FACULTY
OF MATHEMATICS
AND PHYSICS
Charles University

Novel trends in magneto-optics: from Faraday effect to spin photonics

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morp

www.morp.cz

What is magneto-optics?

Optics vs. magnetism

Optical response of magnetically altered media

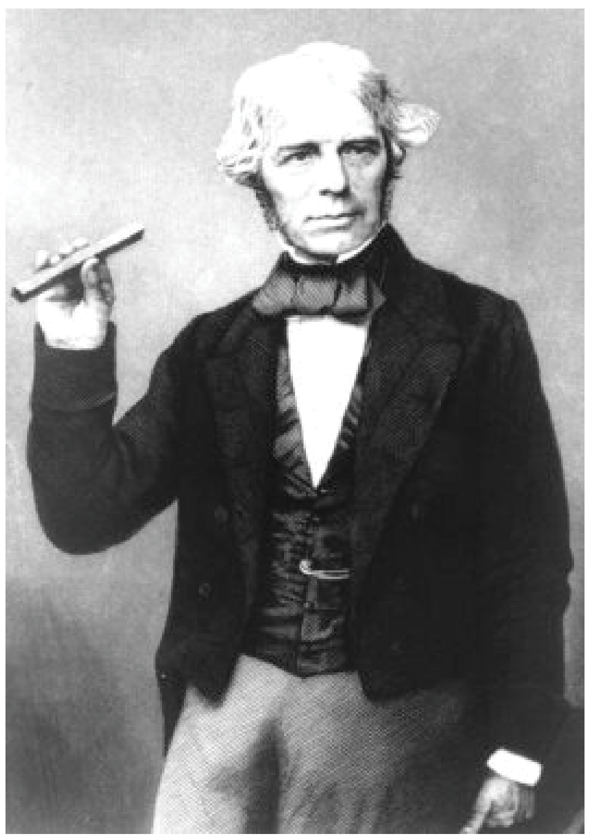
↓

Change of the polarization state of incident light
(different propagation of LCP and RCP light)

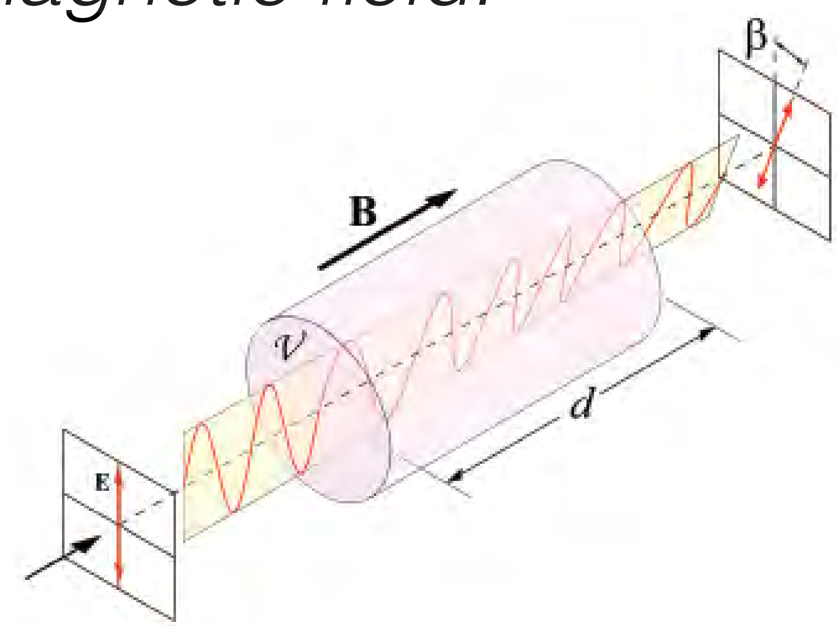
Various phenomena

What is magneto-optics?

Michael Faraday: 1845



Polarization rotation of a linearly polarized light during the propagation through a rubic glass rod in magnetic field.



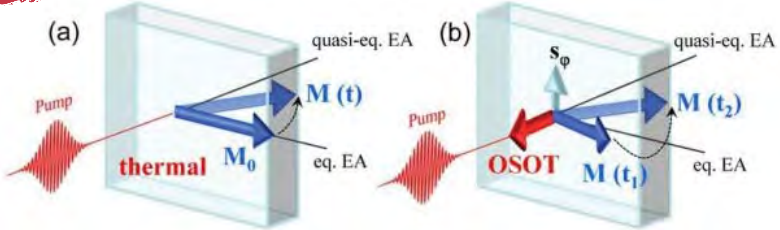
On 13 Sept. 1845, in paragraph #7504, under the rubric Heavy Glass, he wrote:
… BUT, when the contrary magnetic poles were on the same side, **there was an effect produced on the polarized ray, and thus magnetic force and light were proved to have relation to each other**. …
— Faraday, Paragraph #7504, Daily notebook

on 30 Sept. 1845, in paragraph #7718, famously writing:
… Still, I have at last succeeded in illuminating a magnetic curve or line of force, and in magnetizing a ray of light. …
— Faraday, Paragraph #7718, Daily notebook

What is magneto-optics?

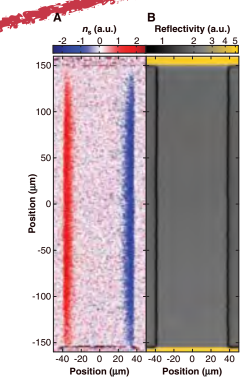
History:

2012, 2013: OSTT, OSOT



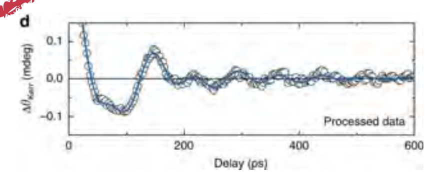
N. Tesarova, et al., Nat. Phot. 492 (2013)

2004: SHE



Y. K. Kato et al., Science 1105514 (2004)

1980's/1990's: TRMOKE



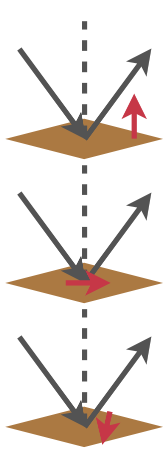
1986: XMCD

1966: MO modulator Synchronic detection

1965: MO memory

1952: A. Kastler - optical orientation

1902: Voigt - quadratic effect



1876: Kerr

1845: Faraday

Theory of magneto-optical effects

Optical properties of magnetized materials are described by the permittivity tensor

$$\mu = \mu_{vac}$$

Collinear magnetic order

$$\begin{aligned}\varepsilon_{ij} &= \varepsilon_{ij}^{(0)} + \left(\frac{\partial \varepsilon_{ij}}{\partial M_k}\right)_{M=0} M_k + \frac{1}{2}\left(\frac{\partial^2 \varepsilon_{ij}}{\partial M_k M_l}\right)_{M=0} M_k M_l + \cdots \\ &= \varepsilon_{ij}^{(0)} + K_{ijk} M_k + G_{ijkl} M_k M_l.\end{aligned}$$

↓

Magnetization dependent - information about magnetism

General form of permittivity tensor

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

Magneto-optics

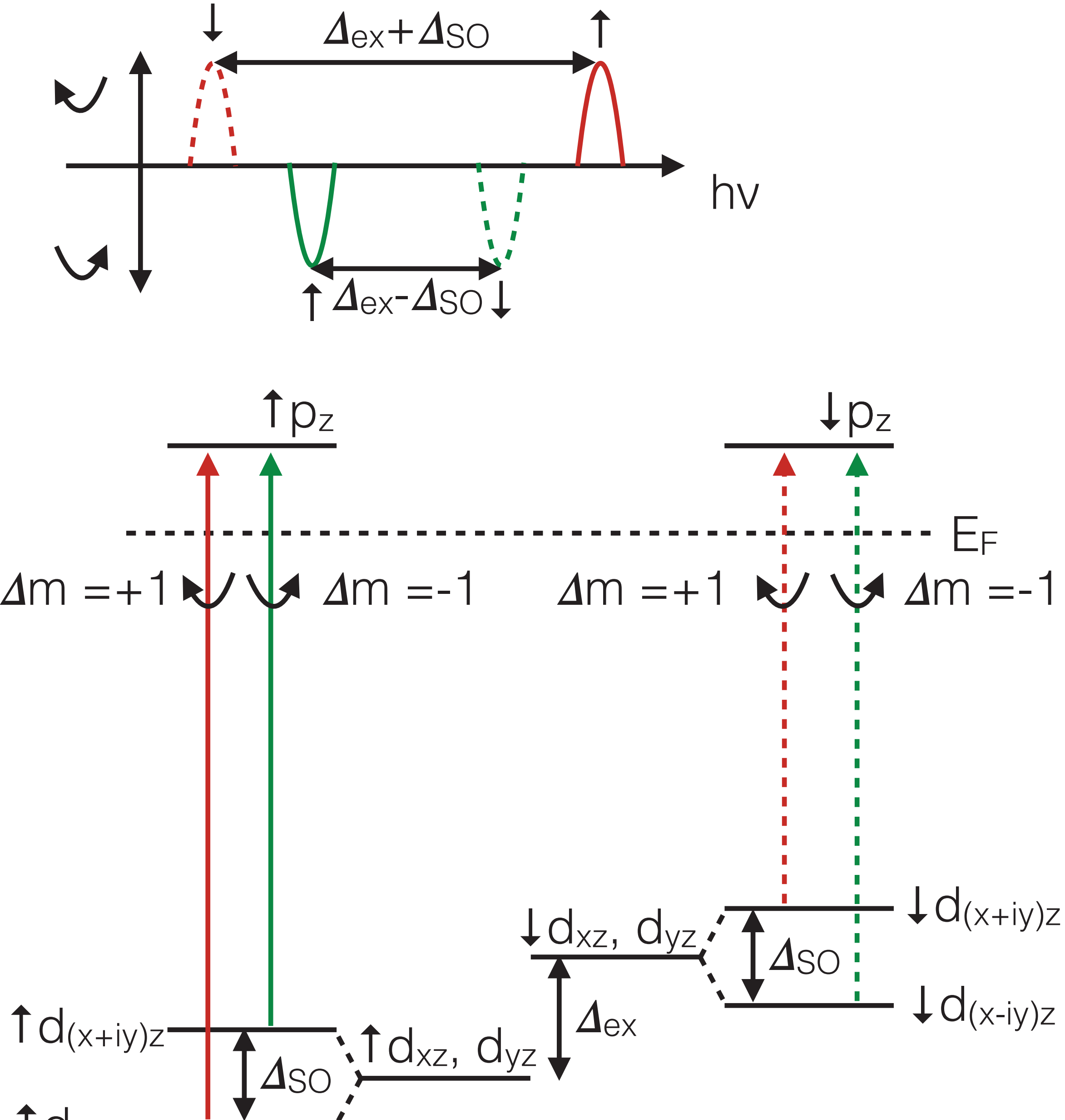
Magneto-optics

Optics

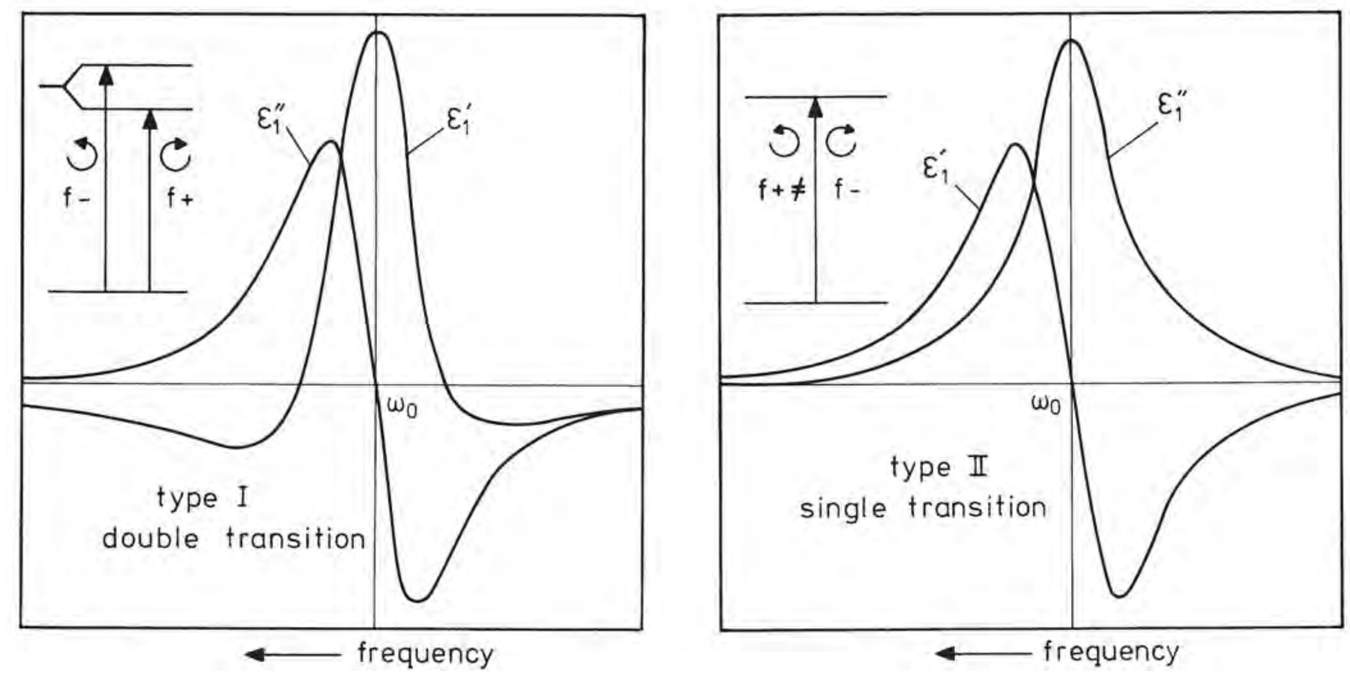
↓

Spectrally dependent - information about electronic structure

Microscopic picture of magneto-optics



P. Bruno, *et al.*. PRB 53, 9214 (1996)

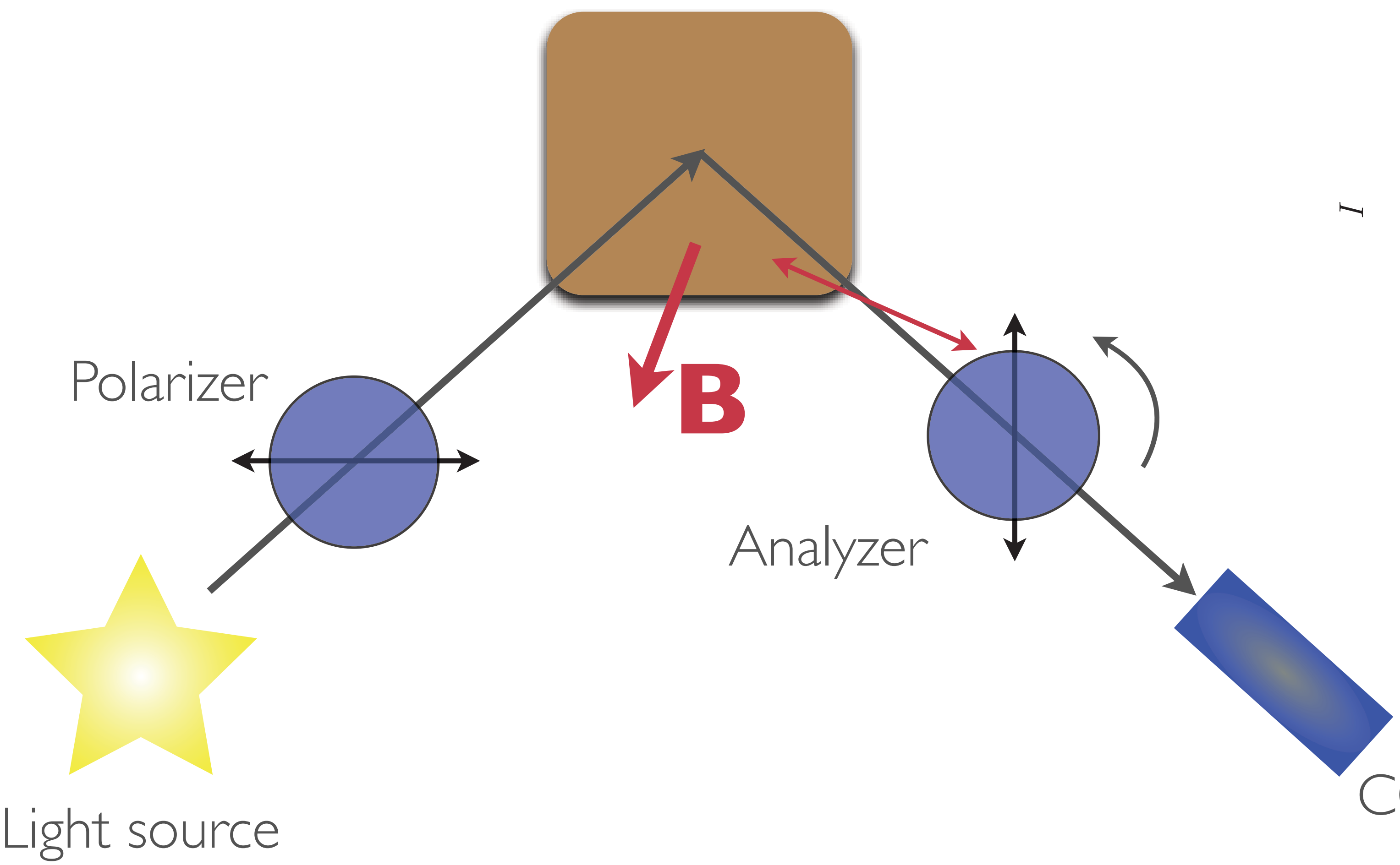


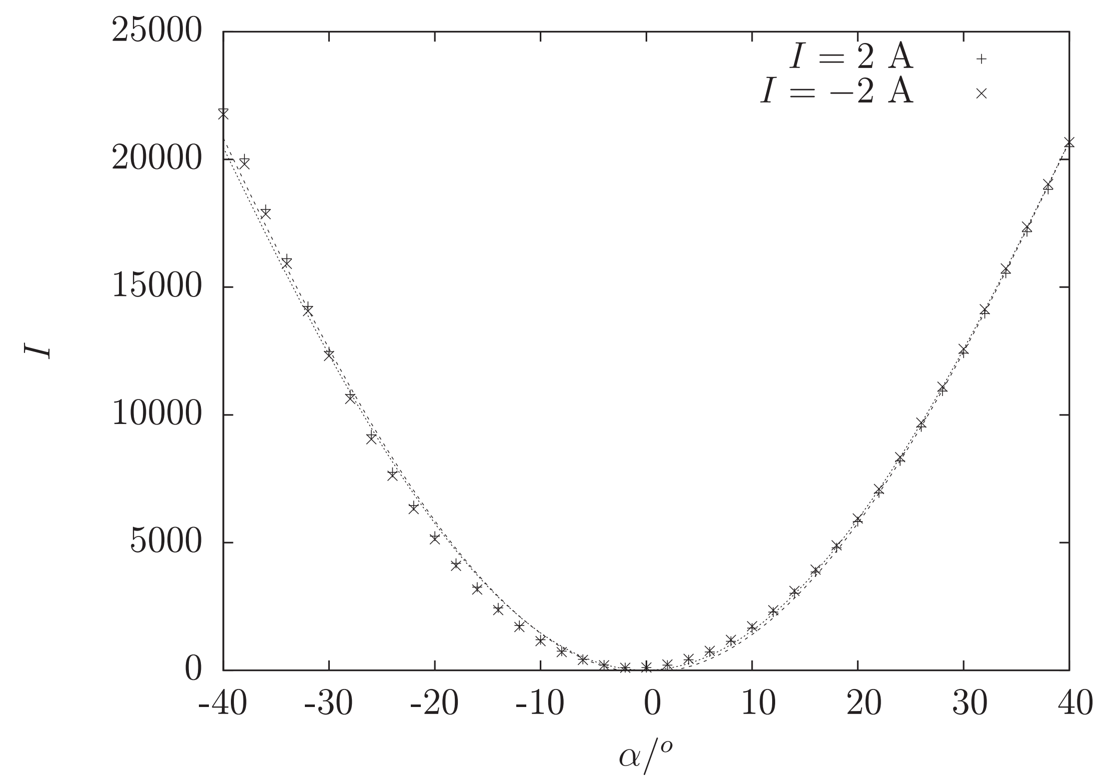
$$J_R = \begin{bmatrix} r_{ss} & r_{ps} \\ r_{sp} & r_{pp} \end{bmatrix} \rightarrow \phi_{Ks} = \theta_{Ks} + j\epsilon_{Ks} = \frac{r_{sp}}{r_{ss}}$$

Spectrally dependent - information about electronic structure

Very small angles of polarization rotation (mdeg)!

Rotating analyzer setup:





$$I \approx \frac{R}{2}(\sin^2\alpha + (\theta_K \cos\delta + \varepsilon_K \sin\delta)\sin(2\alpha))$$

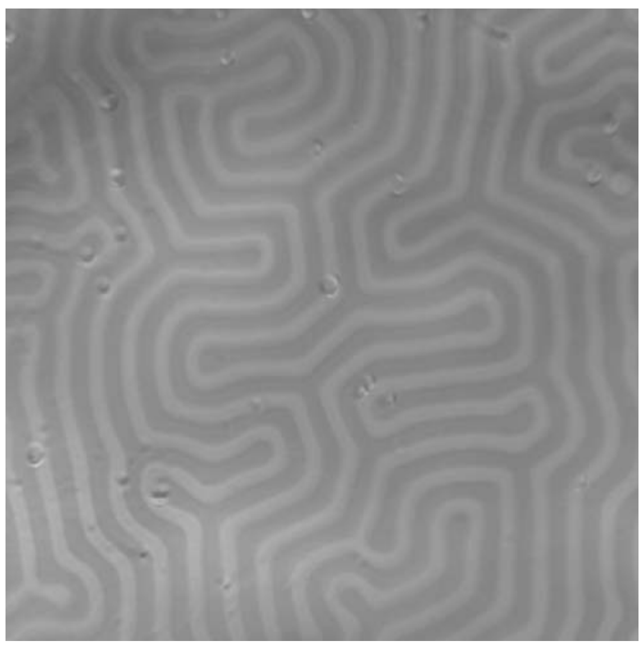
Fast and accurate (bellow 1 mdeg) spectroscopic measurements.

Quadratic MOKE measurements.

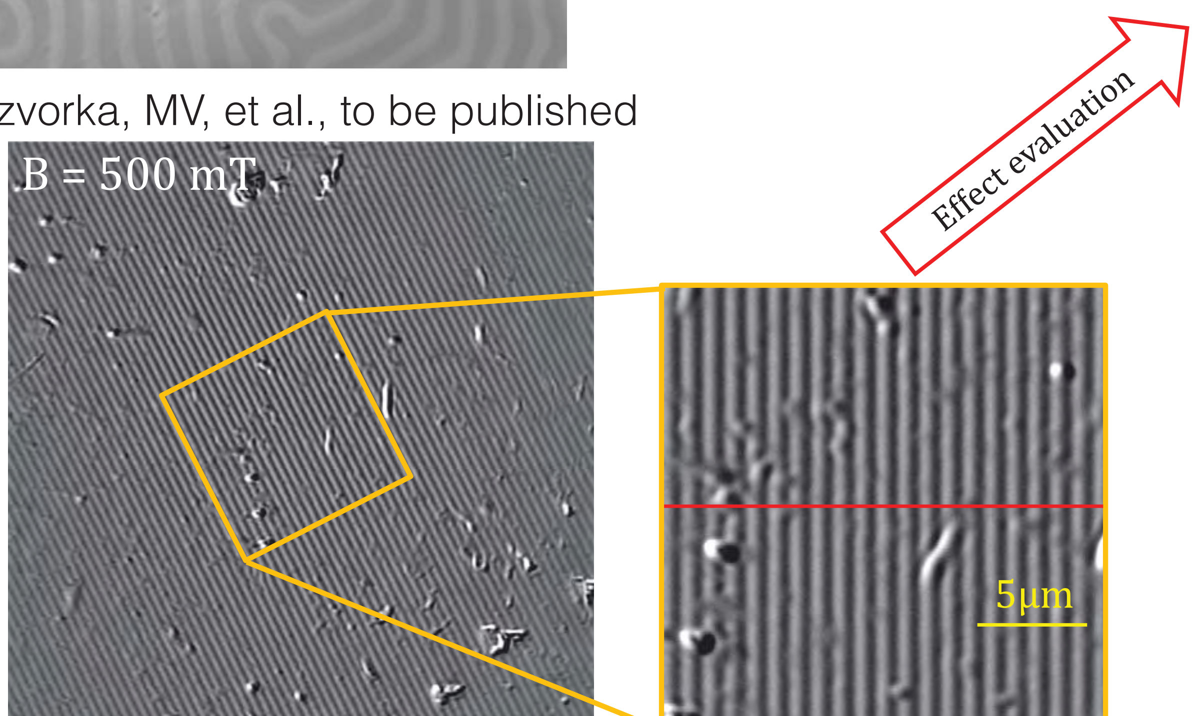
How to measure magneto-optical effects?

Very small angles of polarization rotation (mdeg)!

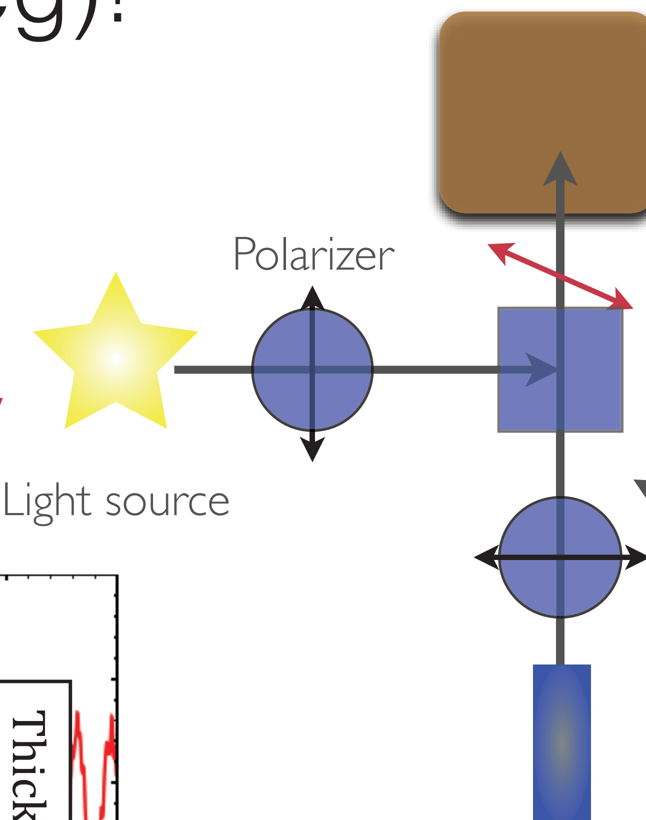
Rotating analyzer setup: extension to microscopy

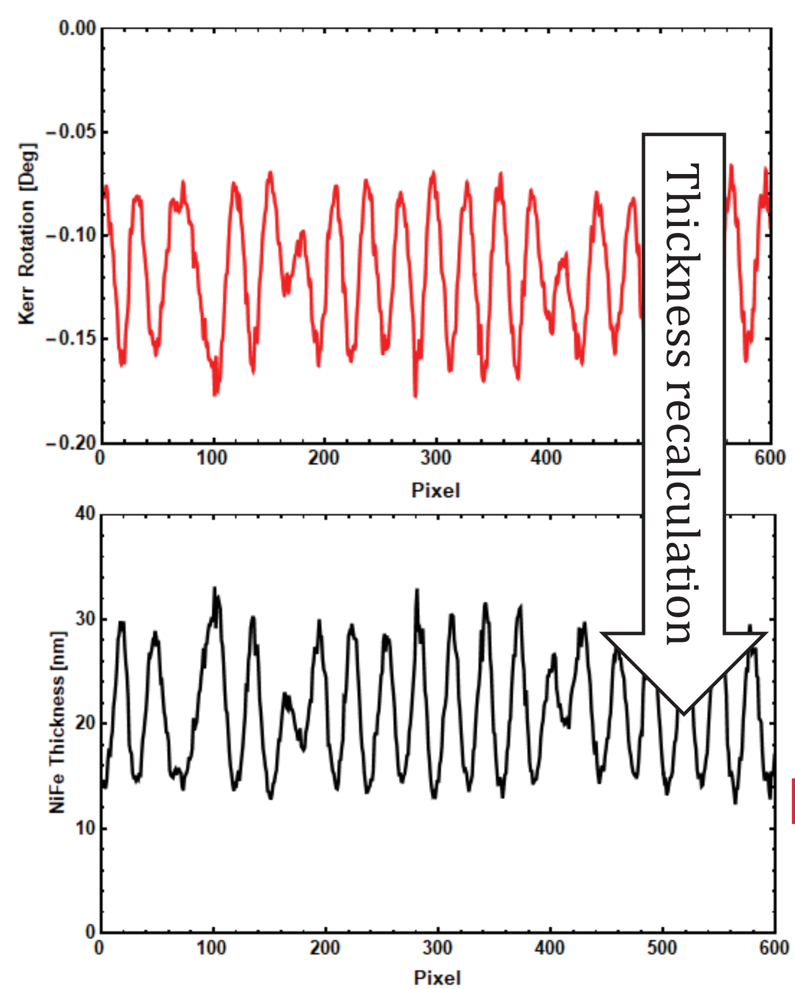


J. Zazvorka, MV, et al., to be published



Accurate value of Kerr effect for each pixel - depth sensitivity

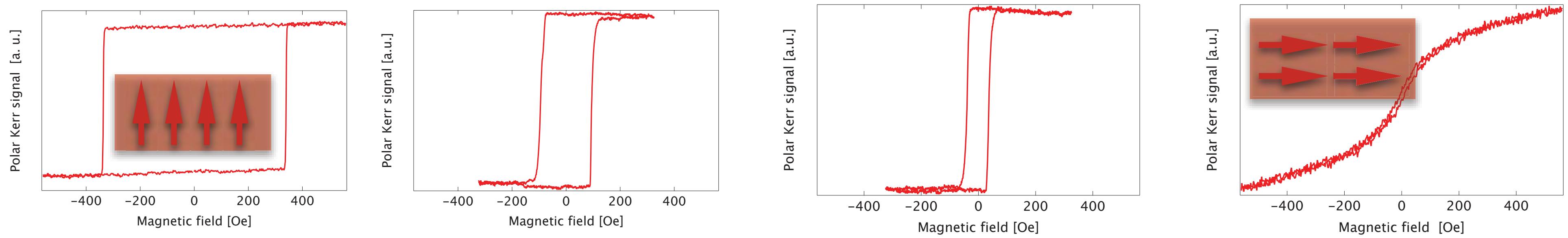


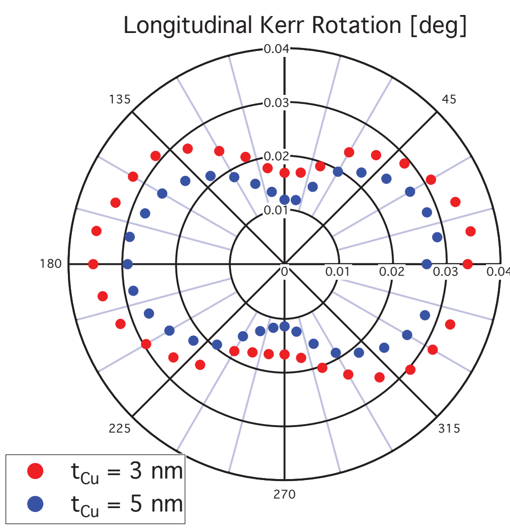


Possible time resolved measurements

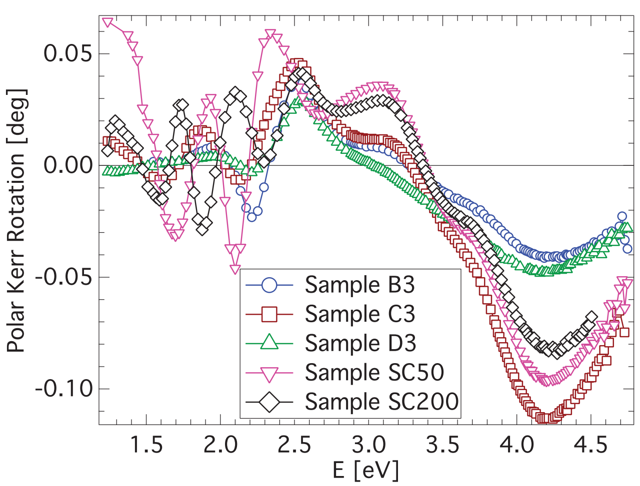
Aims of magneto-optical research

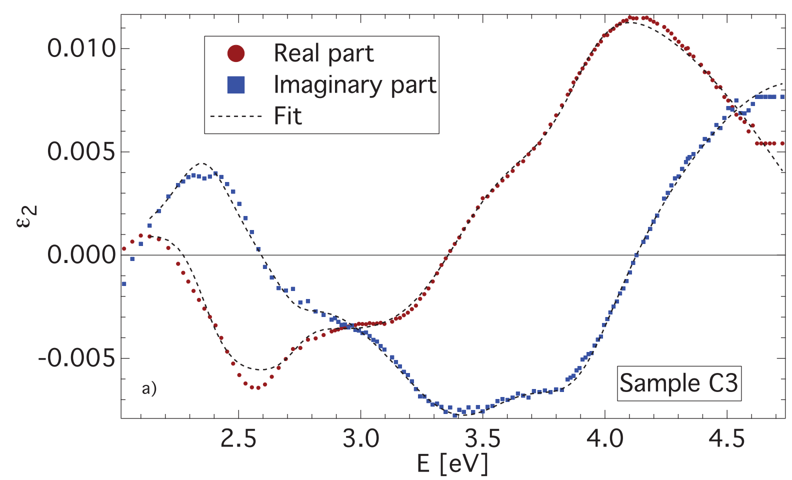
Magnetometry - information about magnetization

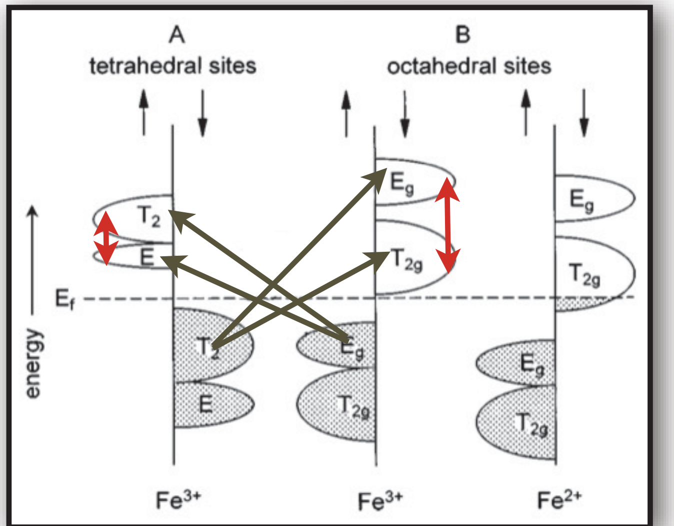




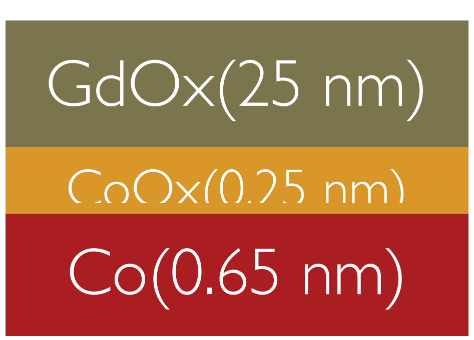
Spectroscopy - information about el. structure

