Physics and Applications of Epsilon-Near-Zero Materials

How Light Behaves when the Refractive Index Vanishes

Robert W. Boyd

Department of Physics and
Max-Planck Centre for Extreme and Quantum Photonics
University of Ottawa

Institute of Optics and Department of Physics and Astronomy
University of Rochester

The visuals of this talk are posted at boydnlo.ca/presentations

Presented at Photonics West, San Francisco, February 2, 2019

Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
- Huge NLO Response of ENZ Materials and Metastructures
- Non-perturbative Nature of the NLO Response
- Some Applications of ENZ Materials

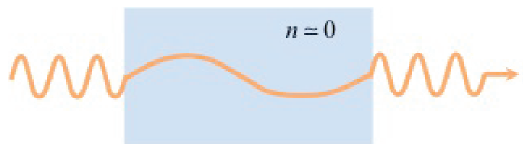
Physics of Epsilon-Near-Zero (ENZ) Materials

- ENZ materials possess exotic electromagnetic properties

Recall that $n = \sqrt{\epsilon\mu}$ where ϵ is the permittivity and μ is the magnetic permeability

Many opportunities in photonics are afforded by ENZ materials and ZIM (zero-index materials)

$$\lambda = \lambda_{\text{vac}}/n \qquad v = c/n$$



For $n = 0$ the wavelength is stretched and the phase velocity becomes infinite

Light oscillates in time but not in space; oscillations are in phase everywhere

Silveirinha and Engheta, Phys. Rev. Lett. 97, 157403 (2006).

- Radiative processes are modified in ENZ materials

Einstein A coefficient (spontaneous emission lifetime = $1/A$)

$A = n\, A_{\text{vac}}$

We can control (inhibit!) spontaneous emission!

Einstein B coefficient

Stimulated emission rate = B times EM field energy density

$B = B_{\text{vac}} / n^2$

Optical gain is very large!

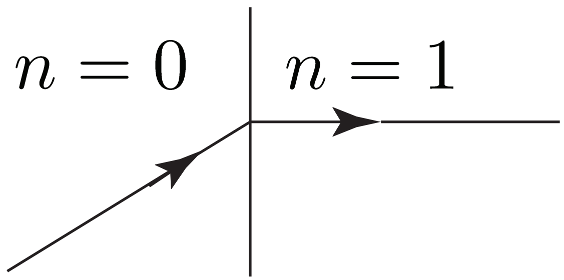
Einstein, Physikalische Zeitschrift 18, 121 (1917).
Milonni, Journal of Modern Optics 42, 1991 (1995).

Physics of Epsilon-Near-Zero (ENZ) Materials -- More

- Snell's law leads to intriguing predictions

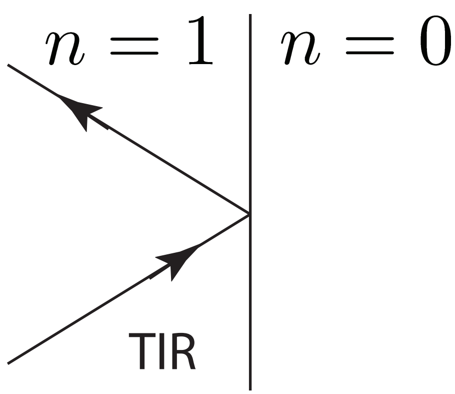
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

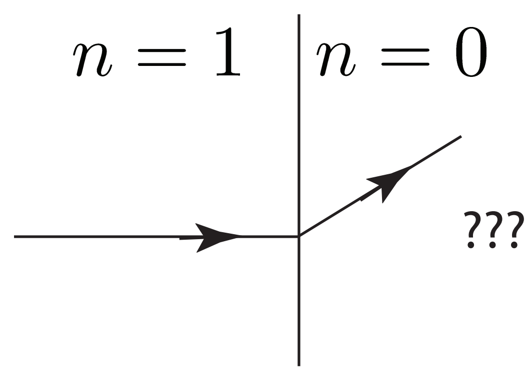
- Light always leaves perpendicular to surface of ENZ material!



Y. Li, et al., Nat. Photonics 9, 738, 2015; D. I. Vulis, et al., Opt. Express 25, 12381, 2017.

- Thus light can enter an ENZ material only at normal incidence!

