FOUNDATION FOR RESEARCH AND TECHNOLOGY – HELLAS

University of Crete

# Combining chirality with Parity-Time (PT) symmetry in metamaterials

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Photonic Metamaterials

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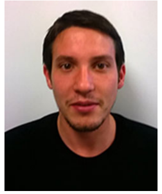

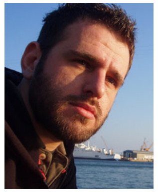

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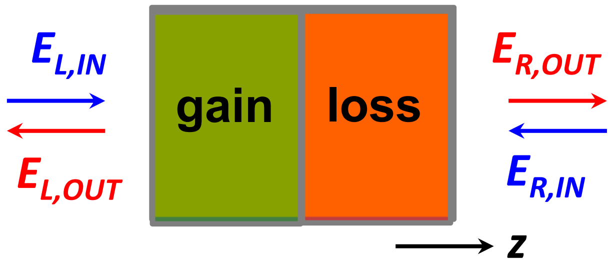
# Outline

- Introduction
  - Parity-Time (PT) symmetry
  - chirality and chiral metamaterials
- Combining **chirality with PT symmetry**
  - **conditions** for PT symmetry with chirality
  - **scattering** by a PT chiral double-slab
    - normal incidence
    - oblique incidence



- Practical implementations
- PT symmetry for **molecular chirality sensing**

# The concept of Parity-Time (PT) symmetry

Hamiltonian

**Schrödinger Equation:** $\hat{H}\Psi(x)=E\Psi(x)$

$$\hat{H}=-\frac{\hbar^2}{2m}\frac{d^2}{dx^2}+V(x)$$

**Parity-Time-symmetric Hamiltonians can have real eigenvalues even if not-Hermitian**

*Bender, Phys. Rev. Lett. 80, 5243, 1998*

**PT-symmetric Hamiltonian:** $[\hat{P}\hat{T},\hat{H}]=0\Rightarrow\hat{P}\hat{T}\hat{H}=\hat{H}\hat{P}\hat{T}$

*Parity: spatial inversion*

$$\hat{P}:\begin{cases}\mathbf{r}\rightarrow-\mathbf{r}\\ \mathbf{p}\rightarrow-\mathbf{p}\\ \mathbf{E}\rightarrow-\mathbf{E} & \textit{polar vector}\\ \mathbf{H}\rightarrow\mathbf{H} & \textit{axial vector}\end{cases}$$

$$\hat{T}:\begin{cases}t\rightarrow-t\\ i\rightarrow-i\\ \mathbf{r}\rightarrow\mathbf{r}\\ \mathbf{E}\rightarrow\mathbf{E}\\ \mathbf{H}\rightarrow-\mathbf{H}\end{cases}$$

# The concept of Parity-Time (PT) symmetry

***PT-symmetric Hamiltonians can have real eigenvalues even if not-Hermitian***

$$\hat{H}\Psi(x) = E\Psi(x)$$

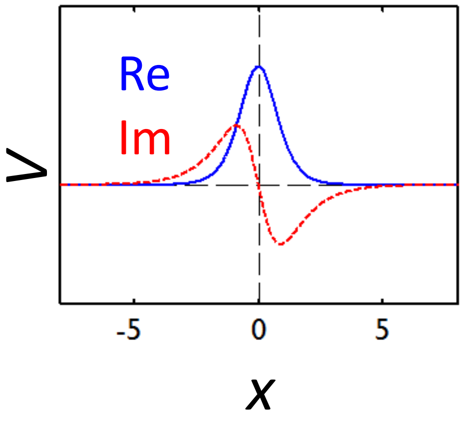
$$[\hat{P}\hat{T},\hat{H}] = 0 \Rightarrow \hat{P}\hat{T}\hat{H} = \hat{H}\hat{P}\hat{T}$$

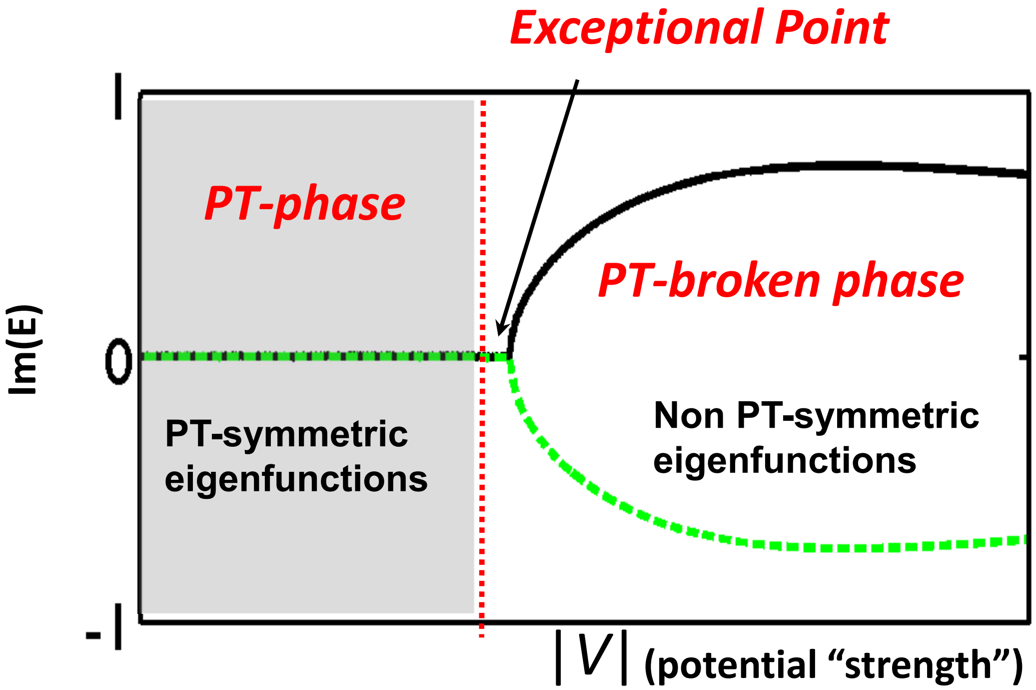
$$\hat{H} = -\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + V(x)$$

**Condition:** $V(x) = V^{*}(-x)$

$$\begin{cases} \mathrm{Re}[V(x)] = \mathrm{Re}[V(-x)] & \text{(even in } x\text{)} \\ \mathrm{Im}[V(x)] = -\mathrm{Im}[V(-x)] & \text{(odd in } x\text{)} \end{cases}$$

***Example of PT-symmetric potential***

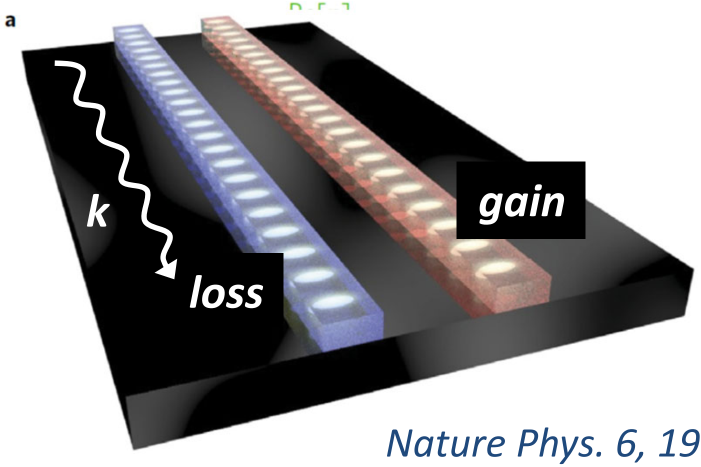




*Bender, Phys. Rev. Lett. 80, 5243, 1998*

# Parity-Time (PT) symmetry in optics

***In optics, wave propagation in paraxial approximation is governed by a Schrödinger-like equation***



*Nature Phys. 6, 192 (2010)*

*n(x): réfractive index*
*$k_0$: free space wave number*

$$\overbrace{\left[-\frac{1}{2k_0n_0}\frac{\partial^2}{\partial x^2}-\underbrace{\boxed{\frac{\omega}{c}n(x)}}_{\text{potential}}\right]}^{\text{Hamiltonian}}E(x)=k_zE(x)$$

***PT-symmetric potential: $n(x) = n^*(-x)$***

***PT-symmetry requirements***
***beyond paraxial approximation***

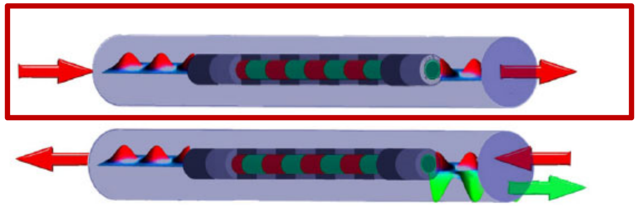
$$\varepsilon(\mathbf{r}) = \varepsilon^*(-\mathbf{r})$$
$$\mu(\mathbf{r}) = \mu^*(-\mathbf{r})$$

*Phys Rev Lett. 110, 173901 (2013)*

***Realization by proper combination of loss and gain media***

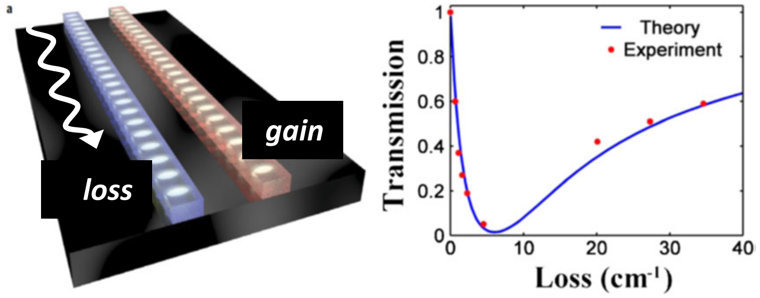
# Novel effects in PT symmetric optical systems

## *Unidirectional reflectionless propagation and invisibility*



**PRL 106, 213901 (2011)**

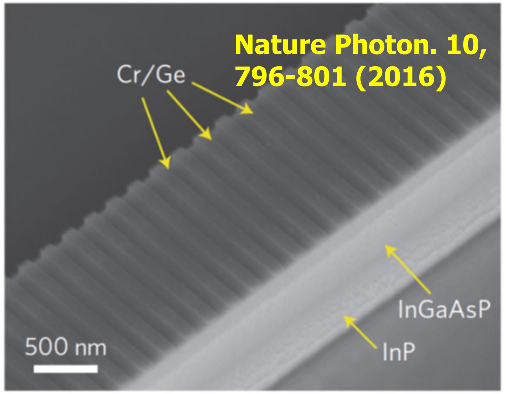
## *Loss-induced transparency*



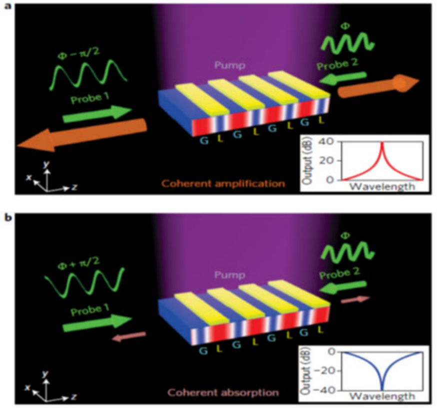
**PRL 103, 093902(2009), Nature Phys. 14, 11 (2018) -review**

## *Coherent perfect absorption (CPA) and lasing at same frequency*

**PRA 82, 031801(R) (2010), PRL 106, 093902 (2011)**
**Science 346 (6212), 975 (2014)**



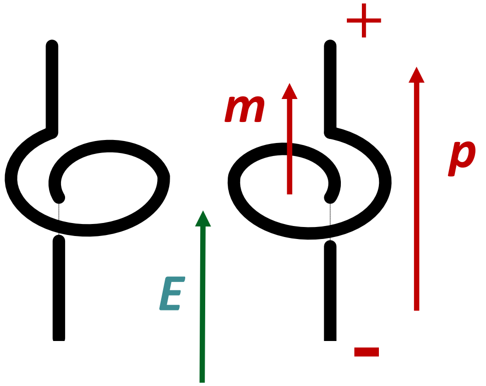
**Nature Photon. 10, 796-801 (2016)**



***How can we extend these effects in chiral systems?***

# Chirality and chiral metamaterials

## *Chiral structure: not identical to its mirror image*



*chirality is expressed via the parameter κ*

$$\boxed{\begin{aligned}\boldsymbol{D} &= \varepsilon\varepsilon_0\boldsymbol{E} + i(\kappa/c)\boldsymbol{H}\\ \boldsymbol{B} &= \mu\mu_0\boldsymbol{H} - i(\kappa/c)\boldsymbol{E}\end{aligned}}$$

