LA-UR- 11-03462

Approved for public release; distribution is unlimited.

Title: Recent Developments in Terahertz Metamaterials

Author(s): Hou-Tong Chen

Intended for: Invited talk @ 2011 International Symposium on Microwave/Terahertz Science and Applications (MTSA 2011)
Nanjing, China; 06/19-22/2011
Seminar @ Zhejiang University
Hangzhou, China; 06/24/2011

Los Alamos
NATIONAL LABORATORY
EST.1943

Recent Developments in Terahertz Metamaterials

Hou-Tong Chen
Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Abstract

Metamaterials are a new class of man-made effective media that exhibit exotic electromagnetic properties which are difficult or impossible in naturally occurring materials. It is most likely that practical application of metamaterials will first happen in the underdeveloped THz frequency range. In this talk I will present a few recent developments in THz metamaterials from our group at LANL, which include: 1) actively and dynamically switchable and tunable hybrid THz metamaterials incorporated with semiconductors; 2) thermally and optically tunable high temperature superconducting THz metamaterials; and 3) metamaterial antireflection and perfect absorption. Both the experimental results and underlying mechanism will be presented.

Recent Developments in Terahertz Metamaterials

Hou-Tong Chen

Center for Integrated Nanotechnologies
Los Alamos National Laboratory
Los Alamos, New Mexico, USA

chenht@lanl.gov

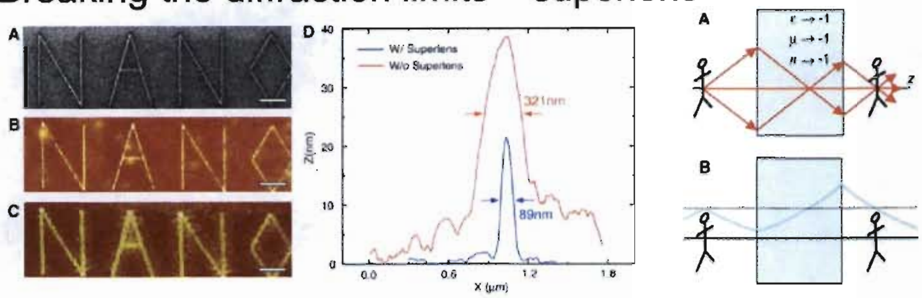
2011 International Symposium on Microwave/Terahertz Science and Applications
Nanjing, China

Outline

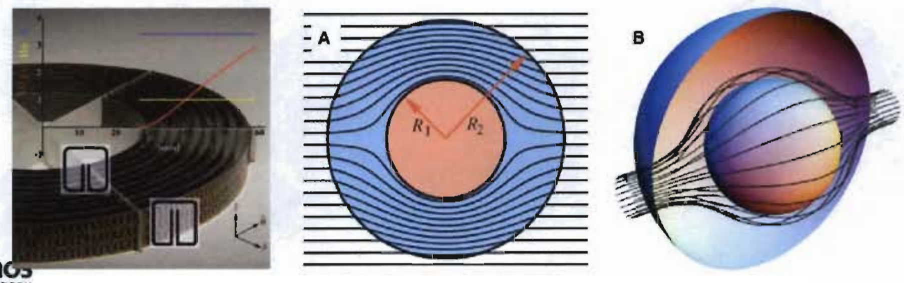
- Introduction
- Actively and dynamically tunable THz metamaterials
  - Hybrid semiconductor metamaterials
  - Tuning through photoexcitation, voltage, temperature
  - Device applications
- High temperature superconducting metamaterials
  - Temperature tuning
  - Optical tuning
  - Theoretical investigation
- Metamaterials as surface coatings
  - Antireflection coatings
  - Perfect absorbers
  - Theory
- Summary

Emergent Phenomena in Metamaterials

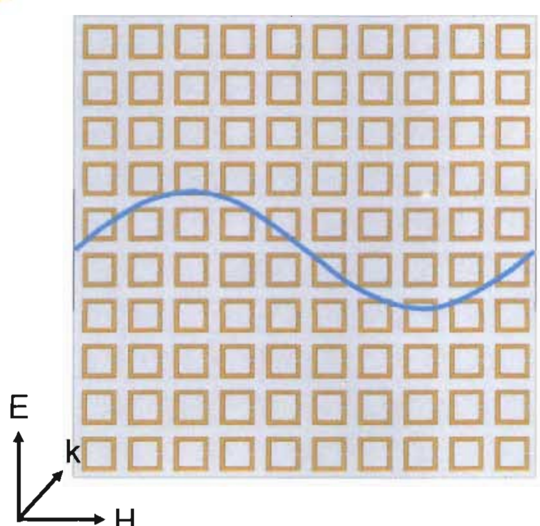
- Breaking the diffraction limits – superlens

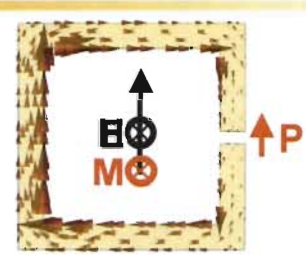


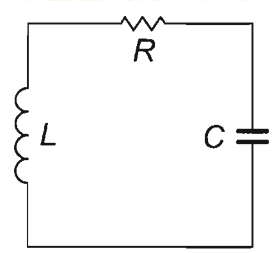
- Electromagnetic cloaking – transformation optics:



Resonances in Split Ring Resonators

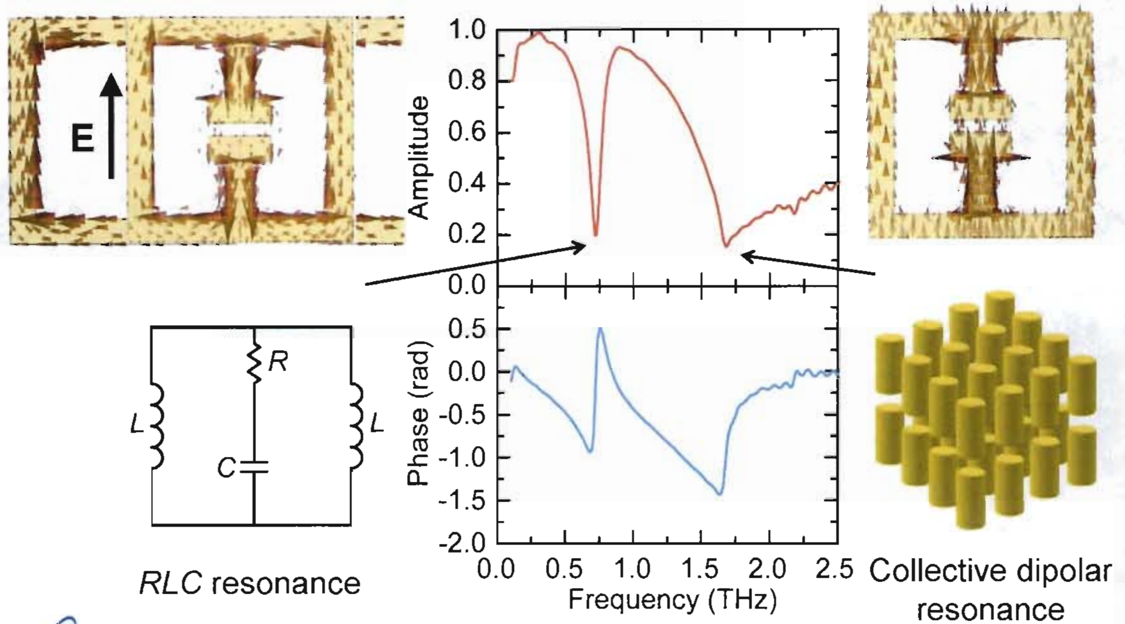




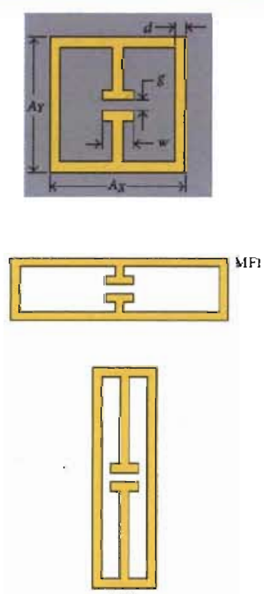


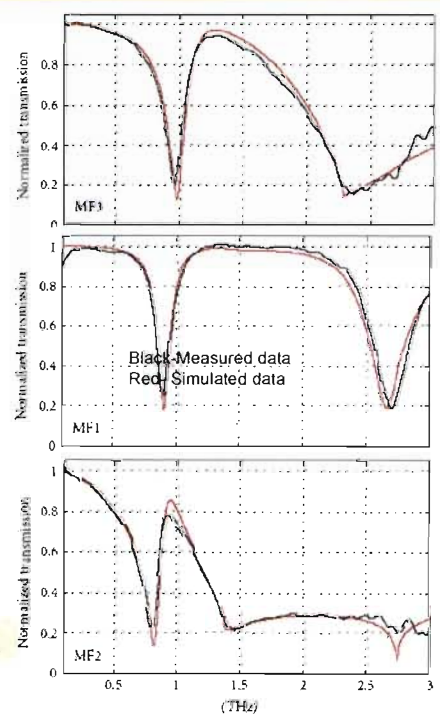
- Resonance frequency: $\omega^2 = \frac{1}{LC} - \cancel{\frac{R^2}{4L^2}}$
- Electromagneto effect in general
- Under normal incidence: purely electric response

