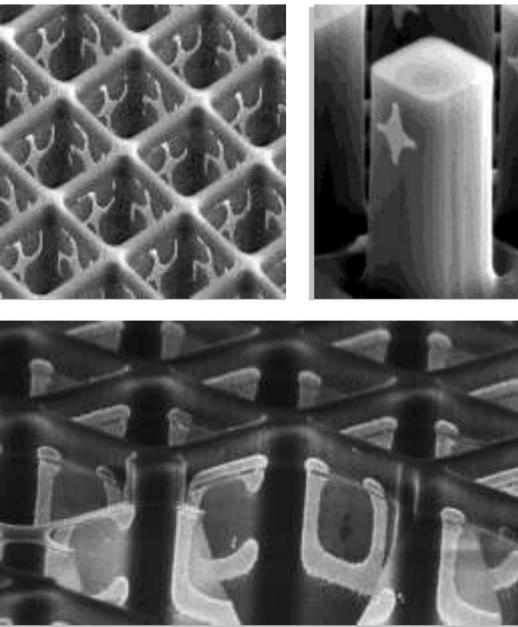




This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SPIE Optics and Photonics 2013 SAND2019-10743C



Coupling effects in dense arrays of 3D optical metamaterials

August 19, 2018

Bruce Burkel

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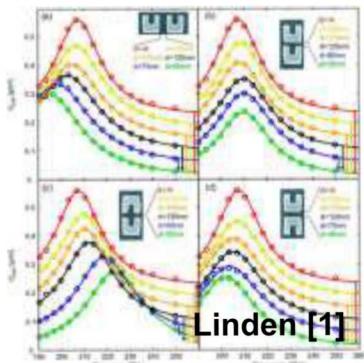
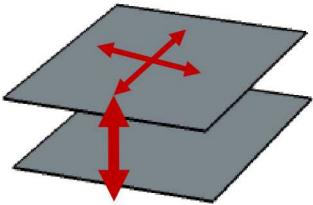
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ENERGY



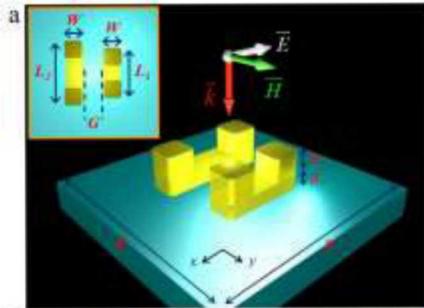
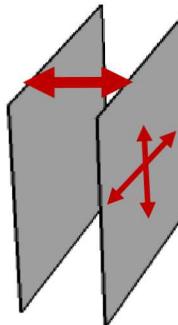
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Comparing Coupling Mechanisms in Planar and Vertical Structures

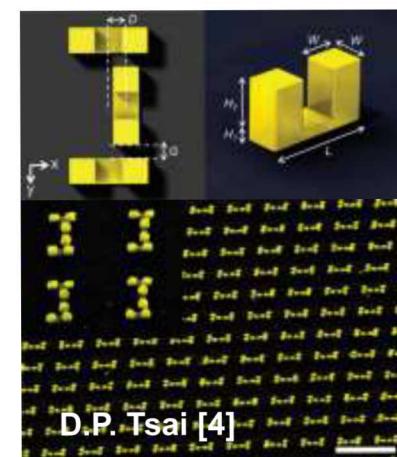
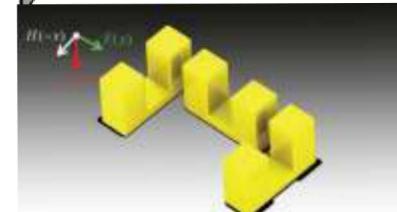
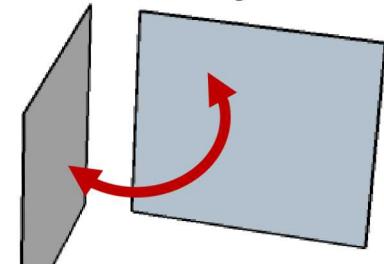
Stacked Planar Geometry



Back-to-back Vertical Geometry

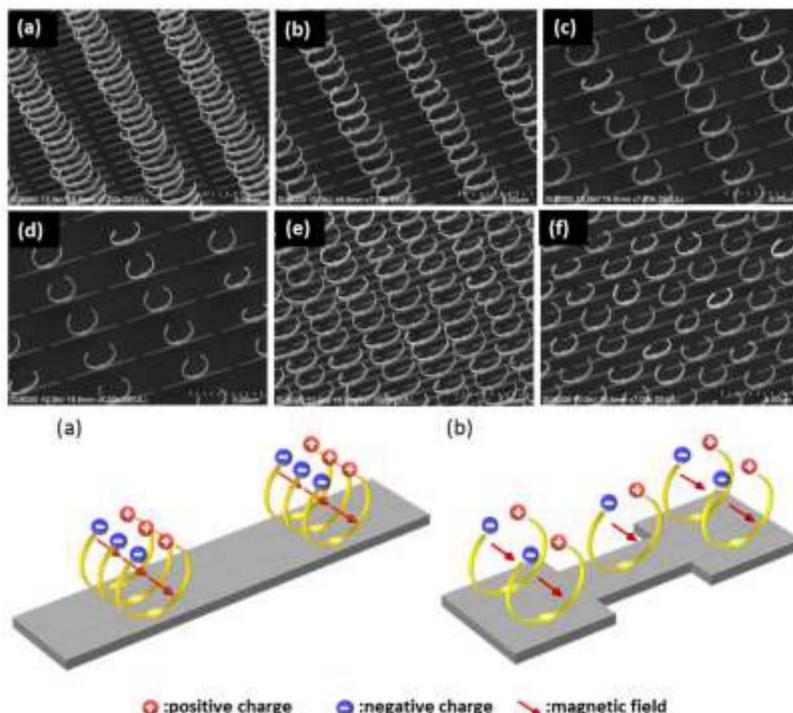


Orthogonal Vertical Geometry



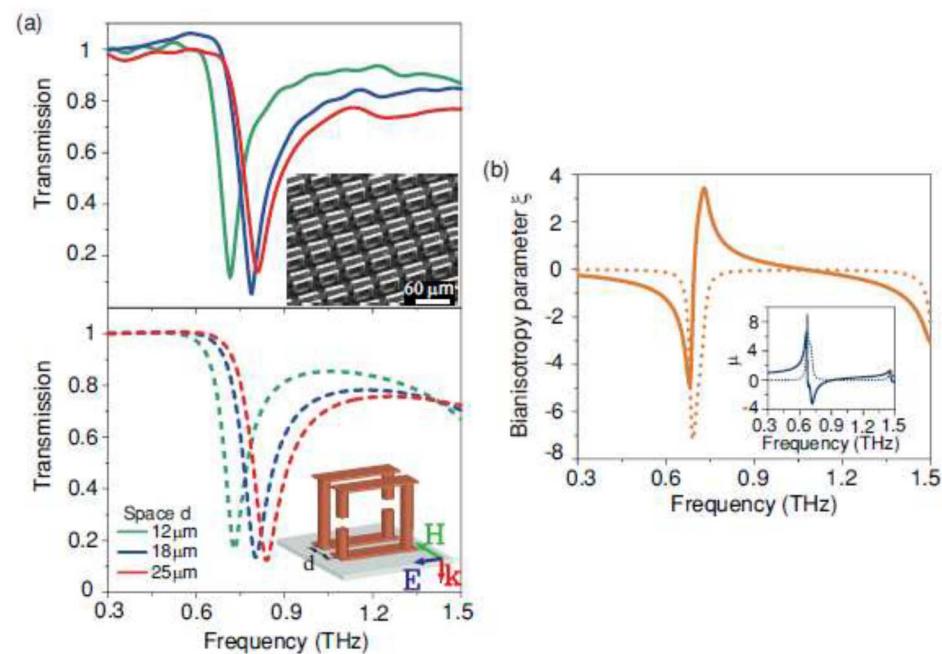
Unique Coupling Mechanisms in Vertical Structures

