MATERIAL STUDIES

into

EO CRYSTALS

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Materials & Photonics Systems (MAPS) Group

① **Fabrication & processing of nanomaterials;**

② **Applied Laser Technology;**

③ **Complex photonics.**

MAPS

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IMPACT & POTENTIAL APPLICATIONS:

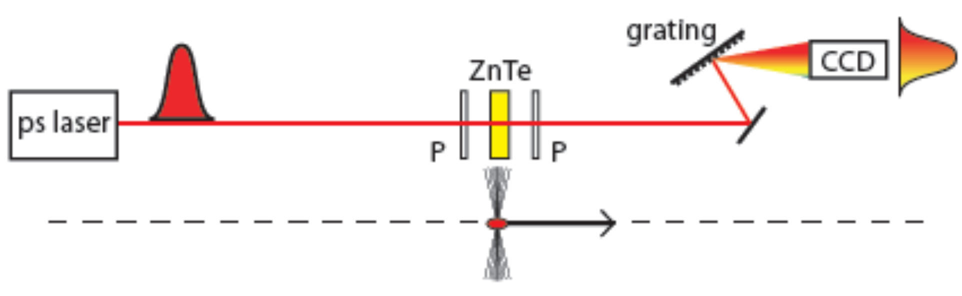
- Storage of information;
- Sensing, Circuitry & Security;
- Energy sector;
- Particle accelerators;
- Healthcare;
- Creative industries;
- Fundamental optical studies;
- Beam shaping; Laser technology.

Stating the problem …

CHALLENGE

Precision measurement of femtosecond relativistic electron bunches.

- **Currently**: Uses electro-optic (EO) effect in crystal that samples Coulomb field of 1 TeV electron beam.
- **How**: "EO transposition scheme" spectrally shifts THz Coulomb field to optical frequency.
- **Limitation**: Now limited by materials properties – inadequate optical bandwidth.



New materials

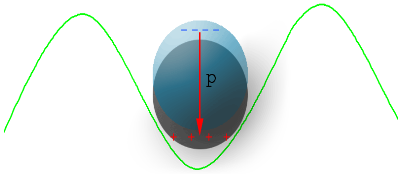
We are attempting to replace inorganic crystals such as GaP and ZnTe by a "*Metamaterial*" based on *Metal-Glass Nanocomposites (MGNs)*.

This talk is about the

fabrication, design & functionalisation of

MGNs

& MAPS efforts to address the challenge



Surface Plasmon Resonance (SPR)

Metal-Glass Nano-composites (MGNs)

Glass with metallic nanoparticles

Lycurgus cup (4th century AD) Roman art in the British Museum.

Mie theory for scattering & absorption of light by spheres

The polarizability α and induced dipole moment p of a metal sphere embedded in dielectric are given by:

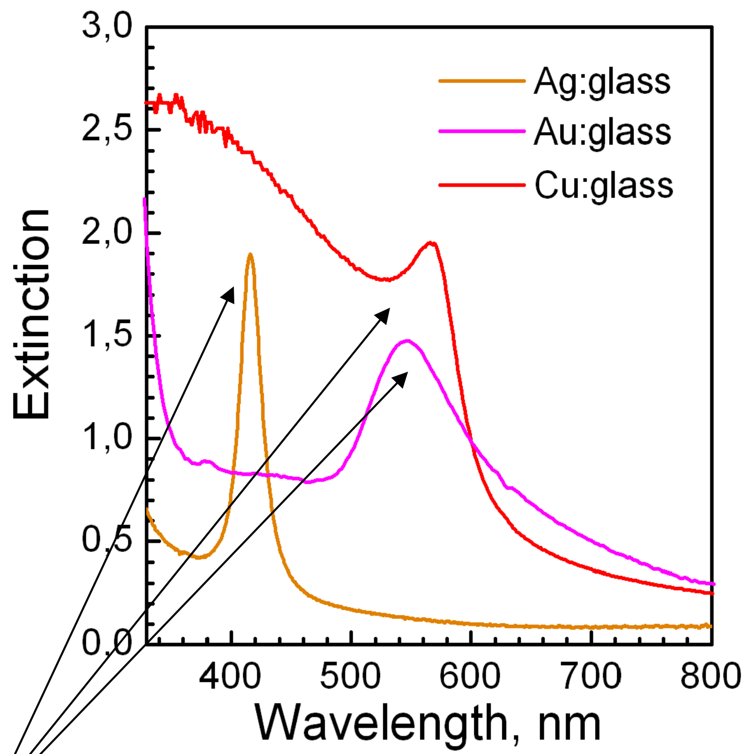
$$\alpha = 4\pi R^3 \frac{\varepsilon_i(\omega) - \varepsilon_h}{\varepsilon_i(\omega) + 2\varepsilon_h}$$

$$\vec{p}(\omega) = \alpha\varepsilon_0 \vec{E}_0(\omega) = 4\pi\varepsilon_0 R^3 \frac{\varepsilon_i(\omega) - \varepsilon_h}{\varepsilon_i(\omega) + 2\varepsilon_h} \vec{E}_0(\omega)$$

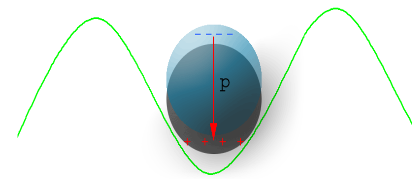
- R Radius of the nanoparticle
- $\varepsilon_i(\omega)$ Complex electric permittivity of the metal
- ε_h Complex electric permittivity of the host matrix
- E_0 Electric field strength of the incident electromagnetic wave
- ε_0 Electric permittivity of vacuum

- Michael Faraday, Phil. Trans. Royal Society 147, 145 (1857).
- Gustav Mie, Ann. Phys. (Leipzig) 25, 377 (1908).
- Kreibig, U. & Volmer, M. Optical Properties of Metal Clusters, Springer (1995).

Absorption (Extinction) spectra of glass containing **spherical** Silver, Gold & Copper nanoparticles.



SPR peaks

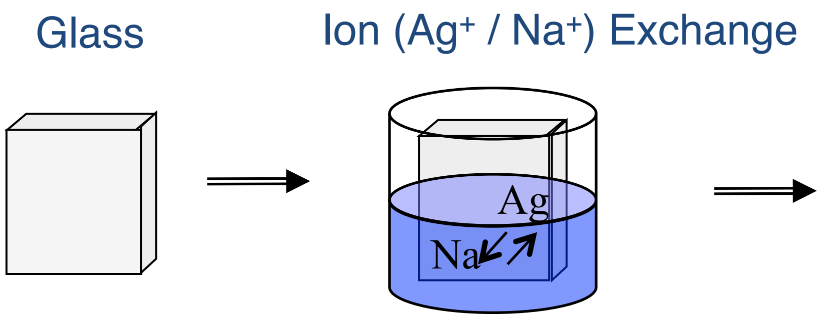


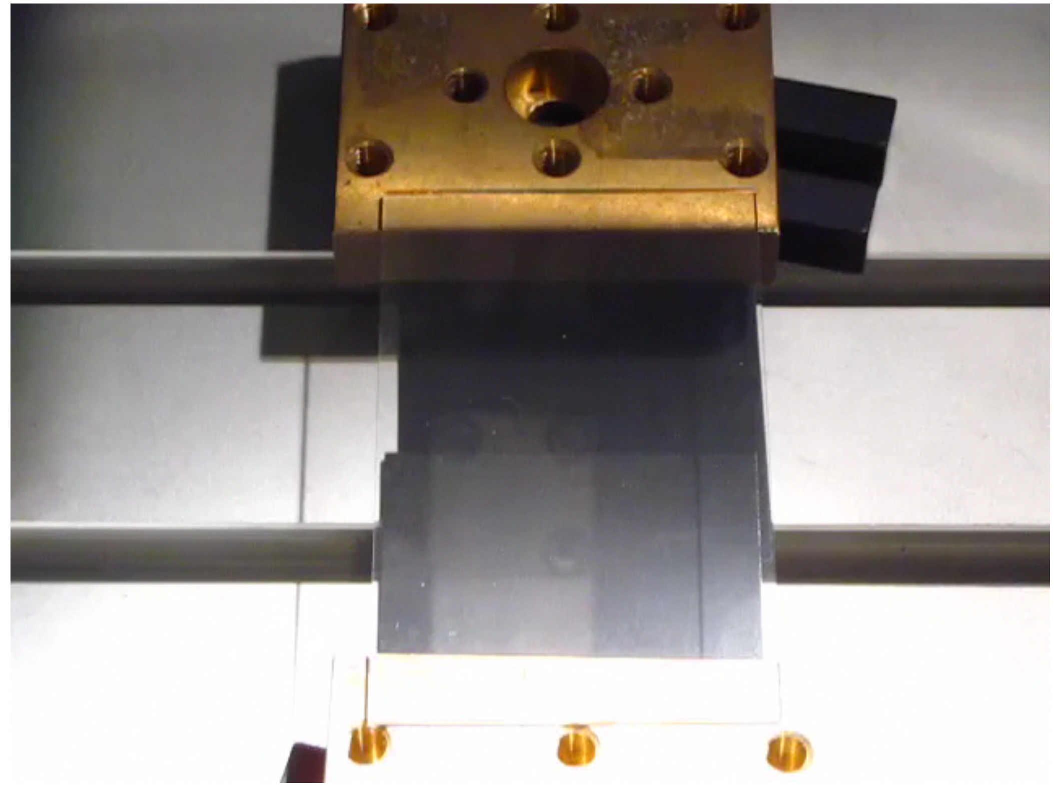
Surface Plasmon Resonance (SPR)

