From magneto-optics to ultrafast manipulation of magnetism

Andrei Kirilyuk

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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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*can this become too-ultrafast?*
Optics

1.5–3.2 eV

Increasing Wavelength ($\lambda$) in nm →

Increasing Frequency ($\nu$)

Visible spectrum

Increasing Frequency ($\nu$)
Why are certain wavelengths “visible”?

Transmission through water

1 km

1 m

1 mm

1 um

Radio

Microwave

IR

UV

X-ray

visible spectrum

wavelength
Optics

\[ \varepsilon = n^2 \]

\[ \vec{D} = \varepsilon_0 \vec{E} \quad \text{or} \quad \vec{P} = \chi \varepsilon_0 \vec{E} \]

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

Increasing Frequency (\( \nu \))

Increasing Wavelength (\( \lambda \)) →

Visible spectrum

1.5–3.2 eV
Anisotropic media

\[
\hat{\mathbf{E}} = \begin{pmatrix}
\varepsilon_{xx} & \varepsilon_{xy} & \varepsilon_{xz} \\
\varepsilon_{yx} & \varepsilon_{yy} & \varepsilon_{yz} \\
\varepsilon_{zx} & \varepsilon_{zy} & \varepsilon_{zz}
\end{pmatrix}
\]

if \( H = 0 \)

\[
\hat{\mathbf{E}} = \begin{pmatrix}
\varepsilon_{xx} & 0 & 0 \\
0 & \varepsilon_{yy} & 0 \\
0 & 0 & \varepsilon_{zz}
\end{pmatrix}
\]

i.e. one could chose such a coordinate system
Driven oscillator model

\[ E_0 \sin \omega t \]

\[ F = eE_0 \sin \omega t \]

\[ \frac{d^2 x}{dt^2} + \omega_0^2 x = \frac{e}{m} E_0 \sin \omega t \]
Driven oscillator model

solution in the form:

\[ x = x_0 \sin \omega t = \frac{eE_0}{m(\omega_0^2 - \omega^2)} \sin \omega t \]

amplitude depends on \( \omega \)

damped oscillator

amplitude

phase

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Sum of the two waves:

\[ E(z = 0) = E_0 \sin \omega t \]
Phase of the light after transmission

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

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

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

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

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

\[ E(z = 0) = E_0 \sin \omega t \]
Absorption en refractive index

amplitude = absorption

phase = refractive index

\[ \alpha = \frac{N e^2}{2 \varepsilon_0 c_0 m_e} \frac{\gamma / 2}{(\omega_0 - \omega)^2 + (\gamma / 2)^2} \]

\[ n - 1 = \frac{N e^2}{4 \varepsilon_0 \omega m_e} \frac{\omega_0 - \omega}{(\omega_0 - \omega)^2 + (\gamma / 2)^2} \]

\( \gamma \) 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

![Dispersion graph showing refractive index vs wavelength for different types of glass: Lanthanum dense flint LaSF9, Dense flint SF10, Flint F2, Barium crown BaK4, Borosilicate crown BK7, Fluorite crown FK51A.](image)
Optical constants of metals

![Graphs showing the refractive index (n) and absorption index (k) for Ni and Au as a function of photon energy (hv) in eV.](image)
Interaction of light with magnetic solids

How does magnetic field (magnetization) modify dielectric tensor?

\[ \vec{D} = \varepsilon \varepsilon_0 \vec{E} \]

\[ \varepsilon = \begin{bmatrix} \varepsilon_{xx} & 0 & 0 \\ 0 & \varepsilon_{yy} & 0 \\ 0 & 0 & \varepsilon_{zz} \end{bmatrix} = n^2 \]

if isotropic


H = 0

H ≠ 0
How does magnetic field modify conductivity?

\[
\vec{j} = \sigma \vec{E}
\]

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

Lorentz force

\[F_L = e[V \times H]\]
**Onsager principle:**

**symmetry of kinetic coefficients**

\[
\begin{bmatrix}
\varepsilon_{xx} & 0 & 0 \\
0 & \varepsilon_{yy} & 0 \\
0 & 0 & \varepsilon_{zz}
\end{bmatrix}
\]