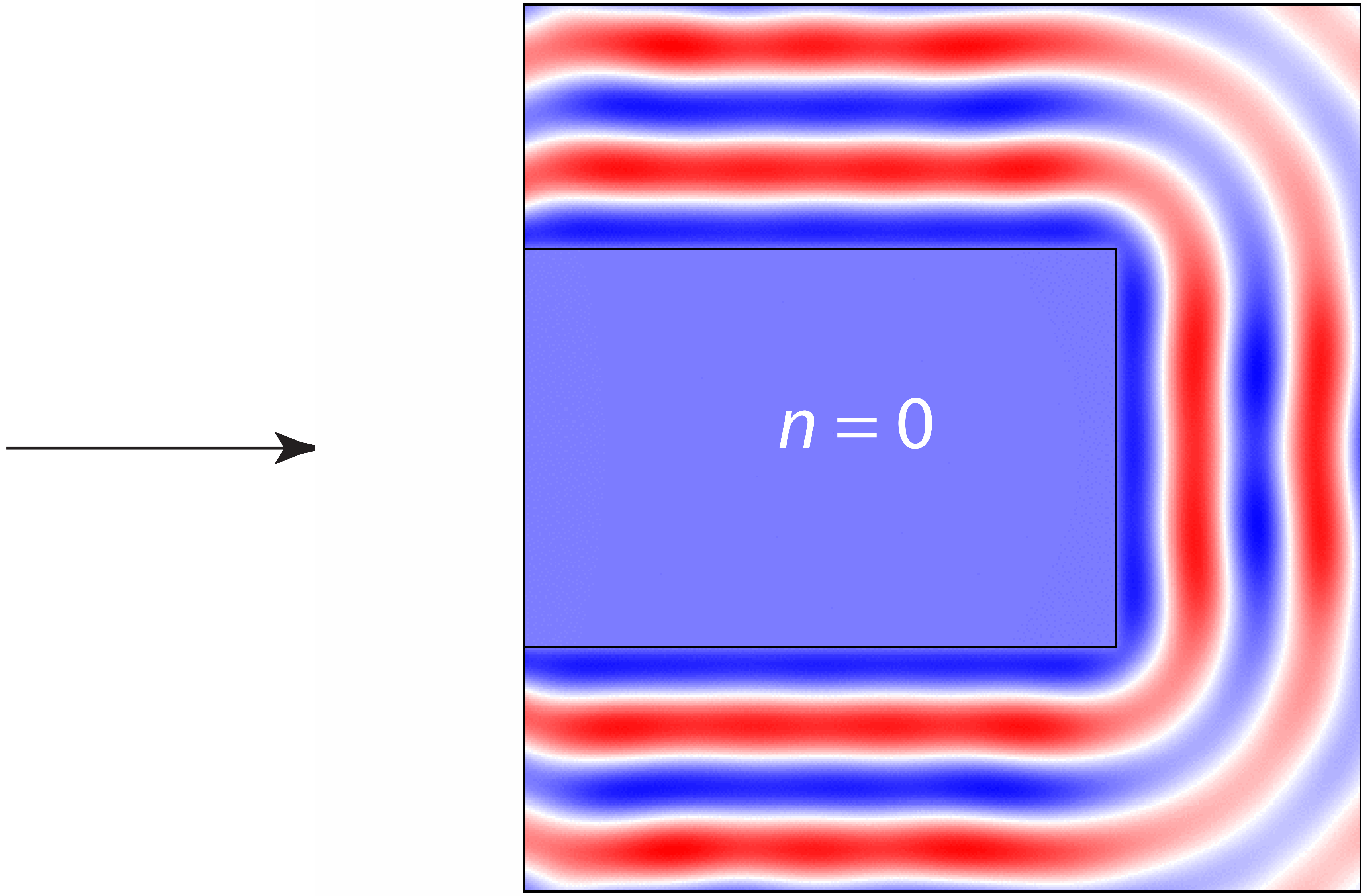




Y. Li, et al., Nat. Photonics 9, 738, 2015.

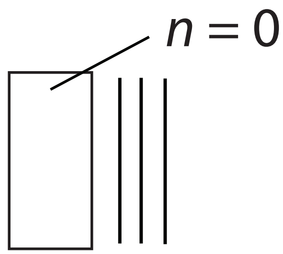
Maxwell Equations Prediction

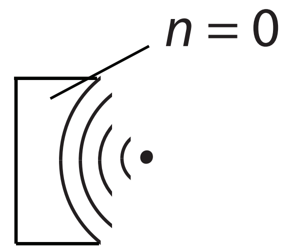
- light enters slab at normal incidence



Some Consequences of ENZ Behaviour - 1

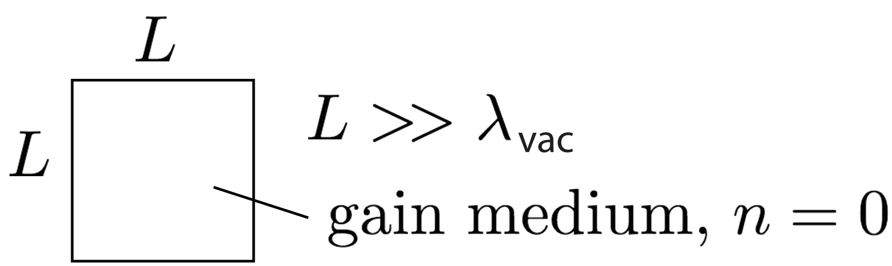
- Funny lenses





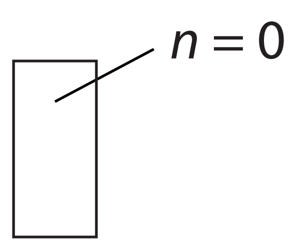
A. Alù et al., Phys. Rev. B 75, 155410, 2007; X.-T. He, ACS Photonics, 3, 2262, 2016.

- Large-area single-transverse-mode surface-emitting lasers



J. Bravo-Abad et al., Proc. Natl. Acad. Sci. USA 109, 976, 2012.

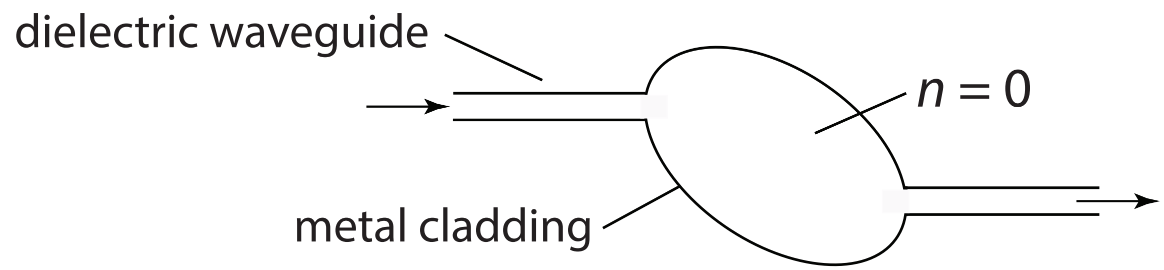
- No Fabry-Perot interference



O. Reshef et al., ACS Photonics 4, 2385, 2017.

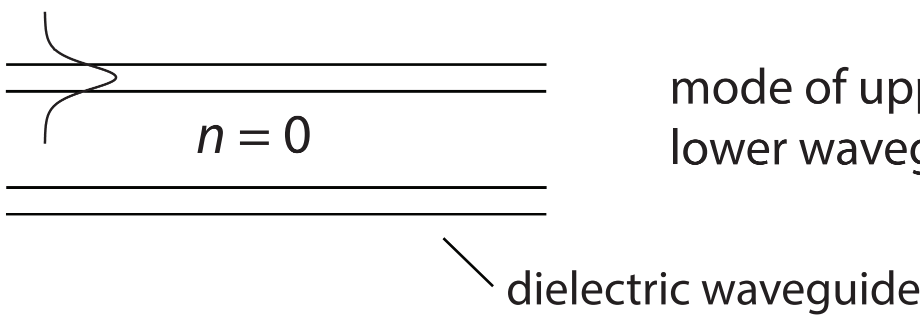
Some Consequences of ENZ Behavior - 2

- Super-coupling (of waveguides)



