How Light Behaves when the Refractive Index Vanishes

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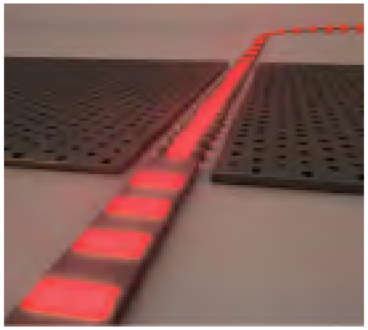
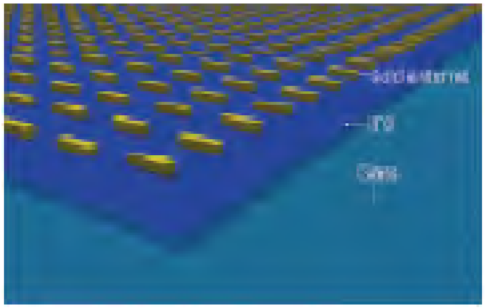
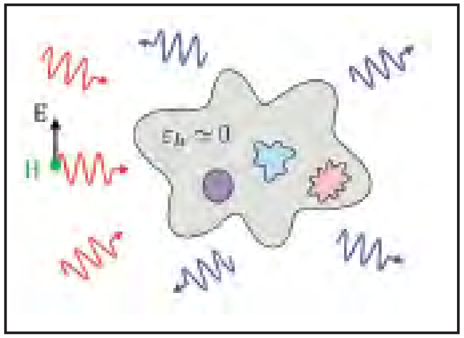






The visuals of this talk are posted at boydnlo.ca/presentations

Presented at the Heidelberg Academy of Sciences, October 25, 2019.

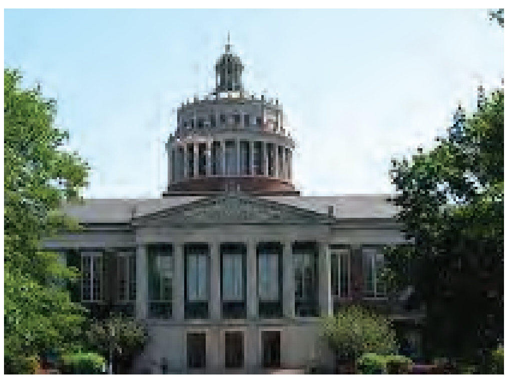
Brief Self-Introduction: Robert Boyd

Born in Buffalo, NY, USA

Bachelor's Degree in Physics from MIT

PhD from University of California, Berkeley

Professor, University of Rochester, 1977 - present



CERC Professor, University of Ottawa, 2010 - present

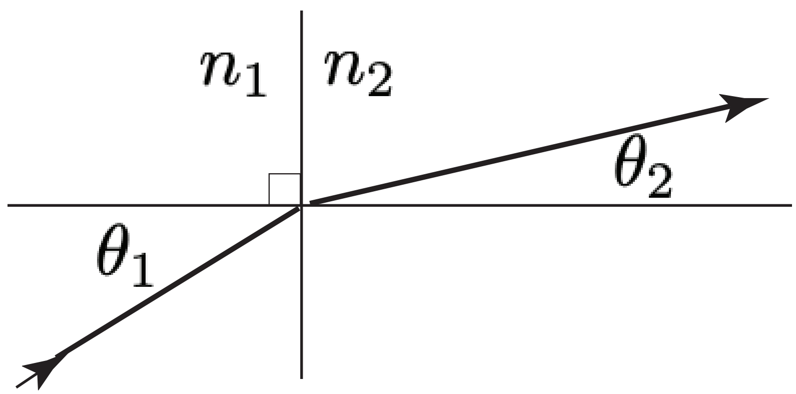
- Research interests: optical physics, nonlinear optics, quantum optics

What is the Refractive Index?

- The refractive index determines how much a beam of light bends (or refracts) when it passes from one material to another.

- This relationship is known as Snell's Law

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



- The refractive index also determines the phase velocity of light v

$$v = c/n$$

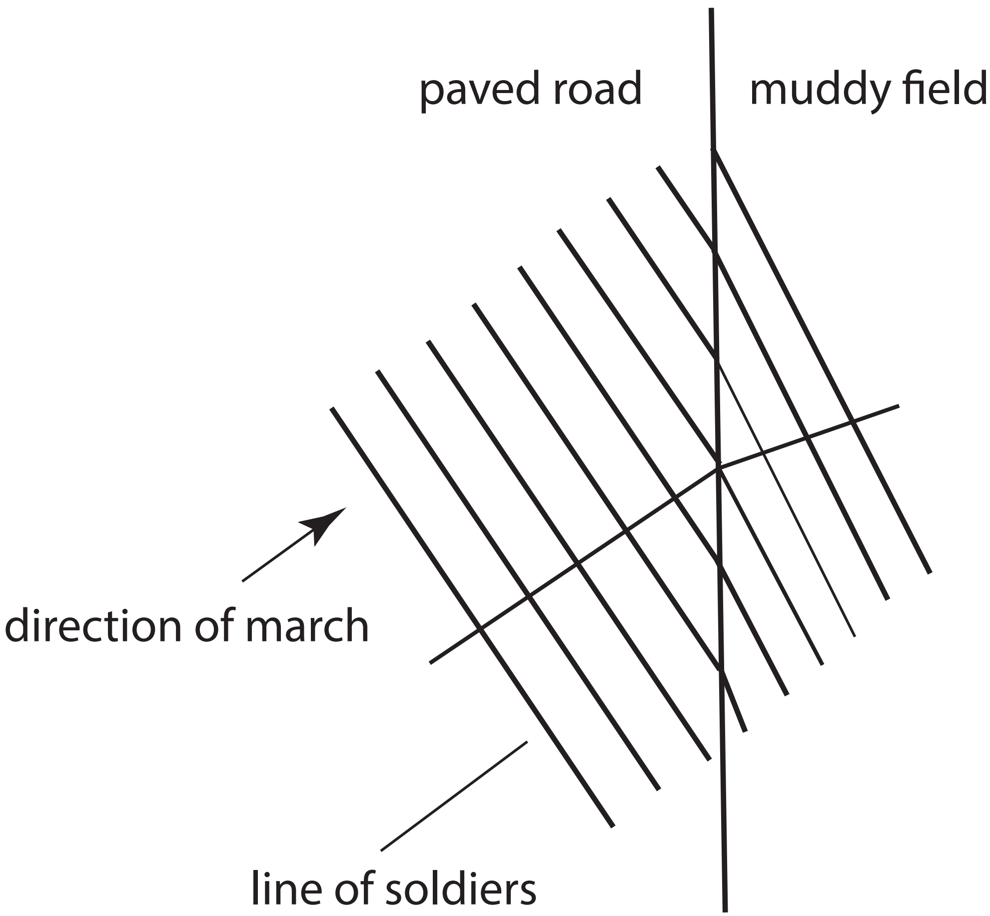
- Refraction at the surface of water explains why things look closer when they are under water.

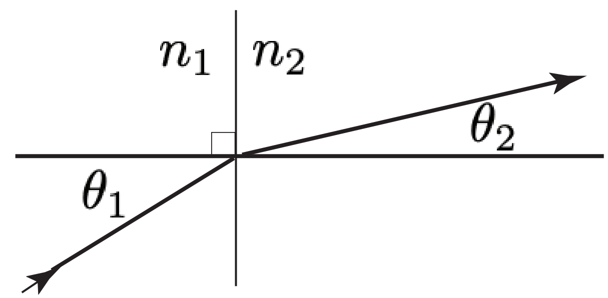
What is the Refractive Index?

- Properties of the refractive index

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad v = c/n$$

- We can understand why these two properties by an analogy to marching soldiers





What is the Refractive Index?

- Refractive index of some common materials

vacuum	1.0
air	1.0003
water	1.33
window glass	1.5
germanium	4.0

- The refractive index can be less that 1.0 for some extreme circumstances

- But can the refractive index ever vanish or at least be close to $n = 0$?
  And what would be the properties of light under these conditions?

How Light Behaves when the Refractive Index Vanishes

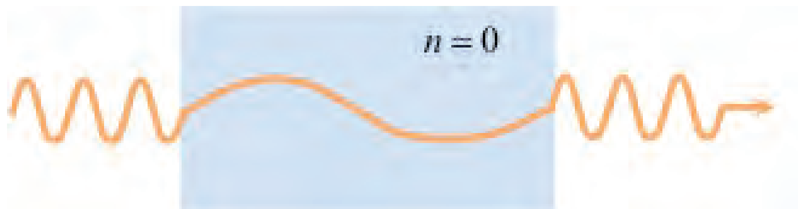
- Physics of Near-Zero Index (NZI) Materials
- Nonlinear Optical Properties of NZI Materials
- Meta-materials for NZI Studies
- Applications of NZI Materials

Physics of Near-Zero-Index (NZI) Materials

- The wavelength of light is given by

$$\lambda = \lambda_{\text{vac}}/n$$

and is significantly lenthened in a NZI material. The wavelength approaches infinity as *n* approaches zero.



- The phase velocity of light is given by

$$v = c/n$$

and also approaches infinity as n approaches zero.

- For n approaching zero, the field oscillates in time but not in space; oscillations are in phase everywhere

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

Physics of Near-Zero-Index (NZI) Materials

- Radiative processes are stongly modified in a NZI material

  - Einstein *A* coefficient (spontaneous decay rate = 1 / (spontaneous emission lifetime)

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

  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).

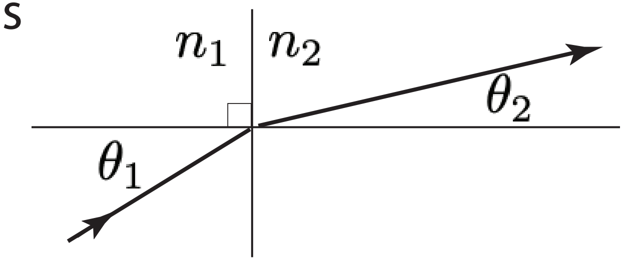
- Implications:

  - If we can inhibit spontaneous emission, we can build thresholdless lasers.
  - Expect superradiance effects to be pronounced in ENZ materials.

