Epsilon Near Zero Material for Electromagnetic Energy Transport through Sub-wavelength Channels

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LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Early Career R&D Program

Sandia National Laboratories
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Problem

Efficient transport of electromagnetic energy through subwavelength channels in the optical regime can dramatically enhance the performance of subwavelength imaging, photovoltaics, sensing and light emission. Current approaches based on plasmonic structures or negative index metamaterials tend to be lossy due to material absorption and have a small bandwidth due to reliance on resonance behavior. Here we propose using epsilon-near-zero (ENZ) material to achieve efficient subwavelength electromagnetic energy transport.

Q: What is an Epsilon Near Zero Material ?
A: Epsilon near zero (ENZ) material is a metamaterial whose effective dielectric constant (ε) is close to zero in a certain wavelength range.

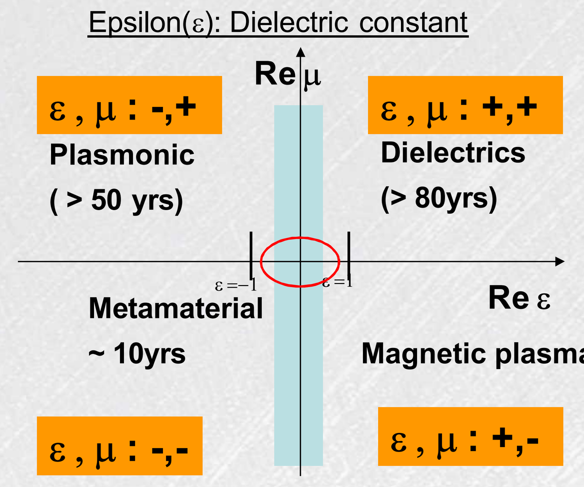
Properties:

- Electric field displacement vector **D**= ε**E** ~0 in these media since ε~0
- Negligible phase variation of EM waves even at optical frequencies

Implications:

- Sub-wavelength squeezing of light (λ/20), Low loss, broadband optical frequency operation and enhancement of non-linearity.

Epsilon(ε): Dielectric constant



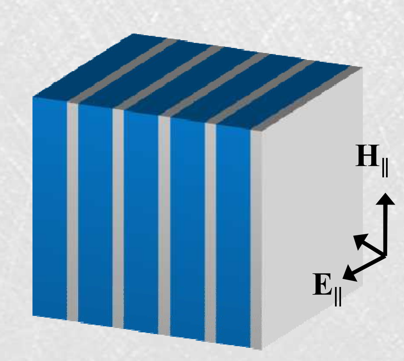
Approach

The basic approach to achieving an ENZ material is to combine a material with positive 'ε' and negative 'ε' in appropriate ratio. The positive 'ε' can be an insulator or a semiconductor with no absorption at the design wavelength and the negative 'ε', a metal.

$$\varepsilon_{effective} = f\varepsilon_{+} + (1-f)\varepsilon_{-}$$

metal

dielectric



Goals

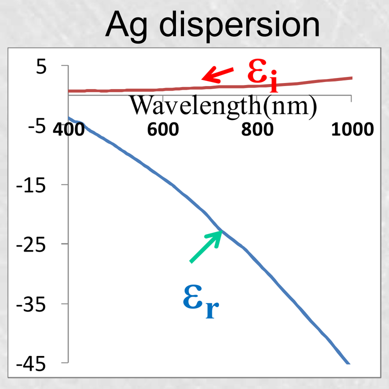
- Minimize losses due to metal
- Effective medium behavior-finer subdivision
- Reduce non-local effects-smoother field distribution
- Easy fabrication , easy characterization

Materials Choice

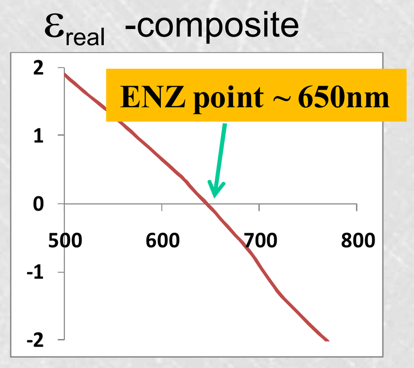
ε_- : Siiver(Ag) (23%)

ε_+ : Titanium dioxiide(TiO_2) (77%)

