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Title: Superconductors and Complex Transition Metal Oxides for Tunable THz Plasmonic Metamaterials

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Superconductors and Complex Transition Metal Oxides for Tunable THz Plasmonic Metamaterials

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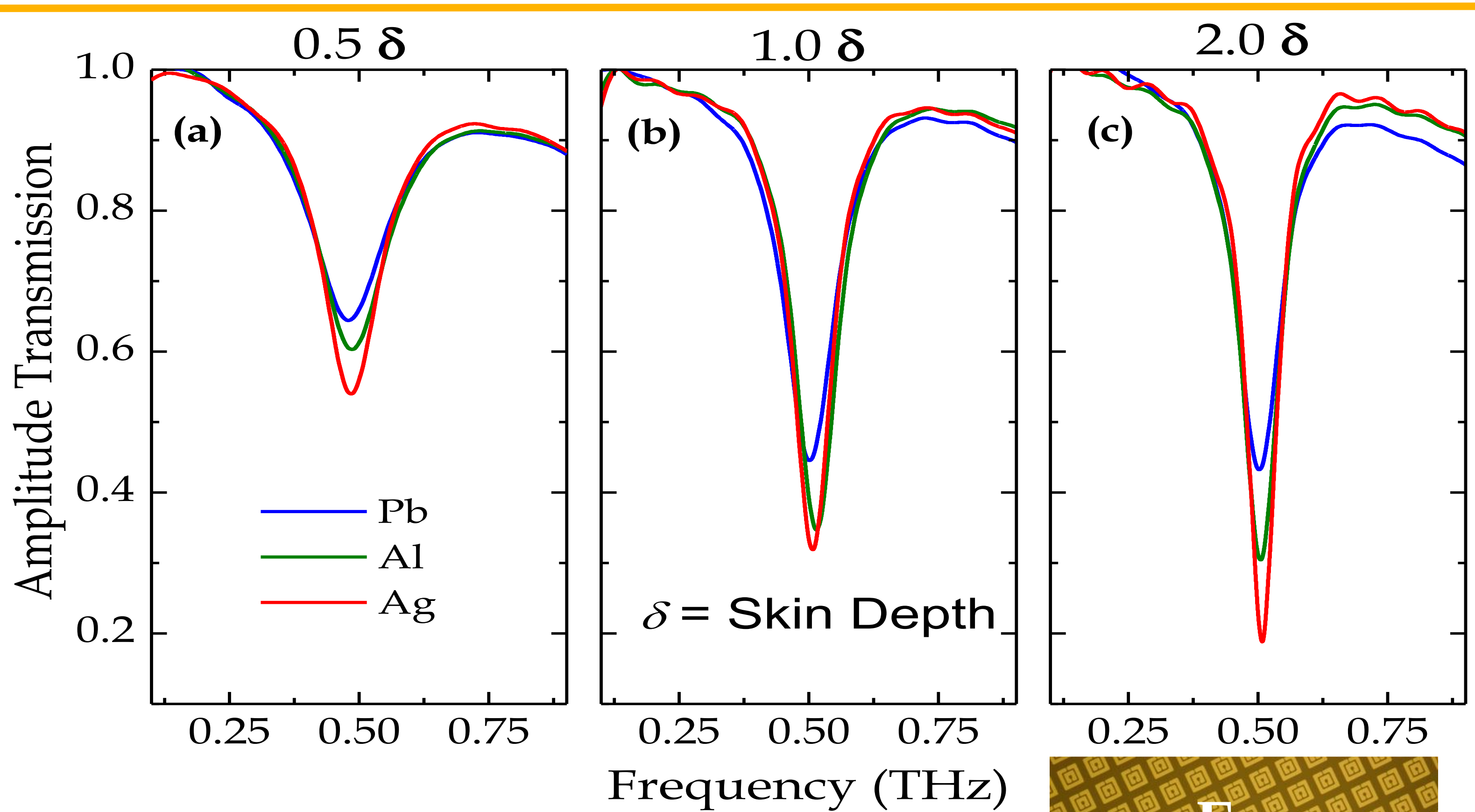
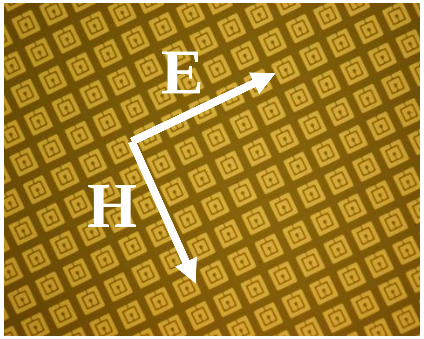
Outline

- Motivation – Non-tunability of metal metamaterials
- Superconductors for temperature tunable metamaterials
- Ultrafast optical switching in superconductor metamaterials
- Controlling the conductivity with infrared pump beam
- Complex metal oxides as active substrates – Strontium Titanate
- Conclusion

