Electromagnetic spatial dispersion in periodic metamaterials

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Outline

❖**Brief introduction on Periodic Metamaterials**

❖ **Spatial dispersion:**

artificial chirality/bi-anisotropy

&

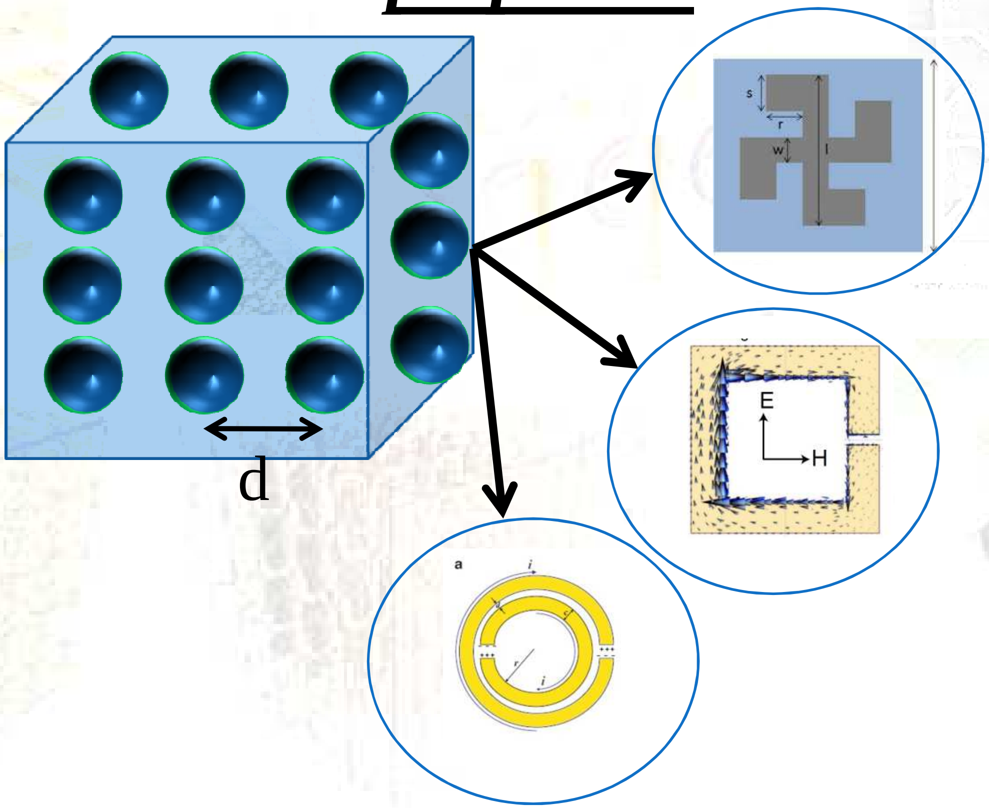
Artificial magnetism

❖ **Homogenization theory: *multi-scale approach***

❖ **1D chiral metamaterials**

Metamaterials

Metamaterials are an arrangement of artificial structural elements, designed to achieve advantageous and/or unusual (electromagnetic) properties

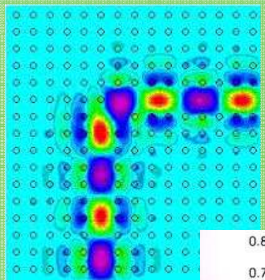


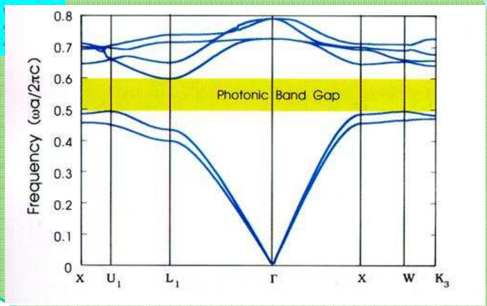
Periodic Metamaterials

Band Gap materials (photonic crystals)

