

# The Fascinating Optics of Metamaterials and Plasmonics

Presented by:



Welcomes  
You!

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 <p><b>Pablo Aitor Postigo</b> Consejo Sup Investigaciones Cientificas, Spain</p>	 <p><b>Nadir Dagli</b> University of California, Santa Barbara, USA</p>
 <p><b>Lin Zhang</b> Tianjin University, China</p>	 <p><b>Jung Soo Park</b> Aurion Inc., USA</p>
 <p><b>Cheng Zhang</b> University Of Michigan, USA</p>	 <p><b>Sachin Kumar Srivastava</b> Nanyang Technological University, Singapore</p>

## What we do?

- Organize Incubators
- Webinars  
(Quarterly, Featuring prominent speakers)
- Special Activities  
(@Conferences: Poster Sessions, Dine & Discover, Blogging)

**OSA Incubator Meeting**  
**Nanophotonic Devices: Beyond Classical Limits**

14-16 May 2014  
 OSA Headquarters • 2010 Massachusetts Ave. NW • Washington, DC, USA

HOSTED BY:

Volker J. Sorger, *The George Washington University, United States*; Jung Park, *Intel Corporation, United States*;  
 Pablo A. Postigo, *Consejo Superior de Investigaciones Cientificas, Spain*; Fengnian Xia, *Yale University, United States*



Poster session at CLEO in San Jose (2016)

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### Nanophotonics (ON)

**Get Involved**

- Technical Divisions**
  - Bio-Medical Optics
  - Fabrication, Design & Instrumentation
  - Information Acquisition, Processing & Display
  - Optical Interaction Science**
    - Fundamental Laser Sciences (OF)
    - Nanophotonics (ON)**
    - Nonlinear Optics (OL)
    - Optical Cooling and Trapping (OT)
    - Optical Material Studies (OM)
    - Optical Metrology (OR)

**Nanophotonics**

This group focuses on the study and design of optics and optical devices that interact with light on the nanometer scale. This new field is enabled by newly developed capabilities to fabricate optical components and devices on a nano-scale.

**Archived Webinars**

- 2D Material Nanophotonics for Optical Information Science
- Silicon Electronic Photonic Integrated Circuits Research Training
- Practical Nanophotonics with Plasmonic Ceramics
- Nanophotonics in the Year of Light
- [Basic Facts About/Archives/Interaction/OSA/Nanophotonics/Platforms](#)

**Announcements**

Join the Nanophotonics Technical Group for a webinar on losses in plasmonics on Monday, 9 May 2016, at 10:30 AM EDT.

In this webinar, Dr. Svetlana Boriskina from MIT will be presenting three viable approaches to mitigate plasmonic losses, which go beyond efforts to compensate losses with optical gain or to synthesize better plasmonic materials.

[Register for the Webinar Now](#)

**Join our Online Community**

[f](#) [in](#) [t](#)

[http://www.osa.org/en-us/get\\_involved/technical\\_communities/ois/nanophotonics\\_\(on\)\\_\(1\)/](http://www.osa.org/en-us/get_involved/technical_communities/ois/nanophotonics_(on)_(1)/)

## Creating a Community

- Do you like to blog?
- Organize an event?
- Interact with colleagues?



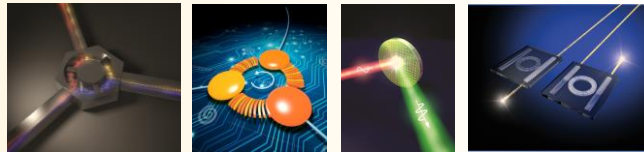
@Nano\_OSA



facebook.com/nanophotonicsosa



osa.org/communities



## THE FASCINATING OPTICS OF METAMATERIALS AND PLASMONICS

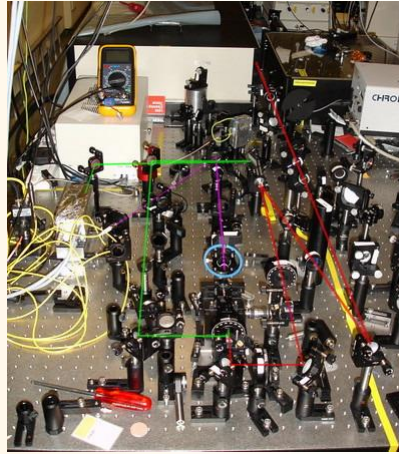
Andrea Alù

Credits to: Dimitrios Sounas, Romain Fleury (now at EPFL), Yakir Hadad, Jason Soric, Nasim Mohammadi Estakhri, Francesco Monticone, Mykhailo Tymchenko, Juan Sebastian Gomez-Diaz, Jongwon Lee, Diego Correas-Serrano,  
Collaborators: Mikhail Belkin (UT Austin), Alex Khanikaev (CUNY)

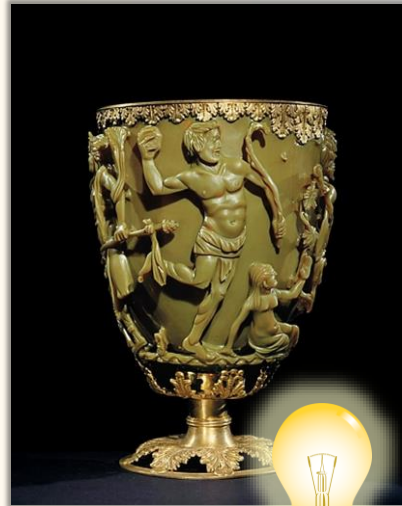
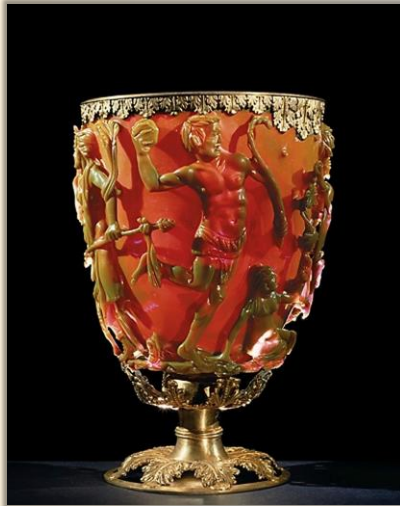
Department of Electrical and Computer Engineering, The University of Texas at Austin,  
Austin, TX, USA

<http://users.ece.utexas.edu/~aalu>, [alu@mail.utexas.edu](mailto:alu@mail.utexas.edu)

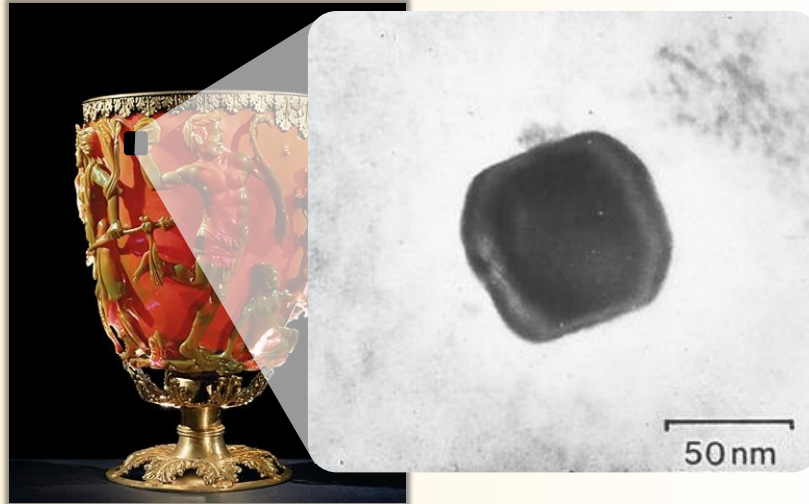
## 'CONVENTIONAL' LIGHT-MATTER INTERACTIONS



