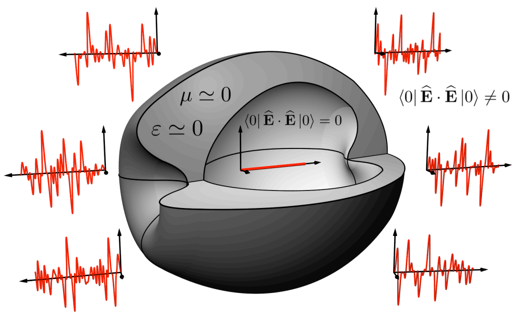
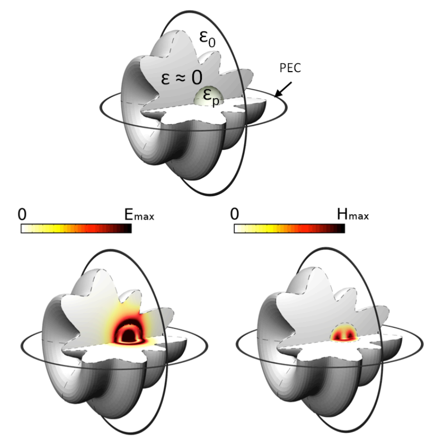
Extreme Platforms for Extreme Photonics





Nader Engheta

With special thanks to

Brian Edwards

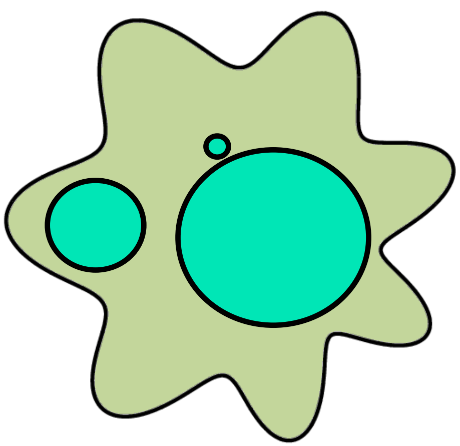
Inigo Liberal

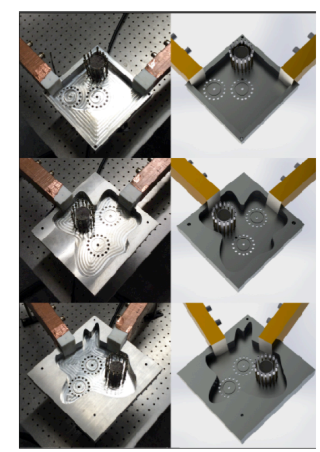
Nasim Mohammadi Estakhri

Ahmed Mahmoud

Yue Li

Yaakov Lumer

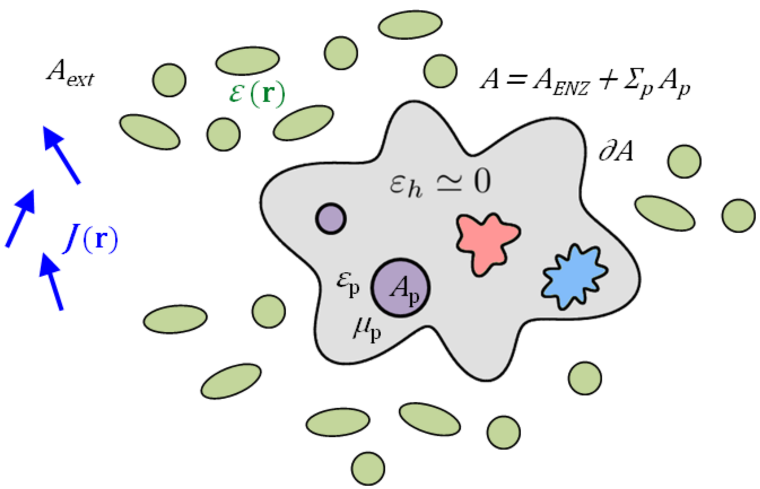




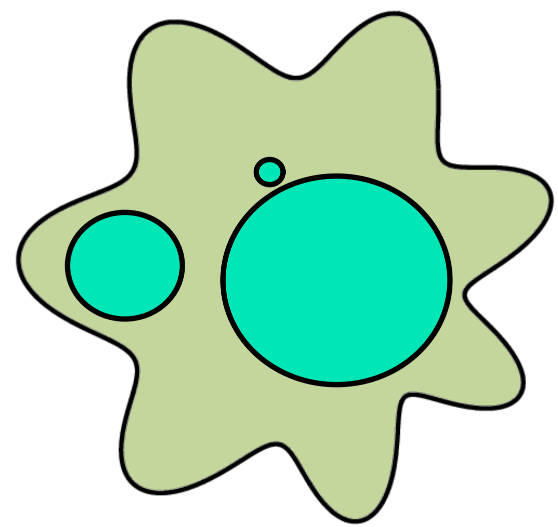
June 6, 2017

Extreme Photonics - 1

Photonic Doping



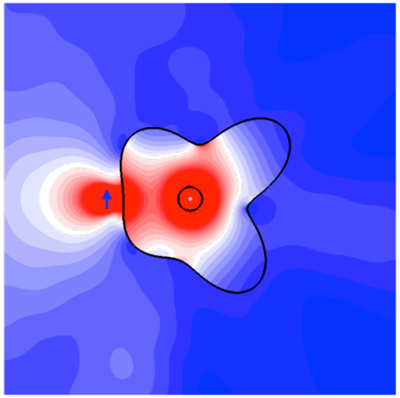
Peculiar Effective Medium Properties



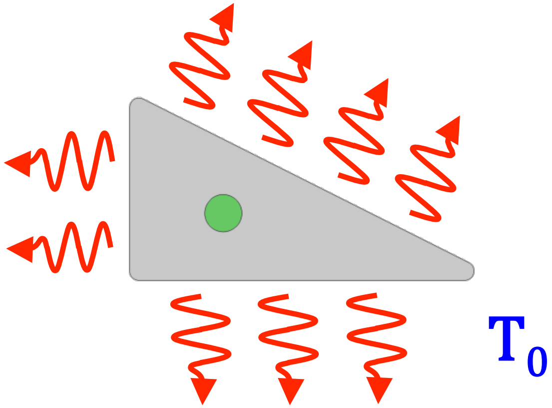
Liberal, Mahmoud, Li, Edwards, Engheta, Science, 2017

Thermal Engineering with Zero-Index Media

Photonic Doping



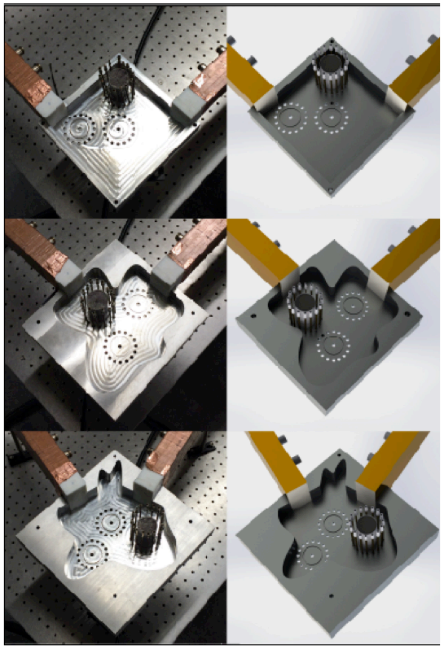
Engineering Thermal Emission



Liberal & Engheta, CLEO Conference, May 15, 2017

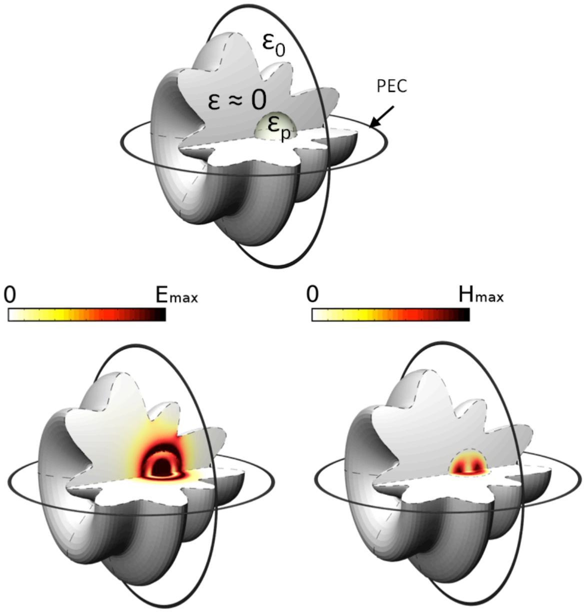
Extreme Resonant Cavities

Geometry-Independent Cavities



Liberal, Mahmoud, Li, Edwards, Engheta, Science, 2017

Bound State in the Continuum



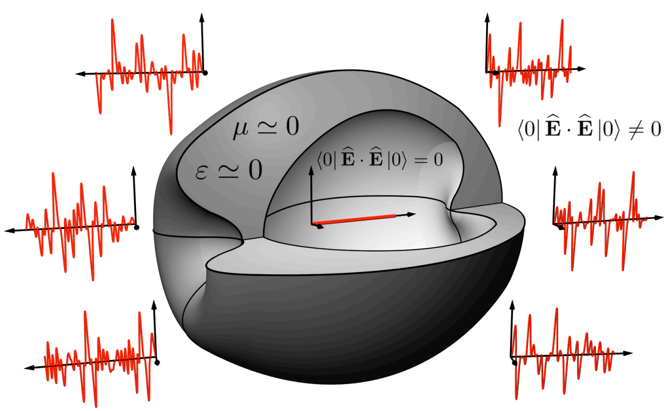
Liberal and Engheta, Nature Photonics, March 2017

Mahmoud, Liberal and Engheta, Nature Communications, 2016

Extreme Photonics - 4

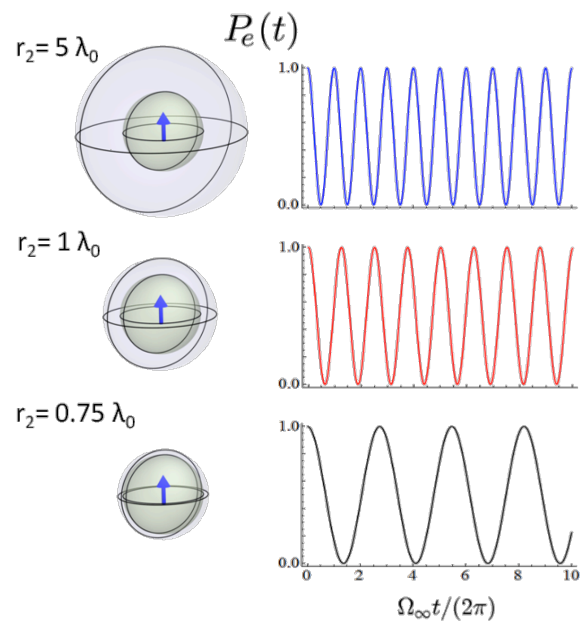
Quantum Optics of ZIM

Extreme Quantum Optics



Liberal and Engheta, PNAS, 2017

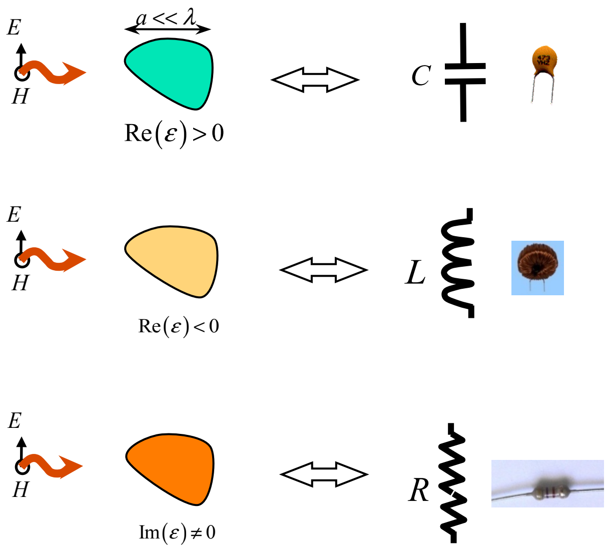
Engineering Rabii Frequencies without detuning



