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Active Terahertz Metamaterials

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ECOC 2013

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- State-of-the-art facilities
- Leverages LANL and Sandia capabilities
- Develop innovative approaches to nanoscale integration



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Collaborators/Acknowledgements

Boston University: Rick Averitt

Boston College: Willie Padilla

Oklahoma State University: Weili Zhang, John O'Hara

Rice University: Dan Mittleman

Sandia National Laboratories: Igal Brener

UCSB: Art Gossard

University of Delaware: Josh Zide

University of South Florida: Jiangfeng Zhou

Nantang Technical University: Ranjan Singh, Dibakar Chowdhury

We gratefully acknowledge the support of the U.S. Department of Energy through the Center for Integrated Nanotechnologies and the LANL/LDRD Program for this work.



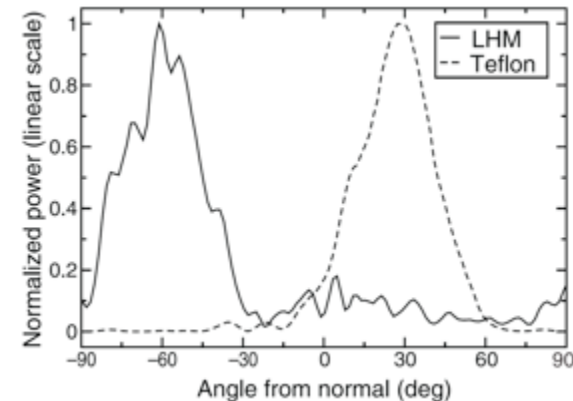
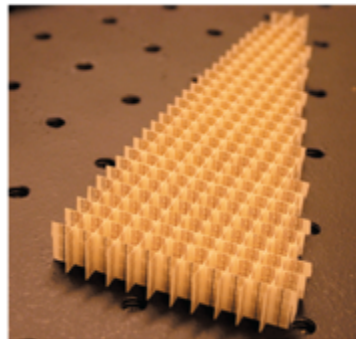
Outline

- **Metamaterials as a solution to the Terahertz (THz) Gap**
- **THz functionalities achieved in few-layered ultrathin planar metamaterials**
 - Antireflection
 - Perfect absorption
 - Linear polarization conversion
 - Anomalous reflection/refraction (generalized Snell's law)
- **Active THz Metamaterials**
 - modulator/switch
 - active frequency tuning
 - spatial modulator
 - thermal and optical tuning using complex oxides
- **Summary**

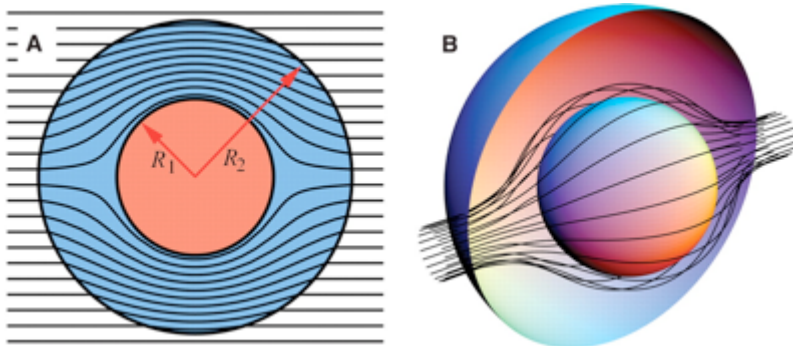


Emergent Phenomena in Metamaterials

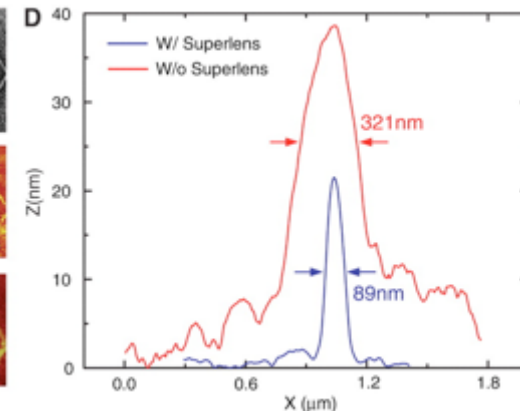
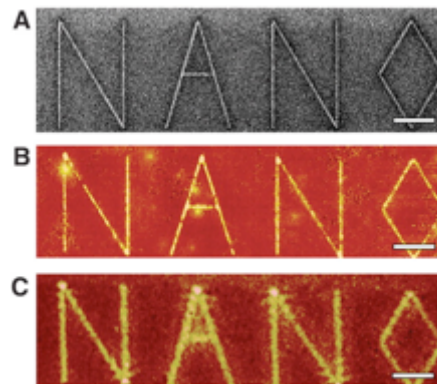
☐ **Metamaterials** are a class of man-made effective media with properties attained from their subwavelength structures rather than the chemical compositions



☐ Negative index of refraction



☐ Cloaking and transformation optics



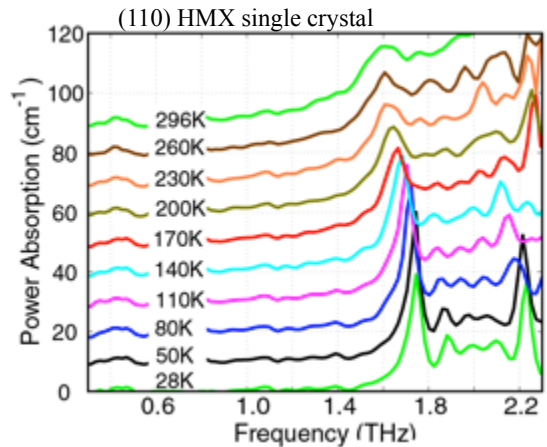
☐ Superlens – breaking the diffraction limits



Terahertz Gap

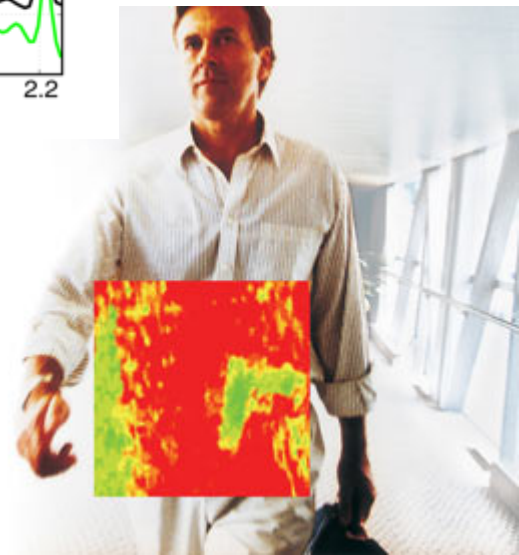


- THz region is located at the interface of electronics and photonics where technologies directly translated from microwave and optical regimes generally fail to operate.
- THz gap is caused by weak materials response at THz frequencies
- Results in a lack of sources, detectors, modulators, filters, polarizers, sensors, etc. in the THz regime.



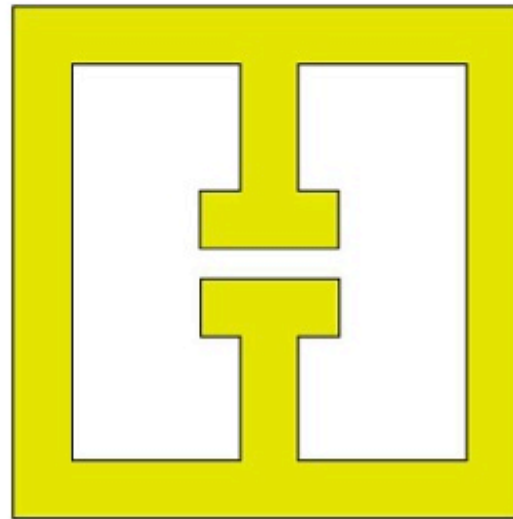
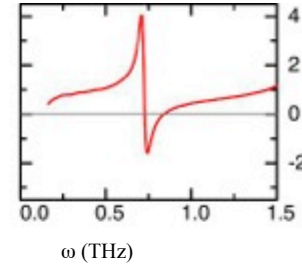
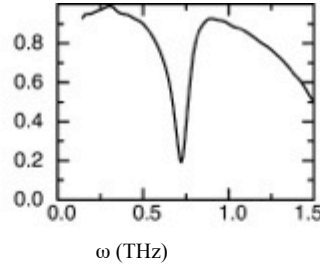
Spectroscopy

Imaging





Metamaterials: A solution to the THz Gap



Typical parameters:
Unit cell: 50 μm
Outer dimension: 36 μm
Line width: 4 μm
Split gap: 2 μm

Resonance enhances THz interactions

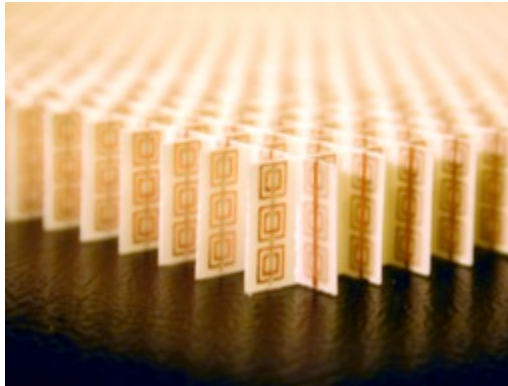
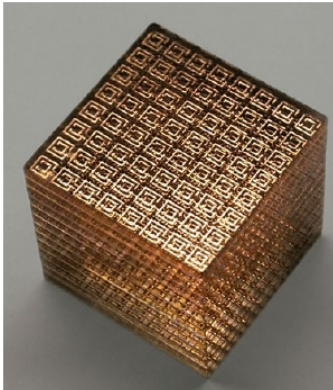
- Modulators (AM, FM, PM)
- Filters
- Sensors



Bulk Metamaterials vs Planar Meta-Surfaces

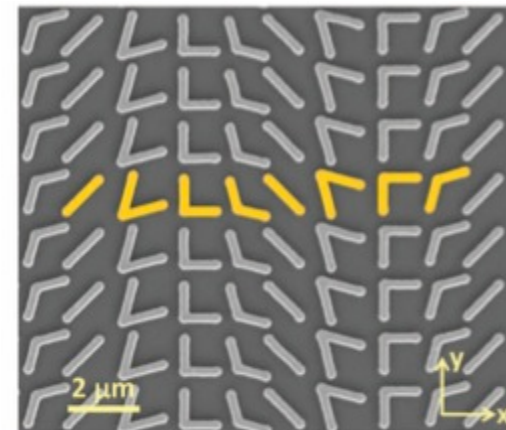
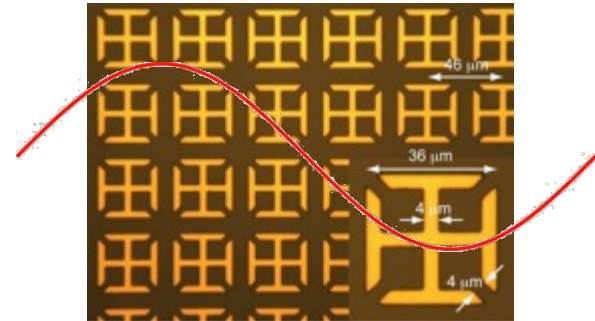
Bulk metamaterials