M. G. Silveirinha and N. Engheta, Phys. Rev. B 76, 245109, 2007; B. Edwards et al., Phys. Rev. Lett. 100, 033903, 2008.

- Large evanescent tails for waveguide coupling

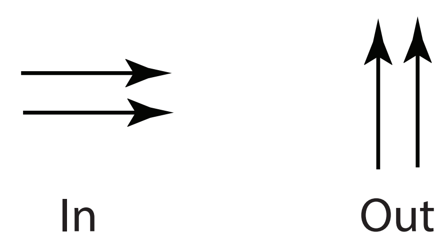


mode of upper waveguide extends to lower waveguide for any separation

- Automatic phase matching of NLO processes

Recall that $k = n\,\omega / c$ vanishes in an ENZ medium.

For example, the following 4WM proces is allowed



H. Suchowski et al., Science 342, 1223, 2013.

Some Consequences of ENZ Behaviour - 3

- How is the theory of self-focusing modified?
- Does the theory of Z-scan need to be modified?
- How is the theory of blackbody radiation modified?
- Do we expect very strong superradiance effects?
- More generally, how is any NLO process modified when $n_0 = 0$?

Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
- Huge NLO Response of ENZ Materials and Metastructures
- Non-perturbative Nature of the NLO Response
- Some Applications of ENZ Materials

Epsilon-Near-Zero Materials

- Metamaterials

  Materials tailor-made to display ENZ behaviour

- Homogeneous materials

  All materials display ENZ behaviour at their (reduced) plasma frequency

  Recall the Drude formula

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

Note that $\mathrm{Re}\,\epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

- Challenge: Obtain low-loss ENZ materials

  Want Im ε as small as possible at the frequency where Re $\varepsilon = 0$.

- We are examining a several materials

  ITO: indium tin oxide

  AZO: aluminum zinc oxide

  FTO: fluorine tin oxide

Epsilon-Near-Zero Materials for Nonlinear Optics

- We need materials with a much larger NLO response

- We recently reported a material (indium tin oxide, ITO) with an n_2 value 100 time larger than those previously reported.

- This material utilizes the strong enhancement of the NLO response that occurs in the epsilon-near zero (ENZ) spectral region.

Large optical nonlinearity of indium tin oxide in its epsilon-near-zero region,
M. Zahirul Alam, I. De Leon, R. W. Boyd, Science 352, 795 (2016).

Implications of ENZ Behavior for Nonlinear Optics

Here is the intuition for why the ENZ condition is of interest in NLO

Recall the standard relation between n_2 and $\chi^{(3)}$

$$n_2 = \frac{3\chi^{(3)}}{4\epsilon_0 c\, n_0\, \mathrm{Re}(n_0)}$$

Note that under ENZ conditions the denominator becomes very small, leading to a very large value of n_2

Footnote:

Standard notation for perturbative NLO

$$P = \chi^{(1)}E + \chi^{(2)}E^2 + \chi^{(3)}E^3 + \ldots$$

P is the induced dipole moment per unit volume and E is the field amplitude.

Also, the refractive index changes according to

$$n = n_0 + n_2 I + n_4 I^2 + \ldots$$

Optical Properties of Indium Tin Oxide (ITO)

ITO is a degenerate semiconductor (so highly doped as to be metal-like).

It has a very large density of free electrons, and a bulk plasma frequency corresponding to a wavelength of approximately 1.24 μm.

Recall the Drude formula

$$\epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)}$$

Note that $\mathrm{Re}\,\epsilon = 0$ for $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

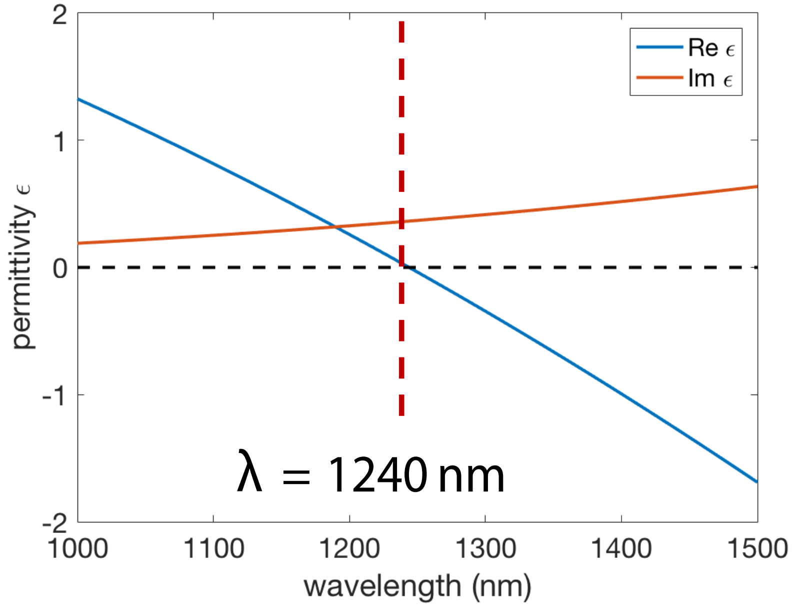
The region near ω_0 is known as the epsilon-near-zero (ENZ) region.