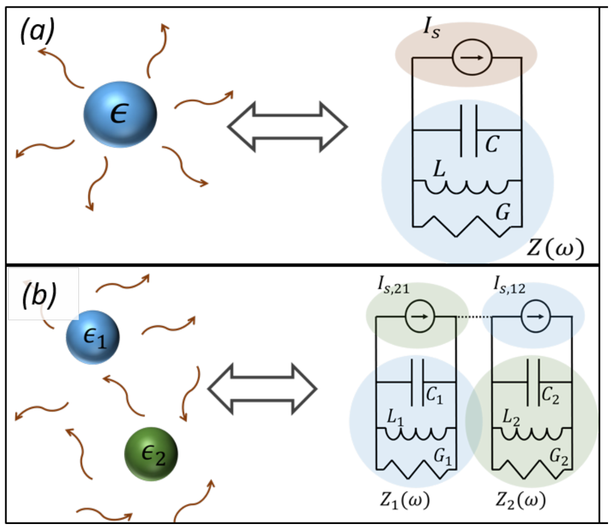
Liberal and Engheta, PNAS, 2017

Optical Metatronics

Optical Metatronics



Quantum Metatronics

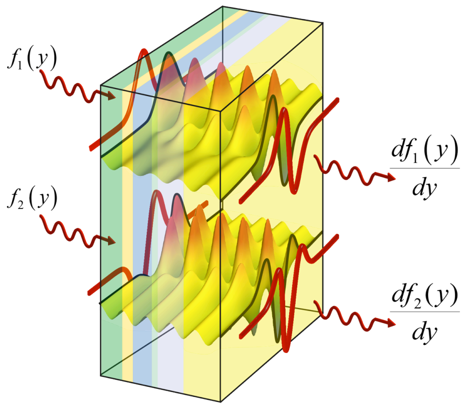


N. Engheta, et al. PRL, 2005
N. Engheta, Science, 2007

Lumer, Liberal and Engheta, CLEO Conference, May 16, 2017

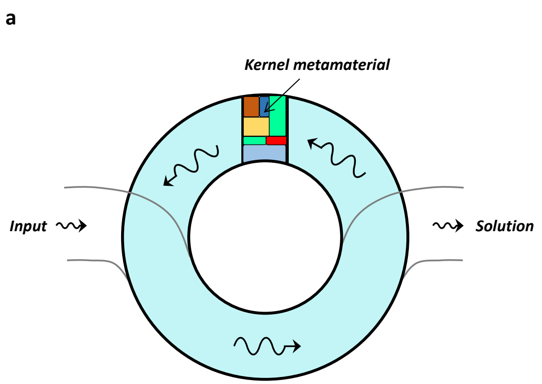
Extreme Platforms for Mathematical Operations

Informatic Metastructures



Silva, Monticone, Castaldi, Galdi, Alu, Engheta, Science, 2014

Metastructures to Solve Equations with Waves

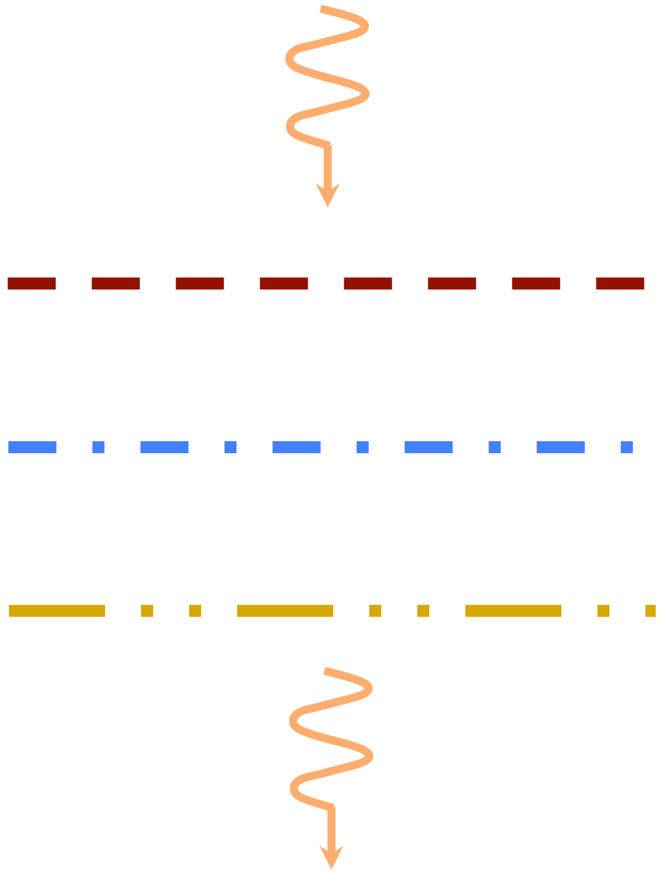


N. Mohammadi Estakhri, B. Edwards, N. Engheta
CLEO Conference, May 18, 2017

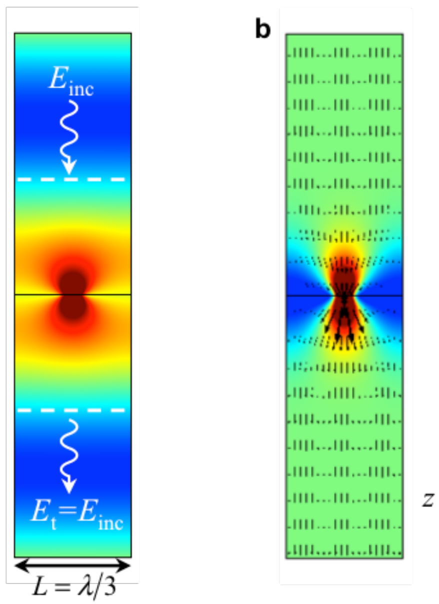
B. Edwards, N. Mohammadi Estakhri, N. Engheta
MRS Spring Meeting, April 11, 2017

Extreme Metasurfaces

Cascaded Metasurfaces



Transparent Metasurfaces with Prescribed Aperture Fields

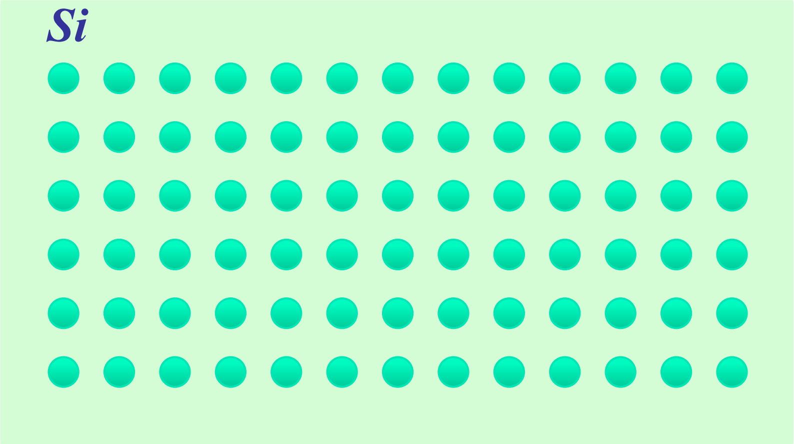


Mohammadi Estakhri, Kastner, Engheta,
IEEE AP-S Symposium, San Diego, July 2017

Photonic Doping

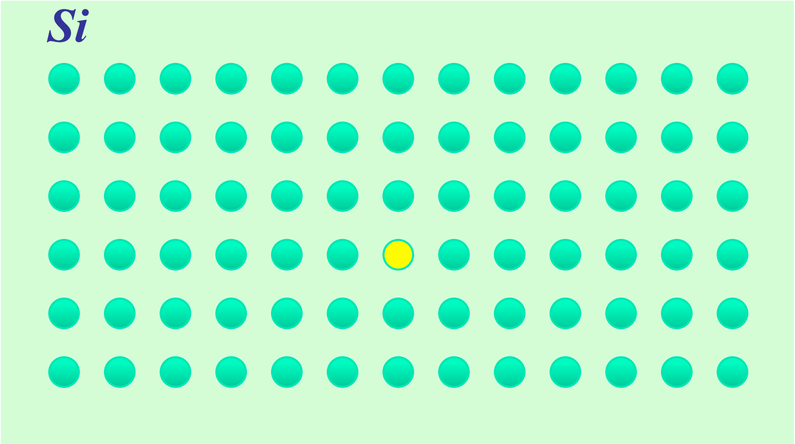
Liberal, Mahmoud, Li, Edwards, Engheta, Science, 355, 1058-1062, March 10, 2017

Background: Electronic Doping



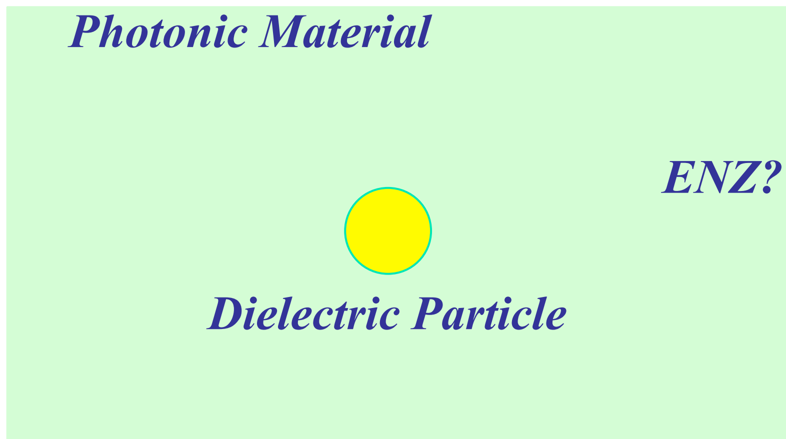
Pure Intrinsic Semiconductor

Background: Electronic Doping



Doped Semiconductor

How about "photonic doping"?