- ❑ Effective material parameters: ϵ , μ , Z , n
- ❑ Feasible mostly at microwave frequencies
- ❑ Difficult to fabricate in the optical regime



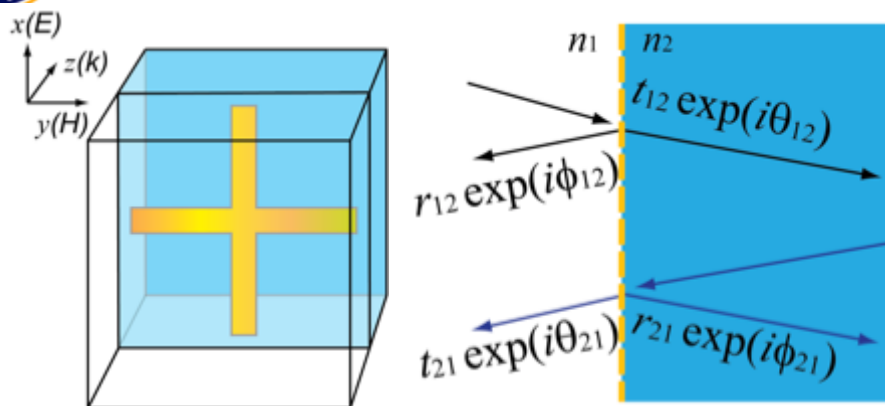
Meta-surfaces

- ❑ Effective surface properties
- ❑ Any relevant frequency
- ❑ Planar structures: ease in fabrication





Tailored Transmission and Reflection



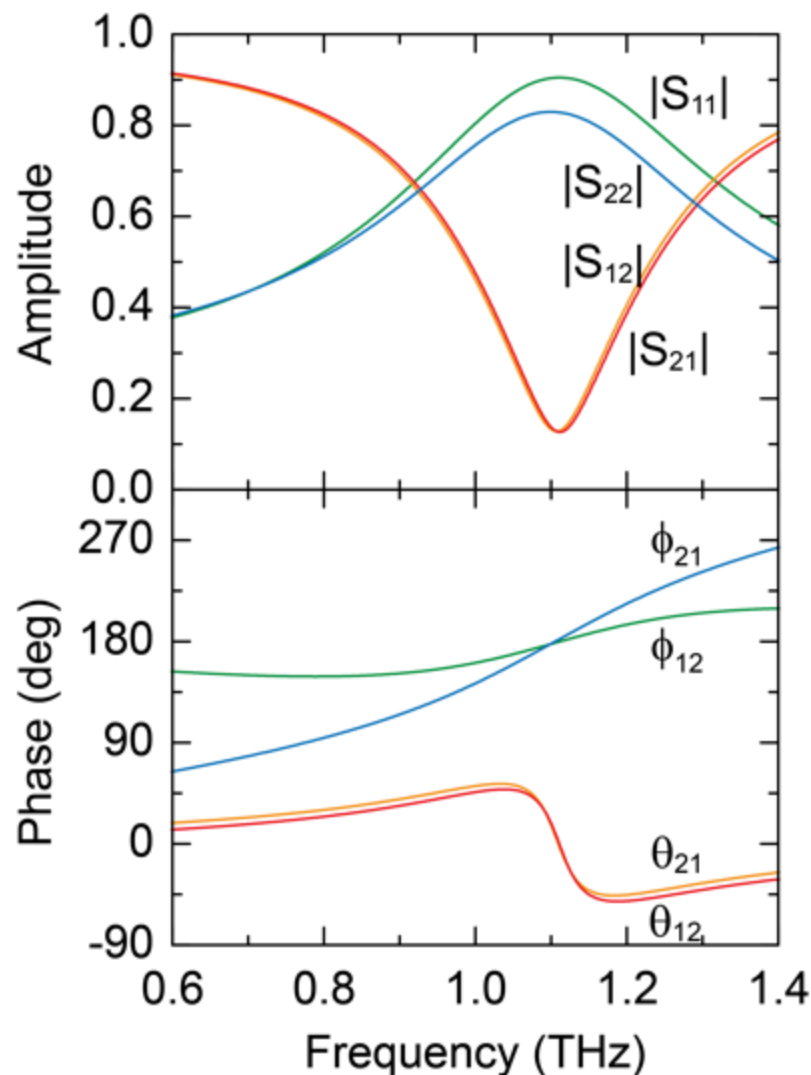
- The resonator array modifies the complex reflection and transmission coefficients at the interface

$$r_{12} = |S_{11}| \quad t_{12} = \sqrt{\frac{n_1}{n_2}} |S_{21}|$$

$$r_{21} = |S_{22}| \quad t_{21} = \sqrt{\frac{n_2}{n_1}} |S_{21}|$$

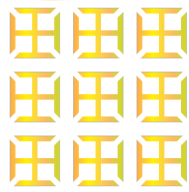
$$\phi_{12} = \arctan(S_{11}) \quad \theta_{12} = \arctan(S_{21})$$

$$\phi_{21} = \arctan(S_{22}) \quad \theta_{12} = \arctan(S_{12})$$

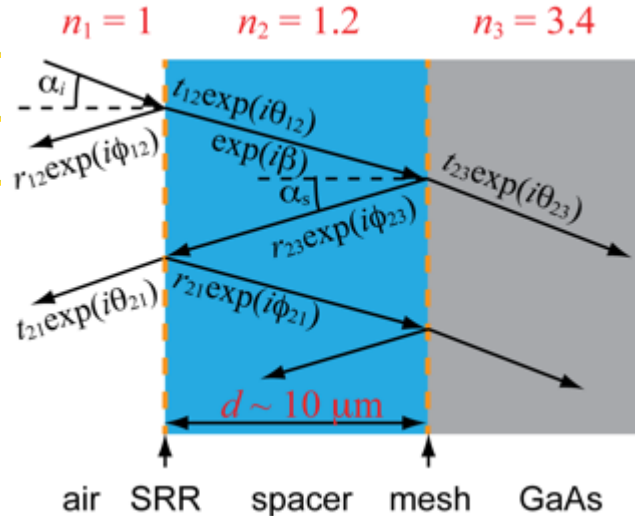
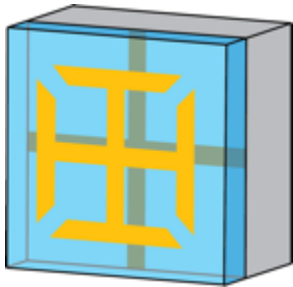
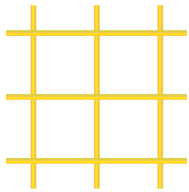




Ultrathin Metamaterial Anti-Reflection Coating

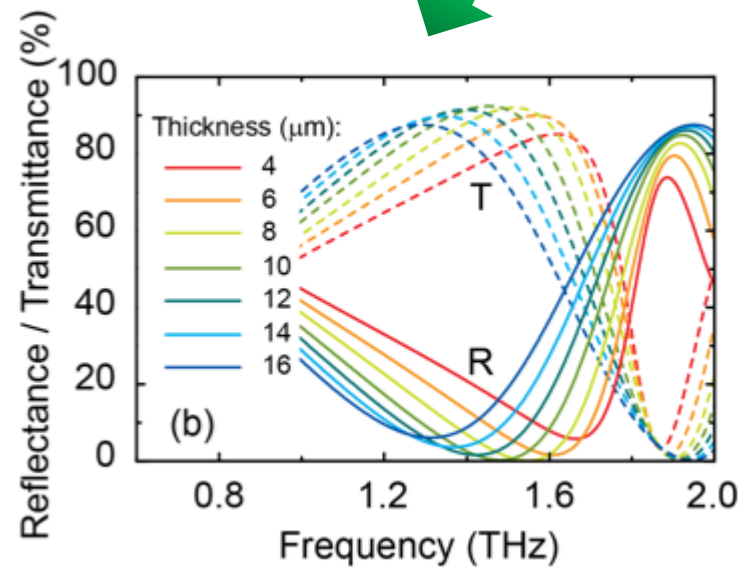
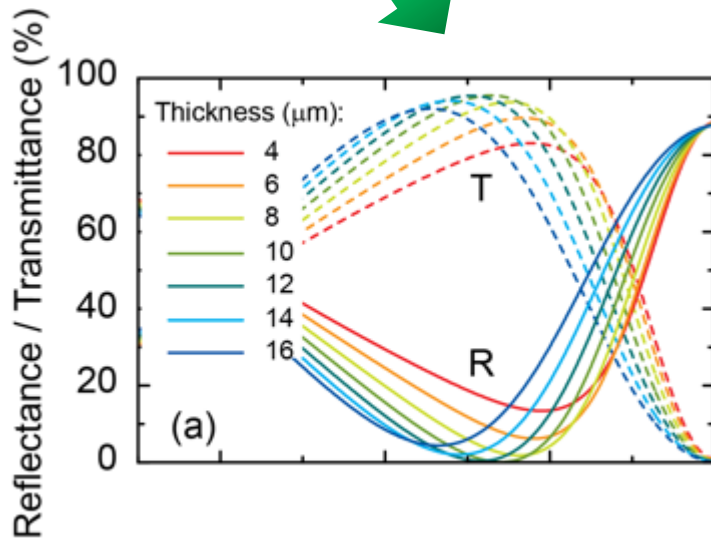


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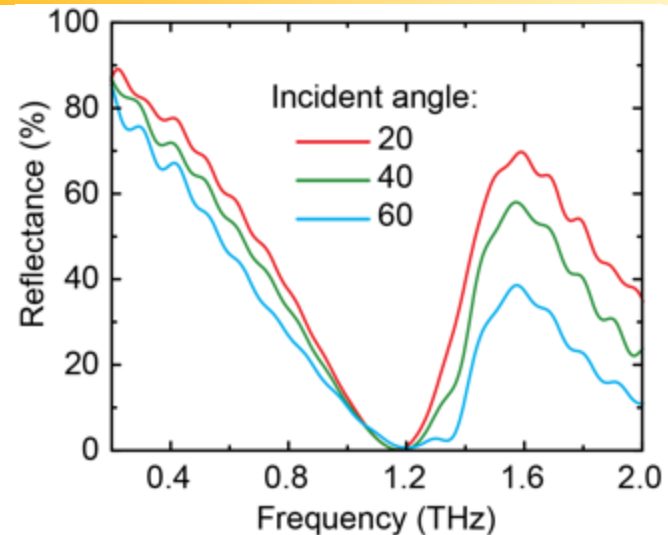
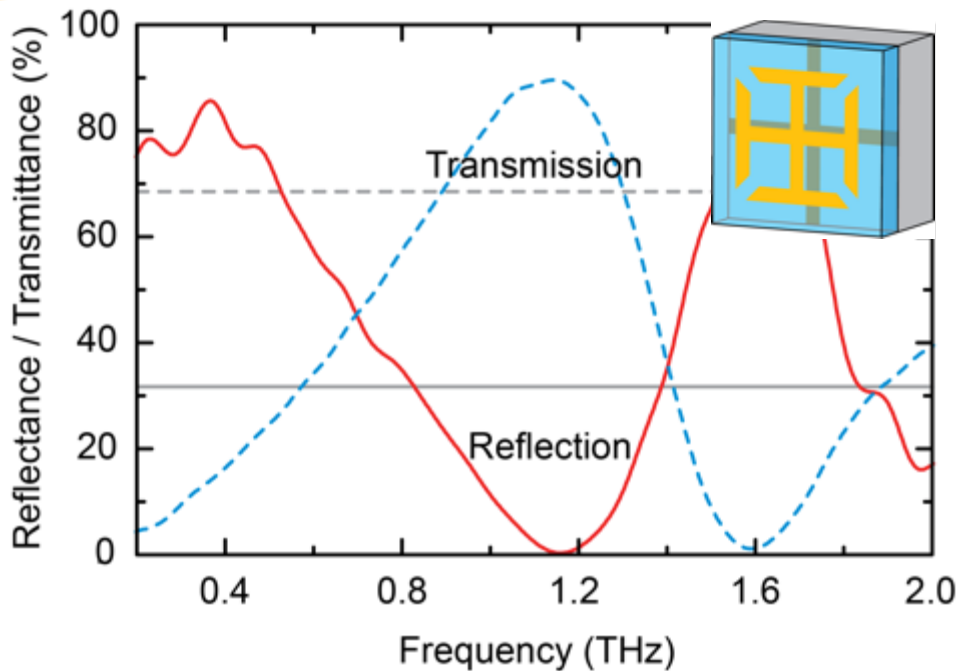
$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

$$\tilde{t} = \frac{\tilde{t}_{12}\tilde{t}_{23}e^{i\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