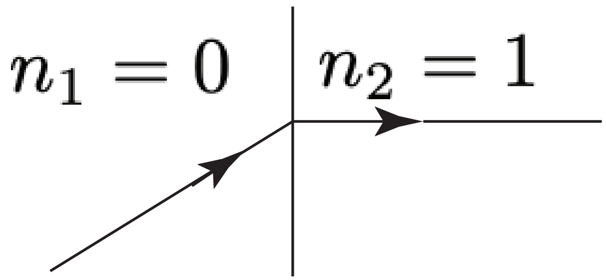
Physics of Near-Zero-Index (NZI) Materials -- More

- Snell's law leads to intriguing predictions

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

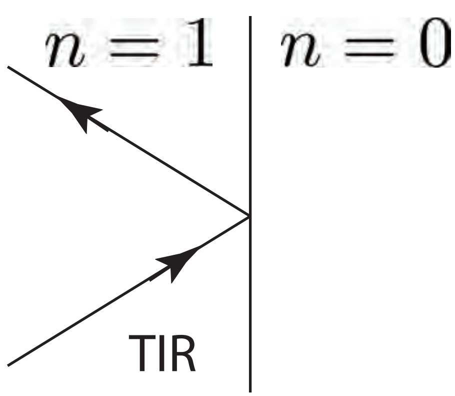


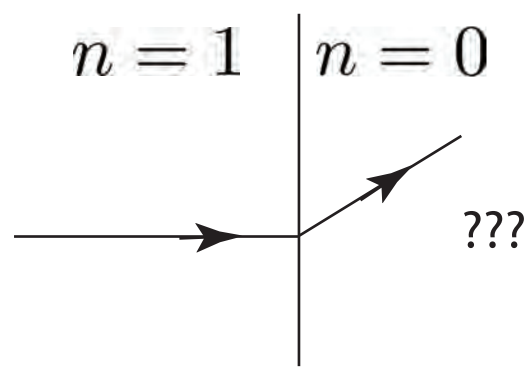
- Light always leaves perpendicular to surface of ENZ material!



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!

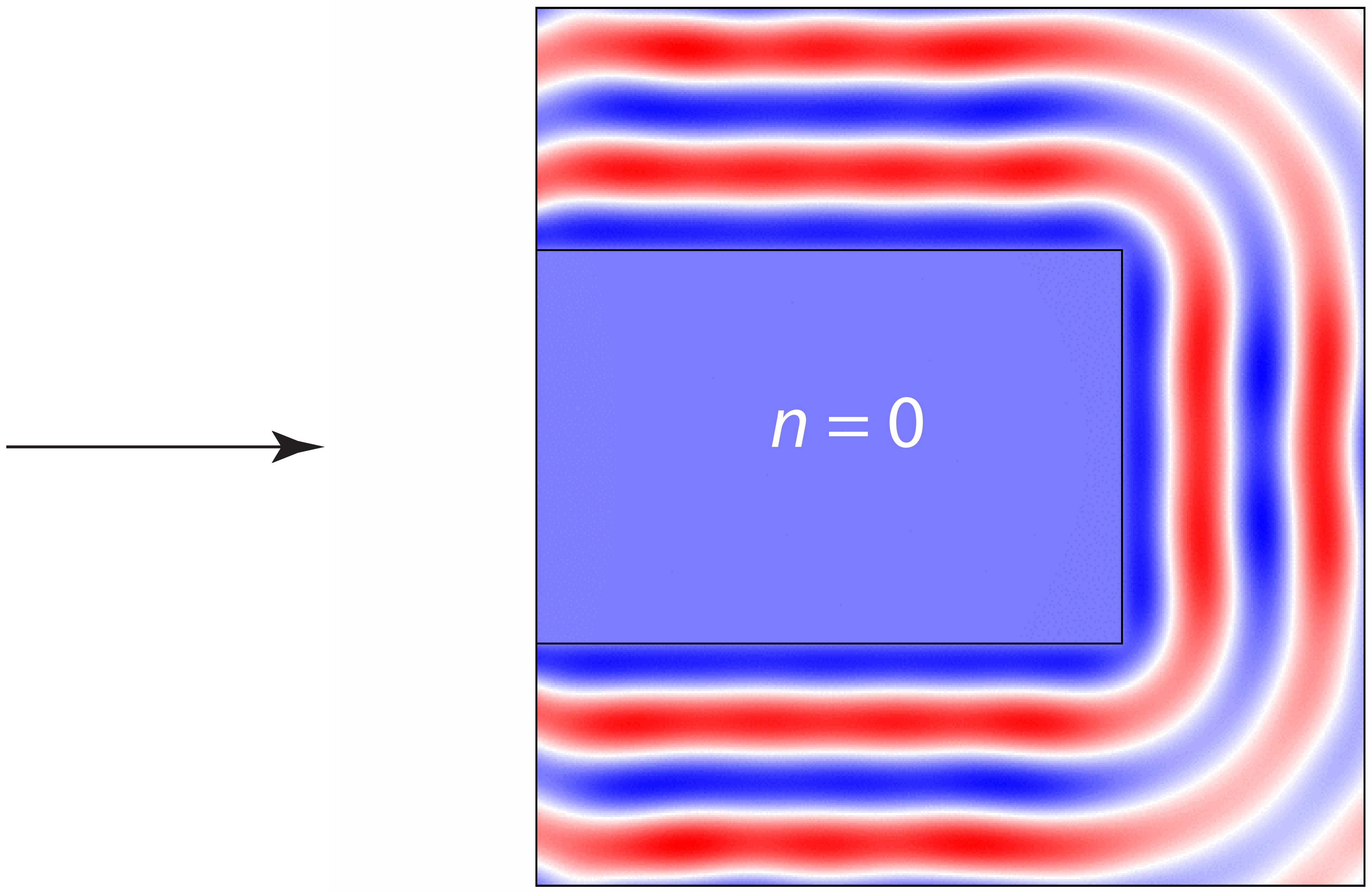




Y. Li, et al., Nat. Photonics 9, 738, 2015.

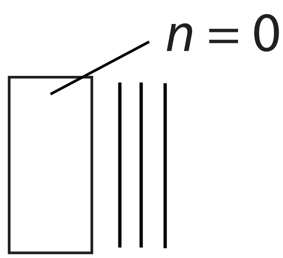
Maxwell Equations Prediction

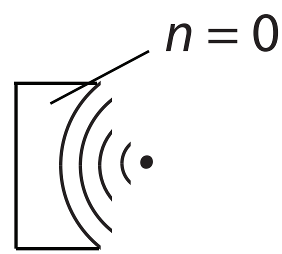
- light enters slab at normal incidence
- but leaves in all directions!



Some Consequences of NZI Behaviour - 1

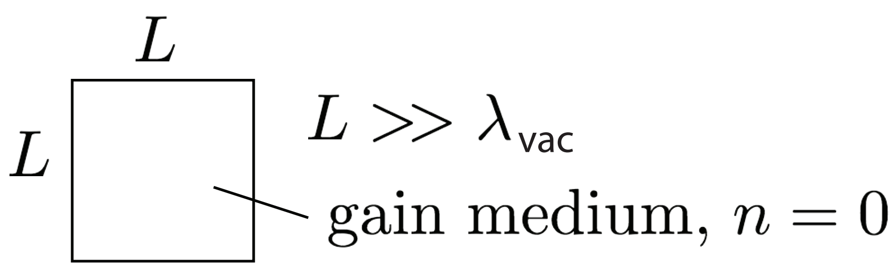
- Funny lenses





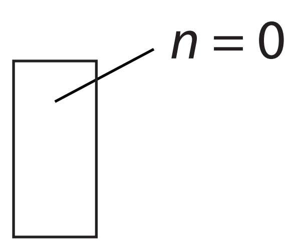
A. Alù et al., Phys. Rev. B 75, 155410, 2007; X.-T. He, ACS Photonics, 3, 2262, 2016.

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



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

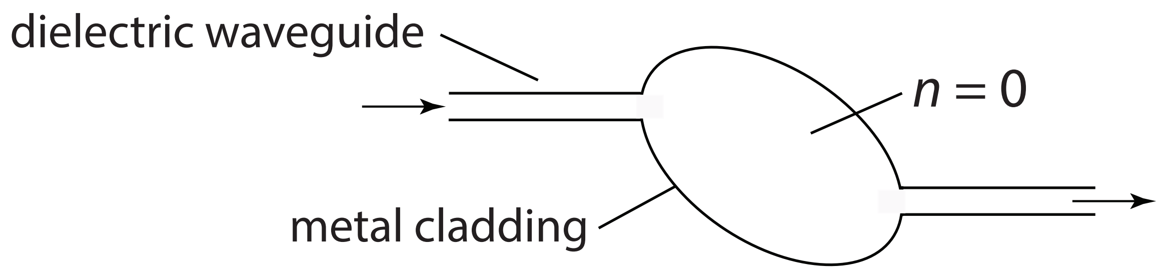
- No Fabry-Perot interference



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

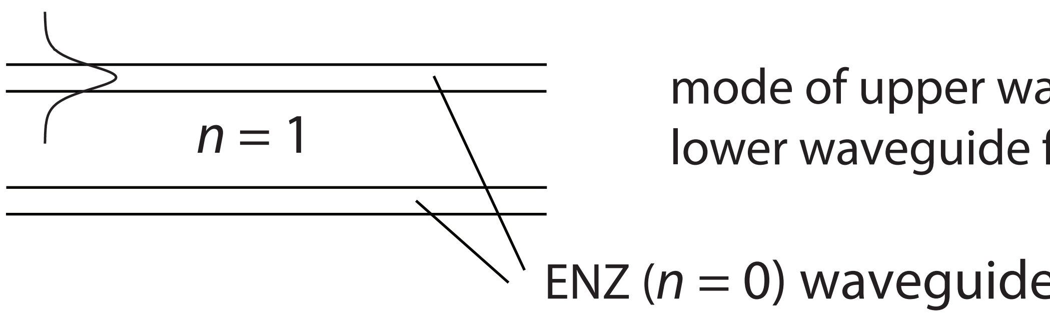
Some Consequences of NZI Behavior - 2

- 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

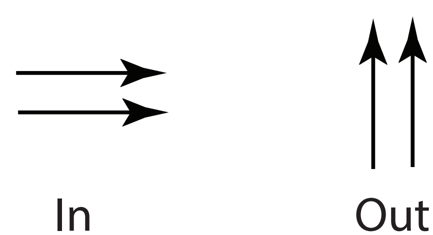


mode of upper waveguide extends to lower waveguide for any separation

- 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 NZI 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 $n_0 = 0$?

Some Technical Details from Electromagnetic Theory

- The linear response of any material to electromagnetic radiation can be described by

  - The dielectric permittivity (dielectric constant) ε define through the relation

$$\mathbf{D} = \epsilon \mathbf{E}$$

where **D**, known as the dielectric displacement, and **E**, known as the electric field, are the two fieldsthat describe the material response to an electric field.