## PLASMONIC INTERACTIONS

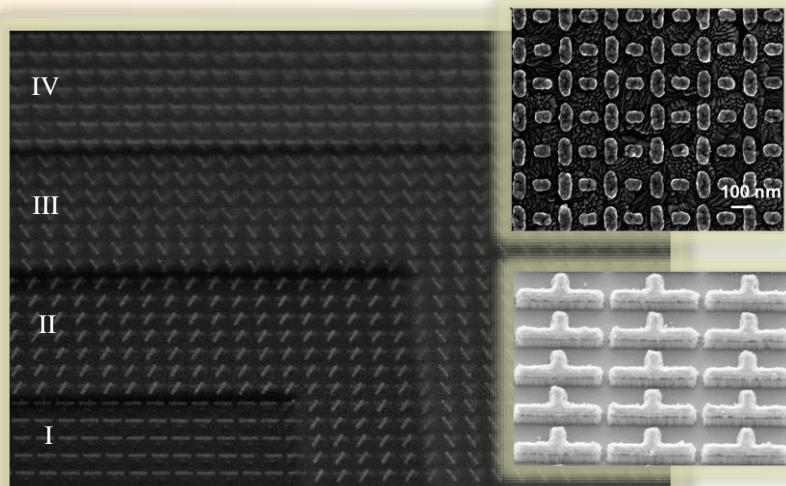


## PLASMONICS AND ENHANCED WAVE-MATTER INTERACTIONS



I. Freestone, et al., *Gold Bulletin* 40, 207 (2007)

## META-MATERIALS: BEYOND NATURE WITH ARTIFICIAL MATERIALS

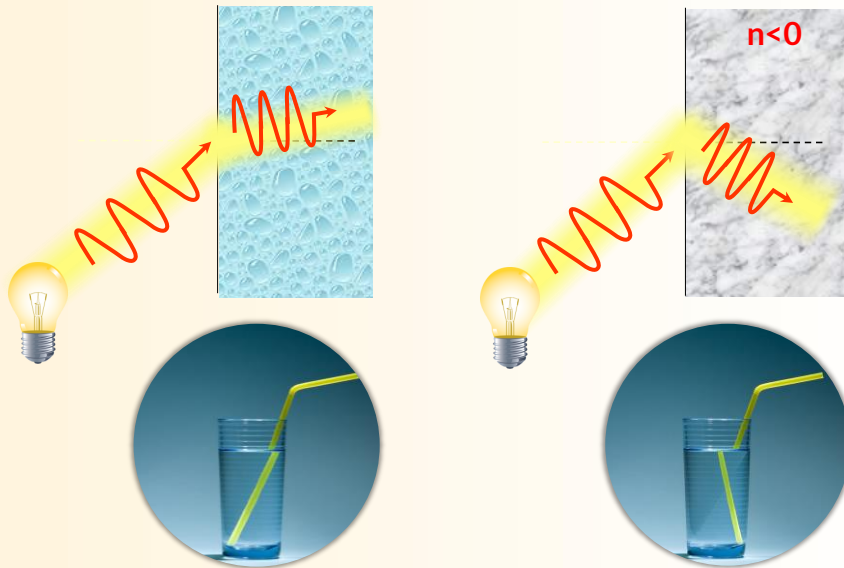


Y. Zhao, M. Belkin, A. Alù, *Nature Comm.* 3, 870 (2012)

Y. Zhao, A. Alù, *Nano Lett.* 13, 1086 (2013)

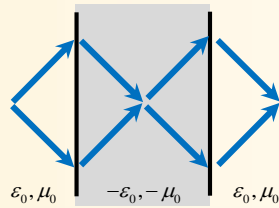
J. Lee, et al., *Nature* 511, 65 (2014)

## NEGATIVE REFRACTION

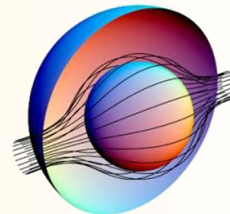


## METAMATERIALS' PROMISES

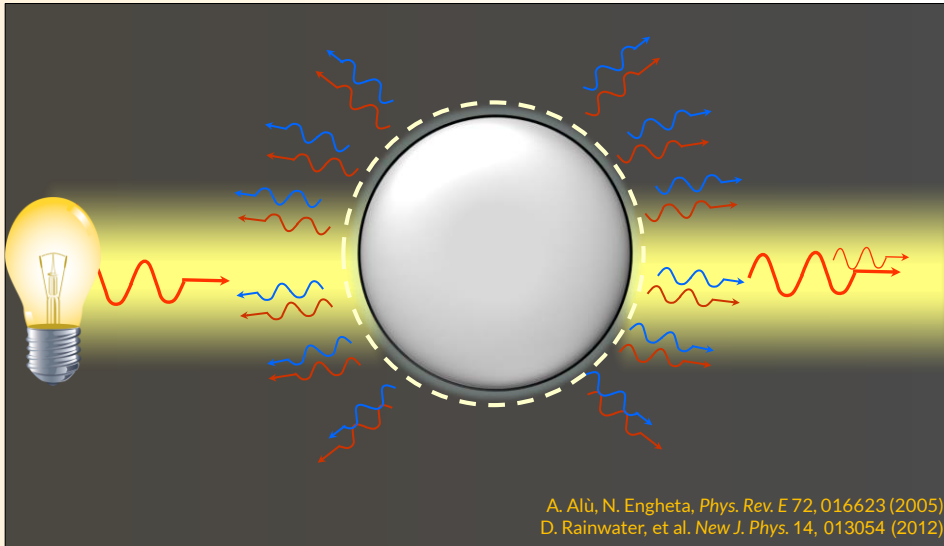
'Perfect' lenses



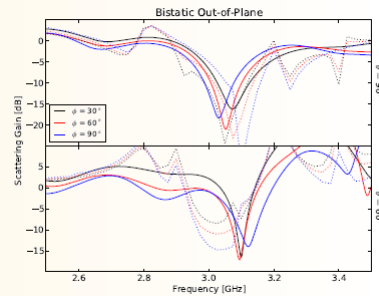
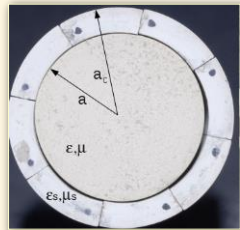
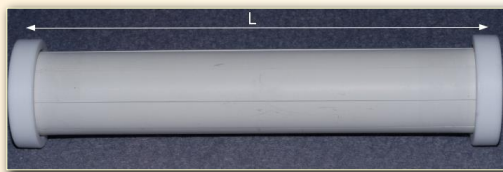
Invisibility cloaks



