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Resonant coupling to a dipole absorber inside a metamaterial: anti-crossing of the negative index response

S. Smolev[1], Zahyun Ku[1], S. R. J Brueck[1], I. Brener[2], M.B. Sinclair[2], G. A. Ten Eyck[1], W. L. Langston[2], and L.I. Basilio[2]

[1]Center for High Technology Materials, University of New Mexico,
email: smolev@chtm.unm.edu

[2]Sandia National Laboratories, Albuquerque, NM

LDRD
LABORATORY DIRECTED RESEARCH & DEVELOPMENT

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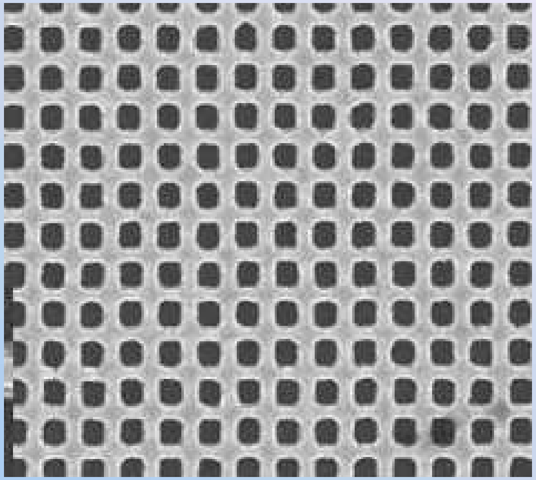
Outline

- *Introduction*
- *Simple physical model*
- *Rigorous coupled wave analysis (RCWA) modeling*
- *Experimental results*
- *Conclusions*

Introduction

Long wavelength infrared spectra (LWIR)



- Has a lot of application:
  - sensing;
  - communications;
  - medical
  - etc.

- Understanding physics and properties of NIM in this spectra is important.

Introduction

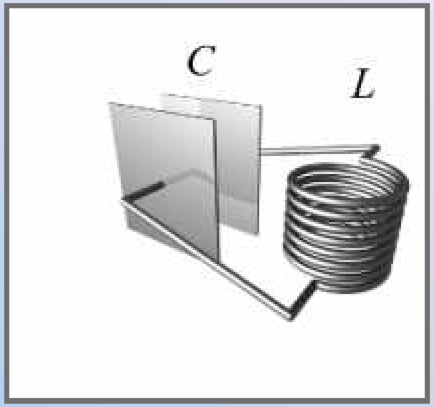
Fishnet based metamaterial in the LWIR:

- Are easy to fabricate due to large dimensions;
- Metals show good "metallic" behavior;
- Dielectric is imbedded in metamaterial:
  - strong coupling;
  - ε is negative everywhere
  - μ is negative at the resonance;
- Most commonly used dielectrics have an absorption peak

Understanding effects of adding an absorption peak in dielectric at the proximity of the fishnet resonance is very important

Simple Physical Model

Can be modeled by



The effective permeability can be described by Lorentzian-like response

$$\mu_{eff} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\omega\gamma_0}$$

- ω_0 - resonance frequency;
- γ_0 – linewidth;
- F is a fill factor.

Simple Physical Model

In terms of equivalent circuit parameters

$$\omega_0^2 = \frac{1}{LC} = \frac{1}{LC_0\varepsilon_{abs}}$$

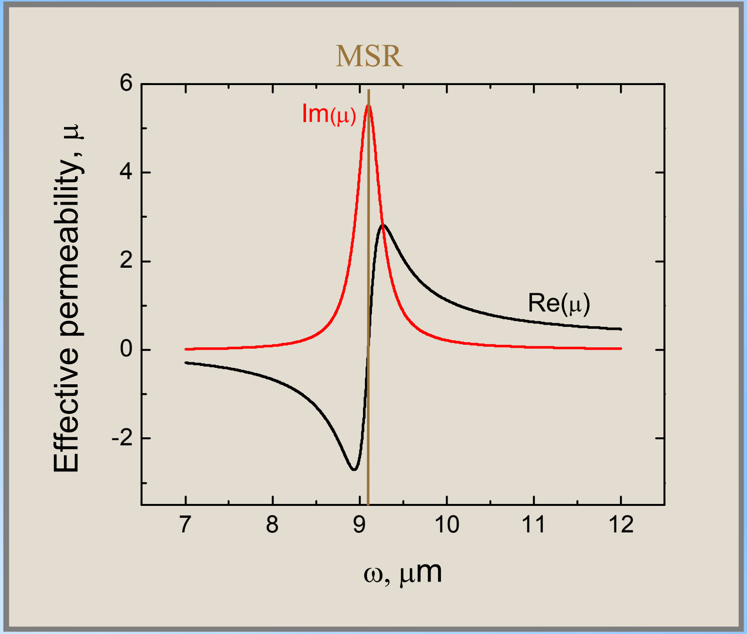
- C_0 - capacitance without the absorber.

$$\frac{1}{\varepsilon_{abs}} = 1 - A\gamma_1\left\{\frac{1}{\omega+\omega_1+i\gamma_1} + \frac{1}{-\omega+\omega_1-i\gamma_1}\right\}$$

- A - related to the oscillator strength;
- γ_1 - the inverse linewidth;
- ω_1 - the resonance frequency of the electric dipole transition.