Horizontally Oriented Magnetic Dipole



Tanaka and Chen [5]

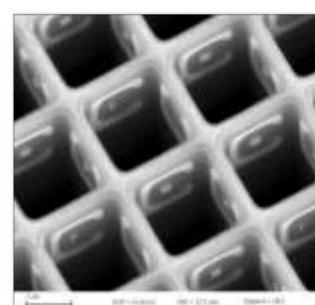
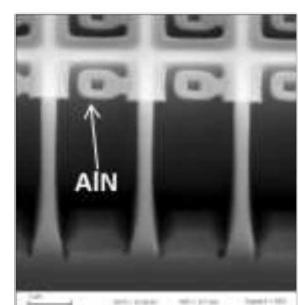
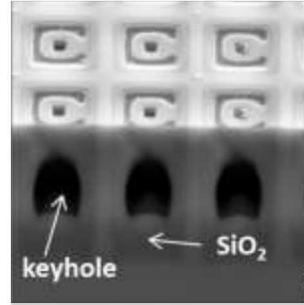
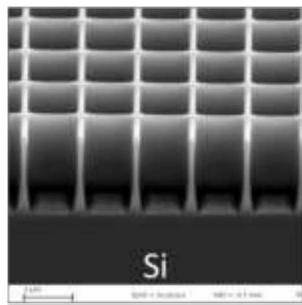
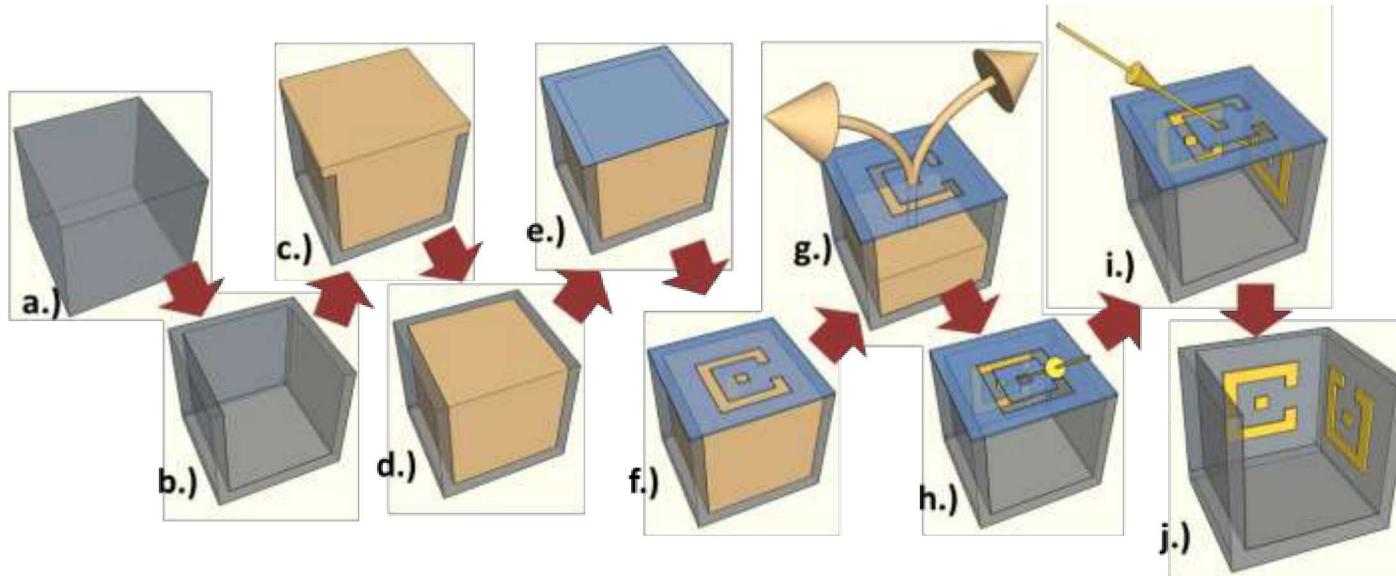
Unambiguous Coupling to Normally Incident Magnetic Field



Averitt [6]

