Planar Chiral Metamaterials for Polarization Control

Yuri Svirko

Department of Physics and Mathematics, University of Joensuu, Joensuu, Finland

JOENSUUN YLIOPISTO

Jari Turunen
Markku Kuittinen
Benfeng Bai

THE UNIVERSITY OF TOKYO

Makoto Gonokami
Kuniaki Konishi

ACADEMY OF FINLAND

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Core Research of Evolutional Science & Technology
Solution-Oriented Research for Science and Technology

OUTLINE

1. Introduction: planar chiral metamaterials

2. Metal nanogratings

3. All-dielectric nanogratings

4. Magneto-optic effects

5. Concluding remarks

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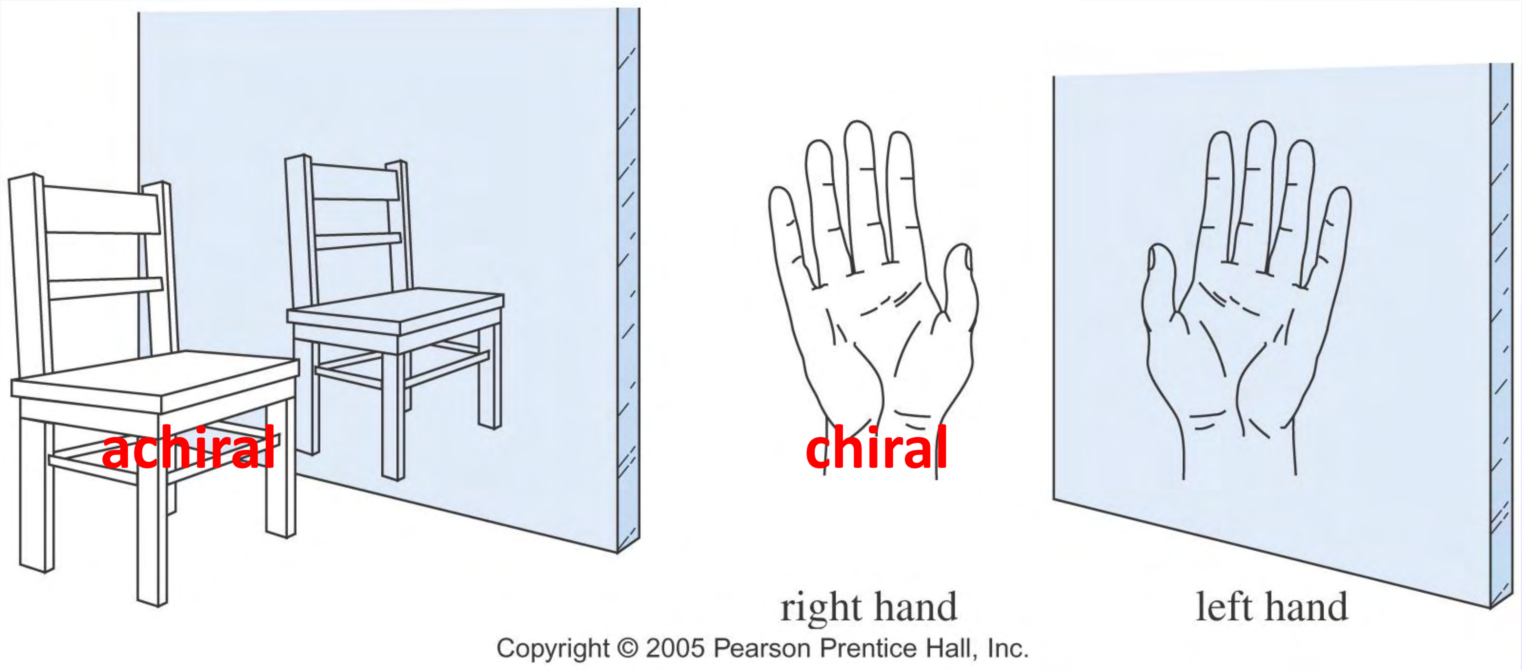
What is Chirality?

- "Handedness": right glove doesn't fit the left hand.
- Mirror-image object is different from the original object.



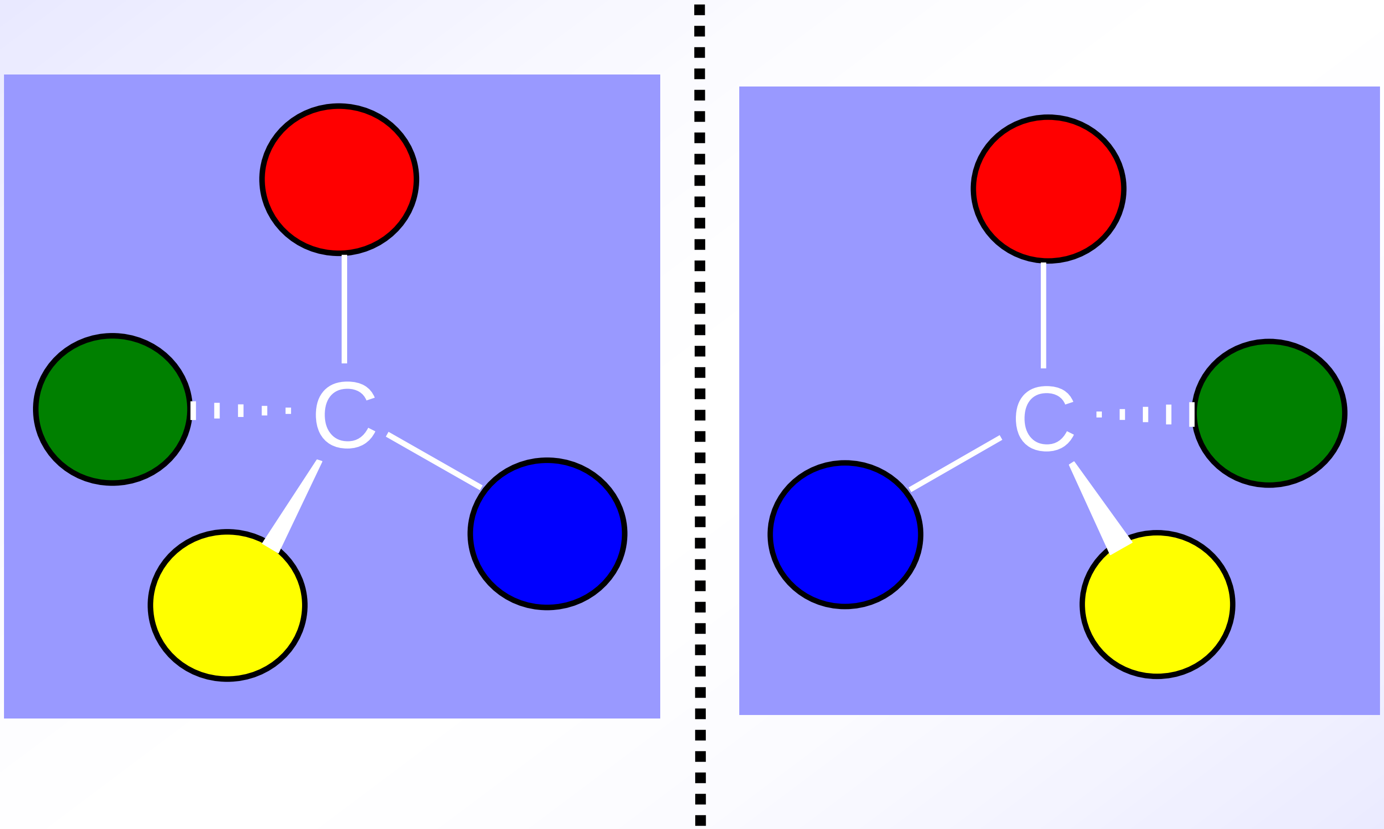
1. *Introduction*

- An object is "chiral" if and only if it is <u>not</u> super imposable on its mirror image.
- The lack of a plane of symmetry is called chirality or handedness

Wikipedia:
Handedness is an attribute of human beings defined by their unequal distribution of fine motor skill between the left and right hands.

- Two not super-imposable forms of a chiral object are called ENANTIOMERS

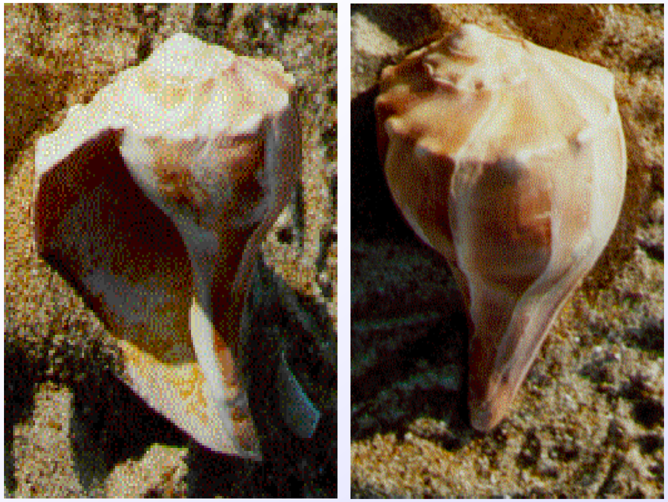
A pair of enantiomeric chiral molecules



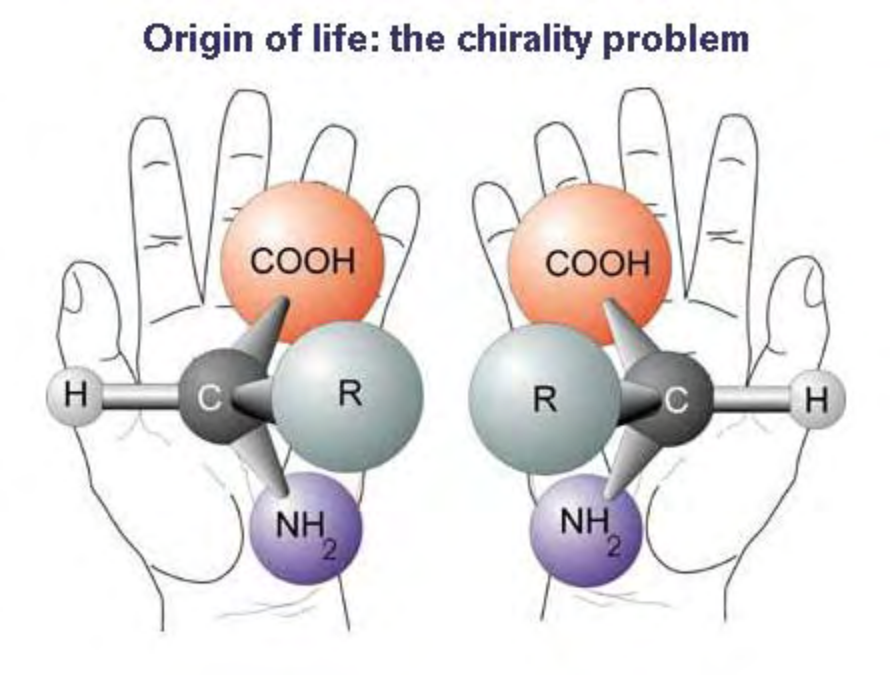
Mirror plane

Knobbed Whelk
Almost always “right handed”

Lightning Whelk
Almost always “left handed”

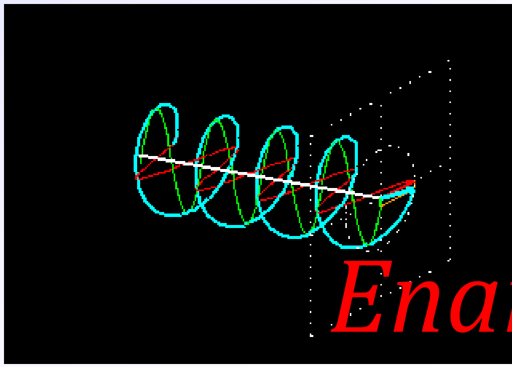


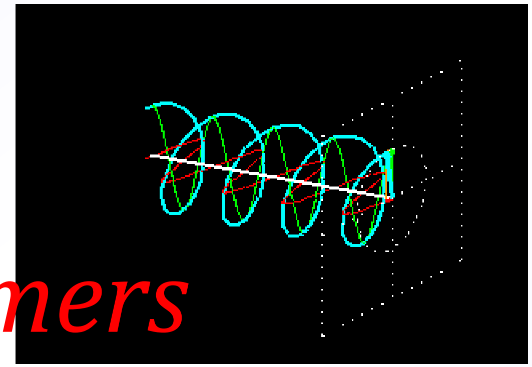
HOMOCHIRALITY
Amino acids in proteins are always LEFT-HANDED
Sugars in DNA and RNA are always RIGHT-HANDED



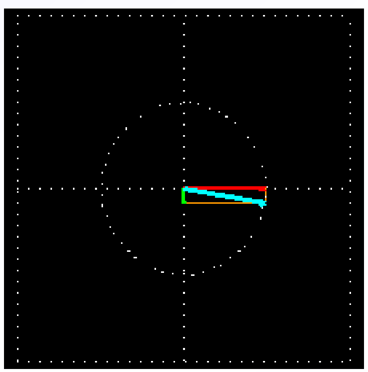
The reason these molecules have such a uniform chirality is not known, but there is no shortage of theories on the subject.