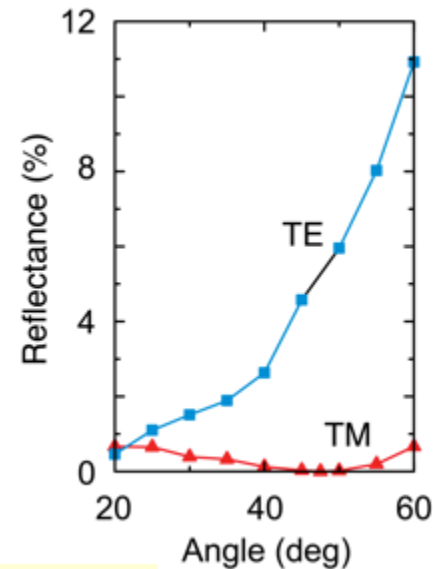




Ultrathin Metamaterial ARC: Experiments



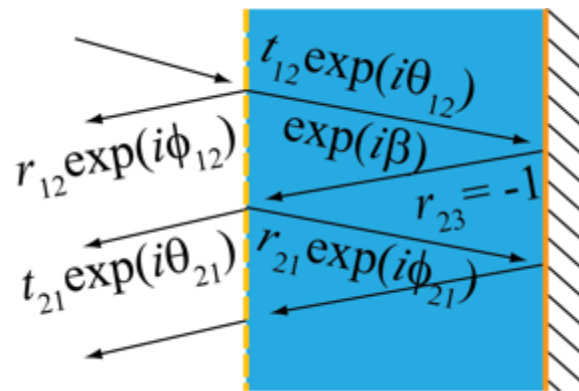
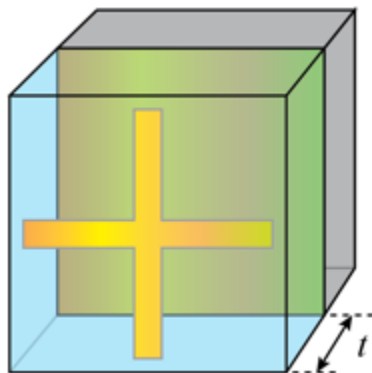
- ❑ Reflectance: 32% \rightarrow ~0
- ❑ Transmittance: 68% \rightarrow 90%
- ❑ Transmittance does not reach 100% due to losses
- ❑ Operate over a wide incident angle range
- ❑ Brewster angle behavior for TM polarization



Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

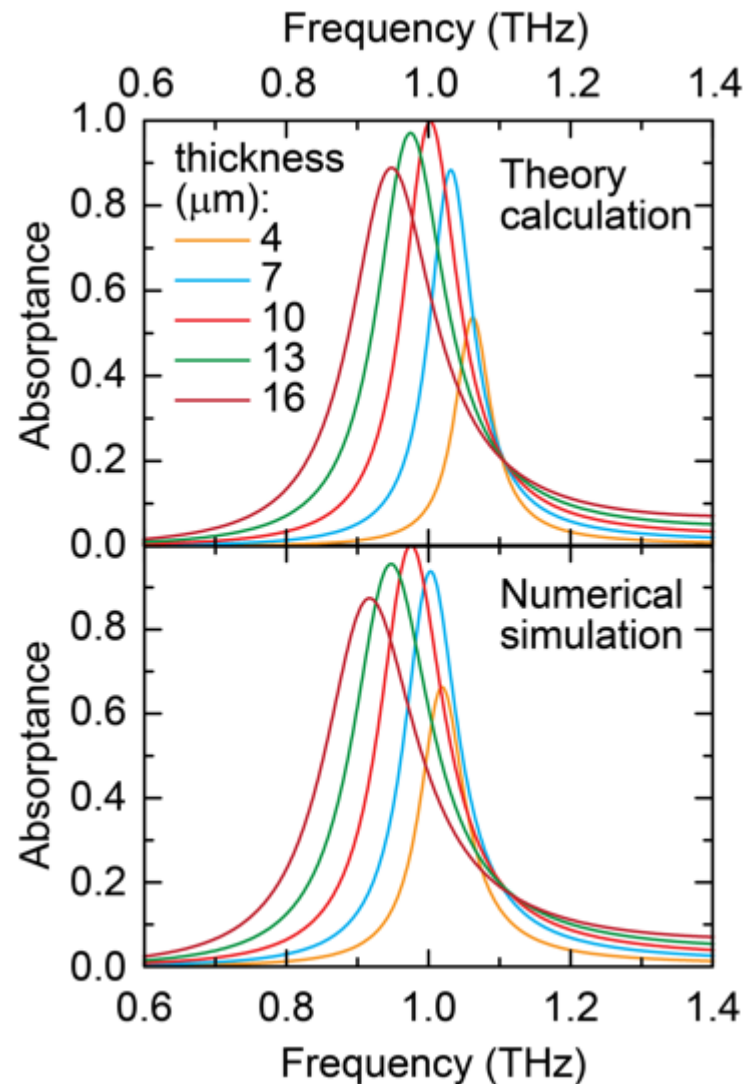


Metamaterial Perfect Absorbers: Trapped Light



$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

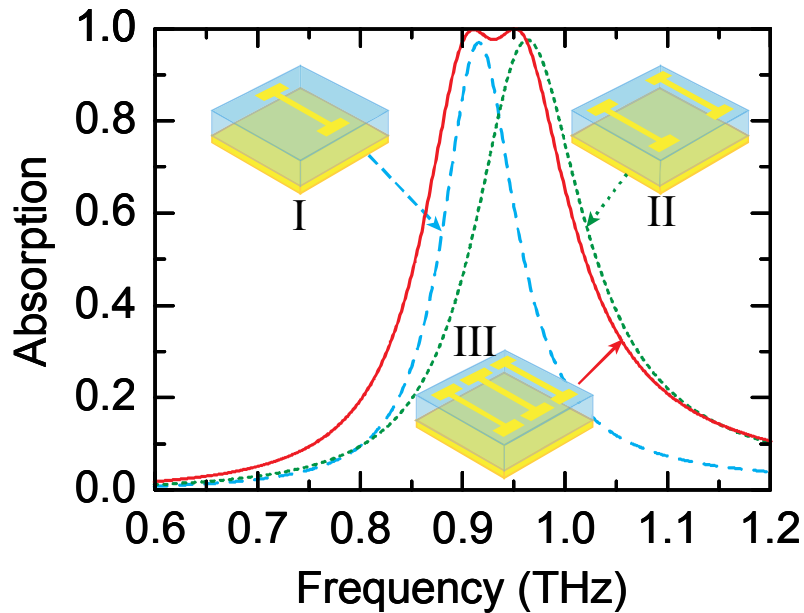
- ❑ Zero transmission due to the metal ground plane
- ❑ Minimizing reflection due to destructive interference of multi-reflection