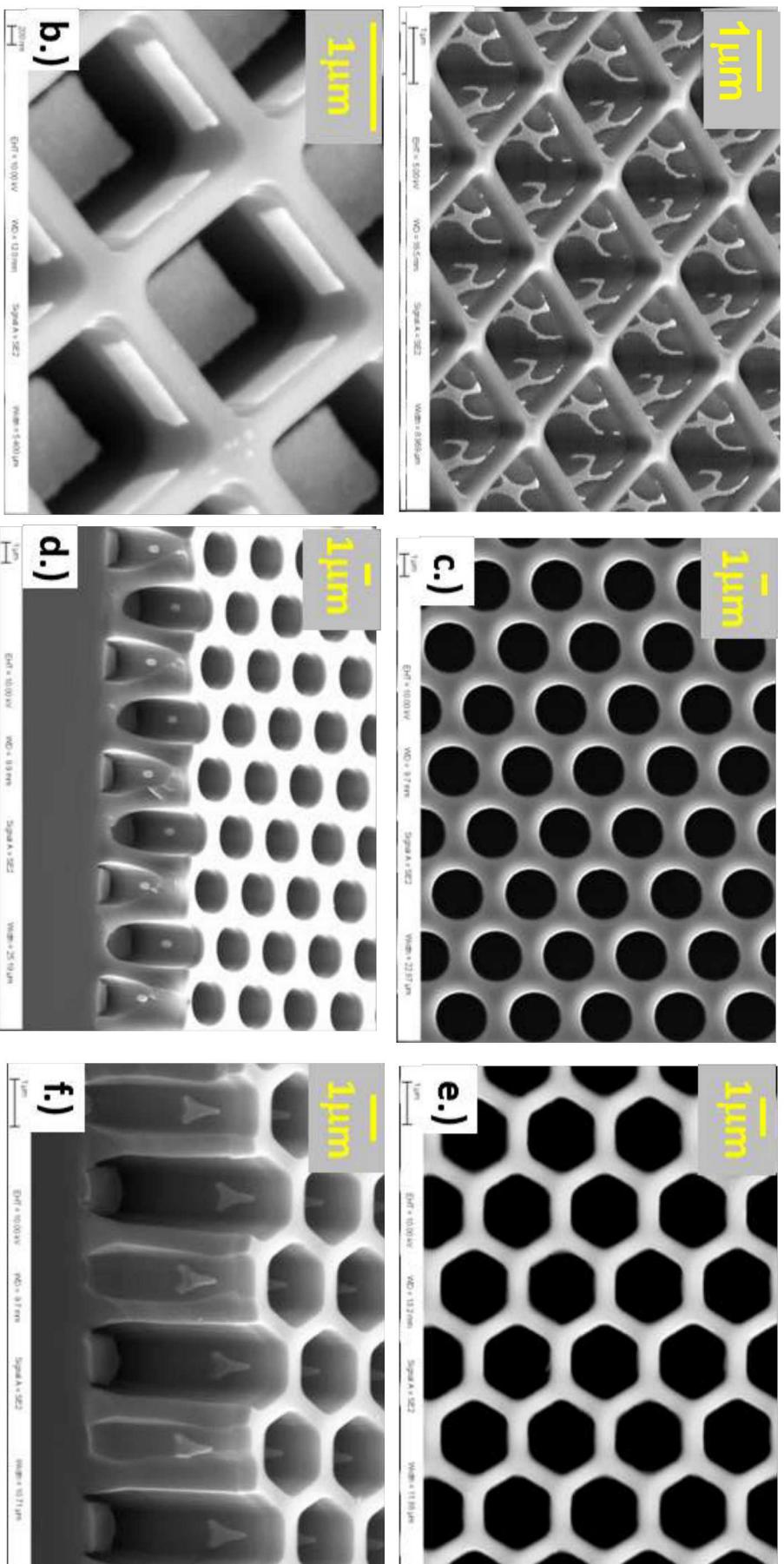
Membrane Projection Lithography (MPL)

3D Micron-scale Fabrication Approach



D. Bruce Burckel, Paul J. Resnick, Patrick S. Finnegan, , Michael B. Sinclair and Paul S. Davids "Micrometer-scale fabrication of complex three dimensional lattice+basis structures in silicon," Optical Materials Express, , 5, 2231-2239, (2015).

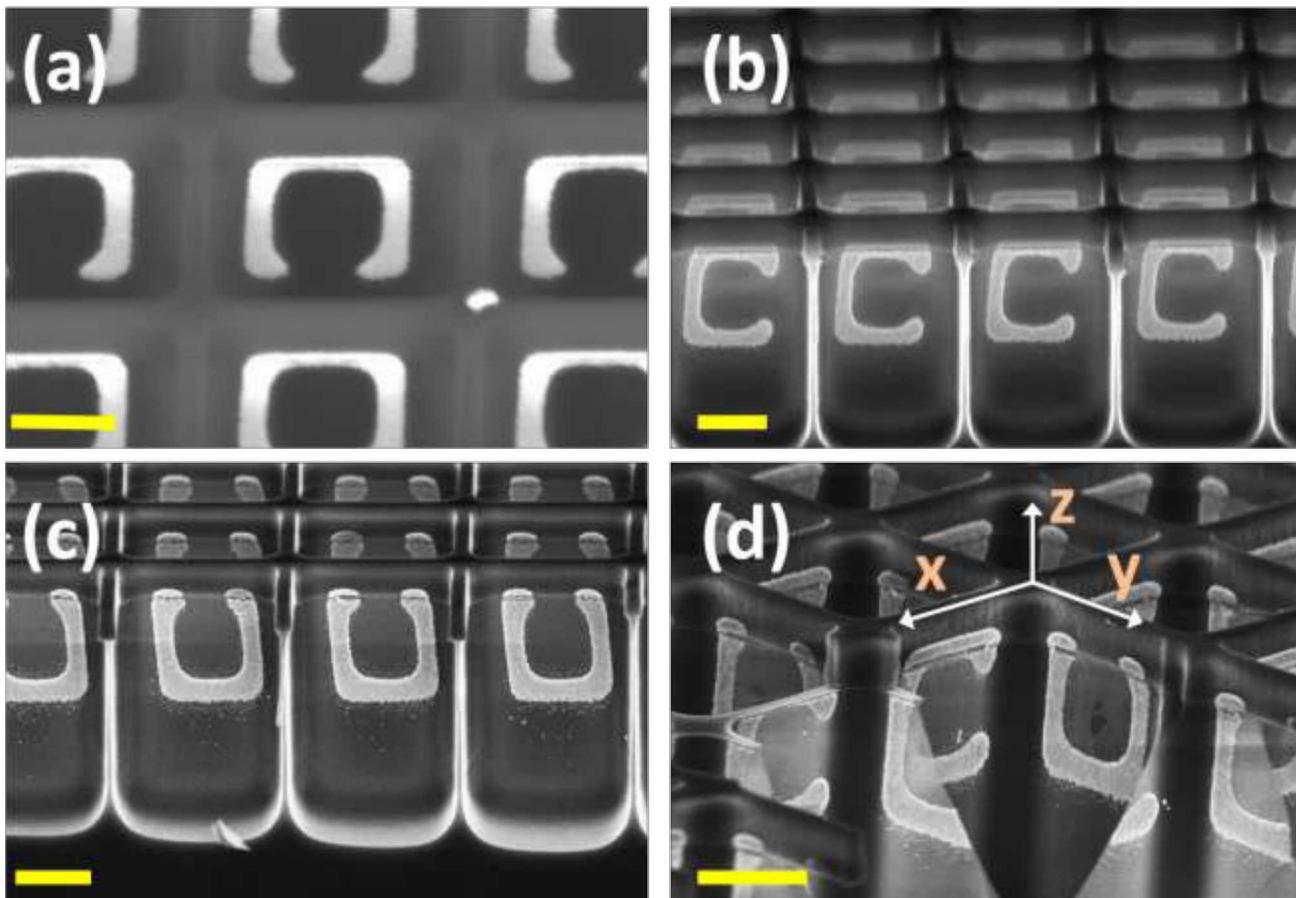
3D micron-scale Metamaterials





Vertical Split Ring Resonators

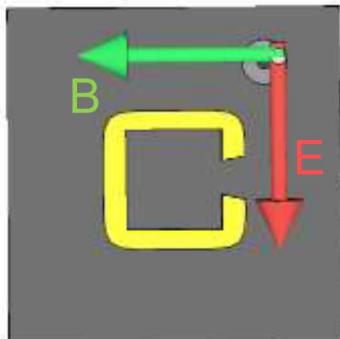
Cubic Unit Cells with 1-SRR and 2-SRR Bases



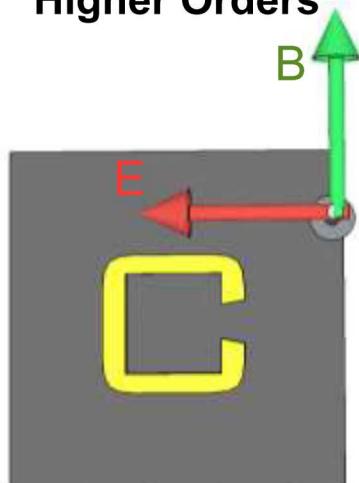
D. Bruce Burckel, Salvatore Campione, Paul S. Davids, and Michael B. Sinclair, "Three dimensional metafilms with dual channel unit cells," *Applied Physics Letters*, 110, 143107, (2017).