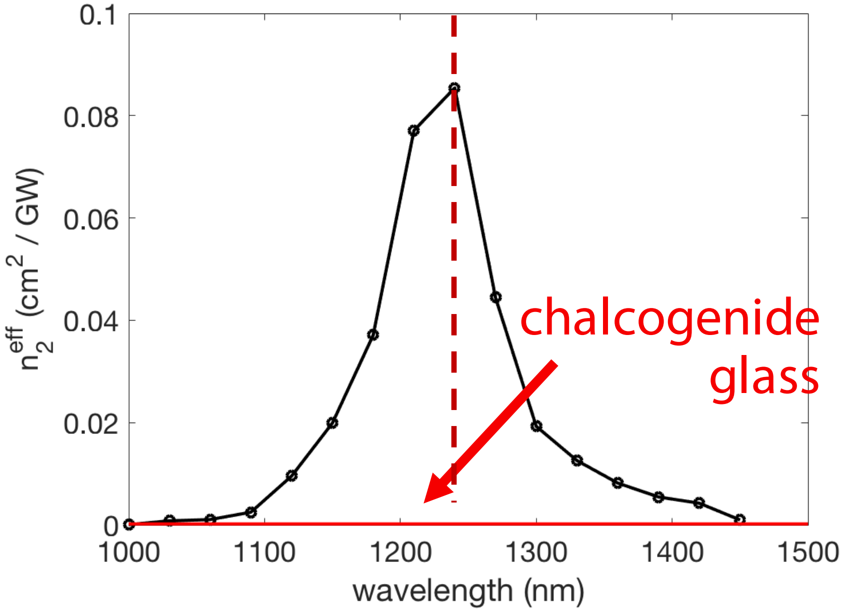
There has been great recent interest in studies of ENZ phenomena:

H. Suchowski, K. O'Brien, Z. J. Wong, A. Salandrino, X. Yin, and X. Zhang, Science 342, 1223 (2013).
C. Argyropoulos, P.-Y. Chen, G. D'Aguanno, N. Engheta, and A. Alu, Phys. Rev. B 85, 045129 (2012).
S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, and F. Capolino, Phys. Rev. B 87, 035120 (2013).
A. Ciattoni, C. Rizza, and E. Palange, Phys. Rev. A 81,043839 (2010).

Huge nonlinear optical response of ITO at its ENZ wavelength

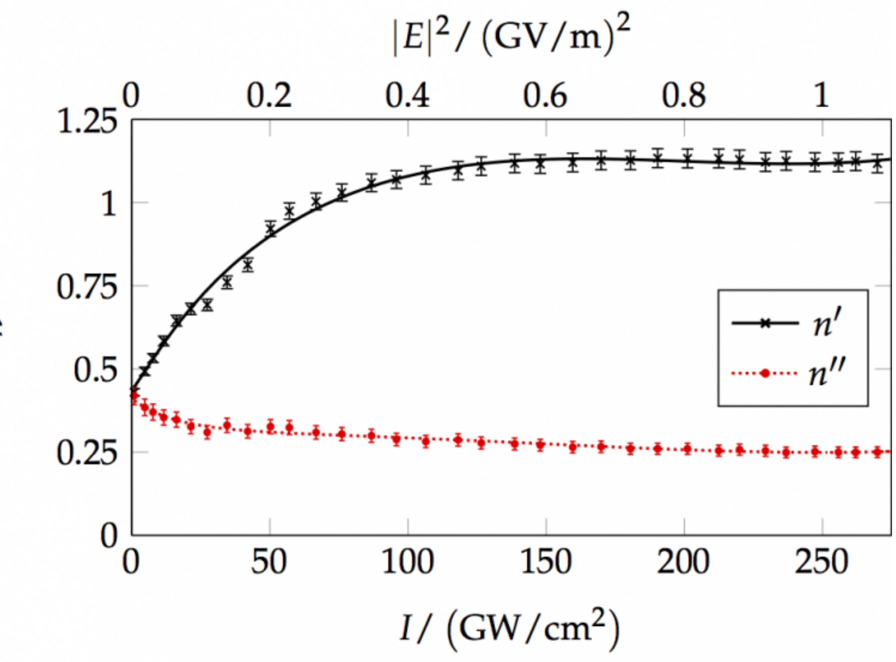
Indium tin oxide (ITO)

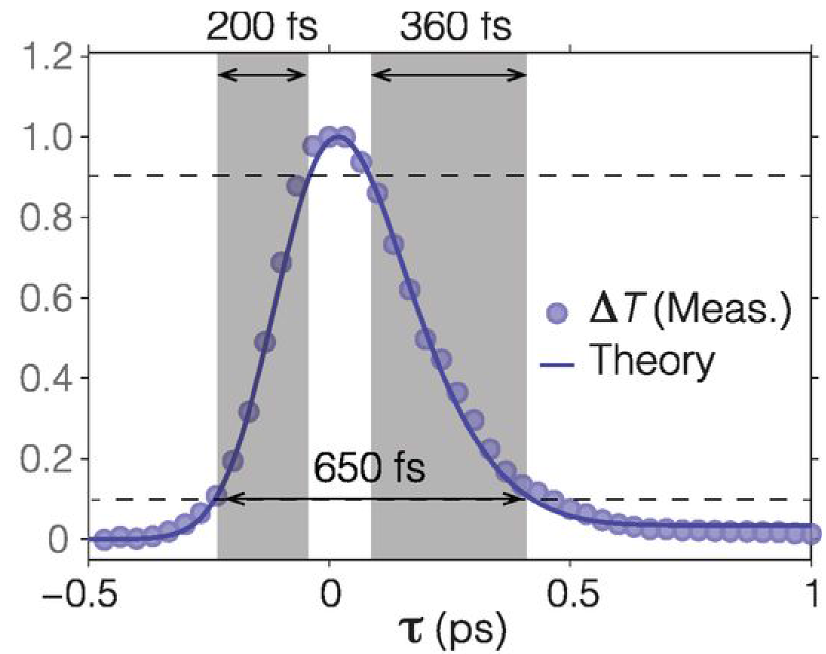




M. Z. Alam et al, Science 352, 795–797 (2016)

Fast, ultra-large response of ITO at its ENZ wavelength





- overall change in refractive index of 0.8

- sub picosecond reponse time

M. Z. Alam et al., Science 352, 795–797 (2016)

Some Nonlinear Optical Materials

Nonlinearity of traditional nonlinear materials:

• SiO_2	$n_2 = 3.2 \times 10^{-20}$ m^2/W	
• SiN	$n_2 = 2.5 \times 10^{-19}$ m^2/W	$10 \times SiO_2$
• Si	$n_2 = 2.7 \times 10^{-18}$ m^2/W	$100 \times SiO_2$
• Chalcogenide glasses	$n_2 = 2.0 \times 10^{-17}$ m^2/W	$600 \times SiO_2$

A new class of materials known as **epsilon-near-zero** materials have demonstrated incredible nonlinear properties

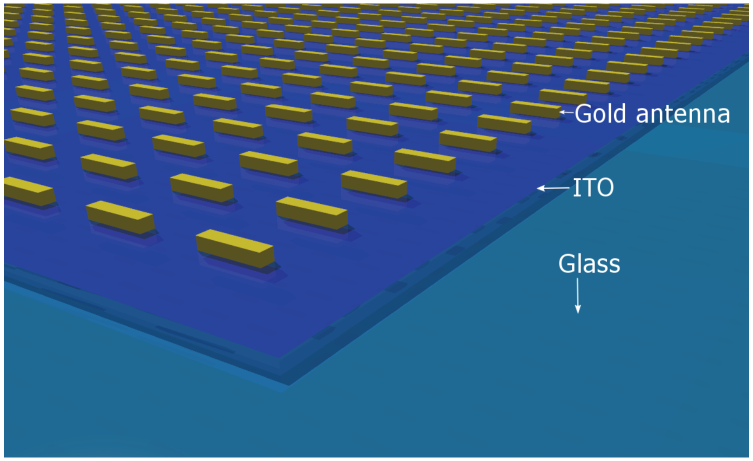
- Indium tin oxide (ITO) $n_2 = 1.1 \times 10^{-14}$ m^2/W 600 × **ChG**
  - $\Delta n = n_2 I = 0.7$
- Al-doped zinc oxide (AZO) $n_2 = 3.5 \times 10^{-17}$ m^2/W 2 × **ChG**
  - $\Delta n/n = 4.4$

R. W. Boyd, *Nonlinear Optics*, Third edition (2008), M. Z. Alam et al., *Science* 352, 795 (2016),
L. Caspani et al., *Physical Review Letters* 116, 233901(2016)

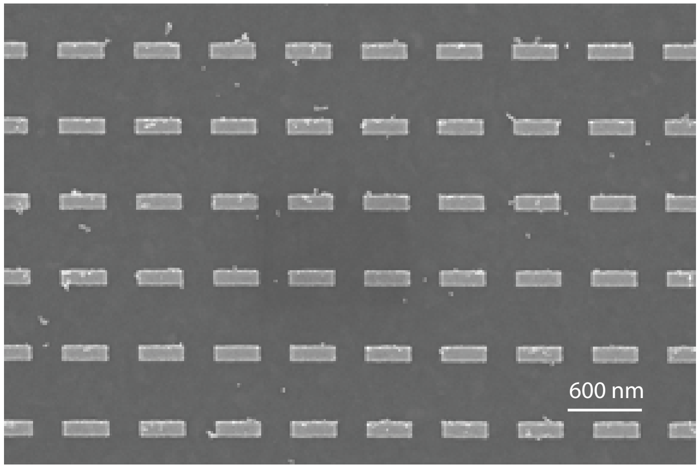
An ENZ Metasurface

- Can we obtain an even larger NLO response by placing a gold antenna array on top of ITO?
- Lightning rod effect: antennas concetrate the field within the ITO
- Coupled resonators: ENZ resonance and nano-antennas

Concept:

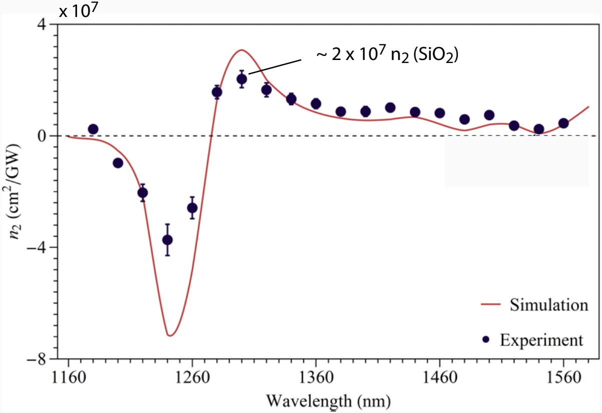


SEM:



Alam, Schulz, Upham, De Leon and Boyd, Nature Photonics 12, 79-83 (2018).

NLO response of the coupled antenna-ENZ system



The material exhibits extremely large n_2 over a broad spectral range. The magnitude of the on-resonance value is 7 orders of magnitude larger than that of SiO_2.

Alam, Schulz, Upham, De Leon and Boyd, Nature Photonics 12, 79-83 (2018).

Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
- Huge NLO Response of ENZ Materials and Metastructures
- Non-perturbative Nature of the NLO Response
- Some Applications of ENZ Materials

Nonperturbative Nature of the NLO Response

1. The conventional equation $n = n_0 + n_2 I$ is not applicable to ENZ and other low-index materials. The nonlinear response is nonperturbative.
2. The problem is that n_2 is not a reliable metric under ENZ conditions. But n_2 is the standard way for quantifying intensity-dependent index changes. What can we do?
3. The nonlinear response can be accurately modeled in the $\chi^{(3)}$ limit by

$$n = \sqrt{n_0^2 + 2n_0 n_2 I}$$

where

$$n_2 = \frac{3\chi^{(3)}}{4n_0 \mathrm{Re}(n_0)\epsilon_0 c}.$$

and

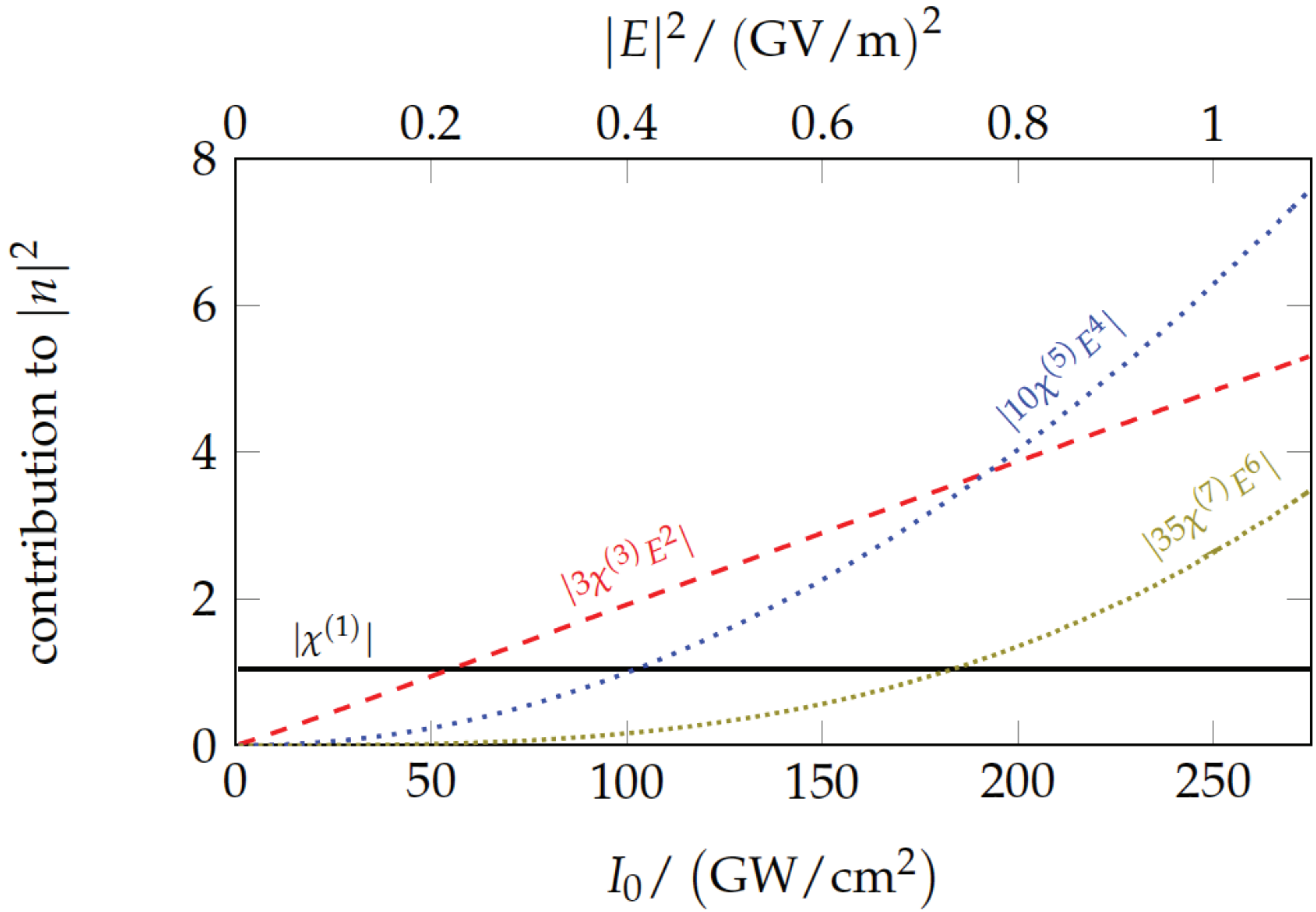
$$I = 2\mathrm{Re}(n_0)\epsilon_0 c|E|^2$$

4. More generally, the intensity dependent refractive index can be described by

$$n = \sqrt{\epsilon^{(1)} + 3\chi^{(3)}|E|^2 + 10\chi^{(5)}|E|^4 + \cdots}$$

Reshef, Giese, Alam, De Leon, Upham, Boyd, Opt. Lett. 42, 3225 (2017).

Nonlinear Response of ITO is Nonperturbative



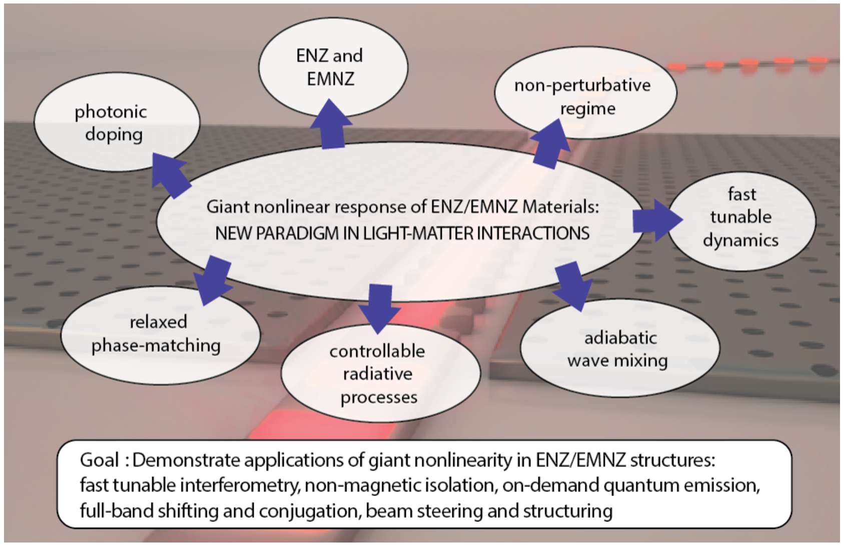
Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
- Huge NLO Response of ENZ Materials and Metastructures
- Non-perturbative Nature of the NLO Response
- Some Applications of ENZ Materials