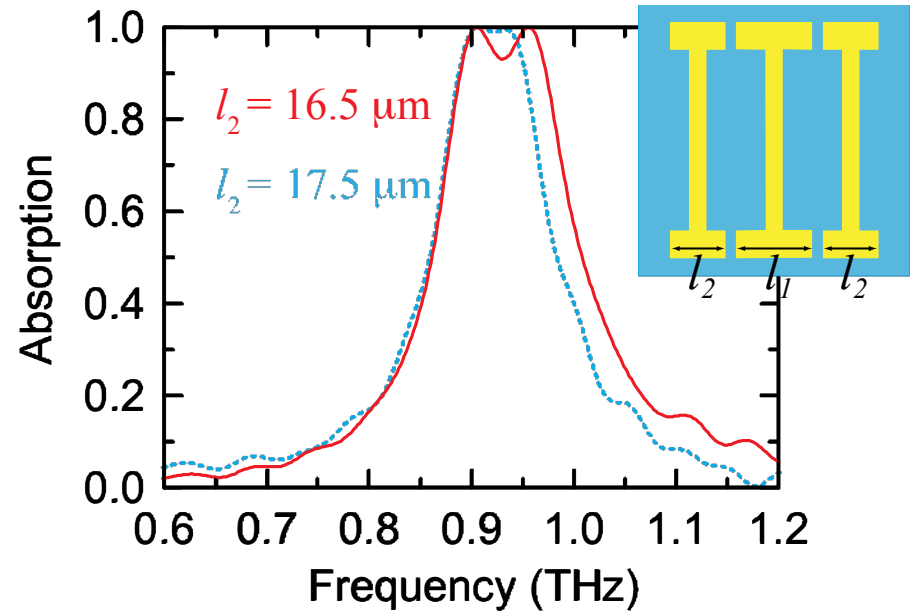


Bandwidth Broadening for Metamaterial Absorbers

Simulations



Experiments

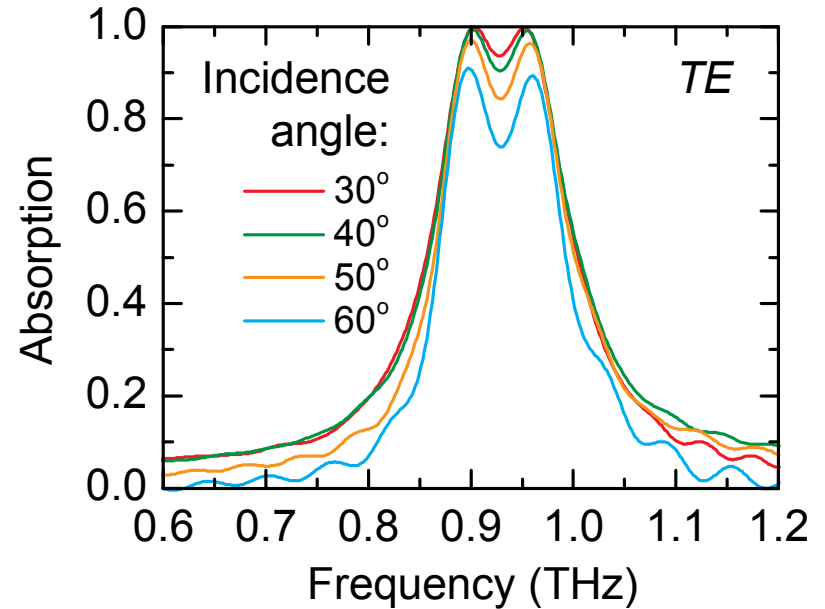
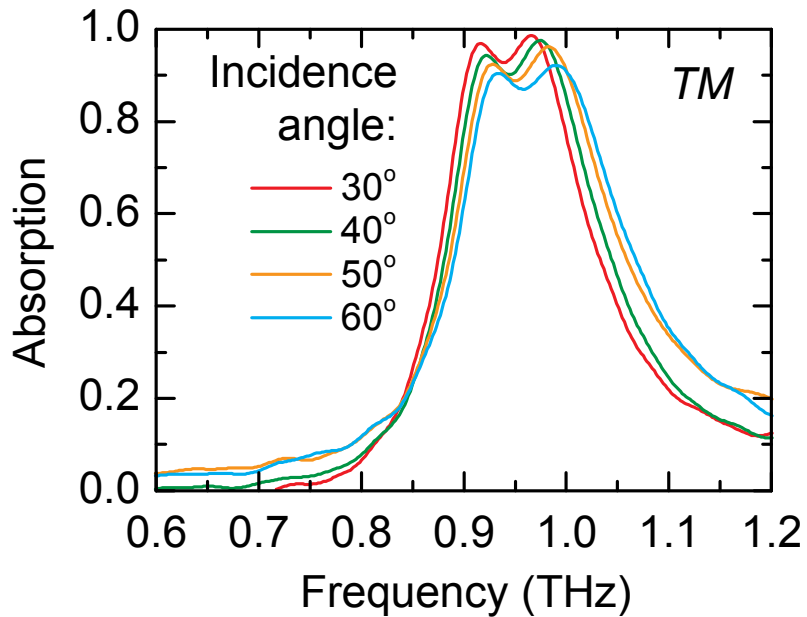
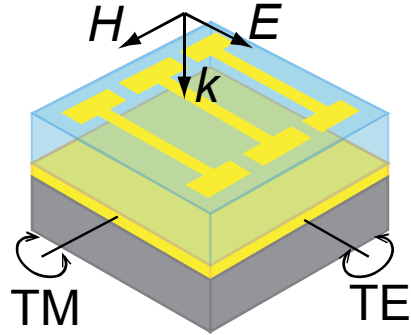


□ Broadening the absorption bandwidth by multiplexing

Huang *et al.*, *Opt. Lett.* **37**, 154 (2012).



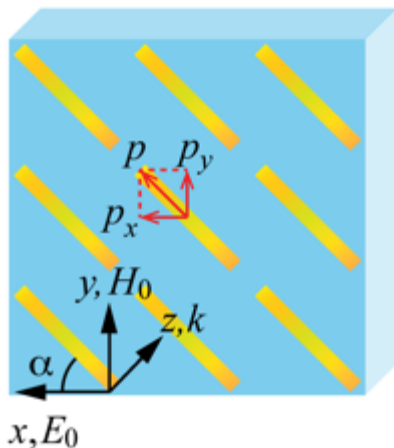
High Absorption over a Wide Incident Angle Range



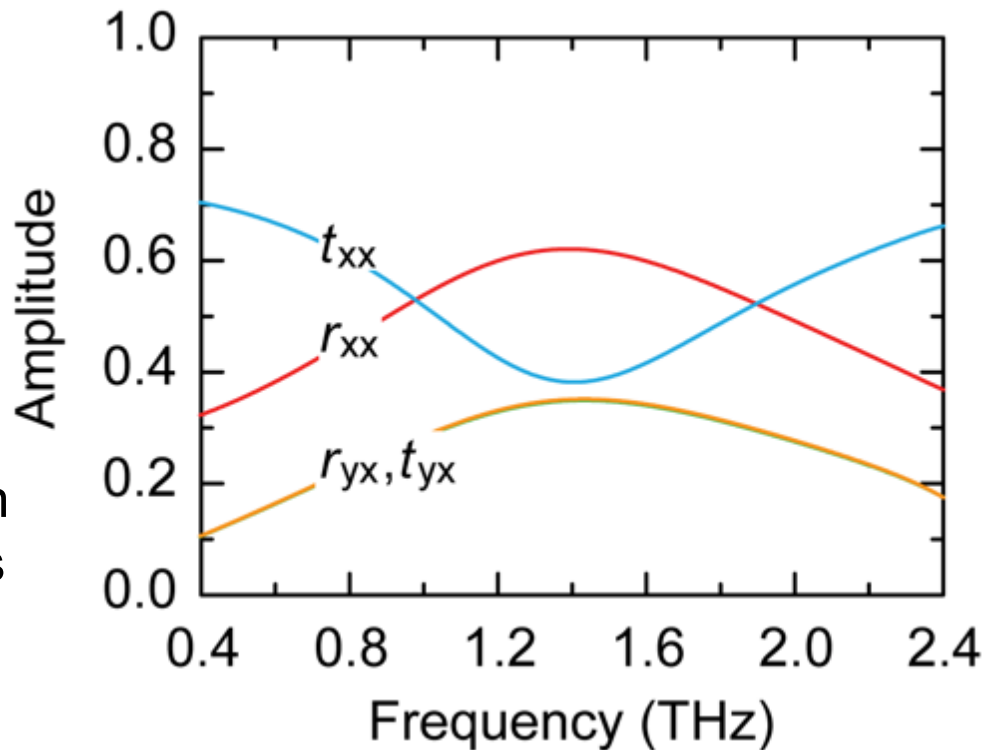
Huang *et al.*, *Opt. Lett.* **37**, 154 (2012).



Polarization Conversion in Anisotropic MMs

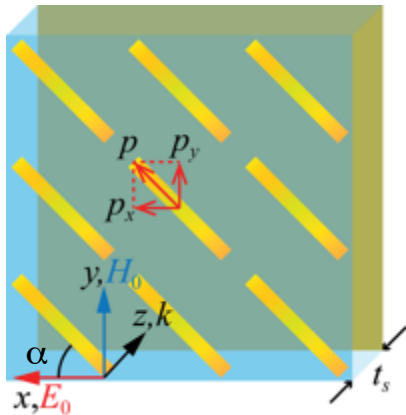


- ❑ Incident field \mathbf{E}_0 along x-direction ($\alpha=45^\circ$): the excited dipole \mathbf{p} has x- and y-components
- ❑ p_x : co-polarized reflection and transmission
- ❑ p_y : cross-polarized reflection and transmission
- ❑ Single-layered metamaterial: polarization conversion is low
- ❑ Output waves are elliptically polarized

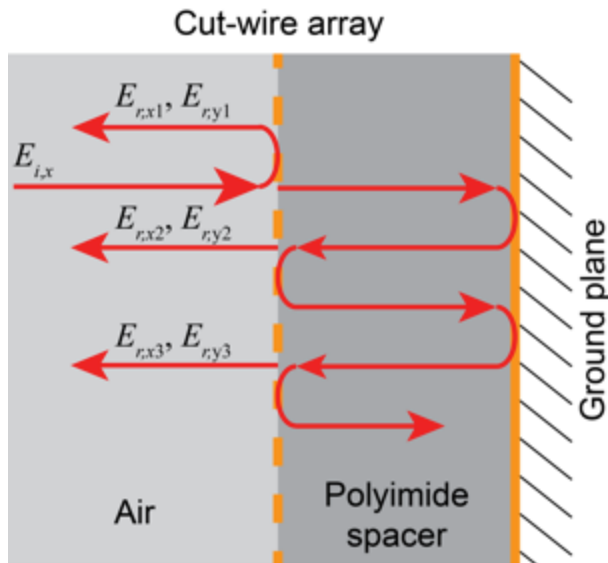




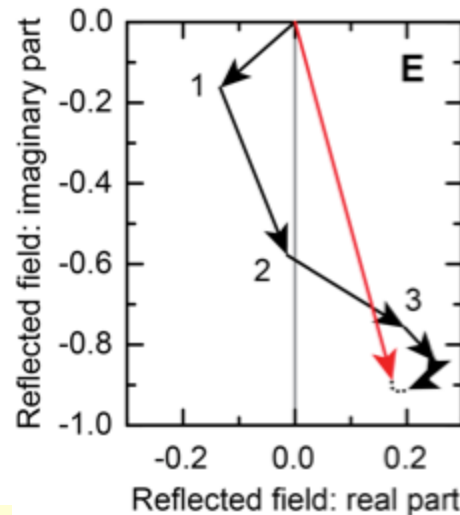
Metamaterial Polarization Converter: Reflection



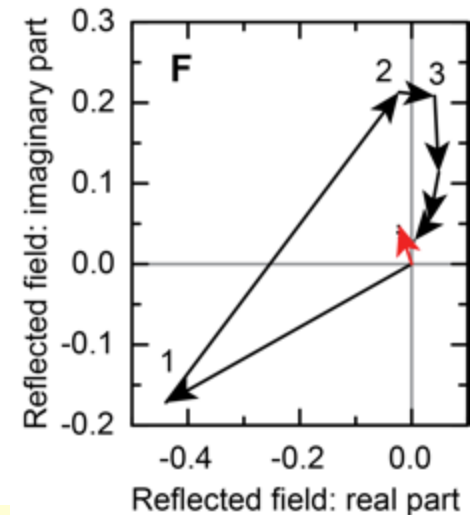
- ❑ Backed with a metal ground plane with appropriate thick dielectric spacer
- ❑ Multiple reflections contain both x and y components
- ❑ The co-polarized multiple reflections interfere destructively, leading to minimal co-polarized reflection
- ❑ The cross-polarized multiple reflections interfere constructively, leading to high cross-polarized reflection