## SCATTERING CANCELLATION AND CLOAKING

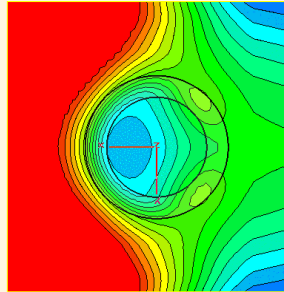


## EXPERIMENTAL REALIZATION OF CLOAKED 3D OBJECTS

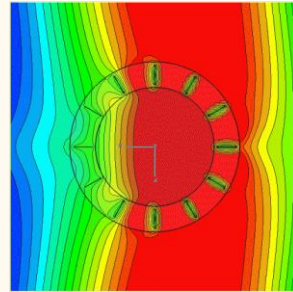


D. Rainwater, A. Kerkhoff, K. Melin, J. C. Soric, G. Moreno, and A. Alù, *New J. Phys.* 14, 013054 (2012)

## EXPERIMENTAL REALIZATION OF CLOAKED 3D OBJECTS

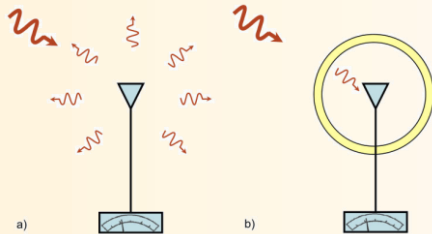


Cylinder without cloak

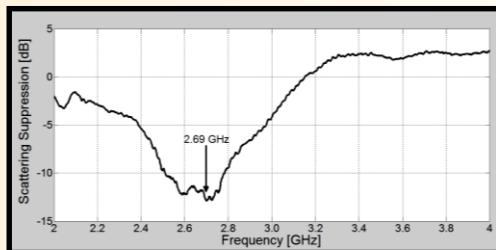


Cylinder with cloak

## INVISIBLE SENSORS

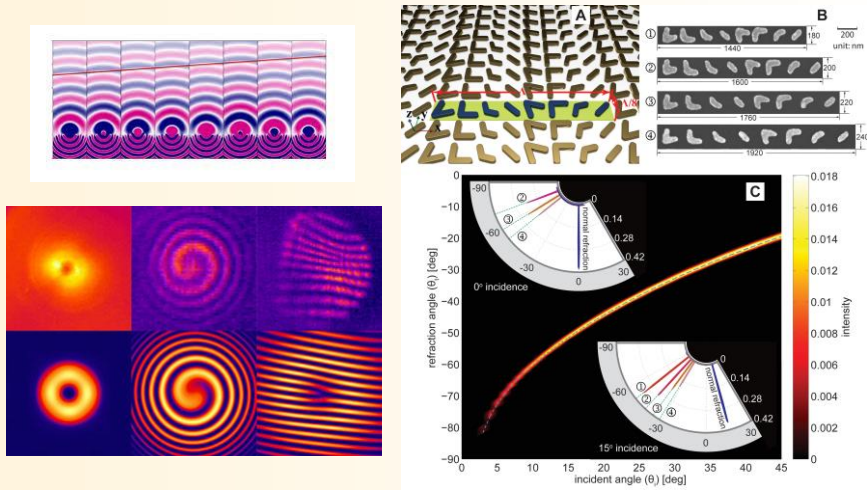


A. Alù, N. Engheta, *Phys. Rev. Lett.* 102, 233901 (2009)  
 J. Soric, A. Alù, *IEEE TAP* (2015)



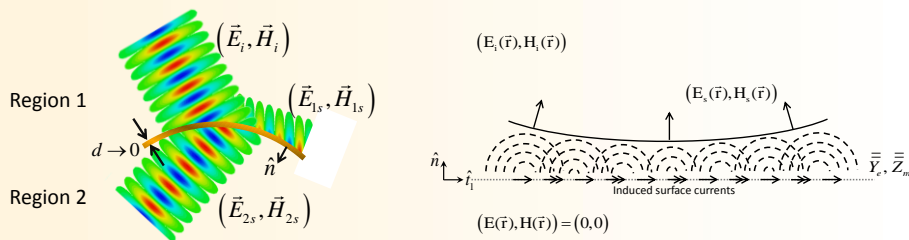


## WAVE-FRONT ENGINEERING OVER A SURFACE



F. Capasso, V. Shalaev's groups, *Science* (2011)

## EQUIVALENCE PRINCIPLE FOR METASURFACES



$$\hat{n} \times (\vec{H}_2 - \vec{H}_1) \Big|_S = \frac{1}{Z} Y_e (\vec{E}_{2t} + \vec{E}_{1t}) \Big|_S$$

$$\hat{n} \times (\vec{E}_2 - \vec{E}_1) \Big|_S = -\frac{1}{Z} Z_m (\vec{H}_{2t} + \vec{H}_{1t}) \Big|_S$$

$$\vec{Y}_e = \begin{pmatrix} -2 \frac{H_{t2}}{E_{t1}} & 0 \\ 0 & 2 \frac{H_{t1}}{E_{t2}} \end{pmatrix}, \vec{Z}_m = \begin{pmatrix} 2 \frac{E_{t2}}{H_{t1}} & 0 \\ 0 & -2 \frac{E_{t1}}{H_{t2}} \end{pmatrix}$$

N. Mohammadi Estakhri, and A. Alù, *Phys. Rev. X* in press (2016)

## A FLAT RETROREFLECTOR

**Mirror**

$k_{x,i} = k_{x,s}$

**Retroreflector**

$k_{x,s} = k_{x,i} + k_p$

**all-angle retroreflection:**

corner-cube

Cat's eye

<https://en.wikipedia.org>

**narrow-angle retroreflection (Littrow grating):**

Gratings with 400nm Blaze Wavelengths >100 \$

<https://en.wikipedia.org>      [https:// thorlabs.com](https://thorlabs.com)

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## A FLAT RETROREFLECTOR

$$R(x) = \frac{-1 + \cos \theta_0 - e^{-\frac{2i\pi x}{\Lambda}} (1 + \cos \theta_0)}{-1 - \cos \theta_0 + e^{-\frac{2i\pi x}{\Lambda}} (-1 + \cos \theta_0)}$$

$\Lambda = \frac{\lambda_0}{2 \sin \theta_0}$

$\theta_m = \theta_0$

Graded metasurface

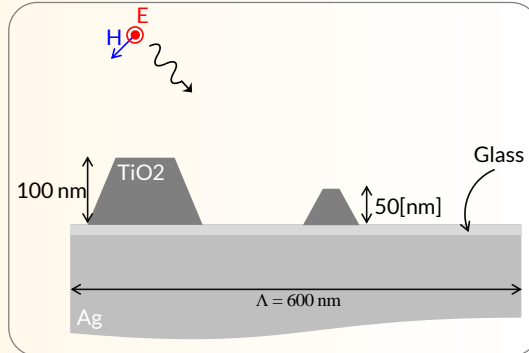
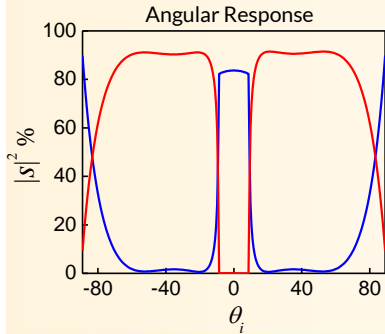
**Angular Response**

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## PHYSICAL IMPLEMENTATION

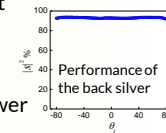
High index dielectric rods are used to implement the surface profile, providing large field concentration and low-loss.

Metasurface is 100 nm thick, designed for operation around 700 nm.

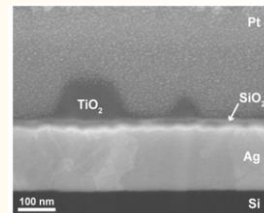
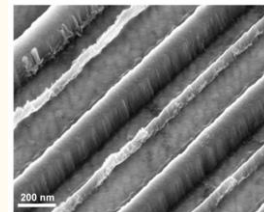
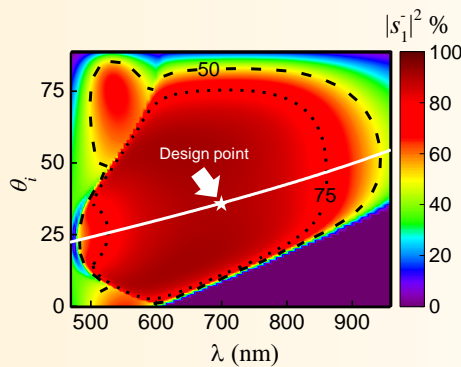


More than 80% efficiency for incident angle between 12 and 72 degrees.

90% coupling efficiency at the retroreflection angle (1.6% of the power is coupled to specular reflection).



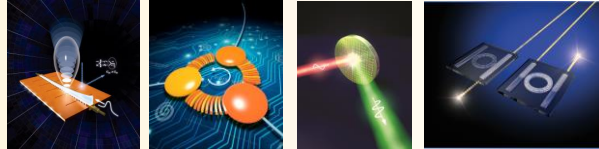
## PHYSICAL IMPLEMENTATION



The metasurface operates over a broad half-power wavelength range  $\lambda = 490 - 940$  nm in terms of retroreflection efficiency.

## METAMATERIALS: CHALLENGES, AND DIRECTIONS FORWARD

- Passive, often affected by losses
- Time-invariance, lack of reconfigurability
- Linear, or weakly nonlinear
- Limited by symmetry constraints

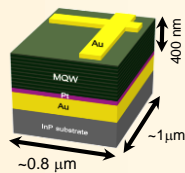
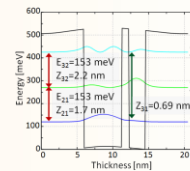


- Hybrid metasurfaces
- Multi-physics responses
- Active, time-varying, time-modulated
- Opto-mechanical interactions

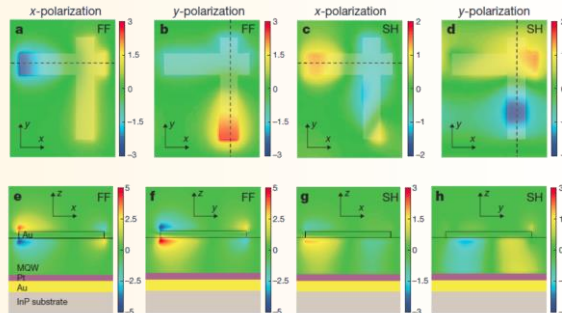
## ENABLING LARGE NONLINEAR EFFECTS AT THE NANOSCALE

$$\chi_{zzz}^{(2)}(\omega \rightarrow 2\omega) \sim 10^5 \text{ pm/V}$$

N-doped multiple quantum wells (MQW)