Electric Resonant Resonance



Rectangular eSRR – Engineering Resonances



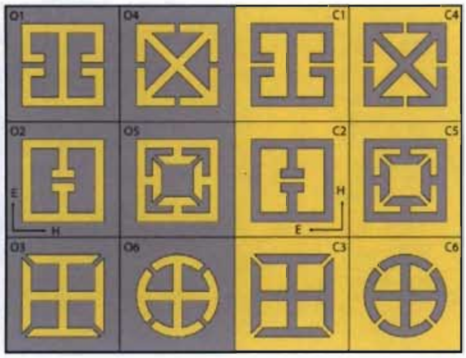


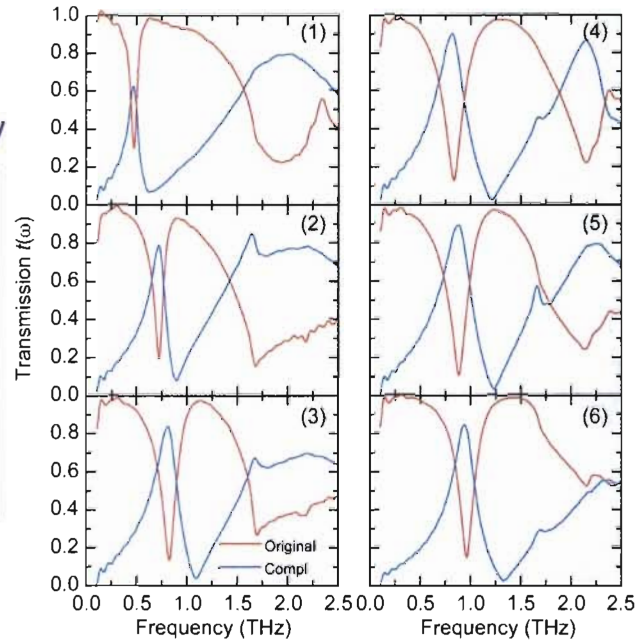
Azad *et al.*, *Appl. Phys. Lett.* **92**, 011119 (2008).

Complementary THz Electric Metamaterials

A series of electric SRRs:

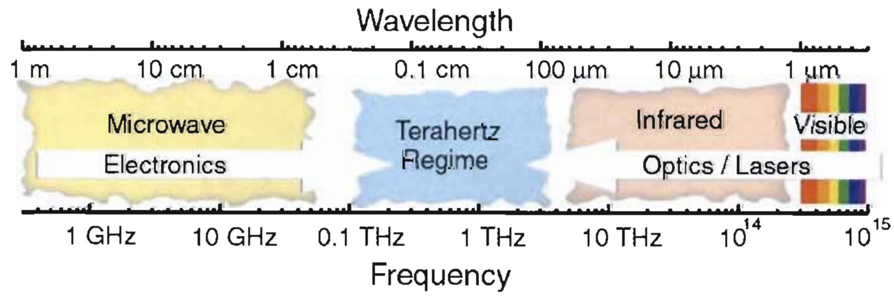
Original Complementary





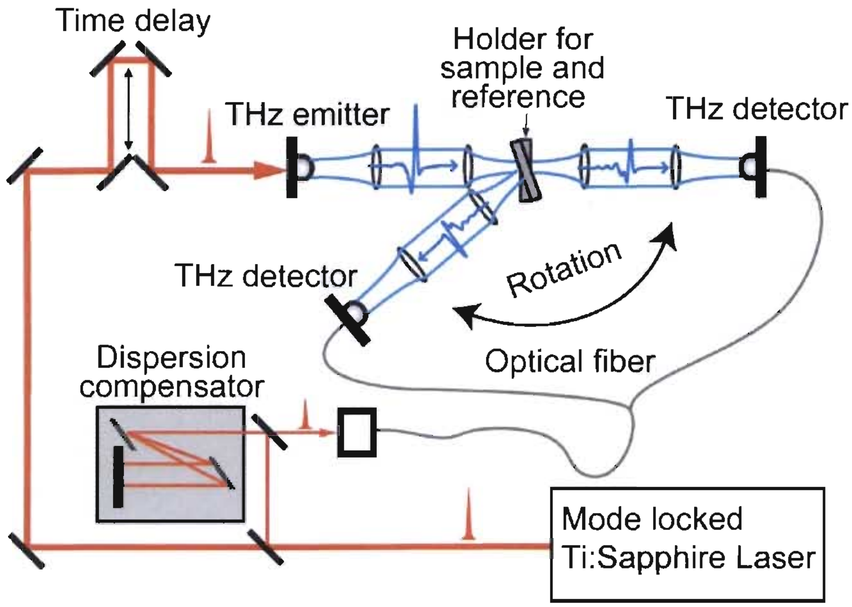
Chen *et al.*, *Opt. Express* **15**, 1084 (2007).

Why Terahertz Metamaterials?



- THz is one of the least developed and most challenging regimes in the electromagnetic spectrum
- Classical electronics and quantum photonics in general cannot be directly translated to the THz regime
- THz sources and detectors are limited
- Functional THz devices and components are not widely available

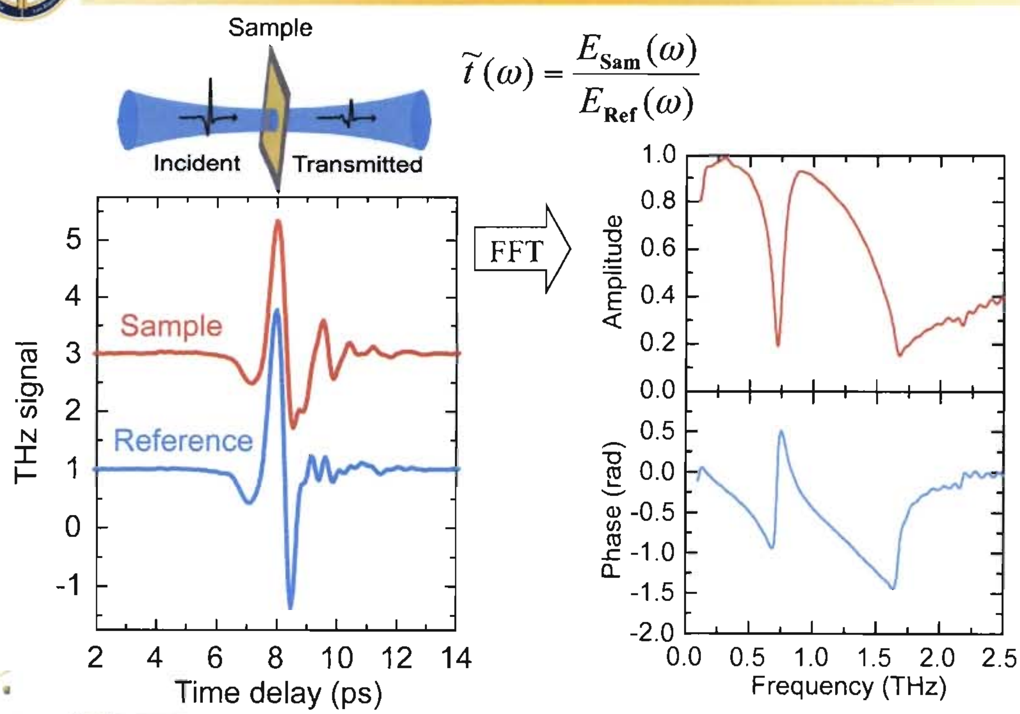
Terahertz Time-Domain Spectroscopy



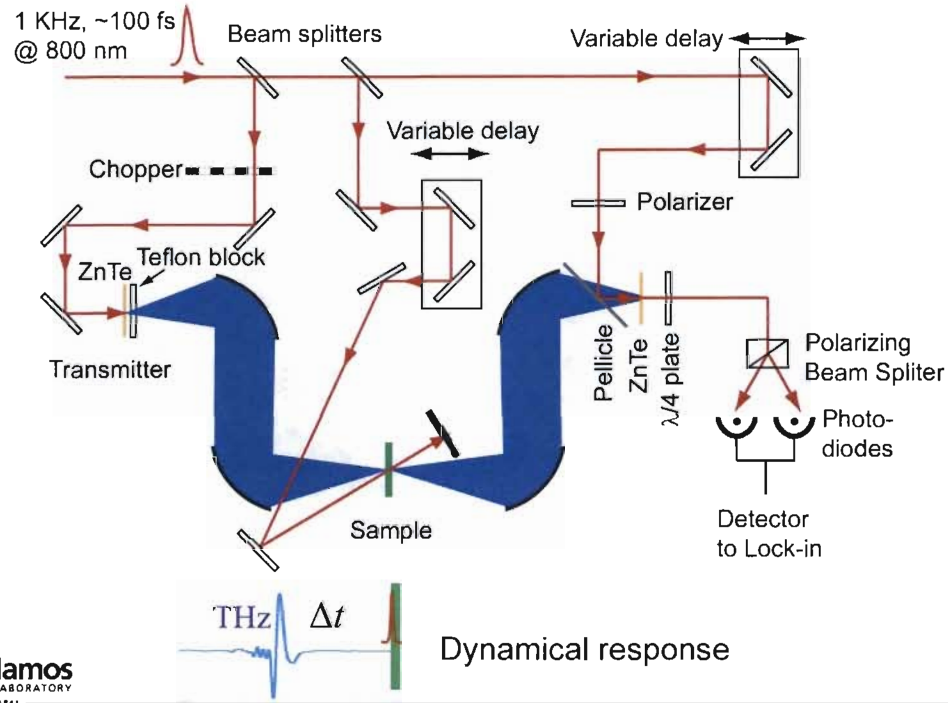
Transmission and reflection, angular dependence