cross-polarized

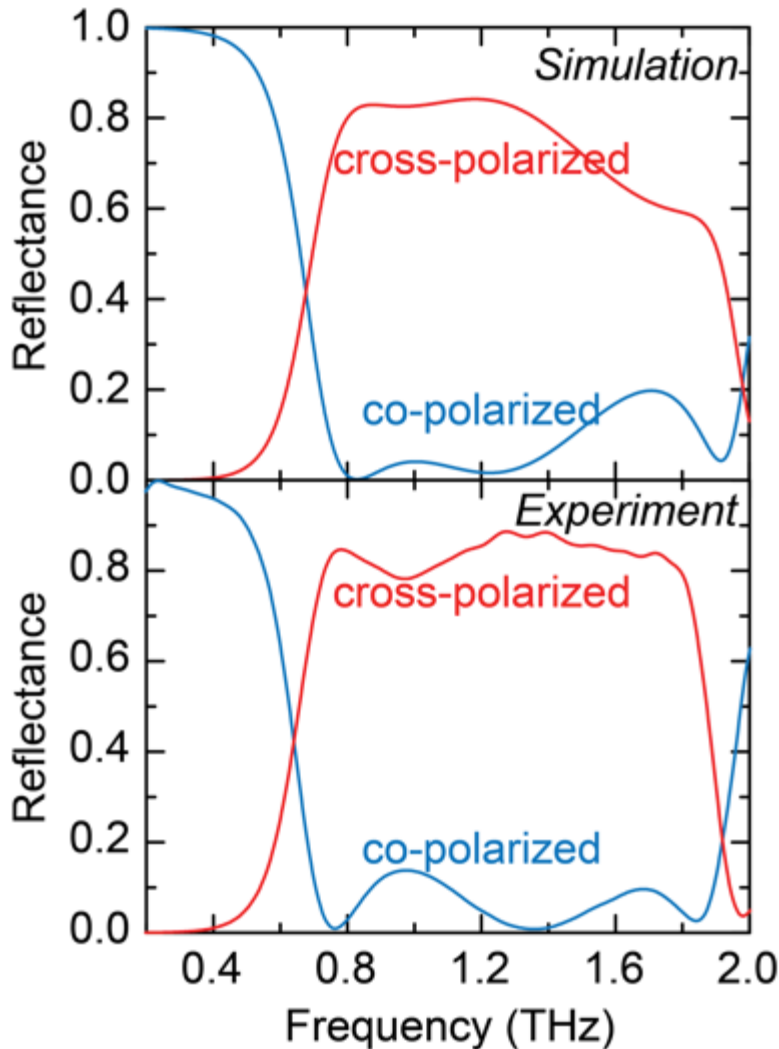


co-polarized





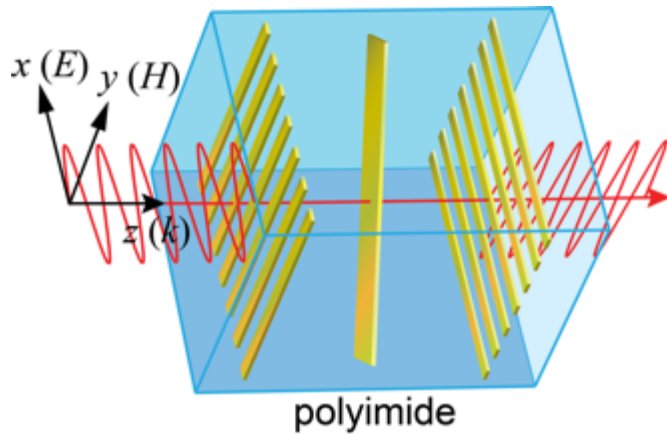
Metamaterial Polarization Converter: Reflection



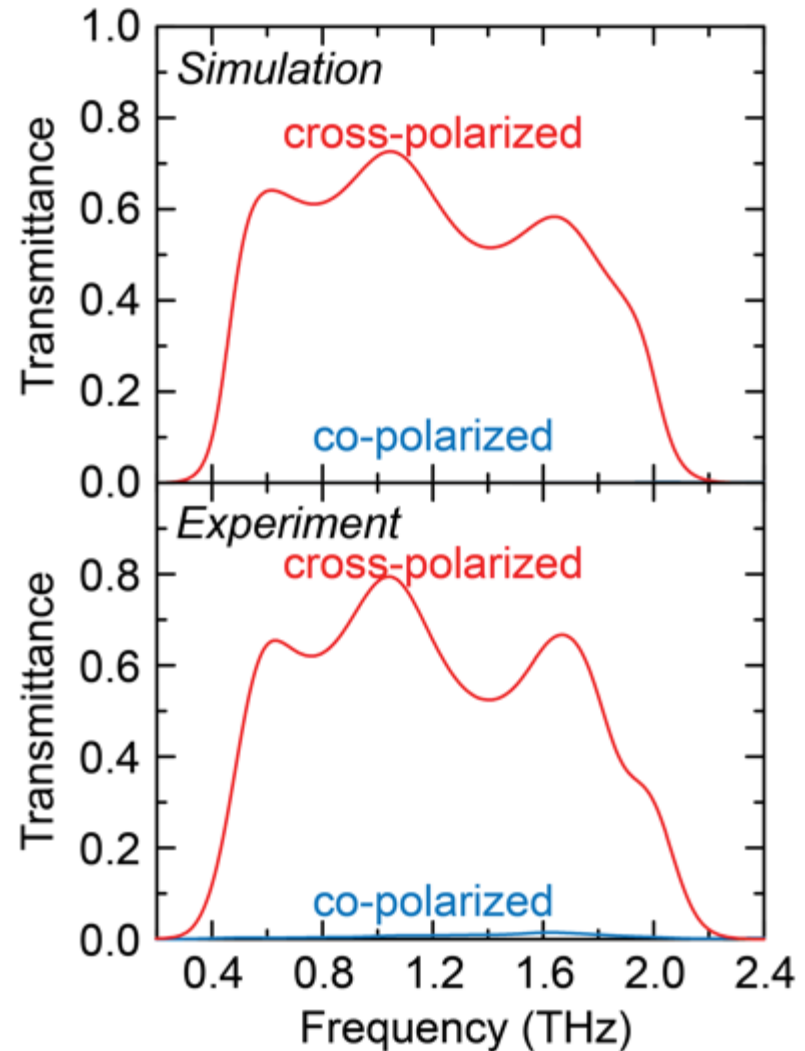
- ❑ Demonstrated in both simulations and experiments
- ❑ Device thickness 33 μm
- ❑ Co-polarized reflection is minimal
- ❑ Cross-polarized reflectance is more than 80%
- ❑ Broadband: destructive interference at multiple frequencies



Polarization Converter: Transmission

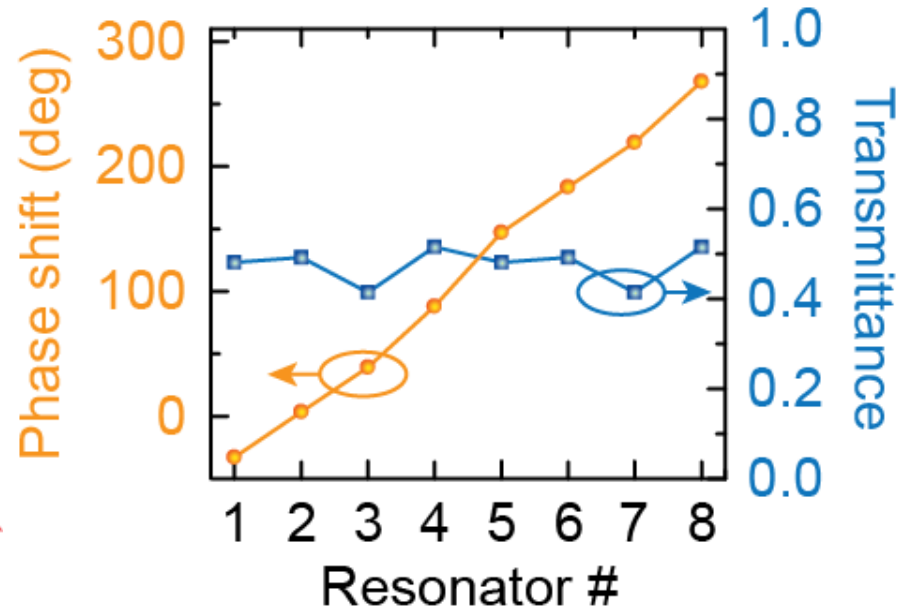
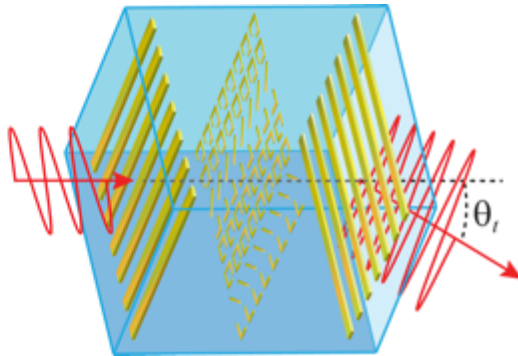
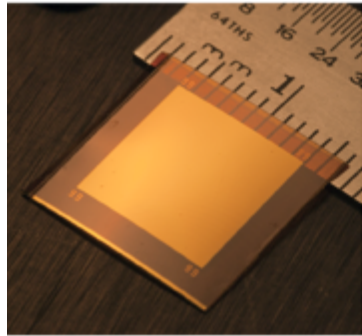


- ❑ The gratings are equivalent to ground plane for electric field polarized along the grating lines.
- ❑ The back grating prevents co-polarized light from transmitting through
- ❑ The front grating prevents the converted cross-polarized light from reflecting back





Anomalous Refraction: Generalized Snell's Law



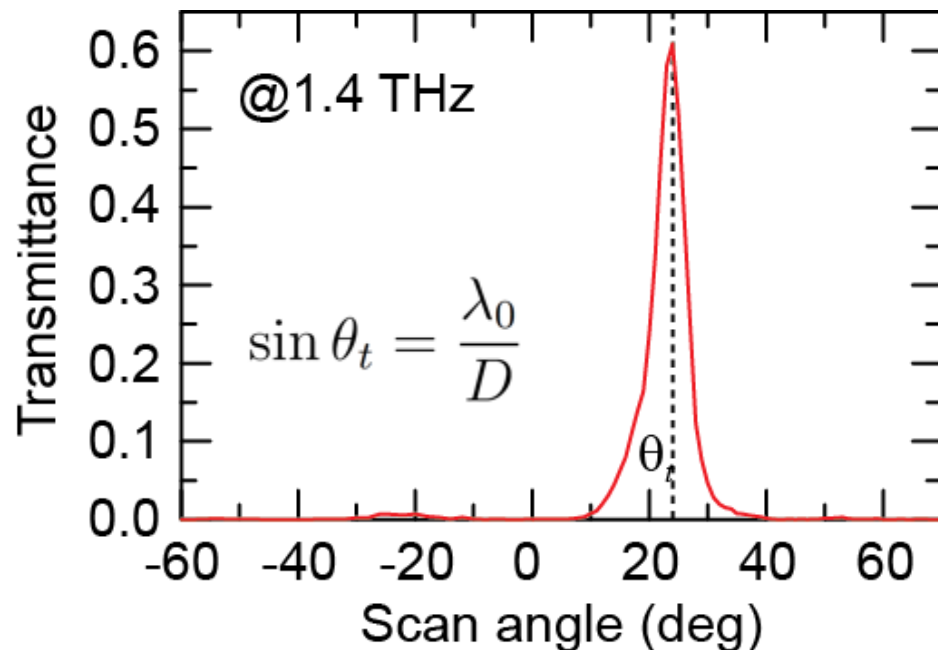
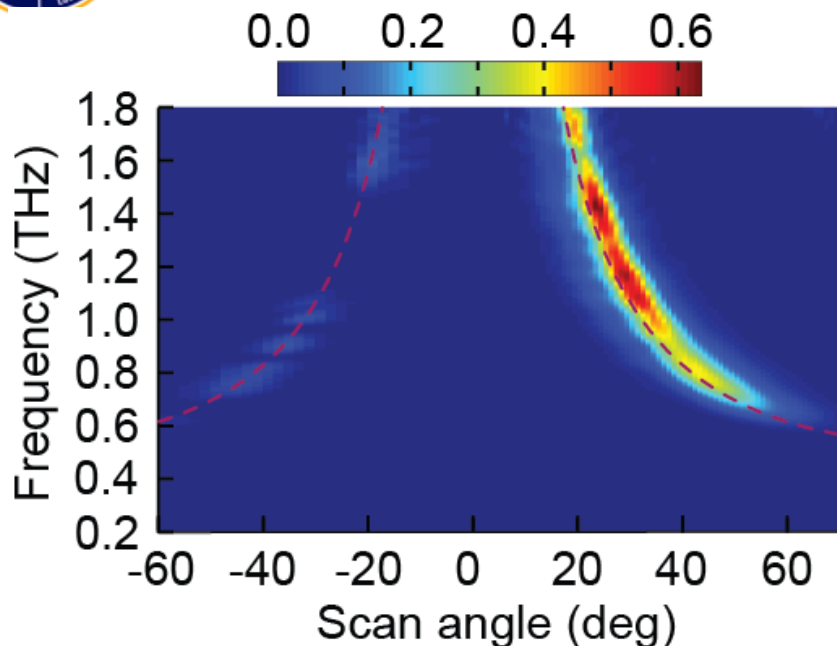
$$\sin \theta_t - \sin \theta_i = \frac{\lambda_0}{2\pi} \frac{d\Phi}{dx}$$

- Each individual element can be used in polarization converter
- Conversion efficiency is designed to be largely constant
- 8 elements form the unit cell, with a linear phase shift spanning a 2π range

Grady et al., *Science* **340**, 1304 (2013).