Simple Physical Model

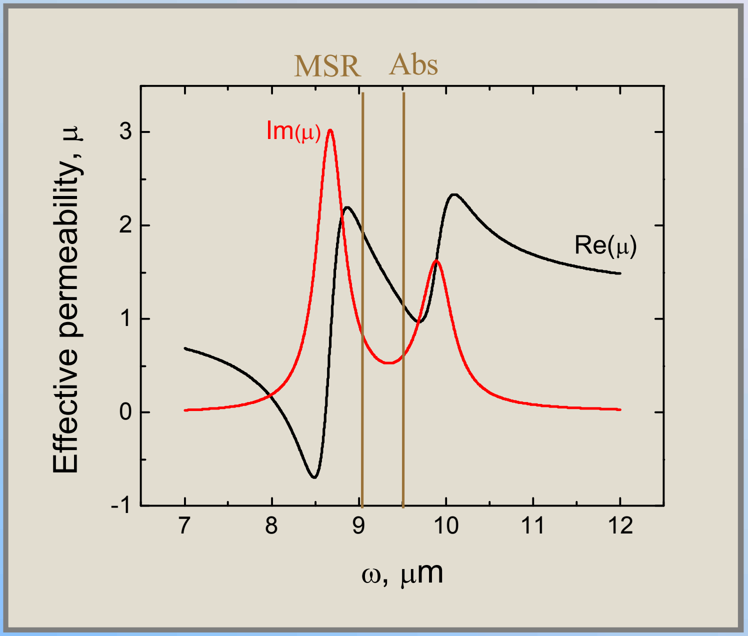
Without absorbing dielectric media



$F = 0.2; \gamma_0 = 0.33$

✓ *Metamaterial structural resonance (MSR) at 9.1 μm*

With absorbing dielectric media



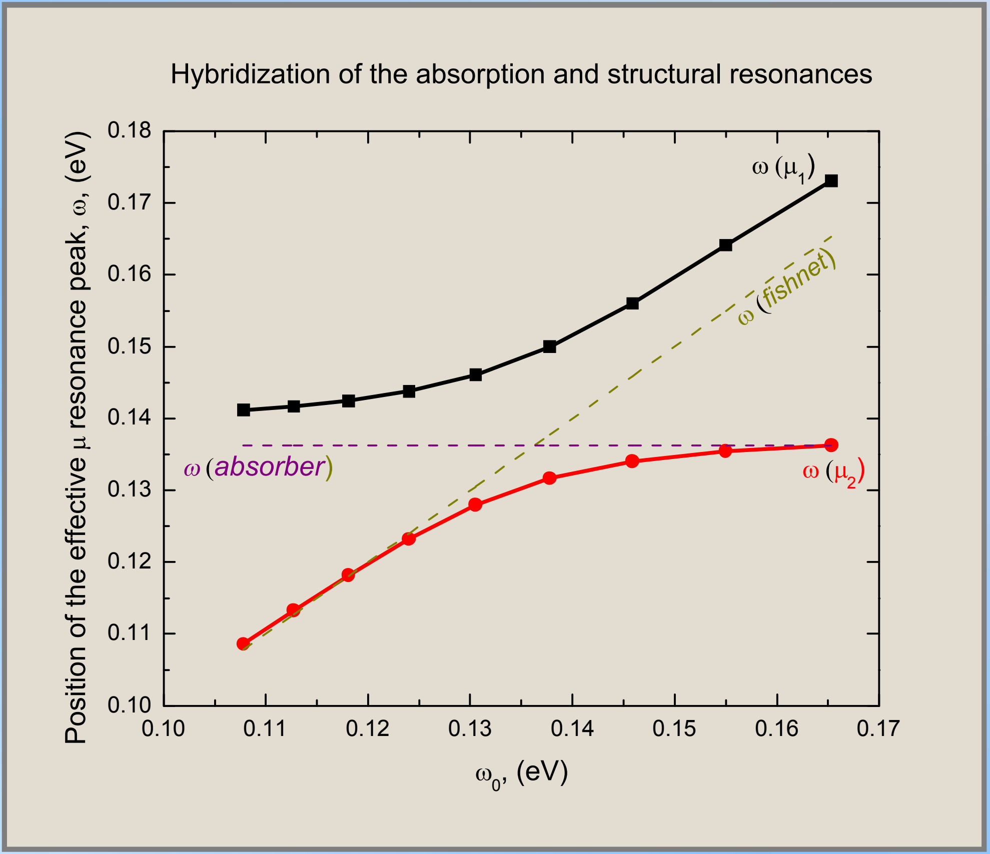
$F = 0.2; \gamma_0 = 0.33; A = 8x10^{-4} ; \gamma_1 = 3.5\ x10^{-3}$

✓ *(MSR) at 9.1 μm;*

✓ *Absorption peal at 9.5 μm.*

Simple Physical Model

- As the metamaterial structural resonance is tuned through the absorption resonance



✓ **We obtain hybridization of resonances with an anti-crossing behavior and sharing of oscillator strength .**

