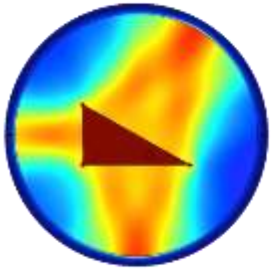
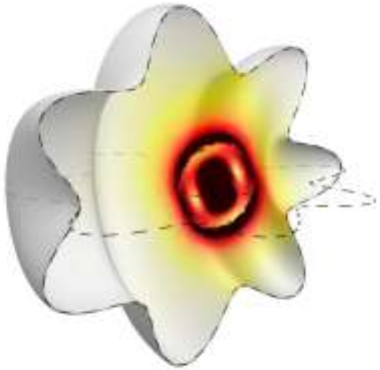
Low-Index Photonics





Nader Engheta with special thanks to

Inigo Liberal

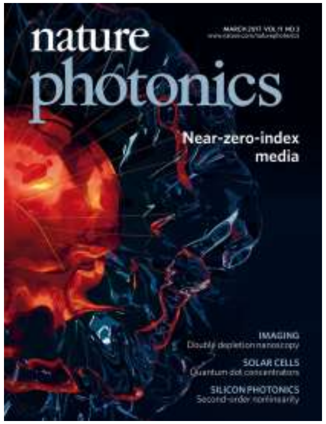
Brian Edwards

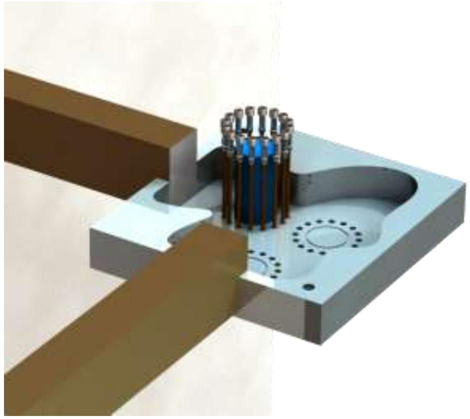
Yue Li

Ahmed Mahmoud

Arthur Davoyan

Trisha Ramadoss





November 2, 2017

"Extreme Parameters" and "Extreme Structures"

- Time-Harmonic Macroscopic Equations

$$\nabla \times \boldsymbol{H} = -i\omega\varepsilon\,\boldsymbol{E}$$

$$\nabla \times \boldsymbol{H} = 0 \qquad n = \sqrt{\varepsilon\,\mu} \to 0$$

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

$$\nabla \times \boldsymbol{E} = 0$$

Light-Matter Interaction

Spatial Distribution: "Static-like"
Temporal Variation: "Dynamic"

"Near-Zero-Index" Optics Low-Index Photonics

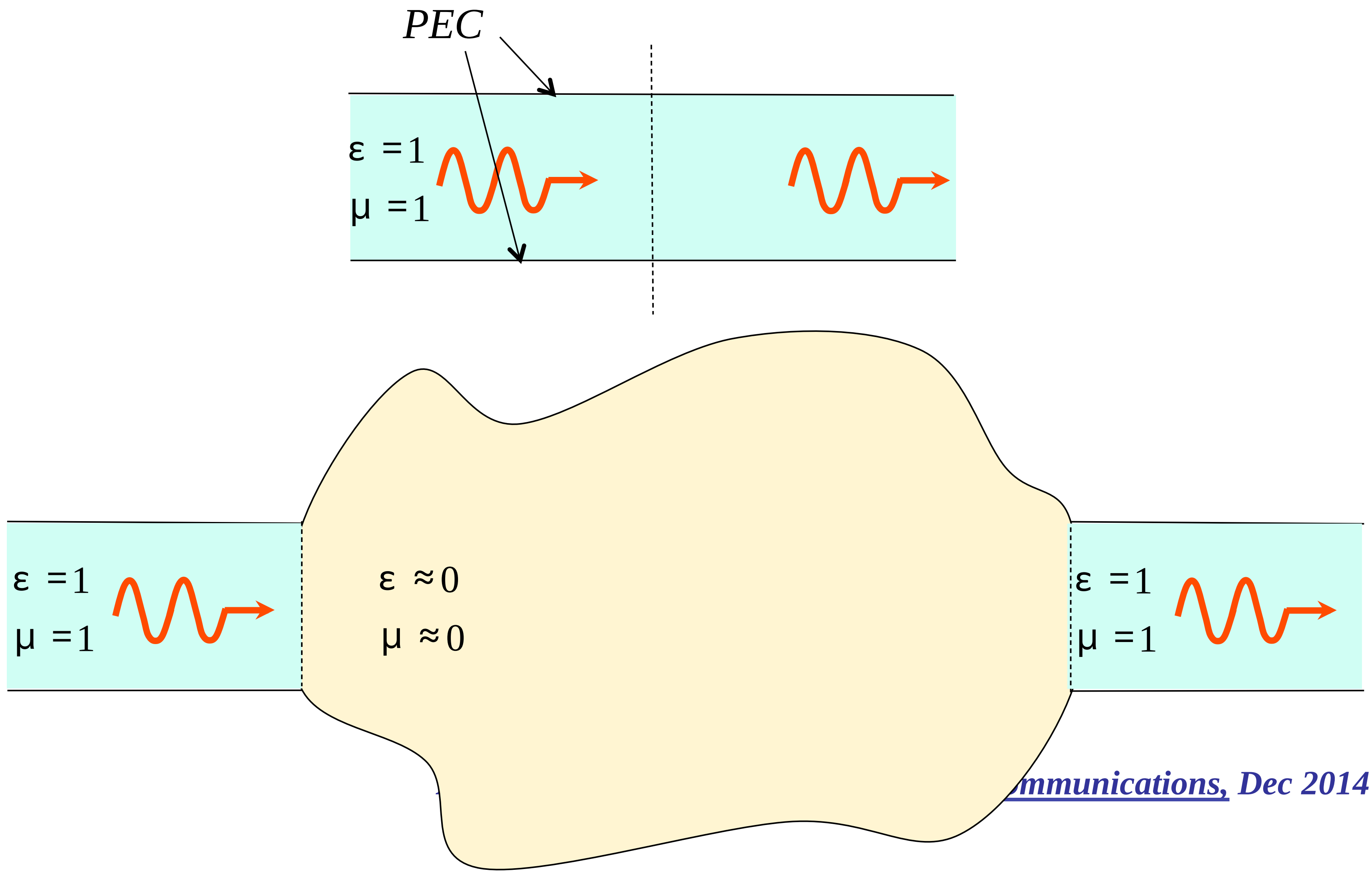
R. Ziolkowski, Phys. Rev. E (2004) ***M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006***

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

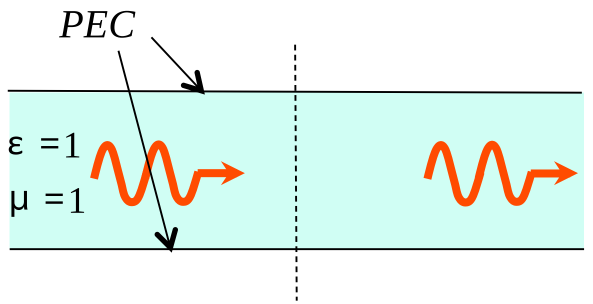
A. Mahmoud and N. Engheta, Nature Communications, Dec 2014

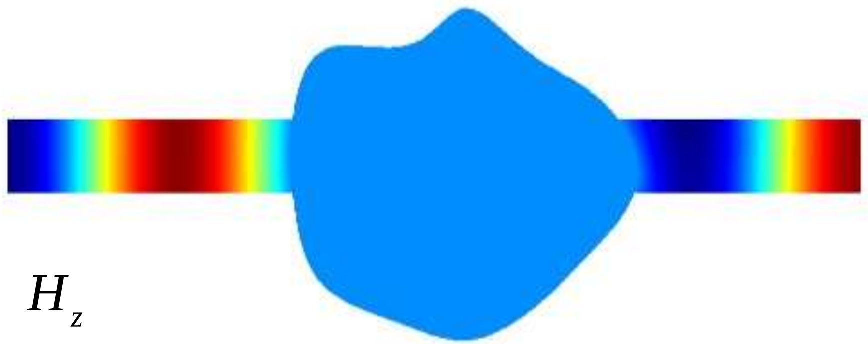
“Near-Zero” Optics

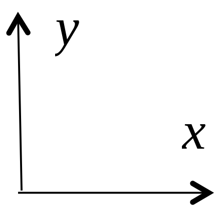
A. Mahmoud and N. Engheta, Nature Communications, Dec 2014

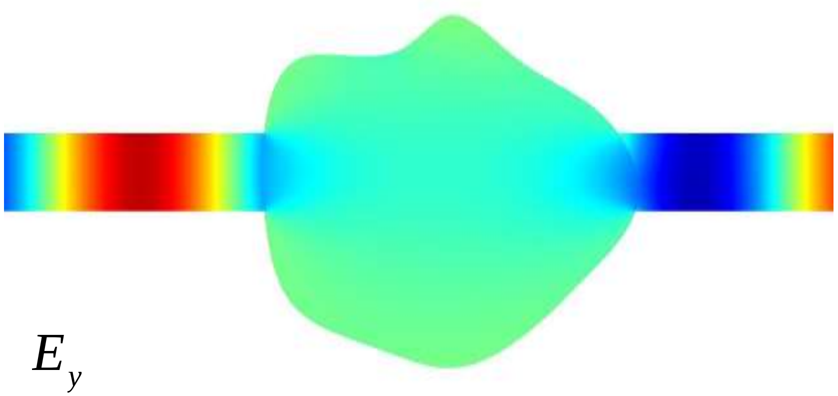

PEC
ε =1
μ =1
ε =1
μ =1
ε ≈0
μ ≈0
ε =1
μ =1

Epsilon-and-Mu-Near-Zero (EMNZ)

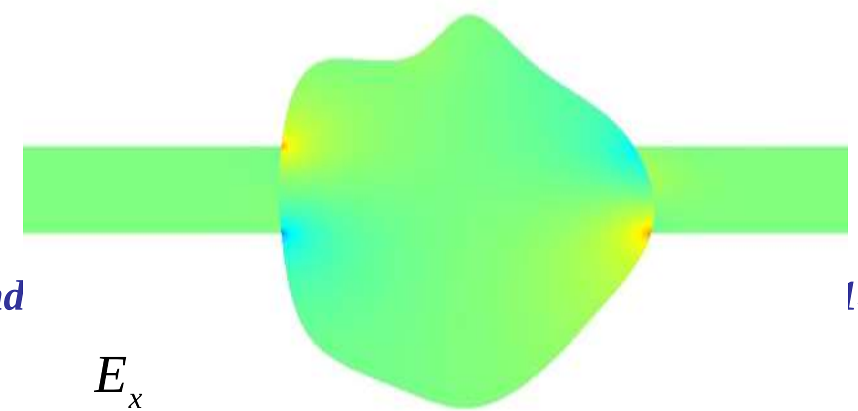






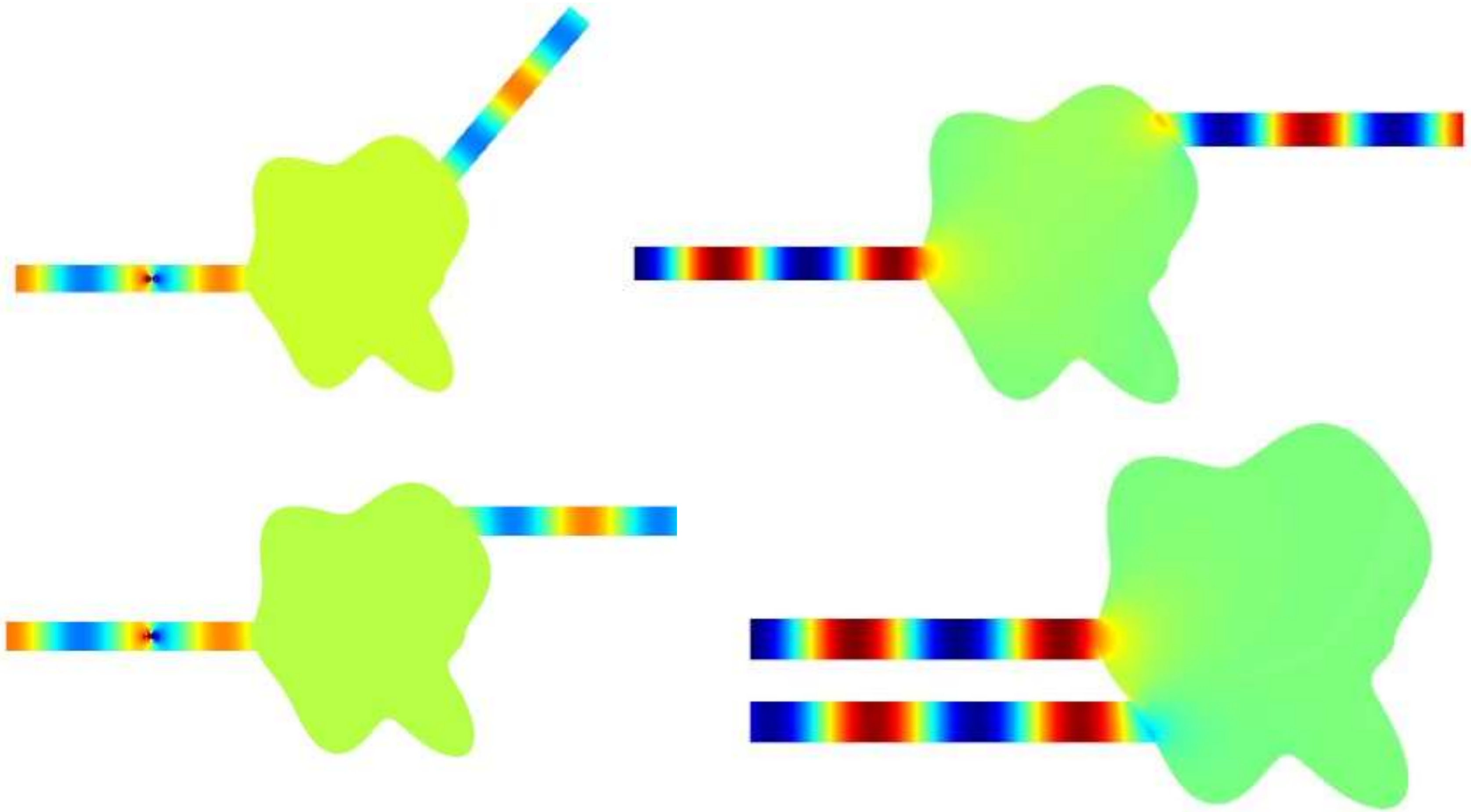


and



14

EMNZ Junctions



A. Mahmoud and N. Engheta, <u>Nature Communications,</u> Dec 2014

Background: ENZ Materials

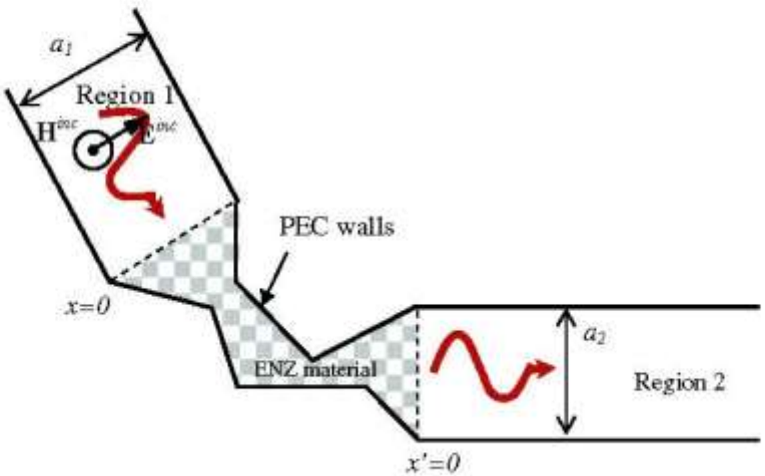
PRL **97**, 157403 (2006) PHYSICAL REVIEW LETTERS week ending 13 OCTOBER 2006