*magneto-electric coupling*

***Consequences of chirality:***

*1. **eigenmodes: circularly polarized waves***
  *- Right Circularly Polarized (RCP or +)*
  *- Left Circularly Polarized (LCP or – )*

$$E_{\pm}(\hat{x} \pm i\hat{y})$$

*2. **different index** for RCP (+) and LCP (–) waves!*

$$\boxed{n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa}$$

# Chirality-originated effects

$$\boxed{n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa}$$

**Optical activity**

**Rotation of linear polarization**

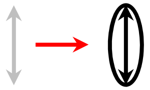
**measured by:**

**Optical Rotation** $\theta = \frac{1}{2}[\arg(t_{++}) - \arg(t_{--})]$

**transmittance of RCP (+) waves**

**transmittance of LCP (–) waves**

**Circular dichroism (CD)**



**Different absorption for RCP/LCP waves**

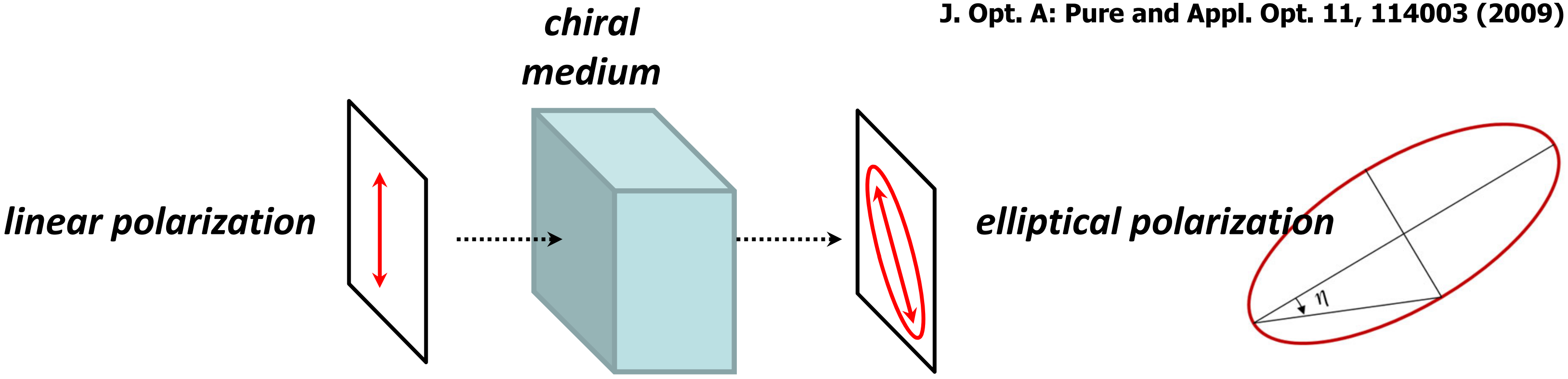
**CD=A$_{++}$-A$_{--}$**

**measured by:**

**Ellipticity** $\eta = \frac{1}{2}\tan^{-1}\left(\frac{|t_{++}|^{2} - |t_{--}|^{2}}{|t_{++}|^{2} + |t_{--}|^{2}}\right)$

$\eta = 0$: linear, $\eta = 45^{\circ}$: circular

**J. Opt. A: Pure and Appl. Opt. 11, 114003 (2009)**



# Questions

***Can we achieve Parity-Time symmetry in chiral media?***

***if yes***

***Under what conditions?***

*See Droulias et. al., Phys. Rev. Lett 122, 213201 (2019)*
*Katsantonis et. al., Photonics 7, 43 (2020)*

# To answer the questions…

**Maxwell's Eqs.**

$$\nabla \times \mathbf{E} = i\omega \mathbf{B}$$

$$\nabla \times \mathbf{H} = -i\omega \mathbf{D}$$

**Constitutive relations**

$$\mathbf{D} = \varepsilon\varepsilon_0 \mathbf{E} + i(\kappa/c)\mathbf{H}$$

$$\mathbf{B} = \mu\mu_0 \mathbf{H} - i(\kappa/c)\mathbf{E}$$

$$\boxed{\hat{H}\begin{bmatrix} \mathbf{B} \\ \mathbf{D} \end{bmatrix} = \omega \begin{bmatrix} \mathbf{B} \\ \mathbf{D} \end{bmatrix}}$$

$$\hat{\Omega}(\mathbf{r}) = \begin{bmatrix} 0 & -\frac{\partial}{\partial z} & \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} & 0 & -\frac{\partial}{\partial x} \\ -\frac{\partial}{\partial y} & \frac{\partial}{\partial x} & 0 \end{bmatrix}$$

$$\hat{H} = \left[\begin{array}{c|c} -i\hat{\Phi}_{11}(\mathbf{r}) - i\phi_{11}(\mathbf{r})\hat{\Omega}(\mathbf{r}) & -i\hat{\Phi}_{12}(\mathbf{r}) - i\phi_{12}(\mathbf{r})\hat{\Omega}(\mathbf{r}) \\ \hline +i\hat{\Phi}_{21}(\mathbf{r}) + i\phi_{21}(\mathbf{r})\hat{\Omega}(\mathbf{r}) & +i\hat{\Phi}_{22}(\mathbf{r}) + i\phi_{22}(\mathbf{r})\hat{\Omega}(\mathbf{r}) \end{array}\right]$$

$$\overline{\overline{\Phi}}_{ij}(\mathbf{r}) = \begin{bmatrix} 0 & -\frac{\partial \phi_{ij}(\mathbf{r})}{\partial z} & \frac{\partial \phi_{ij}(\mathbf{r})}{\partial y} \\ \frac{\partial \phi_{ij}(\mathbf{r})}{\partial z} & 0 & -\frac{\partial \phi_{ij}(\mathbf{r})}{\partial x} \\ -\frac{\partial \phi_{ij}(\mathbf{r})}{\partial y} & \frac{\partial \phi_{ij}(\mathbf{r})}{\partial x} & 0 \end{bmatrix}$$

$$\boxed{\hat{P}\hat{T}\hat{H} = \hat{H}\hat{P}\hat{T}}$$

*See Droulias et. al., Phys. Rev. Lett 122, 213201 (2019)*

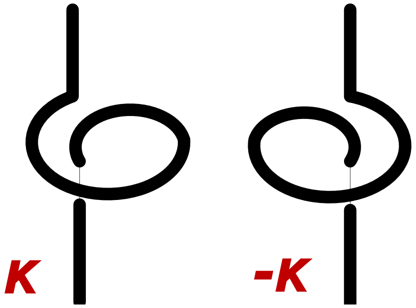
$$\phi_{11}(\mathbf{r}) = -\phi_{22}(\mathbf{r}) = -\frac{i\kappa/c}{\left(\varepsilon\mu - \kappa^2\right)/c^2}$$

# Questions

***Can we achieve Parity-Time symmetry in chiral media?***

***if yes***

***Under what conditions?***



$$\boxed{\begin{aligned} \varepsilon(\mathbf{r}) &= \varepsilon^*(-\mathbf{r}) \\ \mu(\mathbf{r}) &= \mu^*(-\mathbf{r}) \\ \kappa(\mathbf{r}) &= -\kappa^*(-\mathbf{r}) \end{aligned}}$$

***as in non-chiral systems***

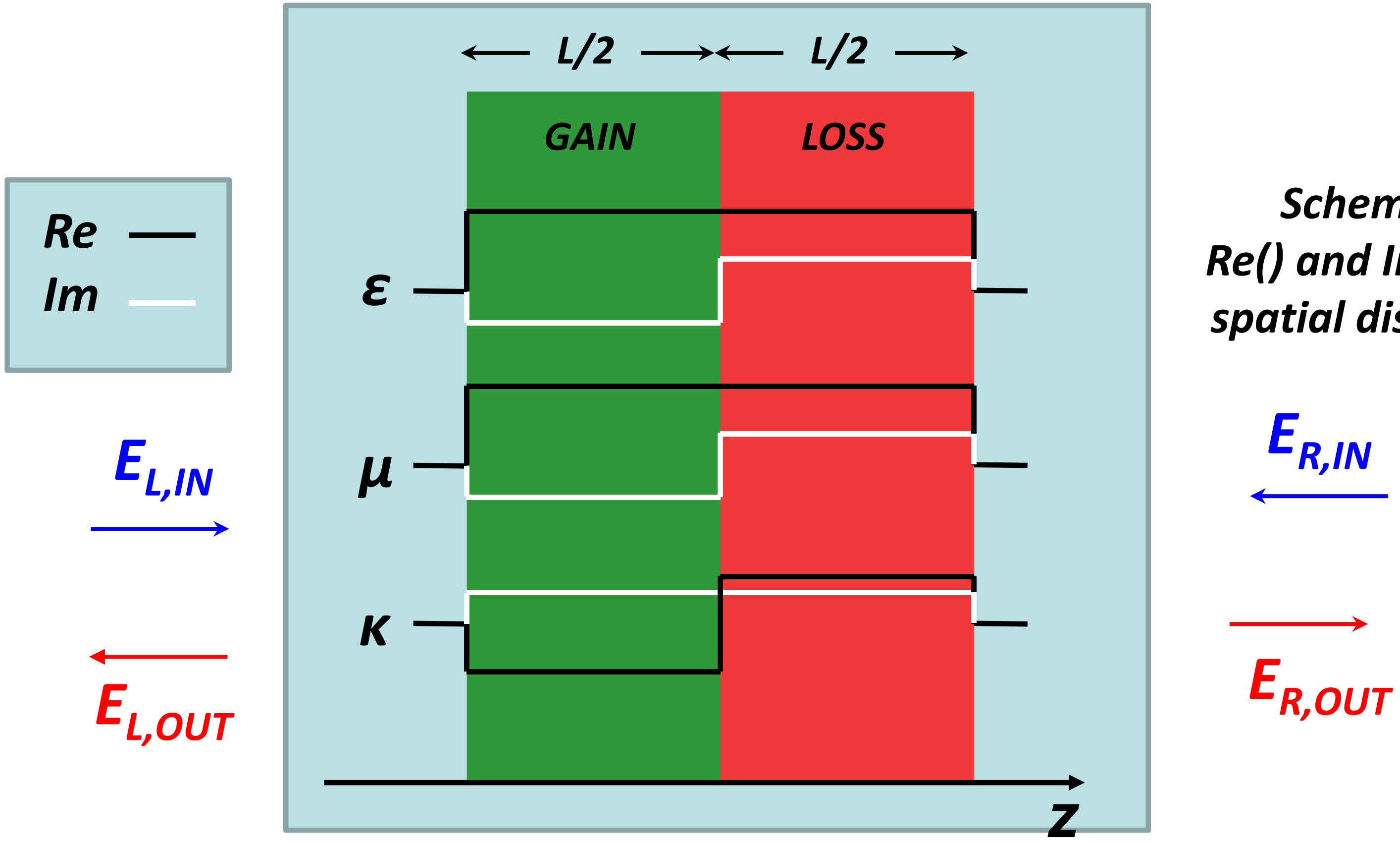
← ***additional condition***

*See Droulias et. al., Phys. Rev. Lett 122, 213201 (2019)*
*Katsantonis et. al., Photonics 7, 43 (2020)*

# Our PT-chiral system/bilayer

***Homogenous, non-dispersive, chiral media***

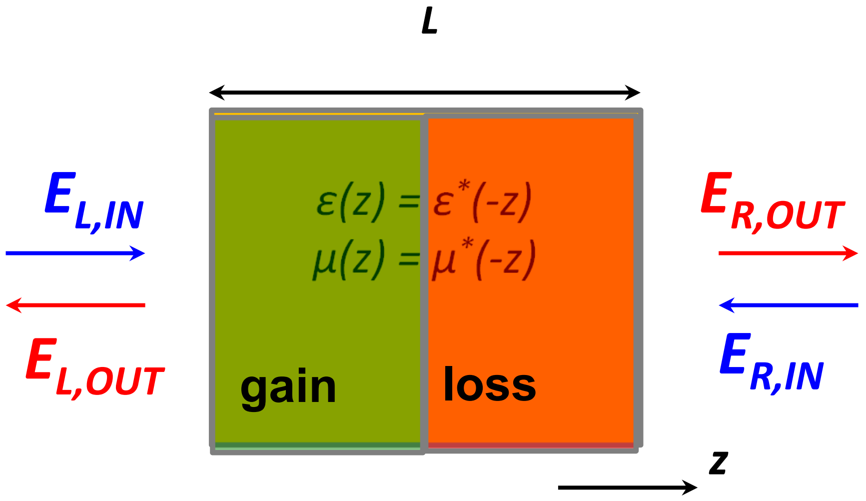
***Investigation of scattering (transmission/reflection) properties***