Rigorous Coupled Wave Analysis

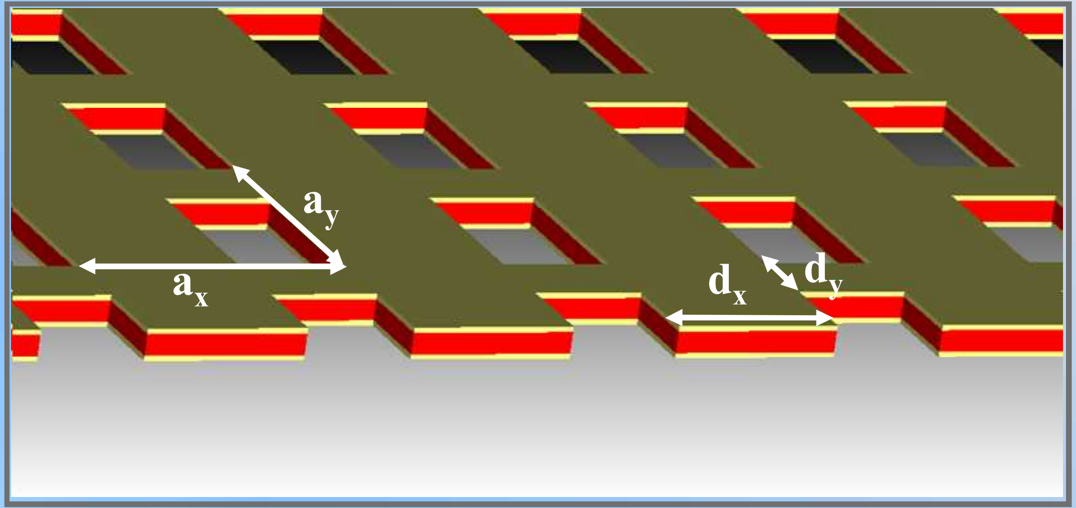
- Common algorithm to extract T and R coefficients;

- Effective parameters such as:
  - n - refractive index;
  - μ - permeability;
  - ε – permittivity;
  - η - impedance can be calculated;

- In the modeling incident light is normal to the surface;

- Incident and outgoing media are air.

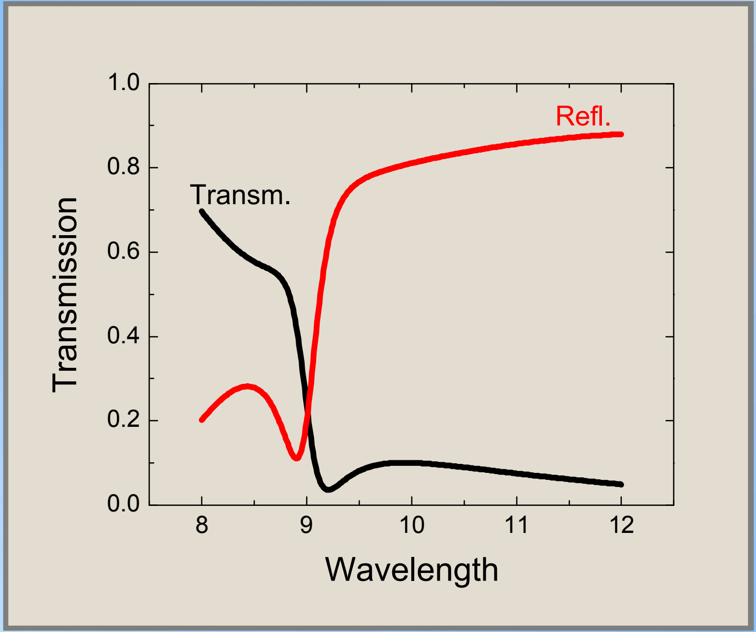
Rigorous Coupled Wave Analysis

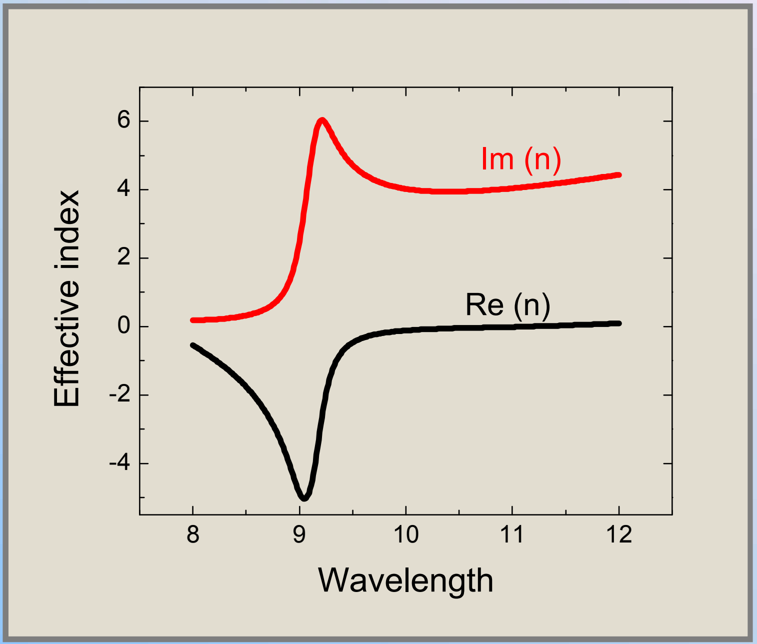


Geometrical parameters for a fishnet structure with resonance at ~ 9.2 µm.