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

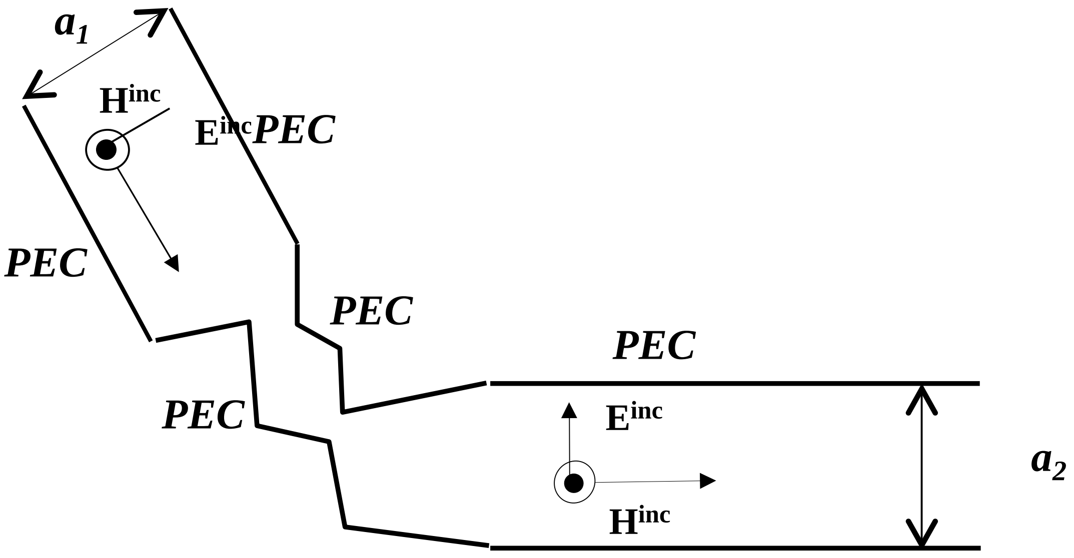
Mário Silveirinha* and Nader Engheta†

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

(Received 23 March 2006; published 10 October 2006)



Background: ENZ Materials

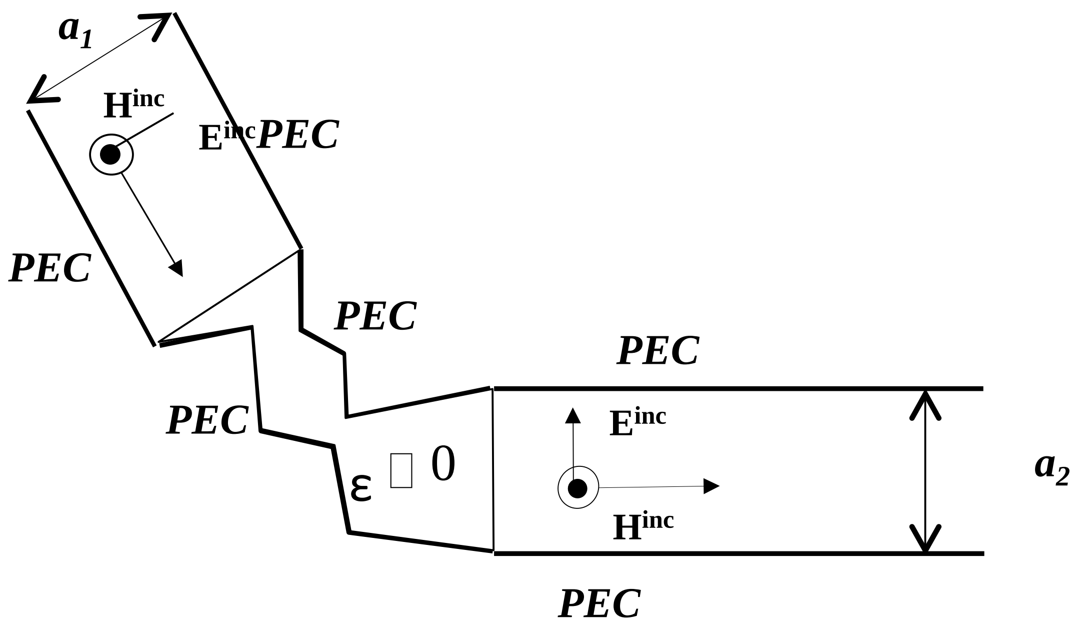


Background: ENZ Materials

PEC

M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

Background: ENZ Materials

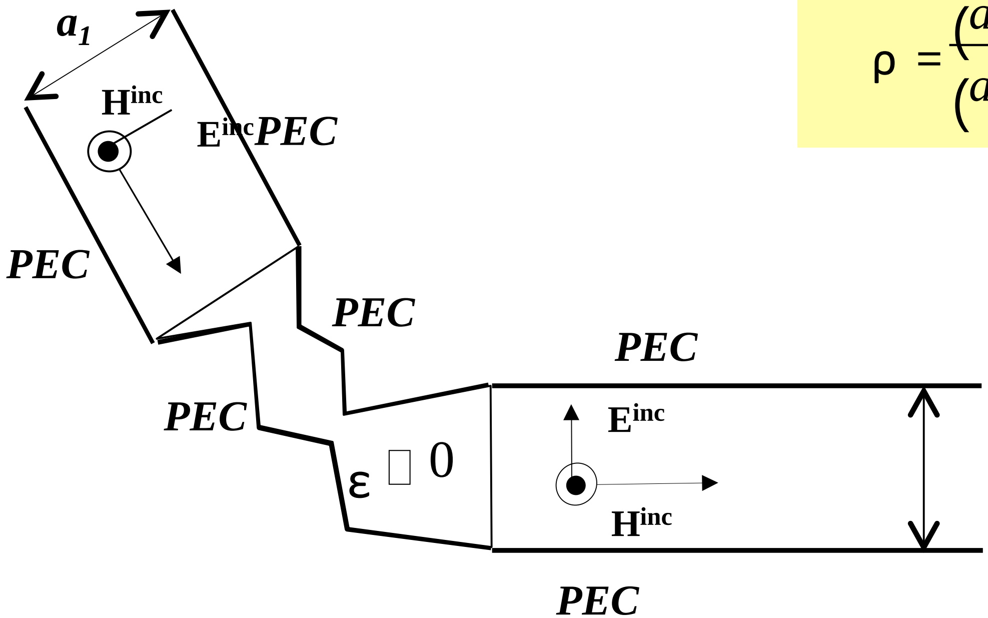


Background: ENZ Materials

M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

Background: ENZ Materials

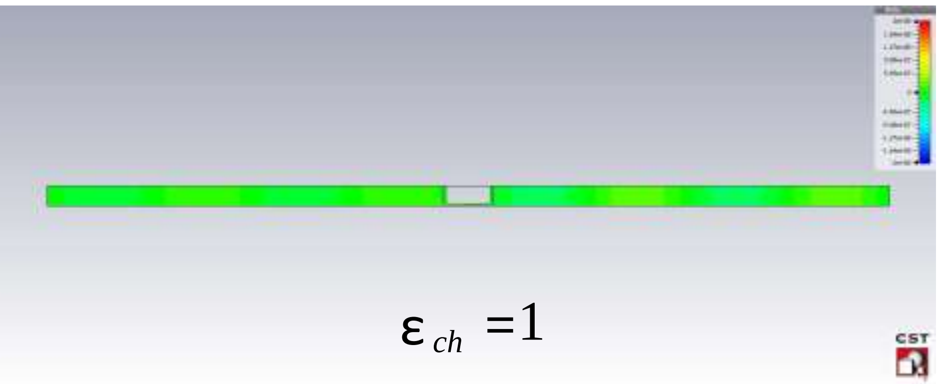
$$\rho = \frac{(a_1 - a_2) + ik_0\mu_r A_D}{(a_1 + a_2) - ik_0\mu_r A_D}$$

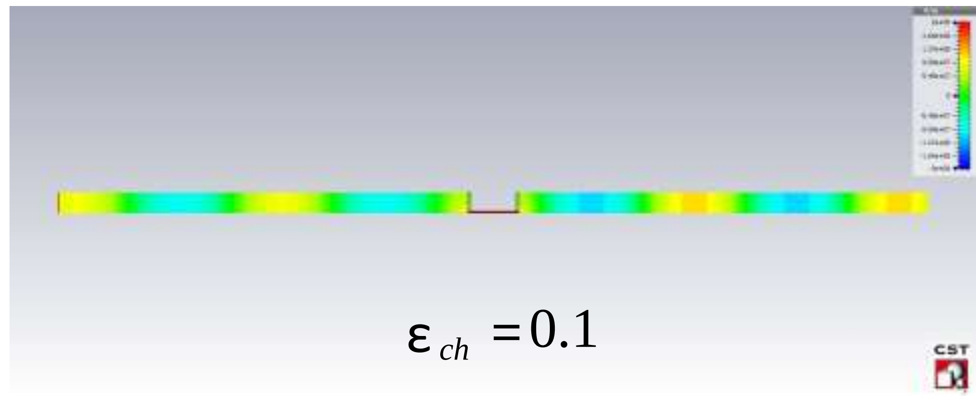


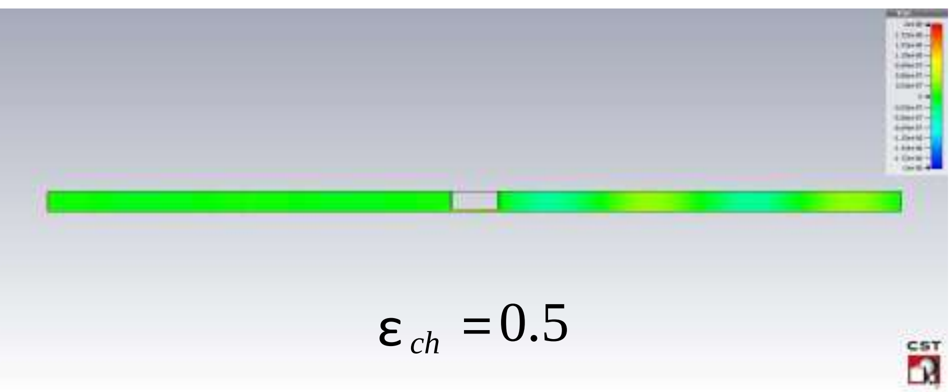
***a*2**

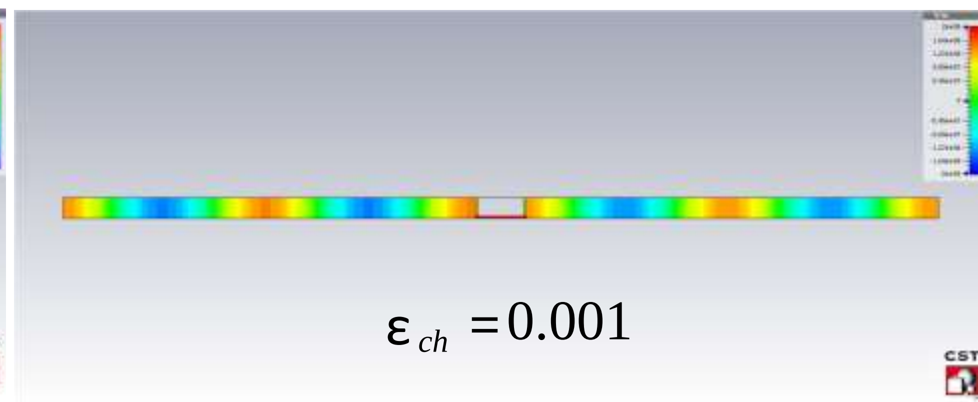
M. Silveirinha & N. Engheta, Phys. Rev. Lett. 97, 157403, Oct 2006