Core electrons define the position of the SPR in the extinction spectra for different noble metals.

• Kreibig, U & Volmer, M. Optical Properties of Metal Clusters. Springer (1995).
• Bohren, C. F.; Huffman, D. R. Absorption & Scattering by Small Particles. Wiley (1983).

Traditional ion-exchange technique & “modern” laser annealing in air





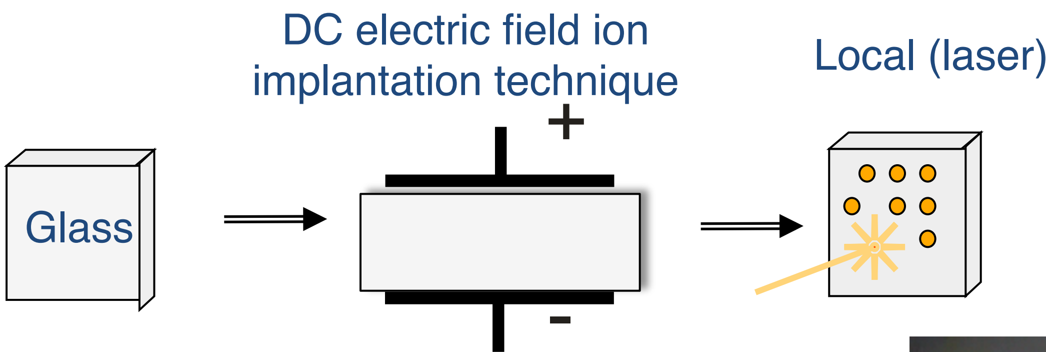
Case in point

Material: window glass after ion-exchange
Wavelength: 355 nm
Pulse length: 10 ns at 80 kHz
Focal spot diameter: 30 µm
Processing speed: 20 mm/s

MAPS

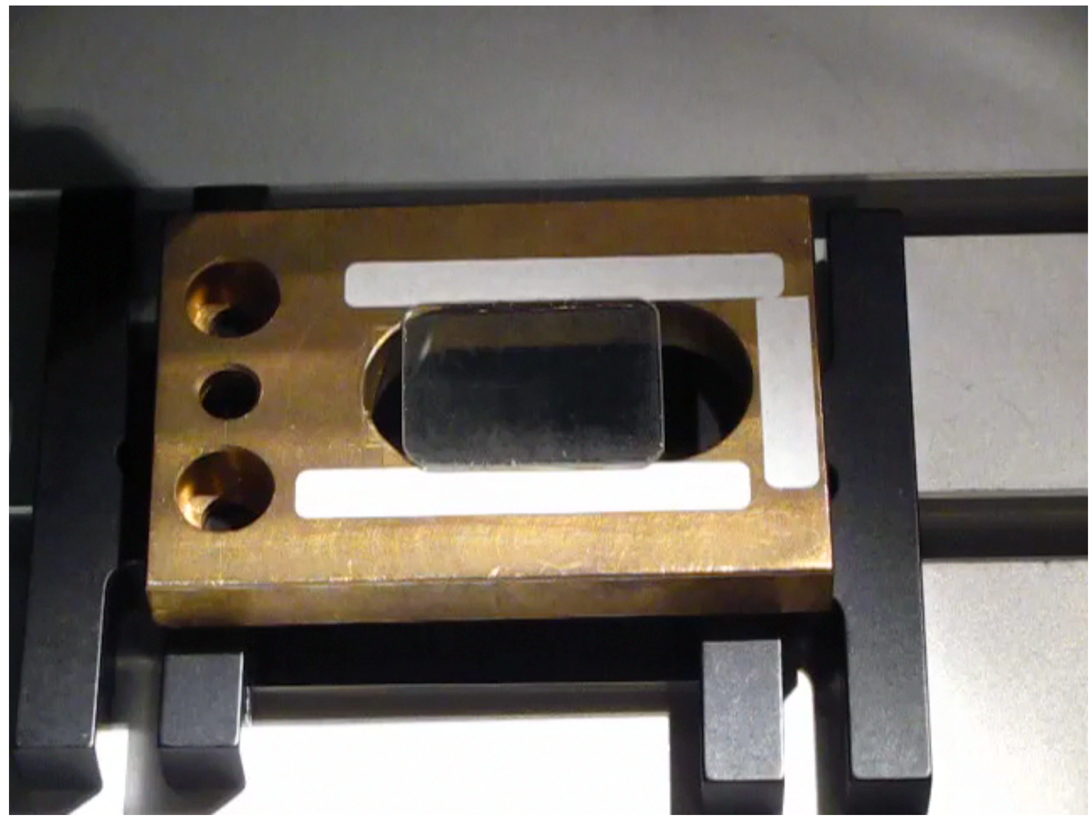
- Patent

DC electric field-assisted ion exchange & laser reduction in air



Case in point

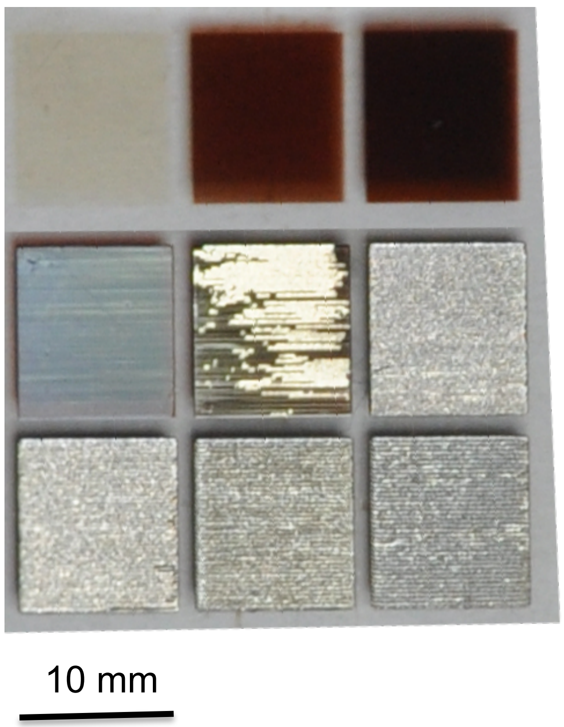
Wavelength: 355 nm
Pulse length: ~ 6 ps at 80 kHz
Focal spot diameter: 30 μm
Processing speed: 20 mm/s

