Extreme Platforms for Extreme Photonics

Nader Engheta
With special thanks to
Brian Edwards
Inigo Liberal
Nasim Mohammadi Estakhri
Ahmed Mahmoud
Yue Li
Yaakov Lumer

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**Extreme Photonics - 1**

**Photonic Doping**

\[ A_{\text{ext}} \]

\[ \varepsilon(r) \]

\[ A = A_{ENZ} + \sum_p A_p \]

\[ \varepsilon_h \approx 0 \]

\[ \partial A \]

\[ \mu_p \]

\[ \xi_p \]

**Peculiar Effective Medium Properties**

\[ \text{Liberal, Mahmoud, Li, Edwards, Engheta, Science, 2017} \]
Thermal Engineering with Zero-Index Media

Photonic Doping

Engineering Thermal Emission

Liberal & Engheta, CLEO Conference, May 15, 2017
Extreme Photonics - 3

Extreme Resonant Cavities

Geometry-Independent Cavities

Bound State in the Continuum

Liberal and Engheta, Nature Photonics, March 2017

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

Mahmoud, Liberal and Engheta, Nature Communications, 2016
Quantum Optics of ZIM

Extreme Quantum Optics

Engineering Rabii Frequencies without detuning

Liberal and Engheta, *PNAS*, 2017
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


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

Si

Doped Semiconductor
How about “photonic doping”?

“Pure” Photonic Material

Dielectric Particle

ENZ?
Conventional Effective Medium Theory (EMT)

2D structure

Small particles $a \ll \lambda_0$

Small inter-particle separations $d \ll \lambda_0$

Large number of particles $N \gg 1$

Difficulties on boundaries with a small curvature radius

Difficulties on the interaction with near fields

$\varepsilon_{\text{eff}}$

$\mu_{\text{eff}}$
What if the host is an ENZ medium?

Arbitrary particle size
a < \lambda_0, a \sim \lambda_0 or a > \lambda_0

Arbitrary number of particles
N = 1 or N >> 1

Arbitrary inter-particle separation
d < \lambda_0, d \sim \lambda_0 or d > \lambda_0

Arbitrary boundaries

2D structure

\[ \epsilon_{\text{host}} \approx 0 \]

\[ \epsilon_{\text{eff}} \approx 0 \]

\[ \mu_{\text{eff}} = 1 + \sum_d \Delta \mu_d \]

I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017
Background on Epsilon-Near-Zero (ENZ)

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)

\[ \varepsilon_{ch} = 0.001 \]
**Background: ENZ Structures**

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

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

**From:** N. Zheludev (Southampton)
*Oue et al., Nat. Commun. (2014)*

**From:** C. T. Chan's

**From:** V. Vesselov, et al., *PRL (2013)*

**From:** Zayat & Podolskiy
*Pollard, et al., PRL (2009)*

**StackSEM from:** Mass, et al., *Nat. Photon. (2013)*
**Background: One of ENZ Properties**

- **Maxwell Equations**
  \[ \nabla \times H = -i \omega \varepsilon E \quad \nabla \times H = 0 \]
  \[ \nabla \times E = i \omega \mu H \]

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

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

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**References**

Photonic “Doping”

\[ \varepsilon_{\text{eff}} \approx 0 \]

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

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

\[
\mu_{\text{eff}} = \frac{1}{A} \left[ A_h + \frac{2\pi r_p}{k_p} \frac{J_1 (k_p r_p)}{J_0 (k_p r_p)} \right]
\]
Photonic “Doping”
2D Generic Structures

\[ A = A_{ENZ} + \sum p A_p \]

\[ \varepsilon_h \approx 0 \]

\[ \varepsilon_{eff} \approx 0 \]

\[ \mu_{eff} = 1 + \sum_d \Delta \mu_d \]

\[ \Delta \mu_d = \frac{1}{A} \left[ \int_{A_d} \psi^d (r) dA - A_d \right] \]
Example 1: EMNZ

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

Rod in ENZ

$\varepsilon_0$

$2r_p \varepsilon_h \approx 0$

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

EMNZ Body

$\varepsilon_0$

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

$\mu_{\text{eff}}$

EMNZ

$\varepsilon_0$

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

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 \[ \mu_{\text{eff}} = \infty \]

**Rod in ENZ**

A

\[ \varepsilon_0, 2r_p, \varepsilon_n \simeq 0 \]

C

\[ \varepsilon_{\text{eff}} \simeq 0, \mu_{\text{eff}} \to \infty \]

**PMC Body**

B

\[ \varepsilon_0, \mu_{\text{eff}} \]

**PMC**

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** \((\omega = 0.985 \, \omega_p)\) \quad **EMNZ Point** \((\omega = \omega_p)\)
“Extreme” Cavity Resonators
Conventional Cavity

$\omega_n \neq \omega'_n$
“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, Science, 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

\[ \varepsilon_{\text{eff}} \approx 0 \]

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

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

\[ \mu_{\text{eff}} = 1 + \sum \Delta \mu_d \]

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

I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017
ENZ-based Metasurface with PEC rods

Filling ENZ Metasurface with conducting parts

\[ \varepsilon_{\text{eff}} \approx 0 \]

\[ \mu_{\text{eff}} \approx 1 - \frac{A_{\text{PEC}}}{A} \]

\[ \mu_{\text{eff}} \to 0 \]

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