Epsilon-Near-Zero Materials: How Light Behaves When the Refractive Index Vanishes

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

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In Memoriam: Emil Wolf – July 30, 1922 to June 2, 2018

Friend, Gentleman, Scientist, Educator

Physics of Epsilon-Near-Zero (ENZ) Materials

- ENZ materials possess exotic electromagnetic properties

  Silveirinha, Engheta, Phys. Rev. Lett. 97, 157403, 2006.

- If the dielectric permittivity ε is nearly zero, then refractive index $n = \mathrm{sqrt}\,(\varepsilon)$ is nearly zero.

  Thus $v_{\mathrm{phase}} = c\,/\,n$ is nearly infinite

  $\lambda = \lambda_{\mathrm{vac}}\,/\,n$ is nearly infinite

  Light oscillates in time but not in space; everyhing is in phase

  Light "oscillates" but does not "propagate."

- Radiative processes are modified in ENZ materials

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

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

  We can control (inhibit!) spontaneous emission!

  Einstein B coefficient

  Stimulated emission rate = B times EM field energy density

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

  Optical gain is very large!

  Einstein, Physikalische Zeitschrift 18, 121 (1917).

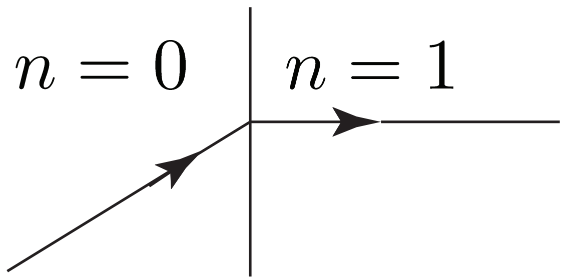
  Milonni, Journal of Modern Optics 42, 1991 (1995).

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

- Snell's law leads to intriguing predictions

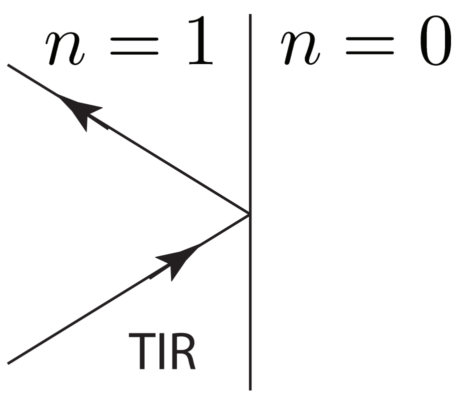
$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

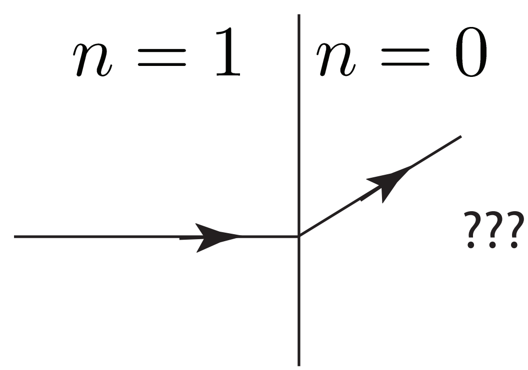
- Light always leaves perpendicular to surface of ENZ material!



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!