Pitch (a_x, a_y)	CD (d_x)	CD (d_y)	$n_{dielectric}$	Al Thickness	Diel. Thickness
5.2 µm	3.12 µm	1.56 µm	1.5	100 nm	800 nm

Rigorous Coupled Wave Analysis

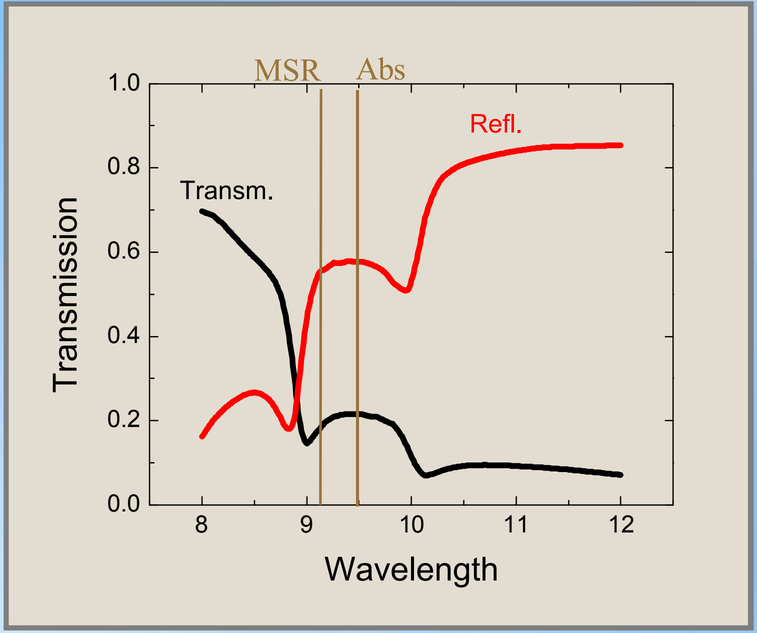


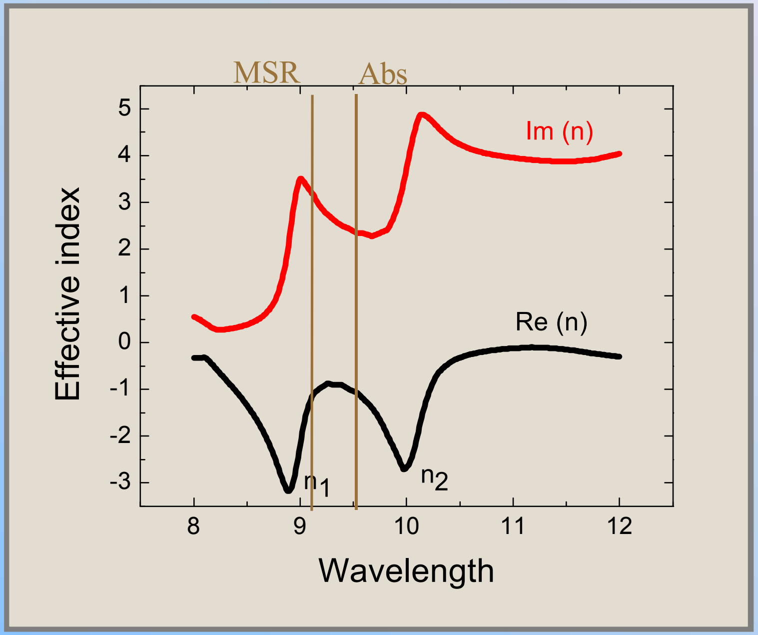


- ✓ RCWA calculated T (left) and effective *n* (right) of the fishnet structure;
- ✓ A single resonance at ~ 9.2 μm with dielectric material (n = 1.5) without an absorber.

