The Fascinating Optics of Metamaterials and Plasmonics

Presented by:

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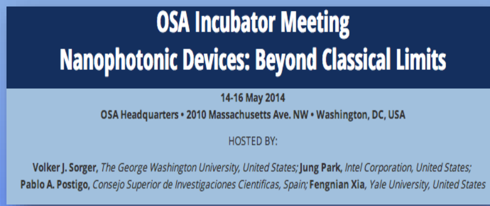
Nanyang Technological University, Singapore

OSA Nanophotonics Technical Group

Welcomes You!

What we do?

- Organize Incubators



- Webinars

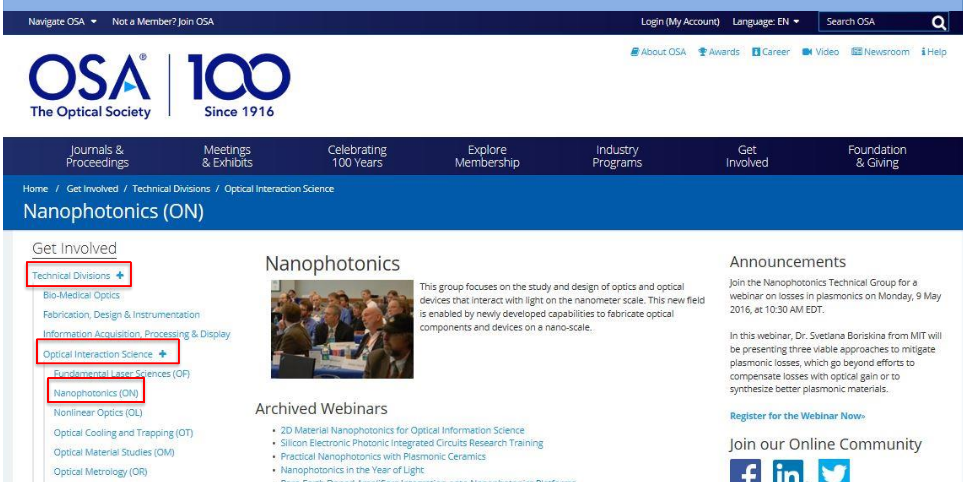
  (Quarterly, Featuring prominent speakers)

- Special Activities

  (@Conferences: Poster Sessions, Dine & Discover, Blogging)

Poster session at CLEO in San Jose (2016)

Where to find us?



http://www.osa.org/en-us/get_involved/technical_communities/ois/nanophotonics_(on)_(1)/

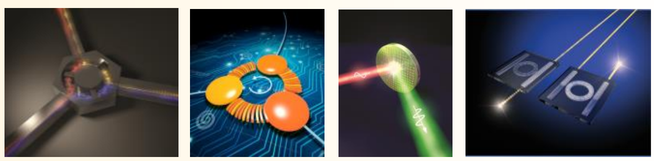
Creating a Community

- 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)**

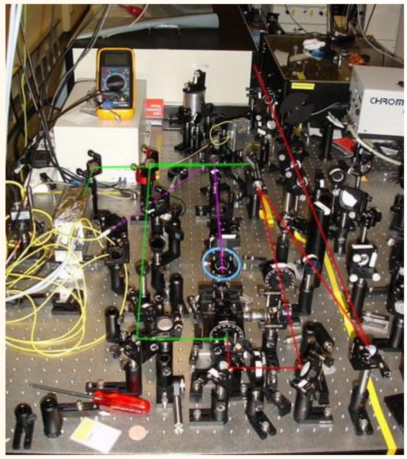
Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX, USA

http://users.ece.utexas.edu/~aalu, alu@mail.utexas.edu

UT ECE | THE UNIVERSITY OF TEXAS AT AUSTIN | DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

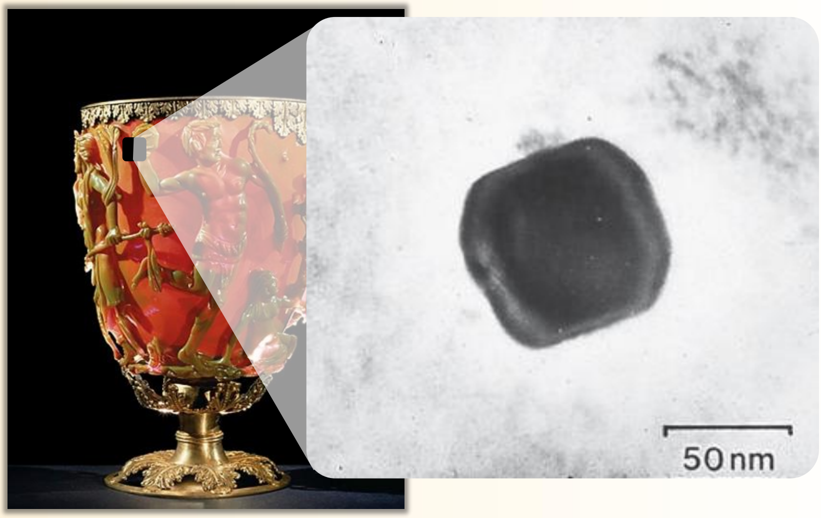
METAMATERIALS & PLASMONICS RESEARCH LABORATORY

'Conventional' Light-Matter Interactions



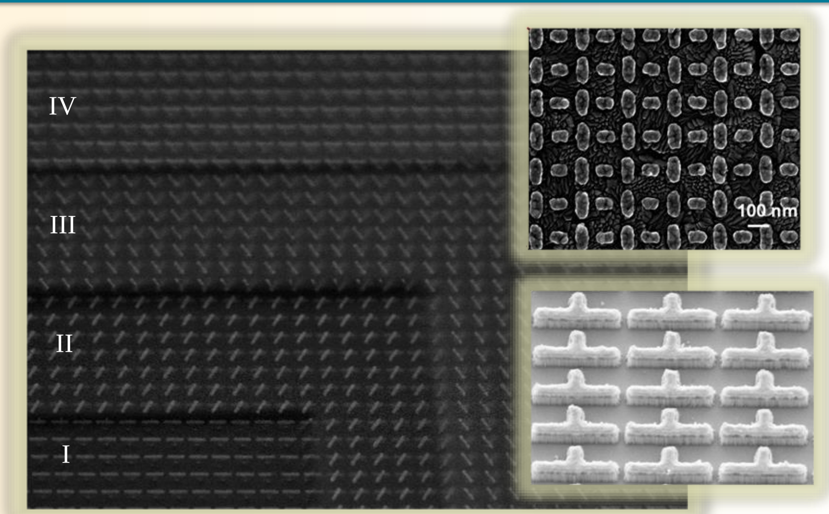
Plasmonic Interactions

Plasmonics and Enhanced Wave-Matter Interactions



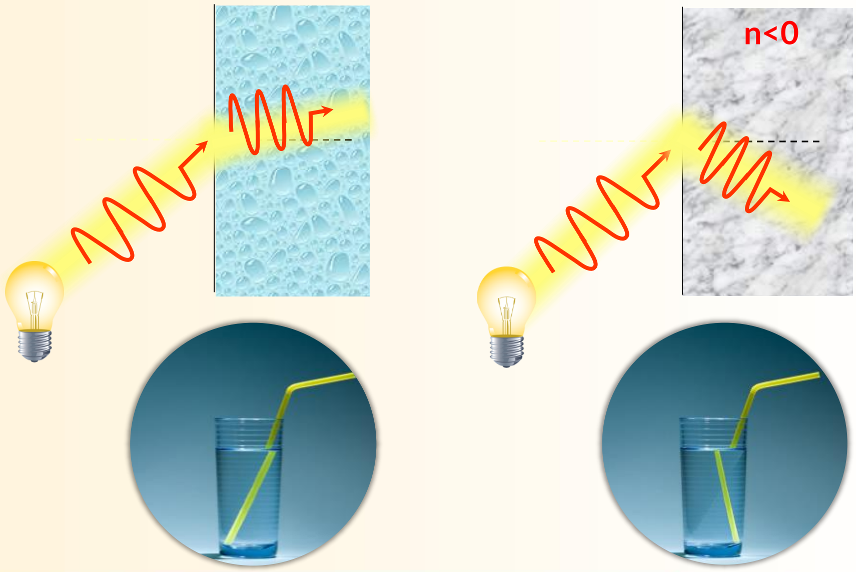
I. Freestone, *et al.*, *Gold Bulletin* **40**, 207 (2007)