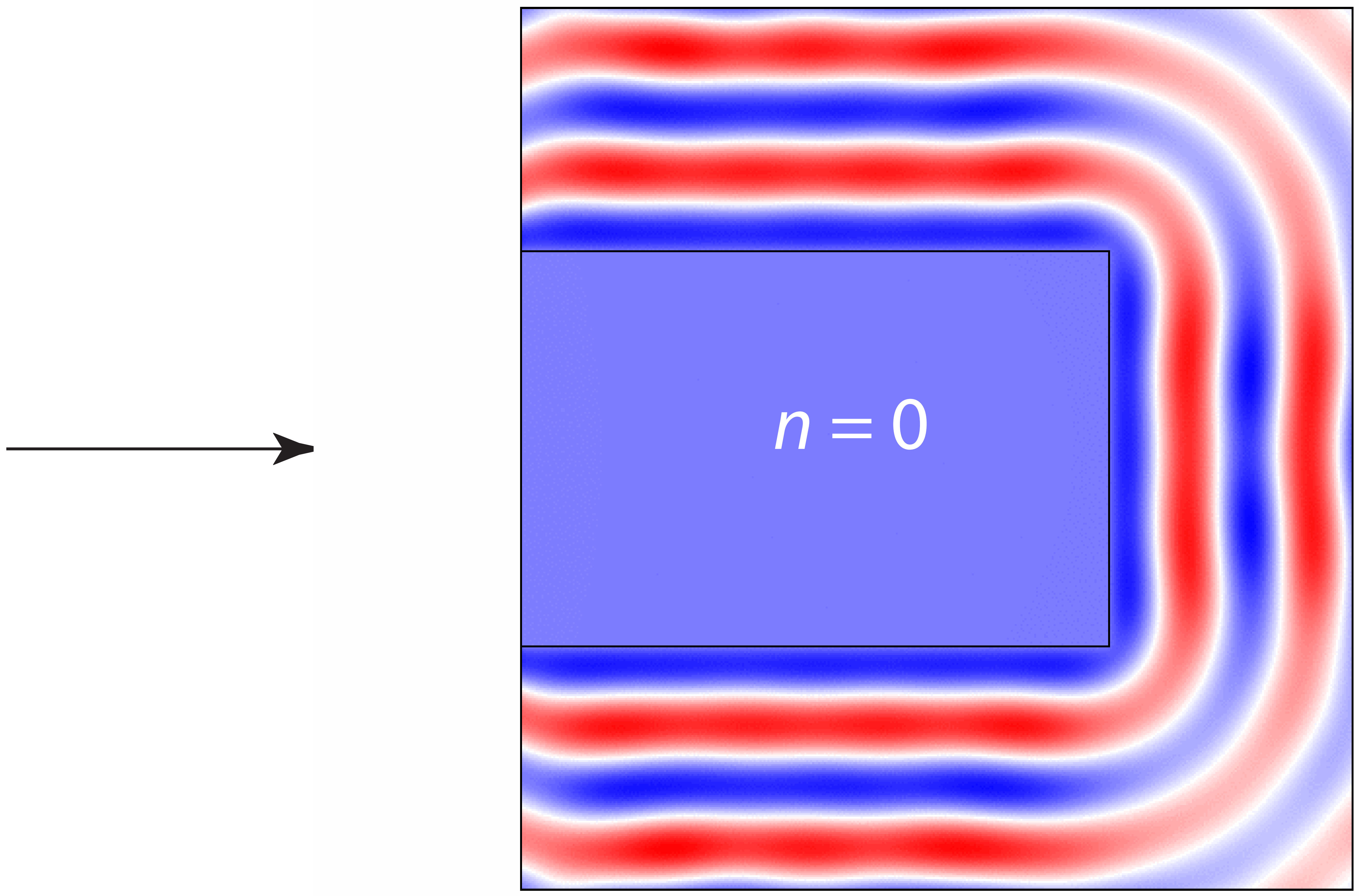




Y. Li, et al., Nat. Photonics 9, 738, 2015.

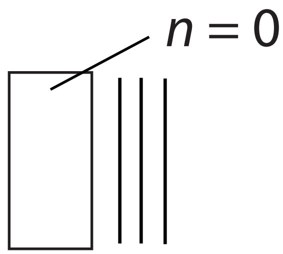
Maxwell Equations Prediction

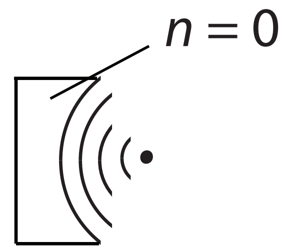
- light enters slab at normal incidence



Some Consequences of ENZ Behaviour - 1

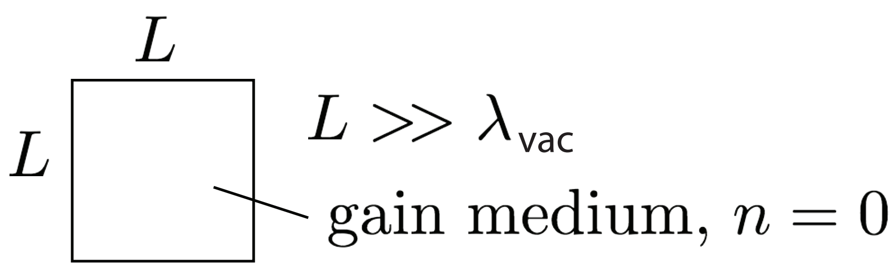
- Funny lenses





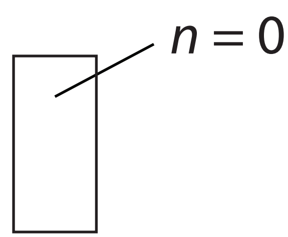
A. Alù et al., Phys. Rev. B 75, 155410, 2007; X.-T. He, ACS Photonics, 3, 2262, 2016.