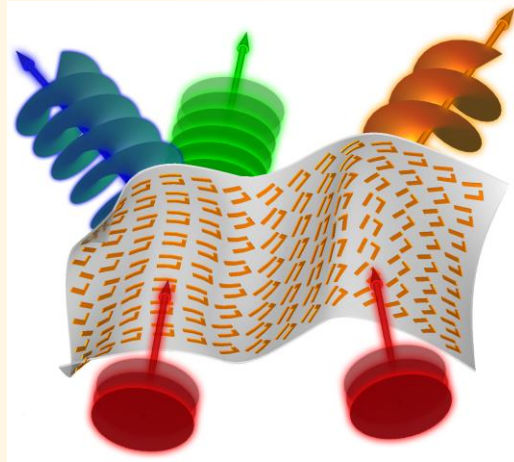


Phase matching at the nanoscale



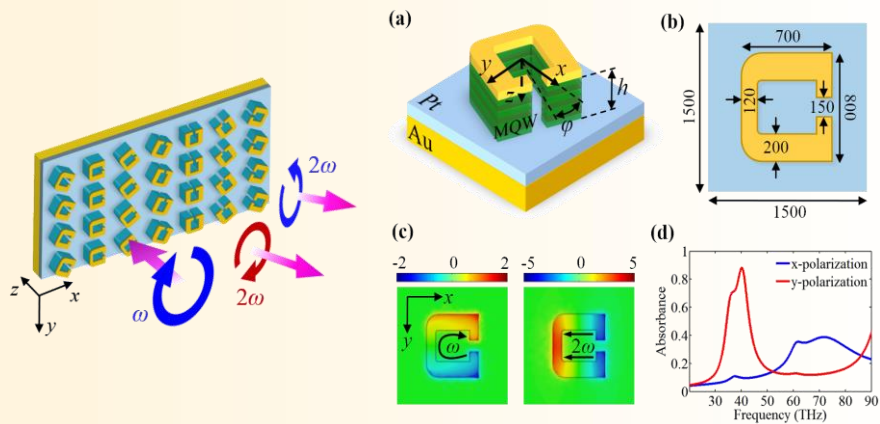
J. Lee, C. Argyropoulos, P.Y. Chen, M. Tymchenko, F. Lu, F. Demmerle, G. Boehm, M. C. Amann, A. Alù, and M. A. Belkin, *Nature* **511**, 65 (2014)

FLATLAND NONLINEAR OPTICS



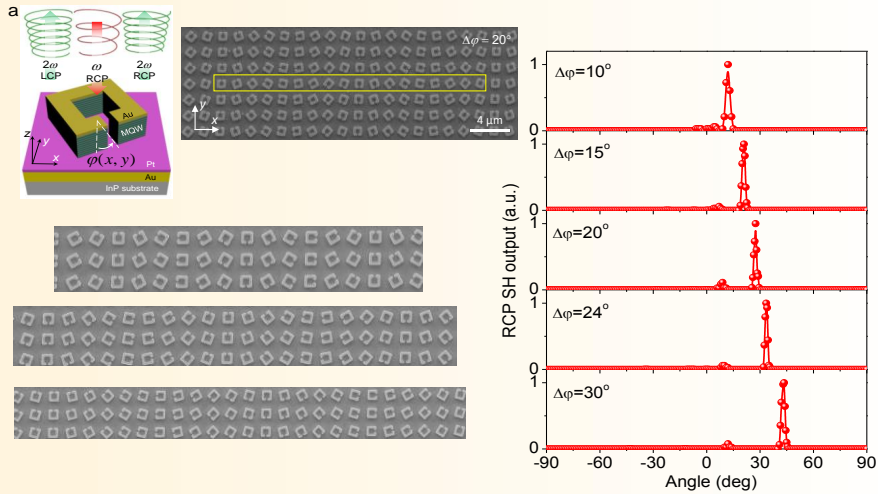
J. S. Gomez-Diaz, M. Tymchenko, J. Lee, M. Belkin, A. Alù, *Phys. Rev. B* **92**, 125429 (2015)

FLATLAND NONLINEAR OPTICS



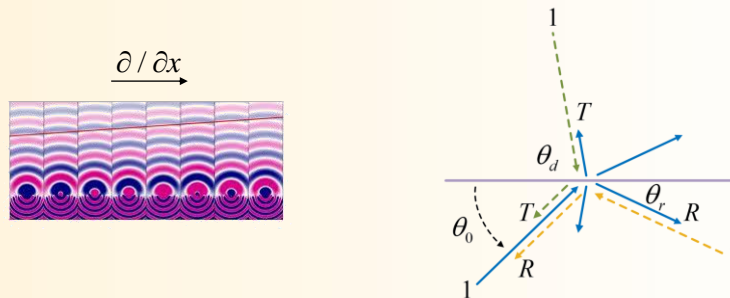
M. Tymchenko, J. S. Gomez-Diaz, M. Belkin, A. Alù, *Phys. Rev. Lett.* **115**, 207403 (2015)

## EXPERIMENTAL RESULTS



J. Lee, N. Nookala, J. S. Gomez-Diaz, M. Tymchenko, F. Demmerle, G. Boehm, K. Lai, G. Shvets, M. C. Amann, A. Alù, and M. A. Belkin., *Optica* 3, 283 (2016)

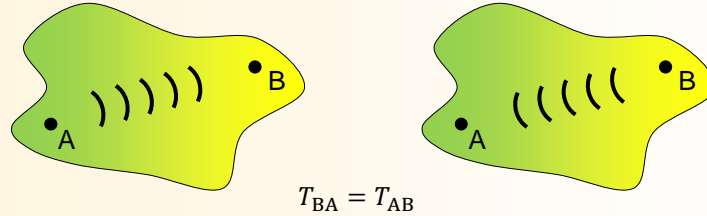
## FUNDAMENTAL SYMMETRY CONSTRAINTS



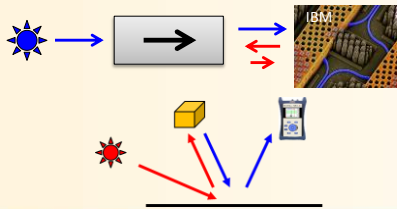
Y. Hadad, D. Sounas, and A. Alù, *Phys. Rev. B* 92, 100304R (2015)  
A. Shaltout, A. Kildishev, V. Shalaev, *Opt. Mat. Expr.* 5, 2459 (2015)

## LORENTZ RECIPROCITY AND TIME-REVERSAL SYMMETRY

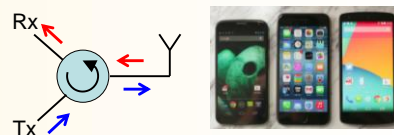
Reciprocity: *symmetry in transmission for opposite propagation directions*



Isolators



Duplexers



## NON-RECIPROCALITY WITH MAGNETIC MATERIALS

Lorentz reciprocity theorem

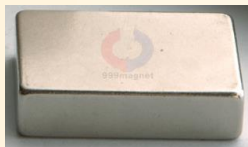
$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

$$\begin{aligned} \bar{\epsilon} &= \bar{\epsilon}^T \\ \bar{\mu} &= \bar{\mu}^T \end{aligned}$$

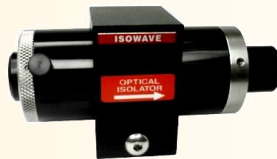
Time-invariant materials

Linear materials

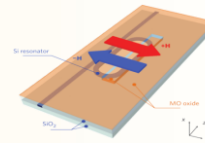
Static Magnets



Weak Effect →  
Massive Devices



Difficult to integrate



Bi, Nature Photon. 5, 758

## BREAKING RECIPROCITY CONSTRAINTS

Lorentz reciprocity theorem

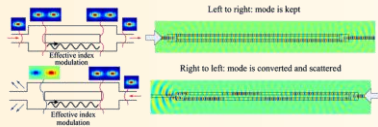
$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

$$\bar{\epsilon} = \bar{\epsilon}^T$$

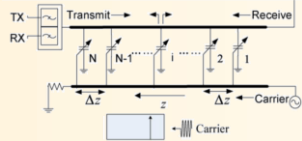
$$\bar{\mu} = \bar{\mu}^T$$

Time-invariant materials

Linear materials



Lira, *PRL* **109**, 033901 (2012)



Qin, *IEEE TAP* **62**, 2260 (2014)



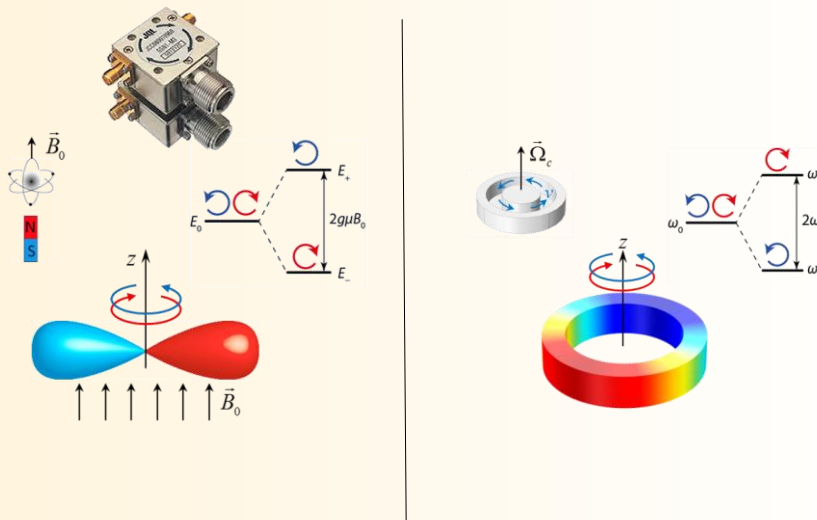
Sounas, *Nature Commun.* **4**, 2407 (2013)