Giant Nonlinear Response of ENZ Metastructures

Boyd (Rochester), **Engheta** (UPenn), **Mazur** (Harvard), **Willner** (USC)

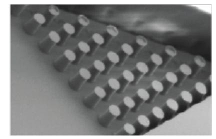
CONCEPT



APPROACH

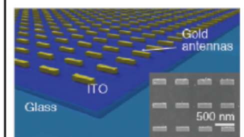
EXPLOIT RANGE OF NLO-ENZ/EMNZ SYSTEMS

Dirac cone metamaterial



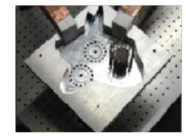
- CMOS compatible
- low loss

nano-antennas on ENZ metasurface



- plasmonic nanostructure
- control of nonlinearity sign

photonically doped ENZ metastructure



- control of permeability
- tailorable reflection

- Re-formulate nonlinear optics for non-perturbative regime
- Explore experimental characteristics of ENZ/EMNZ platforms
- Fabricate devices to exploit novel features

IMPACT

new FUNDAMENTAL UNDERSTANDING of light-matter interaction in ENZ/EMNZ materials

↓

complete DYNAMIC CONTROL of beam parameters: amplitude, phase, polarization, wavelength, and propagation direction

↓

low-threshold NLO DEVICES that are integrated, fast, tunable, broadband, power-efficient

↓

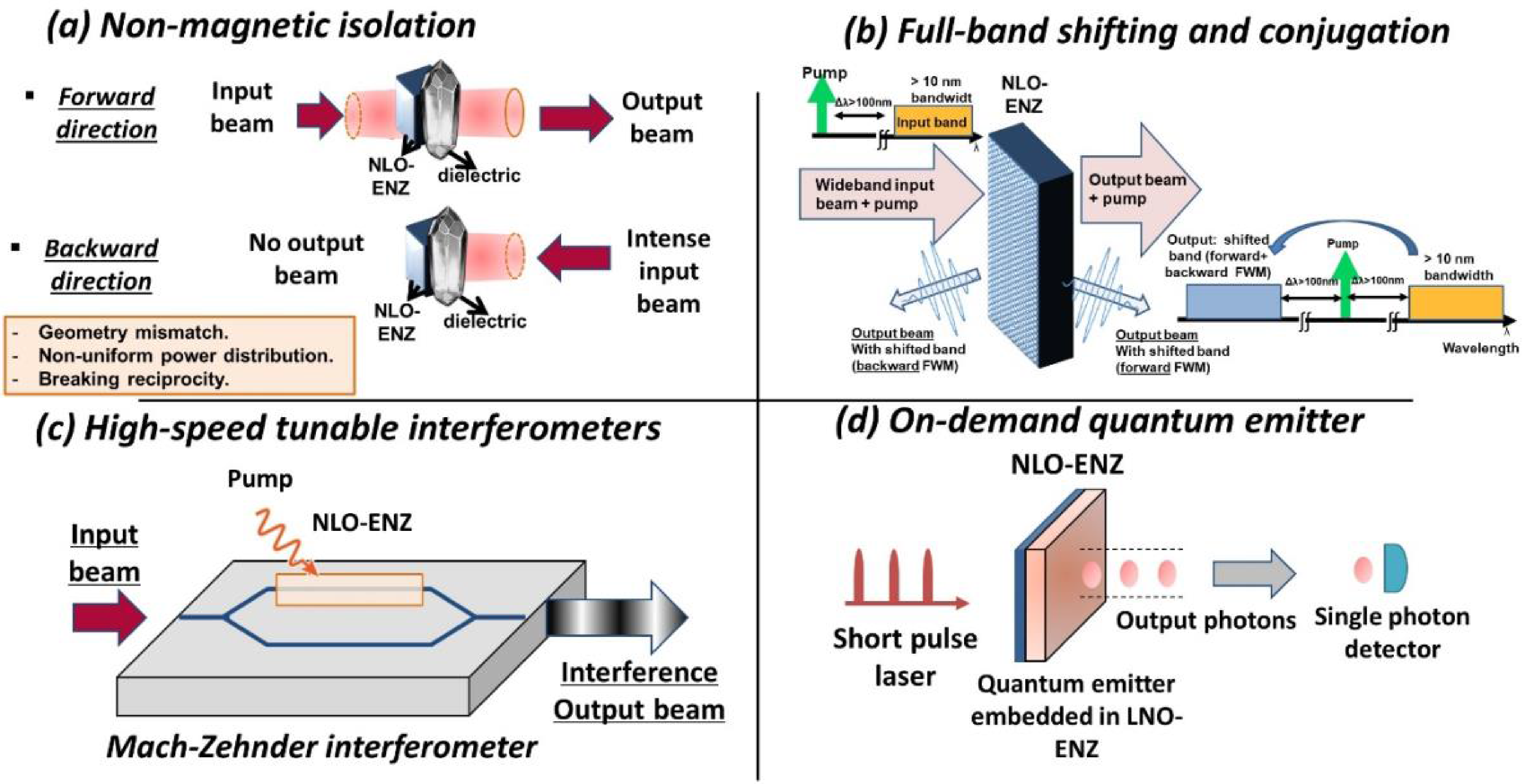
- ultrafast optical modulators
- ultrafast beam-steering
- high-extinction isolators
- wideband wavelength converters
- on-demand quantum emitters