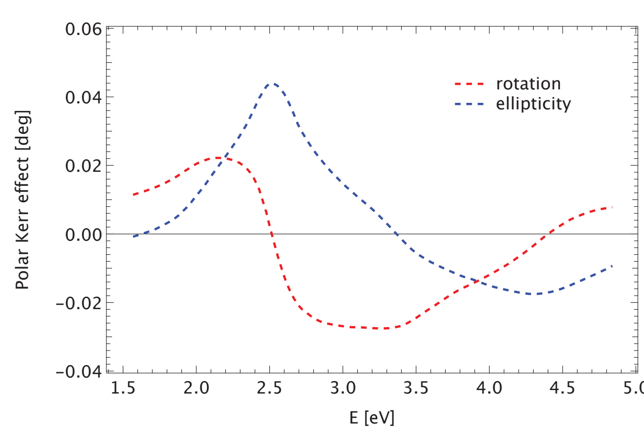


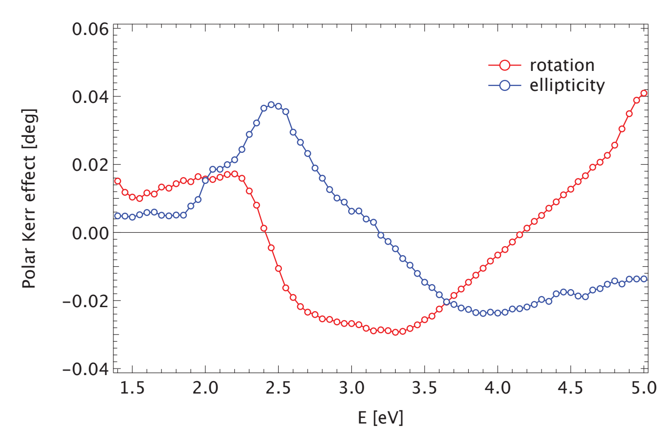




Spectroscopy - information about interfaces





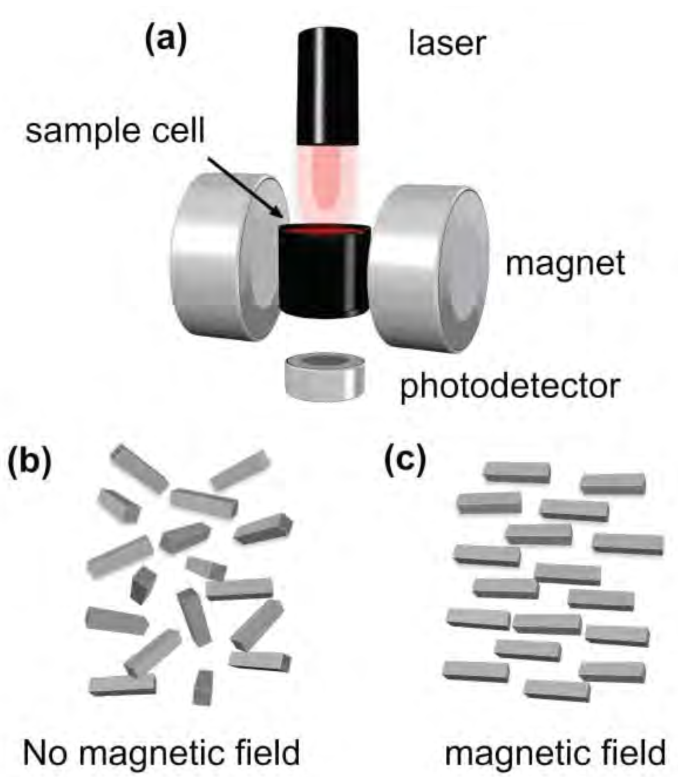


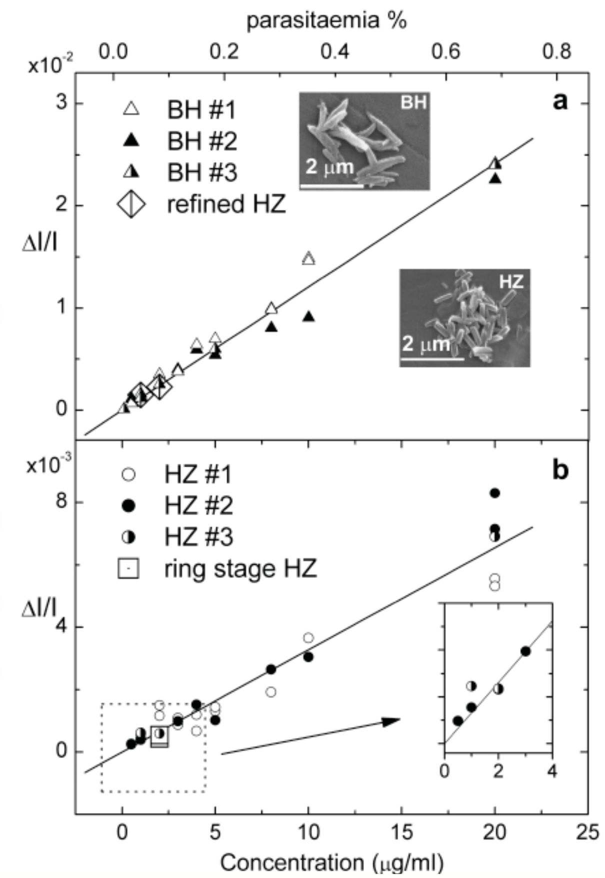
Current research on the potential magneto-optical applications

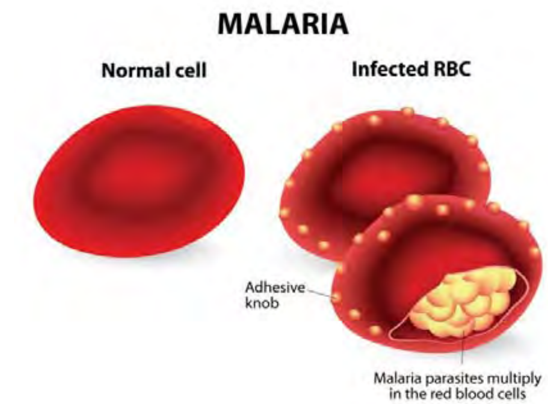
Route to spin-photonics

Magneto-optical diagnostics

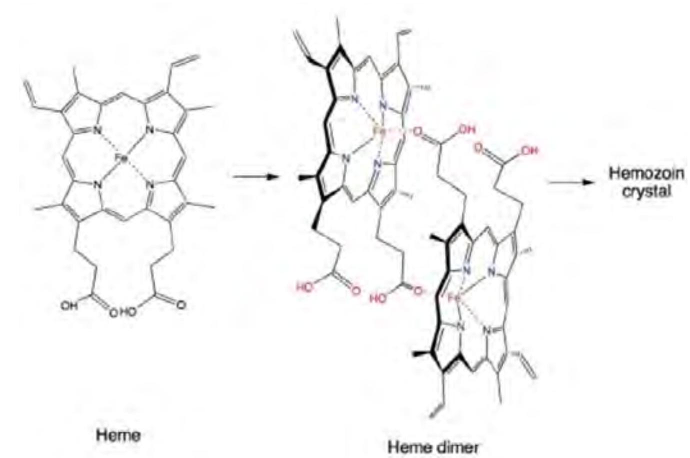
Magneto-optical detection of malaria:

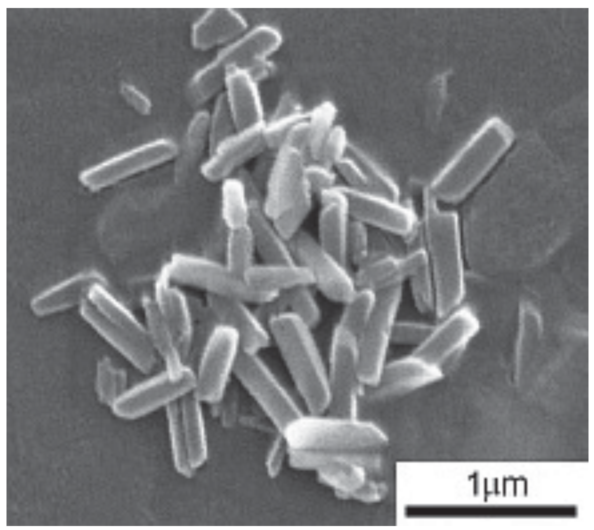


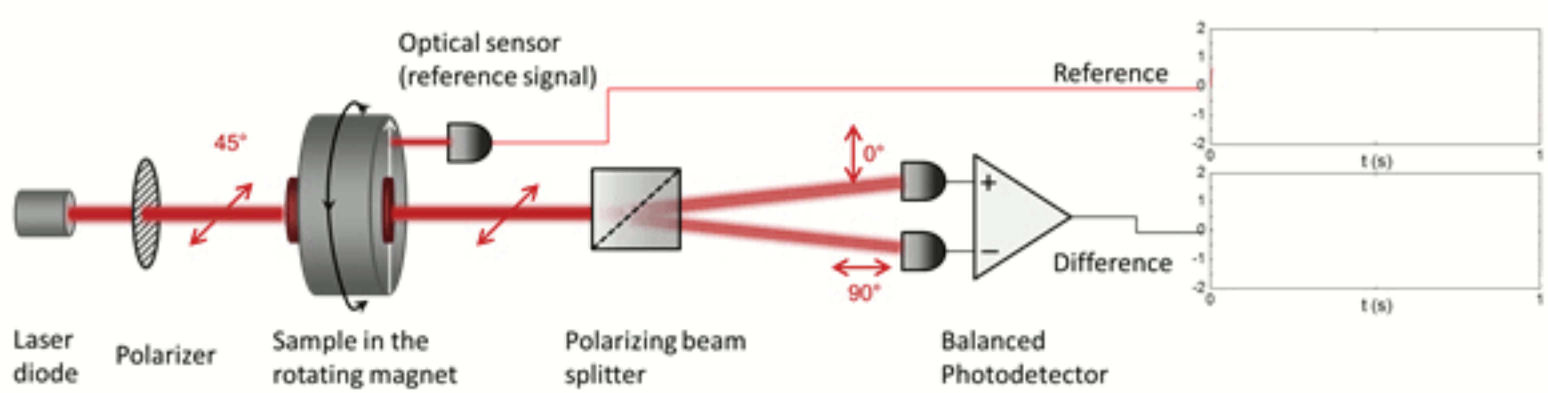




Hemozoin crystals







In-vivo measurements
High success rate

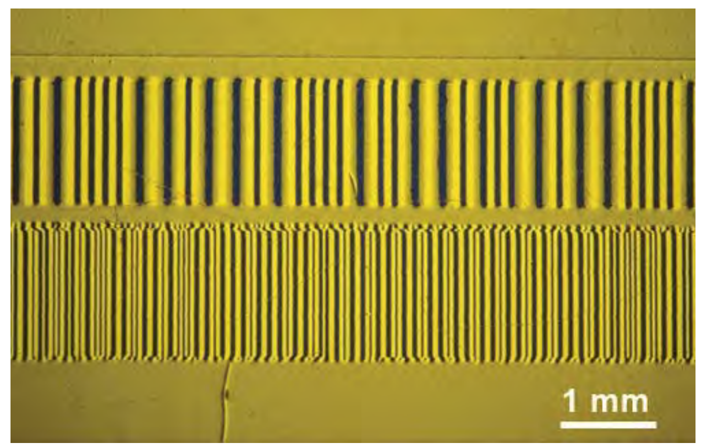
Courtesy of University of Exeter

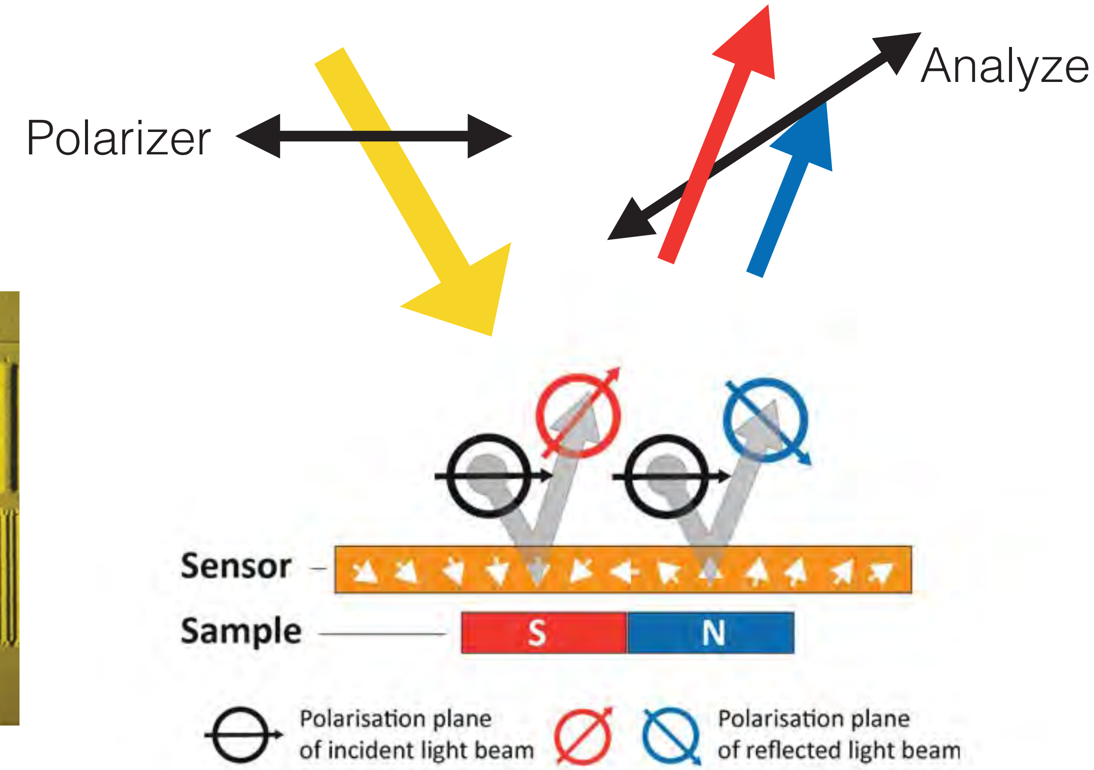
Magneto-optical imaging systems:

Cash machines safety devices

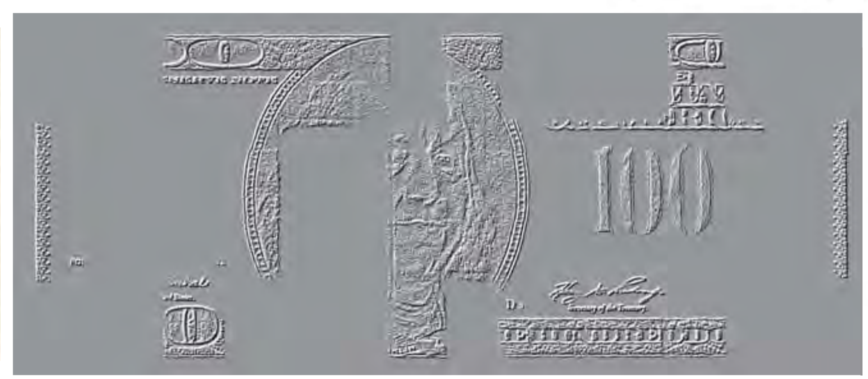
Integration in CM, instant analysis

MO image of card magnetic stripe





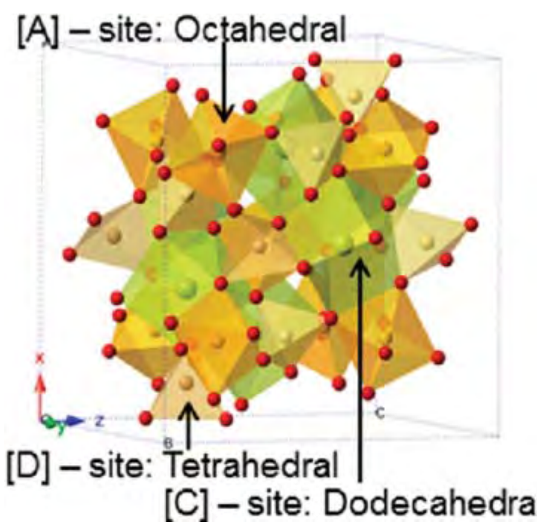
www.matesy.de

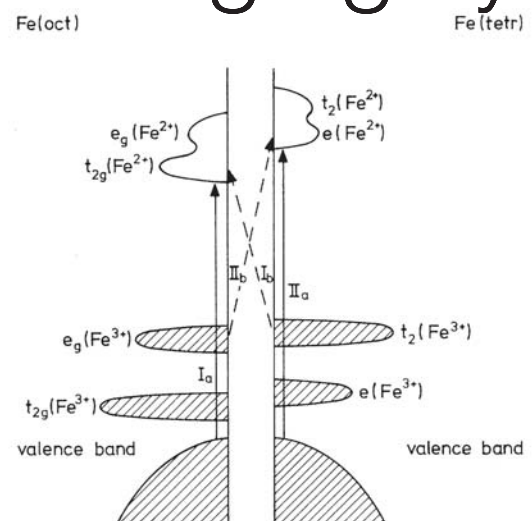


regulaforensics.com

Transparent materials with high MO rotation of large sizes are necessary

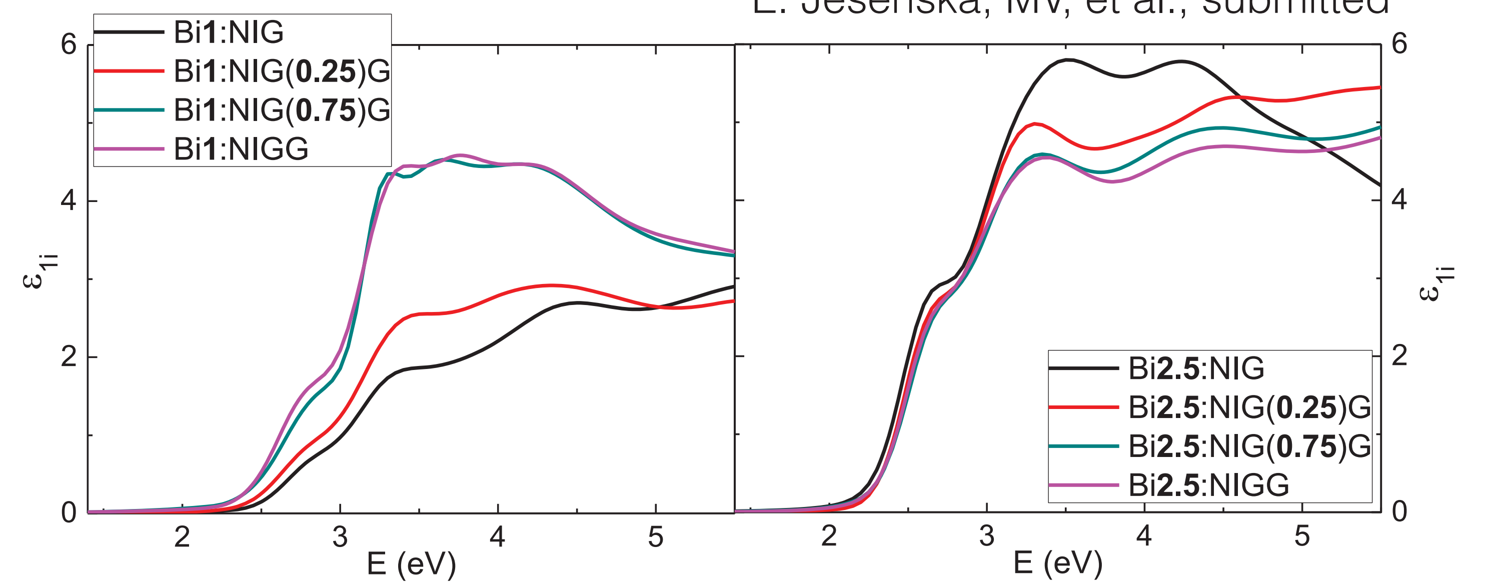
Magneto-optical imaging systems: Magnetic garnets





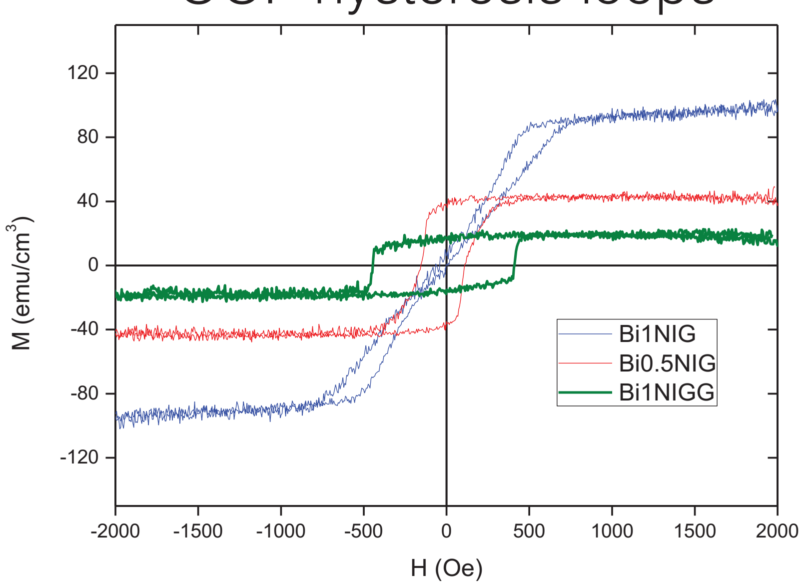
S. Wittekoek, et al., PRB 6, 2777 (1975)

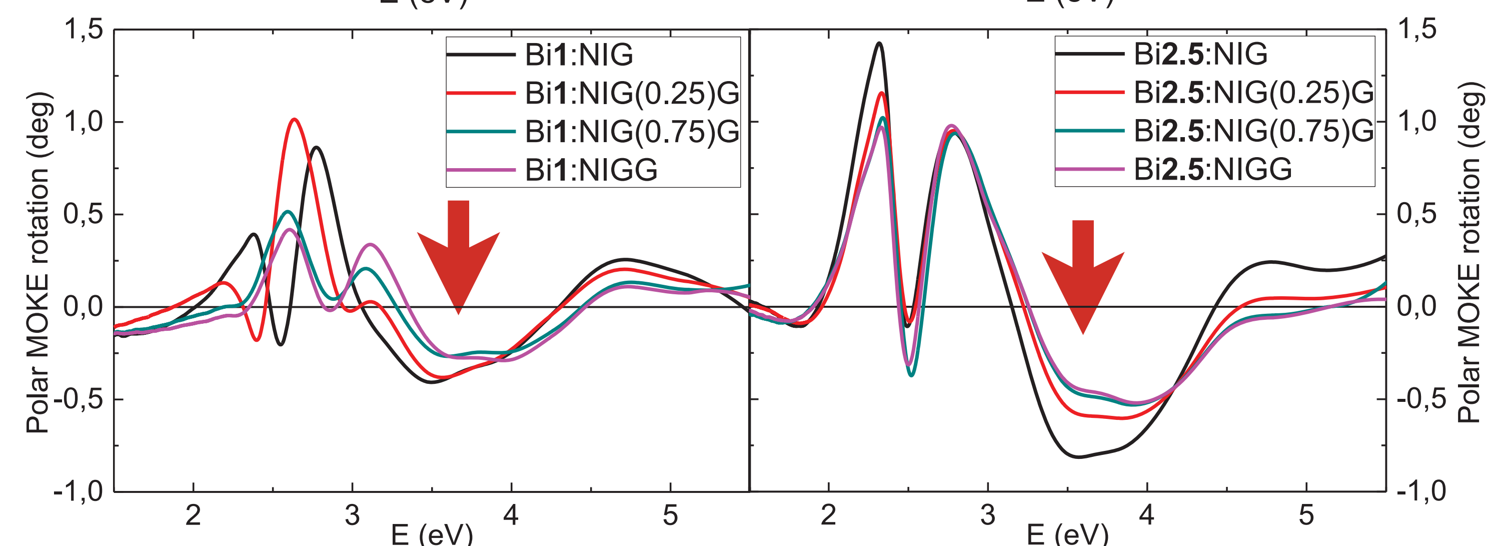
E. Jesenska, MV, et al., submitted



$Nd_2Bi_1Fe_{(5-x)}Ga_xO_{12}$ (Bi *1*:NIG*x*G)
$Nd_{0.5}Bi_{2.5}Fe_{(5-x)}Ga_xO_{12}$ (Bi *2.5* :NIG*x*G)
Ga concentrations : x=0, 0.25, 0.75, 1

OOP hysteresis loops





Bi content increases SO interaction
High magneto-optical activity
Ga influences crystal field
Energy shifting of main peaks

Perpendicular anisotropy

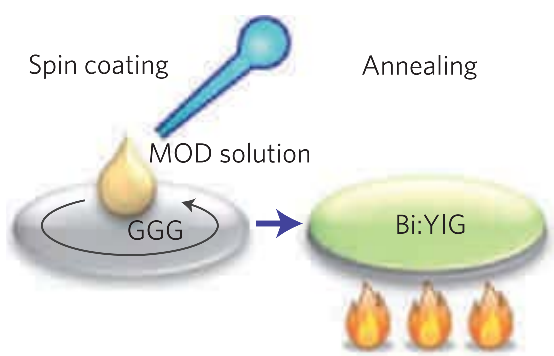
E. Jesenska, MV, et al., Opt. Mat. Expr. 6, 1986 (2016)

Metal organic decomposition:

MOD liquids were consisting of solutions made of Bi, Y, and Fe carboxylates.
The total concentration of carboxylates in those MOD liquids was 4%.

Cleaning of Substrates

Spin Coating	3000rpm	60sec
Drying	100℃	30 min
Pre annealing	450℃	30min
Annealing	700℃	3 hours



Effective, low cost, large scale technique

Slow growth, not suitable for thick layers

LETTERS
PUBLISHED ONLINE: 17 JUNE 2012 | DOI: 10.1038/NMAT3360
nature materials

Spin-current-driven thermoelectric coating

Akihiro Kirihara[1★], Ken-ichi Uchida[2,3], Yosuke Kajiwara[2,3], Masahiko Ishida[1], Yasunobu Nakamura[1†], Takashi Manako[1], Eiji Saitoh[2,3,4,5] and Shinichi Yorozu[1]

nature COMMUNICATIONS

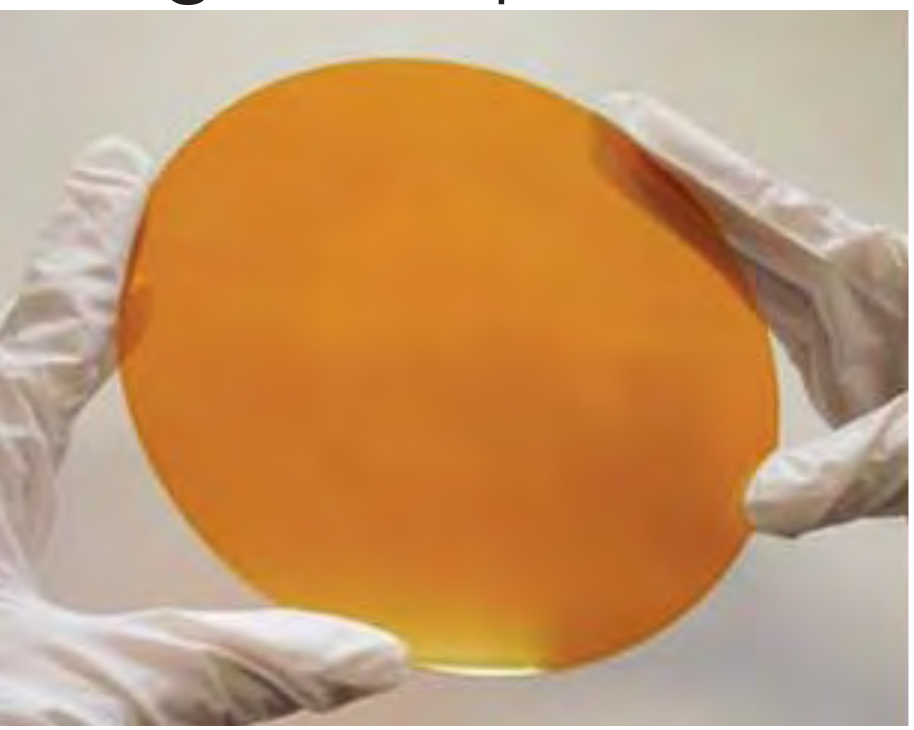
ARTICLE
Received 27 Jun 2014 | Accepted 20 Nov 2014 | Published 8 Jan 2015 DOI: 10.1038/ncomms6910 OPEN

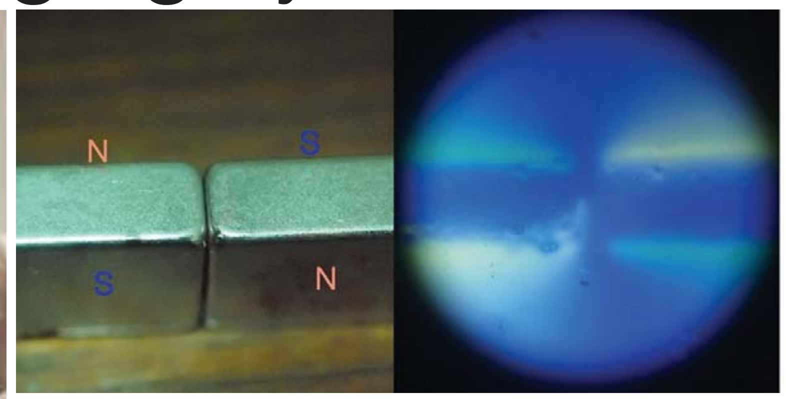
Generation of spin currents by surface plasmon resonance

K. Uchida[1,2], H. Adachi[3,4], D. Kikuchi[1,5], S. Ito[1], Z. Qiu[5], S. Maekawa[3,4] & E. Saitoh[1,3,4,5]

Magneto-optical applications of tomorrow

Magneto-optical imaging systems:





High magneto-optical contrast

High resolution

200 nm thick layer!

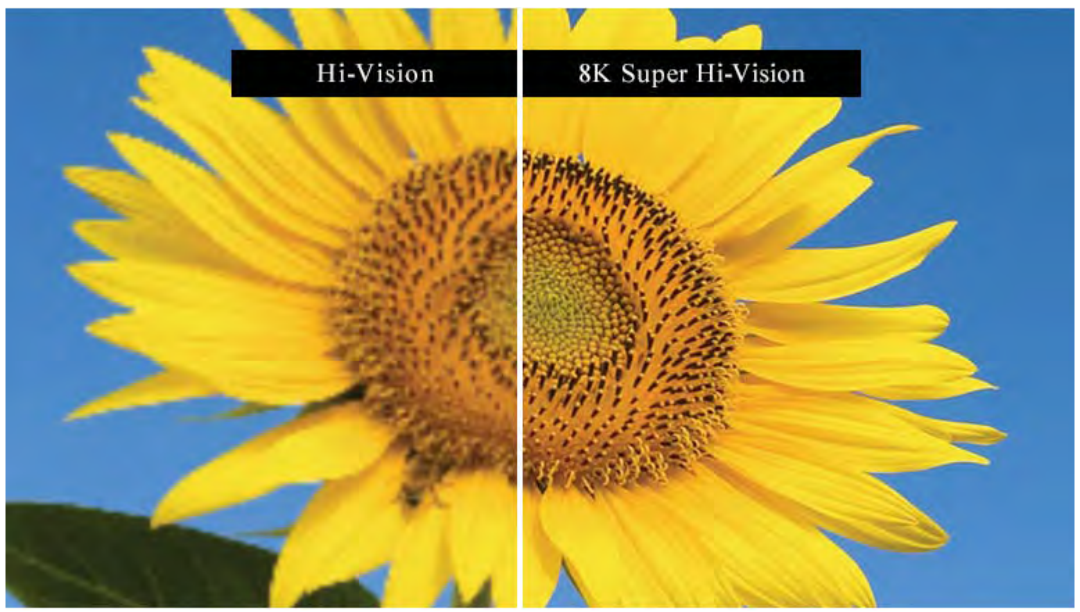
Size limited by spin-coater

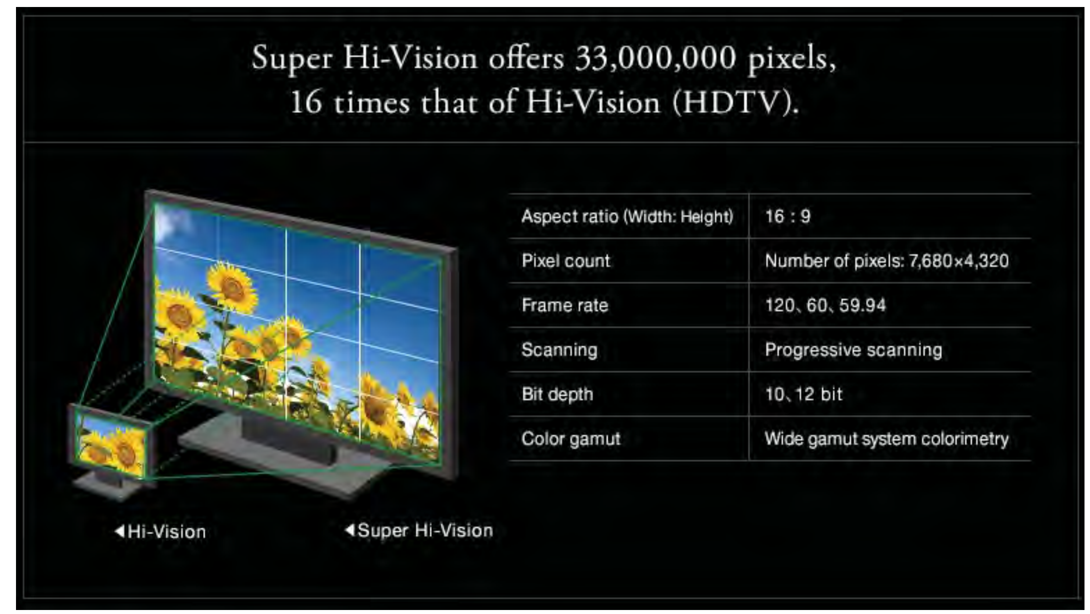
2 GHz response (up to 5 GHz)

T. Ishibashi, NUT, Japan

Magneto-optical applications of tomorrow

Rapid development and requests of display industry





http://www.nhk.or.jp

HD TV (1920x1080): 127 cm - pixel pitch: 576 μm
4K TV (3840x2160): 127 cm - pixel pitch: 288 μm
8K TV (7680x4320): 127 cm - pixel pitch: 144 μm
iPhone (1920x1080): 14 cm - pixel pitch: 63 μm
8K iPhone (7680x4320): 14 cm - pixel pitch: 15 μm

1 movie = 4TB of data

Requirements of the display industry:

- Accurate color gamut
- High contrast
- Fast pixel switching
- High pixel density (small pixel pitch)
- Low energy consumption
- 3D imaging

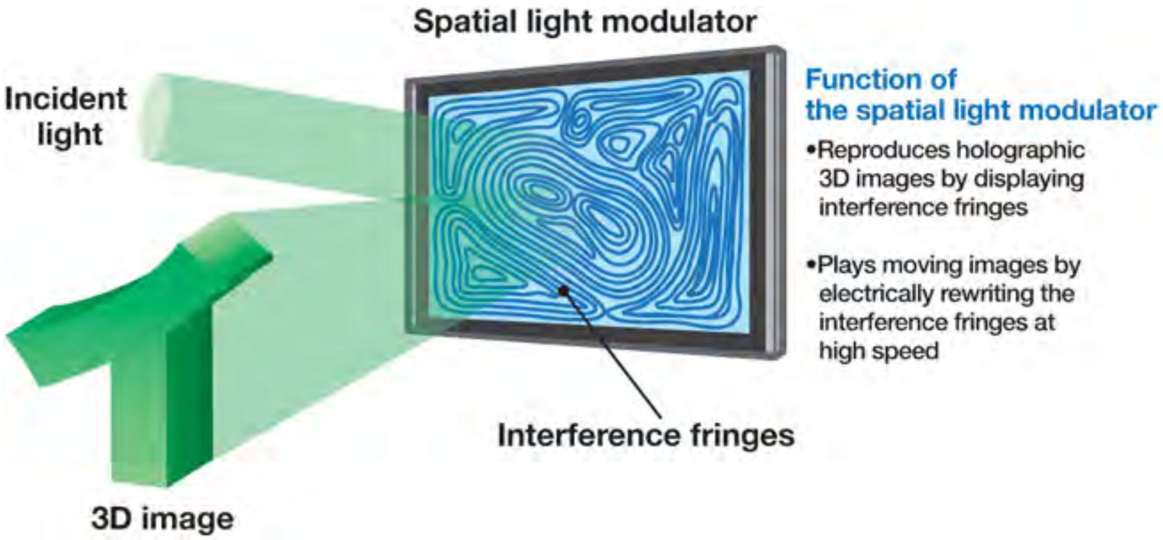
Magneto-optical applications of tomorrow

Current 3D display technology:

- Special glasses
- Narrow viewing angles
- Crosstalks

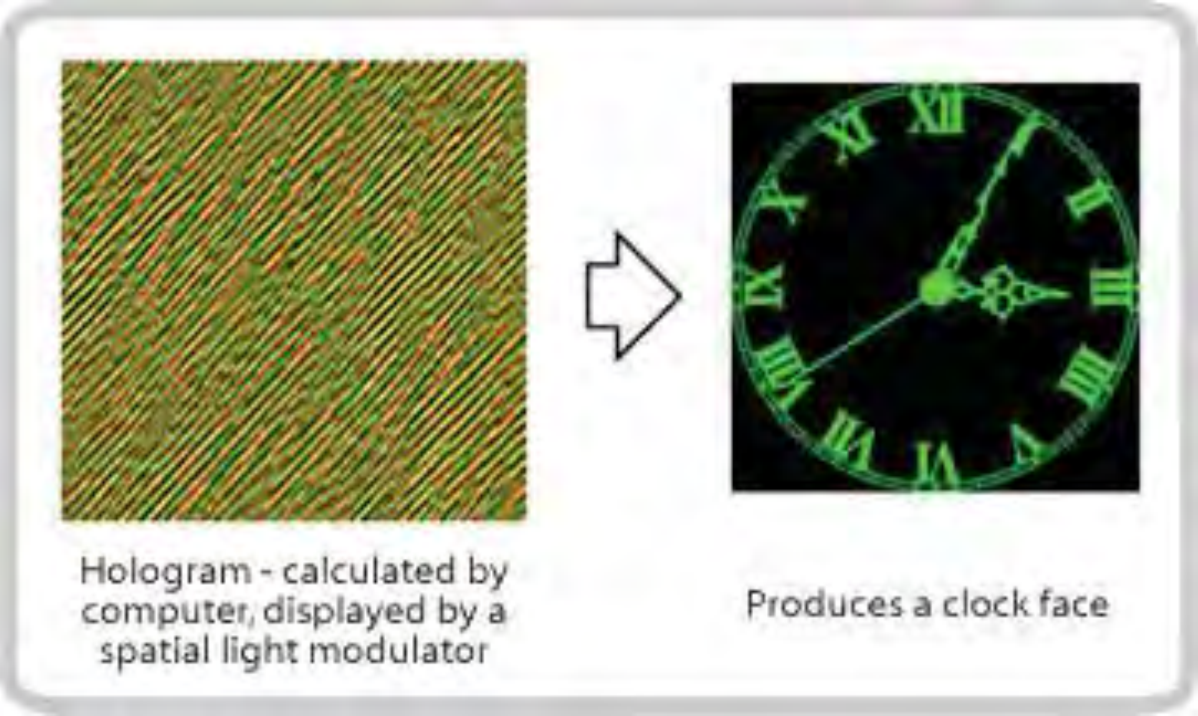
Bad user experience

Magneto-optical spatial light modulators:



Reconstructed 3D moving images by using SLM

http://www.nhk.or.jp



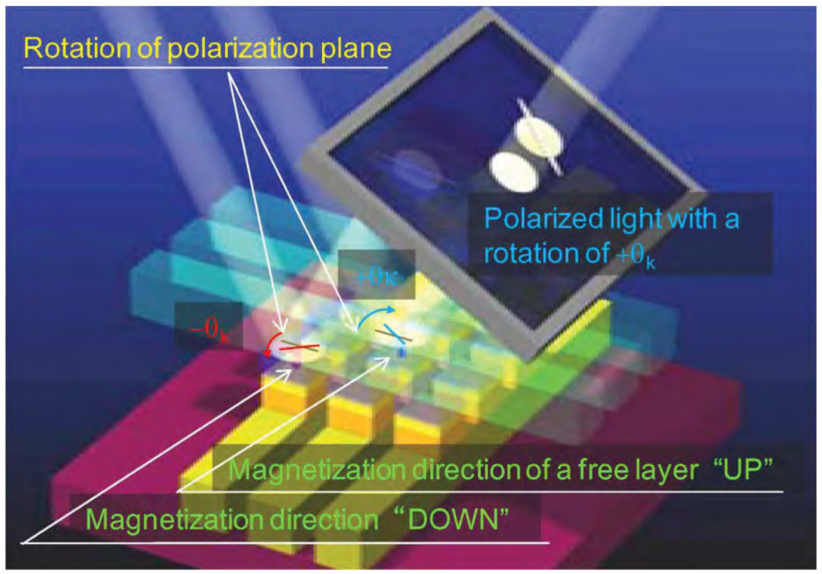
Holographic data storage

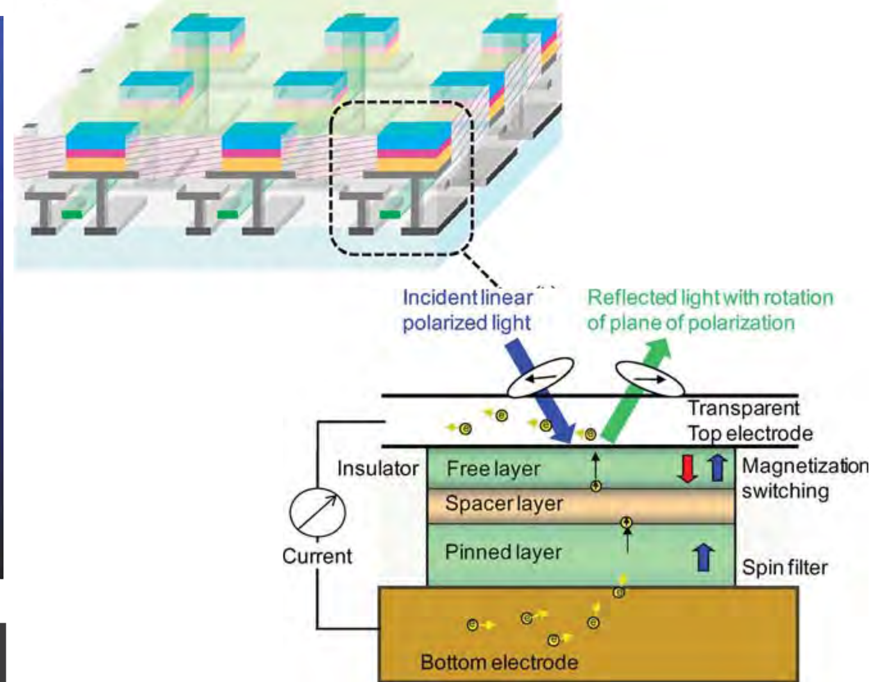
http://www-g.eng.cam.ac.uk

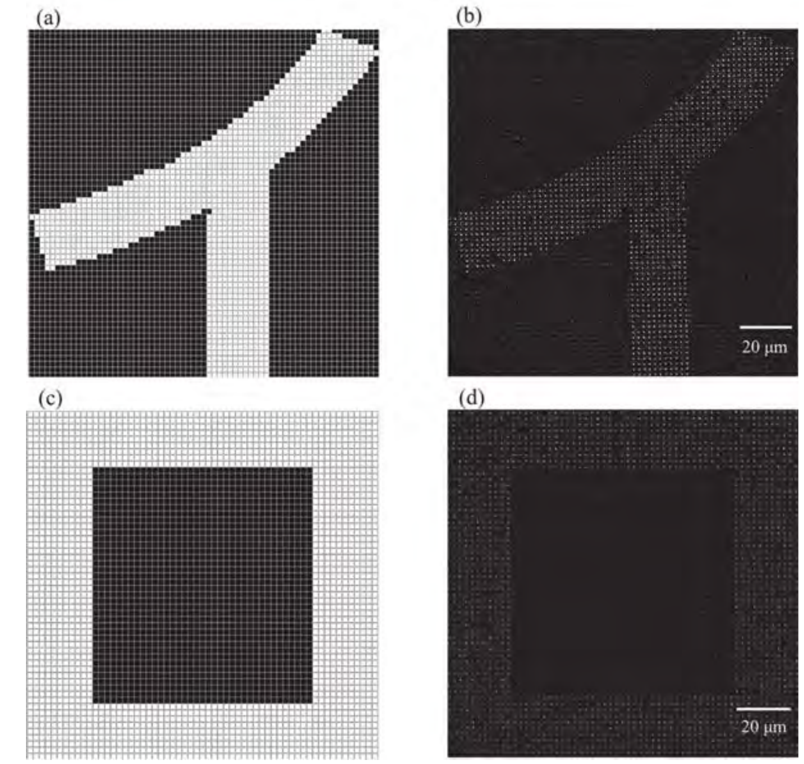
Magneto-optical applications of tomorrow

Magneto-optical spatial light modulators:

H. Kinjo, et al., Electronics 5, 55 (2016)

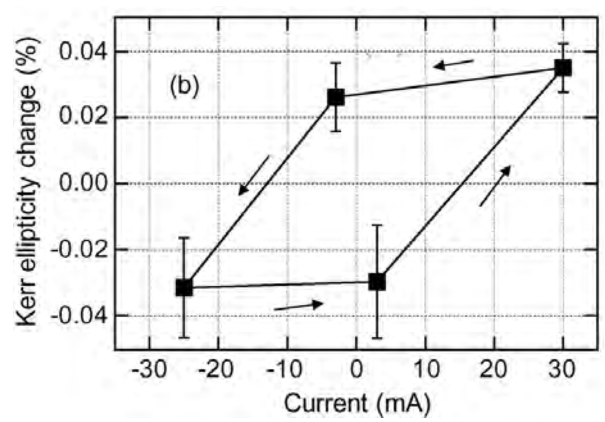


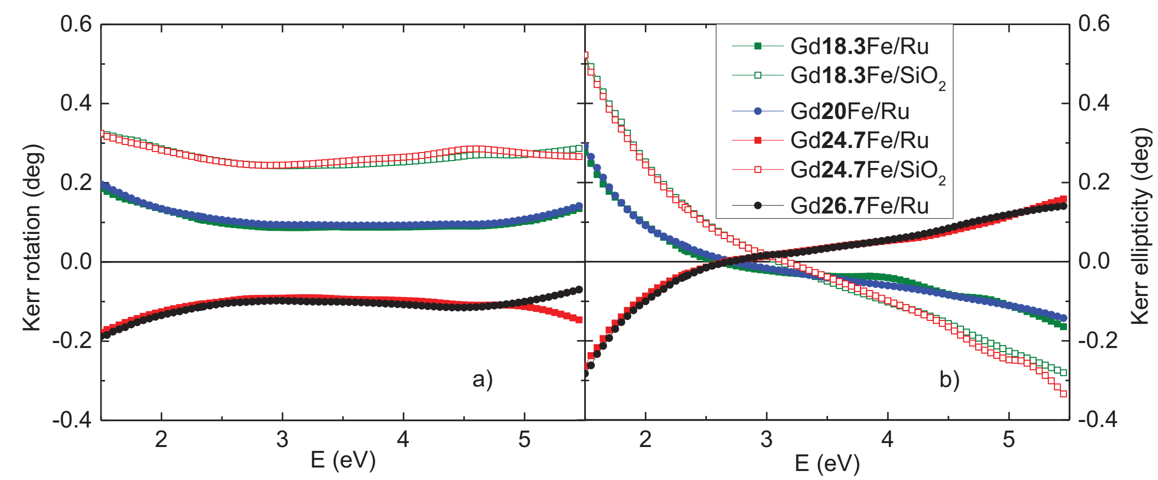




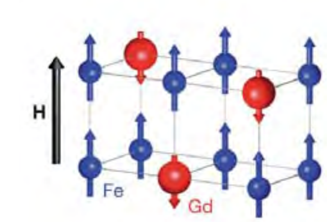
	LCD	Digital Micro-Mirror	Magneto-Optic SLM	STS MO-SLM
Pixel size (μm)	5.0	10.8	10	0.5
Response time (μs)	100	~10	0.015	~0.015
Modulation method	Liquid crystal	Micro-mirror	Magneto-Optical	Magneto-Optical

K. Aoshima, et al., J. Disp. Tech. 6, 374 (2010)





3D image without necessity of additional glasses with high viewing angle and high frequency

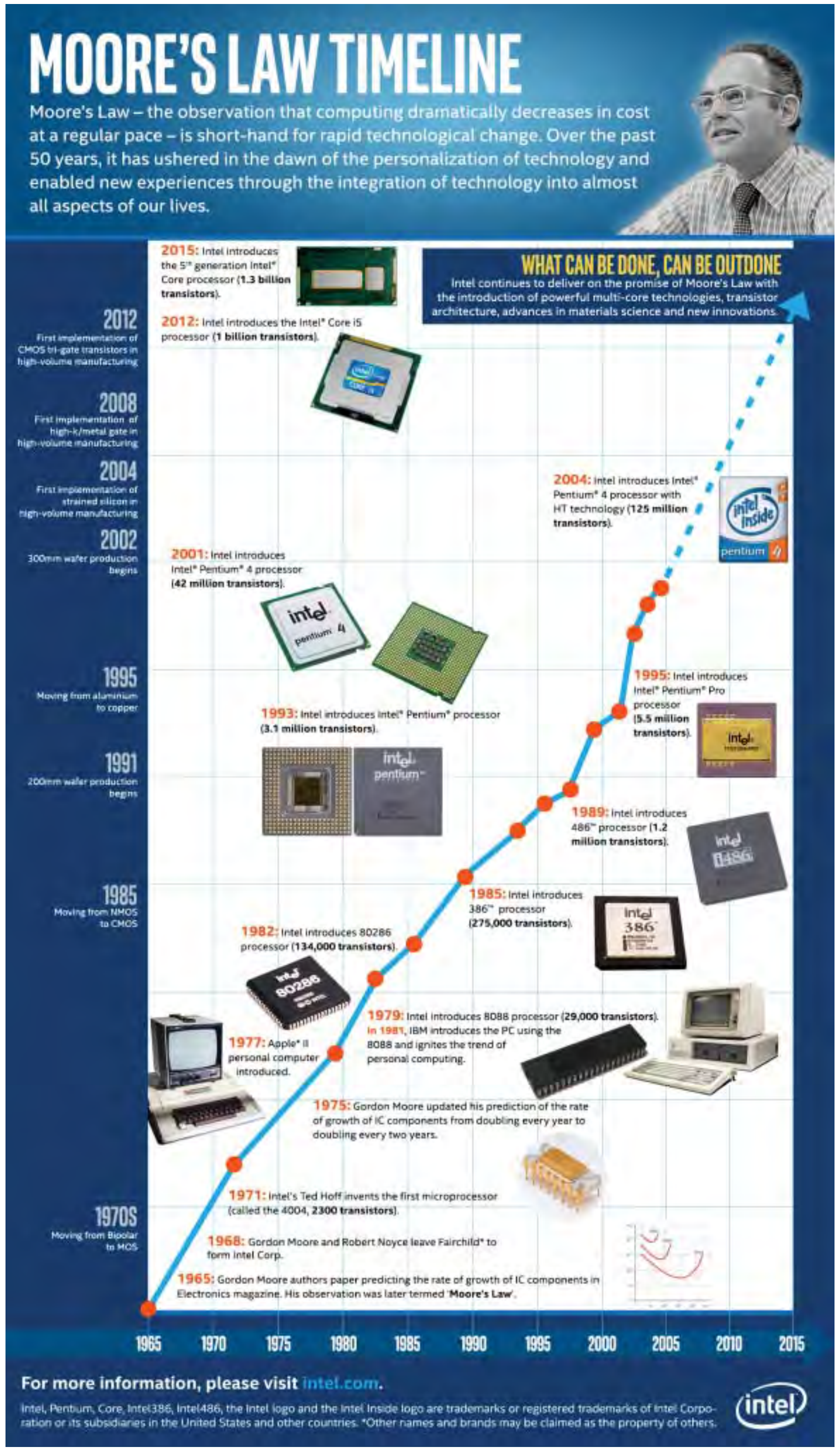


Problems of the classical integrated electronics

Future apocalypse?

Magneto-optical applications of tomorrow

Moore’s law is dead



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Archive > Volume 530 > Issue 7589 > News Feature > Article

NATURE | NEWS FEATURE

عربي

The chips are down for Moore’s law

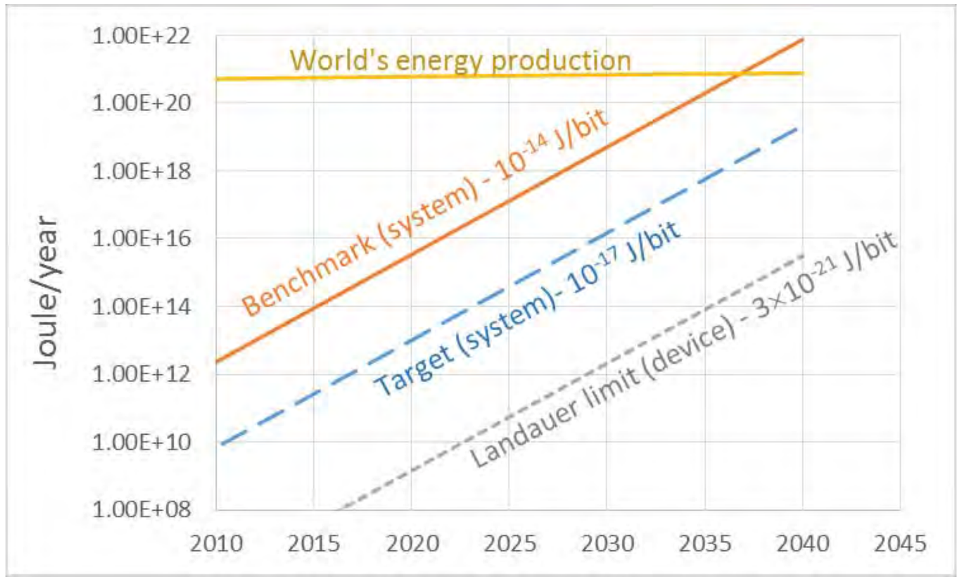
The semiconductor industry will soon abandon its pursuit of Moore's law. Now things could get a lot more interesting.

M. Mitchell Waldrop

09 February 2016

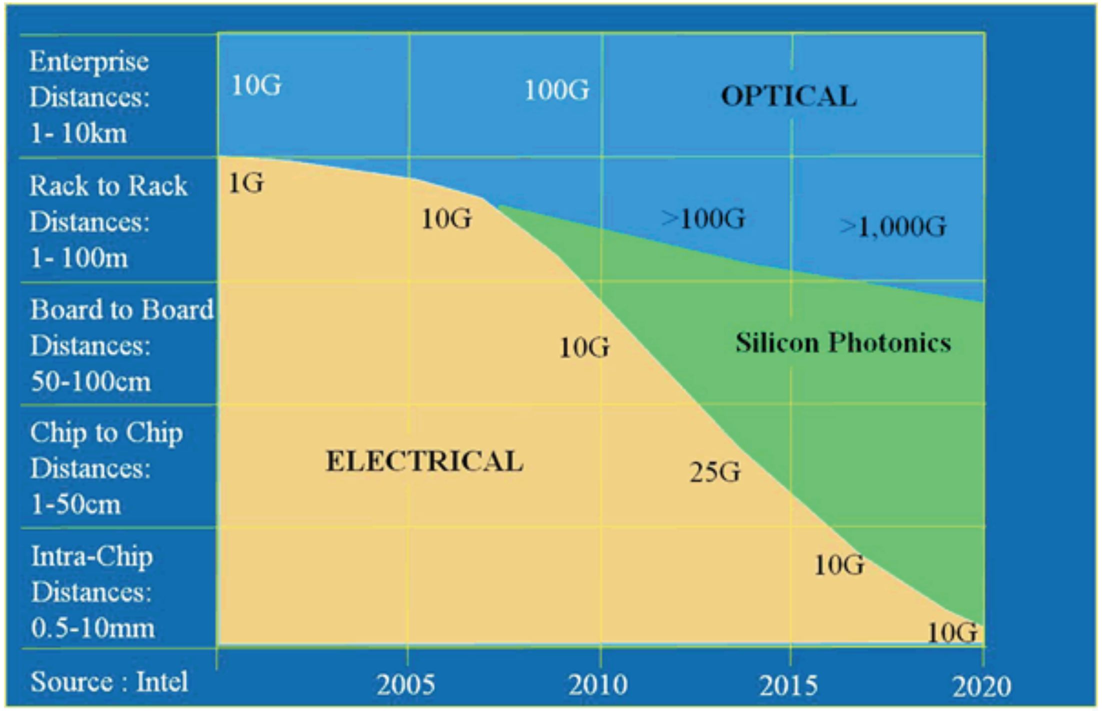
Computer technology predictions: Energy

Energy consumption growth:



All opt. switch: 10 fJ
HD switch: 10-100 nJ
Flash: 10 nJ
STT RAM:450 pJ-100fJ

Energy consumption is very important!!!



Communication speed is very important!!!

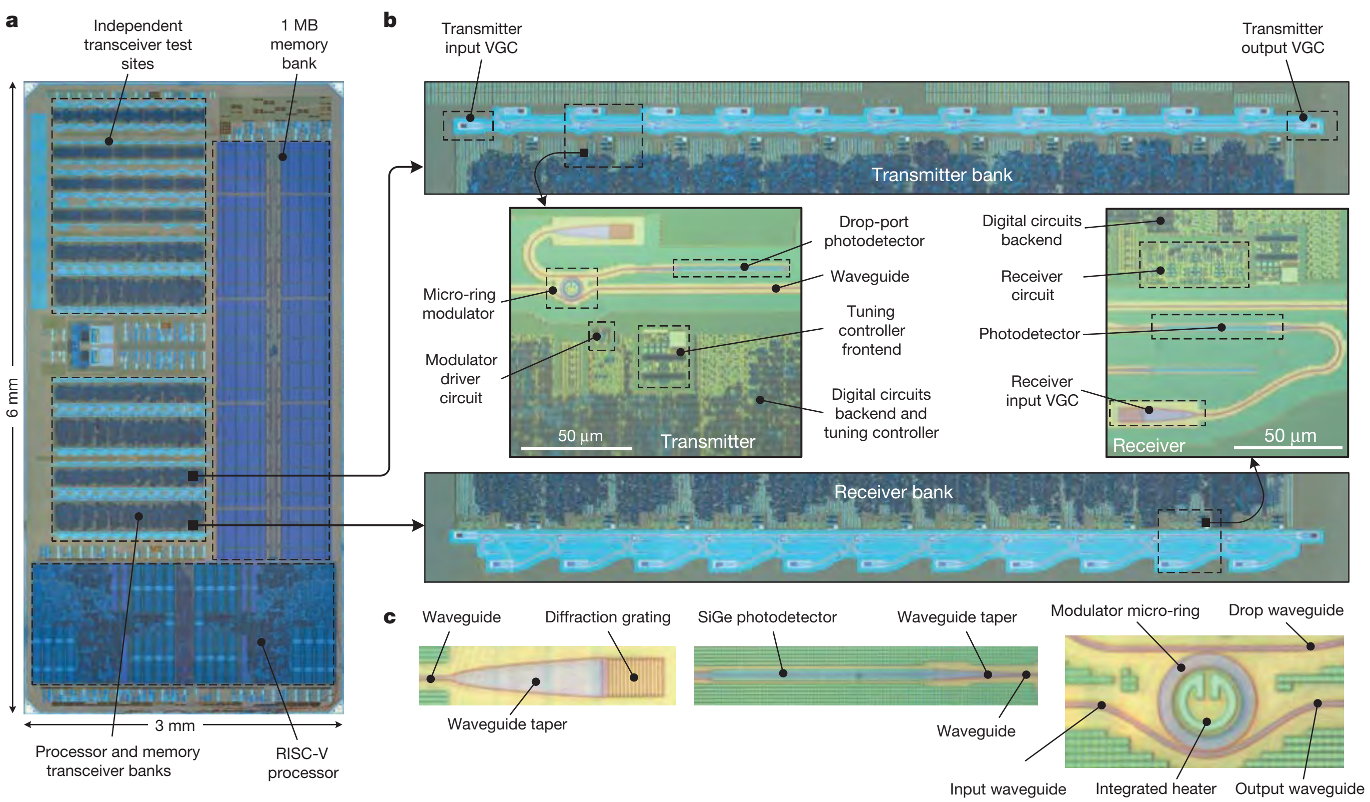
Magneto-optical applications of tomorrow

LETTER

doi:10.1038/nature16454

Single-chip microprocessor that communicates directly using light

Chen Sun[1,2]*, Mark T. Wade[3]*, Yunsup Lee[1]*, Jason S. Orcutt[2]†*, Luca Alloatti[2], Michael S. Georgas[2], Andrew S. Waterman[1], Jeffrey M. Shainline[3]†, Rimas R. Avizienis[1], Sen Lin[1], Benjamin R. Moss[2], Rajesh Kumar[3], Fabio Pavanello[3], Amir H. Atabaki[2], Henry M. Cook[1], Albert J. Ou[1], Jonathan C. Leu[2], Yu-Hsin Chen[2], Krste Asanović[1], Rajeev J. Ram[2], Miloš A. Popović[3] & Vladimir M. Stojanović[1]



No isolator, electro-optical modulator (high energy consumption)

Integrated magneto-optical isolator

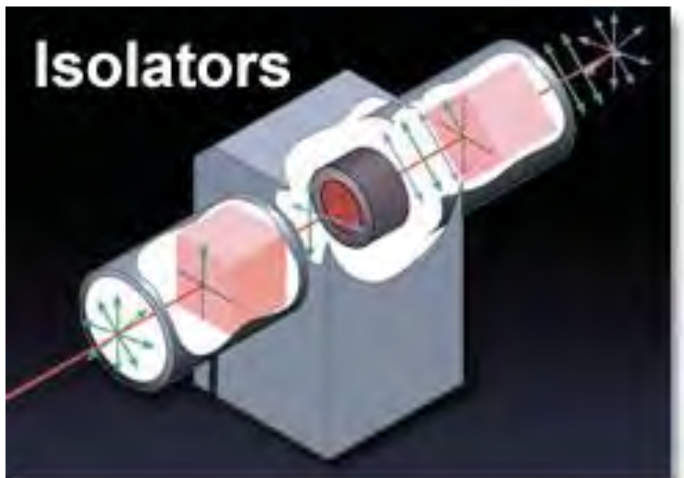
High isolation ratio

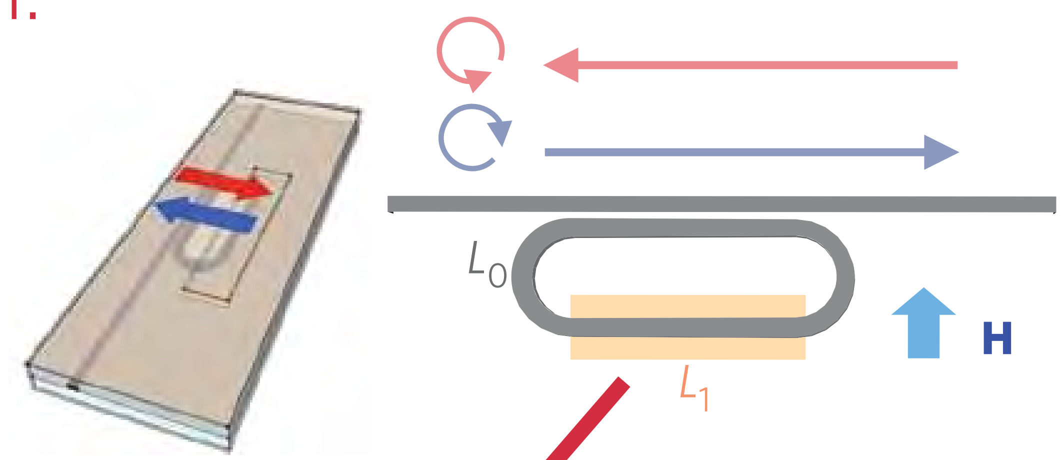
Low energy consumption and high frequency modulator

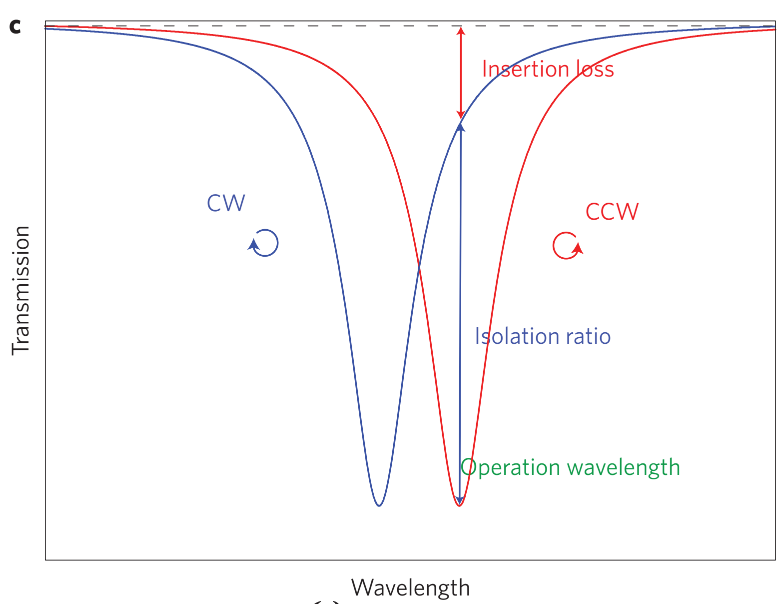
Multiplexing

Magneto-optical applications of tomorrow

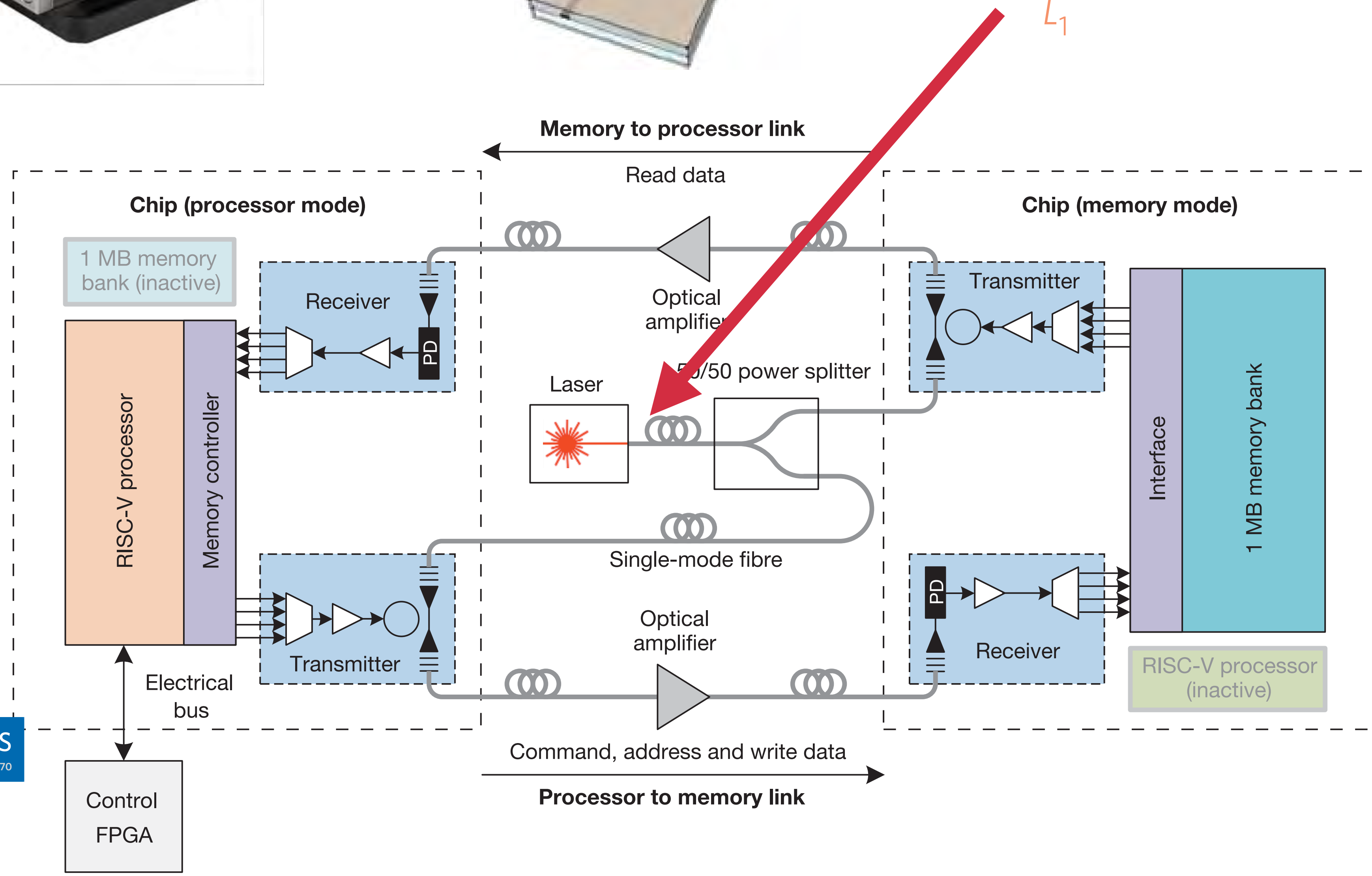
MO Isolators - non-reciprocal propagation:







$$\theta_F = \frac{\omega}{2c}(n_+ - n_-)d.$$

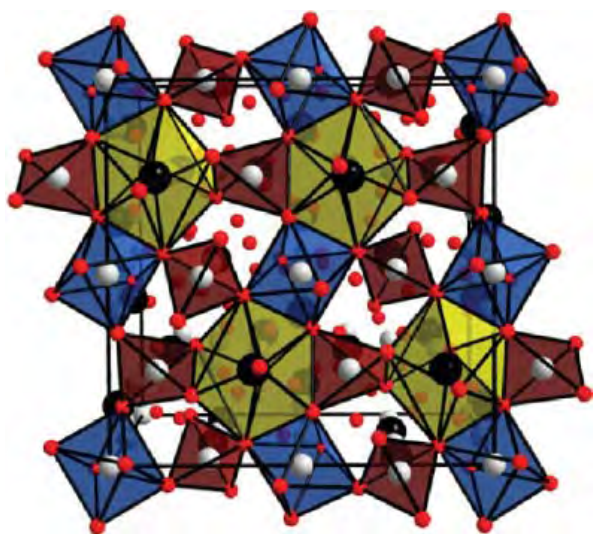


nature photonics
LETTERS
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI: 10.1038/NPHOTON.2011.270

On-chip optical isolation in monolithically integrated non-reciprocal optical resonators

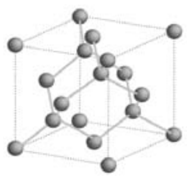
Lei Bi[1]*, Juejun Hu[2], Peng Jiang[1], Dong Hun Kim[1], Gerald F. Dionne[1], Lionel C. Kimerling[1] and C. A. Ross[1]*

Magneto-optical applications of tomorrow

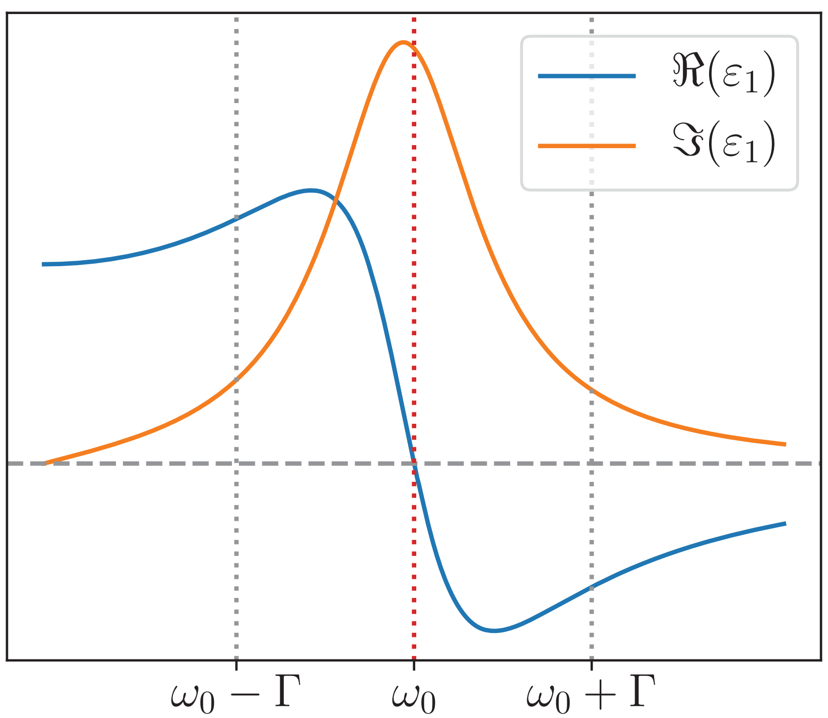


Garnet: a=12.376 Å

Magnetic garnets:
Large lattice mismatch
Impossible to grow directly on silicon



Silicon: a=5.431 Å



Requirements:

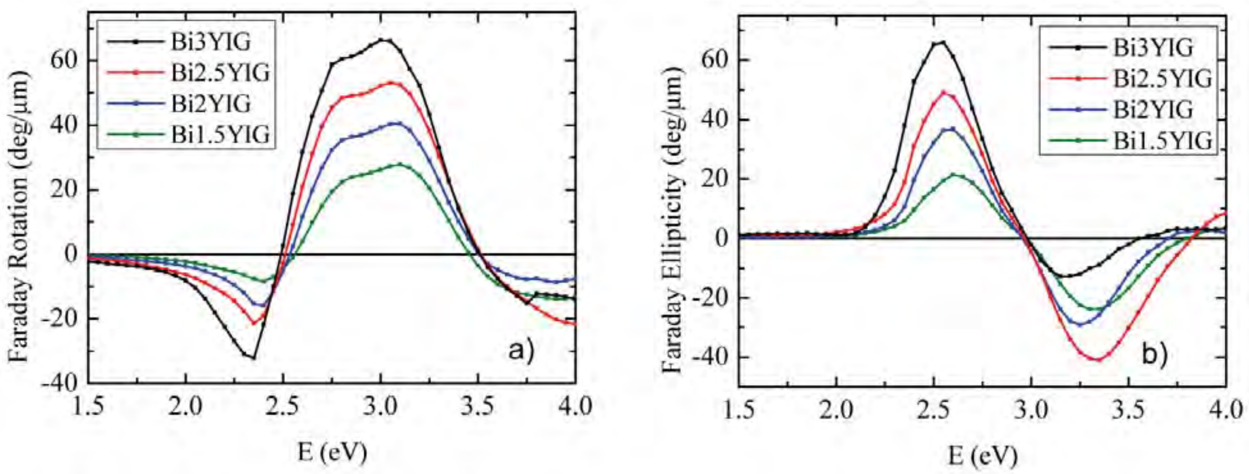
- Strong SO coupling (high MO activity)
- Far from resonance (low absorption)
- High figure of merit (deg/dB)

High demand for new, silicon compatible materials

Magneto-optical applications of tomorrow

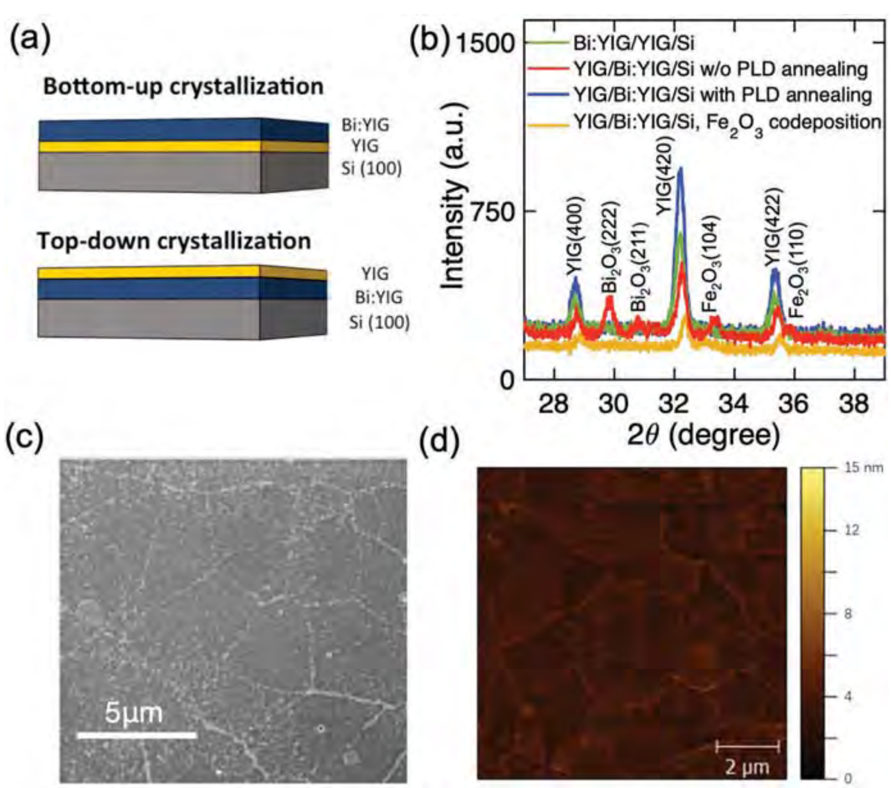
How to increase MO activity at telecommunication wavelength 1550 nm (0.8 eV)?