Meta-Materials: *Beyond* Nature with Artificial Materials



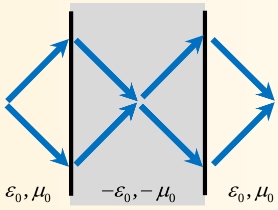
Y. Zhao, M. Belkin, A. Alù, *Nature Comm.* **3**, 870 (2012)
Y. Zhao, A. Alù, *Nano Lett.* **13**, 1086 (2013)
J. Lee, et al., *Nature* **511**, 65 (2014)

Negative Refraction

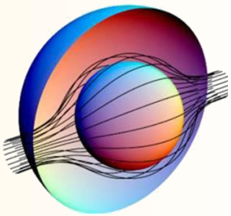


Metamaterials' Promises

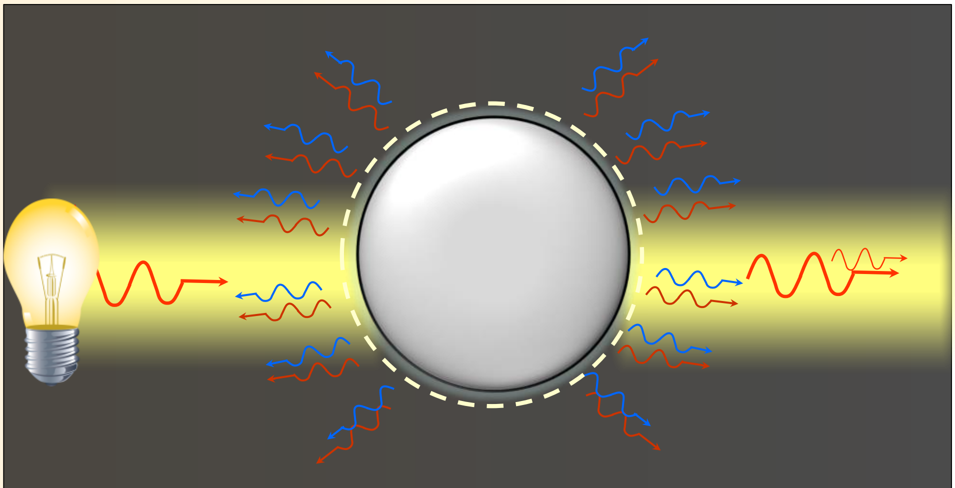
'Perfect' lenses



Invisibility cloaks

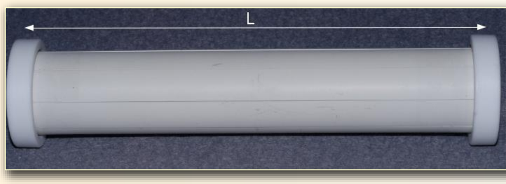


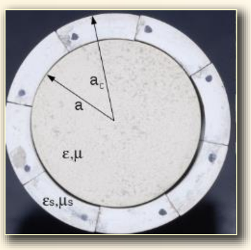
Scattering Cancellation and Cloaking

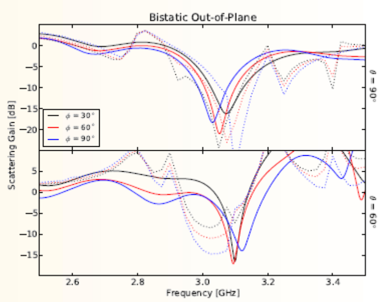


A. Alù, N. Engheta, *Phys. Rev. E* 72, 016623 (2005)
D. Rainwater, et al. *New J. Phys.* 14, 013054 (2012)

Experimental Realization of Cloaked 3D Objects

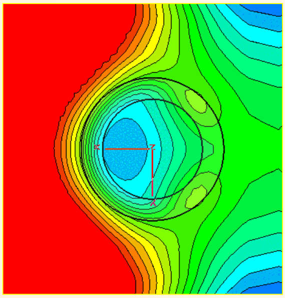




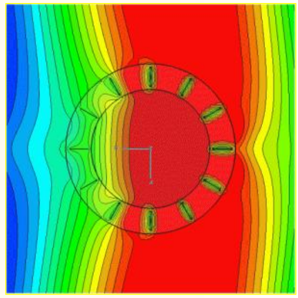


D. Rainwater, A. Kerkhoff, K. Melin, J. C. Soric, G. Moreno, and A. Alù, *New J. Phys.* 14, 013054 (2012)

Experimental Realization of Cloaked 3D Objects

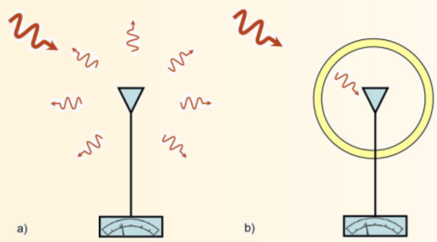


Cylinder without cloak

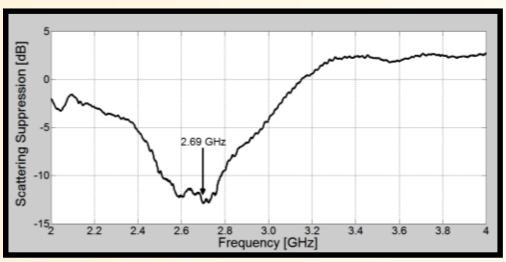


Cylinder with cloak

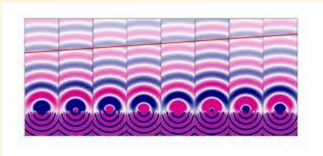
Invisible Sensors

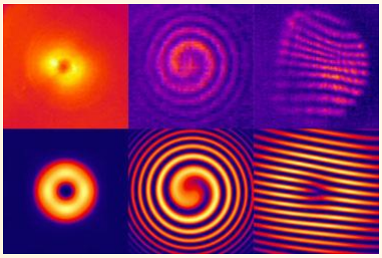


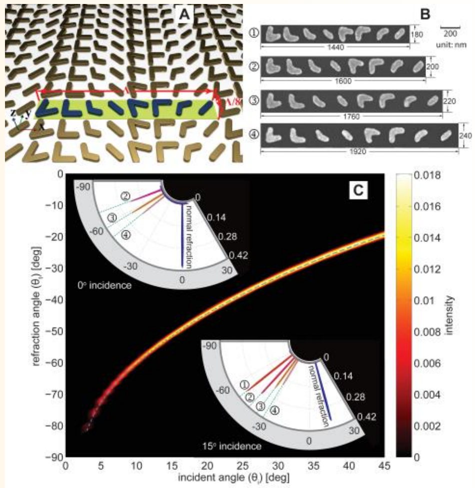
A. Alù, N. Engheta, *Phys. Rev. Lett.* 102, 233901 (2009)
J. Soric, A. Alù, *IEEE TAP* (2015)