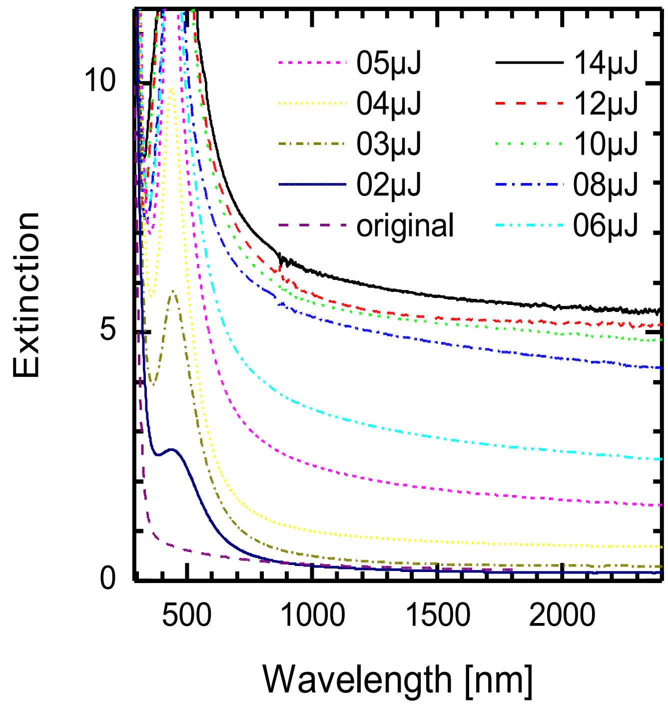


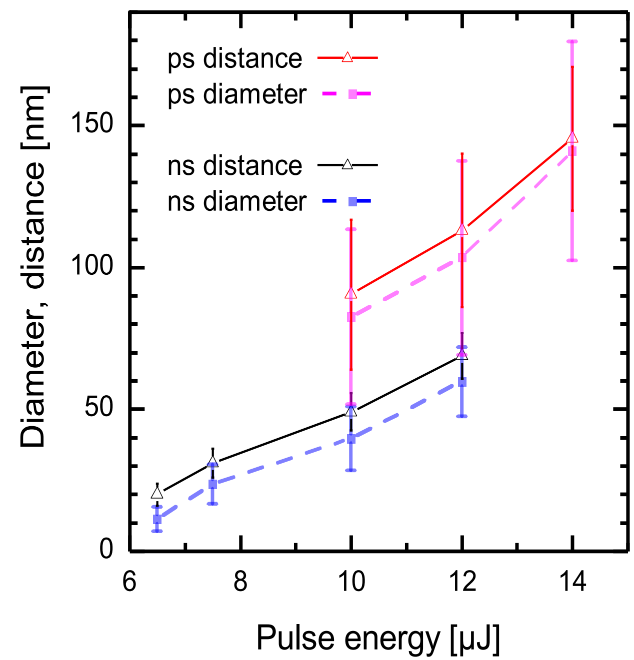
MAPS

- Appl. Phys. A (Rapid Commun.) 109, 45 (2012).
- Optics Express 22, 5076 (2014). + Patent

Picosecond pulsed laser irradiation of silver-ion doped glass

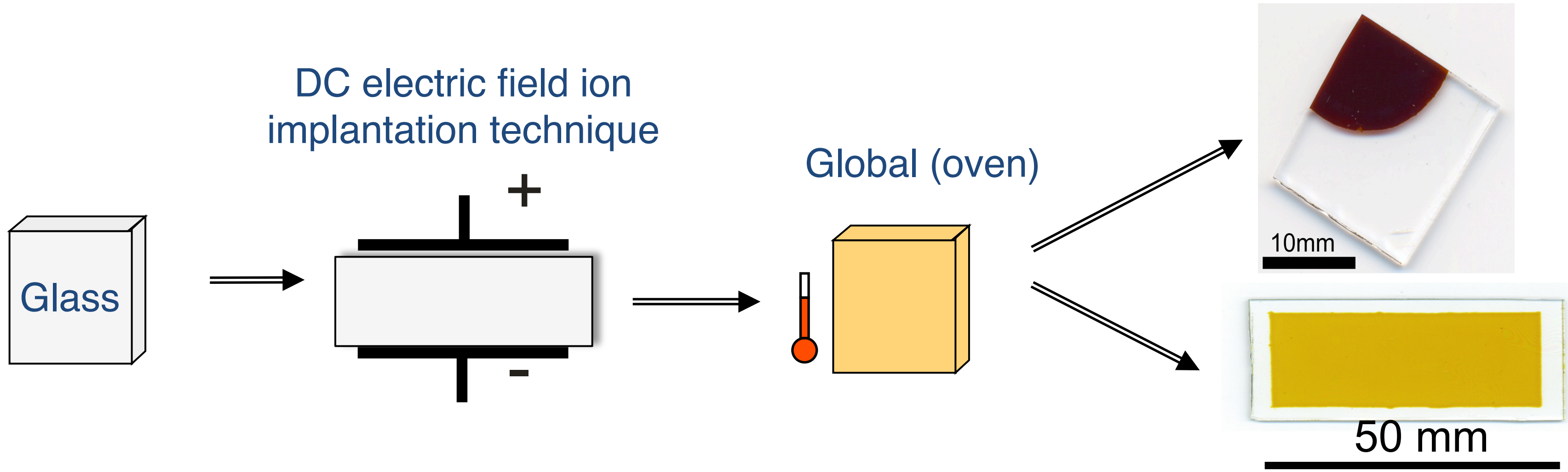




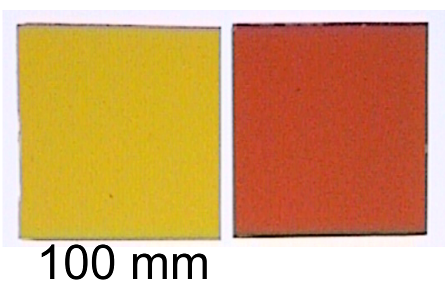


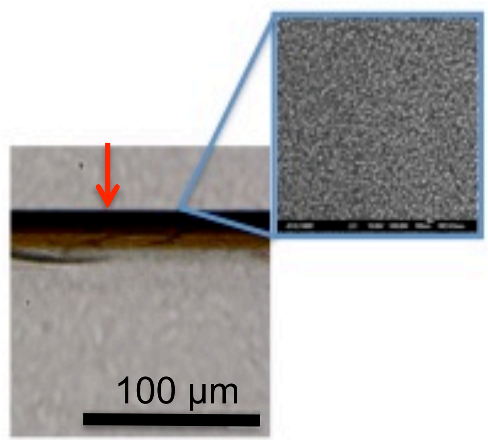
- Optics Express 22, 5076 (2014).
- Appl. Phys. A (Rapid Commun.) 109, 45 (2012).
- Patent – 2012.

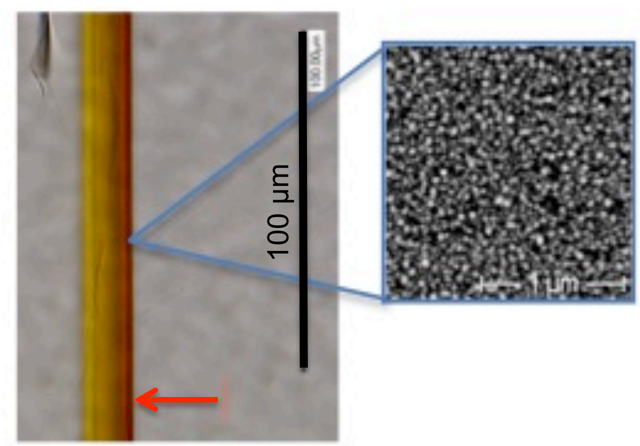
DC electric field-assisted ion exchange & reduction in air



- ➢ Control over the size of the embedded nanoparticles (up to 50nm in diameter);
- ➢ Control over the thickness of the nanoparticle-containing layer in glass (500nm – 250μm);
- ➢ Control over the spatial distribution (filling factor) of the nanoparticle-containing layer.







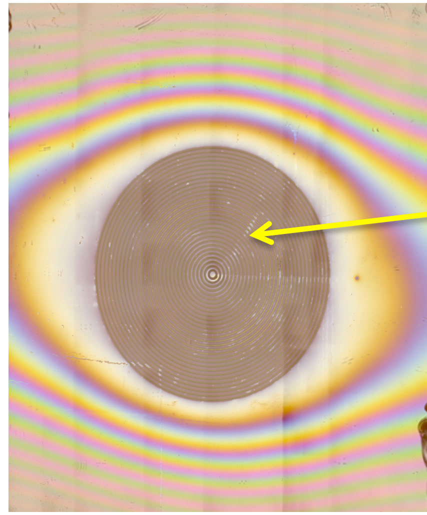
MAPS

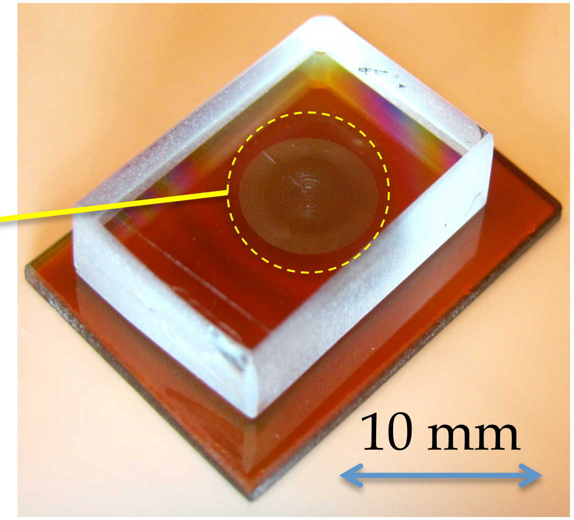
- Optical Materials Express 1, 1224 (2011).
- Optics Express 20, 23227 (2012).
- Patent.