D. L. Sounas, *ACS Photonics* **1**, 198 (2014)

Fleury, *Science* **343**, 516 (2014)

Estep, *Nature Phys.* **10**, 923 (2014)

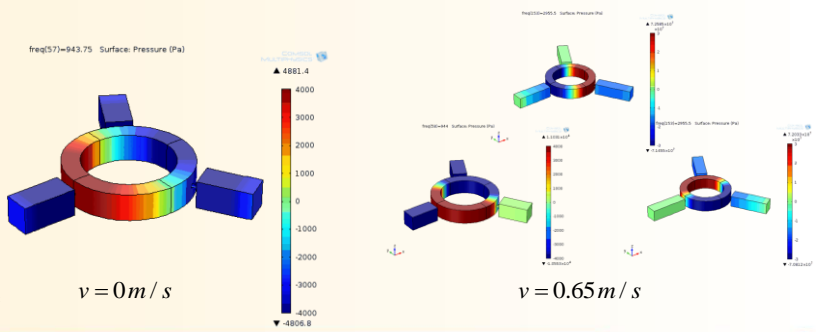
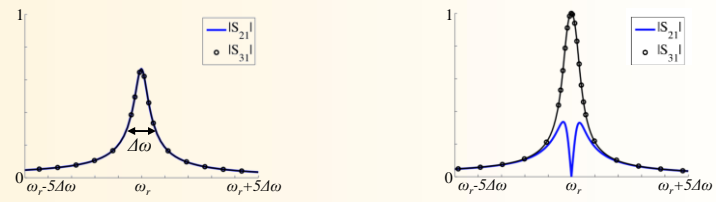
## ANGULAR-MOMENTUM BIASING: A ZEEMAN META-MOLECULE



R. Fleury, D. L. Sounas, C. Sieck, M. Haberman, A. Alù, *Science* **343**, 516 (2014)

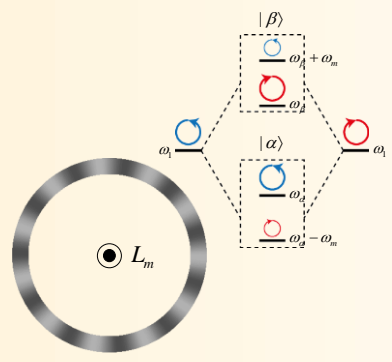


## AN ACOUSTIC CIRCULATOR

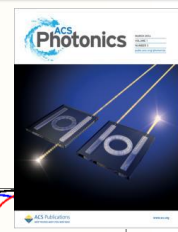
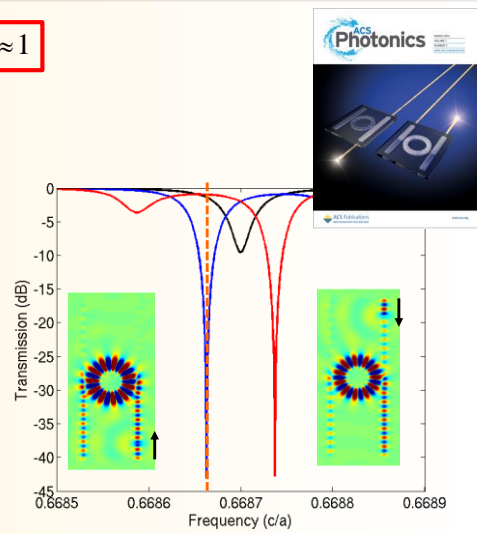


## ANGULAR-MOMENTUM-BIAS IN NANOPHOTONICS

$\Delta\epsilon_m = 5 \times 10^{-4} \epsilon$  !  
 $Q \sim 7,000$        $Q\Delta\epsilon_m \approx 1$

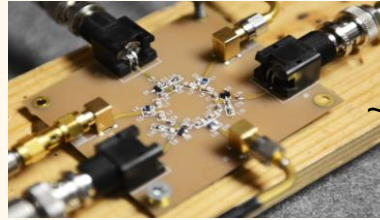
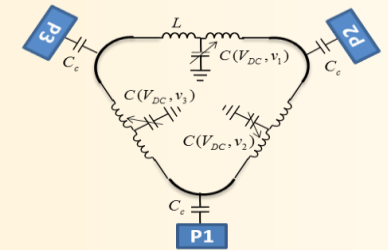


$\Delta\epsilon(\varphi, t) = \Delta\epsilon_m \cos(\omega_m t - L_m \varphi)$

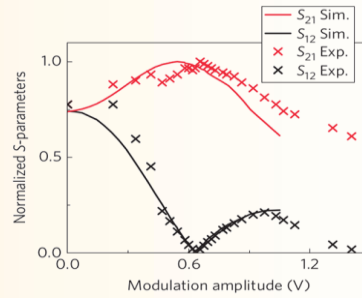
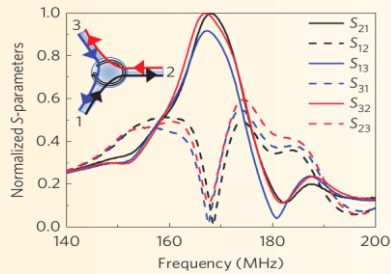


D. L. Sounas, A. Alù, ACS Photonics 1, 198 (2014)

## RF MAGNET-LESS INTEGRATED CIRCULATOR

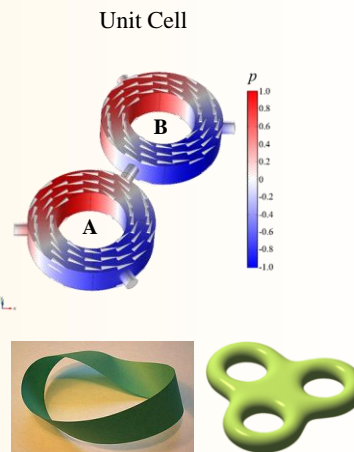
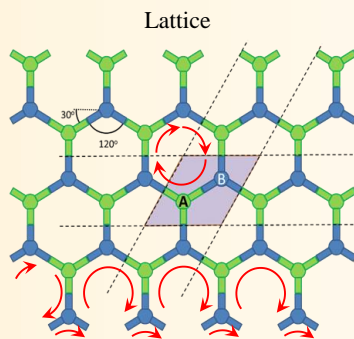


$\sim \lambda/70$



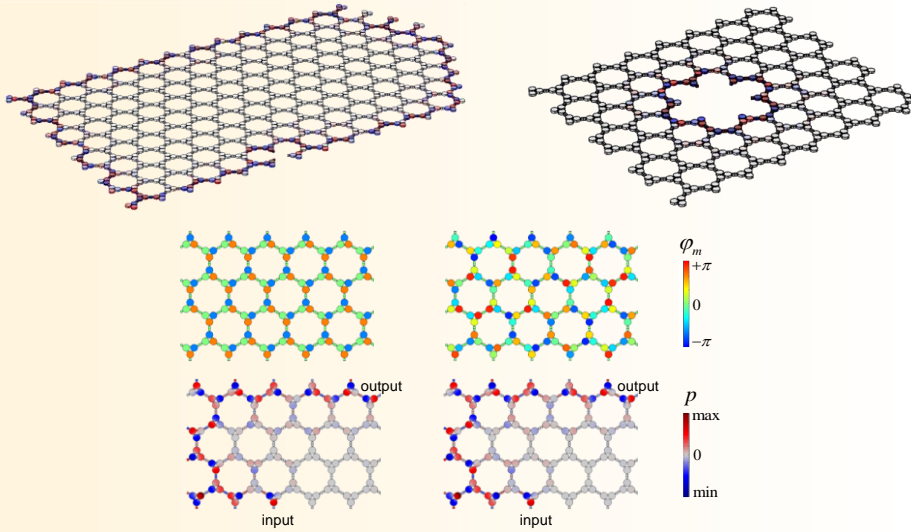
N. A. Estep\*, D. L. Sounas\*, J. Soric, and A. Alù, *Nature Phys.*, **10**, 923 (2014)