Terahertz Time-Domain Spectroscopy

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



Optical-Pump Terahertz-Probe

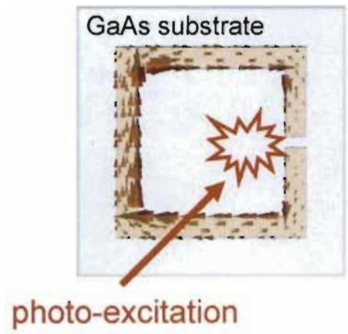


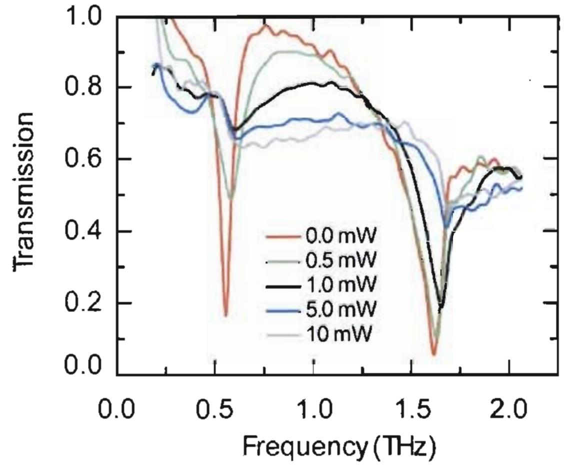
Dynamical response

Outline

- ❑ Introduction
- ❑ Actively and dynamically tunable THz metamaterials
  - ➢ Hybrid semiconductor metamaterials
  - ➢ Tuning through photoexcitation, voltage, temperature
  - ➢ Device applications
- ❑ High temperature superconducting metamaterials
  - ➢ Temperature tuning
  - ➢ Optical tuning
  - ➢ Theoretical investigation
- ❑ Metamaterials as surface coatings
  - ➢ Antireflection coatings
  - ➢ Perfect absorbers
  - ➢ Theory
- ❑ Summary

Dynamically Switchable THz Metamaterials



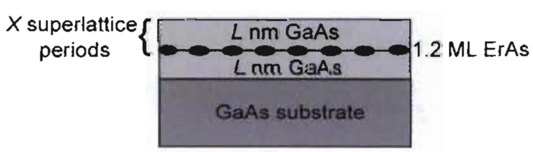


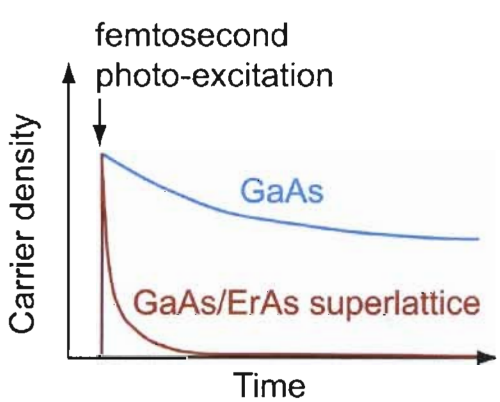
Performance:

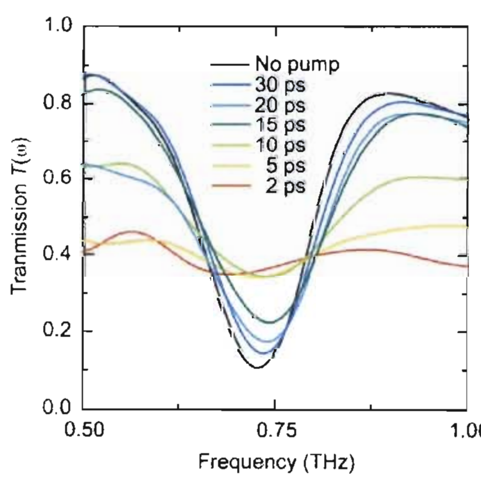
- High efficiency with low fluence
- Ultrafast in Switching Off
- Slow in Switching Recovery

Padilla *et al.*, *Phys. Rev. Lett.* **96**, 107401 (2006).

Ultrafast Dynamical Switching



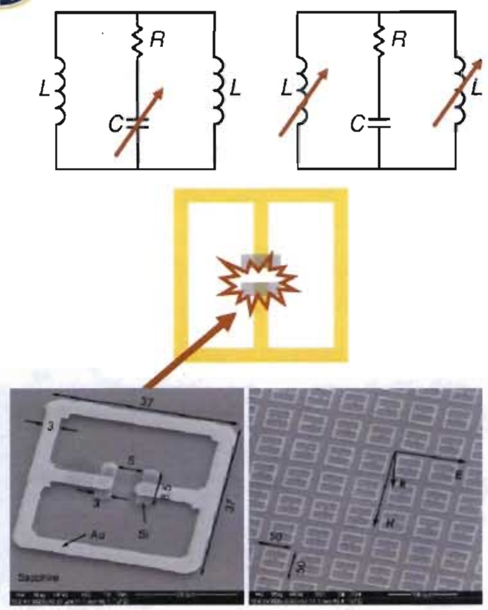


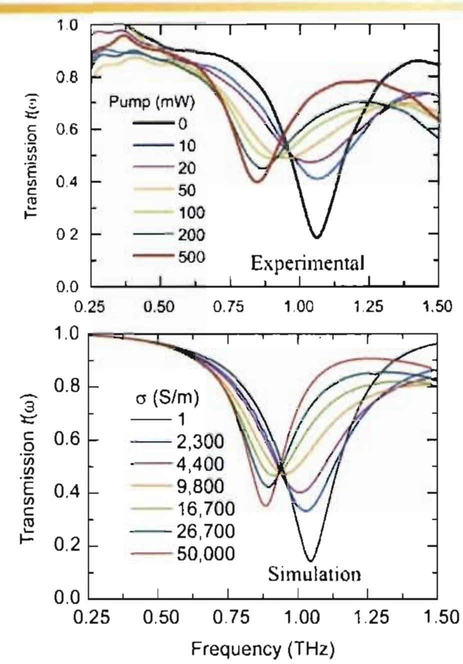


Ultrafast switching recovery ~ 20 ps
(with carrier lifetime ~10 ps)

Chen *et al.*, *Opt. Lett.* **32, 1620 (2007)**.

Frequency Agile THz Metamaterials



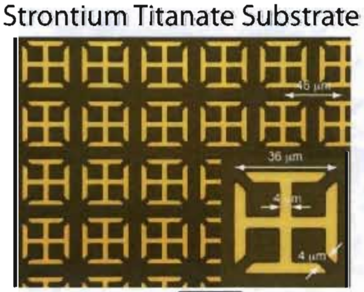


unit: μm

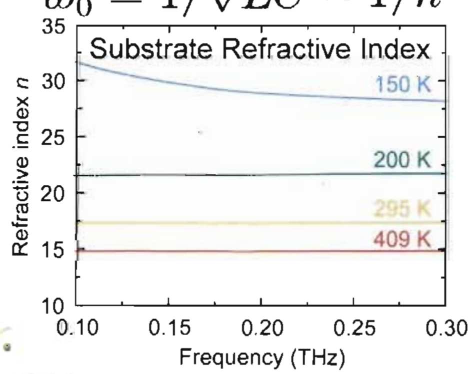
Chen *et al.*, *Nature Photon.* **2**, 295 (2008).

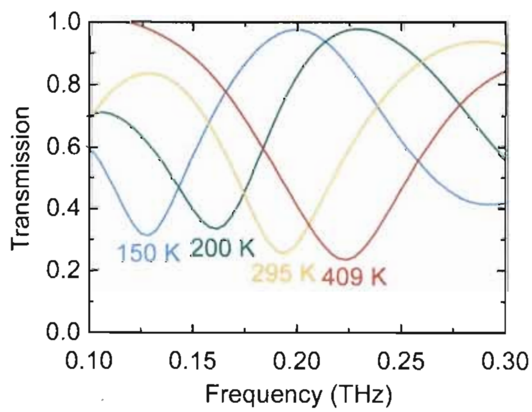
Thermally Tunable Terahertz Metamaterials

Strontium Titanate Substrate



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

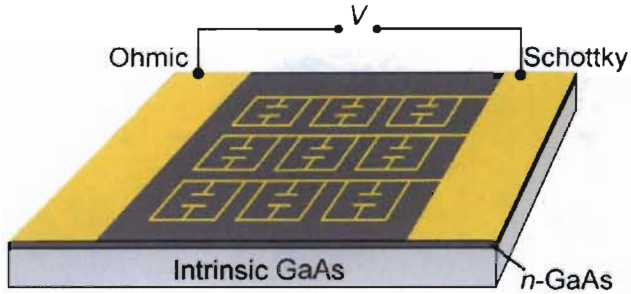


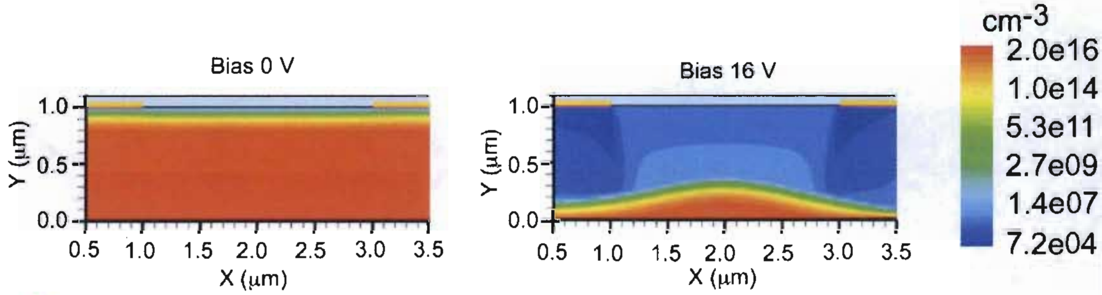


- Continuously frequency tuning
- No significant change in resonance strength

Singh *et al.*, *Opt. Lett.* in press (2011).

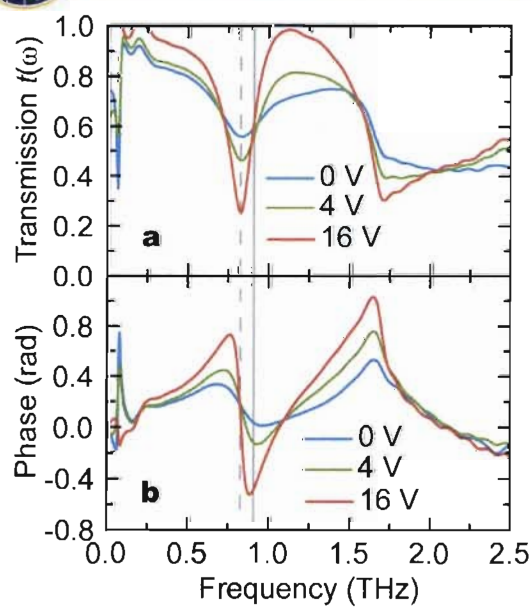
Electrically Switchable THz Metamaterials





Chen *et al.*, *Nature* **444**, 597 (2006).