Bi substituted YIG:



Bi substituted YIG, higher MO activity due to stronger spin-orbit coupling.

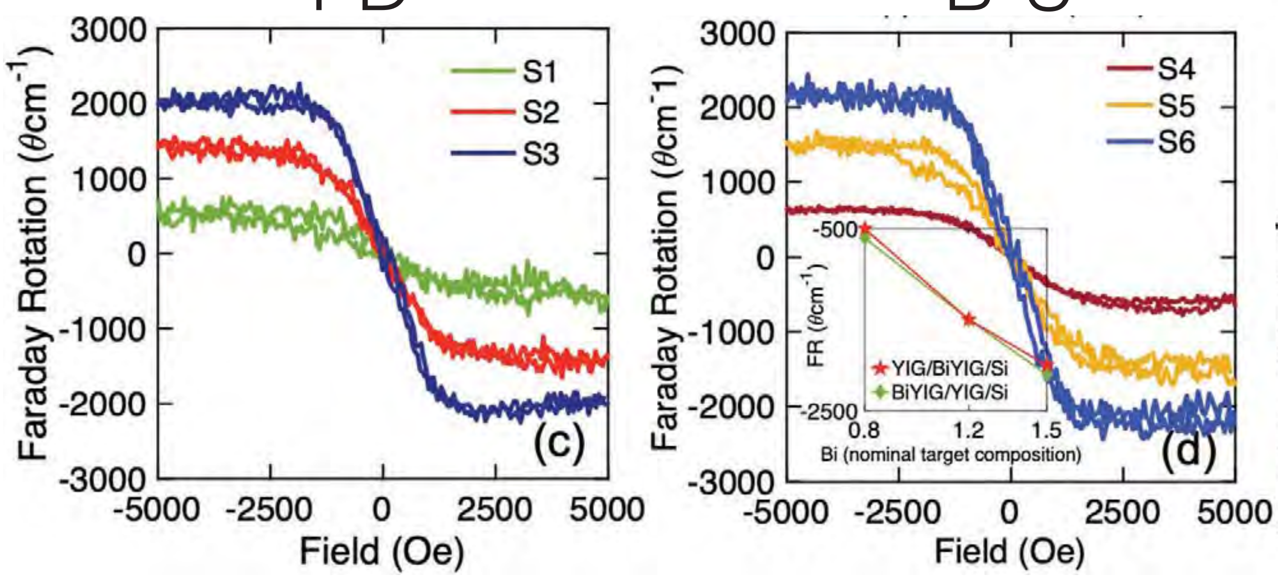
E. Jesenska, MV, et al., Opt. Mat. Expr. 6, 1986 (2016)

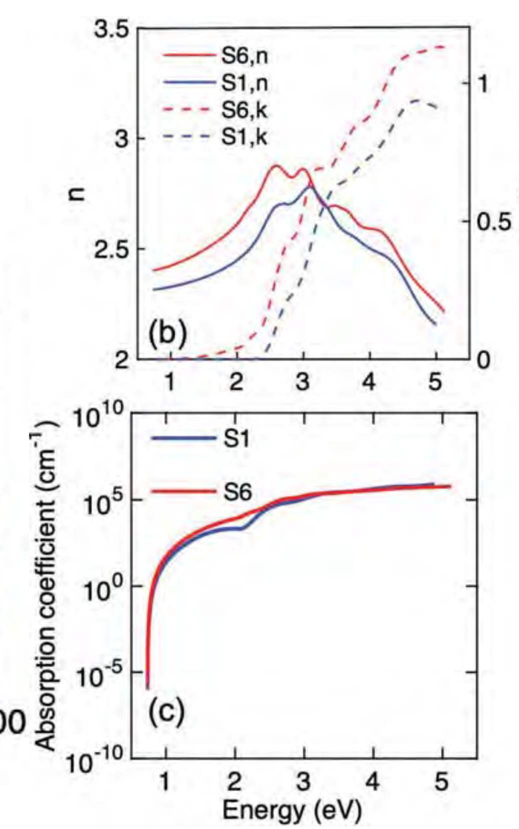


High FoM (769) on Si substrate

T-D

B-U





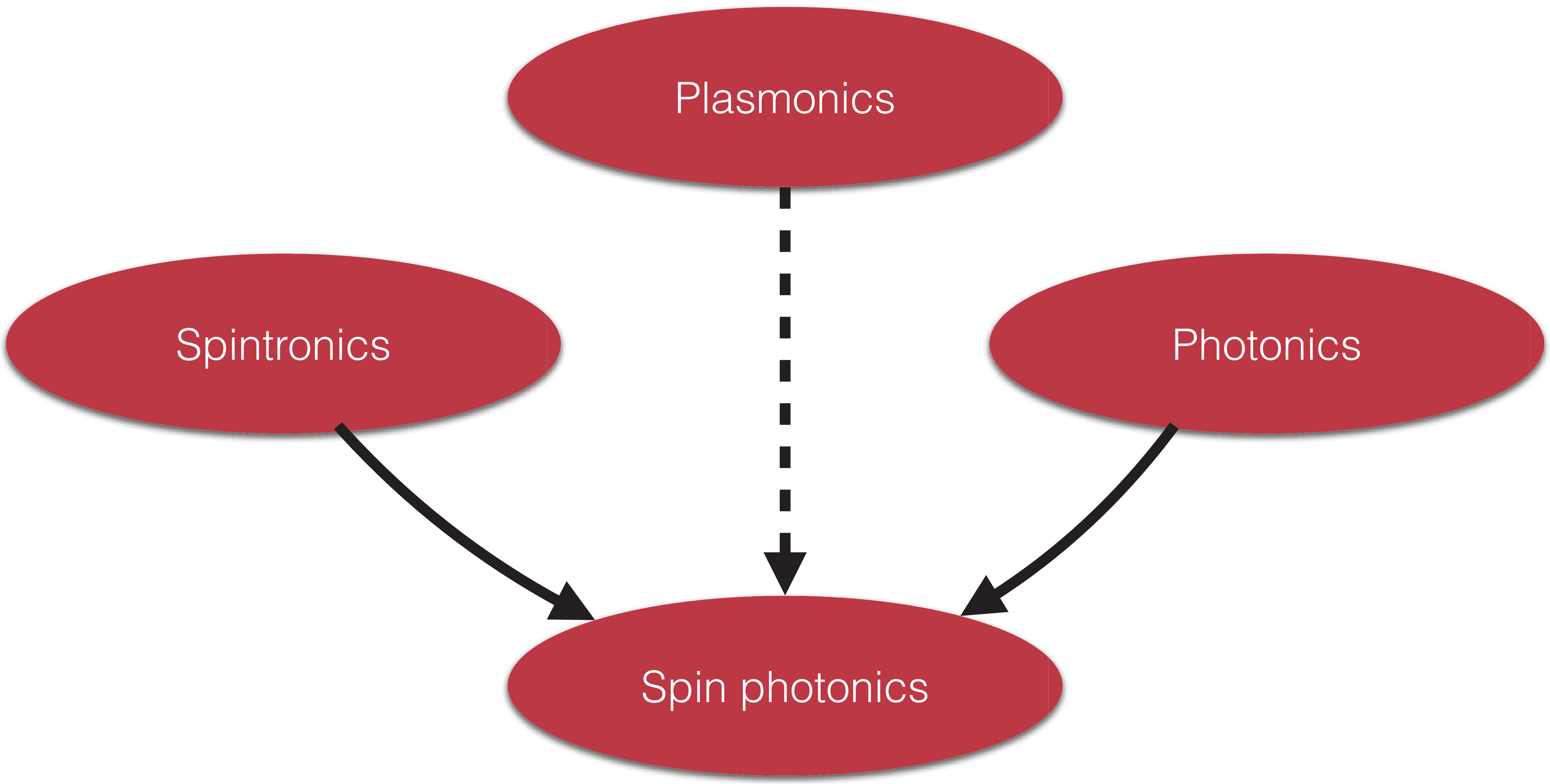
T. Fakhrul, MV, et al., Adv. Opt. Mat., 1900056 (2019)

Magneto-optics of the future

Vision of the future magneto-optics

Still advanced experimental tool

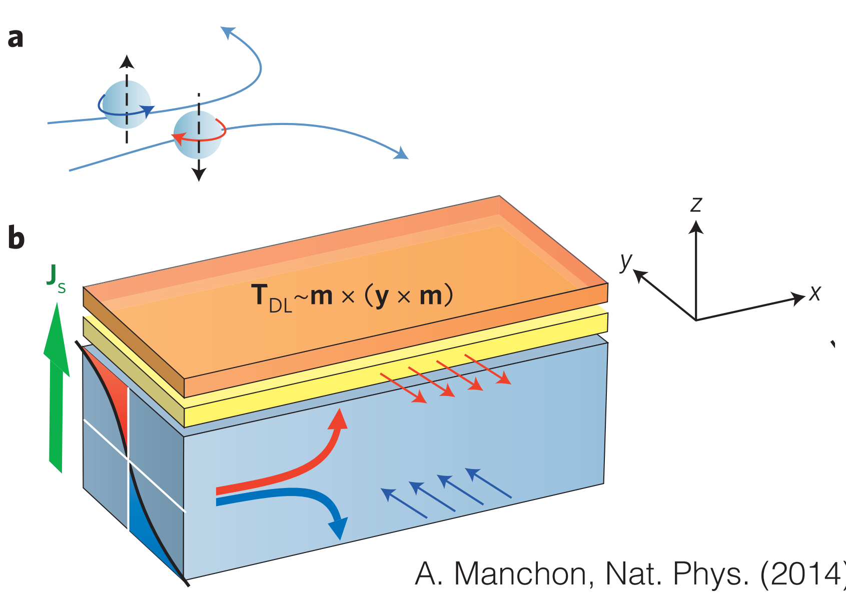
Magneto-optics of the future



Magneto-optics of the future

Spintronics approaches to control magnetization

- Strain induced
- Ionic migration
- Spin-transfer torque
- Spin-orbit torque

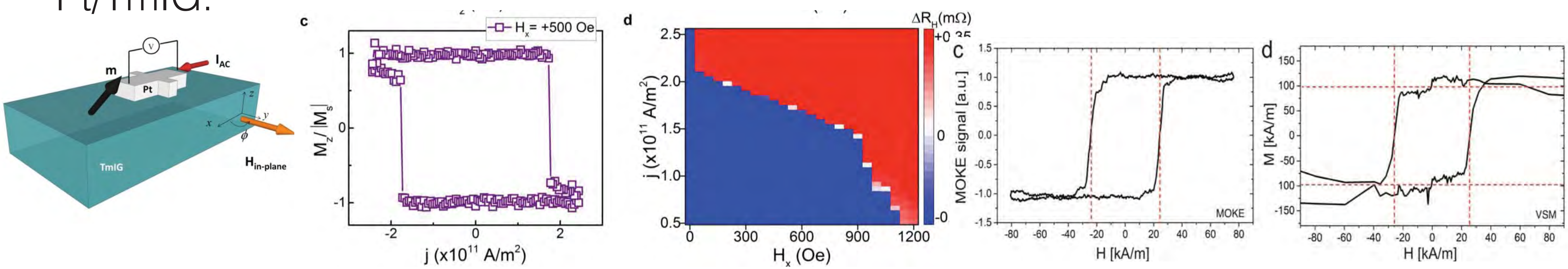


A. Manchon, Nat. Phys. (2014)

Magneto-optics of the future

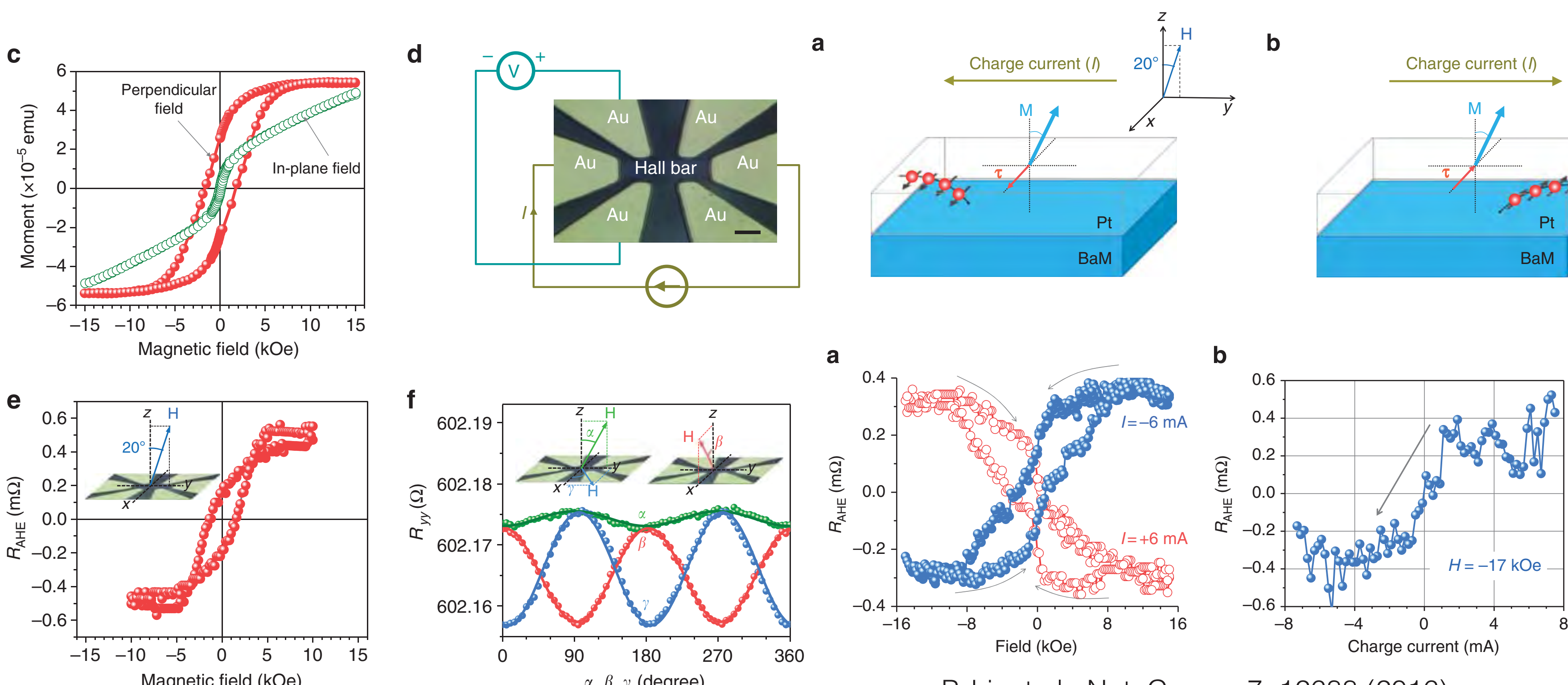
Spin orbit torque switching of FIM insulators:

Pt/TmIG:



C. Avci, et al., Nat. Materials 16, 309 (2017)

Pt/BaM:



P. Li, et al., Nat. Comm. 7, 12688 (2016)

Transparent materials
Good MO response
Fast and low energy switching

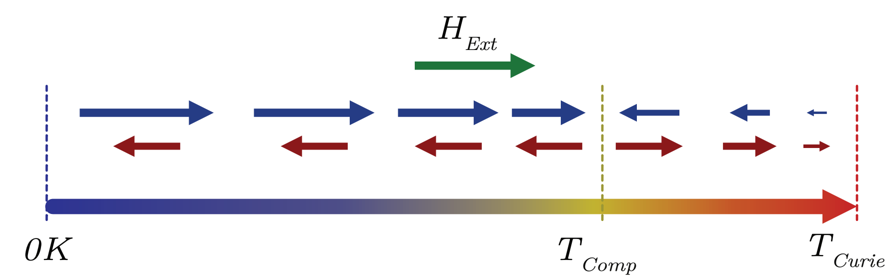
Novel generation of integrated modulators and MO-SLM

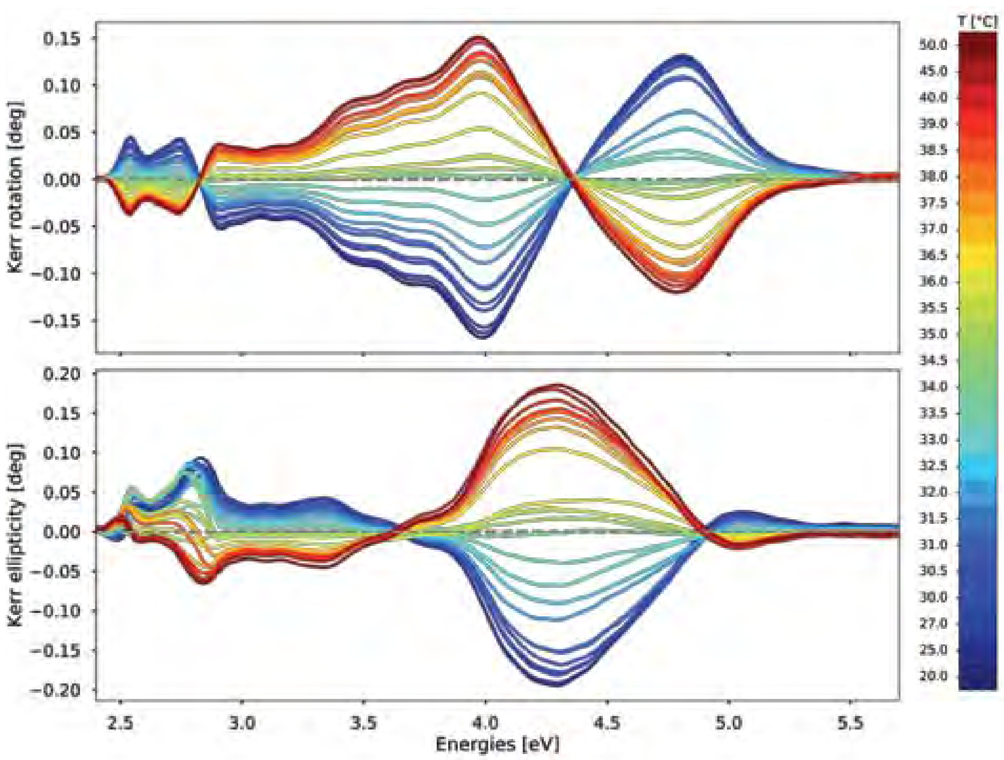
Antiferromagnetic materials

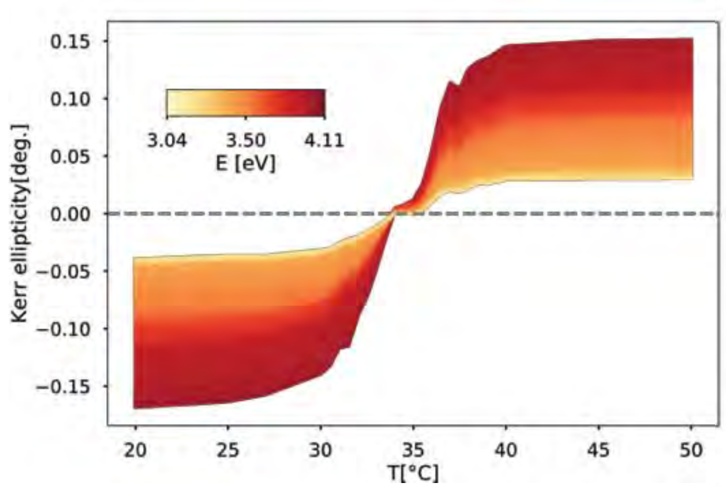
Magneto-optics of the future

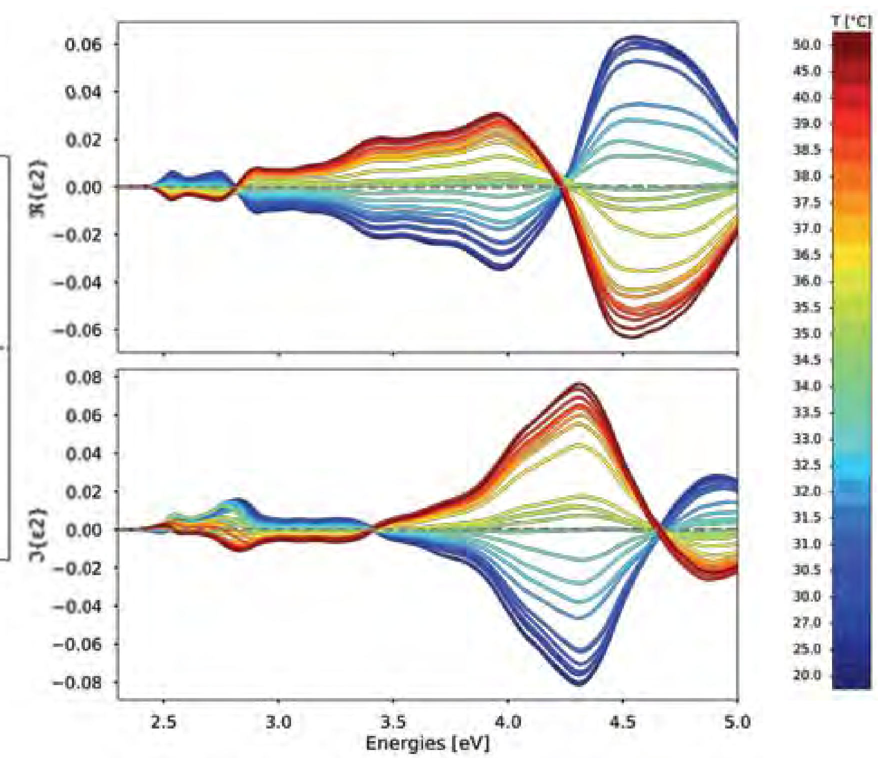
PLD deposited TBIG garnets on GGG: thicknesses ~ 15 nm

Compensation temperature above RT









L. Beran, MV, et al., submitted

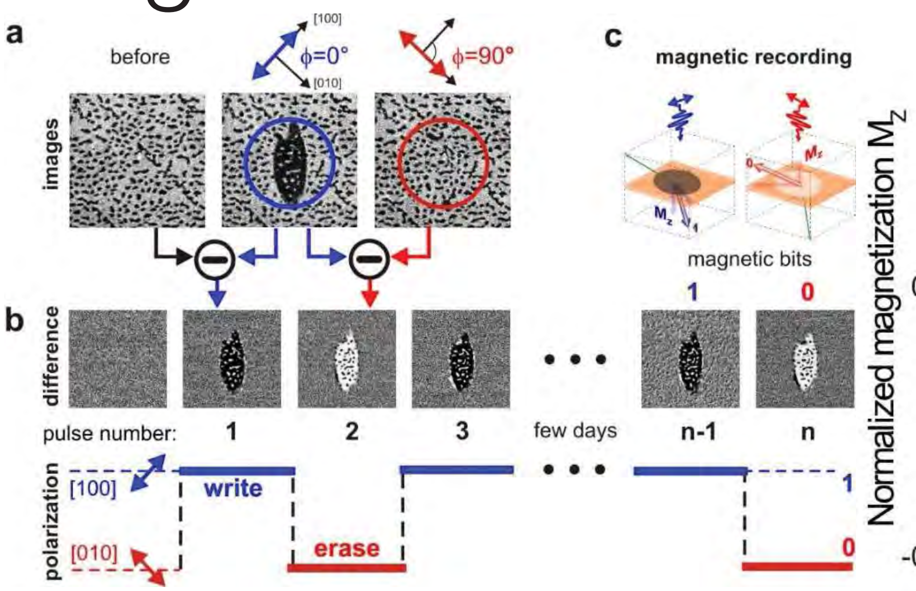
Large magneto-optical effect even for 15 nm films

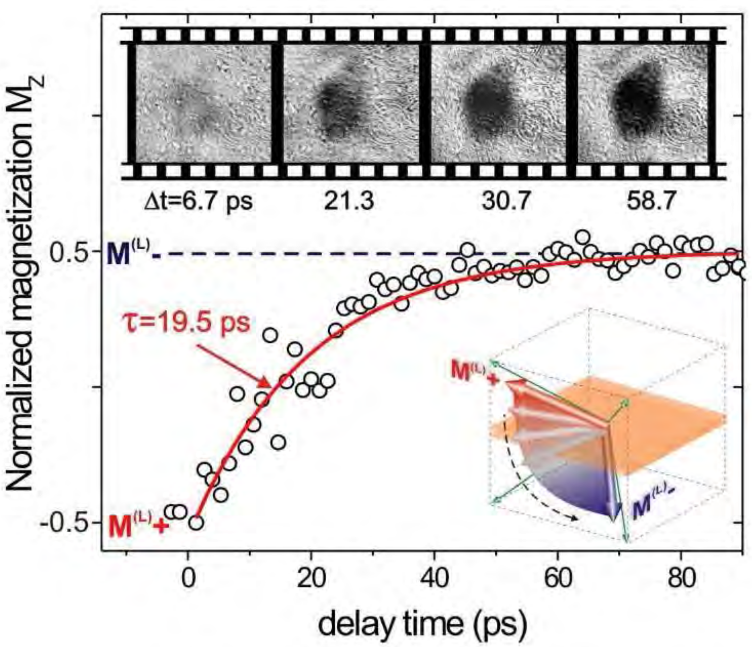
The sign change of Kerr effect - crossing the compensation temperature

Suitable for MO-SLM

Magneto-optics of the future

Magnetization switching by polarized light:





A. Stupakiewicz, et al., Nature 542, 71 (2017)

LETTER

doi:10.1038/nature20807

Ultrafast nonthermal photo-magnetic recording in a transparent medium

A. Stupakiewicz[1], K. Szerenos[1], D. Afanasiev[2], A. Kirilyuk[2] & A. V. Kimel[2]

Fastest ever write-read event (<20 ps)!!!

Low heat - 20x20x10 nm³ - 22 aJ!!!

Plasmonics:

PRL 102, 256801 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009

Cross Resonant Optical Antenna

P. Biagioni,[1,*] J. S. Huang,[1] L. Duò,[2] M. Finazzi,[2] and B. Hecht[1,†]
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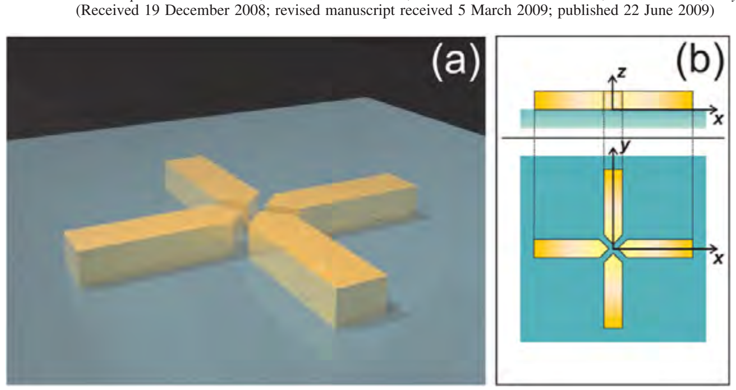
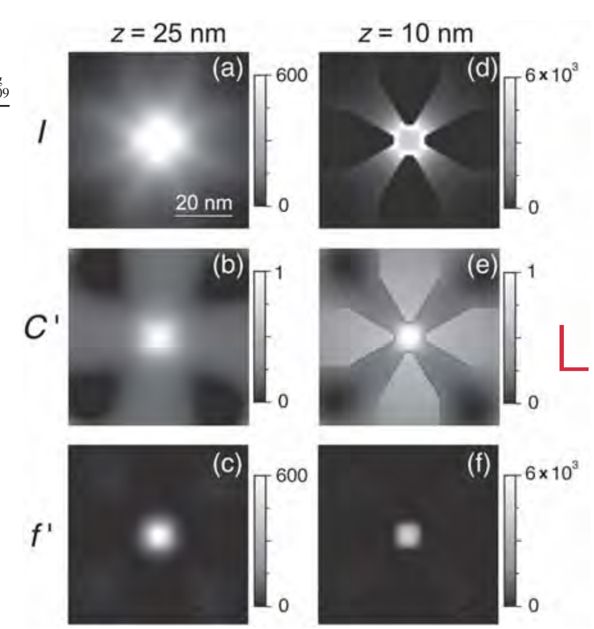
(Received 19 December 2008; revised manuscript received 5 March 2009; published 22 June 2009)





Local confinement and enhancement of polarized light via surface plasmons

Light switching by light via magnetic material

Route to optical transistor???

Conclusions

- Magneto-optical phenomena play an important role in physics.
- Magneto-optical phenomena can be used as experimental probes or for applications.
- Novel magneto-optical devices can help to overcome the physical limits of current electronics
- Design of novel magneto-optical devices is possible using macroscopic theoretical models.
- Combination of spintronic concepts and magneto-optical phenomena can open the way to so-called spin-photonics

Prague magneto-optical group

www.morp.cz

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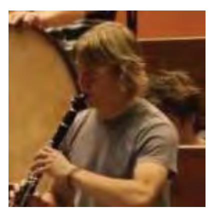

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K. Tikuisis

D. Kral

MSc. Students

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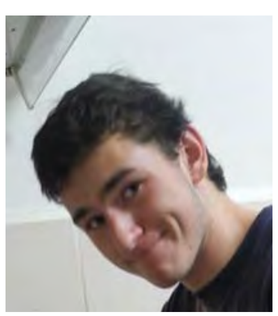
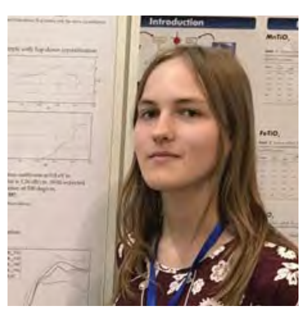
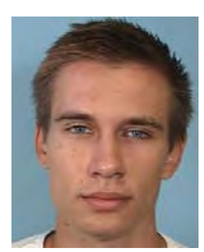


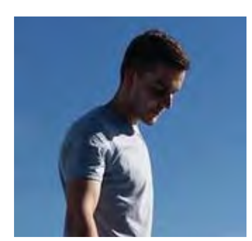
J. Strelecek



S. Tazlaru

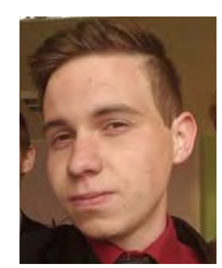


O. Novak



M. Vancik

J. Setina



L. Nowak

Thank you for your attention

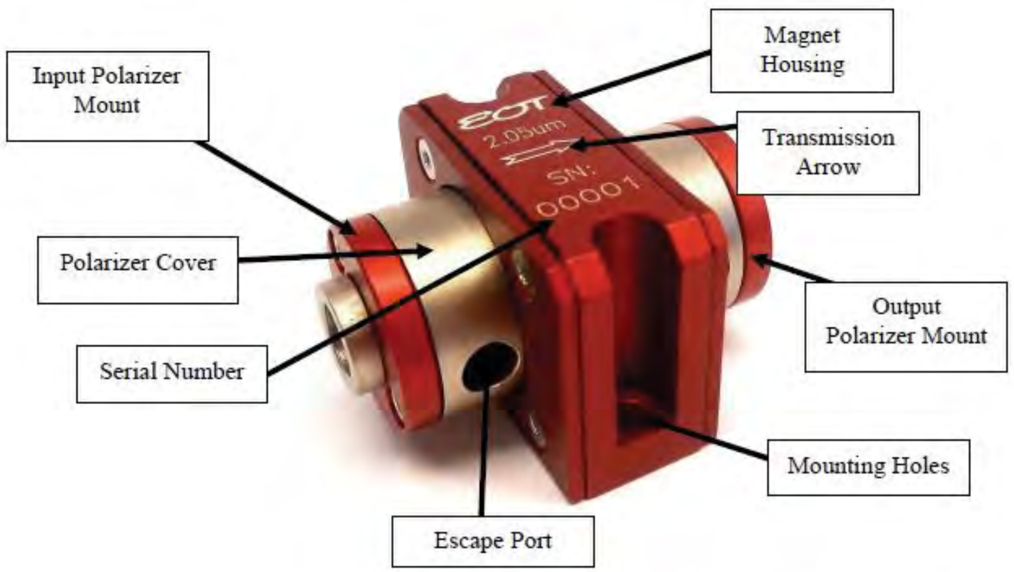
Current magneto-optical applications

Are there some magneto-optical devices on the market right now?

