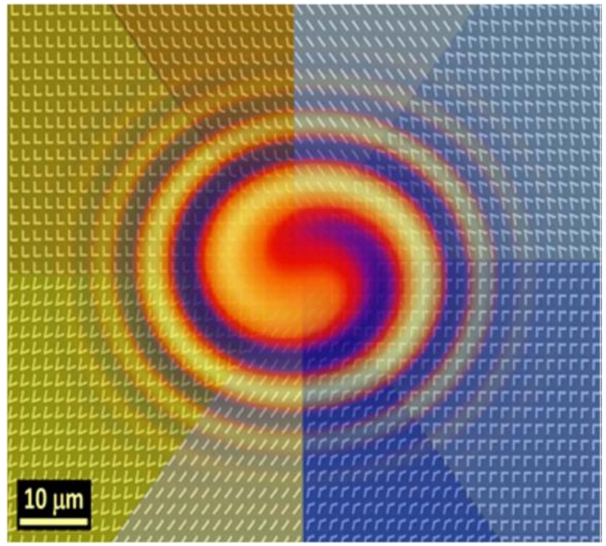
Singular Metaphotonics: A framework to address light scattering



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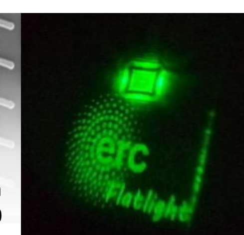
European Research Council

FLATLIGHT – Grant agreement 639109

Horizon 2020



CRHEA, Sophia-Antipolis

Metaphotonics @ CRHEA Group

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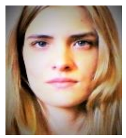
Postdoctoral Fellows

Renato Martins



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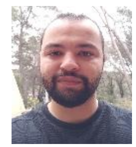
Nicolas Kossowski

Rémi Colom

PhD Students



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European Innovation Council

Funded by the European Union

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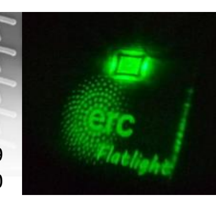
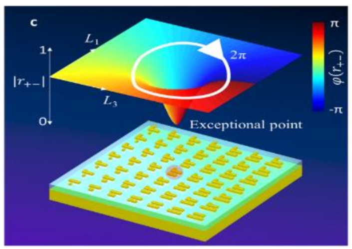
FLATLIGHT – Grant agreement 639109
Horizon 2020



My group activities

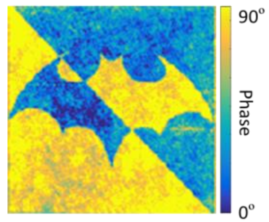
From fundamental concepts to the conception of devices

Topological Metasurfaces

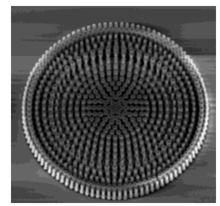


Science 373 (6559), 1133-1137 (2021)

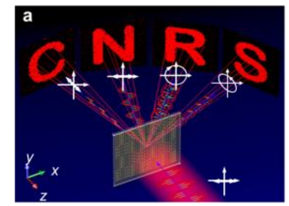
Wavefront engineering and metrology of Metasurfaces



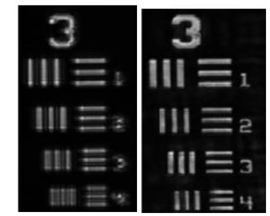
ACS Photonics 8 (2), 603-613 (2021)



ACS Photonics 8 (8), 2498-2508 (2021)

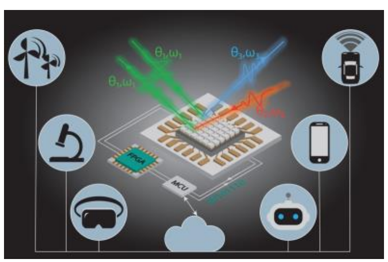


Science Adv. 7 (5), eabe1112 (2021)
Nat. Comm.11 (1), 1-8 (2020)
Nat. Comm. 10 (1), 1-8 (2019)



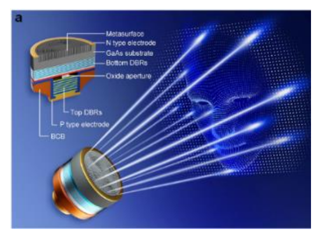
Optica 8 (11), 1405-1411 (2021)

Programmable Active Metasurfaces

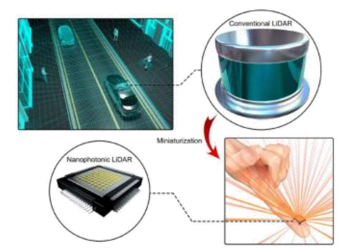


ACS Photonics 9 (5), 1458-1482 (2022)

State-of-the-art Metasurface Applications in imaging systems



Nature nano. 15 (2), 125-130 (2020)



Nature nano 16, 508–524 (2021)
Nature Comm. 13, 1–8 (2022)

P. Genevet, CRHEA, CNRS, France

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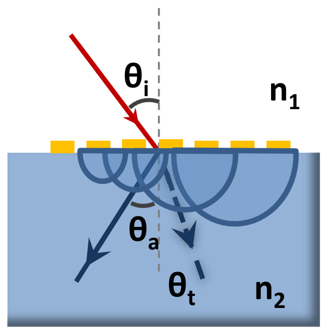
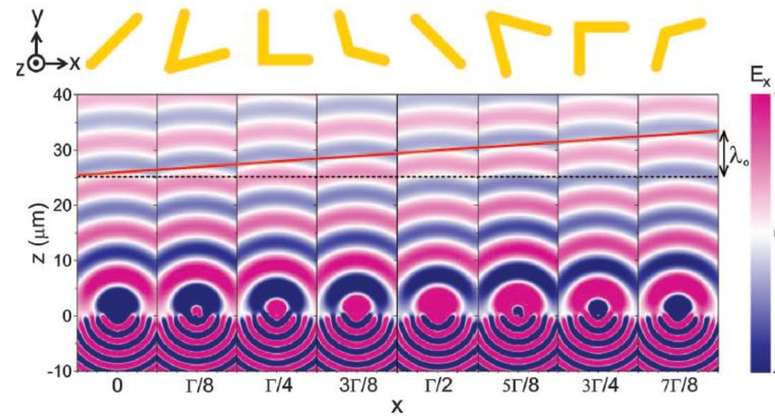
Metaphotonics, a brief introduction

Locally engineering of the surface response



Phase gradient direction

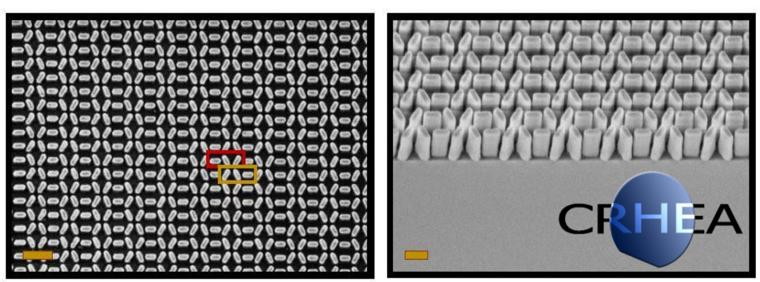
$$\frac{d\varphi}{dx}$$



N. Yu, P. Genevet, M. A. Kats, F. Aieta, J.P. Tetienne, F. Capasso and Z. Gaburro, ***Science* 334**,333 (2011).

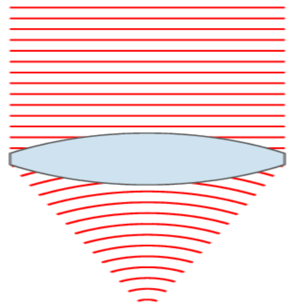
Generalized Snell laws

$$n_2 \sin\theta_2 - n_1 \sin\theta_1 = 1/k_0 . \partial\phi/\partial x$$

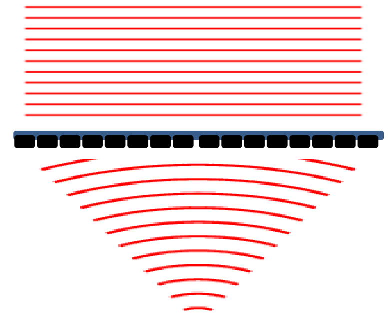


Metaphotonics, a brief introduction

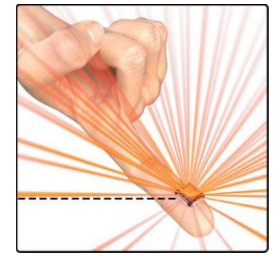
Wavefront control



Classical lens (~ cm)

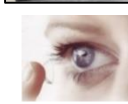


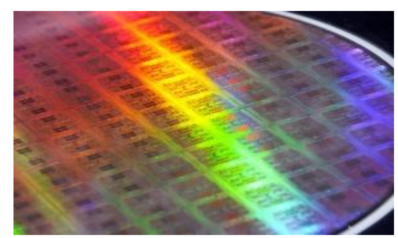
Meta-lens (~nm)

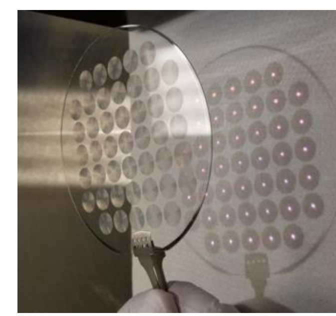


Engineering of the phase, amplitude, and polarization of light at an interface

Wafer level fabrication of optical components







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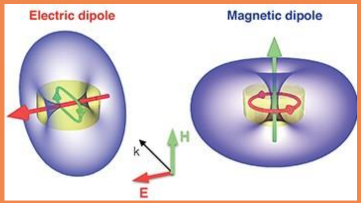
Generalities

Phase Addressing Mechanisms

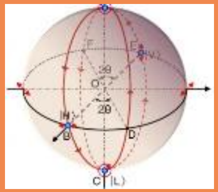
SINGULAR SCATTERING



Decker at al., 2015

2π Topological phase encircling singularities

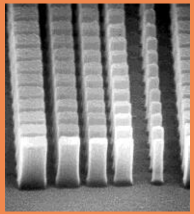
Pancharatnam-Berry (PB) Phase



E. Hasman group , Optics Letters, 27, 1141 (2002)

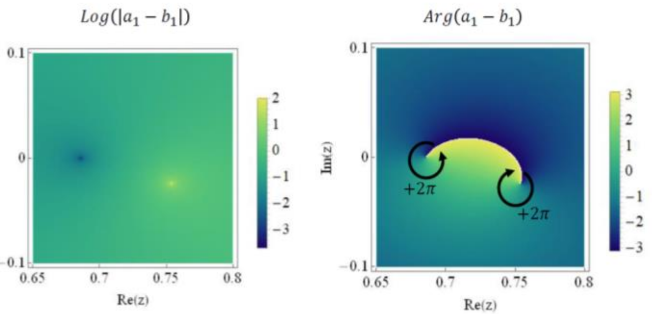
-Polarization conversion
-Birefringent plasmonic or Dieletrics
-full 2π phase coverage

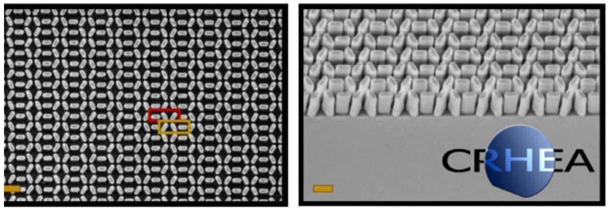
Effective index waveguides

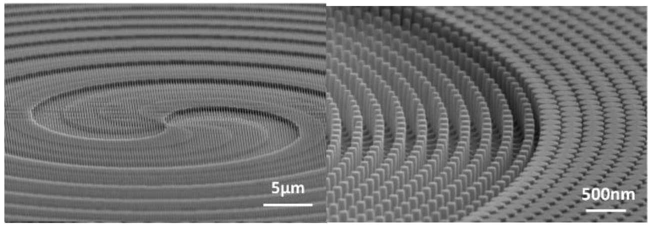


P. Lalanne, & al. *Opt. Lett.* 23, 1081-1083 (1998)
C. Chang Hasnain et al. .

- Not subwavelength in thickness
- Strong NF coupling







Y. Xie et al., Nat. Nanotechnol. **15,** 125–130 (2020)

P Genevet, F Capasso, F Aieta, M Khorasaninejad, R Devlin, **Optica** 4 (1), 139-152 (2017)

P. Genevet, CRHEA, CNRS, France
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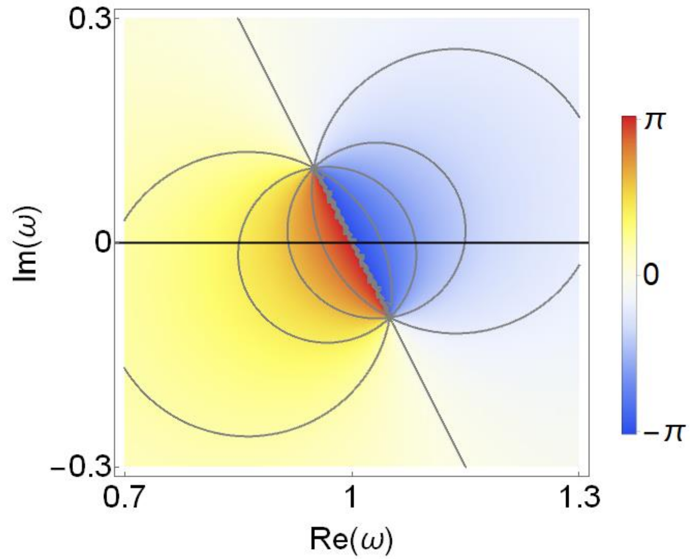
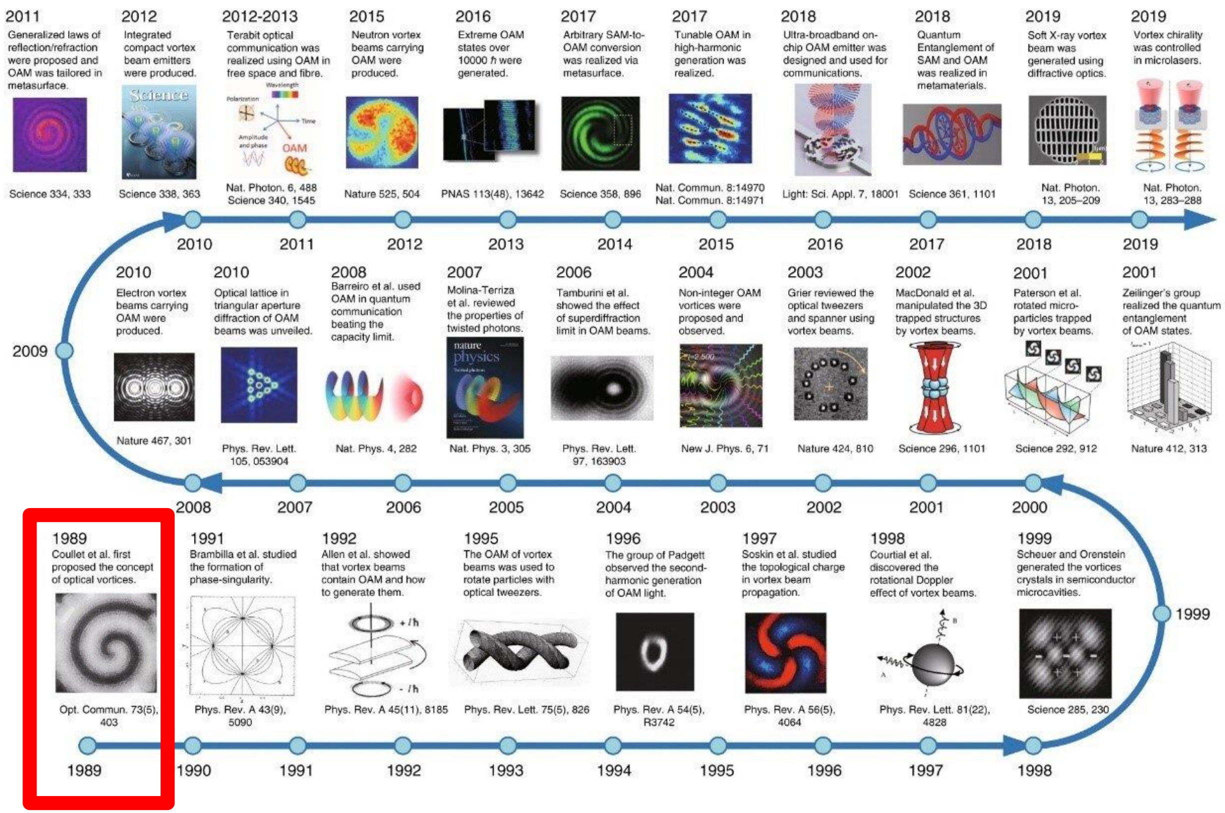
Motivation