$d \sim \lambda$

Bragg scattering





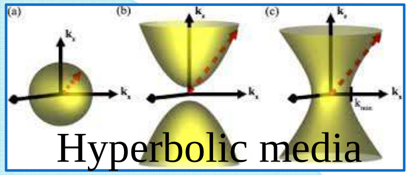
$d < \lambda$

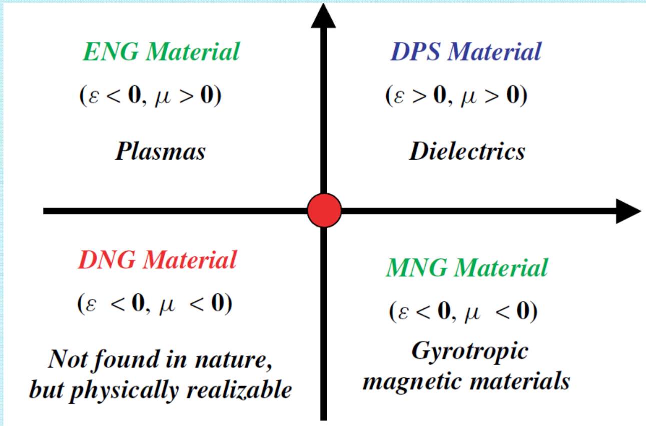
Artificial Bianisotropy

Artificial magnetism

Effectively continuous metamaterials

$d \ll \lambda$





Structure organitation of conventional media

Spatial dispersion- optical nonlocality

Spatial dispersion

$$\mathbf{D}(\mathbf{r}) = \int_V d\mathbf{r}' K(\mathbf{r},\mathbf{r}')\mathbf{E}(\mathbf{r}')$$

Spatial dispersion- optical nonlocality

$d \sim \lambda$ Photonic crystals

Weak Dispersive media

Effectively continuous media $d \ll \lambda$

Second-order spatial dispersion

$$D_i = \varepsilon_0\left(\varepsilon_{ij}E_j + \alpha_{ijk}\partial_k E_j + \beta_{iklj}\partial_k\partial_l E_j\right)$$

Maxwell's equations are invariant with respect to transformation:

$$\mathbf{D}' = \mathbf{D} + \nabla\times\mathbf{Q}, \quad \mathbf{H}' = \mathbf{H} - i\omega\mathbf{Q}$$

$\mu \neq 1$

$(non\ magnetic\ inclusions!!)$

First-order spatial dispersion
Bi-anisotropic response

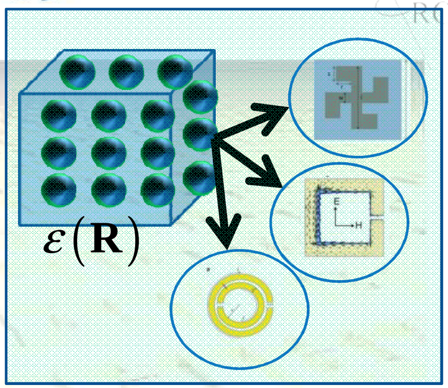
$$\mathbf{D}' = \varepsilon_0\varepsilon\mathbf{E} - \frac{i}{c}\kappa^T\mathbf{H}', \quad \mathbf{B} = \frac{i}{c}\kappa\mathbf{E} + \mu_0\mu\mathbf{H}'$$

$(non\ bi-anisotropic\ inclusions!!)$

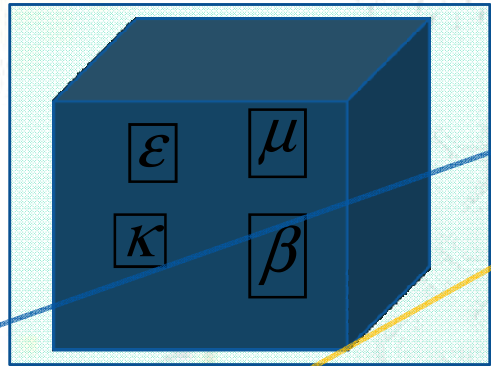
Chiral tensor

Homogenization theory

A suitable homogenization theory is the key ingredient to develop metamaterials allowing to mold the flow of electromagnetic waves in unprecedented ways.