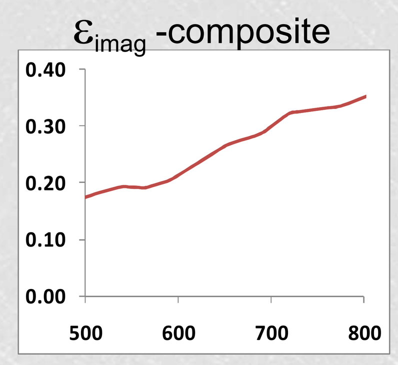
Ag dispersion



ε_{real} -composite



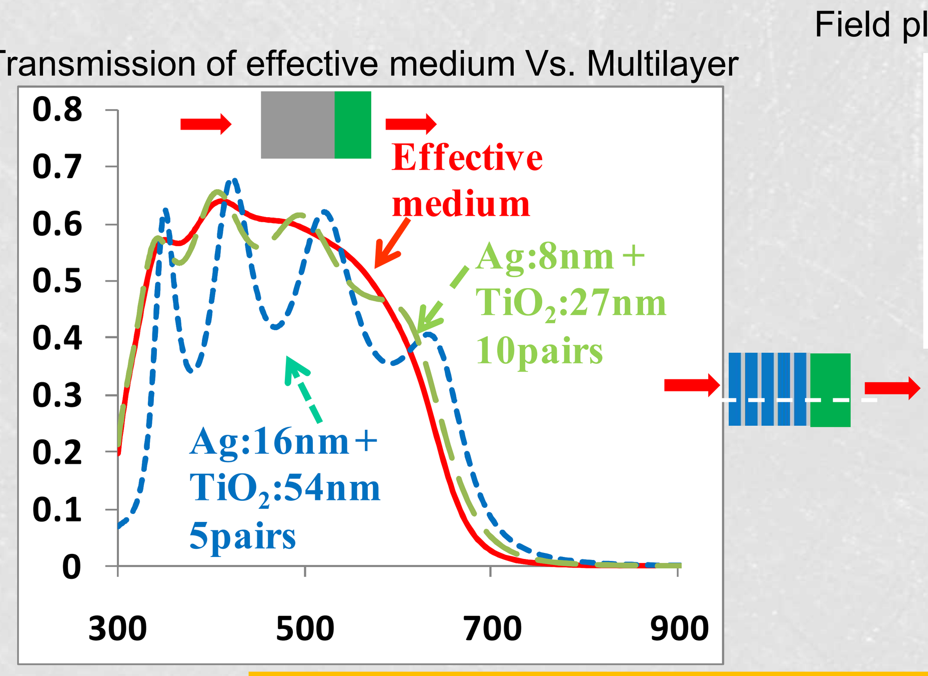
ε_{imag} -composite



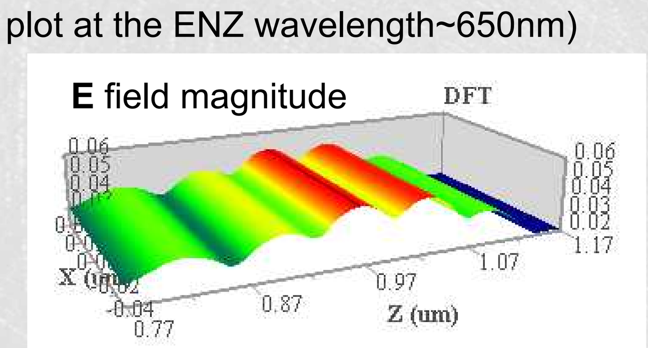
Results

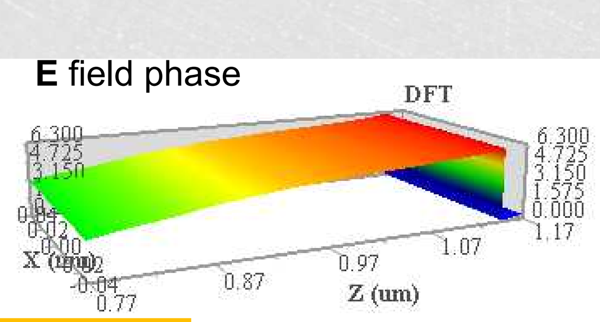
Simulation of the structure - Finite Difference Time Domain

Transmission of effective medium Vs. Multilayer



Field plot at the ENZ wavelength~650nm)





