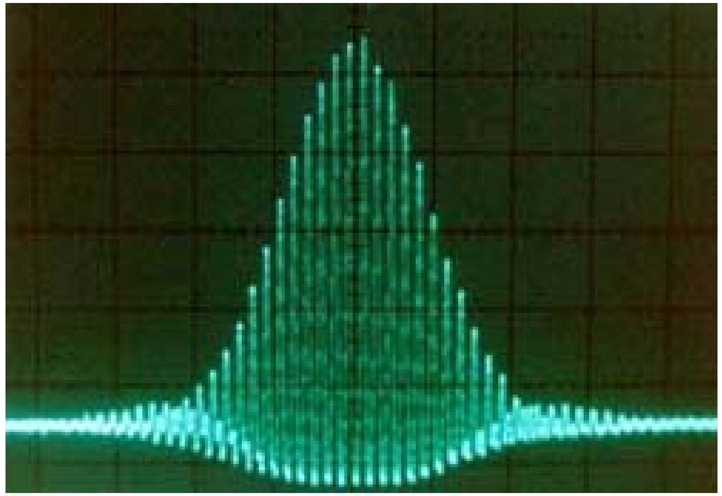
Experimental know-how: time-resolved pump-probe setup

What you need: a femtosecond laser





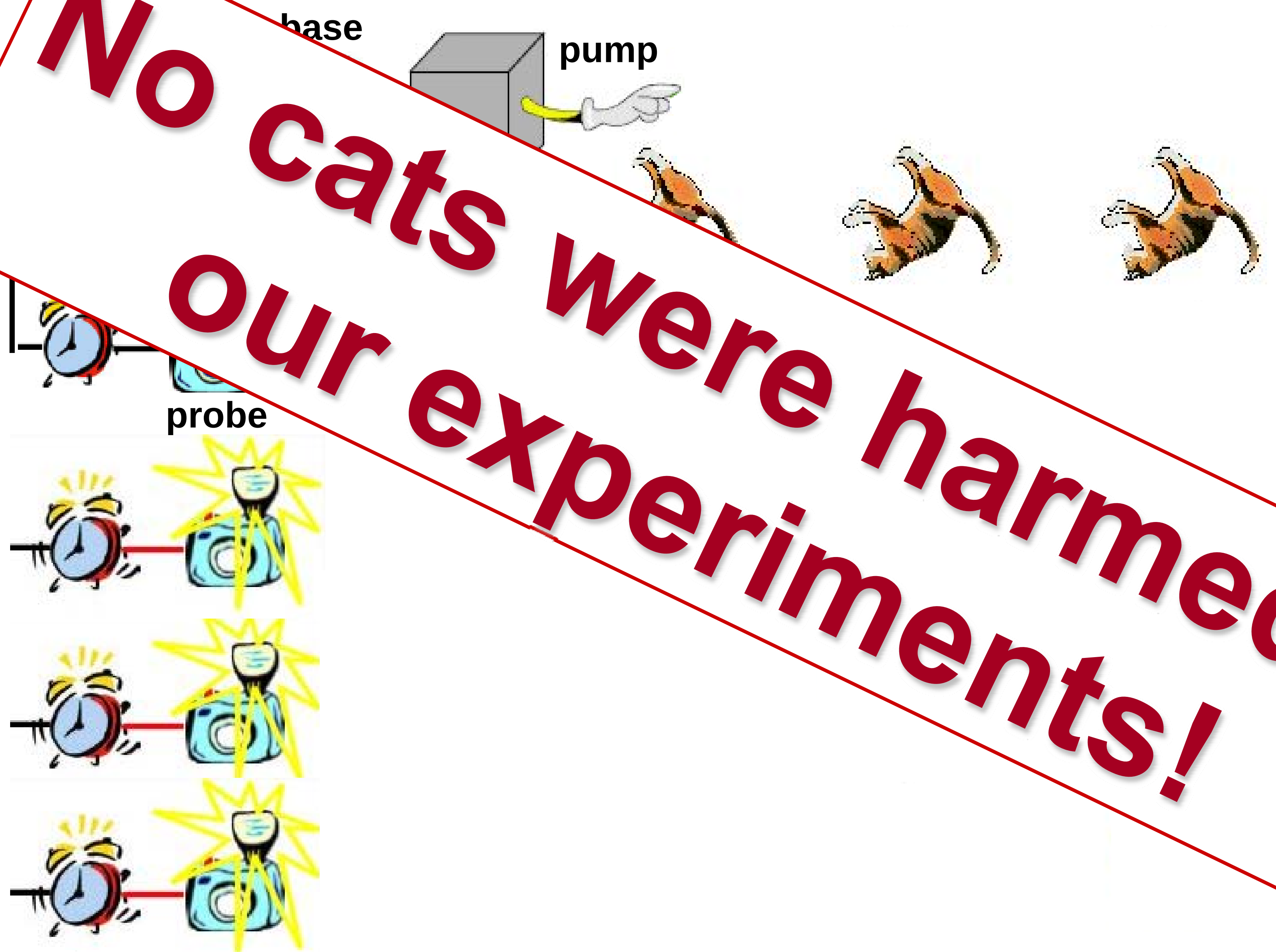
	Model TISSA20	Model TISSA50	Model TISSA100
Pump Power[1)]	3-5 W	3-7 W	5-10 W
Output Power at 800 nm	150 - 250 mW	150-500 mW	>10% efficiency
Pulse Duration[2)]	<20 fs [3)]	< 50 fs	<100 fs
Tuning Range	800 ± 20 nm	740 - 950 nm[4)]	720 - 980 nm[4)]
Repetition Rate	70 - 140 MHz		



Interferometric autocorrelation function of 16 fs pulse obtained with external group velocity dispersion compensation

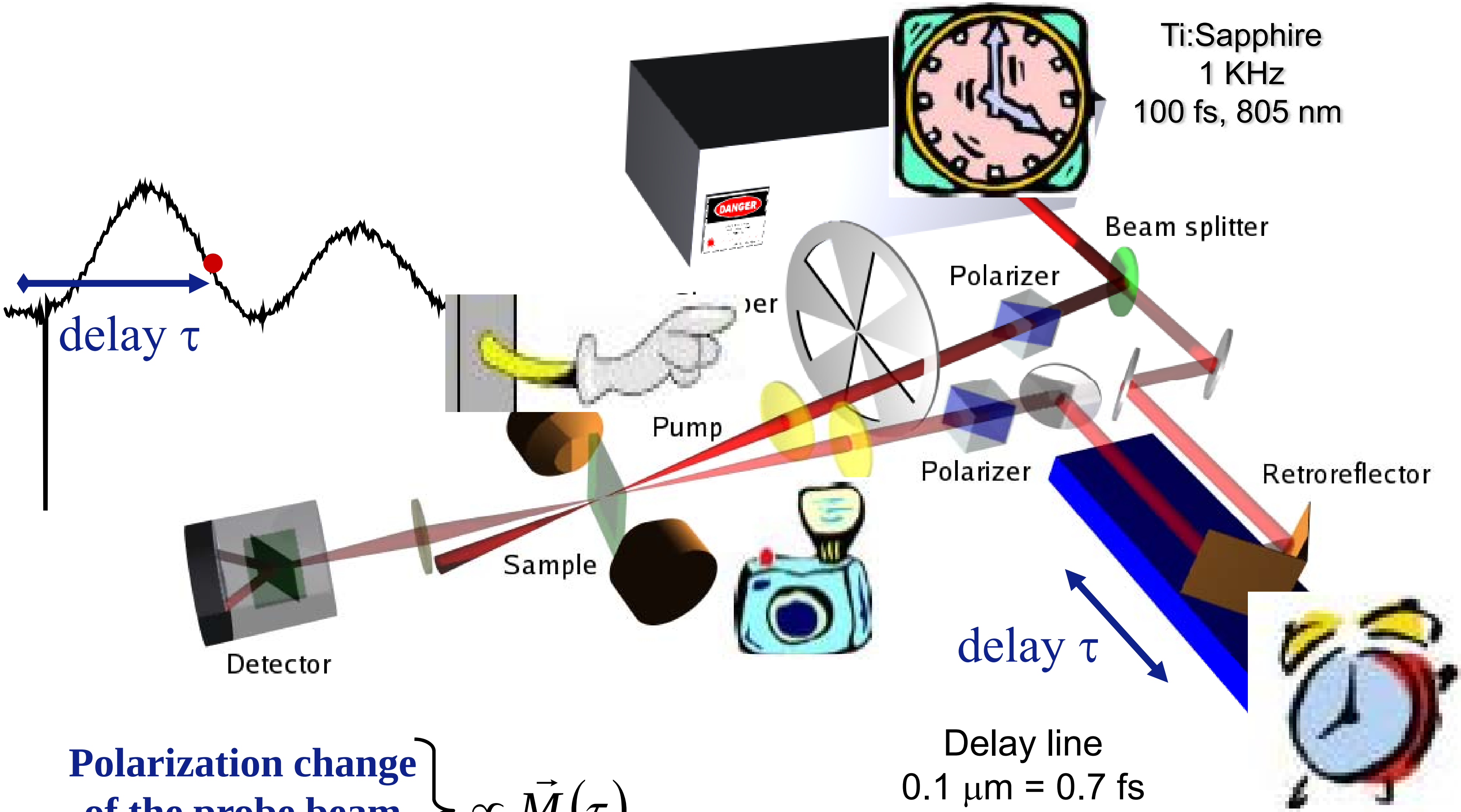
you have some choice!

pump & probe technique



No cats were harmed in our experiments!