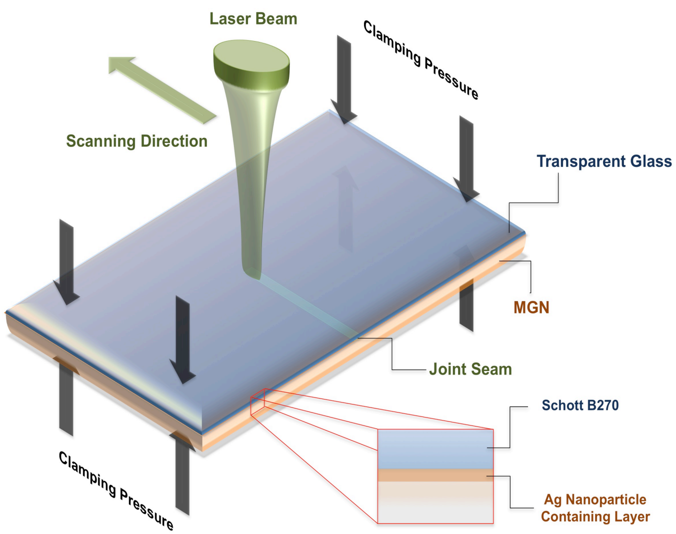
Application Example
Plasmonics-assisted rapid laser joining of glass

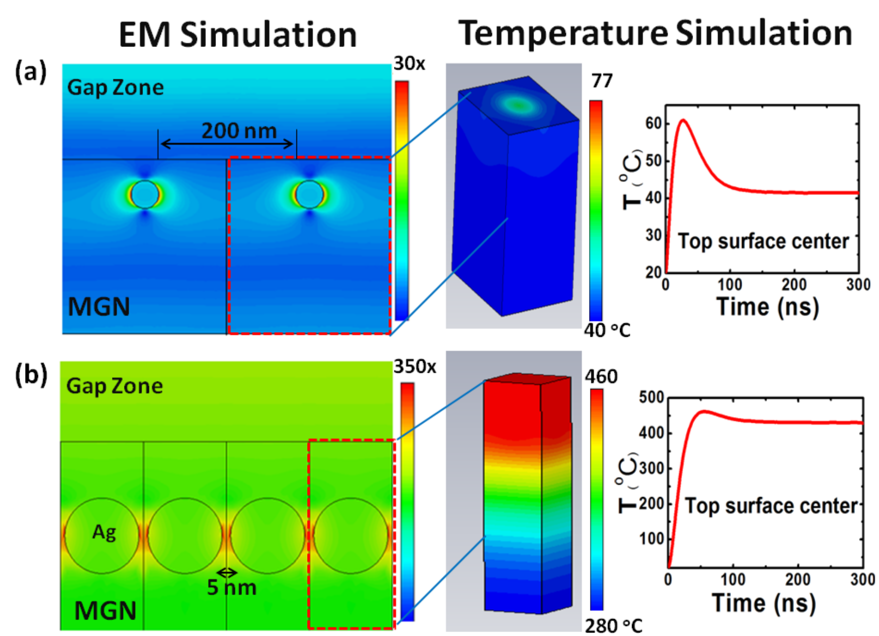
Case in point

Wavelength: 532 nm
Pulse length: ~ 40 ns at 100 kHz
Laser fluence: ~ 0.2 J/cm^2
Focal spot diameter: 60 µm
Processing speed: 10 mm/s
Weld strength: ~ 13 MPa





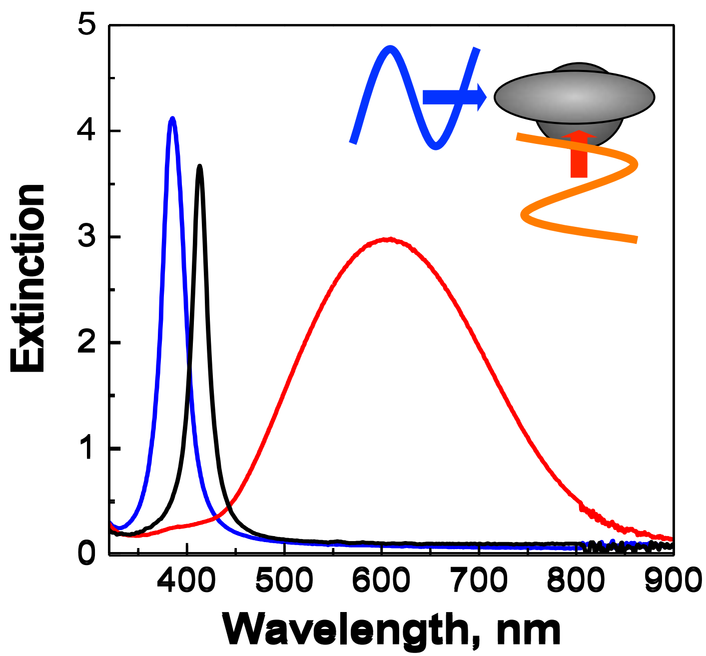




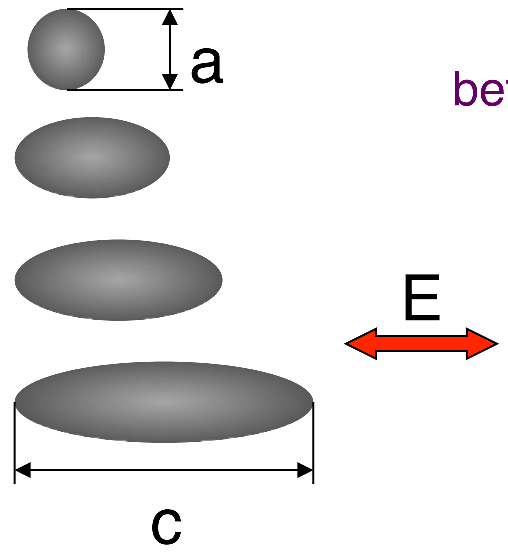
MAPS: **Applied Physics Letters** 105, 0831091 (2014).
Patent. – 2013.

Non-spherical nanoparticles

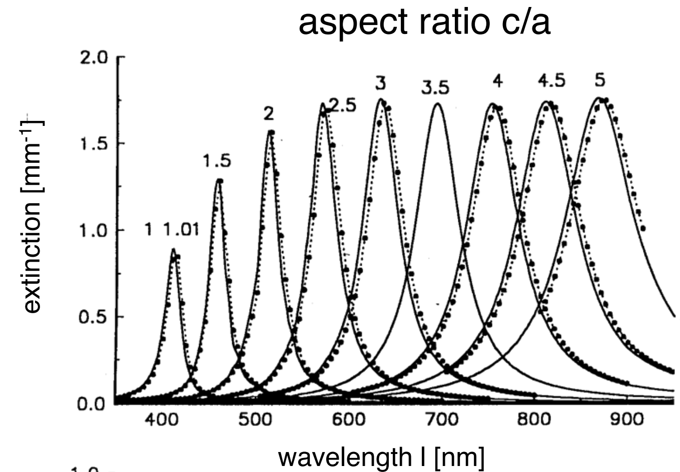
SPR position is size & **shape** dependent. Therefore metal nanoparticles with non-spherical shape should demonstrate <u>several SPR</u> in their spectra.

