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Title: Tuning the Resonance in Superconducting Terahertz Metamaterials

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Tuning the Resonance in Superconducting Terahertz Metamaterials

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Abstract: We report tunable resonances in terahertz metamaterials made from high-temperature superconducting YBCO films. The resonance switching and frequency tuning are accomplished through temperature change or photoexcitation. Taking in account the temperature-dependent complex conductivity, we carry out numerical simulations and develop a theoretical model for correct interpretation of the observed resonance switching and frequency tuning. The theoretical model further predicts the thickness dependent resonance tuning, which is validated by experiments.

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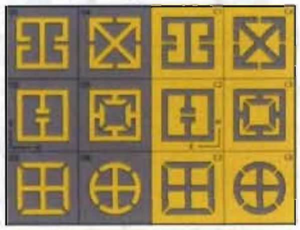
Outline

- Background information
- Resonance tuning through temperature change in high-temperature superconducting (HTS) metamaterials
- The underlying physics of the resonance tuning
- Thickness dependent resonance tuning
- Ultrafast resonance tuning through photoexcitation
- Summary

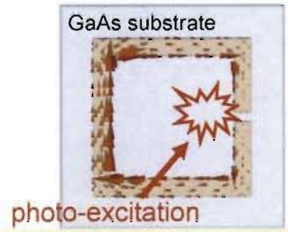
Switchable and Frequency Tunable THz MMs

Complementary THz metamaterials



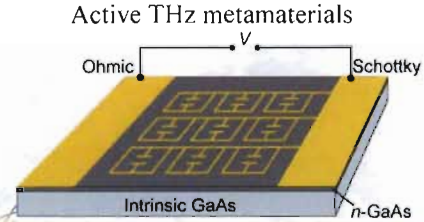
Opt. Express **15**, 1084 (2007).

Dynamical THz metamaterials



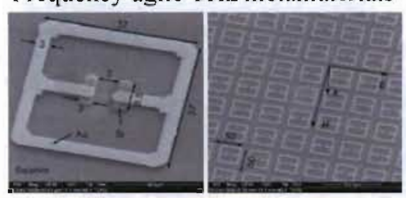
PRL **96**, 107401 (2006); *Opt. Lett.* **32**, 1620 (2007).

Active THz metamaterials



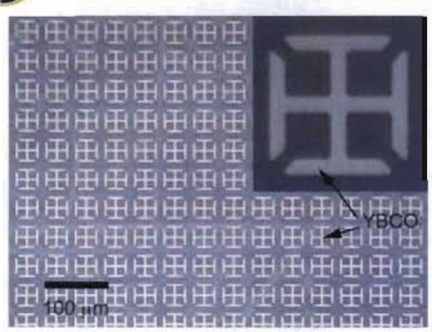
Nature **444**, 597 (2006); *Nature Photon.* **3**, 148 (2009).

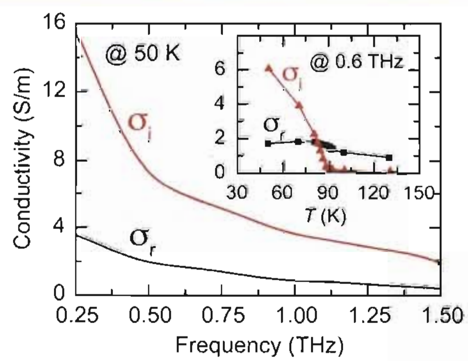
Frequency agile THz metamaterials



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

Temp-Dependent Complex Conductivity in HTS





- High complex conductivity with $\sigma_i > \sigma_r$ at low temperatures
- Highly tunable conductivity at THz frequencies
- Epitaxial YBCO films with $T_c \sim 90$K
- Photolithography and wet chemical etching

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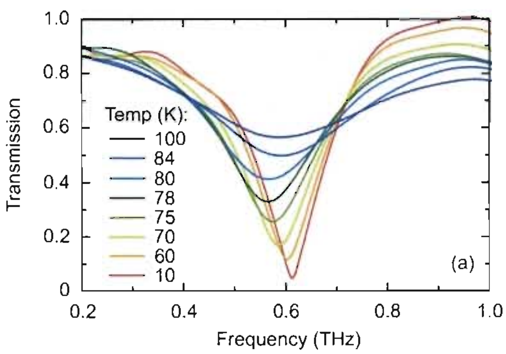
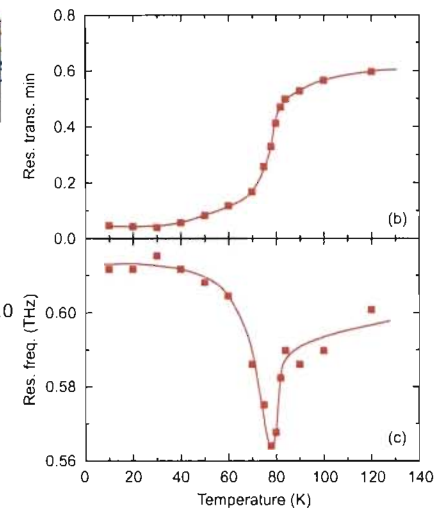
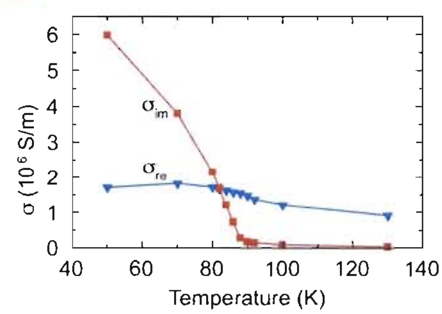
Thermally Tunable Metamaterial Resonance