Fast



Slow

"Microscopic" equations

$$\nabla\times\mathbf{E}=i\omega\mu_0\mathbf{H},\quad \nabla\times\mathbf{H}=-i\omega\mu_0\mathbf{D}$$
$$\mathbf{D}=\varepsilon_0\varepsilon(\mathbf{R})\mathbf{E},\quad \bar{\mathbf{B}}=\mu_0\bar{\mathbf{H}}$$

$$\varepsilon(\mathbf{R})\quad \mathbf{R}=\frac{\mathbf{r}}{\eta}\quad \eta=d/\lambda\ll 1$$

$$\mathbf{A}=\sum_{n=0}^{+\infty}\left[\bar{\mathbf{A}}_n(\mathbf{r})+\tilde{\mathbf{A}}_n(\mathbf{r},\mathbf{R})\right]\eta^n$$

"Macroscopic" equations

$$\nabla\times\bar{\mathbf{E}}=i\omega\mu_0\bar{\mathbf{H}}',\quad \nabla\times\bar{\mathbf{H}}'=-i\omega\mu_0\bar{\mathbf{D}}'$$
$$\bar{\mathbf{D}}'=\varepsilon_0\varepsilon^{(eff)}\bar{\mathbf{E}}-\frac{i}{c}\kappa^{(eff)T}\bar{\mathbf{H}}',\quad \bar{\mathbf{B}}=\frac{i}{c}\kappa^{(eff)}\bar{\mathbf{E}}+\mu_0\bar{\mathbf{H}}'$$

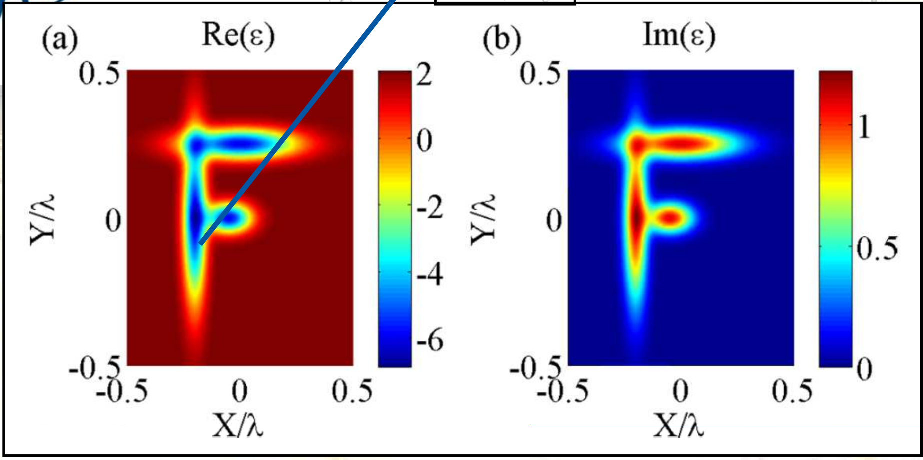
$$\nabla_{\mathbf{R}}\cdot\left(\varepsilon\nabla_{\mathbf{R}}f_j\right)=-\partial_j\varepsilon,\quad \tilde{\mathbf{E}}_0=\hat{e}_i\partial_i f_j\bar{\mathbf{E}}_{0j}$$
$$\varepsilon_{ij}^{(eff)}=\overline{Q_{ij}+Q_{ji}},\quad Q_{ij}=\varepsilon\left(\delta_{ij}+\partial_i f_j\right)$$
$$\kappa_{ij}^{(eff)}=\eta k_0\left[e_{imj}\overline{\varepsilon f_m}+\left(e_{imn}\delta_{jq}+\frac{1}{2}e_{mqn}\delta_{ij}\right)\overline{\varepsilon f_m\partial_q f_n}\right]$$

New!!!