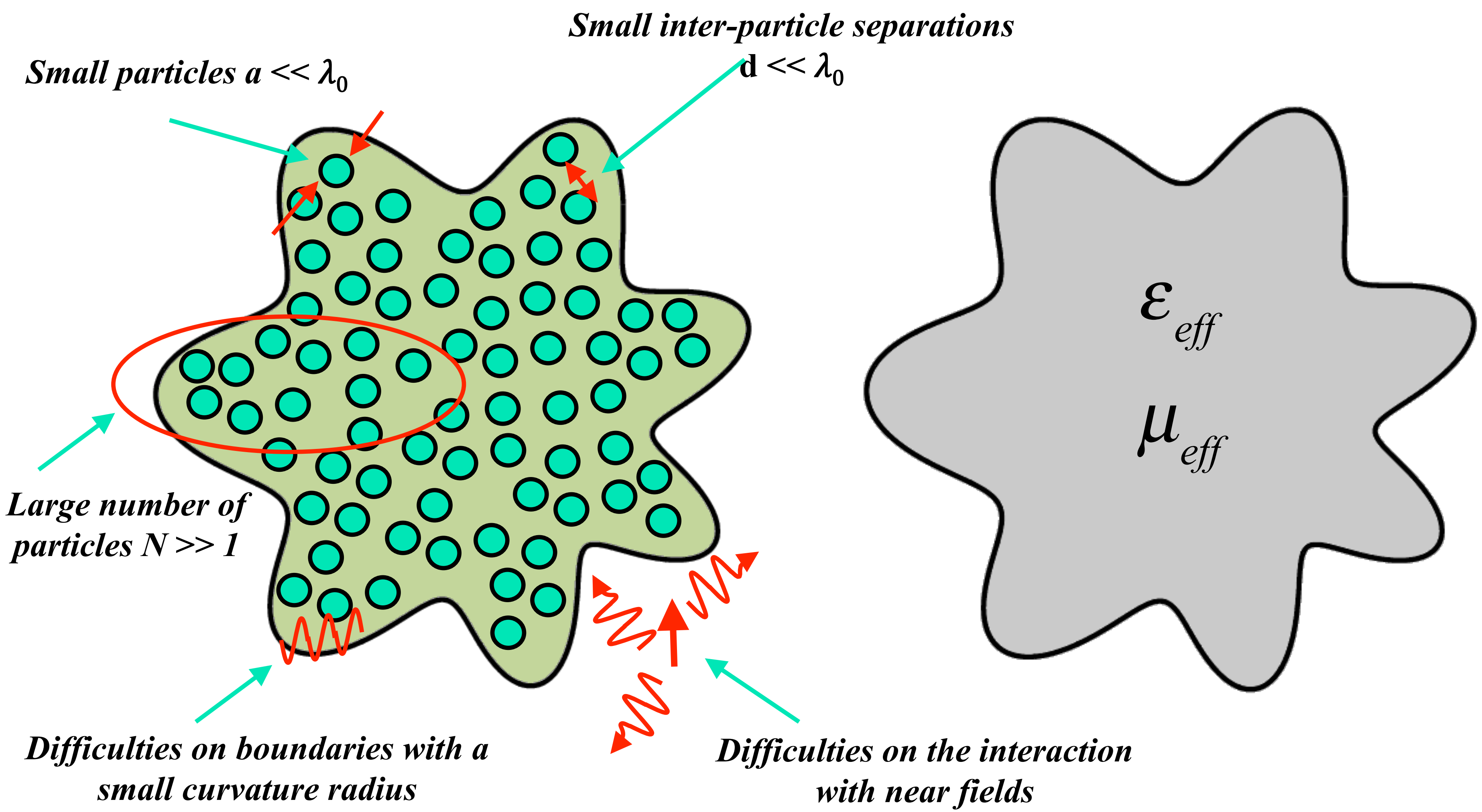


"Pure" Photonic Material

I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

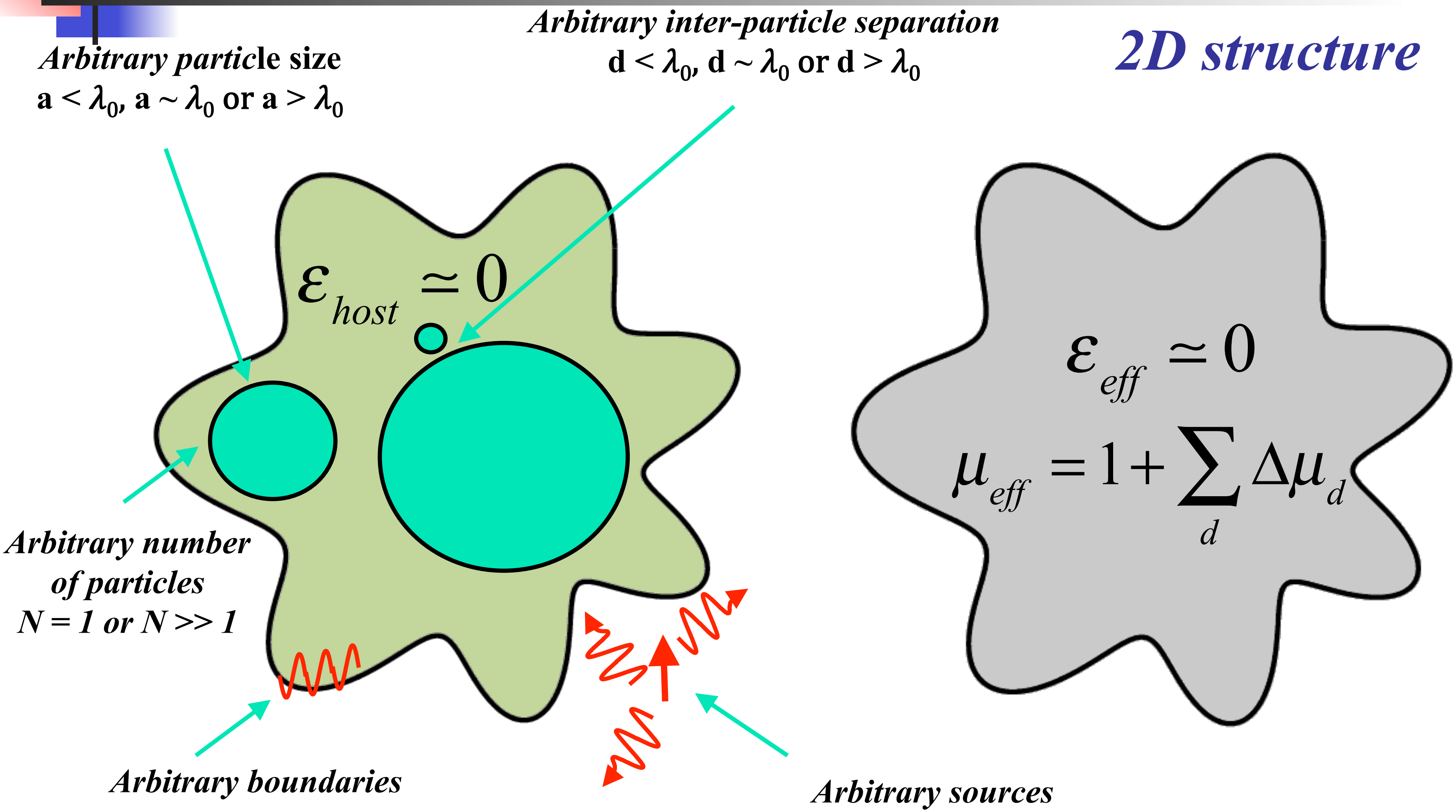
Conventional Effective Medium Theory (EMT)

2D structure



What if the host is an ENZ medium?

2D structure



I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

Background on Epsilon-Near-Zero (ENZ)

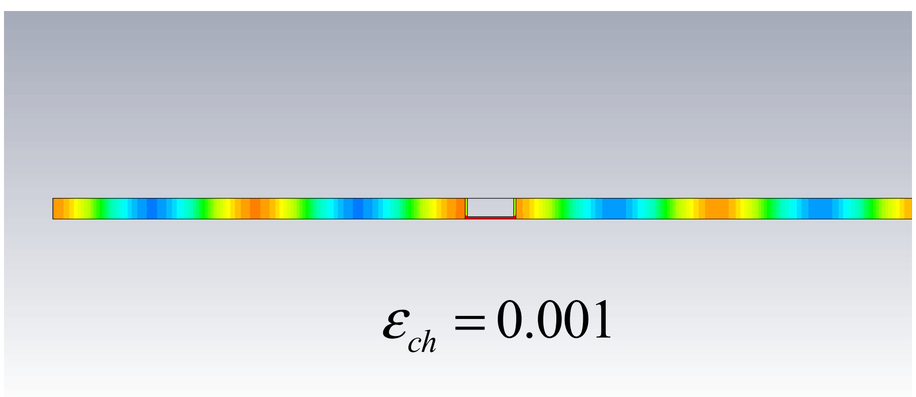
PRL **97,** 157403 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

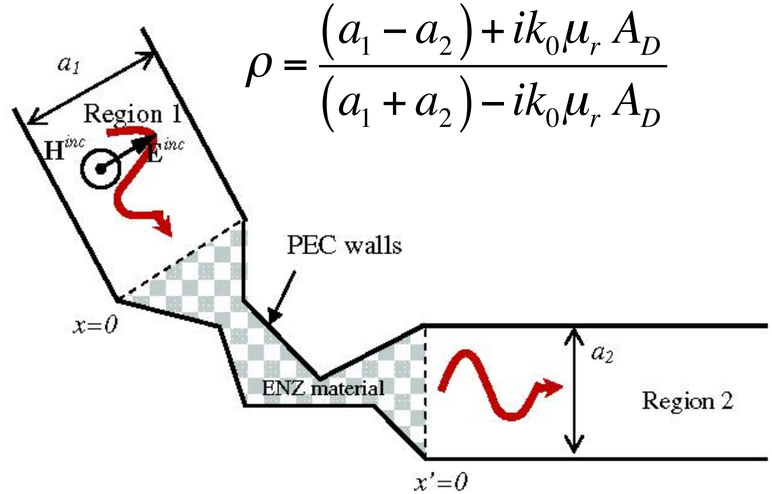
Tunneling of Electromagnetic Energy through Subwavelength Channels and Bends using ε-Near-Zero Materials

Mário Silveirinha* and Nader Engheta†

Department of Electrical and Systems Engineering, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA

(Received 23 March 2006; published 10 October 2006)

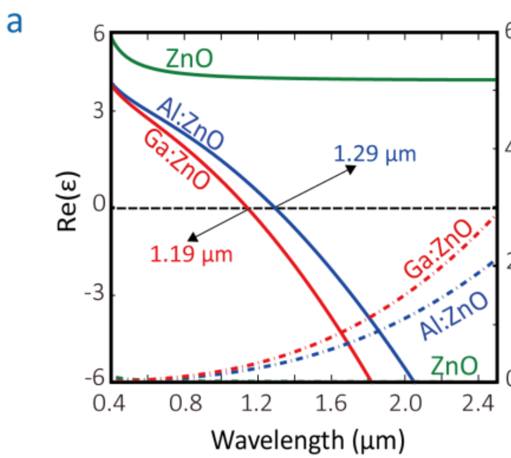




$$\rho = \frac{(a_1 - a_2) + ik_0\mu_r A_D}{(a_1 + a_2) - ik_0\mu_r A_D}$$

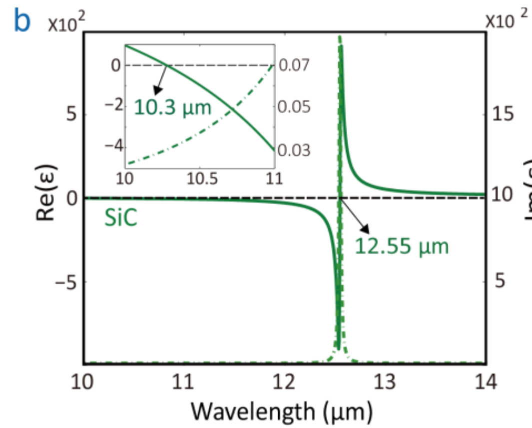
Background: ENZ Structures

TCO



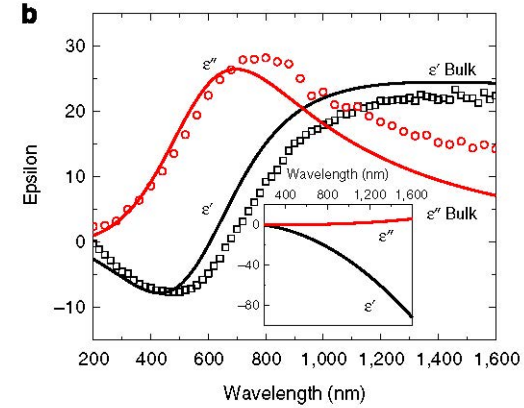
From : *A. Boltasseva (Purdue)*
Kim, et al., Optica (2016)

SiC

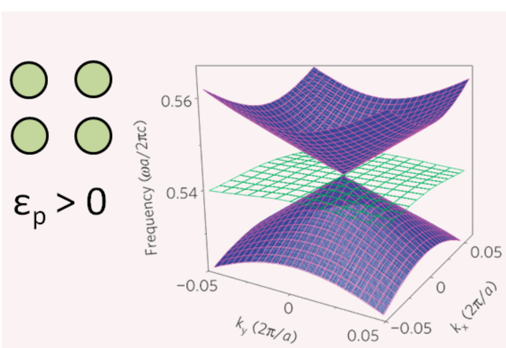


From : *J. Caldwell (NRL)*
Kim, et al., Optica (2016)