Rigorous Coupled Wave Analysis

➢ Add absorbing media with peak at ~ 9.5 μm

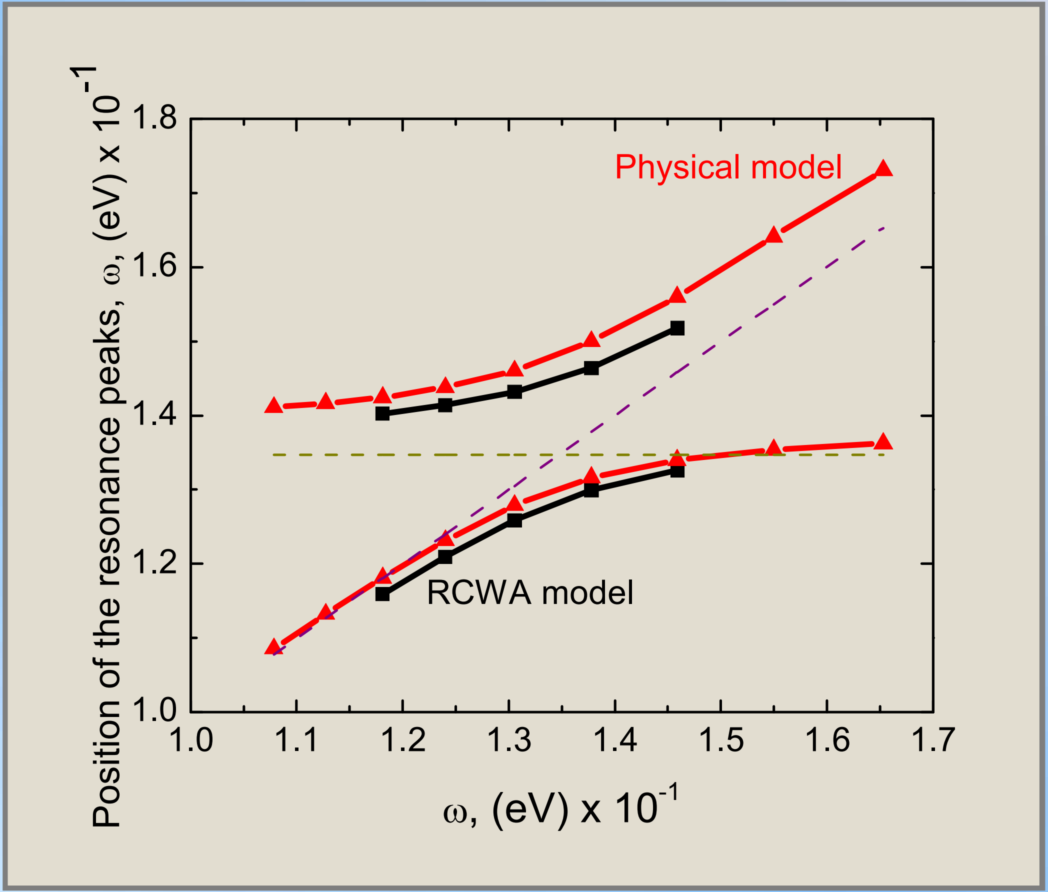




✓ **Two resonances are observed with the addition of a dipole absorption resonance in the dielectric.**

Rigorous Coupled Wave Analysis

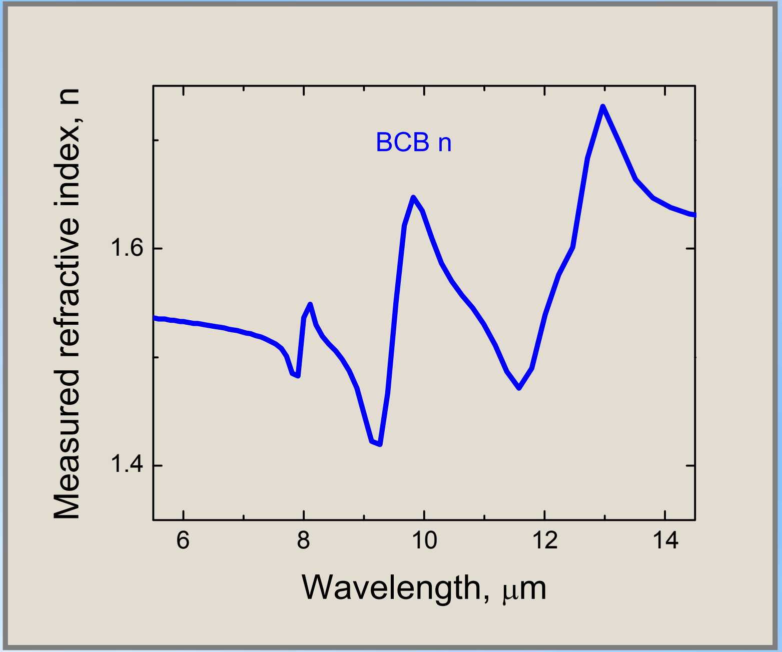
- As the structural metamaterial resonance is tuned through the absorber resonance

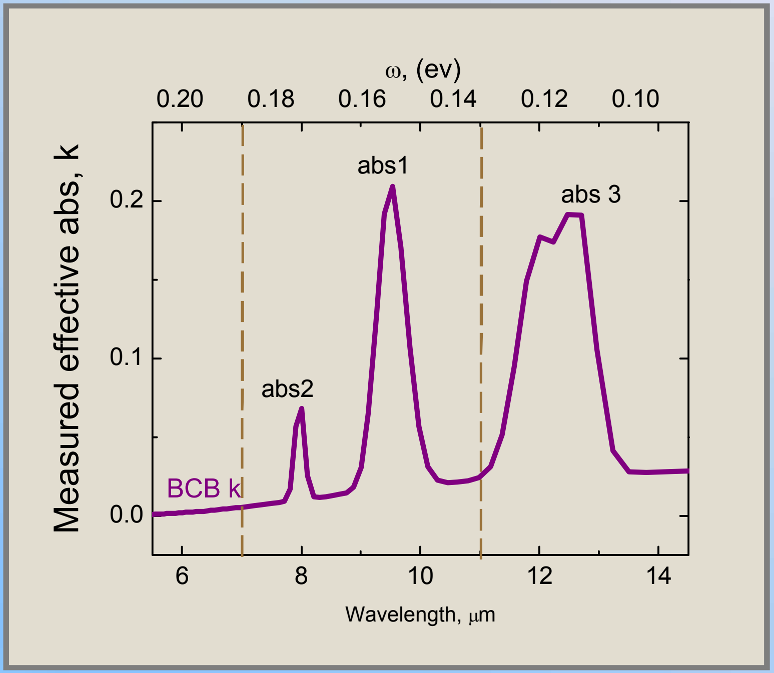


✓ We obtain an anti-crossing behavior of the resonances

Design of Experiment

Use benzocyclobutene (**BCB**) as the absorber in the dielectric media of the fishnet metamaterial.