***Schematic of***
***Re() and Im() part of***
***spatial distributions***

# Scattering by Parity-Time (PT) symmetric systems

***The PT-symmetry phases can be identified from the eigenvalues (s) of the scattering matrix***

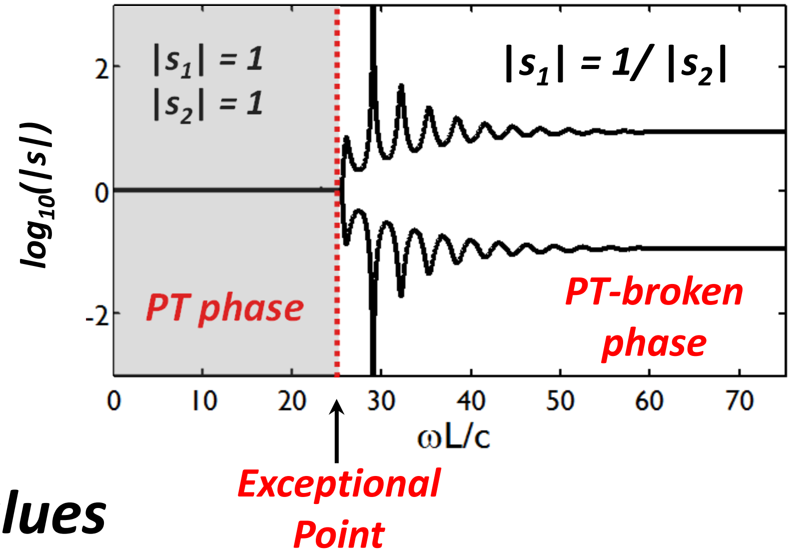


$$\begin{bmatrix} E_{L,OUT} \\ E_{R,OUT} \end{bmatrix} = \begin{bmatrix} r^{(L)} & t^{(R)} \\ t^{(R)} & r^{(R)} \end{bmatrix} \begin{bmatrix} E_{L,IN} \\ E_{R,IN} \end{bmatrix}$$

***Scattering matrix***

$t^{(L)}$ transmission for left-incidence

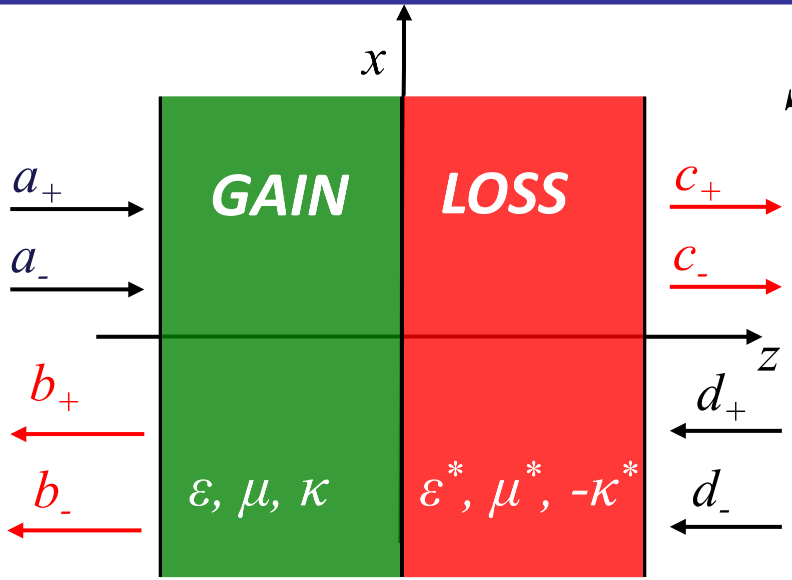
$r^{(R)}$ reflection for right-incidence



***PT-phase ⟺ Unimodular eigenvalues***

$^{(*)}$ *PRL 106, 093902 (2011)*

# The “chiral” scattering matrix, $S$



*Subscripts: + : RCP wave, - : LCP wave*
*a, b, c, d: amplitudes of incoming and outgoing waves*

$$S \equiv 4 \times 4$$

$$\begin{pmatrix} Left - \\ Right + \\ Left + \\ Right - \end{pmatrix} = S \begin{pmatrix} Left + \\ Right - \\ Left - \\ Right + \end{pmatrix}$$

$$S = \begin{pmatrix} r^{(L)} & t_{--} & 0 & 0 \\ t_{++} & r^{(R)} & 0 & 0 \\ 0 & 0 & r^{(L)} & t_{++} \\ 0 & 0 & t_{--} & r^{(R)} \end{pmatrix}$$

*Superscripts: (L)/(R): Left/Right incidence*

## *Generalized unitarity relation for S*

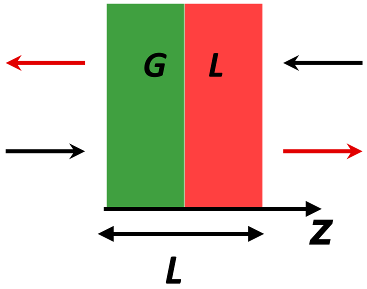
$$PTS(\omega^*)PT = S^{-1}(\omega)$$

*L. Ge et al, Phys. Rev. A 85, 023802 (2012)*

***See Droulias et. al., Phys. Rev. Lett 122, 213201 (2019)***
***Katsantonis et. al., Photonics 7, 43 (2020)***

# Transmission – Reflection for normal incidence

***Analytical calculations for a general chiral bi-layer***



***For both*** ↕ ↻

$$t^{(L)} = t^{(R)}$$

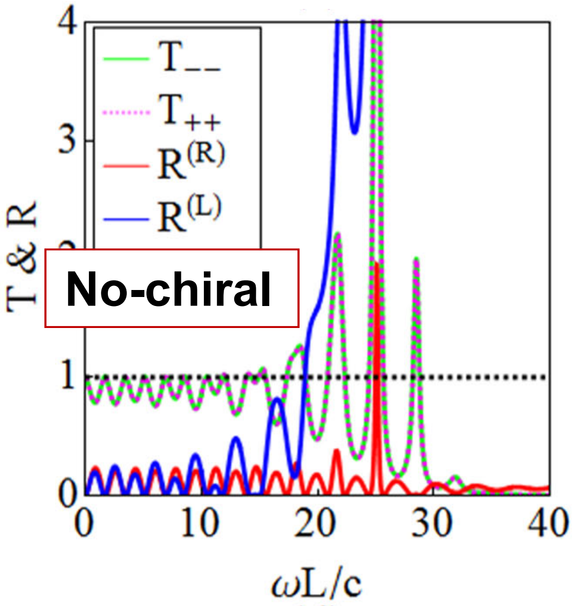
$$r^{(L)} \neq r^{(R)}$$

$$\boxed{\begin{aligned} r^{(L)} &= r^{(L)}{}_{nonchiral} \\ r^{(R)} &= r^{(R)}{}_{nonchiral} \end{aligned}}$$

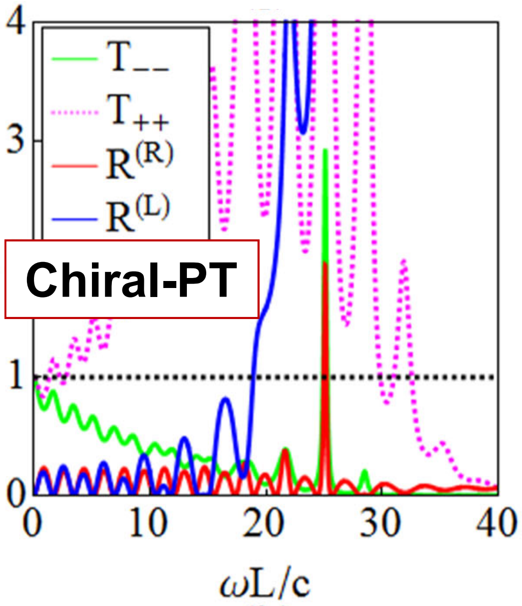
***Reflection, r, independent of chirality, κ***

*Superscripts (R) and (L) refer to right- and left-incidence*

***κ=0***



***κ=0.04(1+i)***



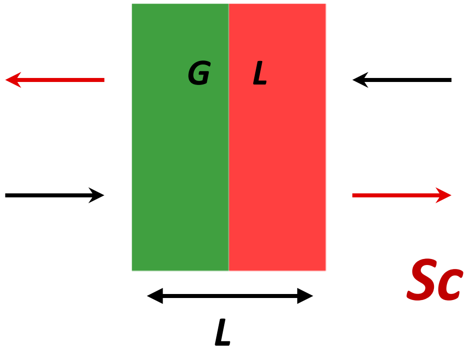
***Transmission (T=|t |²) resonance-position independent of chirality***

$$\boxed{t_{++}t_{--} = t^2{}_{nonchiral}}$$

***T=|t|² = transmission, R=|r|² = reflection***

$$\varepsilon = 3 \pm 0.4i, \mu = 1.1 \pm 0.1i$$

# $S$-matrix (4x4) features for normal incidence



***Scattering matrix eigenvalues, σ (two degenerate pairs)***

$$\sigma_{1,2} = \frac{1}{2}\left(r^{(L)} + r^{(R)} \pm \sqrt{(r^{(L)} - r^{(R)})^2 + 4t_{++}t_{--}}\right.$$

***Scattering matrix eigenvalues independent of chirality***

*Exceptional point, PT-phases, CPA-laser points* ***independent of chirality!!***

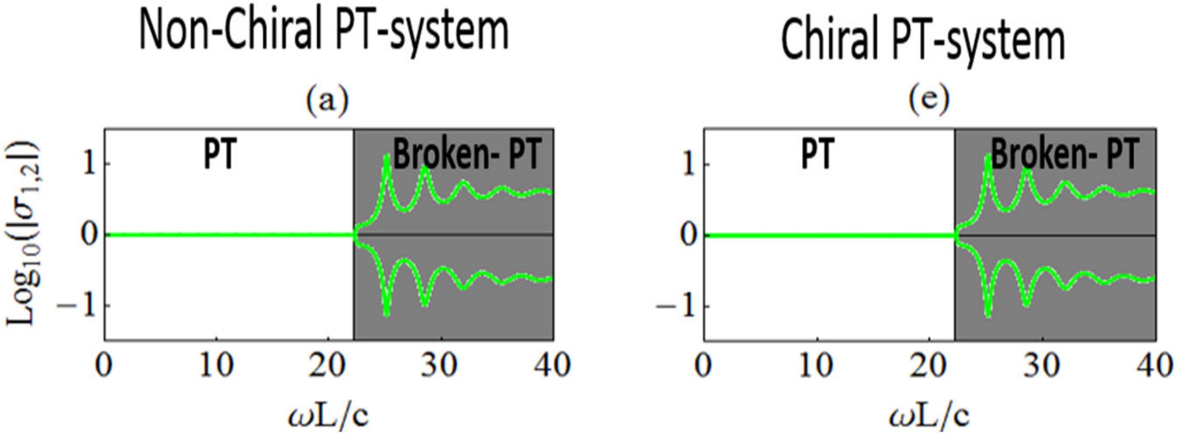
***Conservation relation***

$$|\sqrt{T_{++}T_{--}} - 1| = \sqrt{R^{(L)}R^{(R)}}$$

$$T = |t|^2, R = |r|^2$$

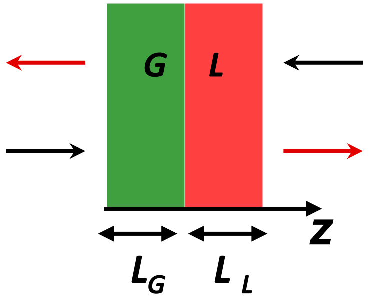
***Exceptional point location***

$$\frac{R^{(L)} + R^{(R)}}{2} - \sqrt{T_{++}T_{--}} = 1$$



$$\varepsilon = 3 \pm 0.4i, \mu = 1.1 \pm 0.1i, \kappa = \pm 0.04 - 0.04i$$

# Optical activity and ellipticity – normal incidence



*Subscripts G and L refer to Gain and Loss*

*For a general chiral bi-layer*

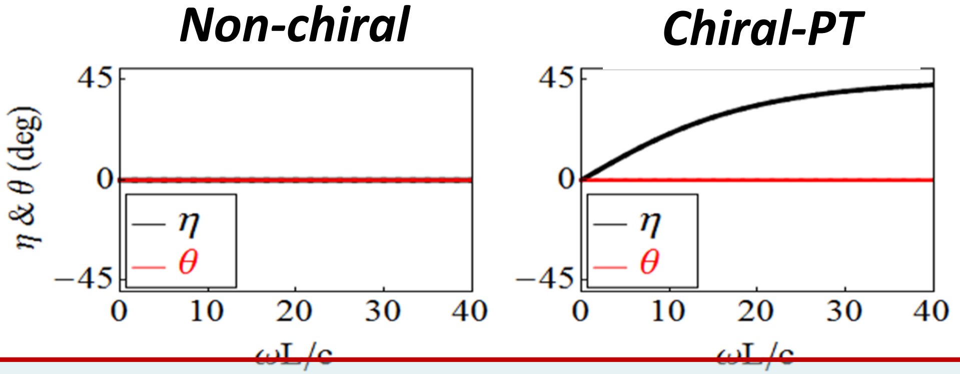
***optical activity***

$$\boxed{\theta = \frac{1}{2} k_0 \left( L_G \operatorname{Re}(\kappa_G) + L_L \operatorname{Re}(\kappa_L) \right) = 0}$$