Simulation Results: 2D scenario

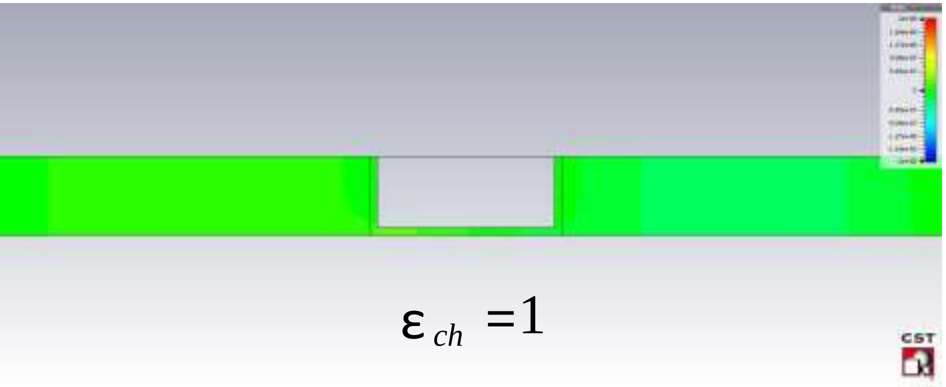




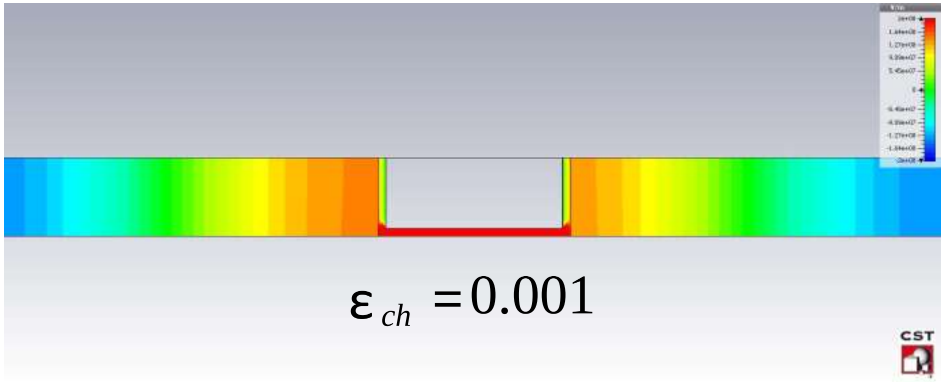




Simulation Results: 2D scenario



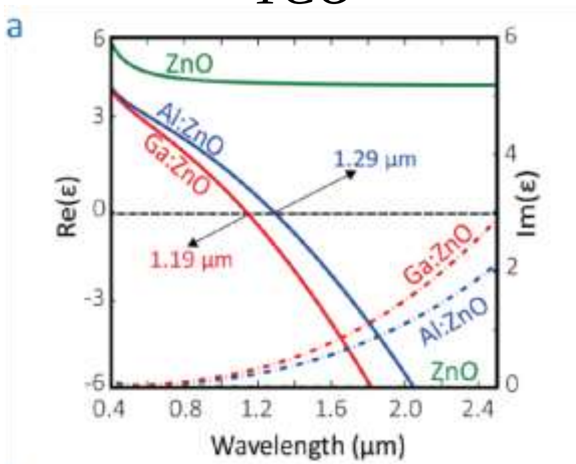
$\varepsilon_{ch} = 1$



$\varepsilon_{ch} = 0.001$

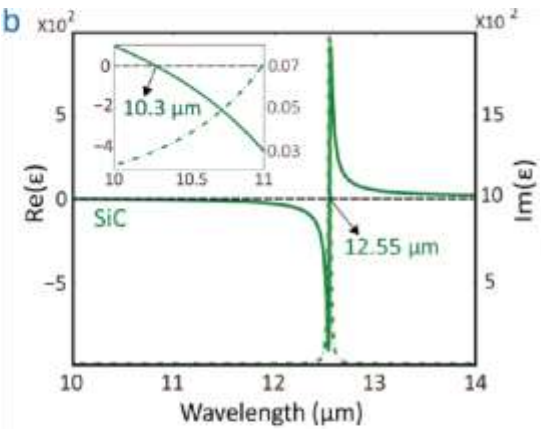
ENZ Structures

TCO



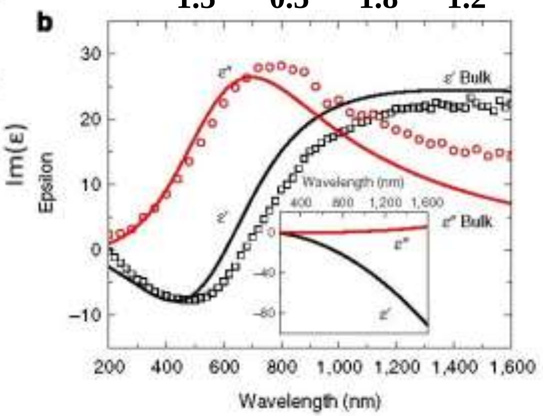
From: A. Boltasseva (Purdue)

SiC

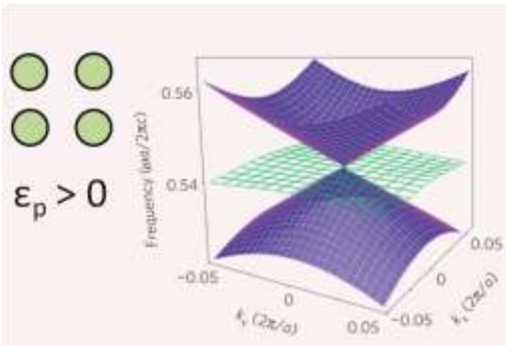


From: J. Caldwell (NRL)

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



From: N. Zheludev (Southmapton)



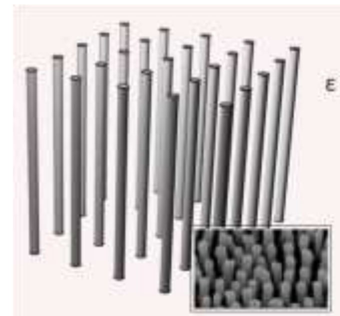
$\mathrm{Re}(\varepsilon) \cong 0$

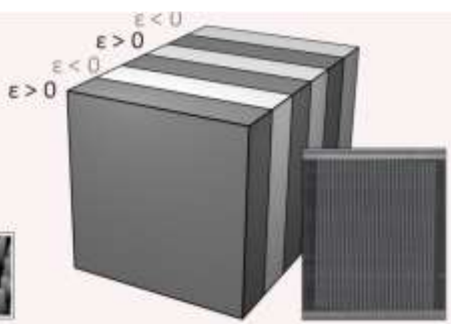
From:*CT Chan's*

SEM from:*Polman's& Engheta's*

Wire SEM from:*Zayat & Podolskiy*

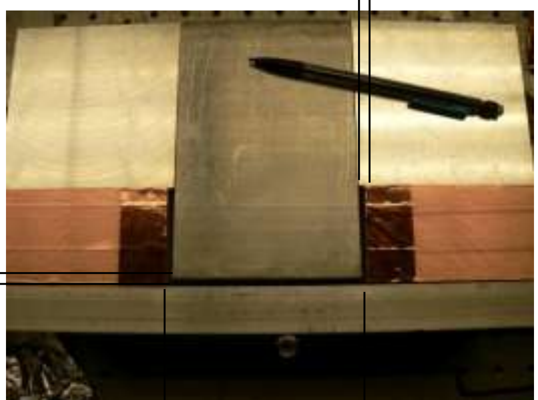
StackSEM from:*Polman& Engheta*

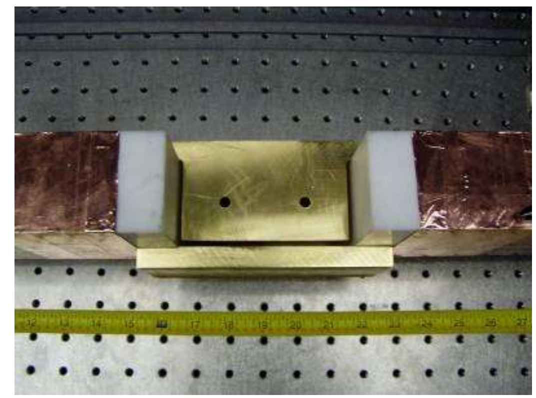




Experimental Verification

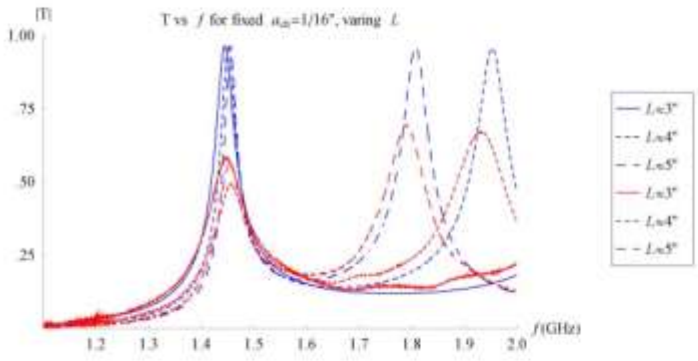
a_{ch}



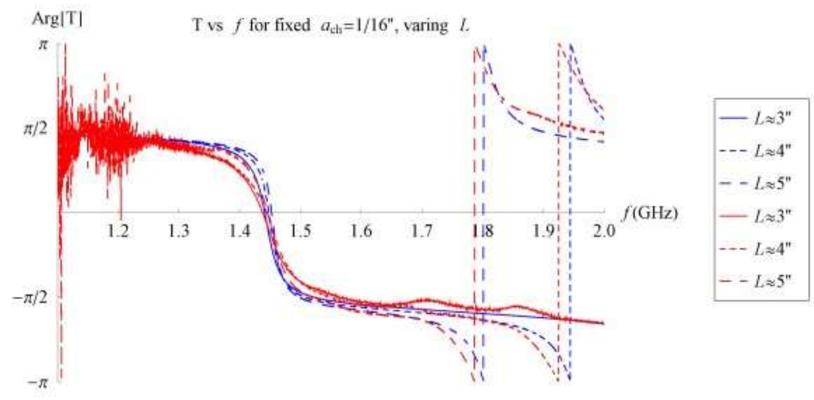


L

B. Edwards, A. Alù, M. Young, M. Silveirinha, N. Engheta
Phys. Rev. Lett. 100, 033103 (2008)



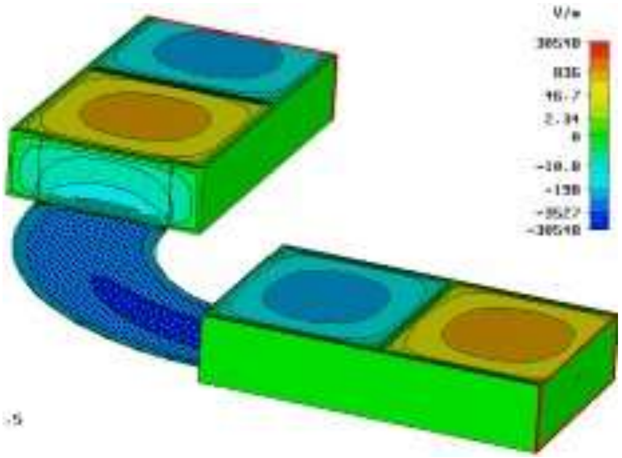
|T|
T vs f for fixed a_{ch}=1/16", varing L
1.00
.75
.50
.25
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
f(GHz)
L≈3"
L≈4"
L≈5"
L≈3"
L≈4"
L≈5"

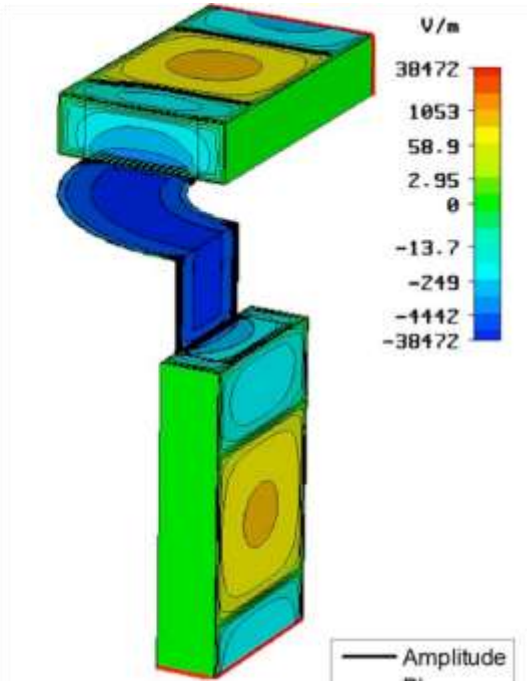


Arg[T]
T vs f for fixed a_{ch}=1/16", varing L
π
π/2
−π/2
−π
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2.0
f(GHz)
L≈3"
L≈4"
L≈5"
L≈3"
L≈4"
L≈5"

Channels

Waveguide Bends with Narrow



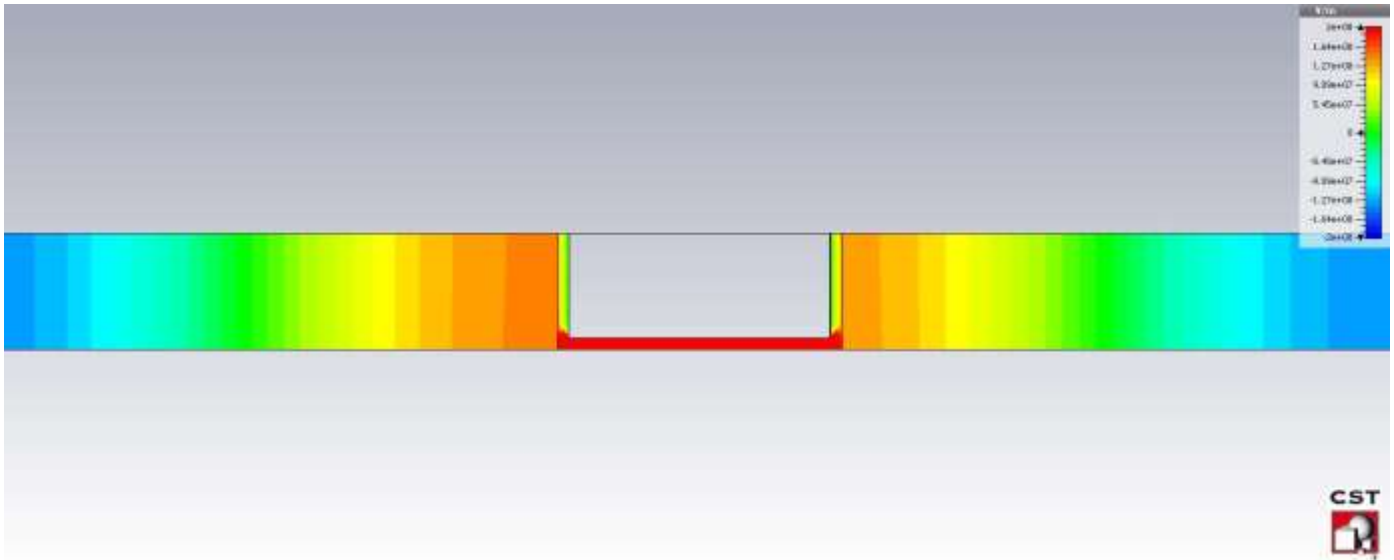


A. Alu, M. Silveirinha, N. Engheta, Phys. Rev. E., 78, 016604 (2008)

Field Enhancement Using ENZ

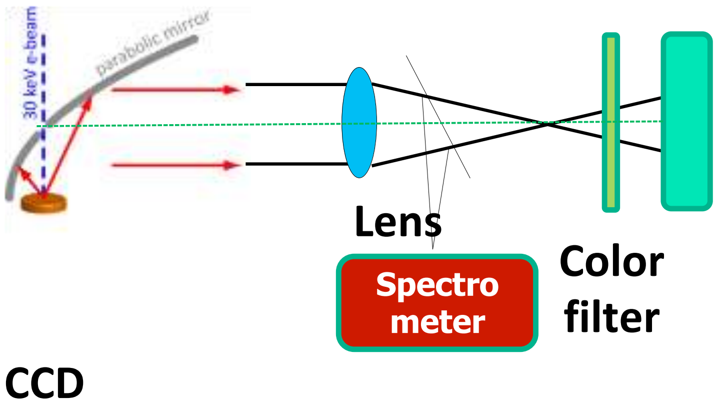
ENZ and Emission Rate of Optical Dipoles