❖ Understand which are the tuning mechanisms available for the design of MS



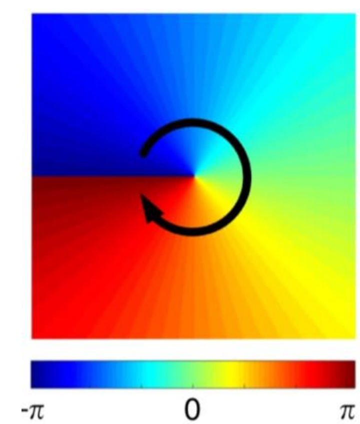
R. Colom, E. Mikheeva, K. Achouri, J. Zuniga-Perez, O. Martin, N. Bonod, S. Burger, and P. Genevet (Laser & Photonics Review, in press 2023, [arXiv:2202.05632](https://arxiv.org/abs/2202.05632))

Singularities in Photonics



Optical vortices 30 years on: OAM manipulation from topological charge to multiple singularities, *Light: Science & Applications* (2019). DOI: 10.1038/s41377-019-0194-2

Pierre Coullet



2π –Phase circulation and region of undefined amplitude

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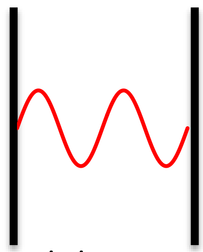
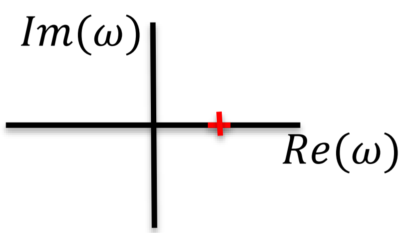
How Metasurfaces are related to singular physics ?

Hermitian system = Cavity with perfectly mirrors



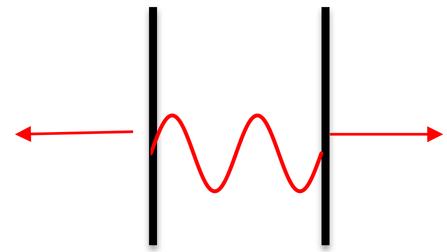
Energie is conserved

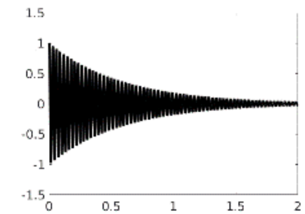
Real Eingenfrequency



Normal modes

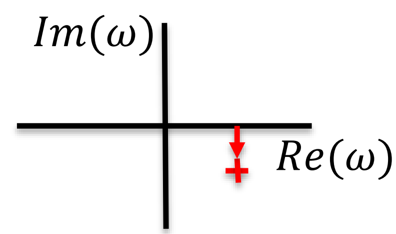
Non-Hermitian system = transmission or absorption losses



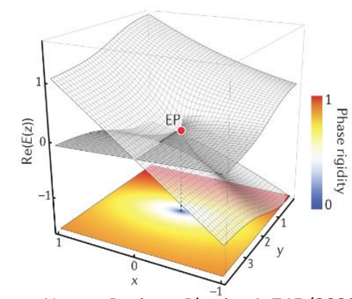


time

Complex Eigenfrequencies



Quasi-normal modes



Nature Reviews Physics 4, 745 (2022)

Optical systems are generally non-Hermitian

- Existence of parametric singularities where multiple eigenstates become coalescent (EPs)
- Completeness of corresponding Hilbert space breaks down.

=> anomalous effects (spontaneous symmetry-breaking phase transition, direction selectivity, chiral state transfer, & divergent resonance shifts)

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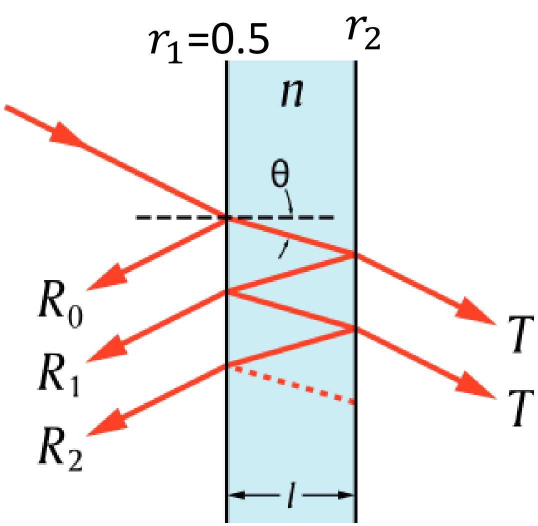
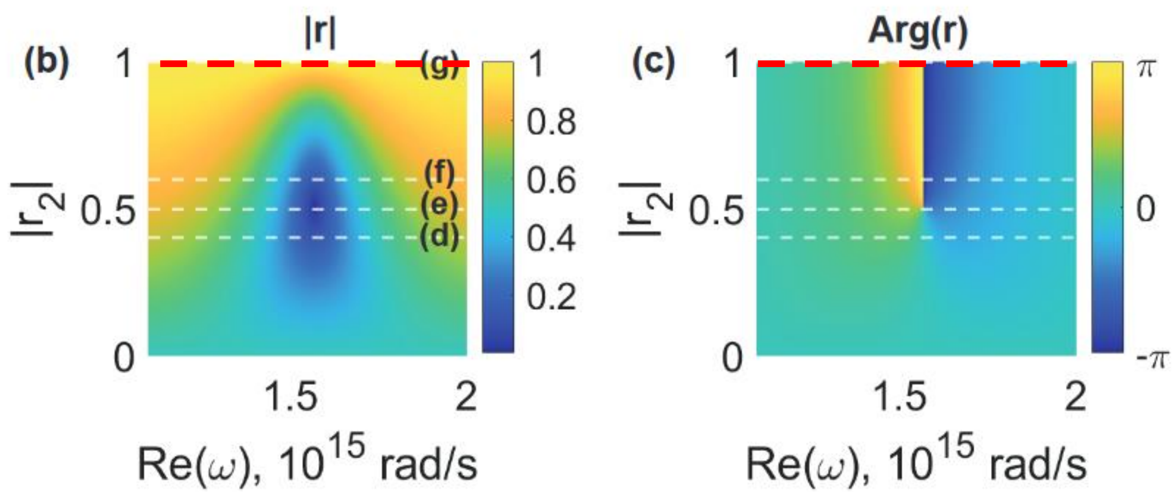
Fabry-Pérot is a non-Hermitian system



Reflection at normal incidence

$$r = \frac{E_r}{E_{in}} = \frac{r_1 + r_2\, e^{i\delta}}{(1 + r_1 r_2 e^{i\delta})}$$



R, T , … have complex eigenfrenquencies

$$r(\omega) = \prod_m \frac{\omega - \omega_{z,m}}{\omega - \omega_{p,m}}$$

Zeros and poles singularities =>Complex plane analysis

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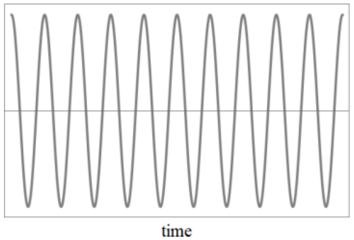
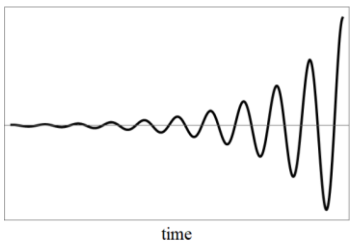
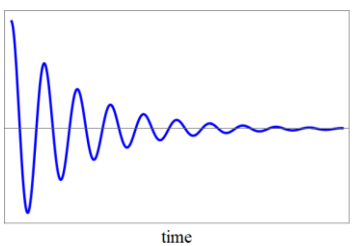
Study of the response at complex frequencies



$e^{-i\omega t}$ ω real : steady state response



$\omega = \omega_r + i\omega_i$ exponentially increasing



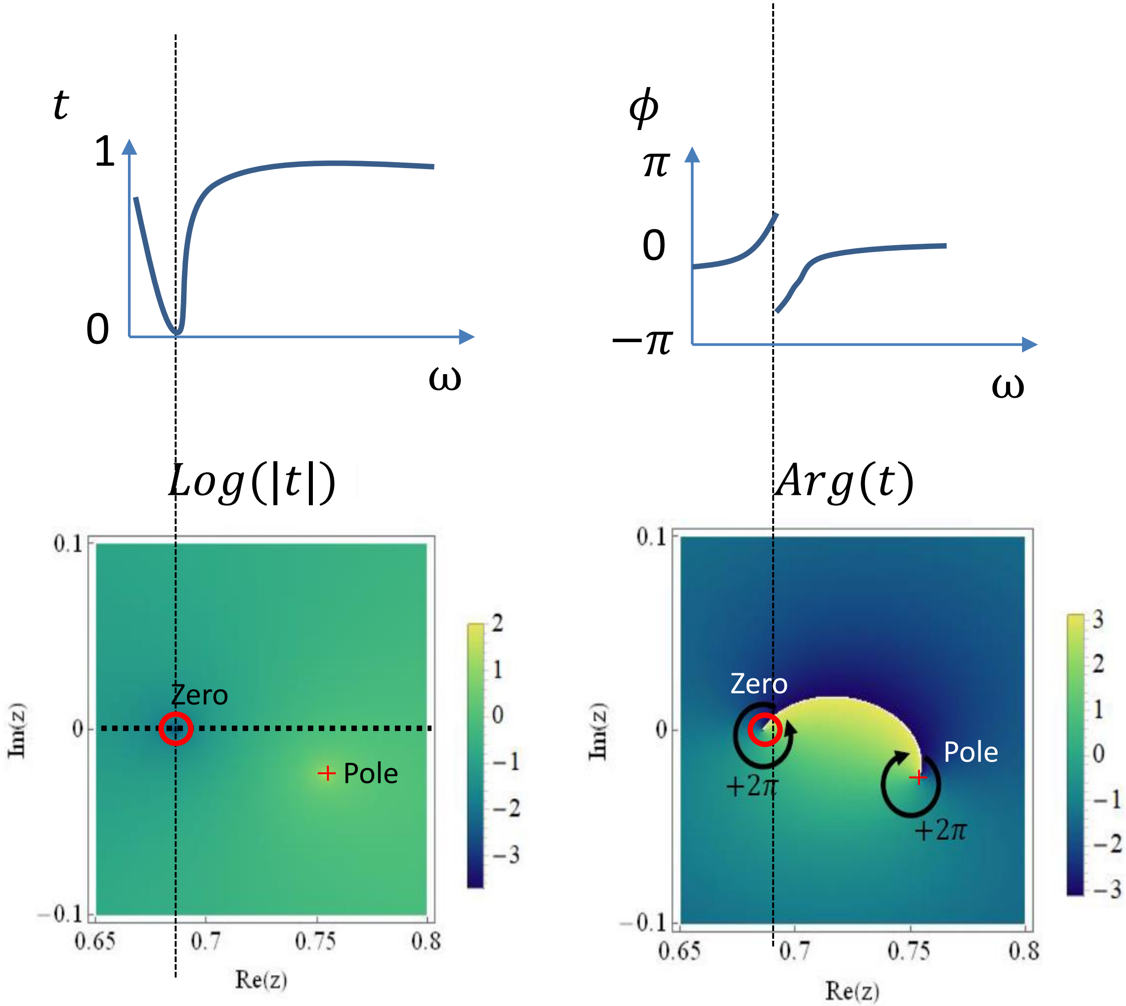
$\omega = \omega_r - i\omega_i$ exponentially decreasing

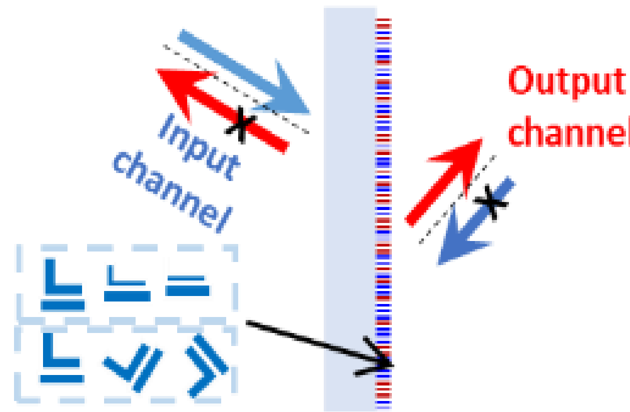
Virtual loss or gain

H. Li, A. Mekawy, A. Krasnok, & A. Alù (2020) *Physical Review Letters*, *124*(19), 193901.

P. Genevet, CRHEA, CNRS, France email: pg@crhea.cnrs.fr

1. How to exploit singularities?

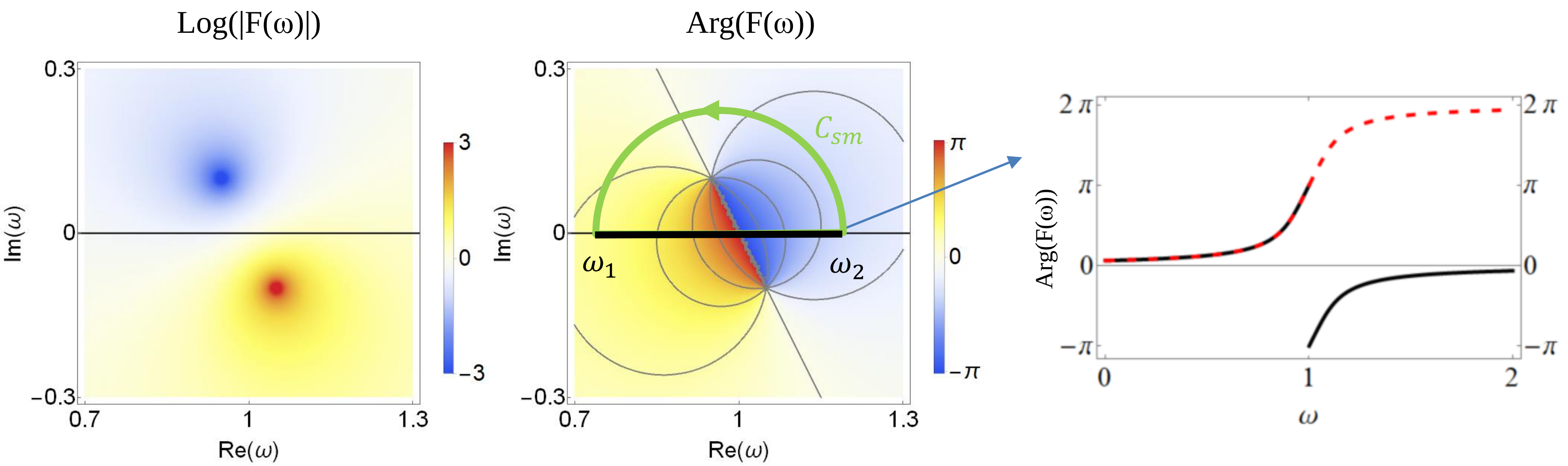




Detecting singularities

$$Log(t) = Log(|t|) + i\,Arg(t)$$

How relative position of singularities influence the phase



$\frac{1}{2\pi}\oint_{C_l} \frac{dArg(F(\omega))}{d\omega} d\omega$: topological charge of a phase singularity

= +1 for zeros

=-1 for poles

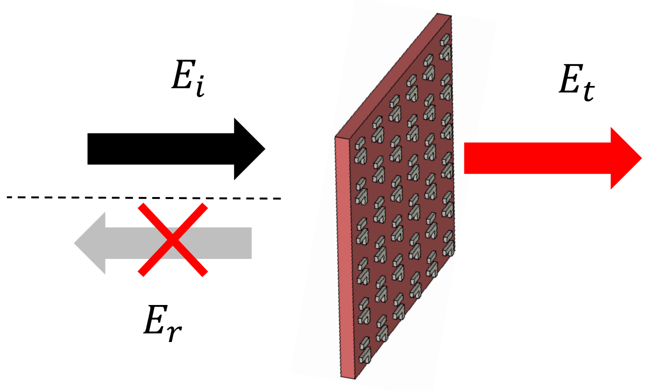
Pole and zero should be separated by the real axis

=> $Im(\omega_z) > 0$

Crossing of the branch cut: the topological origin of a universal 2π −phase retardation in non-Hermitian metasurfaces

R. Colom, E. Mikheeva, K. Achouri, J. Zuniga-Perez, O. Martin, N. Bonod, S. Burger, and P. Genevet
arXiv:2202.05632, Laser & Photonics Review (in press 2023)

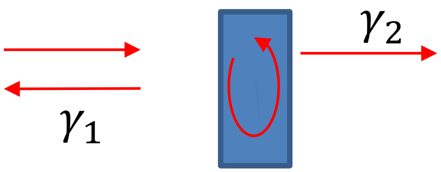
Reflection zero



Condition for 2π resonant phase gradient in reflection?