Amplitude and Phase Modulations

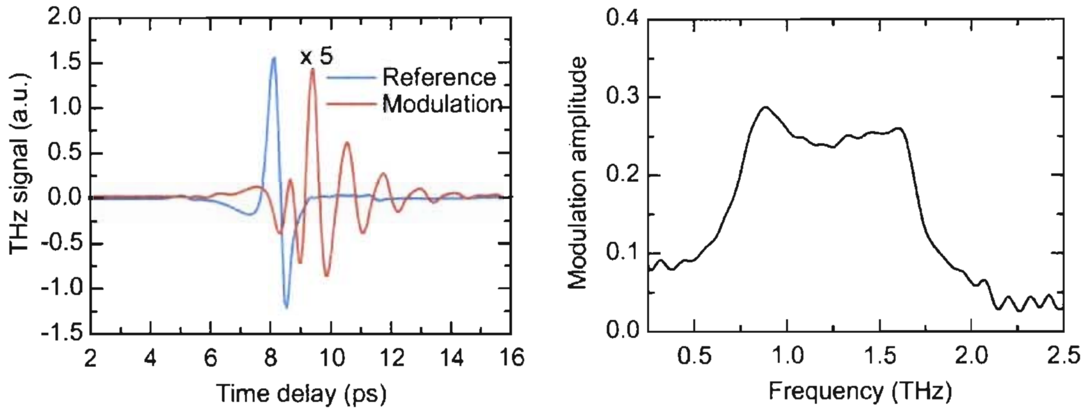


- Power modulation depth:
  $M = (T_{0V} - T_{16V}) / T_{0V}$ = 80%, or amplitude modulation depth 55%
- Phase modulation $\Delta\varphi = \pi/6$
- Amplitude and phase modulations are correlated
- In THz-TDS, both amplitude and phase modulations contribute to the modulation signal
  - ✓ Broadband modulation

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

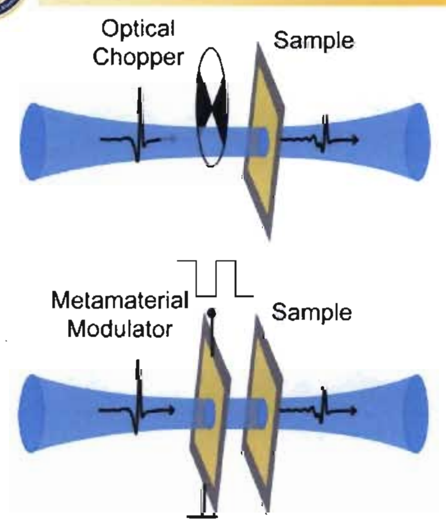
Chen *et al.*, *Nature Photon.* **3**, 148 (2009).

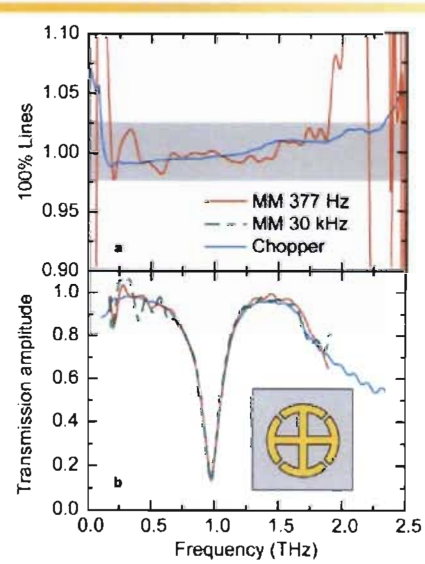
Broadband THz Modulation



Bandwidth: roughly between the two resonances

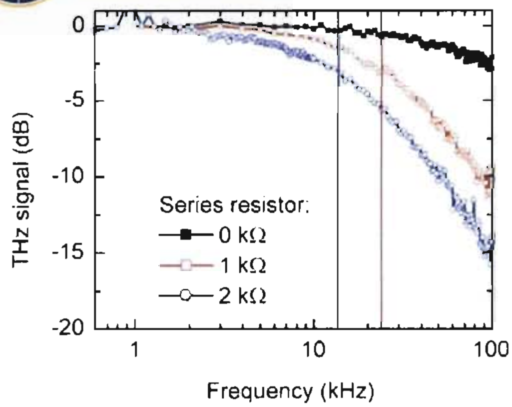
Serving as the Optical Chopper in THz-TDS





The metamaterial modulator is integrable, broadband, and high speed, without any moving part, room temperature operation

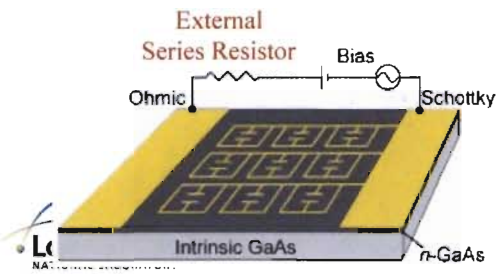
Fast Electrical Modulation of THz Waves



$$f = \frac{1}{2\pi RC}$$

Series resistance:
$R_{Schottky}$ = 126 ohm
R_{Fgen} = 50 ohm
R_{Series} =176 ohm

$$C_{dep} = A\left(\frac{qN_d\varepsilon_s}{2(V_{bi}-V)}\right)^{1/2} = 8.9 \text{ nF @ 0 volt}$$

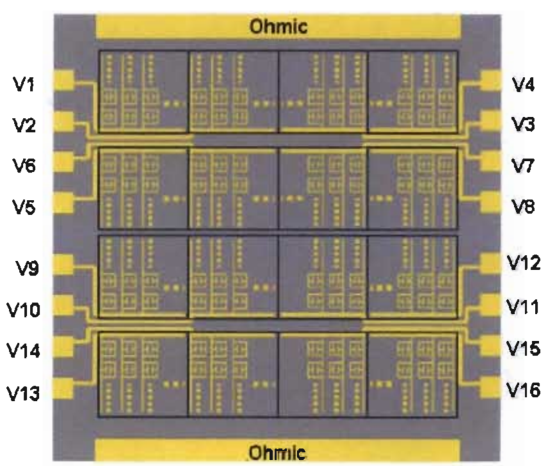


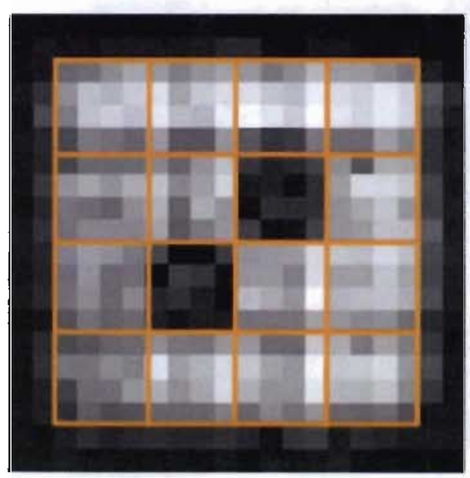
Solution: Connected with external series resistor

External series resistor	0 kΩ	1 kΩ	2 kΩ
Roll off frequency (Experimental)	100~200 kHz	24 kHz	14 kHz
Roll off frequency (Calculation)	101 kHz	15 KHz	8 kHz

Chen *et al.*, *Appl. Phys. Lett.* **93**, 091117 (2008).

THz Metamaterial Spatial Modulator



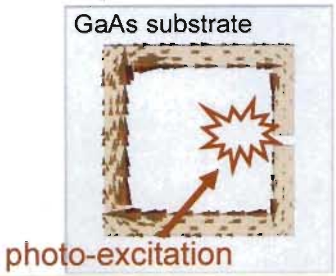


4 × 4 pixels, each pixel is independently controlled by voltage bias

Chan *et al.*, *Appl. Phys. Lett.* **94**, 213511 (2009).

Switchable and Tunable THz Metamaterials

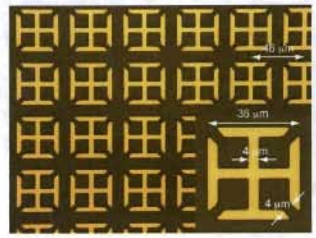
Optical Switch



PRL **96**, 107401 (2006); *Opt. Lett.* **32**, 1620 (2007).

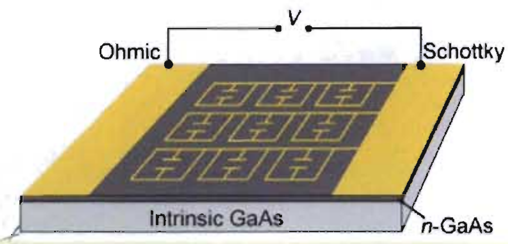
Temperature Tuning

Strontium Titanate Substrate



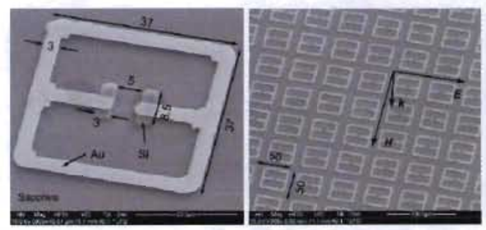
Opt. Lett. **36**, 1230 (2011).

Electrical Switch



Nature **444**, 597 (2006); *Nature Photon.* **3**, 148 (2009).