Wave-Front Engineering over a Surface

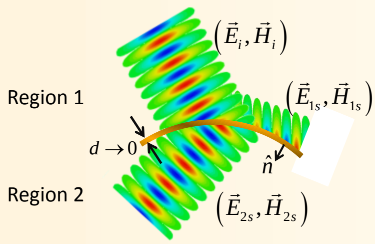


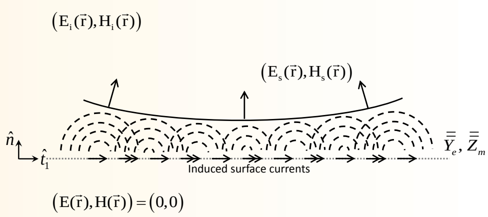




F. Capasso, V. Shalaev's groups, *Science* (2011)

Equivalence Principle for Metasurfaces





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

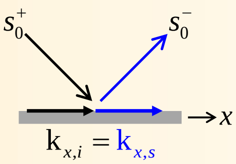
$$\hat{n} \times \left(\vec{E}_2 - \vec{E}_1\right)\Big|_S = -\frac{1}{2} Z_m \left(\vec{H}_{2t} + \vec{H}_{1t}\right)\Big|_S$$

$$\bar{\bar{Y}}_e = \begin{pmatrix} -2\frac{H_{t_2}}{E_{t_1}} & 0 \\ 0 & 2\frac{H_{t_1}}{E_{t_2}} \end{pmatrix}, \quad \bar{\bar{Z}}_m = \begin{pmatrix} 2\frac{E_{t_2}}{H_{t_1}} & 0 \\ 0 & -2\frac{E_{t_1}}{H_{t_2}} \end{pmatrix}$$

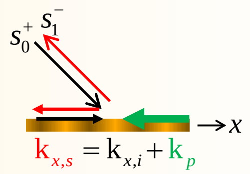
N. Mohammadi Estakhri, and A. Alù, *Phys. Rev. X* in press (2016)

A Flat Retroreflector

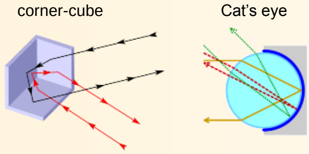
Mirror



Retroreflector

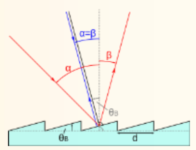


all-angle retroreflection:



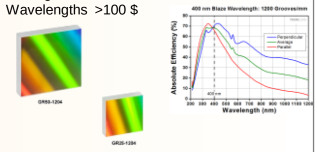
https://en.wikipedia.org

narrow-angle retroreflection (Littrow grating):



https://en.wikipedia.org

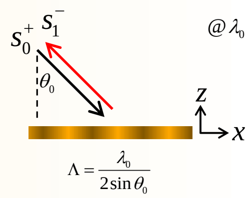
Gratings with 400nm Blaze Wavelengths >100 $

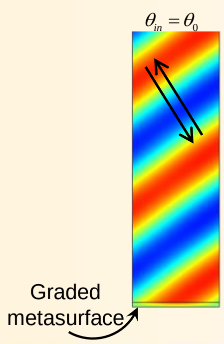


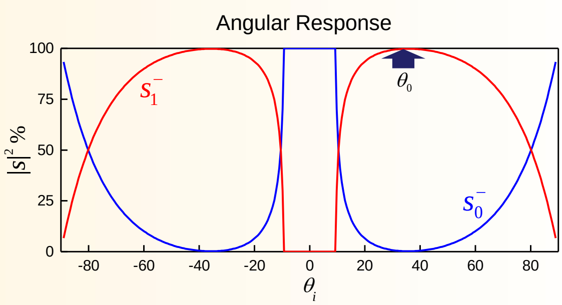
https:// thorlabs.com

A Flat Retroreflector

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



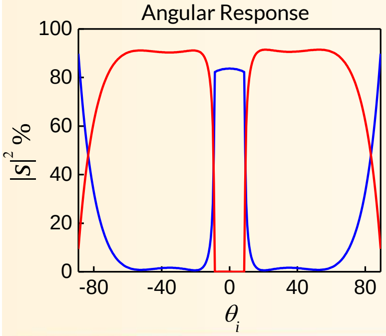


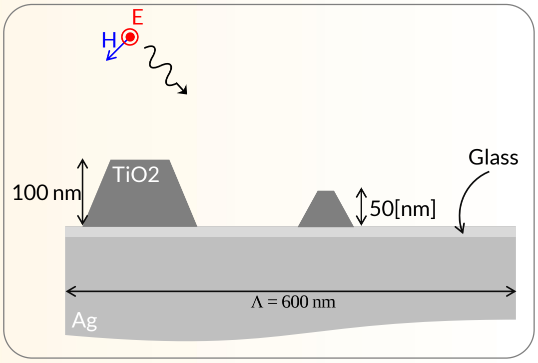


Physical Implementation

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

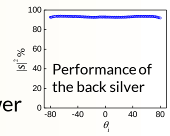
Metasurface is **100 nm** thick, designed for operation around **700 nm**.



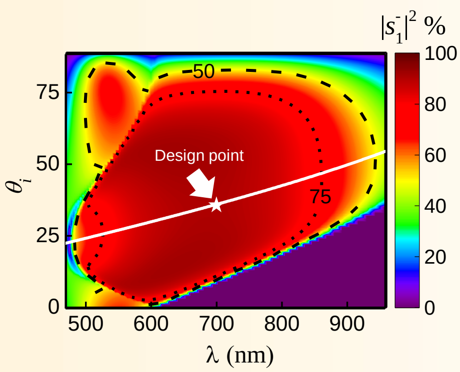


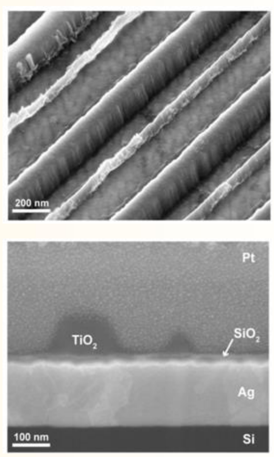
More than **80%** efficiency for incident angle between 12 and72 degrees.

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



Physical Implementation

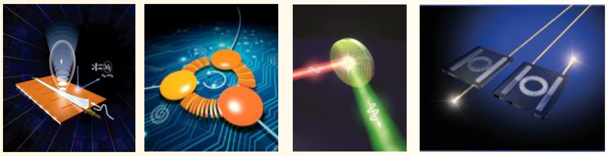




The metasurface operates over a broad half-power wavelength range $\lambda = 490 - 940$ nm in terms of retroreflection efficiency.

Metamaterials: Challenges, and Directions Forward

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

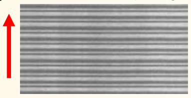


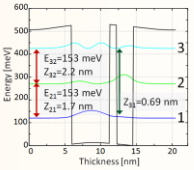
- Hybrid metasurfaces
- Multi-physics responses
- Active, time-varying, time-modulated
- Opto-mechanical interactions

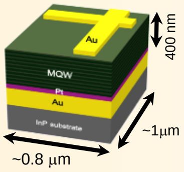
Enabling Large Nonlinear Effects at the Nanoscale

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

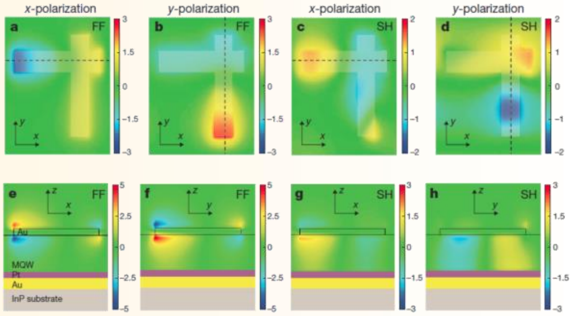
N-doped multiple quantum wells (MQW)