## MOLDING THE TOPOLOGY OF A METAMATERIAL



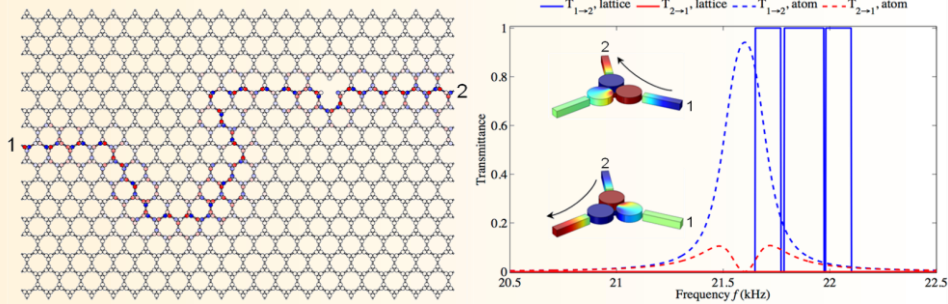
A. Khanikaev, R. Fleury, H. Mousavi, and A. Alù, *Nat. Comm.* **6**, 8260 (2015)

## FLOQUET TOPOLOGICAL INSULATORS FOR LIGHT



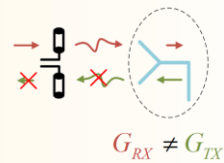
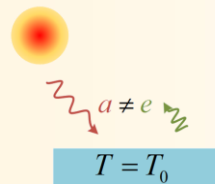
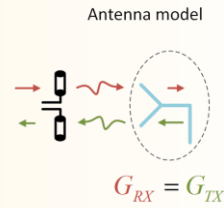
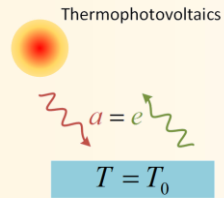
R. Fleury, A.B. Khanikaev and A. Alù, *Nature Communications*, 7, 11744 (2016)

## CONTINUOUS BANDWIDTH OF ISOLATION



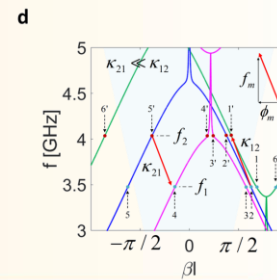
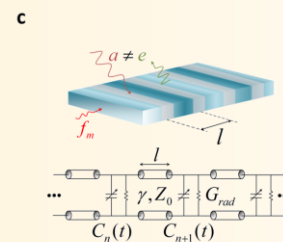
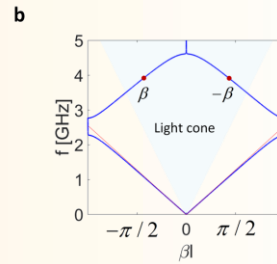
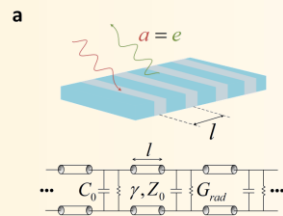
R. Fleury, A.B. Khanikaev and A. Alù, *Nature Communications*, 7, 11744 (2016)

## NON-RECIPROCAL EMITTERS

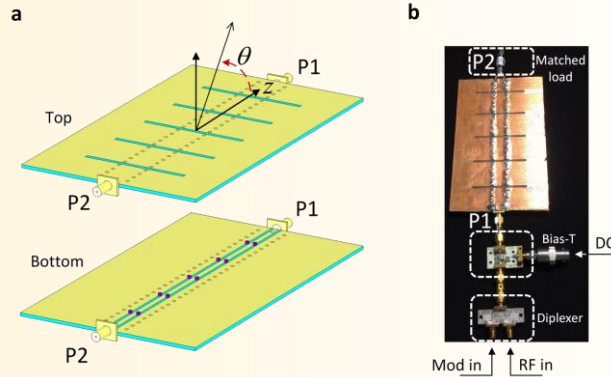


Y. Hadad, J. C. Soric, and A. Alù, PNAS 113, 33471 (2016)

## NON-RECIPROCAL METASURFACES BASED ON ST MODULATION



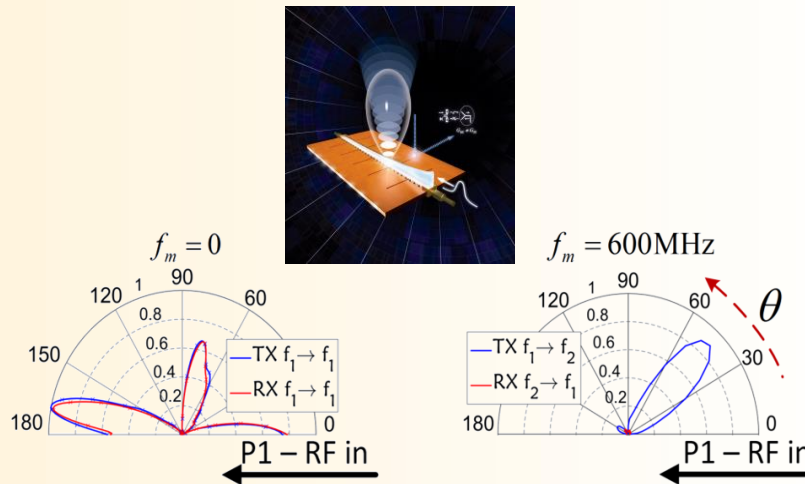
## NON-RECIPROCAL METASURFACES BASED ON ST MODULATION



Y. Hadad, J. C. Soric, and A. Alù, PNAS 113, 33471 (2016)



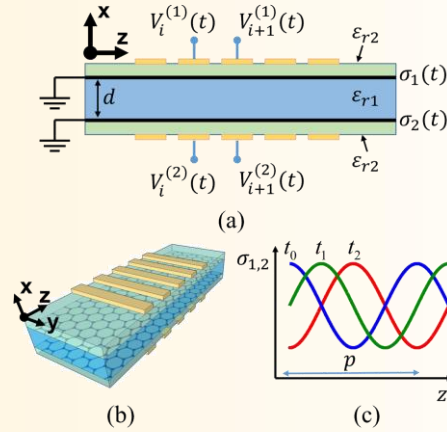
## NON-RECIPROCAL METASURFACES BASED ON ST MODULATION



Y. Hadad, J. C. Soric, and A. Alù, PNAS 113, 33471 (2016)



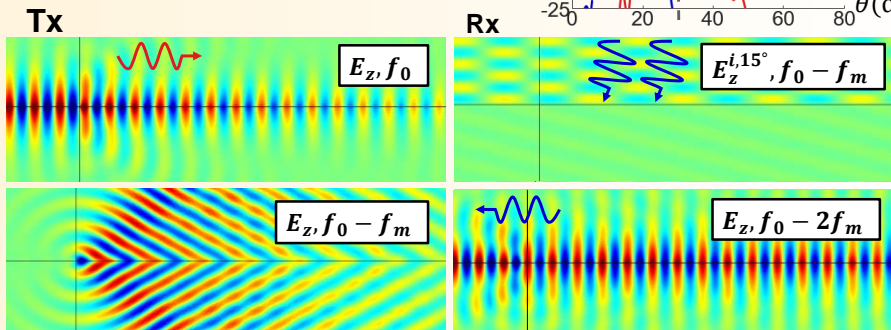
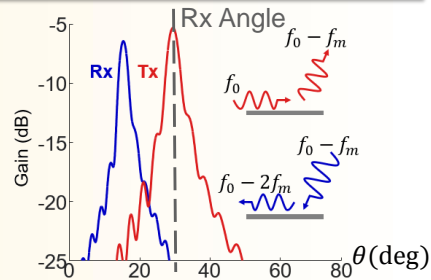
## NON-RECIPROCAL METASURFACES BASED ON ST MODULATION



D. Correas-Serrano, J. S. Gomez-Diaz, D. L. Sounas, Y. Hadad, A. Alvarez-Melcon, and A. Alù, *IEEE AWPL* (2016)

## NON-RECIPROCAL METASURFACES BASED ON ST MODULATION

- Non-reciprocity is two fold
  - Radiation diagram in Tx - Rx
  - Frequency conversion in far field – surface wave coupling