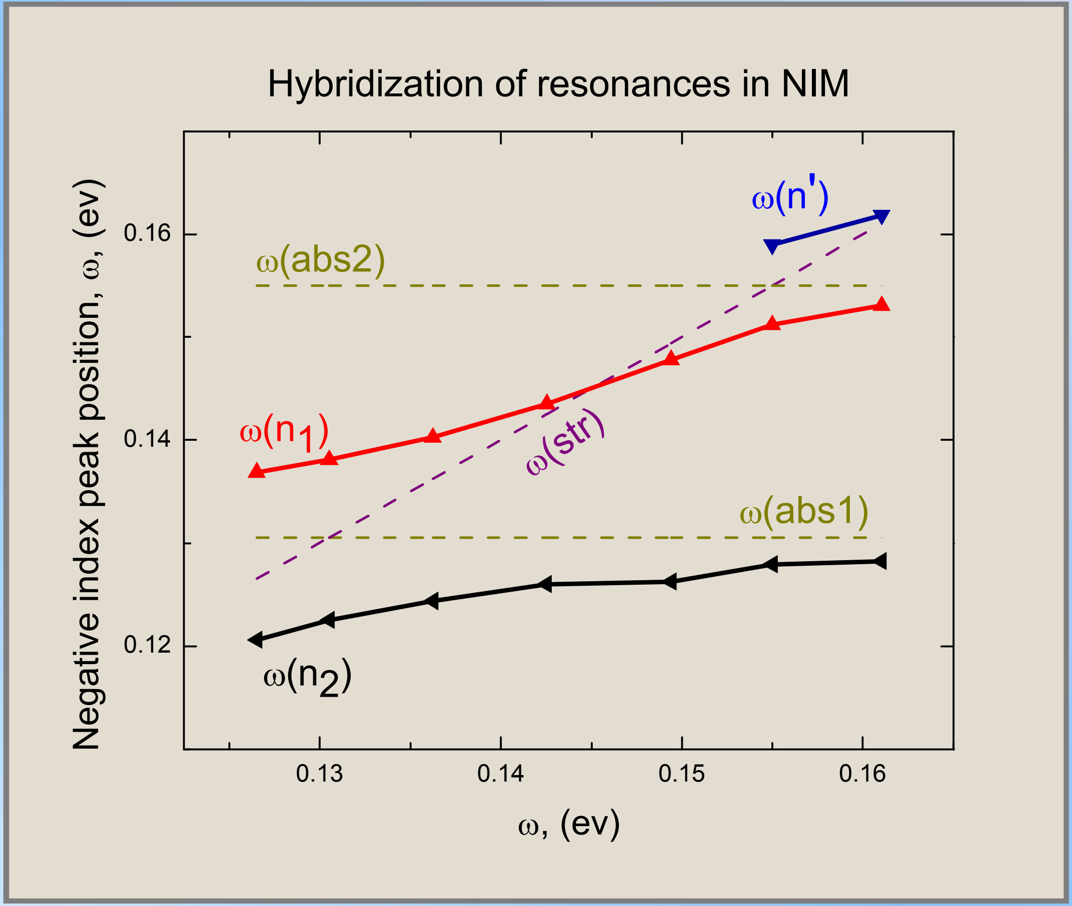


2 distinguishable absorption peak are visible in BCB characteristics in the region of interest.

Measurement data by courtesy of G. Bormann

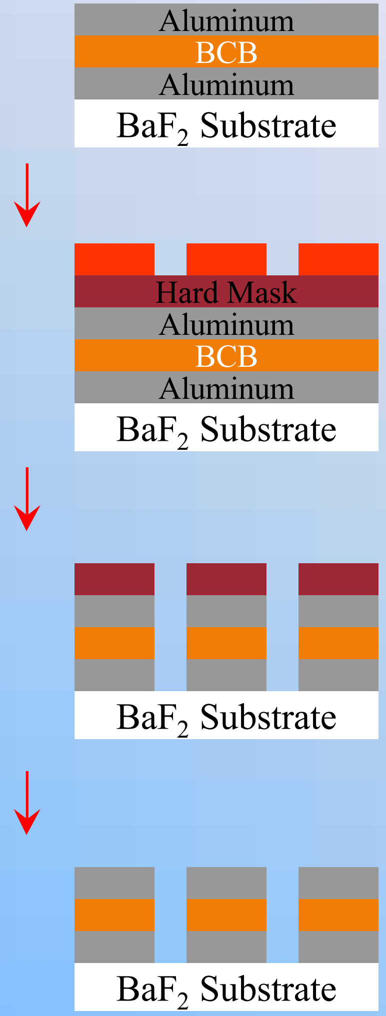
Design of Experiment

Designed hybridization behavior as structural NIM resonances is scanned through absorption resonances.