Stroboscopic magneto-optical pump-probe measurements



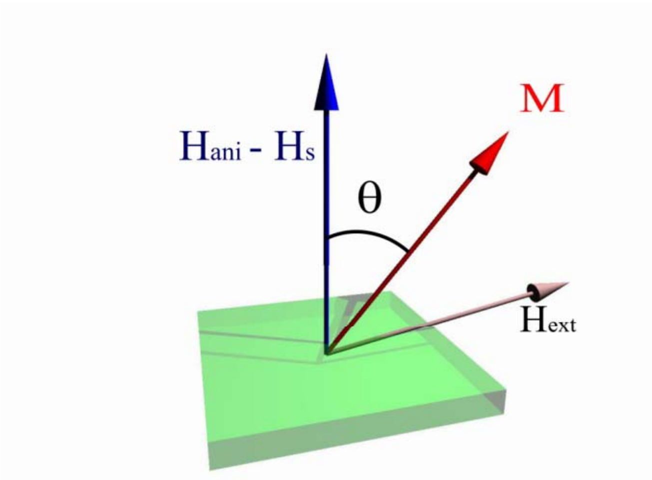
Delay line
0.1 μm = 0.7 fs

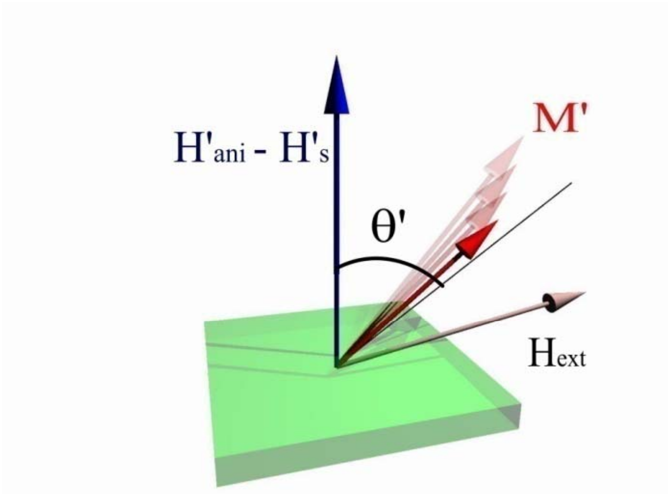
Polarization change of the probe beam is detected $\} \propto \vec{M}(\tau)$

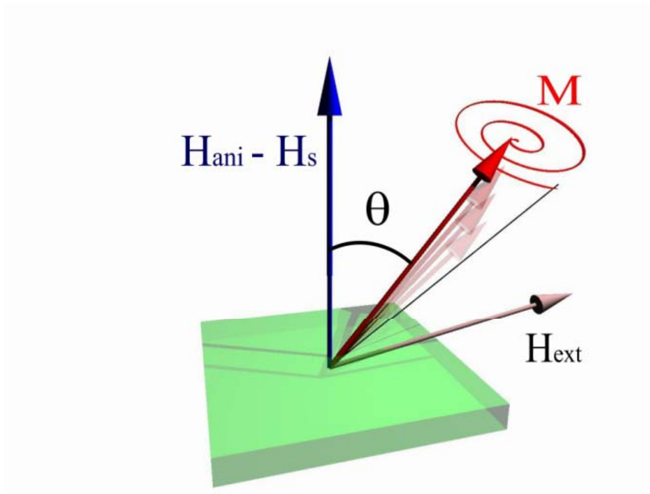
Optical pump-probe measurements of FMR

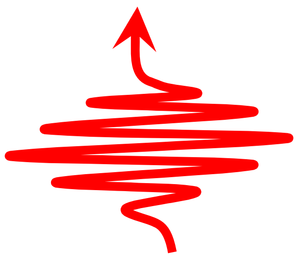
before pump pulse arrives

after pump has arrived









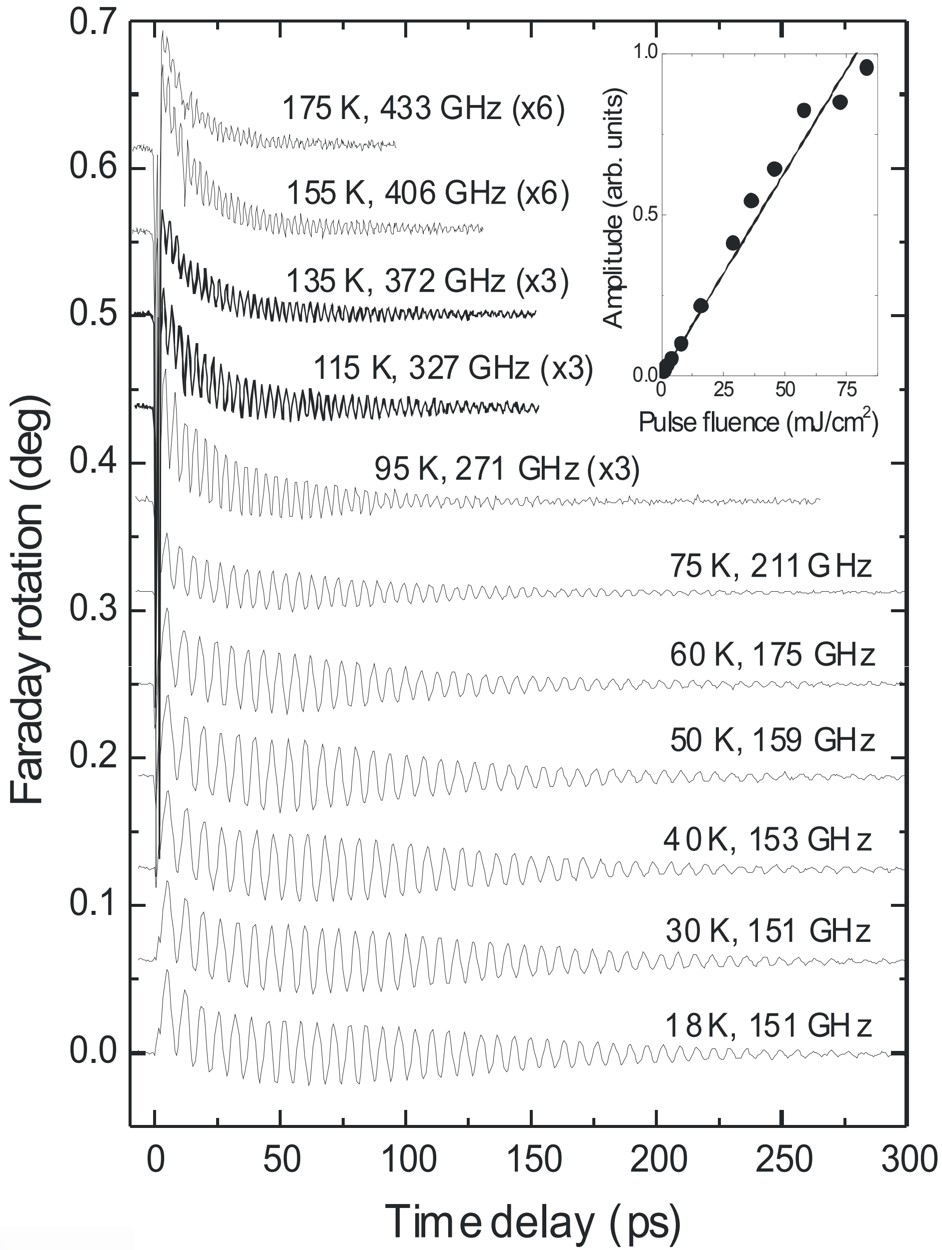
Pump pulse

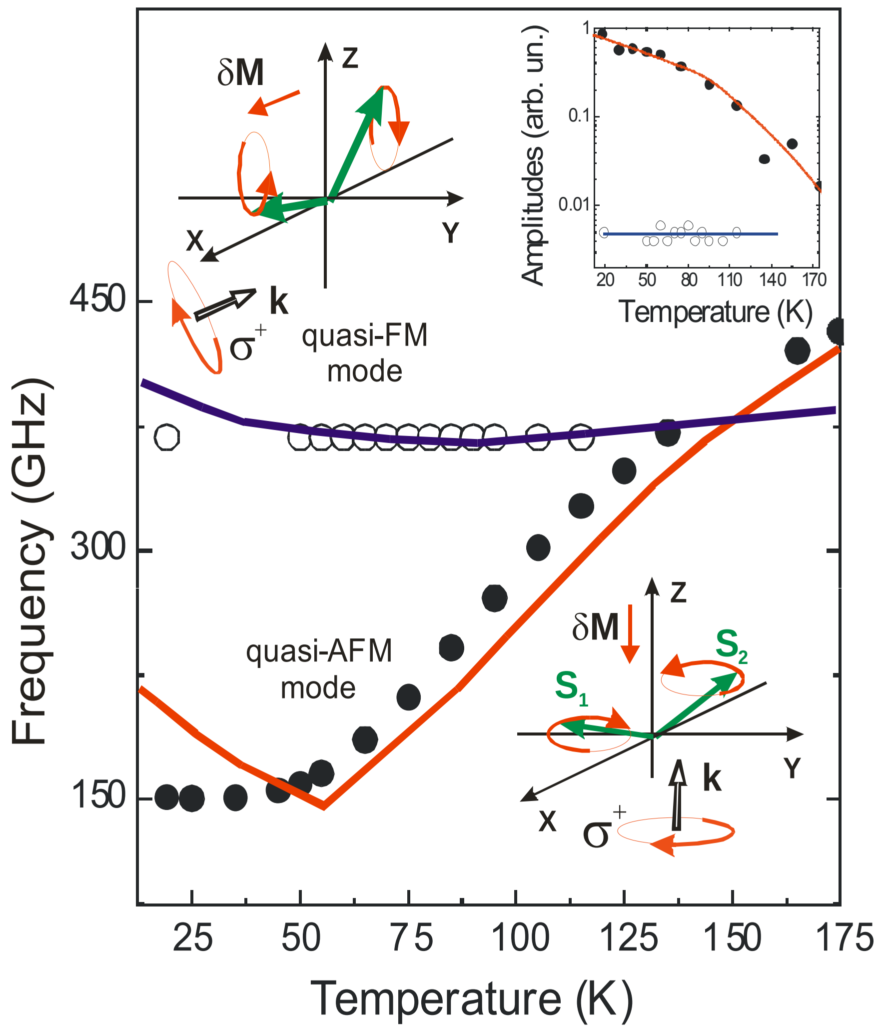
external field

$$\vec{H}^{eff} = \vec{H}_{ext} + \underbrace{\vec{H}_{ani} + \vec{H}_{s}}_{\text{affected by the laser}}$$

affected by the laser

All-optical magnetic resonance in antiferromagnets





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- *can this become too-ultrafast?*

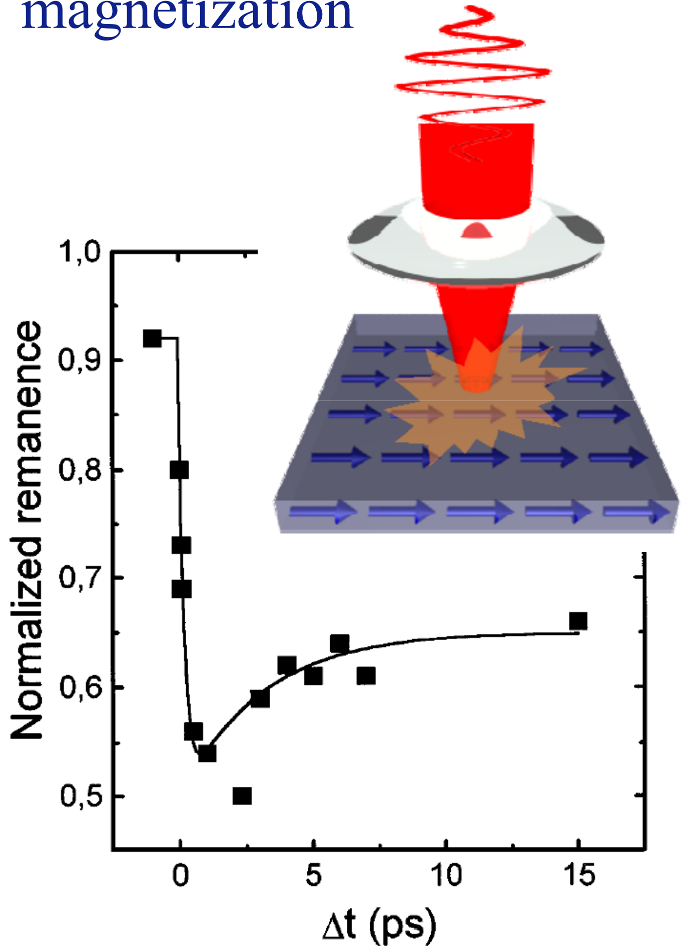
Effects of the laser pulse: classification