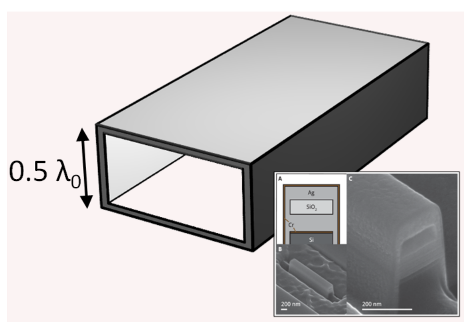
$Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$



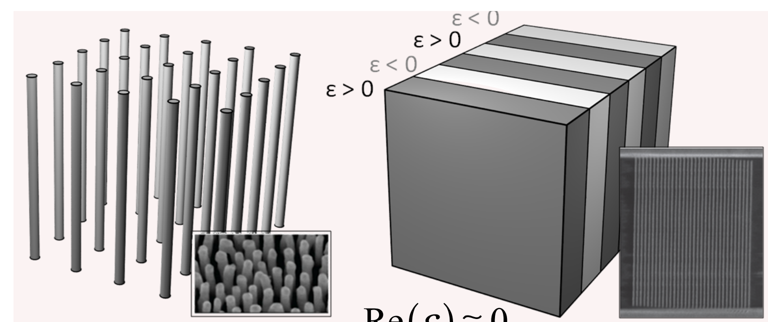
From : *N. Zheludev (Southmapton)*
Ou et al., Nat. Commun. (2014)



From : CT Chan's
Huang, et al., Nat. Mater. (2011)



SEM from :
Vesseur, et al., PRL (2013)



Wire SEM from : Zayat & Podolskiy
Pollard, et al., PRL (2009)
Stack SEM from :
Mass, et al., Nat. Photon. (2013)

Background: One of ENZ Properties

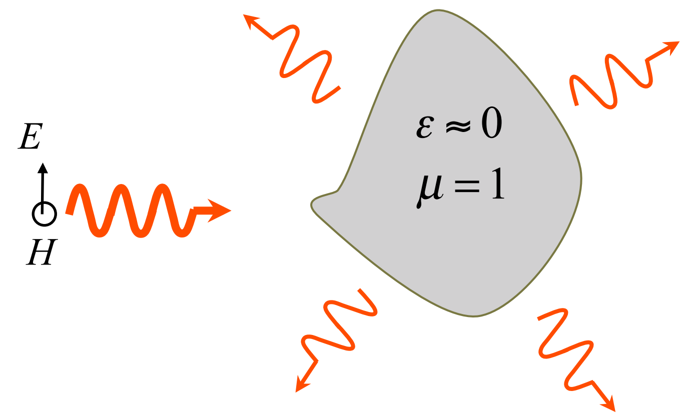
- ***Maxwell Equations*** $\nabla \times \boldsymbol{H} = -i\omega\varepsilon \boldsymbol{E}$ → $\nabla \times \boldsymbol{H} = 0$

  $\nabla \times \boldsymbol{E} = i\omega\mu \boldsymbol{H}$

- ***2-D Scenario with TM polarization***

$$\mathbf{H} = H(x, y)\ \hat{\mathbf{u}}_z$$

$$\mathbf{E} = \frac{1}{-i\omega\varepsilon} \nabla H(x, y) \times \hat{\mathbf{u}}$$

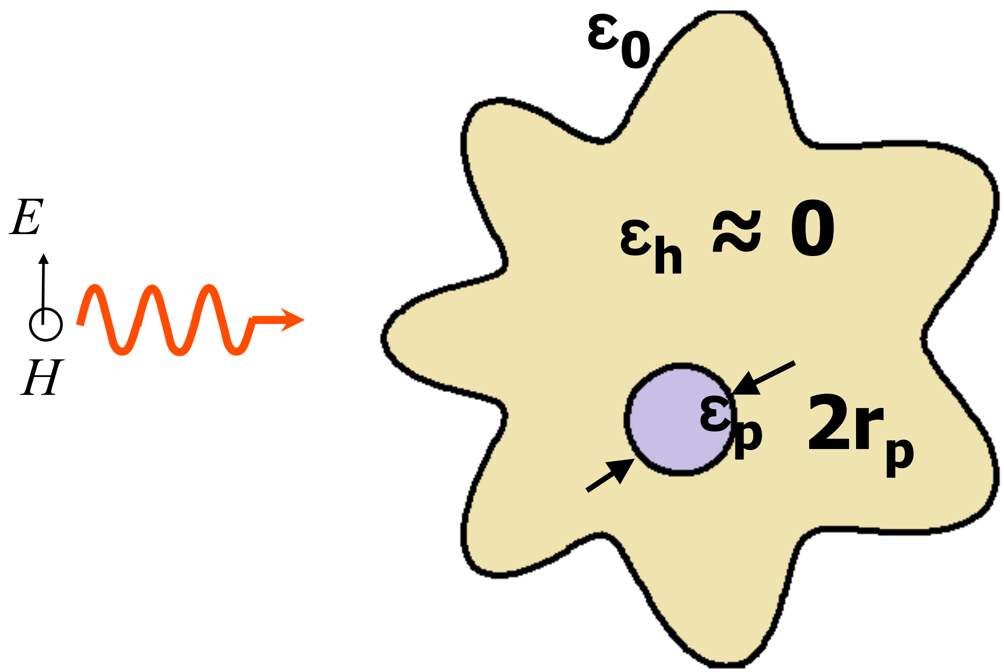


R. W. Ziolkowski, PRE, (2004)

N. Engheta, Science, 340, 286 (2013)

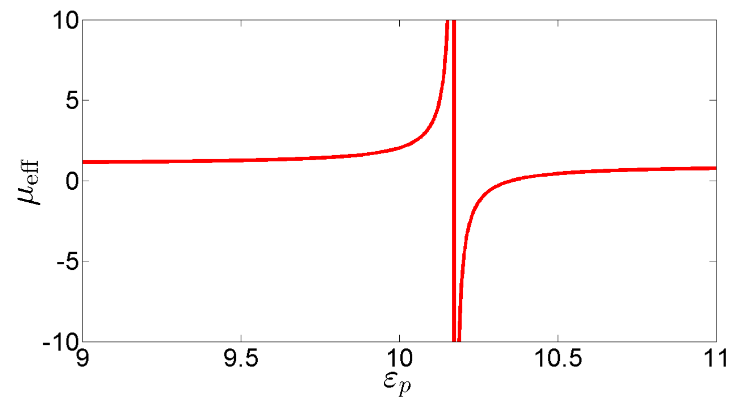
M. Silveirinha & N. Engheta, PRL, (2006)

Photonic "Doping"



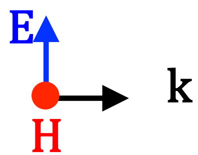
$$\varepsilon_{\text{eff}} \simeq 0$$

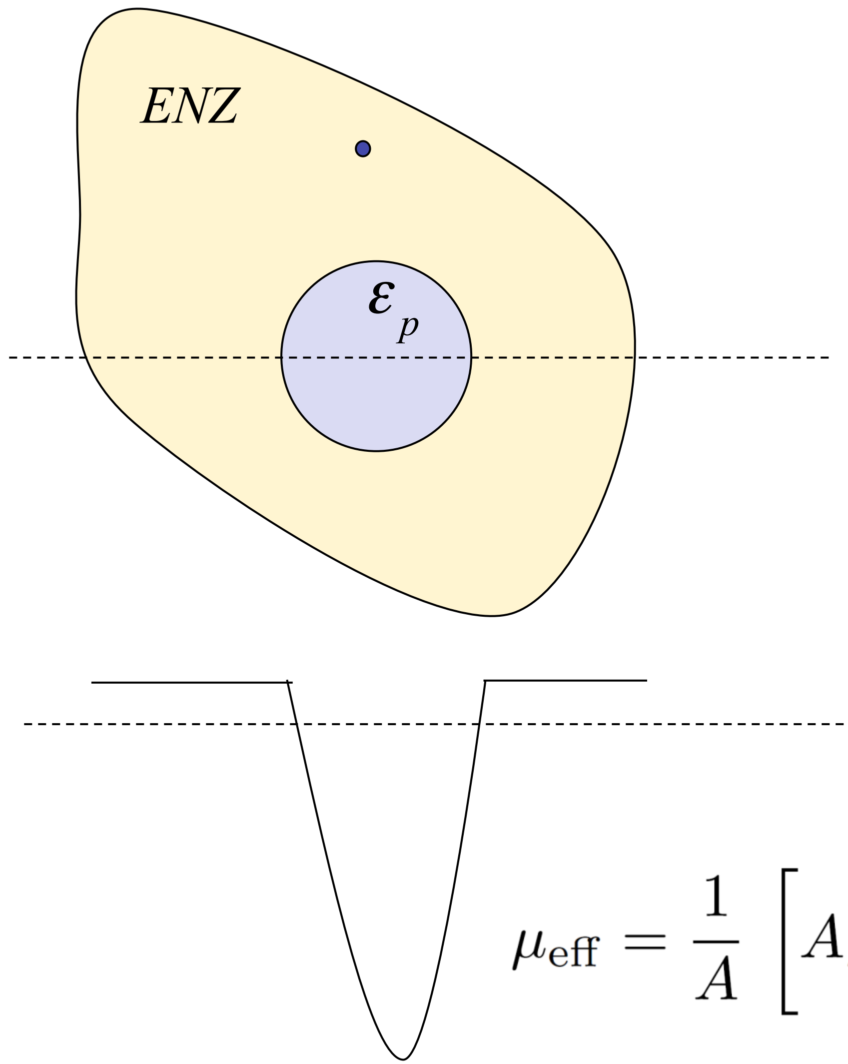
$$\mu_{\text{eff}} = \frac{1}{A}\left[A_h + \frac{2\pi r_p}{k_p}\frac{J_1\left(k_p r_p\right)}{J_0\left(k_p r_p\right)}\right]$$



I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

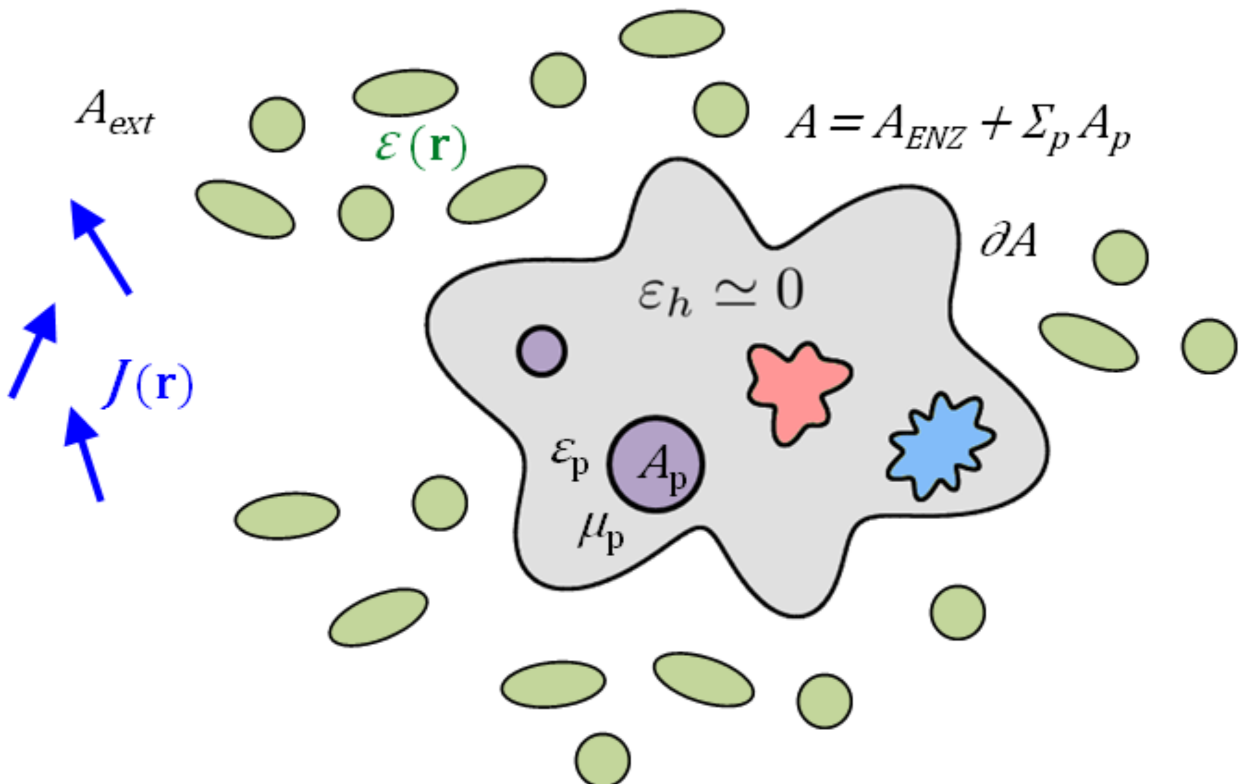
Physical Explanation





$$\mu_{\text{eff}} = \frac{1}{A}\left[A_h + \frac{2\pi r_p}{k_p}\frac{J_1\left(k_p r_p\right)}{J_0\left(k_p r_p\right)}\right]$$