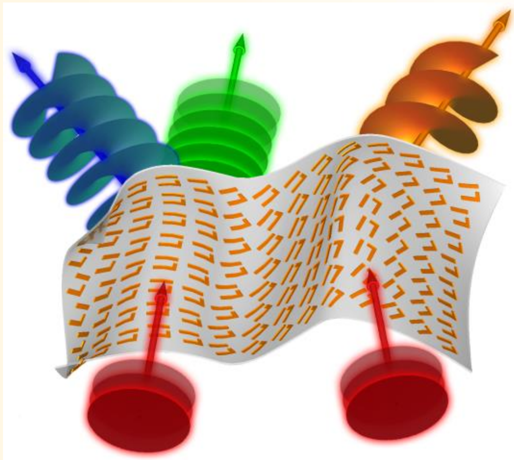


Phase matching at the nanoscale



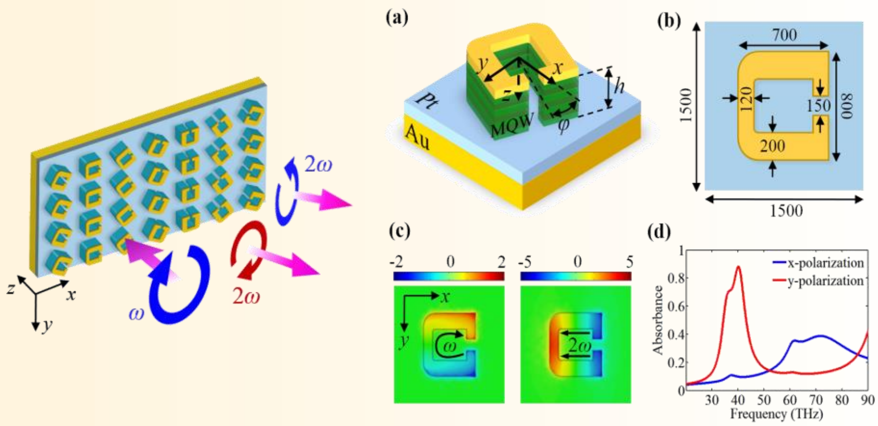
J. Lee, C. Argyropoulos, P. Y. Chen, M. Tymchenko, F. Lu, F. Demmerle, G. Boehm, M. C. Amann, A. Alù, and M. A. Belkin, *Nature* **511**, 65 (2014)

Flatland Nonlinear Optics



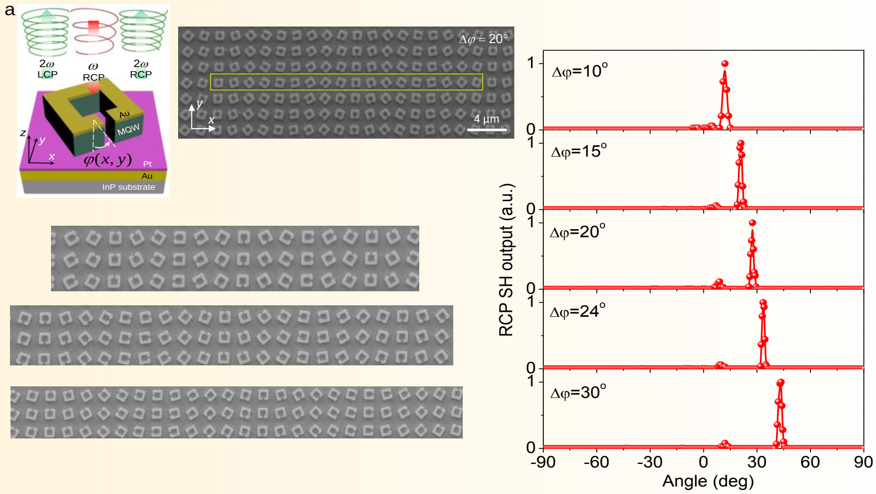
J. S. Gomez-Diaz, M. Tymchenko, J. Lee, M. Belkin, A. Alù., *Phys. Rev. B* **92**, 125429 (2015)

Flatland Nonlinear Optics



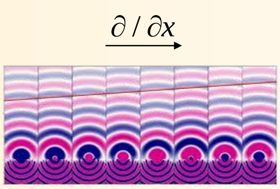
M. Tymchenko, J. S. Gomez-Diaz, M. Belkin, A. Alù., *Phys. Rev. Lett.* **115**, 207403 (2015)

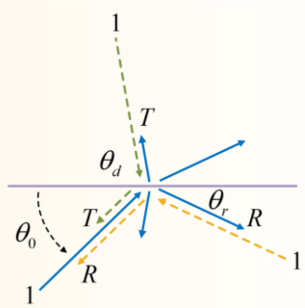
Experimental Results



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

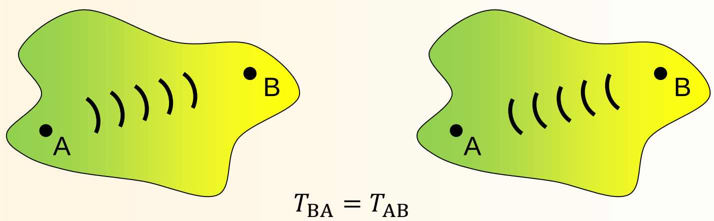




Y. Hadad, D. Sounas, and A. Alù, *Phys. Rev. B* **92**, 100304R (2015)
A. Shaltout, A. Kildishev, V. Shalaev, *Opt. Mat. Expr.* **5**, 2459 (2015)

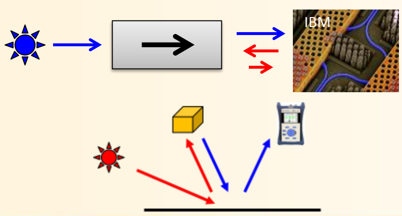
Lorentz Reciprocity and Time-Reversal Symmetry

Reciprocity: *symmetry in transmission for opposite propagation directions*

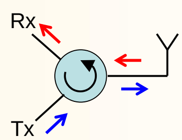


$$T_{\mathrm{BA}} = T_{\mathrm{AB}}$$

Isolators



Duplexers



Non-Reciprocity with Magnetic Materials

Lorentz reciprocity theorem

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

$$\bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}^{\mathrm{T}} \qquad \bar{\bar{\mu}} = \bar{\bar{\mu}}^{\mathrm{T}}$$

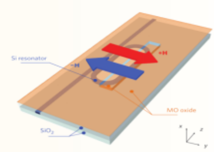
Time-invariant materials

Linear materials

Static Magnets

Weak Effect → Massive Devices

Difficult to integrate



Bi, Nature Photon. 5, 758

Breaking Reciprocity Constraints

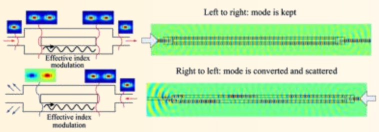
Lorentz reciprocity theorem

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

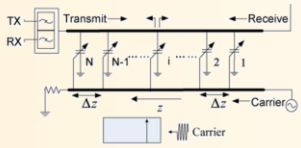
$$\bar{\bar{\varepsilon}} = \bar{\bar{\varepsilon}}^{\mathrm{T}}$$
$$\bar{\bar{\mu}} = \bar{\bar{\mu}}^{\mathrm{T}}$$

Time-invariant materials

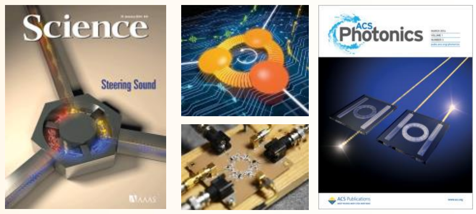
Linear materials



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

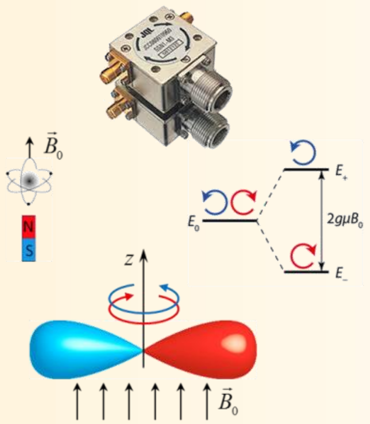


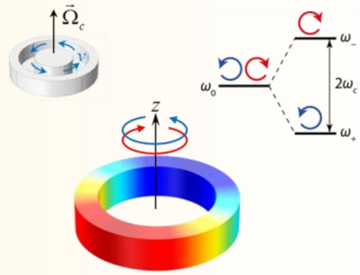
Qin, *IEEE TAP* **62**, 2260 (2014)