I. Thermal effects:

change of M is a result of change of T

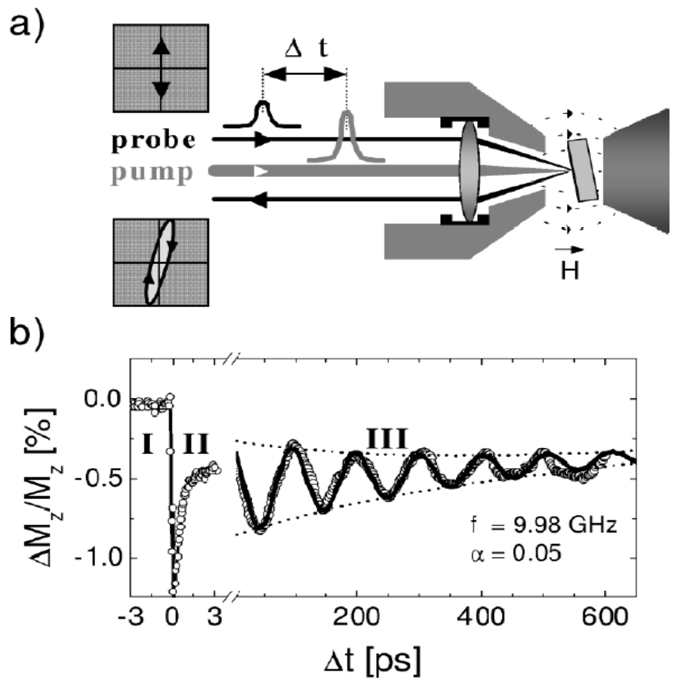
Thermal laser-induced effects

laser-induced collapse of magnetization



Beaurepaire et al, PRL **76**, 4250 (1996)

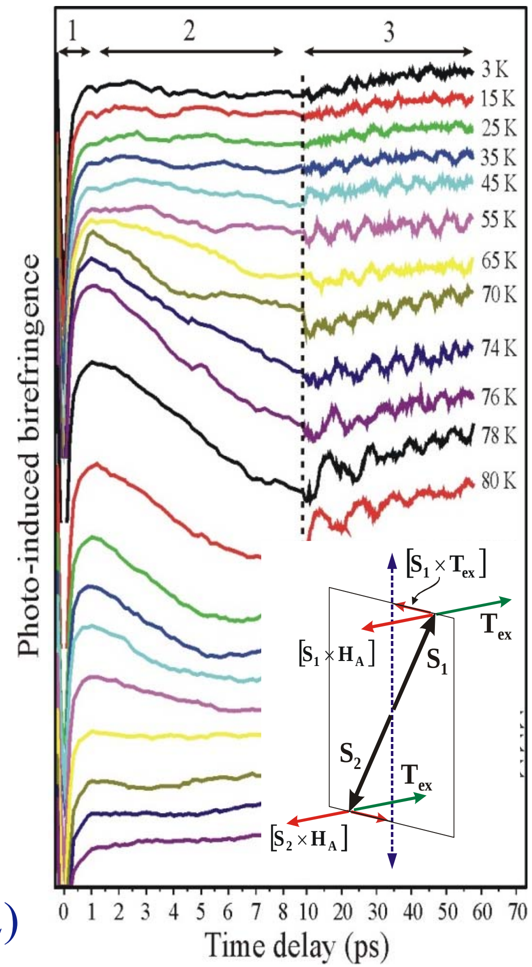
excitation and study of spin waves



Ju et al., PRL **82**, 3705 (1999)

van Kampen et al, PRL **88**, 227201 (2002)

ultrafast phase transitions



Kimel et al., Nature **429**, 850 (2004)

Ju et al, PRL **93**, 197403 (2004)

Thiele et al, APL **85**, 2857 (2004)

Effects of the laser pulse: classification

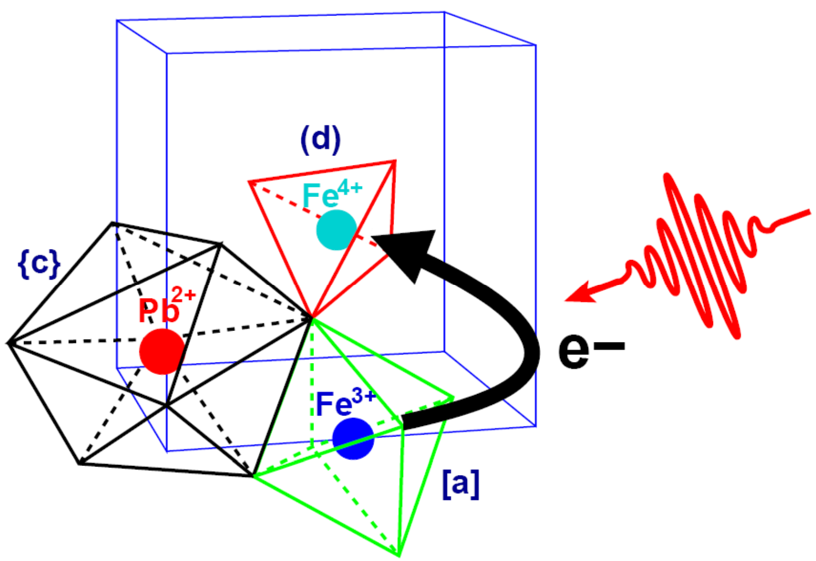
I. Thermal effects:

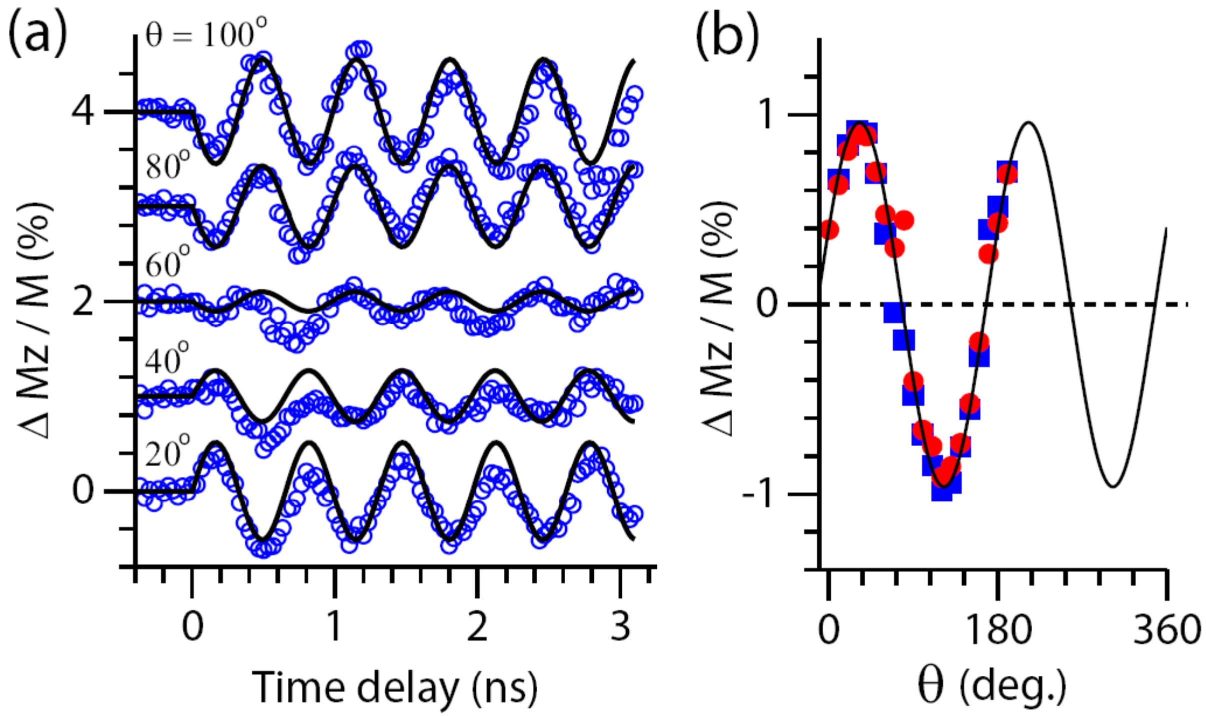
change of M is a result of change of T

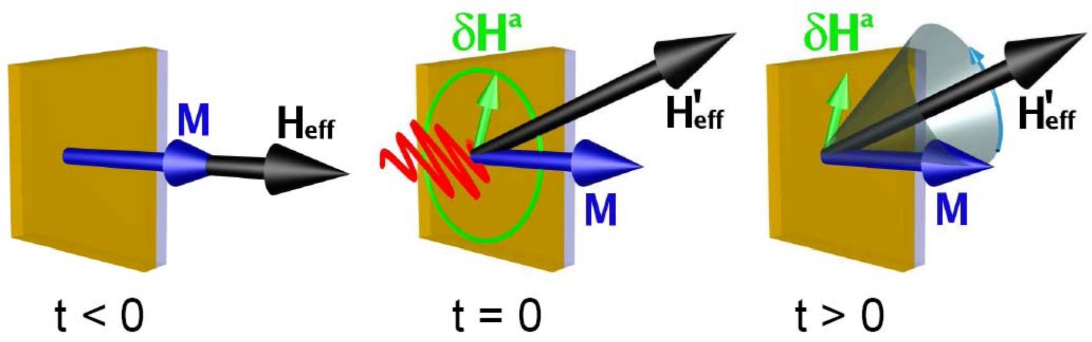
II. Nonthermal photo-magnetic effects:

based on photon absorption

Photo-magnetic effects: modification of anisotropy







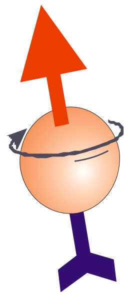
polarization-dependent effect => nonthermal!

Hansteen *et al.*, PRL **95**, 047402 (2005); Phys. Rev. B **73**, 014421 (2006).