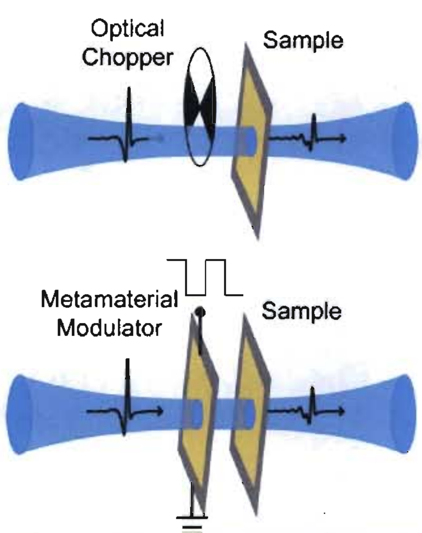
Optical Tuning



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

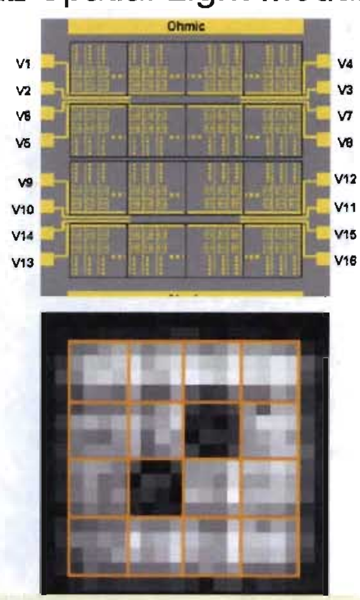
Towards Applications

Broadband THz Modulator



Chen *et al.*, *Nature Photon.* **3**, 148 (2009).

THz Spatial Light Modulator

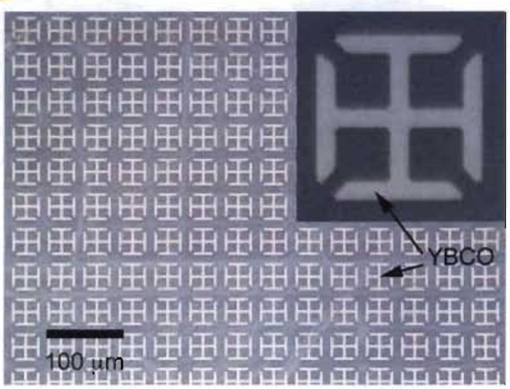


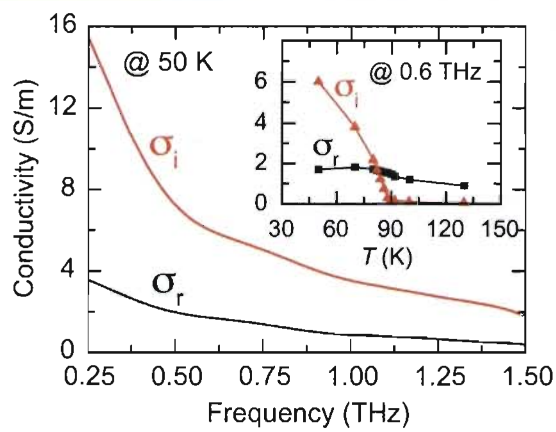
Chan *et al.*, *APL* **94**, 213511 (2009).

Outline

- Introduction
- Actively and dynamically tunable THz metamaterials
  - Hybrid semiconductor metamaterials
  - Tuning through photoexcitation, voltage, temperature
  - Device applications
- **High temperature superconducting metamaterials**
  - Temperature tuning
  - Optical tuning
  - Theoretical investigation
- Metamaterials as surface coatings
  - Antireflection coatings
  - Perfect absorbers
  - Theory
- Summary

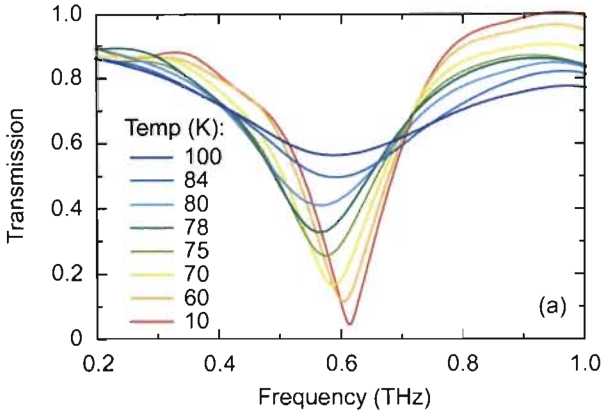
Temp-Dependent Complex Conductivity in HTS

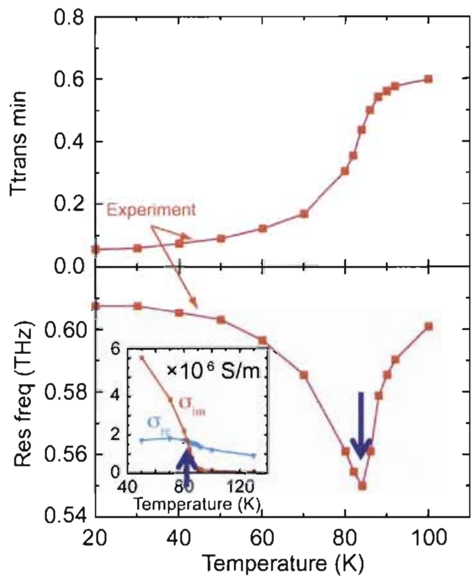




- HTS films: epitaxial YBCO films ($T_c \sim 90$K) by PLD
- Fabrication: photolithography and wet chemical etching
- High complex conductivity with $\sigma_i > \sigma_r$ at low temperatures
- Highly tunable conductivity at THz frequencies

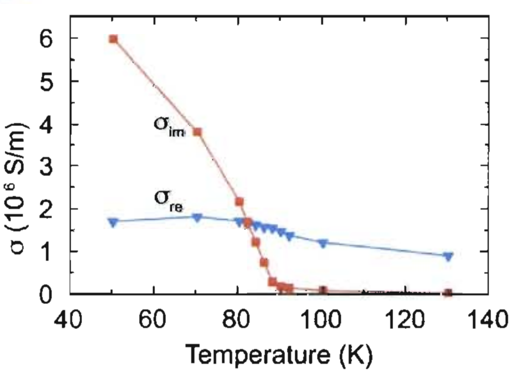
Thermally Tunable Metamaterial Resonance

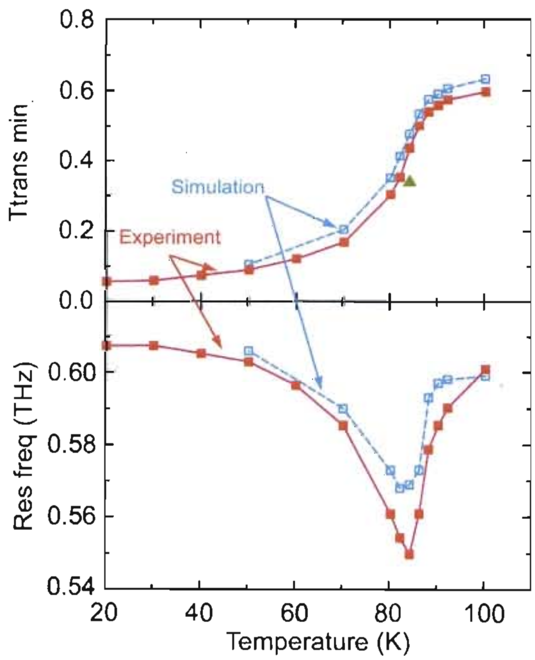




- Switching resonance strength
- Shifting resonance frequency
- Unique feature at $\sigma_i = \sigma_r$

Numerical Simulations





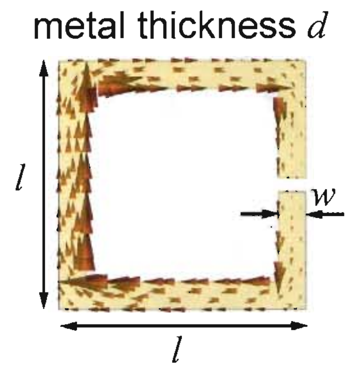
- Use experimental complex conductivity at 0.6 THz
- Finite-element numerical simulations using Comsol Multiphysics

LC Resonance in Superconducting SRRs

- Resonance frequency is given by: $\omega^2 = \dfrac{1}{LC} - \dfrac{R^2}{4L^2}$
- Total inductance $L=L_G+L_S$, where L_G is the loop inductance:

$$L_G = 0.02339\left[2l\log\left(\frac{2l^2}{w+d}\right) - 2l\log(2.414l)\right.$$
$$\left. + 0.01016[1.828l + 0.447(w+d)]\right]$$

  - ✓ l, w, d in inches, L_G in μH
  - ✓ Additional (kinetic) inductance L_S from SRR superconductor strips



- Capacitance: $C = \dfrac{1}{L_G \omega_0^2}$
  - ✓ Assuming perfect conductor with resonance frequency ω_0 through numerical simulations

SRR Resistance and Inductance

- Surface impedance: $\tilde{Z}_S = R_S - iX_S = Z_0 \dfrac{n_3 + i\tilde{n}_2 \cot\tilde{\beta}}{\tilde{n}_2^2 - n_3^2}$

$\tilde{\beta} = \tilde{n}_2 d\omega / c_0 \quad \tilde{n}_2 = \sqrt{i\tilde{\sigma}/\varepsilon_0\omega}$ d: film thickness

σ: film complex conductivity

Z_0: vacuum impedance, n_3: substrate index

- When $|\tilde{n}_2| >> n_3$, it can be simplified as: $\tilde{Z}_S = i\dfrac{Z_0}{\tilde{n}_2}\cot\tilde{\beta}$
- By considering the non-uniform currents, the surface resistance of the *SRR array* is given by:

$$R = \frac{A}{w} R_S$$

- Kinetic inductance:

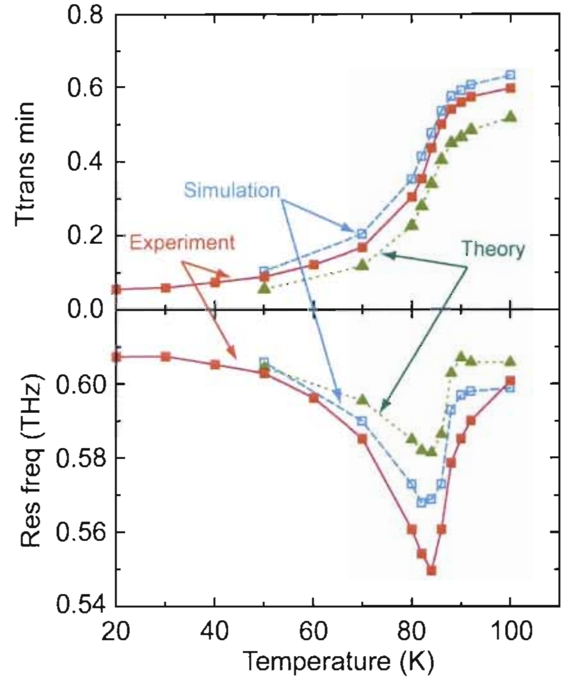
$$L_S = \frac{1}{\omega}\frac{A}{w} X_S$$

A: loop circumference
w: SRR line width
R_S and X_S units: /square

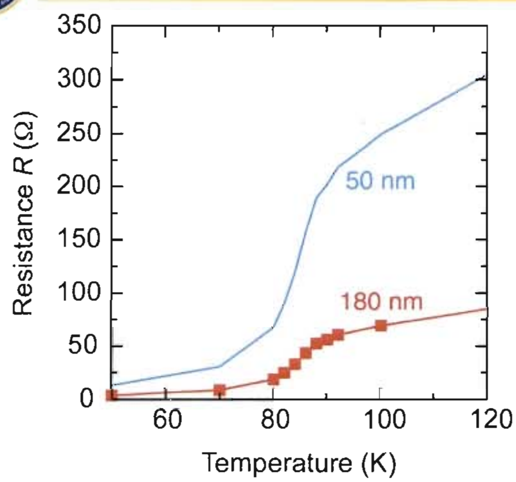
A Comparison: Exp, Sim, and Theory

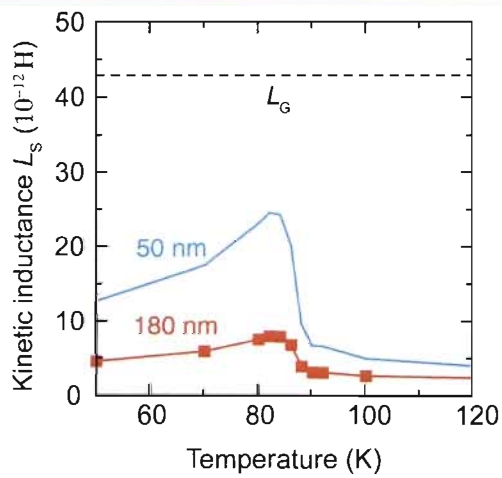
$$\omega^2 = \frac{1}{(L_G + L_S)C} - \frac{R^2}{4(L_G + L_S)^2}$$

$$T_{\min} = \frac{(1+n_3)R_S}{(1+n_3)R_S + Z_0}$$



Thickness Dependent Surface Impedance

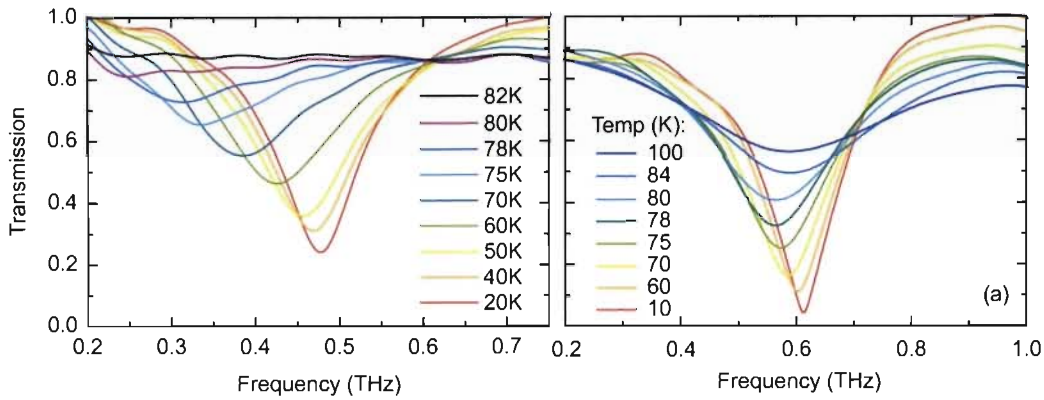




- Higher R indicates easier to switch the resonance.
- Higher L_S indicates lower resonance frequency
- Higher L_S indicates more resonance frequency shifting

Thickness Dependent Resonance Tuning

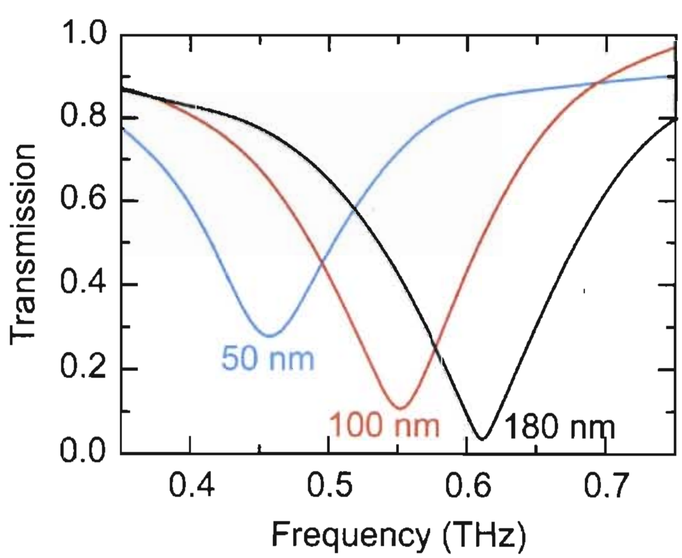
50 nm thick YBCO MM | 180 nm thick YBCO MM



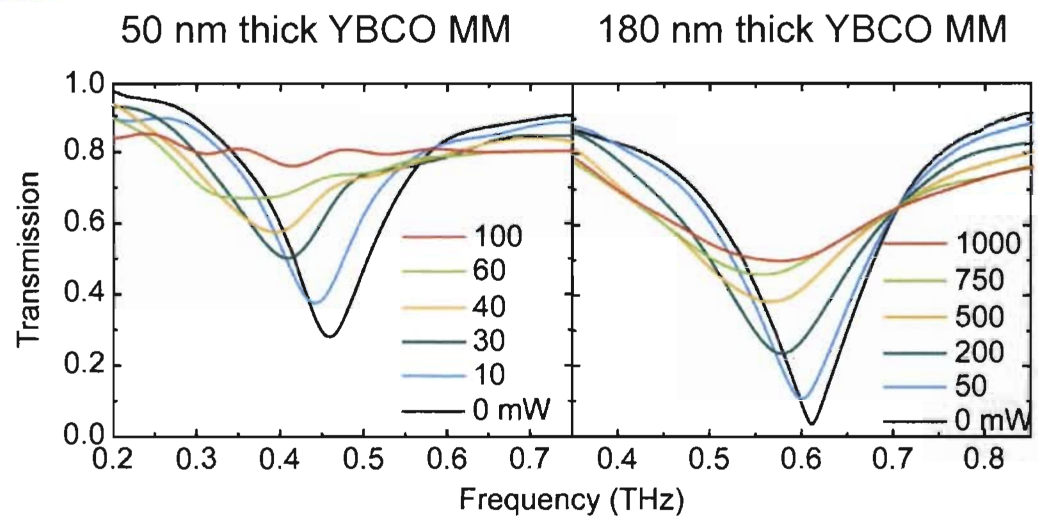
- 50 nm HTS MM is easier to switch off resonance
- Identical structure has a lower resonance frequency
- Resonance frequency tuning range is larger

Thickness Dependent MM Resonance

Thinner HTS MMs result in a lower resonance frequency



Resonance Tuning by Photoexcitation

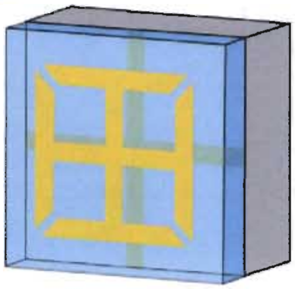


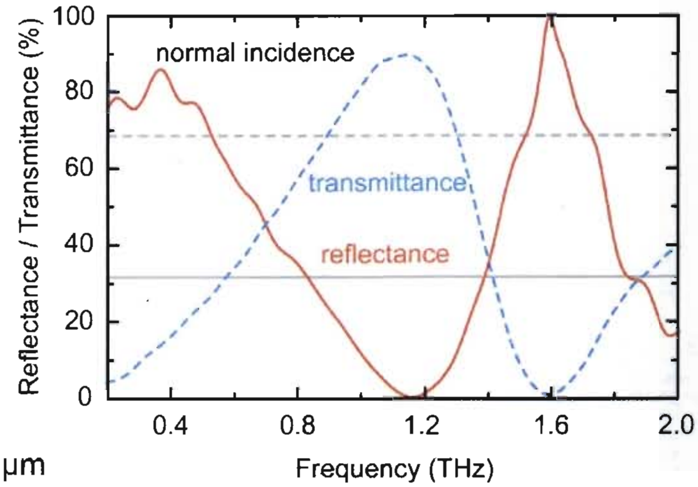
Similar behaviors as in temperature tuning

Outline

- ❑ Introduction
- ❑ Actively and dynamically tunable THz metamaterials
  - Hybrid semiconductor metamaterials
  - Tuning through photoexcitation, voltage, temperature
  - Device applications
- ❑ High temperature superconducting metamaterials
  - Temperature tuning
  - Optical tuning
  - Theoretical investigation
- ❑ **Metamaterials as surface coatings**
  - Antireflection coatings
  - Perfect absorbers
  - Theory
- ❑ Summary