NON-RECIPROcity BASED ON NON-LINEAR EFFECTS

Lorentz reciprocity theorem

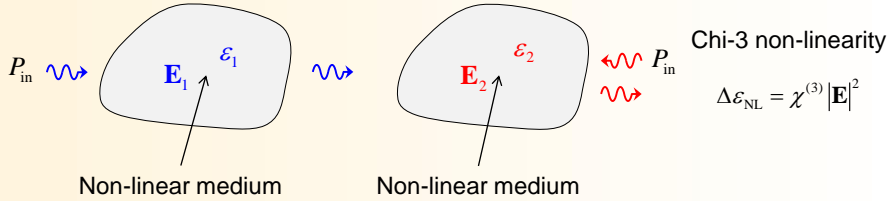
$$\iiint \mathbf{J}_1 \cdot \mathbf{E}_2 dV = \iiint \mathbf{J}_2 \cdot \mathbf{E}_1 dV$$

$$\bar{\epsilon} = \bar{\epsilon}^T$$

$$\bar{\mu} = \bar{\mu}^T$$

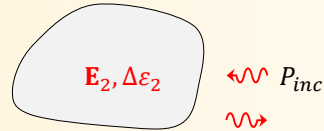
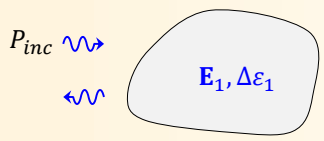
Time-invariant materials

Linear materials



P. Saboo, J. Joseph, *Appl. Opt.* **52**, 8252–8257 (2013)  
 L. Fan, et al., *Opt. Lett.* **38**, 1259–1261 (2013)  
 Y. Shi, Z. Yu, S. Fan, *Nature Photon.* **9**, 388–392 (2015)  
 A. M. Mahmoud, A. Davoyan, N. Engheta, *Nature Comm.* **6**, 8359 (2015)

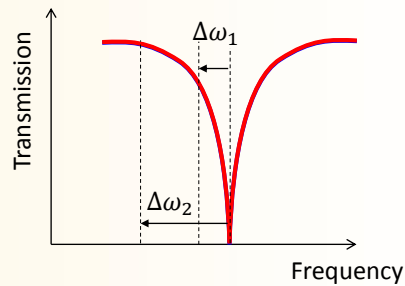
BASIC OPERATION – SINGLE RESONANCE



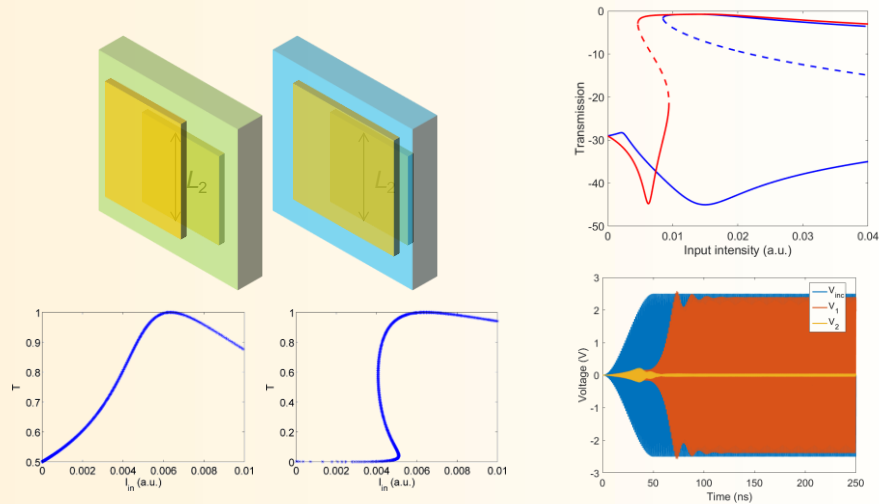
$$\kappa = \frac{|\mathbf{E}_2|^2}{|\mathbf{E}_1|^2} > 1$$

$$\epsilon_{NL} = \epsilon + \chi^{(3)} |\mathbf{E}|^2$$

$$\Delta\omega = -\omega_0 \frac{\int \Delta\epsilon |\mathbf{E}_0|^2 dV}{\int \epsilon |\mathbf{E}_0|^2 dV}$$

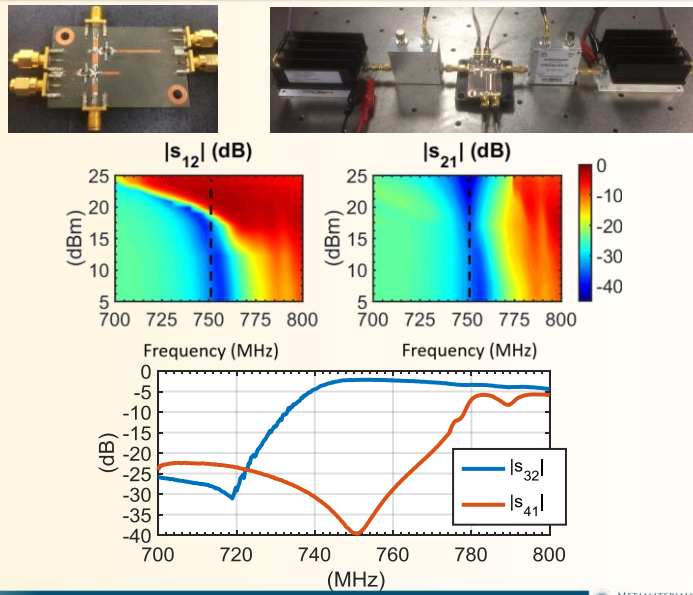


## IDEAL ISOLATOR BASED ON TWO NON-LINEAR RESONATORS



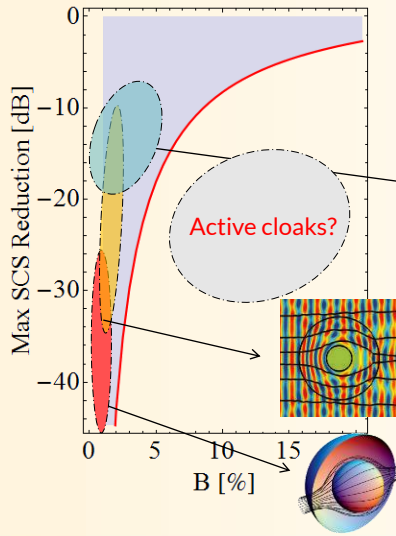
D. L. Sounas, J. Soric, and A. Alù, *in preparation* (2016)

## EXPERIMENTAL RESULTS AT RF



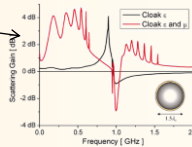


## PASSIVITY BOUNDS ON CLOAKING



**Hard physical bound on bandwidth and scattering reduction, valid for any passive and causal cloaking scheme.**

F. Monticone, A. Alù, *Optica* 3, 718 (2016)



**Plasmonic cloaks  
Mantle cloaks**

A. Alù, N. Engheta, *Phys. Rev. E* 78, 045602R (2008)

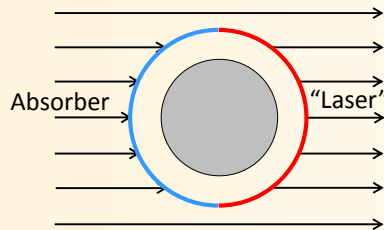
**Reduced transformation-optics cloaks**

W. Cai, et al., *Nat. Photon.* 1, 224 (2007)

**Ideal transformation-optics cloaks**

D. Schurig, et al., *Science* 314, 977 (2006)

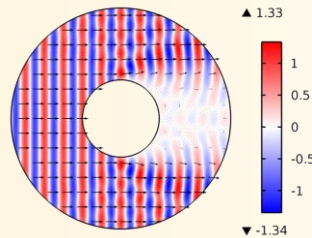
## CLOAKING WITH BALANCED LOSS AND GAIN



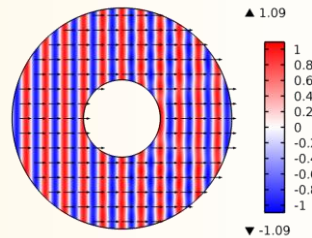
$$\text{Re}\{Y_s\} = \begin{cases} Y_0 |\cos \varphi|, & \text{left side} \\ -Y_0 |\cos \varphi|, & \text{right side} \end{cases}$$

$$\text{Im}\{Y_s\} = -Y_0 \left[ \frac{1}{k(d-a)} - \frac{1}{2ka} \right]$$

Only passive

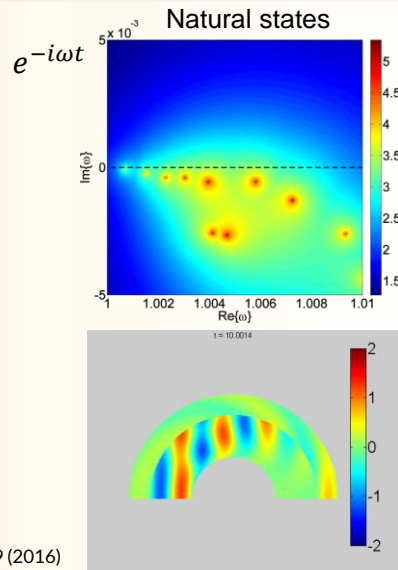
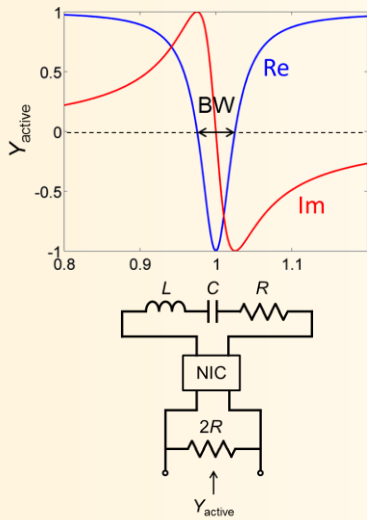