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)

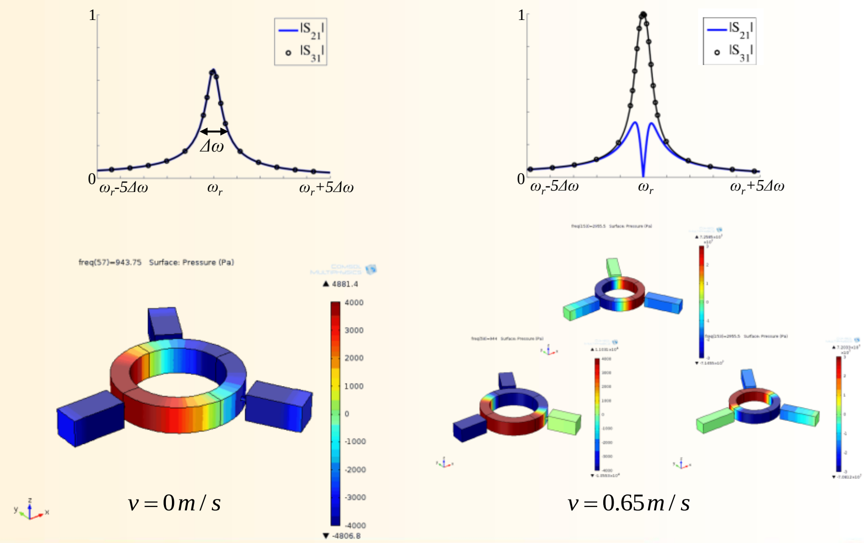
Angular-Momentum Biasing: a Zeeman Meta-Molecule





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

An Acoustic Circulator

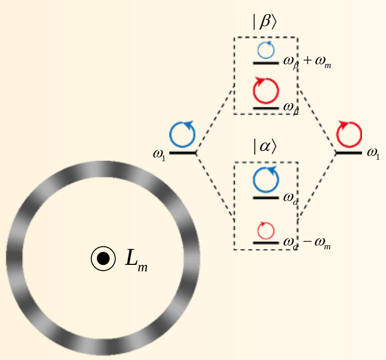


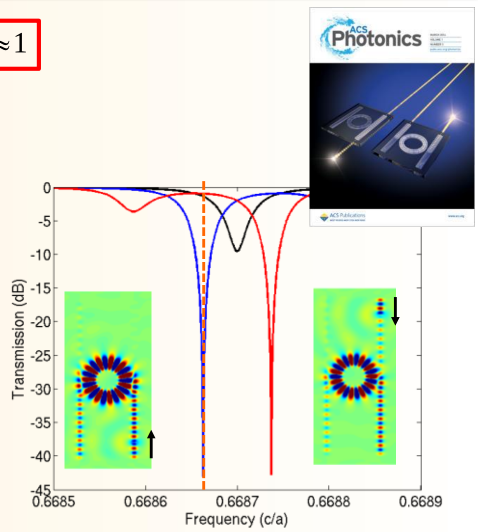
Angular-Momentum-Bias in Nanophotonics

$\Delta\varepsilon_m = 5\times10^{-4}\varepsilon$!

$Q \sim 7{,}000$

$Q\Delta\varepsilon_m \approx 1$

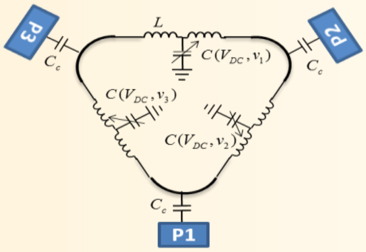


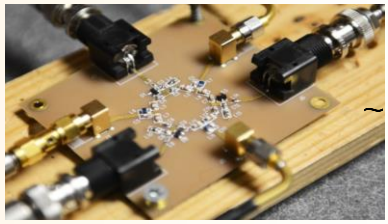


$$\Delta\varepsilon(\varphi,t) = \Delta\varepsilon_m \cos(\omega_m t - L_m\varphi)$$

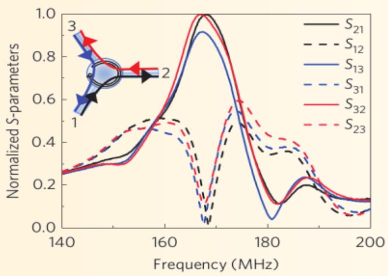
D. L. Sounas, A. Alù, *ACS Photonics* 1, 198 (2014)

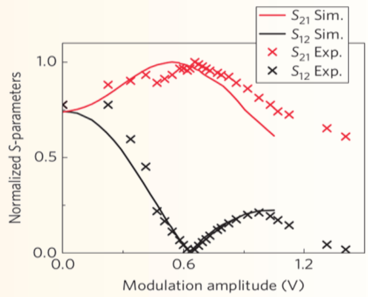
RF Magnet-Less Integrated Circulator





$\sim \lambda/70$

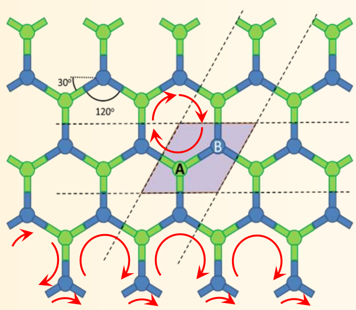




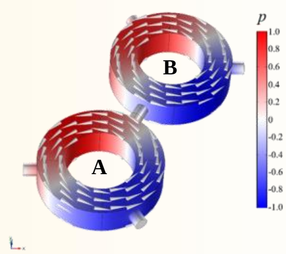
N. A. Estep*, D. L. Sounas*, J. Soric, and A. Alù, *Nature Phys.*, **10**, 923 (2014)

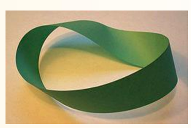
Molding the Topology of a Metamaterial

Lattice



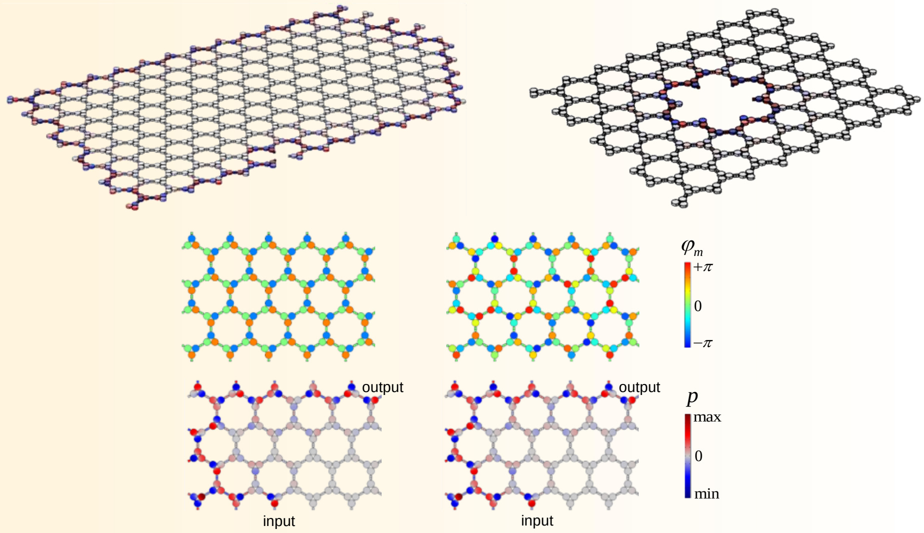
Unit Cell





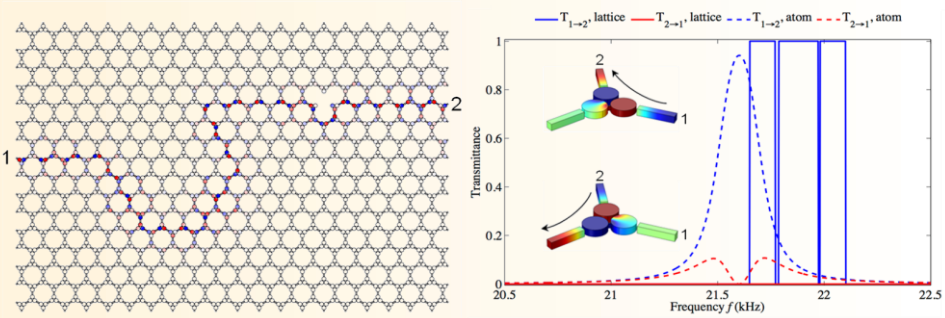
A. Khanikaev, R. Fleury, H. Mousavi, and A. Alù, *Nat. Comm.* **6**, 8260 (2015)