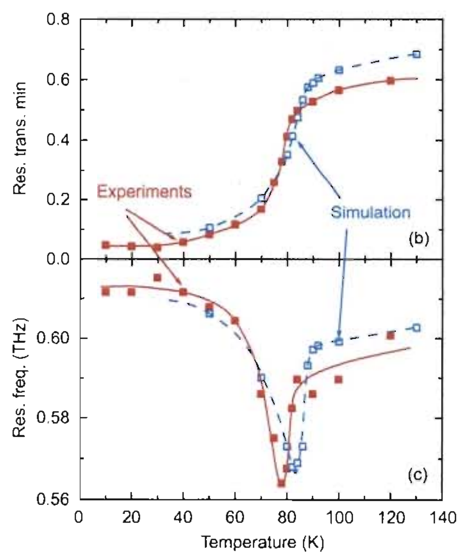




- Switching resonance strength
- Shifting resonance frequency
- Unique feature at $\sigma_i = \sigma_r$

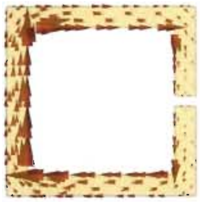
Numerical Simulations

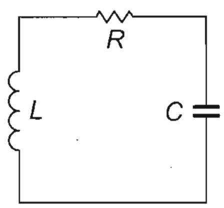




- Use experimental complex conductivity at 0.6 THz
- Finite-element numerical simulations using Comsol Multiphysics

Resonance in Split Ring Resonators





- The resonance frequency is given by:

$$\omega^2 = \frac{1}{LC} - \frac{R^2}{4L^2}$$

- The capacitance *C*:
  - ✓ Geometry and dimensions of the split gap
- The inductance *L*:
  - ✓ Loop L_G
  - ✓ Additional (kinetic) inductance L_S from SRR superconductor strips
- L_S becomes important when the film thickness is comparable or smaller than the skin depth

SRR Resistance and Inductance

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

$$\tilde{n}_2 = \sqrt{i\tilde{\sigma}/\varepsilon_0\omega} \qquad \tilde{\beta} = \tilde{n}_2 d\omega/c_0$$

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

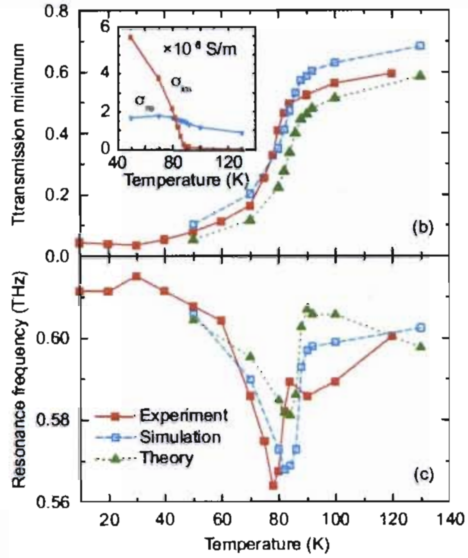
$$R = \frac{A}{w} R_S$$

- Additional kinetic inductance

A is the loop circumference
w is the SRR line width

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

A Comparison: Exp, Sim, and Theory



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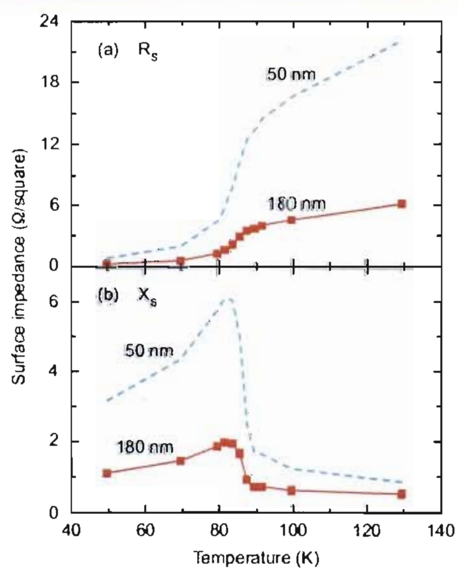
Thickness Dependent Surface Impedance