  - The magnetic permeability μ define through the relation

$$\mathbf{B} = \mu \mathbf{H}$$

where **B,** known as the magnetic field, and **H**, known as the magnetic intensity, are the two fields that describe the magnet response of a material to an applied field.

- It is straightforward to shown from the equations of electromagnetism that

$$n = \sqrt{\epsilon\mu}$$

- Thus, *n*=0 when either ε =0 or μ=0 (or both ε and μ equal zero).

- Terminology:

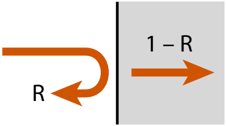
  ENZ: epsilon near zero
  MNZ: mu near zero
  EMNZ: epsilon and mu near zero

Surface Reflection

- There is a problem getting light into a zero-index material.
- There is always reflection from the boundary between two materials
- The impedance and surface reflectivity are given by

$$Z = \sqrt{\mu/\epsilon} \qquad\qquad R = \left|\frac{Z-1}{Z+1}\right|^2$$

- Thus the reflectivity will be 100% if $\epsilon = 0$ unless $\mu = 0$ as well.



- This is one reason for the interest in developing EMNZ materials (epsilon and mu near zero materials.

How Light Behaves when the Refractive Index Vanishes

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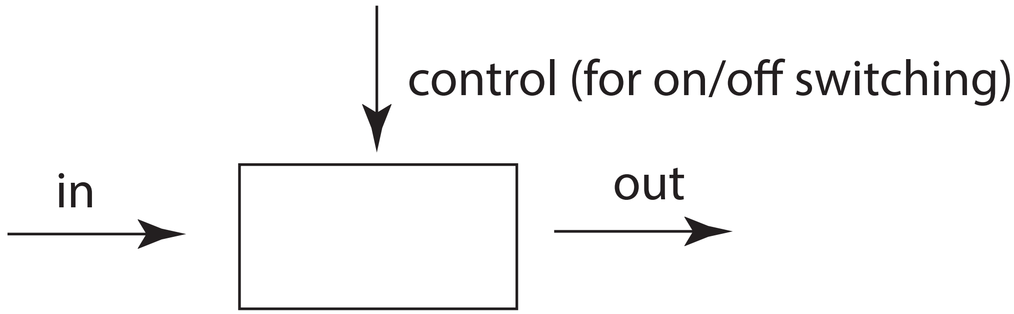
Nonlinear Optics and Optical Switching

- An important application in photonic technologies is optical switching.



- One wants a switch with fast switching times and that operates with weak control fields.
- One needs a nonlinear interaction in order for one optical field to control another field.
- A strong nonlinear response is needed. How does one quantify the strength of a nonlinear response? Two standard methods:

$$n = n_0 + n_2 I$$

$$P^{\mathrm{NL}} = 3\chi^{(3)}|E|^2 E$$

- The nonlinear coefficients are n_2 and $\chi^{(3)}$

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

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

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

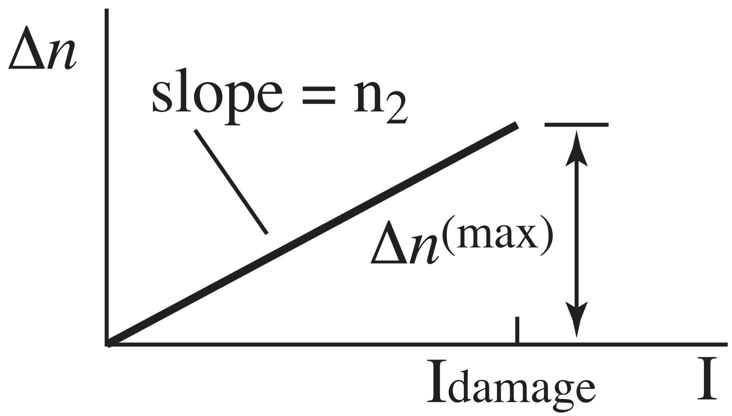
New Nonlinear Optical Material for Quantum Photonics

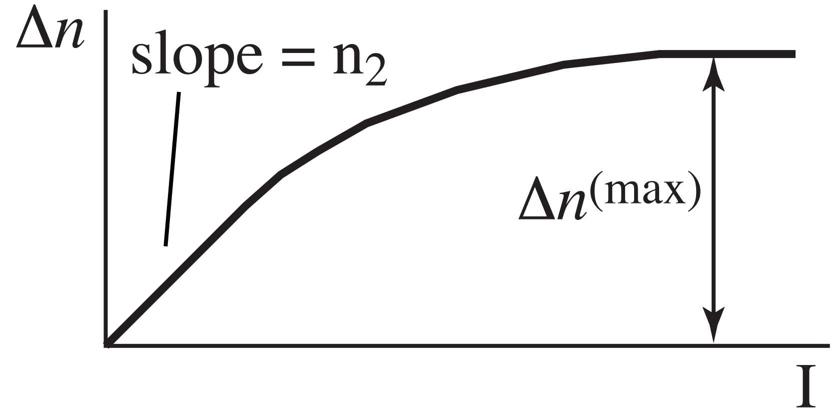
- We want all-optical switches that work at the single-photon level
- We need photonic materials with a much larger NLO response
- We recently reported a new NLO material with an n_2 value 100 times larger than those previously reported (but with some background absorption).
- Material makes use of strong enhancement that occurs in the epsilon-near zero (ENZ) spectral region.
- A potential game changer for the field of photonics

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).

What Makes a Good (Kerr-Effect) Nonlinear Optical Material?

- We want n_2 large ($\Delta n = n_2 I$). We also want $\Delta n^{(max)}$ large.
  These are distinct concepts! Damage and saturation can limit $\Delta n^{(max)}$





- For ITO at ENZ wavelength, both n_2 and $\Delta n^{(max)}$ are extremely large ($n_2 = 1.1 \times 10^{-10}$ cm^2/W and $\Delta n^{(max)} = 0.8$)

- n_2 is 3.4×10^5 times larger than that of silica glass
  $\Delta n^{(max)}$ is 2700 times larger that that of silica glass

  (For silica glass $n_2 = 3.2 \times 10^{-16}$ cm^2/W, $I_{damage} = 1$ TW/cm^2, and thus $\Delta n^{(max)} = 3 \times 10^{-4}$)

M. Z. Alam, I. De Leon, R. W. Boyd, Science 352, 795 (2016).

Optical Properties of Indium Tin Oxide (ITO)

- ITO is a degenerate semiconductor (so highly doped as to be metal-like).
- It has a 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 $\omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0$.

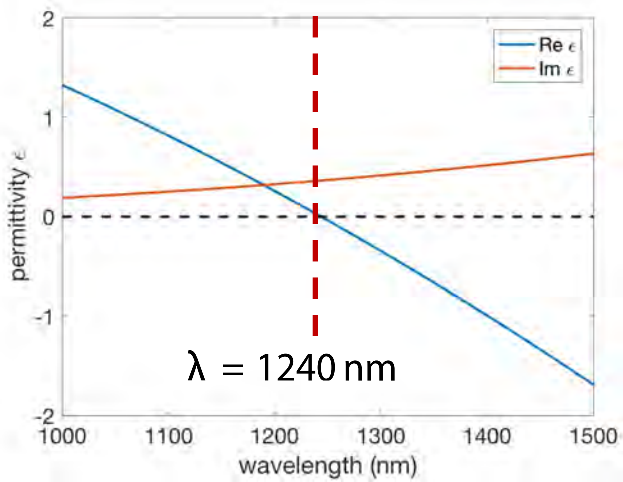
The region near ω_0 is known as the epsilon-near-zero (ENZ) region.

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

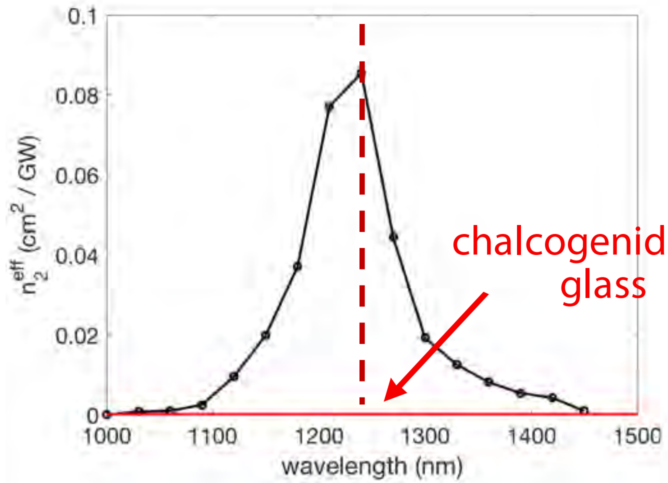
H. Suchowski, K. O'Brien, Z. J. Wong, A. Salandrino, X. Yin, and X. Zhang, Science 342, 1223 (2013).
C. Argyropoulos, P.-Y. Chen, G. D'Aguanno, N. Engheta, and A. Alu, Phys. Rev. B 85, 045129 (2012).
S. Campione, D. de Ceglia, M. A. Vincenti, M. Scalora, and F. Capolino, Phys. Rev. B 87, 035120 (2013).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

Huge, Fast NLO Response of Indium Tin Oxide at its ENZ Wavelength

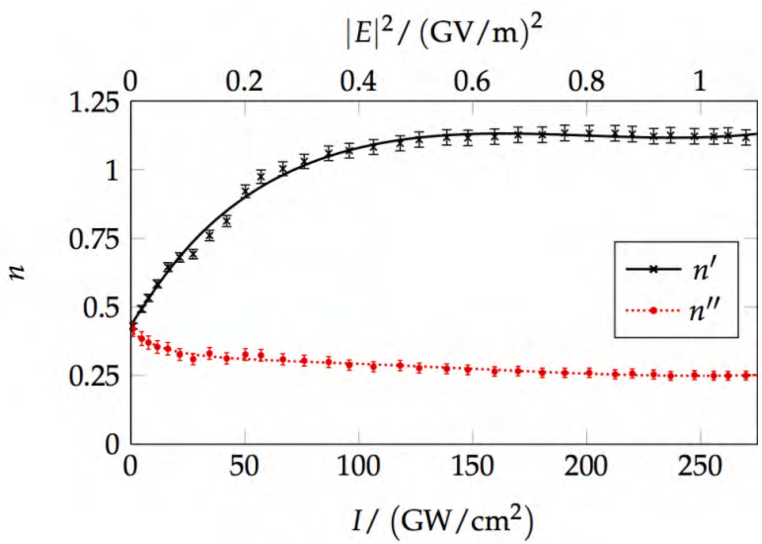
- ellipsometry



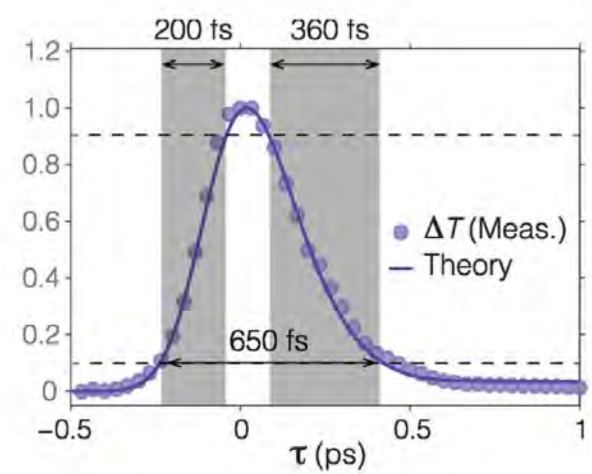
- n_2 can be 3.4 x10^5 times larger than that of silica glass