CONTEXT

- Nonlinear optical phenomena currently require high-intensity sources, which are generally incompatible with nanophotonics
- Photonics could have an enormous impact on many new fields if nonlinearity is fundamentally enhanced
- ENZ metastructures provide giant tailorable nonlinearity
- Enhanced nonlinearity will open door to manipulating light on the nanoscale

Source Selection Information – see FAR 2.101 & 3.104

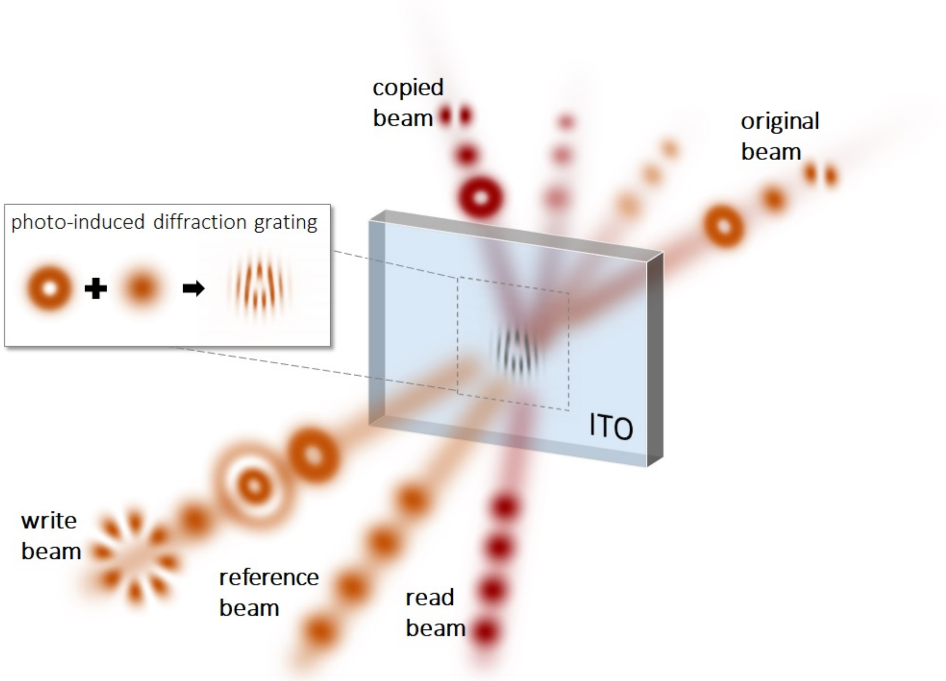
Some Potential Applications of ENZ Behavior



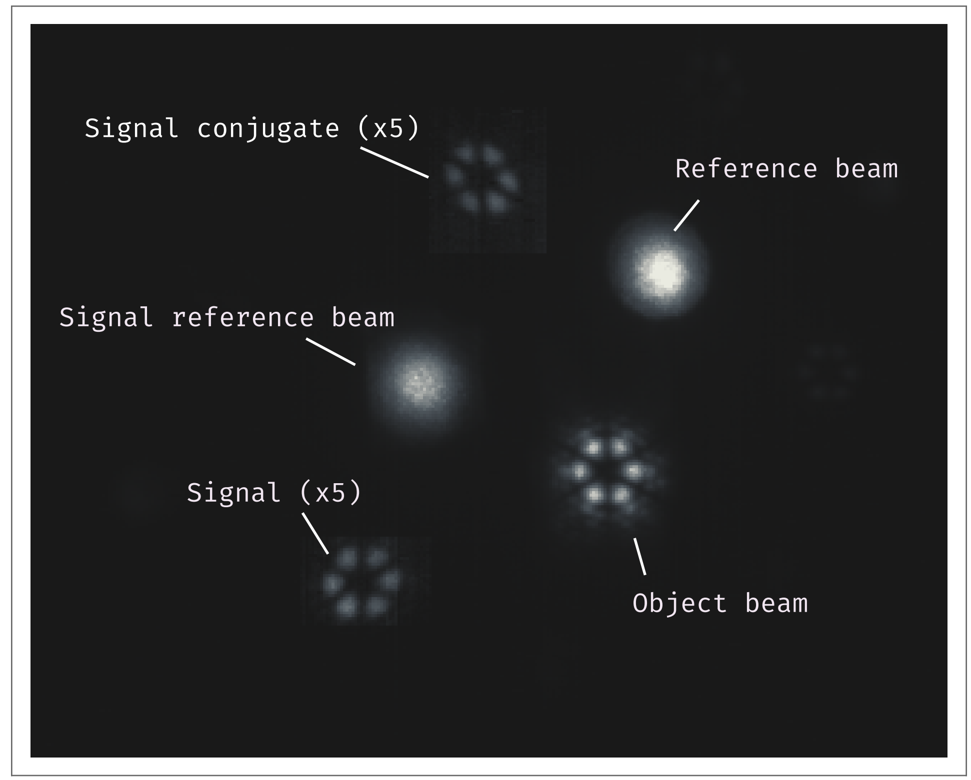
Ultrafast Holography and Beam Copying

- Real-time holography with sub-picosecond response time

- Schematic of beam-copying procedure



- Laboratory results



Summary: Physics and Applications of ENZ Materials

- Extremely interesting physical processes occur in ENZ materials
- ENZ materials, metamaterials, and metastructures display extremely large NLO response
- The huge, ultrafast NLO response of ENZ materials lend themselves to many important applications

The visuals of this talk are posted at boydnlo.ca/presentations

Max Planck Centre for Extreme and Quantum Photonics

Research Interests:
Nonlinear optics, quantum optics
integrated photonics, metamaterials, etc.

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group