LA-UR-15-22077

Title: Applying Metamaterials to Solve Terahertz Challenges

Author(s): Chen, Houtong

Intended for: Seminar at University of Notre Dame, 2015-03-20 (South Bend, Idaho, United States)

Issued: 2015-03-21

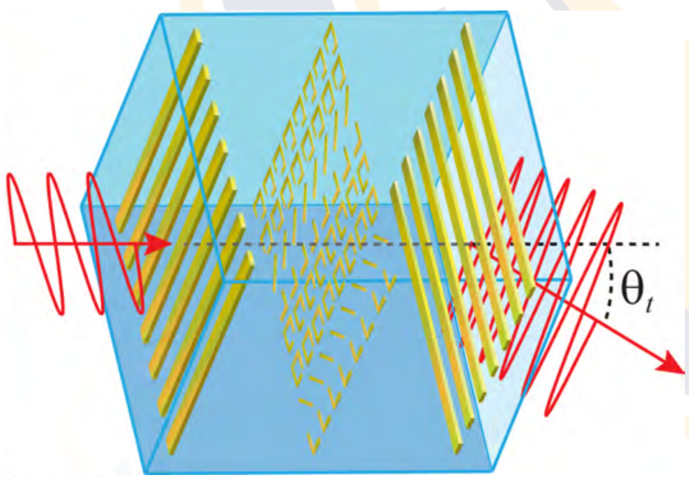
Seminar @ University of Notre Dame
March 20, 2015

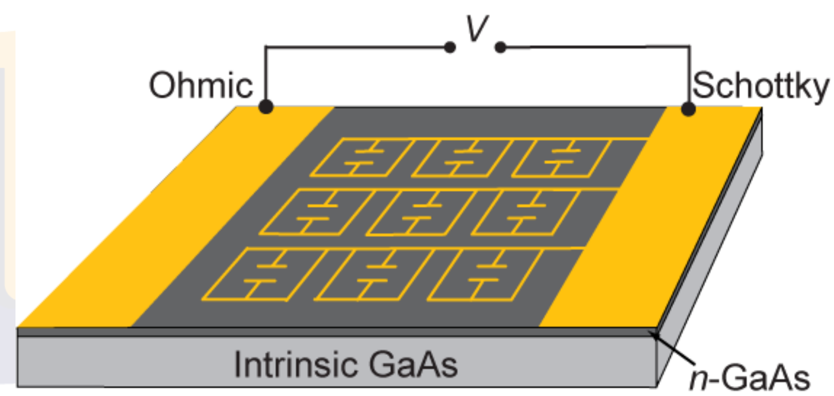
Applying Metamaterials to Solve Terahertz Challenges

Hou-Tong Chen

Center for Integrated Nanotechnologies

Los Alamos National Laboratory





Center for Nanoscale Materials
Argonne National Laboratory

Molecular Foundry
Lawrence Berkeley National Laboratory

Center for Functional Nanomaterials
Brookhaven National Laboratory

Center for Integrated Nanotechnologies
Los Alamos National Laboratory &
Sandia National Laboratory

Center for Nanophase Materials Sciences
Oak Ridge National Laboratory

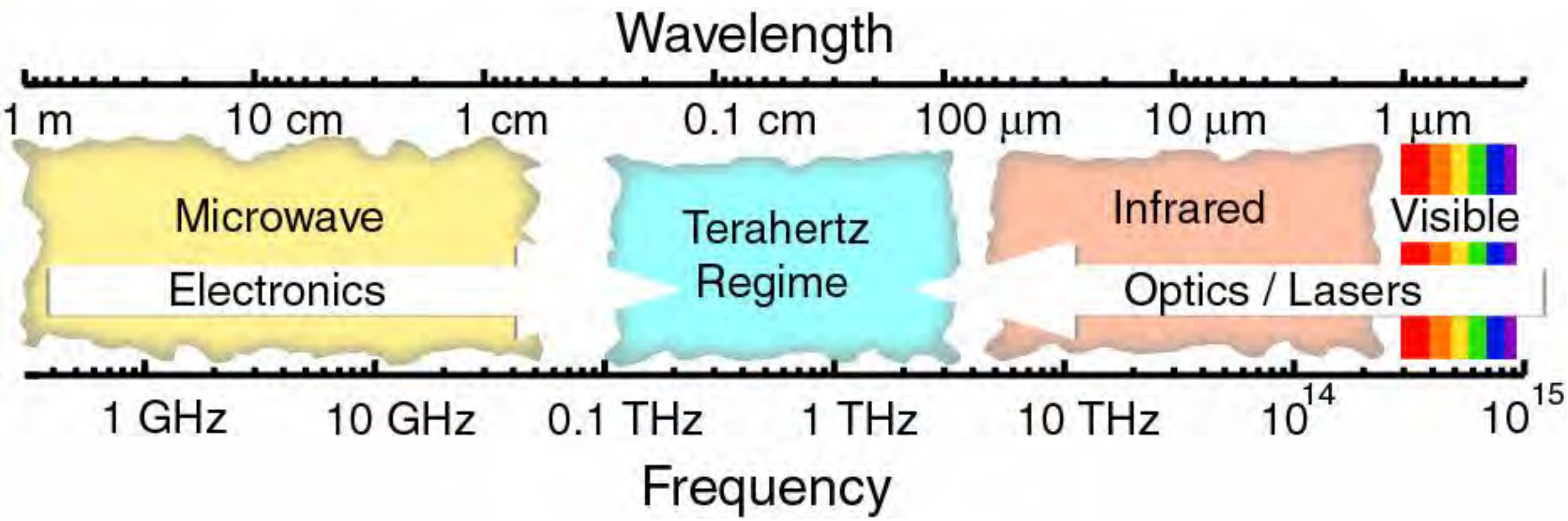
http://cint.lanl.gov/

Los Alamos NATIONAL LABORATORY EST.1943

U.S. DEPARTMENT OF ENERGY Office of Science

NNSA

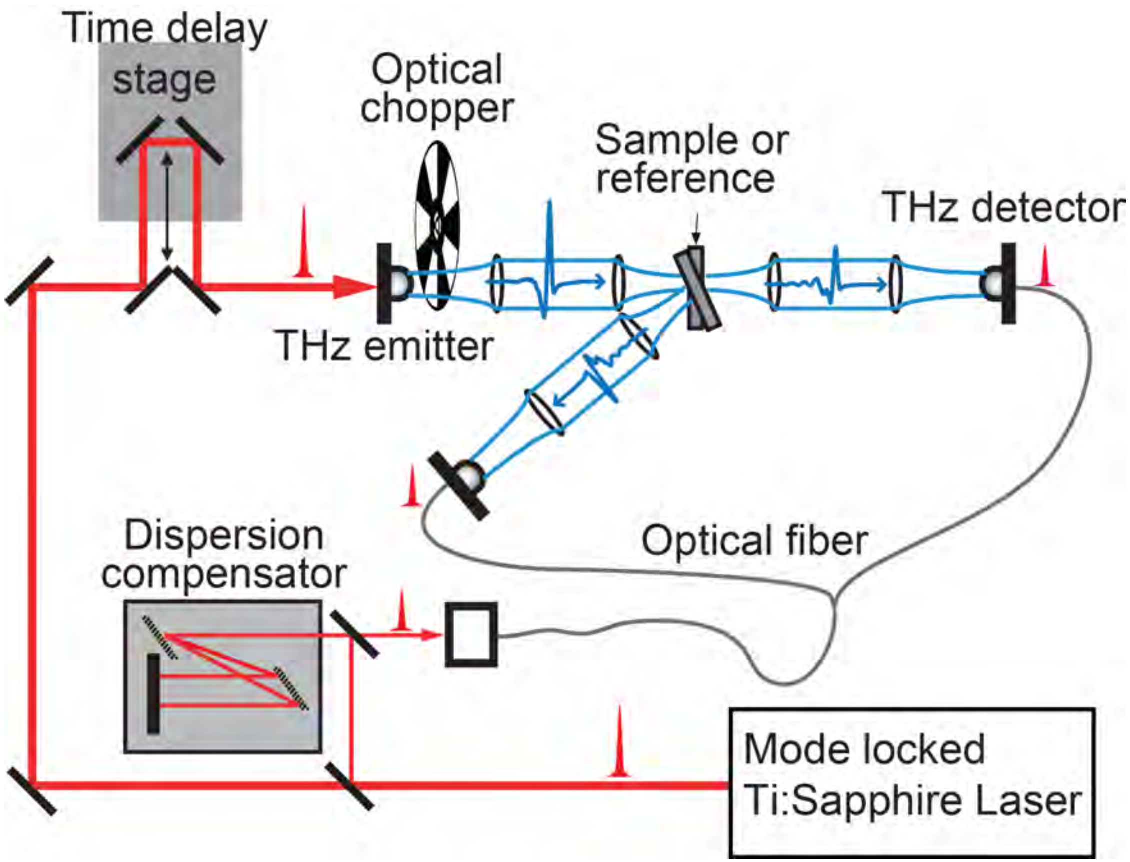
Challenges in THz Science and Technology



- THz is one of the least developed and most challenging regimes in the electromagnetic spectrum
- Functional THz devices and components are not widely available
- Metamaterials provide excellent opportunities in solving the material challenges associated with the "THz gap"

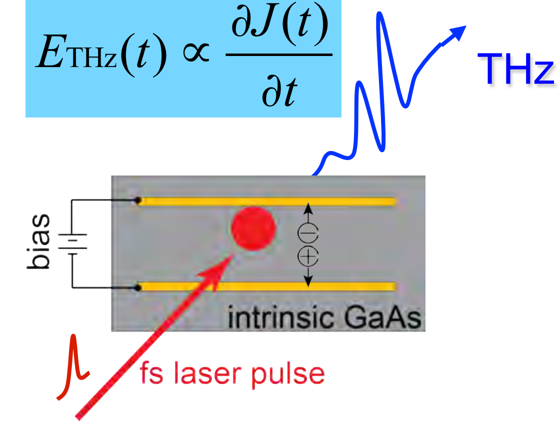
Terahertz Generation and Detection

Schematic of a THz time-domain spectrometer

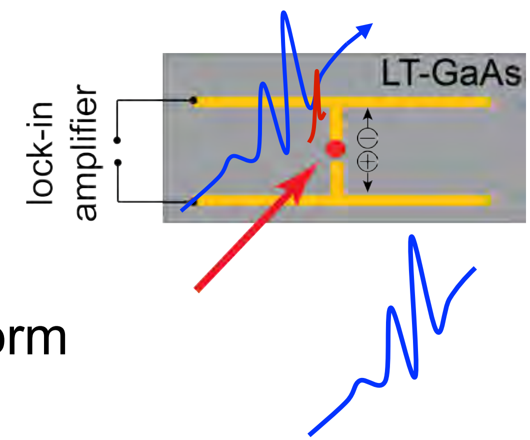


THz generation:

$$E_{\mathrm{THz}}(t) \propto \frac{\partial J(t)}{\partial t}$$

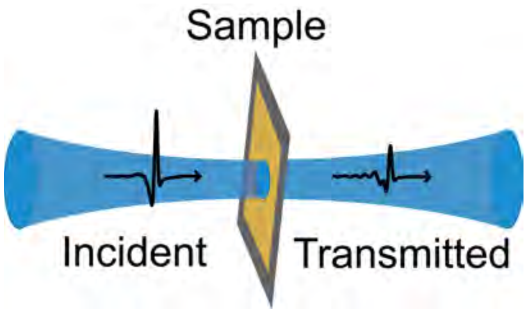


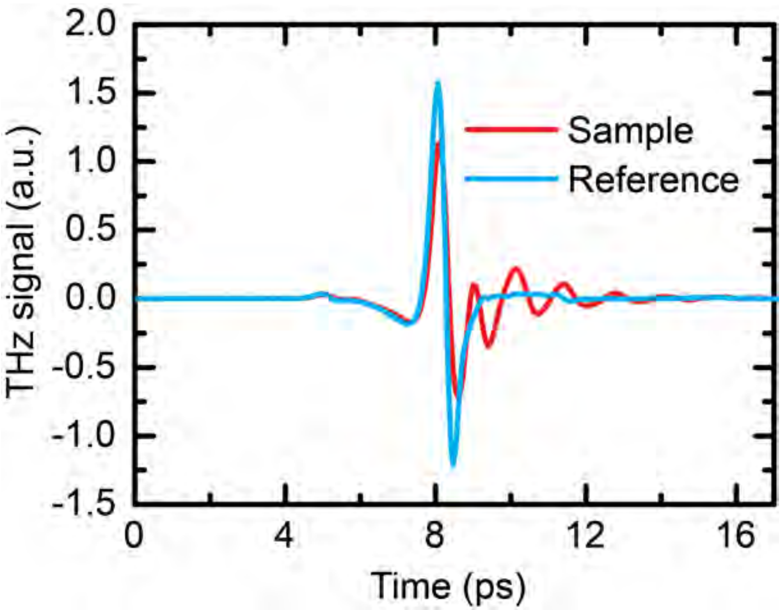
THz-detection:



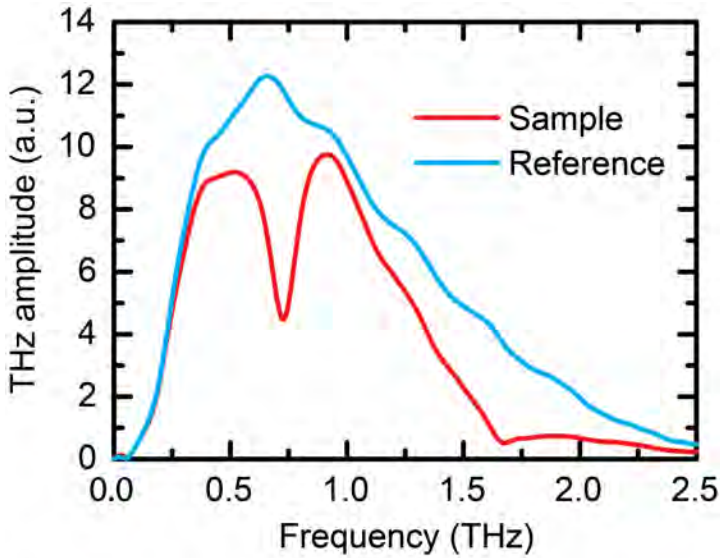
Measure the THz pulse waveform in the time-domain

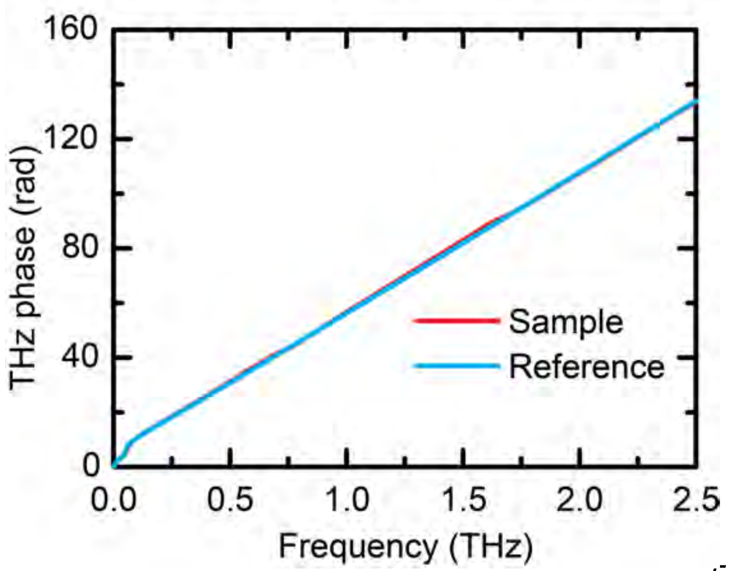
Terahertz Time-Domain Spectroscopy





FFT

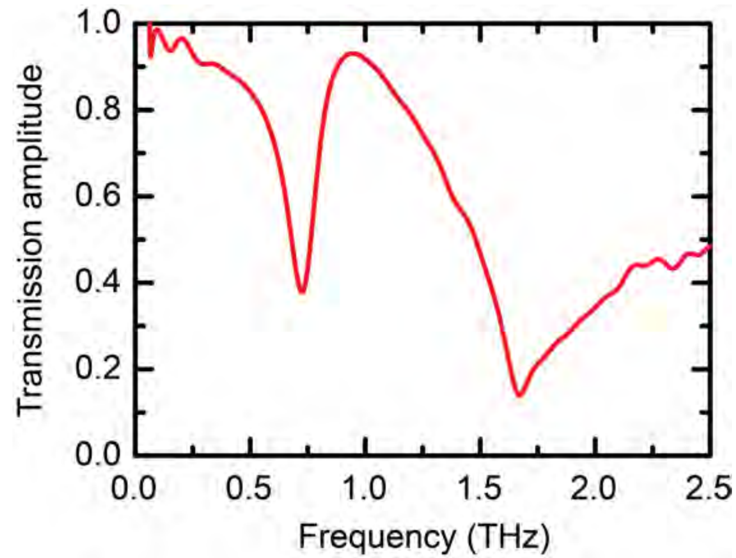


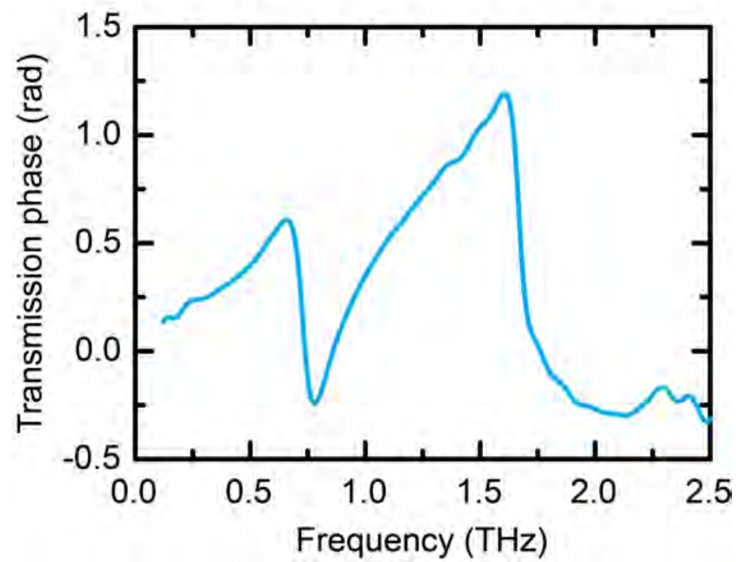


Terahertz Time-Domain Spectroscopy

$$\tilde{t}(\omega) = \frac{E_{\mathrm{Sam}}(\omega)}{E_{\mathrm{Ref}}(\omega)}$$

- Obtain simultaneously the amplitude and phase information
- To extract complex dielectric function $\varepsilon(\omega)$ over a broad frequency range (non-magnetic materials)
- Reflection measurement is also required to further extract the complex permeability $\mu(\omega)$ for materials with magnetic response