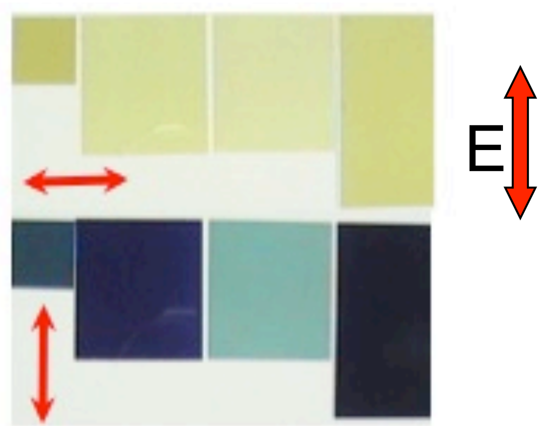


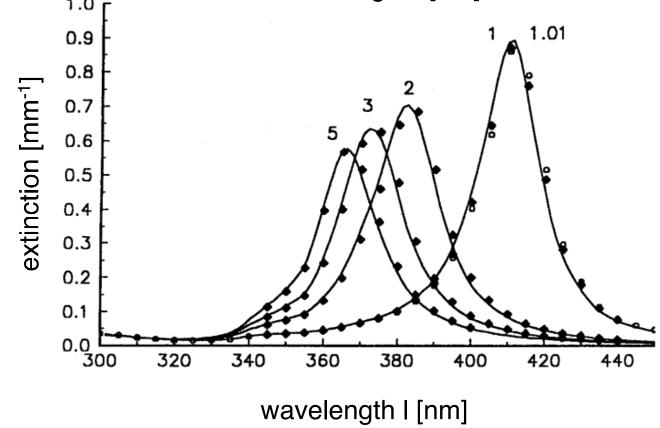
Polarised extinction spectra of spherical & spheroidal silver particles in glass



Increase of the aspect ratio leads to the rise of spectral separation between SPRs in polarised spectra



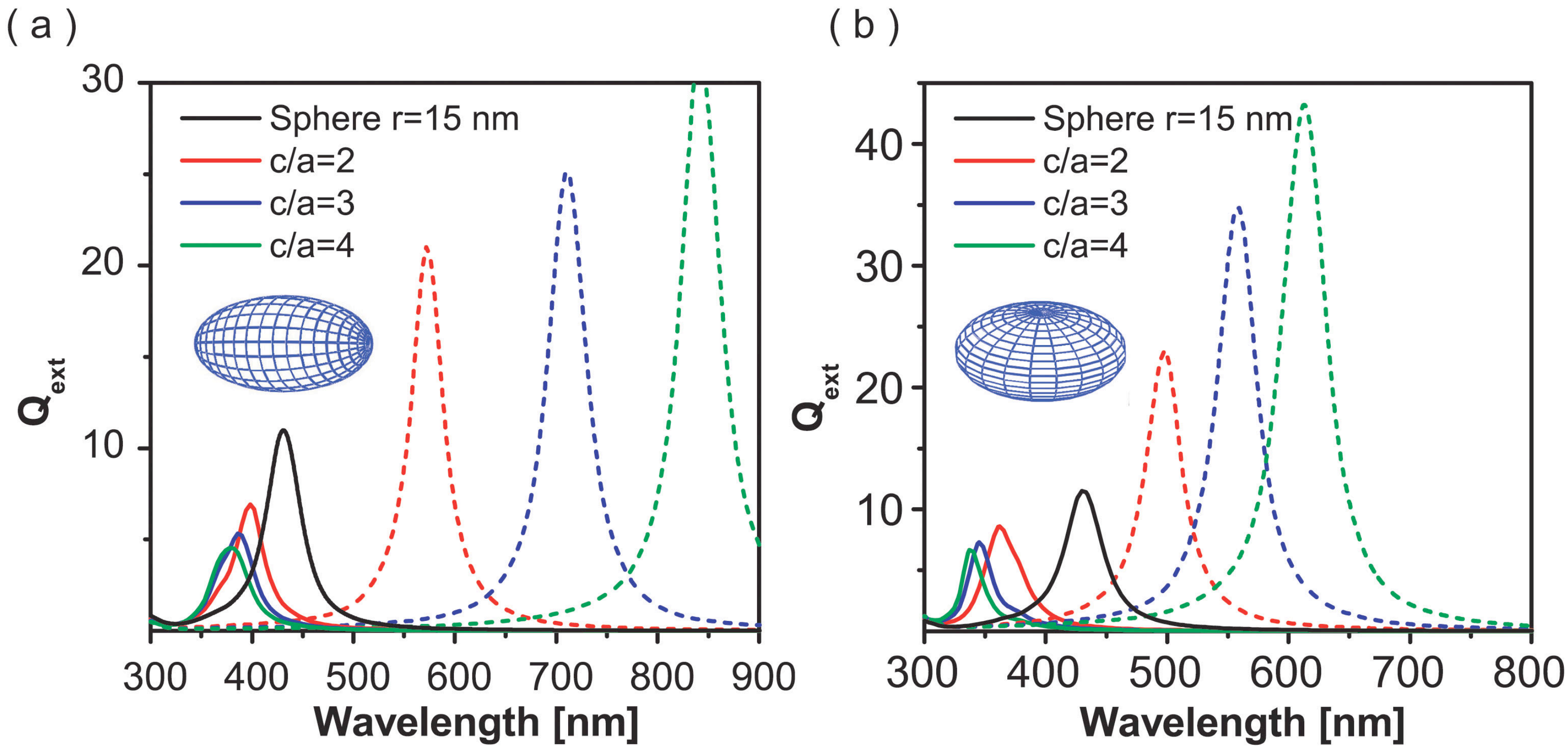




Non-spherical nanoparticles

Mie theory for silver spheroids embedded in glass - with different aspect ratios

Polarization extinction spectra for (a) **prolate** and (b) **oblate** silver spheroids



- The volume of the spheroids is equal to the volume of a nanosphere with radius of 15 nm;
- **Dashed curves:** polarization of the light is **parallel** to the **long axis**;
- **Solid curves:** polarization of the light is **parallel** to the **short axis**.

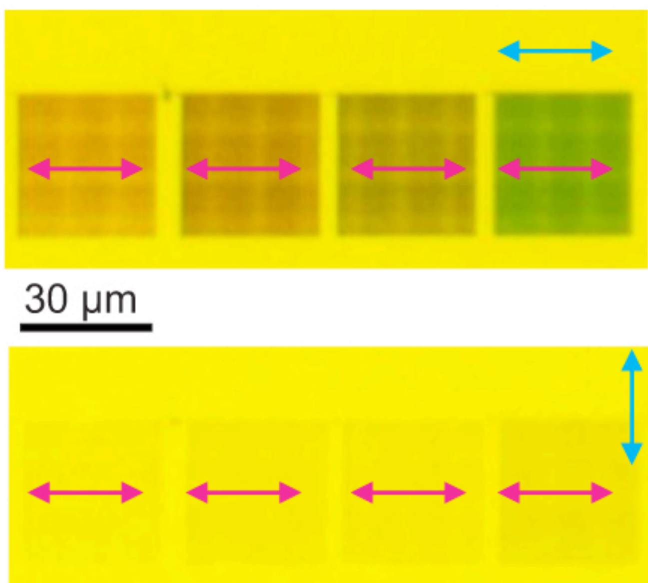
Astrophys. Space Sci. **204**, 19 (1993).

Non-spherical nanoparticles

Femtosecond laser irradiation of glass with embedded silver nanoparticles

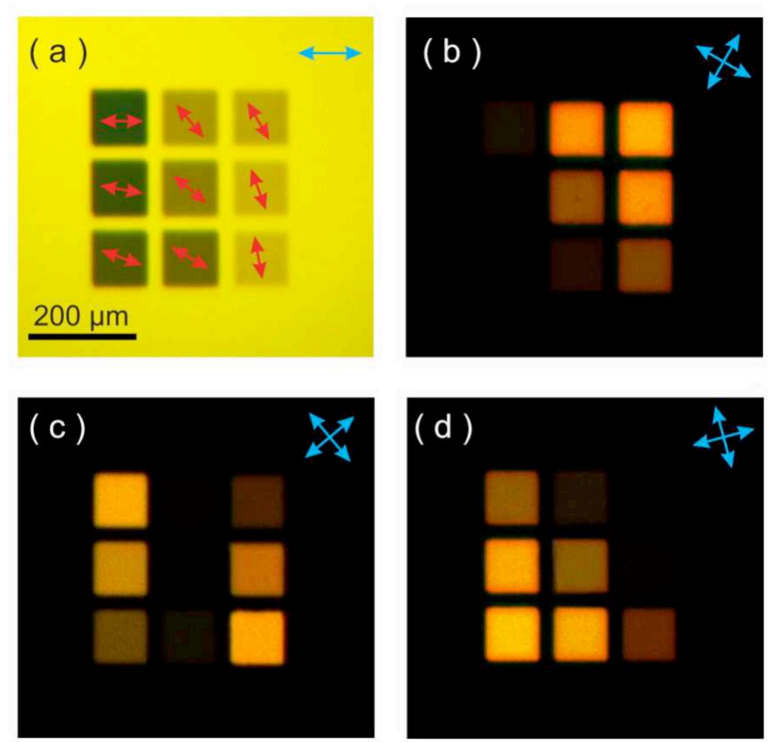
Case in point

Wavelength: 515 nm
Pulse length: ~ 300 fs
Laser fluence: ~ 30 mJ/cm^2
Dichroic spots: ~ 500 nm
left to right: 200, 300, 400, 500 pulses per spot