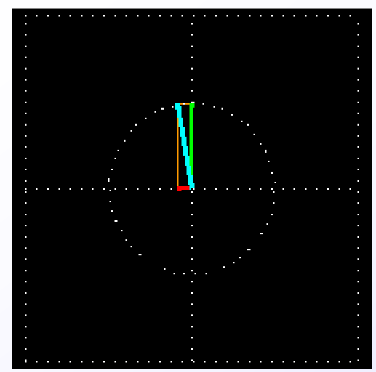
Jon Cohen, *Science,* 1995, 267 (5202), 1265-6





Enantiomers



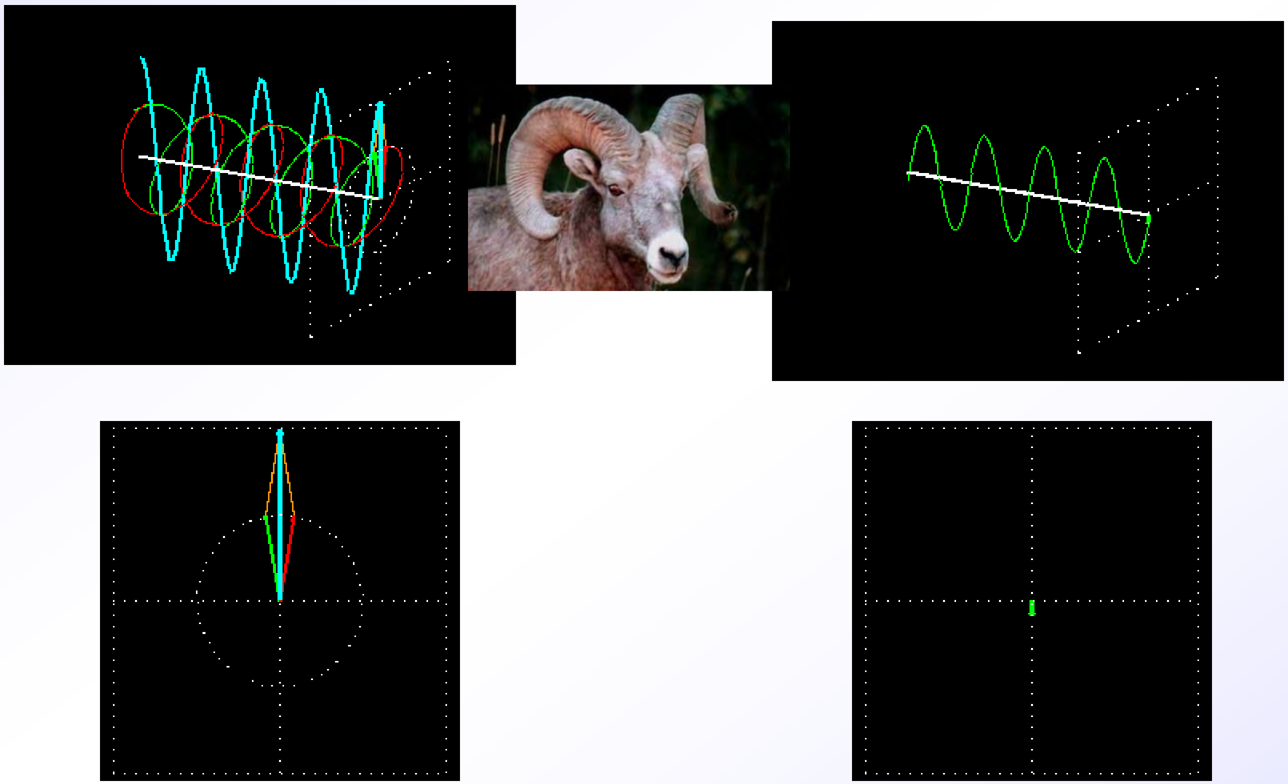


Right circular polarization produces a right threaded screw.

Left circular polarization produces a left threaded screw.

1. *Introduction*

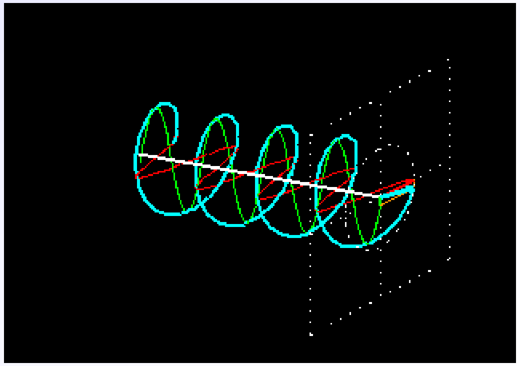
Linearly Polarized Light



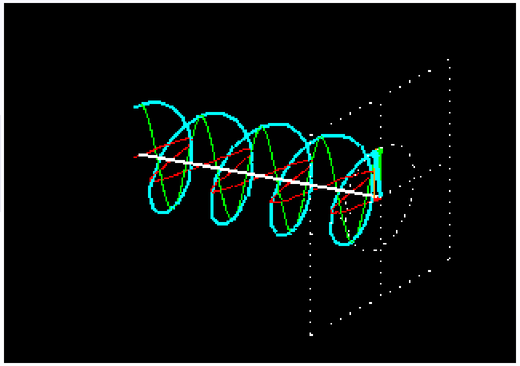
Superposition of left- and right circularly polarized waves of the same amplitude gives an achiral linear polarized light wave

1. *Introduction*

RCP



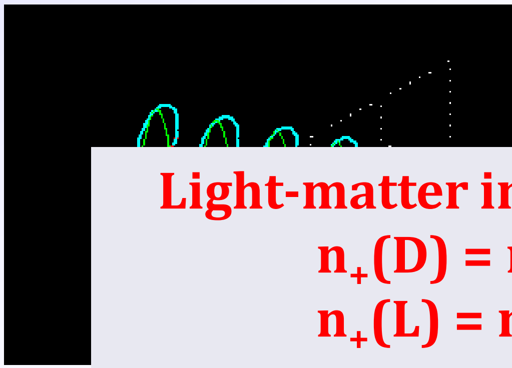
LCP

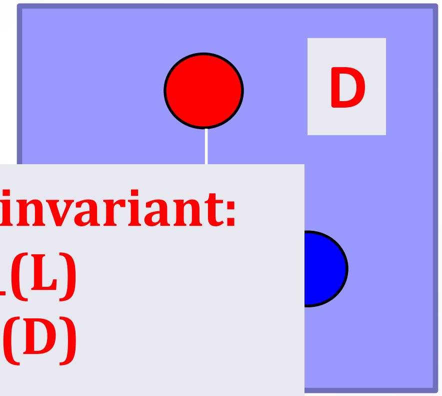


In a chiral medium, left- and right-circular polarized light interacts with medium differently. The difference is a measure of the chiral influence, which can be visualized by comparing the polarization state of the light before and after interaction.

Direct scenario: RCP wave interacts with D-molecule

RCP





Light-matter interaction is PT-invariant:

$n_+(D) = n_-(L) \quad \alpha_+(D) = \alpha_-(L)$

$n_+(L) = n_-(D)\,,\ \alpha_+(L) = \alpha_-(D)$

Natural optical activity

$\phi \propto n_+ - n_- \Rightarrow \phi(L) = -\phi(D)$

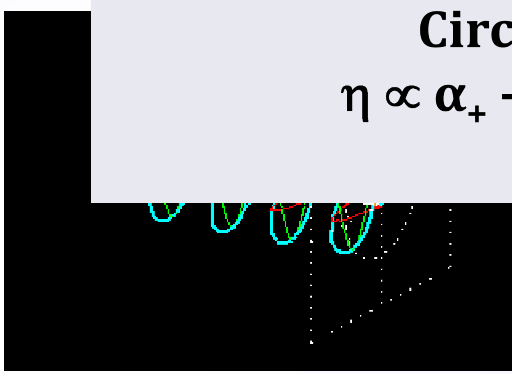
Circular dichroism

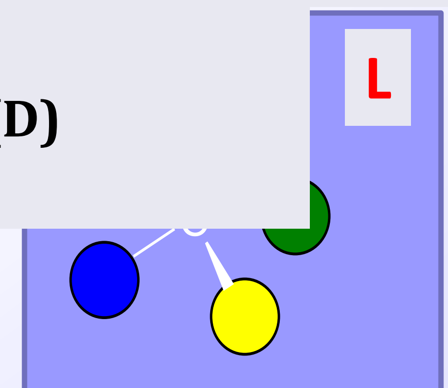
$\eta \propto \alpha_+ - \alpha_- \Rightarrow \eta(L) = -\eta(D)$

PT-rev

cule

LCP





1. *Introduction*

Natural optical activity

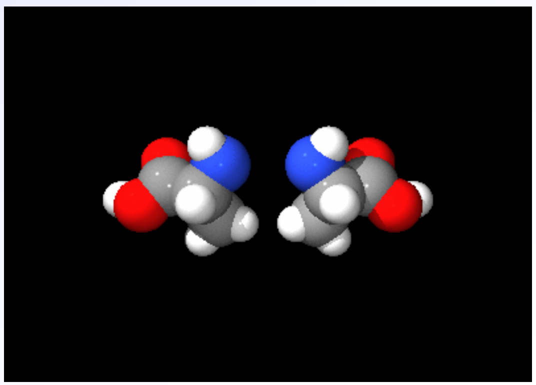
Polarization rotation and circular dichroism are induced by molecular chirality

Natural optical activity

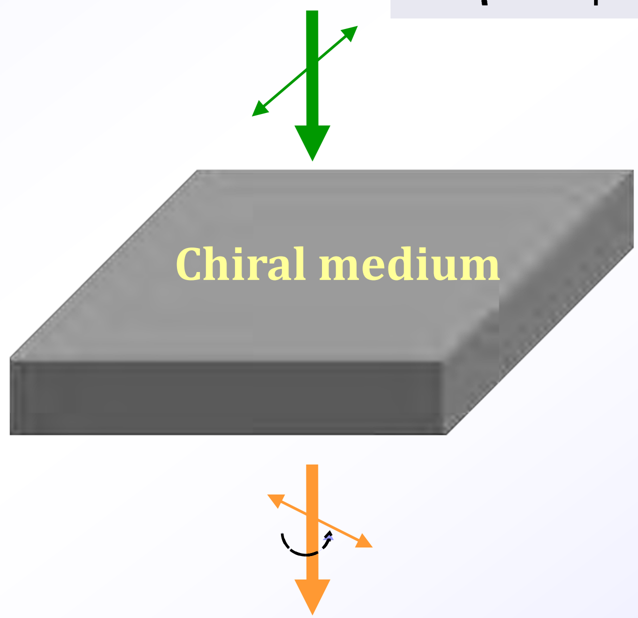
$$\phi \propto n_+ - n_- \Rightarrow \phi(L) = -\phi(D)$$

Circular dichroism

$$\eta \propto \alpha_+ - \alpha_- \Rightarrow \eta(L) = -\eta(D)$$



A pair of enantiomeric chiral molecules



Constitutive equation

$$\boldsymbol{D} = \varepsilon \boldsymbol{E} + i\gamma \boldsymbol{k} \times \boldsymbol{E}$$

Reciprocal effect

Molecular chirality - - - - - - - - - - - → Optical activity

Can interaction of light with 2D chiral object lead to the optical activity of circular dichroism?