- overall change in refractive index of 0.8



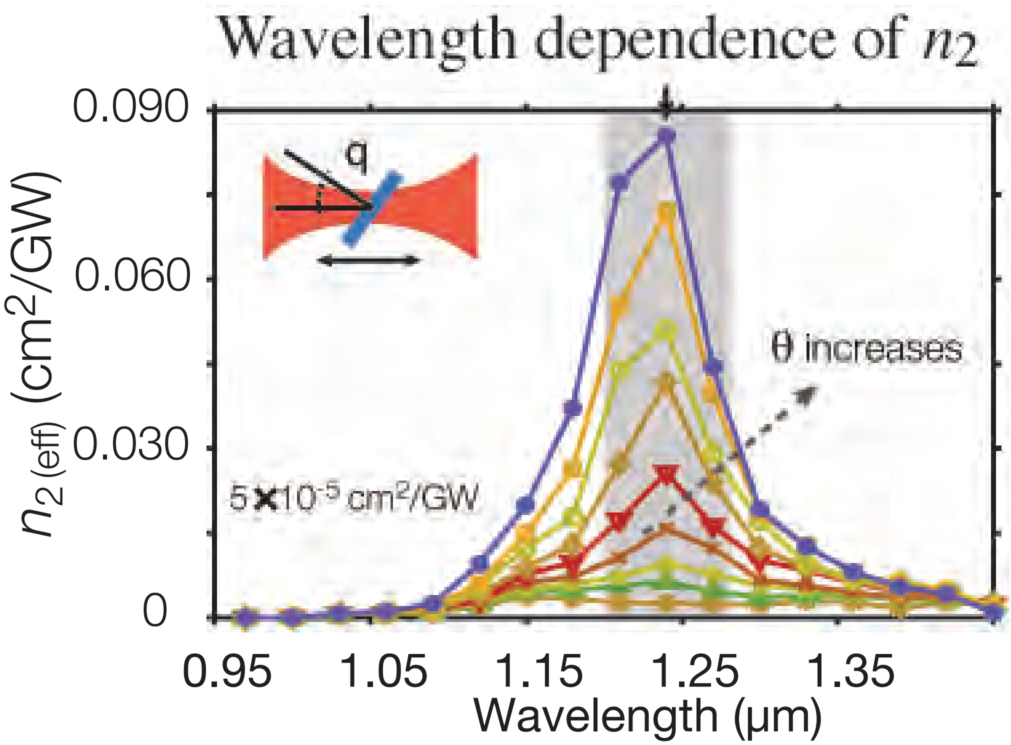
- sub picosecond reponse time

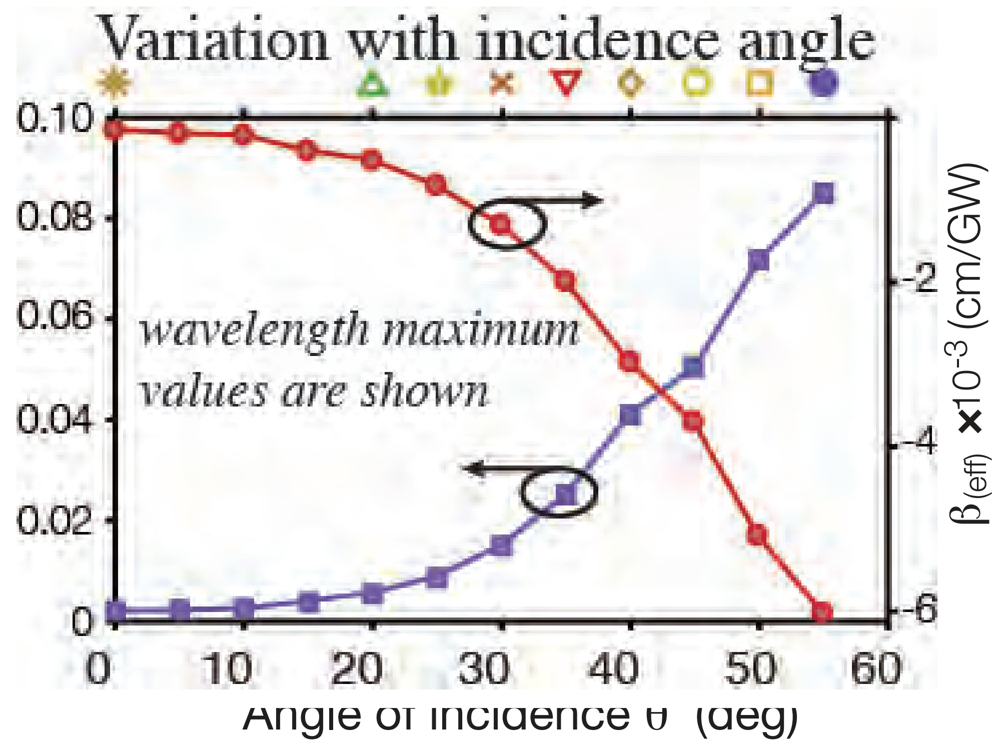


M. Z. Alam et al., Science 352, 795-797 (2016)

Huge Nonlinear Optical Response of ITO

- Z-scan measurements for various angles of incidence





peak laser intensity was 50 GW cm-2

- Note that n_2 is positive (self focusing) and β is negative (saturable absorption).

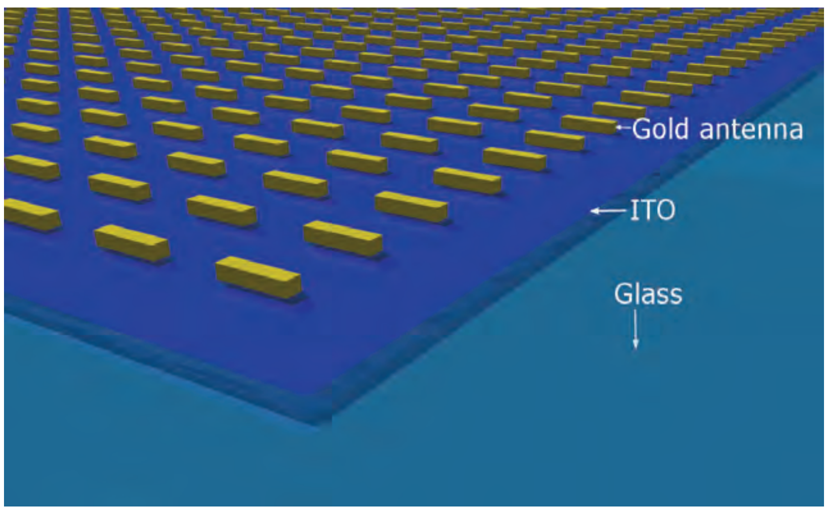
- Both n_2 and nonlinear absorption increase with angle of incidence

- n_2 shows a maximum value of 0.11 cm^2/GW = 1.1 x 10^{-10} cm^2/W at 1.25 μm and 60 deg. This value is 2000 times larger than that away from ENZ region.

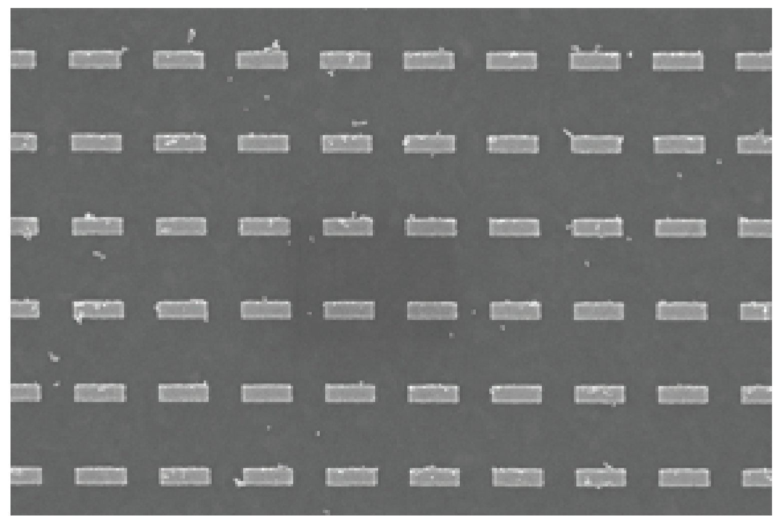
An ENZ Metasurface

- We functionalize ITO by creating a photonic metasurface
- 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:

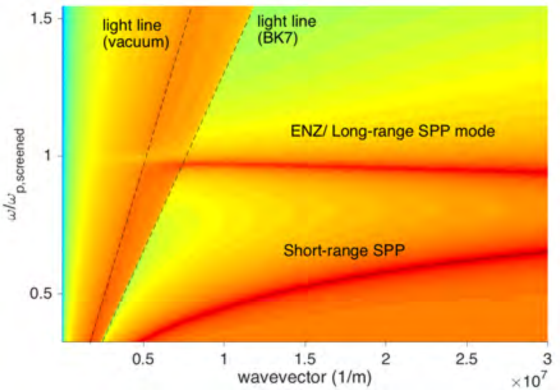


SEM:



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

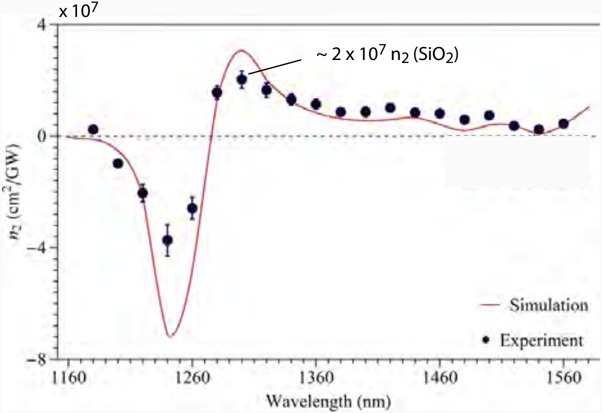
A thin ENZ medium supports a bulk plasma mode.