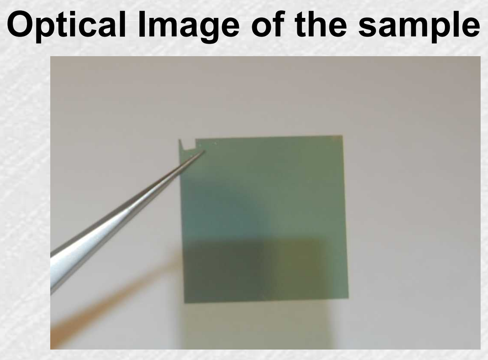
The phase variation is uniform at the ENZ wavelength

Results

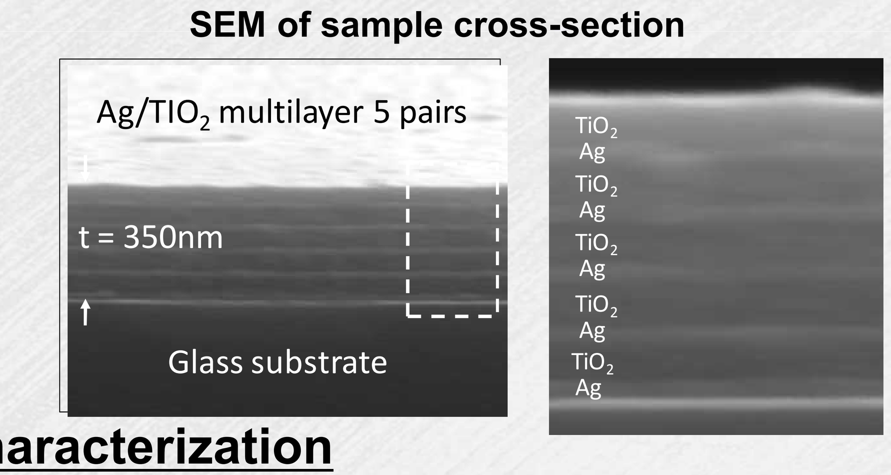
Sample Fabrication

The ENZ structure was fabricated by electron beam evaporation of alternating layers of Ag (16nm) and TiO_2 (54nm).