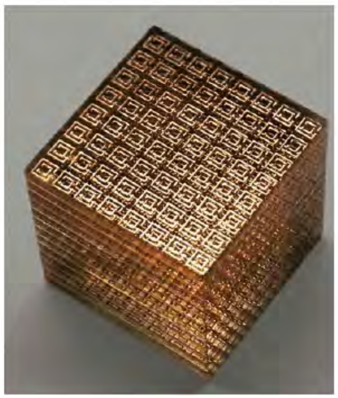


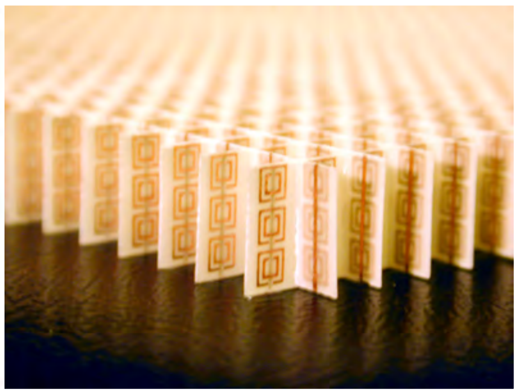


Bulk Metamaterials vs Meta-Surfaces

Bulk metamaterials

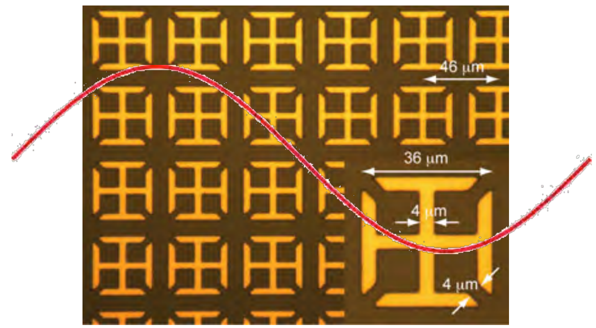
- ❑ Effective material parameters: ε, μ, n, Z
- ❑ Difficult to fabricate in the optical regime
- ❑ High loss and narrow bandwidth issues

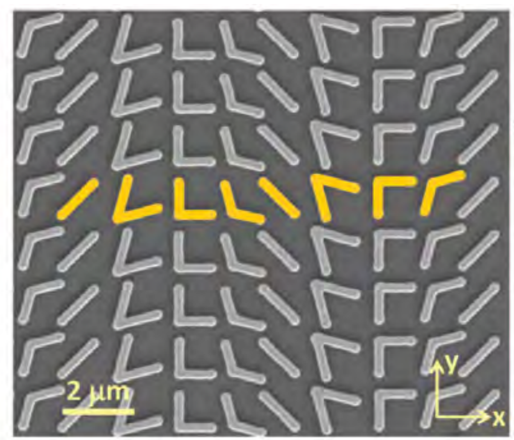




Meta-surfaces

- ❑ Interface properties
- ❑ Planar structures: ease in fabrication
- ❑ Limited interaction with EM waves

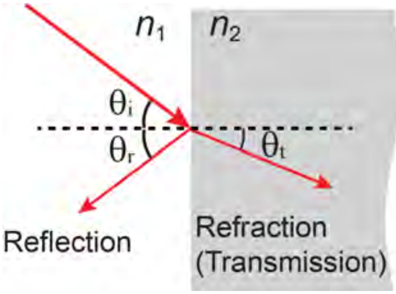




Tailored Reflection and Transmission at Meta-Surfaces

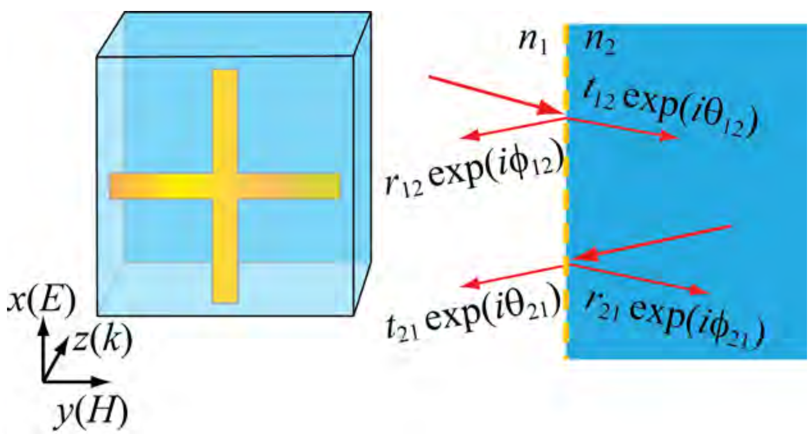
- For a bare dielectric surface:

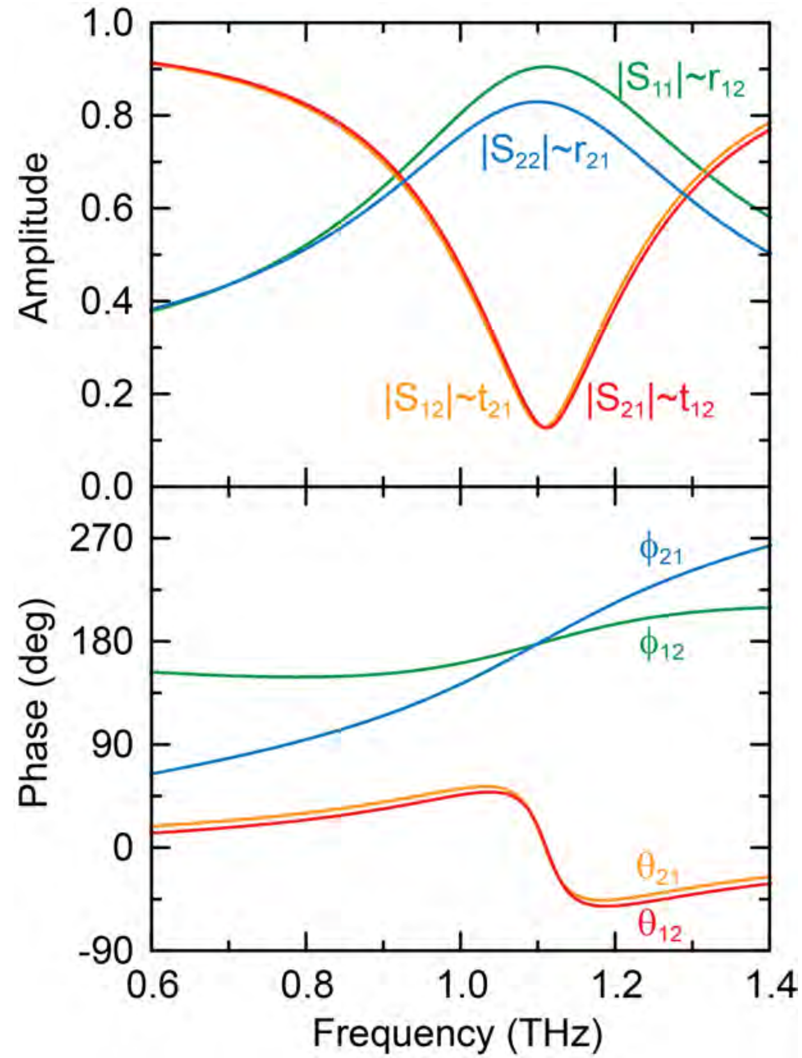
$$r = \frac{n_1 - n_2}{n_1 + n_2} \qquad t = \frac{2n_1}{n_1 + n_2}$$



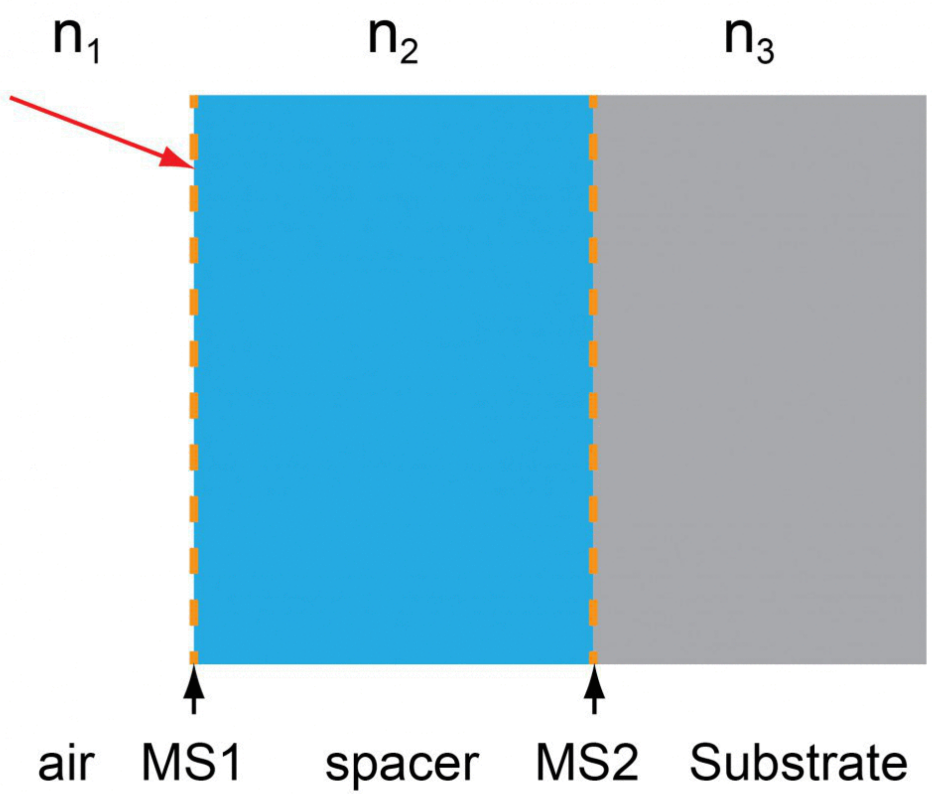
at normal incidence with constant values

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





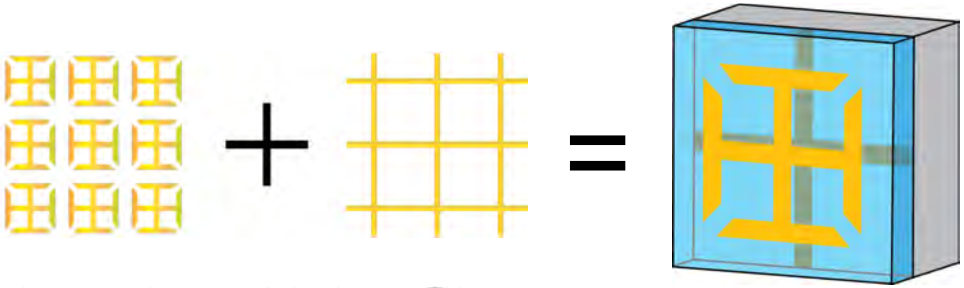
Interference in Few-Layer Metamaterials

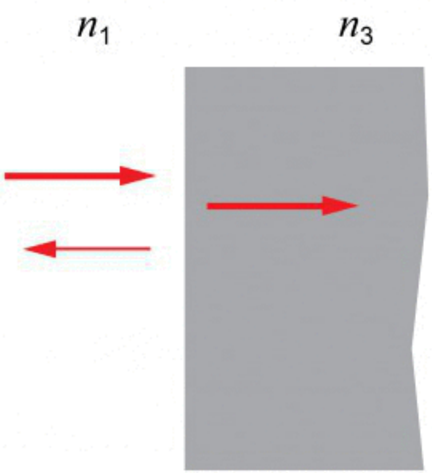


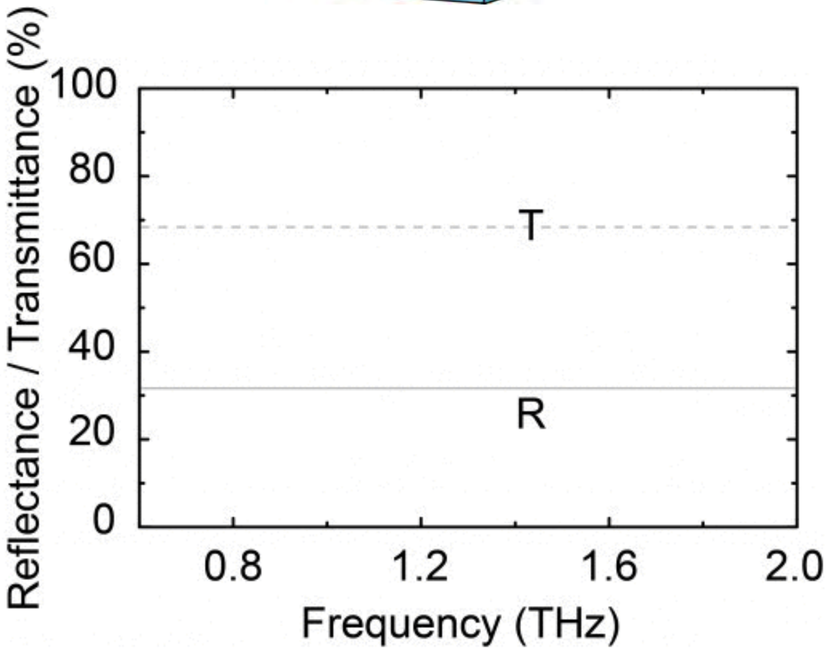
$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}} \qquad \tilde{t} = \frac{\tilde{t}_{12}\tilde{t}_{23}e^{i\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

Chen, *Opt. Express* **20**, 7165 (2012).

Ultrathin Bi-Layer Metasurface Antireflection Coatings



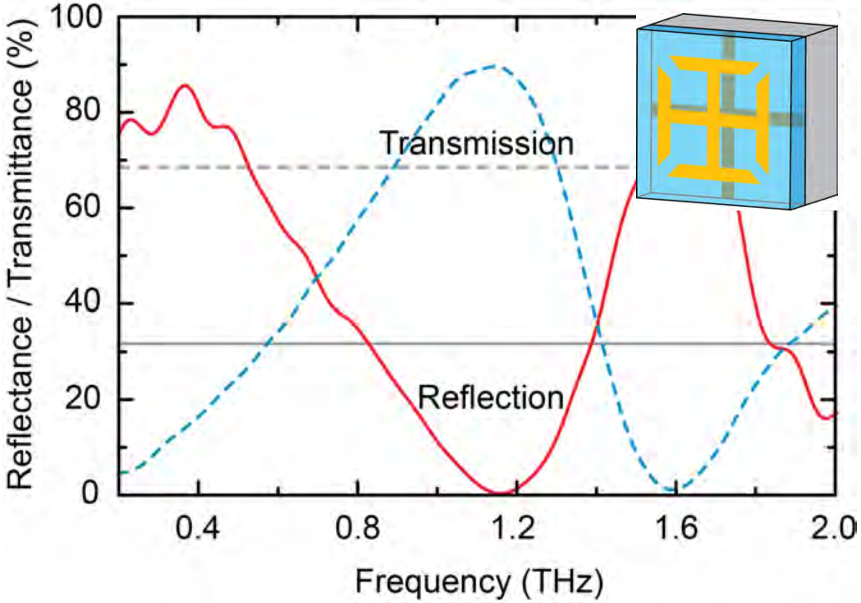


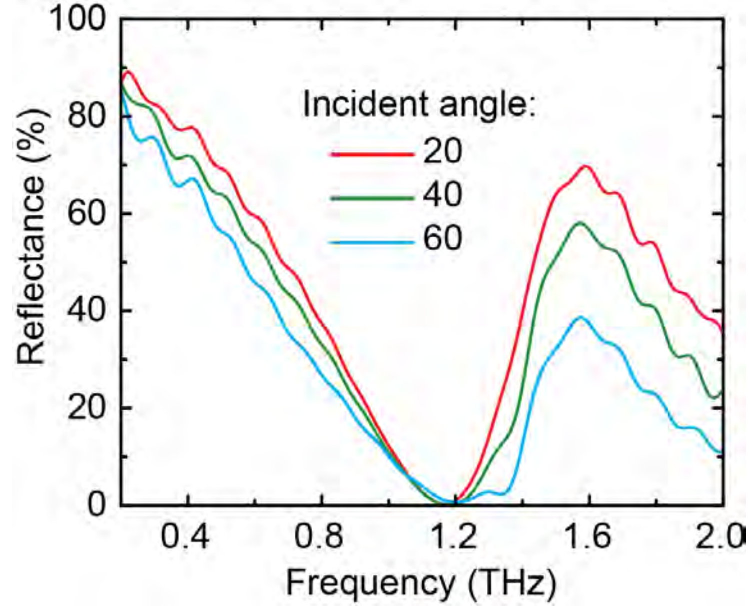


$n_1 = 1, n_2 = 1.2, n_3 = 3.4$

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

Ultrathin Bi-Layer Metasurface ARC: Experiments





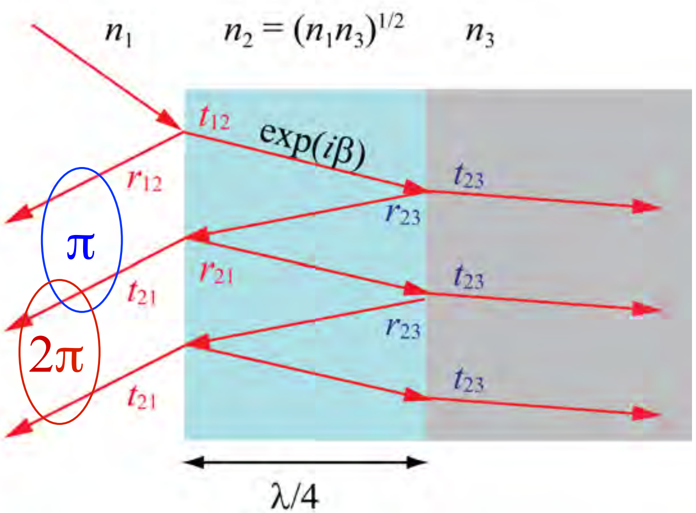
- **Structure:**
  - Period (46 μm); gold width (4 μm); SRR outer dimension (36 μm); gold thickness (200 nm); gap (4 μm)
  - Polyimide spacer thickness (~13 μm), dielectric constant (~3), loss tangent: (~5%)

- **Performance**:
  - Reflectance: 32% → ~0
  - Transmittance: 68% → 90%
  - Wide incidence angle range
  - No requirement of index matching

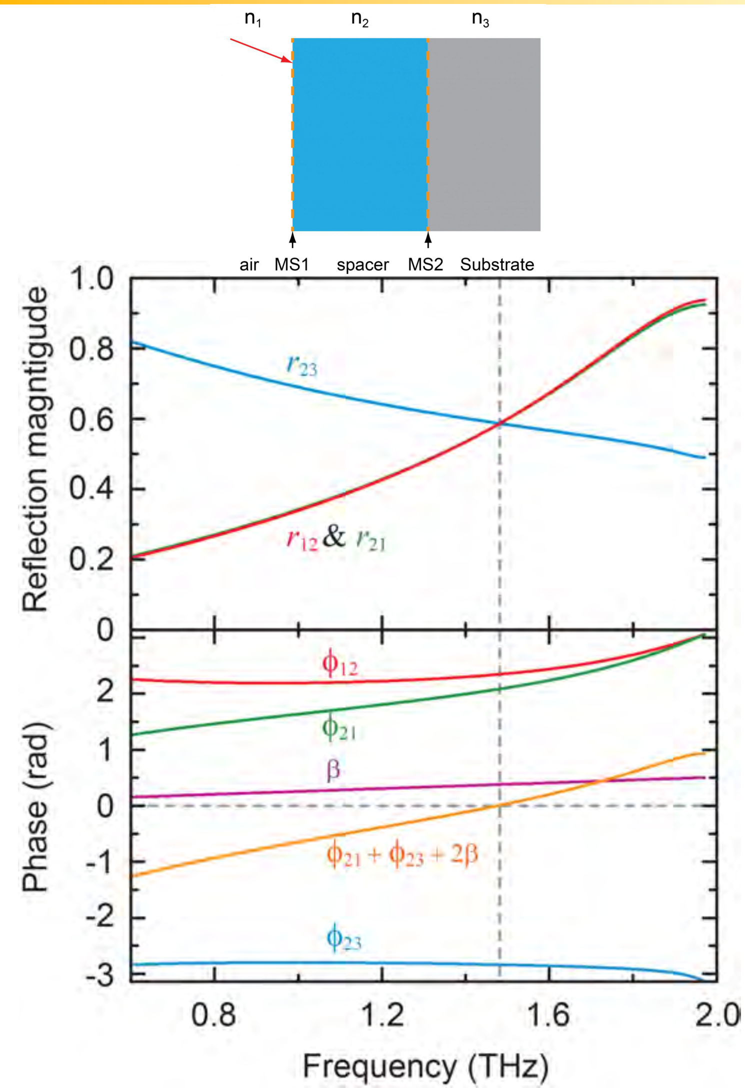
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Mechanism of Metamaterial Antireflection