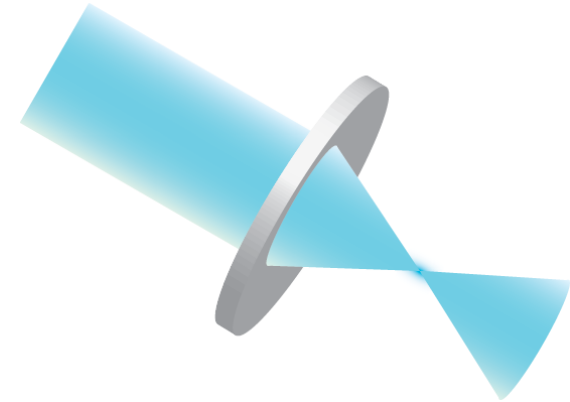
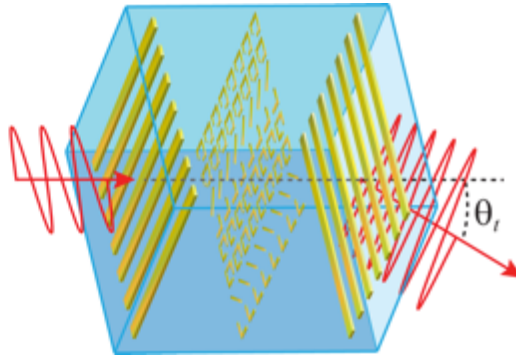
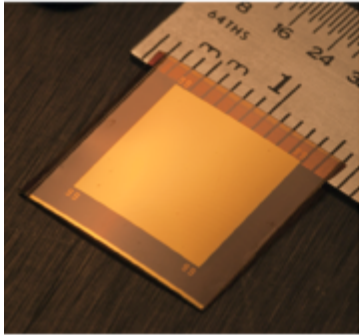
Near-Perfect Anomalous Refraction: Exp.



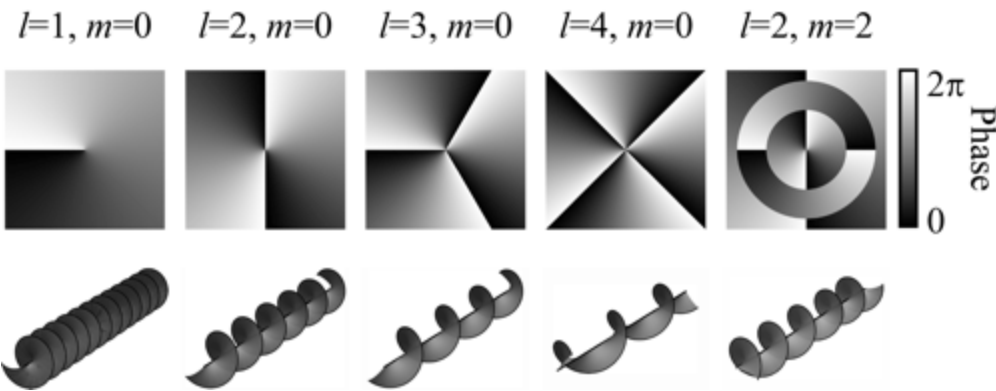
- ❑ At a specific frequency, the “refraction angle” is determined by periodicity
- ❑ At 1.4 THz, the anomalous refraction carries 60% of the incident power
- ❑ Measure the cross-polarized transmission vs. scanning angle
- ❑ Operate over a broad bandwidth



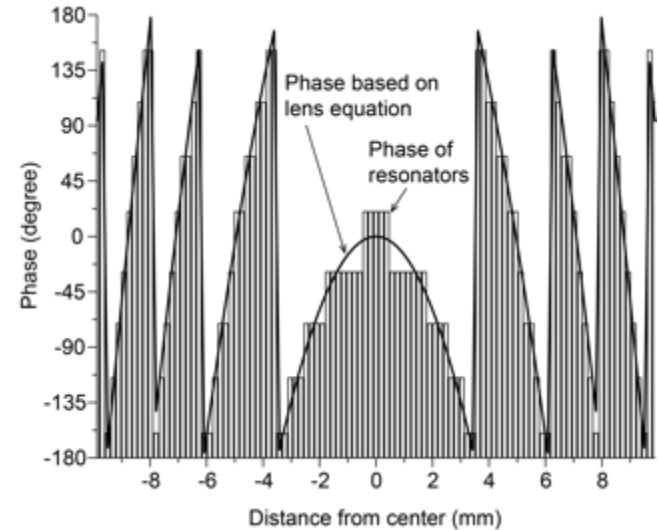
Flat Optics



Flat prism for beam steering



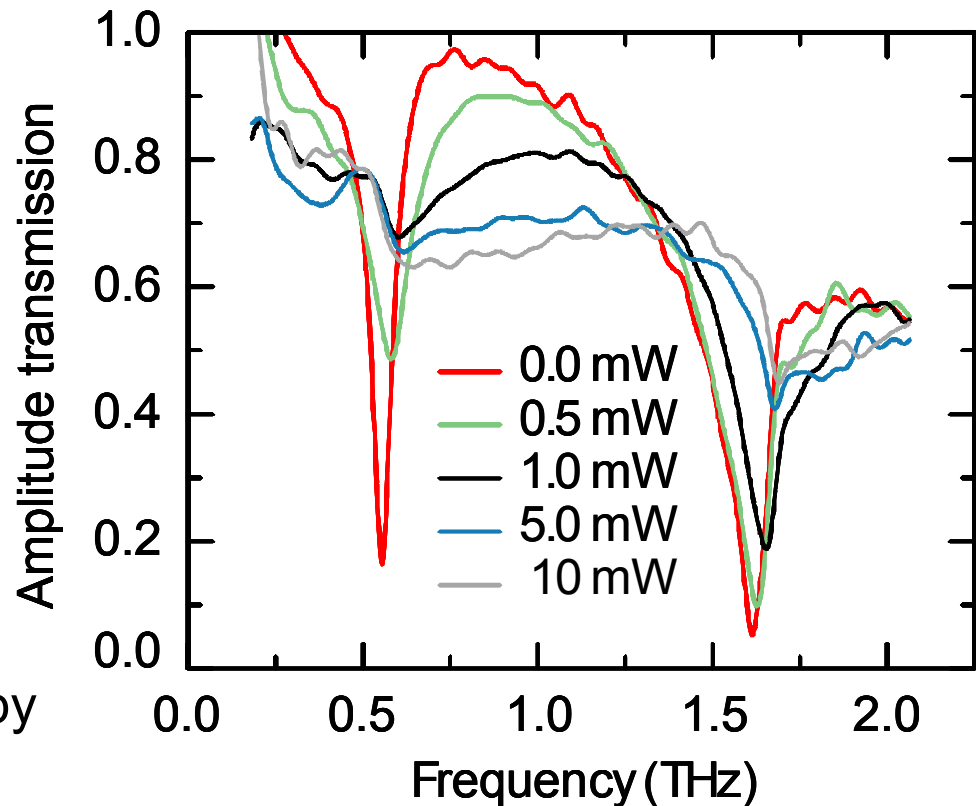
Wave front shaping



Flat lens for beam focusing



Optically Switchable Terahertz Metamaterials

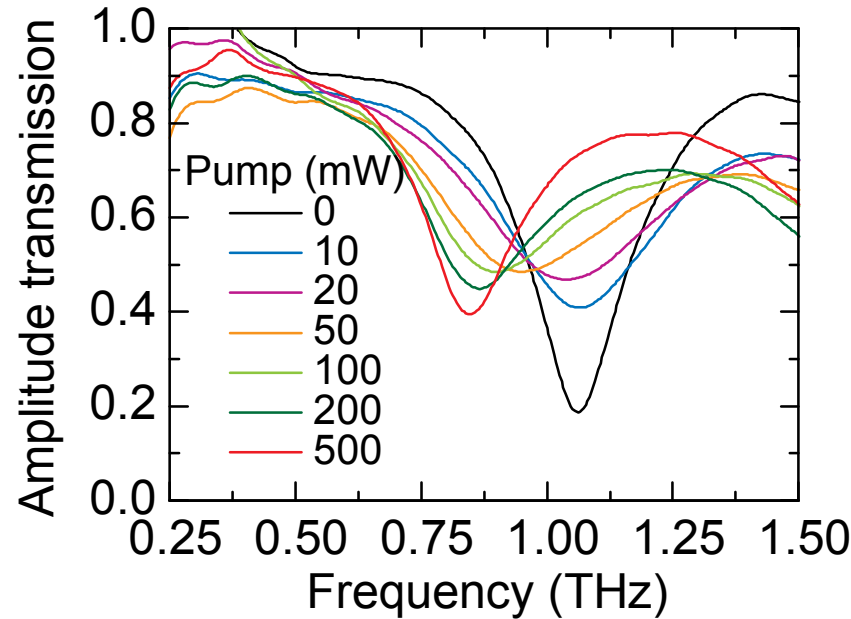
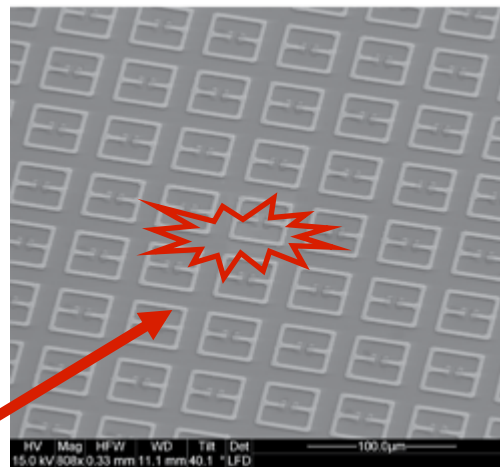
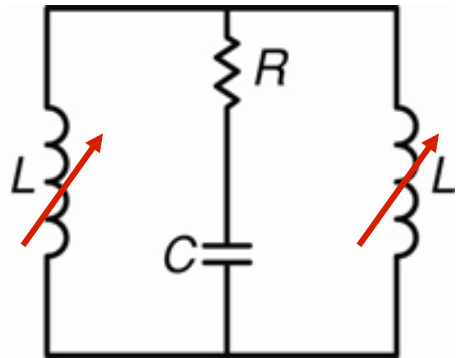
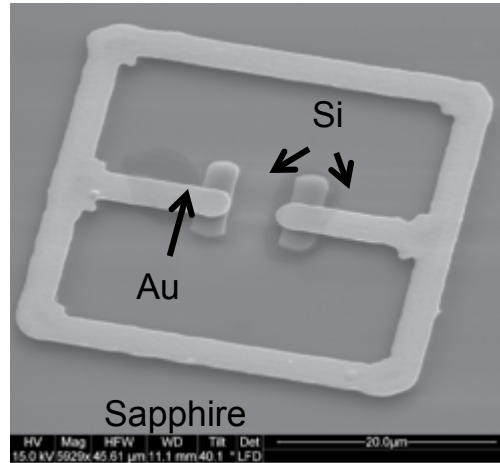
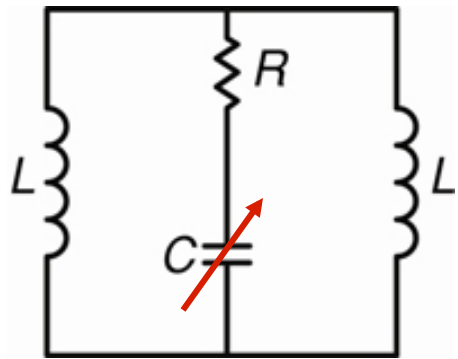


- Switching speed is only limited by carrier lifetime (\sim ns for GaAs)
- \sim ps by reducing the carrier lifetime (GaAs:ErAs nano superlattice)

Padilla *et al.*, *Phys. Rev. Lett.* **96**, 107401 (2006).
Chen *et al.*, *Opt. Lett.* **32**, 1620 (2007).