A thin layer of ITO supports two modes

- the bulk plasma mode, also called the ENZ or long-range SPP mode
- the short range surface plasmon polariton (SPP) mode

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).

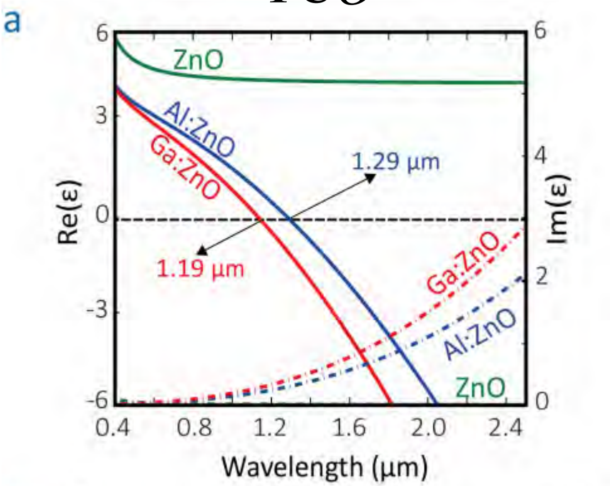
Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
- Huge NLO Response of ITO and ITO Metastructures
- Materials for ENZ
- Applications of ENZ Materials

Epsilon-Near-Zero (ENZ) and Near Zero-Index (NZI) Examples

Homogeneous materials

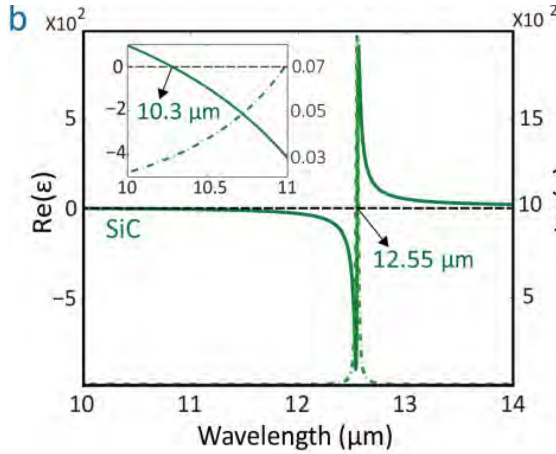
TCO



A. Boltasseva (Purdue)

Kim et al., Optica (2016)

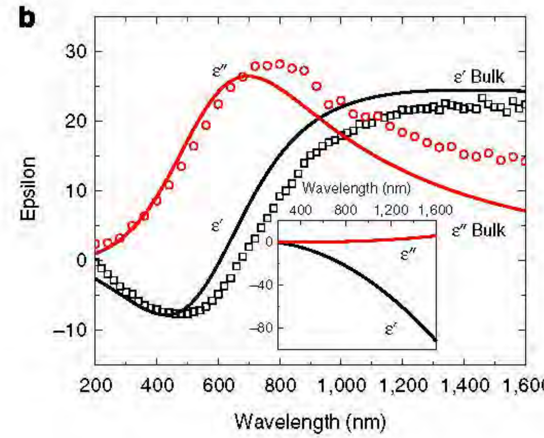
SiC



J. Caldwell (Vanderbilt)

Kim et al., Optica (2016)

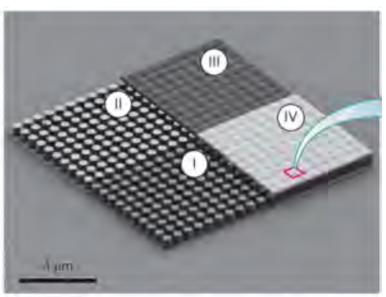
$Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$

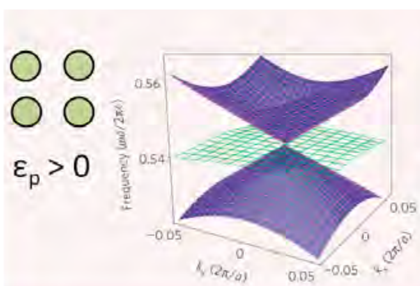


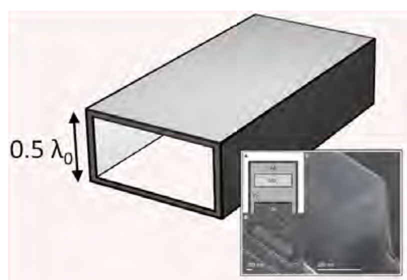
N. Zheludev (Southmapton)

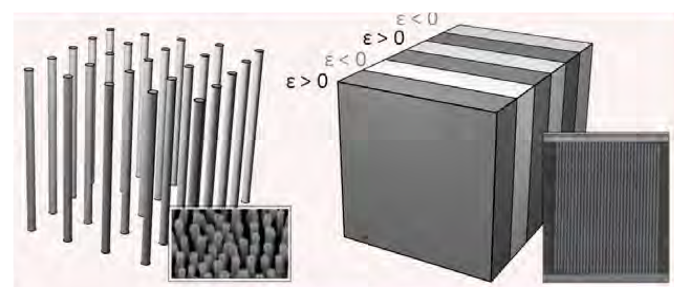
Ou et al., Nat. Commun. (2014)

Metamaterials









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

E. Mazur Li et al.,
Nat. Photon. (2015)

Chan, Huang et al.,
Nat. Mater. (2011)

SEM from: Polman's & Engheta's
Vesseur et al., PRL (2013)

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

Giant Nonlinear Response of ENZ Metastructures: Our Team

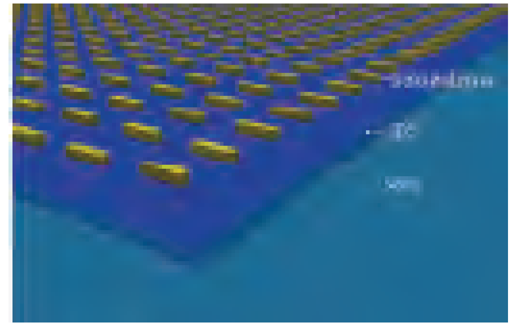
Nader Engheta
- H. Nedwill Ramsey Professor at the University of Pennsylvania
- B.S. degree from the University of Tehran and his M.S and Ph.D. from Caltech.
- Activities include ENZ, photonics, metamaterials, nano-optics, graphene optics, electrodynamics, microwave and optical antennas, studies of fields and waves.
- Many awards including the Streifer Award of IEEE and the Gold Medal from SPIE

Eric Mazur
- Balkanski Professor of Physics and Applied Physics at Harvard University
- Ph.D. University of Leiden.
- Activities include light-matter interactions with ultrashort laser pulses, nonlinear optics at the nanoscale, and zero-index dielectric metamaterials.
- Awards include the Beller Award of OSA and the Millikan Medal of the AAPT

Alan Willner
- Steven & Kathryn Sample Chair in Engineering at the University of Southern California.
- Ph.D. Columbia University
- Honors include Member of US National Academy of Engineering; Int'l Fellow of UK Royal Academy of Engineering; President of OSA and of IEEE Photonics Society.
- Activities include using nonlinearity for signal processing and wave manipulation.

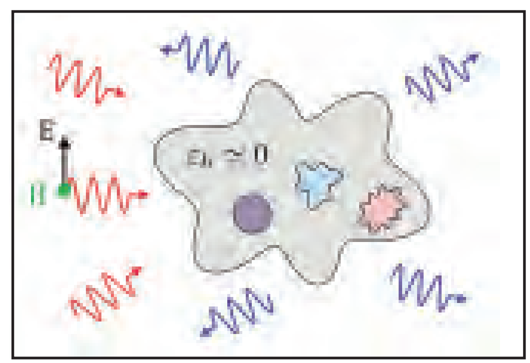
Three Material Platforms Under Investigation

- Nanoantennas coupled to ENZ substrate
  (out of plane; free-space coupling)
  (Rochester)

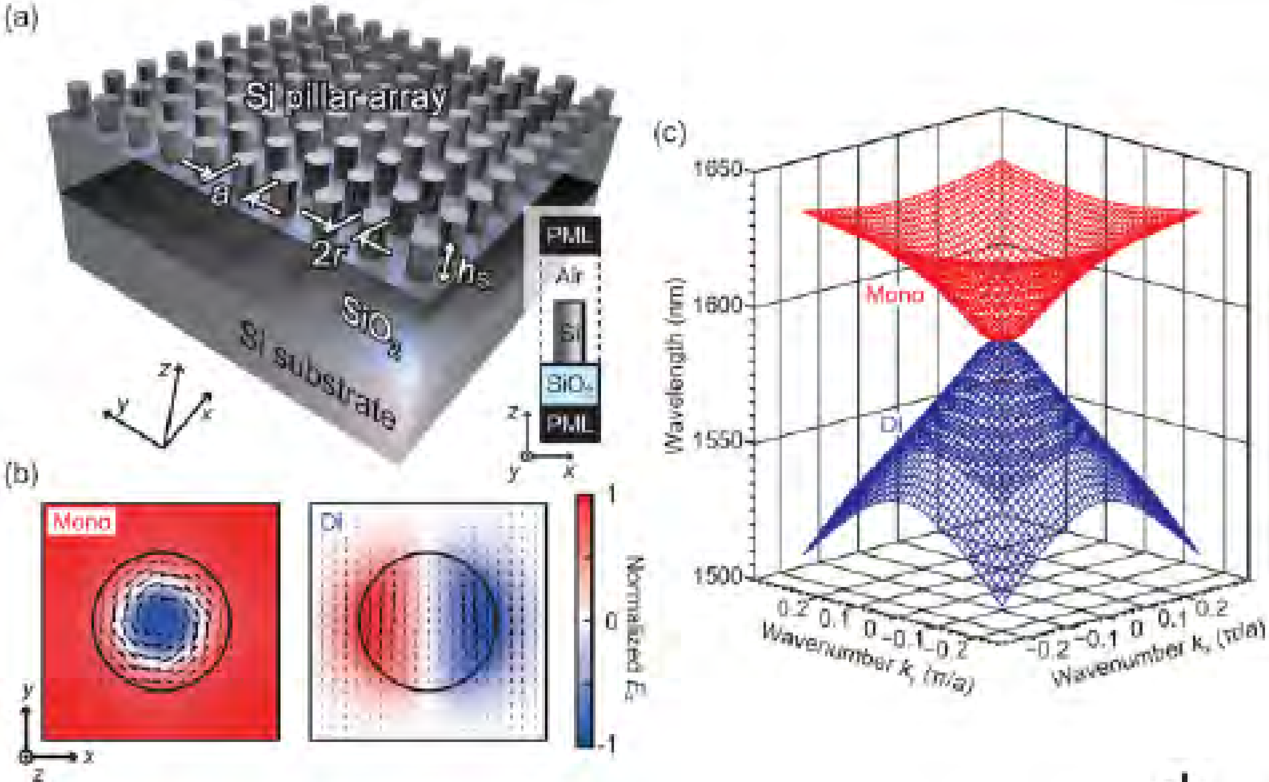


- Dirac cone metamaterials
  (in plane; compatible with integrated optics)
  (Harvard)