What do we learn from these expressions?

Assume one input and one output channels, 1 resonance, no absorption losses



Reflection zeros:

$$\omega_{RZ} = \omega_0 + i\underbrace{\frac{|d_1|^2}{2}}_{\gamma_1} - i\underbrace{\frac{|d_2|^2}{2}}_{\gamma_2}$$

effective gain

effective loss

Reflection poles:

$$\omega_P = \omega_0 - i\gamma_1 - i\gamma_2$$

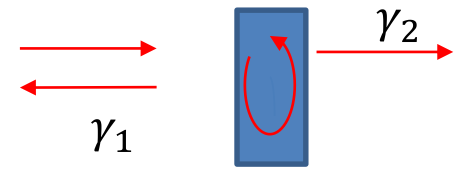
$$Im(\omega_P) < 0$$

$Im(\omega_{RZ}) < 0$	$\gamma_1 < \gamma_2$	Undercoupling
$Im(\omega_{RZ}) = 0$	$\gamma_1 = \gamma_2$	Critical coupling
$Im(\omega_{RZ}) > 0$	$\gamma_1 > \gamma_2$	Overcoupling

(Unpublished 2023)

Simple example with a Faby-Pérot cavity

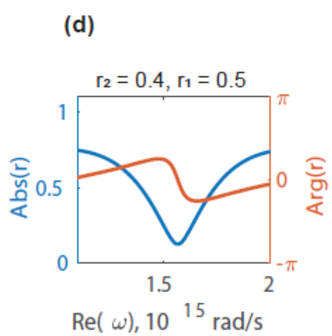
Zeros of a simple Fabry-Perot resonator with only one input and output channels



$$\omega_{RZ} = \omega_0 + i\gamma_1 - i\gamma_2$$

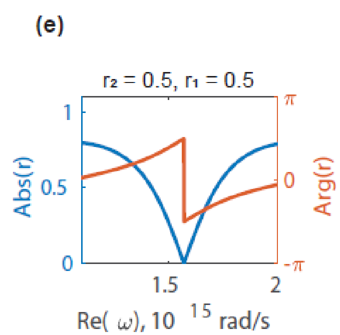
Undercoupling

$Im(\omega_{RZ}) < 0$



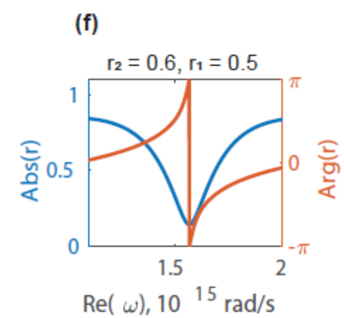
Critical coupling

$Im(\omega_{RZ}) = 0$



Overcoupling

$Im(\omega_{RZ}) > 0$



Overcoupling creates resonant phase jump of 2π

(Unpublished 2023)

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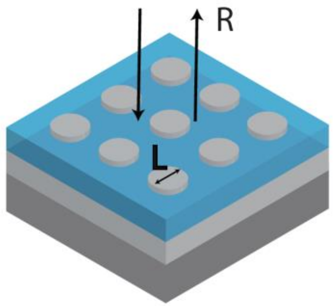
Absorption loss: an additional channel

Suppose we have a structure with a mirror (only one scattering channel, $\boldsymbol{\gamma_2 = 0}$) and absorption losses $\boldsymbol{\gamma_0}$:



Reflection zeros:

$$\omega_{RZ} = \omega_0 - i\gamma_0 + i\gamma_1 - \cancel{i\gamma_2}$$

absorption loss

scattering gain

Reflection poles:

$$\omega_P = \omega_0 - i\gamma_0 - i\gamma_1 - \cancel{i\gamma_2}$$

Note that in this example with 1 channel and absorption system, the complex values of poles and zeros can be used to calculate the losses

$$\begin{cases} \omega_{RZ} = \omega_0 + i\gamma_1 - i\gamma_0 \\ \omega_P = \omega_0 - i\gamma_1 - i\gamma_0 \end{cases} \longrightarrow \begin{cases} Im(\omega_{RZ}) = \gamma_1 - \gamma_0 \\ |Im(\omega_P)| = \gamma_1 + \gamma_0 \end{cases} \longrightarrow \begin{aligned} \gamma_1 &= \frac{|Im(\omega_P)| + Im(\omega_{RZ})}{2} \\ \gamma_0 &= \frac{|Im(\omega_P)| - Im(\omega_{RZ})}{2} \end{aligned}$$

(Unpublished 2023)

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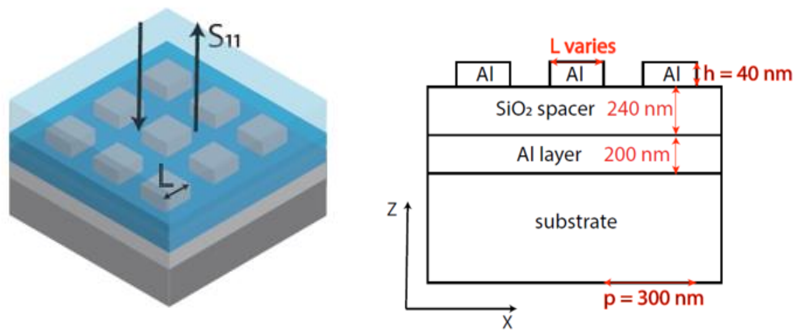
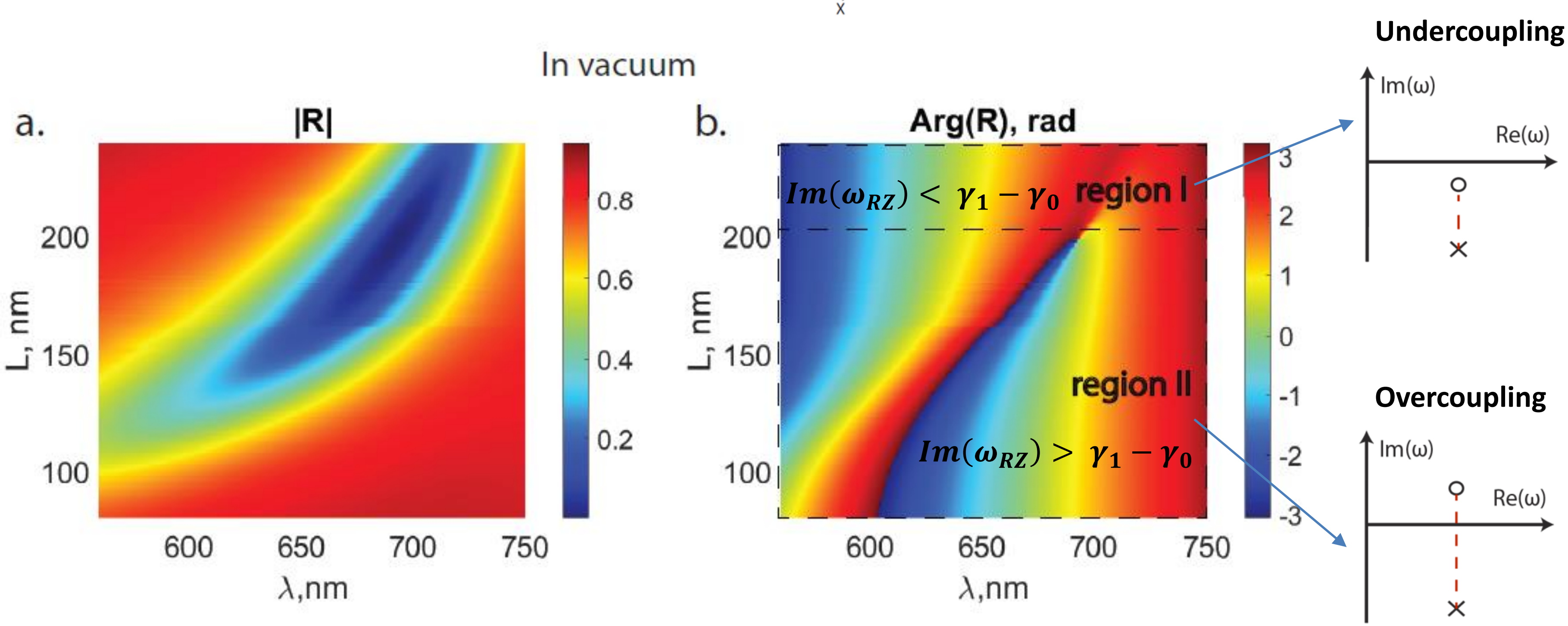
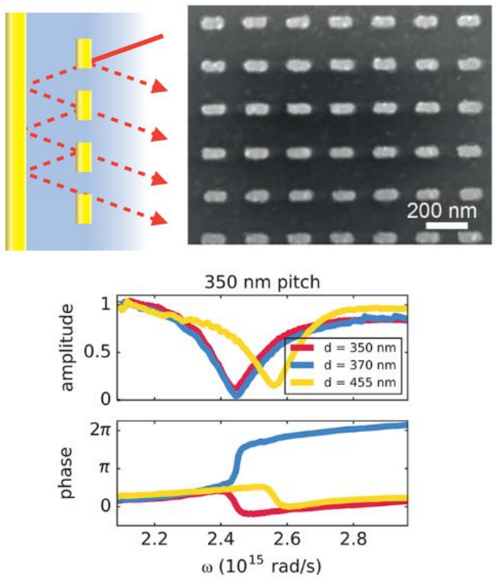
Role of singularities via complex analysis



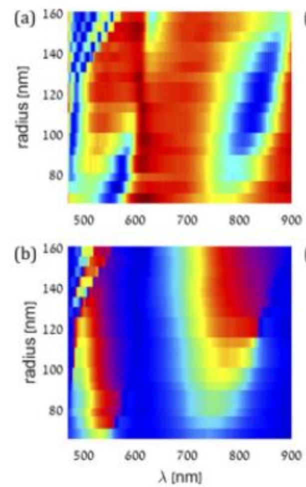


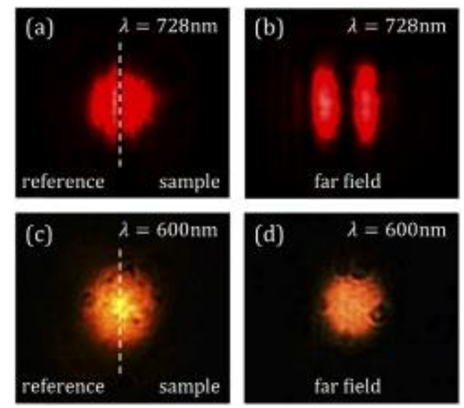
Metal-insulator-metal structure around zero reflection singularity



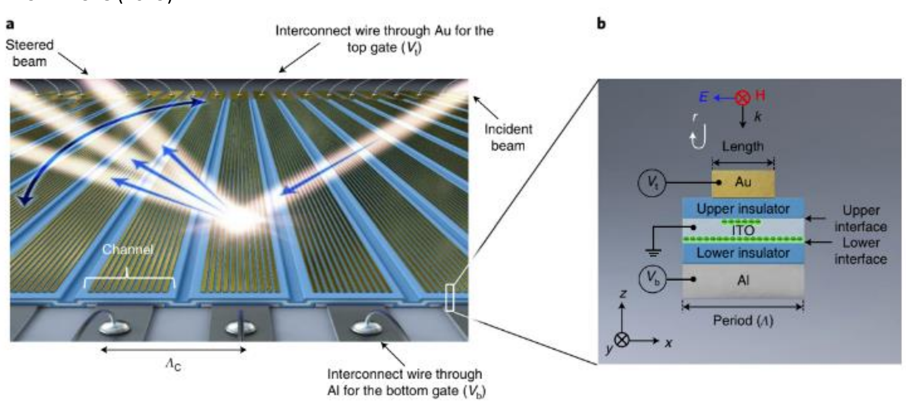
Berkhout, A. & Koenderink, A. F. Perfect Absorption and Phase Singularities in Plasmon Antenna Array Etalons. *ACS Photonics* **6**, 2917–2925 (2019).

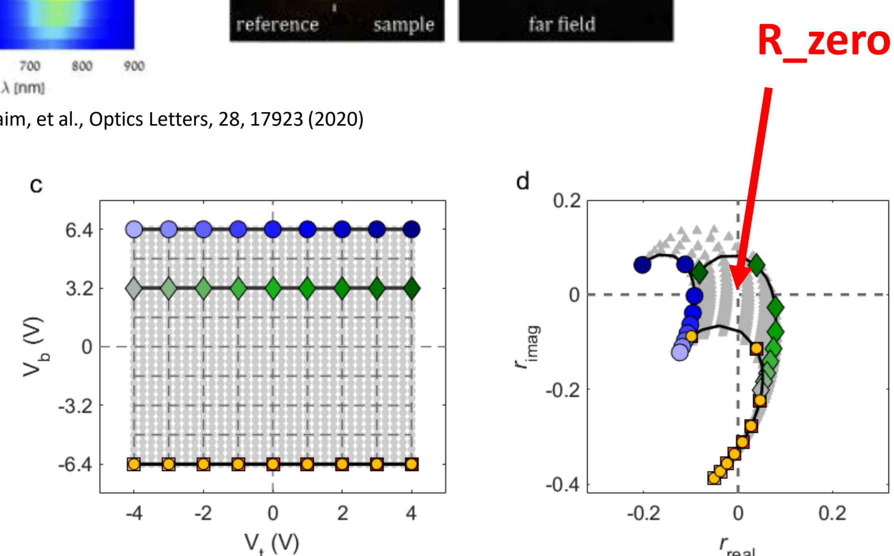
HG10 beam-shaping using binary phase mask of 0 and π.