Photonic "Doping"
2D Generic Structures

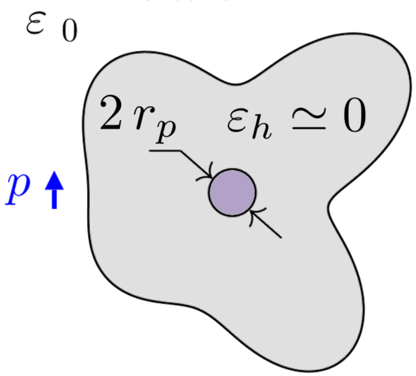


$$\varepsilon_{eff} \simeq 0 \qquad \mu_{eff} = 1 + \sum_d \Delta\mu_d \qquad \Delta\mu_d = \frac{1}{A}\left[\int_{A_d} \psi^d(\mathbf{r})\, dA - A_d\right]$$

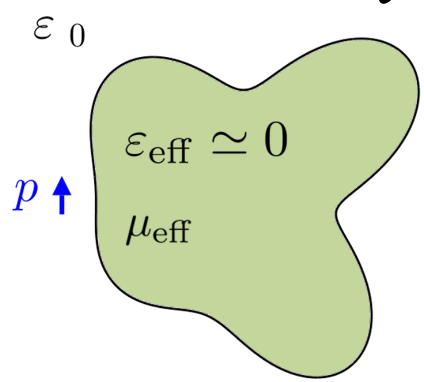
I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

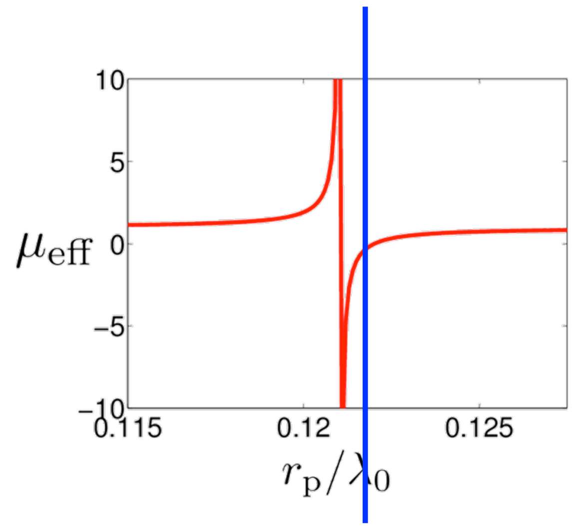
Example 1: EMNZ $\mu_{eff} = 0$

Rod in ENZ



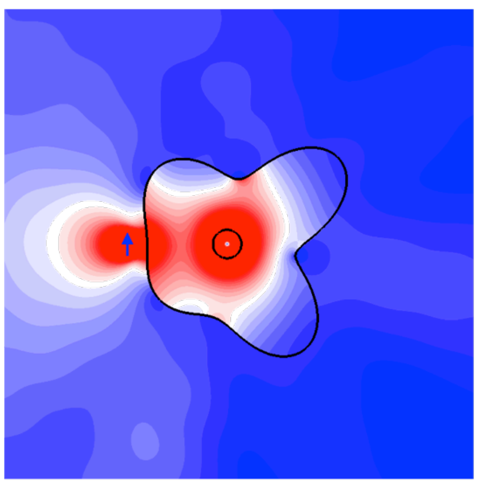
EMNZ Body

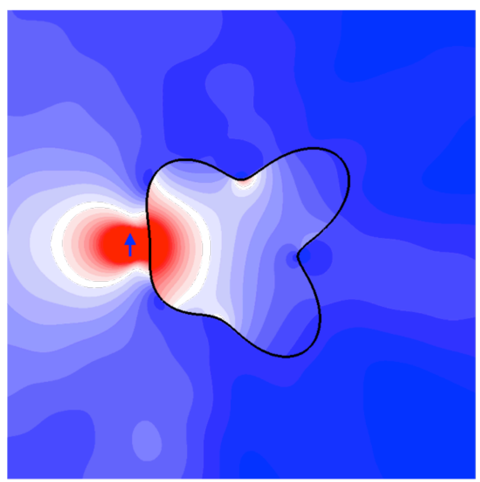


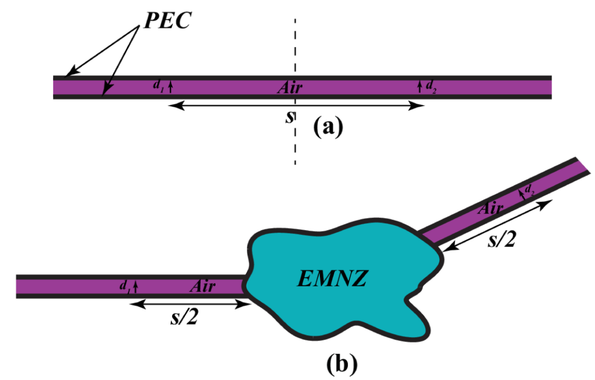


$\varepsilon_{eff} = 0$ $\mu_{eff} = 0$

EMNZ



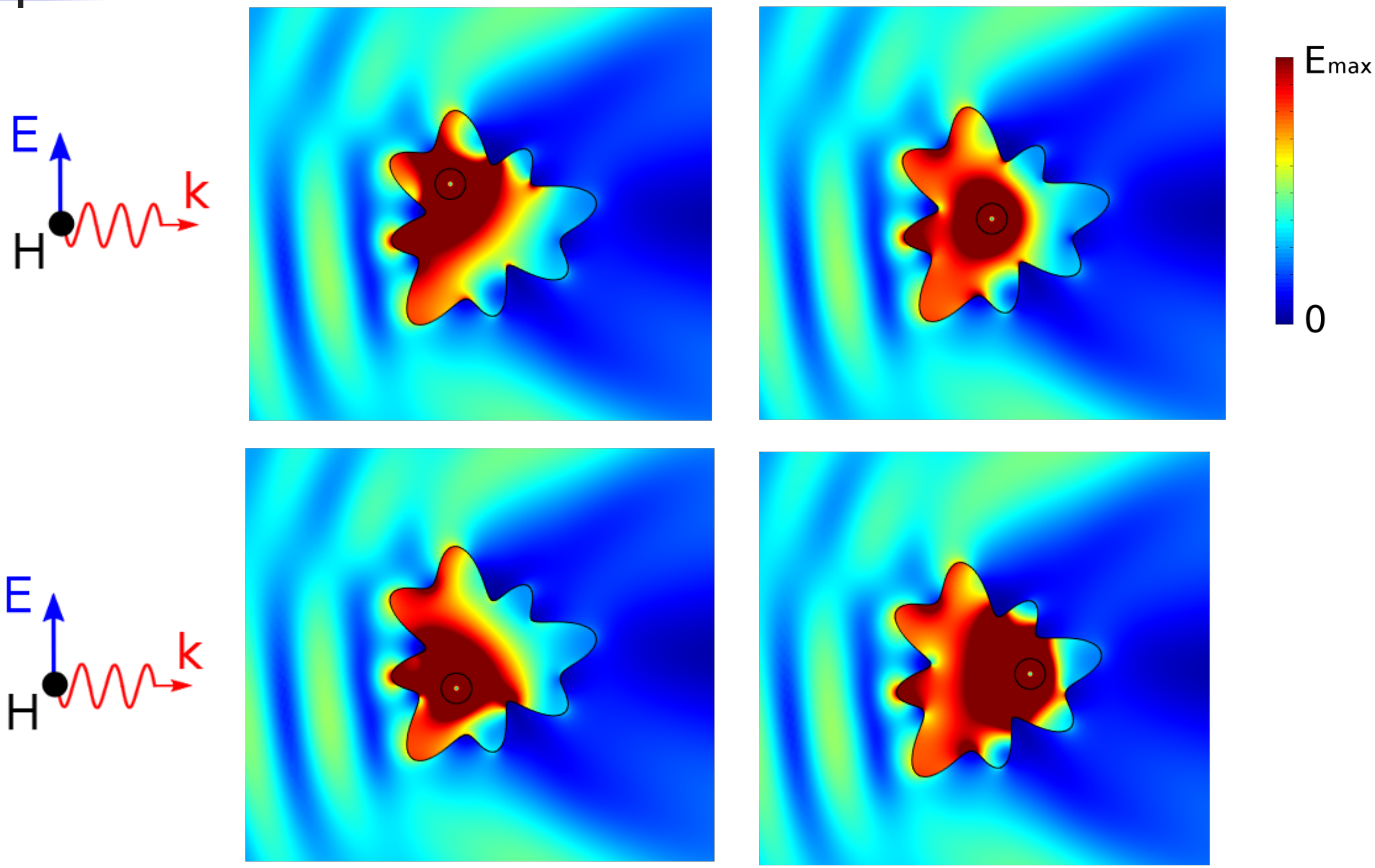




Mahmoud, Liberal & Engheta
Optical Materials Express, Feb 2017

I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

Rod Position Independence



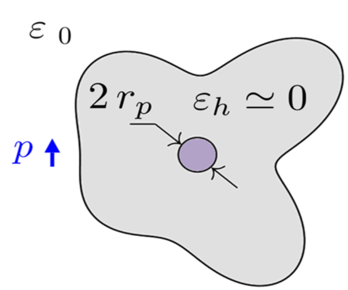
I. Liberal, Y. Li, A. Mahmoud, B. Edwards and N. Engheta, Science, March 10, 2017

