Physics and Applications of Epsilon-Near-Zero Materials

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

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Physics and Applications of Epsilon-Near-Zero Materials

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

- Nonlinear Optics is important for a variety of reasons:
  - Photonic Devices
    - All-optical switching, buffers and routers based on slow light
    - Used to create quantum states of light for
      - Quantum Computing/Communications/Imaging
    - Fundamental understanding of light-matter interactions
    - Not “just” Lorentz oscillator formalism
    - Understand rogue waves
    - Control filamentation process

- However, the nonlinear response is usually much weaker than the linear response

- Means to enhance the nonlinear response
  - Resonance interactions (atomic vapors)
  - Plasmonic systems
  - Electromagnetically induced transparency (EIT)
  - Metamaterials (composite materials)

- Our approach: Use epsilon-near-zero (ENZ) materials and metamaterials
Physics of Epsilon-Near-Zero (ENZ) Materials

• ENZ materials possess exotic electromagnetic properties

Recall that

\[ n = \sqrt{\varepsilon \mu} \]

where \( \varepsilon \) is the permittivity and \( \mu \) is the magnetic permeability

• Many opportunities in photonics are afforded by ENZ and ZMI materials

\[ \lambda = \lambda_{\text{vac}}/n \quad \nu = c/n \]

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


Terminology: ZIM= zero-index material; ENZ=epsilon near zero; EMNZ= epsilon and mu near zero
Physics of Epsilon-Near-Zero (ENZ) Materials

• 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
\[ B = B_{\text{vac}} / (n \, n_g) \]
Optical gain is very large!

Equations are shown for nonmagnetic (\( \mu = 1 \)) materials

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

Einstein, Physikalische Zeitschrift 18, 121 (1917).
Optics of Zero-Index Materials

• 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!

\[ n = 0 \quad | \quad n = 1 \]


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

Some Consequences of ENZ Behavior - 2

- Super-coupling (of waveguides)
  
  ![Diagram of super-coupling](image)

- Coupling between two distant waveguides
  
  ![Diagram of coupling](image)

- Automatic phase matching of NLO processes
  
  - Recall that we need $\Delta k = 0$, but when $n=0$
    
    $k = n\omega/c$ vanishes and so does $\Delta k$.

  - We have observed this effect in a Dirac-cone, zero-index metamaterial.

  - Usual four-wave mixing process
    
    ![Diagram of four-wave mixing](image)

  - With zero-index materials we can have
    
    ![Diagram of zero-index](image)


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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 $\chi^{(3)}$

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

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

$$n = n_0 + n_2 I + n_4 I^2 + \ldots$$
How to Choose an Epsilon-Near-Zero Material

• Electrical conductors
  All conductors display ENZ behavior at their (reduced) plasma frequency
  Recall the Drude formula
  \[ \epsilon(\omega) = \epsilon_\infty - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \]
  Note that \( \text{Re} \epsilon = 0 \) for \( \omega = \omega_p/\sqrt{\epsilon_\infty} \equiv \omega_0 \).
  ENZ wavelength usually restricted to a limited range in the visible.

• Electrical insulators (dielectrics)
  Dielectrics can show ENZ behavior at their (optical) phonon resonance.
  ENZ wavelength restricted to a limited range in the mid-IR.

• Metamaterials
  Can design the material so that the ENZ or EMNZ wavelengths are at any desired value.

• Challenge (for any material system). For low loss, we want \( \text{Im} \epsilon \) as small as possible at the wavelength where \( \text{Re} \epsilon = 0 \).
Nonlinear Optics of Indium Tin Oxide (ITO)

• We recently reported that, at its ENZ wavelength, ITO possesses a nonlinear coefficient $n_2$ that is 100 times larger than those of previously reported materials [1].

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

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

• Dielectric properties of ITO are well described by the Drude formula.

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

• Note that aluminum-doped zinc oxide (AZO), another transparent conducting oxide, also has strong nonlinear response at its ENZ wavelength [2].

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

- ellipsometry

\[ \lambda = 1240 \text{ nm} \]

- overall change in refractive index of 0.8

- sub picosecond response time

\[ n_2 \text{ can be } 3.4 \times 10^5 \text{ times larger than that of silica glass} \]

M. Z. Alam et al., Science 352, 795-797 (2016)
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 concentrate the field within the ITO
  - Coupled resonators: ENZ resonance and nano-antennas

Concept:

SEM:

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$_2$.

Nonlinear Optical Properties of a Layered Metamaterial in its ENZ Region

Do layered metamaterials also show enhanced NLO response at ENZ wavelength?

- By controlling the metallic fill fraction $\rho$, we can set the ENZ wavelength to be anywhere from 300 to 700 nm. We use $\rho = 0.2$, which corresponds to 500 nm. We deposit five layer pairs.
- Note that the real part of epsilon vanishes at 508 nm, close to the design wavelength. The SEM shows our structure. Ag thickness = 16 nm; silica thicness = 65 nm.
- We perform Z-scan measurements on the sample. Note the enhanced response of the composite as compared to a single layer of silver.
- Note the pronounced peak in the value of $n_2$ around the ENZ wavelength. We find a good but not perfect agreement with a simple effective medium theory.

Suresh, Reshef, Alam, Upham, Karimi and Boyd
Physics and Applications of Epsilon-Near-Zero Materials

- Physics of ENZ Materials
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- Materials for ENZ
- Applications of ENZ Materials
Wavelength Conversion by Time Refraction

- Recall that in space refraction (normal refraction) frequency is conserved but the wavelength is changed

\[ \frac{c}{f} = n \cdot \lambda \quad \rightarrow \quad n_1 \lambda_1 = n_2 \lambda_2 \]

- Time refraction (analog of space refraction)

\[ \frac{c}{f} = n \cdot \lambda \quad \rightarrow \quad n_1 f_1 = n_2 f_2 \]

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:

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

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

Real-Time Holography with THz Refresh Rates

• Goal: Real-time holography with video or much faster refresh rates.

• The ultrafast response of ITO permits THz refresh rates.

• Important applications involve image processing and signal processing.

• Current real-time holographic materials cannot even support video frame rates.

• Demonstration of image processing (edge enhancement).

Alam, Fickler, Reshef, Giese, Upham, and Boyd
Some Potential Applications of ENZ Behavior

(a) Non-magnetic isolation
- Forward direction
  - Geometry mismatch.
  - Non-uniform power distribution.
  - Breaking reciprocity.
- Backward direction
  - Input beam
  - No output beam
  - Intense input beam

(b) Full-band shifting and conjugation
- Pump
- > 10 nm bandwidth
- Input beam
- Output beam
- NLO-ENZ
- Dielectric
- Wideband input beam + pump
- Output beam
- NLO-ENZ
- Dielectric
- Output beam
- Forward FWM
- Backward FWM
- Output photons
- Single photon detector
- Interference

(c) High-speed tunable interferometers
- Input beam
- NLO-ENZ
- Mach-Zehnder interferometer
- Interference
- Output beam

(d) On-demand quantum emitter
- Pump
- Short pulse laser
- Quantum emitter embedded in NLO-ENZ
- Output photons
- Single photon detector
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