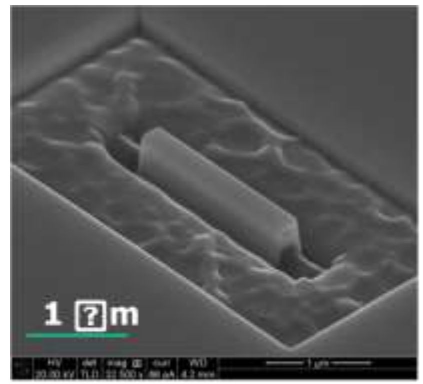
A. Alu and N. Engheta, Phys. Rev. Lett. 103, 043902 (2009)

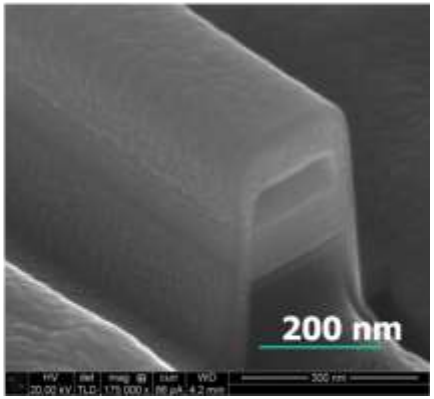

2e+08
1.27e+08
0
-1.27e+08
-2e+08
CST

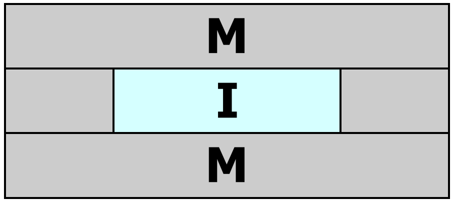
Experimental Verification Using CL Spectroscopy

Collaboration with Albert Polman's Group in AMOLF





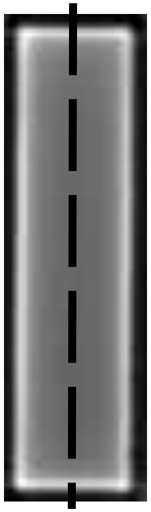


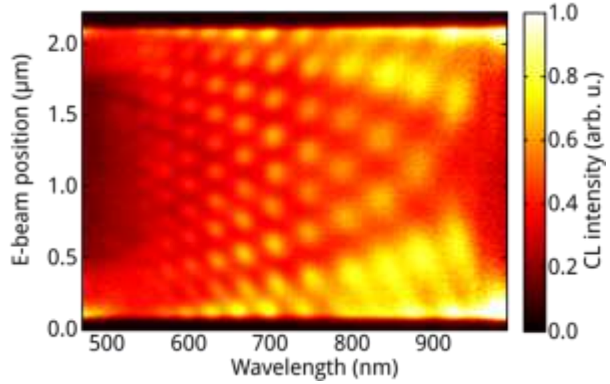


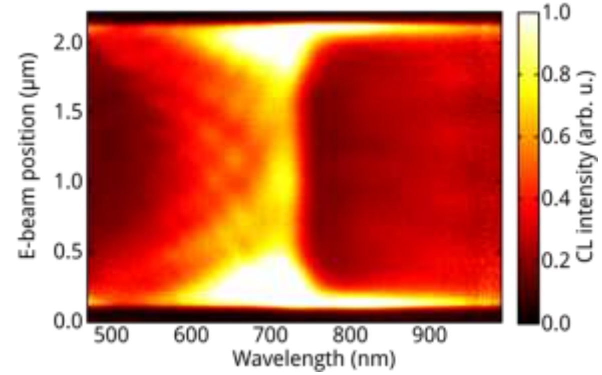
E. J. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman ***Phys. Rev. Lett., 110, 013902 (2013)***

Experimental Verification Using CL Spectroscopy

Collaboration with Albert Polman' s Group in AMOLF





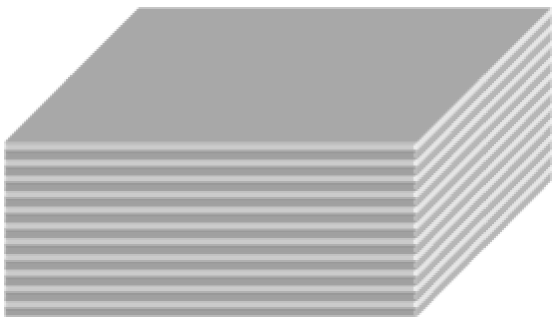


Waveguide Width = 240 nm **Waveguide Width = 180 nm**

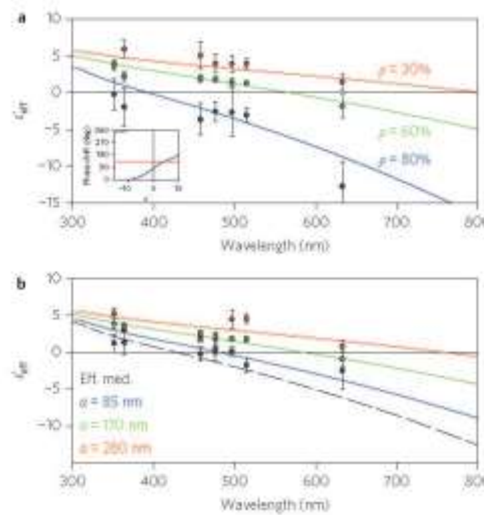
E. J. Vesseur, T. Coenen, H. Caglayan, N. Engheta, A. Polman ***Phys. Rev. Lett., 110, 013902 (2013)***

Experimental Verification ENZ Stack

Collaboration with Albert Polman's Group in AMOLF

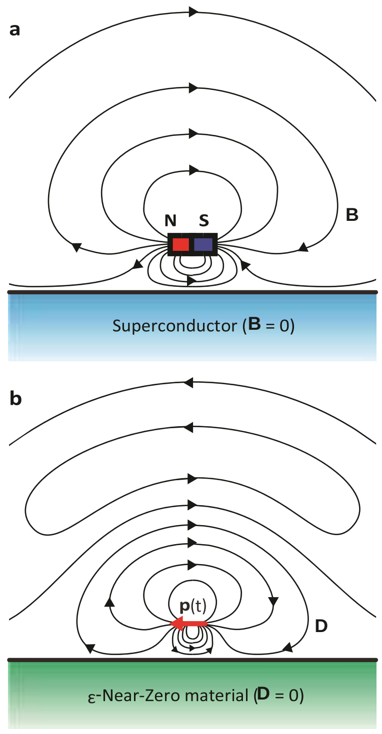


$\mathrm{Re}(\varepsilon) \cong 0$

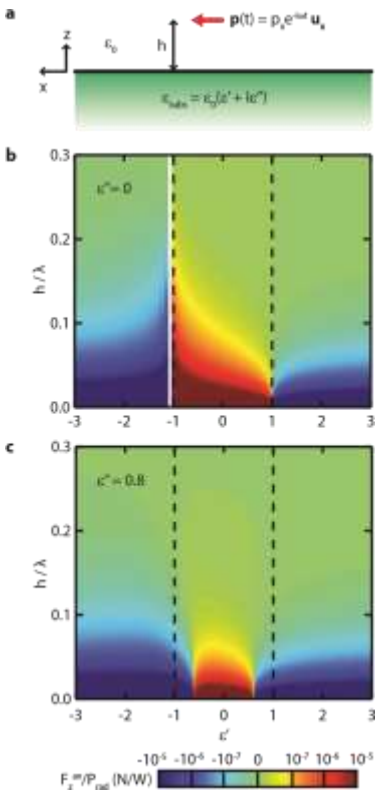


R. Maas, J. Parsons, N. Engheta, A. Polman <u>Nature Photonics,</u> 7(11), 907-912 (2013)

E-Field Levitation with ENZ Substrate: Analogous to Meissner Effect in SC



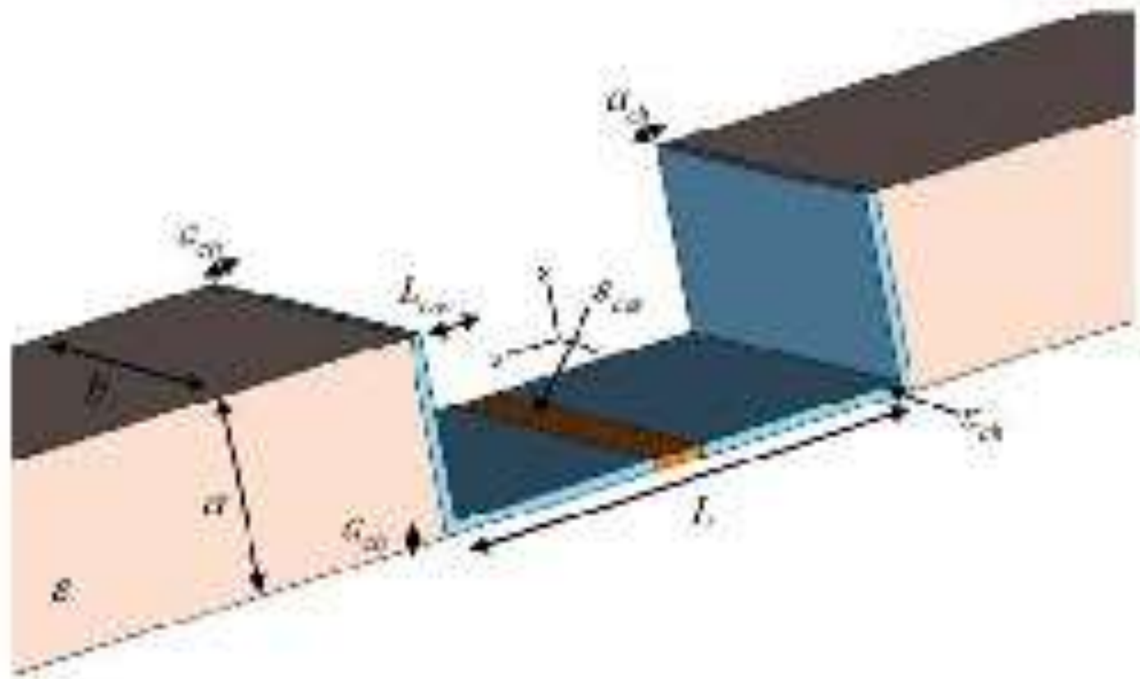
a
N
S
B
Superconductor (B = 0)
b
p(t)
D
ε-Near-Zero material (D = 0)

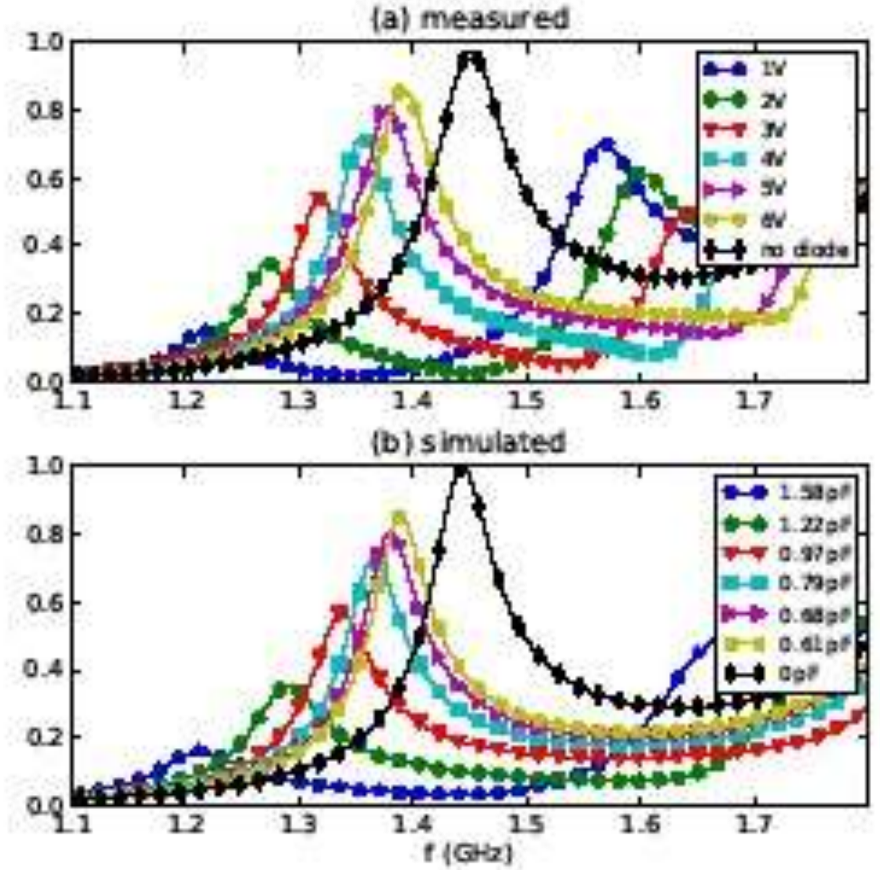


a
b
c
h / λ
ε'
F_z/P_rad (N/W)

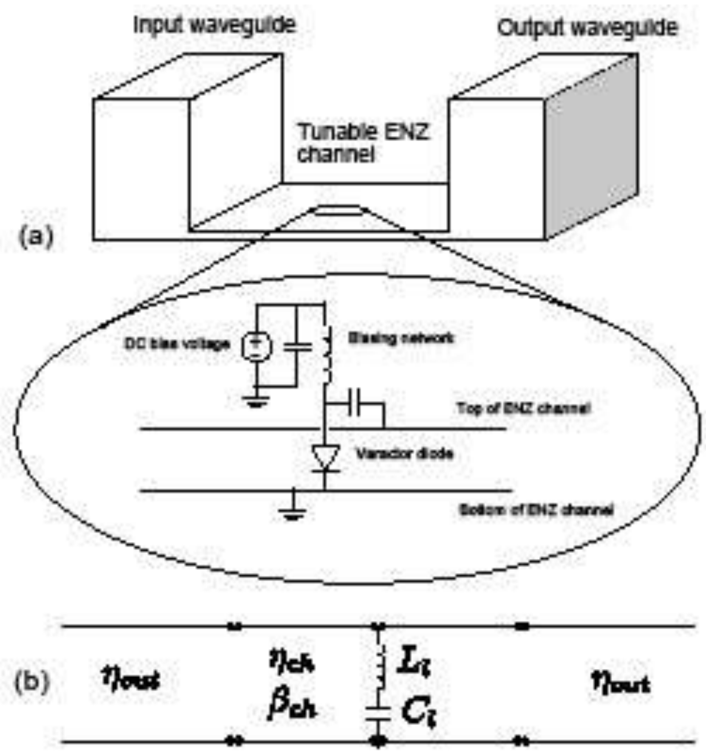
F. Rodriguez-Fortuno, A. Vakil, N. Engheta, Phys. Rev. Lett., 112, 033902 (24 Jan 2014)