- Photonically doped metamaterials
  (out of plane; free-space coupling)
  (Penn)



Dirac Cone Metamaterials



An EMNZ (epsilon and mu near zero) metamaterial

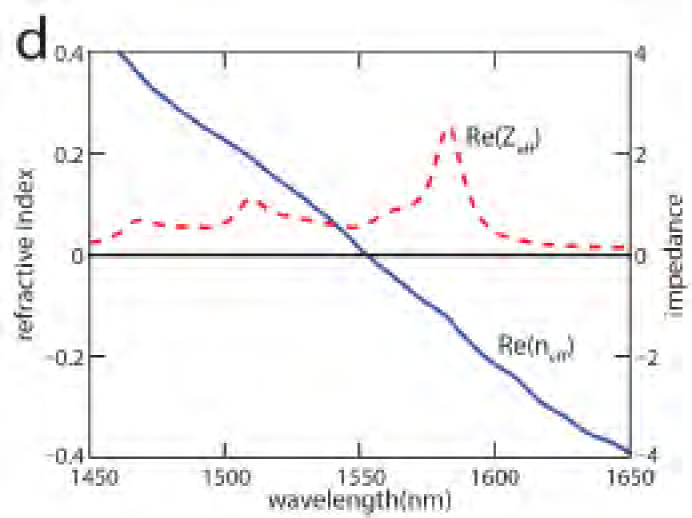
Opt Express 25, 8326 (2017)

It is also a ZIM
(zero index material)

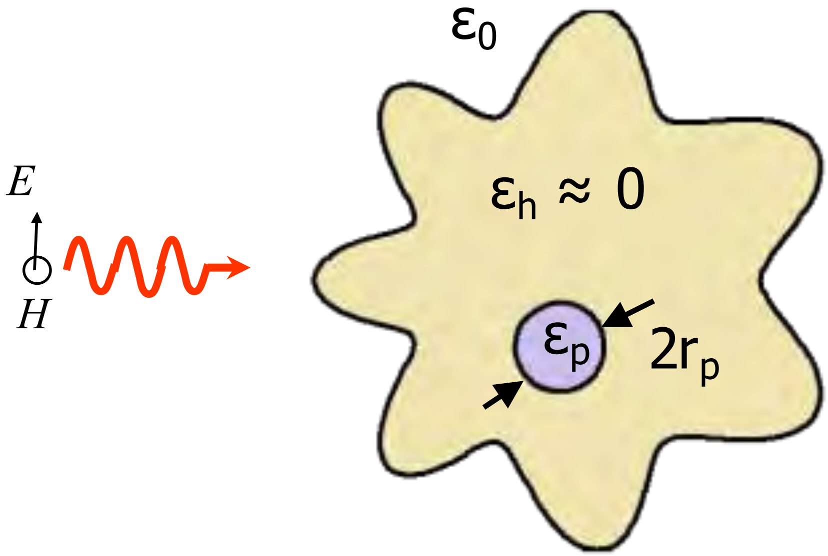
$$n = \sqrt{\epsilon\mu}$$

$$Z = \sqrt{\mu/\epsilon}$$

$$R = \frac{1 - Z}{1 + Z}$$

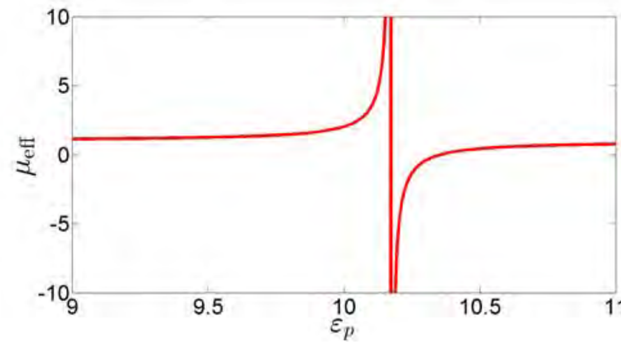


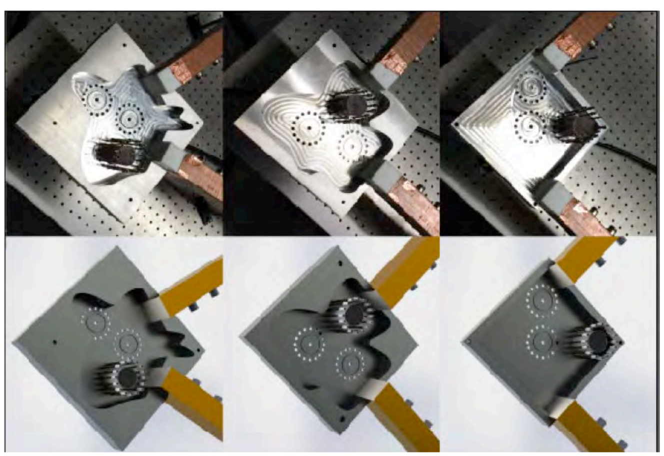
Photonic Doping of ENZ

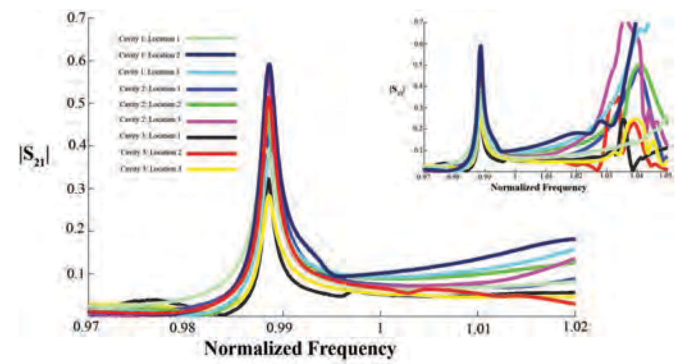


$$\varepsilon_{\text{eff}} \simeq 0$$

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





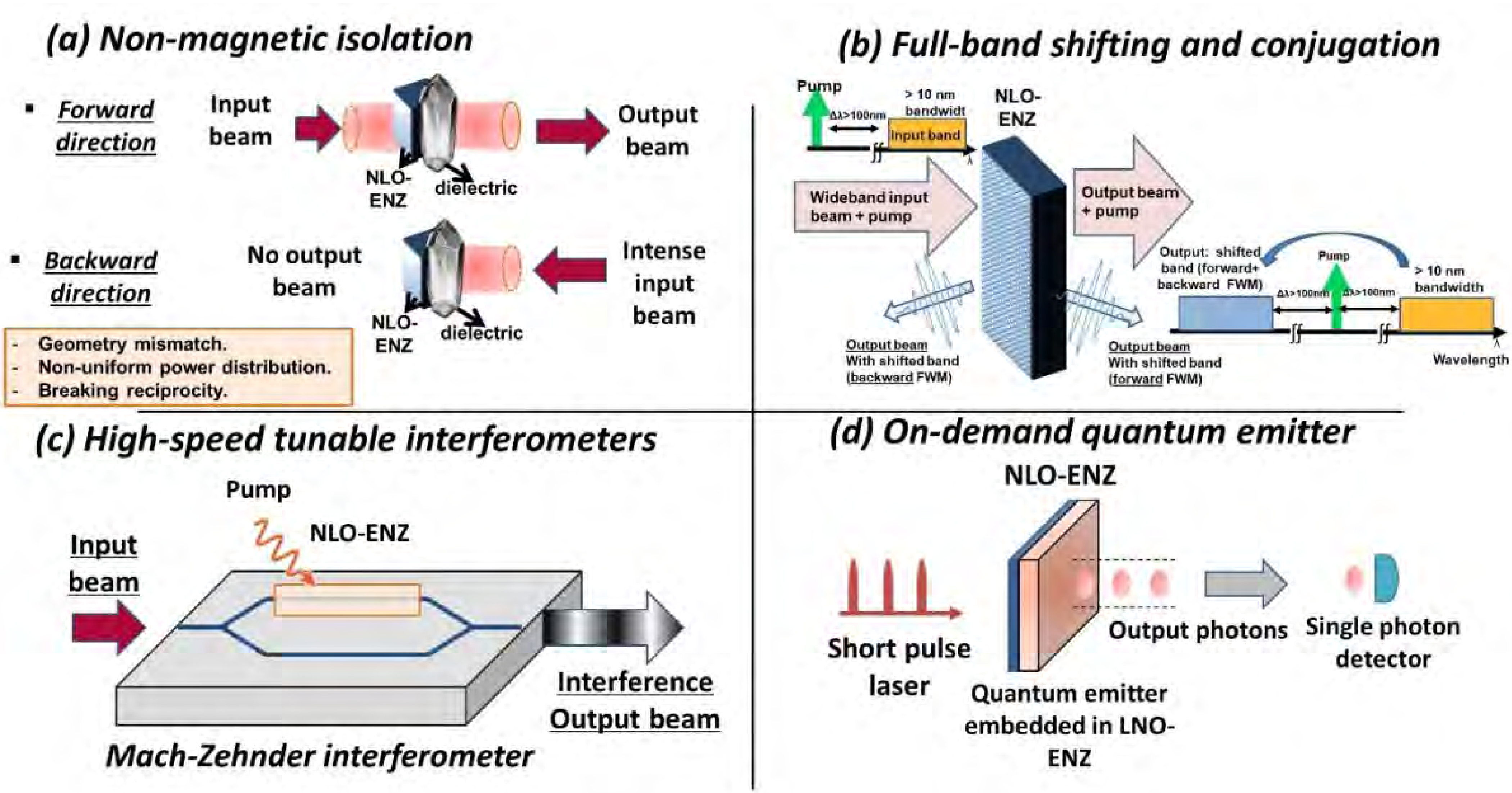


I. Liberal, A. Mahmoud, Y. Li, B. Edwards and N. Engheta, Science, 355, March 10, 2017

Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
- Huge NLO Response of ITO and ITO Metastructures
- Materials for ENZ
- Applications of ENZ Materials