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



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

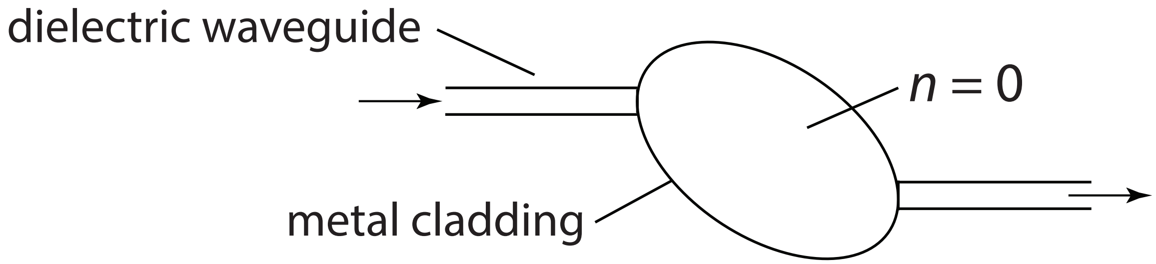
- No Fabry-Perot interference



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

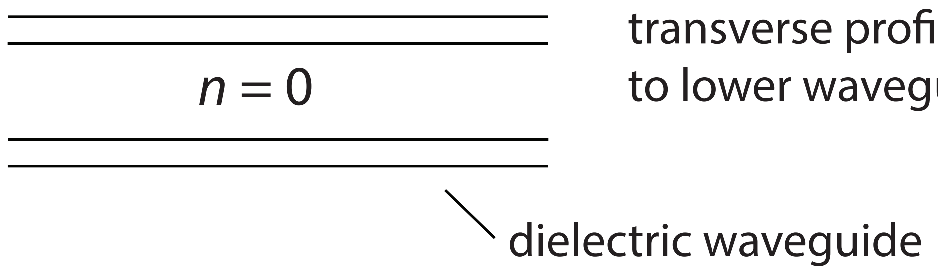
Some Consequences of ENZ Behaviour - 2

- 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

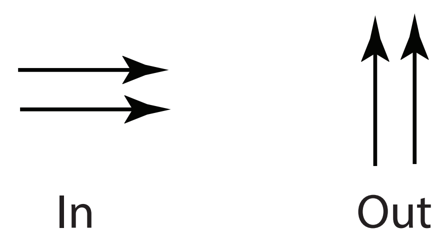


transverse profile of upper waveguide extends to lower waveguide for any distance

- 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 $n_0 = 0$?

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

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

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

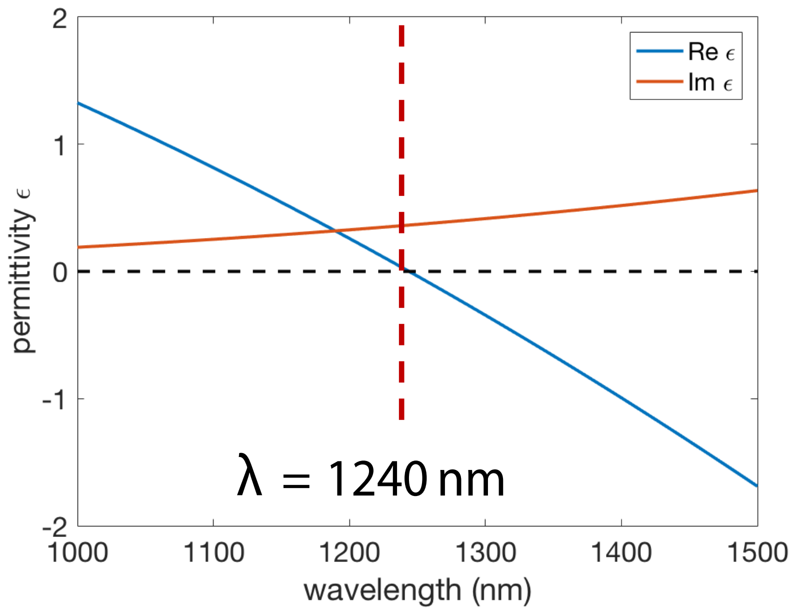
P is the induced dipole moment per unit volume and E is the field amplitude.