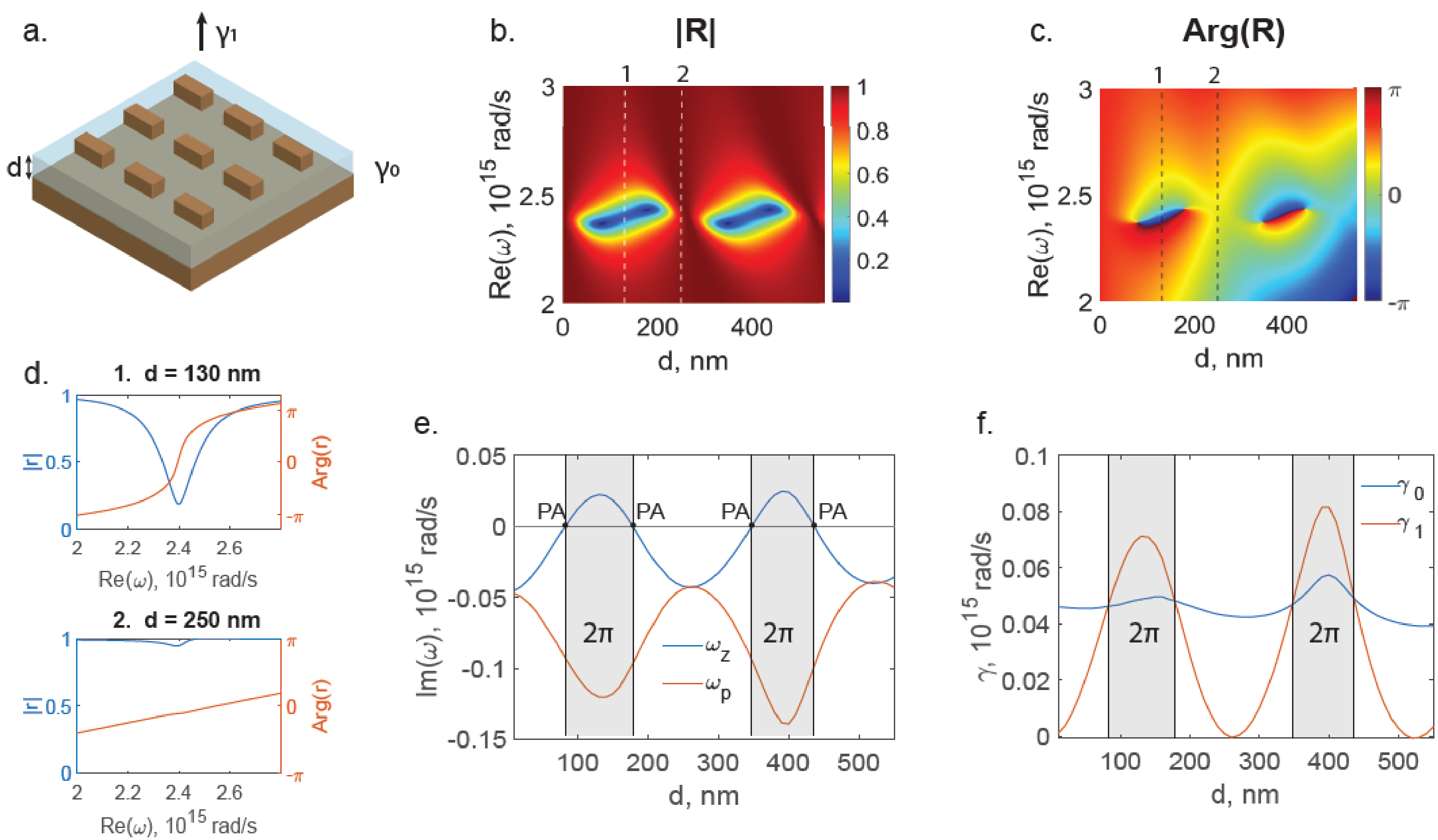
D. Ben Haim, et al., Optics Letters, 28, 17923 (2020)





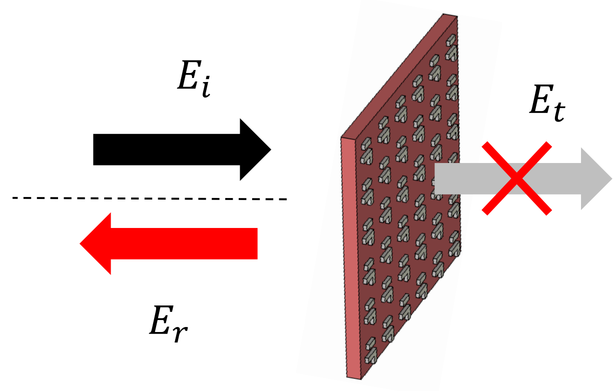
Park, J. *et al.* All-solid-state spatial light modulator with independent phase and amplitude control for three-dimensional LiDAR applications. *Nat. Nanotechnol.* **16**, 69–76 (2021).

Generalization of multimode MIM metasurfaces



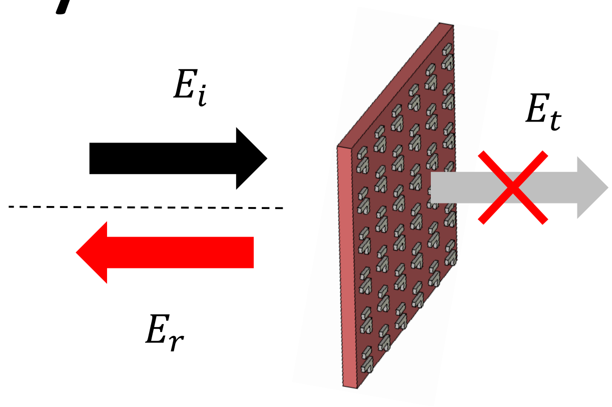
(Unpublished 2023)

Transmission zero

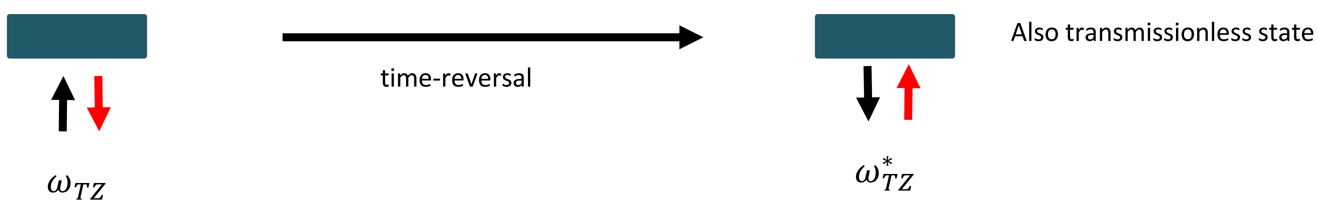


2π resonant phase gradient in transmission?

Symmetry considerations for T_{Zero}



T_{Zero} states for lossless structures: Time-reversal symmetry

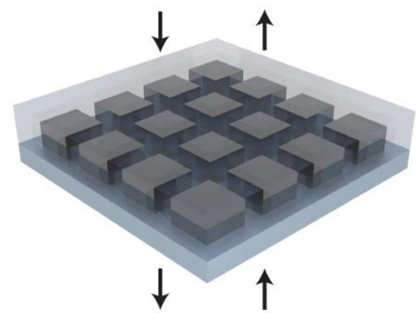


T_{Zero} states

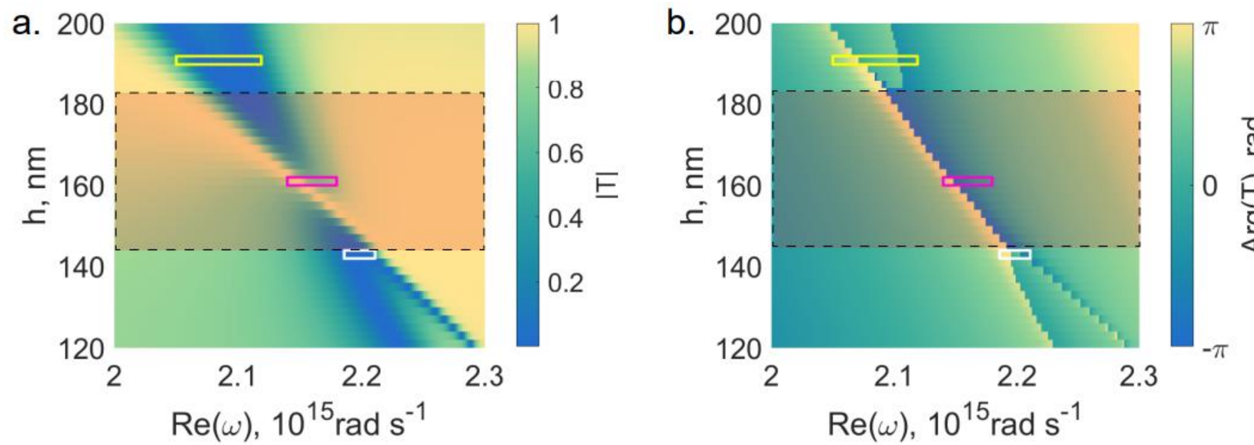
- Real frequency : own time-reversed couterpart
- Complex frequency : conjugated pair

Explaining the Huygens Metasurface with singular optics

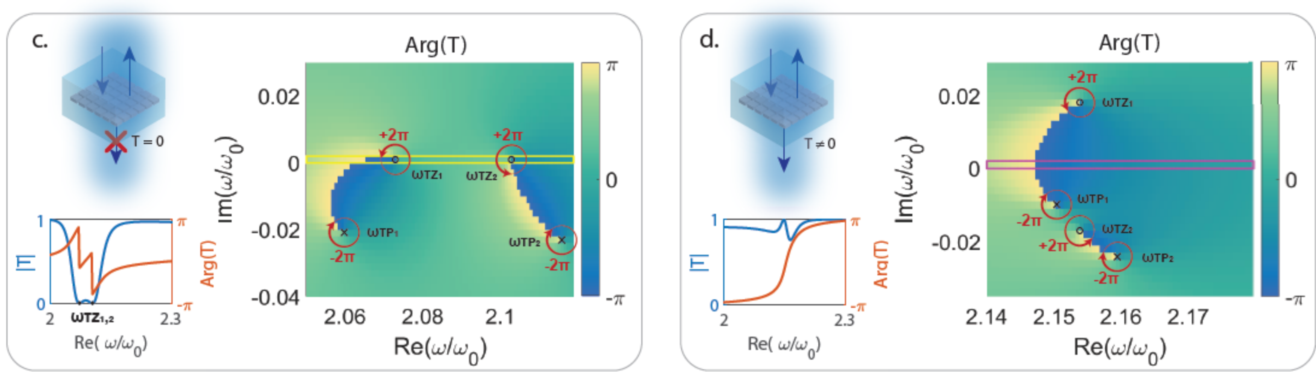
Link between T_{Zero} and Huygens MS



L = 350 nm
Period p = 500 nm,
Nanoparticule ε = 8.05,
Embedding medium ε = 2.25



Spontaneous T - symmetry breaking

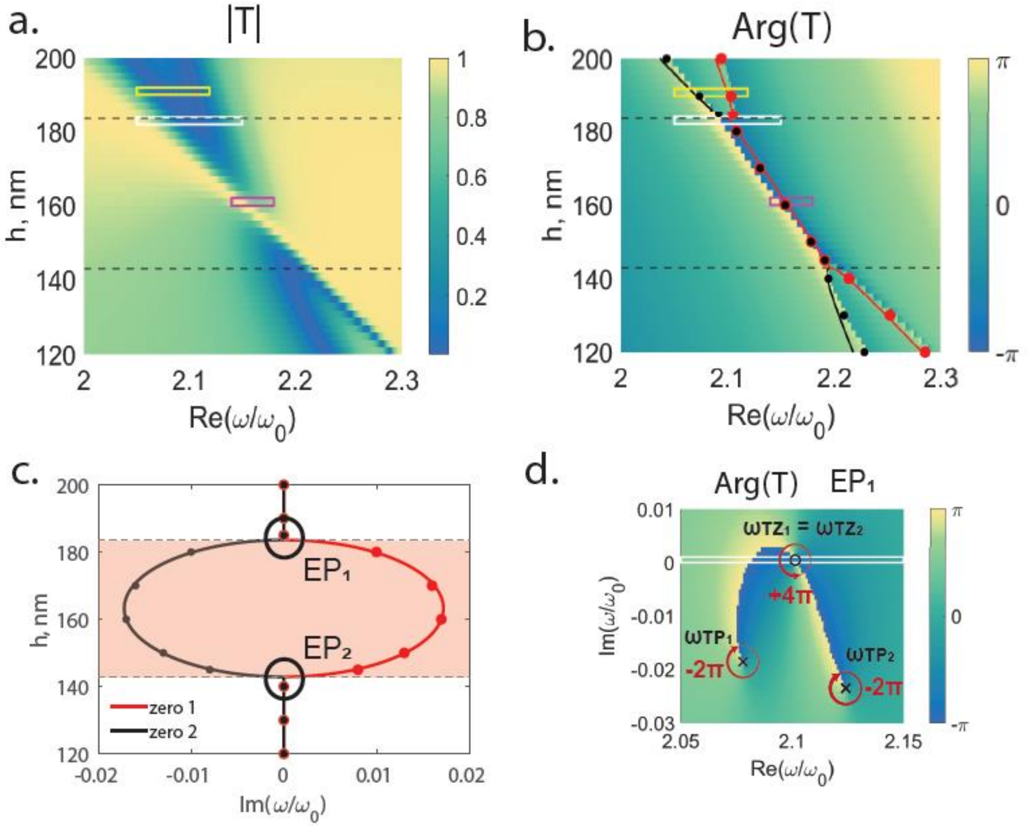


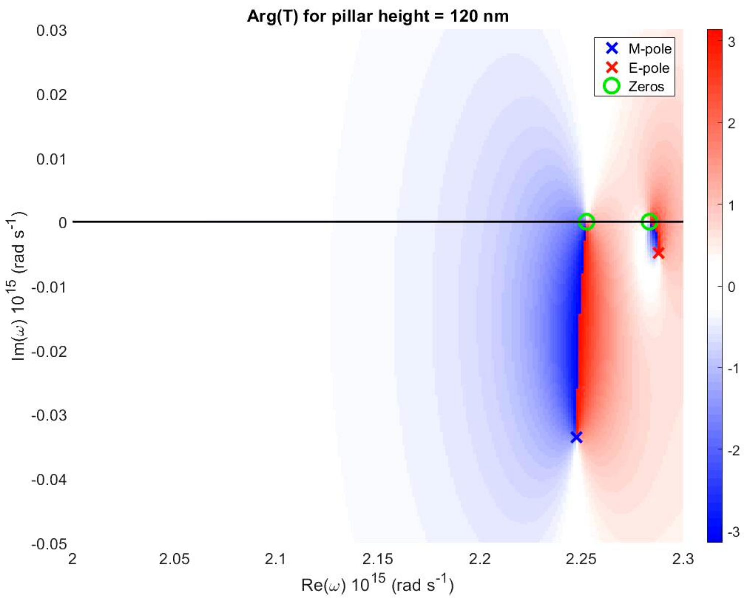
R. Colom, E. Mikheeva, K. Achouri, J. Zuniga-Perez, O. Martin, N. Bonod, S. Burger, and P. Genevet, **Laser Photonics Rev., 2200976 (2023)**