- **Quarter-wave antireflection:**

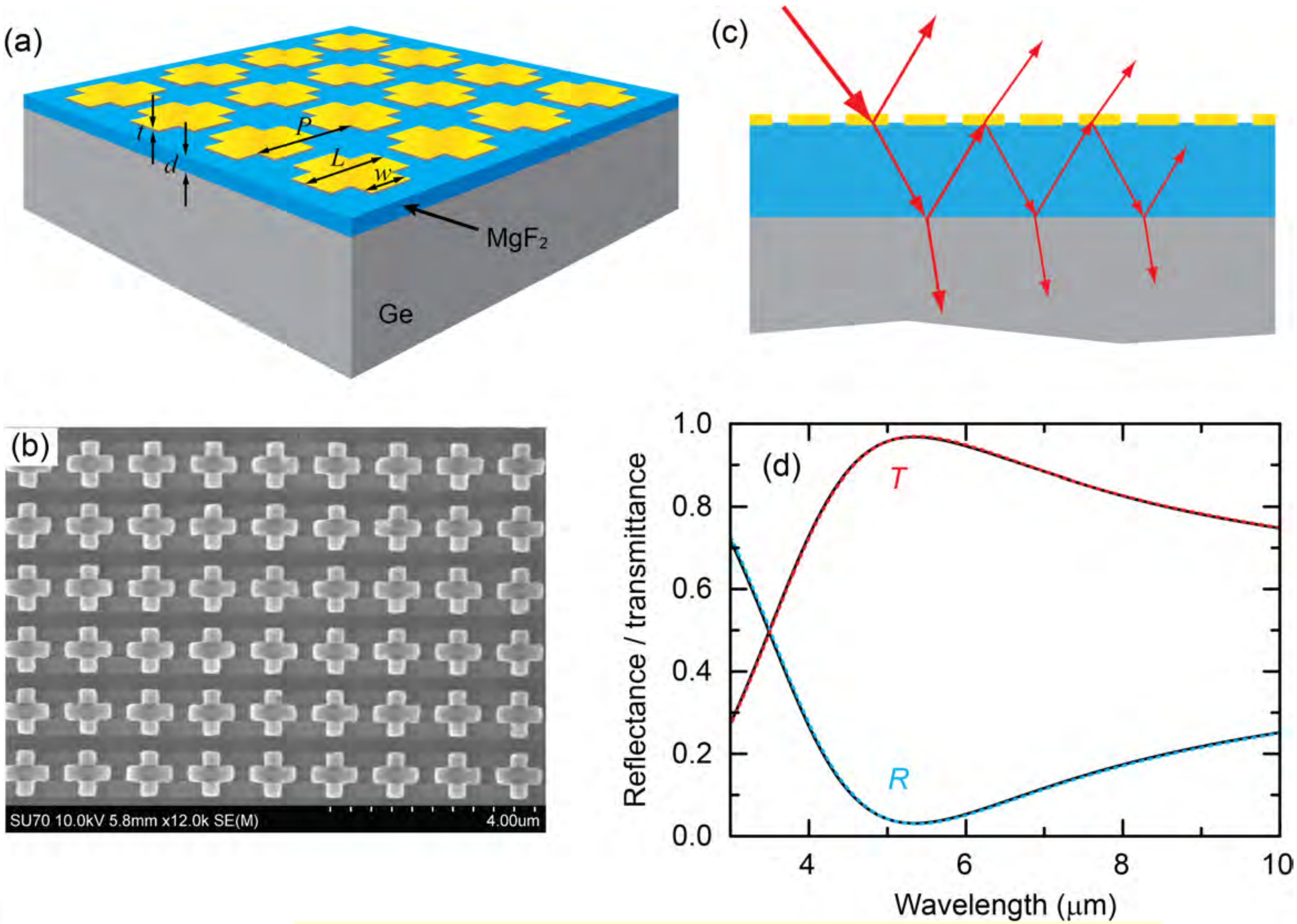


- **Metasurface antireflection:**
  - $r_{12} = r_{21} = r_{23}$
  - $\theta_{12} + \phi_{23} + \theta_{21} + 2\beta - \phi_{12} = \pi$
  - $\phi_{21} + \phi_{23} + 2\beta = 0$



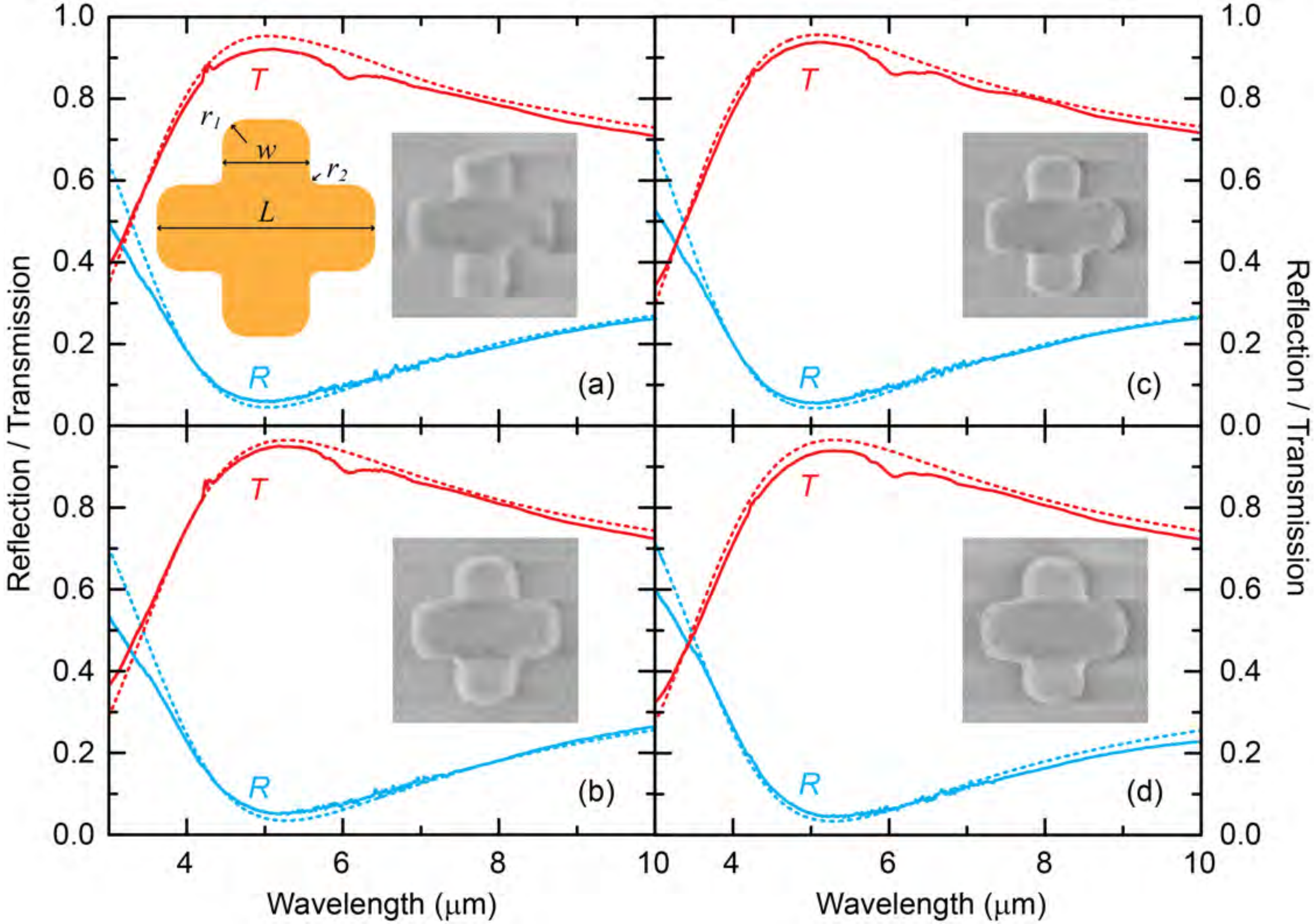
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Single-Layer Metasurface ARC in MIR



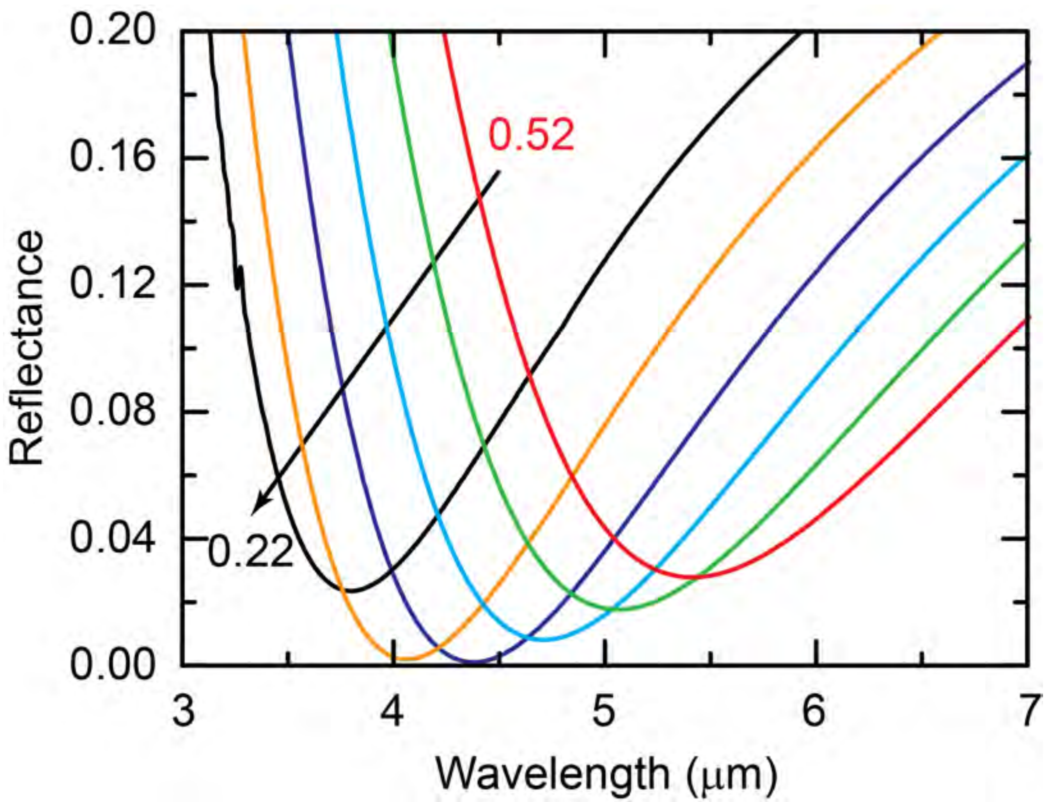
Zhang *et al.*, *Appl. Phys. Lett.* **105**, 241113 (2014).

Single-Layer Metasurface ARC in MIR



Zhang *et al.*, *Appl. Phys. Lett.* **105**, 241113 (2014).

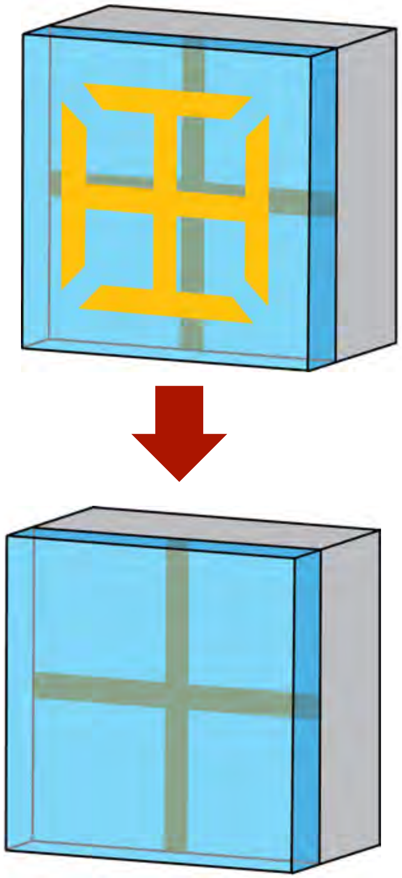
Spacer Thickness Dependence

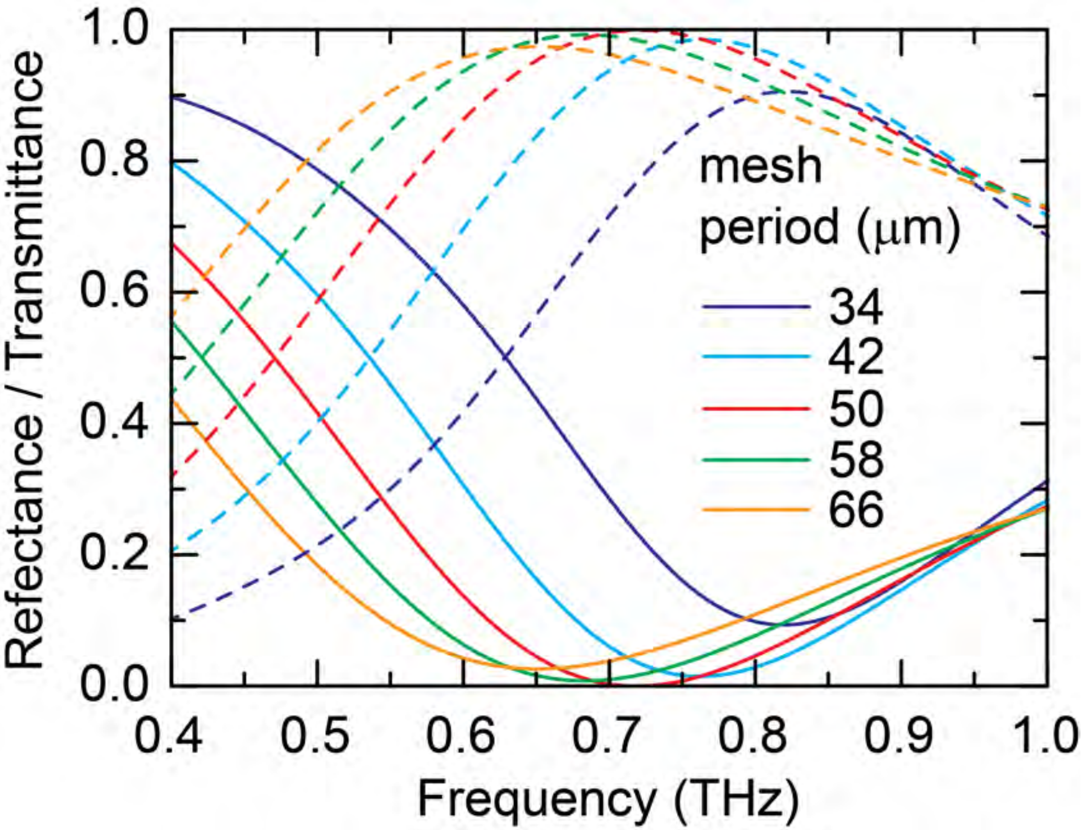


- The spacer thickness (520 nm) is too much in our experiments
- The optimized spacer thickness is ~320 nm

Zhang *et al.*, *Appl. Phys. Lett.* **105**, 241113 (2014).

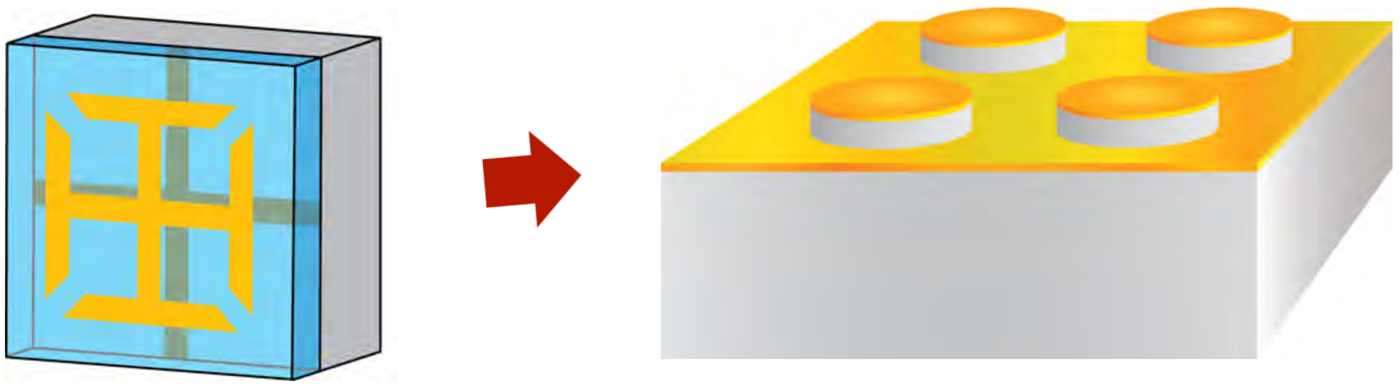
Laminating Silicon on Metal Mesh as ARC



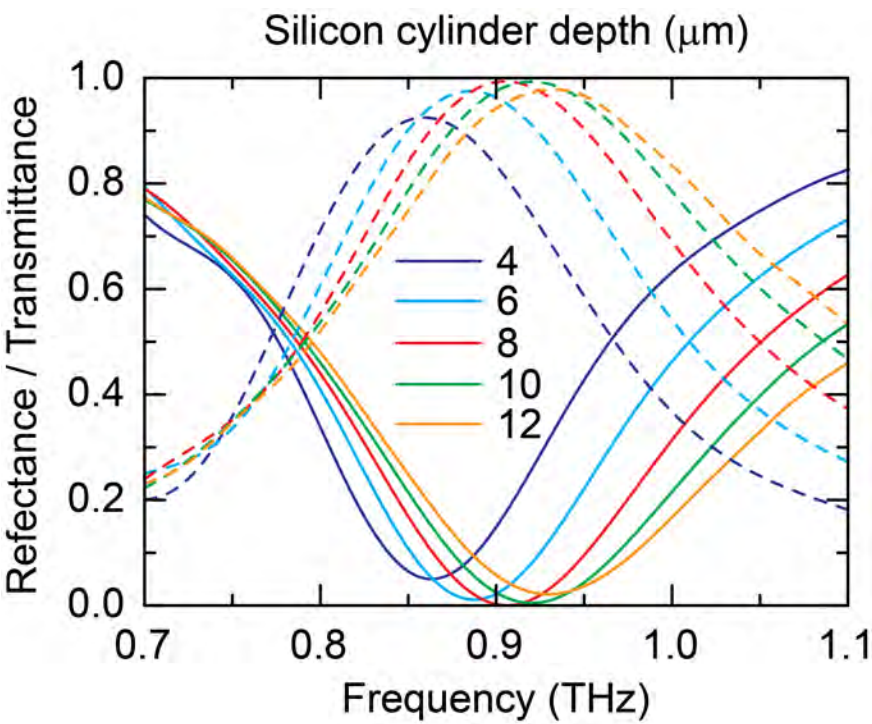


- Define metal mesh on top of the silicon substrate
- Laminate thin silicon superstrate (~20 μm thick)