Sensing and ENZ "Transistor"


b
a
L



Nonlinearity in ENZ Channels


Input waveguide
Output waveguide
Tunable ENZ channel
(a)
DC bias voltage
Biasing network
Top of ENZ channel
Varactor diode
Bottom of ENZ channel
(b)
η_{out}
η_{ch}
β_{ch}
L_t
C_t
η_{out}

D. Powell, A. Alù, B. Edwards, A. Vakil, Y. Kivshar, and N. Engheta,
Phys. Rev. B. 2009.

ENZ and Nonlinearity

1500 OPTICS LETTERS / Vol. 40, No. 7 / April 1, 2015

Enhanced third-harmonic generation in Si-compatible epsilon-near-zero indium tin oxide nanolayers

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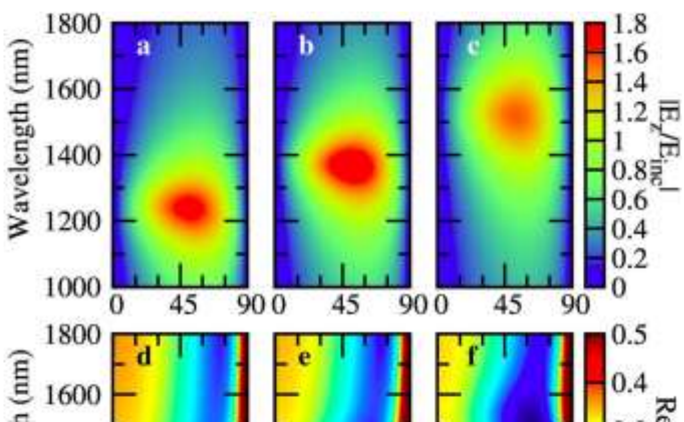
[1]*Department of Electrical and Computer Engineering and Photonics Center, Boston University, 8 Saint Mary's Street, Boston, Massachusetts 02215, USA*

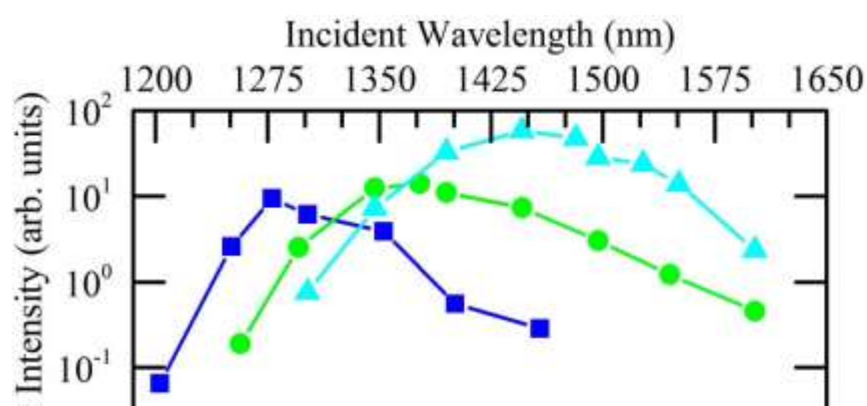
[2]*CNR-SPIN, Complesso MonteSantangelo, Via Cinthia, 80126 Napoli, Italy*

[3]*Department of Electrical and Systems Engineering, University of Pennsylvania, 200 South 33rd Street, Philadelphia, Pennsylvania 19104, USA*

[4]*Division of Materials Science and Engineering, Boston University, 15 Saint Mary's Street, Brookline, Massachusetts 02446, USA*

**Corresponding author: dalnegro@bu.edu*

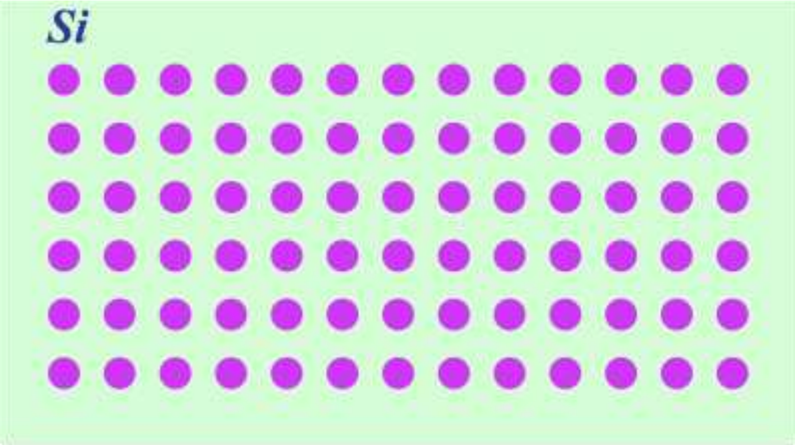




Background: Electronic Doping

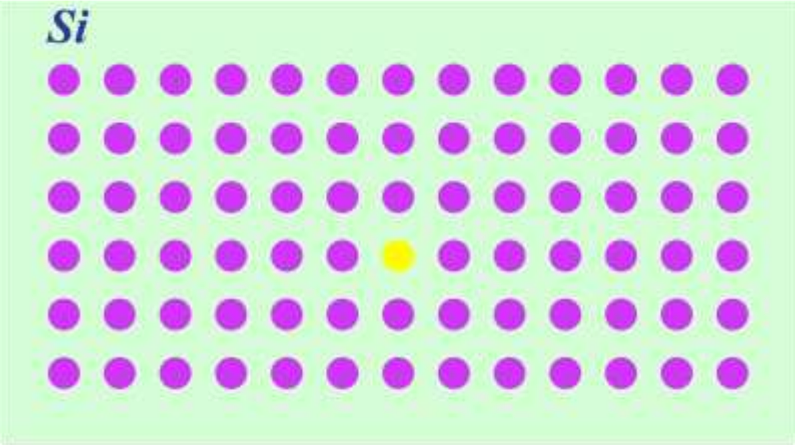
"Photonic Doping" in ENZ Materials

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



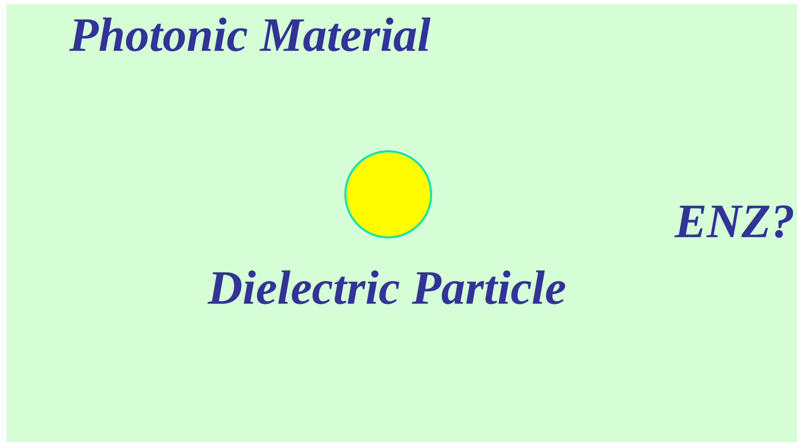
Pure Intrinsic Semiconductor

Background: Electronic Doping



Doped Semiconductor

How about "photonic doping"?



"Pure" Photonic Material

Background: One of ENZ Properties

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

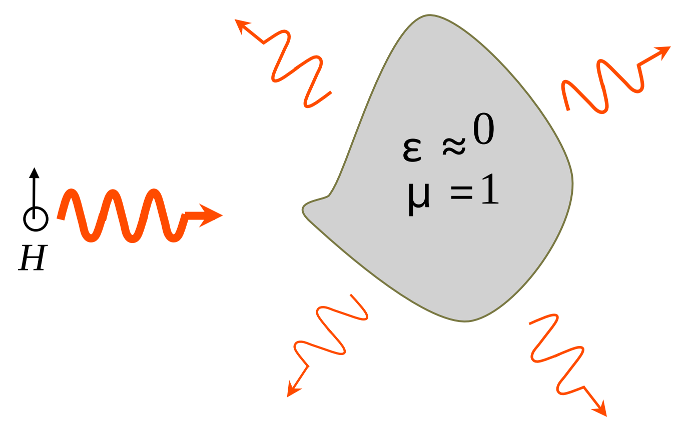
$$\nabla \times \boldsymbol{E} = i\omega\mu \boldsymbol{H}$$

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

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

E

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



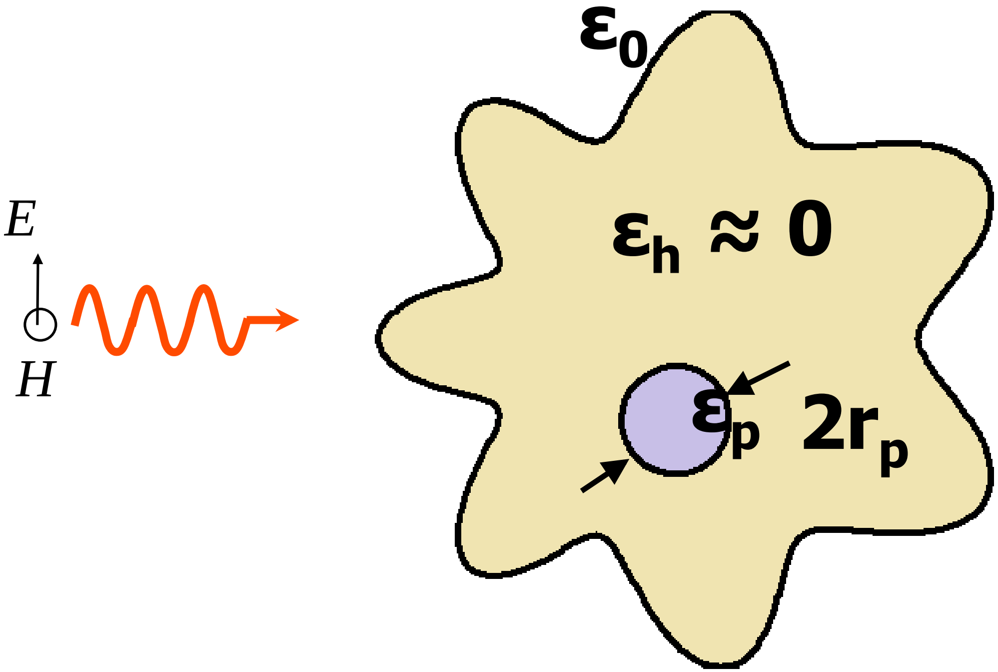
N. Engheta, Science, 340, 286 (2013)

R. W. Ziolkowski, PRE, (2004)

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

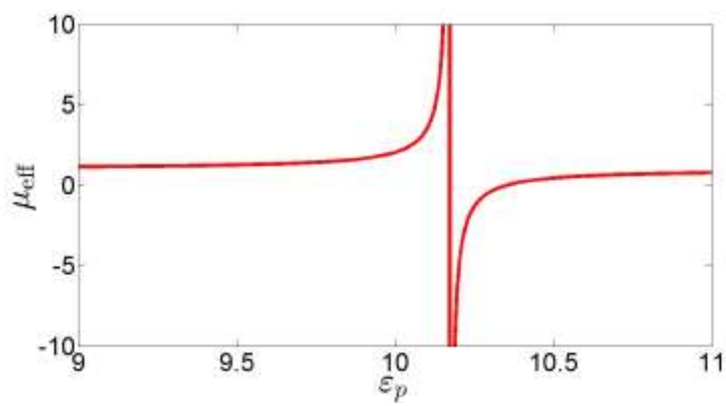
Photonic “Doping”

$h \quad p \quad p \quad h \quad p$



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

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



$2\delta_p(\varepsilon_p - \varepsilon_h) + \varepsilon_p + 2\varepsilon$

$$\varepsilon_{eff} = \varepsilon$$

$$h \; h$$

$$2\varepsilon + \varepsilon + \delta\left(\varepsilon - \varepsilon\right)$$

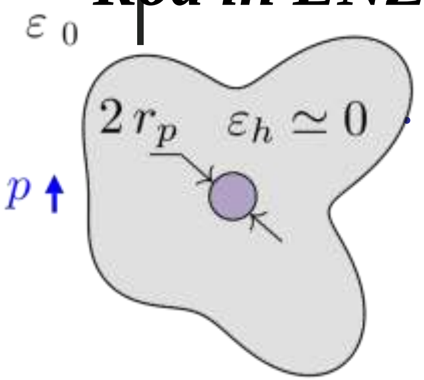
I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, <u>Science,</u> 355, March 10, 2017