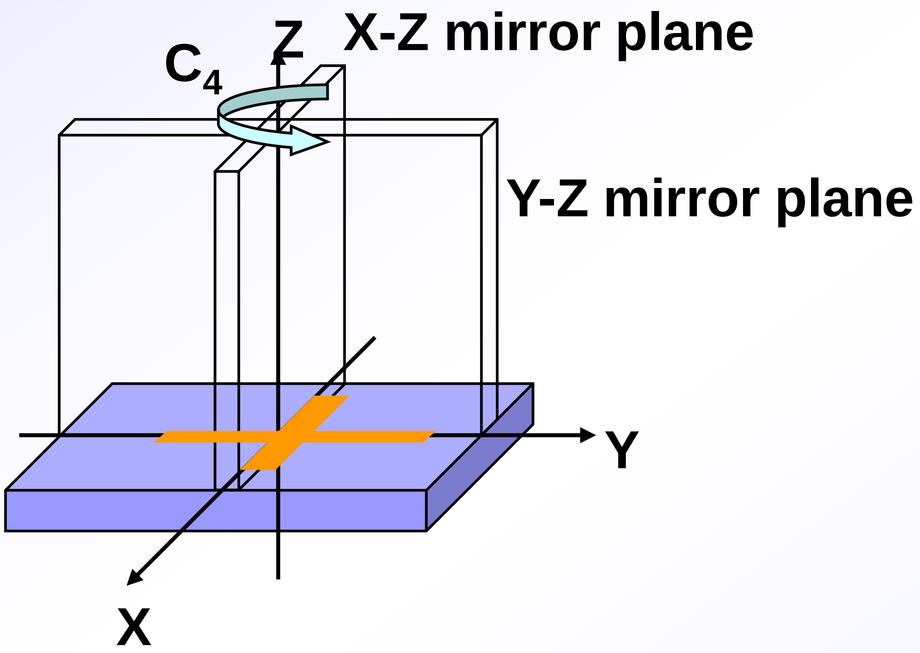
The answer is NO.
2D object in 3D space has a plane of symmetry
$\Rightarrow$ NO CHIRALITY

A film with a set of holes of arbitrary shape have the same transmission coefficients for left- and right-circular polarized waves

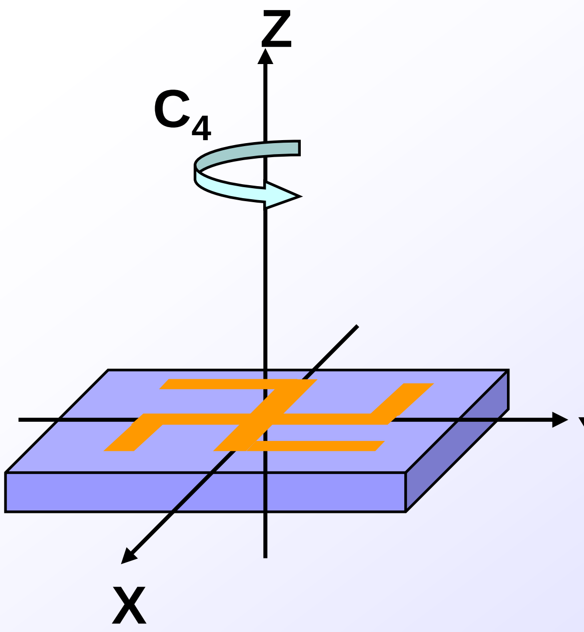
Nonsuperimposable

1. *Introduction*

In a planar structure, in-plane mirror symmetry is broken by the substrate

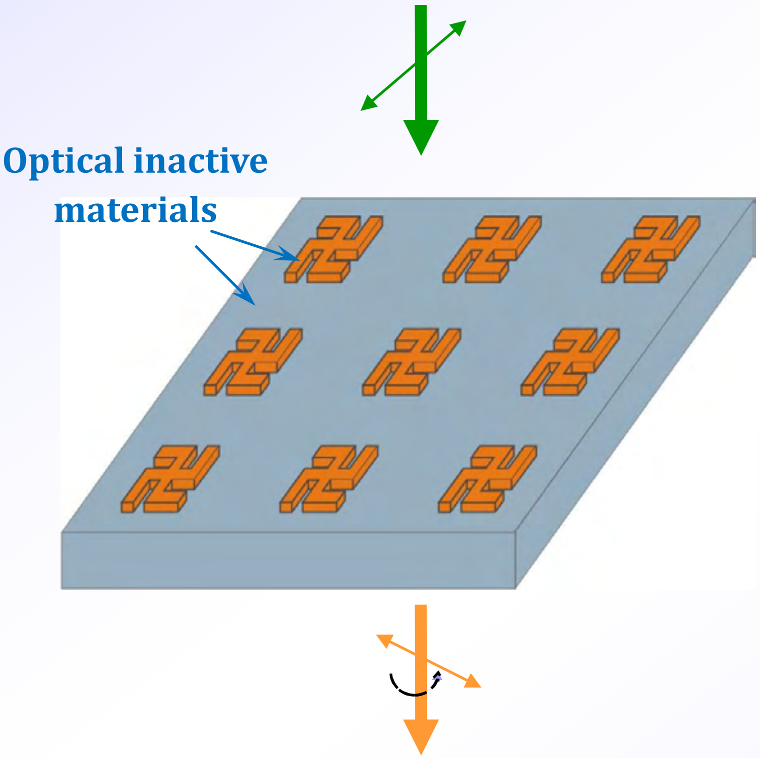


Planar achiral object



Planar chiral object

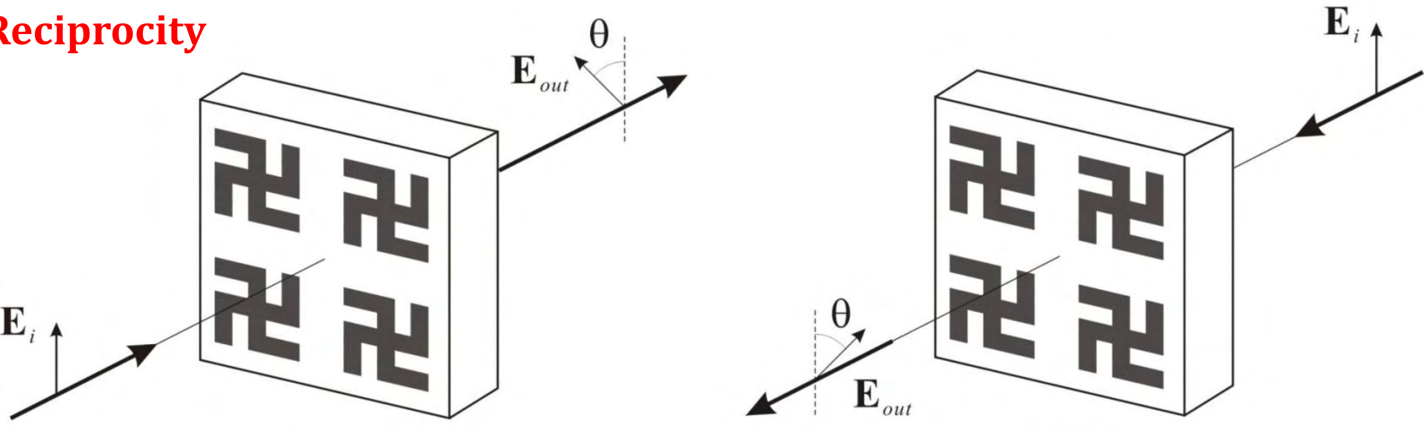
Artificial optically active nanostructured material



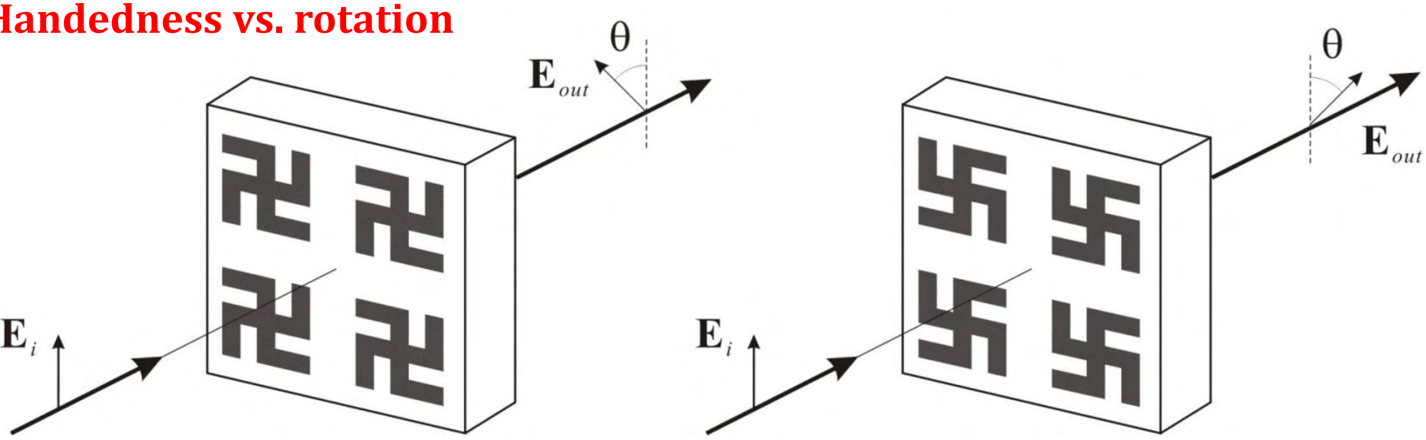
- Array of gammadion nanoparticles with C_4 symmetry
- Resembles chiral uniaxial crystal
- Chirality comes from the pattern
- Optical activity enhanced by optical resonances (such as SP resonance)
- Works in the visible and near-IR spectral range

Basic properties

(1) Reciprocity

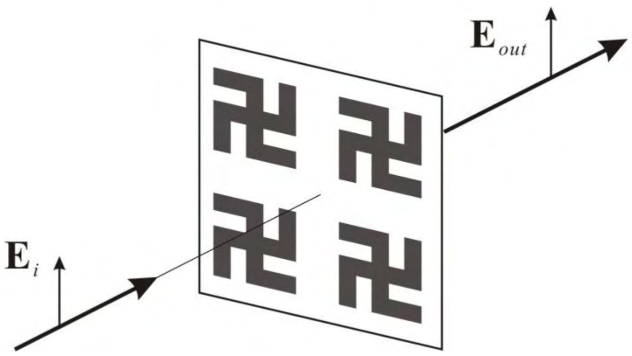


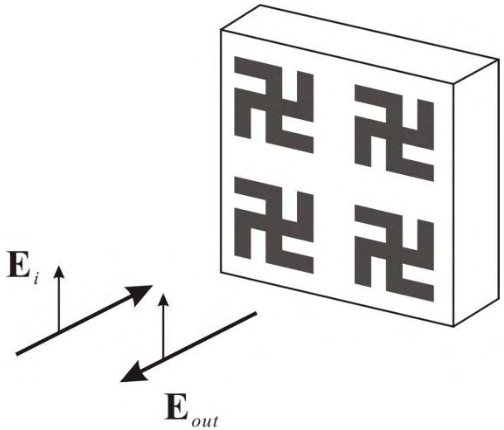
(2) Handedness vs. rotation



(3) $\theta = 0$ in presence of the symmetry plane

(4) $\theta = 0$ in reflected light

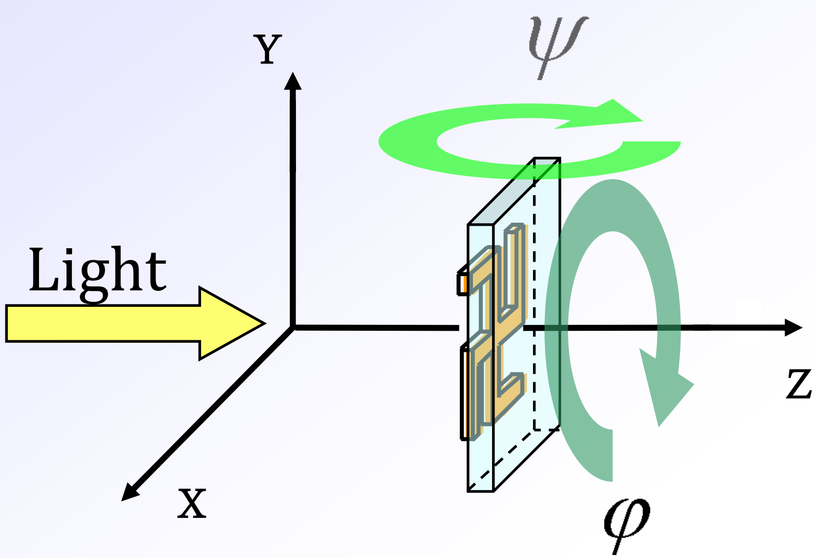




(5) The effect does not depend on the incident polarization direction (due to the C_4 symmetry)