YES!

Current magneto-optical applications

Magneto-optical isolator:



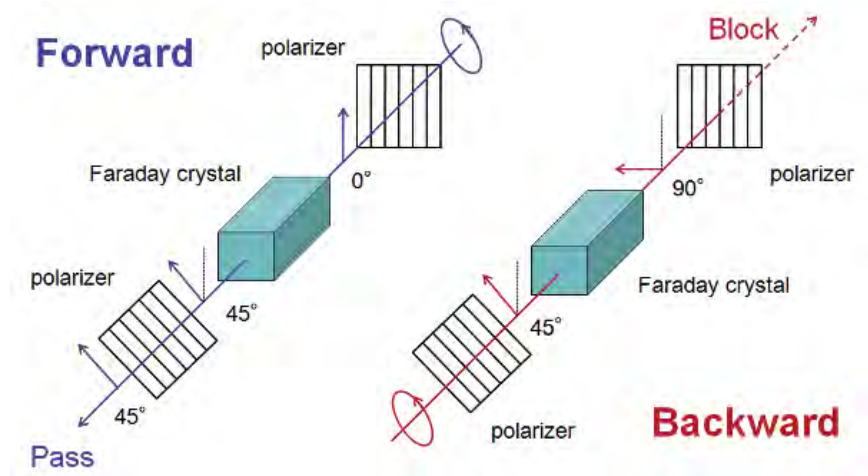
www.eotech.com

www.roshelop.co.il

Onsager principle:

simultaneous reversal of time and magnetic field

$$\varepsilon_{ij}(\boldsymbol{M}) = \varepsilon_{ji}(-\boldsymbol{M})$$

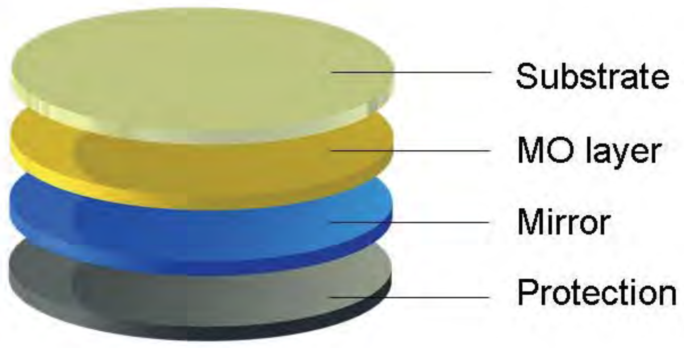


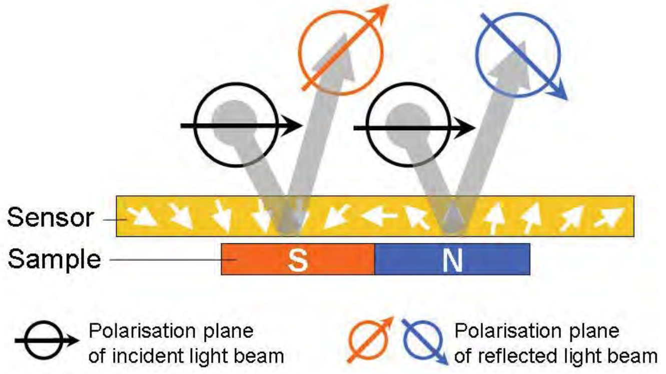
Optical one way

Ferrimagnetic garnets with high Faraday rotation

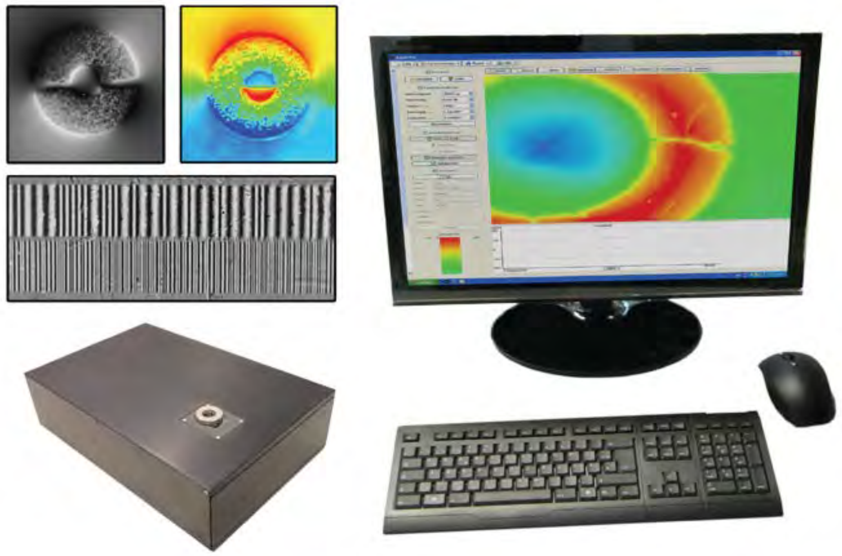
Current magneto-optical applications

Magneto-optical imaging systems:





banknote serial number



Ferrimagnetic garnets as magneto-optical indicators

LPE growth - thick layers

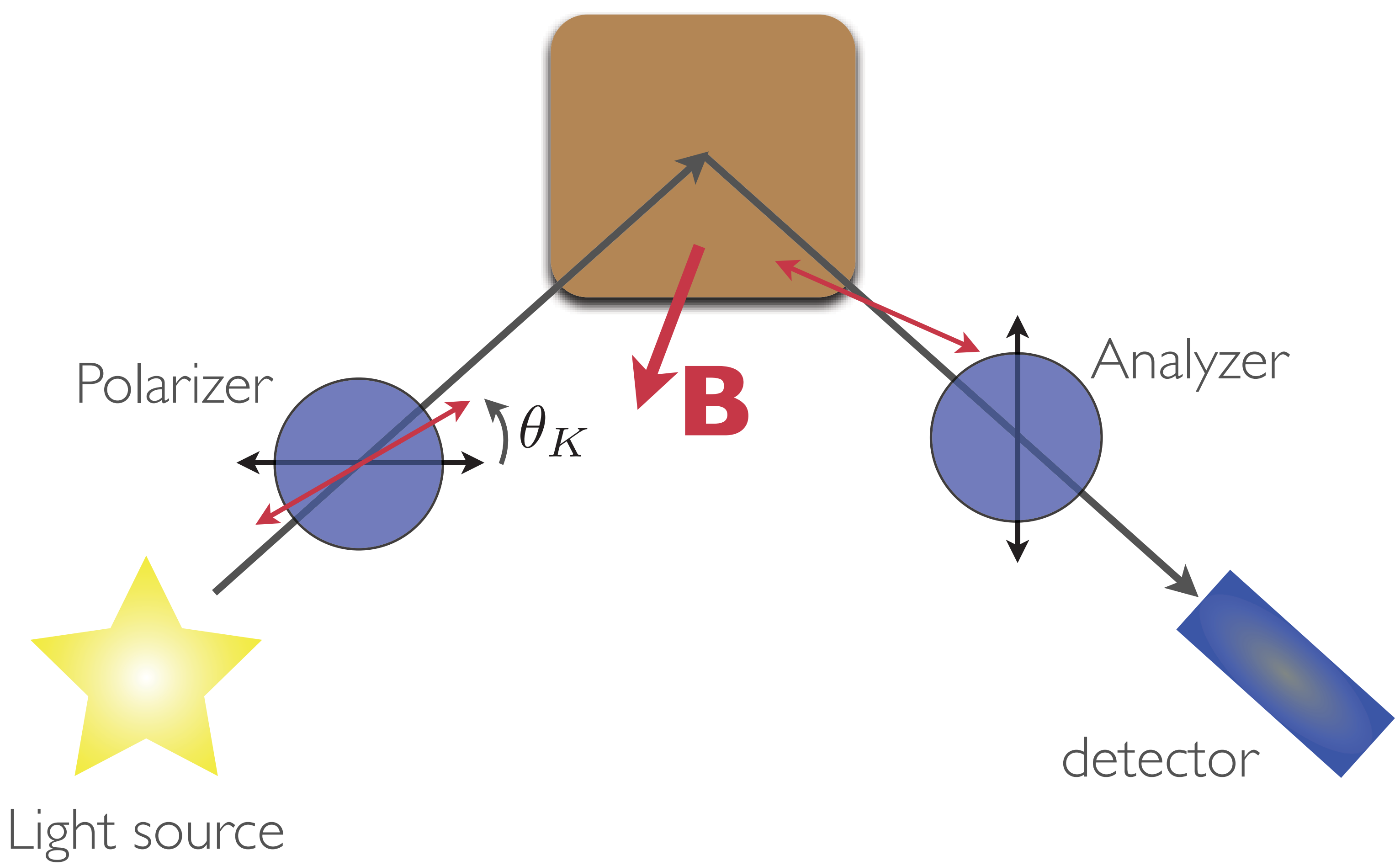
Visualisation of magnetic structures and determination of the flux density

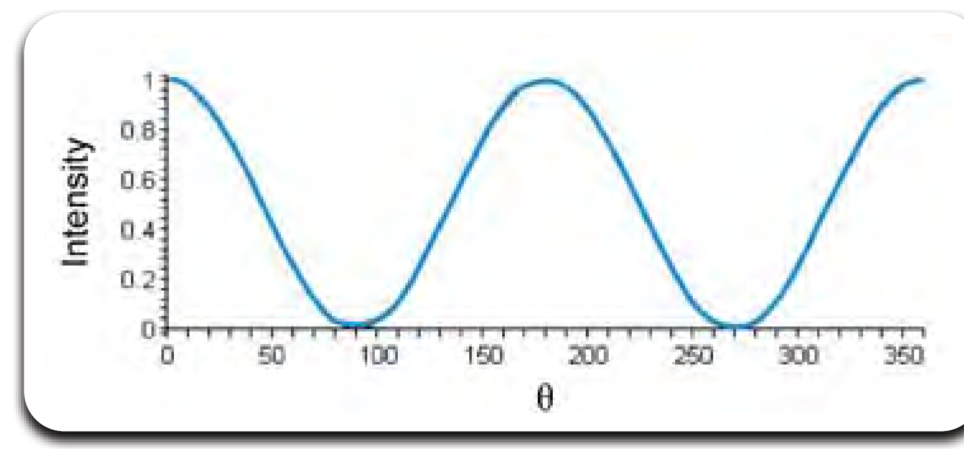
How to measure magneto-optical effects?

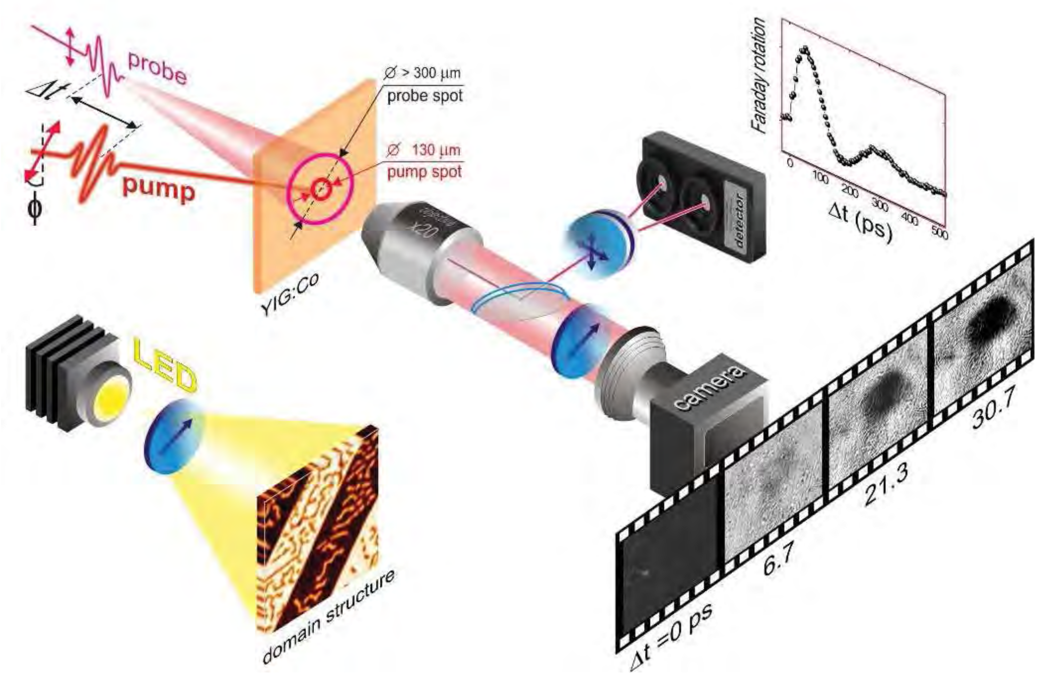
Very small angles of polarization rotation (mdeg)!

Crossed polarisers:

Malus' law: $I = I_0 \cos^2 \theta_i$







A. Stupakiewicz, et al., arXiv:1609.05223 (2016)

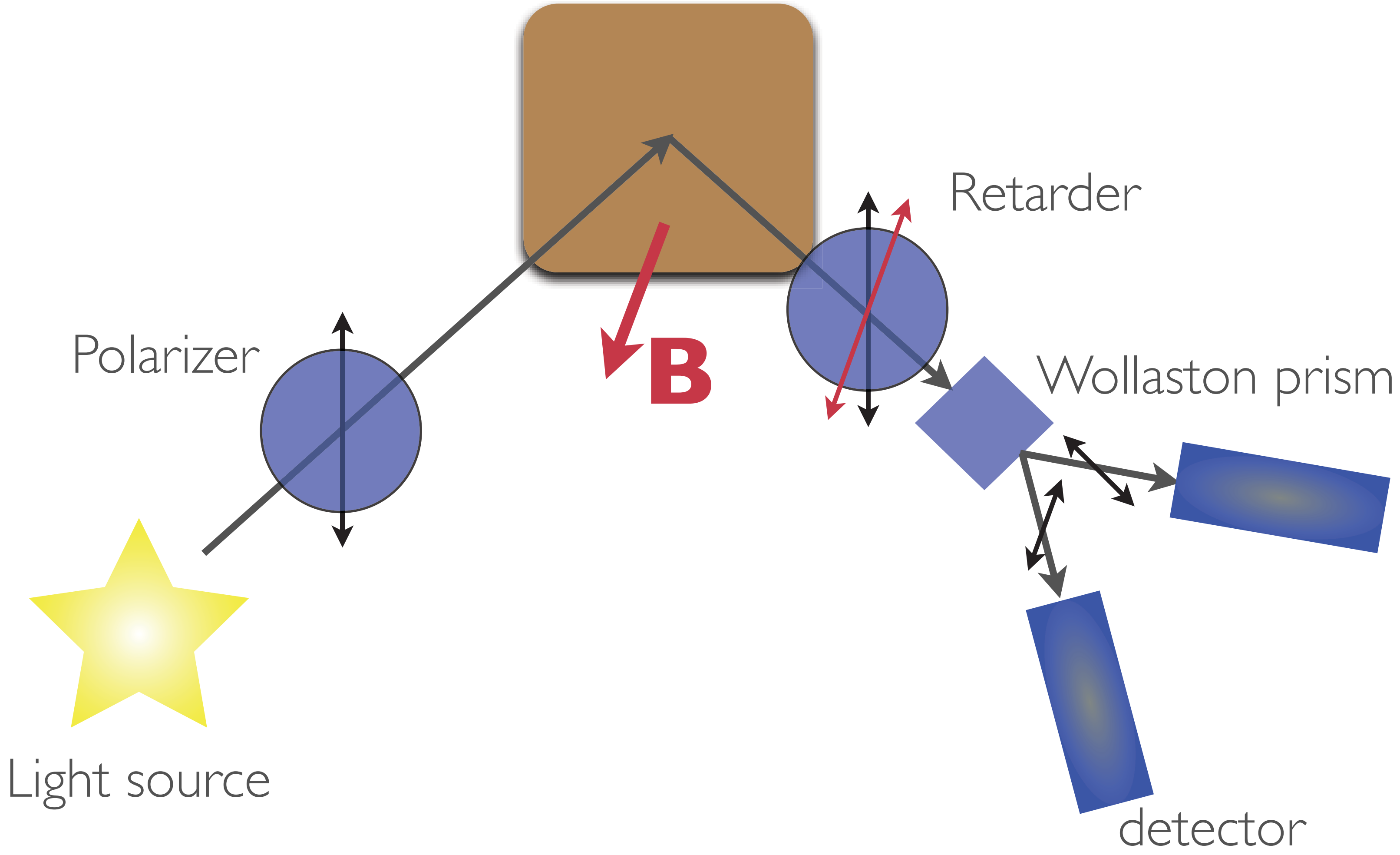
Used in magneto-optical imaging

Image processing necessary

How to measure magneto-optical effects?

Very small angles of polarization rotation (mdeg)!

Differential method:



fast measurements

Additional modulation increases signal to noise ratio

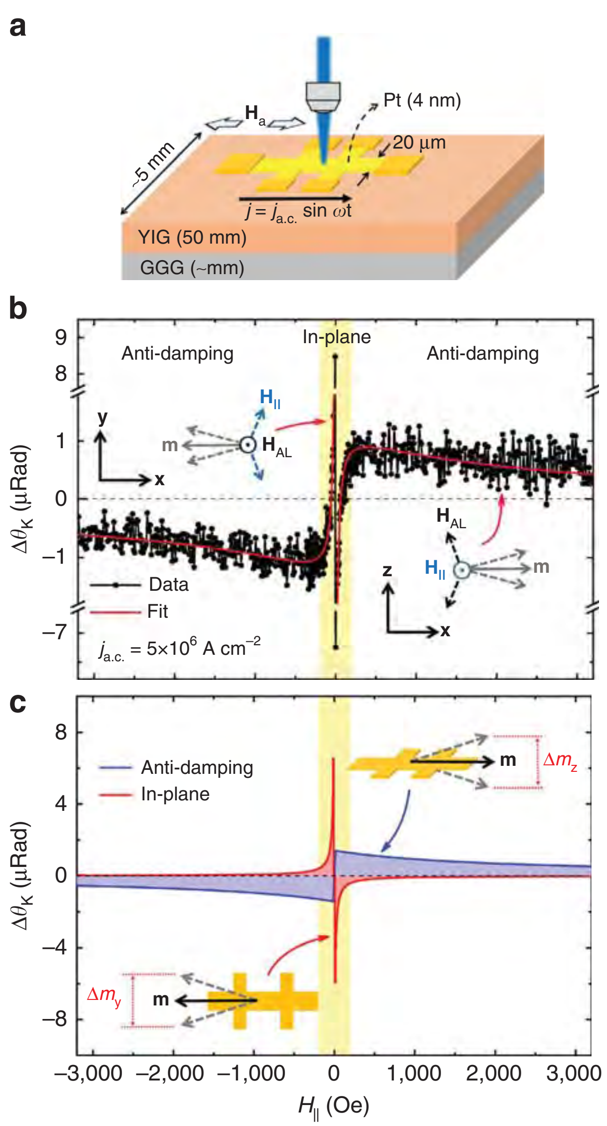
$$\Delta I = I_1 - I_2 = I_0 |r_{ss}|^2 \theta_{Ks}$$

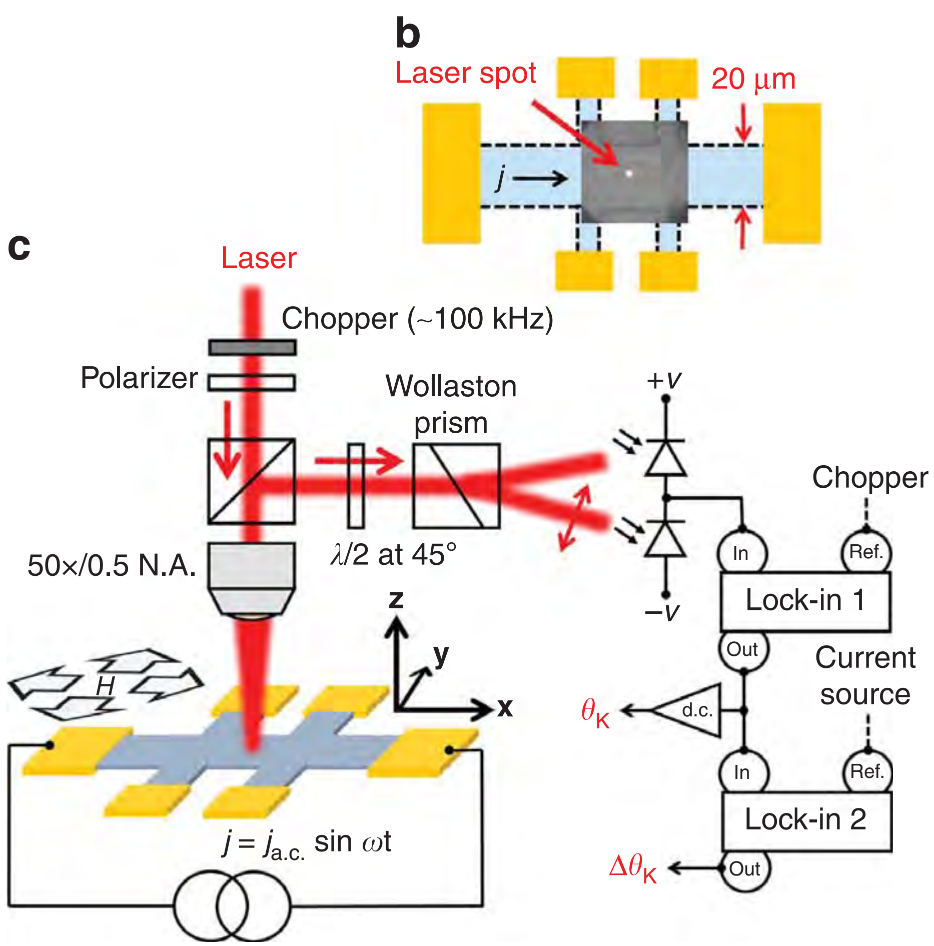
Used in magneto-optical magnetometry and time resolved measurements

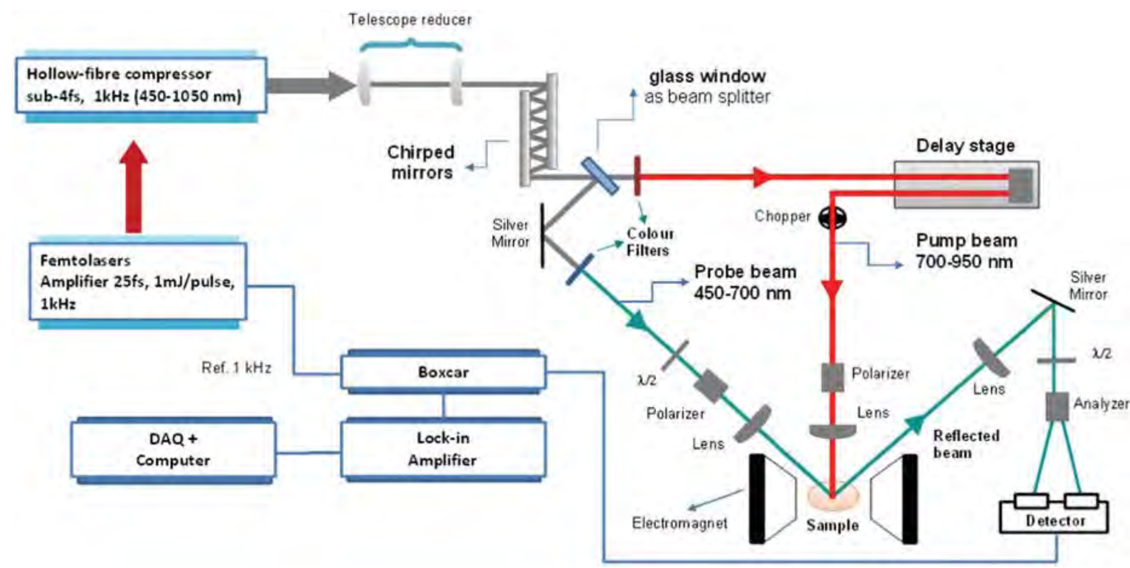
How to measure magneto-optical effects?

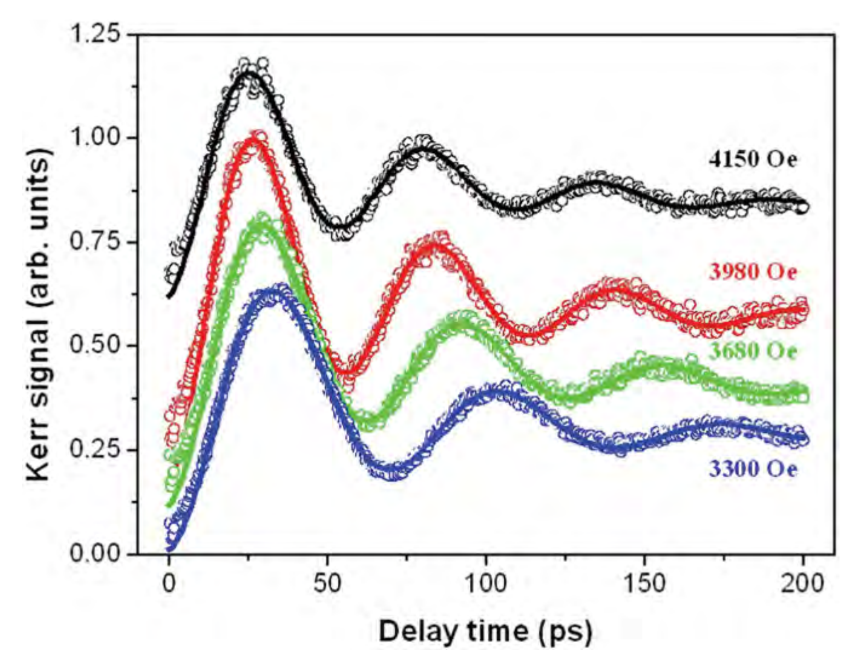
Very small angles of polarization rotation (mdeg)!

Differential method:







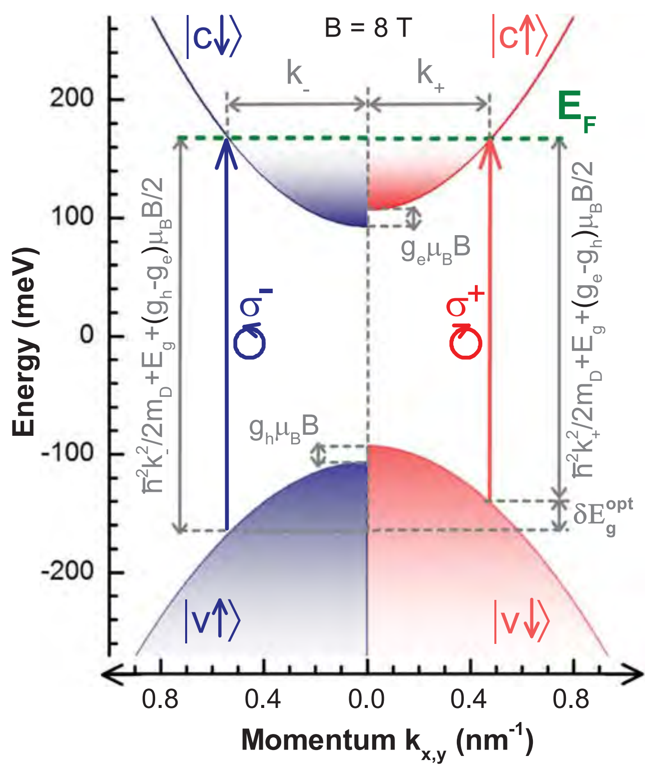


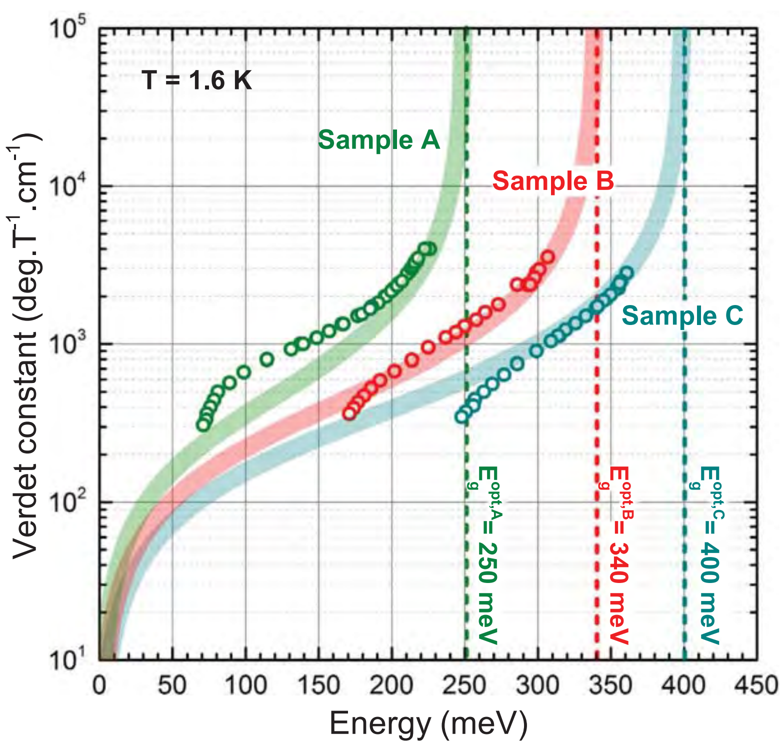
M. Montanzeri, et al., Nat. Comm. 6, 8958 (2015)

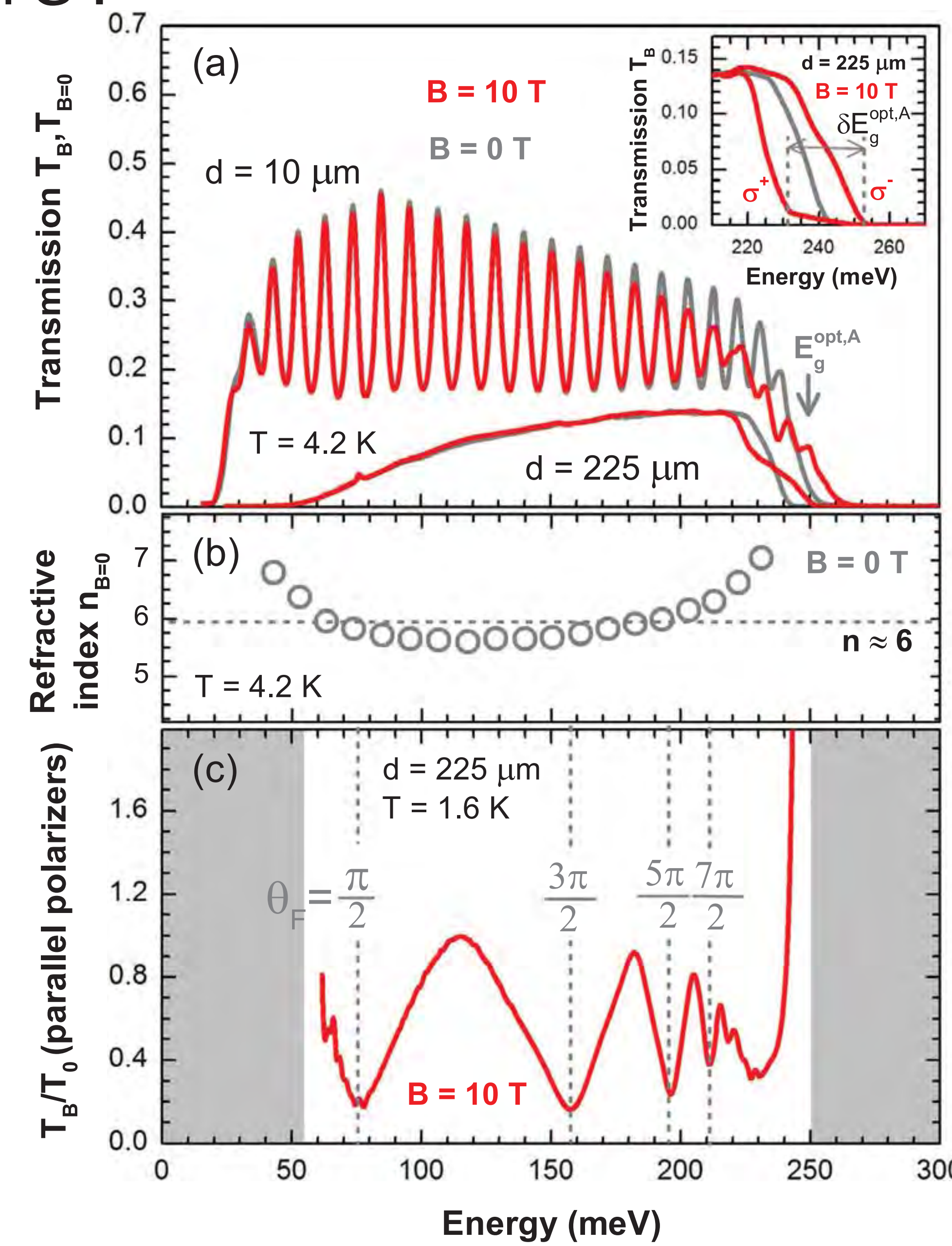
C.S. Goncalves, Sci. Rep. 6, 22872 (2016)

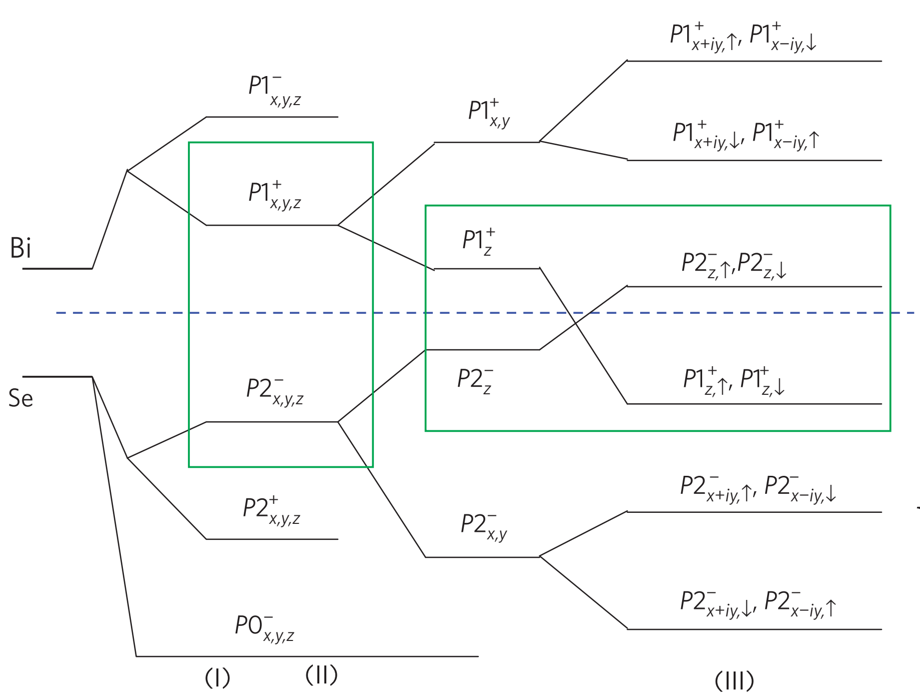
Magneto-optical applications of tomorrow

Another materials: Topological insulators?