***ellipticity***

$$\boxed{\eta = \frac{1}{2} \tan^{-1} \left( \frac{1 - \exp\left[ 2k_0 \left( L_G \operatorname{Im}(\kappa_G) + L_L \operatorname{Im}(\kappa_L) \right) \right]}{1 + \exp\left[ 2k_0 \left( L_G \operatorname{Im}(\kappa_G) + L_L \operatorname{Im}(\kappa_L) \right) \right]} \right)}$$

***Optical activity and ellipticity depend exclusively on chirality, κ***

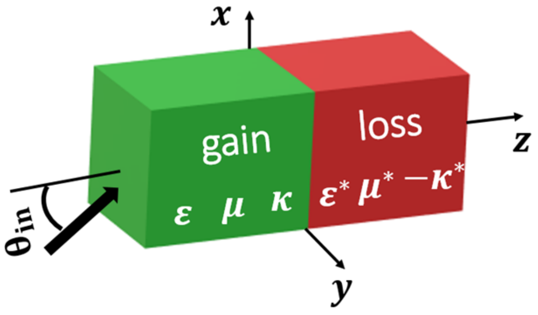


***Possibility for independent control of PT properties (exceptional point, reflection/transmission resonances, CPA-laser points) and transmitted wave polarization (θ,η)!***

***E.g. CPA-laser for circularly polarized waves!***

$\varepsilon = 3 \pm 0.4i, \mu = 1.1 \pm 0.1i, \kappa = \pm 0.04 - 0.04i$

# Off-normal incidence: Mixed-PT phase

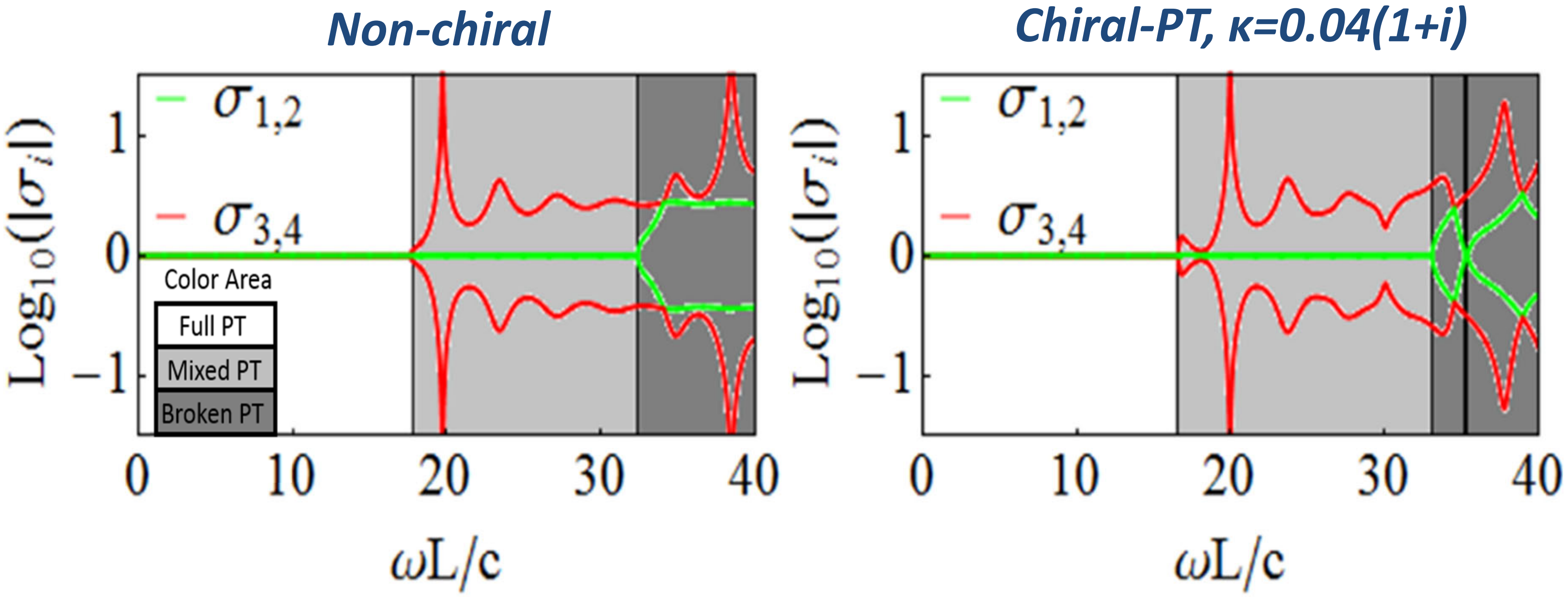


## *Eigenvalues depend on chirality, κ*

*Eigenvalues don't form two degenerate pairs*

***Appearance of a mixed-PT phase***

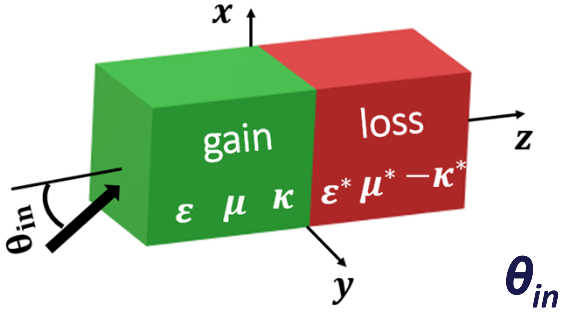
*Scattering matrix eigenvalues, σ*


*Non-chiral*

*Chiral-PT, κ=0.04(1+i)*

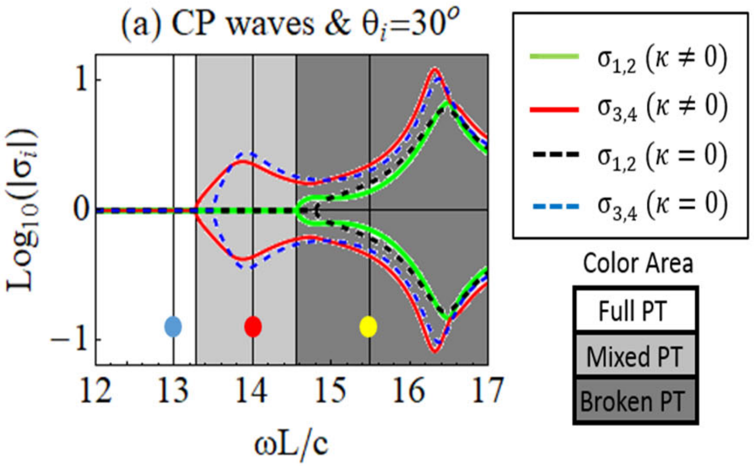
$$\varepsilon = 3 \pm 0.4i, \mu = 1.1 \pm 0.1i$$