P. Genevet, CRHEA, CNRS, France
email: pg@crhea.cnrs.fr

Explaining the Huygens Metasurface with singular optics

Huygens MS regime has topological origin



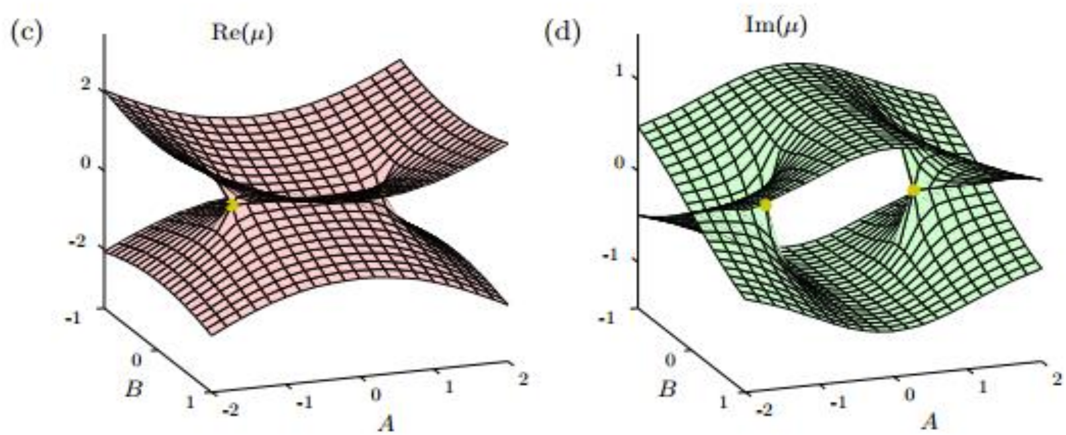


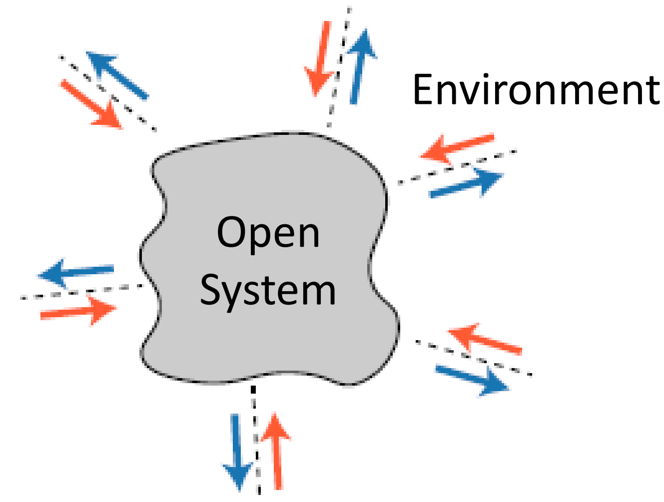
R. Colom, E. Mikheeva, K. Achouri, J. Zuniga-Perez, O. Martin, N. Bonod, S. Burger, and P. Genevet, **Laser Photonics Rev., 2200976 (2023)**

Any other types of zeros around ?

EV Degeneracy: another way of creating zero

MS behaves are Non-Hermitian system





Scattering: Radiation losses induces non-Hermiticity

$$V_1, \lambda_1 = V_2, \lambda_2$$

$\Longrightarrow$

Extremely rich Physics:

Non-Hermitian Hamiltonian

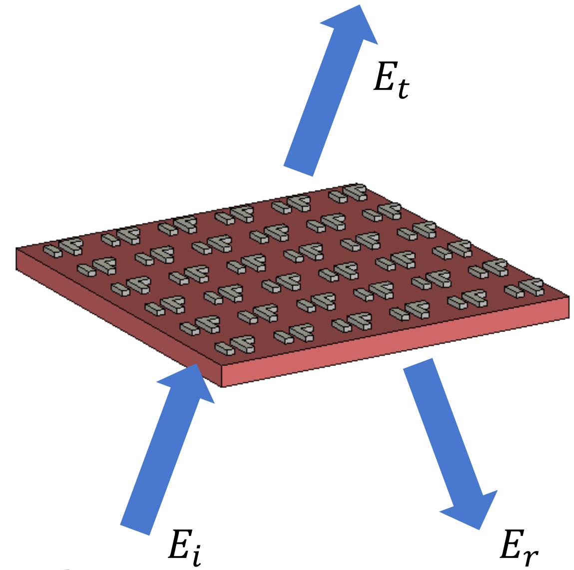
Complex eigenenergies: **Zero and Poles**

Encircling Singularities at polarization EP ?

Mathematical point of view: $\boldsymbol{E_{r,t}} = \hat{J}(\omega)\boldsymbol{E_{in}}$

Consider a complex Jones matrix $\hat{J}$ with a, b, c, $d \in$ C:

$$\hat{J} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$



Therefore, all the matrix can be degraded as the form of: $\hat{J} = \begin{pmatrix} a & b \\ c & -a \end{pmatrix}$

The eigenvalues are: $\mu_{1,2} = \pm\sqrt{a^2 + bc},$

In case of degeneracy: $\mu_1 = \mu_2 = 0, \ \ \sqrt{a^2 + bc} = 0.$

We get: $a = i\sqrt{bc},$ or $a = -i\sqrt{bc}.$

With degenerate eigenstates $\vec{J}$ are given as: $\vec{J}_{1,2} = \begin{pmatrix} \sqrt{b} \\ -i\sqrt{c} \end{pmatrix},$ or $\vec{J}_{1,2} = \begin{pmatrix} \sqrt{b} \\ i\sqrt{c} \end{pmatrix}.$

P. Genevet, CRHEA, CNRS, France

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Encircling Singularity at polarization EP

Exceptional Points in Metasurface

Jones Matrix

$$\hat{J} = \begin{pmatrix} a & b \\ c & -a \end{pmatrix},$$

Eigenvalues

$$\mu_{1,2} = \pm\sqrt{a^2 + bc},$$

Eigenstates

$$\vec{v} = \begin{pmatrix} \sqrt{b} \\ \mp i\sqrt{c} \end{pmatrix}.$$

Degeneracy Condition

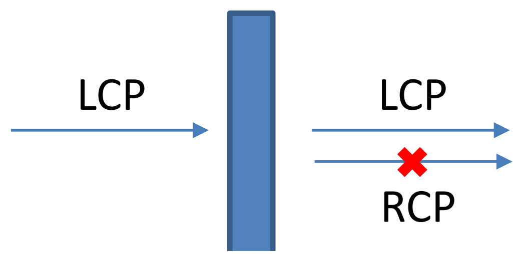
$$a = \pm i\sqrt{bc},$$

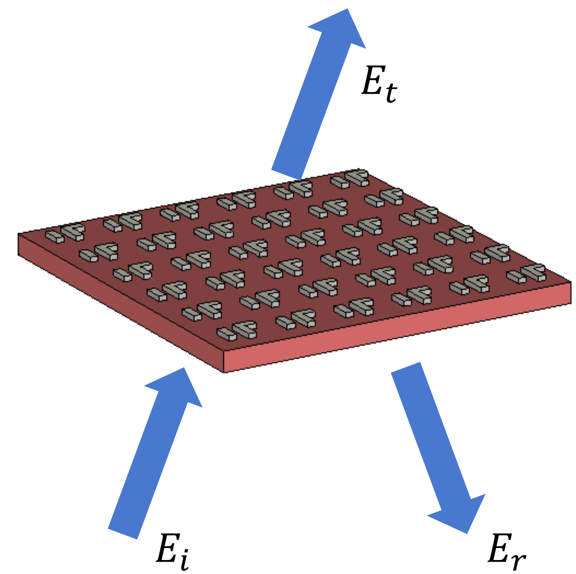
If $b = c$ *(reciprocity)*, the eigenstates are $\vec{v} \propto \begin{pmatrix} 1 \\ \mp i \end{pmatrix}$ circularly polarized.

$$\boldsymbol{b = c,\ a = -i\sqrt{bc} = -ib,}$$

$$\vec{v}_{1,2} \propto \begin{pmatrix} 1 \\ i \end{pmatrix} \quad \text{(LCP)}$$

$$\hat{J}\vec{v}_{1,2} = \mu_{1,2}\vec{v}_{1,2}$$





$$J_{-+} = 0$$

Q.Song, M. Odeh, J.Zúñiga-Pérez, B. Kanté, and P. Genevet, ***Science*** 373 (6559), 1133-1137 (2021)

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Encircling Singularity at polarization EP

$J_{-+} = 0$ at the exceptional point.

Considering J_{-+} in an arbitrary parameter space $\boldsymbol{R}$

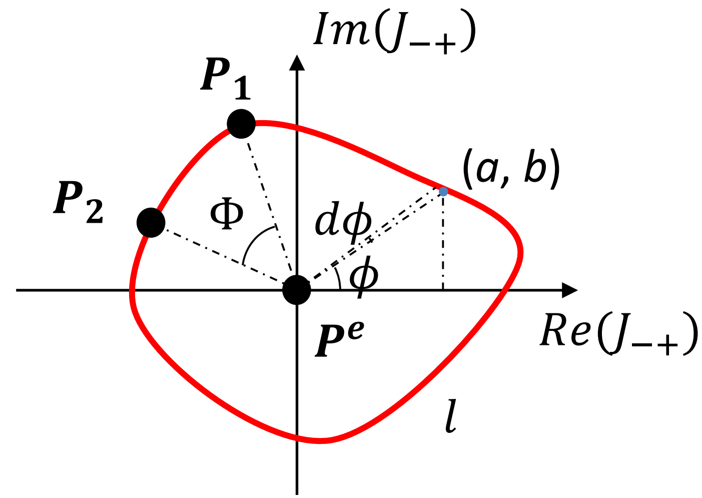
$$J_{-+}(\boldsymbol{R}) = Re(J_{-+}) + i\, Im(J_{-+})$$

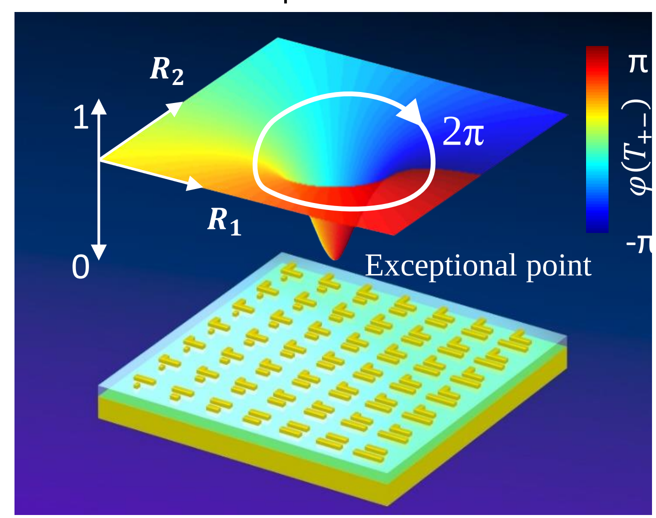
At the exceptional point $\boldsymbol{P^e}$, we have a singularity

$$J_{-+}(\boldsymbol{P^e}) = 0$$

Encircling with closed path *l*, the winding number around the origin is 1, and thus the accumulated phase is:

$$\Phi = \oint_l d\phi = 2\pi$$





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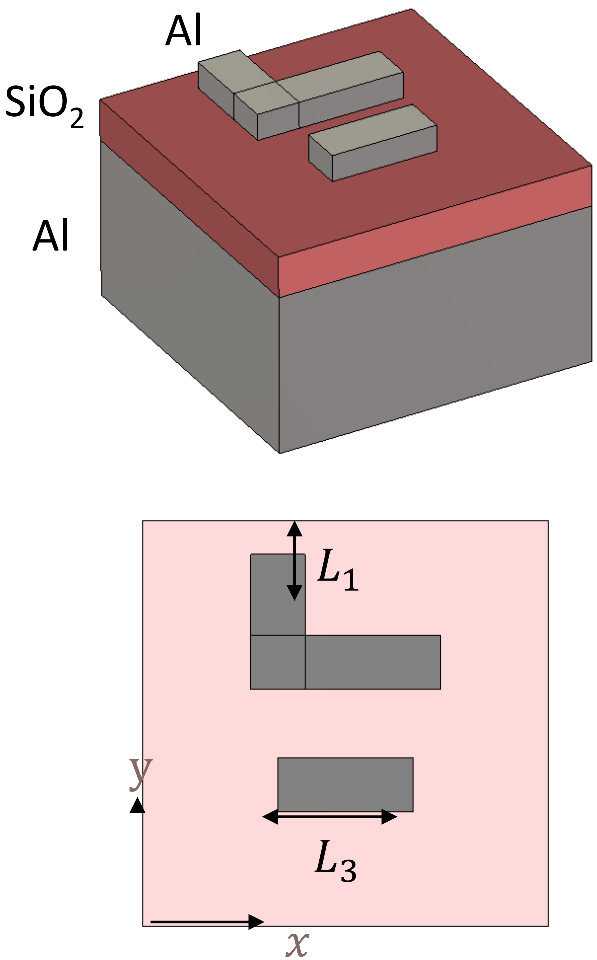
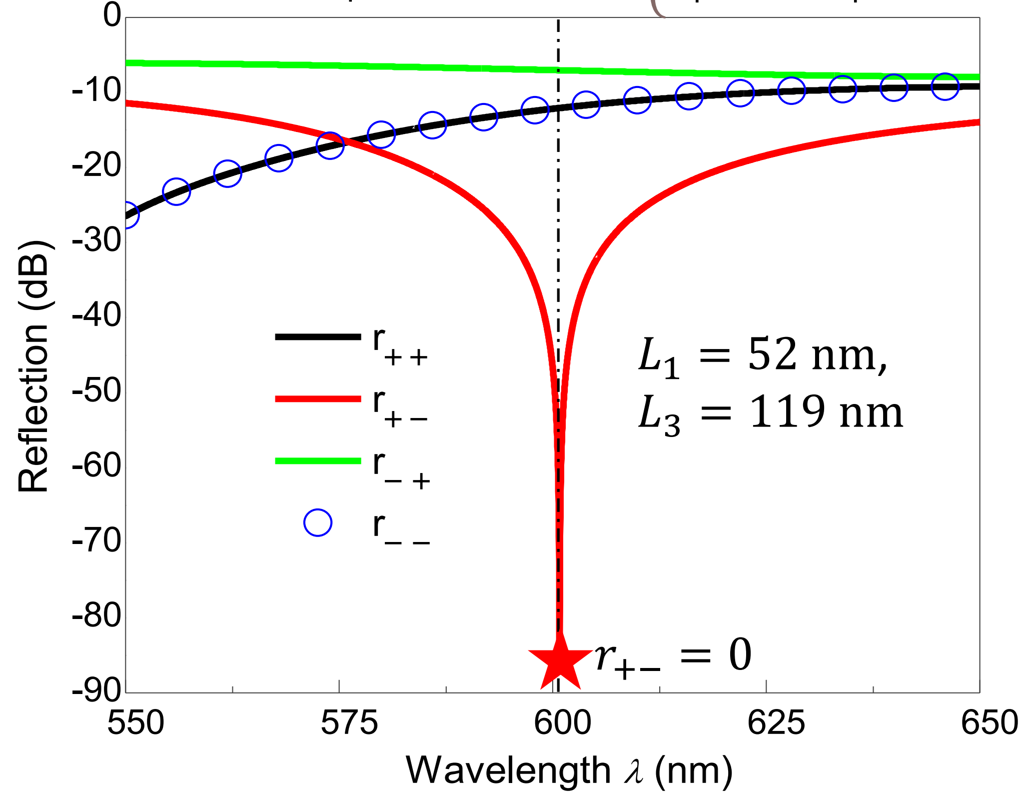
Reflection in Circular Polarization Base



$$\hat{r} = \begin{pmatrix} r_{++} & r_{+-} \\ r_{-+} & r_{--} \end{pmatrix} \qquad \begin{cases} r_{++} = r_{--} \\ r_{+-} \neq r_{-+} \end{cases}$$



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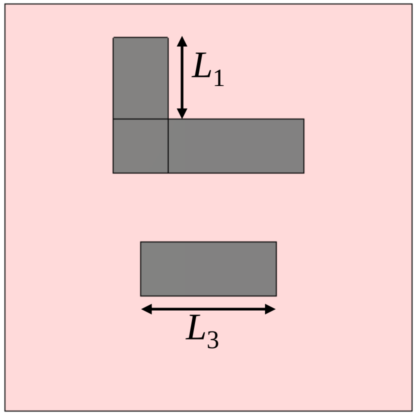
Eigenvalues at λ = 600 nm