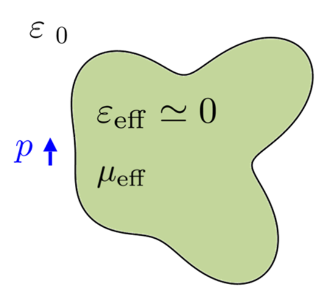
Example 2: PMC $\mu_{eff} = \infty$

Rod in ENZ

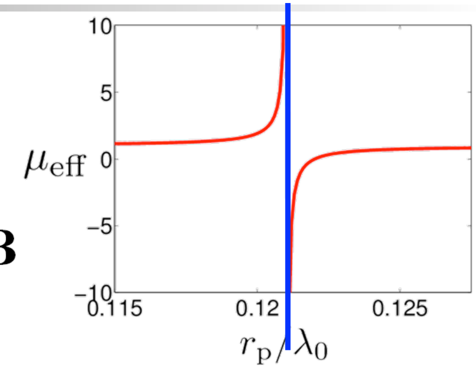
PMC Body

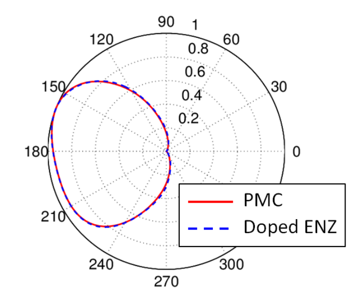
A



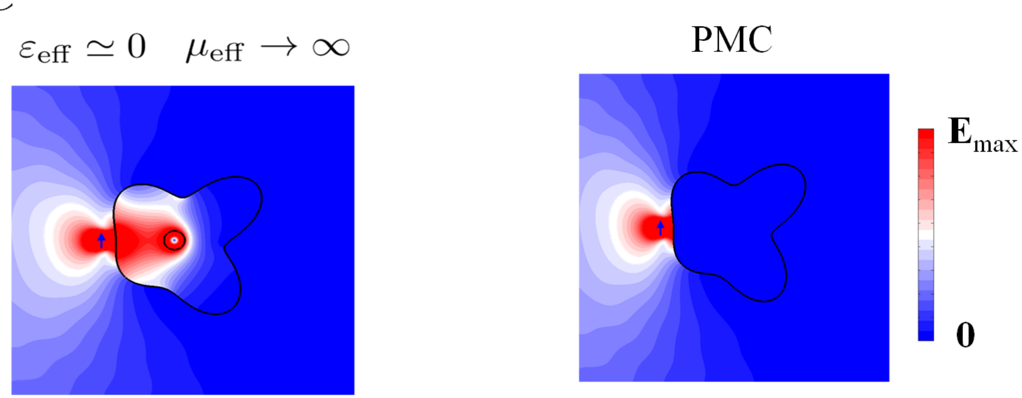


B



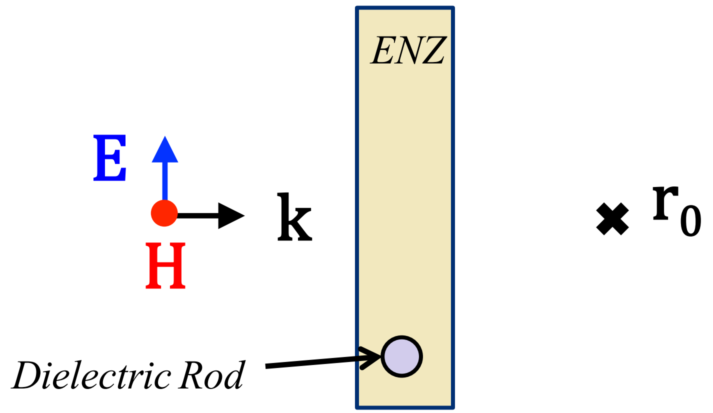


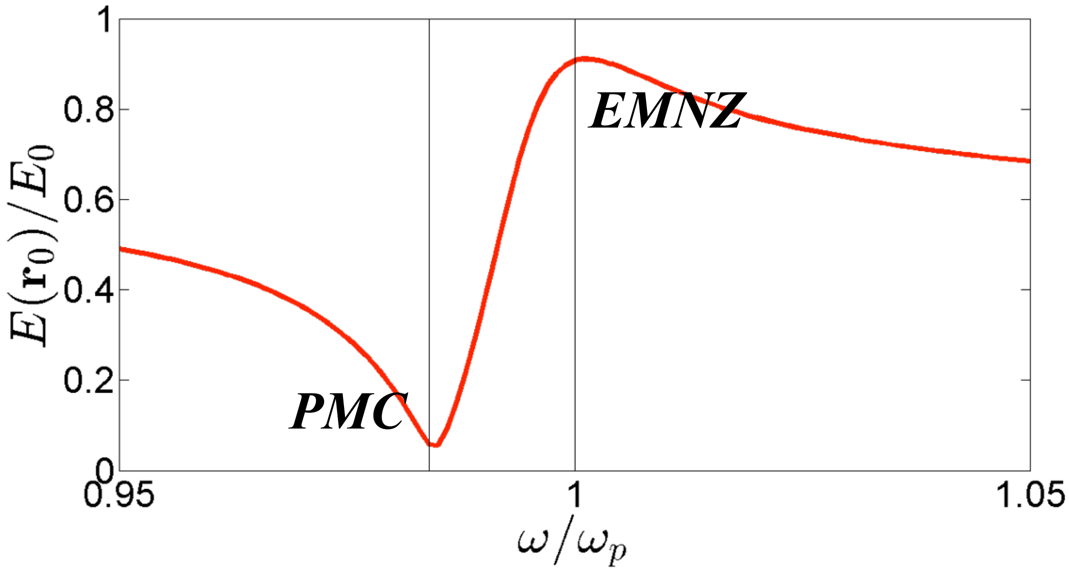
C



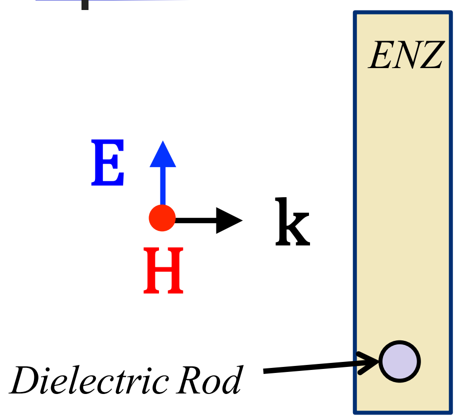
I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

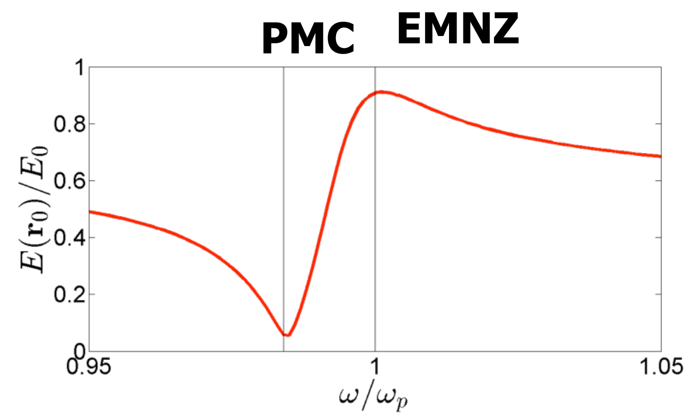
Example 3: Single ENZ 2D slab



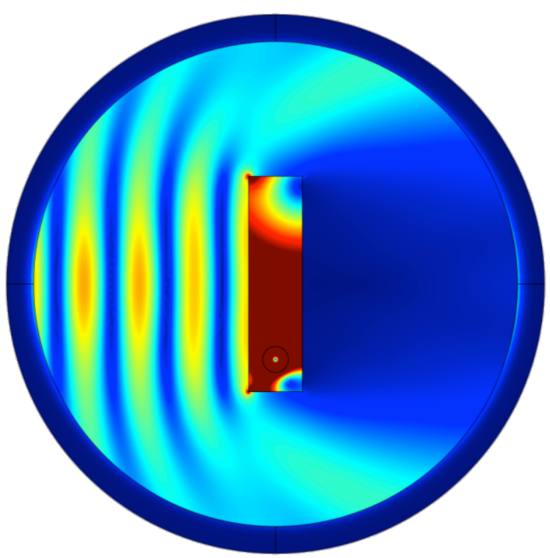


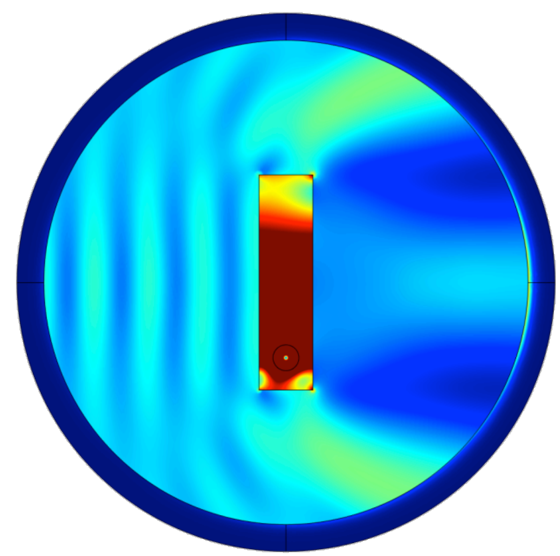
Example 3: Single ENZ 2D slab





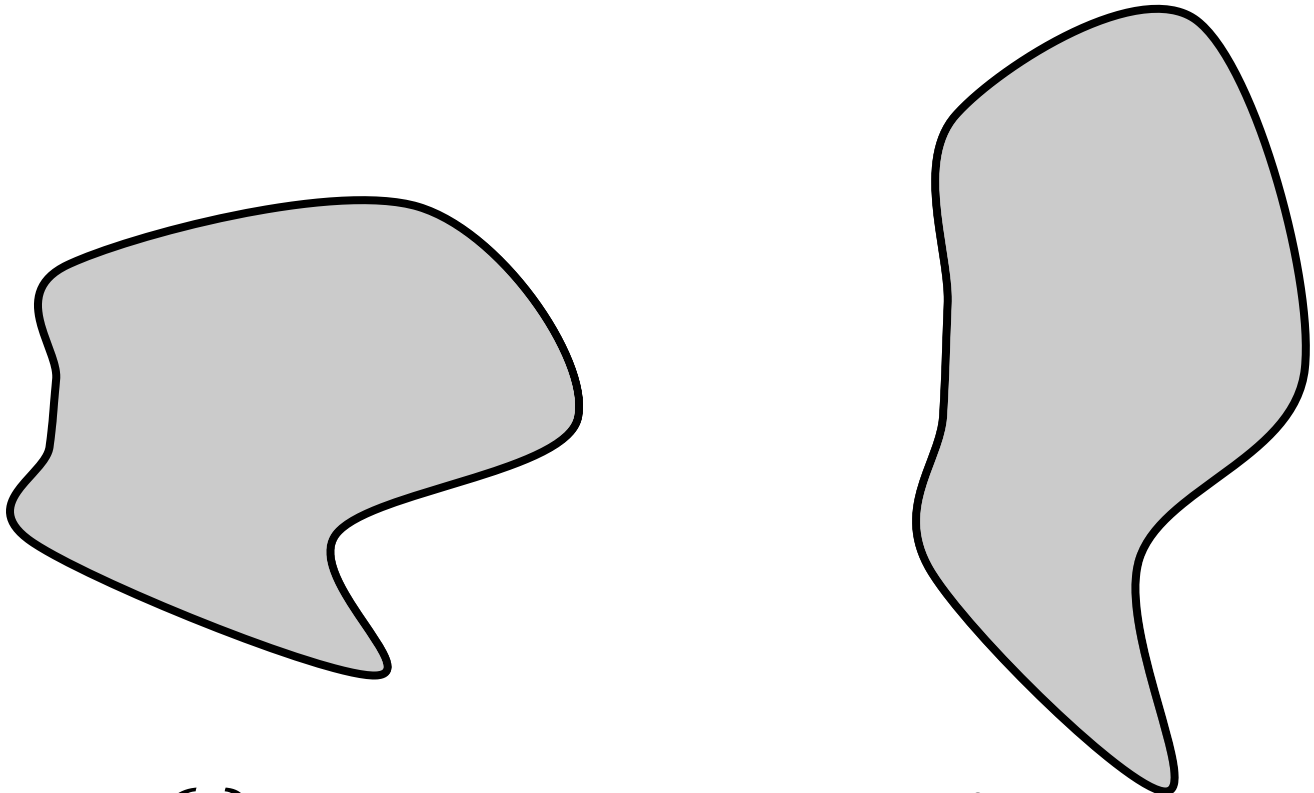
PMC **point (ω = 0.985 ω_p)** ***EMNZ*** **Point (ω = ω_p)**