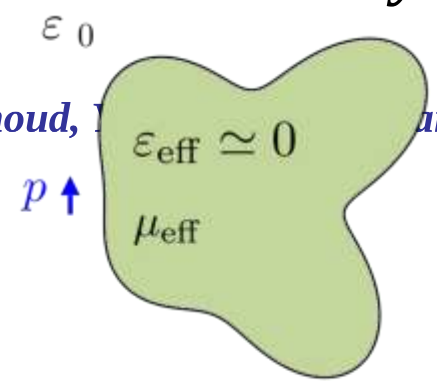
Example 1: EMNZ $\mu_{eff} = 0$

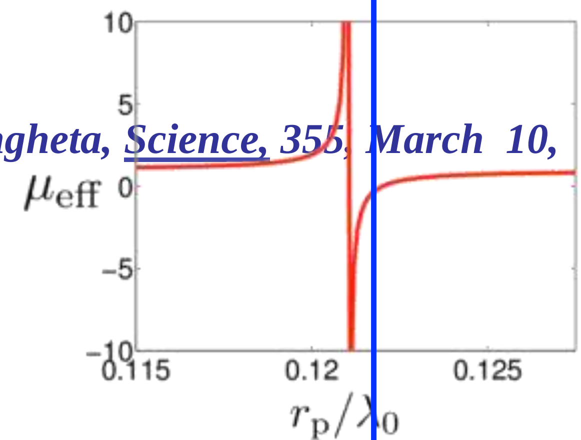
Rod in ENZ

EMNZ Body

. Mahmoud, ... and N. Engheta, Science, 355, March 10,

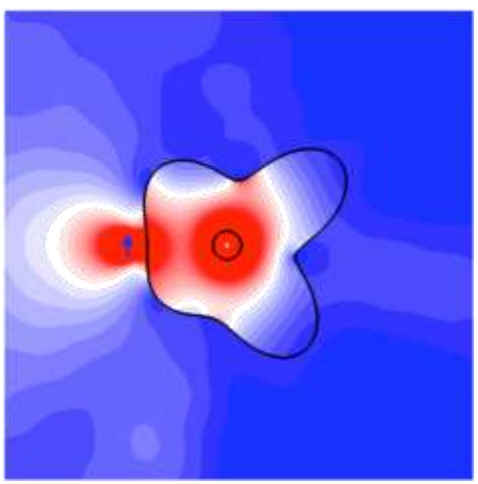


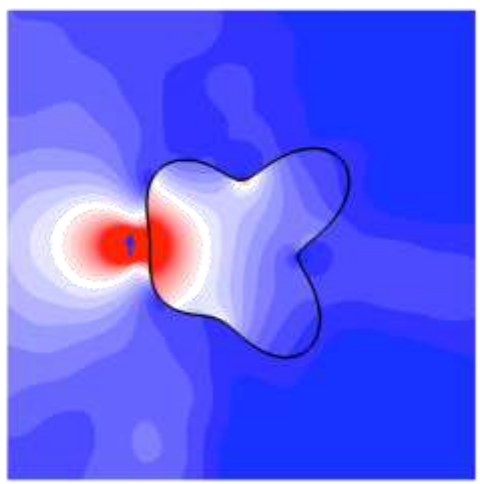


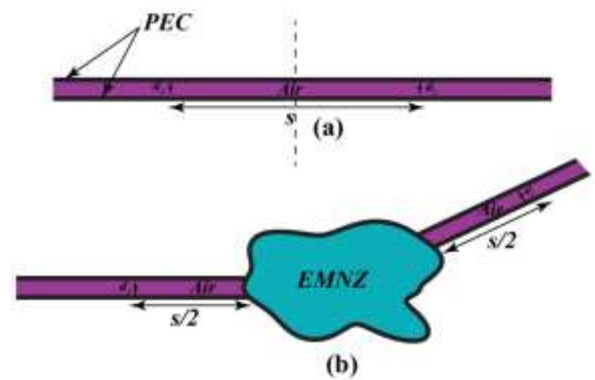


$\varepsilon_{eff} = 0$ $\mu_{eff} = 0$

EMNZ



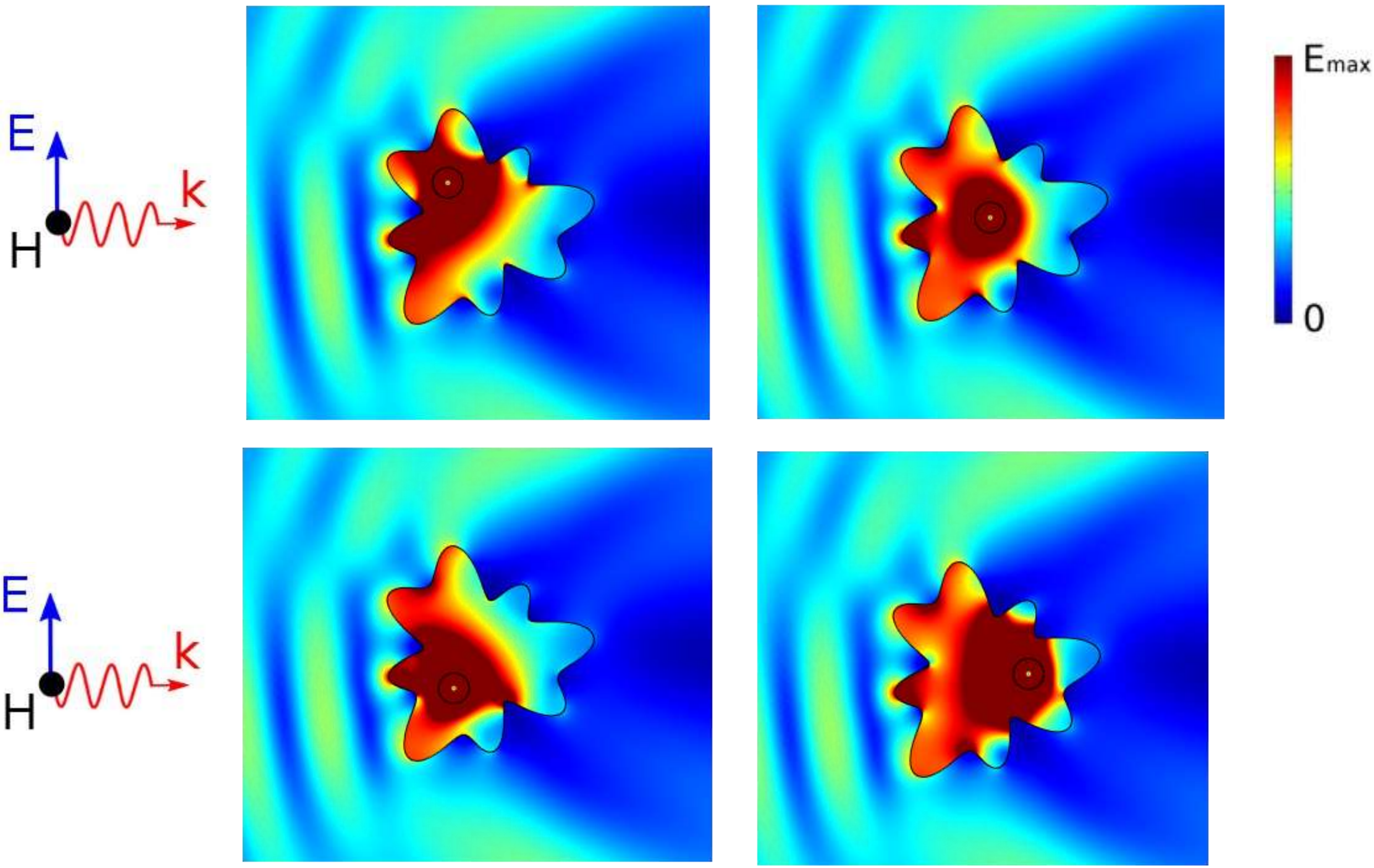




Mahmoud, Liberal & Engheta
Optical Materials Express, Feb 2017

2017

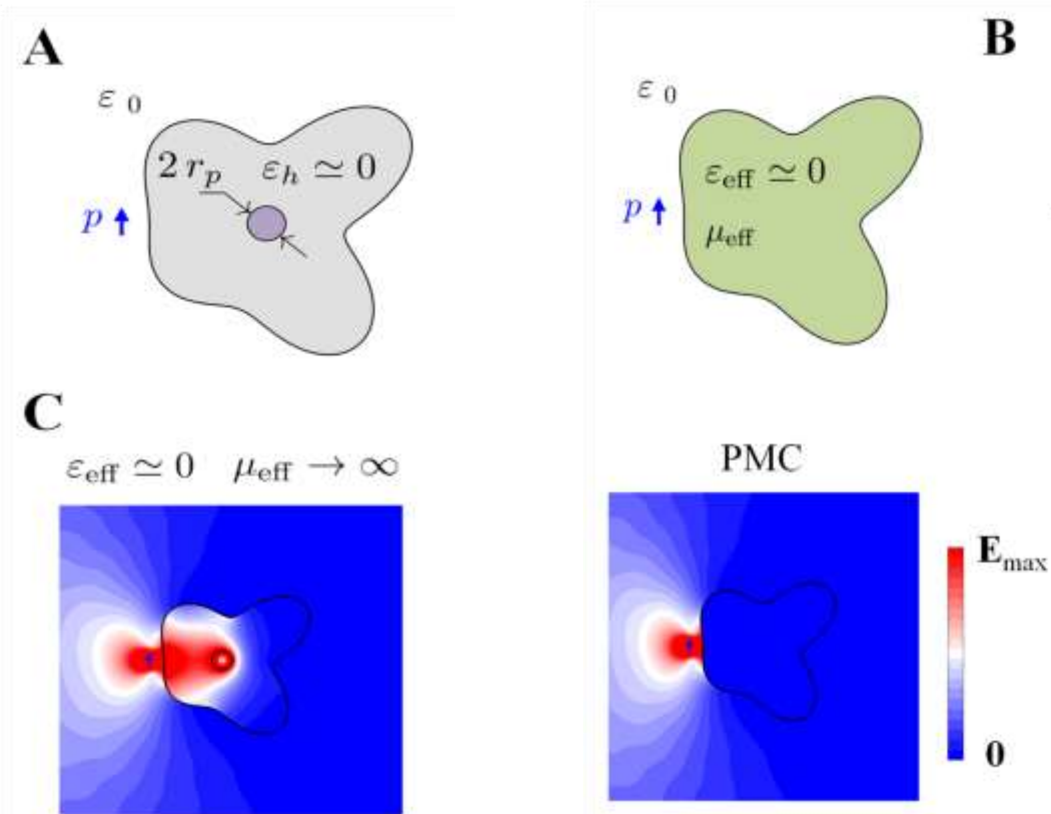
Rod Position Independence


E
k
H
E
k
H
Emax
0

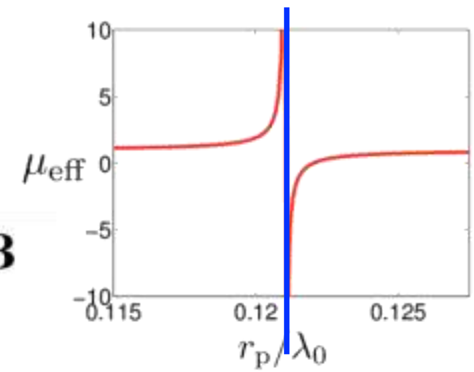
I. Liberal, Y. Li, A. Mahmoud, B. Edwards and N. Engheta, Science, March 10, 2017

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

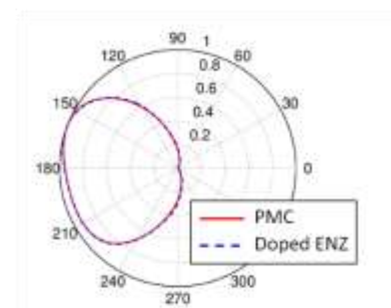
PMC Body



A
ε_0
$2\,r_p$
$\varepsilon_h \simeq 0$
p
ε_0
$\varepsilon_{\rm eff} \simeq 0$
$\mu_{\rm eff}$
p
B
C
$\varepsilon_{\rm eff} \simeq 0 \quad \mu_{\rm eff} \rightarrow \infty$
PMC
$\mathbf{E}_{\rm max}$
0



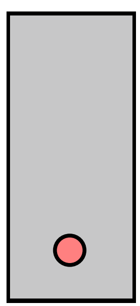
$\mu_{\rm eff}$
$r_{\rm p}/\lambda_0$
10
5
0
−5
−10
0.115
0.12
0.125

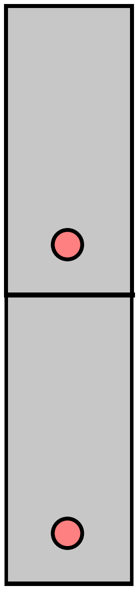


90
120
60
150
30
180
0
210
240
270
300
1
0.8
0.6
0.4
0.2
PMC
Doped ENZ

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

ENZ-based Metasurfaces





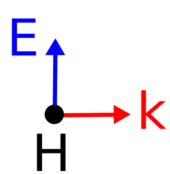
ω_c/ω_p	ΔT (%)	$\Delta\varepsilon_p$ (%)

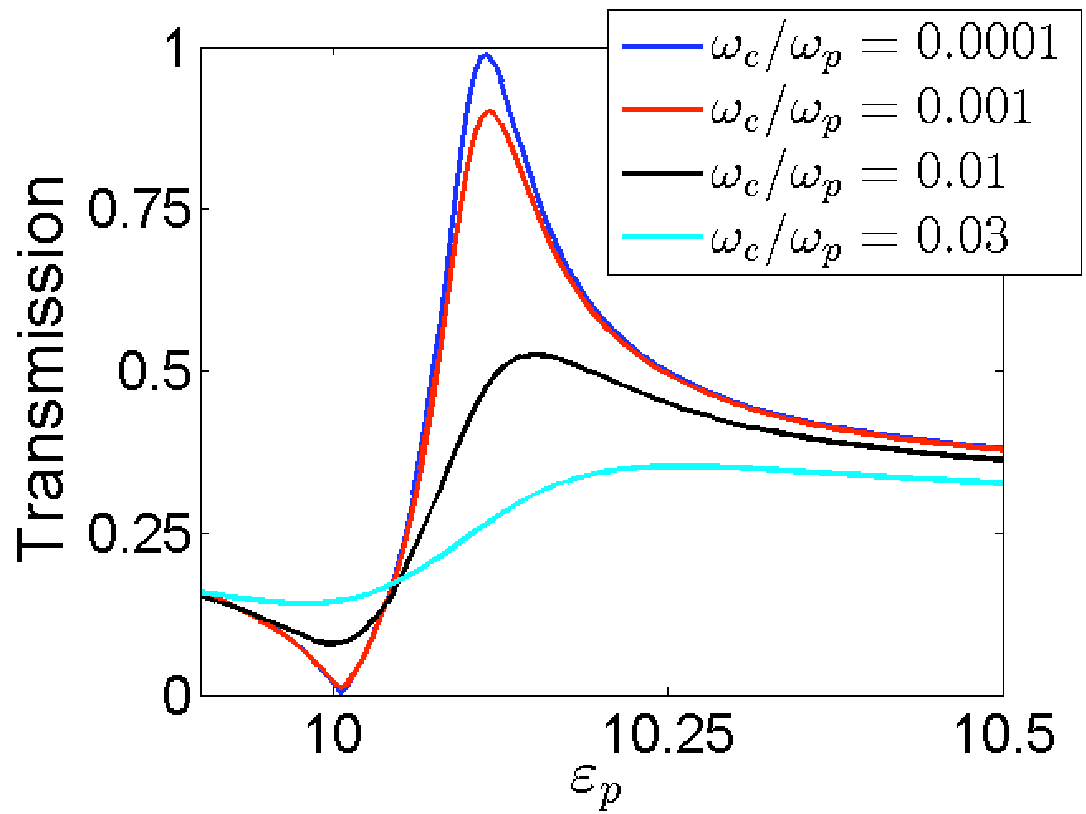
0.0001	98.49	1.09
0.001	88.96	1.09
0.01	44.61	1.49
0.03	21.18	2.77