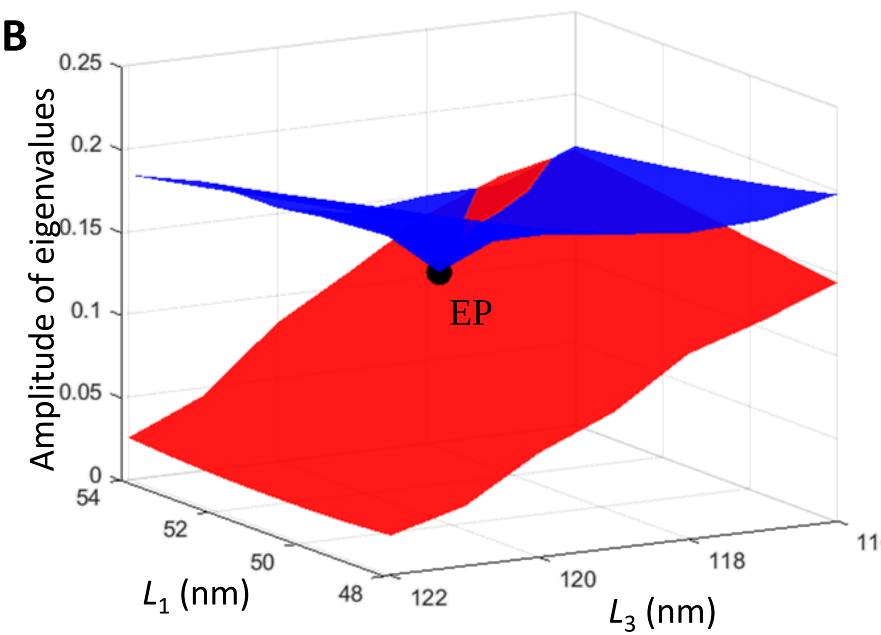
A



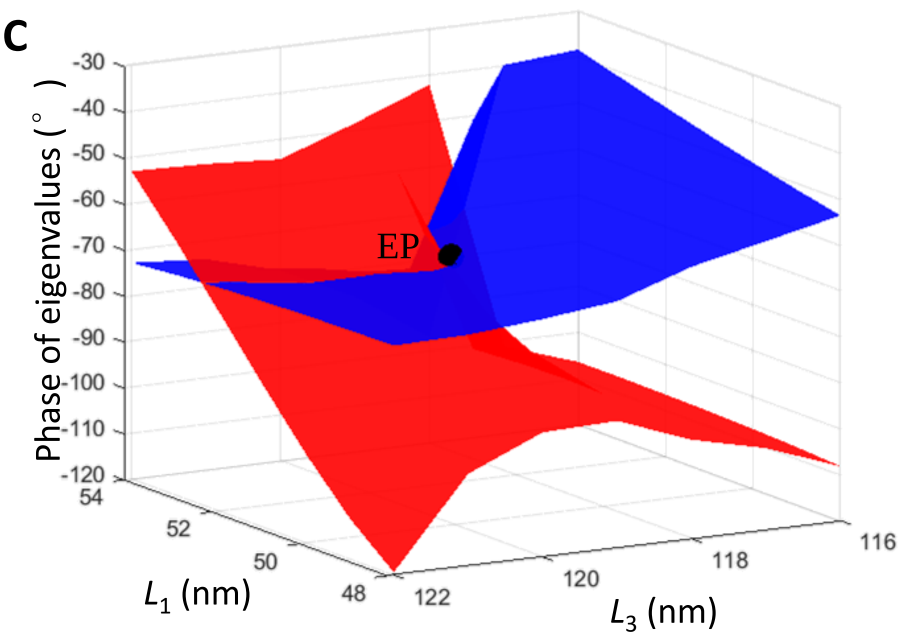
A self-intersecting Riemann surface is shown for the two eigenvalues in the parameter space (L1, L3).

At the exceptional point (EP), the eigenvalues degenerate.

B



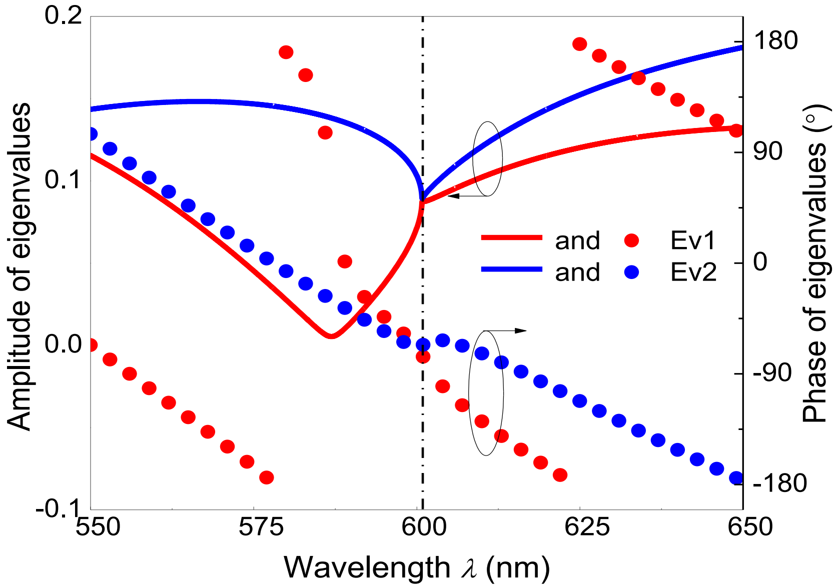
C

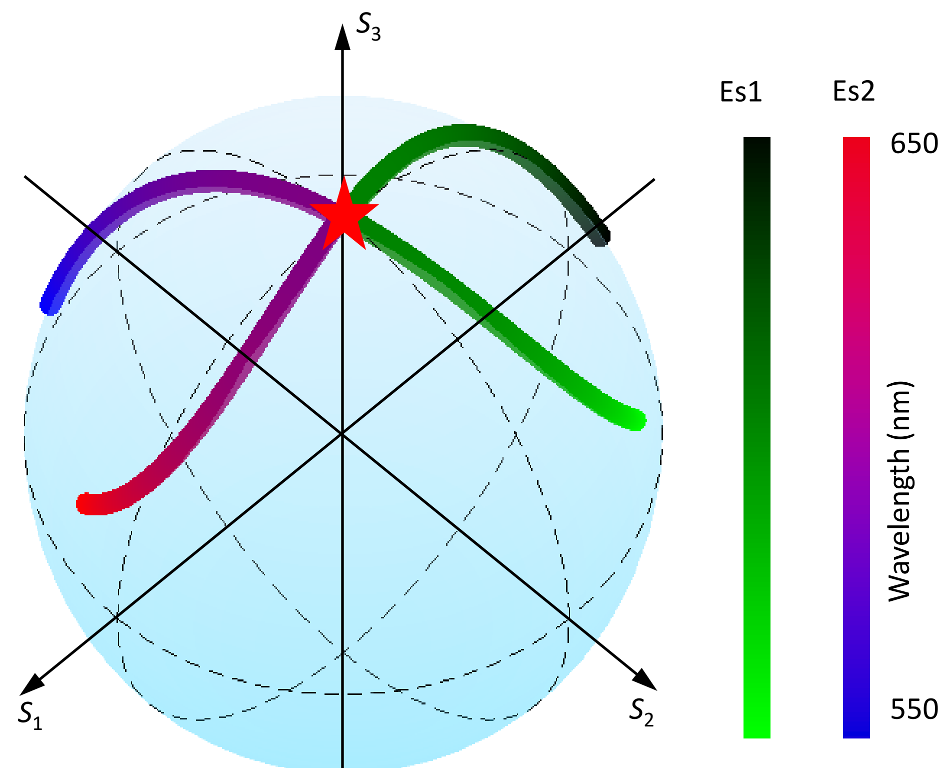


EP at $L_1 = 52$ nm, $L_3 = 119$ nm

Encircling Singularity at polarization EP

Degenerated Eigenvalues and Eigenstates





Poincaré sphere

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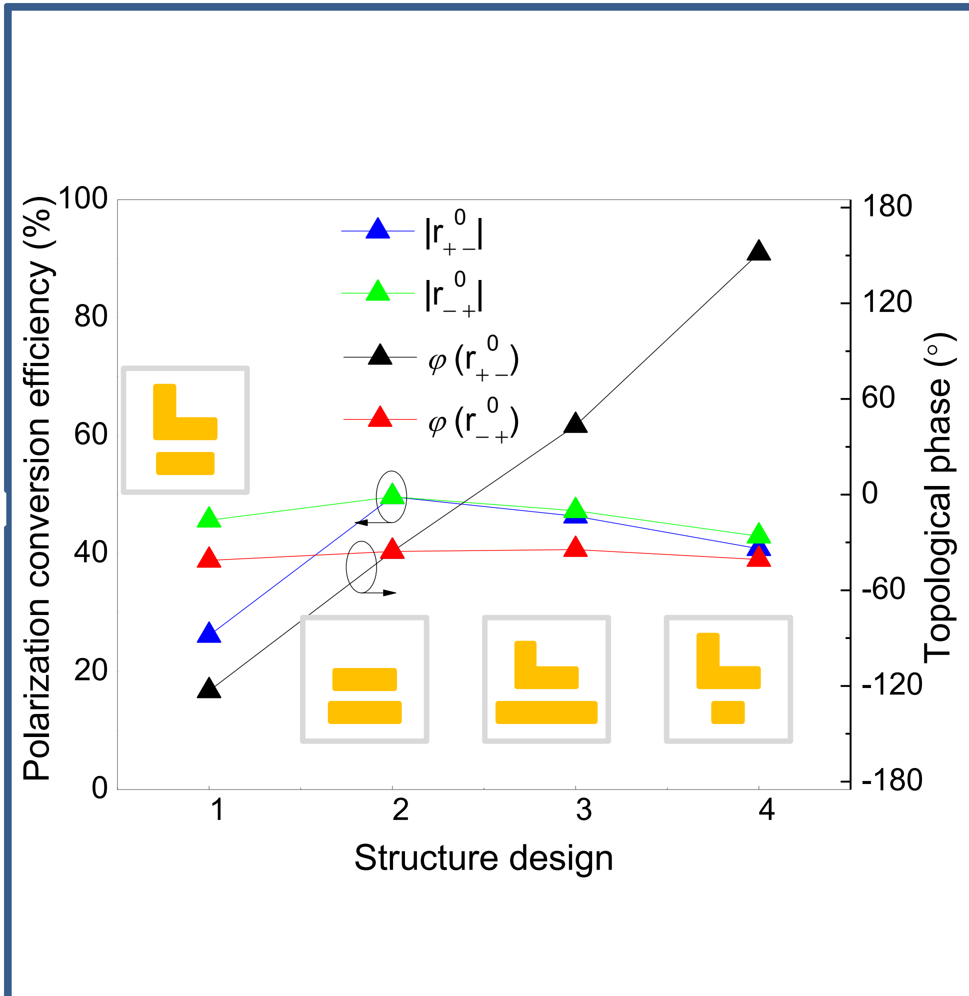
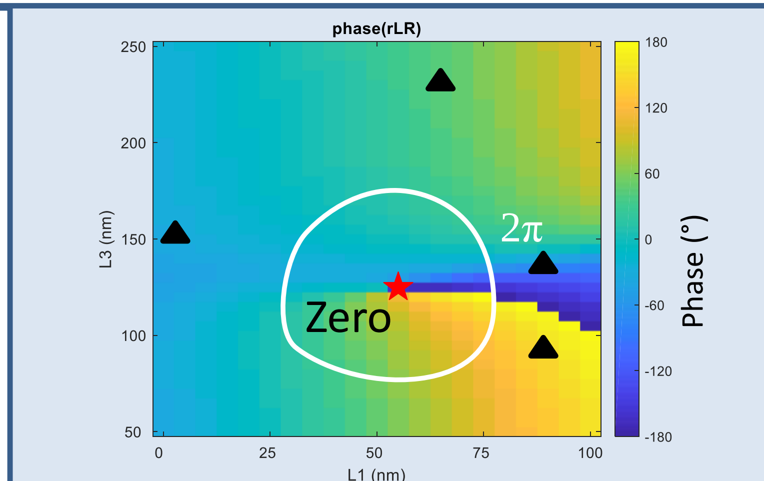
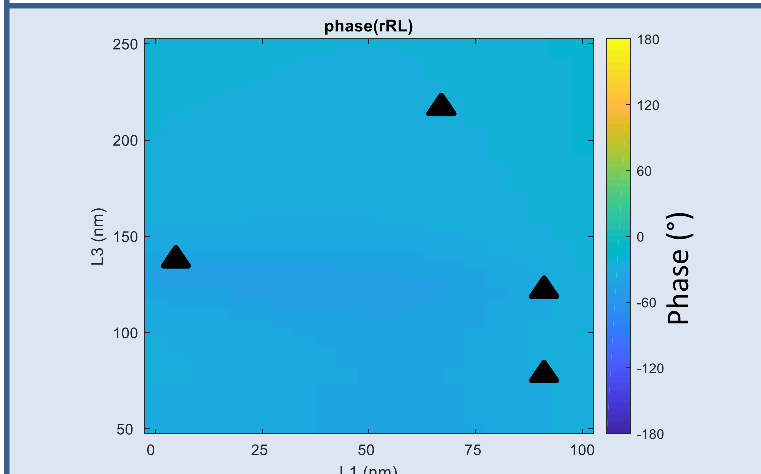
Encircling Singularity at polarization EP

Circular Polarization conversion at λ = 600 nm







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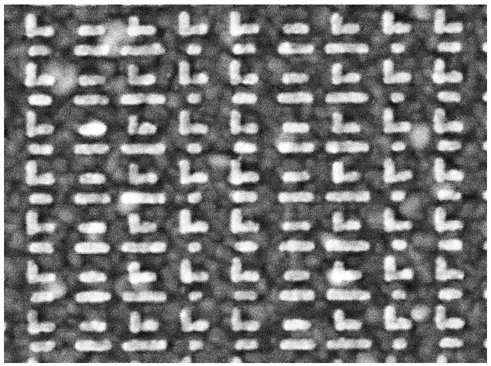
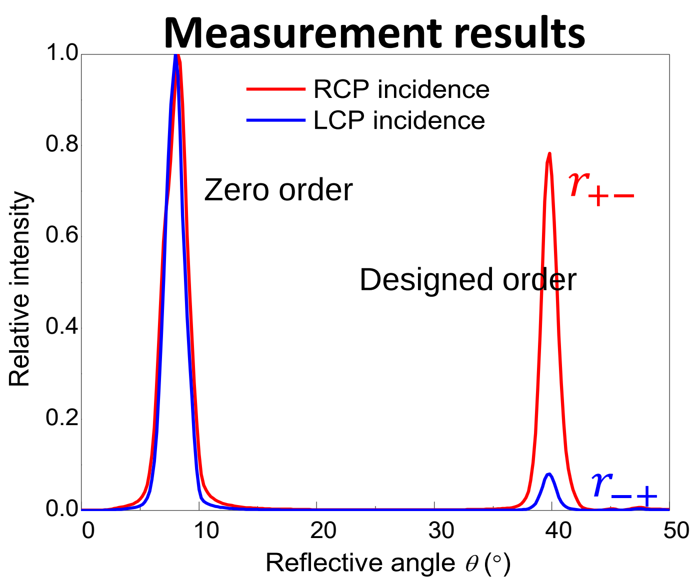
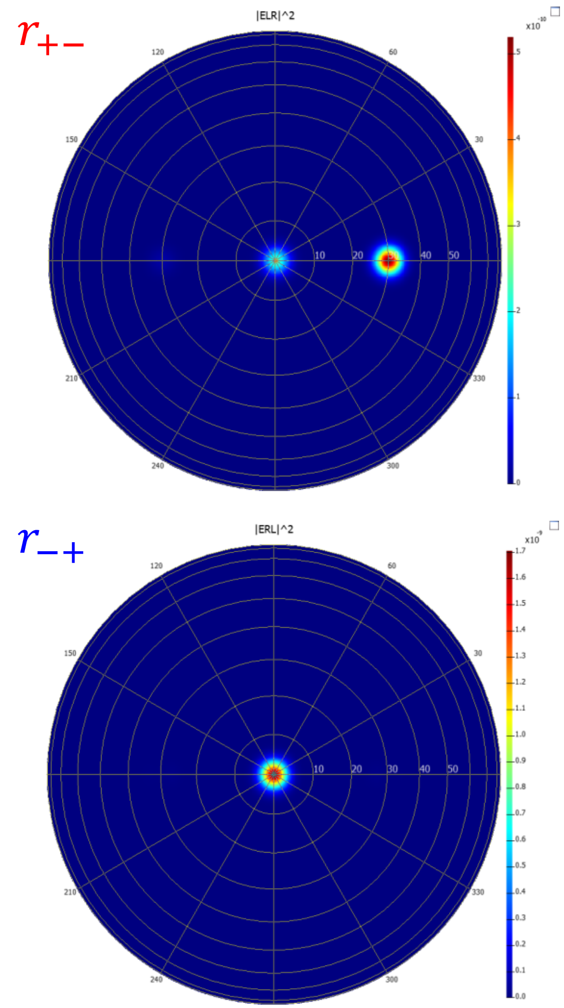
Encircling Singularity at polarization EP