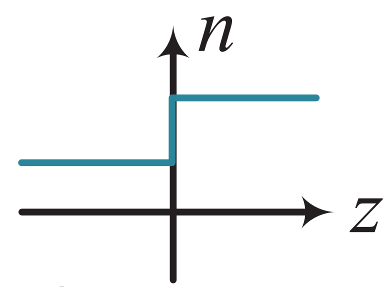
Some Potential Applications of ENZ Behavior



Space Refraction and Time Refraction

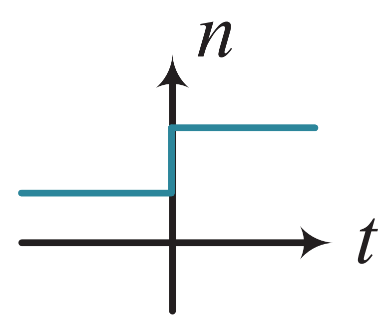
- Space refraction

$$\frac{c}{f} = n \cdot \lambda \longrightarrow n_1\lambda_1 = n_2\lambda_2$$



- Time refraction (analog of space refraction)

$$\frac{c}{f} = n \cdot \lambda \longrightarrow \boxed{n_1 f_1 = n_2 f_2}$$



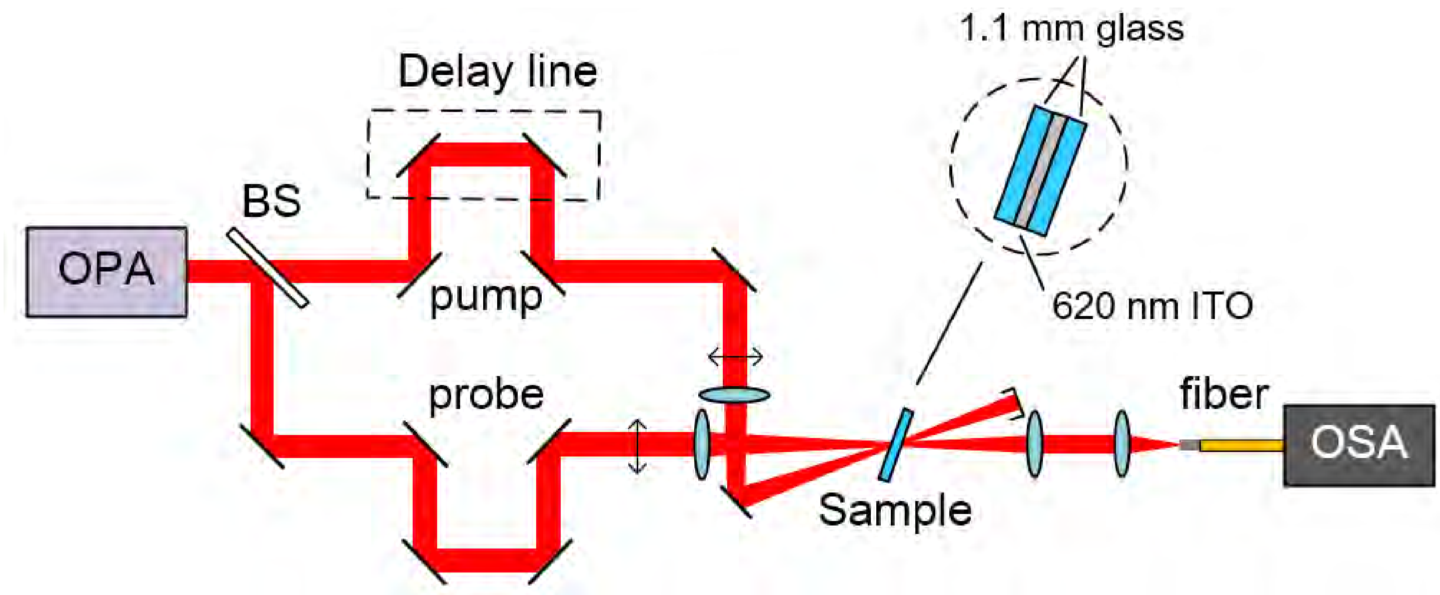
Photon frequency (energy) is changed because of the temporal change in index, but the wavelength (inverse of momentum) is conserved in the absence of any spatial asymmetry

- Time refraction is an alternative way of understanding frequency broadening and shifting by self-phase modulation:

$$\delta\omega(t) = \frac{d}{dt}\phi_{\mathrm{NL}} = \frac{d}{dt}[n_2 I(t)\omega/c]$$

Laboratory Study of Wavelength Conversion by Time Refraction

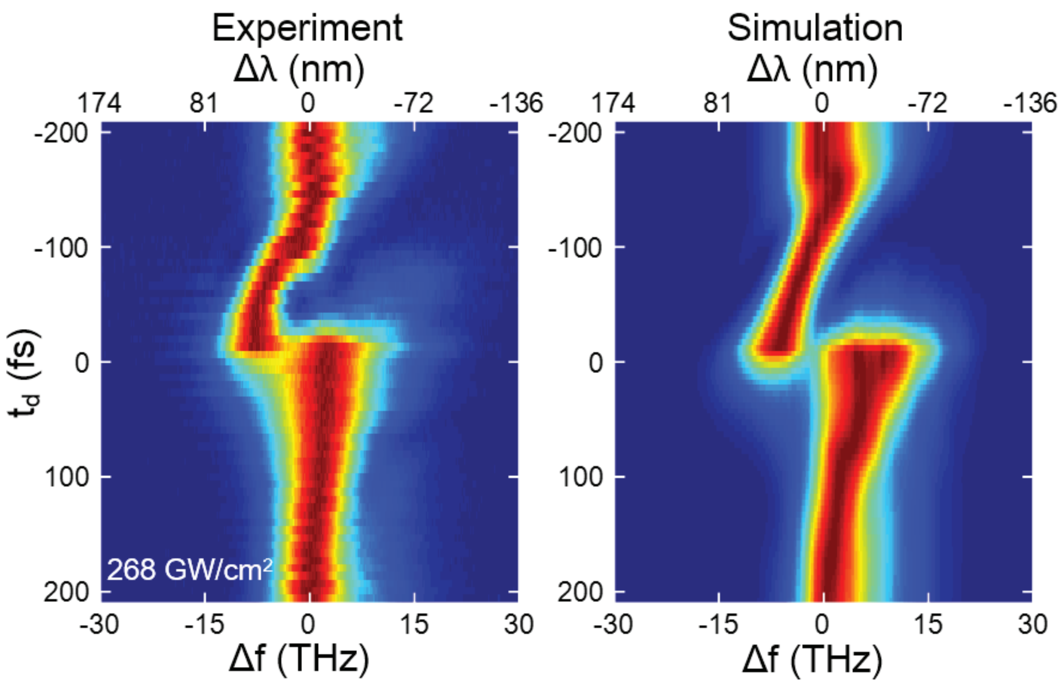
- Pump beam creates a time-varying refractive index in ITO sample
- Frequency of probe beam is thereby modified.

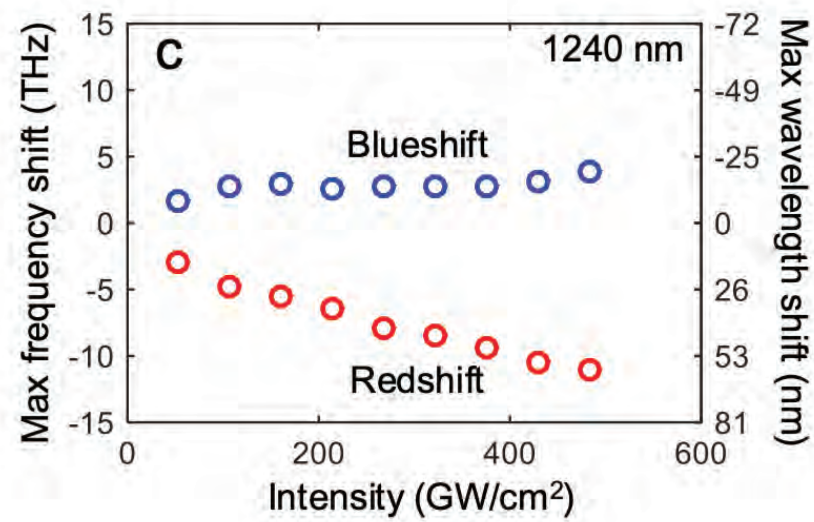


OPA = optical parametric amplifier
wavelength = 1240 nm
pulse duration = 120 fs
OSA = optical spectrum analyzer

Results: Adiabatic Wavelength Conversion by Time Refraction

Experimental results at 1240 nm





Probe phase and amplitude are measured by frequency-resolved optical gating (FROG)

The wavelength shift can be controlled by the pump intensity and the sign of the time delay.

- The observed effect is 100 times larger with almost 100 times smaller propagation distance than previous reports of AWC.
- Application: wavelength-division multiplexing for telecom

Ultrafast Real-Time Holography with an Epsilon-Near-Zero Material

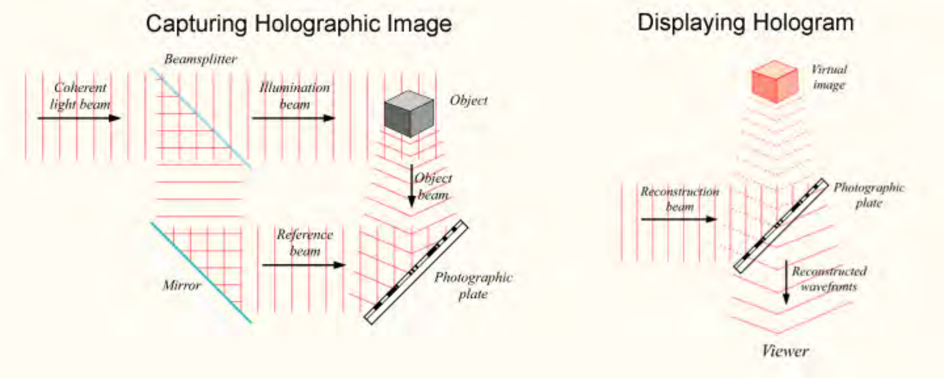
M. Zahirul Alam, Robert Fickler, Orad Reshef, Enno Giese, Jeremy Upham, Robert W. Boyd

May 19, 2019

Department of Physics, University of Ottawa, Ottawa, Canada

Motivation:

In optical holography an interference pattern is stored in a material to be read later by another light beam.