*A. Ciattoni, C. Rizza, PHYSICAL REVIEW B **91,** 184207 (2015)*

2D chiral metamaterials

$\mathrm{Re}(\varepsilon_{in})$



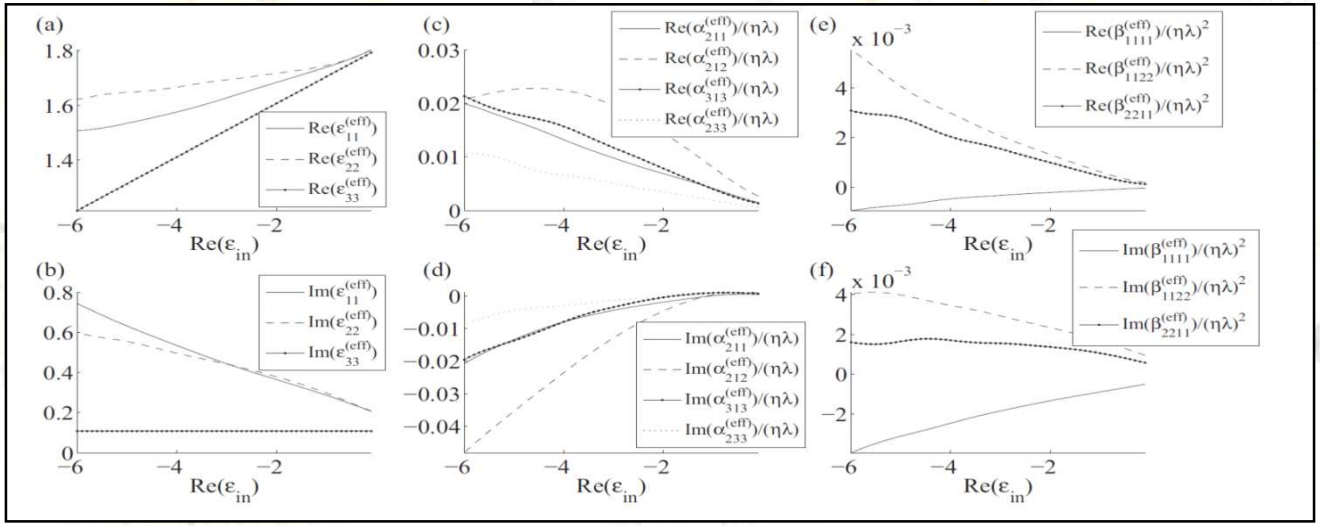
$$\nabla_{\mathbf{R}}\cdot\left(\varepsilon\nabla_{\mathbf{R}} f_j\right) = -\partial_j \varepsilon$$

periodic boundary condition

$$\bar{D}_i = \varepsilon_0\left(\varepsilon_{ij}^{(eff)}E_j + \alpha_{ijk}^{(eff)}\partial_k E_j + \beta_{iklj}^{(eff)}\partial_k\partial_l E_j\right)$$

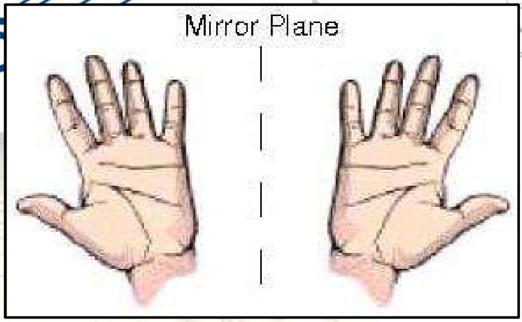
$$\bar{D}'_i = \varepsilon_0\varepsilon_{ij}^{(eff)}\bar{E}_j - \frac{i}{c}\kappa_{ji}^{(eff)}\bar{H}'_j + \beta_{iklj}^{(eff)}\partial_k\partial_l\bar{E}_j,$$

$$\bar{B}_i = \frac{i}{c}\kappa_{ij}^{(eff)}\bar{E}_j + \mu_0\bar{H}'_i$$

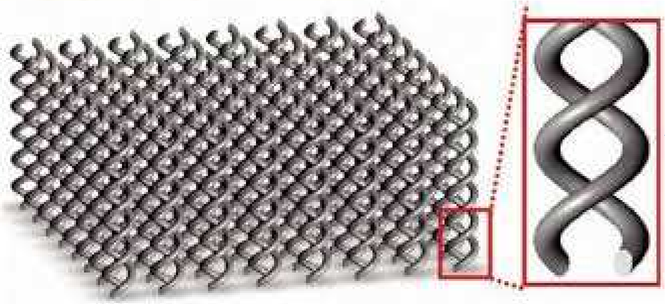


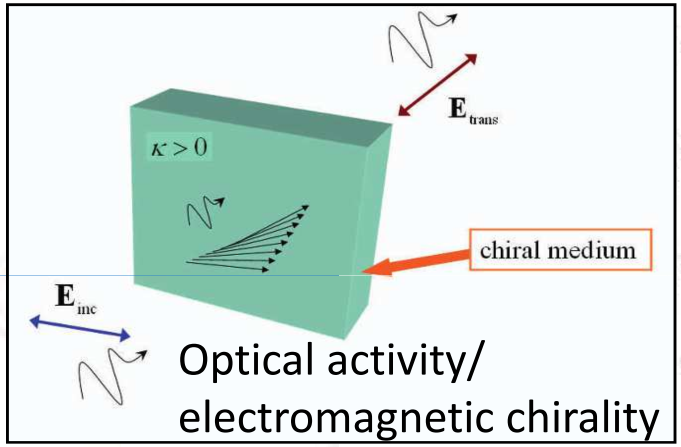
*A. Ciattoni, C. Rizza, PHYSICAL REVIEW B **91,** 184207 (2015)*