# Tuning the different phases and the exceptional points

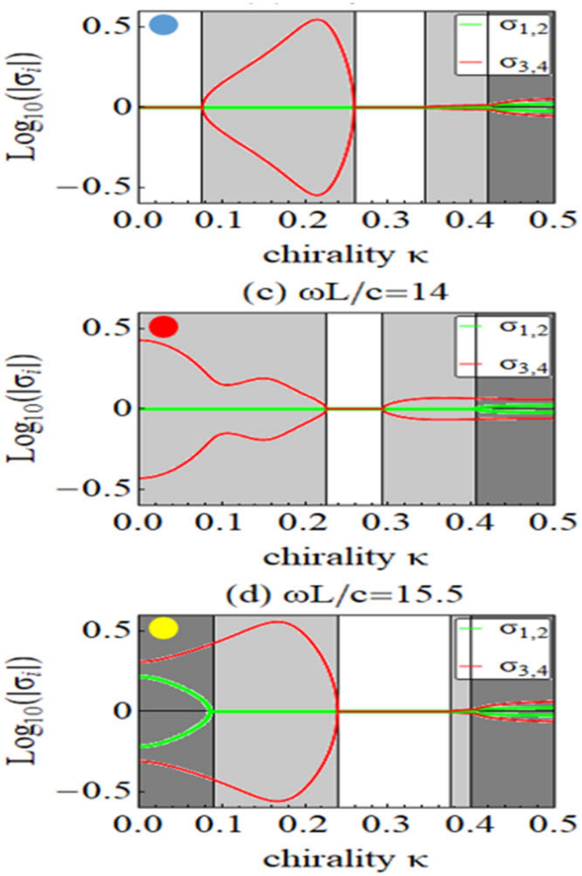


***$\theta_{in}$=30$^o$***

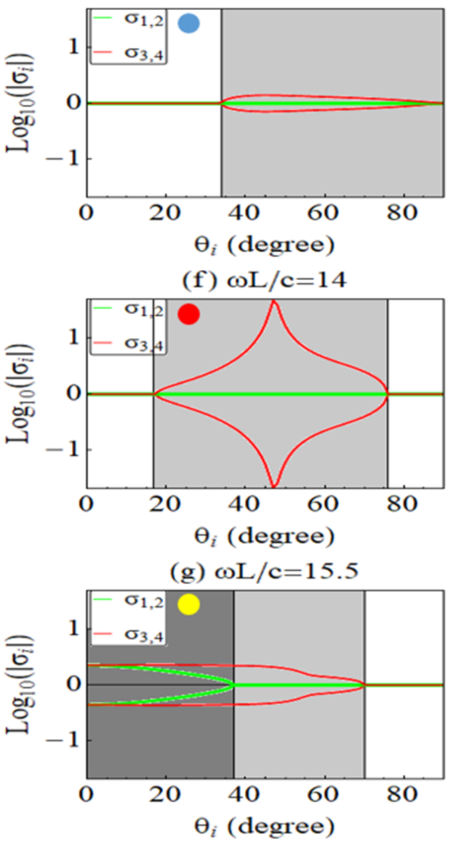
### *Scattering matrix eigenvalues, σ*



### *Tuning through κ*



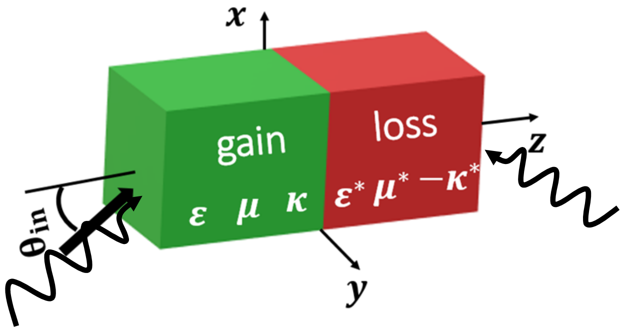
### *Tuning through $\theta_{in}$*



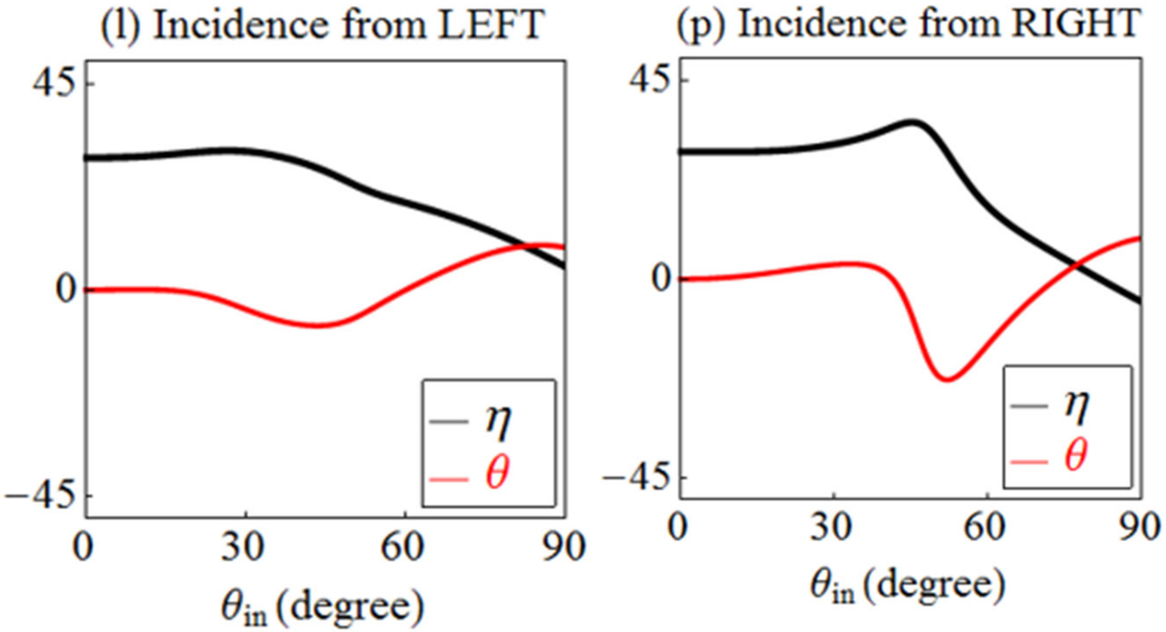
***Control of PT-features (exceptional points) through chirality and incidence angle***

$\varepsilon$

# Angle-dependent and asymmetric chiral effects



***Optical activity (θ) - Ellipticity (η)***



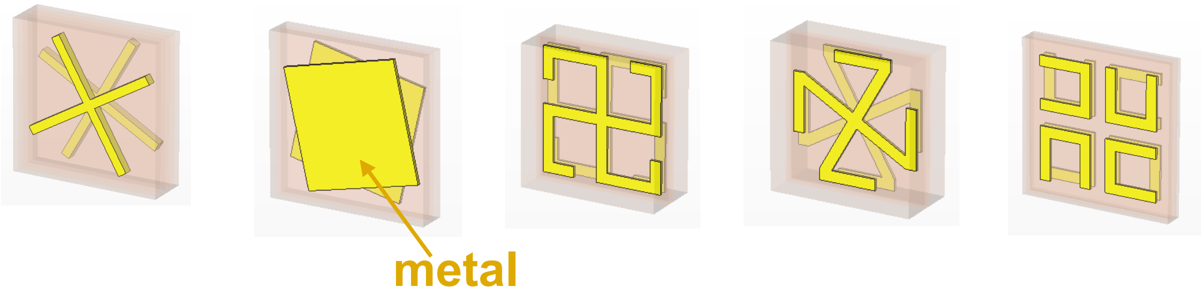
***Angle-dependent* optical activity and ellipticity**

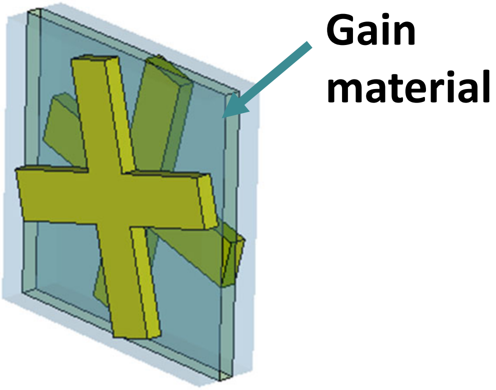
***Asymmetric* optical activity and ellipticity**

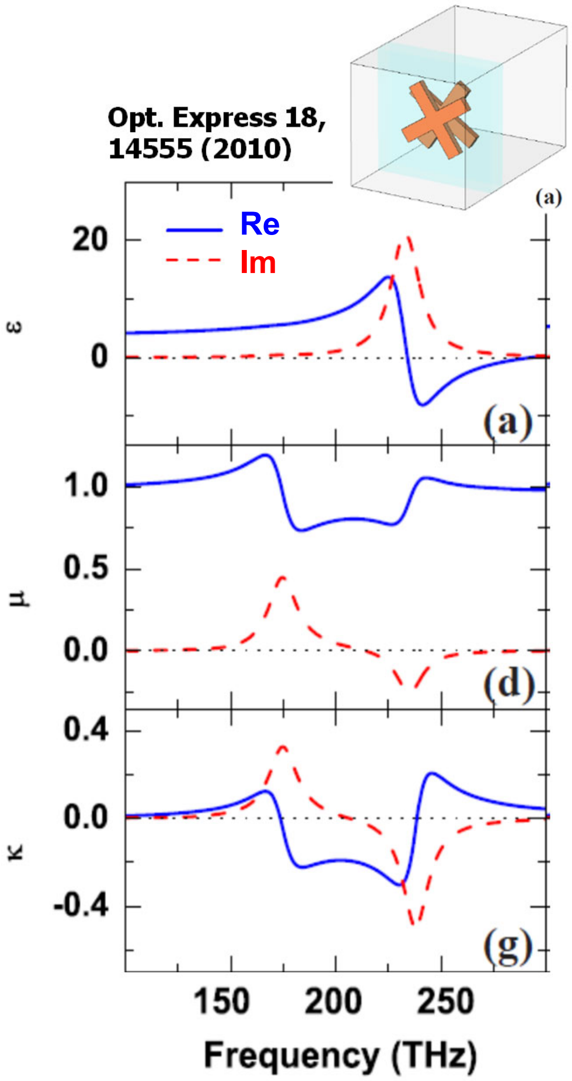
$$\varepsilon = 3 \pm 0.4i, \mu = 1.1 \pm 0.1i, \kappa = \pm 0.04 - 0.04i$$

# PT symmetric chiral metamaterial practical realization?

*Bilayer-metal structures (unit cells)*





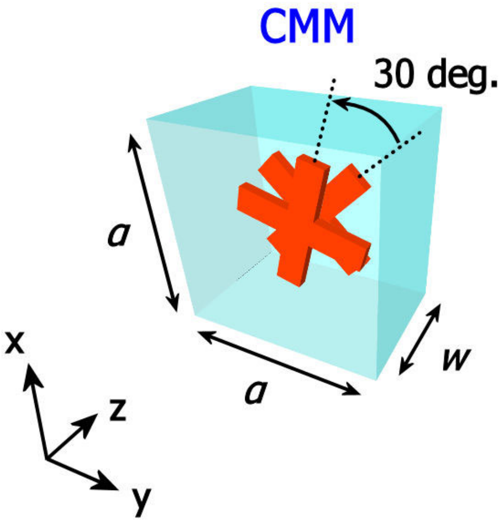

Opt. Express 18, 14555 (2010)

***Advantages***

- **Fabrication by planar technologies**
- **Enhancement of effective loss and gain**
- **"Independent" control of κ and ε, μ**

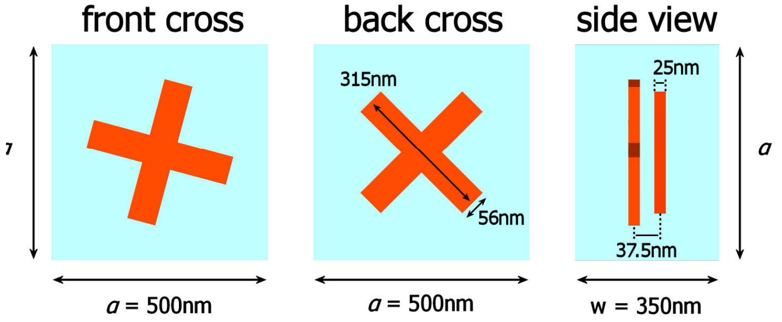
# PT-phase transition in a realistic system

**Gold crosses** $n_{host} = 1.41 - i0.09$

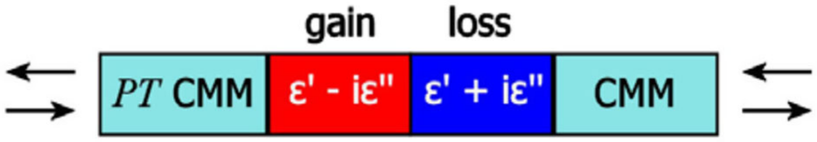


**PT @ 220 THz**

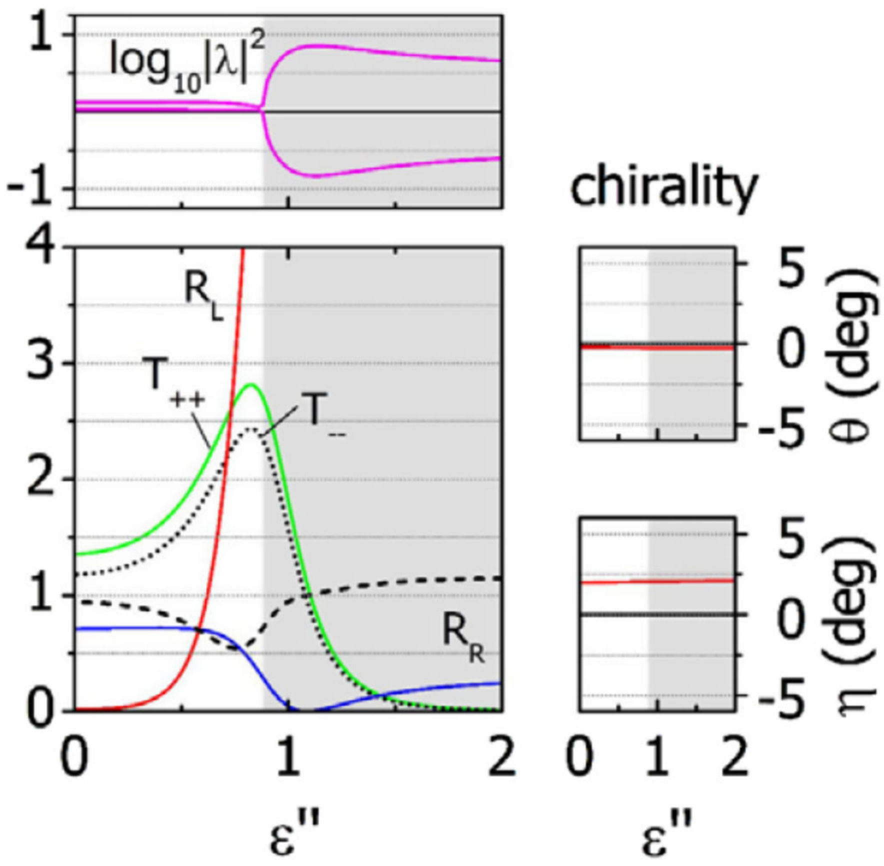
$a$ = 500nm
w = 350nm



*Droulias et. al., Phys. Rev. Lett **122**, 213201 (2019)*



$$\kappa_{PT\text{-}CMM} = -\kappa^*_{CMM}$$



# Summarizing

**Combining PT-symmetry with chirality:**

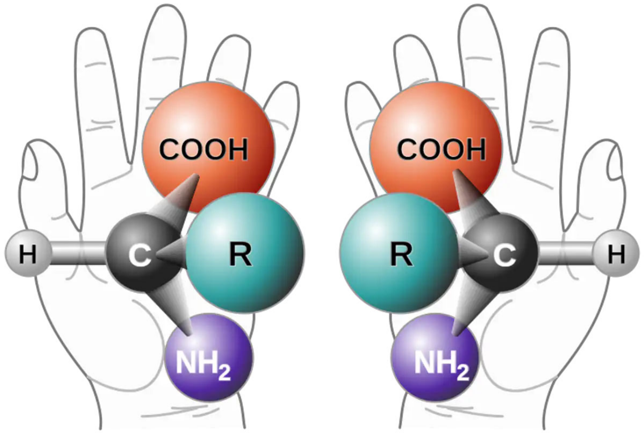
***Normal incidence*** → **possibility of independent control of PT-effects and polarization**