Coupling to SRRs

Planar SRRs

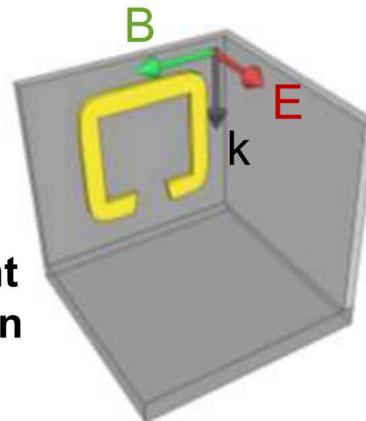


LC Resonance +
Higher Orders

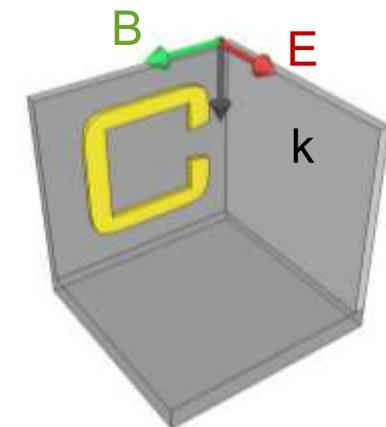


Higher Order
Resonances

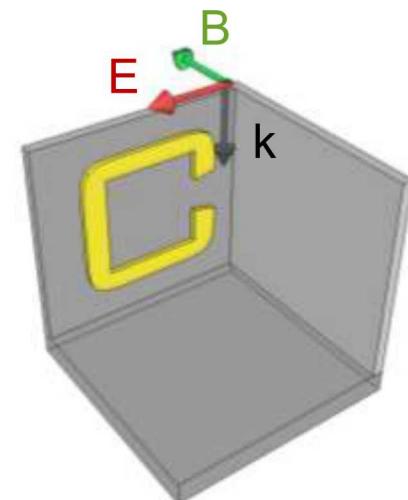
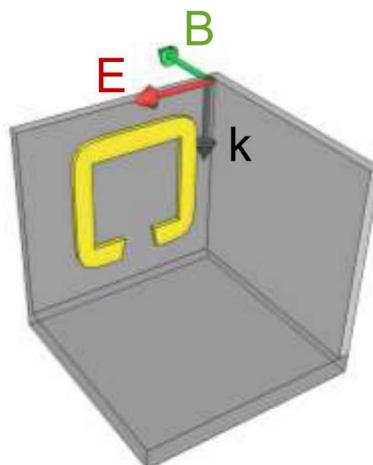
Vertical SRRs



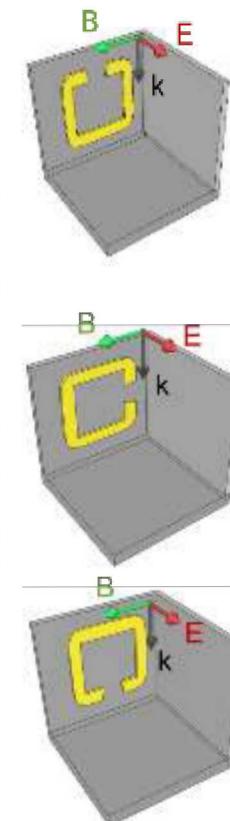
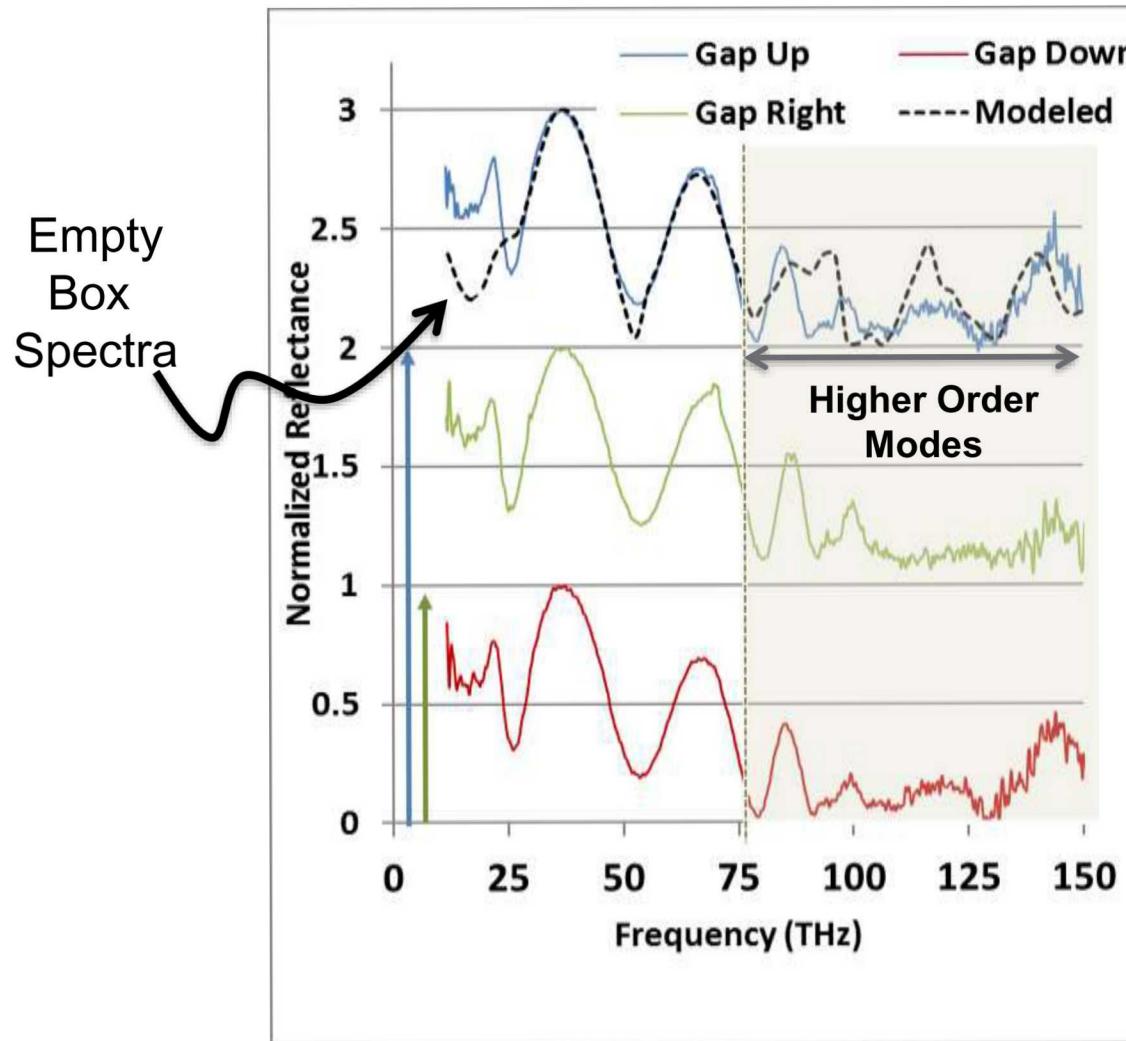
Transparent
Polarization