Optical Image of the sample

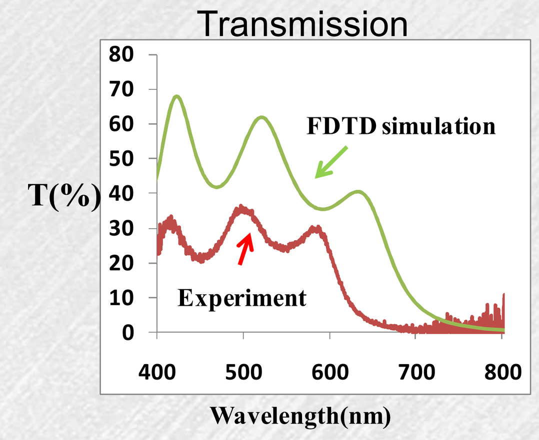


SEM of sample cross-section

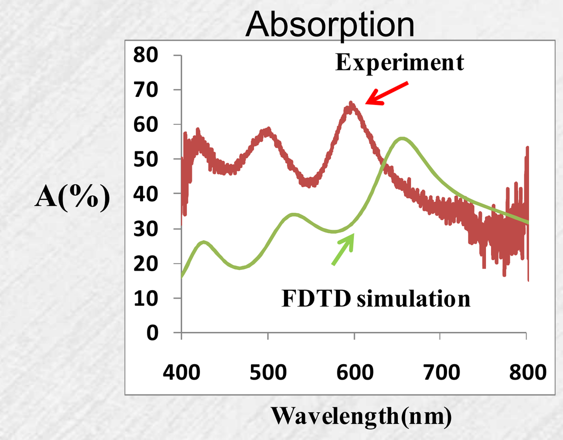


Optical Characterization

Transmission

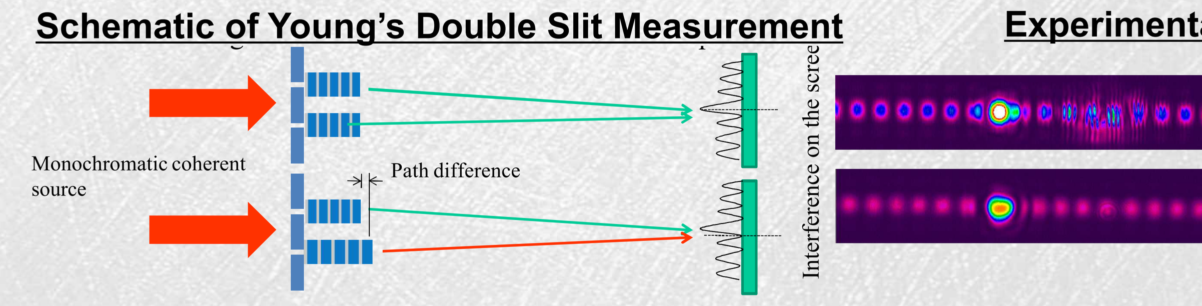


Absorption

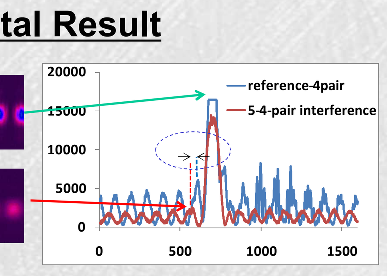


The wavelength at which the fabricated multilayer composite structure displays ENZ behavior can be experimentally determined by performing Young's double slit type experiment which measures the amplitude and the phase difference between ENZ composite structure of different thickness deposited on each slit. Since the multilayer structures are highly anisotropic this approach enables near normal incidence measurements unlike ellipsometry, which is done at large angles.

Schematic of Young's Double Slit Measurement



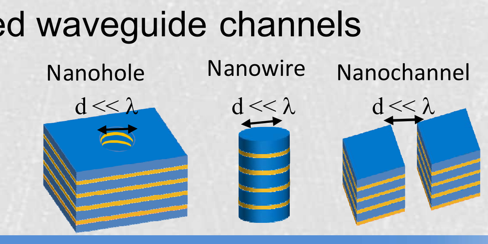
Experimental Result



- An additional phase shift is introduced for the electromagnetic wave traveling through the slit containing 5 pairs of multilayers versus 4, resulting in a shift in the interference fringes (shown in red above) compared to the case when both slits have 4pairs (blue) .
- The amplitude of the fringes for the 4/5pair case (red) is also reduced which is due to absorption.
- The experimental fringe pattern will be compared with that obtained by FDTD simulations to extract the effective dielectric function of the ENZ material as a function of the wavelength.

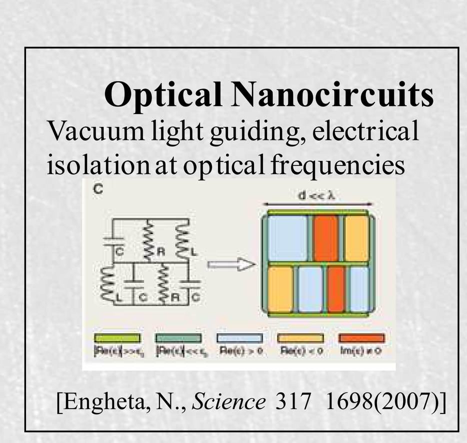
Next Steps …

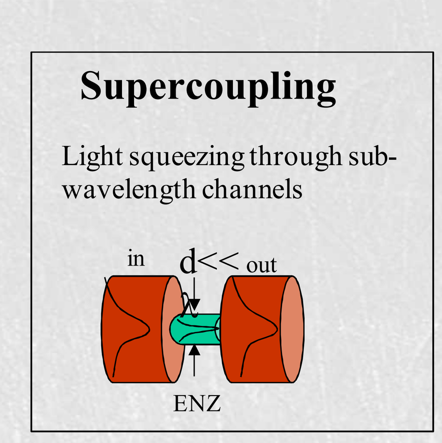
- ❑ Create different nanochannel slits in the ENZ substrate to explore energy transport.
- ❑ Explore transfer of near field light through ENZ based waveguide channels
- ❑ Investigate non-linearity near the ENZ wavelength

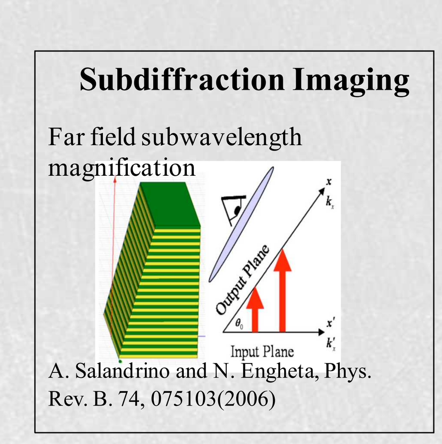


Significance

ENZ materials' ability to transport electromagnetic energy through sub-wavelength channels can have a significant impact on nanophotonics, sensors, efficient solar cells, and importantly, optical nanocircuitry that can overcome Moore's law in turn impacting Sandia and DOE's core energy security mission.







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