Optically Frequency Tunable Terahertz Metamaterials

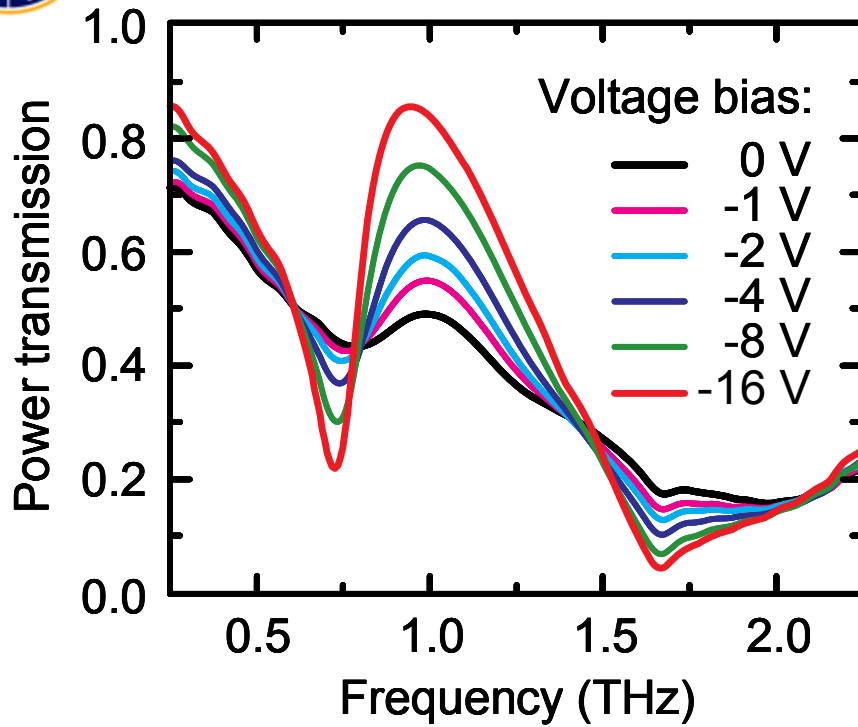


- ~20% frequency tuning range
- Could be red or blue shifting

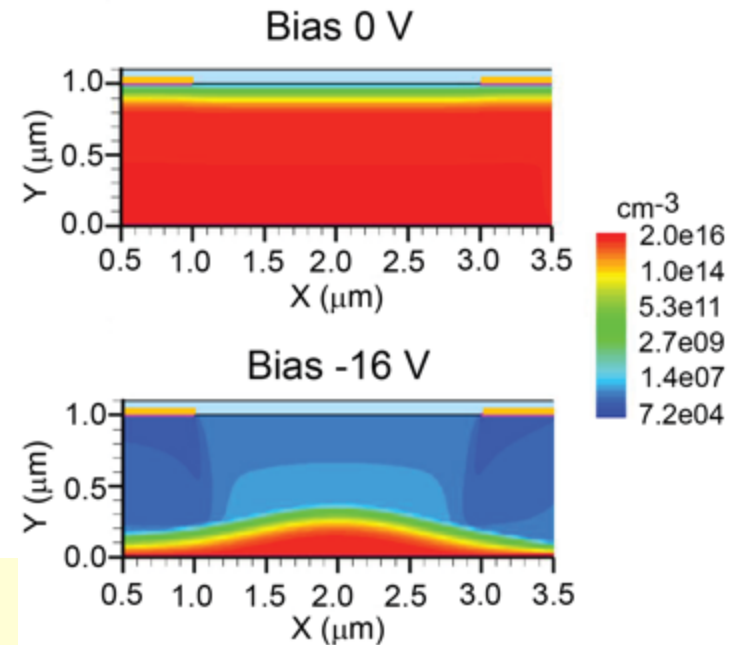
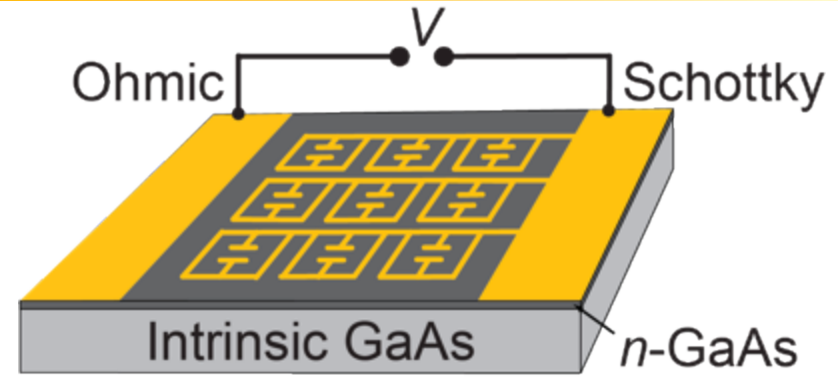
Chen *et al.*, *Nature Photon.* 2, 295 (2008).



Electrically Switchable Terahertz Metamaterials



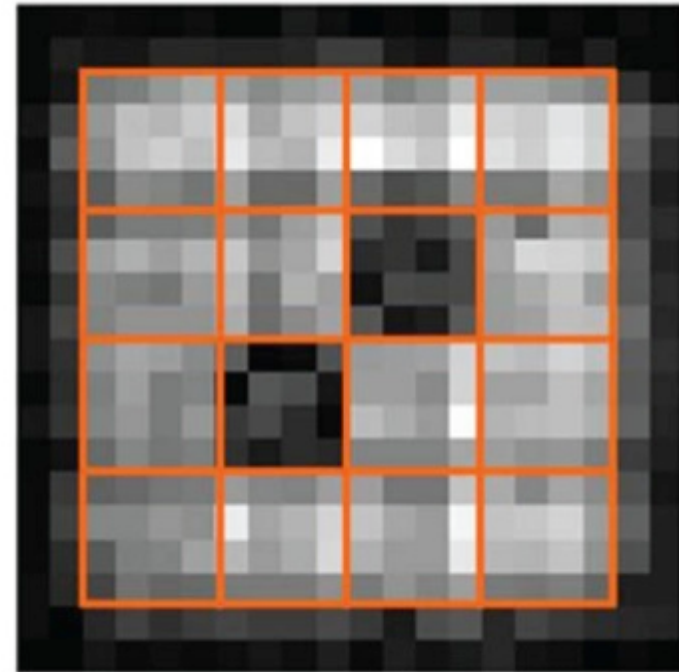
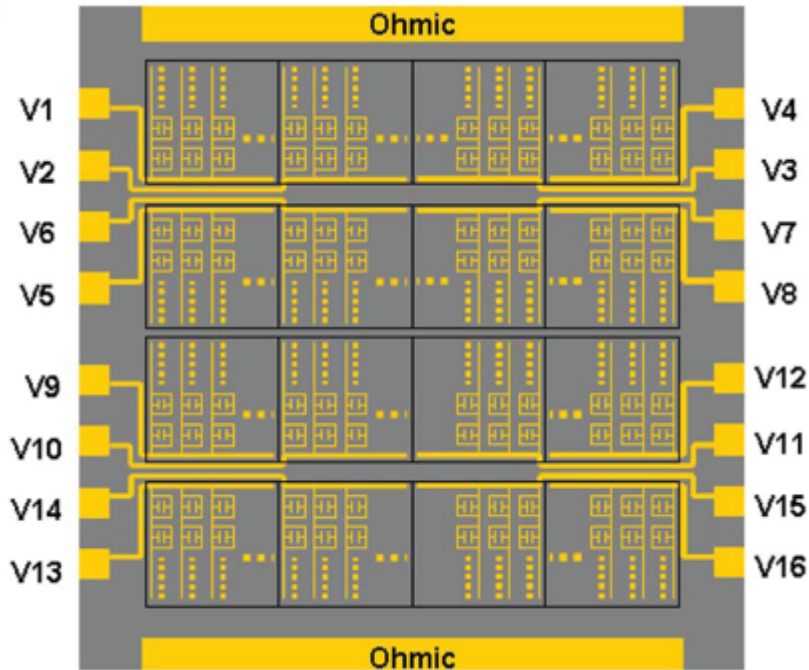
- Amplitude modulation depth 50%
- Phase modulation of $\Delta\phi = \pi/6$
- Operate at room temperature



Chen *et al.*, *Nature* **444**, 597 (2006).
Chen *et al.*, *Nat. Photon.* **3**, 148 (2009).
Chen *et al.*, *Opt. Express* **16**, 7641 (2008).
Chen *et al.*, *APL* **93**, 091117 (2008).