1. *Introduction*

Effective parameters



$$\varepsilon_{ij}^{effective} = \begin{pmatrix} n^2 - \Omega & \delta & 0 \\ -\delta & n^2 + \Omega & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}$$

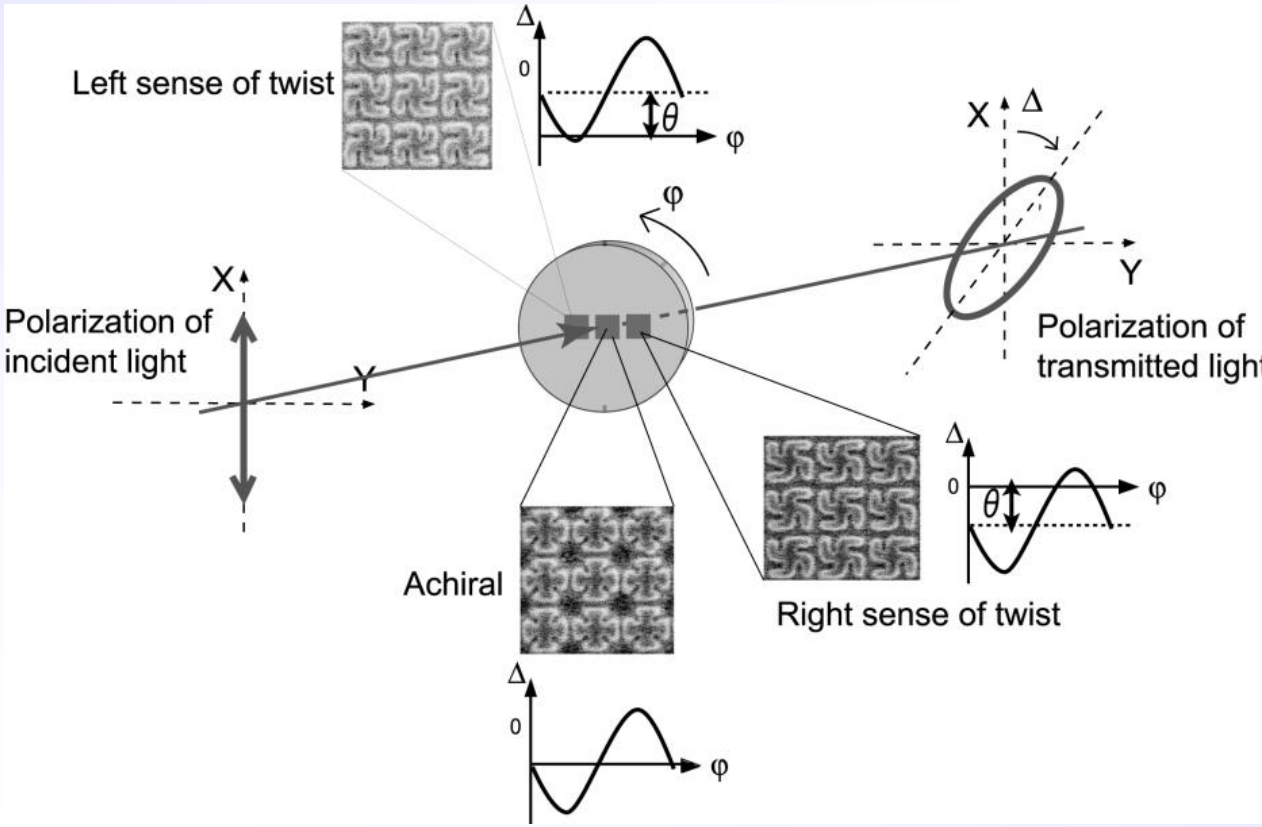
Polarization rotation angle *Δ*

$$\Delta \approx \frac{\omega L}{2nc} \operatorname{Im} \left\langle \left\{ \delta \left[1 + \psi^2 \left(\frac{1}{2} - \frac{n^2}{\varepsilon} \right) \right] + \Lambda \Omega \sin\ 2\varphi + \alpha\ - \frac{\psi^2}{2\varepsilon} \Omega^2 \sin 4\varphi \right\} \right\rangle$$

$$\Lambda = \sqrt{\left(\delta \frac{\psi^2}{\varepsilon} \right)^2 + \left[1 + \psi^2 \left(\frac{1}{2} - \frac{n^2}{\varepsilon} \right) \right]^2} \qquad \sin \alpha = \delta \frac{\psi^2}{\varepsilon \Lambda} \qquad \cos \alpha = \frac{1}{\Lambda} \left[1 + \psi^2 \left(\frac{1}{2} - \frac{n^2}{\varepsilon} \right) \right]$$

2. Metal grating

Experiment



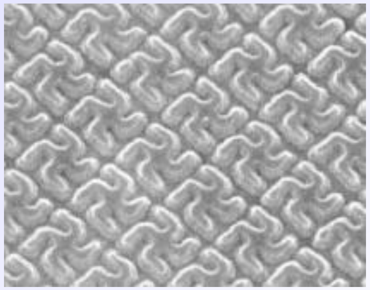
$$\varepsilon_{ij}=\begin{pmatrix} n^2-\Omega & \delta & 0 \\ -\delta & n^2+\Omega & 0 \\ 0 & 0 & \varepsilon \end{pmatrix}$$

Polarization rotation at normal incidence

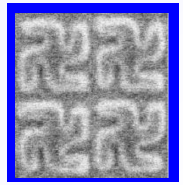
$$\Delta \approx \frac{\omega L}{2nc}\,\mathrm{Im}\;\delta+\Omega\sin 2\varphi$$

2. *Metal grating*

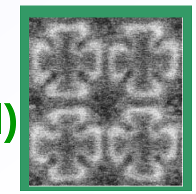
Plasmon enhancement



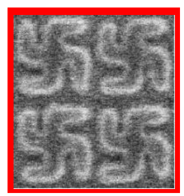
Left (chiral)



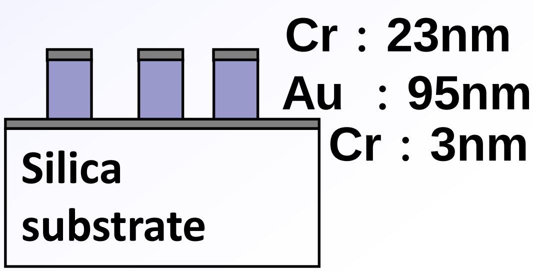
Cross (achiral)

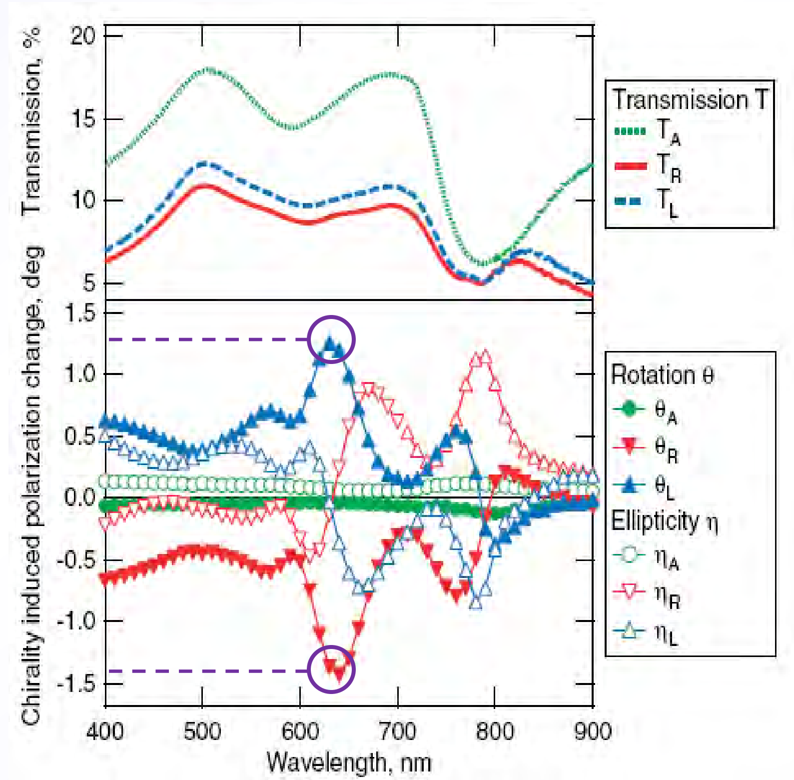


Right (chiral)



Sample side view





Large polarization rotation (~10^4 º/mm) enhances by the surface plasmon resonance

Transmission vs rotation spectra

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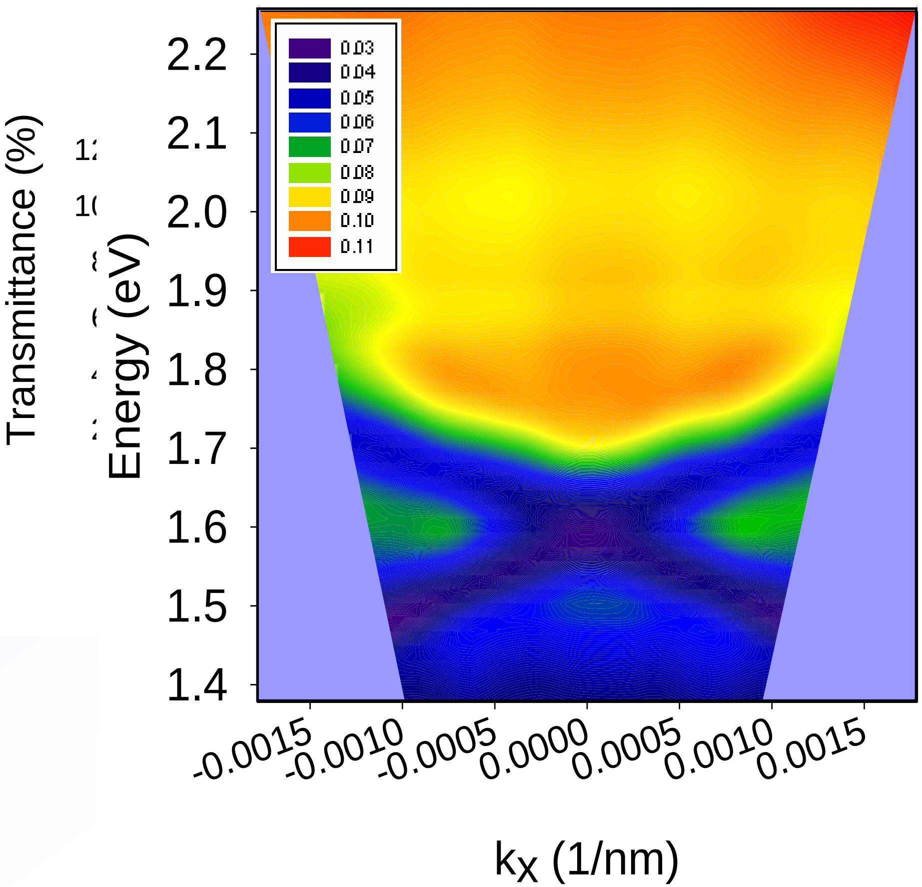
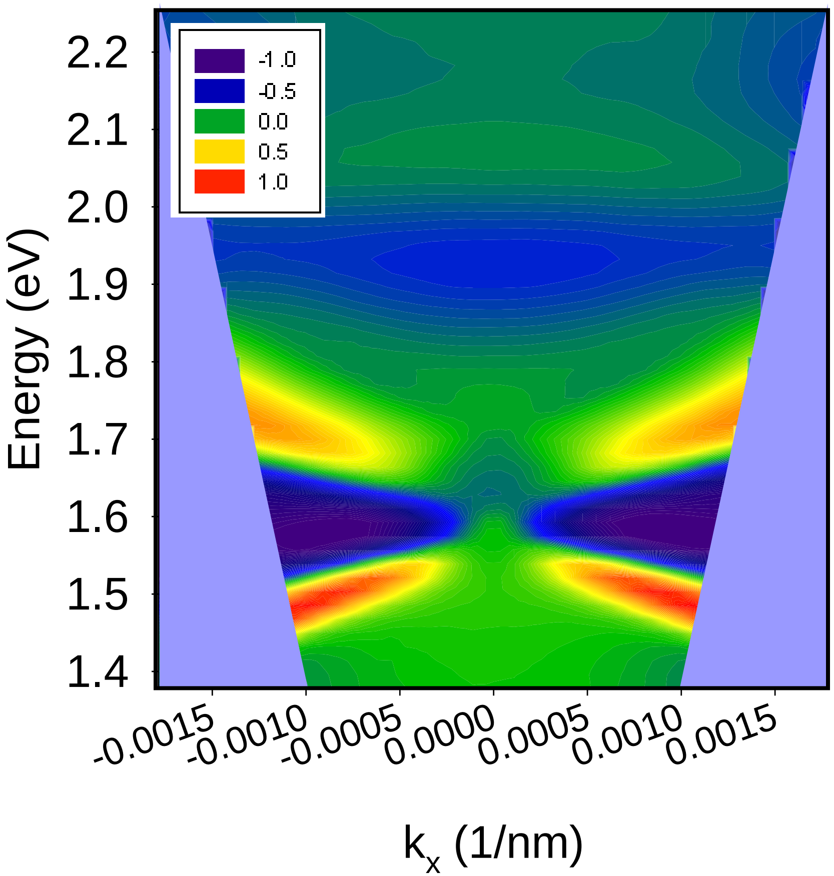
Transmission $\propto$ ε