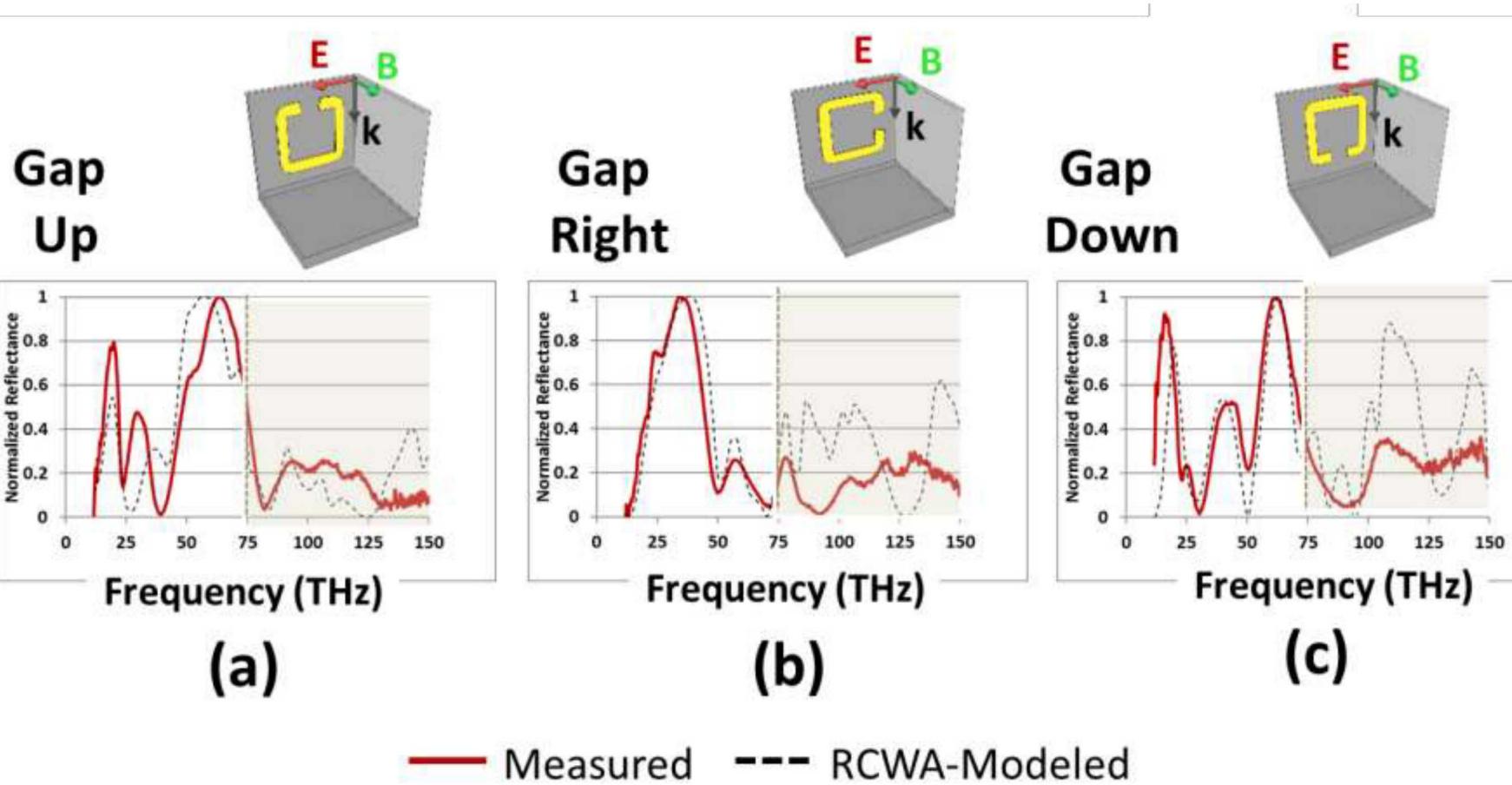
Resonant
Polarization



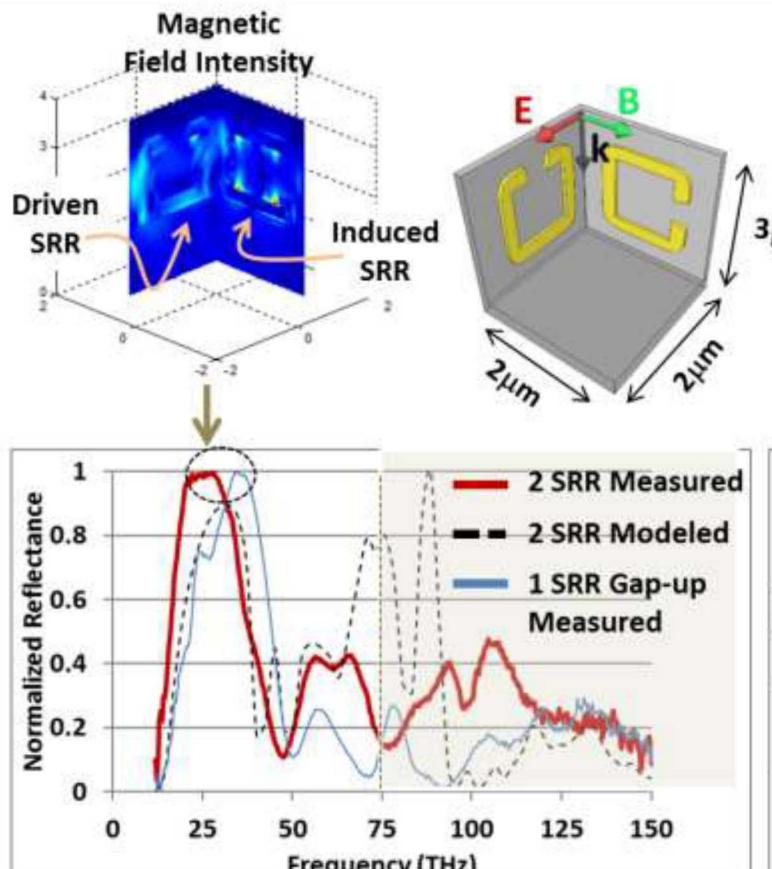
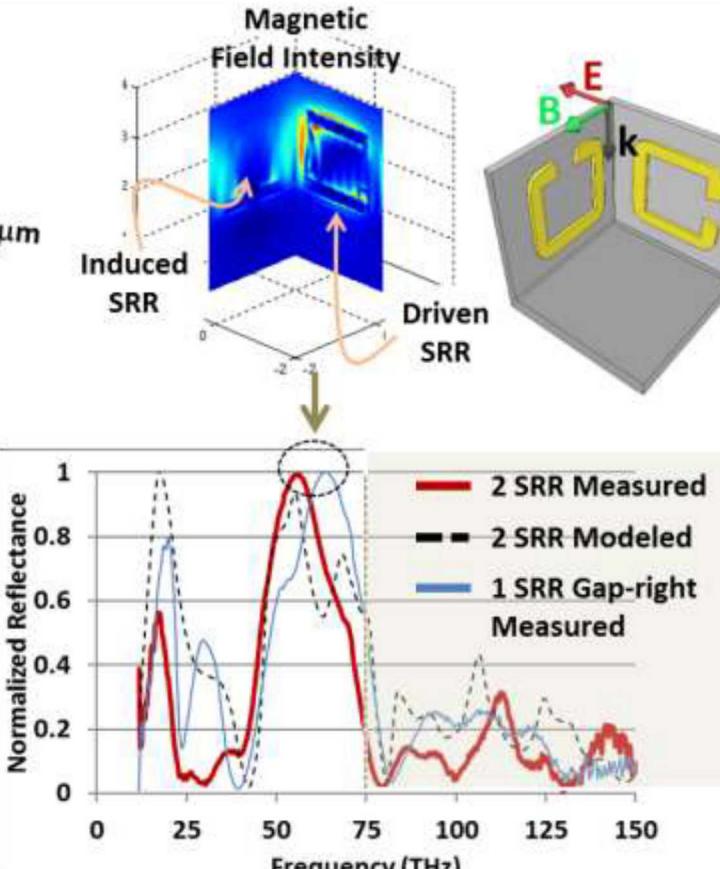
Transparent Polarization