Wavefront Control - Beam Steering







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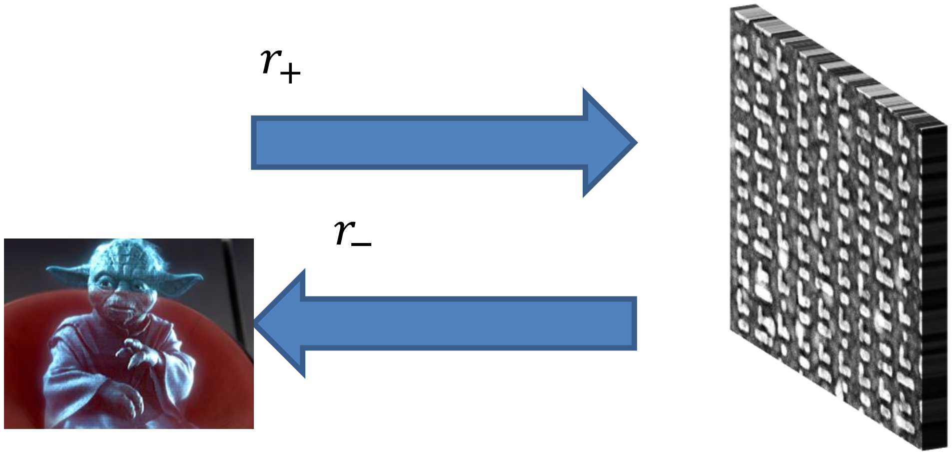
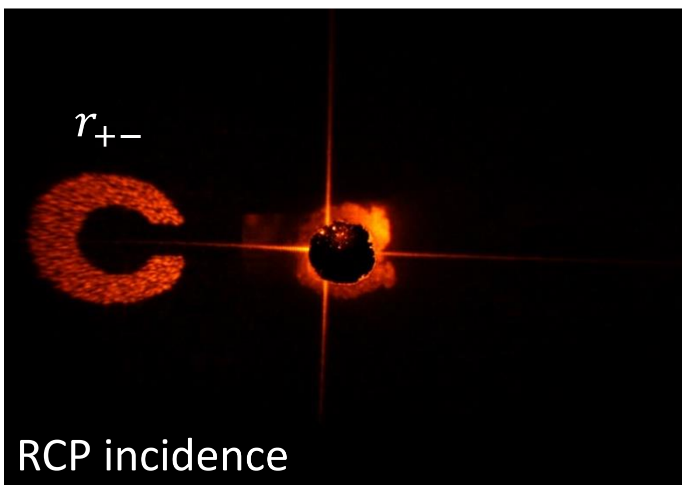
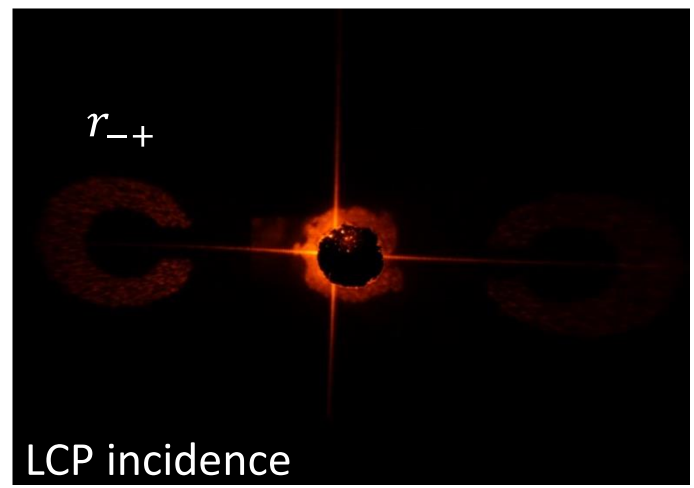
Wavefront Control - Meta-Hologram







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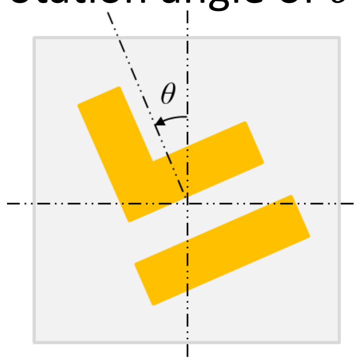
EP+PB phase

Adding rotation angle of θ:

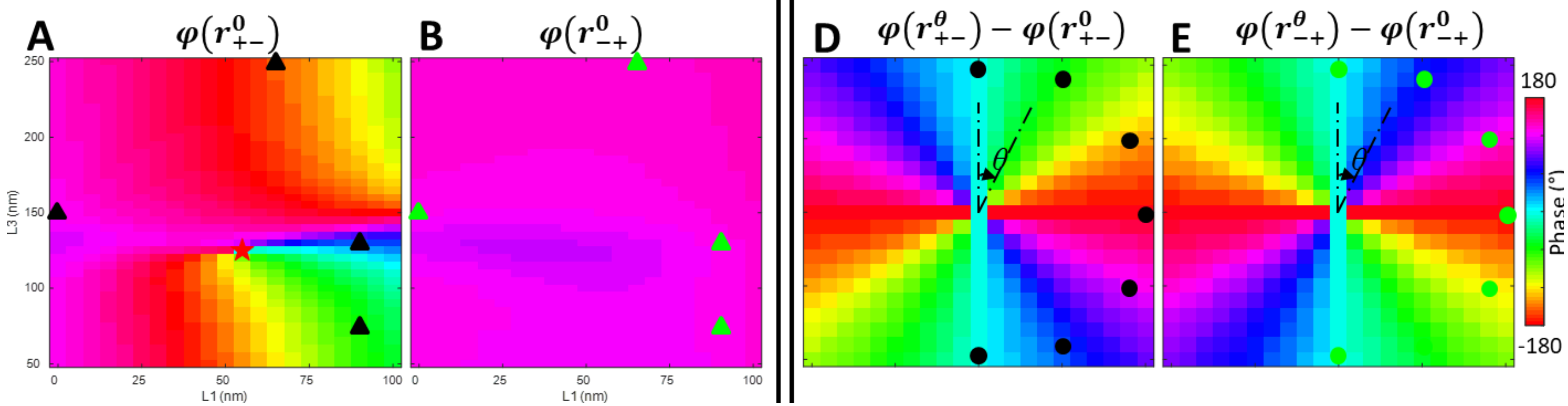


CP conversion:

$$r_{\pm\mp}^{\theta}(\boldsymbol{R}) = \left|r_{\pm\mp}^{0}(\boldsymbol{R})\right| e^{i\varphi\left(r_{\pm\mp}^{0}(\boldsymbol{R})\right)} e^{\mp i2\theta}$$

The total phase is the sum of ET and PB phase: $\varphi\left(r_{\pm\mp}^{\theta}(\boldsymbol{R})\right) = \varphi\left(r_{\pm\mp}^{0}(\boldsymbol{R})\right) \mp 2\theta$

Exceptional topological (ET) phase | **Pancharatnam-Berry (PB) phase**



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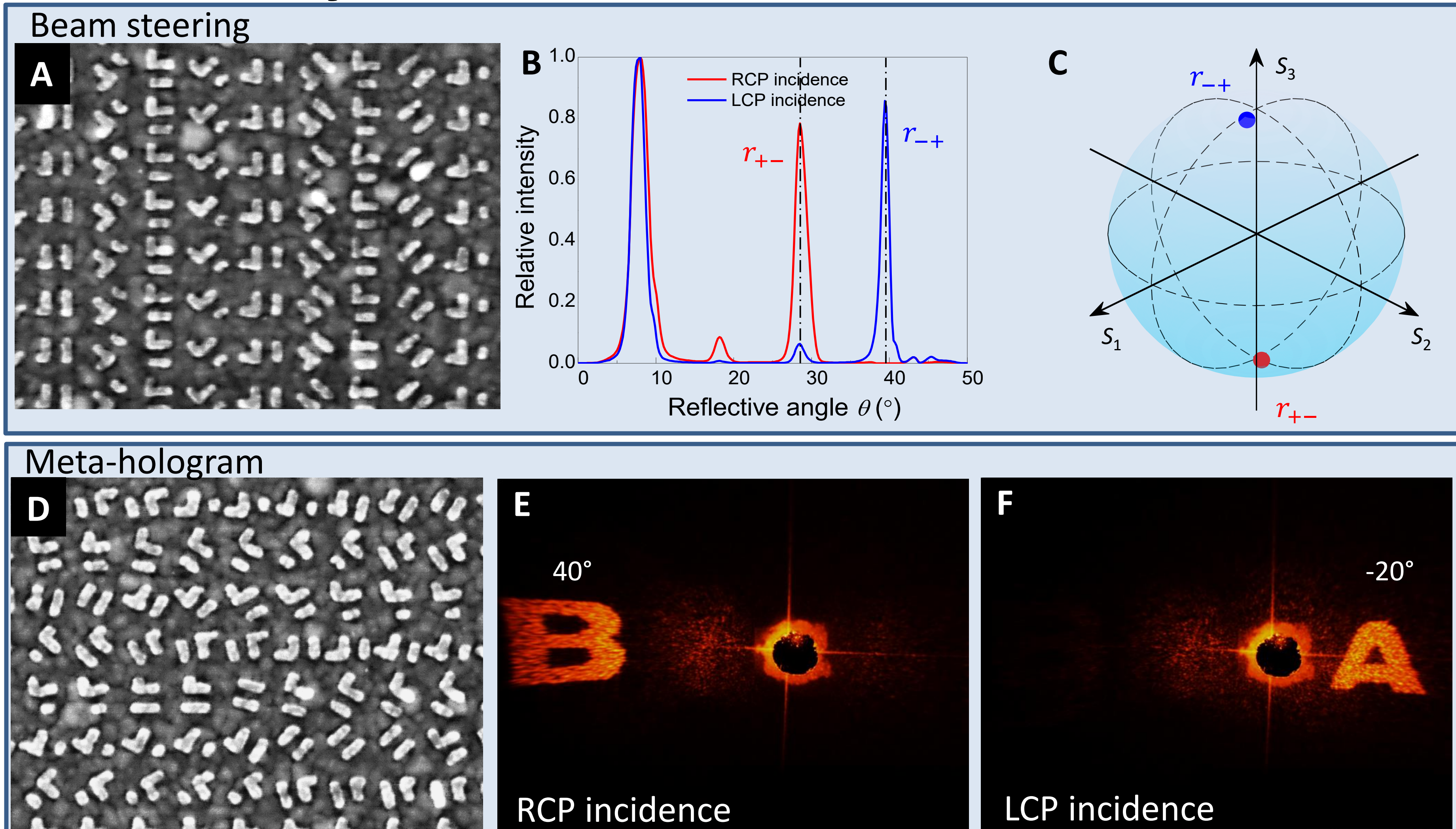
Encircling Singularity at polarization EP

Asymmetric Wavefront Control



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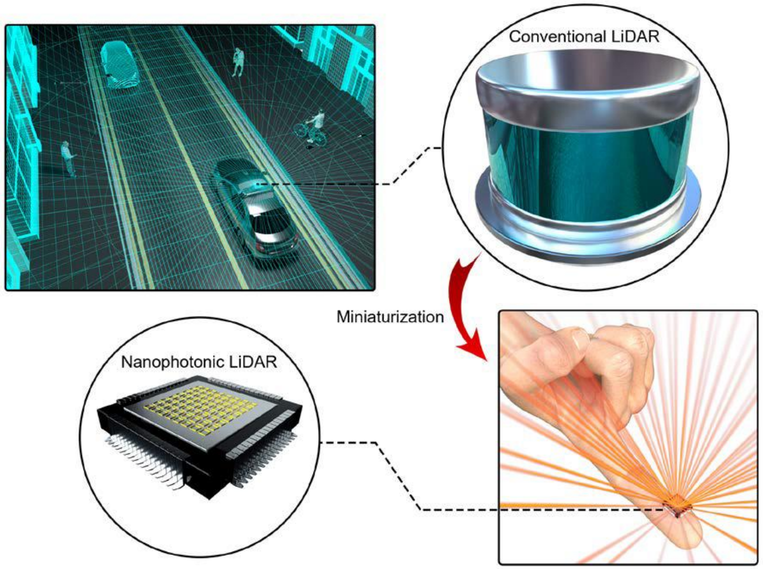
Q.Song, M. Odeh, J.Zúñiga-Pérez, B. Kanté, and P. Genevet, ***Science*** 373 (6559), 1133-1137 (2021)