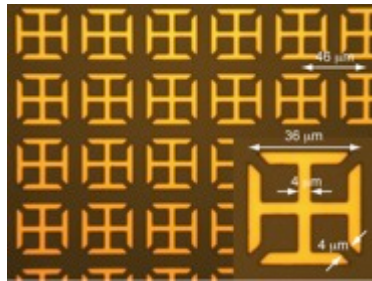
Terahertz Spatial Light Modulator



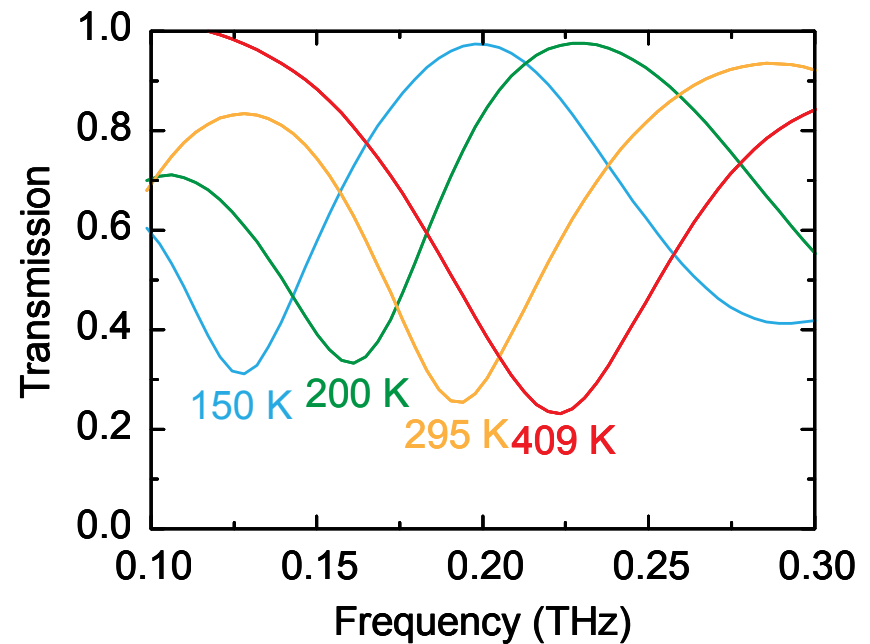
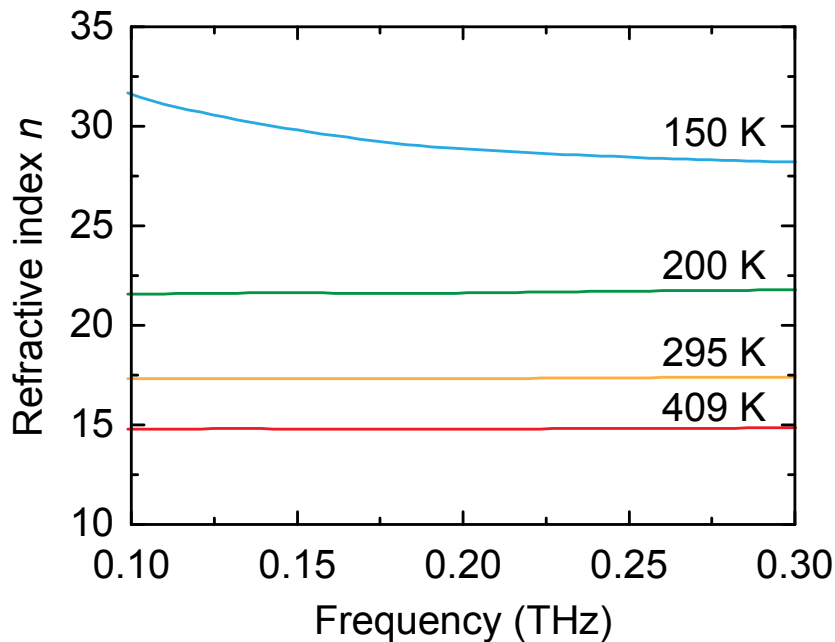
- Each pixel consisting of hundreds of SRRs
- Resonance can be independently switched at each pixel
- For high-speed terahertz imaging



Thermally Tunable Metamaterials Using Ferroelectric Substrate (Strontium Titanate)



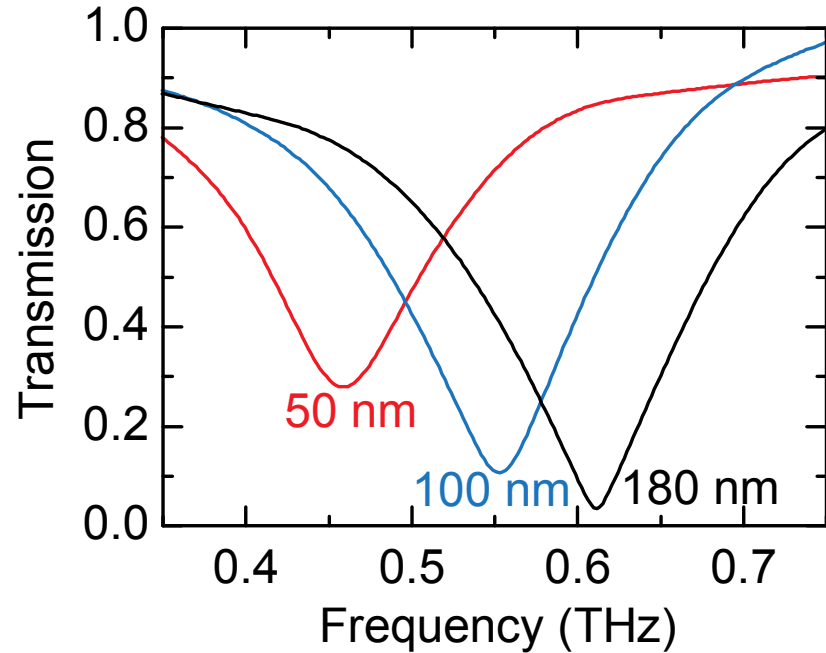
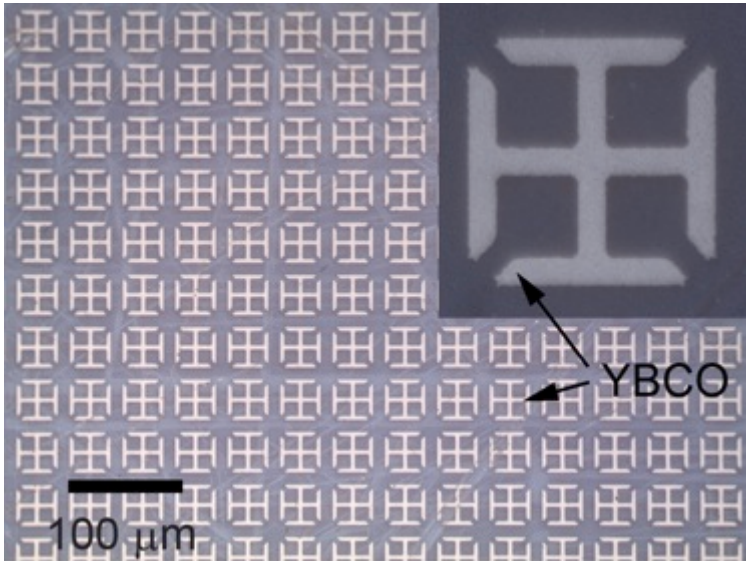
- Substrate refractive index (dielectric constant) decreases with decreasing temperature
- Resonance frequency red-shifts with decreasing temperature



Singh *et al.*, *Opt. Lett.* **36**, 1230 (2011).



High-Temperature Superconducting (HTS) Metamaterials



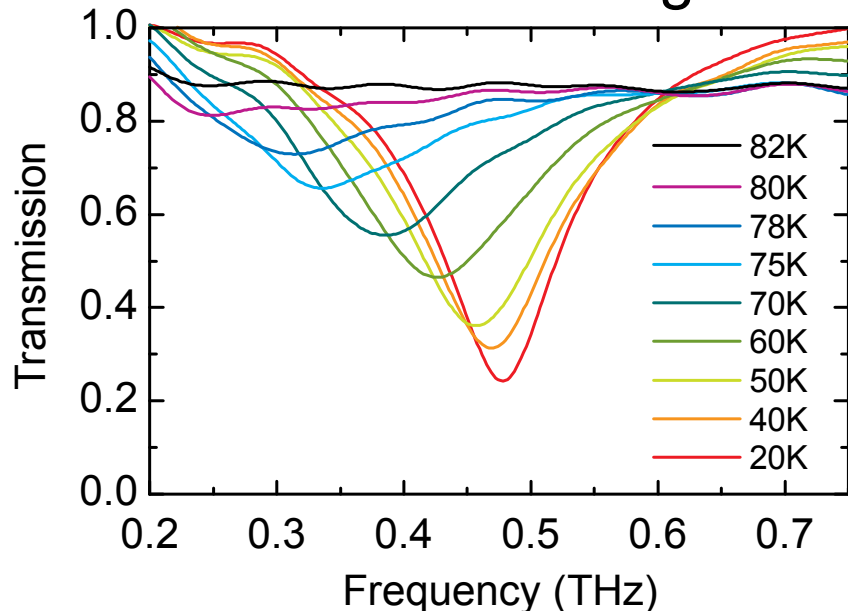
- Strong resonant response at low temperatures
- Resonance frequency strongly depend on the nano-scale thickness
- Need to take into account the kinetic inductance in YBCO metamaterials

Singh et al., Nanophotonics 1, 117 (2012).

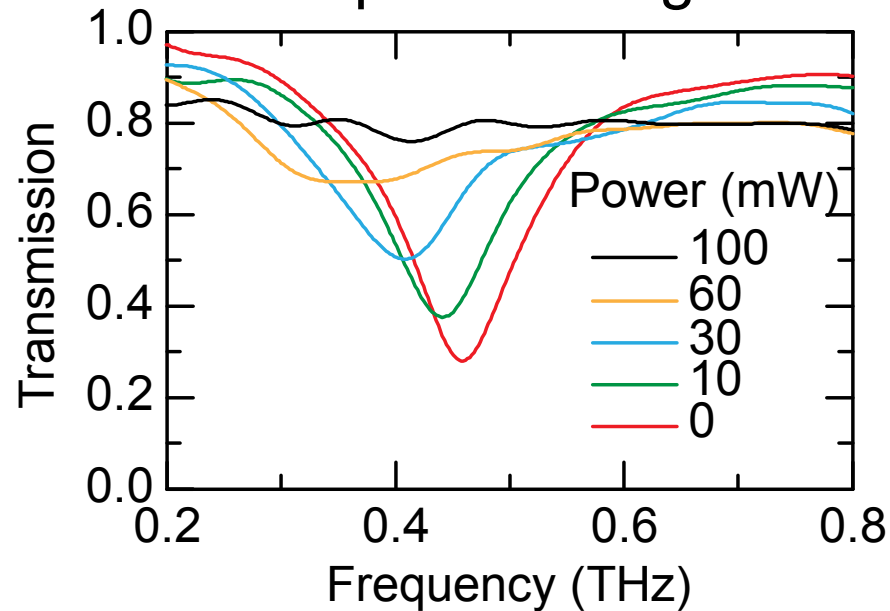


Thermal & Optical Resonance Tuning in HTS Metamaterials

Thermal tuning



Optical tuning



- 50 nm thick YBCO metamaterial
- Resonance strength and frequency are both tuned by temperature
- Imaginary conductivity plays a key role
- The resonance tuning is more significant in thinner YBCO metamaterials

Chen *et al.*, *PRL*. **105**, 247402 (2010).

Singh *et al.*, *Nanophotonics* **1**, 117 (2012).



Metamaterials will play an increasingly important role in THz S&T

- ❑ Few-layered ultrathin planar metamaterials can accomplish many optical functionalities of bulk materials
 - Ultrathin metamaterial perfect absorbers
 - Ultrathin metamaterial antireflection coatings
 - Thin film like metamaterial linear polarization converters
 - Near perfect anomalous reflection/refraction: generalized Snell's law

- ❑ Electrically switchable THz metamaterials
 - High modulation (intensity and phase) depth
 - Integration into spatial modulator
 - Broadband modulation

- ❑ Optically switchable, frequency tunable THz metamaterials
 - Low optical fluence, high efficiency
 - Ultrafast switching
 - 20% frequency tunability
 - Temperature & optical tunability with complex oxide metamaterials