Resonant Polarization

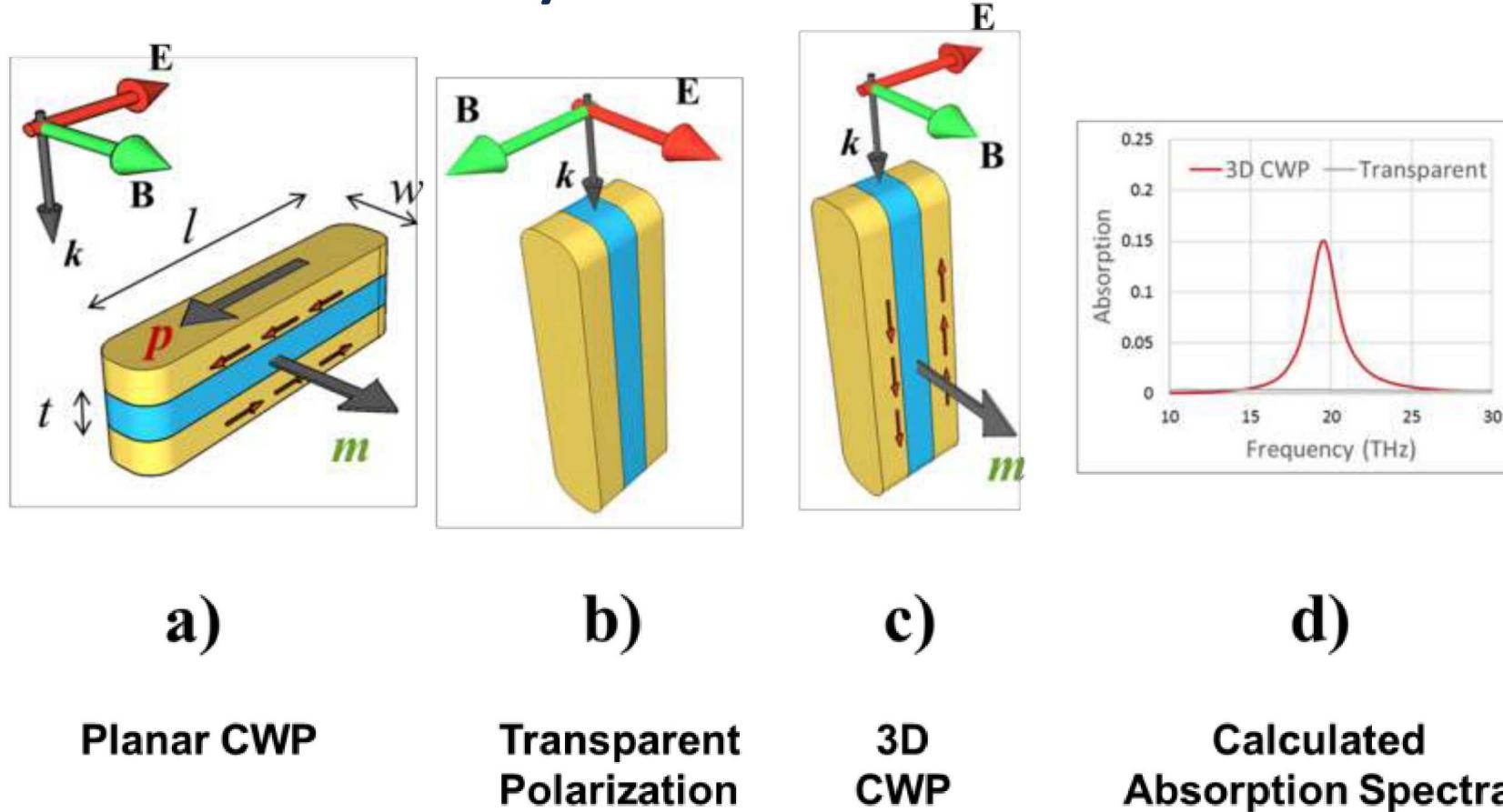


2-SRR Basis Unit Cell – Two Channels

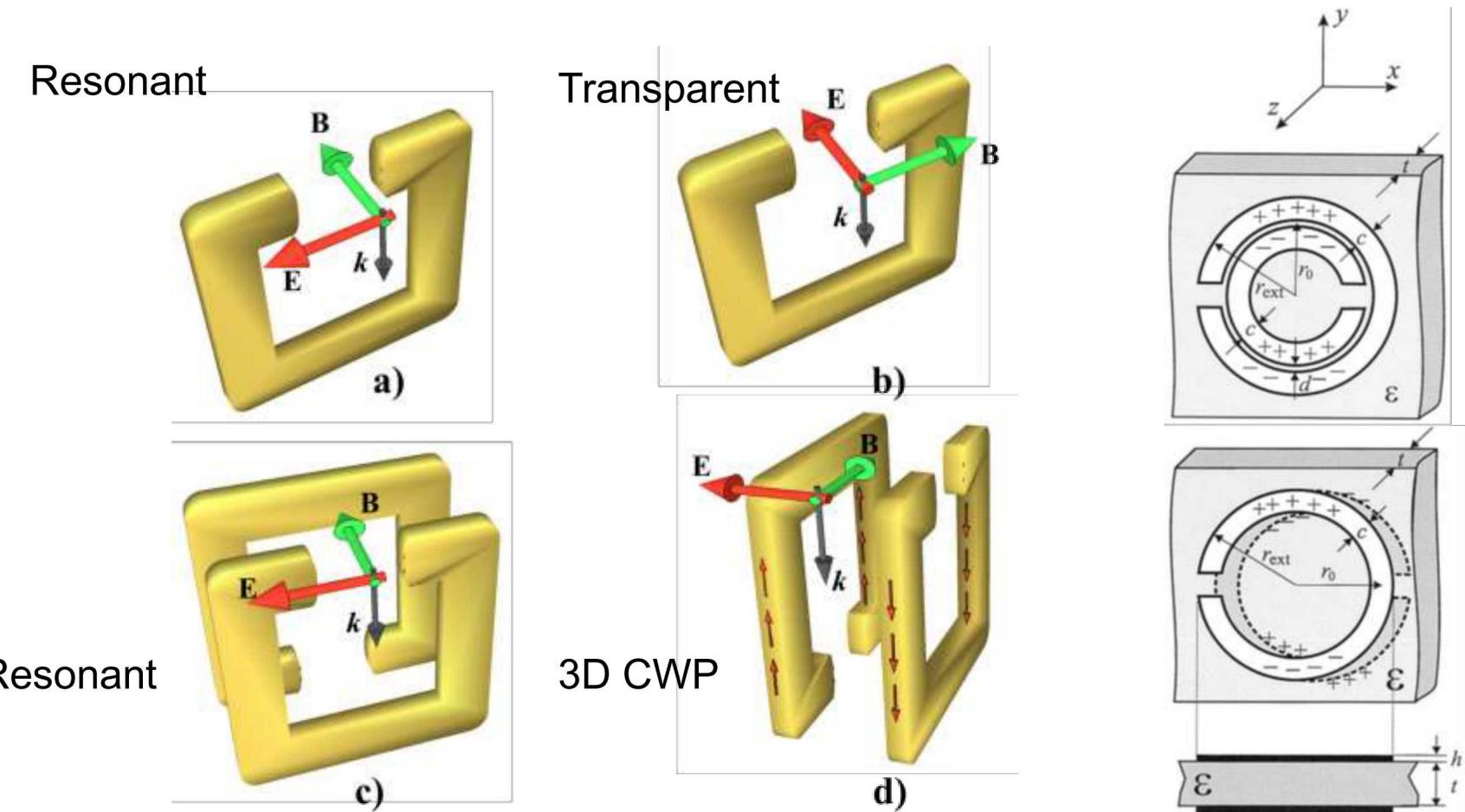
**(a)****(b)**

3D Cut-Wire Pair Coupling Mechanism

Comparing Planar CWPs to Vertically Oriented CWP

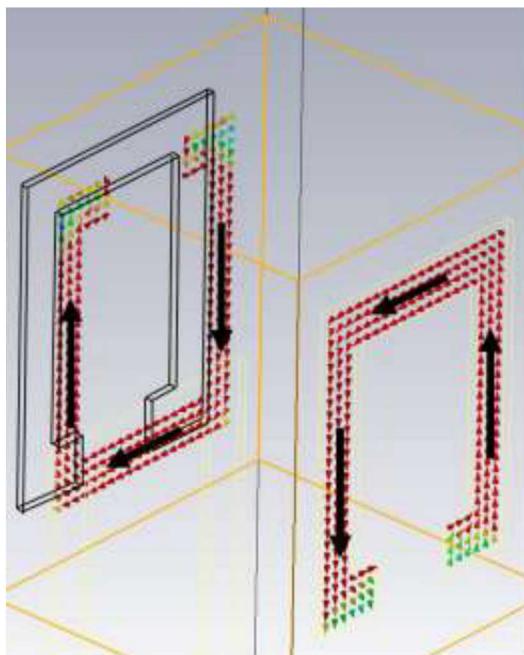


D. Bruce Burckel, Bryan M. Adomanis, Michael B. Sinclair and