Bi_2Se_3:
direct semiconductor,
almost parabolic bands,
large g-factor

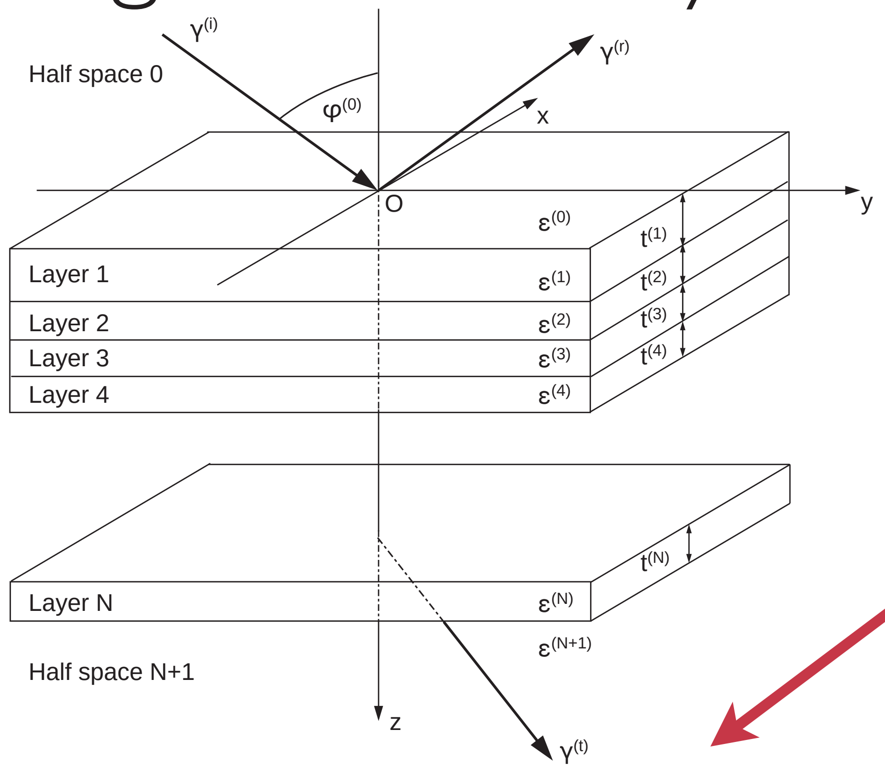
$$V(\omega) = v_D \frac{8e\alpha}{\pi n} \frac{\sqrt{E_F E_g}}{E_g^{opt}} \frac{\hbar\omega}{\left(E_g^{opt}\right)^2 - \hbar^2\omega^2}$$

Strong Faraday rotation

L. Ohnoutek, MV, et al., Sci. Reports 6, 19087 (2016)

Theory of magneto-optical effects

Magnetic multilayers:



Optical properties of magnetic materials are described by the permittivity tensor

Polar Kerr effect:

$$\boldsymbol{\varepsilon} \approx \begin{bmatrix} \varepsilon_1 & j\varepsilon_2 & 0 \\ -j\varepsilon_2 & \varepsilon_1 & 0 \\ 0 & 0 & \varepsilon_1 \end{bmatrix}$$

Wave equation:

$$\nabla \times (\nabla \times \boldsymbol{E}) = -c^{-2}\boldsymbol{\varepsilon}\frac{\partial^2 \boldsymbol{E}}{\partial t^2}$$

Solution:

$$\boldsymbol{E} = \boldsymbol{E_0} \exp[j(\omega t - \boldsymbol{\gamma} \cdot \boldsymbol{r})]$$

$$\boldsymbol{\gamma} = \frac{\omega}{c}(N_x \hat{\boldsymbol{x}} + N_y \hat{\boldsymbol{y}} + N_z \hat{\boldsymbol{z}})$$

Four eigenmodes:

$$\boldsymbol{E} = \sum_{j=1}^{4} E_{0j}\boldsymbol{e}_j \exp\{j\omega t - j\frac{\omega}{c}[N_y y + N_{zj} z]\}$$

Continuity requirements:

$$\sum_{j=1}^{4} E_{0j}^{(n-1)}\boldsymbol{e}_j^{(n-1)} \cdot \hat{\boldsymbol{x}} = \sum_{j=1}^{4} E_{0j}^{(n)}\boldsymbol{e}_j^{(n)} \cdot \hat{\boldsymbol{x}} \exp\left(j\frac{\omega}{c}N_{zj}^{(n)}t^{(n)}\right)$$

$$\sum_{j=1}^{4} E_{0j}^{(n-1)}\boldsymbol{e}_j^{(n-1)} \cdot \hat{\boldsymbol{y}} = \sum_{j=1}^{4} E_{0j}^{(n)}\boldsymbol{e}_j^{(n)} \cdot \hat{\boldsymbol{y}} \exp\left(j\frac{\omega}{c}N_{zj}^{(n)}t^{(n)}\right)$$

$$\sum_{j=1}^{4} E_{0j}^{(n-1)}\boldsymbol{b}_j^{(n-1)} \cdot \hat{\boldsymbol{x}} = \sum_{j=1}^{4} E_{0j}^{(n)}\boldsymbol{b}_j^{(n)} \cdot \hat{\boldsymbol{x}} \exp\left(j\frac{\omega}{c}N_{zj}^{(n)}t^{(n)}\right)$$

$$\sum_{j=1}^{4} E_{0j}^{(n-1)}\boldsymbol{b}_j^{(n-1)} \cdot \hat{\boldsymbol{y}} = \sum_{j=1}^{4} E_{0j}^{(n)}\boldsymbol{b}_j^{(n)} \cdot \hat{\boldsymbol{y}} \exp\left(j\frac{\omega}{c}N_{zj}^{(n)}t^{(n)}\right)$$

Matrix form:

$$\boldsymbol{D}^{(n-1)}\boldsymbol{E}_0^{(n-1)} = \boldsymbol{D}^{(n)}\boldsymbol{P}^{(n)}\boldsymbol{E}_0^{(n)}$$

$$\begin{aligned} \boldsymbol{E}_0^{(0)}(z_0) &= (\boldsymbol{D}^{(0)})^{-1}\boldsymbol{D}^{(1)}\boldsymbol{P}^{(1)}(\boldsymbol{D}^{(1)})^{-1}\boldsymbol{D}^{(2)}\boldsymbol{P}^{(2)} \cdots \\ &\quad \cdots (\boldsymbol{D}^{(N-1)})^{-1}\boldsymbol{D}^{(N)}\boldsymbol{P}^{(N)}(\boldsymbol{D}^{(N)})^{-1}\boldsymbol{D}^{(N+1)}\boldsymbol{E}_0^{(N+1)}(z_N) \\ &= \left[\prod_{n=1}^{N+1}\boldsymbol{T}^{n-1,n}\right]\boldsymbol{E}_0^{N+1}(z_N) = \boldsymbol{M}\boldsymbol{E}_0^{(N+1)}(z_N). \end{aligned}$$

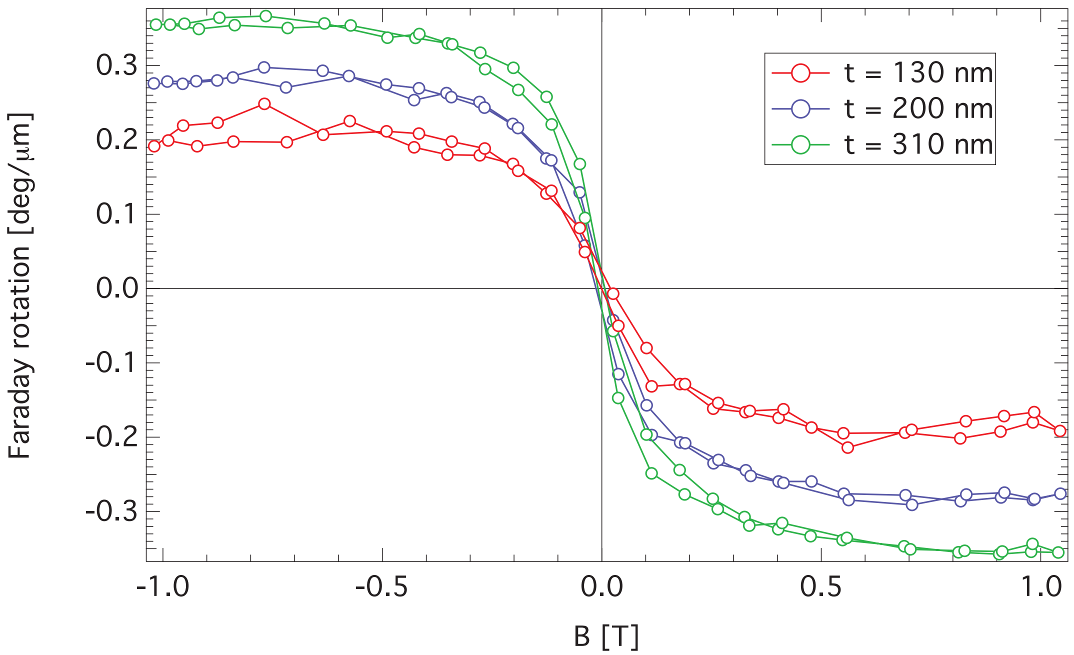
$$J_R = \begin{bmatrix} r_{ss} & r_{ps} \\ r_{sp} & r_{pp} \end{bmatrix}$$

$$\phi_{Ks} = \theta_{Ks} + j\epsilon_{Ks} = \frac{r_{sp}}{r_{ss}}$$

Magneto-optical applications of tomorrow

Another materials: $SrGa_{0.7}Co_{0.3}O_3$ with Co nanoparticles

MV, et al., JAP 115, 17A746 (2015)



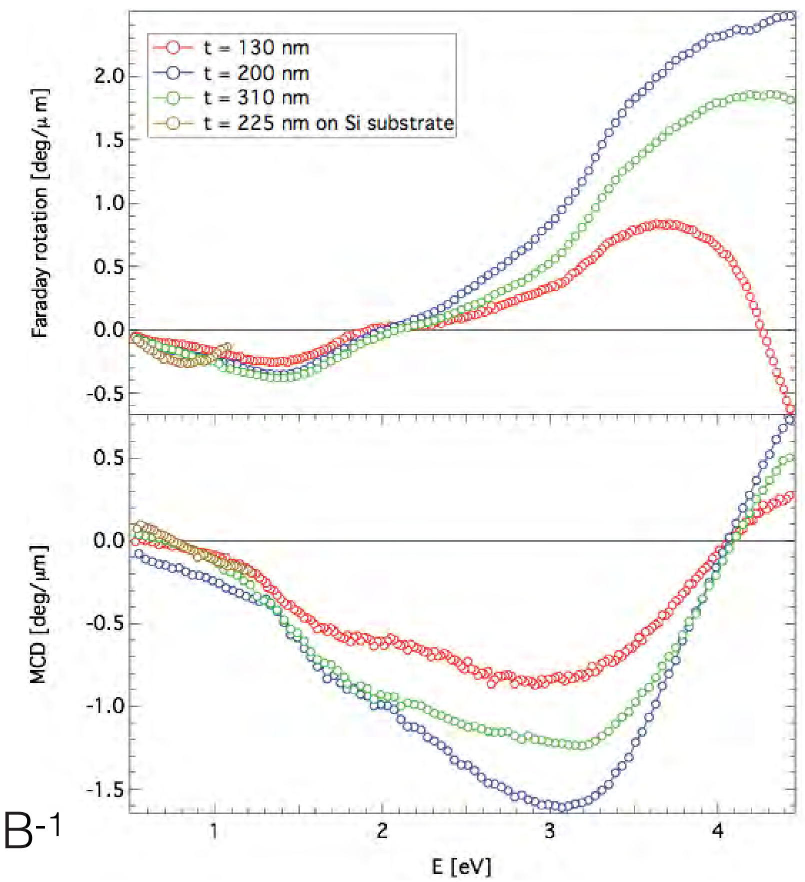
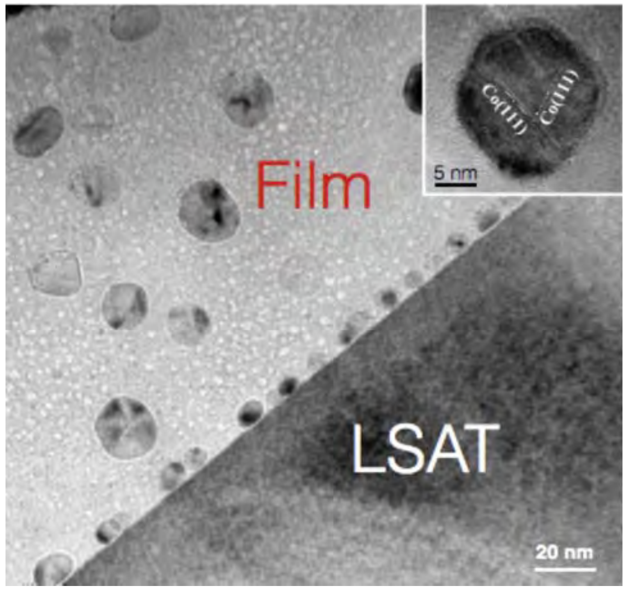
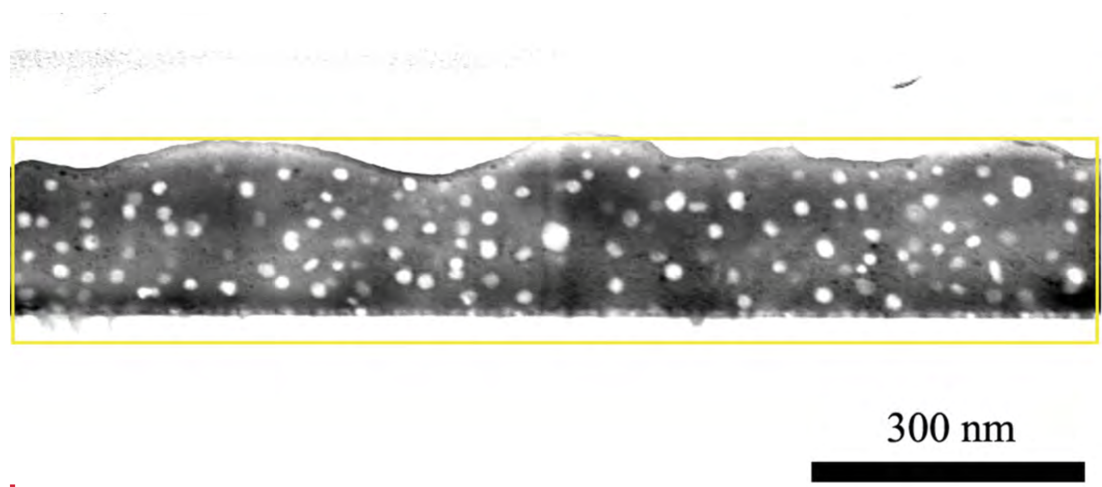
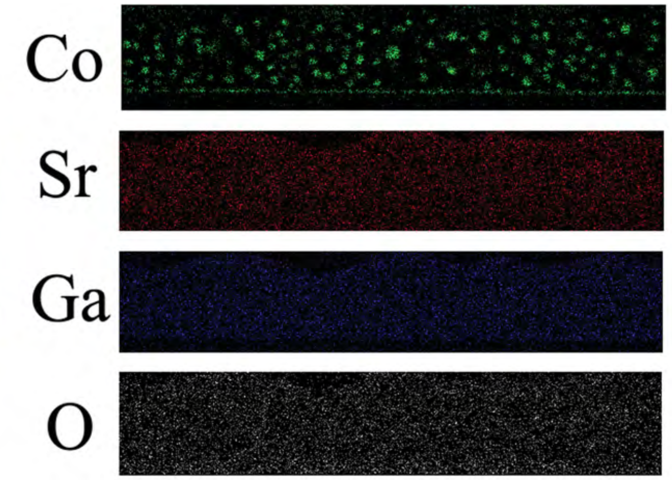


Figure of merit 1.09 deg dB^{-1} and 0.03 deg dB^{-1}







Compatibility with silicon

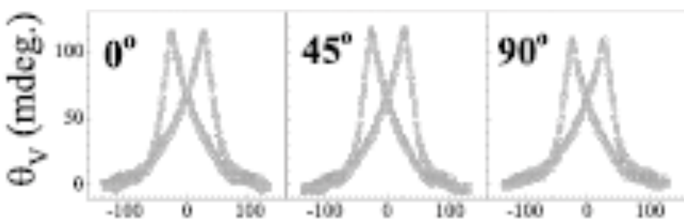
X. Sun, MV, et al., Nanotechnology 26, 115701 (2015)

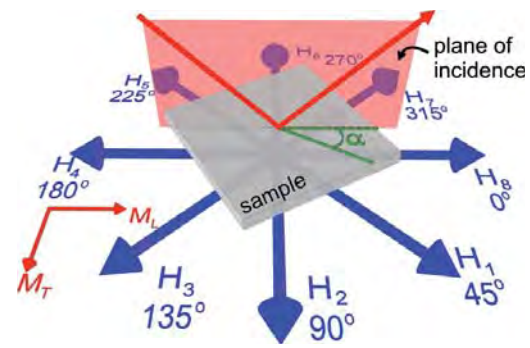
Magneto-optics of the future

Quadratic effects: A novel direction in magneto-optics

S. Trudel, *et al.*. Rev. Sci. Inst. **81**, 026105 (2010)

$$\begin{bmatrix} \varepsilon_{11}^{(2)} \\ \varepsilon_{22}^{(2)} \\ \varepsilon_{33}^{(2)} \\ \varepsilon_{23}^{(2)} \\ \varepsilon_{31}^{(2)} \\ \varepsilon_{12}^{(2)} \end{bmatrix} = \begin{bmatrix} G_{1111} & G_{1122} & G_{1133} & 2G_{1123} & 2G_{1131} & 2G_{1112} \\ G_{2211} & G_{2222} & G_{2233} & 2G_{2223} & 2G_{2231} & 2G_{2212} \\ G_{3311} & G_{3322} & G_{3333} & 2G_{3323} & 2G_{3331} & 2G_{3312} \\ G_{2311} & G_{2322} & G_{2333} & 2G_{2323} & 2G_{2331} & 2G_{2312} \\ G_{2311} & G_{2322} & G_{2333} & 2G_{2323} & 2G_{2331} & 2G_{2312} \\ G_{2311} & G_{2322} & G_{2333} & 2G_{2323} & 2G_{2331} & 2G_{2312} \end{bmatrix} \begin{bmatrix} M_1^2 \\ M_2^2 \\ M_3^2 \\ M_2M_3 \\ M_3M_1 \\ M_1M_2 \end{bmatrix}$$





$$\Phi_s = \mathcal{A} \cdot K M_L + \mathcal{B}\left[\left(-\frac{K^2}{\tilde{n}^2} + 2G_{44} + \frac{\Delta G}{2}\right) M_L M_T - \frac{1}{2}\Delta G \cos 4\,\alpha \cdot M_L M_T - \frac{1}{4}\Delta G \sin 4\,\alpha (M_L^2 - M_T^2)\right]$$

Antiferromagnets come into play

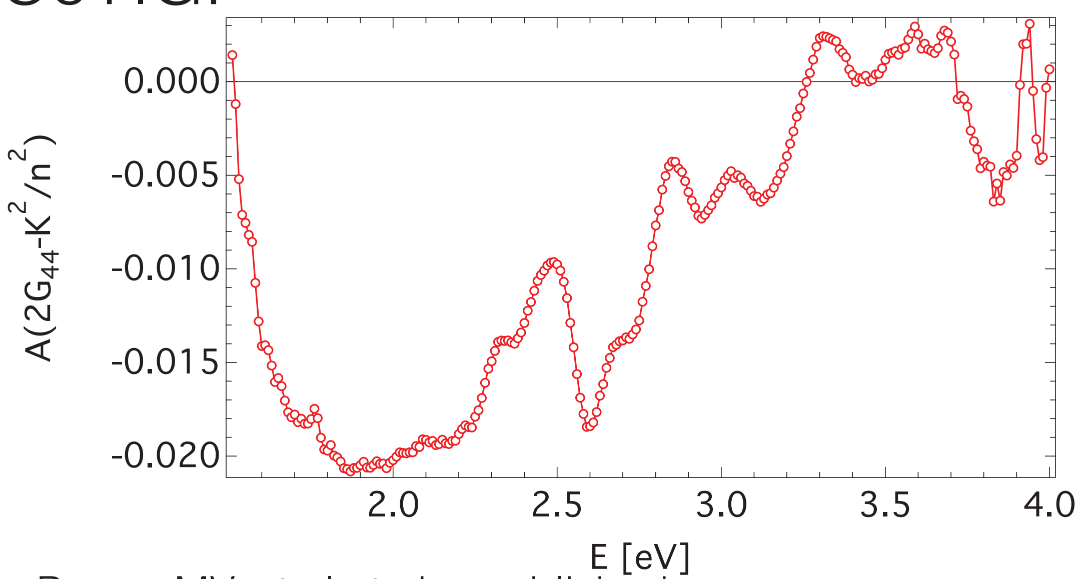
Linear polarization control (MLD)

Rotation of magnetization only by 90 degree

High quadratic MO effects in antiferromagnetic oxides (CoO, NiO)

Easy growth

CeYIG:



L. Beran, MV, et al., to be published

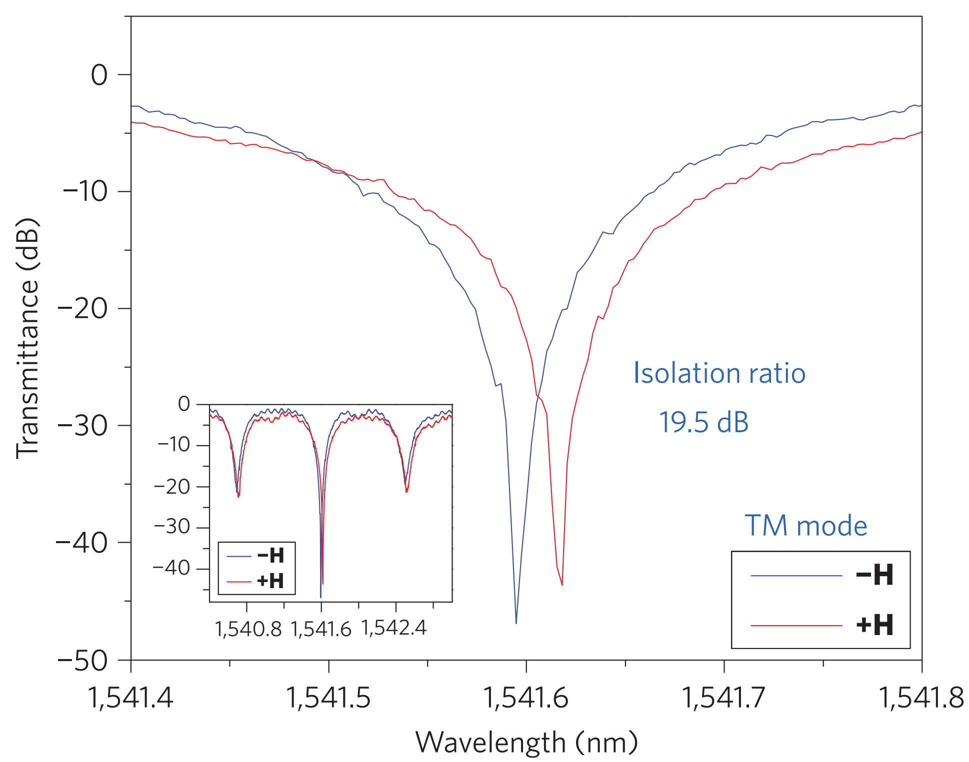
Novel generation of integrated modulators and MO-SLM

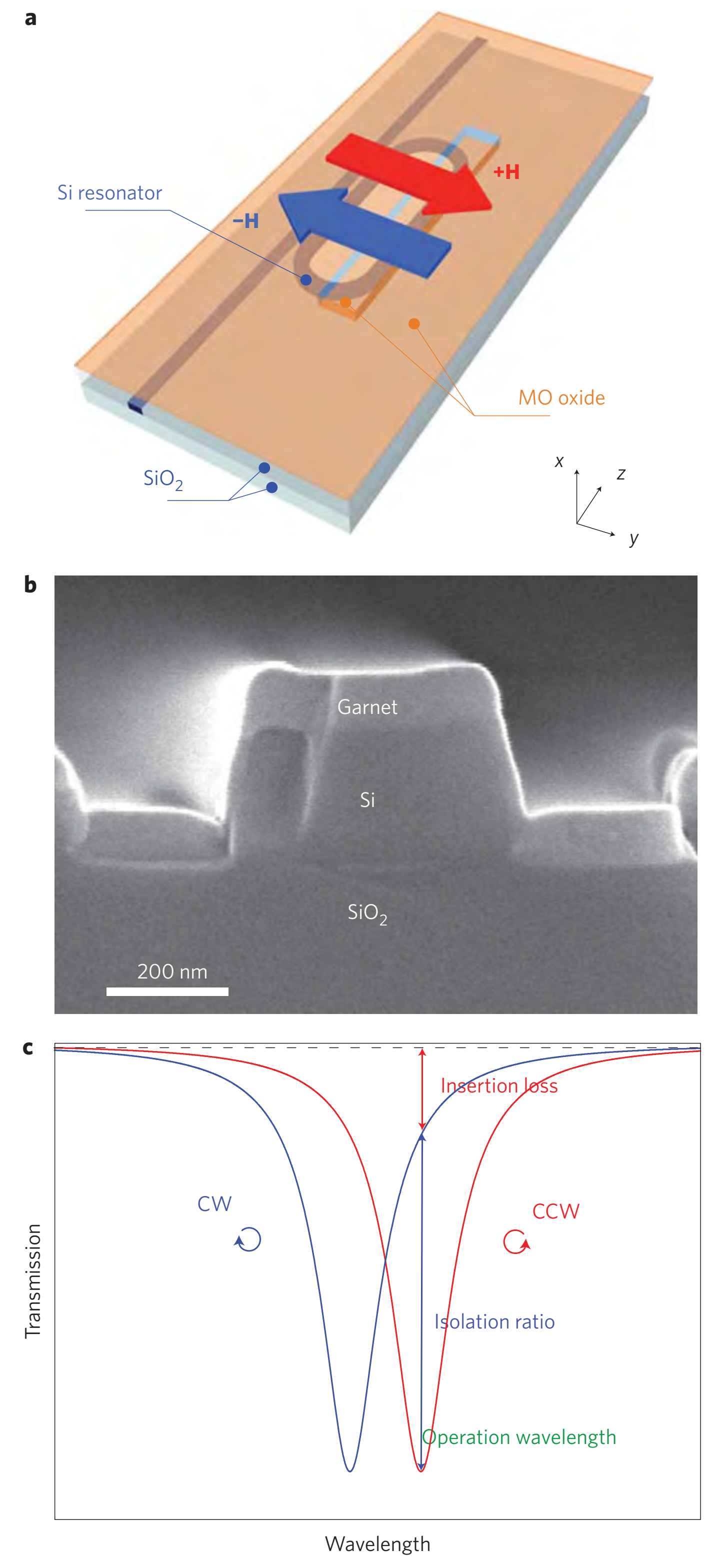
Magneto-optical applications of tomorrow

nature photonics | LETTERS
PUBLISHED ONLINE: 13 NOVEMBER 2011 | DOI: 10.1038/NPHOTON.2011.270

On-chip optical isolation in monolithically integrated non-reciprocal optical resonators

Lei Bi[1]*, Juejun Hu[2], Peng Jiang[1], Dong Hun Kim[1], Gerald F. Dionne[1], Lionel C. Kimerling[1] and C. A. Ross[1]*





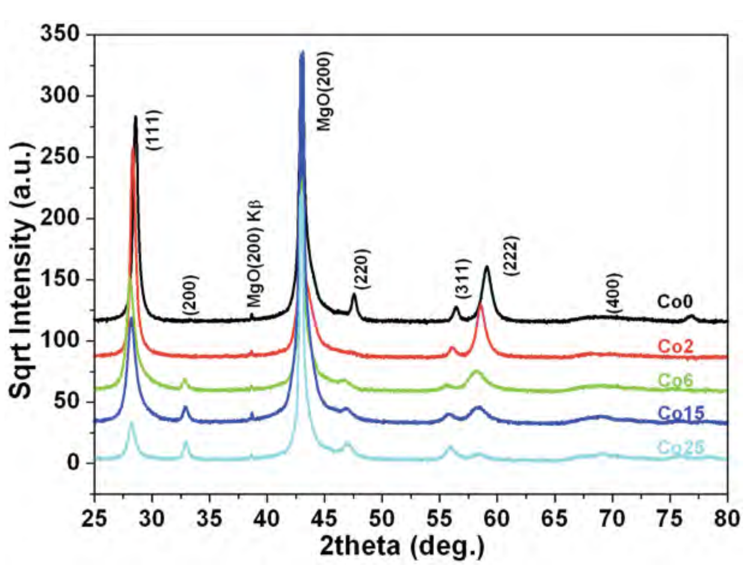
Low isolation ratio, high losses

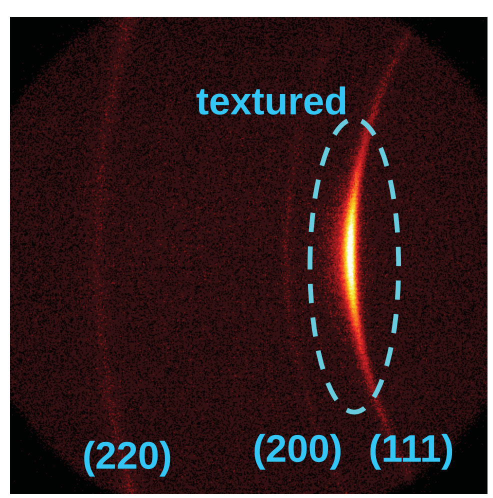
Magneto-optical applications of tomorrow

Other materials: Co doped CeO_2

MO Material and Substrate	MO Figure-of-merit (°dB^{-1})	Growth method	Optical Loss (dB·cm^{-1})	Reference
$Y_{2.82}Ce_{0.18}Fe_5O_{12}$ (no substrate, bulk crystal)	1420	Traveling solvent floating zone	0.52	44
Single crystalline epitaxial Ce:YIG on GGG substrates	31, 943	PLD	11.2, 6	This study
Single crystalline CeYIG on $Gd_3Sc_2Ga_3O_{12}$	340	Sputtering	9.7	23
$Ce_1Y_2Fe_5O_{12}$ on (111) doped-$Gd_3Ga_5O_{12}$	321	Sputtering	14	45
Polycrystalline CeYIG on YIG deposited at 550 °C on Si substrate	20	PLD	40	25
Polycrystalline CeYIG on YIG deposited at 100 °C on Si substrate	38	PLD	29	7
$Ce_1Y_2Fe_5O_{12}$ (Ce:YIG) on Silica	56	Sputtering	48	16
Ce:YIG on Si	21.8	PLD	58	5
Fe:InP	23.8	(not mentioned)	1.66	56
Fe:InGaAsP	23	(not mentioned)	4.34	57
STCo30 (20 mTorr) on STO	0.064	PLD	390.6	58
$SrTi_{0.77}Co_{0.23}O_{3-\delta}$ on (001) $LaAlO_3$	0.57	PLD	877	59
$SrTi_{0.6}Fe_{0.4}O_{3-\delta}$ on (001) $LaAlO_3$	1.11	PLD	700	60

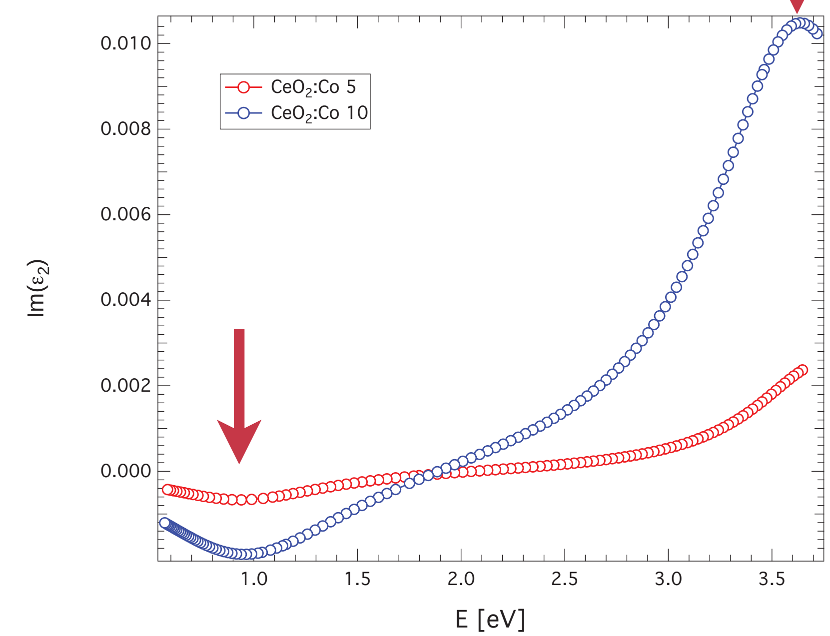
M. Onbasli, L. Beran, MV, et al., Sci. Rep. 6, 23640 (2016)

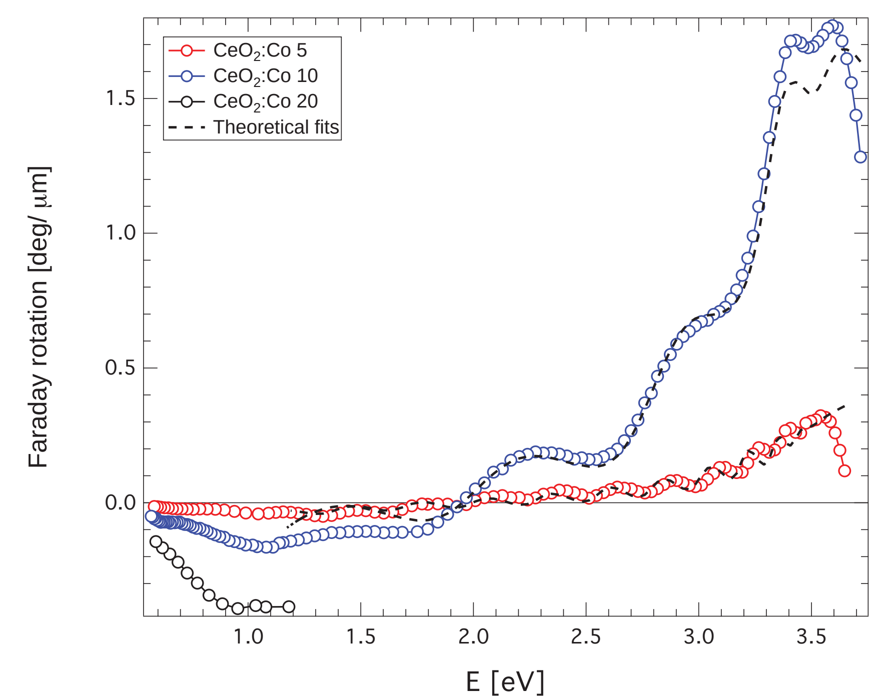




Compatibility with silicon

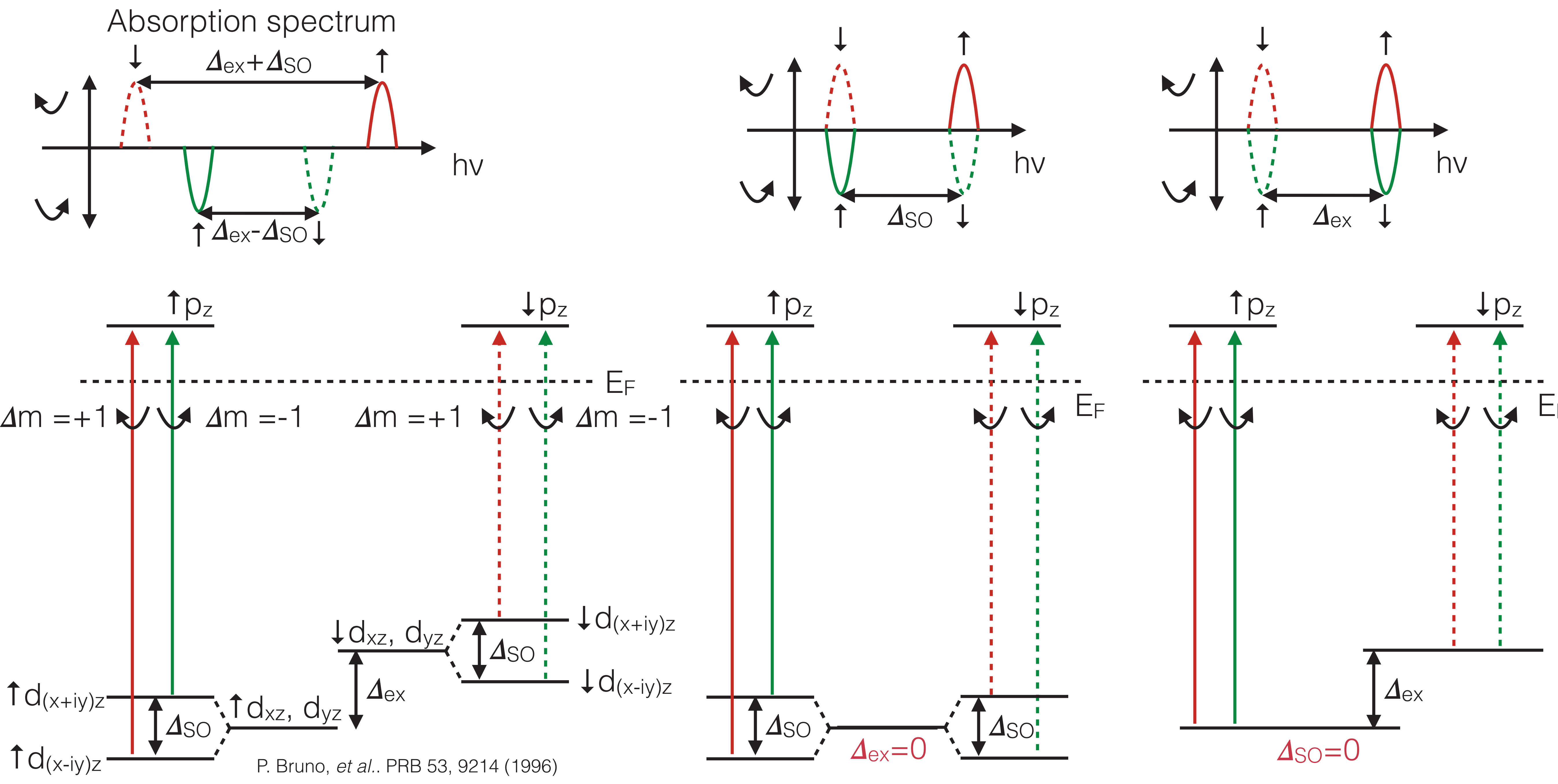
CF transition of Co





MV, et al., JAP 115, 17A940 (2015)