Onsager principle is applicable to \( \varepsilon \)

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

*If S is a function of magnetic field*

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

Landau & Lifshitz, Theoretical Physics, vv. 5 and 8.
Faraday effect – 1

Isotropic medium in a magnetic field:

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

\[
\varepsilon_{xy} \propto M_z
\]

\[
\varepsilon_{zz} \propto M_z^2
\]

\[
\vec{E}_{in} = i \vec{E}_x + j \vec{E}_y
\]

\[
\vec{H} = \vec{H}_z
\]

\[
\vec{E}_{out} = \vec{E}_{out}
\]

\[
\vec{E}_{out} = ???
\]
To find the eigenvalues of the problem:

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

\[ \begin{pmatrix} \varepsilon_0 & -i\varepsilon_{xy} \\ i\varepsilon_{xy} & \varepsilon_0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = n^2 \begin{pmatrix} E_x \\ E_y \end{pmatrix} \]

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

\[
n \approx \sqrt{\varepsilon_0} \pm \frac{1}{2} \frac{\varepsilon_{xy}}{\varepsilon_0} \quad \varepsilon_{xy} \sim 10^{-3} - 10^{-4}
\]

eigenmodes \[ E_x = \pm iE_y \], or \[ \begin{pmatrix} 1 \\ i \end{pmatrix} \] and \[ \begin{pmatrix} 1 \\ -i \end{pmatrix} \]
Two circularly polarized waves with different refractive indices:

\[ E_x = \pm i E_y \]

\[ n_{\pm} \approx \sqrt{\varepsilon_0} \pm \frac{1}{2} \frac{\varepsilon_{xy}}{\varepsilon_0} \]

Faraday rotation:

\[ \alpha_F = \frac{2\pi l}{\lambda} \frac{\varepsilon_{xy}}{\varepsilon_0} \]

Kerr effect: various geometries

- **polar**
  - $\theta \approx 0^\circ$

- **longitudinal**
  - $\theta >> 0^\circ$

- **transverse**
  - $\theta >> 0^\circ$
light propagates along x axis, so that

\[ \vec{E}_{in} = jE_y + kE_z \]

\[ \hat{\mathcal{E}} = \begin{pmatrix} \varepsilon_0 & -i\varepsilon_{xy} & 0 \\ i\varepsilon_{xy} & \varepsilon_0 & 0 \\ 0 & 0 & \varepsilon_0 + \varepsilon_{zz} \end{pmatrix} \]

Eigenvalues \( \varepsilon_0, \varepsilon_0 + \varepsilon_{zz}, \varepsilon_{zz} \propto M^2 \)

Eigenmodes \( \vec{E}_y, \vec{E}_z \)
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 $\rightarrow$ orbits $\rightarrow$ light wave

exchange + spin-orbit
What could be measured?


hysteresis
dynamics
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*can this become too-ultrafast?*
Electromagnetic wave equation and source term

\[
\frac{\partial^2 \vec{E}}{\partial t^2} - c^2 \cdot \nabla^2 \vec{E} = \vec{S} \quad \vec{S} = \frac{\partial^2 \vec{P}}{\partial t^2} + \nabla \times \frac{\partial \vec{M}}{\partial t} - \nabla \frac{\partial^2 \vec{Q}}{\partial t^2}
\]

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

or \ldots

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

\[+ \chi^{(2,d)} E^\omega E^\omega + \chi^{(2,m)} E^\omega H^\omega + \chi^{(2,q)} E^\omega \nabla E^\omega \ldots\]

electric dipole approximation
magnetic dipole electric quadrupole
Harmonic oscillator

Linear response

\[ U(x) = k_1 x^2 \]

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

\[ m \frac{d^2 x}{dt^2} + F_{el} = eE \]

\[ P_i^{(L)}(\omega) = \chi_{ij}(\omega)E_j(\omega) \]
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.