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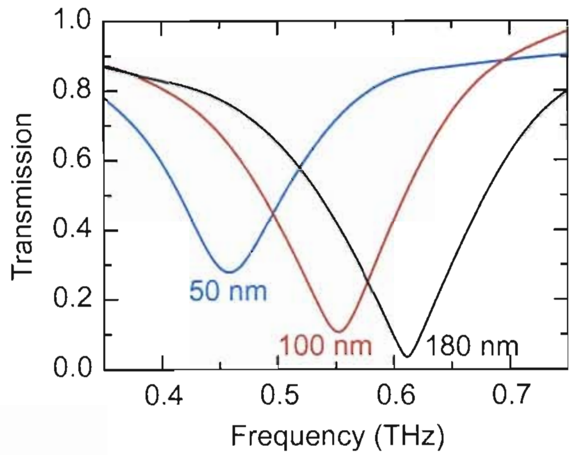
Thickness Dependent MM Resonance

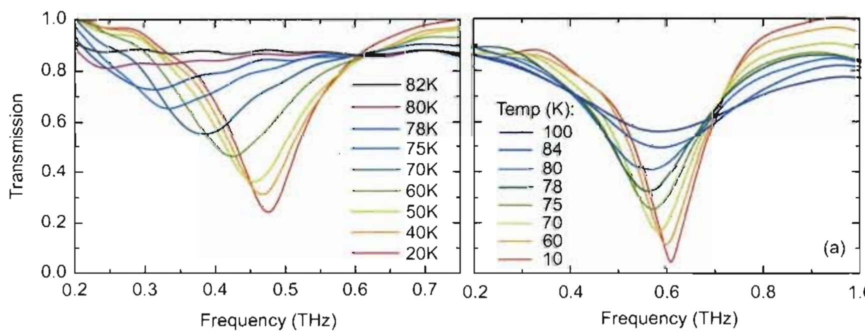
Metamaterials made from different thickness of YBCO films

➢ decreasing the thickness results in a red-shift of resonance



Thickness Dependent Resonance Tuning

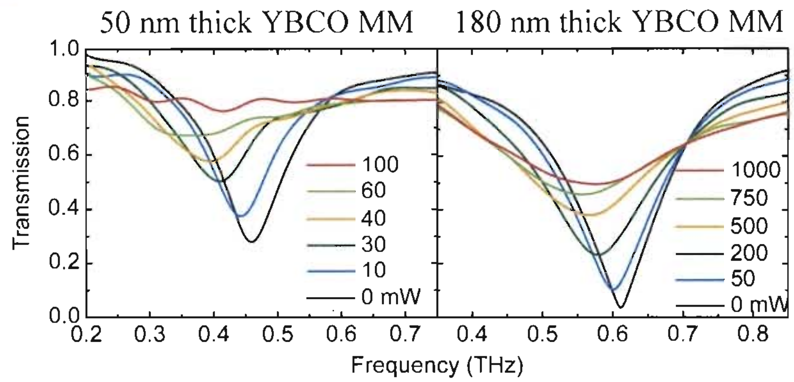
50 nm thick YBCO MM   180 nm thick YBCO MM



Metamaterials made from different thickness of YBCO films

➢ decreasing the thickness results in a larger tuning range and higher tuning efficiency

Tune MM Resonance by Photoexcitation



Metamaterials made from different thickness of YBCO films

➤ Resonance tuning by photoexcitation depends on thickness

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13

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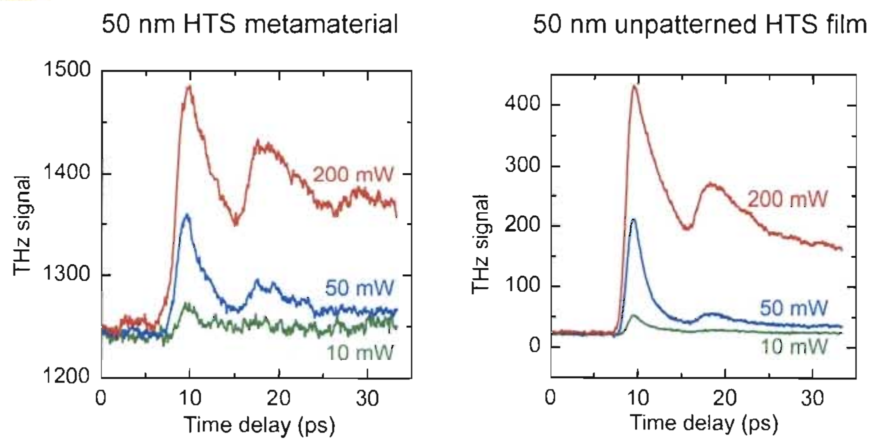
Ultrafast Dynamics



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

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14

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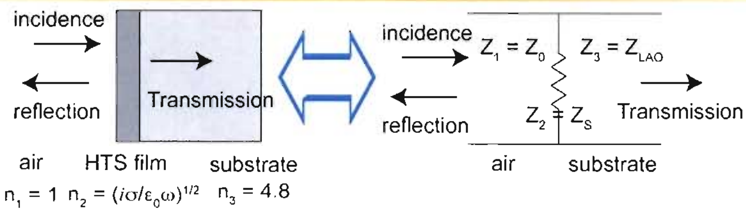
Summary

- We developed high-temperature superconducting metamaterials
- We Investigated their resonance properties as a function of temperature
- We achieved reasonable understanding of the underlying physics
- We further investigated their resonance tuning through ultrafast photoexcitation, as well as the thickness dependence.

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.

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

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