Floquet Topological Insulators for Light



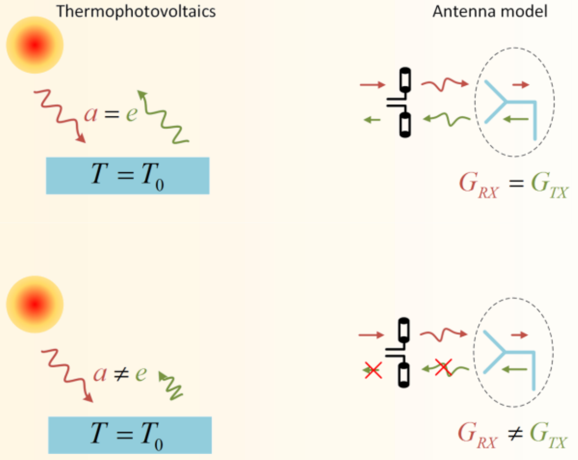
R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

Continuous Bandwidth of Isolation



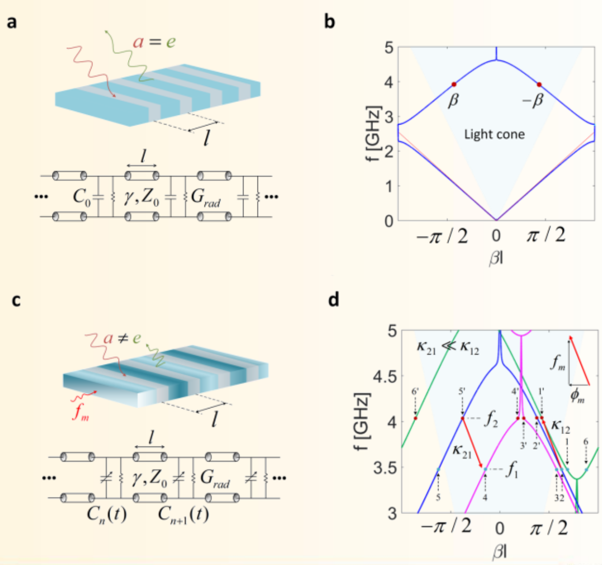
R. Fleury, A.B. Khanikaev and A. Alù,, *Nature Communications*, **7**, 11744 (2016)

Non-Reciprocal Emitters

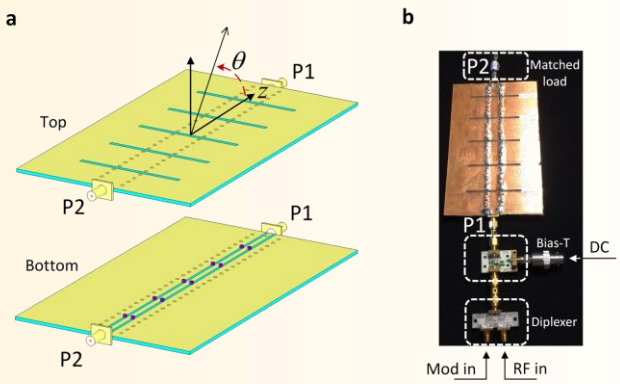


Y. Hadad, J. C. Soric, and A. Alù, *PNAS* **113**, 33471 (2016)

Non-Reciprocal Metasurfaces Based on ST Modulation

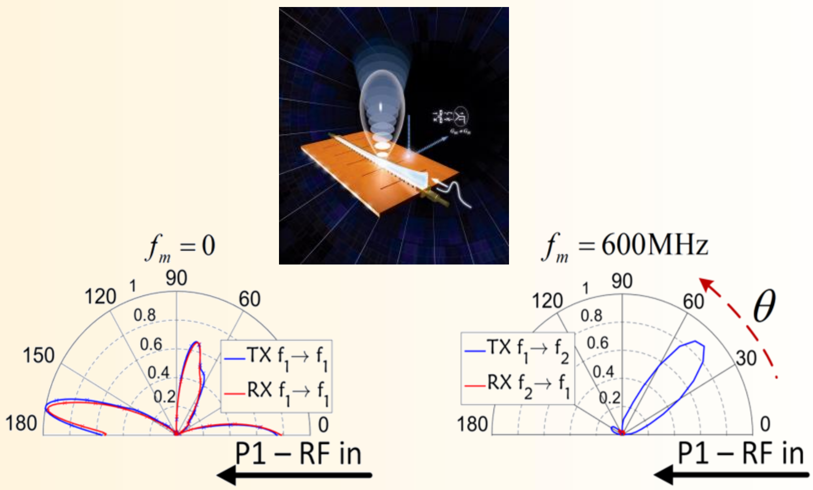


Non-Reciprocal Metasurfaces Based on ST Modulation



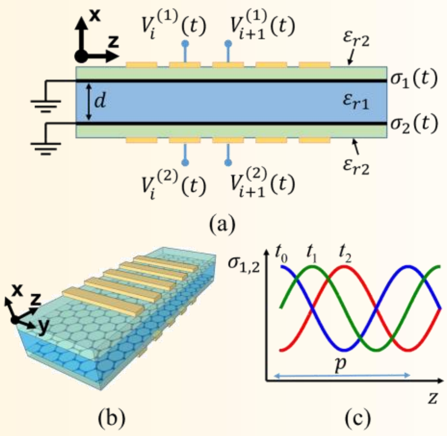
Y. Hadad, J. C. Soric, and A. Alù, *PNAS* **113**, 33471 (2016)

Non-Reciprocal Metasurfaces Based on ST Modulation



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

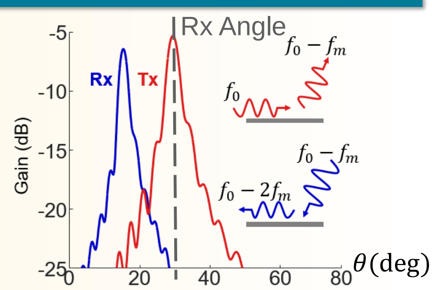
Non-Reciprocal Metasurfaces Based on ST Modulation