Passive + active



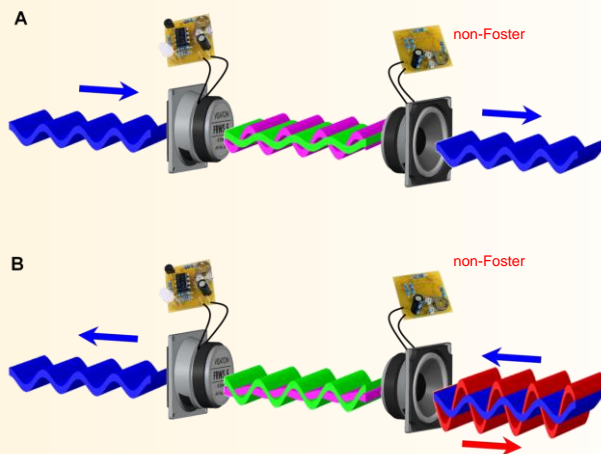
D. L. Sounas, R. Fleury, and A. Alù, *Phys. Rev. Appl.* 4, 014005 (2015)

## STABILITY CONSIDERATIONS



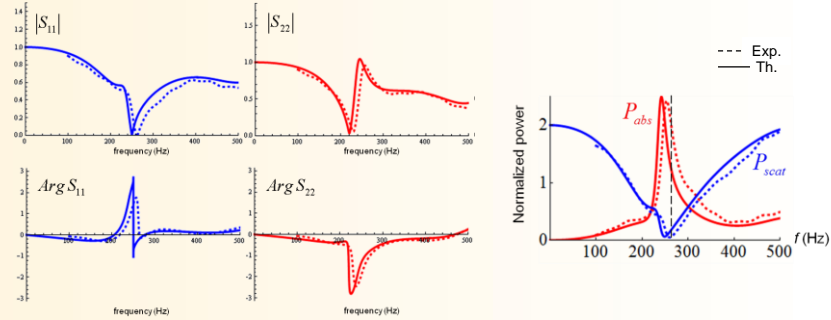
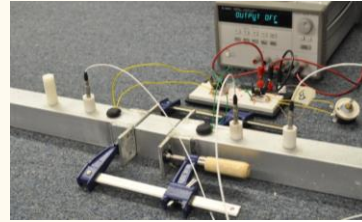
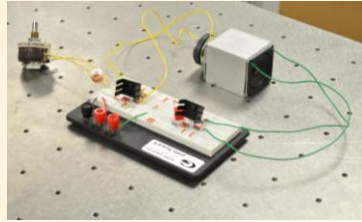
D. L. Sounas, R. Fleury, A. Alù, *IEEE JSTQE* 22, 5000809 (2016)

## A CLOAKED ACOUSTIC SENSOR: PT-SYMMETRY



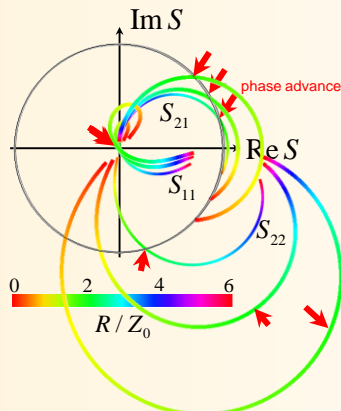
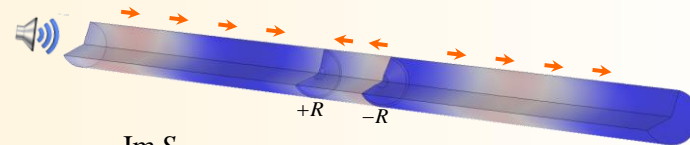
R. Fleury, D. L. Sounas, and A. Alù, *Nat. Commun.* 6, 5905 (2015)

## A PT-SYMMETRIC ACOUSTIC SENSOR

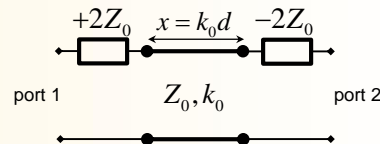


R. Fleury, D. L. Sounas, and A. Alù, *Nat. Commun.* **6**, 5905 (2015)

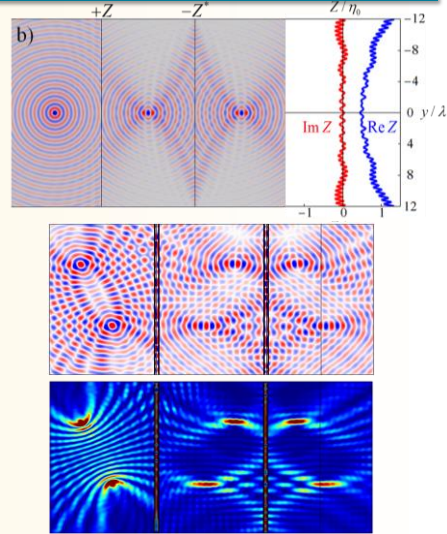
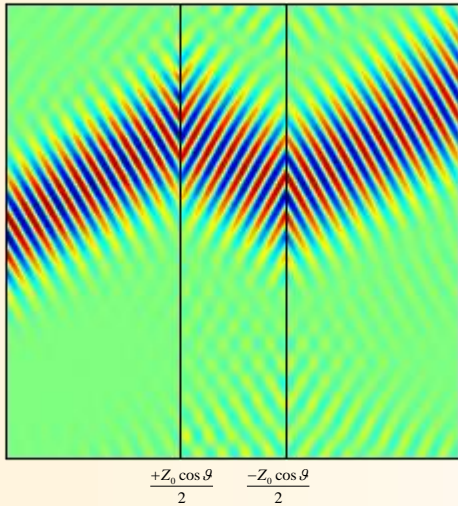
## LOSS-FREE NEGATIVE REFRACTION



$$S = \begin{pmatrix} 0 & e^{jx} \\ e^{jx} & 2 - 2e^{2jx} \end{pmatrix}$$



## NEGATIVE REFRACTION AND FOCUSING

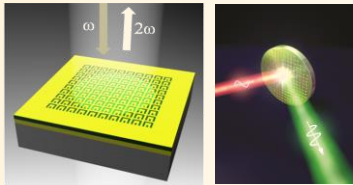


R. Fleury, D. Sounas, and A. Alù, *Phys. Rev. Lett.* **113**, 023903 (2014)

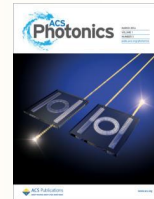
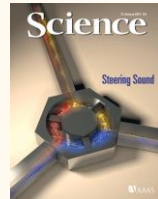
F. Monticone, C. Valagiannopoulos, A. Alù, *J. Opt.* **18**, 044028 (2015); *Phys. Rev. X* in press (2016)



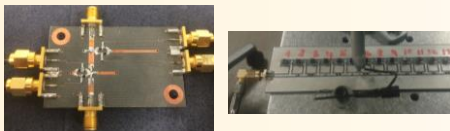
## A BRIGHT FUTURE FOR METAMATERIALS



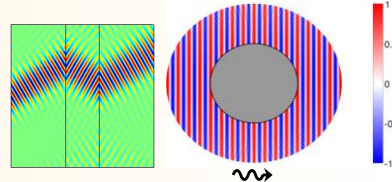
Giant nonlinearities in hybrid metasurfaces



Magnetic-free, linear nonreciprocity at the subwavelength scale: angular-momentum biased meta-atoms



Nonlinearity and asymmetry to build optimal isolators and non-reciprocal devices



Loss-free negative refraction and planar focusing, ideal cloaking, invisible sensors based on active and PT metasurfaces