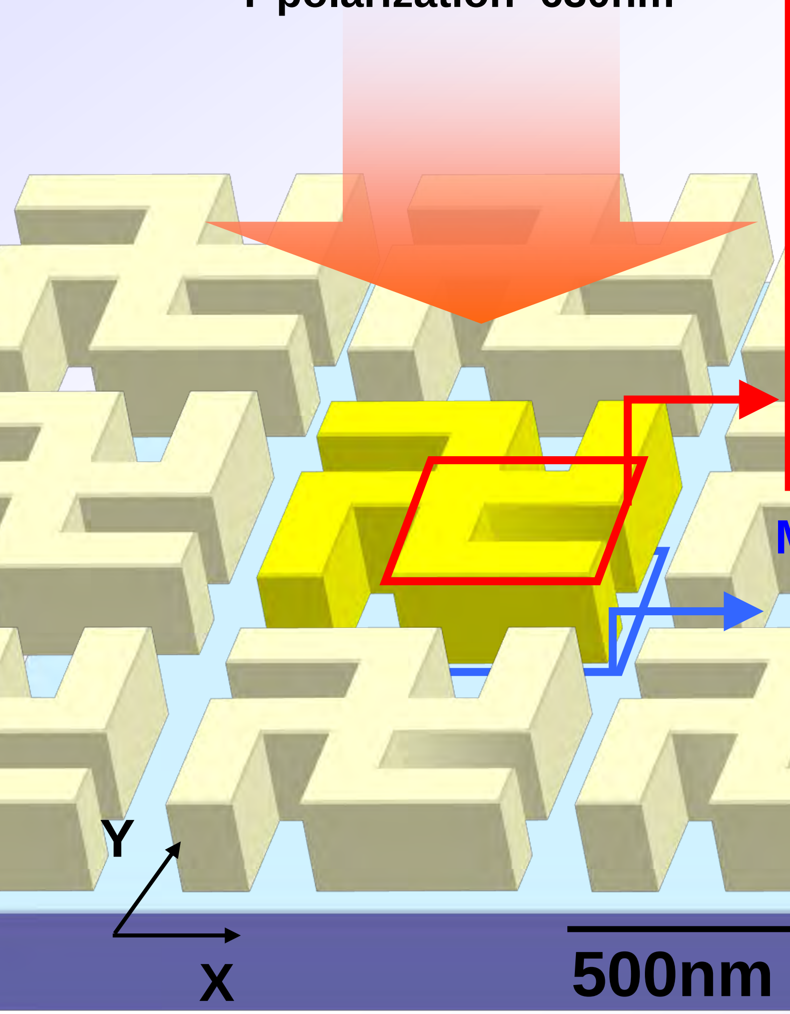
Polarization rotation $\propto$ δ



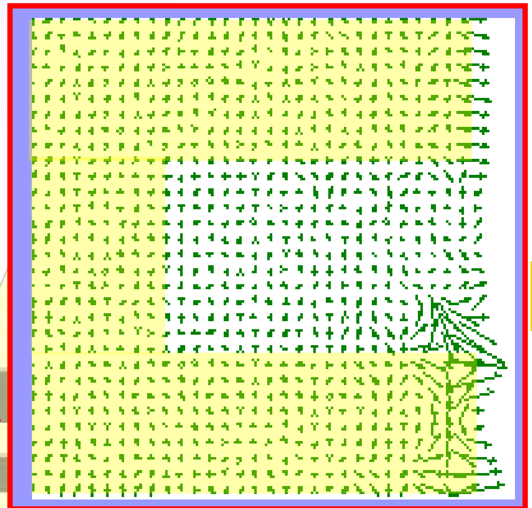
2. Metal grating

Local electric filed

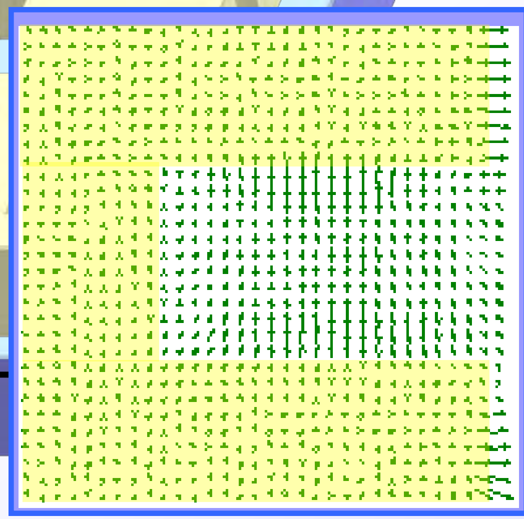
Y-polarization 630nm



Air-Metal interface



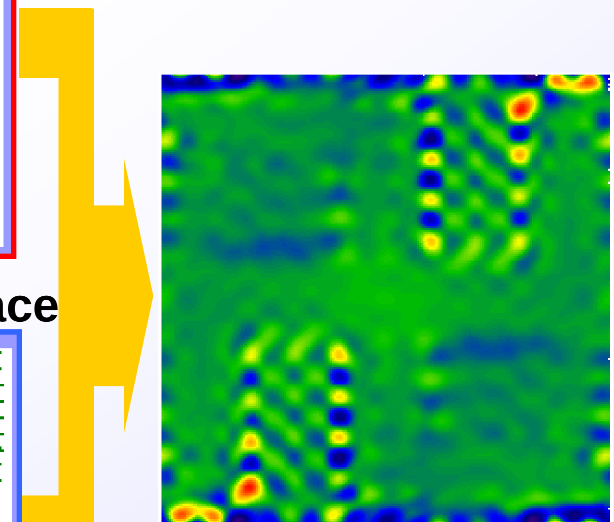
Metal-Substrate interface

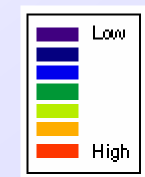


Non-parallel electric field at both interface

$$\mathbf{n}\cdot \mathbf{E}^{air} \times \mathbf{E}^{sub} =$$

$$\mathrm{Re}\ E_x^{air} E_y^{sub} - E_y^{air} E_x^{sub}$$



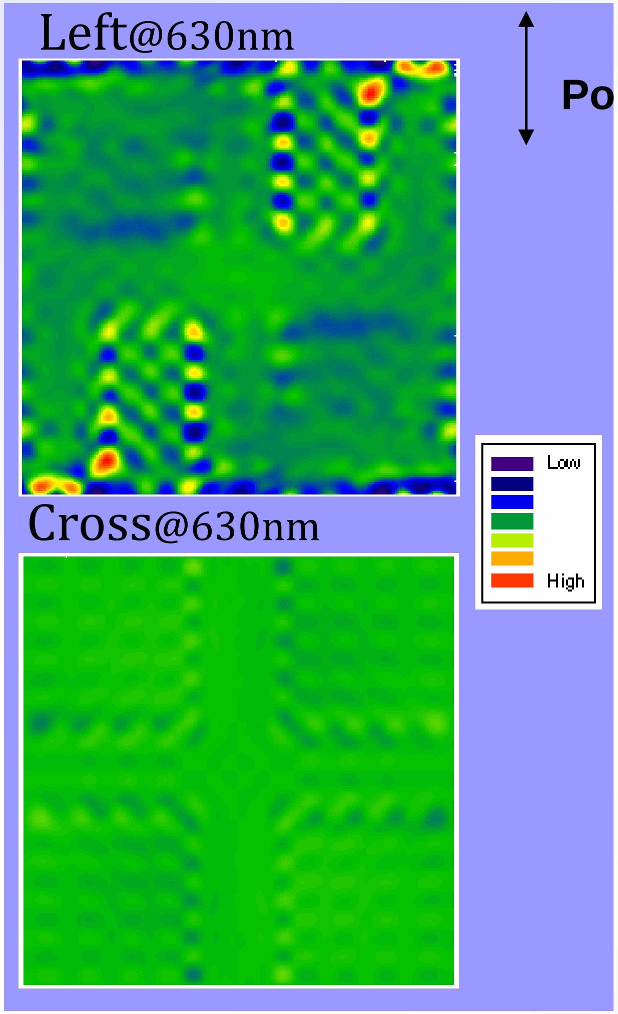


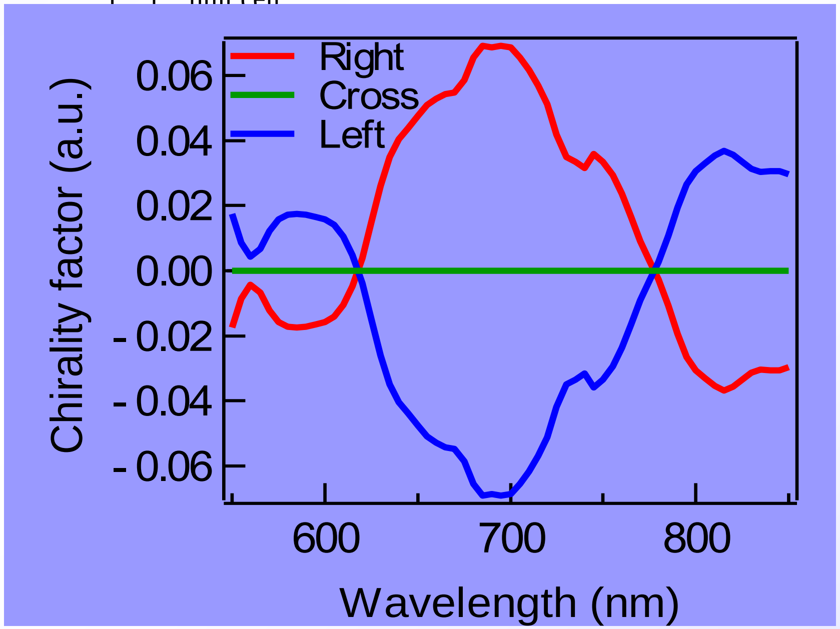
2. Metal grating

Chirality factor

$$\mathrm{Re}\left[E_x^{air}E_y^{sub}-E_y^{air}E_x^{sub}\right]$$

$$\frac{1}{A|\mathbf{E}|^2}\int_{\text{unit cell}}\mathrm{Re}\left[E_x^{air}E_y^{sub}-E_y^{air}E_x^{sub}\right]dxdy$$