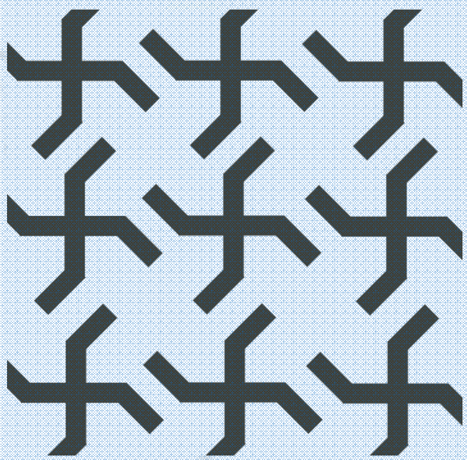
3D-2D chiral metamaterials



<u>3D chirality</u>: A left and right hand are mirror images of one another. Unlike a ball and its mirror image, a hand and its mirror image are not identical.



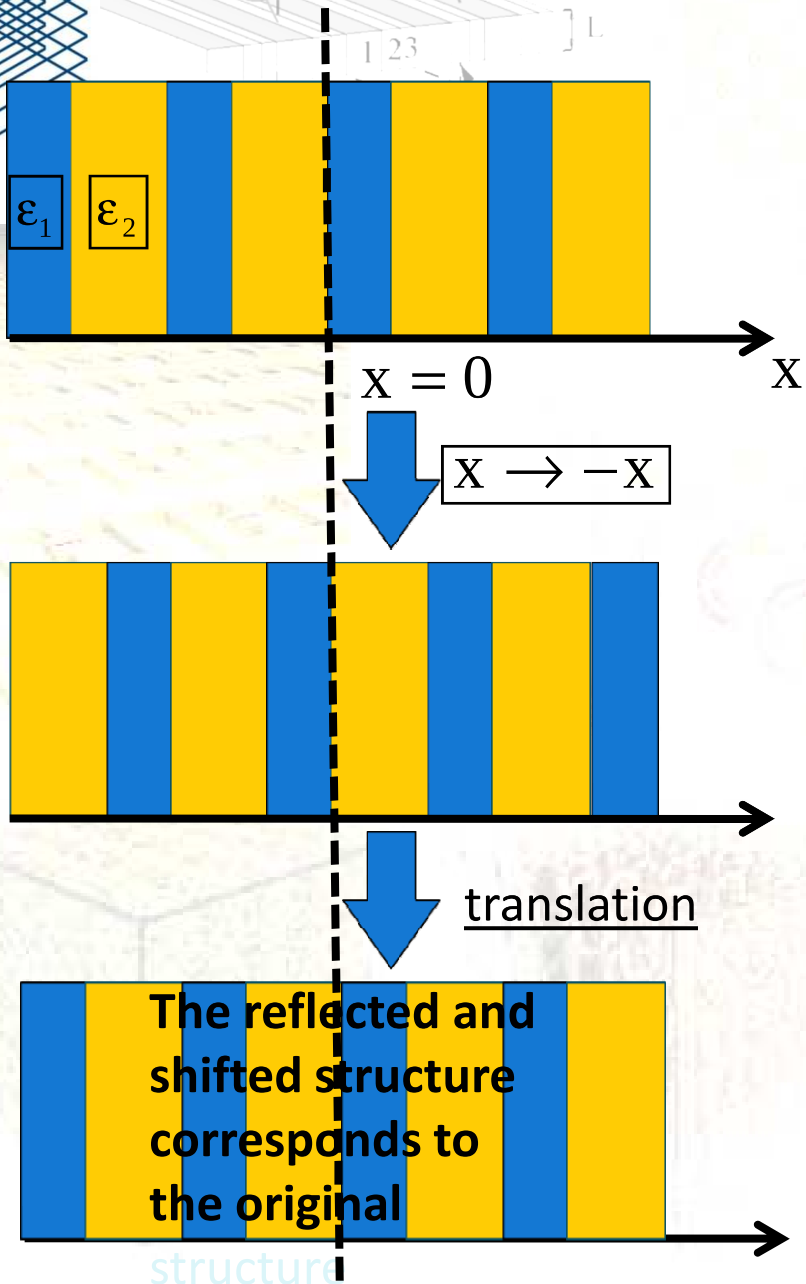




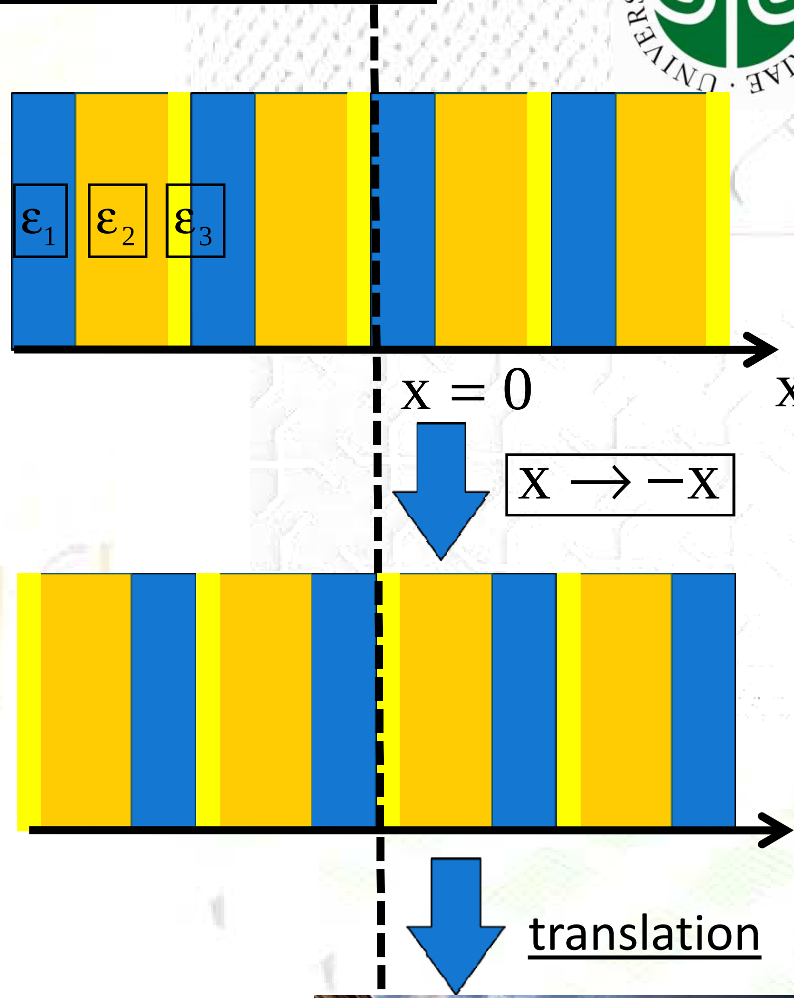
Planar object is said to be **<u>2D chiral</u>** if it cannot be brought into congruence with its mirror image unless it is lifted from the **plane.2D chirality produces bi-anisotropic effects**

A. Papakostas *et al.*, "*Optical Manifestations of Planar Chirality*" PRL 90, 107404 (2003)

1D chiral metamaterials



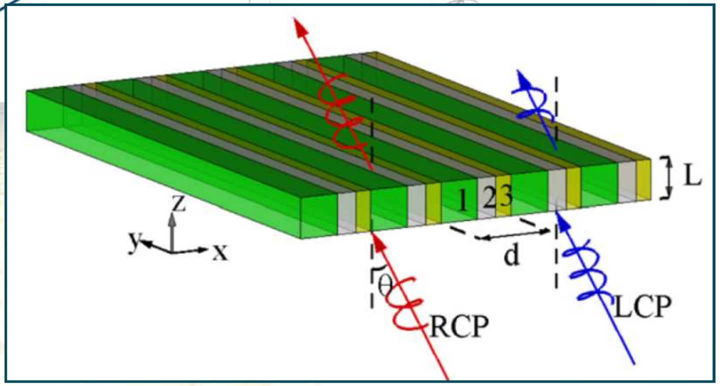
The reflected and shifted structure corresponds to the original structure



The structure does not correspond to the original one whichever translation is applied !!!