Salvatore Campione, "Three-dimensional cut wire pair behavior and controllable bianisotropic response in vertically oriented meta-atoms," *Optics Express*, 25, 32198-32205, (2017).



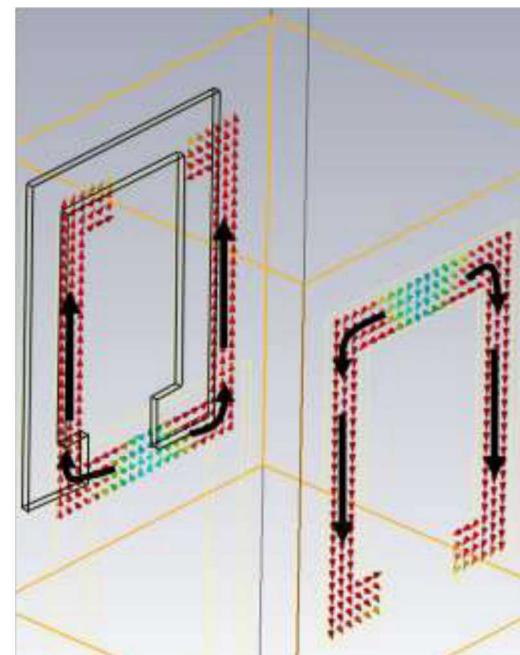
Submitted for publication

**Resonant
Polarization**

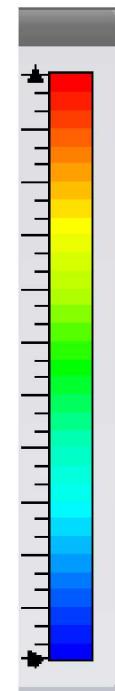


a)

**3D CWP
Polarization**



b)