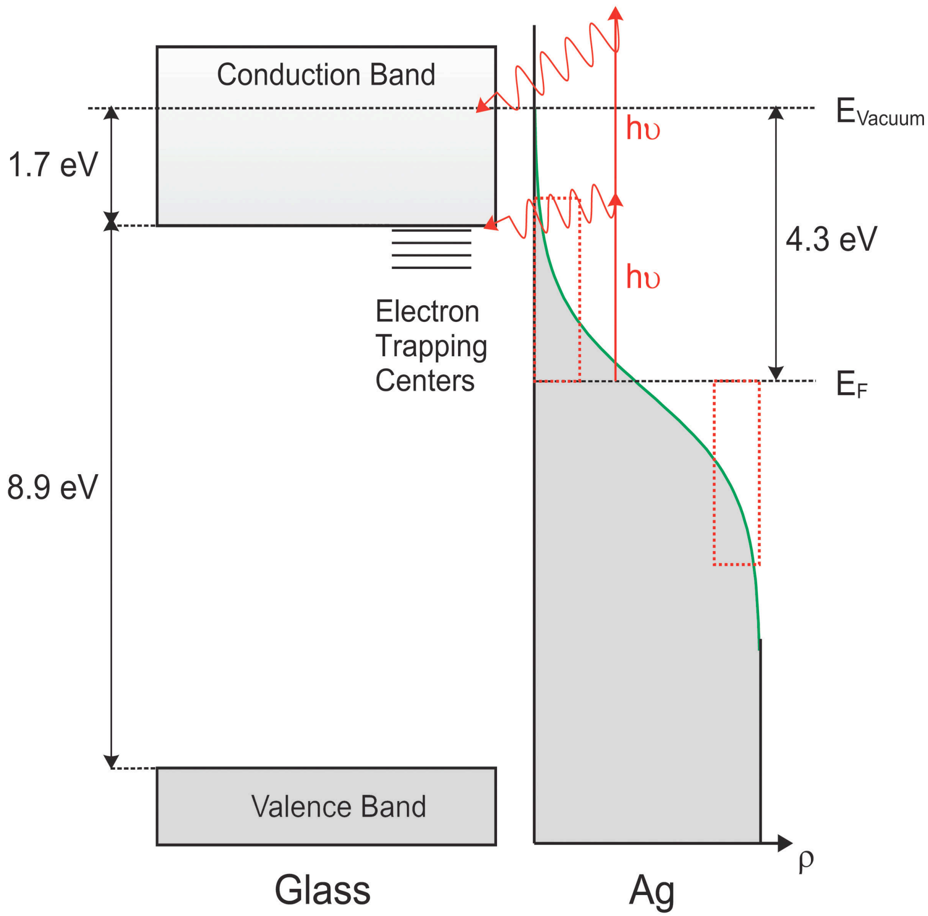
: Laser polarization
: Readout polarizer

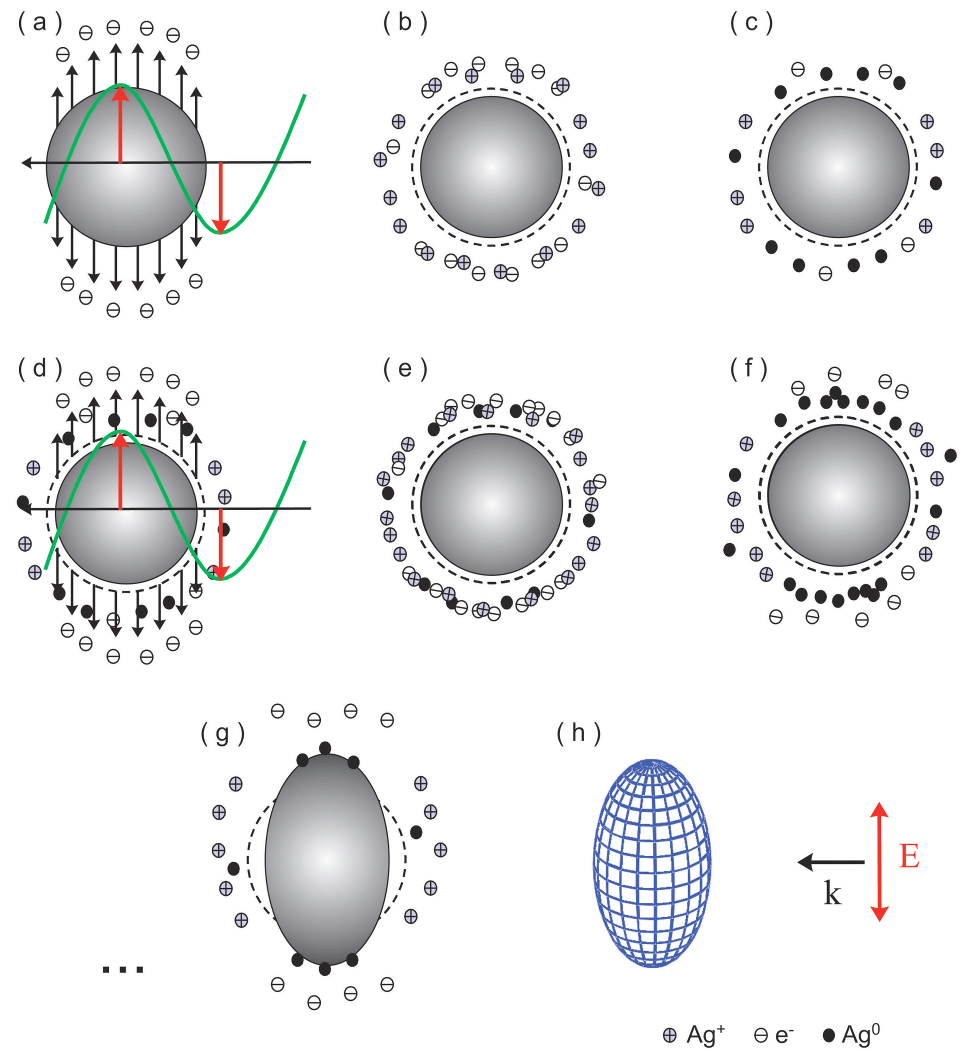
(a) Horiz. Pol. 0^0
(b) Cross Pol. 20^0
(c) Cross Pol. 45^0
(d) Cross Pol. 70^0



- MAPS: **Applied Physics Letters** 99, 201904 (2011).

Energy level scheme of the electrons in a composite glass containing silver inclusions. The red dotted line indicates a non-thermal distribution of the electrons in the Ag nanoparticle caused by excitation of SPR. Green line –distribution of the electrons after thermalisation.