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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

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

(\text{electric dipole approximation})

\[ e^{i\omega t} \cdot e^{i\omega t} = e^{i2\omega t} \]

second-harmonic generation

\[ e^{i\omega t} \cdot e^{-i\omega t} = e^{i0t} \]

optical rectification

inversion symmetry:

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

\[ -1 \quad -1 \quad -1 \]

\[ P(2\omega) = 0 \]

except at surface/interface
Magnetization-sensitive SHG

\[ P_i^{(2\omega)} = \chi_{ijk} E_j^{(\omega)} E_k^{(\omega)} = (\chi^{(cr)}_{ijk} \pm \chi^{(m)}_{ijk}) E_j^{(\omega)} E_k^{(\omega)} \]

crystallographic ± magnetic

space inversion:

time reversal:


Example: surface/interface sensitivity

Fe(110) surface

ultrathin Co/Cu(001) films

at 4 ML, both interfaces are formed


Phys. Rev. Lett. 74, 1462 (1995);
General phenomenology

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

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

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

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

Source term:

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

sum- and difference frequency generation, including SHG and optical rectification
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- Light as a probe ✓
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- 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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*can this become too-ultrafast?*
Experimental know-how: time-resolved pump-probe setup
What you need: a femtosecond laser

<table>
<thead>
<tr>
<th></th>
<th>Model TISSA20</th>
<th>Model TISSA50</th>
<th>Model TISSA100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pump Power¹</td>
<td>3-5 W</td>
<td>3-7 W</td>
<td>5-10 W</td>
</tr>
<tr>
<td>Output Power at 800 nm</td>
<td>150 - 250 mW</td>
<td>150-500 mW</td>
<td>&gt;10% efficiency</td>
</tr>
<tr>
<td>Pulse Duration²</td>
<td>&lt;20 fs³</td>
<td>&lt;50 fs</td>
<td>&lt;100 fs</td>
</tr>
<tr>
<td>Tuning Range</td>
<td>800 ± 20 nm</td>
<td>740 - 950 nm⁴</td>
<td>720 - 980 nm⁴</td>
</tr>
<tr>
<td>Repetition Rate</td>
<td>70 - 140 MHz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

you have some choice!
pump & probe technique

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Radboud University Nijmegen

No cats were harmed in our experiments!
Stroboscopic magneto-optical pump-probe measurements

Polarization change of the probe beam is detected

\[ \propto \hat{M}(\tau) \]

Delay line
0.1 \( \mu \text{m} = 0.7 \text{ fs} \)
Optical pump-probe measurements of FMR

before pump pulse arrives

\[ H_{\text{ani}} - H_s \]
\[ M \]
\[ H_{\text{ext}} \]
\[ \theta \]

after pump has arrived

\[ H'_{\text{ani}} - H'_s \]
\[ M' \]
\[ H_{\text{ext}} \]
\[ \theta' \]

external field

\[ H^{\text{eff}} = H_{\text{ext}} + H_{\text{ani}} + H_s \]

Pump pulse

affected by the laser
All-optical magnetic resonance in antiferromagnets

Faraday rotation (deg)

Time delay (ps)

Frequency (GHz)

Temperature (K)

Amplitude (arb. un.)

Pulse fluence (mJ/cm²)

175 K, 433 GHz (x6)
155 K, 406 GHz (x6)
135 K, 372 GHz (x3)
115 K, 327 GHz (x3)
95 K, 271 GHz (x3)
75 K, 211 GHz
60 K, 175 GHz
50 K, 159 GHz
40 K, 153 GHz
30 K, 151 GHz
18 K, 151 GHz

115 K, 327 GHz (x3)
95 K, 271 GHz (x3)
75 K, 211 GHz
60 K, 175 GHz
50 K, 159 GHz
40 K, 153 GHz
30 K, 151 GHz
18 K, 151 GHz

quasi-FM mode

quasi-AFM mode

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  - can this become too-ultrafast?
I. Thermal effects:
change of $M$ is a result of change of $T$
Thermal laser-induced effects

laser-induced collapse of magnetization

excitation and study of spin waves

Ju et al., PRL 82, 3705 (1999)
van Kampen et al, PRL 88, 227201 (2002)
Beaurepaire et al, PRL 76, 4250 (1996)

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

Photo-magnetic effects: modification of anisotropy


polarization-dependent effect => nonthermal!
Circular polarization, photon spin, and absorption

$S_z = +1$

$S_z = -1$

1 photon / site $= 20000 \, K \, \Delta T$

$\sim 0.01$ photon/site max

$\leq 0.01$ efficiency

Effect $\leq 10^{-4}$

very fast and easy?