Metamaterial Antireflection Coating

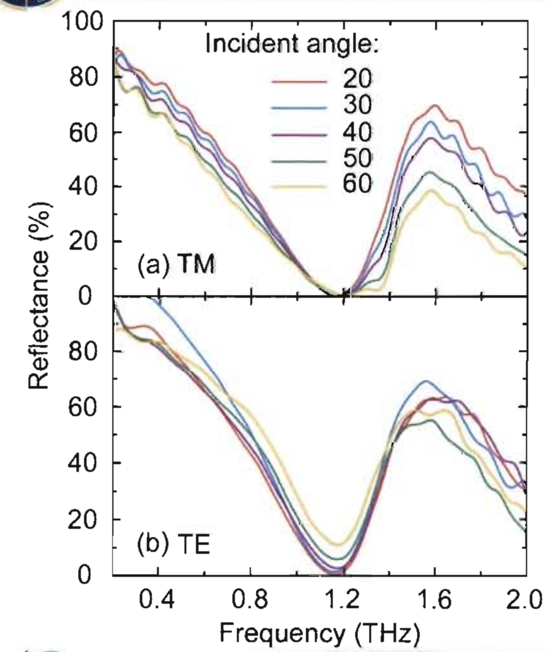


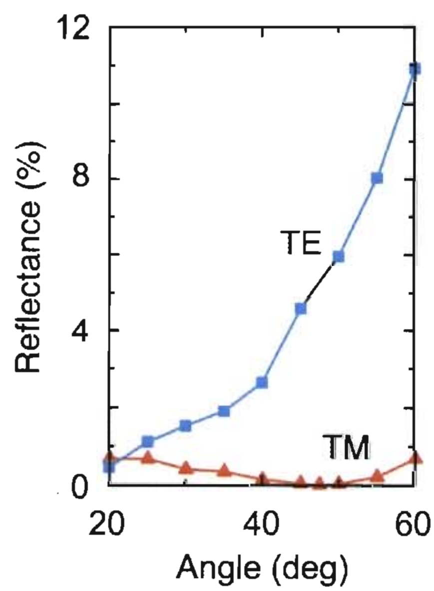


- GaAs substrate
- Gold mesh
- Polyimide spacer ~10 μm
- Gold SRR
- Reflectance minimum 0.14%; Transmittance maximum ~90%

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

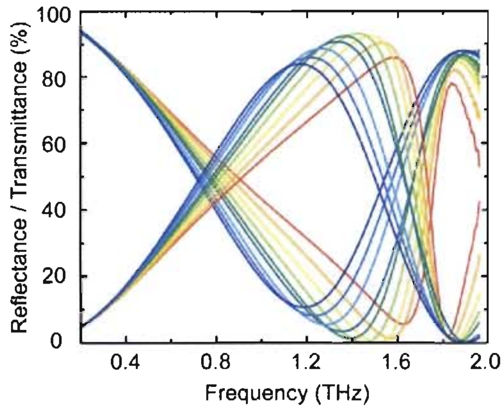
Angular-Dependent Anti-Reflection





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

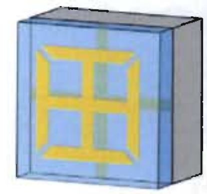
Numerical Simulations: Spacer Thickness



Simulation:

Substrate: ε_{GaAs} = 12.7

MM spacer: ε_{spacer} =1.5



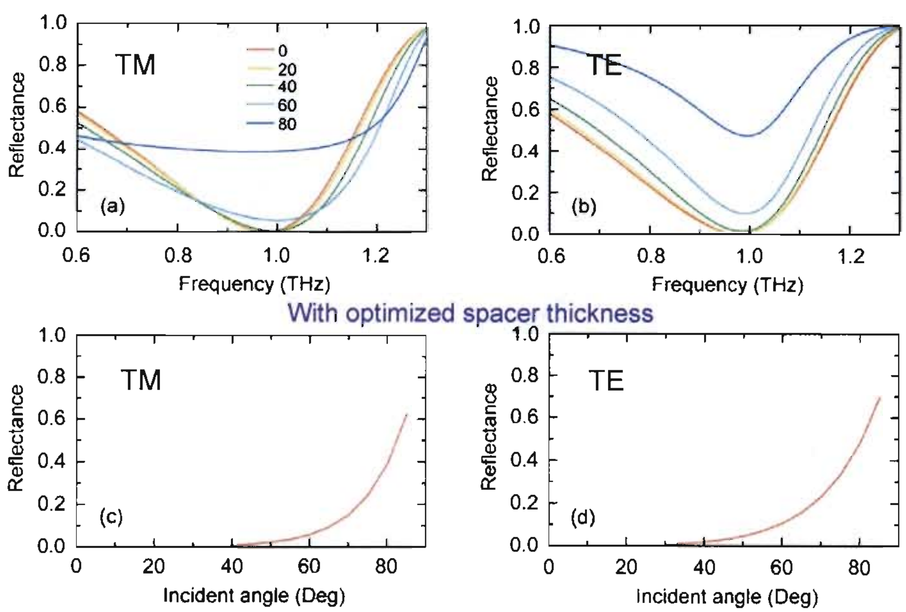
From red to blue:

Increasing the spacer thickness from 4 μm to 20 μm

- With any dielectric constant of the spacer material, there is always a thickness achieving excellent antireflection, even the spacer dielectric constant is larger than the substrate
- The losses in metal and the spacer material mainly affect the transmittance, but has little effect on the reflectance

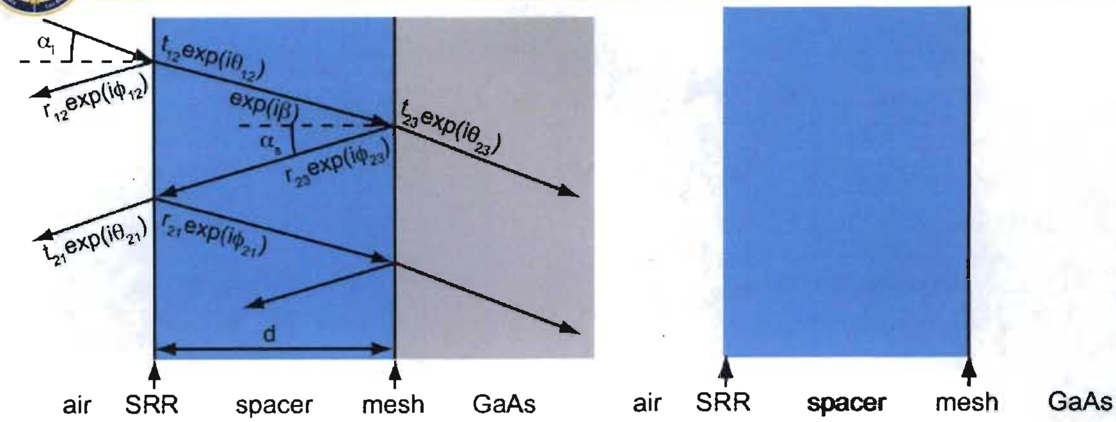
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Numerical Simulations: Angular Dependence



Chen *et al.*, *THz Sci. & Technol.* **3**, 66 (2010).

Antireflection Mechanism



$$\tilde{r} = \frac{r_{12}e^{i\phi_{12}} - r_{12}r_{21}r_{23}e^{i\zeta_1} + t_{12}r_{23}t_{21}e^{i\zeta_2}}{1 - r_{21}r_{23}e^{i(\phi_{21}+\phi_{23}+2\beta)}}, \quad \zeta_1 = \phi_{12}+\phi_{21}+\phi_{23}+2\beta$$

$$\zeta_2 = \theta_{12}+\phi_{23}+\theta_{21}+2\beta$$

$$\tilde{t} = \frac{t_{12}t_{23}e^{i(\theta_{12}+\theta_{23}+\beta)}}{1 - r_{23}r_{21}e^{i(\phi_{23}+\phi_{21}+2\beta)}}, \quad \beta = -\sqrt{\tilde{\varepsilon}_{\text{spacer}}}k_0 d/\cos(\alpha_s)$$

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

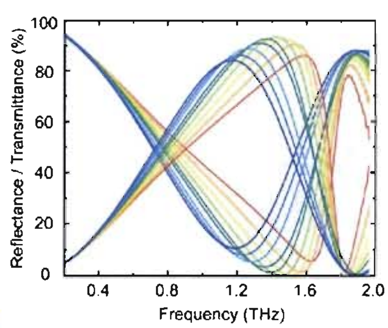
Antireflection Mechanism: Modeling Results

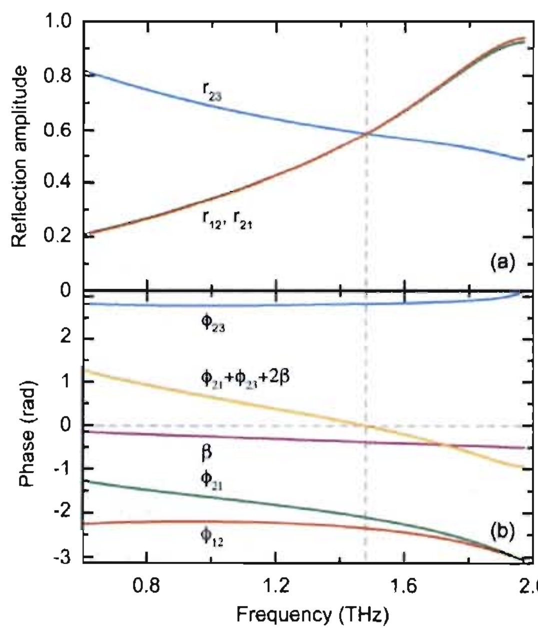
- Antireflection requirements:

$$r_{12} = r_{21} = r_{23},$$

$$\phi_{21} + \phi_{23} + 2\beta = 2m\pi$$

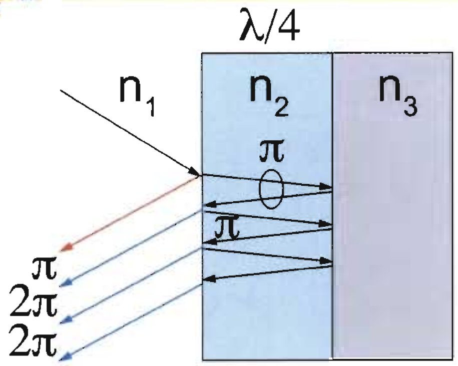
- Varying β (spacer thickness) reproduces the thickness dependent reflection and transmission