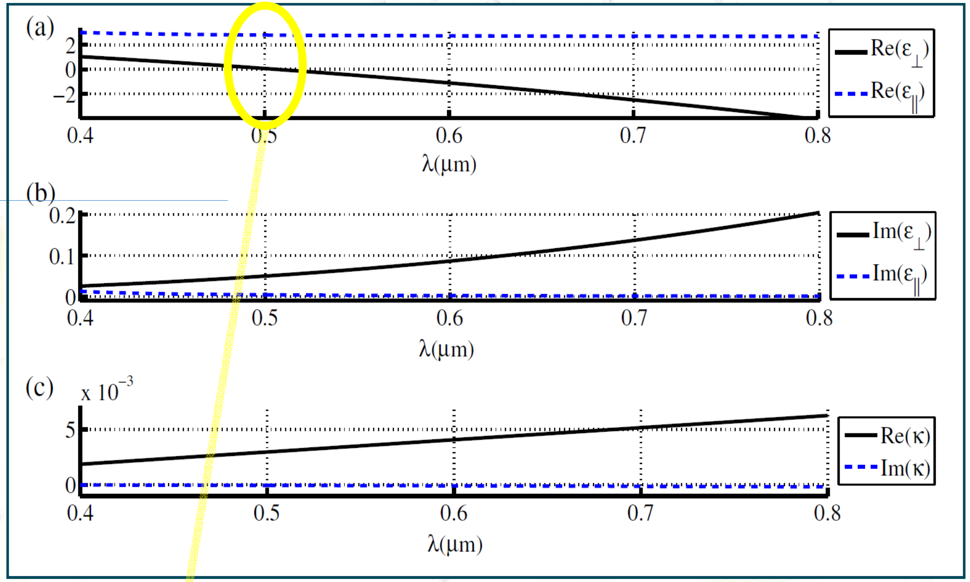
1D chiral Metamaterials

$$\varepsilon^{(eff)} = \varepsilon_0 diag\left(\varepsilon_{\parallel}, \varepsilon_{\perp} + \kappa^2, \varepsilon_{\perp} + \kappa^2\right), \mu^{(eff)} = \mu_0 I$$



$$\kappa^{(eff)} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \kappa \\ 0 & -\kappa & 0 \end{pmatrix}$$

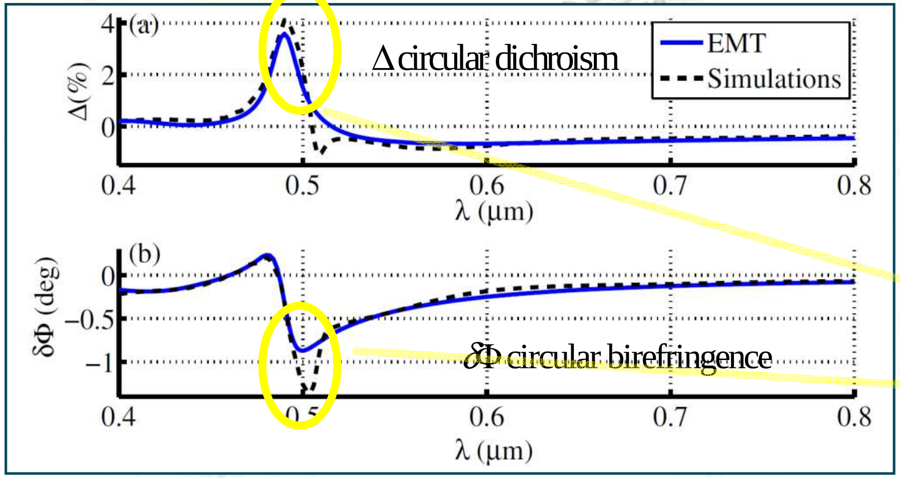
Omega-type response



Periodic 3-layer structure

volume fractions: $f_1 = 0.18$, $f_2 = 0.33$, $f_3 = 1 - f_1 - f_2$, $d(period) = 25nm$

$Ag(1), SiO_2(2), PMMA(3)$



Epsilon-near-zero Enhancement !!!

C. Rizza et al. PRL 115, 057401 (2015)

<u>Conclusions</u>

❖***<u>Nonlocal homogenization theory in metamaterials</u>***

❖ ***<u>1D chirality & 1D chiral metamaterials</u>***

✓ **THz reconfigurable all-optical metamaterials (*in collaboration with THz group, University of Bari*)**

✓ **Metasurfaces, high dielectric contrast,effects of second-order dispersion**

Thanks for your attention

Questions?