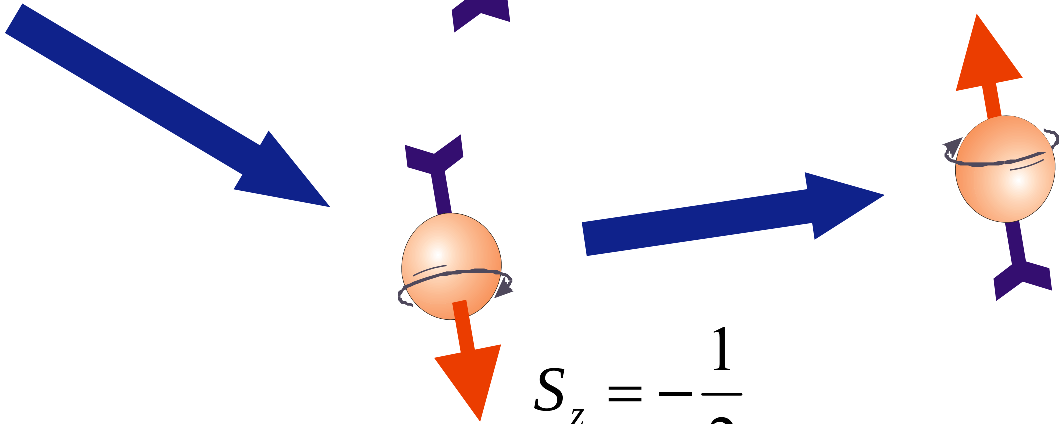
Circular polarization, photon spin, and absorption

$S_z = +1$

$S_z = -1$



$S_z = \frac{1}{2}$



$S_z = -\frac{1}{2}$

1 photon / site = 20000 K ΔT

~0.01 phot/site max
≤0.01 efficiency

} effect ≤ 10^{-4}

very fast and ~~easy~~?

Effects of the laser pulse: classification

I. Thermal effects:

change of M is a result of change of T

II. Nonthermal photo-magnetic effects:

based on photon absorption

III. Nonthermal opto-magnetic effects:

do not require absorption

Extended introduction in laser-induced dynamics

REVIEWS OF MODERN PHYSICS, VOLUME 82, JULY–SEPTEMBER 2010

Ultrafast optical manipulation of magnetic order

Andrei Kirilyuk,* Alexey V. Kimel, and Theo Rasing

Institute for Molecules and Materials, Radboud University Nijmegen, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands

everything you ever wanted to know about laser-induced magnetization dynamics...

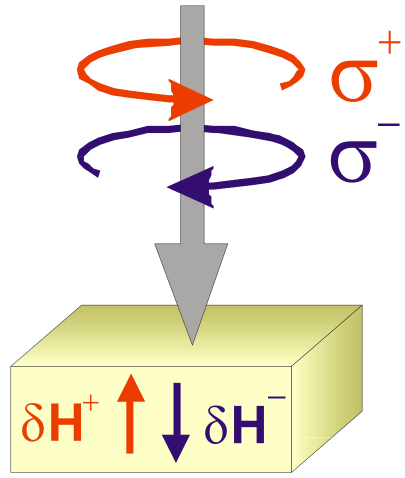
Thermodynamics of magneto-optics

$$\Phi = \varepsilon\varepsilon_0 E(\omega)E^*(\omega)$$

$$H(0) = -\frac{1}{\mu_0}\frac{\partial\Phi}{\partial M(0)} = -\frac{\varepsilon_0}{\mu_0}E(\omega)E^*(\omega)\frac{\partial\varepsilon}{\partial M}$$

$$\hat{\varepsilon} = \begin{pmatrix} \varepsilon_{xx} & -i\alpha M & 0 \\ +i\alpha M & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} + O(M^2) \end{pmatrix}$$

$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]$$



Inverse Faraday effect

Pitaevskii, *Sov. Phys. JETP* **12**, 1008 (1961).
van der Ziel *Phys. Rev. Lett.* **15**, 190 (1965).

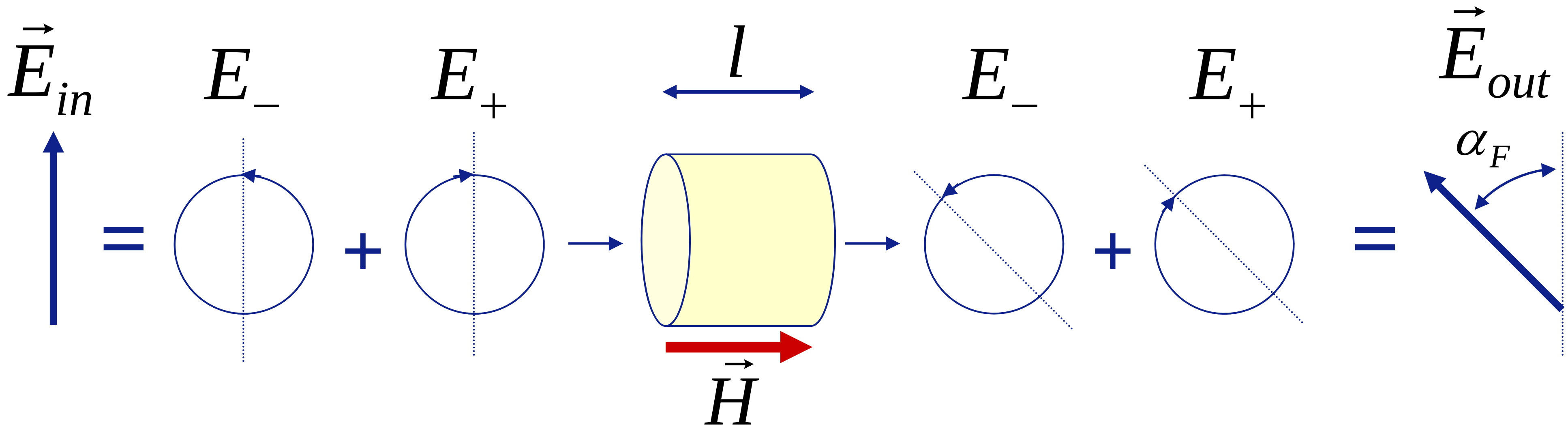
Inverse Faraday effect

Faraday rotation: $\theta_F = \frac{2\pi l}{\lambda} \frac{\alpha M}{\varepsilon_0}$

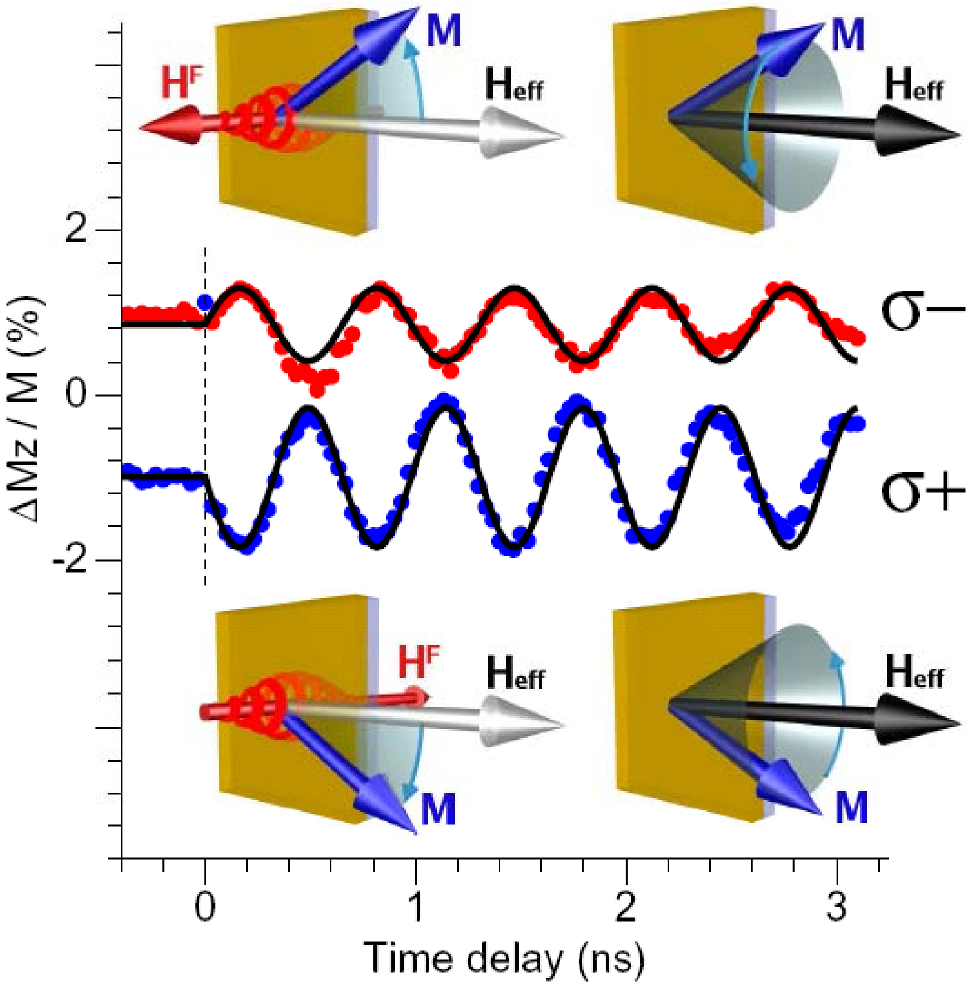
$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0} \alpha \left[\vec{E}(\omega) \times \vec{E}^*(\omega) \right]$$

⇨ **no absorption required!**

⇨ **no angular momentum transfer!**



Effect for opposite pulse helicities



Hansteen *et al.*, PRL **95**, 047402 (2005); Phys. Rev. B **73**, 014421 (2006).