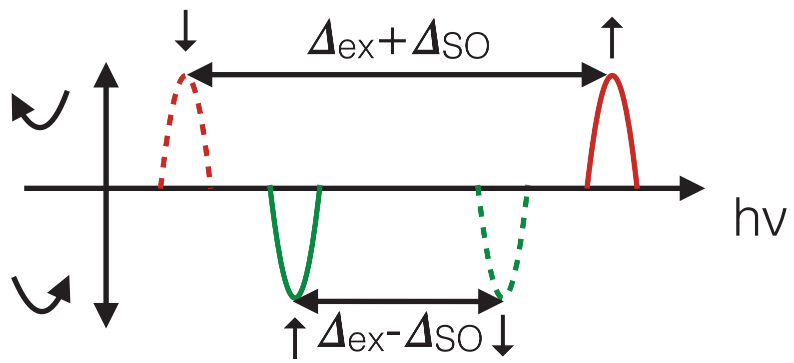
Microscopic picture of magneto-optics

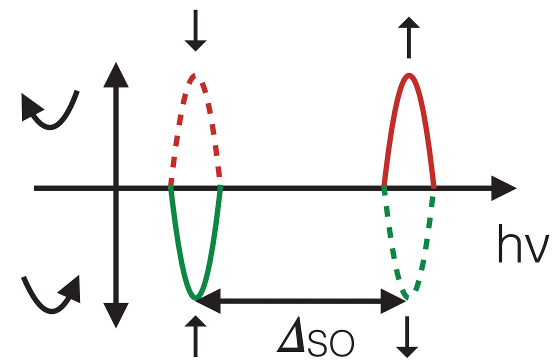


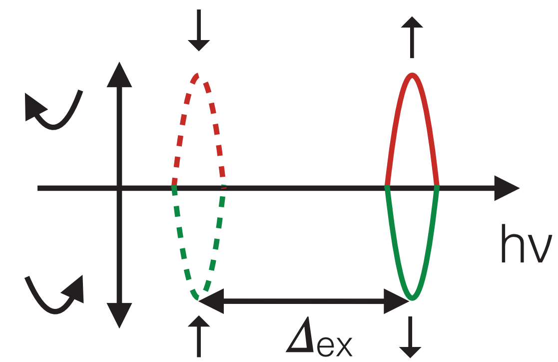
Both spin orbit coupling and exchange are necessary for MO activity

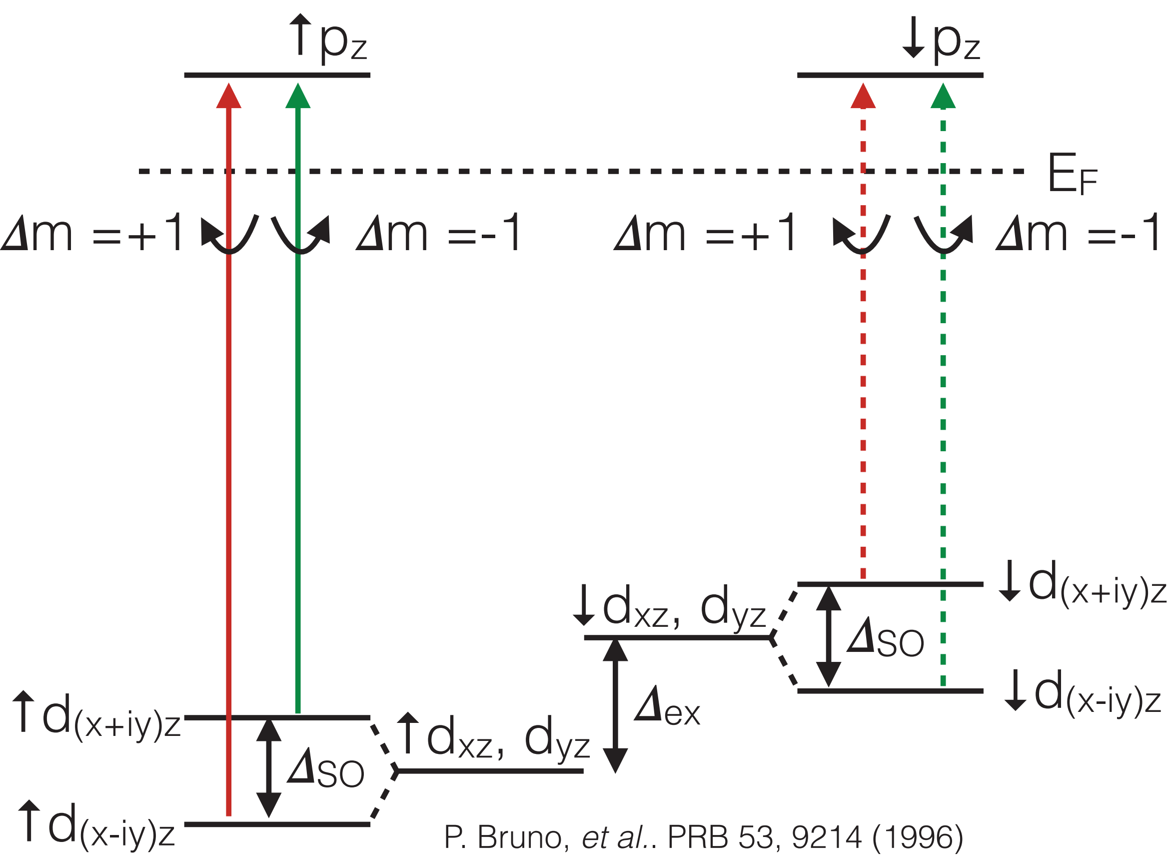
Microscopic picture of magneto-optics

Absorption spectrum

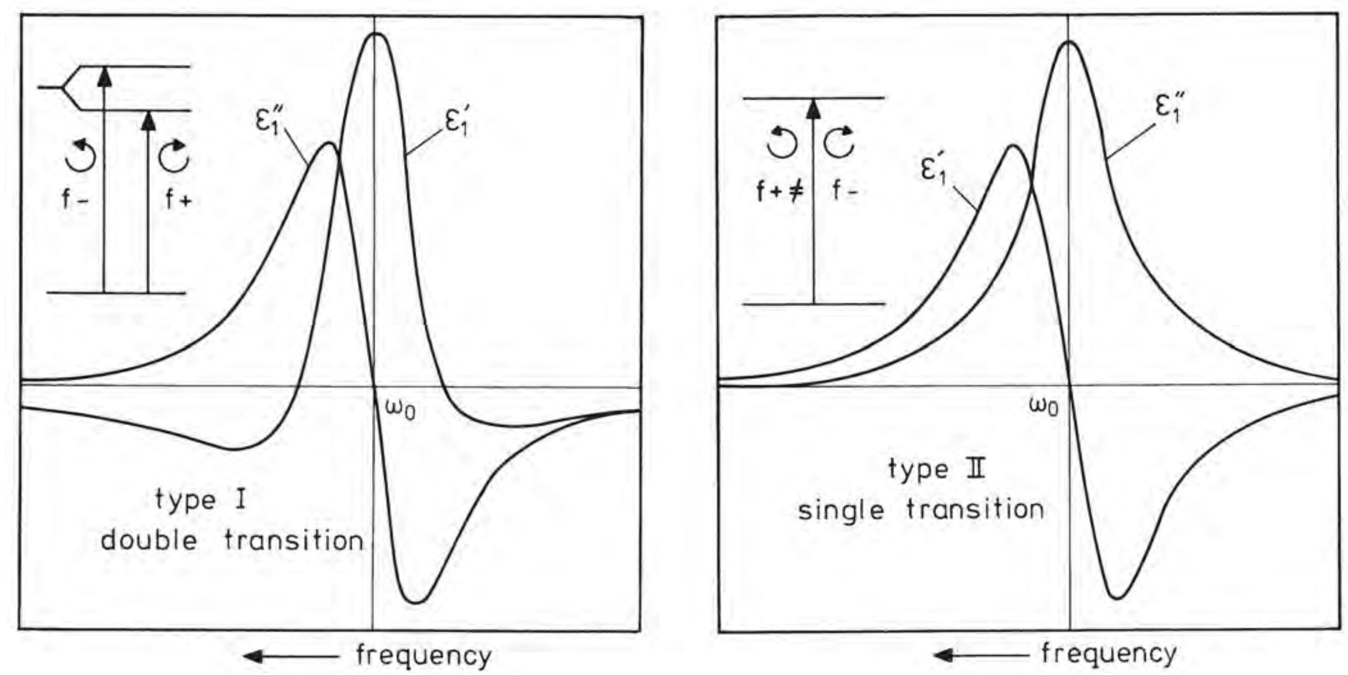








P. Bruno, *et al.*. PRB 53, 9214 (1996)



$$J_R = \begin{bmatrix} r_{ss} & r_{ps} \\ r_{sp} & r_{pp} \end{bmatrix} \longrightarrow \phi_{Ks} = \theta_{Ks} + j\epsilon_{Ks} = \frac{r_{sp}}{r_{ss}}$$

Spectrally dependent - information about electronic structure

Collaborators

Massachusetts Institute of Technology

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長岡技術科学大学
Nagaoka University of Technology

Prof. T. Ishibashi

SCIENTIA IMPERII DECUS ET TUTAMEN

Prof. L. Cohen

ČVUT
ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

Dr. J. Zemen

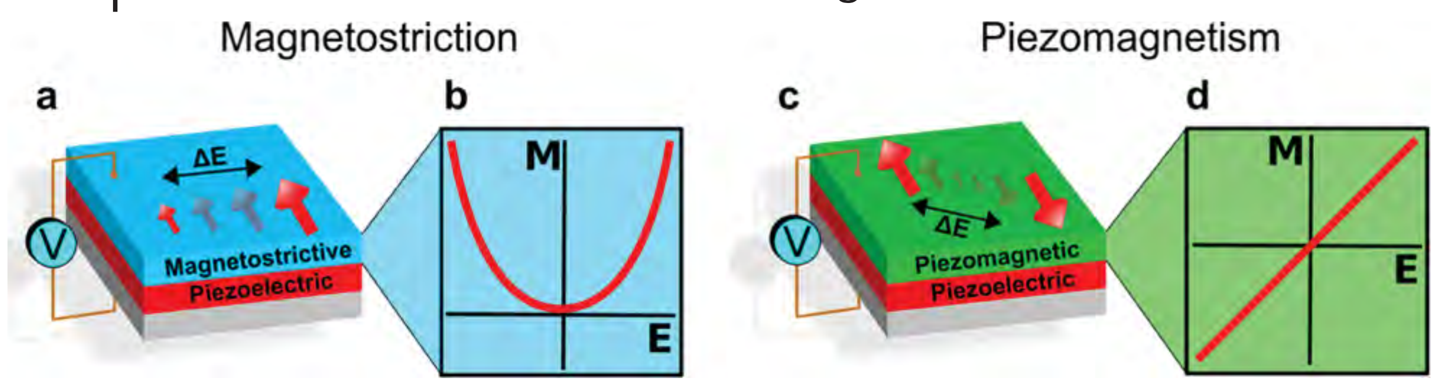
FZU
Fyzikální ústav Akademie věd České republiky

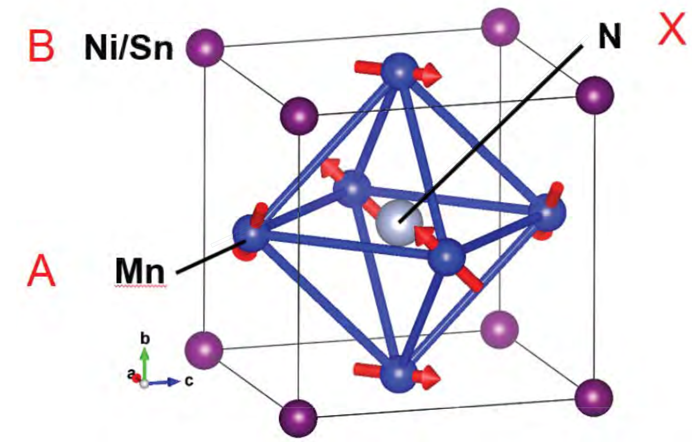
Dr. K. Výborný

Magneto-optical spatial light modulators:

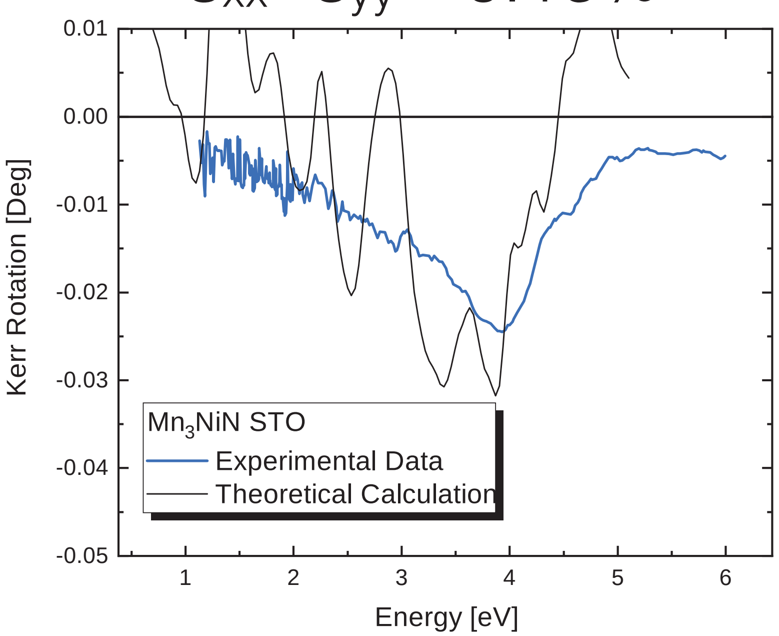
Non-collinear antiferromagnet Mn3NiN - piezomagnetism

Antiperovskite structure A_3BX

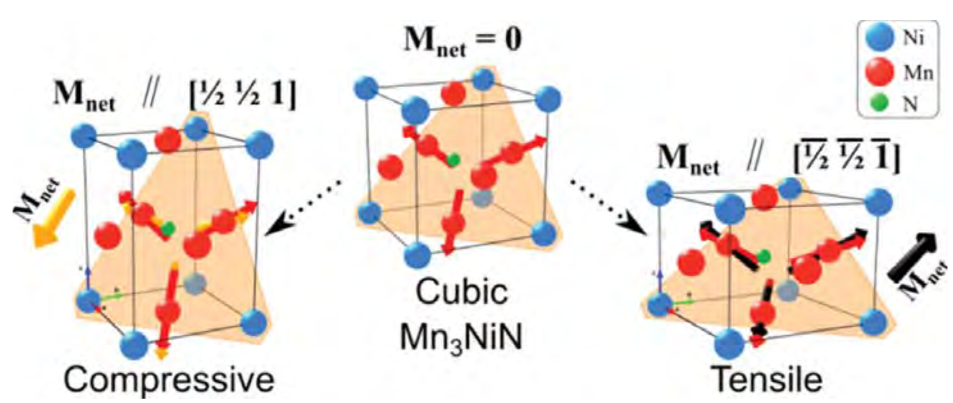




$\varepsilon_{xx}=\varepsilon_{yy}=-0.18\%$

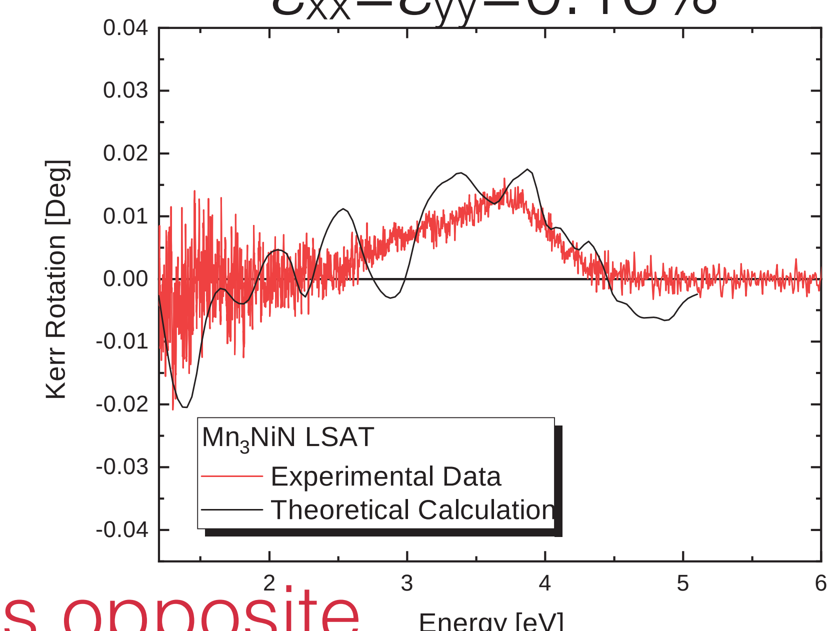


J. Zemen, MV, et al., submitted



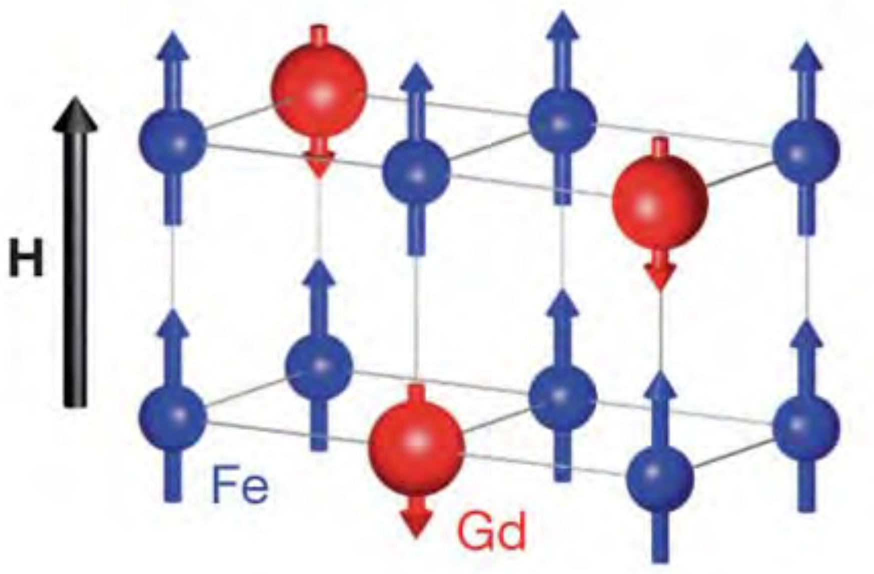
D. Boldrin et al., ACS Appl. Mat. Inter. 10, 18863 (2018)

$\varepsilon_{xx}=\varepsilon_{yy}=0.16\%$

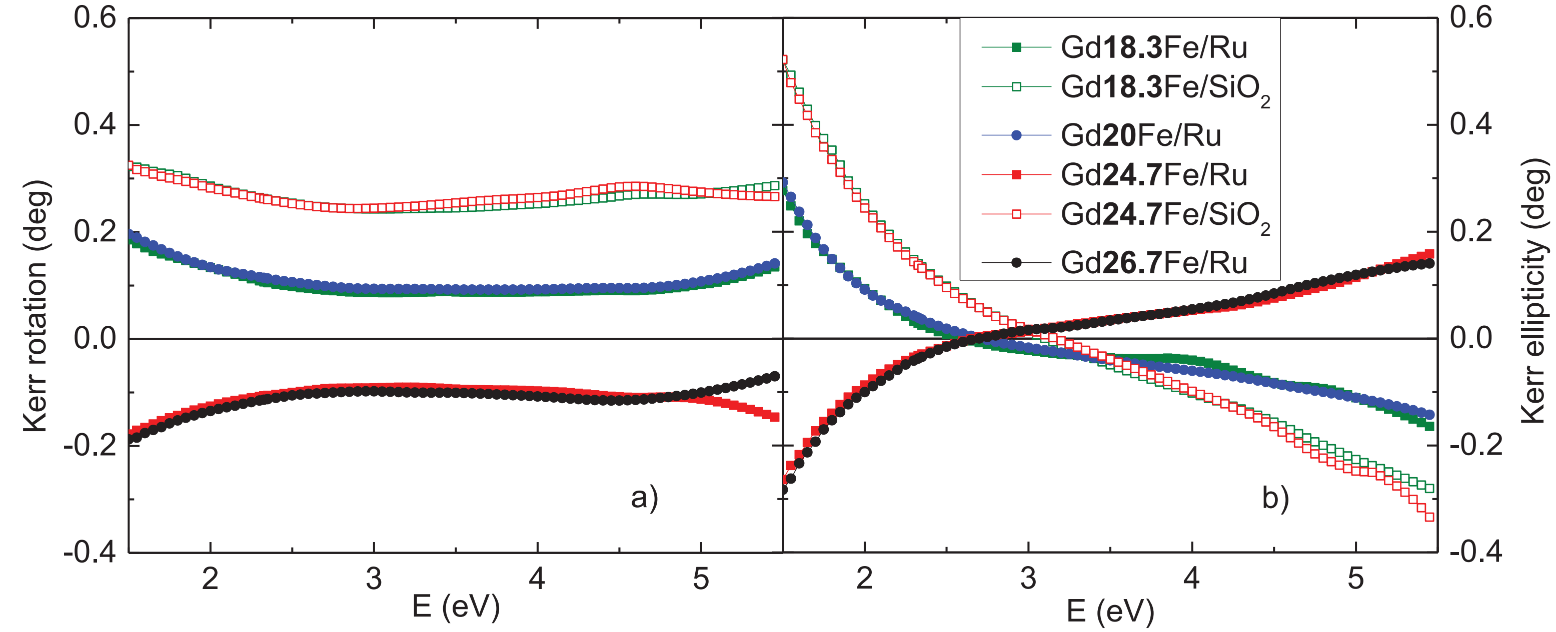


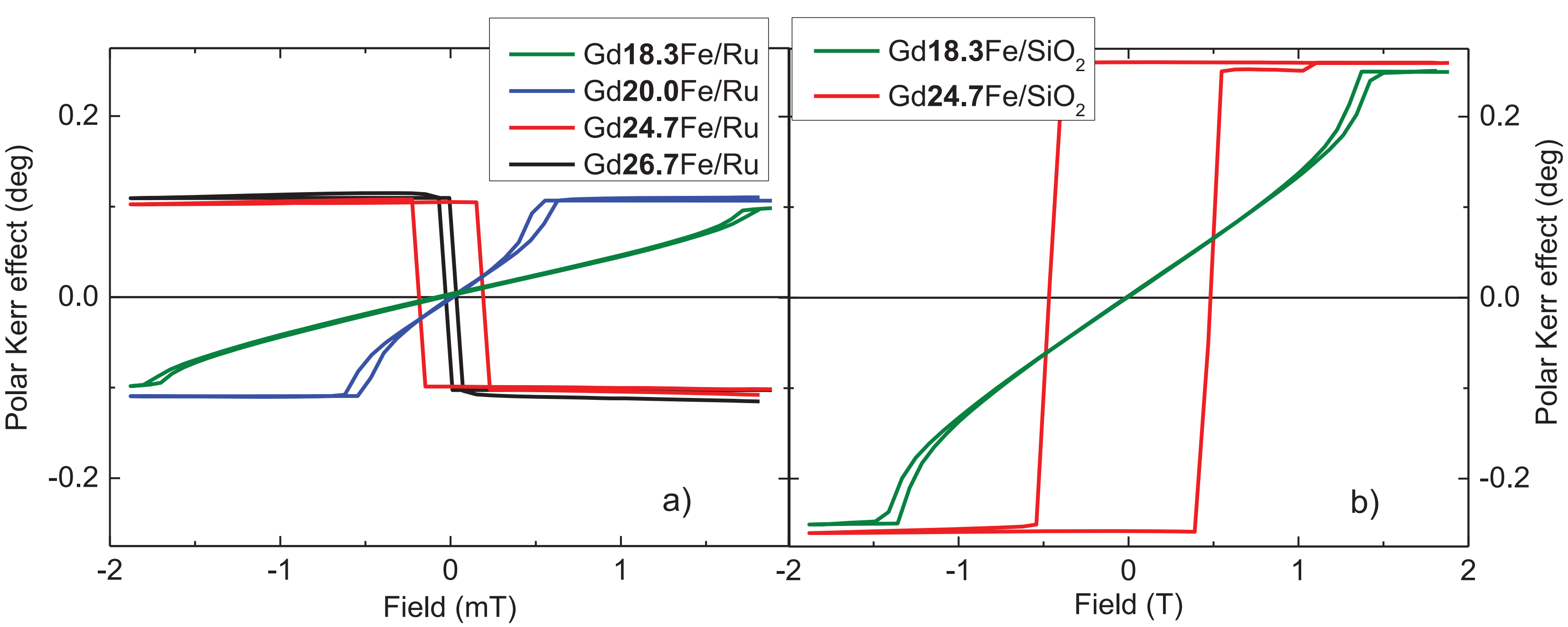
Opposite type of strain exhibits opposite sign of MOKE - piezoelectric control

Magneto-optical spatial light modulators:



E. Jesenska, MV, et al., Materials 9, 23 (2016)





E. Jesenska, MV, et al., Sci. Rep. 9, 16547 (2019)

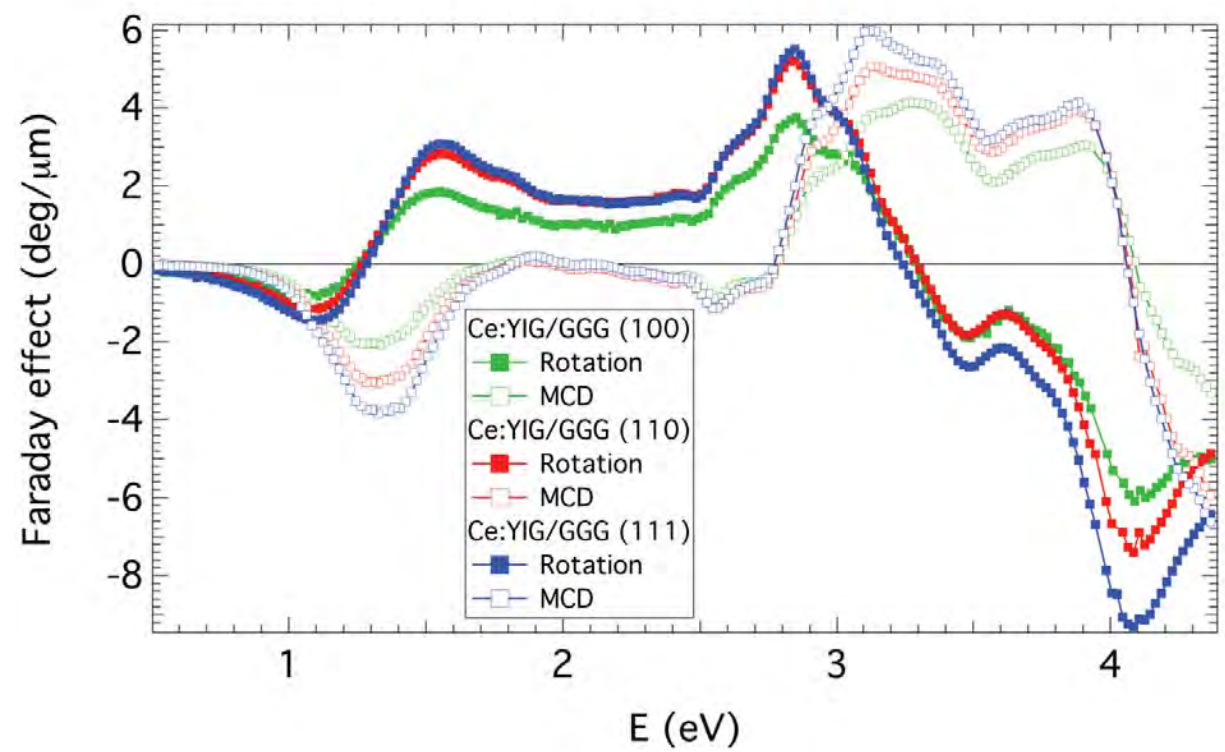
GdFe as light modulation free layer

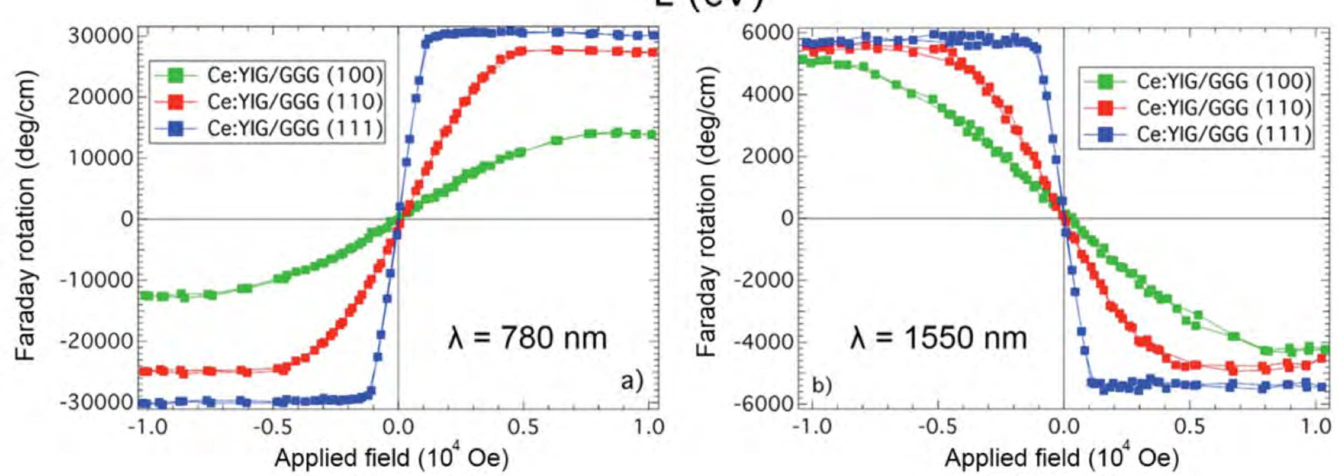
Compensation temperature depends on the composition

Influences MO activity and switching

How to increase MO activity at telecommunication wavelength 1550 nm (0.8 eV)?