“Extreme” Cavity Resonators

Conventional Cavity

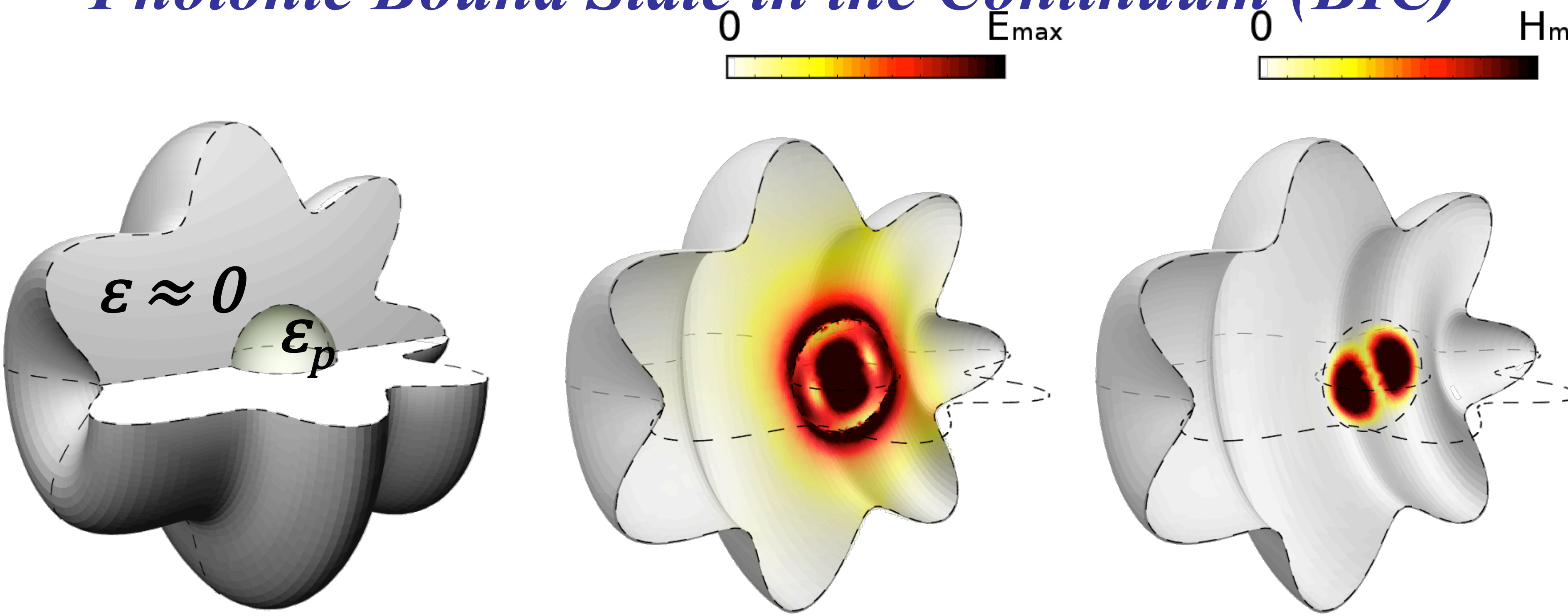


ω_n

$\omega'_n \neq \omega_n$

"Ph-Doped" ENZ and "Open Cavity"

Photonic Bound State in the Continuum (BIC)



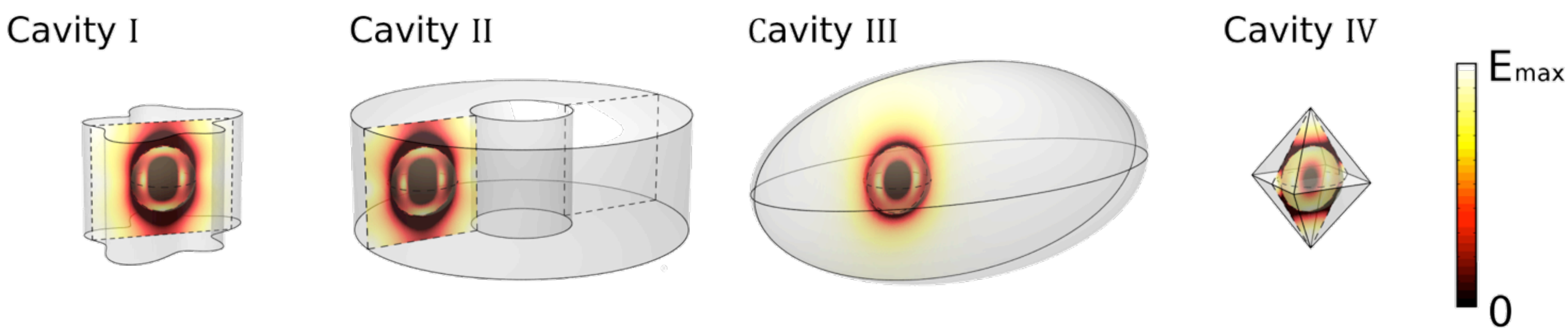
I. Liberal and N. Engheta, Science Advances, 2016

I. Liberal and N. Engheta, Optics and Photonics News (OPN), 2016

I. Liberal and N. Engheta, Nature Photonics, March 2017

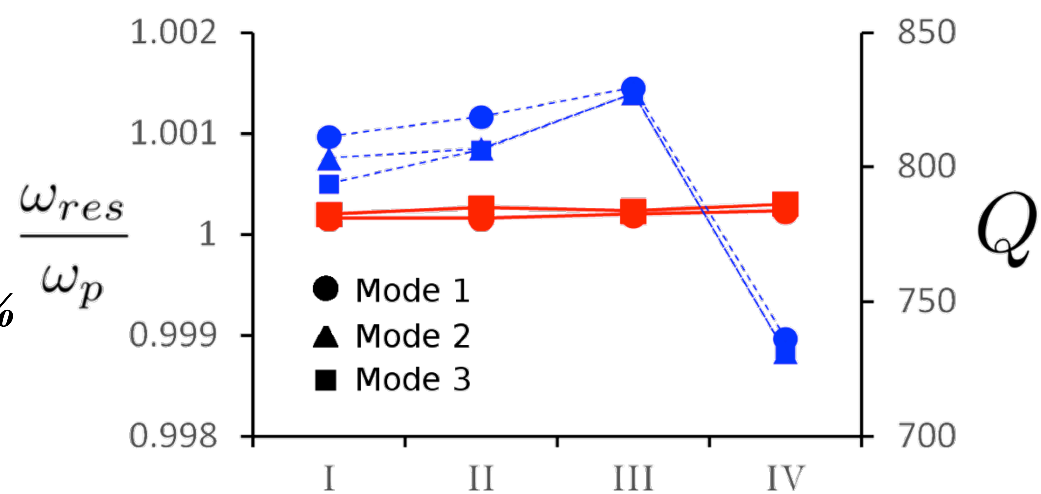
Mahmoud, Liberal and Engheta, Nature Communications, 2016

Flexible "Open" Cavity: Photonic BIC



- ***Three degenerate eigenmodes (spherical defect)***
- ***Eigenfrequency variation < 0.05% (induced by losses)***

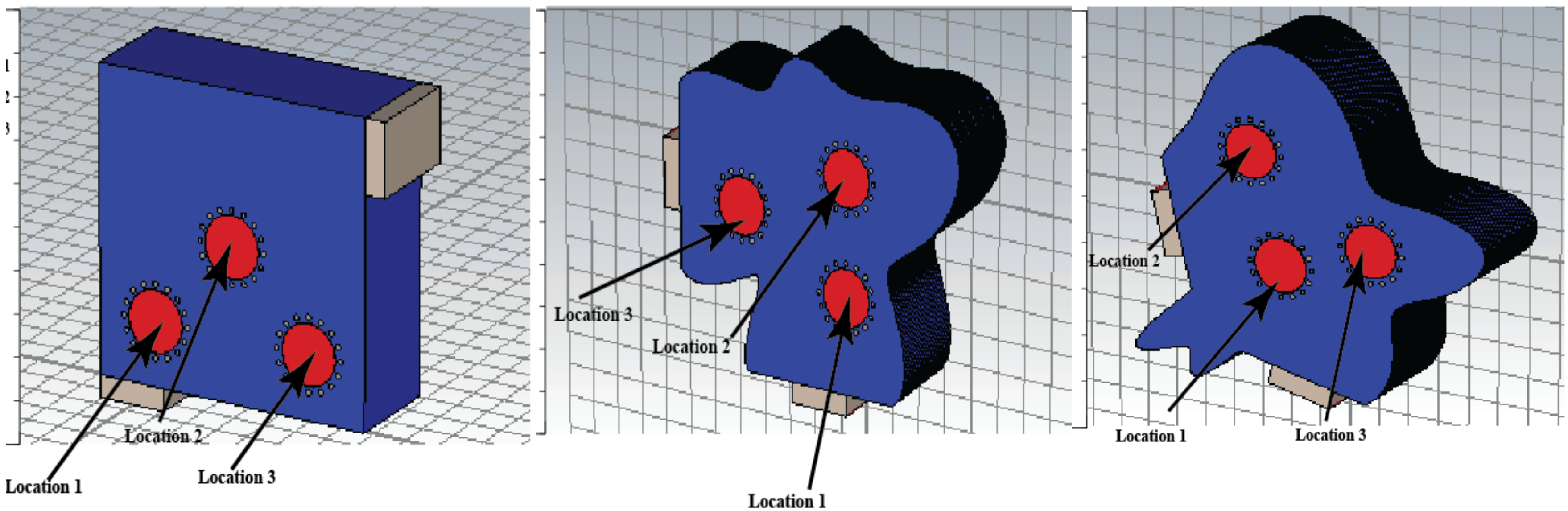
$\varepsilon''(\omega_p) \approx 0.03$



I. Liberal and N. Engheta, Science Advances, 2016

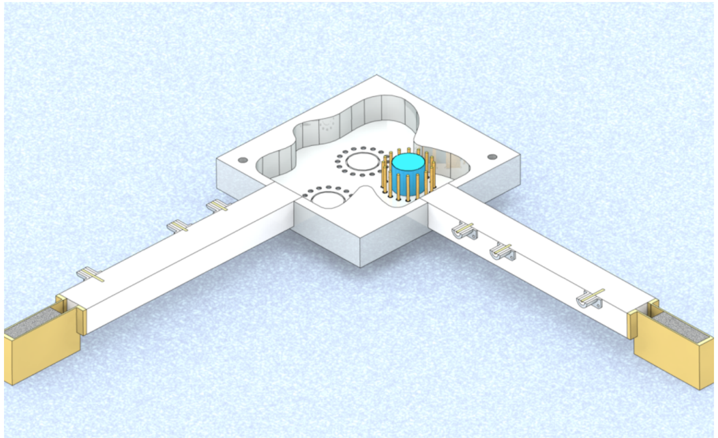
I. Liberal and N. Engheta, Optics and Photonics News (OPN), 2016

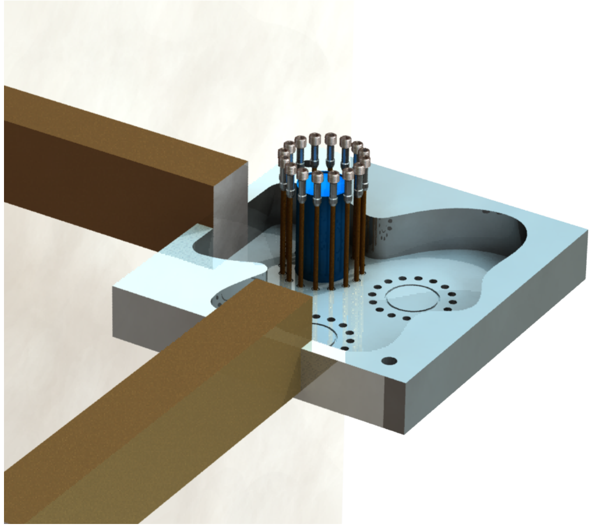
Experimental Verification of EMNZ Cavity