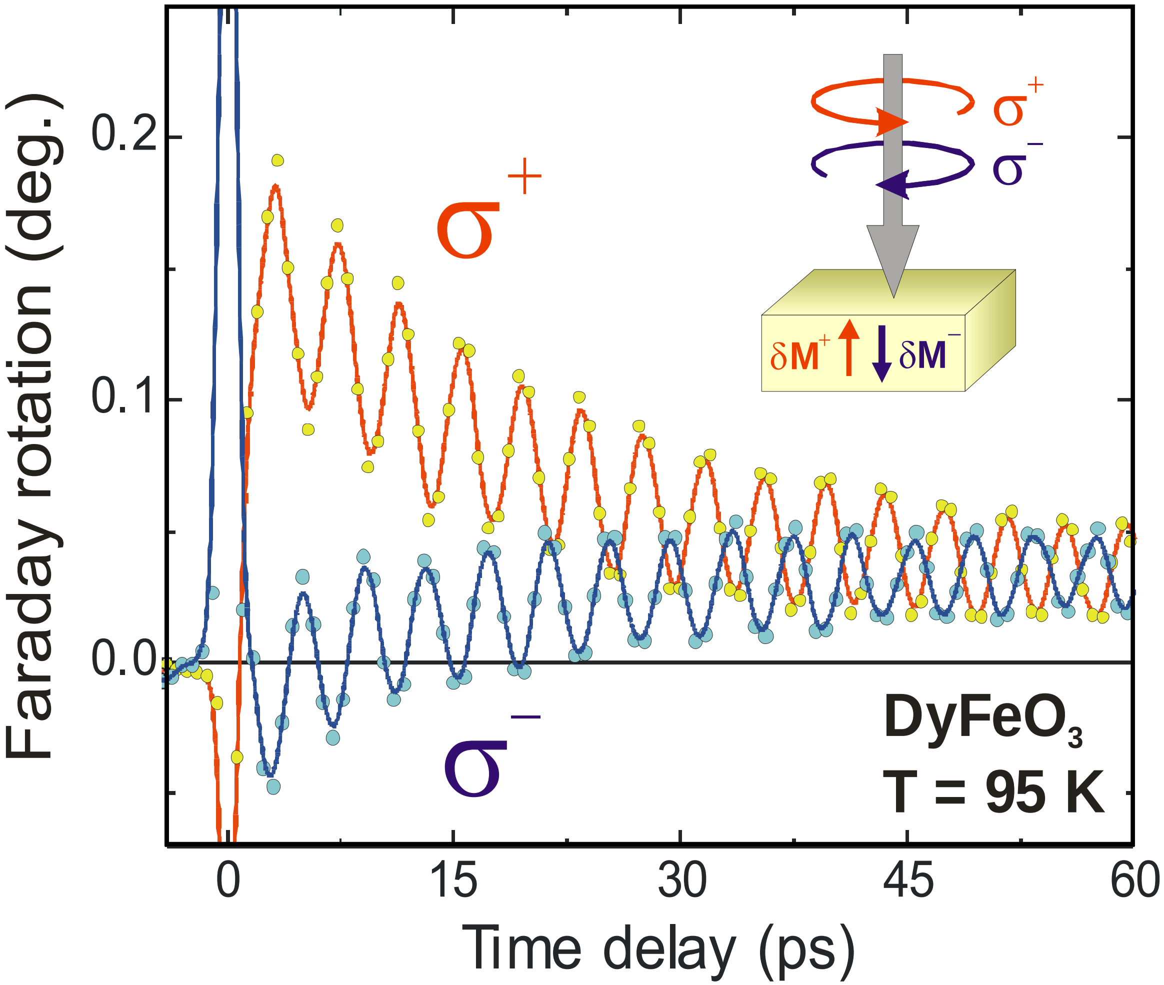
➡ **it works!!!**

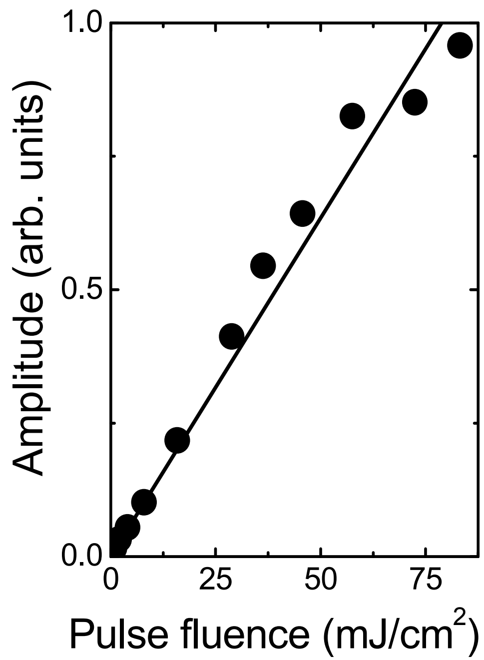
equivalent to a 100 fs magnetic field pulse of some 0.5–1 Tesla!

$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]$$

$$H_{IFE} \sim 0.1-100 \text{ Tesla}$$

Works everywhere! (almost)





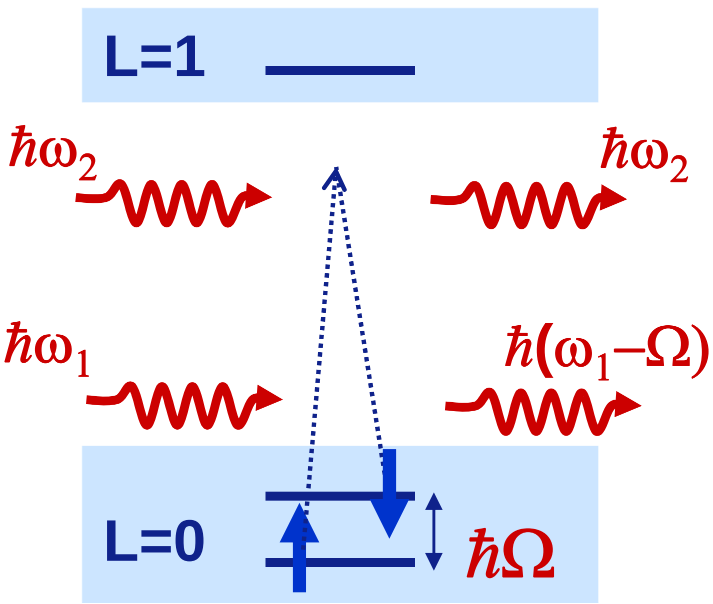
$$\vec{H}(0) = \frac{\varepsilon_0}{\mu_0}\alpha\left[\vec{E}(\omega)\times\vec{E}^*(\omega)\right]$$

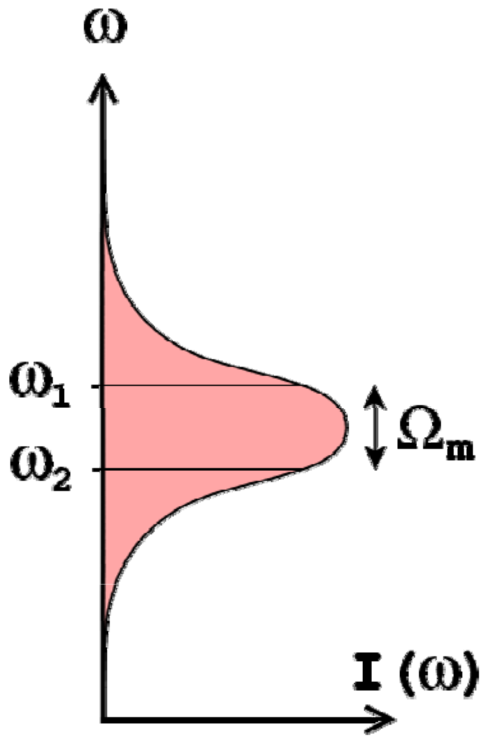
Kimel *et al.*, Nature **435**, 655 (2005)

Microscopic mechanism of the inverse Faraday effect

- Stimulated Raman scattering on magnons (2-photon process)

[Shen et al, Phys. Rev. (1966)]





Number of photons is conserved

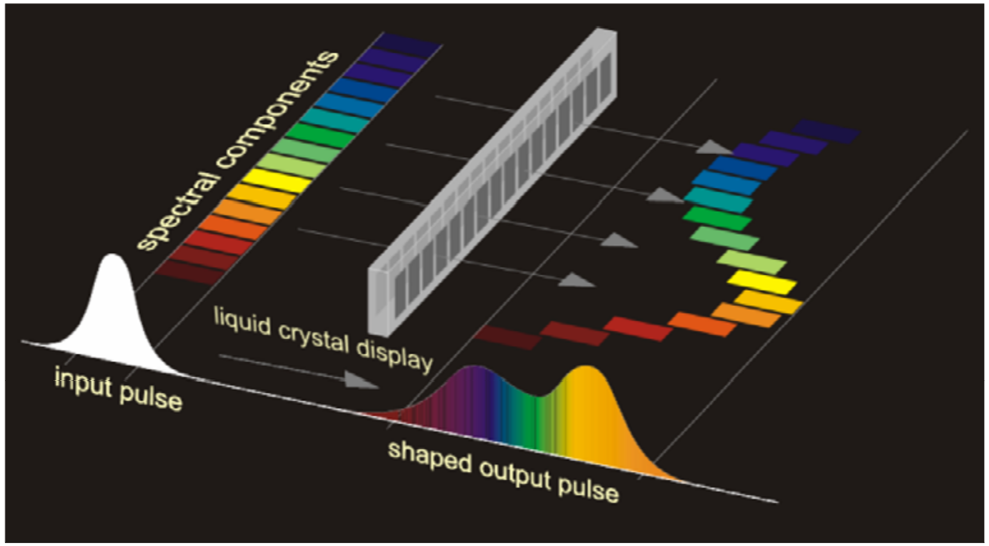
Process can be fast

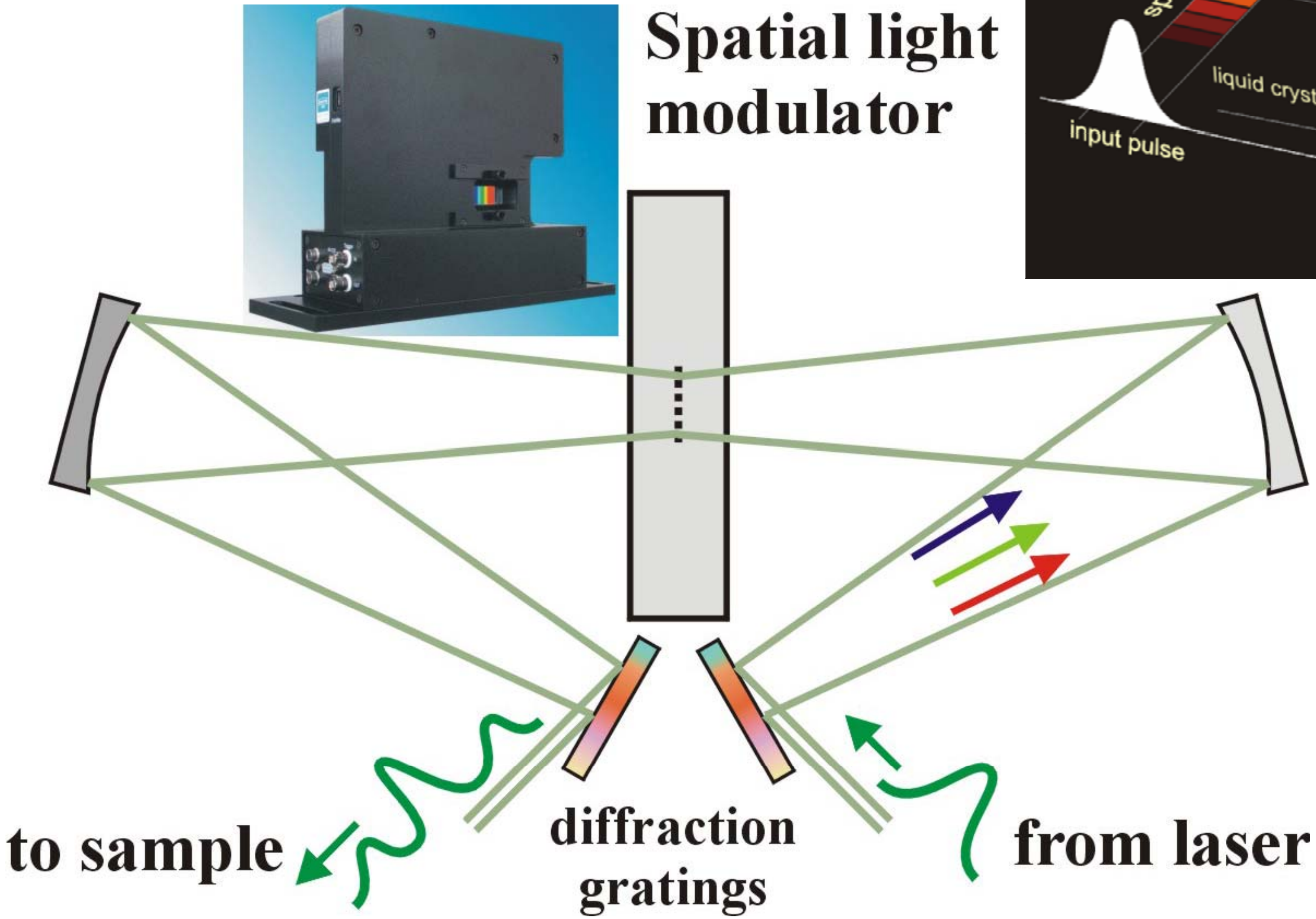
$\tau \sim 1 / \omega \sim 1$ fs

light helicity (= angular momentum) is also conserved!