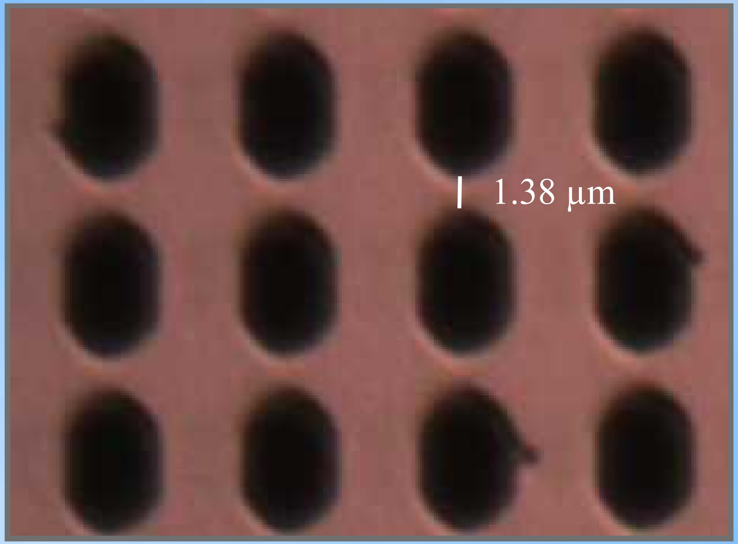
Fishnet Fabrication

- E-beam deposited Al films, spin-on BCB
- Hard mask PECVD deposited SiO_2
- Standard lithographic processing used
- Cl_2 based ICP-RIE Aluminum Etch
- CF_4/O_2 RIE BCB Etch
- Hard mask removal

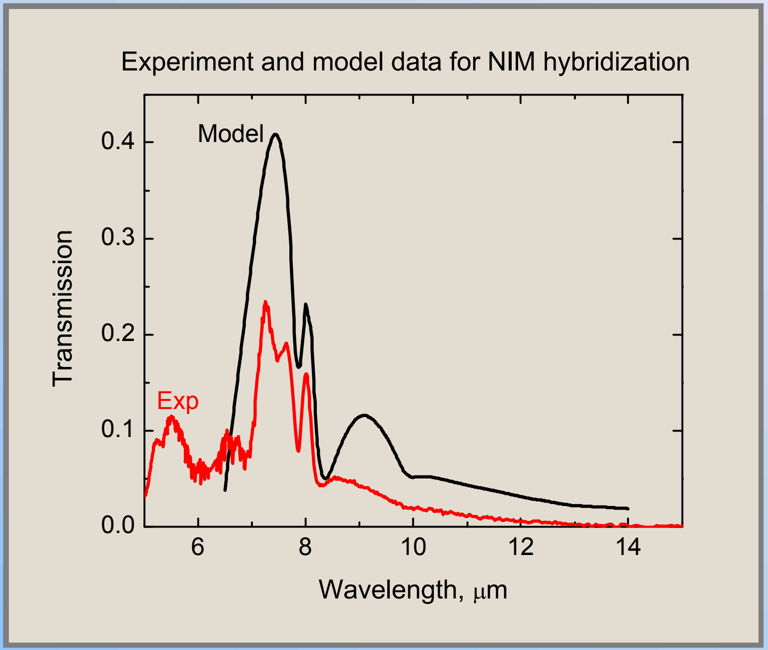


smolev@chtm.unm.edu

Experimental Data



Optical microscope image of the fishnet metamaterial structure with hybridization of resonances.

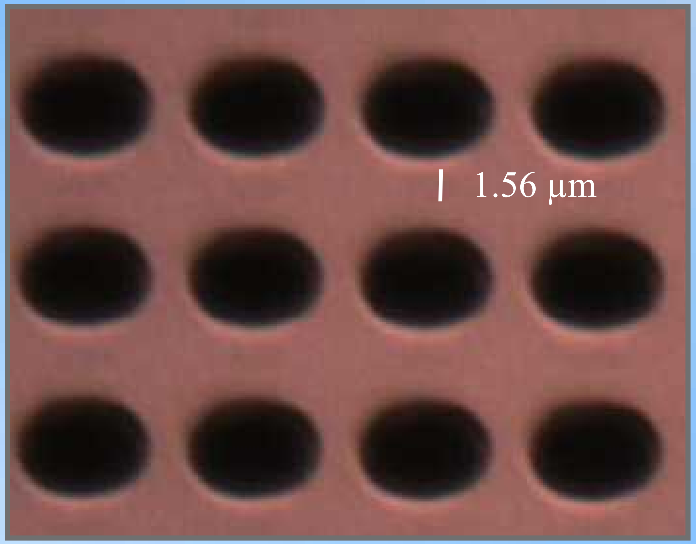


Experimental and model data for the hybridization of resonances:

✓ ***Structural resonance – 8.0 µm***

✓ ***Absorption peaks - 7.9 , 9.5 µm***

Experimental Data



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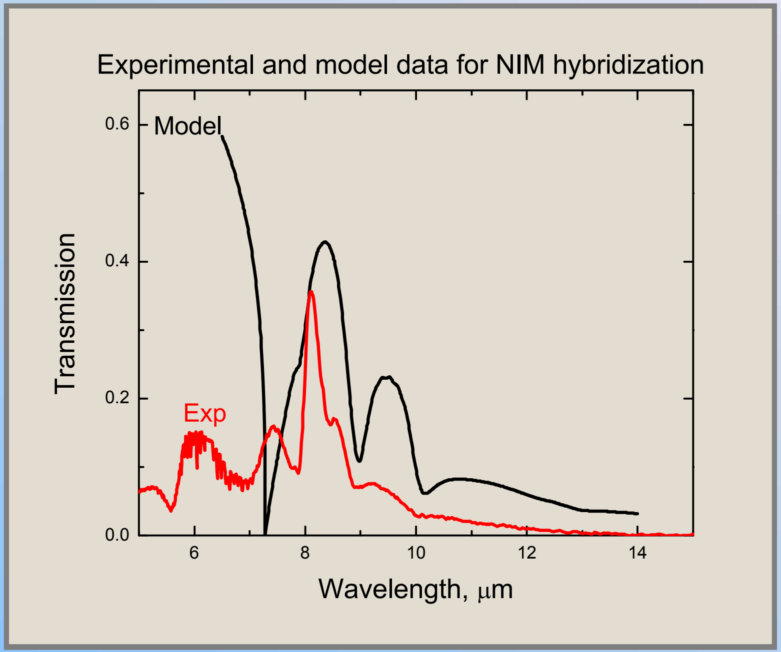