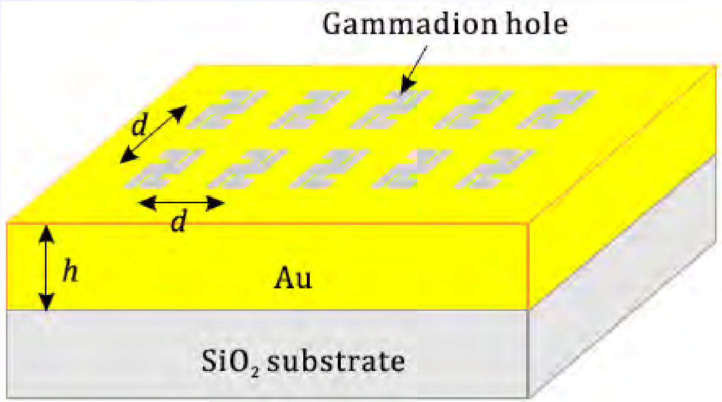
Left, Right $\neq$ 0

Cross =0

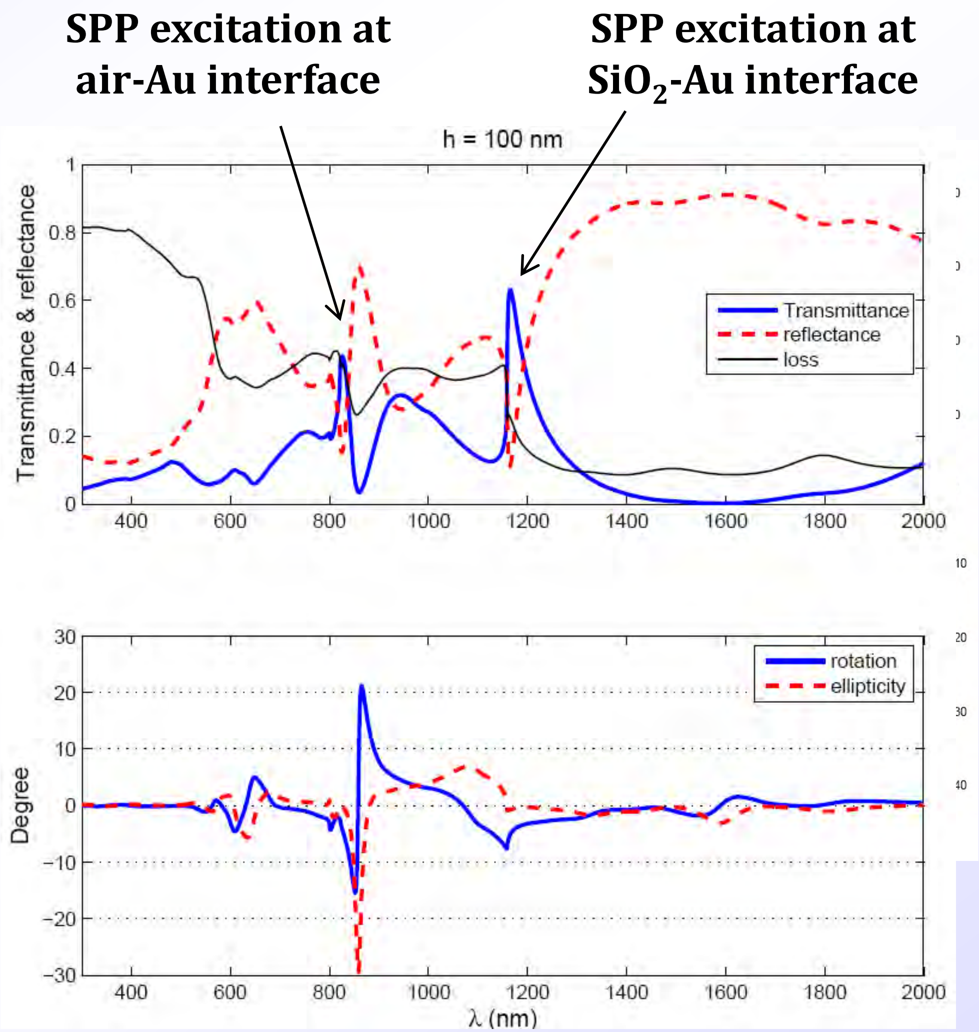
2. *Metal grating*

Complimentary structure

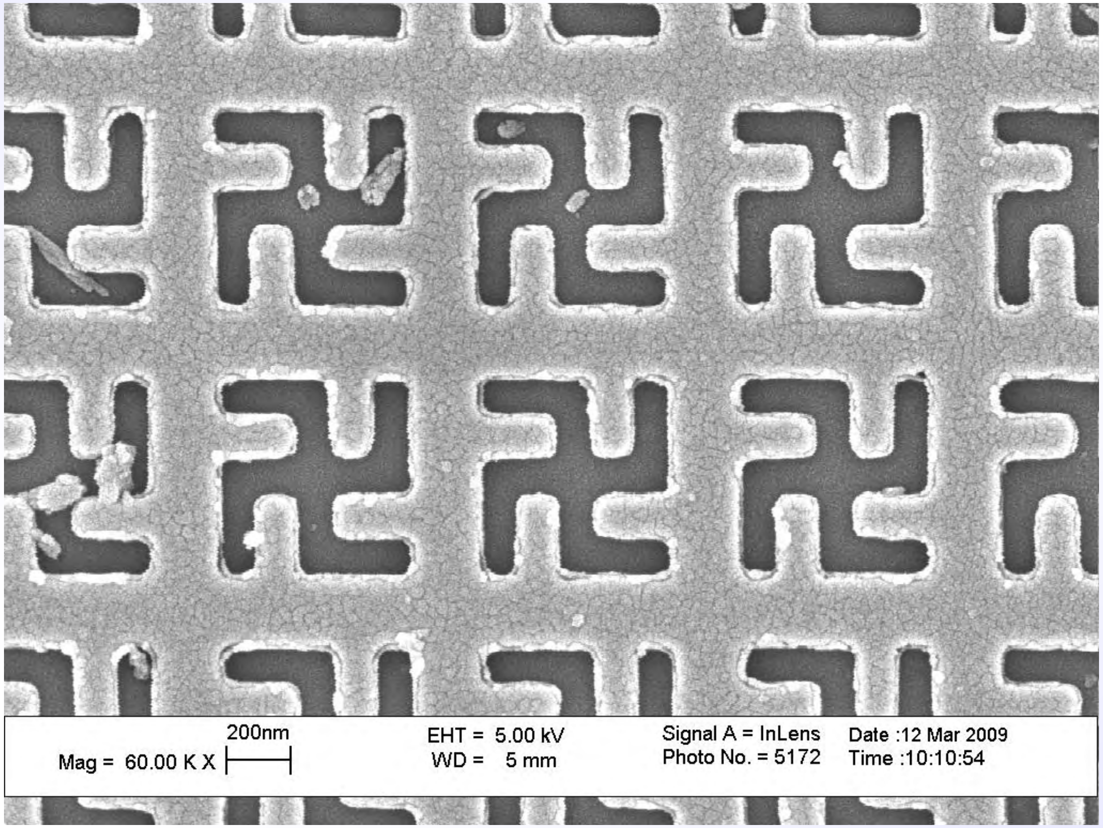
Can we achieve enhanced transmission & enhanced polarization rotation **simultaneously?**



d = 800 nm, *L* = 120 nm



Au gammadion-hole sample

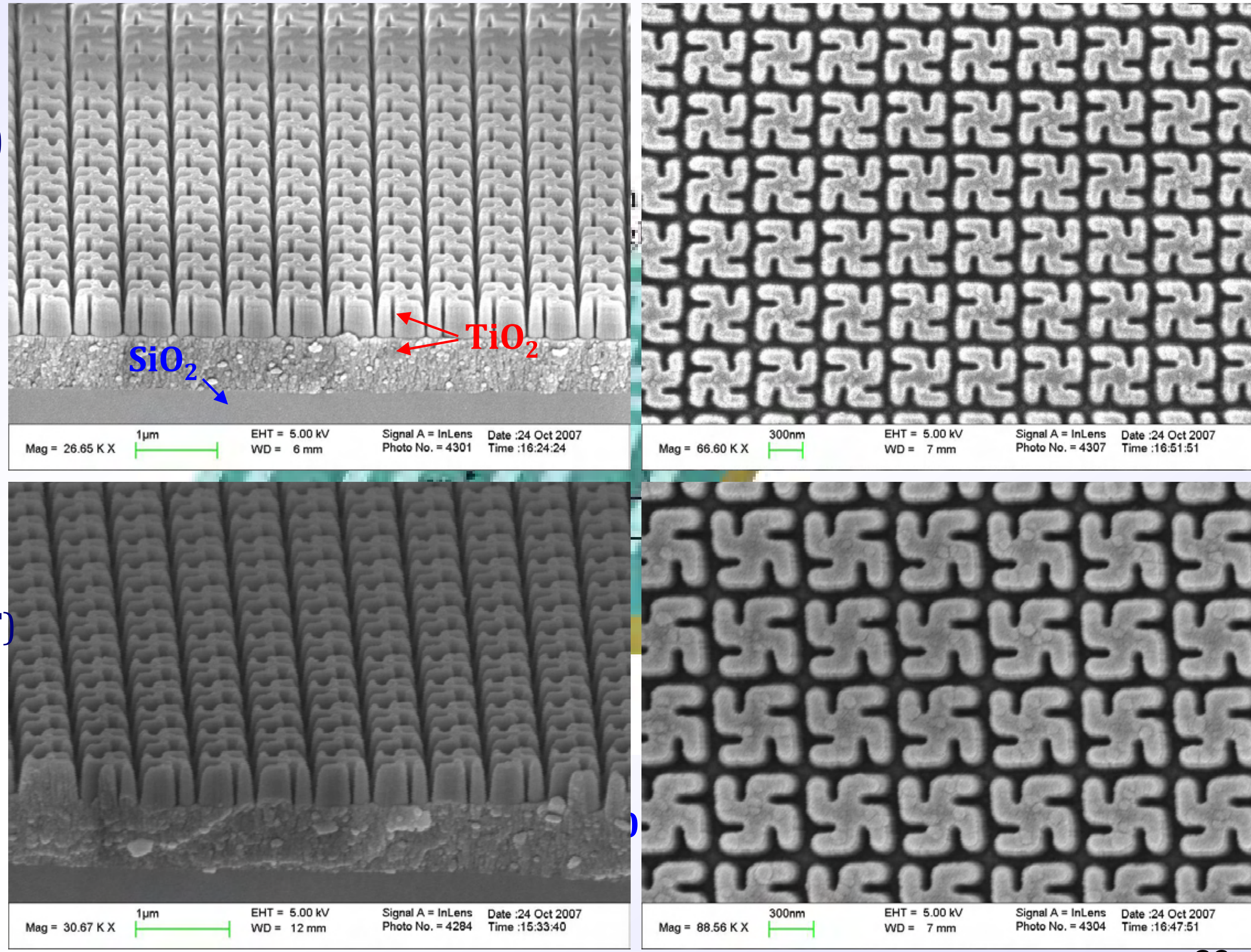


The optical characterization is in progress

3. *Dielectric grating*

Left-twisted (LT)

Right-twisted(RT)