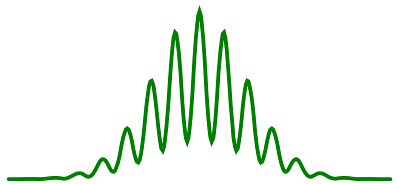
Manipulating pulse frequencies

picture courtesy Th.Baumert

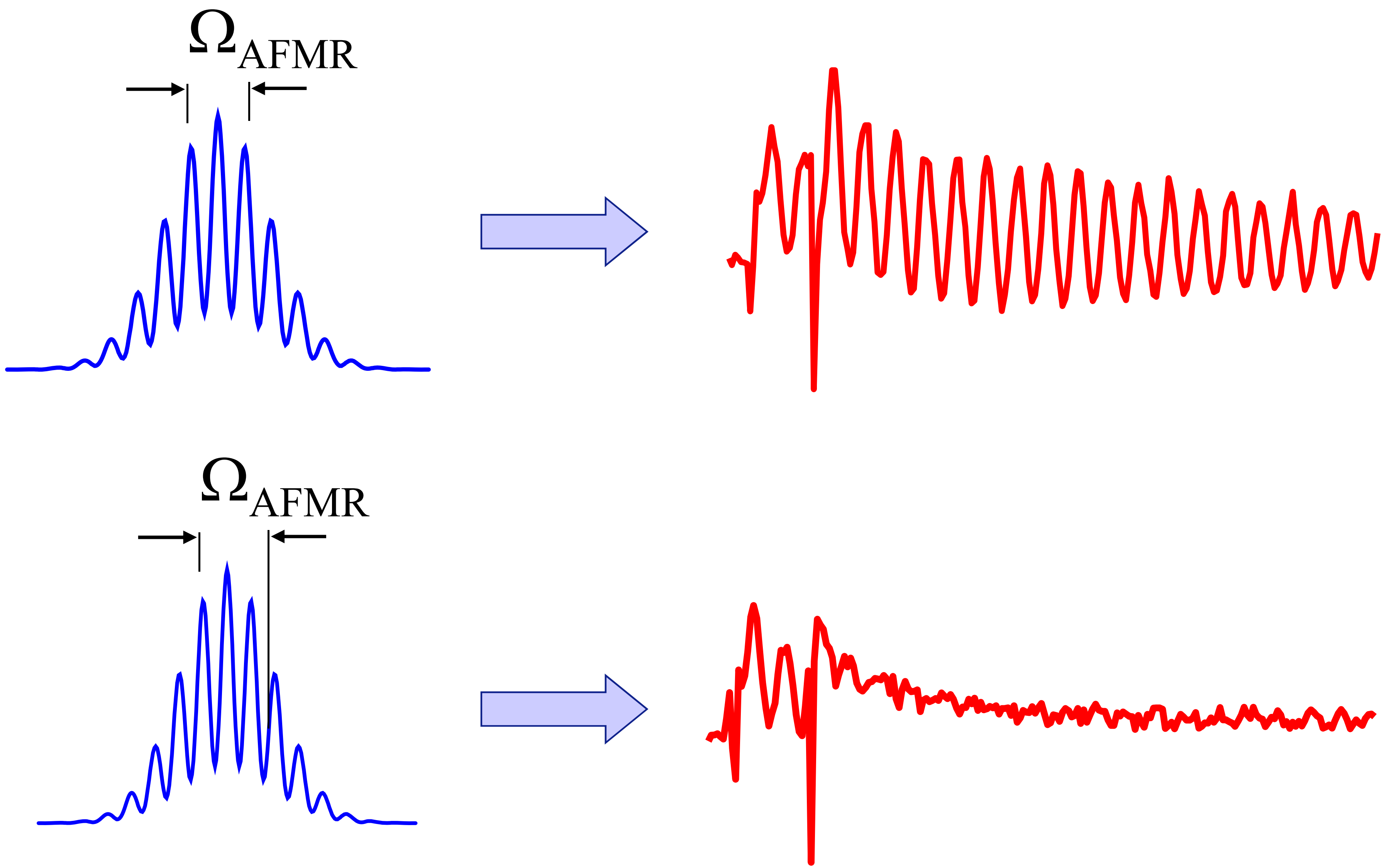




Amplitudes and phases of 320 components



Opto-magnetic effect with “shaped” pulse



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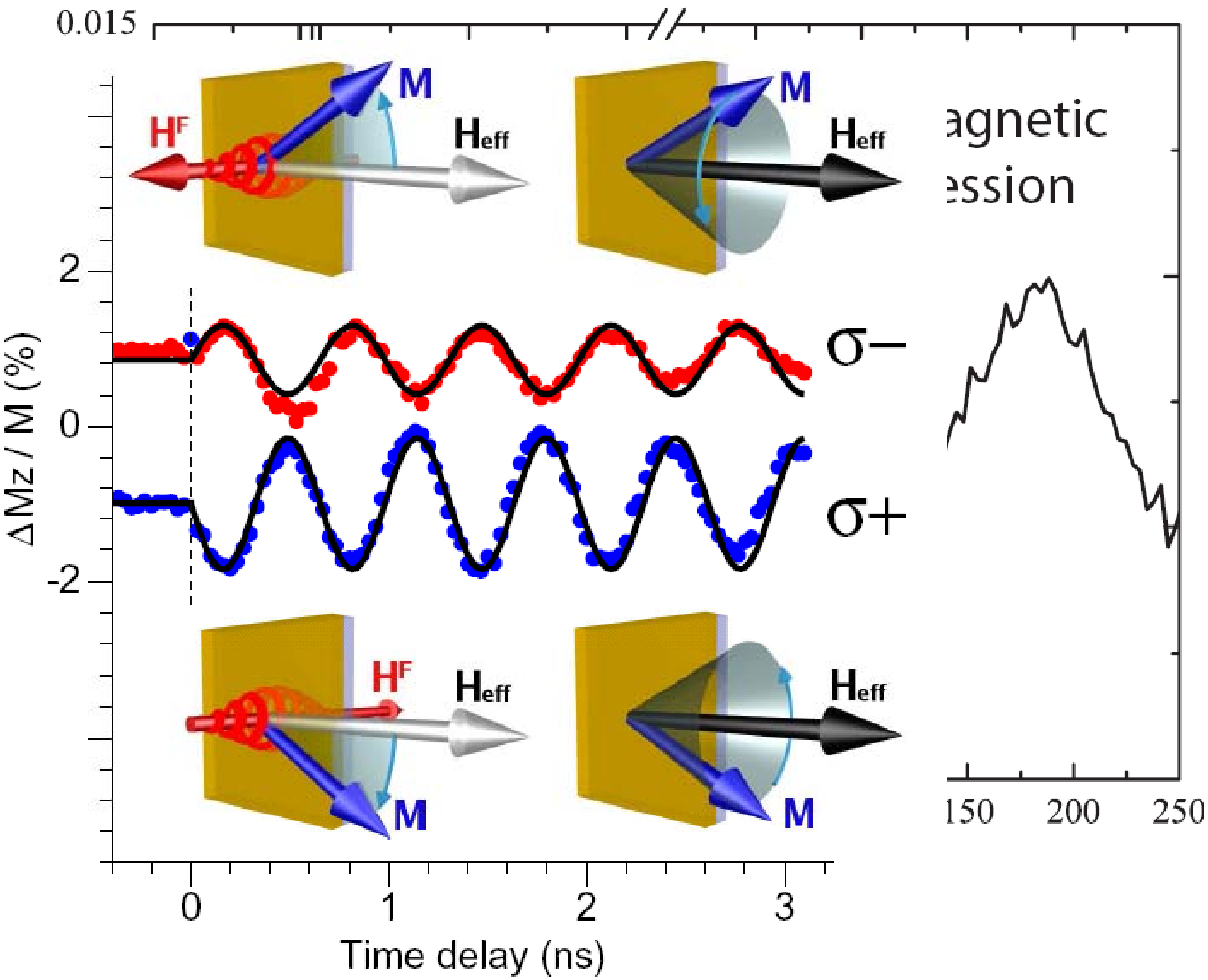
  - **local control of spins**
- *can this become too-ultrafast?*

Higher frequency component?