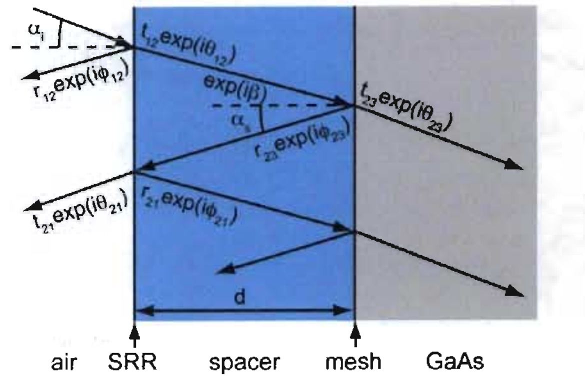




Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

Comparison to Quarter-Wave Antireflection



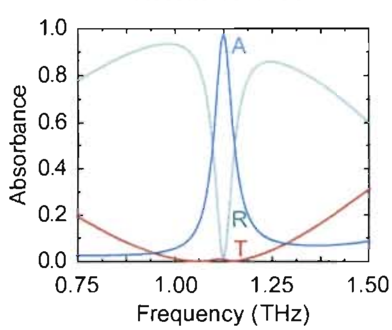


- $n_2 = (n_1 n_3)^{1/2}$ ➔ $r_{12}=r_{21}=r_{23}$
- Phase difference π between direction reflection and second reflection
- Phase difference 2π in the following reflections
- At antireflection frequency $r_{12}=r_{21}=r_{23}$
- $\theta_{12}+\phi_{23}+\theta_{21}+2\beta-\phi_{12}=\pi$ between direction reflection and second reflection
- $\phi_{21}+\phi_{23}+2\beta=0$ in the following reflections

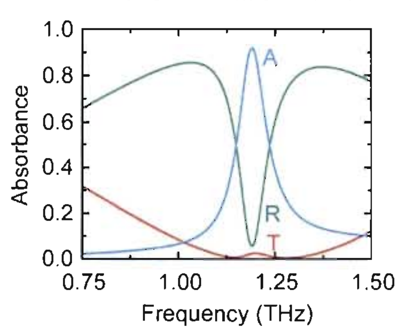
Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).

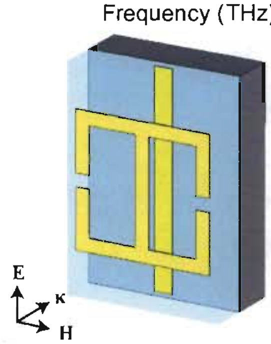
Perfect Metamaterial Absorbers

Results from Tao



Calculation from our model





The claimed magnetic response plays NO significant role in impedance matching

Landy *et al. Phys. Rev. Lett.* **100**, 207402 (2008).
Tao *et al., Opt. Express* **16**,7121 (2008).
Chen *et al., Phys. Rev. Lett.* **105**, 073901 (2010).

Summary

- Actively and dynamically tunable metamaterials will contribute to the development of THz science and technology
- We Investigated resonance switching and tuning in high temperature superconducting THz metamaterials by varying temperature and photoexcitation
- We also investigated metamaterials as THz antireflection coatings and perfect absorbers
- In both investigations we achieved reasonable level understanding of the underlying physics

Acknowledgement

Collaborators:

LANL: Toni Taylor, Abul Azad, John O'Hara, Quanxi Jia, Stuart Trugman, Ranjan Singh, Jiangfeng Zhou, Matt Reiten, Dibakar Chowdhury

Boston Univ: Richard Averitt

UCSB: Arthur Gossard

Rice: Daniel Mittleman

OSU: Weili Zhang

Boston College: Willie Padilla

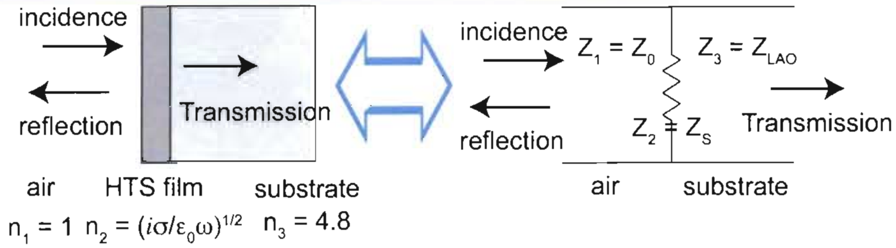
SNL: Igal Brener, Mark Lee, Michael Cich

Duke Univ: David Smith, Nan Jokest

$$$ -- Support from the U.S. DOE through the LDRD/LANL Program

This work was performed, in part, at the Center for Integrated Nanotechnologies (CINT), a U.S. Department of Energy Office of Basic Energy Sciences nanoscale science research center operated jointly by Los Alamos and Sandia National Laboratories.

Surface Impedance of HTS Film



- First calculate the reflection (transmission) coefficient of the HTS film

$$\tilde{r} = re^{i\phi} = \frac{\tilde{r}_{12} + \tilde{r}_{23}e^{i2\beta}}{1 + \tilde{r}_{12}\tilde{r}_{23}e^{i2\beta}} \qquad \tilde{\beta} = \tilde{n}_2 d\omega/c_0$$

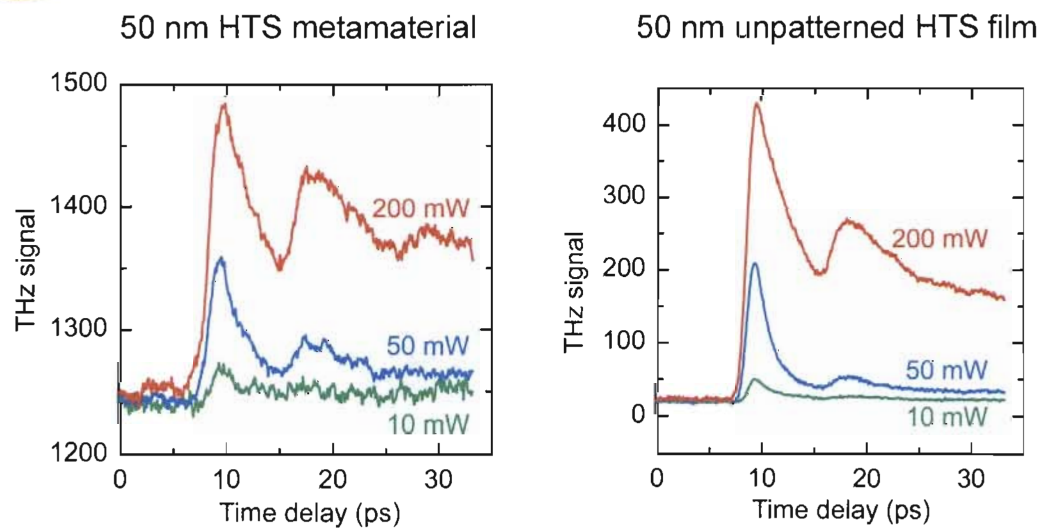
d is the film thickness

- Then calculate the reflection (transmission) coefficient of the TL

$$\tilde{r} = \frac{Z_1 - Z_2//Z_3}{Z_1 + Z_2//Z_3} = \frac{Z_1Z_2 + Z_1Z_3 - Z_2Z_3}{Z_1Z_2 + Z_1Z_3 + Z_2Z_3}$$

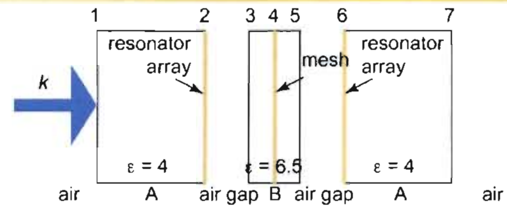
- The two reflection coefficients are equal, we can calculate Z_2

Ultrafast Dynamics

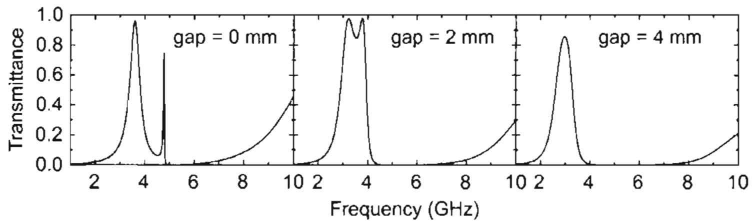


The "bumps" are due to multiple reflection inside the substrate, results in multiple photoexcitation.

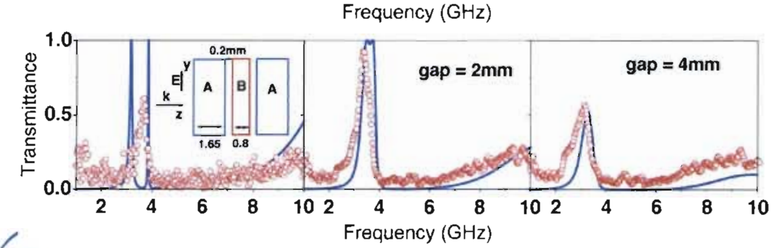
Electromagnetic-Wave Tunneling



We calculate each interface the reflection and transmission coefficients, then calculate the total reflection and transmission



Calculated results from our model



Experimental and simulation results from Zhou

Chen *et al.*, *Phys. Rev. Lett.* **105**, 073901 (2010).
Zhou *et al.*, *Phys. Rev. Lett.* **94**, 243905 (2005).