$L_x = 1\ \lambda_0$

$L_y = 3\ \lambda_0\ r_p =$

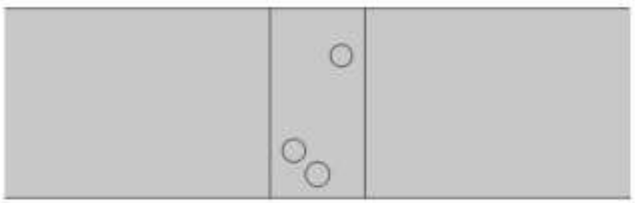
$0.121\ \lambda_0$

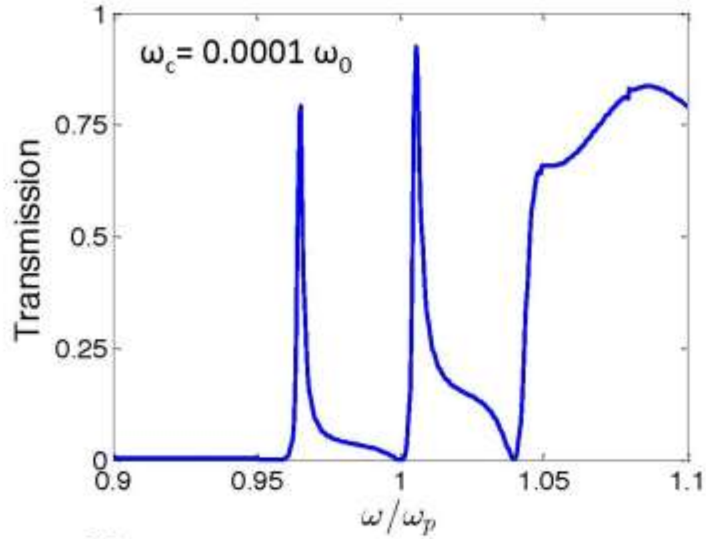




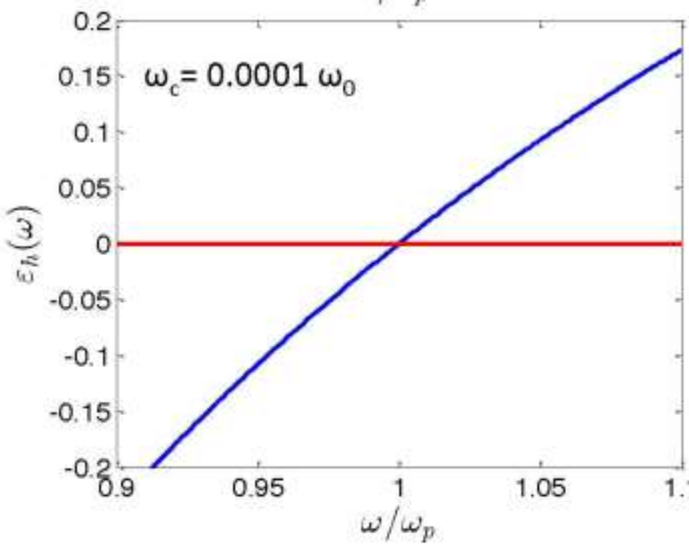
Multi-Rod ENZ-based Metasurface

Multi-Rod ENZ-based Metasurface





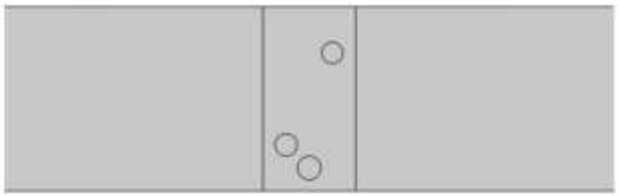
$L_y = 2\ \lambda_p$
$L_x = 1\ \lambda_p$
$\varepsilon_h = 1 - \omega^2{}_p/\omega/(\omega + i\ \omega_c)$
$\varepsilon_p = 10$
$r_1 = 0.1274\ \lambda_p$
$r_2 = 0.121\ \lambda_p$
$r_3 = 0.1153\ \lambda_p$



*Peak values might actually be larger than in the figure due to the number of points simulated.

Multi-Rod ENZ-based Metasurface

Multi-Rod ENZ-based Metasurface



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$\varepsilon_h = 1 - \omega^2_p/\omega/(\omega + i\ \omega_c)$
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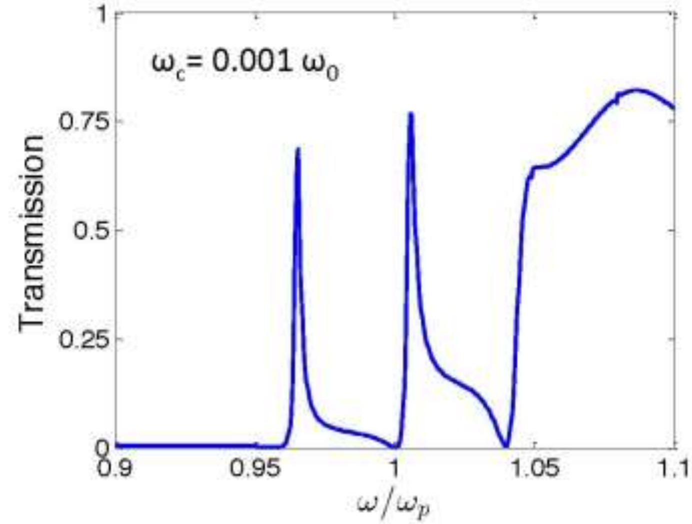
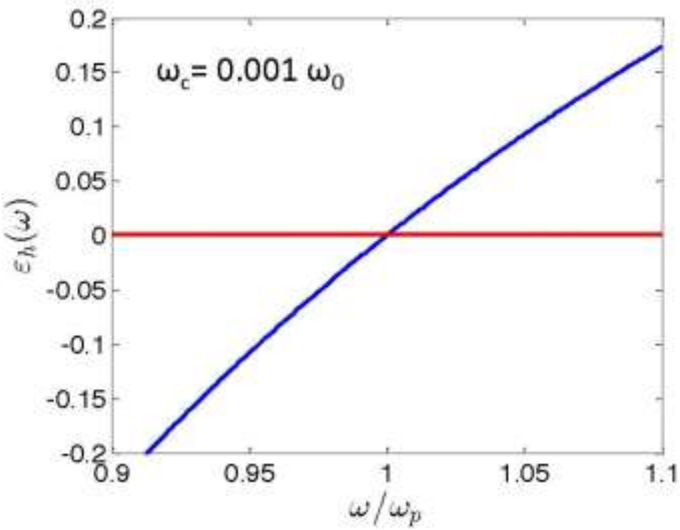
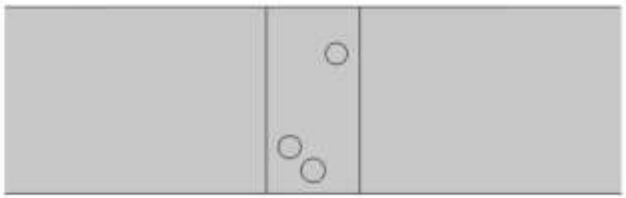
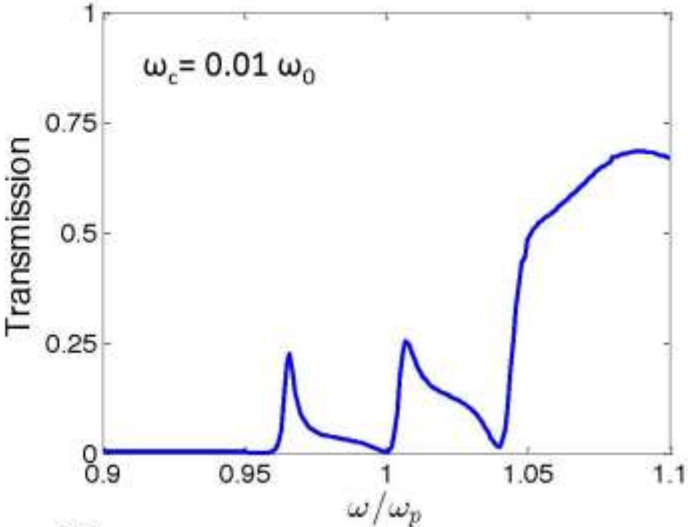




Multi-Rod ENZ-based Metasurface

Multi-Rod ENZ-based Metasurface





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$\varepsilon_h = 1 - \omega^2{}_p/\omega/(\omega + i\ \omega_c)$
$\varepsilon_p = 10$
$r_1 = 0.1274\ \lambda_p$
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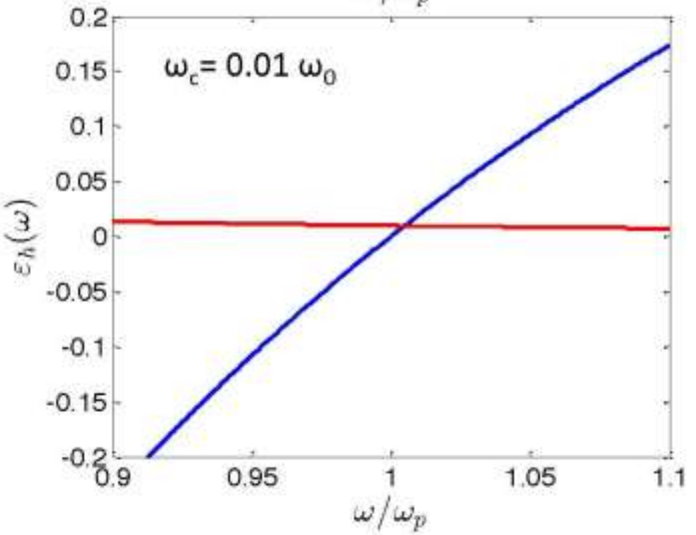
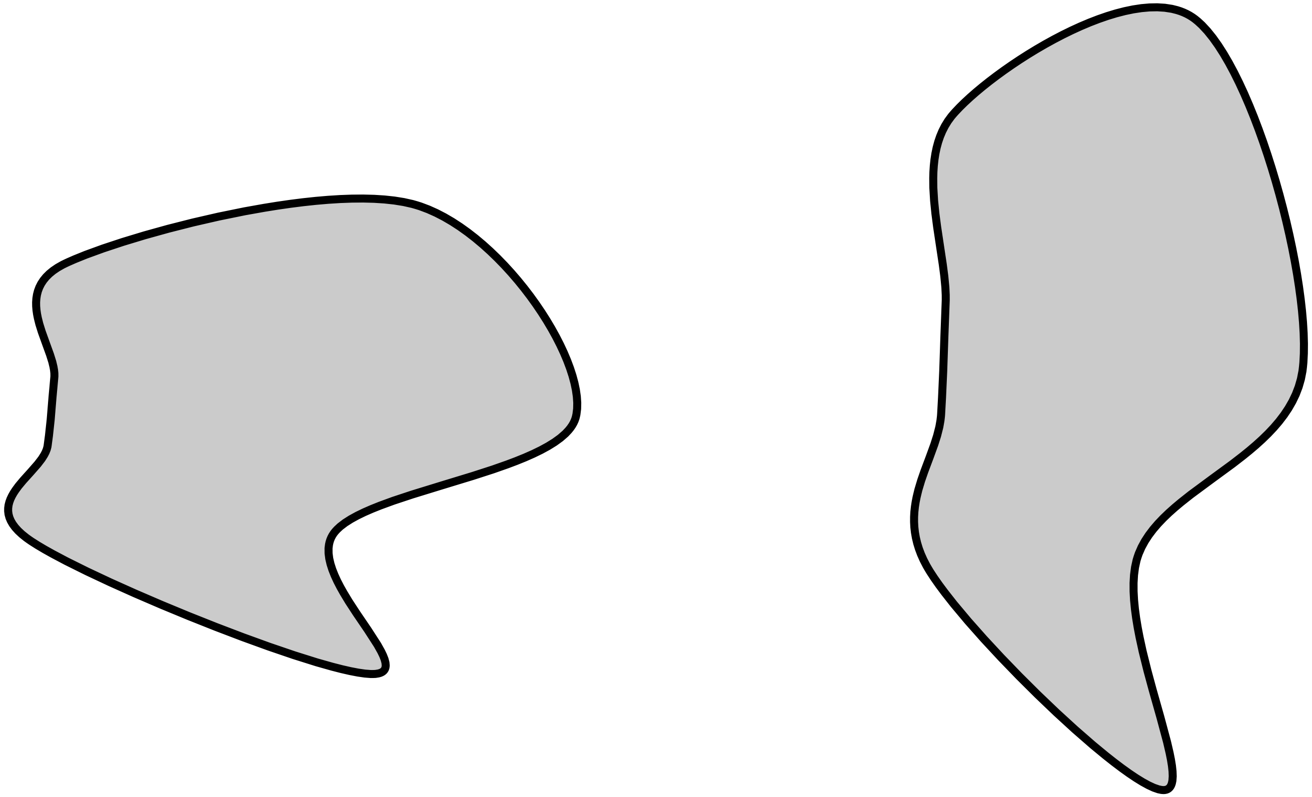


*Peak values might actually be larger than in the figure due to the number of points simulated.

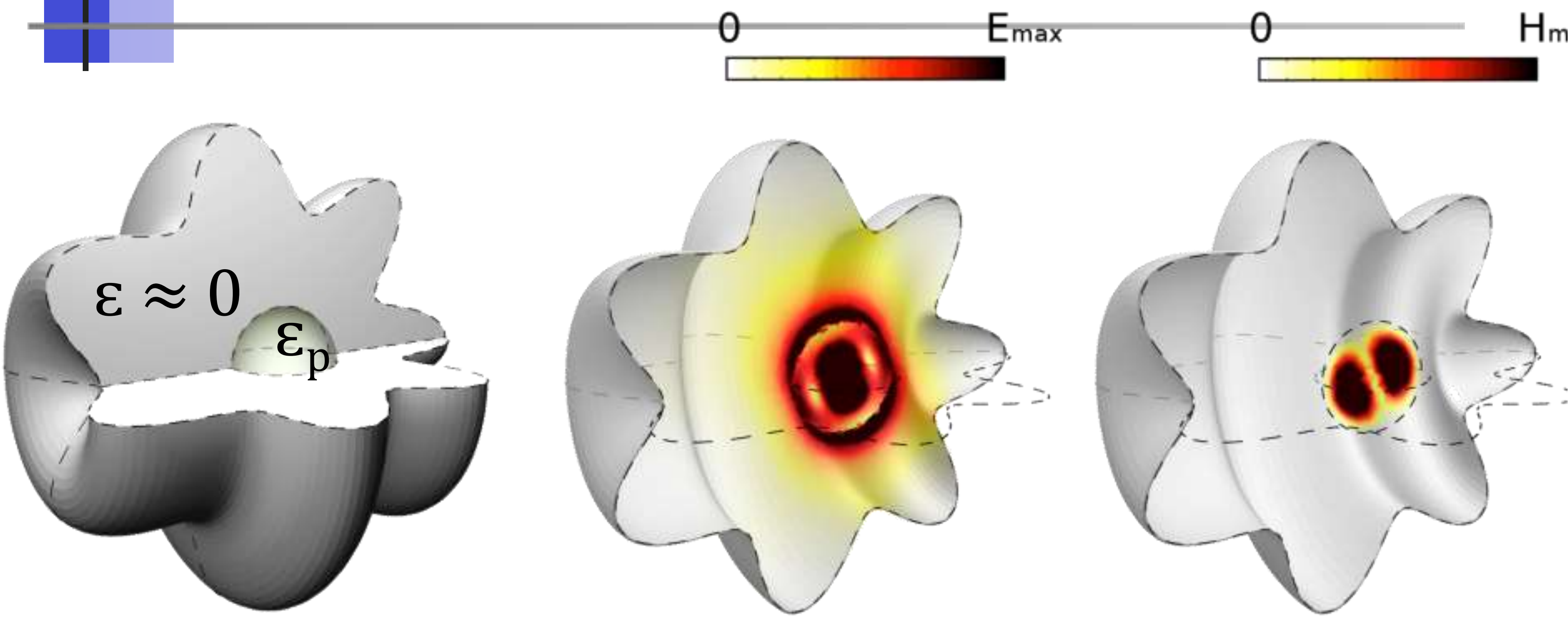
"Extreme" Cavity Resonators

Conventional Cavity



ω_n $\omega'_n \neq \omega_n$

"Ph-Doped" ENZ and "Open Cavity"