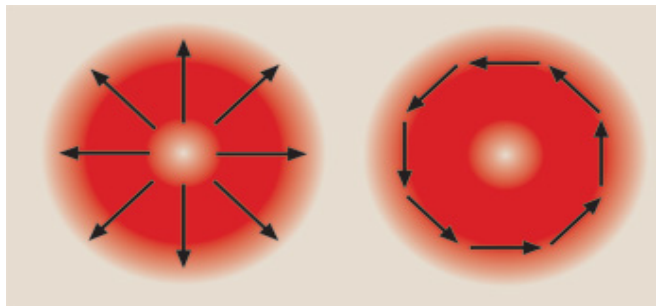


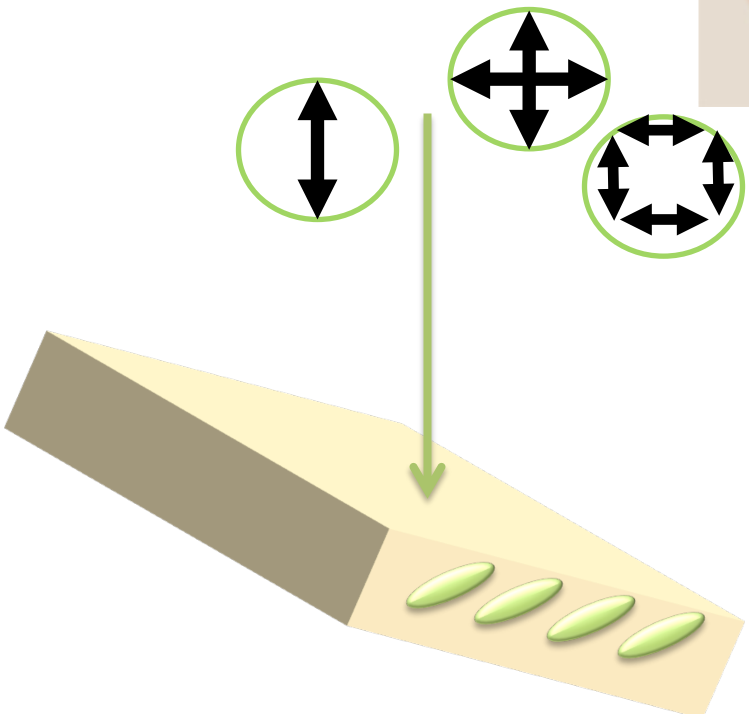


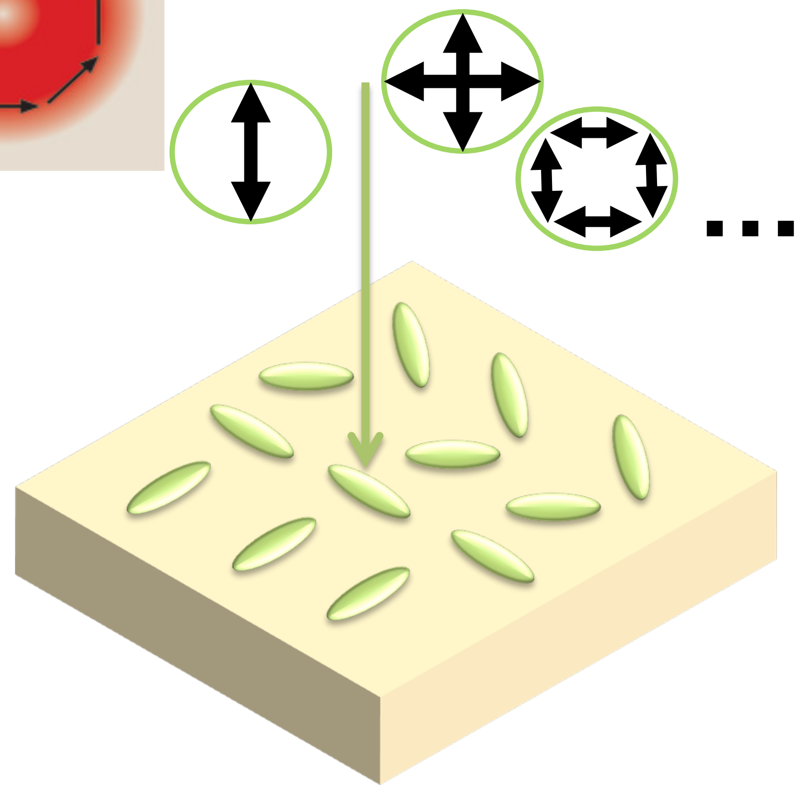
A.Stalmashonak, G.Seifert and A. Abdolvand
Ultra-Short Pulsed Laser Engineered Metal-Glass Nanocomposites in **SpringerBriefs in Physics** (June 2013).

More advanced nanoparticle re-shaping …

We are looking at more esoteric polarisation states for a range of applications:
radial and azimuthal polarisation







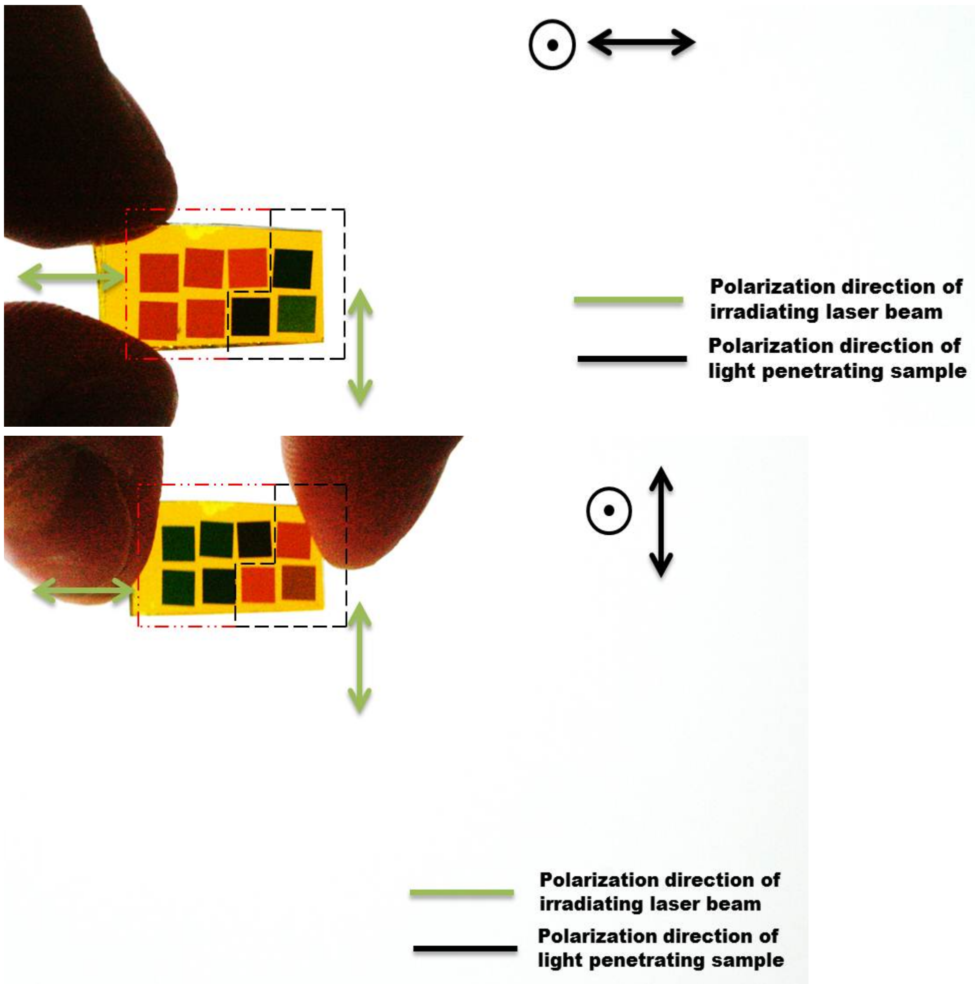
Mateusz A. Tyrk's

work at Dundee

ESR Marie Curie Fellow

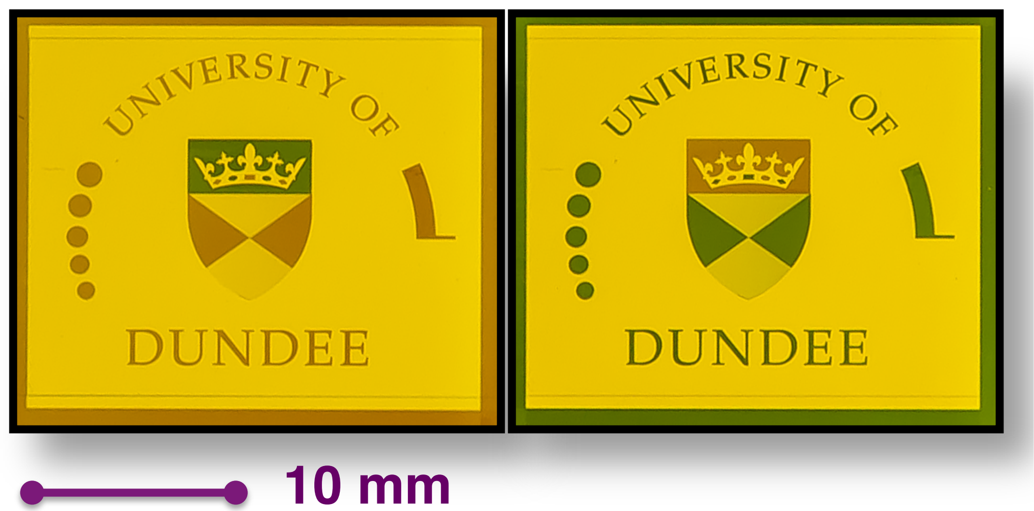
Non-spherical nanoparticles

Picosecond laser irradiation of glass with embedded silver nanoparticles



Case in point

Wavelength: 532 nm
Pulse length: ~ 6 ps at 200 kHz
Laser fluence: ~ 0.3 J/cm^2
Focal spot diameter: 15 µm