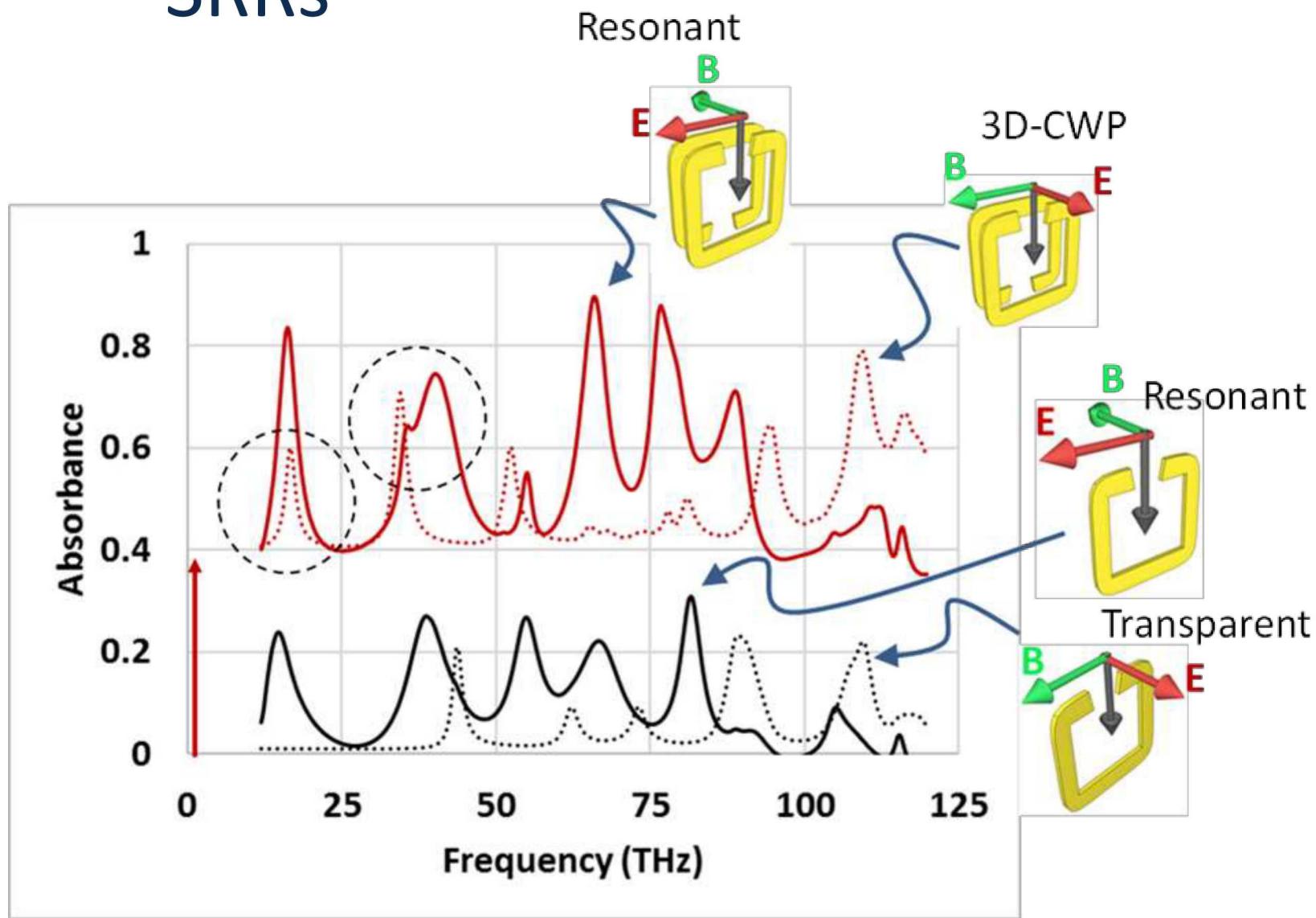


Max

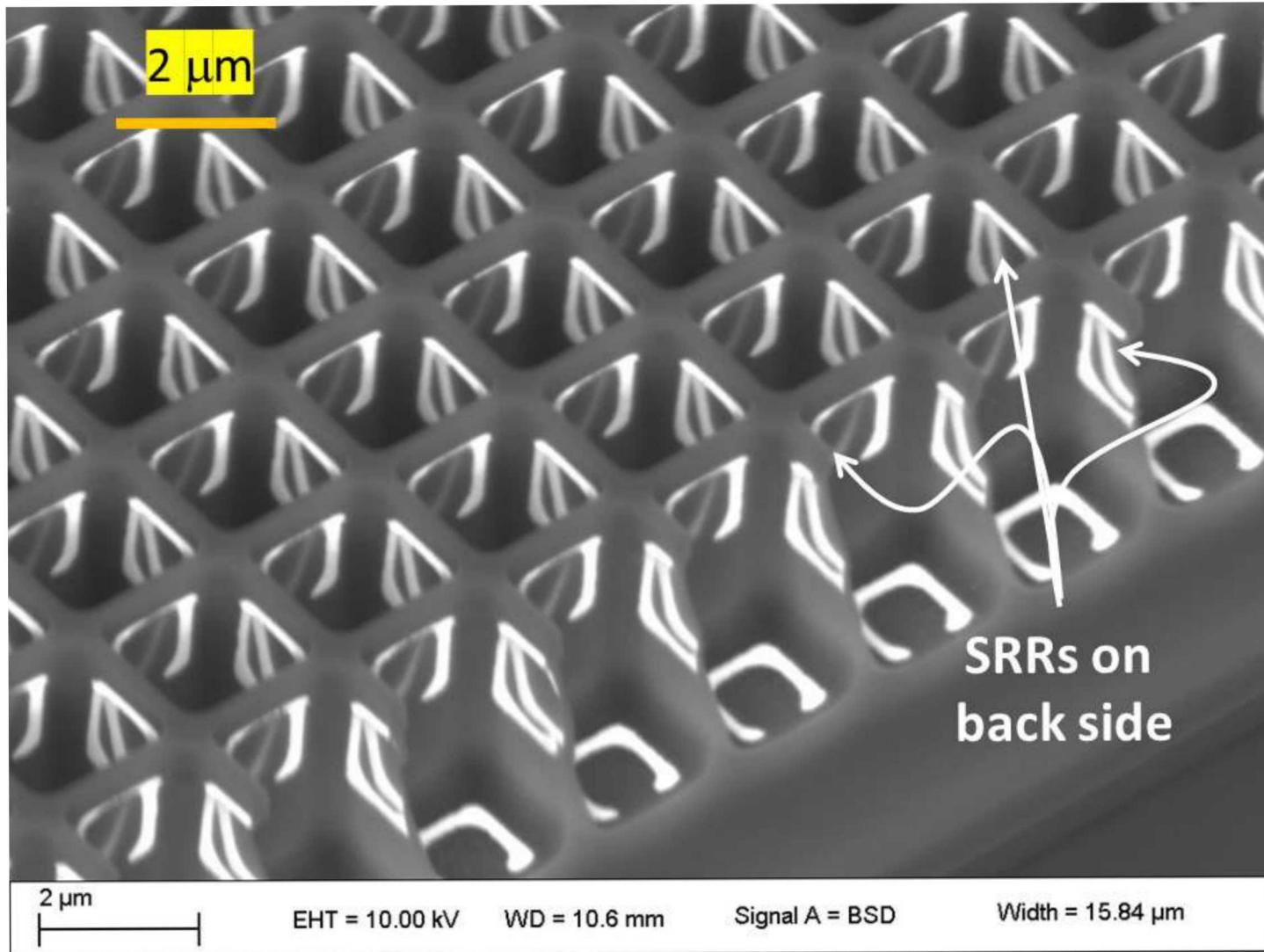
Min

Submitted for publication

Scattering Response for B2B SRRs



Dense Metafilm Arrays





Summary



1. Membrane projection lithography is a versatile fabrication approach capable of fabricating a wide range of 3D metamaterial structures in CMOS compatible material systems.
2. Vertically oriented inclusions demonstrate coupling behaviors which cannot be duplicated by planar structures.
3. Even though CWP and SRRs have been studied for more than 10 Years, there are still subtleties to their scattering behavior which will impact how they perform in next-generation 3D metamaterial components.