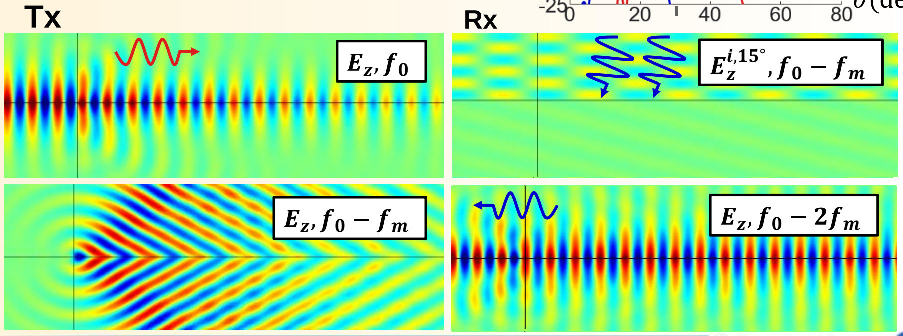


D. Correas-Serrano, J. S. Gomez-Diaz, D. L. Sounas, Y. Hadad, A. Alvarez-Melcon, and A. Alù, *IEEE AWPL* (2016)

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

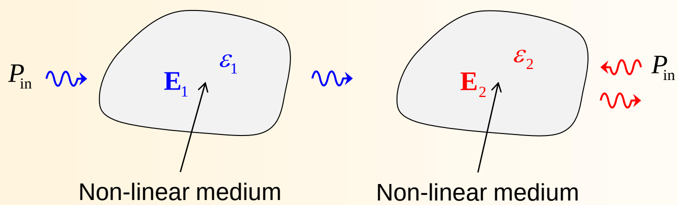
Lorentz reciprocity theorem

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

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

Time-invariant materials

Linear materials

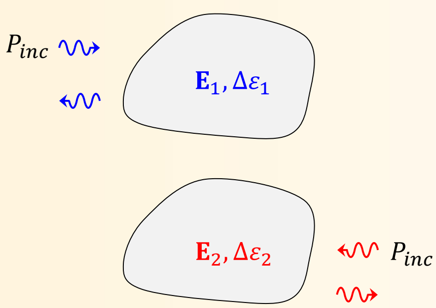


Chi-3 non-linearity

$$\Delta\varepsilon_{\text{NL}} = \chi^{(3)}|\mathbf{E}|^2$$

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)

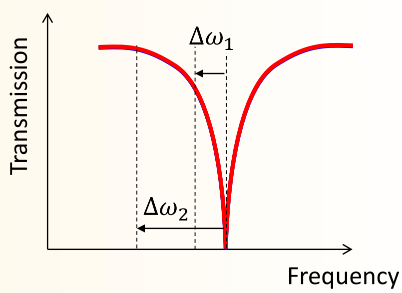
Basic Operation – Single Resonance



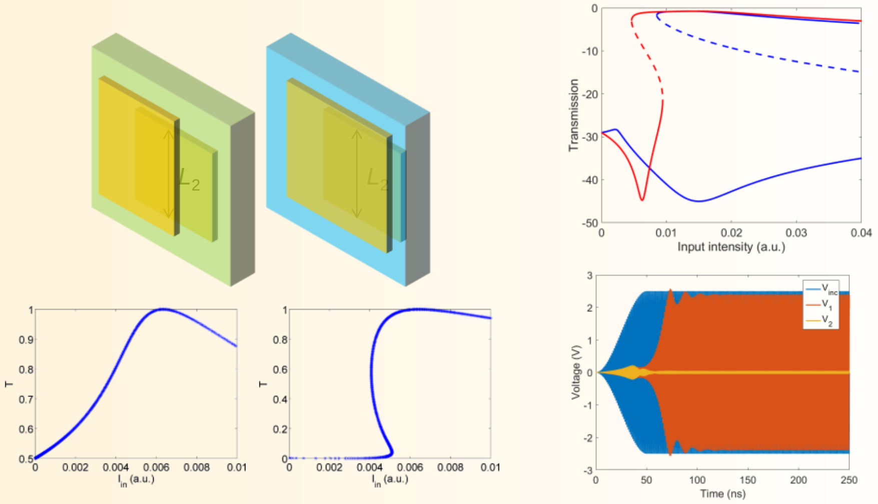
$$\varepsilon_{NL} = \varepsilon + \chi^{(3)}|\boldsymbol{E}|^2$$

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

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

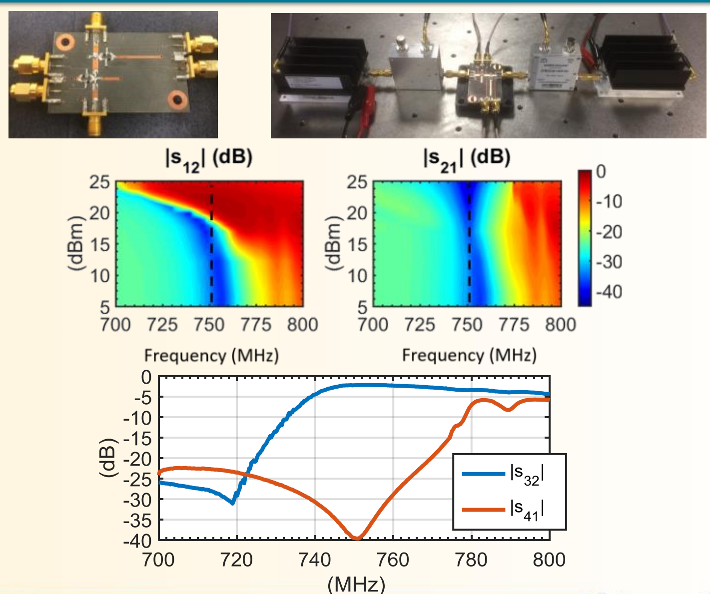


Ideal Isolator Based on Two Non-Linear Resonators

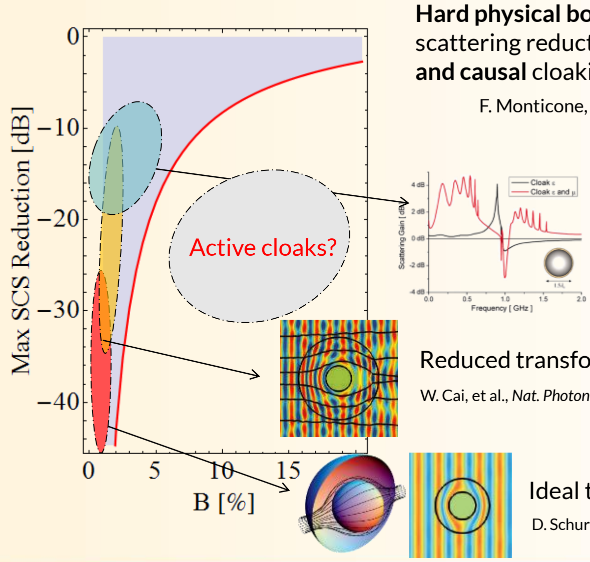


D. L. Sounas, J. Soric, and A. Alù, *in preparation* (2016)

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)

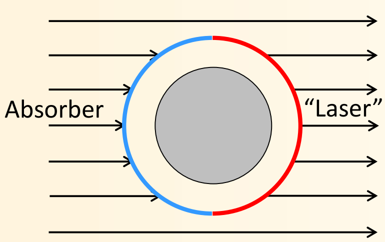
Reduced transformation-optics cloaks

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

Ideal transformation-optics cloaks

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

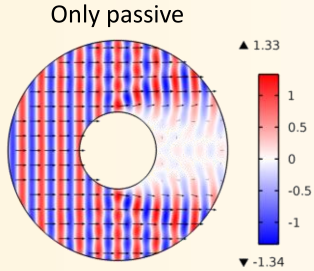
CLOAKING WITH BALANCED LOSS AND GAIN



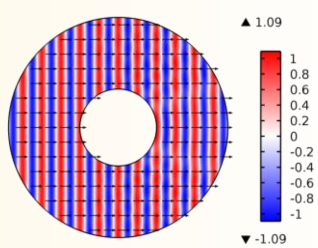
$$\mathrm{Re}\{Y_s\} = \begin{cases} Y_0 |\cos\varphi|, & \text{left side} \\ -Y_0 |\cos\varphi|, & \text{right side} \end{cases}$$