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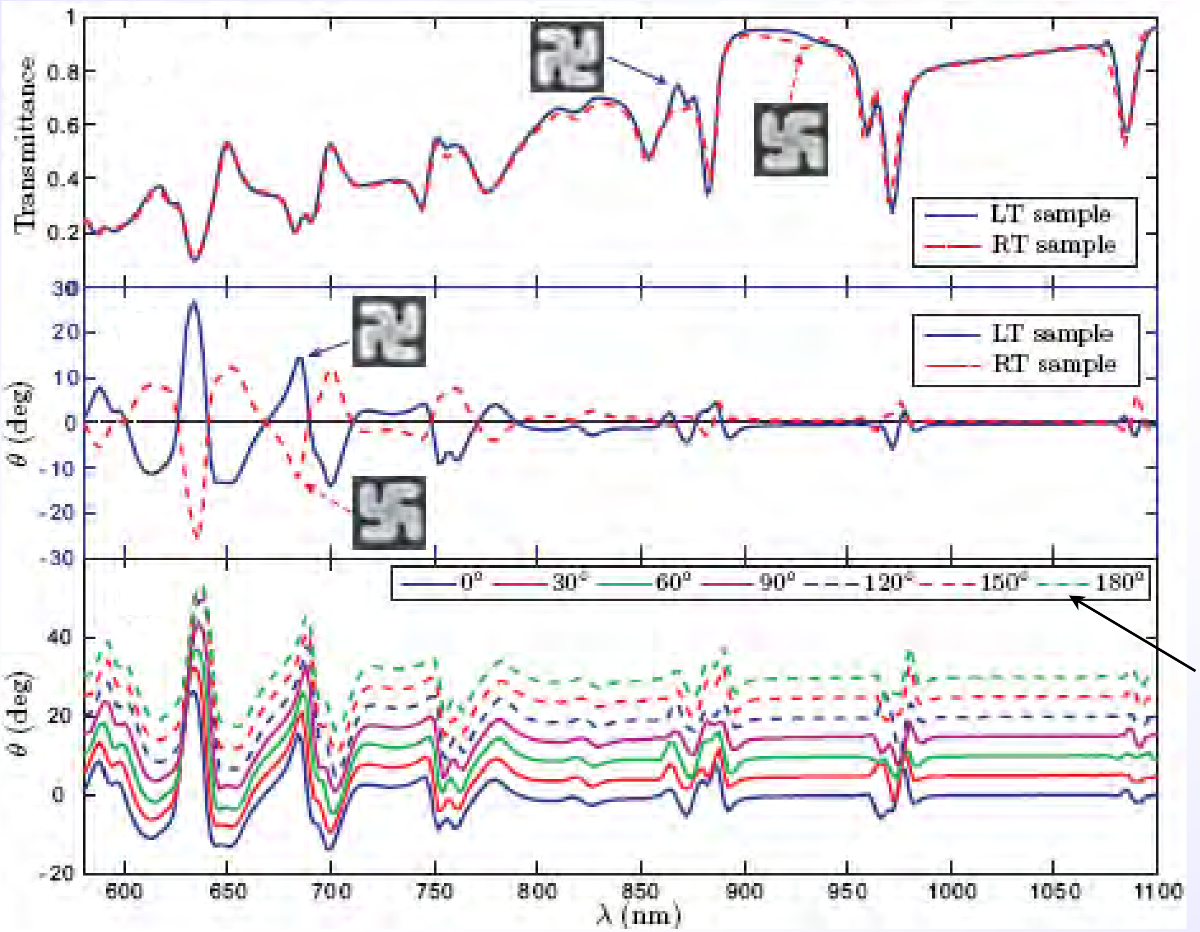
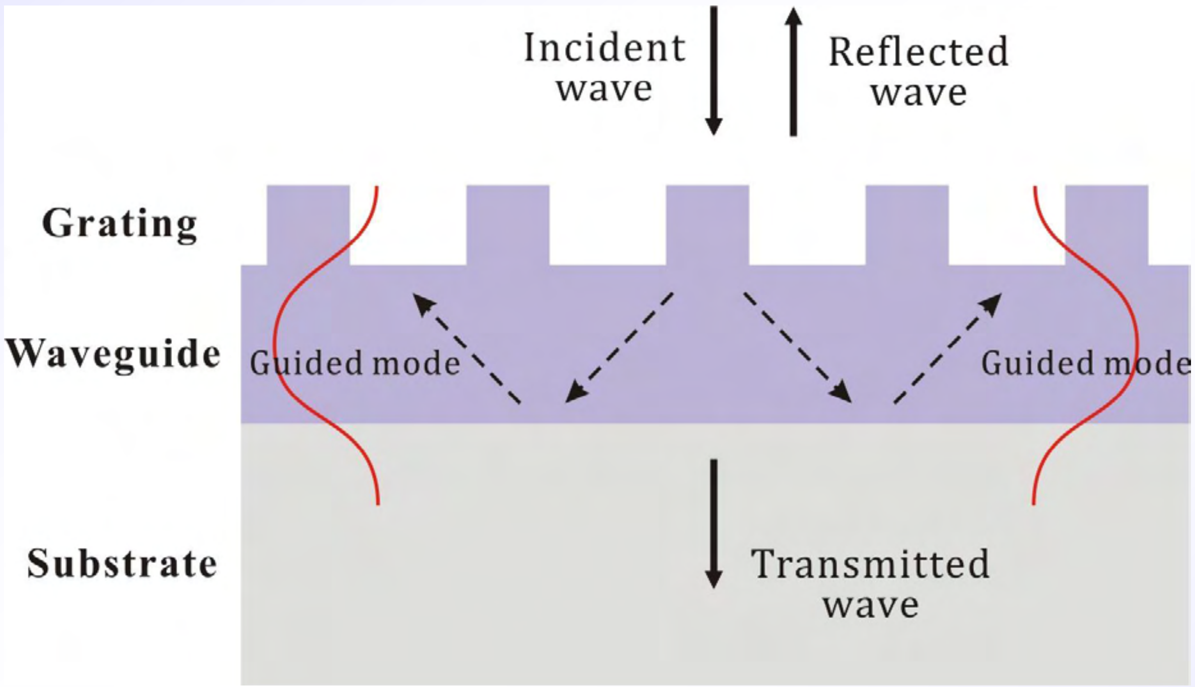
Spectra for LT and RT samples



- Giant polarization rotation (26.5° @ 634 nm) in direct transmission, 10 times larger than in metal gratings.
- Optical activity is enhanced by resonances.

Incident polarization direction

Waveguide grating

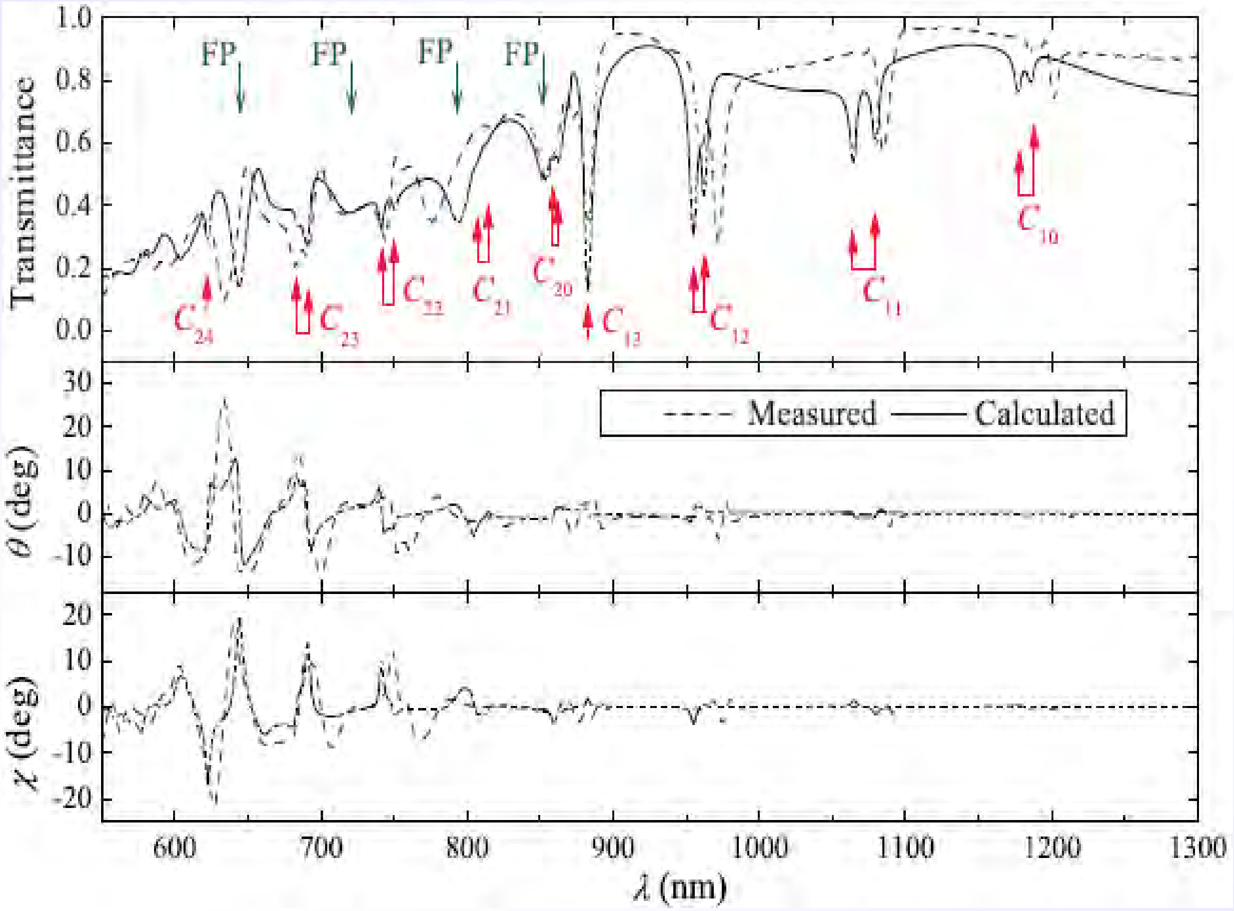


Phase matching at normal incidence $\beta = \sqrt{i^2 + j^2}G, \quad G = 2\pi / d$

Guided modes manifest themselves as transmission dips on a smooth Fabry-Pérot background

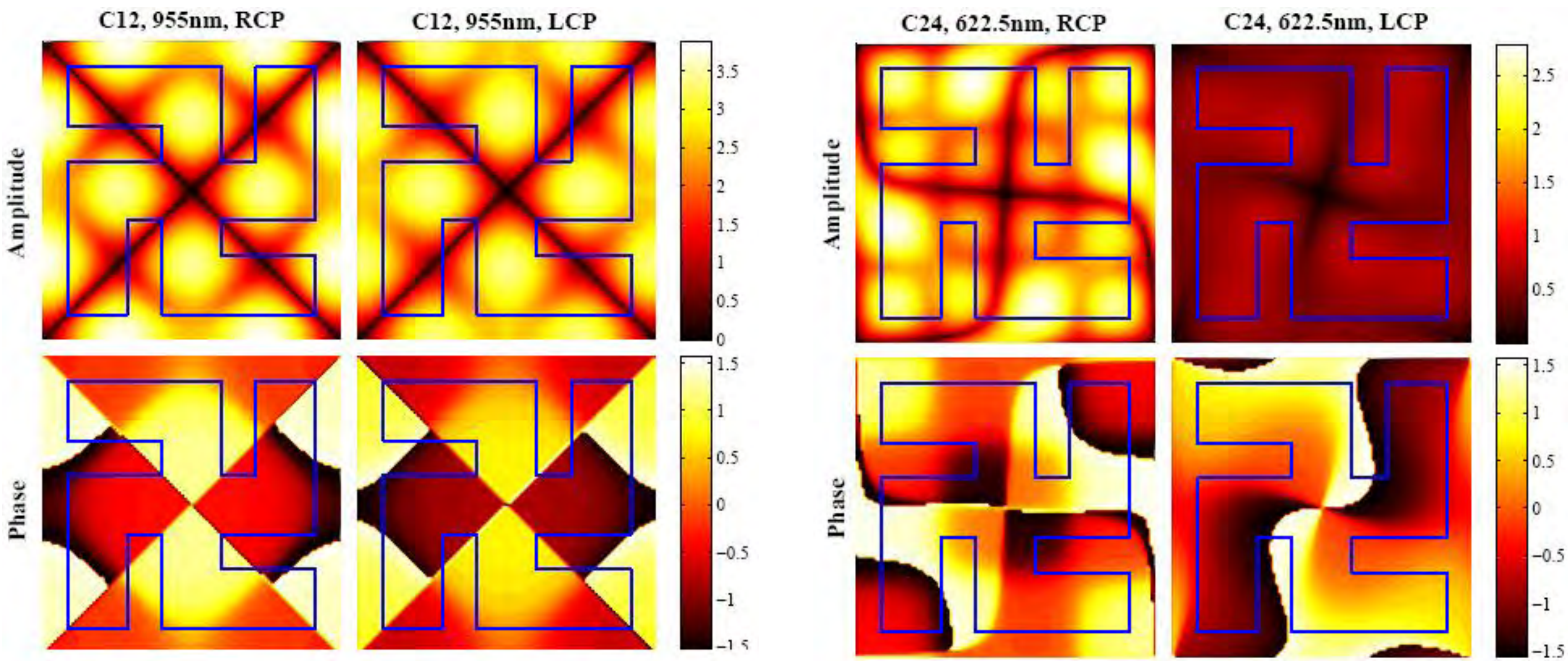
3. *Dielectric grating*

Guided-mode resonance



Measured and calculated spectra

Different coupling of RCP and LCP waves



λ = 955 nm

λ = 622.5 nm

- **Similar RCP and LCP coupling → small CD**
- **Coupled field affected slightly by structural chirality**

- **Different RCP and LCP coupling → large CD**
- **Coupled field affected more drastically by the structural chirality**