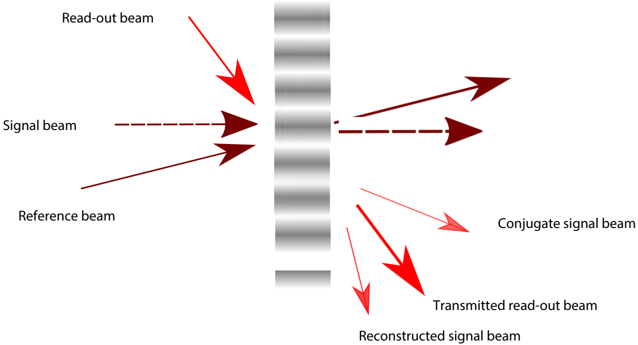
Gabor (1948); Leith and Upatnieks(1964).

Photorefractive and photochromatic materials are typical holographic materials.

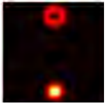
See also works by Lohman, Goodman, Yariv, and Peyghambarian.

Standard holographic methods have very slow write rates.

Holography using ITO

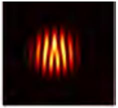


OAM donut beam



Gaussian beam

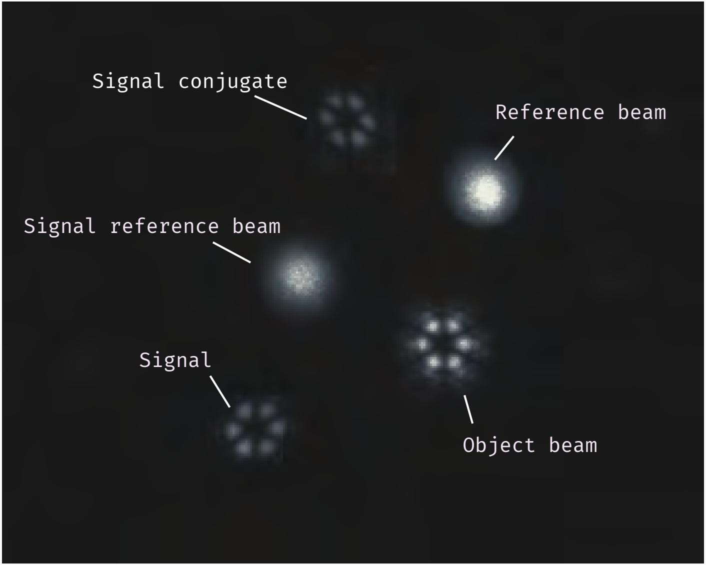
Transient hologram written on ITO



– The interference pattern gets written on the refractive index variation in ITO due to its large intensity-dependent changes in refractive index.

– A second gaussian beam of same or different wavelength can be used to read out the transient hologram.

Holography using ITO: experimental results.



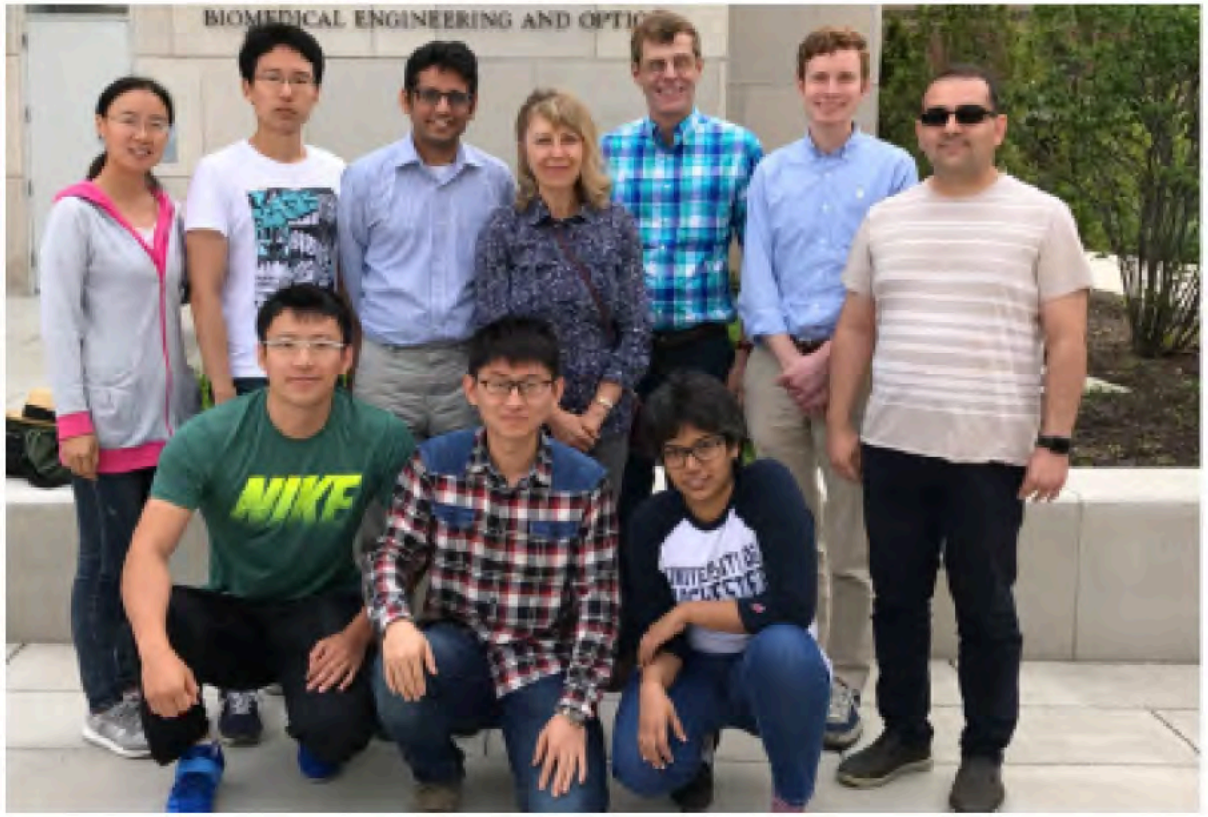
Take home messages.

- **The large nonlinear response of ENZ material can be exploited for real-time holography with an efficiency of 25%.**
- The material is four orders of magnitude thinner (310-nm-thick) than a conventional holographic material.
- **9-12 orders of magnitude larger refresh rate. Limited by the sub-ps recovery time.**
- Broadband response. $1000 - 1500$ nm wavelength range with larger than 1 % diffraction efficiency.
- Might find applications in multimode communications and real-time signal processing such as edge detection, convolution, correlation, etc.
- Essentially we use structured light beams to temporally structure a surface to perform certain mathematical operations.

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group



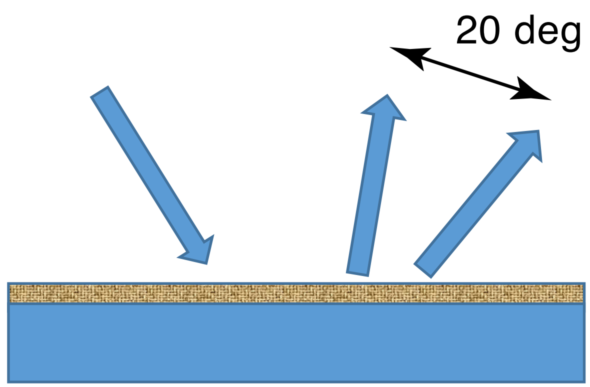
Summary: Physics and Applications of ENZ Materials

- 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

All-Optical, Nanoscale, Sub-Picosecond Beam Steering

- **Concept**



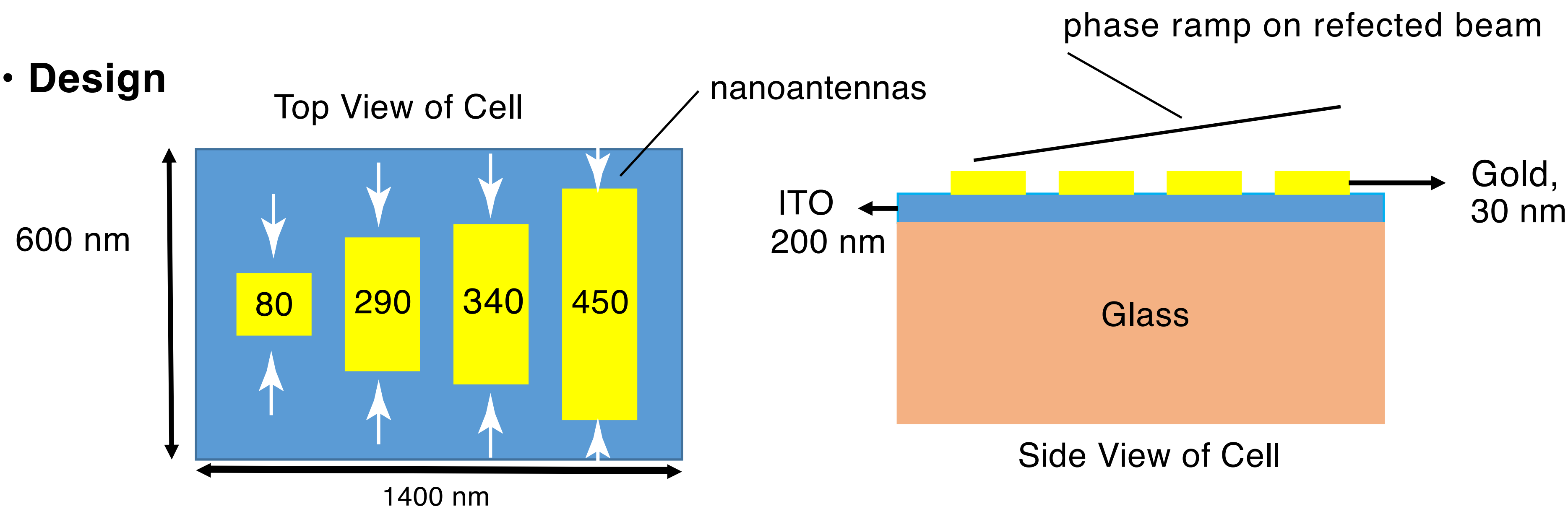
Vary output direction by +/- 20 degrees under all-optical control

Sub-picosecond response time

Beam steerer made of one or many cells

Application: Mode-division multiplexing for telecommunications

- **Design**



Nonlinear response depends on antenna length

- **Characterization**

We have fabricated this design and are currently testing it