Planar Chiral Metamaterials for Polarization Control

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Core Research of Evoluational Science & Technology
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OUTLINE

1. Introduction: planar chiral metamaterials
2. Metal nanogratings
3. All-dielectric nanogratings
4. Magneto-optic effects
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1. Introduction

What is Chirality?

- “Handedness”: right glove doesn’t fit the left hand.
- Mirror-image object is different from the original object.
An object is “chiral” if and only if it is not 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.
1. Introduction

**Chirality**

A pair of enantiomeric chiral molecules

![Mirror plane](image)

Mirror plane
1. *Introduction*  

*Chirality in nature*

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
1. Introduction

Circularly Polarized Light

**Enantiomers**

- Right circular polarization produces a right threaded screw.
- Left circular polarization produces a left threaded screw.
Superposition of left- and right circularly polarized waves of the same amplitude gives an achiral linear polarized light wave.
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.
1. Introduction  Fundamental Symmetry and Chirality

Direct scenario: RCP wave interacts with D-molecule

Light-matter interaction is PT-invariant:

\[ n_+ (D) = n_- (L) \quad \alpha_+ (D) = \alpha_- (L) \]
\[ n_+ (L) = n_- (D) \quad , \quad \alpha_+ (L) = \alpha_- (D) \]

Natural optical activity

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

Circular dichroism

\[ \eta \propto \alpha_+ - \alpha_- \Rightarrow \eta (L) = - \eta (D) \]
1. Introduction

Polarization rotation and circular dichroism are induced by molecular chirality.

A pair of enantiomeric chiral molecules

Natural optical activity
\[ \phi \propto n_+ - n_- \Rightarrow \phi(L) = -\phi(D) \]
Circular dichroism
\[ \eta \propto \alpha_+ - \alpha_- \Rightarrow \eta(L) = -\eta(D) \]

Constitutive equation
\[ D = \varepsilon E + i\gamma k \times E \]

Molecular chirality \[\rightarrow\] Optical activity

Reciprocal effect
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
⇒ 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
In a planar structure, in-plane mirror symmetry is broken by the substrate.
1. Introduction

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
1. Introduction

Gammadion Gratings

Basic properties

(1) Reciprocity

(2) Handedness vs. rotation
1. Introduction

Gammadion Gratings

(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**

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

**Polarization rotation angle \( \Delta \)**

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

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

\[
\sin \alpha = \frac{\delta \psi^2}{\varepsilon \Lambda}
\]

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

\[ \Delta \approx \frac{\omega L}{2nc} \text{Im} \left( \delta + \Omega \sin 2\varphi \right) \]
2. Metal grating

Plasmon enhancement

Sample side view

Cr : 23nm
Au : 95nm
Cr : 3nm
Silica substrate

Large polarization rotation (~$10^4$ °/mm) enhances by the surface plasmon resonance
2. Metal grating

Transmission vs rotation spectra

Transmission $\propto \varepsilon$

Polarization rotation $\propto \delta$
2. Metal grating

Local electric filed

Y-polarization 630nm

Air-Metal interface

Metal-Substrate interface

Non-parallel electric field at both interface

\[ \mathbf{n} \cdot \mathbf{E}_{air} \times \mathbf{E}_{sub} = \]

\[ \text{Re} \left( E_{x,air} E_{y,sub} - E_{y,air} E_{x,sub} \right) \]

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2. Metal grating

Chirality factor

\[
\frac{1}{A|E|^2} \int \text{Re} \left[ E^\text{air}_x E^\text{sub}_y - E^\text{air}_y E^\text{sub}_x \right] \, dx \, dy
\]

Left, Right \neq 0

Cross = 0
2. Metal grating

Can we achieve enhanced transmission & enhanced polarization rotation simultaneously?

\[ d = 800 \text{ nm}, \quad L = 120 \text{ nm} \]

Complimentary structure

SPP excitation at air-Au interface

SPP excitation at SiO\(_2\)-Au interface
2. Metal grating

Complimentary structure

Au gammadion-hole sample

The optical characterization is in progress
3. Dielectric grating

Left-twisted (LT)

Right-twisted (RT)
3. **Dielectric grating**  
*Transmission and rotation spectra*

**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
3. Dielectric grating

Guided-mode resonance

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

\[ \lambda = 955 \text{ nm} \]

- Similar RCP and LCP coupling \( \rightarrow \) small CD
- Coupled field affected slightly by structural chirality

\[ \lambda = 622.5 \text{ nm} \]

- Different RCP and LCP coupling \( \rightarrow \) large CD
- Coupled field affected more drastically by the structural chirality

3. Dielectric grating

Local field pattern
3. Magnetic grating

2D MO resonant nanograting

Bulk MO material

Kerr effect

Faraday effect

B

nanograting

?
3. Magnetic grating

Kerr effect: Numerical analysis

![Graphs showing Kerr effect analysis](image)

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

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

\[ \tan \chi = \frac{a_+ - a_-}{a_+ + a_-} \]

The lifting of the RCP/LCP degeneracy produces strong Kerr rotation
An incident linearly polarized wave is split into a reflected LCP (RCP) and a transmitted RCP (LCP) wave, each with an efficiency of 50%.
3. Magnetic grating

Square holes array film

- $d = 420 \text{ nm}$, $D = 150 \text{ nm}$, $h = 160 \text{ nm}$
- BIG: bismuth iron garnet ($\text{Bi}_3\text{Fe}_5\text{O}_{12}$)
- GGG: gadolinium gallium garnet ($\text{Gd}_3\text{Ga}_5\text{O}_{12}$)
4. Concluding remarks

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