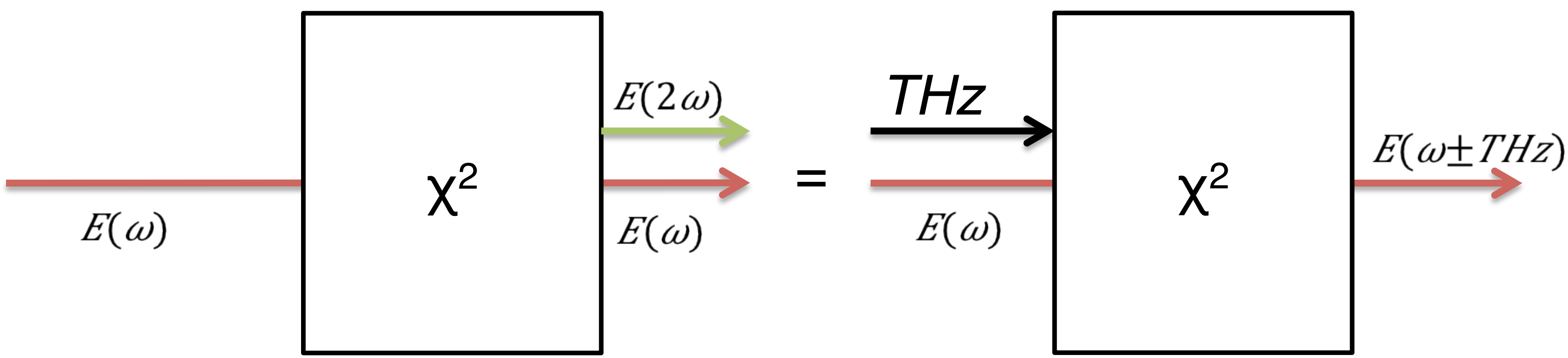


MAPS

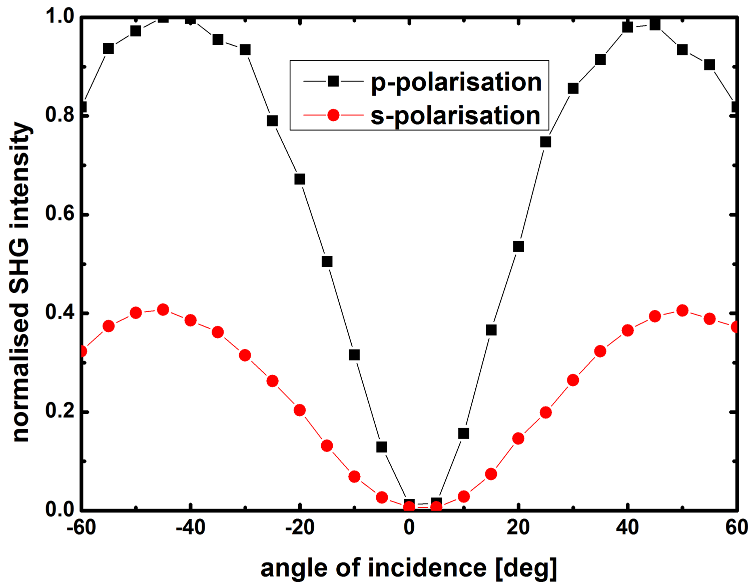
- Optics Express 21, 21823 (2013).

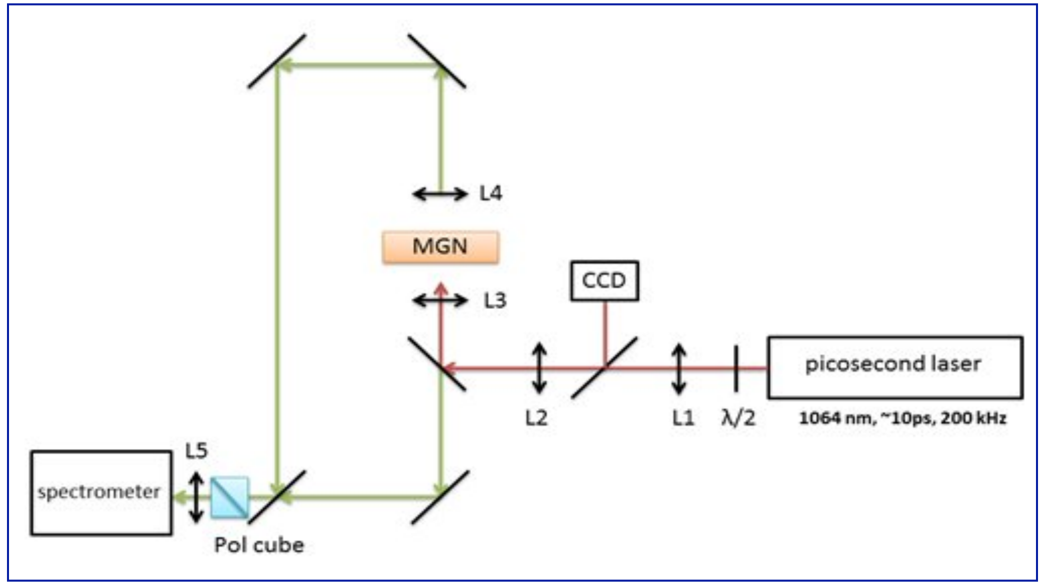
Second Harmonic Generation (SHG) observation

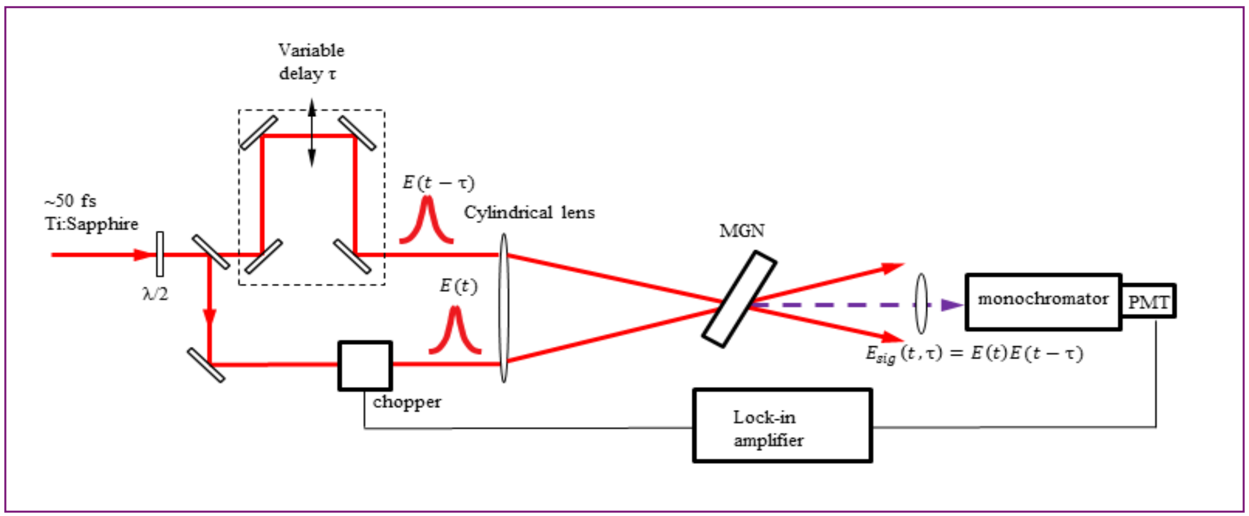
Due to the identical matrix elements in the susceptibility and EO tensors ε_{xx} and r_{52} , a good test of a useful EO effect is to measure SHG from these samples…..



Second Harmonic Generation (SHG) from laser-reshaped silver nanoparticles embedded in glass







Final stage

Results to be reported in June (Liverpool)

Further tests at **Daresbury Laboratory** with a THz antenna will verify the usefulness of our metamaterial (MGNs) for overcoming the challenge with the current EO materials (the bandwidth limitations).

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THANK YOU FOR YOUR ATTENTION!