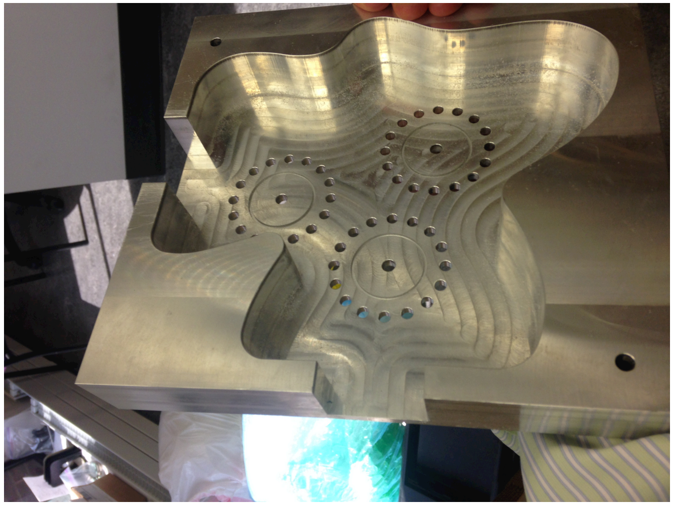


I. Liberal, Y. Li, A. Mahmoud, B. Edwards and N. Engheta, <u>Science,</u> March 10, 2017

Experimental Verification of EMNZ Cavity

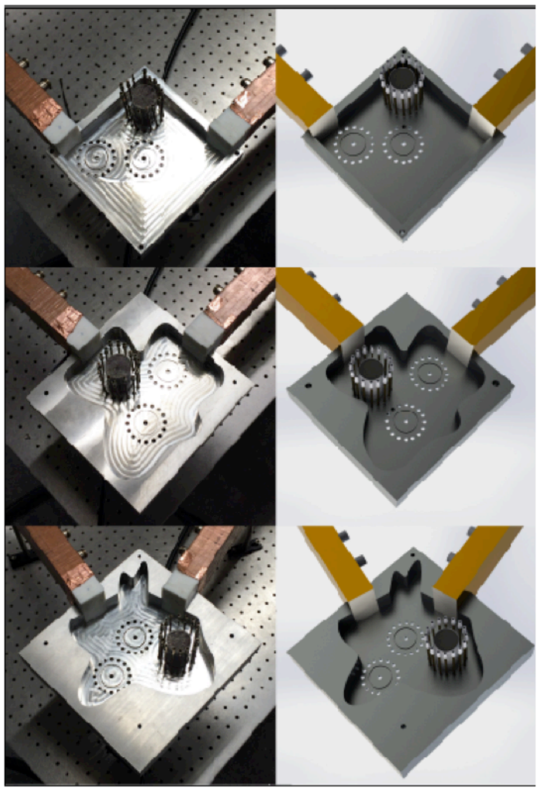


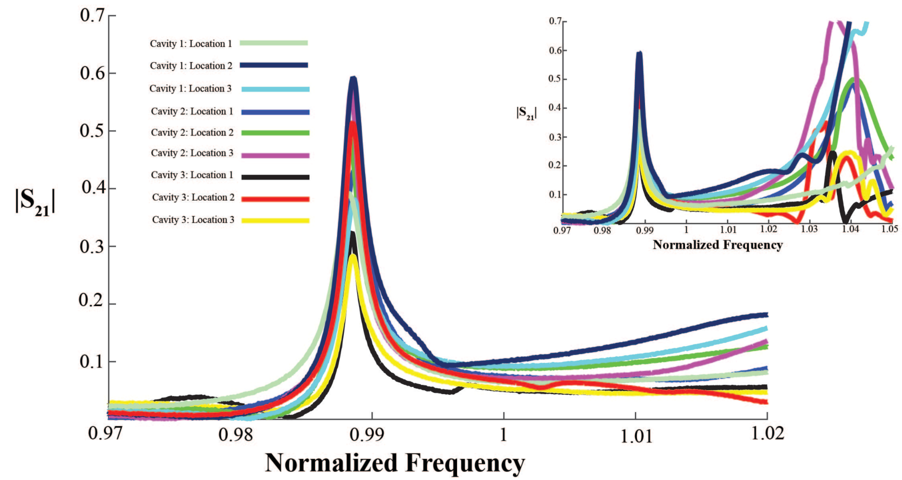




I. Liberal, Y. Li, A. Mahmoud, B. Edwards and N. Engheta, Science, March 10, 2017

Experimental Verification of EMNZ Cavity

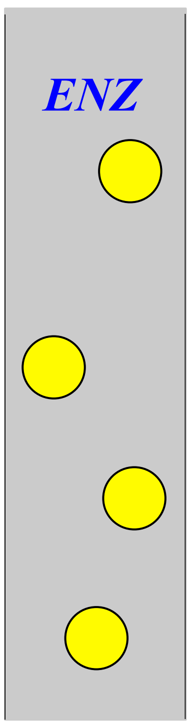




I. Liberal, Y. Li, A. Mahmoud, B. Edwards and N. Engheta, Science, March 10, 2017

Several rods embedded in ENZ metasurface

Filling ENZ Metasurface with several rods

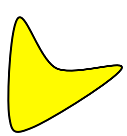


$$\varepsilon_{\text{eff}} \simeq 0$$

$$\mu_{\text{eff}} = \frac{1}{A}\left[A_h + \frac{2\pi r_p}{k_p}\frac{J_1(k_p r_p)}{J_0(k_p r_p)}\right]$$

$$\mu_{eff} = \frac{1}{A}\left[A_{ENZ} + \sum \mu_d \int_{A_d} \psi_d(\mathbf{r})\,dA\right]$$

$$\mu_{eff} = 1 + \sum \Delta\mu_d$$



$$\Delta\mu_d = \frac{1}{A}\left[\mu_d \int_{A_d} \psi_d(\mathbf{r})\,dA - A_d\right]$$

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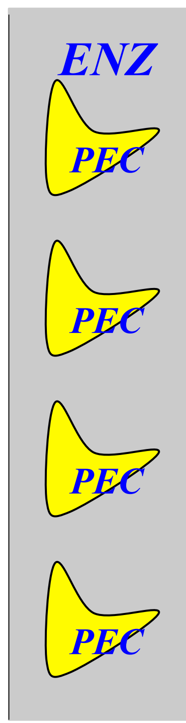
ENZ-based Metasurface with PEC rods

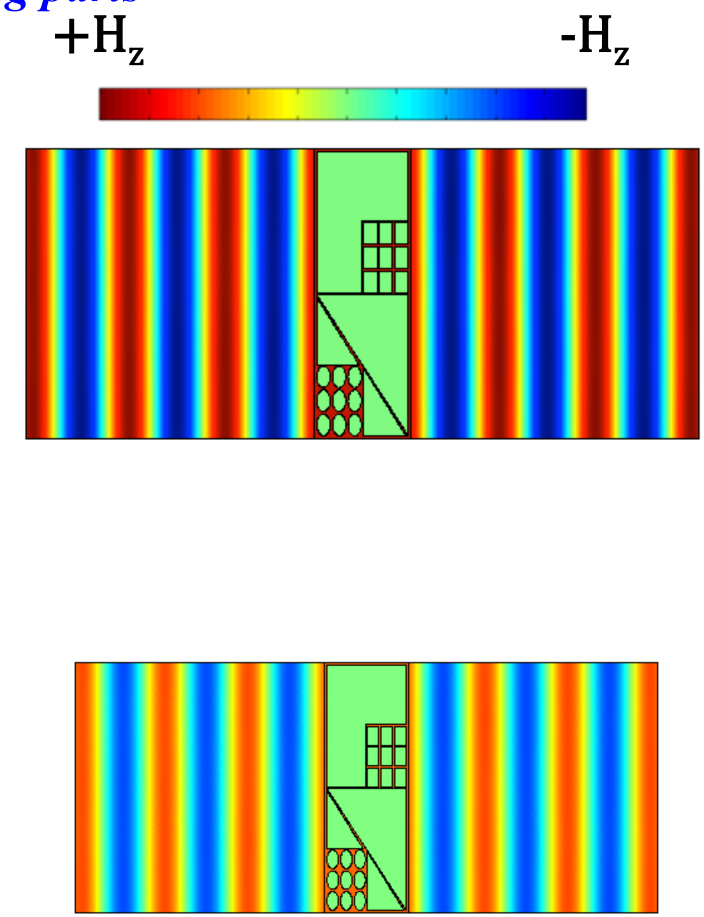
Filling ENZ Metasurface with conducting parts

$$\varepsilon_{\mathrm{eff}} \simeq 0$$

$$\mu_{eff} \approx 1 - \frac{A_{PEC}}{A}$$

$$\mu_{eff} \to 0$$





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ENZ Metasurface filled with Conductors

Filling ENZ Metasurface with conducting parts

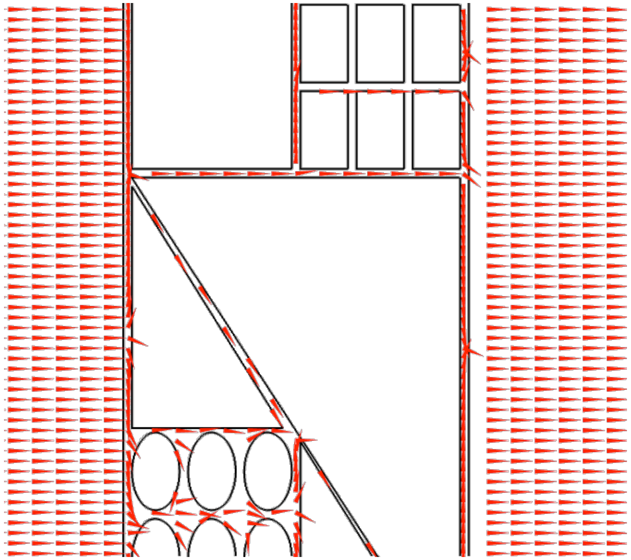
$L_x = 1\,\lambda_0$

$L_y = 3\,\lambda_0$

$$\mu_{\text{eff}} = 1 - \frac{A_{PEC}}{A}$$

$$\varepsilon_{\text{eff}} \simeq 0$$

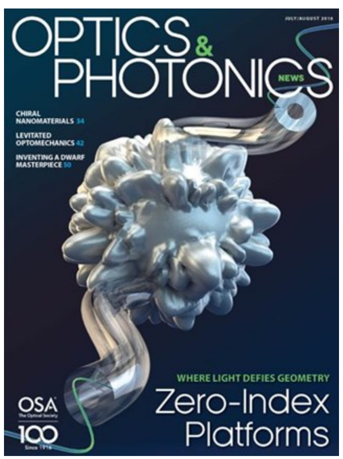
Poynting vector



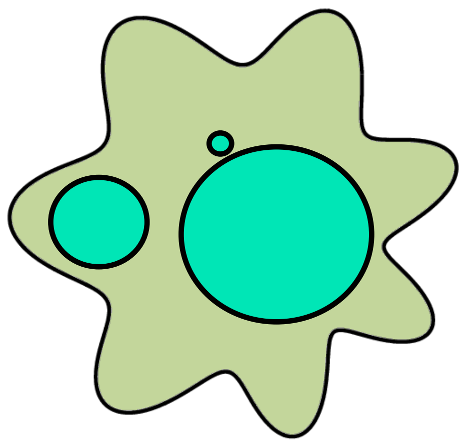
Summary

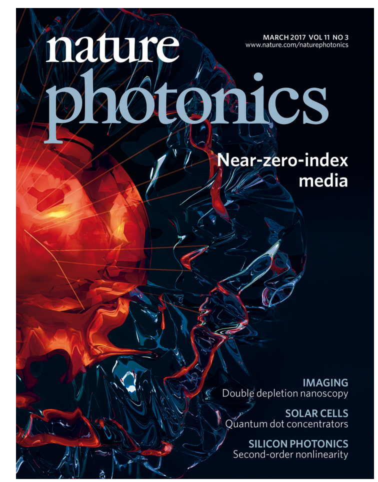
Extreme platforms can play interesting roles in light-matter interaction

Extreme photonics offers unique functionality



July/Aug 2016





March 2017

Thank you very much