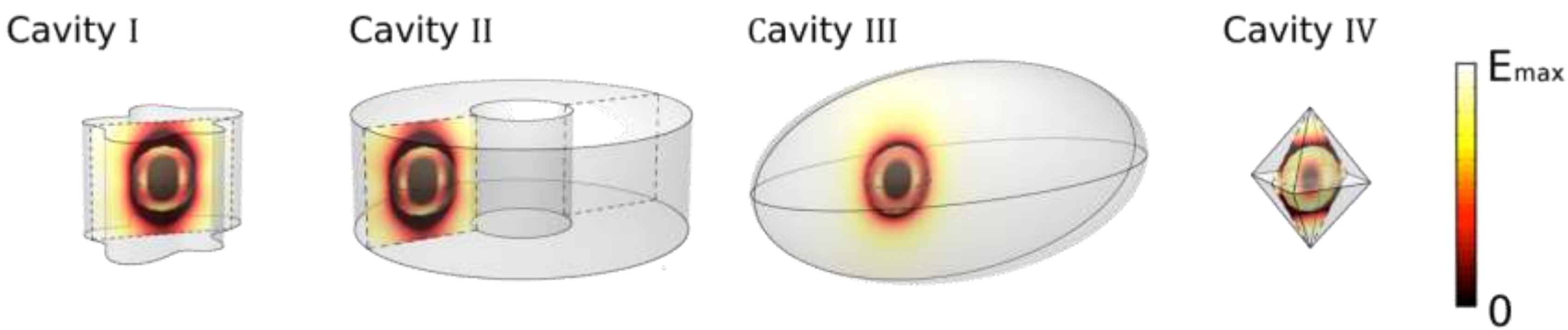


I. Liberal and N. Engheta, Science Advances, 2016

Flexible "Open" Cavity

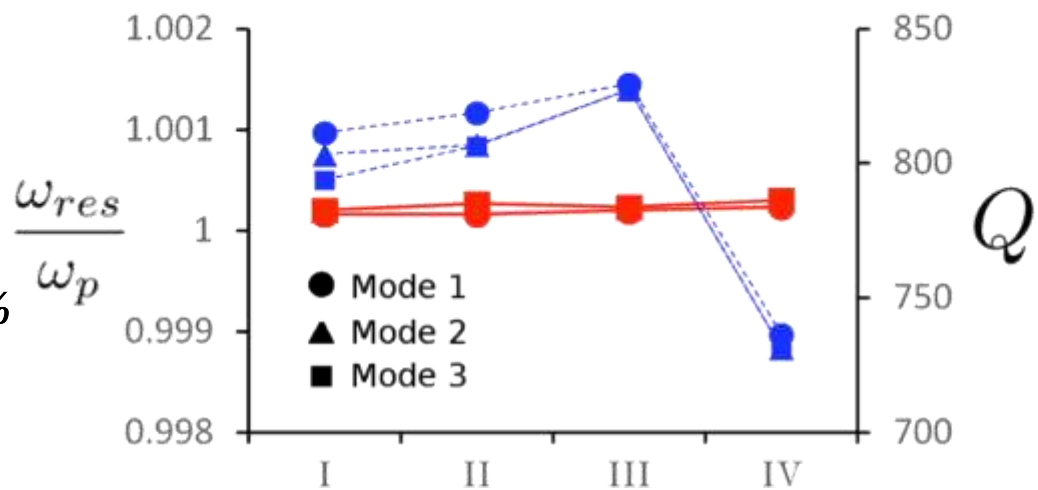
I. Liberal and N. Engheta, Science Advances, 2016

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



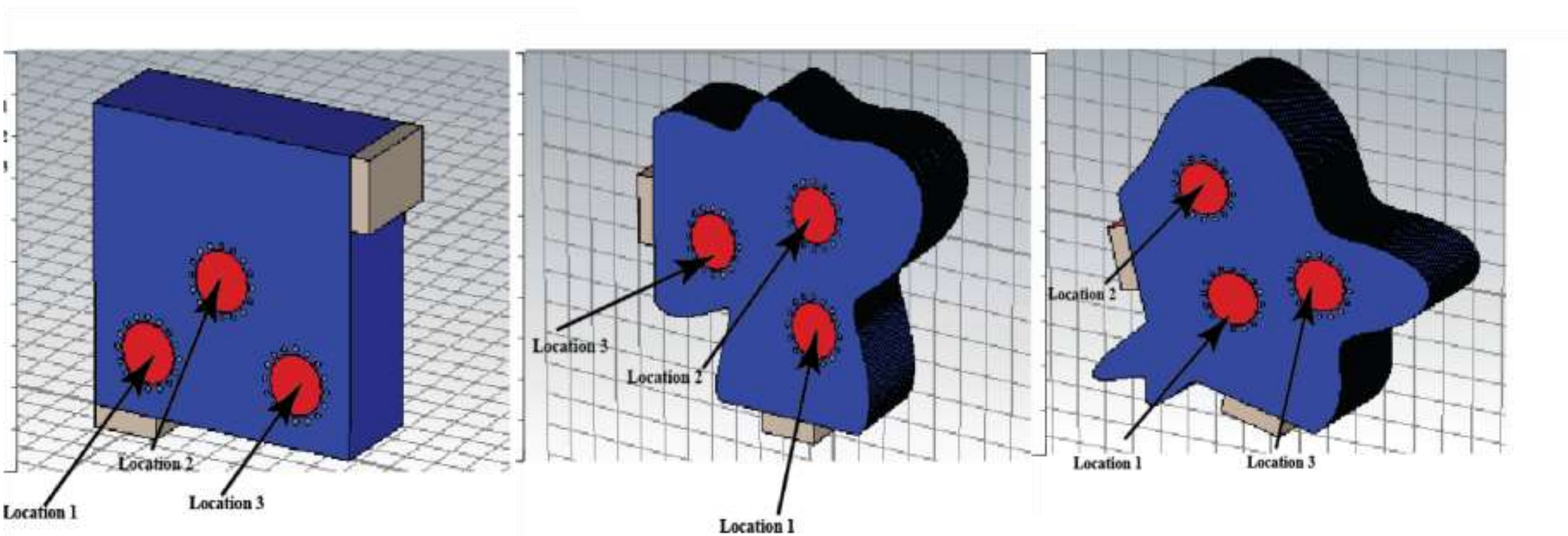
- ***Three degenerate eigenmodes (spherical defect)***
- ***Eigenfrequency variation < 0.05% (induced by losses)***

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



Experimental Verification of

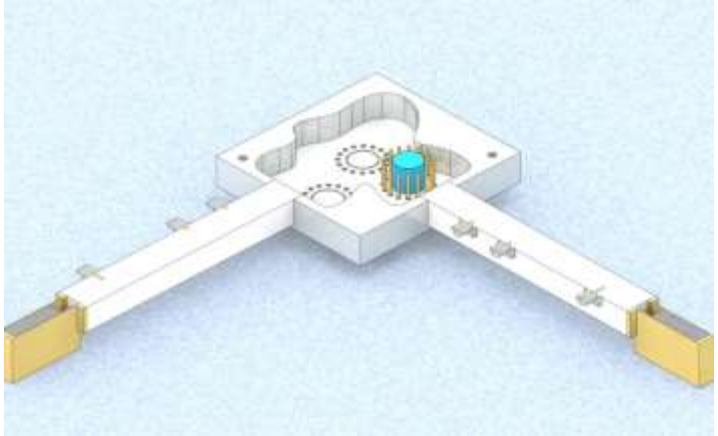
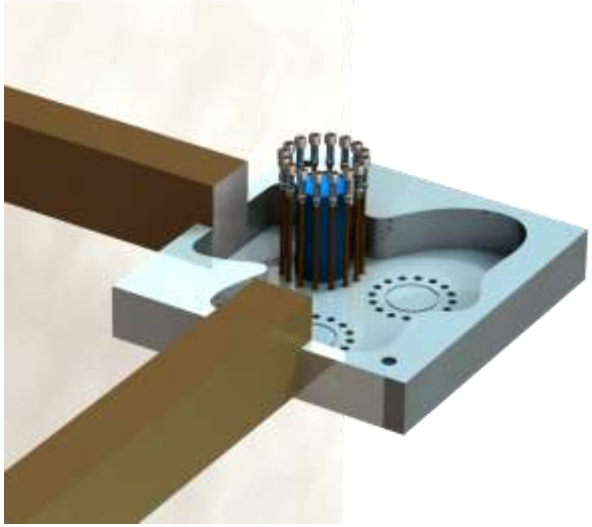
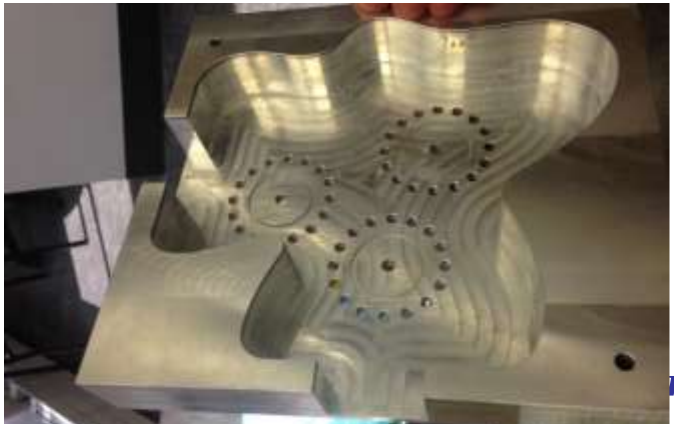
"geometry-invariant" cavities"



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

Experimental Verification of

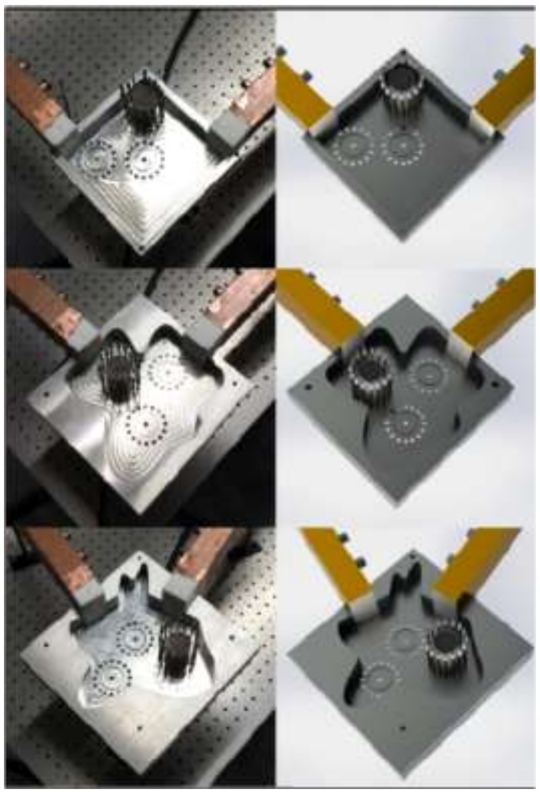
"geometry-invariant cavities"

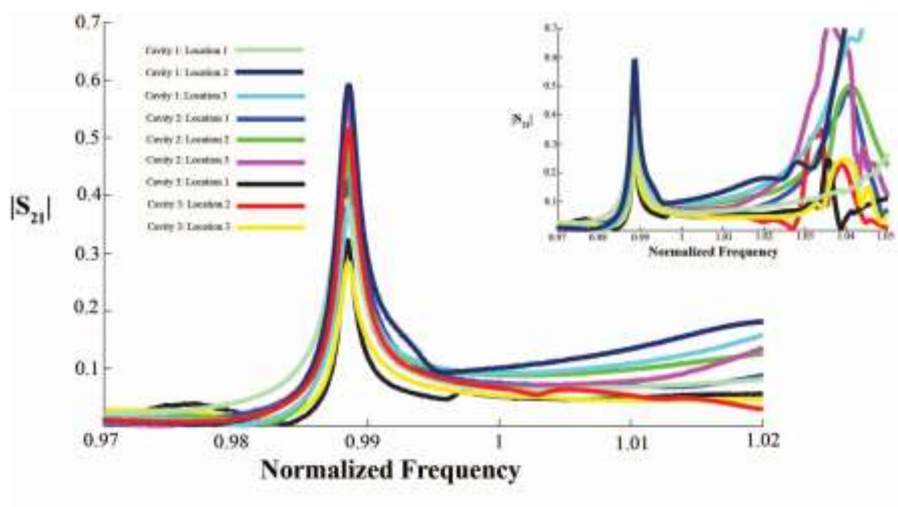





I. ... rds and N. Engheta, Scie...

Experimental Verification of

"geometry-invariant cavities"



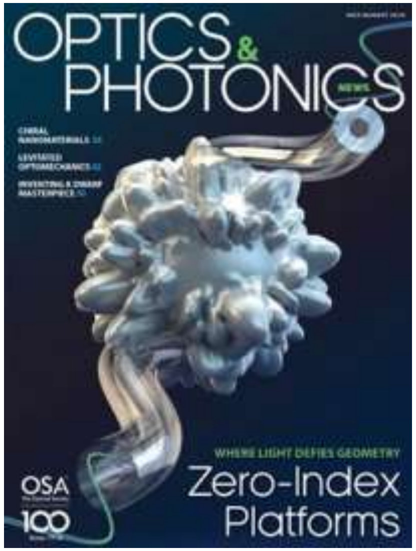


I. Liberal, Y. Li, A. Mahmoud, B. Edwards and N. Engheta, Science, March 10, 2017

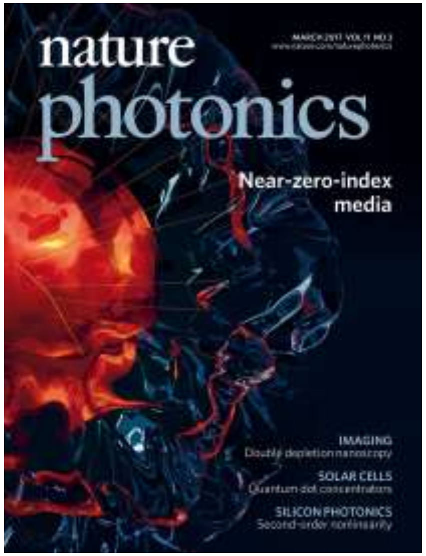
Summary

Low-Index Photonics can play interesting roles in MTM

ENZ/MNZ/EMNZ can play important roles in classical and quantum electrodynamics



I. Liberal & N. Engheta, OPN, July/Aug 2016



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