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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

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

\[ \Phi = \varepsilon \varepsilon_0 E(\omega) E^*(\omega) \]

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

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

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


Inverse Faraday effect

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

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

no absorption required!

no angular momentum transfer!

\[ \vec{E}_{in} = \vec{E}_- + \vec{E}_+ \]

\[ \vec{H} \]

\[ l \]

\[ \vec{E}_{out} = \vec{E}_- + \vec{E}_+ \]

\[ \alpha_F \]
Effect for opposite pulse helicities

it works!!!

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

\[ \tilde{H}(0) = \frac{\varepsilon_0}{\mu_0} \alpha [\tilde{E}(\omega) \times \tilde{E}^*(\omega)] \]

\[ H_{\text{IFE}} \sim 0.1–100 \text{ Tesla} \]

Hansteen et al., PRL 95, 047402 (2005);
Works everywhere! (almost)

\[ \tilde{H}(0) = \frac{\epsilon_0}{\mu_0} \alpha \left[ \tilde{E}(\omega) \times \tilde{E}^*(\omega) \right] \]

Microscopic mechanism of the inverse Faraday effect

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

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

\[ \hbar \omega_1, \hbar (\omega_1 - \Omega), \hbar \omega_2, \hbar (\omega_1 - \omega_2) \]

- Number of photons is conserved

- Process can be fast
  \( \tau \sim 1 / \omega \sim 1 \text{ fs} \)

- Light helicity (= angular momentum) is also conserved!
Manipulating pulse frequencies

Spatial light modulator

Amplitudes and phases of 320 components

to sample

diffraction gratings

from laser

picture courtesy Th. Baumert
Opto-magnetic effect with “shaped” pulse
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- can this become too-ultrafast?
Higher frequency component?


High frequency: 650 GHz

Phase change with pump helicity.

Kaplan–Kittel exchange resonance

Garnet structure $[\text{Lu}_{1.69}\text{Y}_{0.65}\text{Bi}_{0.66}](\text{Fe}_{3.85}\text{Ga}_{1.15})\text{O}_{12}$

(Lu, Y, Bi)$^{+3}$

Fe$^{+3}$

Fe$^{+3}$

O$^{-2}$

“d”–sites

“a”–sites

ferrimagnetic order

different local environment!
Exchange Resonance

\[
\frac{dM_a}{dt} = \gamma_a M_a \times H_a,
\]

\[
\frac{dM_d}{dt} = \gamma_d M_d \times H_d,
\]

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

Shouldn’t be able to see it.

Neither OM nor MO necessarily correlate with M.
Correlation with the IFE

The same spectral dependence

locally driven spin dynamics!

A. Reid et al.,
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- can this become too-ultrafast?
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
\[ \begin{align*}
F(t) &= F_0 \\
G(t) &= G_0
\end{align*} \]
then
\[ \tilde{\theta}(t) = G_0 + F_0 M(t) \]

and
\[ \frac{\Delta \theta(t)}{\theta_0} = \frac{\Delta \varepsilon(t)}{\varepsilon_0} = \frac{\Delta M(t)}{M_0} \]
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)

![Graph showing induced MO response as a function of delay (ps) with data points for 3 nm, 0.6 nJ and 13.1 nm, 1.6 nJ.]

FIG. 1. Comparison of the induced ellipticity ($Δ\psi''/ψ''_0$, open circles) and rotation ($Δψ'/ψ'_0$, 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.

$$\frac{Δθ(t)}{θ_0} = \frac{Δε(t)}{ε_0} = \frac{ΔM(t)}{M_0}$$

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!