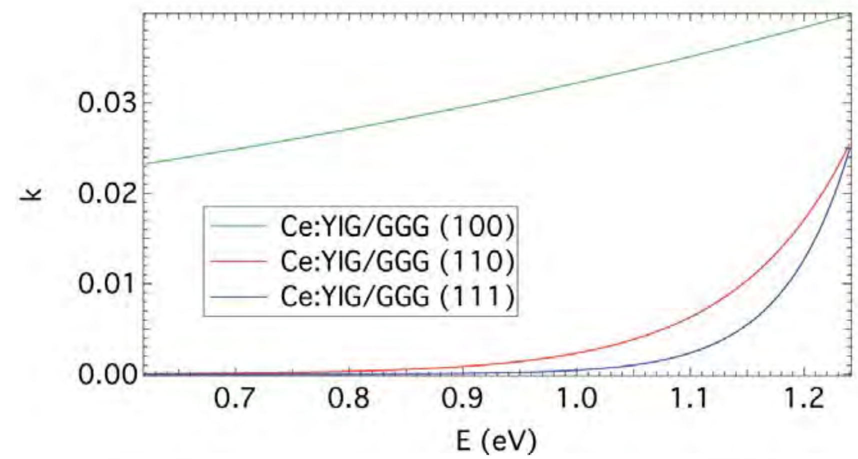
Ce substituted YIG: $Ce_1Y_2Fe_5O_{12}$



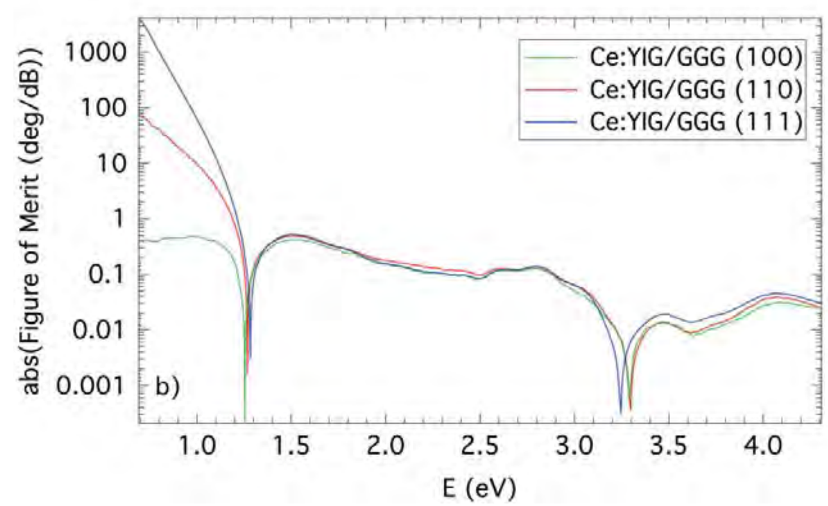


CF transition of Ce^{3+} ions

$4f^1$-$4f^05d^1$ near 1.3 eV



$$FOM = \frac{\theta_f}{\alpha_{db}}$$

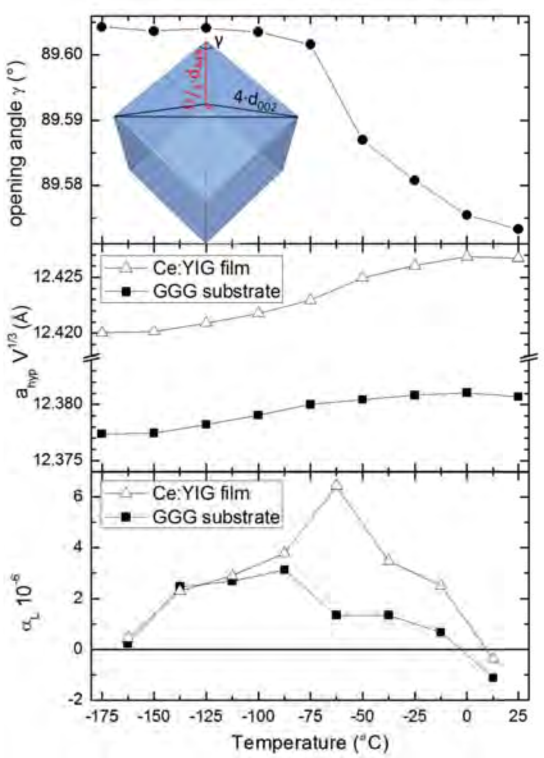


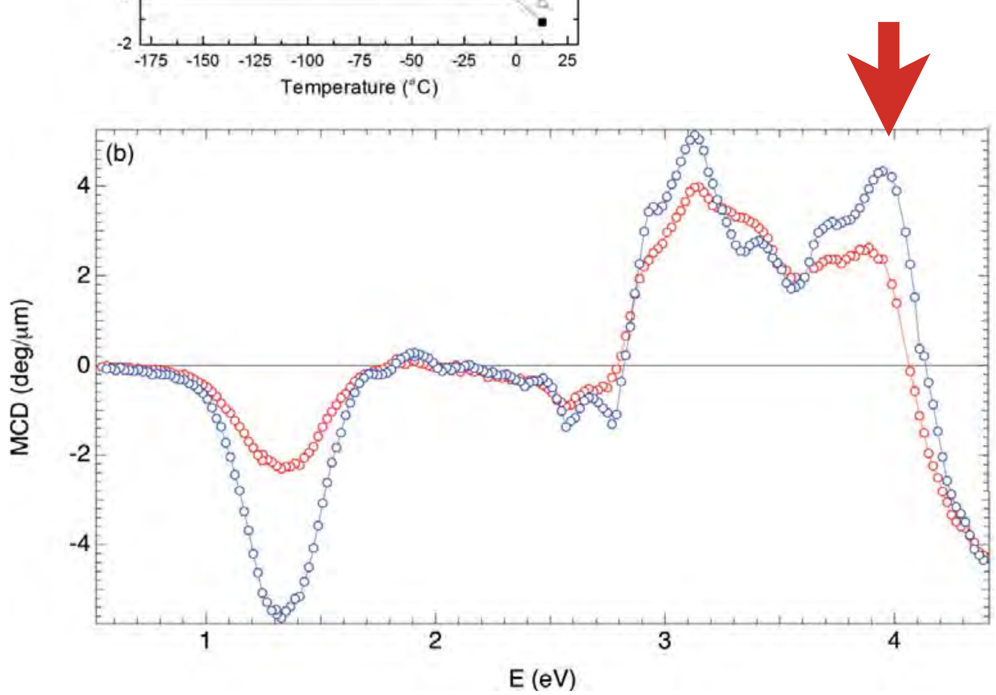
High FR and low absorption

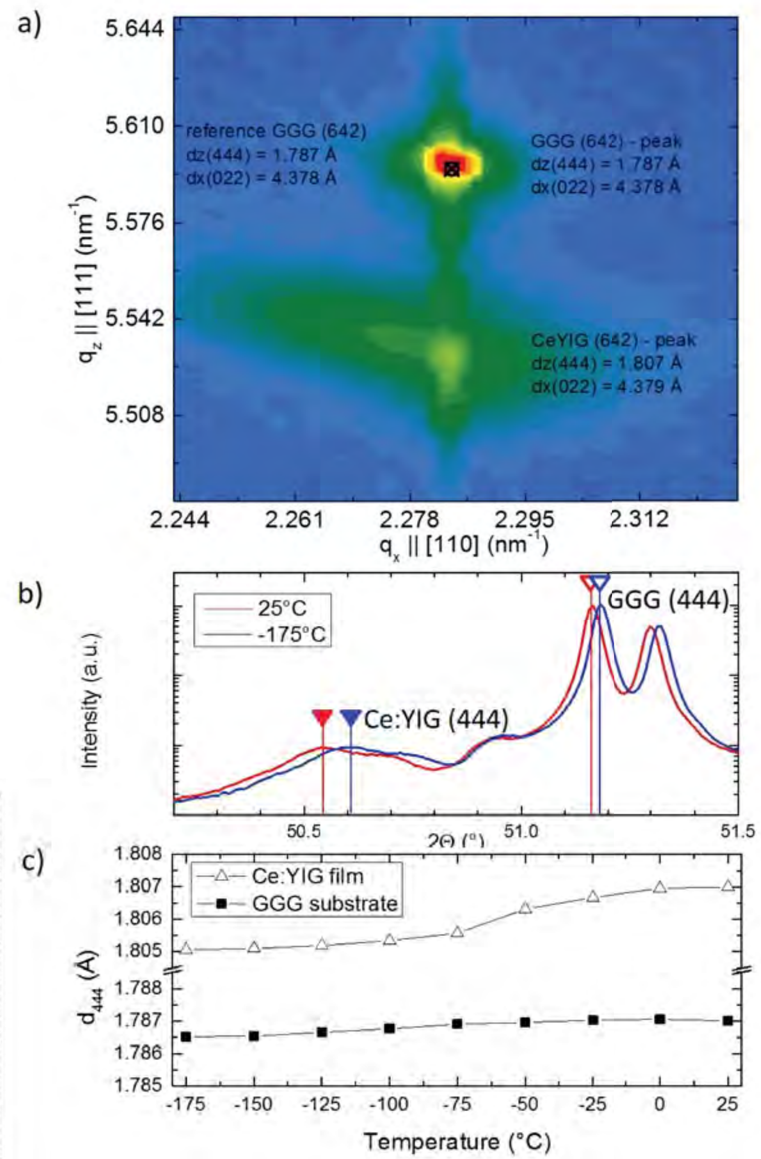
Magneto-crystalline anisotropy is important

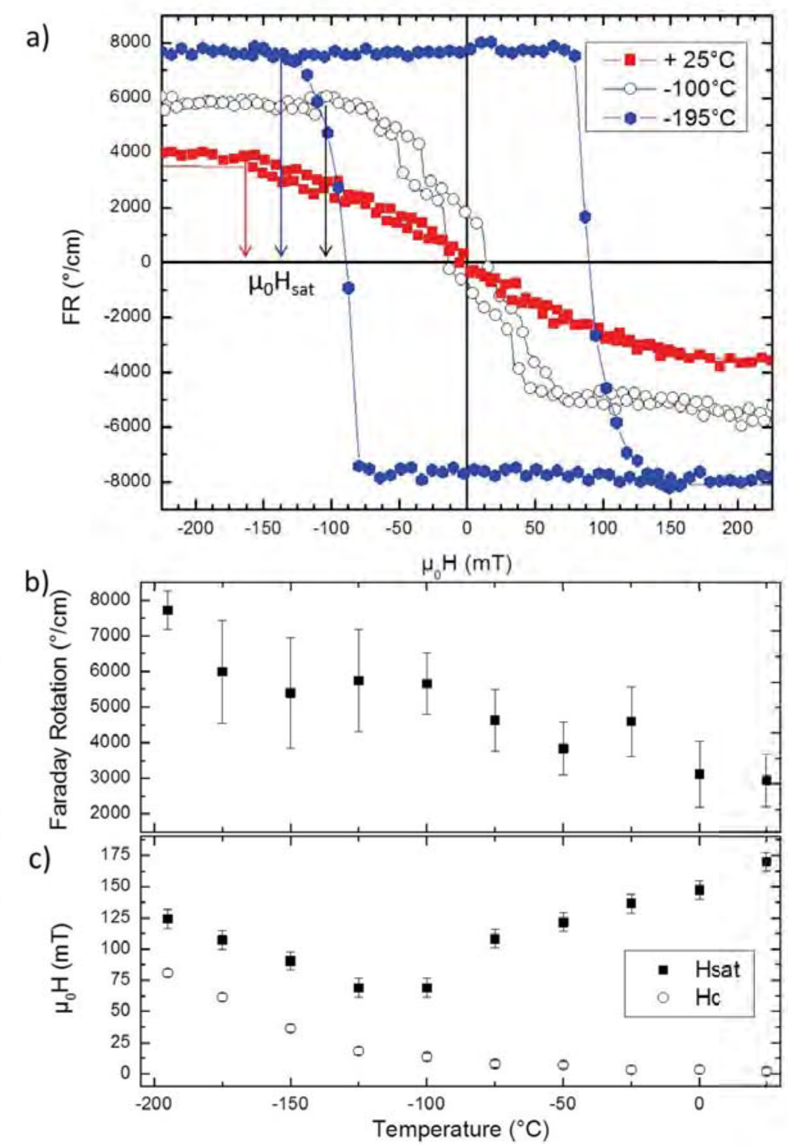
M. Onbasli, L. Beran, MV, et al., Sci. Rep. 6, 23640 (2016)

Ce substituted YIG: $Ce_1Y_2Fe_5O_{12}$









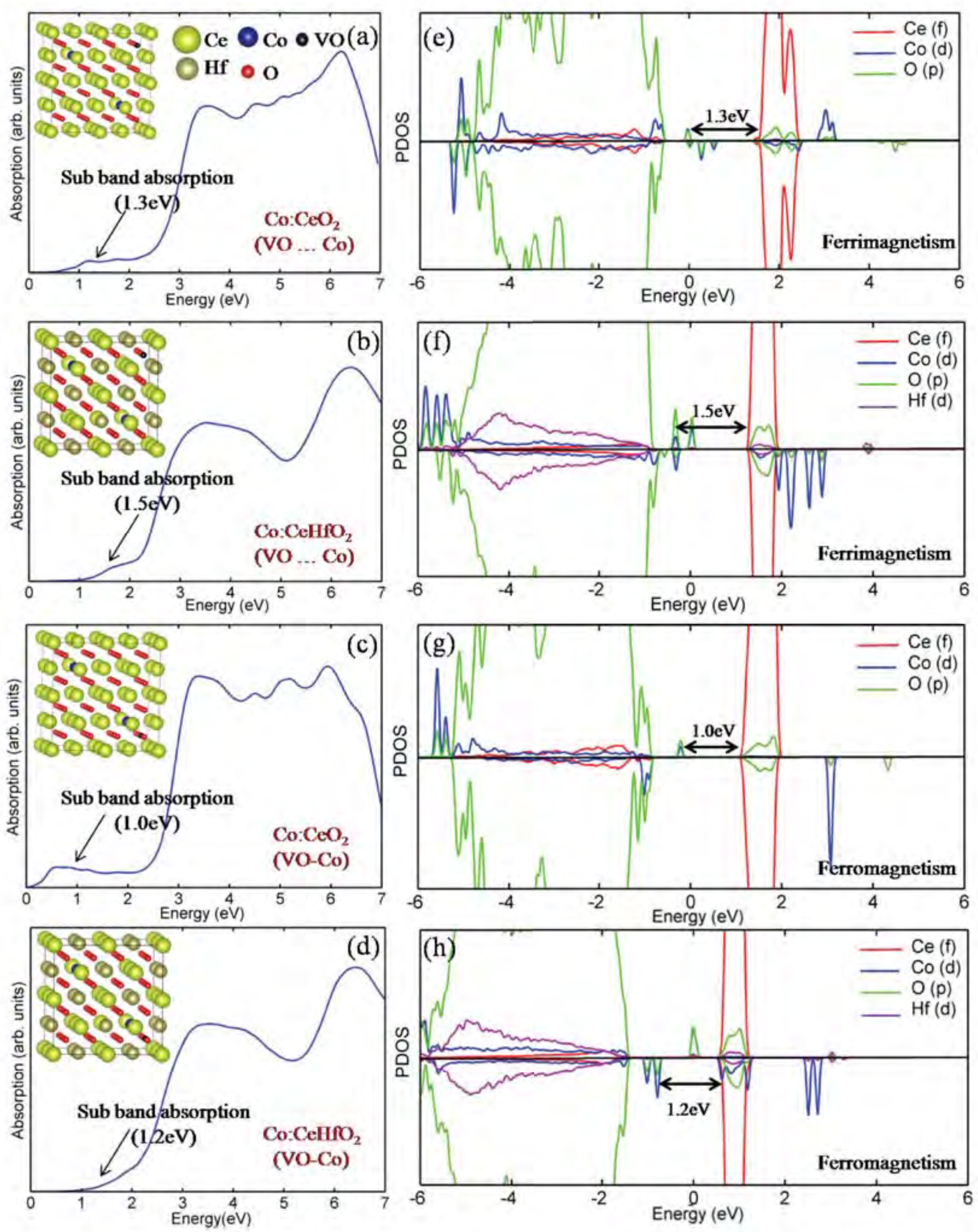
Temperature anisotropy switching

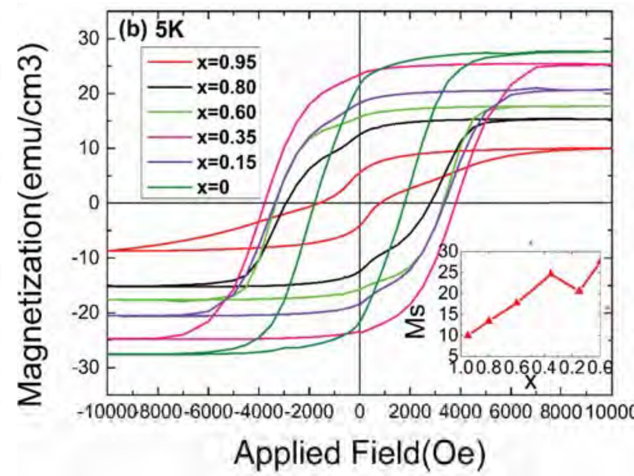
Octahedral iron more suitable for distortion

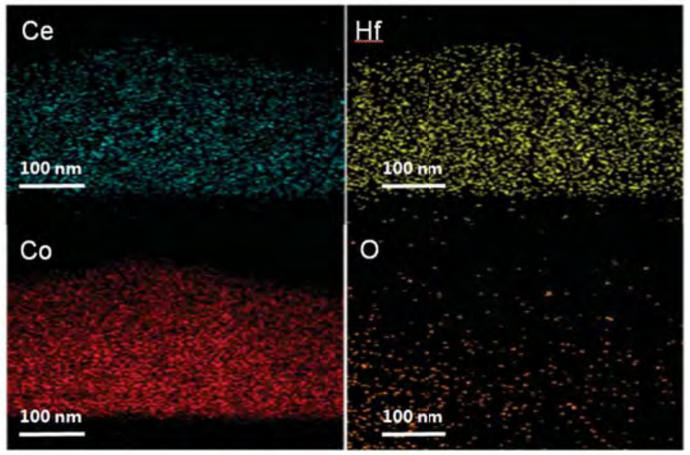
E. Lage, L. Beran, MV, et al., APL materials 5, 036104 (2017)

Other materials: Hf, Co doped CeO_2

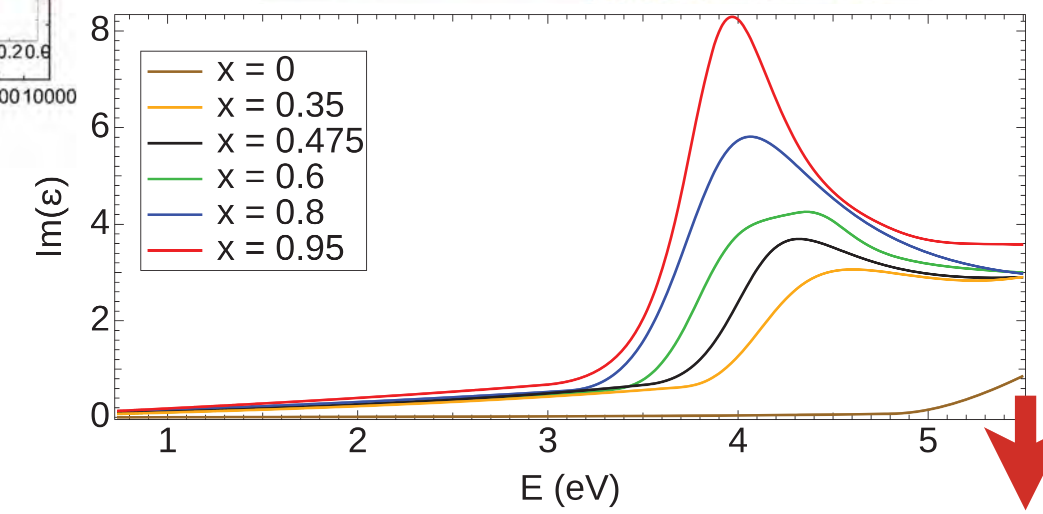
E. Jesenska, MV, et al., submitted

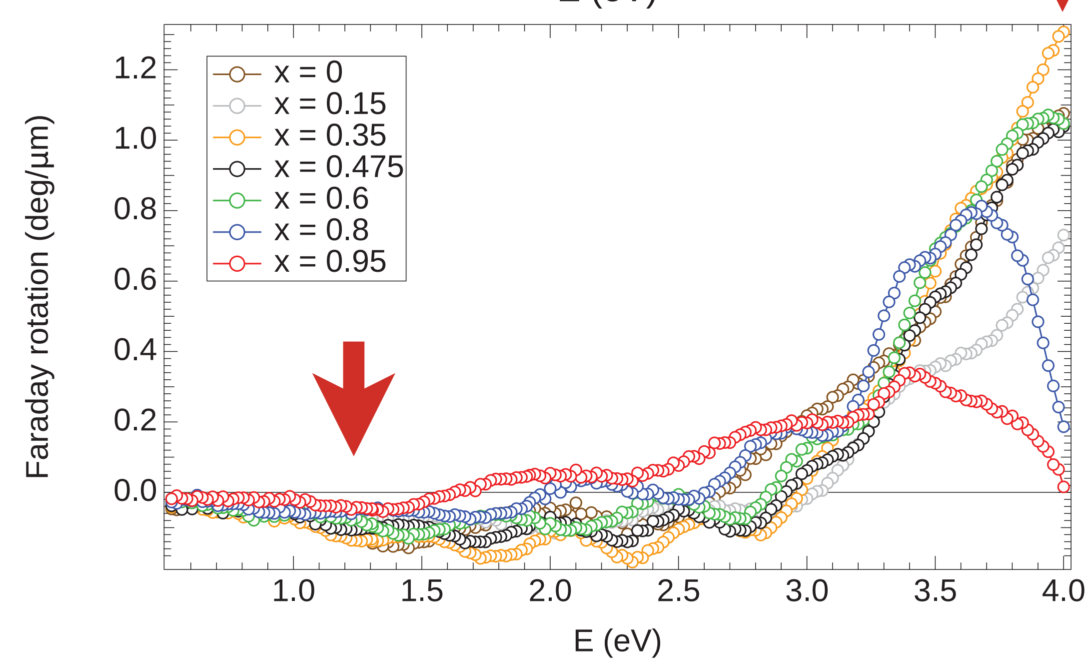






Tunable MO properties



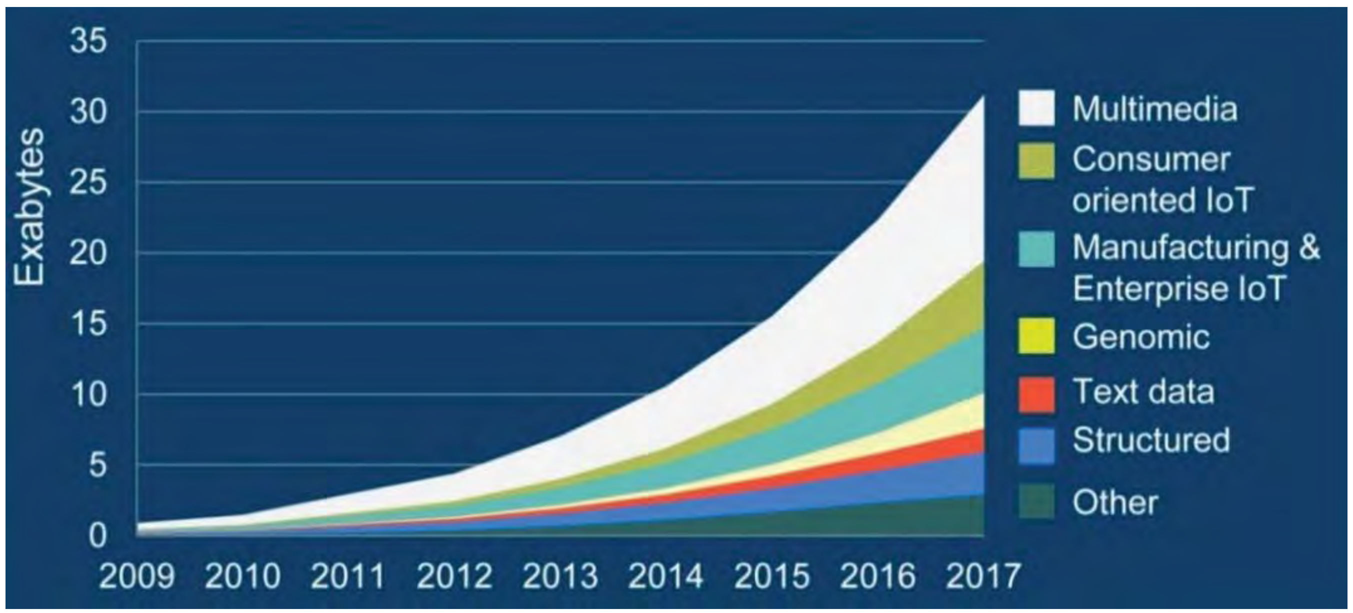


Compatibility with silicon

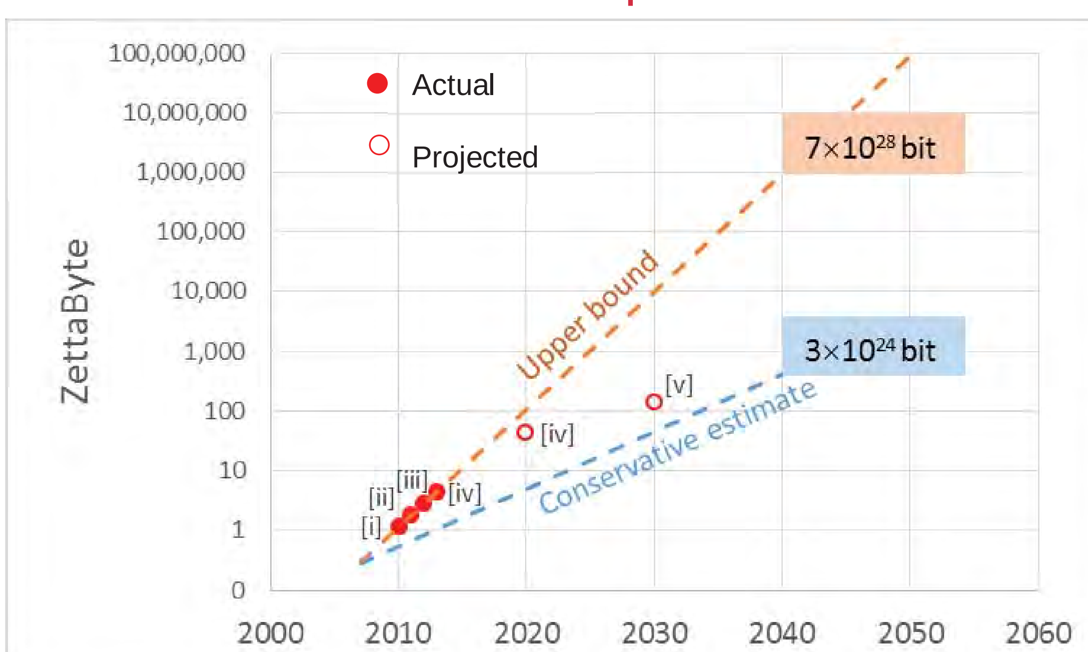
Magneto-optical applications of tomorrow

Computer technology predictions:

Estimated data growth:



Data volume expansion:



SIA SEMICONDUCTOR INDUSTRY ASSOCIATION SRC Semiconductor Research Corporation

High density data storage is necessary

Low cost devices

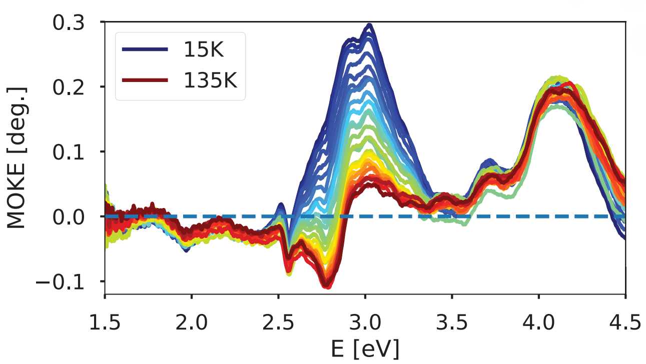
High speed data transfer (fibre optics)

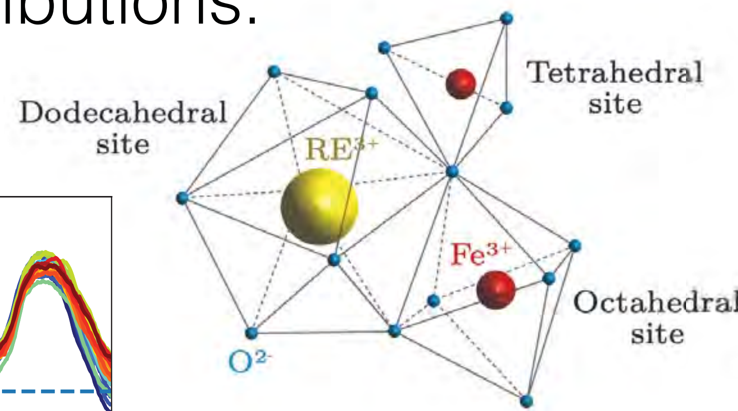
High speed data transfer (computer chip)

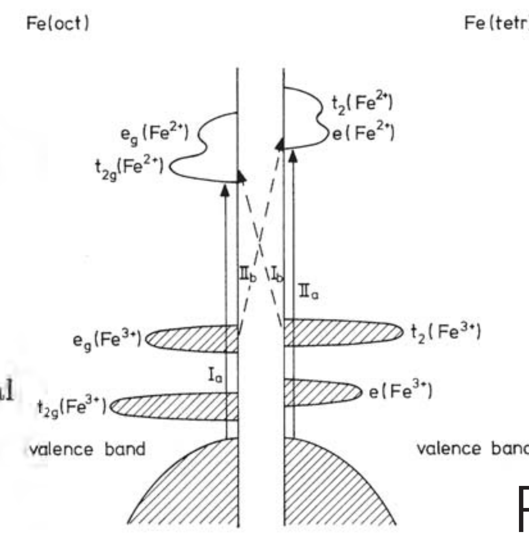
Magneto-optics of the future

PLD deposited TBIG garnets on GGG: thicknesses ~ 15 nm

Sublattice contributions:

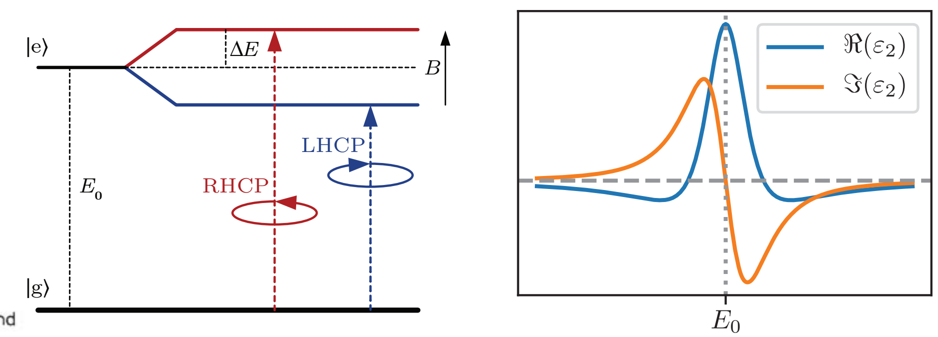




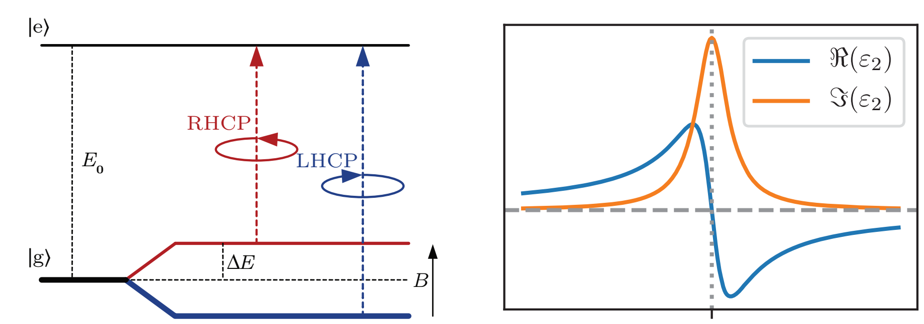


S. Wittekoek, et al., PRB 6, 2777 (1975)

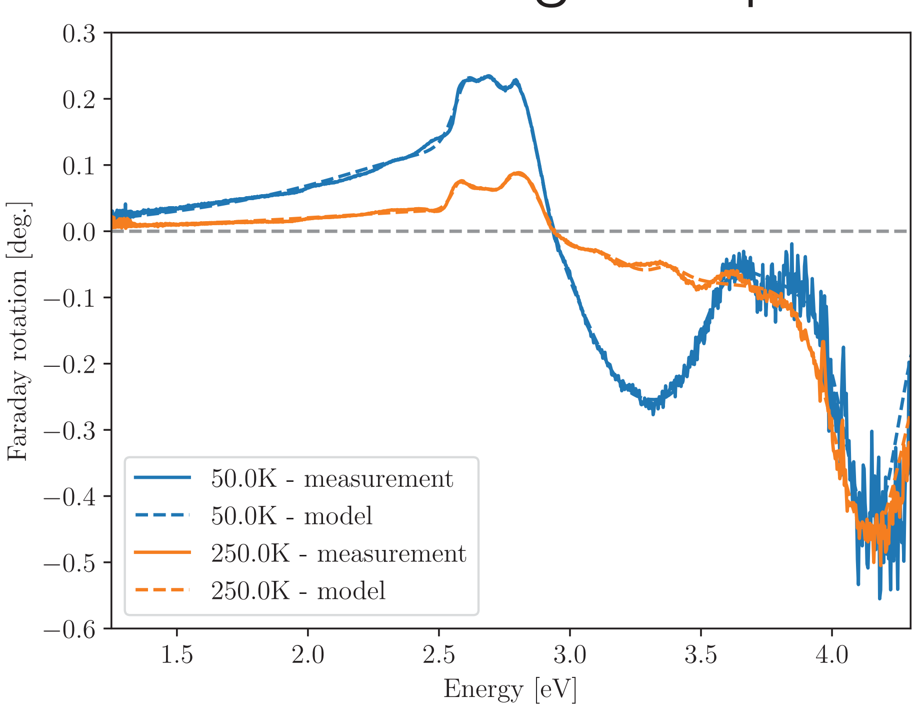
Diamagnetic transition

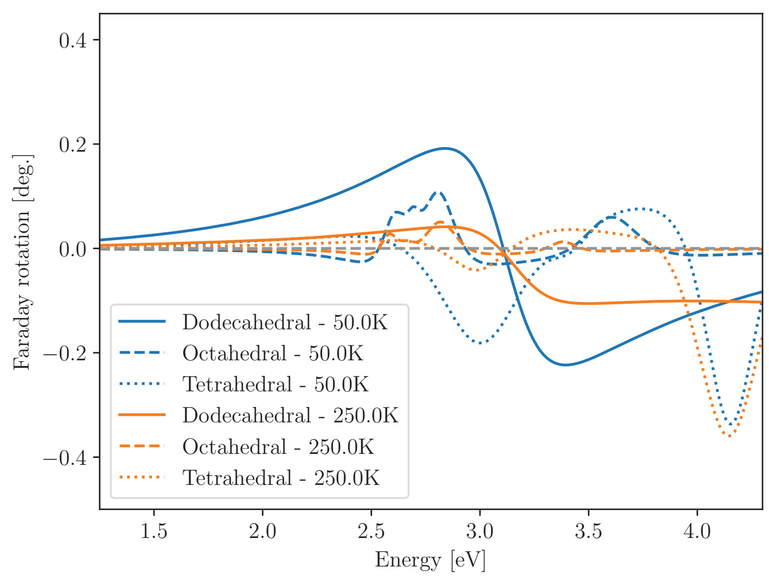


Paramagnetic transition

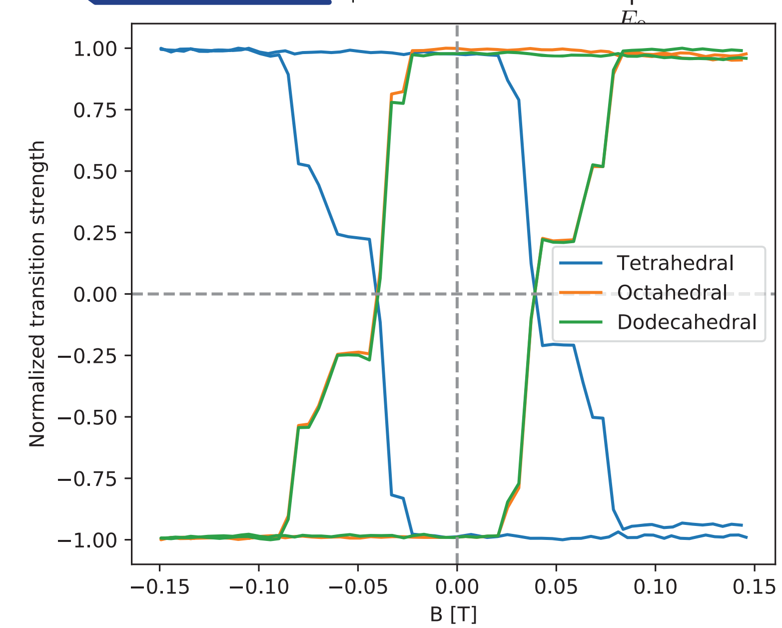


Theoretical fitting of experimental data



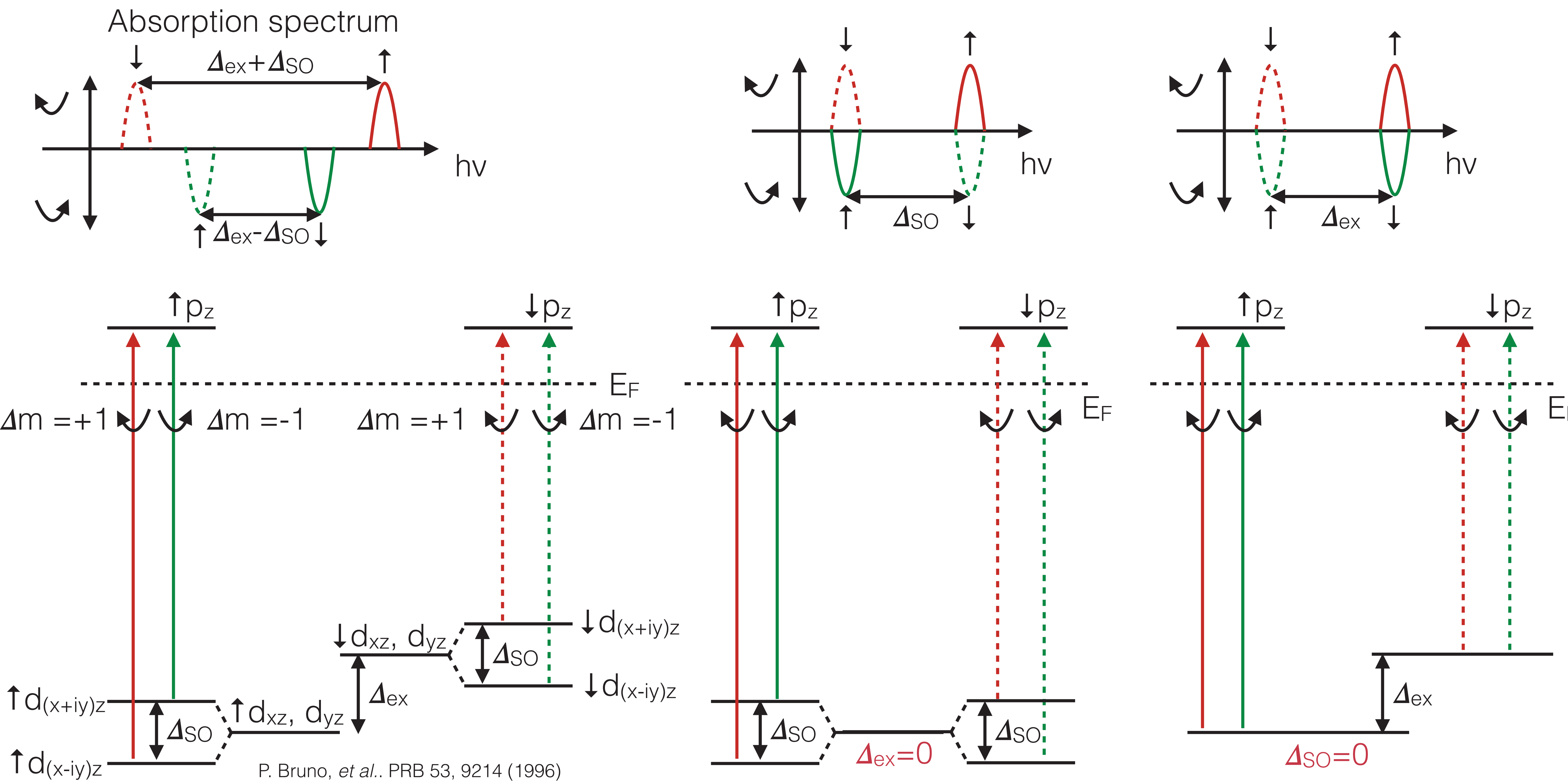


L. Beran, MV, et al., submitted



Particular sublattice sensing - magnetization switching

Microscopic picture of magneto-optics



P. Bruno, *et al.*. PRB 53, 9214 (1996)

Both spin orbit coupling and exchange are necessary for MO activity