***Off-normal incidence*** →

- **mixed PT-phases**
- **multiple exceptional points**
- **angle-dependent and chirality-dependent PT and polarization features**
- **asymmetric (side-dependent) polarization features**

***For more info see***
*Droulias et. al., Phys. Rev. Lett* ***122****, 213201 (2019)*
*Katsantonis et. al., Phy. Rev. B* ***101****, 214109 (2020)*
*Katsantonis et. al., Photonics* ***7****, 43 (2020)*

# PT symmetry for molecular chirality sensing



**Left-handed enantiomer (S - sinister)**

**Right-handed enantiomer (R - rectus)**

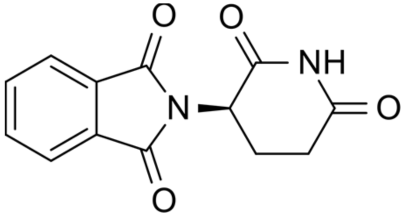
$$\kappa \sim 10^{-4}$$

***Why?***

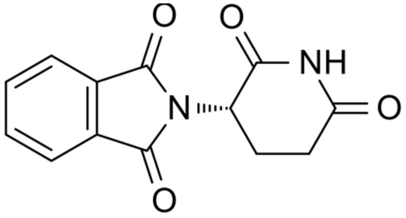
***Opposite enantiomers: Different biological activity***

**Morning sickness treatment**

**Teratogennesis**



**(R)-thalidomide**



**(S)-thalidomide**

***Enantiomer detection and discrimination is of great importance for biology and pharmaceutical industry***

# Chirality effects used for sensing

$$n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa$$

***Optical activity***

**Rotation of linear polarization**

***Circular dichroism (CD)***

**Different absorption for**

**RCP(+)/LCP(-) waves*: CD: $A_{+}$-$A_{-}$***

***measured by:***

$$CD = A_{+} - A_{-} = \underset{\substack{\uparrow \\ \text{transmittance of} \\ \text{LCP (-) waves}}}{\left|t_{--}\right|^{2}} - \underset{\substack{\uparrow \\ \text{transmittance of} \\ \text{RCP (+) waves}}}{\left|t_{++}\right|^{2}}$$

***In natural chiral media κ~$10^{-4}$ → weak chiro-optical signals, e.g. CD~$10^{-5}$***

# Chirality effects used for sensing

$$n_{\pm} = \sqrt{\varepsilon\mu} \pm \kappa$$

***Kuhn's dissymmetry factor, g***

**Relative differential absorption for RCP(+)/LCP(-) waves**

$$g=(A_+-A_-)/[(A_++A_-)/2]$$

**(percentage of enantioselectivity in photoexcitations)**

$$g = \frac{A_+ - A_-}{(A_+ + A_-)/2} = \frac{CD}{(A_+ + A_-)/2}$$

***Circular dichroism (CD)***

**Different absorption for RCP(+)/LCP(-) waves: *CD: $A_+$-$A_-$***

***measured by:***

$$CD = A_+ - A_- = |t_{--}|^2 - |t_{++}|^2$$

***Enhancing g →***

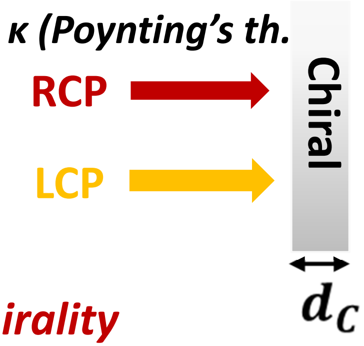
**Enhanced *enantioselectivtiy* in *photoionization, photolysis, fluorescence, photopolymerization*, etc.**

***In natural chiral media κ~$10^{-4}$ → weak chiro-optical signals, e.g. CD~$10^{-5}$***

# Absorption in chiral media

***Absorbed power density** of a CP (+/-) wave by a thin chiral layer of parameters ε, μ, κ (Poynting's th.*

$$A_{\pm} \sim \frac{\omega}{2}[\mathrm{Im}(\varepsilon)\,|\mathbf{E}|^{2} + \mathrm{Im}(\mu)\,|\mathbf{H}|^{2}] \pm \frac{2\omega}{c}\,\mathrm{Im}(\kappa)\,\mathrm{Im}(\mathbf{E}\cdot\mathbf{H}^{*})$$



$$CD = A_{+} - A_{-} = 4c\,\mathrm{Im}(\kappa)[\frac{\omega}{2c^{2}}\,\mathrm{Im}(\mathbf{E}\cdot\mathbf{H}^{*})]$$

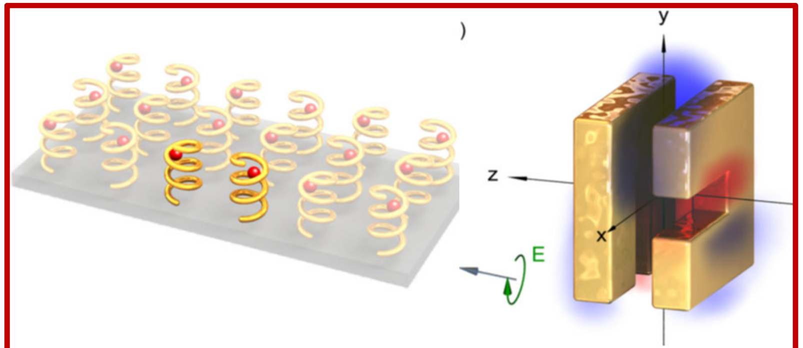
***Field chirality***

$$\boxed{C = -\frac{\omega}{2c^{2}}\,\mathrm{Im}(\boldsymbol{E}\cdot\boldsymbol{H}^{*})}$$

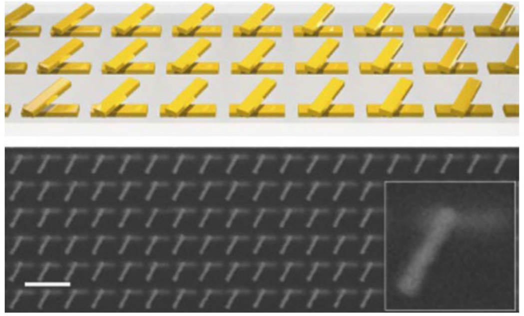
**Tang & Cohen, PRL 104, 163901 (2010)**

***Enhancement through proper resonances – enhanced local fields***

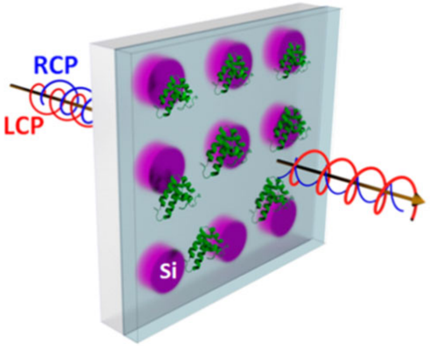
# Nanophotonics for enhancing circular dichroism



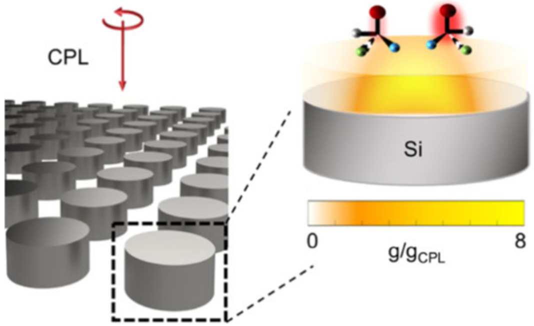
Giessen, PRX 2, 031012 (2012)



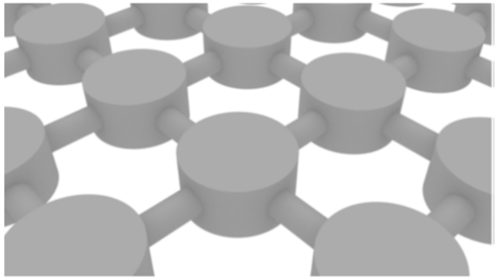
Alu, Nat. Commun. 8, 14180 (2017)



Altug, ACS Photon. 5, 2669 (2018)



Dionne, ACS Photon. 6, 43 (2019)

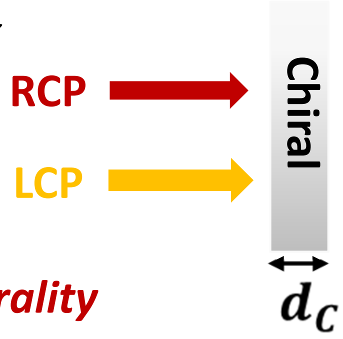


I. Fernandez-Corbaton, ACS Photon. 6, 482 (2019)

*Superiority of achiral structures – Overlapping resonances – up to 150x CD enhancement*

# Absorption in chiral media

***Absorbed power density of a CP wave by a thin chiral layer of parameters ε, μ, κ***



$$A_{\pm} \sim \frac{\omega}{2}[\mathrm{Im}(\varepsilon)\,|\,\mathbf{E}\,|^2 + \mathrm{Im}(\mu)\,|\,\mathbf{H}\,|^2] \pm \frac{2\omega}{c}\mathrm{Im}(\kappa)\,\mathrm{Im}(\mathbf{E}\cdot\mathbf{H}^*)$$

$$CD = A_{+} - A_{-} = 4c\,\mathrm{Im}(\kappa)[\frac{\omega}{2c^2}\mathrm{Im}(\mathbf{E}\cdot\mathbf{H}^*)]$$

***Field chirality***

$$C = -\frac{\omega}{2c^2}\mathrm{Im}(\boldsymbol{E}\cdot\boldsymbol{H}^*)$$

**Tang & Cohen, PRL 104, 163901 (2010)**

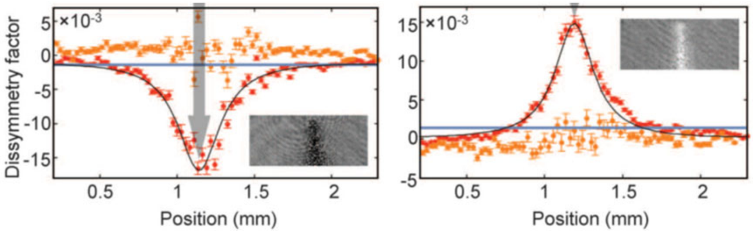
***Enhancement through proper resonances – enhanced local fields***

$$g = \frac{2(A_{+} - A_{-})}{A_{+} + A_{-}} \propto \frac{8c\,\mathrm{Im}(\kappa)C}{\omega[\mathrm{Im}(\varepsilon)\,|\,E\,|^2 + \mathrm{Im}(\mu)\,|\,H\,|^2]}$$