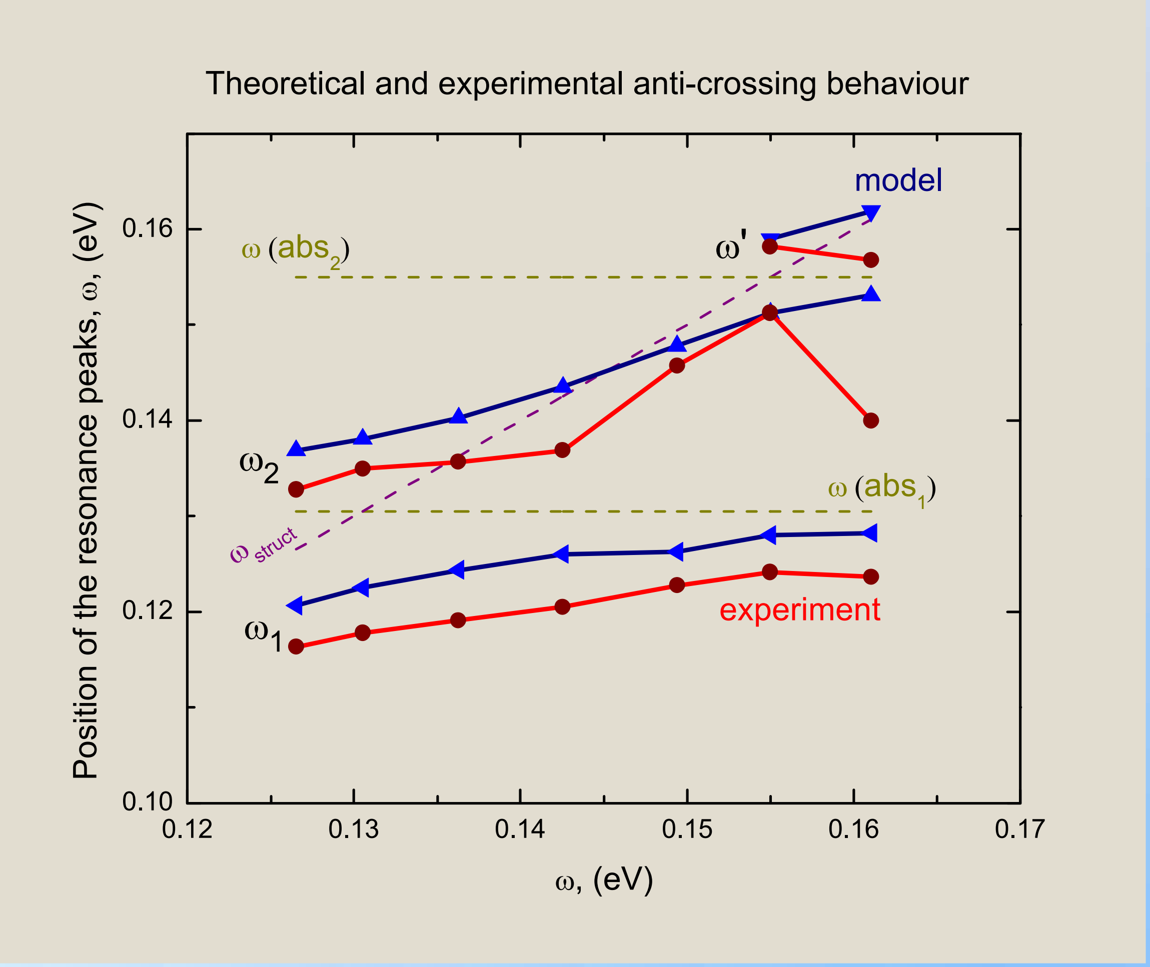
Experimental and model data for the hybridization of resonances:

✓ ***Structural resonance – 9.1 μm***

✓ ***Absorption peaks - 7.9 , 9.5 μm***

Experimental Data

Hybridization behavior of the resonances obtained by scanning structural NIM resonance through absorption resonance.



Conclusion

- ✓ We have demonstrated a novel resonance hybridization effect between metamaterial and dielectric absorption resonances.
- ✓ A simple physical model and more detailed RCWA calculations were performed.
- ✓ Both models are consistent.
- ✓ ***Experimental data clearly show coupling between the resonances with hybridization behavior and sharing of oscillator strength.***
- ✓ Experimental data clearly shows hybridization in good agreement with theoretical modeling.
- ✓ Investigation of potential applications for sensing is currently underway.

Thank you!