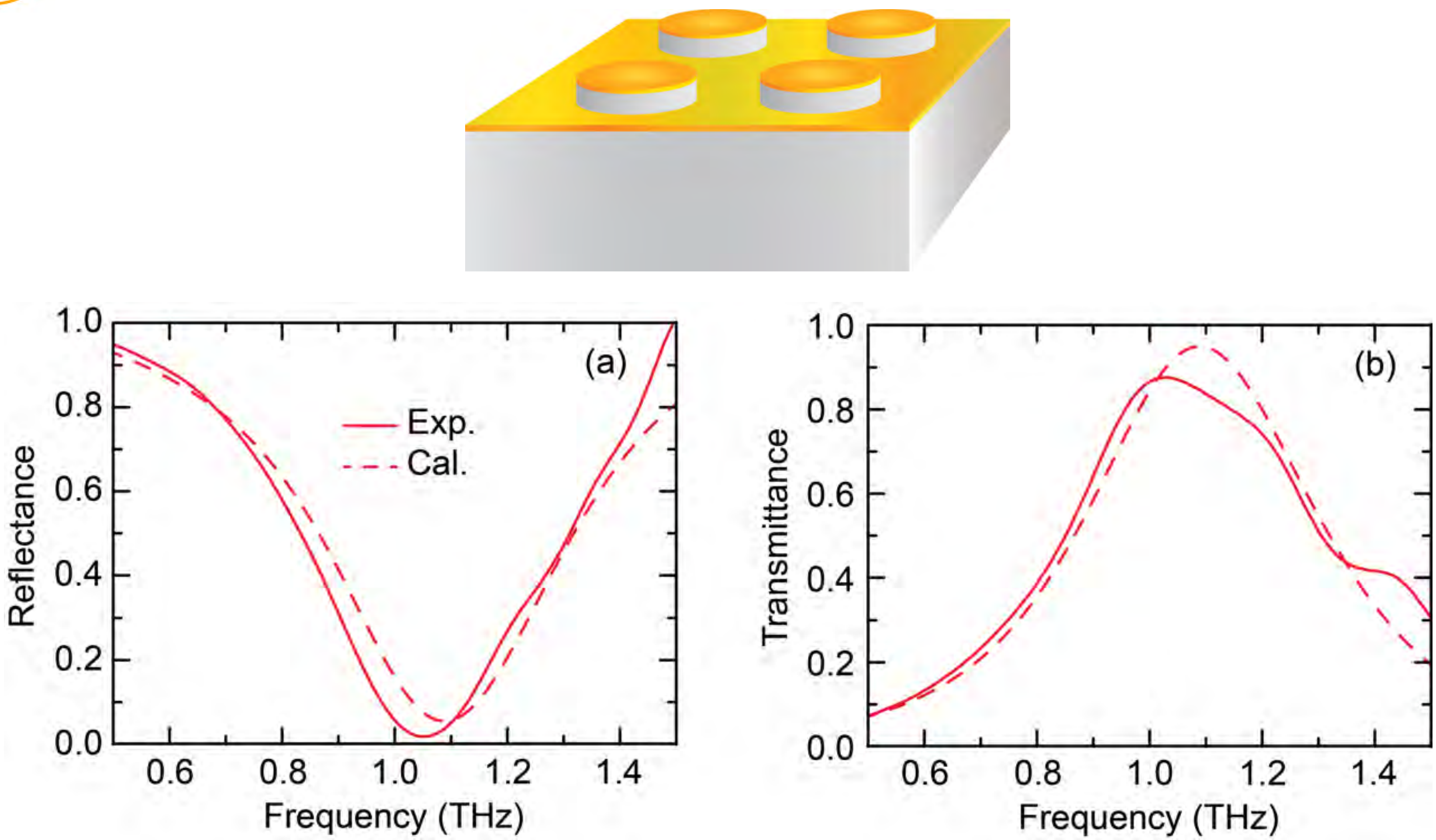
Metal-Coated Silicon Pillar Array for ARC



- **Fabrication**:
  - Photolithography to define the cylinders (diameter~50 μm, period~60 μm)
  - RIE to form the silicon cylinders (~8 μm depth)
  - (Directional) metal deposition (200 nm gold)

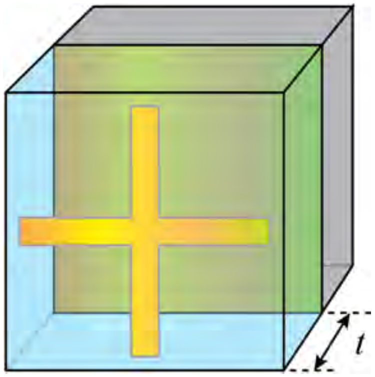


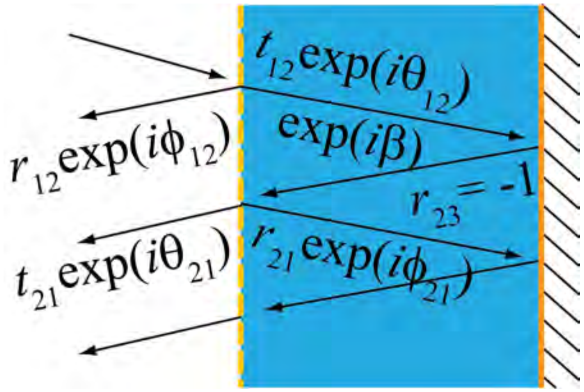
Metal-Coated Silicon Pillar Array for ARC

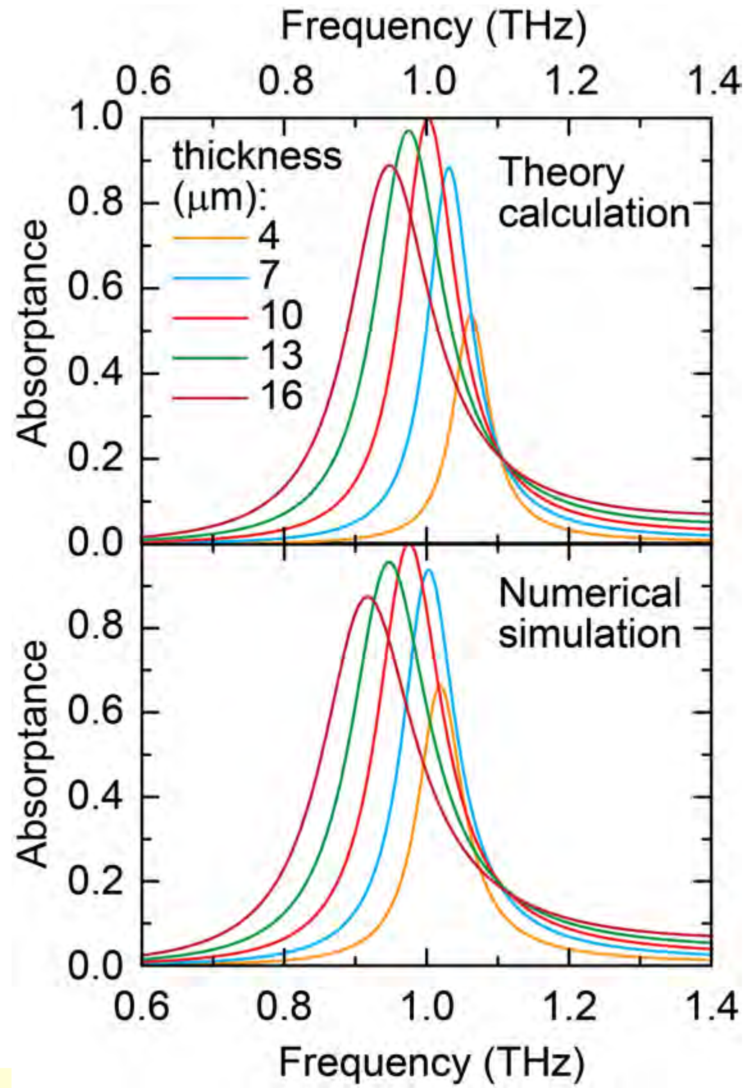


- ❑ Additional sample fabrication and measurements are going on

Metamaterial Perfect Absorbers: Trapped Light





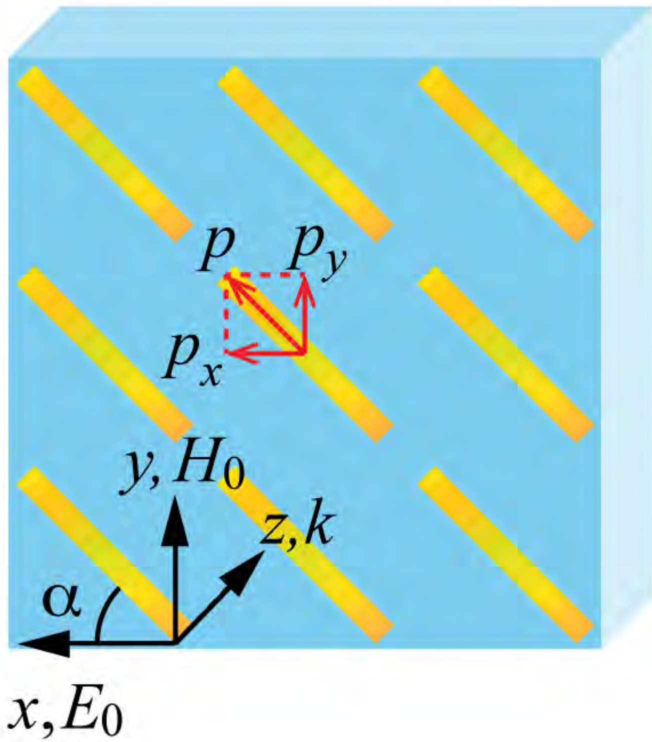


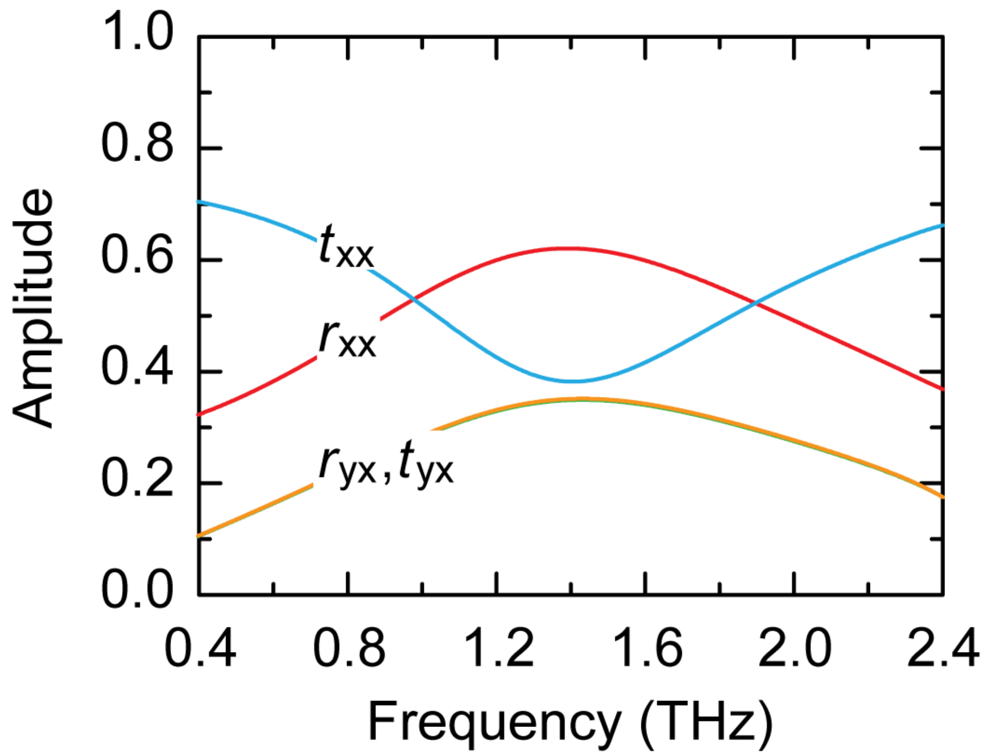
$$\tilde{r} = \tilde{r}_{12} + \frac{\tilde{t}_{12}\tilde{t}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}{1 - \tilde{r}_{21}\tilde{r}_{23}e^{i2\tilde{\beta}}}$$

- Zero transmission due to the metal ground plane
- Minimizing reflection due to destructive interference of multi-reflection
- Absorptance: $A = 1 - R$

Opt. Express **20**, 7165 (2012).
Appl. Phys. Lett. **101**, 101102 (2012).

Anisotropic Metasurfaces

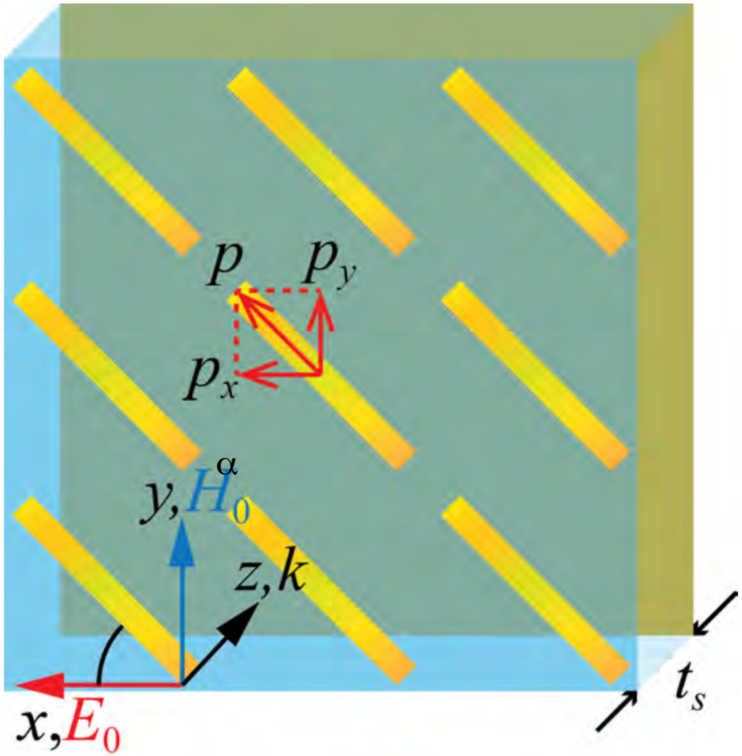




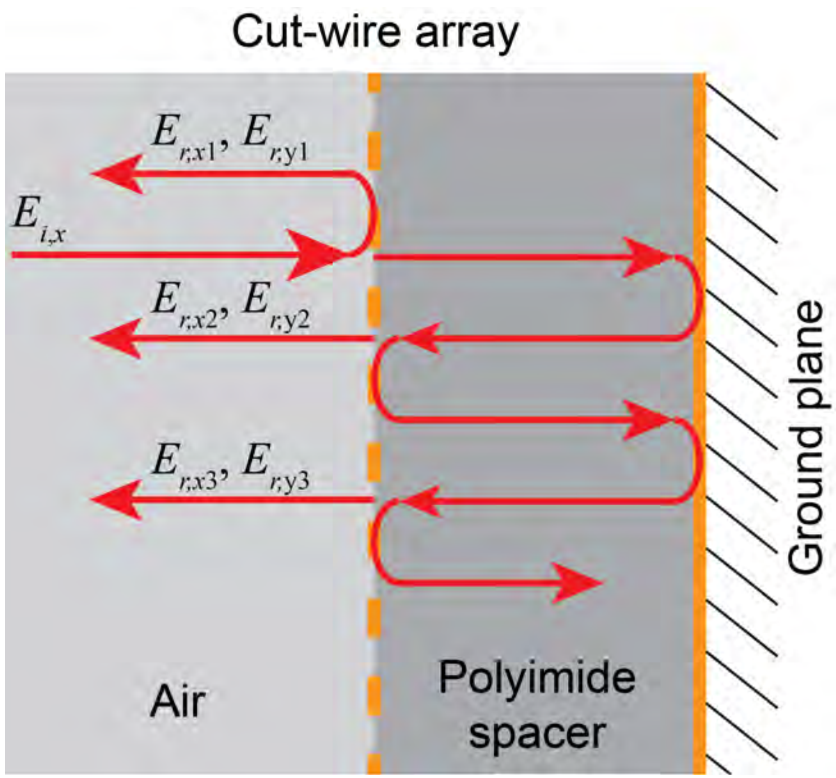
- Incident field $\boldsymbol{E}_0$ along *x*-direction (α=45°): the excited dipole ***p*** has *x*- and *y*-components
- Single-layer metasurface:: Output waves are elliptically polarized

Reflective Linear Polarization Converter

Structure schematics



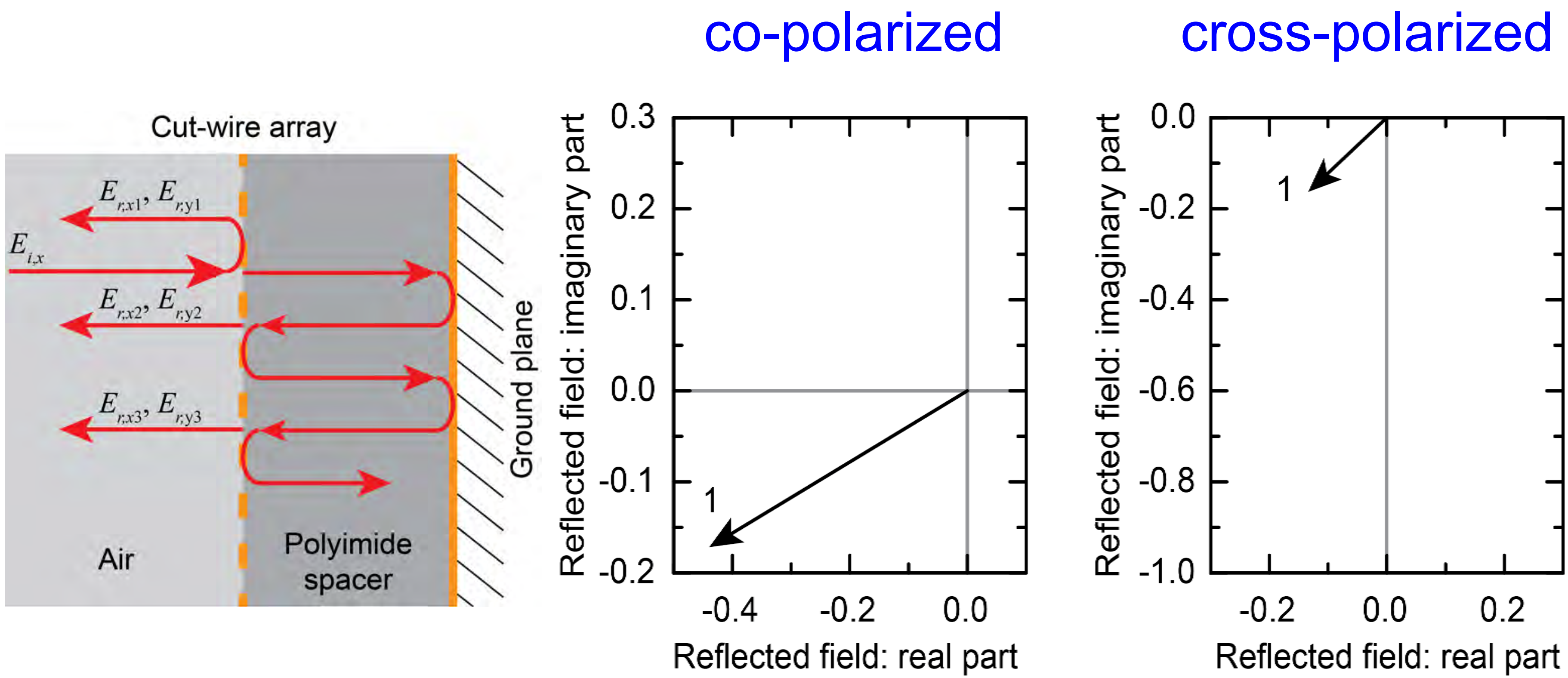
Multireflection and conversion



Science **340**, 1304 (2013).