***Nodes of standing wave in specially designed cavity***

*Tang & Cohen, PRL104, 163901 (2010)*

***11-fold g-enhancement (fluorescence)***



***Tang & Cohen, Science 332, 333 (2011)***

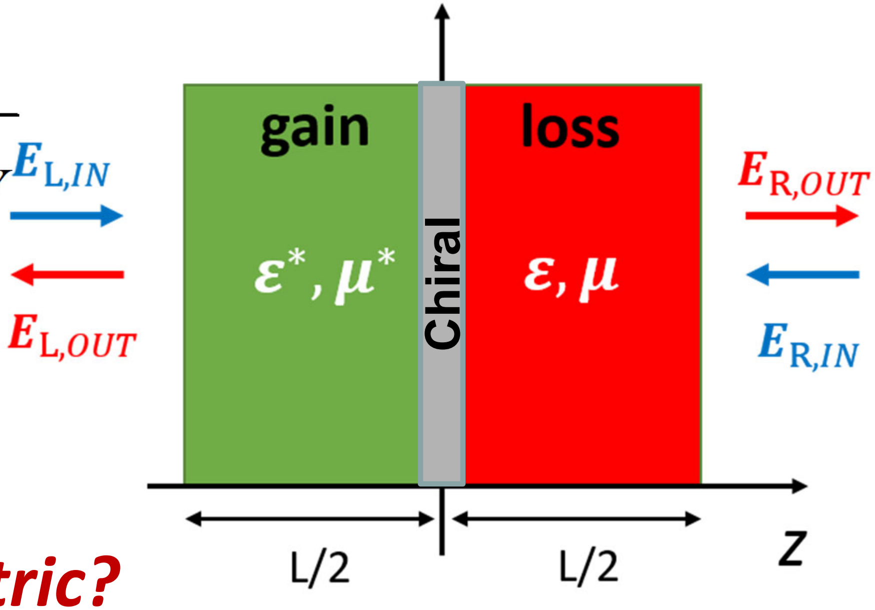
***He et al., Nature Comm. (2018)***

***(Photopolymerization dissymmetry)***

# Our approach: Combine loss and gain media

$$g \propto \frac{\frac{1}{V}\int \mathrm{Im}(\kappa)\,\mathrm{Im}(\mathbf{E}\cdot\mathbf{H}^{*})dV}{\frac{1}{V}\int [\mathrm{Im}(\varepsilon)|\mathbf{E}|^{2} + \mathrm{Im}(\mu)|\mathbf{H}|^{2}]dV}$$

***Parity-Time (PT) symmetric bilayer***



***Why Parity-Time (PT) symmetric?***

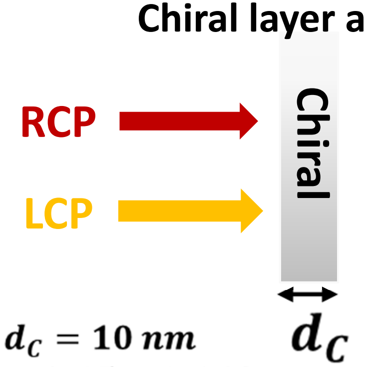
$\varepsilon(z) = \varepsilon^{*}(-z)$

$\mu(z) = \mu^{*}(-z)$

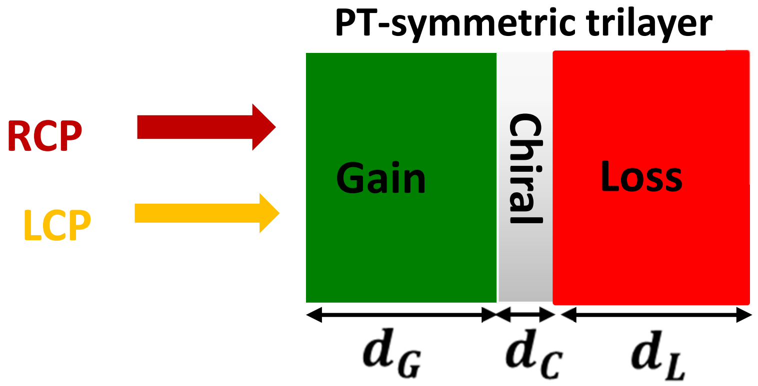
- **Balanced loss and gain $\mathrm{Im}(\varepsilon_{gain})=-\mathrm{Im}(\varepsilon_{loss})$**
- **Strong fields at gain-loss interface**
- **Peculiar, potentially useful electromagnetic effects (unidirectional invisibility, simultaneous coherent perfect absorption & lasing)**

I. Katsantonis et. al., Phys. Rev. B 105, 174112 (2022)

# CD enhancement in the PT-symmetric 3-layer system

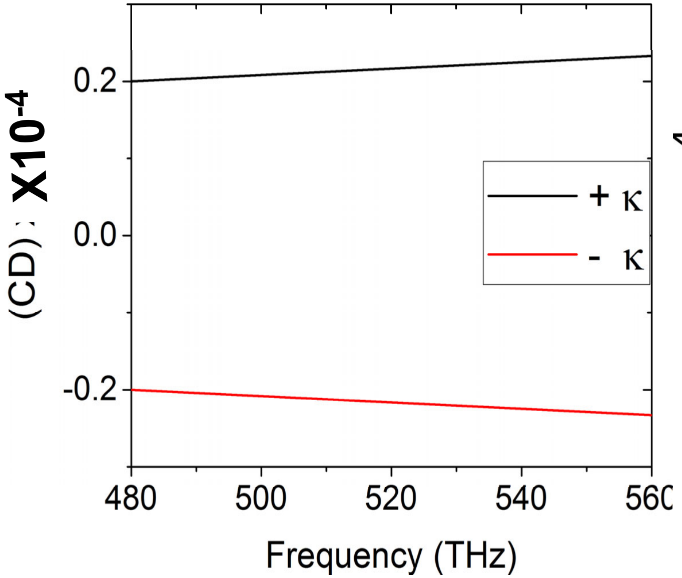


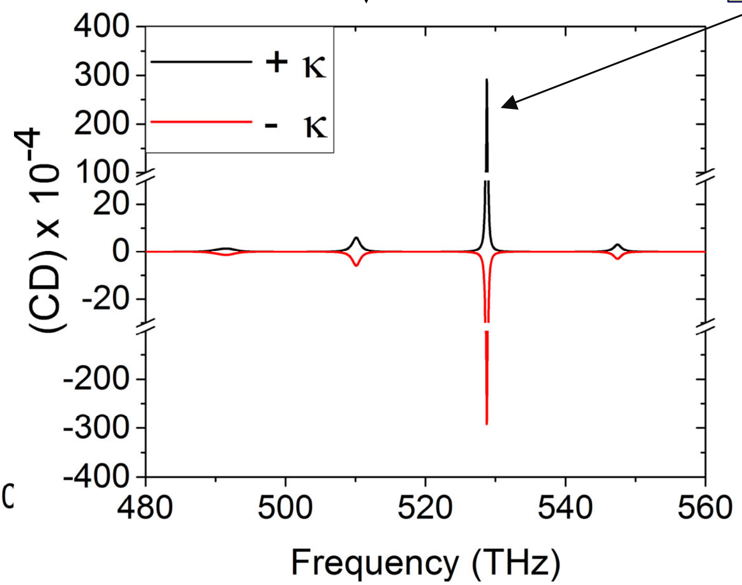
$d_C = 10\ nm$
$n_C = 1.45 + 0.01i$
$\kappa = \pm 5 \times 10^{-5}(1 + i)$



$d_{G/L} = 2.5\ \mu m$
$n_{G/L} = 3.2 -/+ 0.05i$

$$CD = A_+ - A_- = |t_-|^2 - |t_+|^2$$

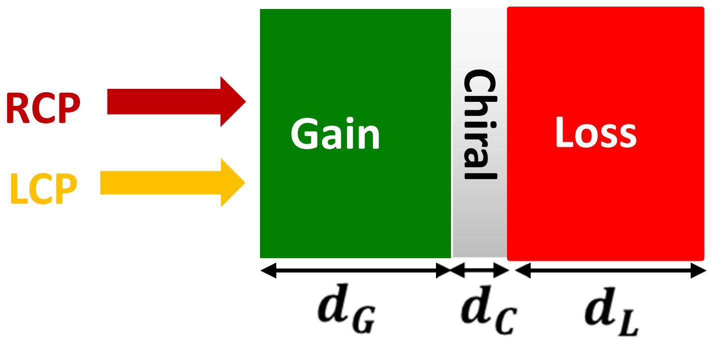


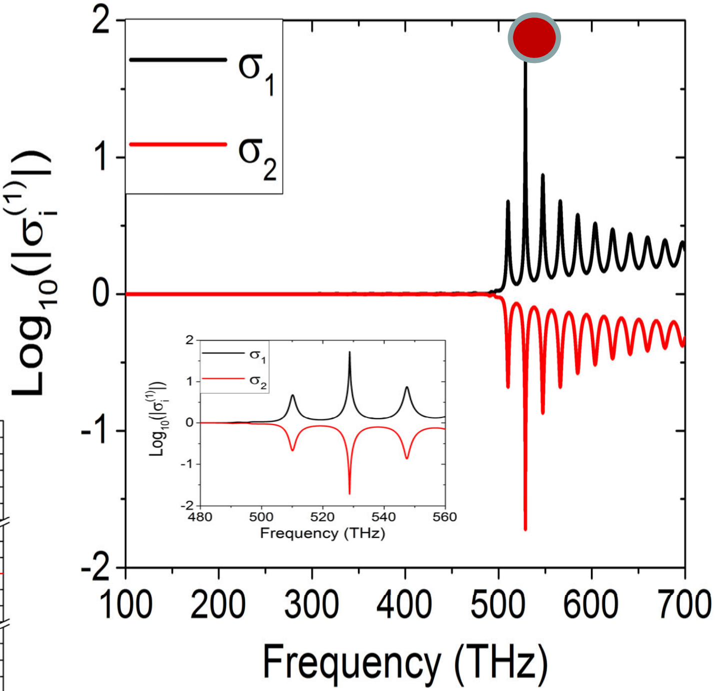


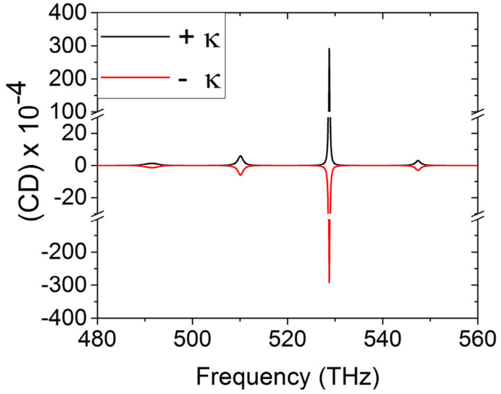
**~1500 times CD enhancement!**

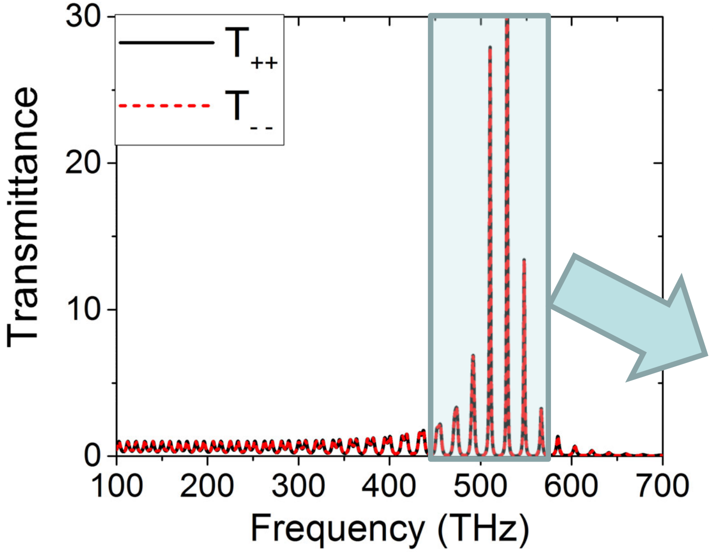
**Many CD peaks of ~20x enhancement**

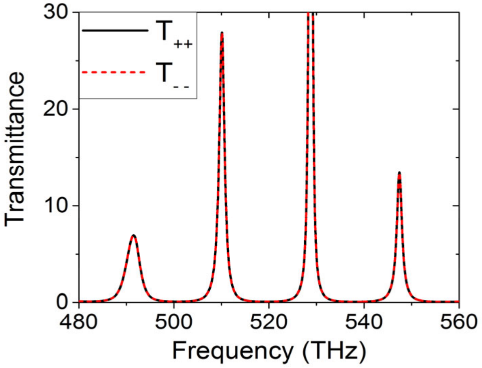
# Transmission / reflection / scattering matrix for the 3-layer PT system