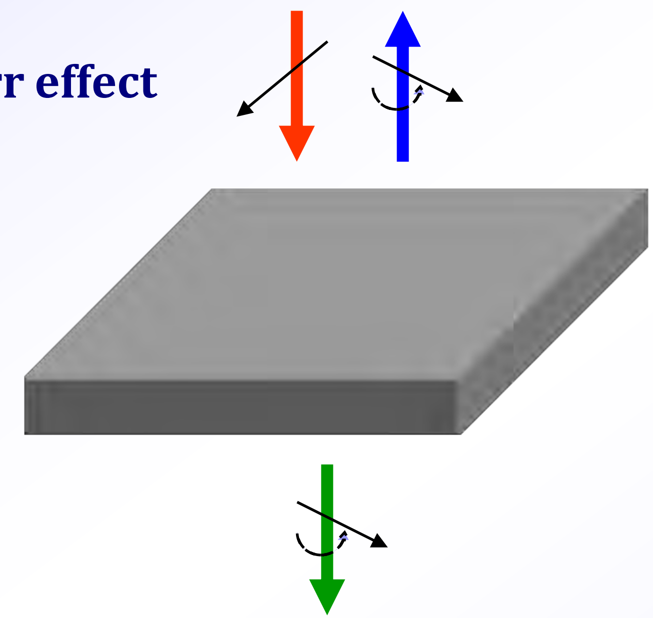
2D MO resonant nanograting

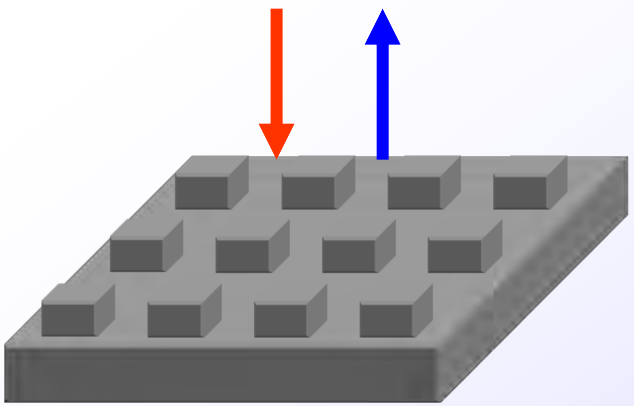
Bulk MO material

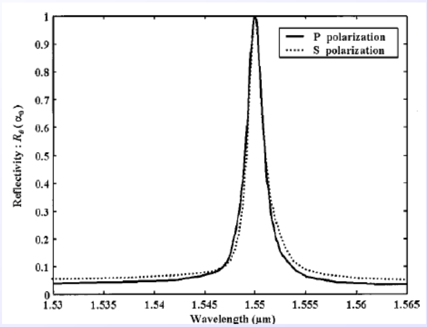
nanograting

Kerr effect

B



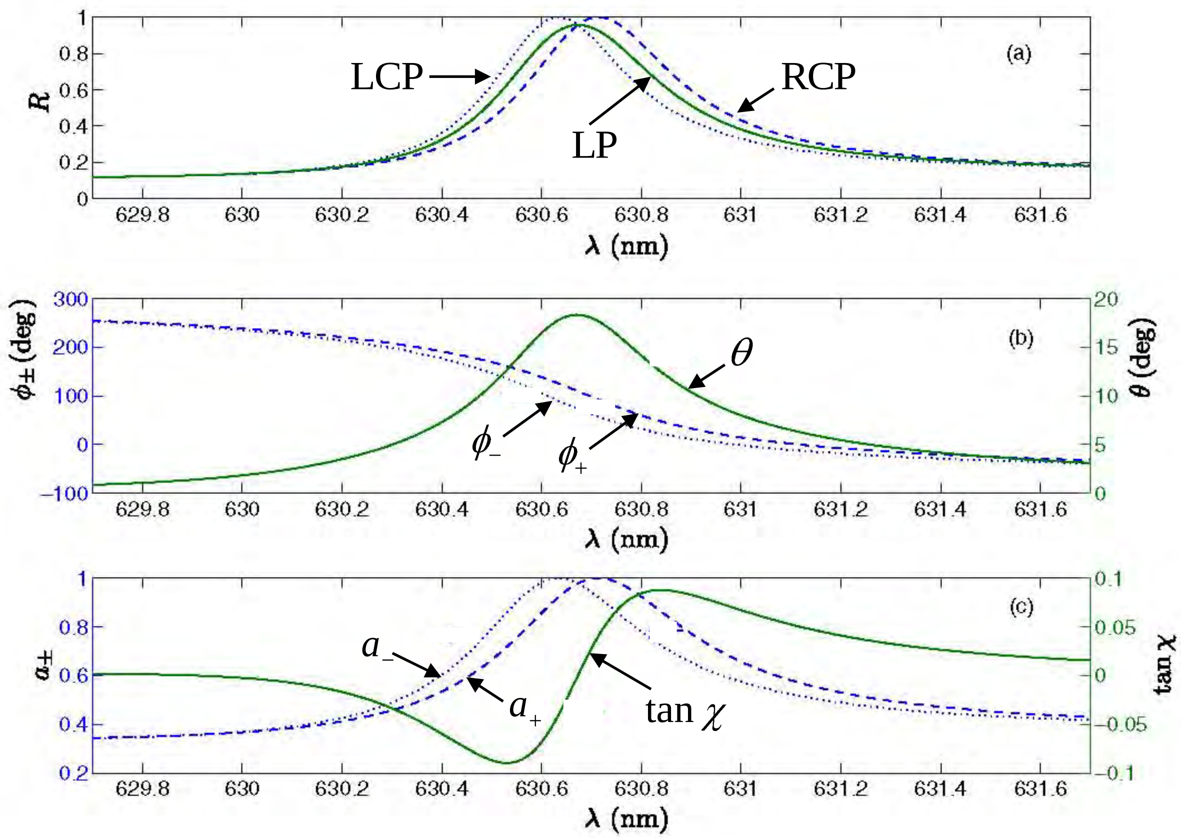




Faraday effect

?

Kerr effect: Numerical analysis



$$R = \frac{1}{2}(R_+ + R_-)$$

$$\theta = \frac{1}{2}(\phi_+ - \phi_-)$$

$$\tan\chi = \frac{a_+ - a_-}{a_+ + a_-}$$

The lifting of the RCP/LCP degeneracy produces strong Kerr rotation

3. Magnetic grating

LCP/RCP beam splitter

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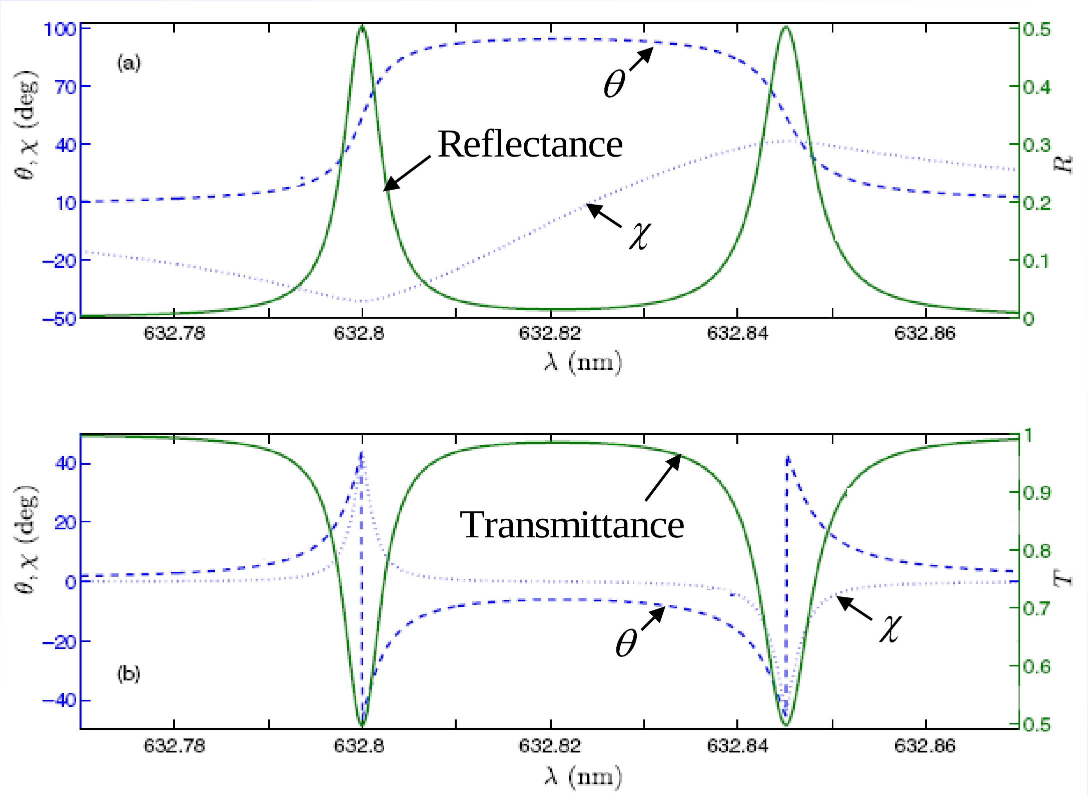
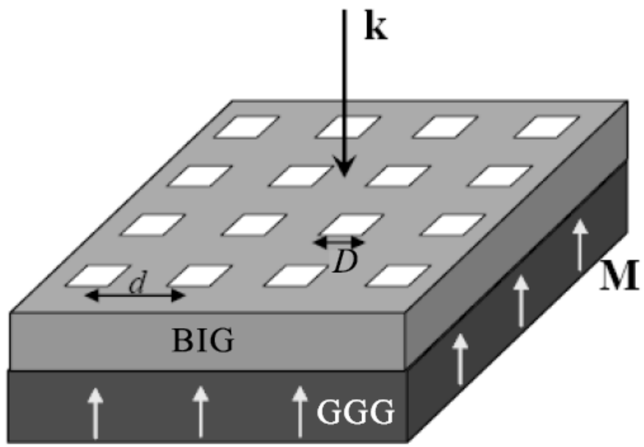
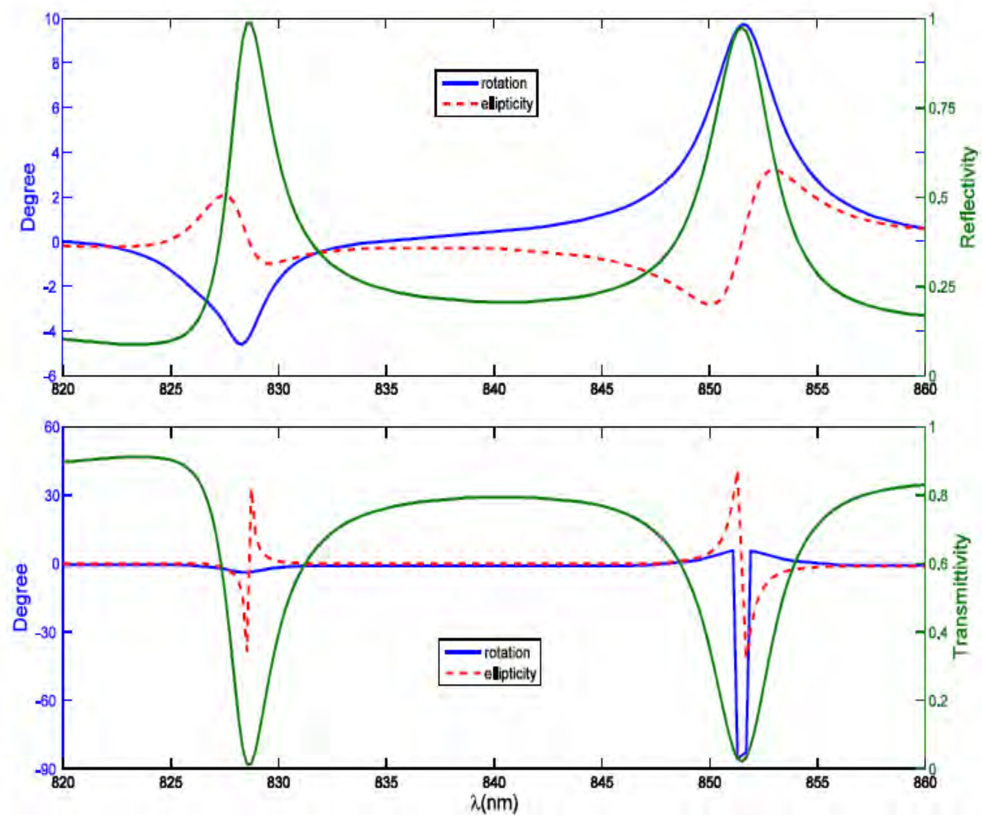


An incident linearly polarized wave is split into a reflected LCP (RCP) and a transmitted RCP (LCP) wave, each with an efficiency of 50%.





Square holes array film

- *d* = 420 nm, *D* = 150 nm, *h* = 160 nm
- BIG: bismuth iron garnet ($Bi_3Fe_5O_{12}$)
- GGG: gadolinium gallium garnet ($Gd_3Ga_5O_{12}$)

Novel metamaterials for polarization control?

- **Artificial media/structure?** ✓
- **The property is not possessed by the composing media?** ✓
- **The property does not exist in nature?** ✓
- $d \ll \lambda$**, i.e. the structure can be seen as homogeneous medium?** x

4. *Concluding remarks*

- **With planar nanogratings we can achieve a gyratory power several orders larger than that of natural or magneto-optically active media.**
- **The developed approach allows us to develop novel planar devices for polarization control**
- **THz optics: light-induced optical activity at terahertz frequencies (CLEO'09)**
- **THz optics: sub-wavelength devices for polarization control can be created by using conventional ink-jet printing technology**
- **Chiral gratings based on novel nanomaterials e.g. graphene**