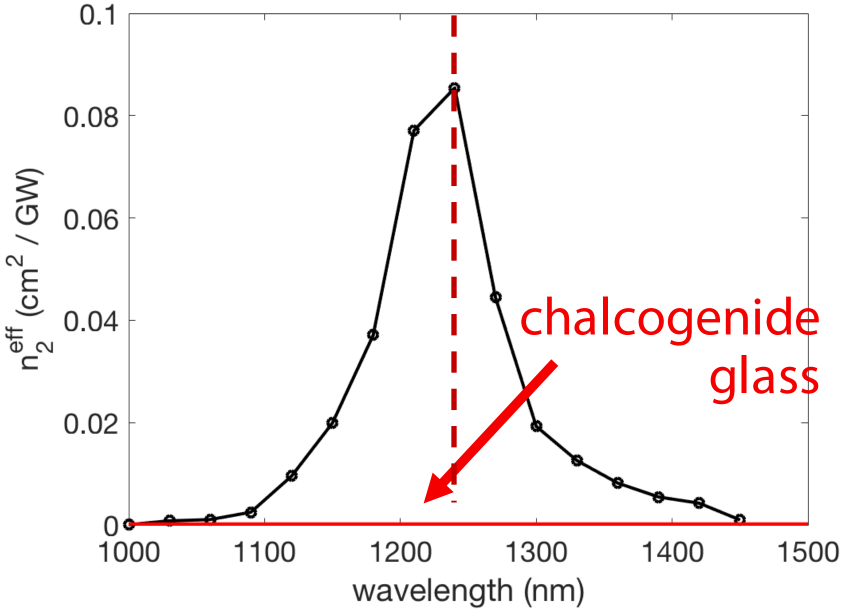
Also, the refractive index changes according to

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

Huge nonlinear optical response of ITO at its ENZ wavelength

Indium tin oxide (ITO)



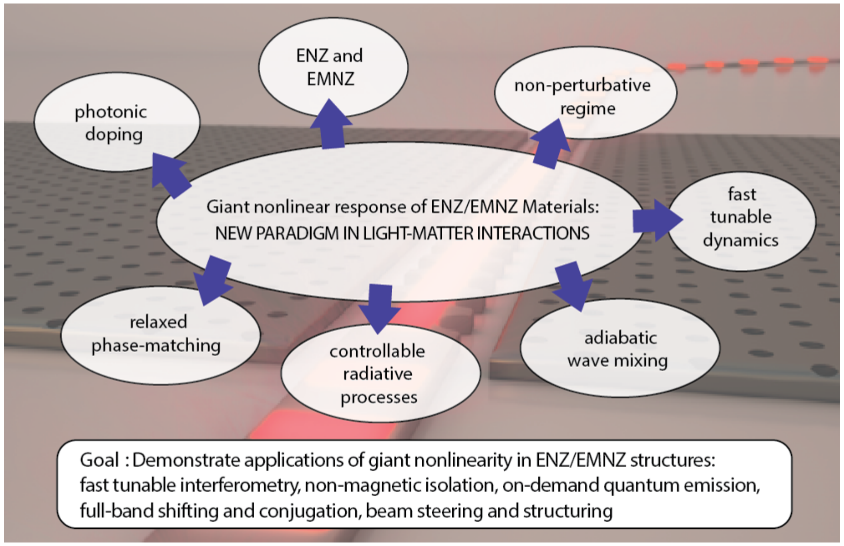


M. Z. Alam et al, Science 352, 795–797 (2016)

Giant Nonlinear Response of ENZ Metastructures

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

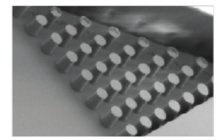
CONCEPT



APPROACH

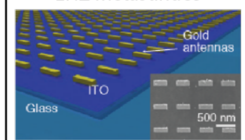
EXPLOIT RANGE OF NLO-ENZ/EMNZ SYSTEMS

Dirac cone metamaterial



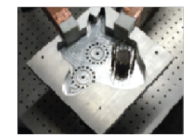
- CMOS compatible
- low loss

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

Special Thanks To My Students and Postdocs!

Ottawa Group

Rochester Group