Reflective Linear Polarization Converter

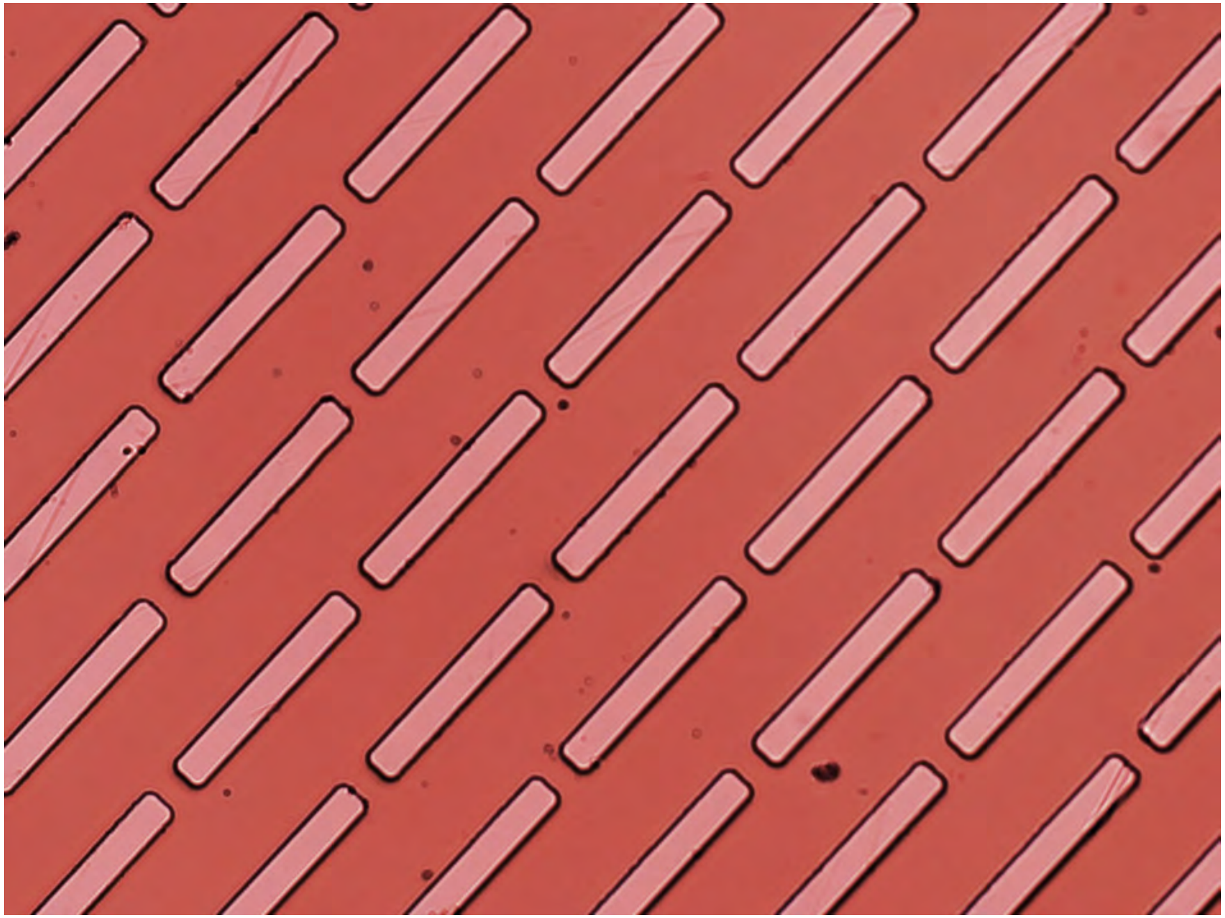
Constructive and destructive interferences



Science **340**, 1304 (2013).

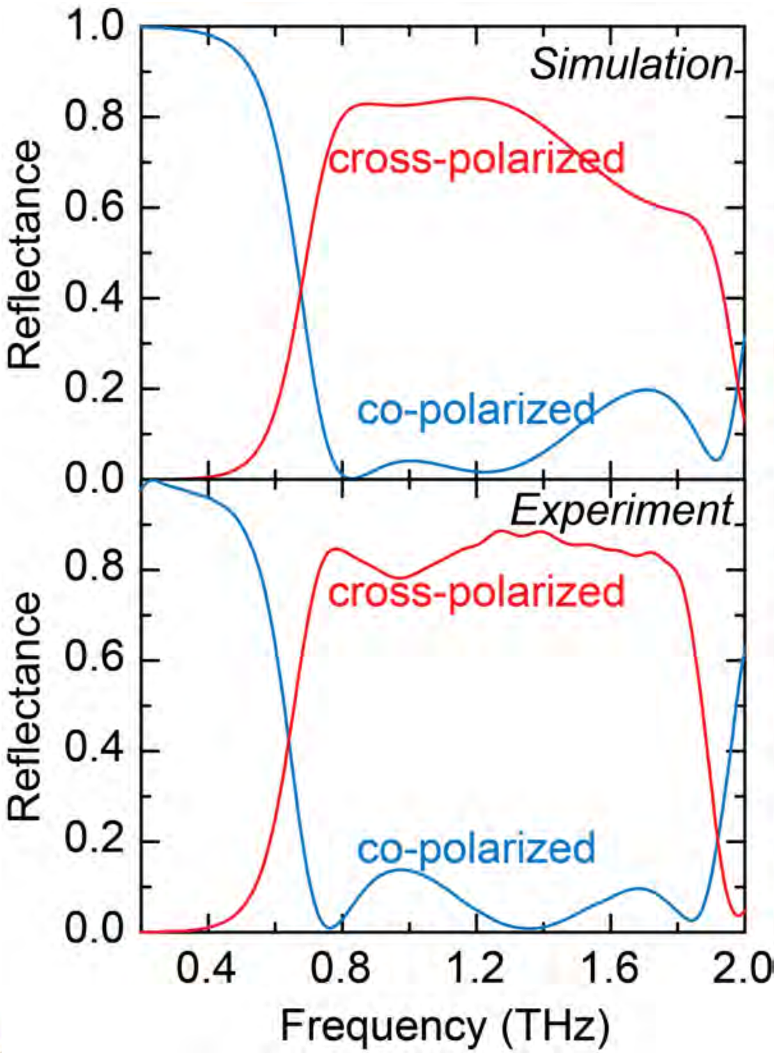
Reflective Linear Polarization Converter

Optical microscopy image



Science **340**, 1304 (2013).

Reflective Linear Polarization Converter



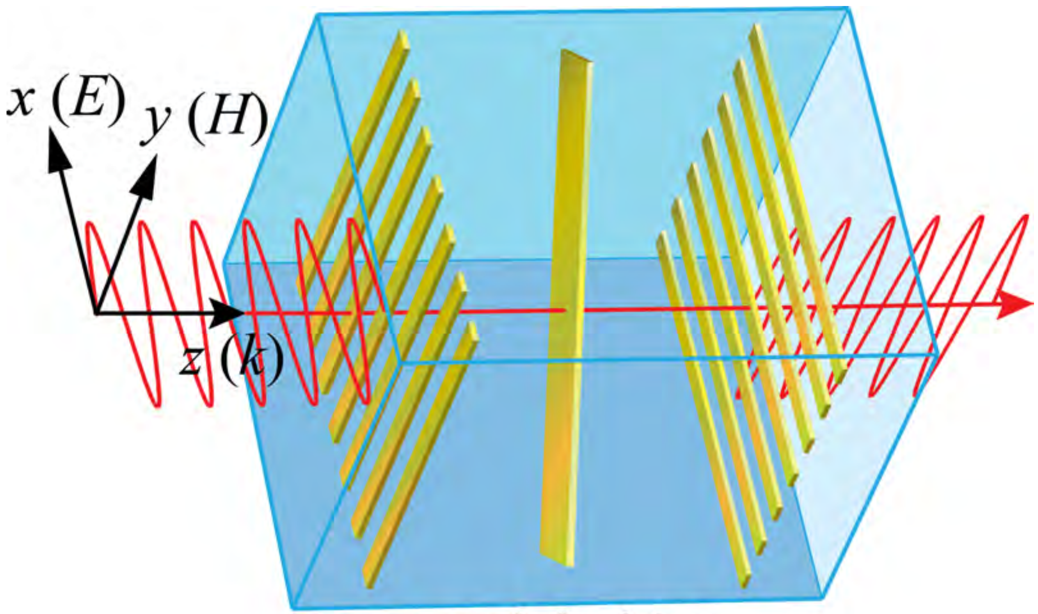
Simulations and experiments

- Device thickness 33 μm
- Operation center wavelength 230 μm
- Co-polarized reflection is minimal
- Cross-polarized reflectance is more than 80%
- Broadband: destructive interference at multiple frequencies

Science **340**, 1304 (2013).

Transmission Linear Polarization Converter

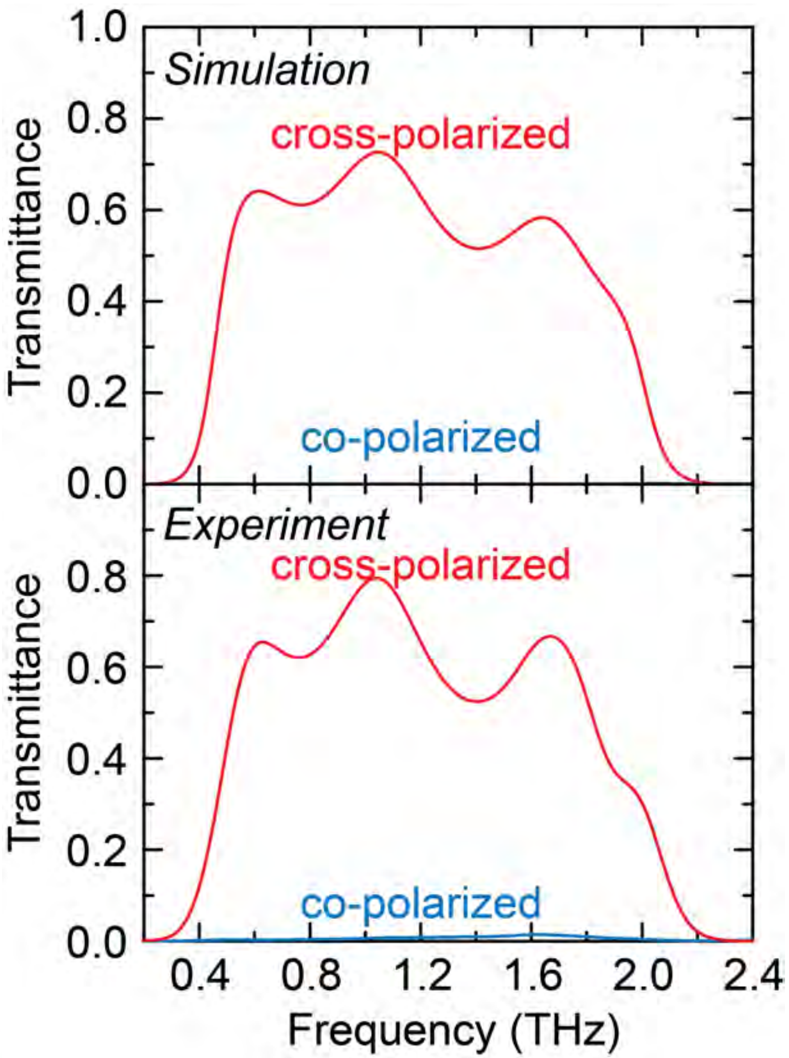
Structure schematic



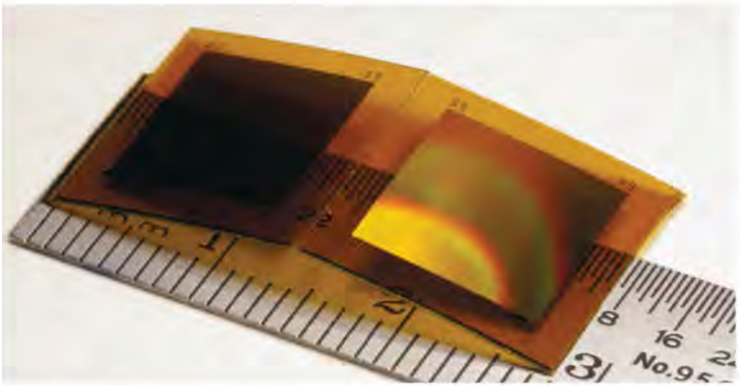
Optical microscopy image

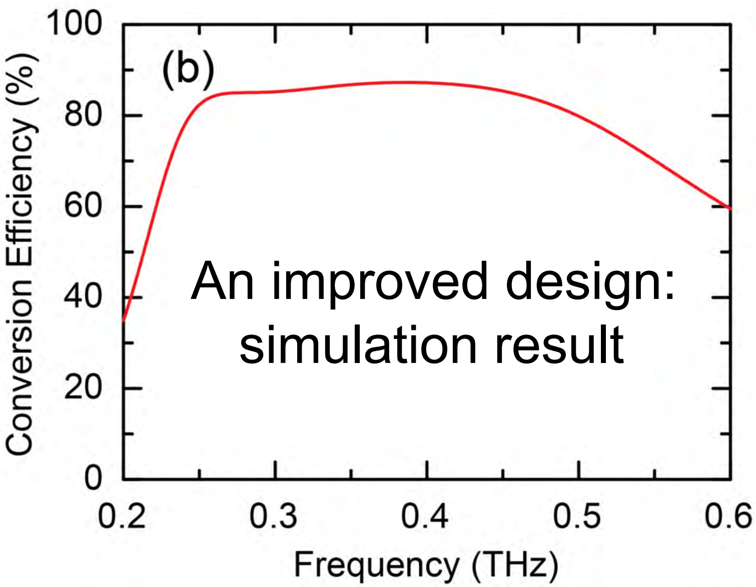
Science **340**, 1304 (2013).

Transmission Linear Polarization Converter



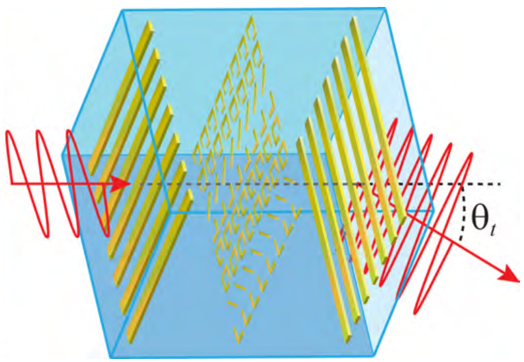
Fabricated thin film device

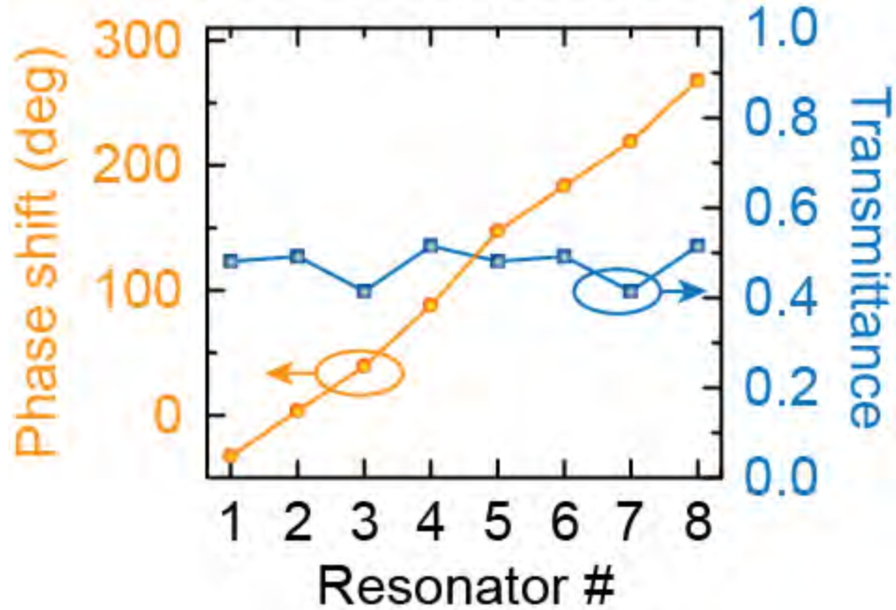




Science **340**, 1304 (2013).

Anomalous Refraction: Generalized Snell's Law



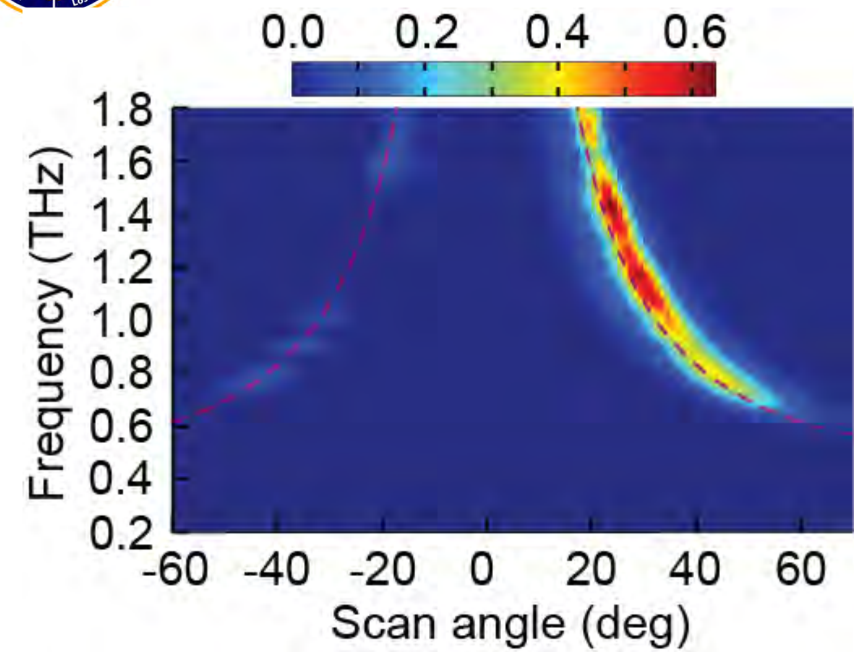


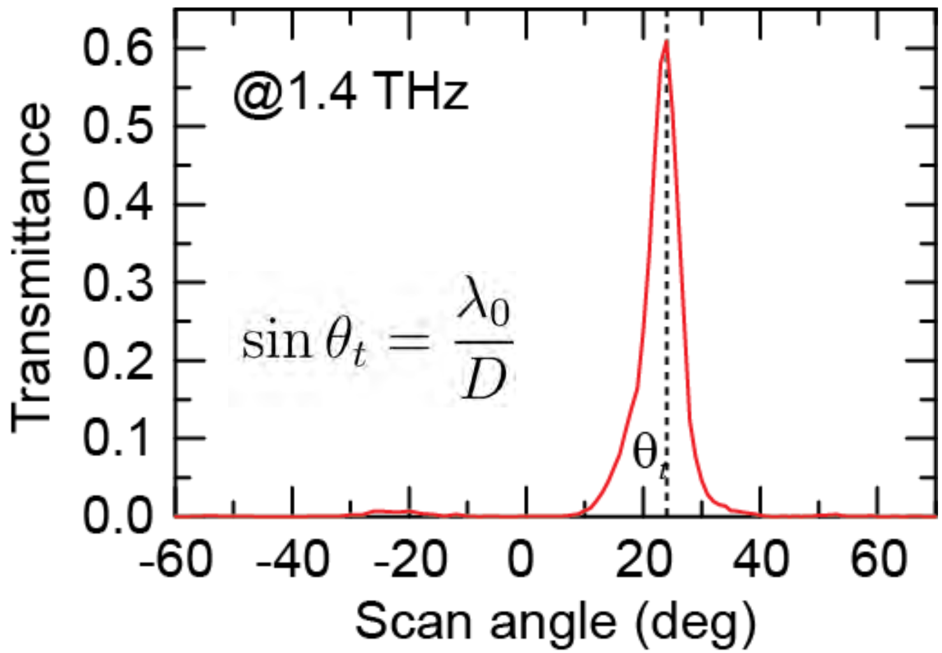
$$\sin\theta_t - \sin\theta_i = \frac{\lambda_0}{2\pi}\frac{d\Phi}{dx}$$

- 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

Science **340**, 1304 (2013).