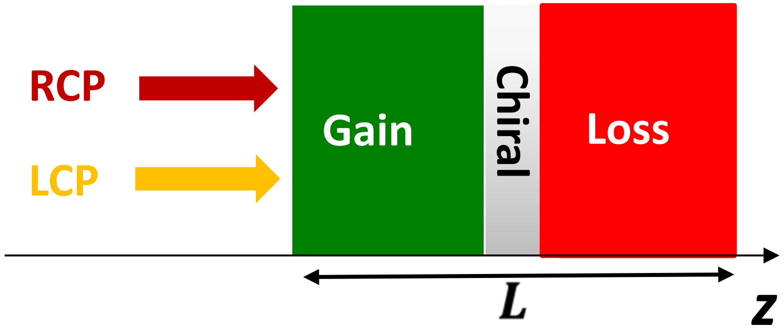


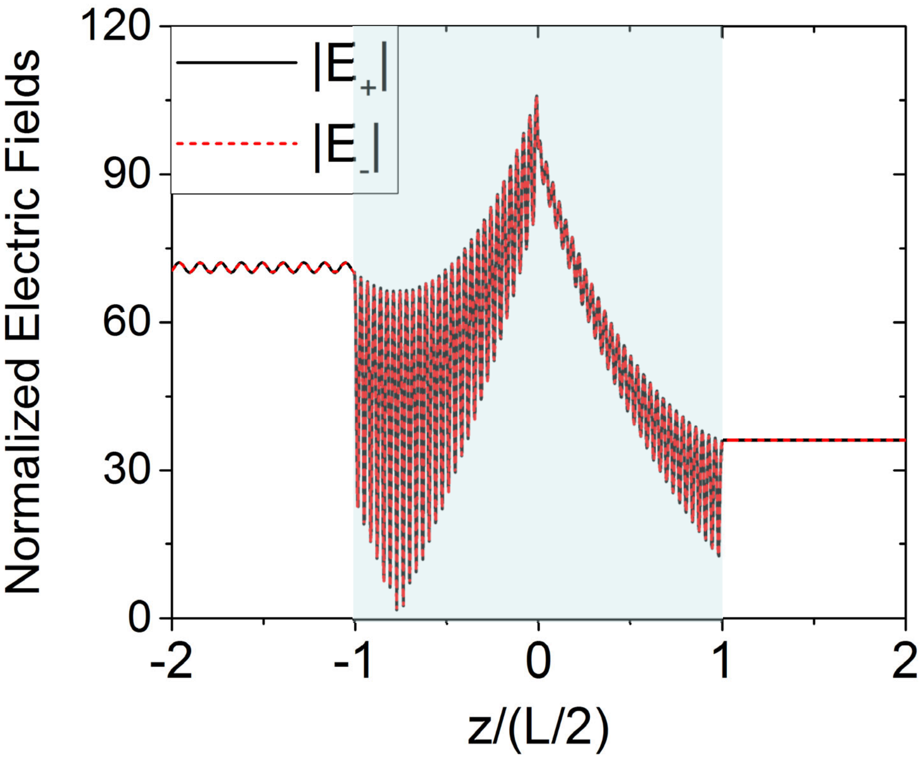




**Largest CD enhancement at lasing threshold**

# Electric field at the CD peak of 3-layer PT system





***Larger field in gain region***

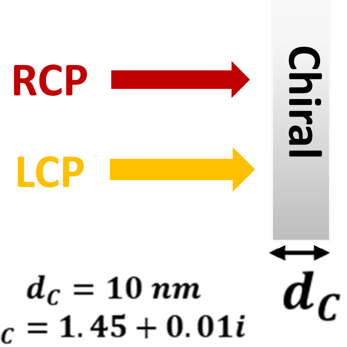
***Large interfacial field intensities***

⇩

***Large optical chirality***

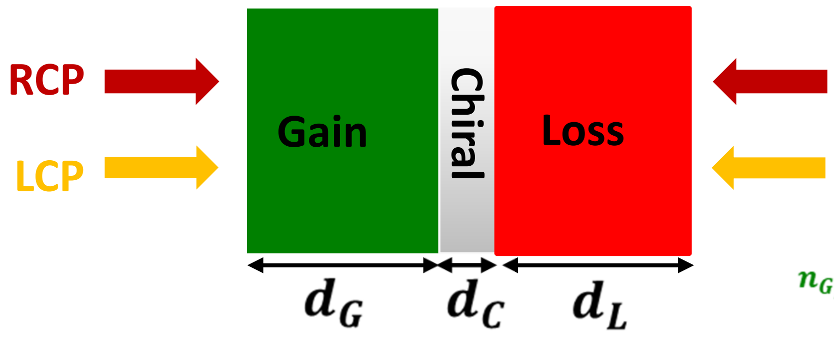
# *g*-enhancement in the PT-symmetric 3-layer system

**Chiral layer alone**

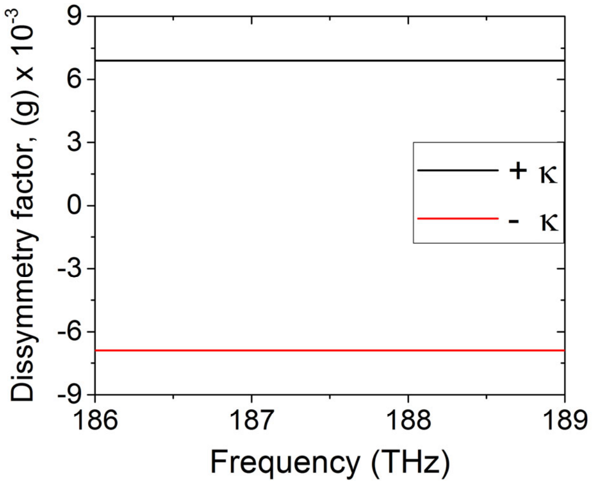


$d_C = 10\ nm$
$n_C = 1.45 + 0.01i$
$\kappa = \pm 5 \times 10^{-5}(1+i)$

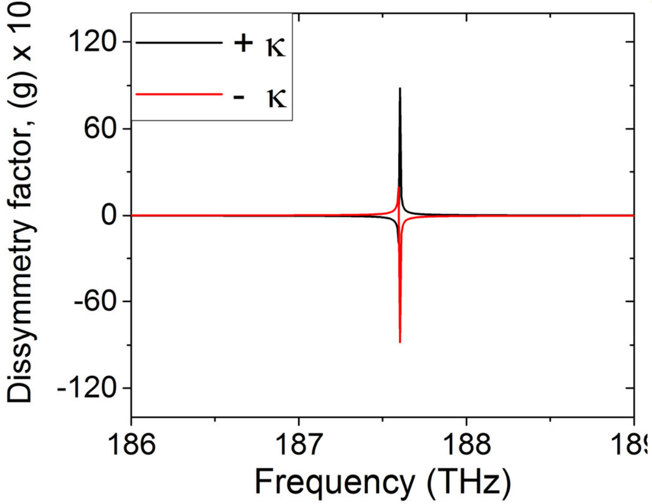
**PT-symmetric trilayer**



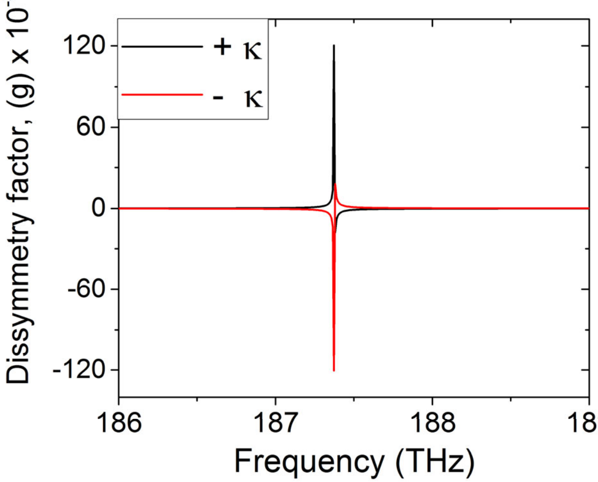
$d_{G/L} = 2.5\ \mu m$
$n_{G/L} = 3.2 -/+ 0.05i$



**Incident from Left**



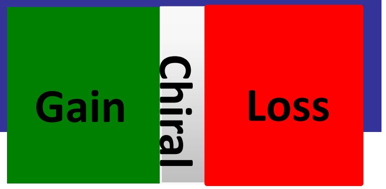
**Incident from Right**



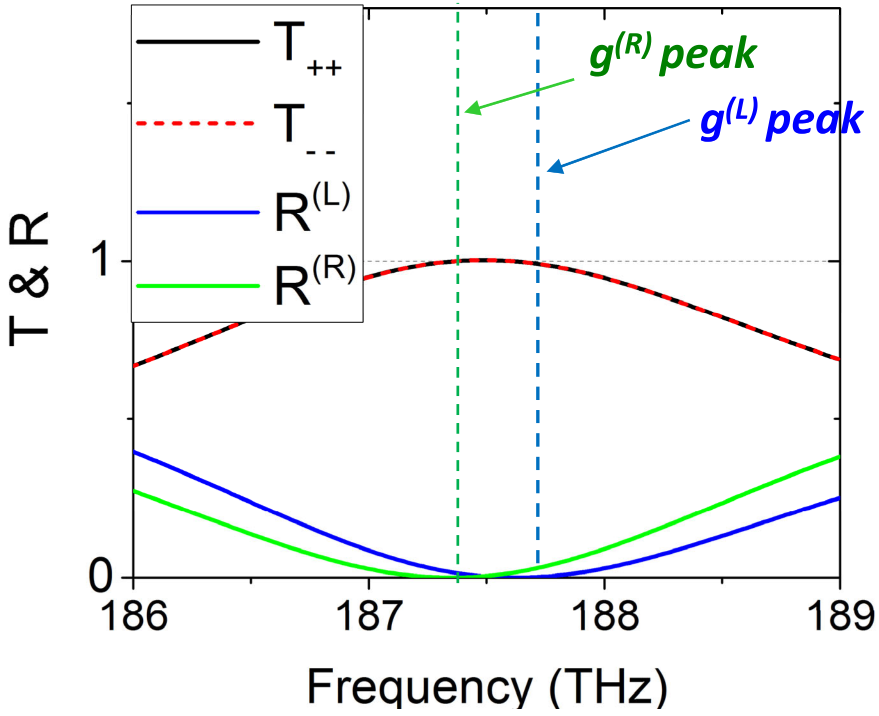
$$g^{(L/R)} = \frac{2(|t_-|^2 - |t_+|^2)}{2 - |t_-|^2 - |t_+|^2 - 2|r^{(L/R)}|^2}$$

***~15x dissymmetry enhancement compared to chiral layer alone***

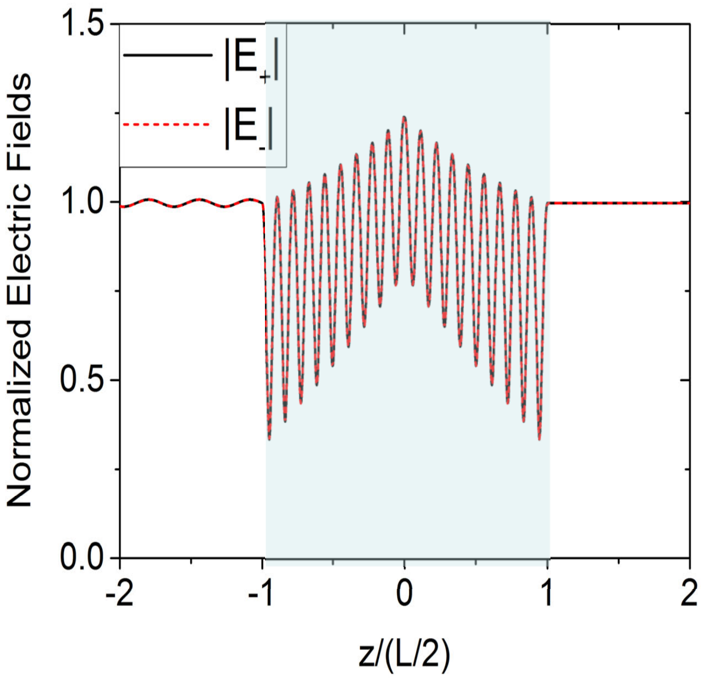
# *g*-enhancement investigation for the PT-symmetric 3-layer system



***g* enhancements @ R=0, T≈1**



***Field intensity along system @ g-peak***



***g* enhancements centered at flux conserving points with R=0, T=1, A=0 - anisotropic transmission resonances**

***g*-enhancement associated with appreciable field intensity**

# Conclusions/summary

**PT-symmetric media provide a promising avenue for molecular chirality sensing and enantioselective field-molecule interactions**

***In such systems:***

**Large Circular Dichroism enhancements**

**Large dissymmetry factor (*g*) enhancements with appreciable field intensities**

**For details: I. Katsantonis et. al., Phys. Rev. B 105, 174112 (2022)**

*Thank you !*

nanoPOLY

Visor SURF

***Ultrachiral***