Metasurface integration

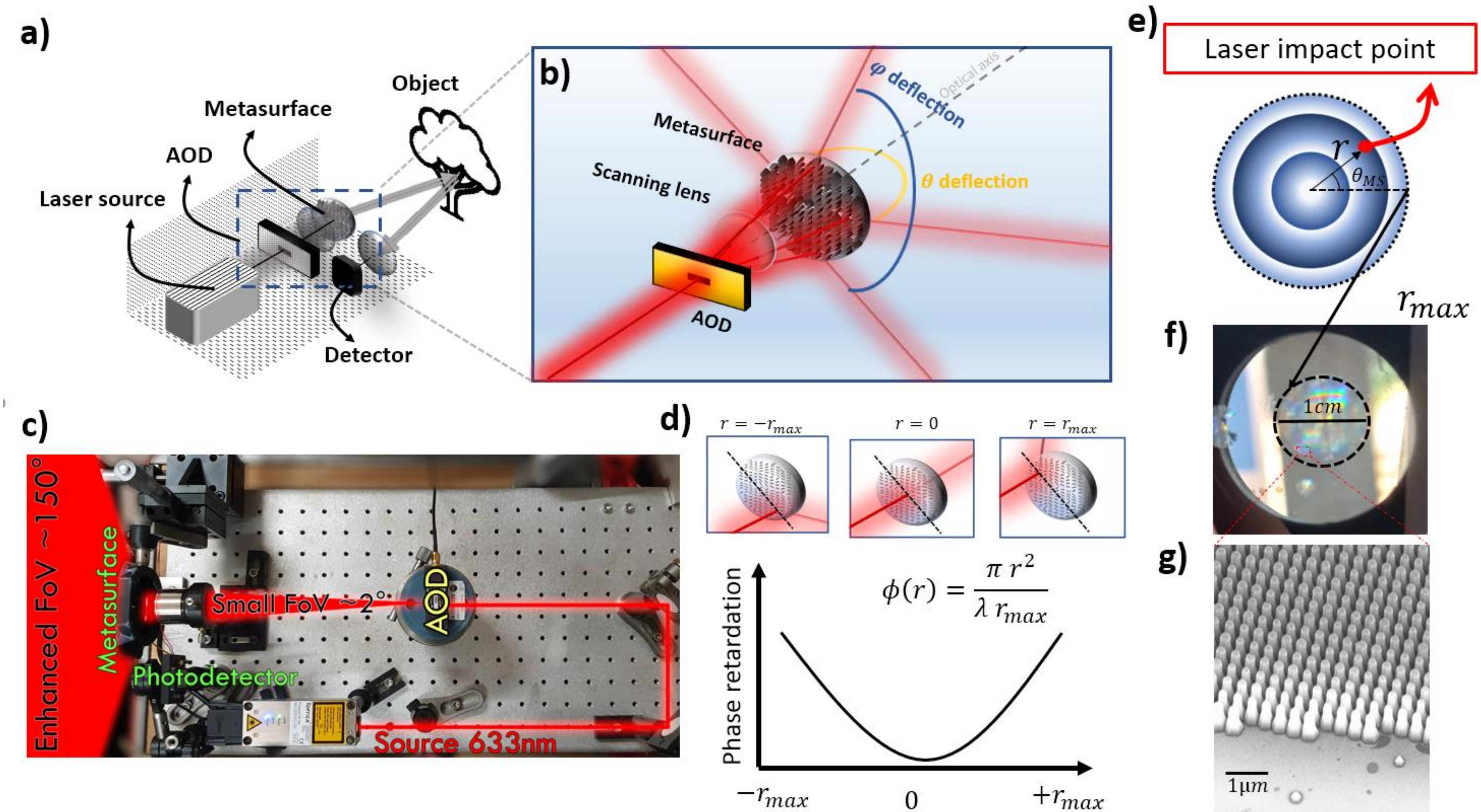
Metasurface-enhanced LiDAR



Nature nano. 16, 508–524 (2021)
Nature comm. 13, 5724 (2022)

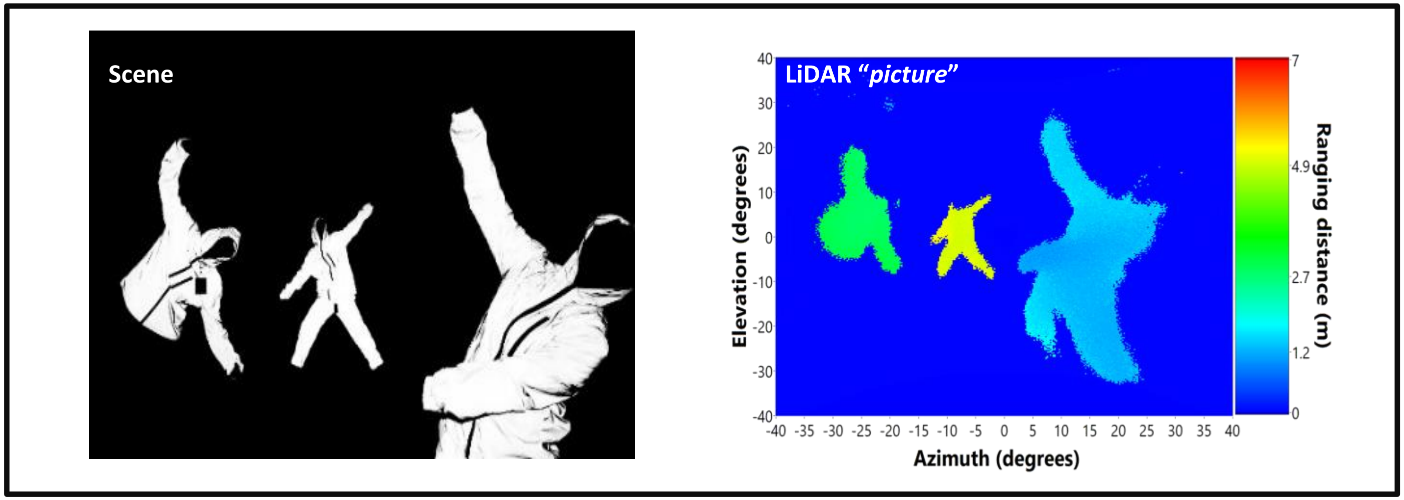
CRHEA MS LiDAR

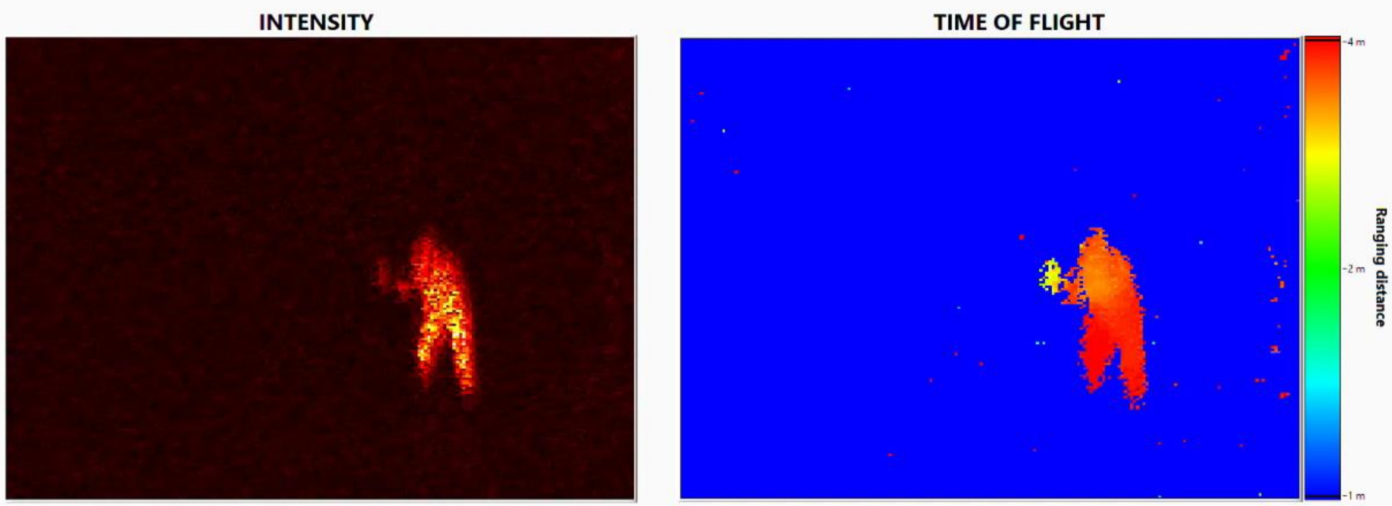
LiDARs applications (MHz beam steering)



Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021) & **Nat. Comm.** 13, 5724 (2022)

MS LiDAR





Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021) & **Nat. Comm. 13**, 1-8 (2022)

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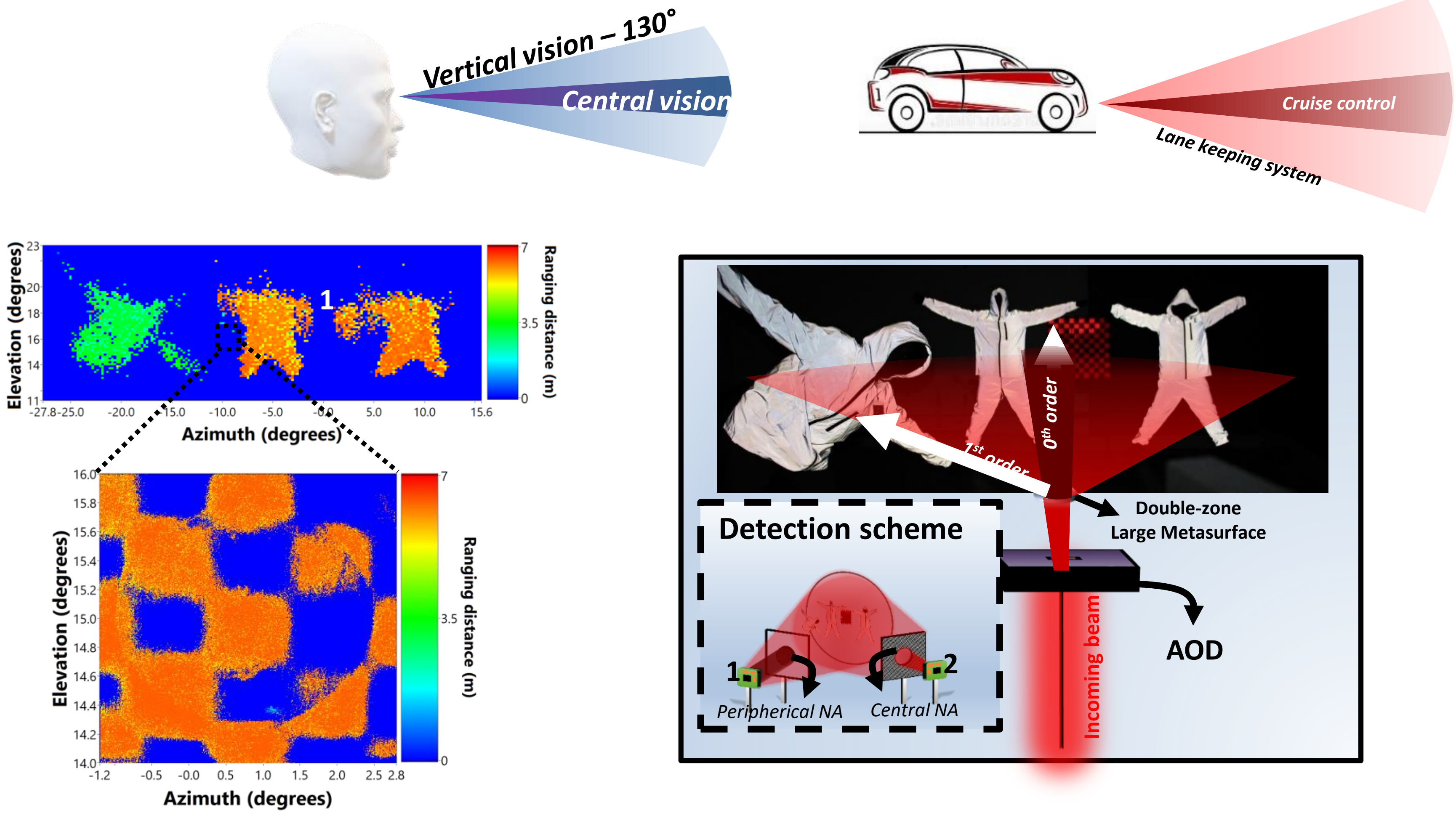
email: pg@crhea.cnrs.fr

MS LiDAR to mimic human vision

Multi-zones ToF LiDAR



Juliano Martins, S. Khadir, M. Giudici and P. Genevet, Patent EP21305472.9 (2021) & **Nat. Comm. 13**, 1-8 (2022)

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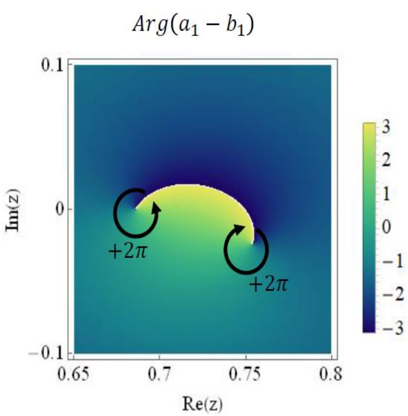
Conclusion

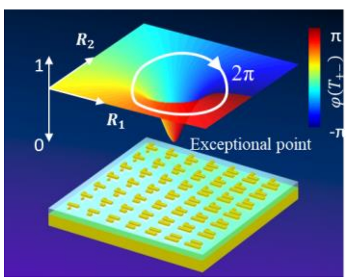
Topological nanophotonics opens up exciting new research directions
Deep fundamental understanding of the underlying scattering mechanisms



❖Crossing branch cut provides 2π-phase accumulation
$\Rightarrow$ Zero and Pole located across the real axis

❖Formal explanation of Huygens MS
$\Rightarrow$ Important role of phase singularities

Laser Photonics Rev., 2200976 (2023)



❖Encircling singularities for wavefront engineering.

Science 373 (6559), 1133-1137 (2021)

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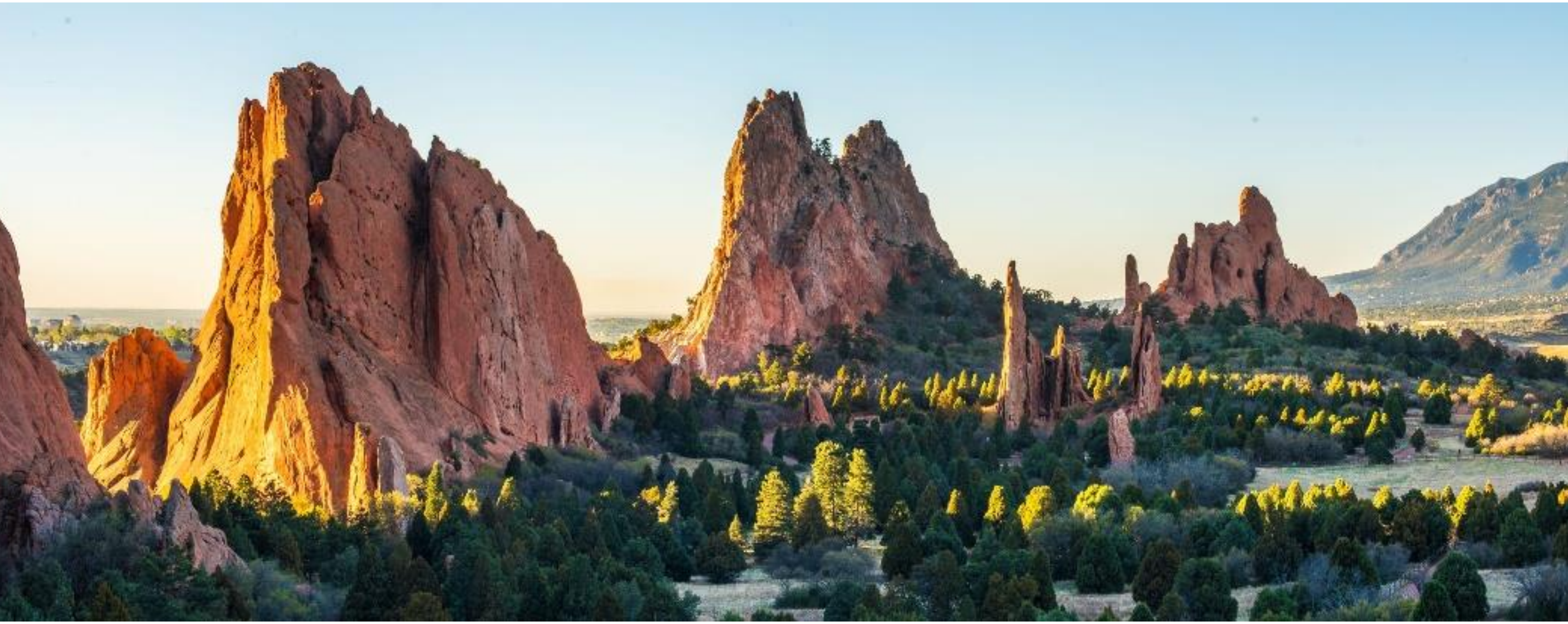
Conclusion

Topological nanophotonics opens up exciting new research directions
Deep fundamental understanding of the underlying scattering mechanisms



My group is moving to the **Colorado School of Mines** and I am looking for PhD candidates
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