Near-Perfect Anomalous Refraction: Exp.

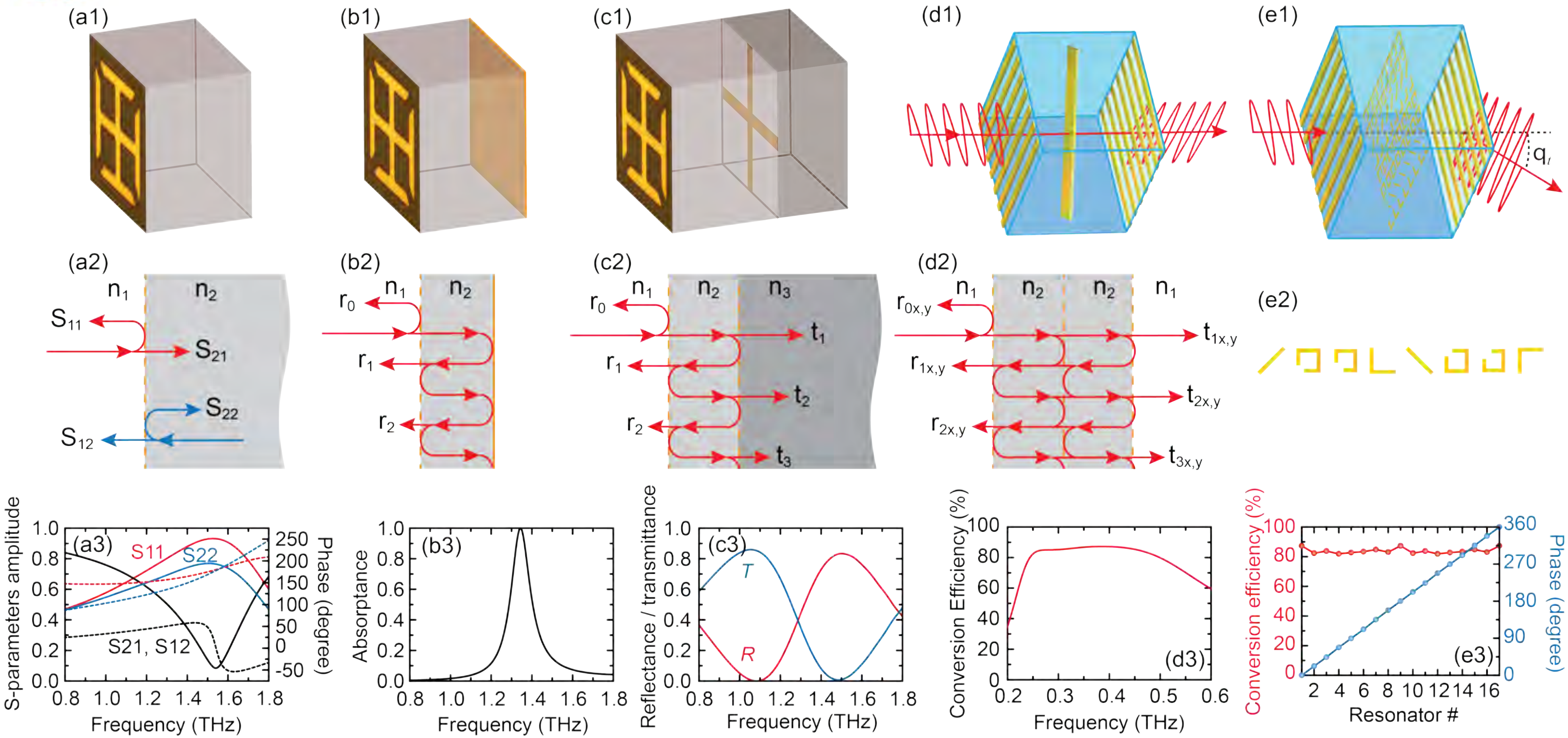


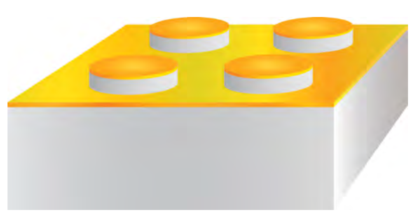


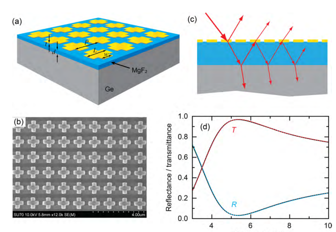
- At a specific frequency, the "refraction angle" is determined by periodicity
- At 1.4 THz, the anomalous refraction carries 60% of the incident power
- Measure the cross-polarized transmission *vs.* scanning angle
- Operate over a broad bandwidth

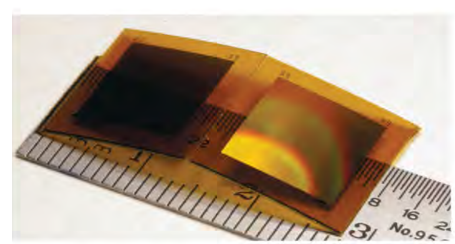
Science **340**, 1304 (2013).

Summary of Few-Layer Metamaterials (Metasurfaces)



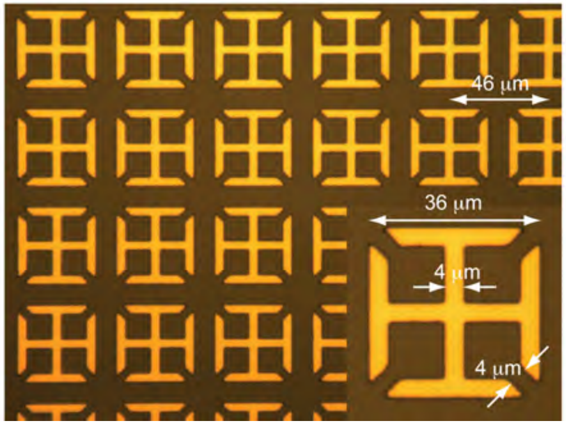




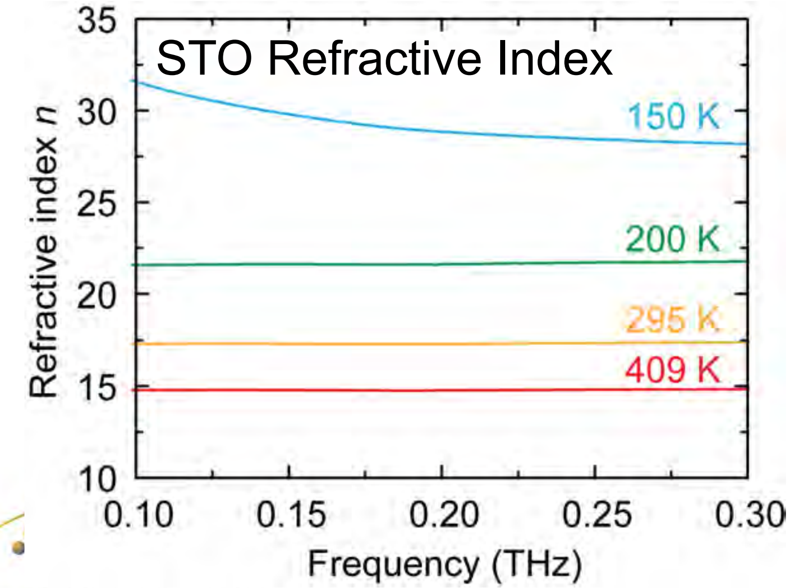


Thermally Tunable Metasurface Resonance

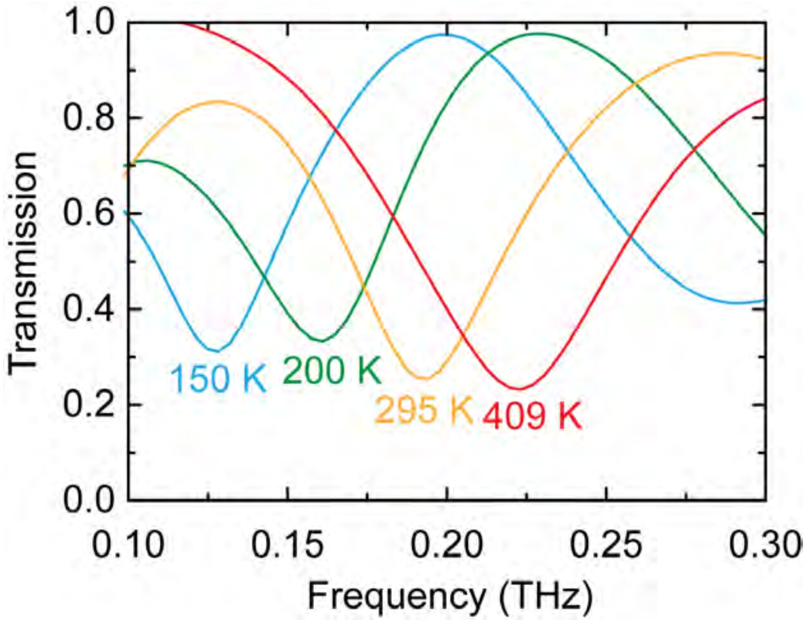
Strontium Titanate Substrate



$$\omega_0 = 1/\sqrt{LC} \sim 1/n$$



- ❑ <u>Fabrication:</u> photolithography, e-beam metal deposition, and lift-off process
- ❑ <u>Substrate:</u> silicon, gallium arsenide, etc.
- ❑ Resonance frequency tuning using strontium titanate (STO) substrate



Opt. Lett. **36**, 1230 (2011).

Optically Switchable THz Metamaterials

GaAs substrate

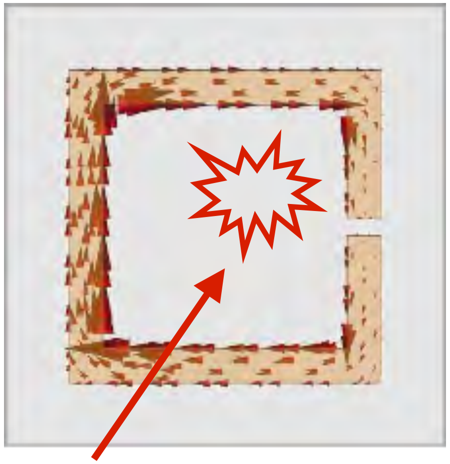
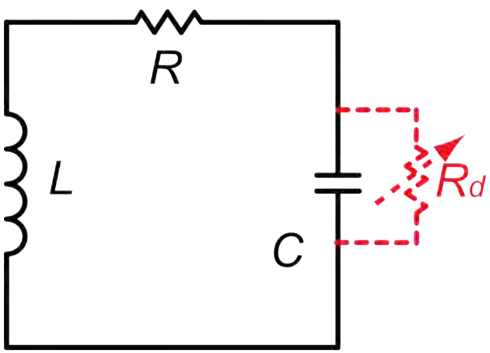
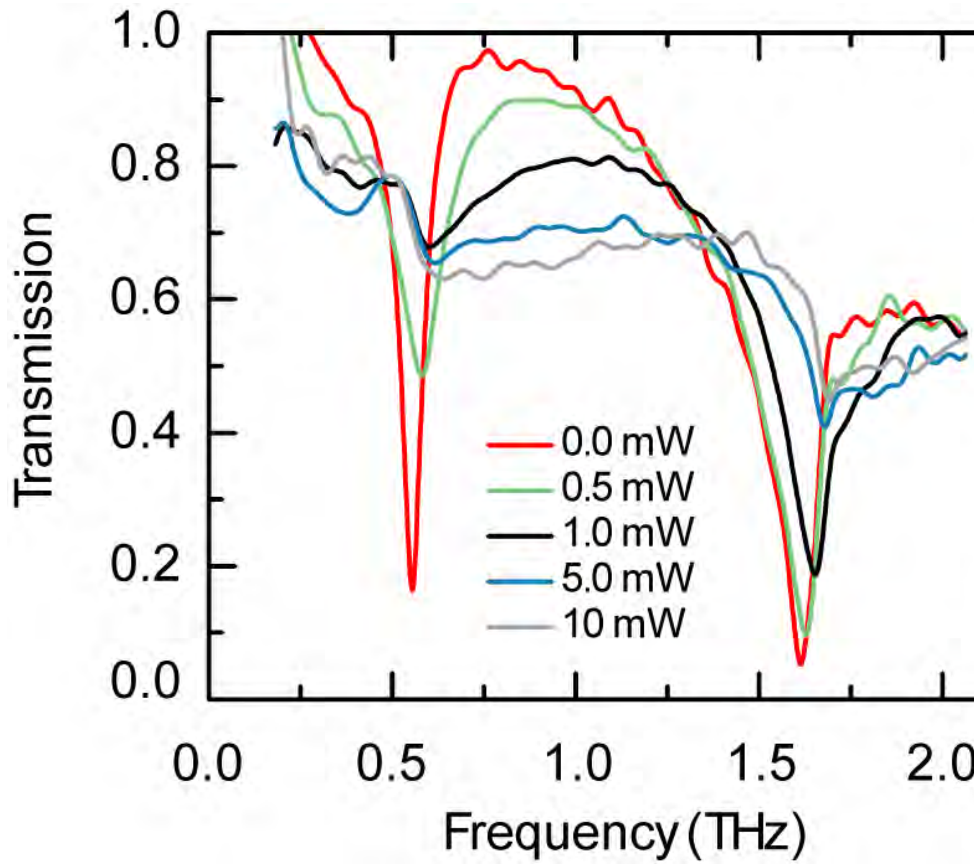


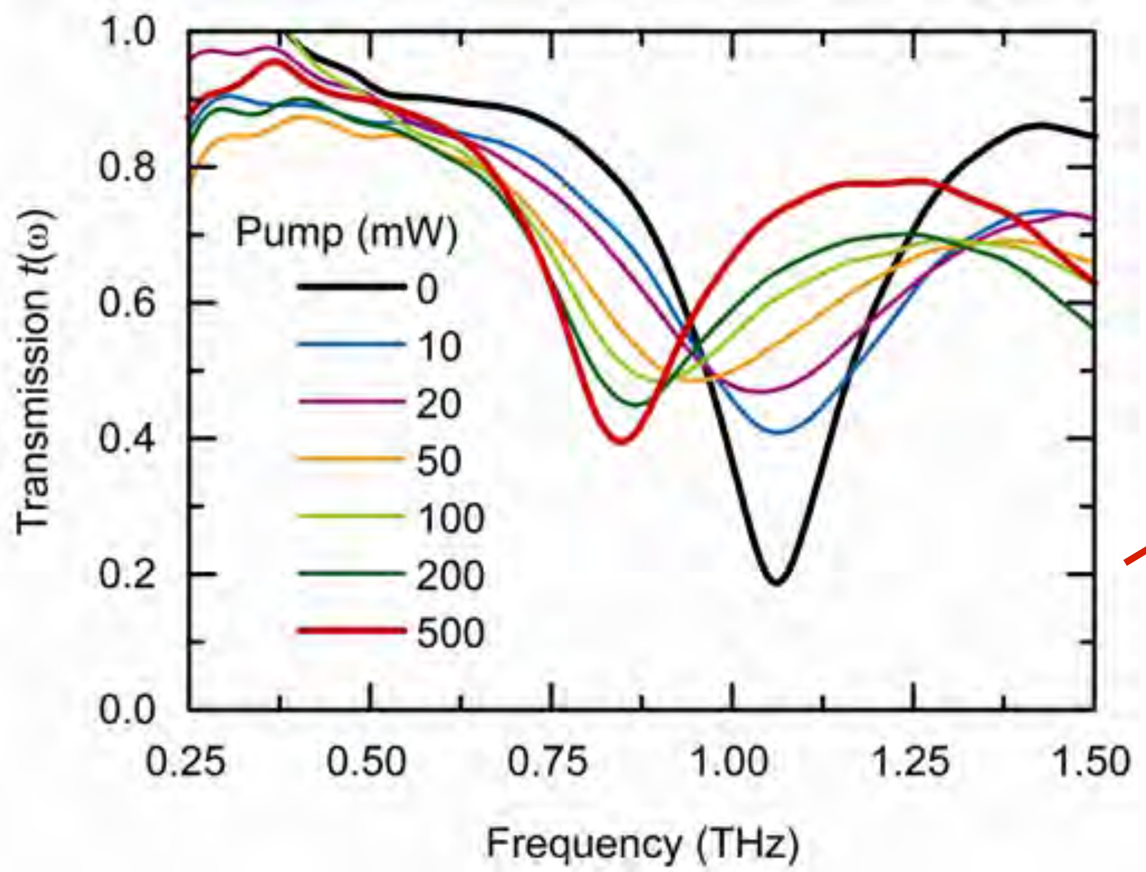
photo-excitation

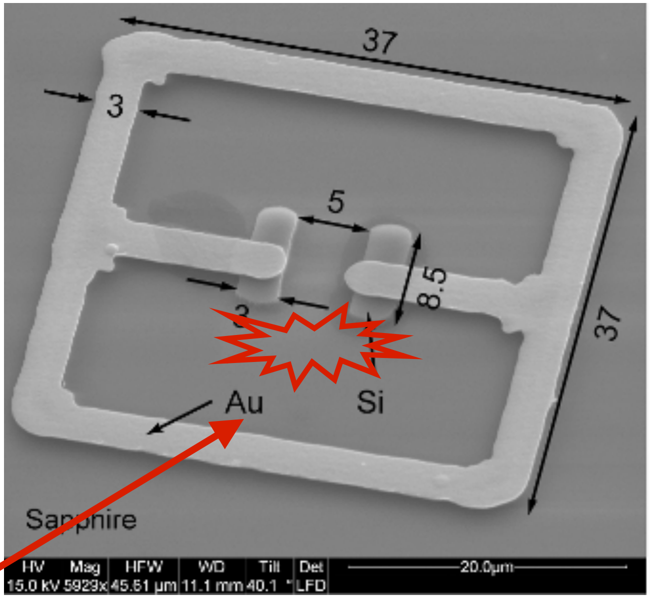


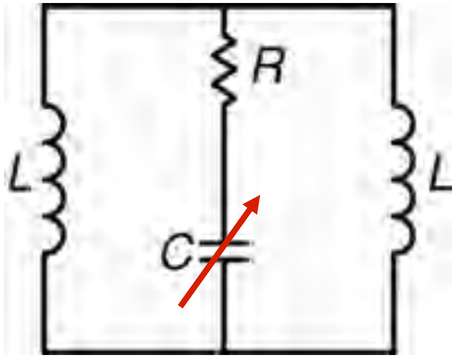


Phys. Rev. Lett. **96**, 107401 (2006).
Opt. Lett. **32**, 1620 (2007).