A. Reid et al.,
Phys. Rev. Lett. **105**, 107402 (2010).



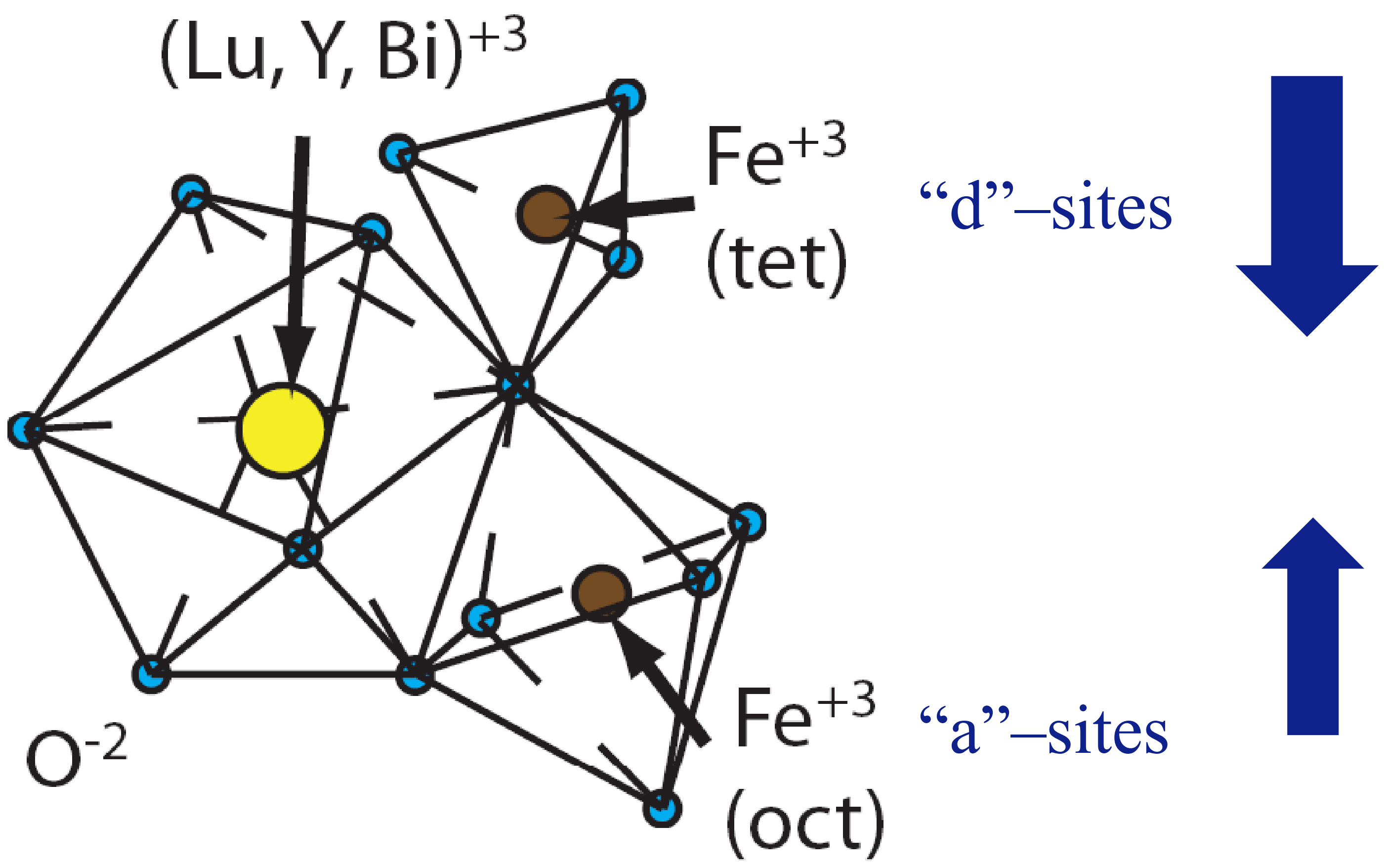
High frequency: 650 GHz

Phase change with pump helicity.

Kaplan–Kittel exchange resonance

J. Kaplan and C. Kittel, *J. Chem Phys.* **21** 760-761 (1953).

Garnet structure $[Lu_{1.69}Y_{0.65}Bi_{0.66}](Fe_{3.85}Ga_{1.15})O_{12}$



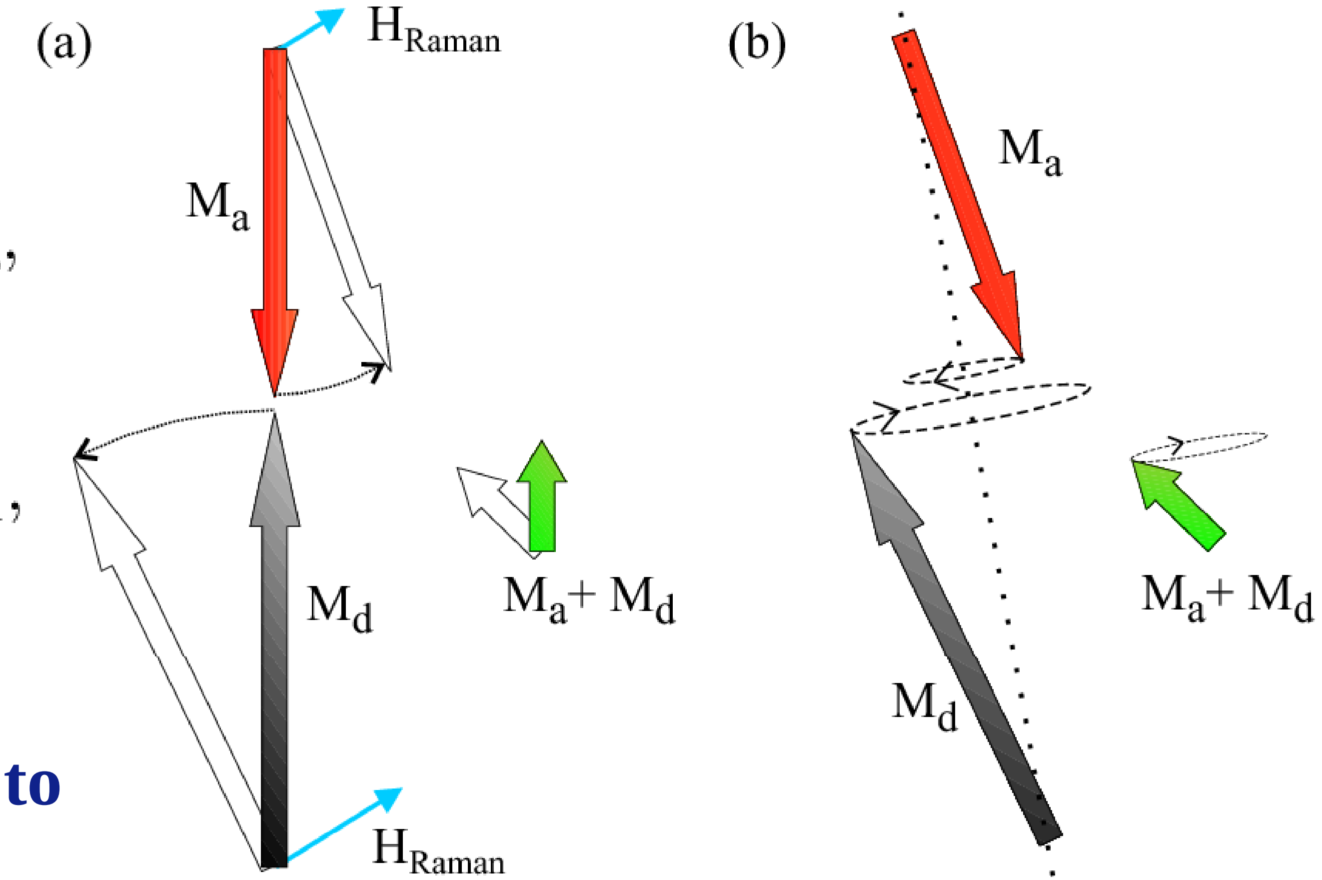
ferrimagnetic order

different local environment!

Exchange Resonance

$$\frac{d\mathbf{M}_a}{dt} = \gamma_a \mathbf{M}_a \times \mathbf{H}_a,$$

$$\frac{d\mathbf{M}_d}{dt} = \gamma_d \mathbf{M}_d \times \mathbf{H}_d,$$



Shouldn't be able to see it.

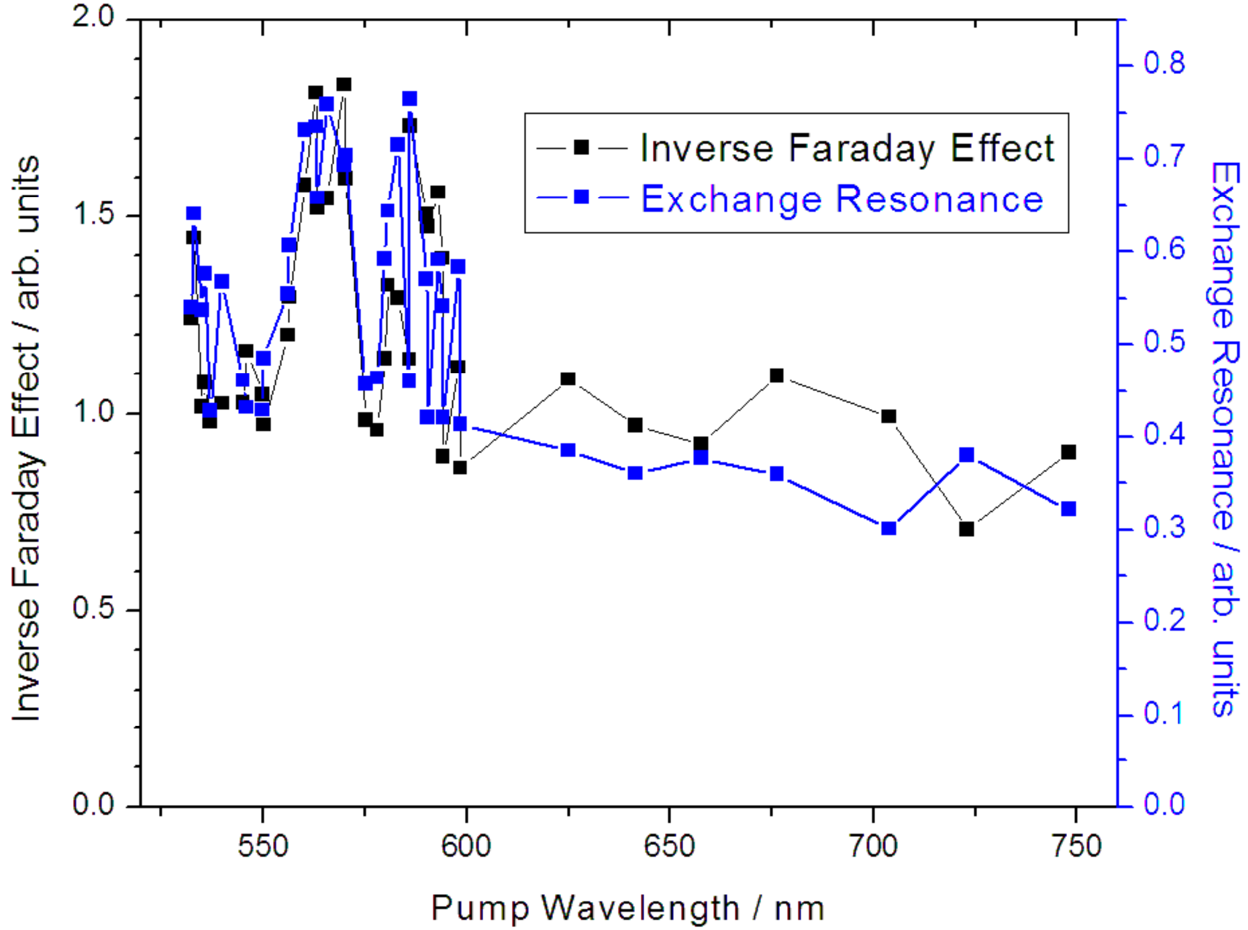
$$\omega_{ex} = |\gamma_a \lambda_{ad} M_a - \gamma_d \lambda_{ad} M_d|,$$