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

Only passive

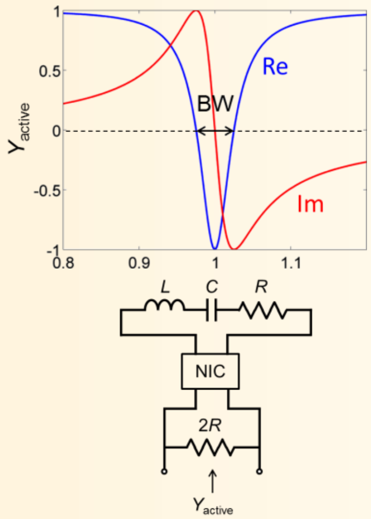


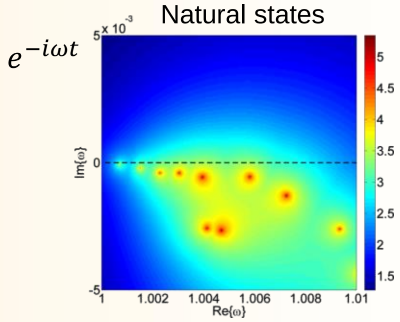
Passive + active

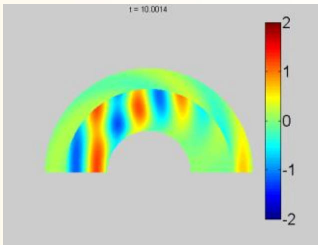


D. L. Sounas, R. Fleury, and A. Alù, *Phys. Rev. Appl.* 4, 014005 (2015)

Stability Considerations

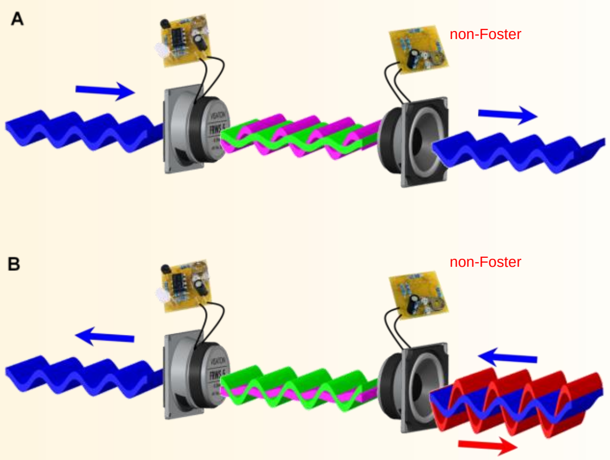






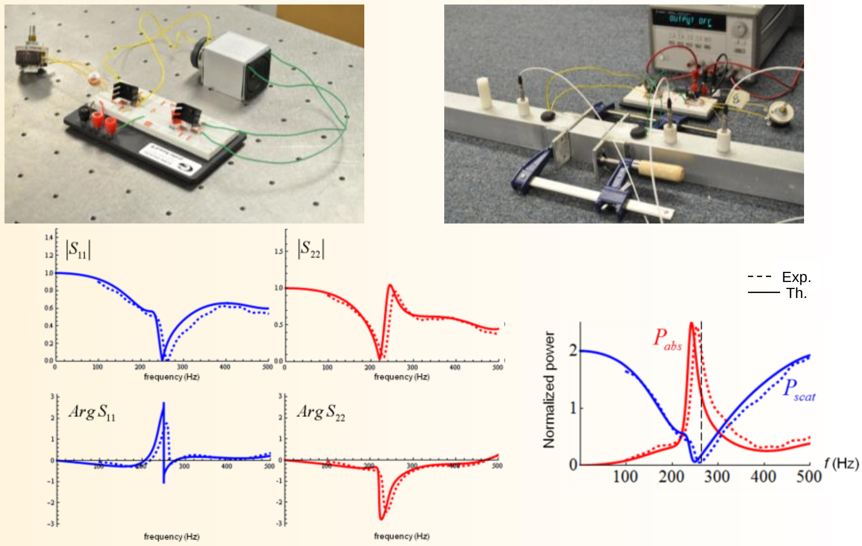
D. L. Sounas, R. Fleury, A. Alù, *IEEE JSTQE* **22**, 5000809 (2016)

A Cloaked Acoustic Sensor: PT-Symmetry



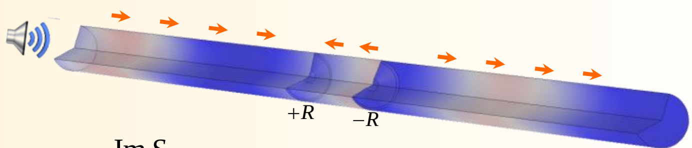
R. Fleury, D. L. Sounas, and A. Alù, *Nat. Commun.* **6**, 5905 (2015)

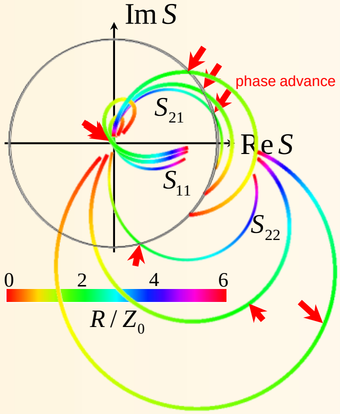
A PT-Symmetric Acoustic Sensor



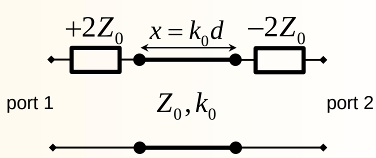
R. Fleury, D. L. Sounas, and A. Alù, *Nat. Commun.* **6**, 5905 (2015)

Loss-Free Negative Refraction

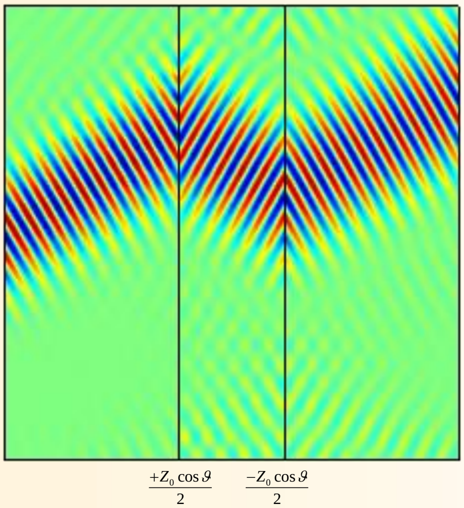


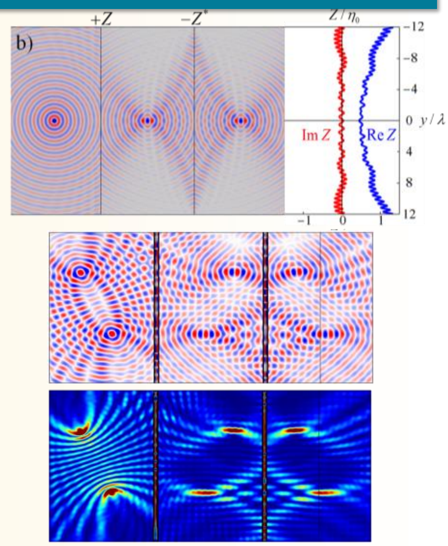


$$S = \begin{pmatrix} 0 & e^{jx} \\ e^{jx} & 2 - 2e^{2jx} \end{pmatrix}$$



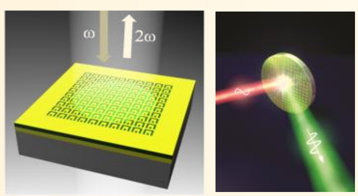
Negative Refraction and Focusing



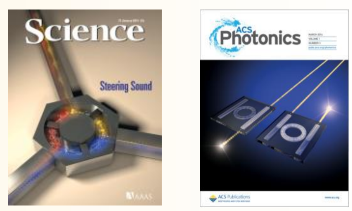


R. Fleury, D. Sounas, and A. Alù, *Phys. Rev. Lett.* **113**, 023903 (2014)
F. Monticone, C. Valagiannopoulos, A. Alù, *J. Opt.* **18**, 044028 (2015); *Phys. Rev. X* in press (2016)

A Bright Future for Metamaterials

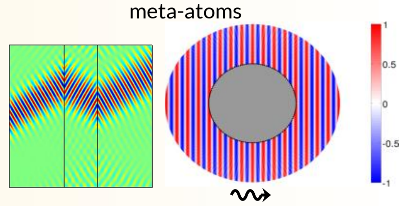


Giant nonlinearities in hybrid metasurfaces



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