Optically Frequency Tunable THz Metamaterials

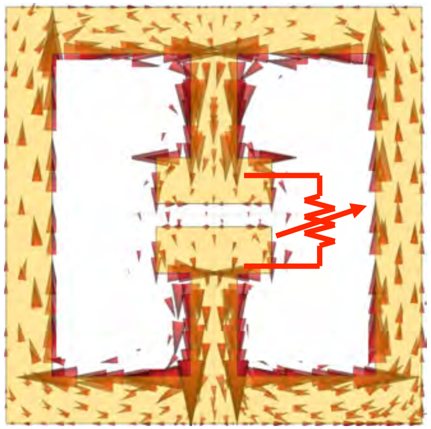


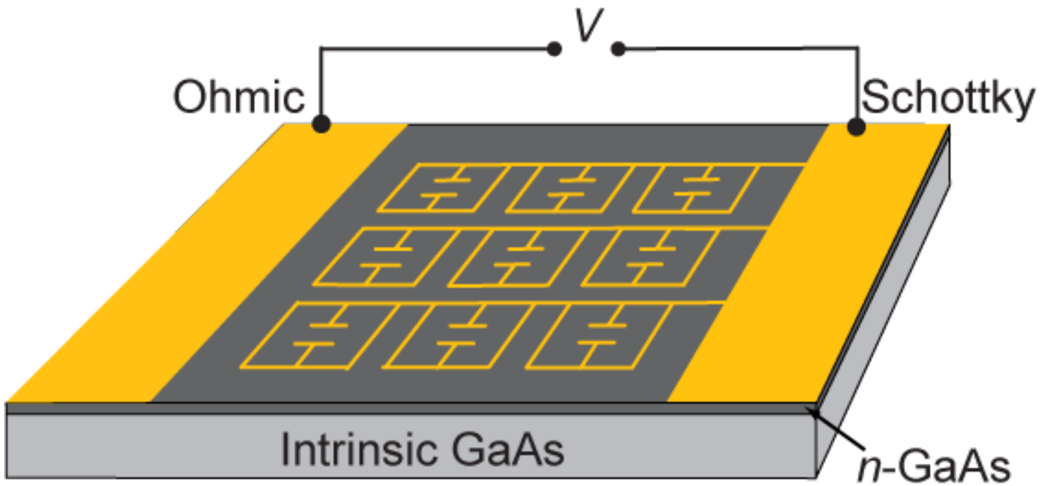


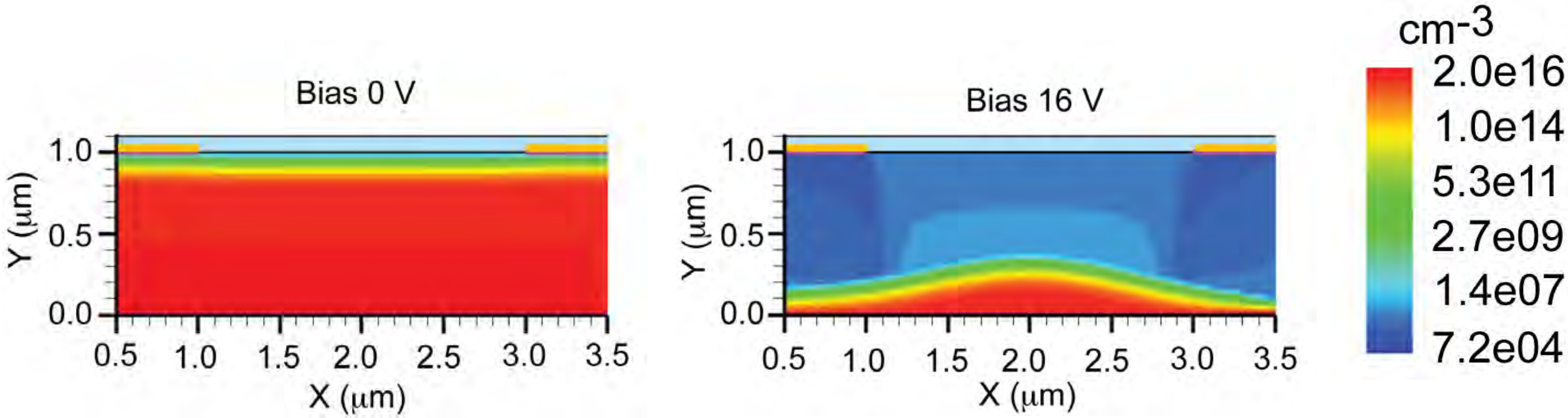


Nat. Photon. **2**, 295 (2008).

Electrically Switchable THz Metamaterials

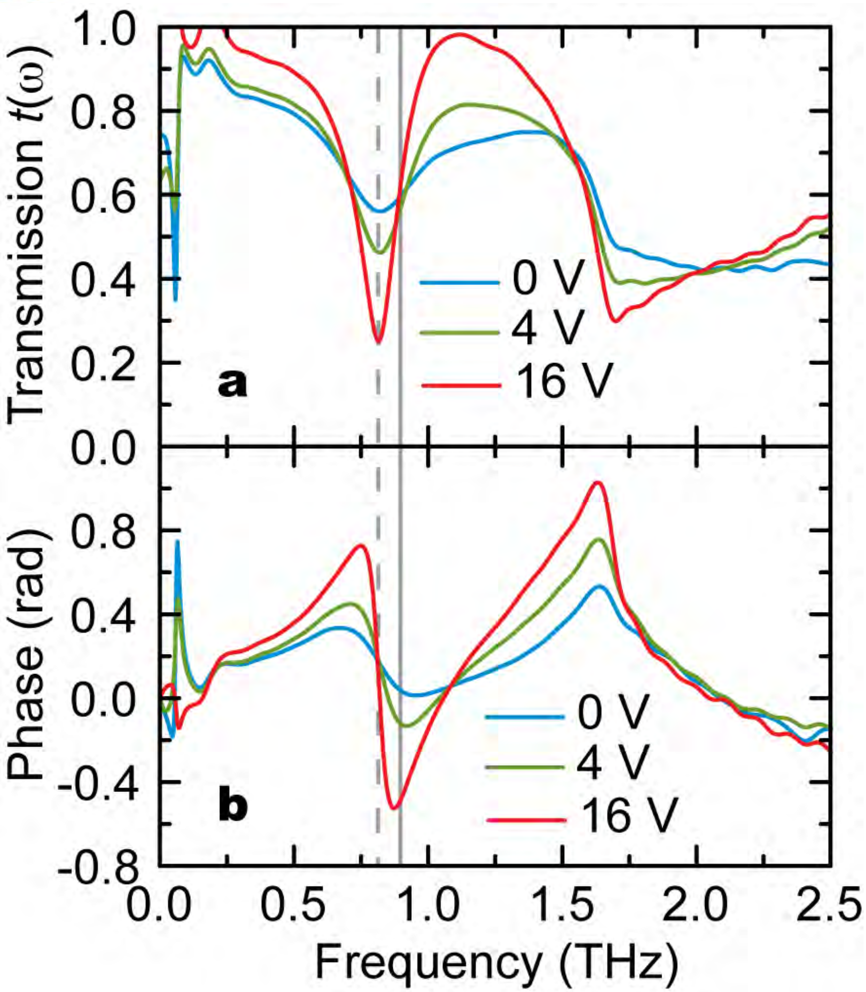






Nature **444**, 597 (2006).

Amplitude and Phase Modulations



- Power modulation depth:

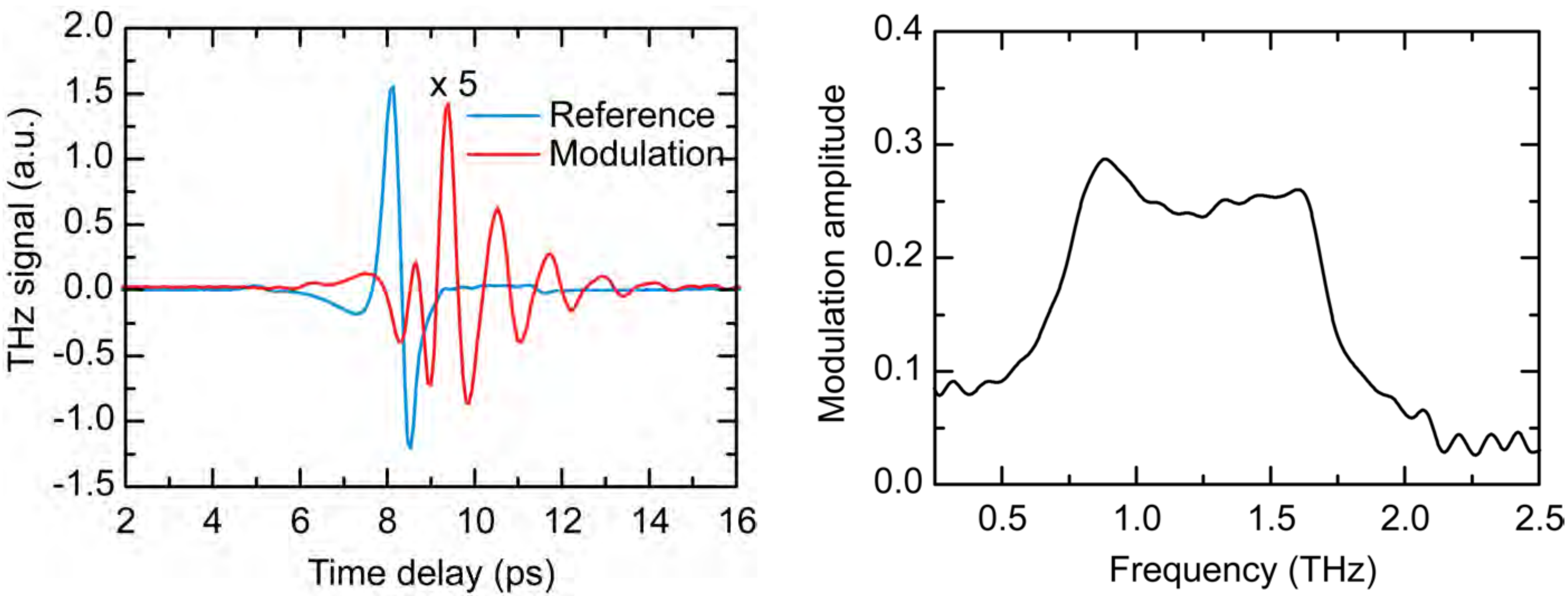
  $M = (T_{0V} - T_{16V}) / T_{0V} = 80\%$,

  or amplitude modulation depth 55%
- Phase modulation $\Delta\varphi = \pi/6$
- Amplitude and phase modulations are correlated
- In THz-TDS, both amplitude and phase contribute to the modulation signal – broadband modulation

$$|\Delta\tilde{t}(\omega)| = \left| t_{V1}(\omega)e^{i\phi_{V1}(\omega)} - t_{V2}(\omega)e^{i\phi_{V2}(\omega)} \right|$$

Nat. Photon. **3**, 148 (2009).

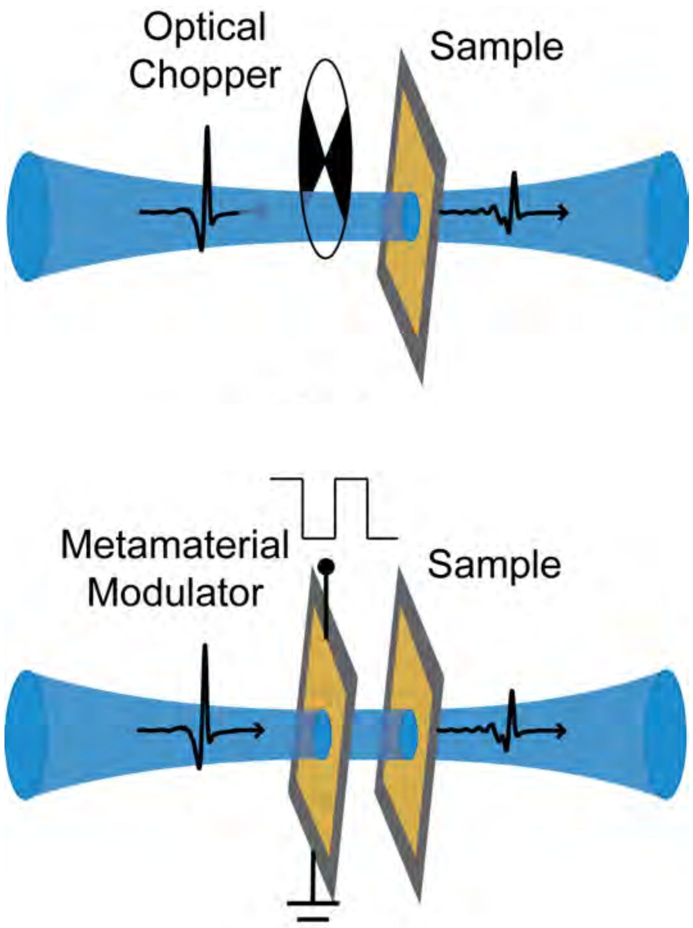
Broaden the Modulation Bandwidth

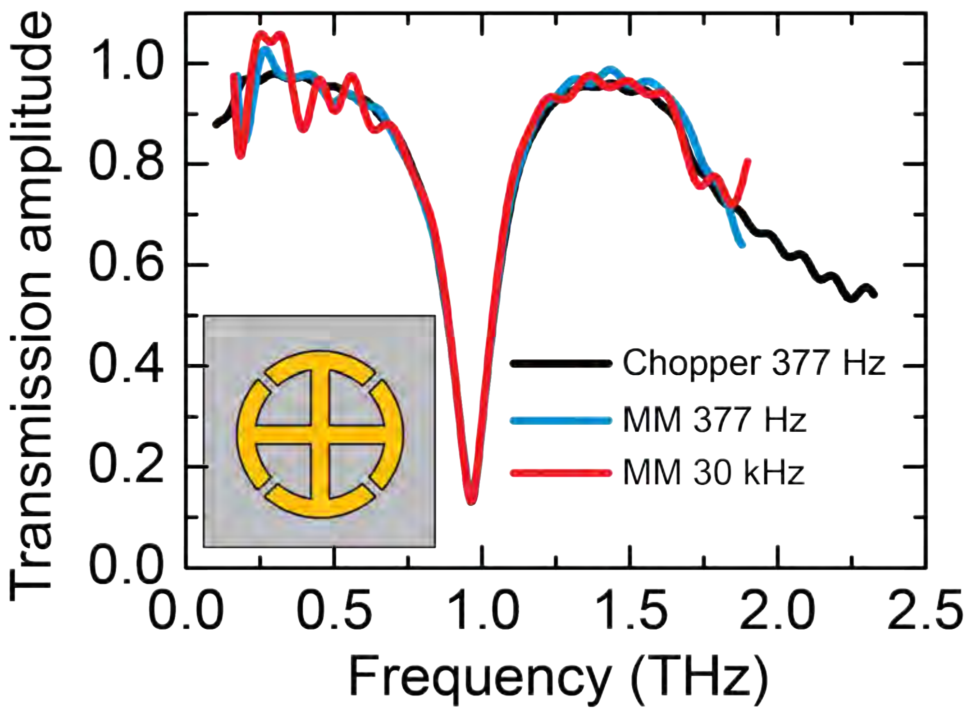


<u>Bandwidth:</u> roughly between the two resonances

Nat. Photon. **3**, 148 (2009).

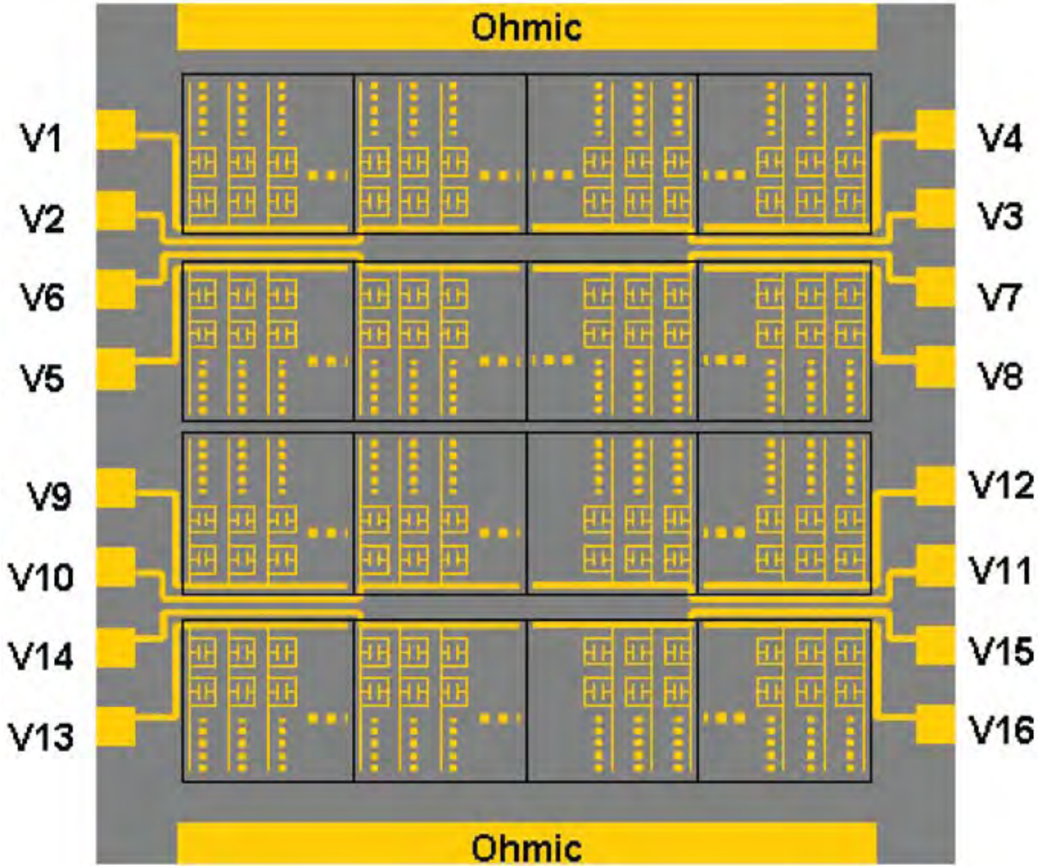
Serving as the Optical Chopper in THz-TDS





Nat. Photon. **3**, 148 (2009).