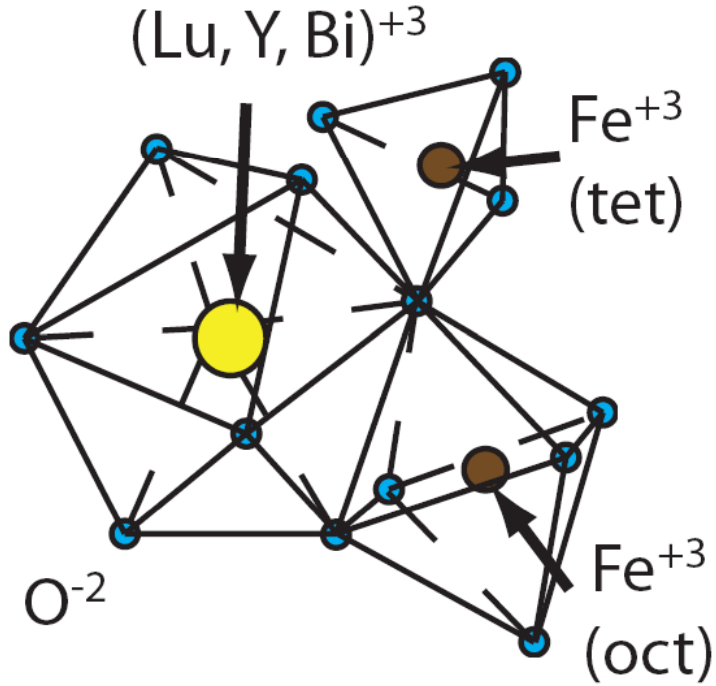
Neither OM nor MO necessarily correlate with **M**.

Correlation with the IFE

A. Reid et al.,
Phys. Rev. Lett. **105**, 107402 (2010).

The same spectral dependence





locally driven spin dynamics!

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Transient magneto-optical response

Transient complex (Kerr or Faraday) rotation

$$\tilde{\theta}(t) = G(t) + F(t)M(t)$$

Pump-induced change $\Delta\tilde{\theta}_T(t) = \Delta G(t) + M_0 \Delta F(t) + F_0 \Delta M(t)$

If, by some chance $\begin{cases} F(t) \equiv F_0 \\ G(t) \equiv G_0 \end{cases}$, then $\tilde{\theta}(t) = G_0 + F_0 M(t)$

and

$$\frac{\Delta\theta(t)}{\theta_0} = \frac{\Delta\varepsilon(t)}{\varepsilon_0} = \frac{\Delta M(t)}{M_0}$$

VOLUME 85, NUMBER 4 PHYSICAL REVIEW LETTERS 24 JULY 2000

Ultrafast Magneto-Optics in Nickel: Magnetism or Optics?

B. Koopmans,* M. van Kampen, J. T. Kohlhepp, and W. J. M. de Jonge
Eindhoven University of Technology, Department of Applied Physics, COBRA Research Institute, P.O. Box 513, 5600 MB, Eindhoven, The Netherlands
(Received 22 February 2000)

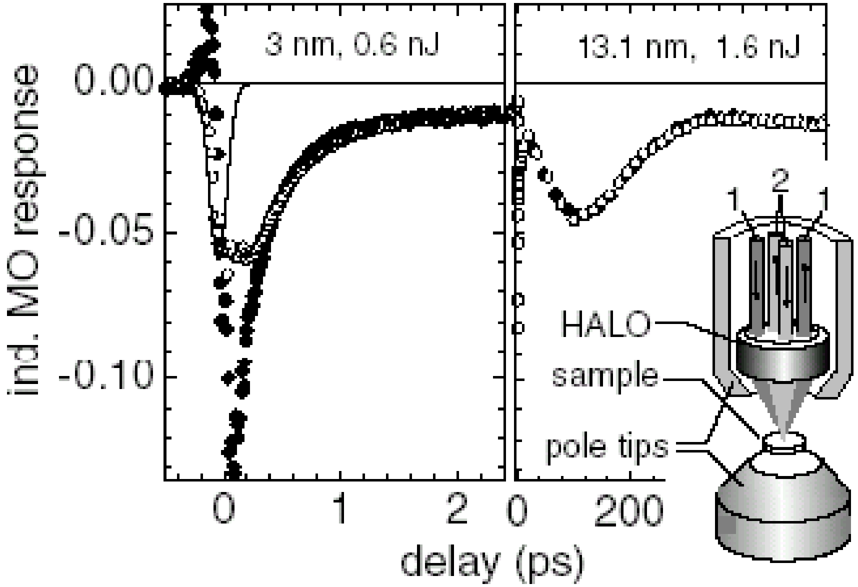


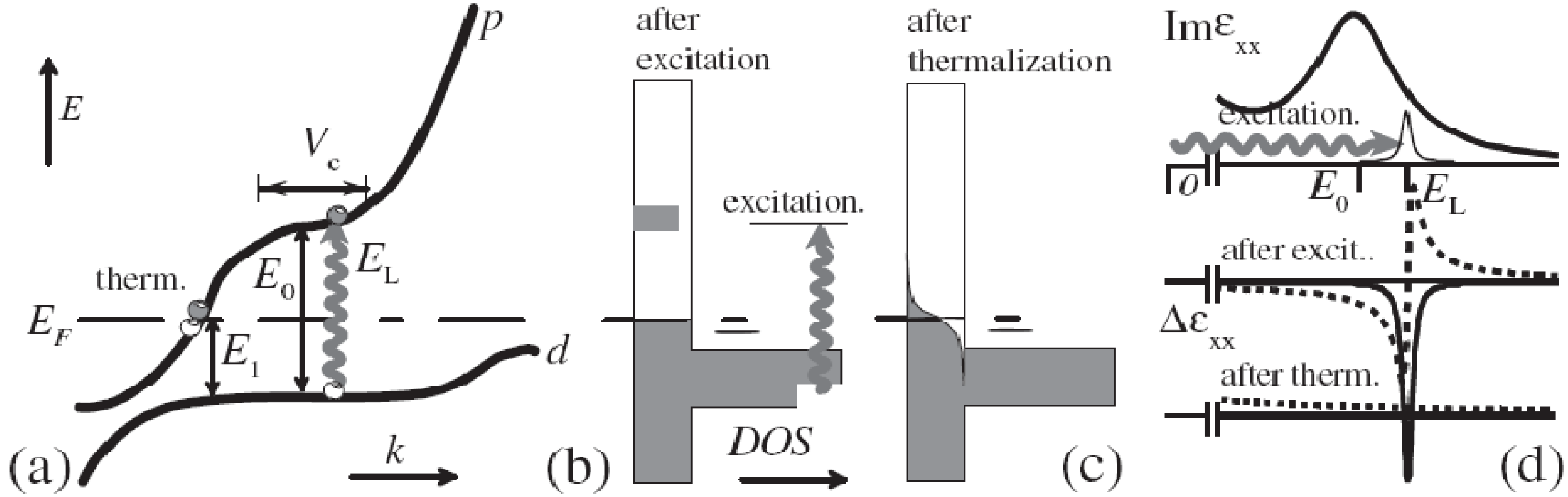
FIG. 1. Comparison of the induced ellipticity ($\Delta\psi''/\psi''_0$, open circles) and rotation ($\Delta\psi'/\psi'_0$, filled diamonds) as a function of pump-probe delay time, for a (111) oriented film at the thicknesses and pulse energies indicated. The thick line represents the pump-probe cross correlation trace. The inset depicts the experimental configuration with pump ("1") and probe ("2") beams.

$$\frac{\Delta\theta(t)}{\theta_0} = \frac{\Delta\varepsilon(t)}{\varepsilon_0} = \frac{\Delta M(t)}{M_0}$$

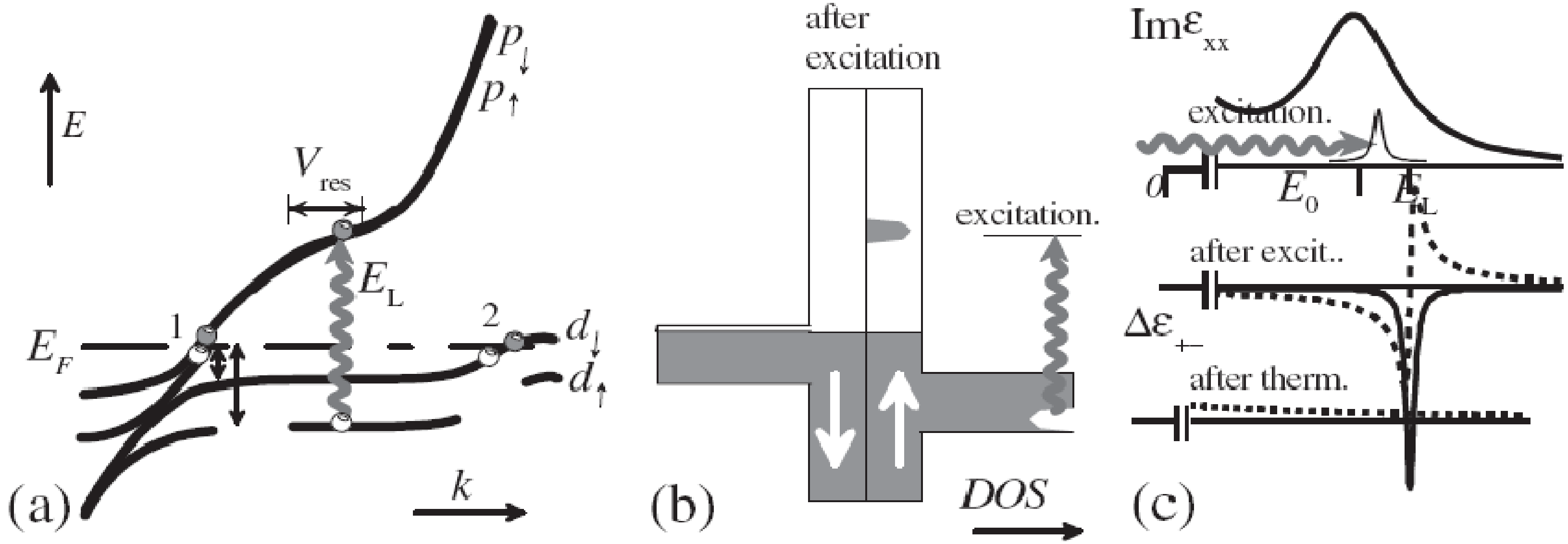
system out of equilibrium

Optical effects?

nonmagnetic



magnetic



Messages to take home

- not everything you measure is magnetization
- opto-magnetic effects lead to real change of M during the pulse
- it is a challenge to show whether there is any other nonthermal mechanism to do this!