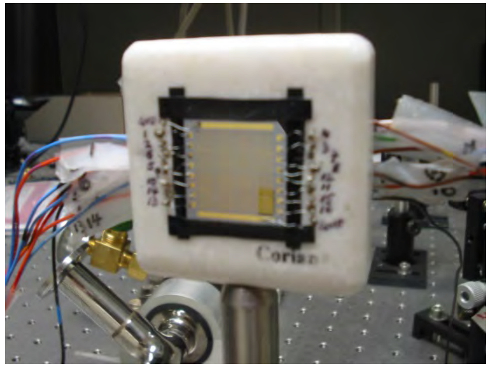
THz Metamaterial Spatial Light Modulator

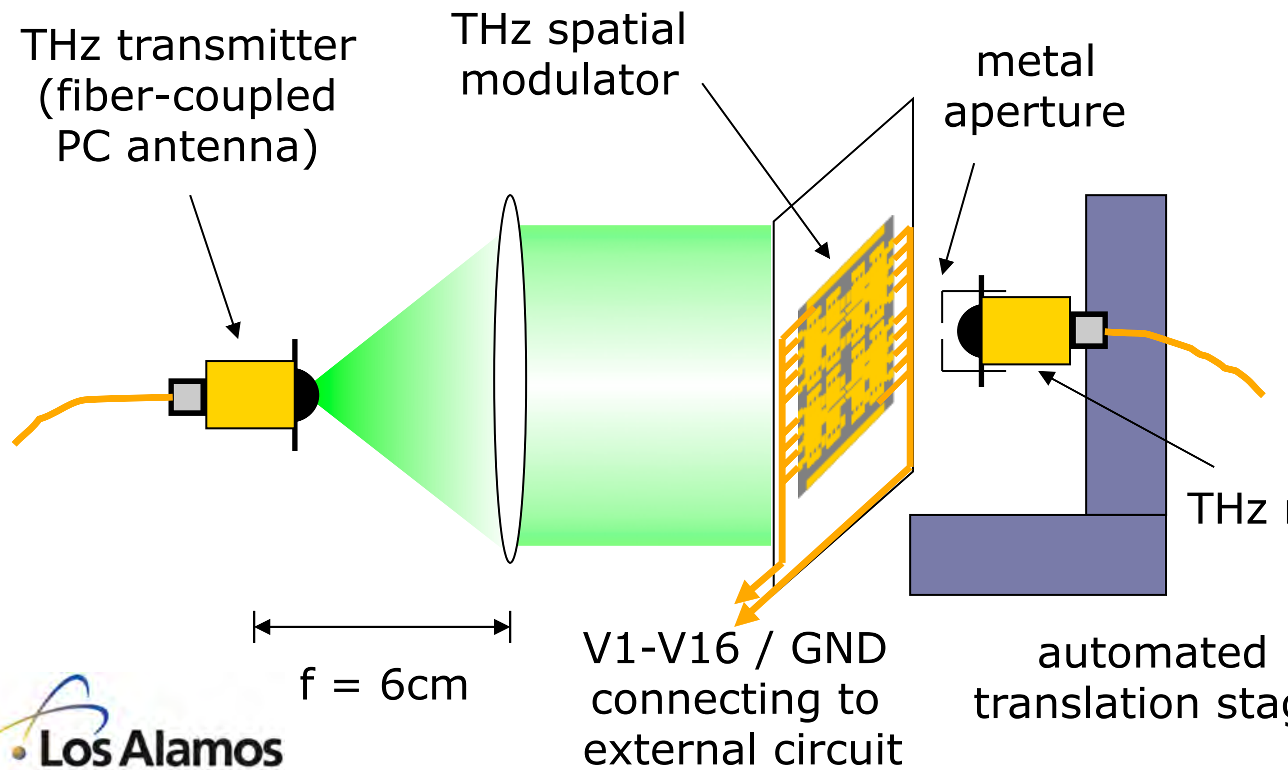


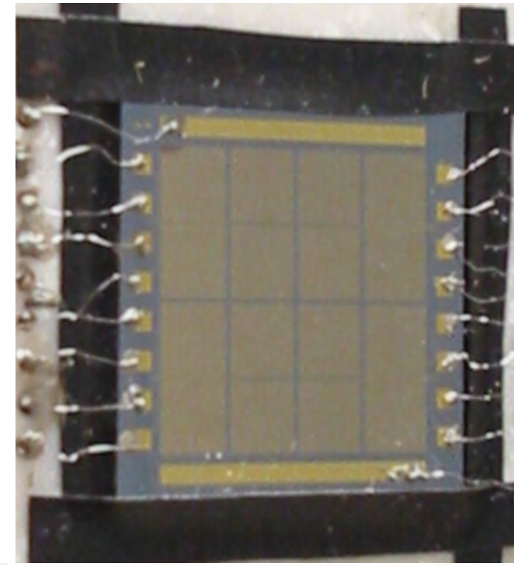
4 × 4 pixels, each pixel is independently controlled by voltage bias

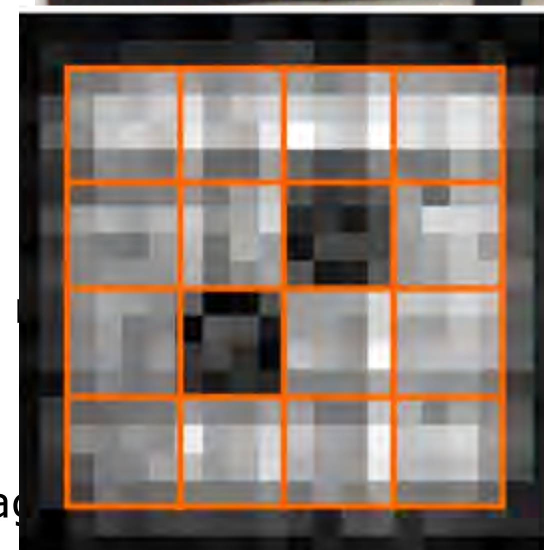
Appl. Phys. Lett. **94**, 213511 (2009).

THz Metamaterial Spatial Light Modulator



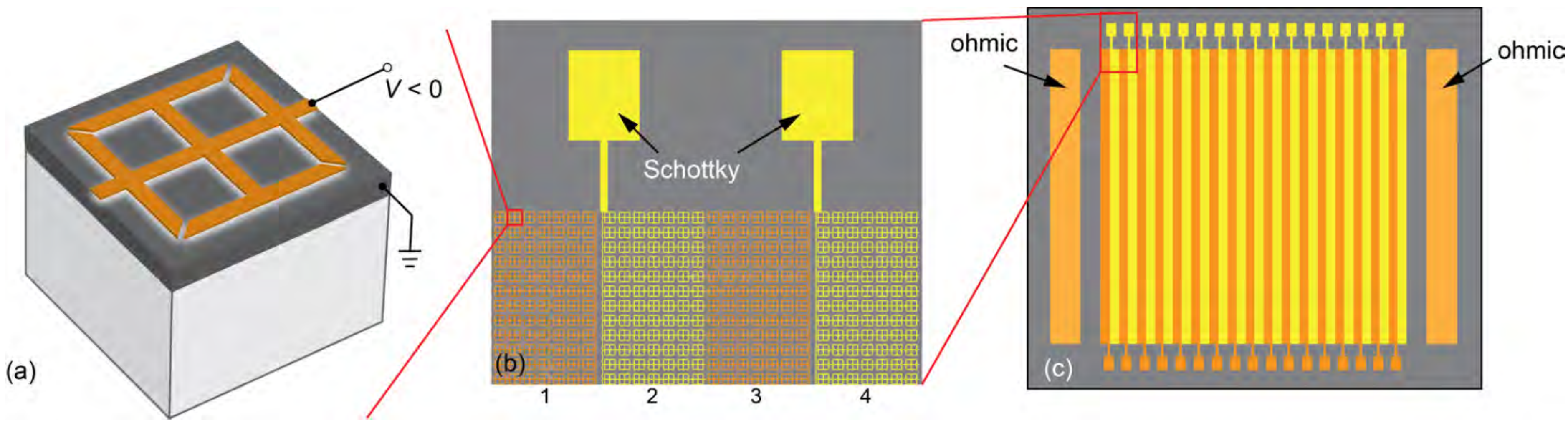






Appl. Phys. Lett. **94**, 213511 (2009).

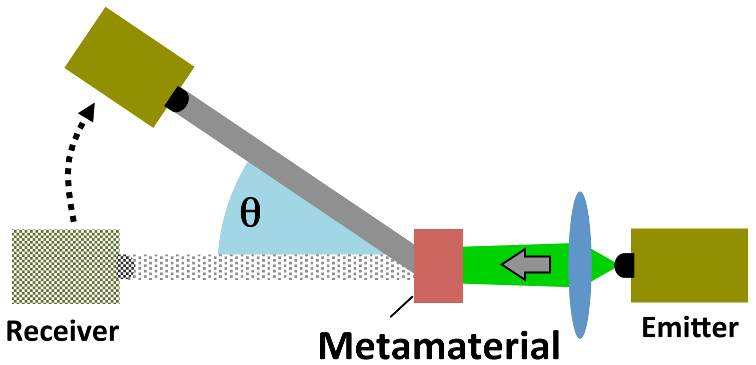
Active Metamaterial Gratings

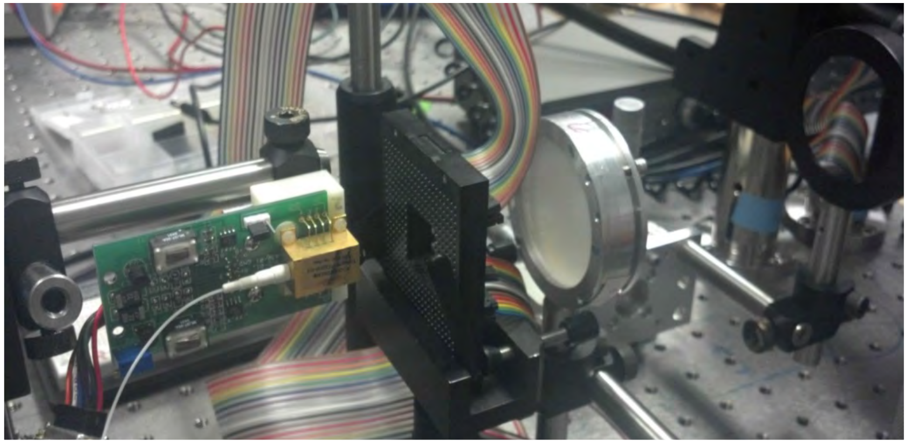


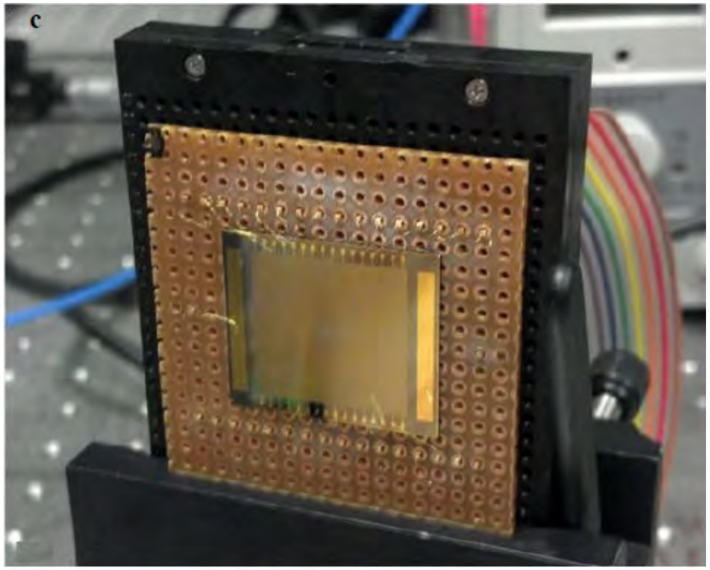
Appl. Phys. Lett., **104**, 091115 (2014).

Active Metamaterial Gratings -- Experiment

- Broadband THz system
- Collimated beam incident on metamaterial surface
- Detect transmitted beam at different angles

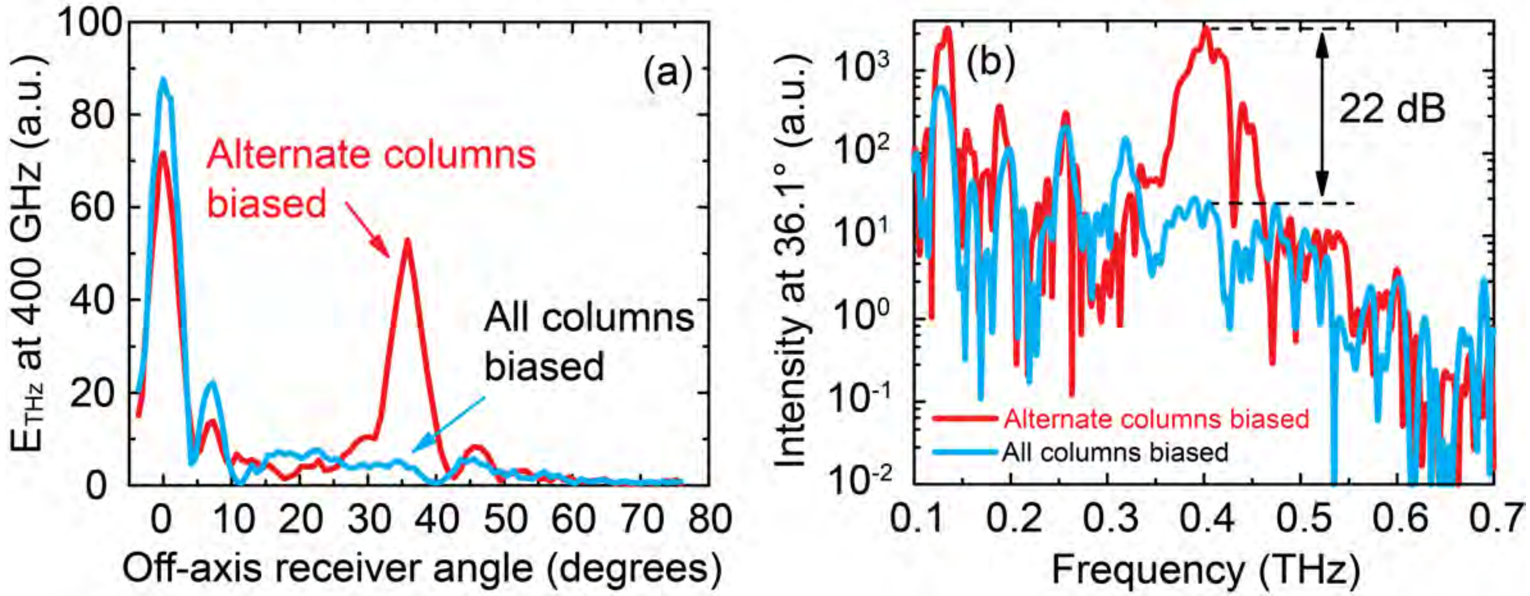




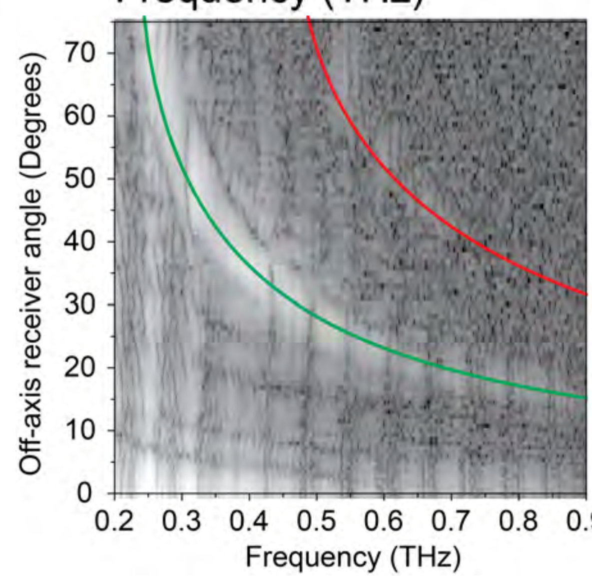


Appl. Phys. Lett., **104**, 091115 (2014).

Active Metamaterial Gratings -- Results



- Switchable grating diffraction
- 22 dB modulation depth
- Broadband operation
- Background-free in principle

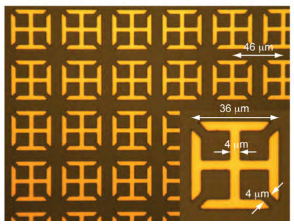


Appl. Phys. Lett., **104**, 091115 (2014).

Summary of Active Metamaterials/Metasurfaces

- Switchable and frequency tunable resonant response in single-layer metasurfaces by active material integration and external excitation

Strontium Titanate Substrate



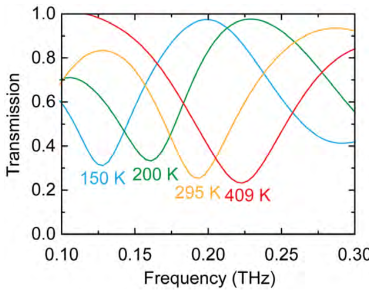
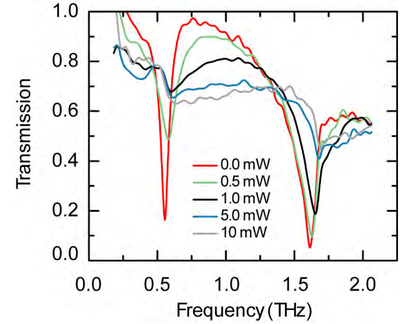
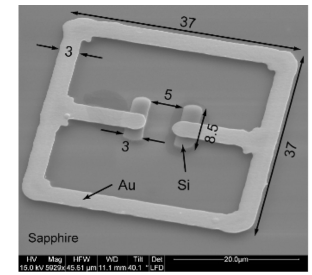
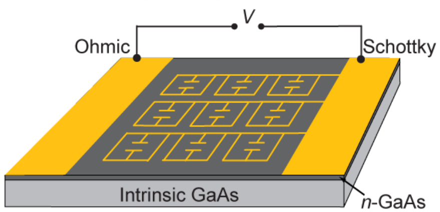


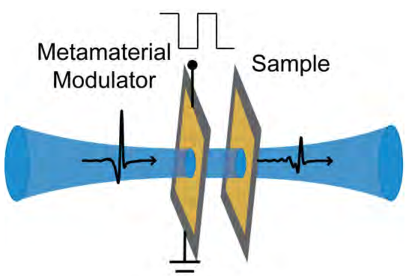
photo-excitation

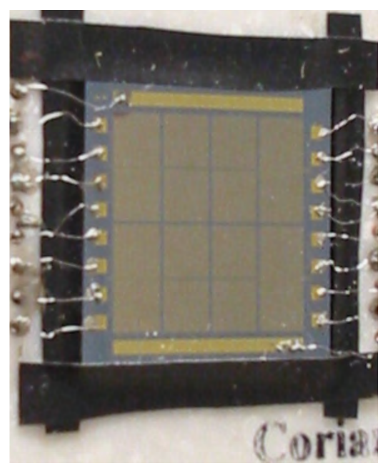


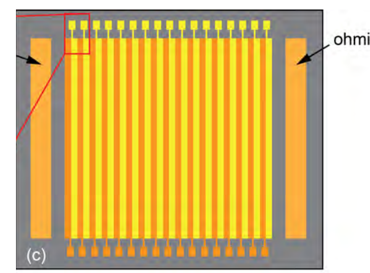


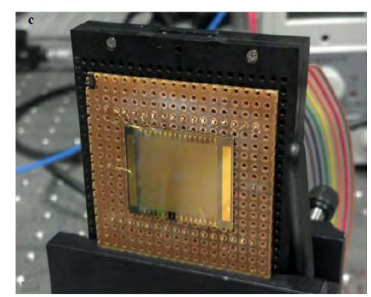
- Electrically switchable metasurface as THz signal modulator for imaging and communication











Acknowledgements

- **Postdocs, visiting students and scholars**
  Li Huang, Nathaniel Grady, Jiangfeng Zhou, Ranjan Singh, Dibakar Roy Chowdhury, Yong Zeng, Matthew Reiten, Jane Heyes

- **Collaborators**
  LANL: Abul Azad, Quanxi Jia, Diego Dalvit, Stuart Trugman, Toni Taylor
  BC/Duke: Willie Padilla
  BU/UCSD: Richard Averitt
  Rice: Daniel Mittleman
  SNL: Igal Brener
  UAH: Junpeng Guo
  OSU: Weili Zhang, John O'Hara
  UCB: Xiang Zhang
  Nankai: Shuqi Chen, Jianguo Tian
  Tianjin: Jianqiang Gu, Weili Zhang

- **Funding and Support:**