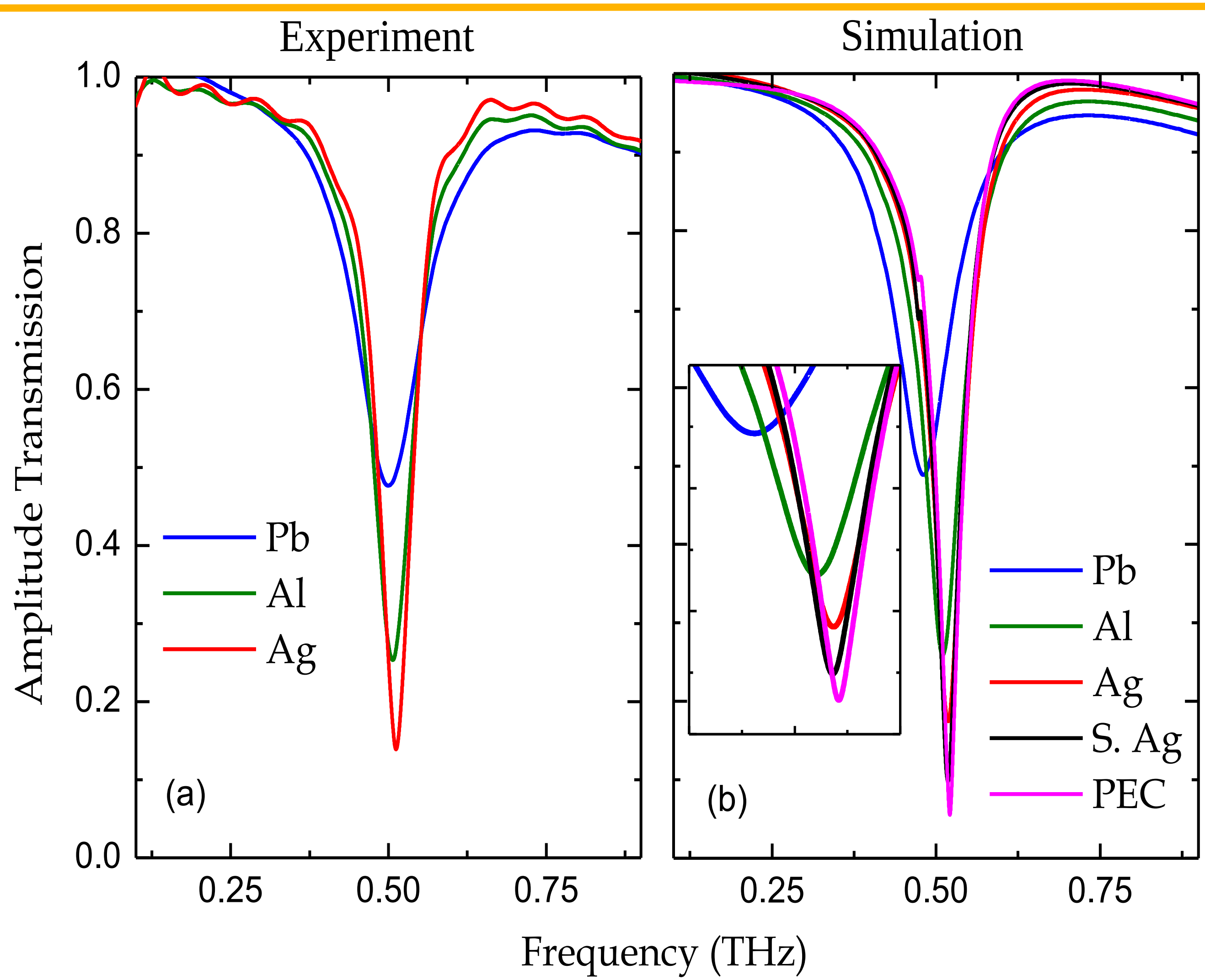
Metal conductivity tuned LC resonance





R. Singh et al., Opt. Lett. **33**, 1506 (2008)

PEC SRRs – No significant loss reduction

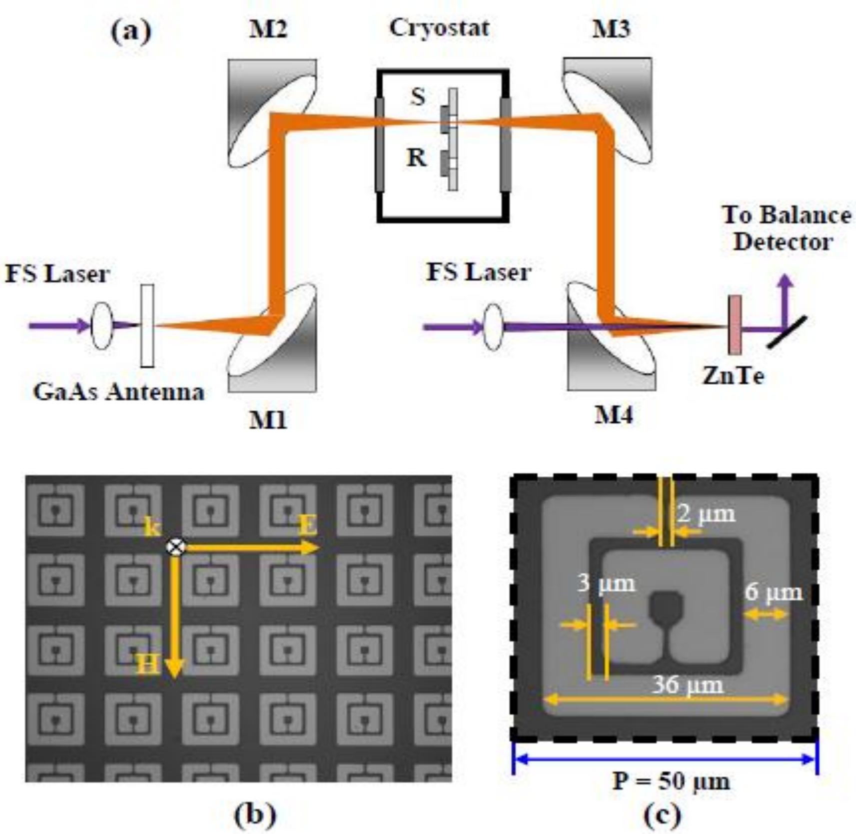


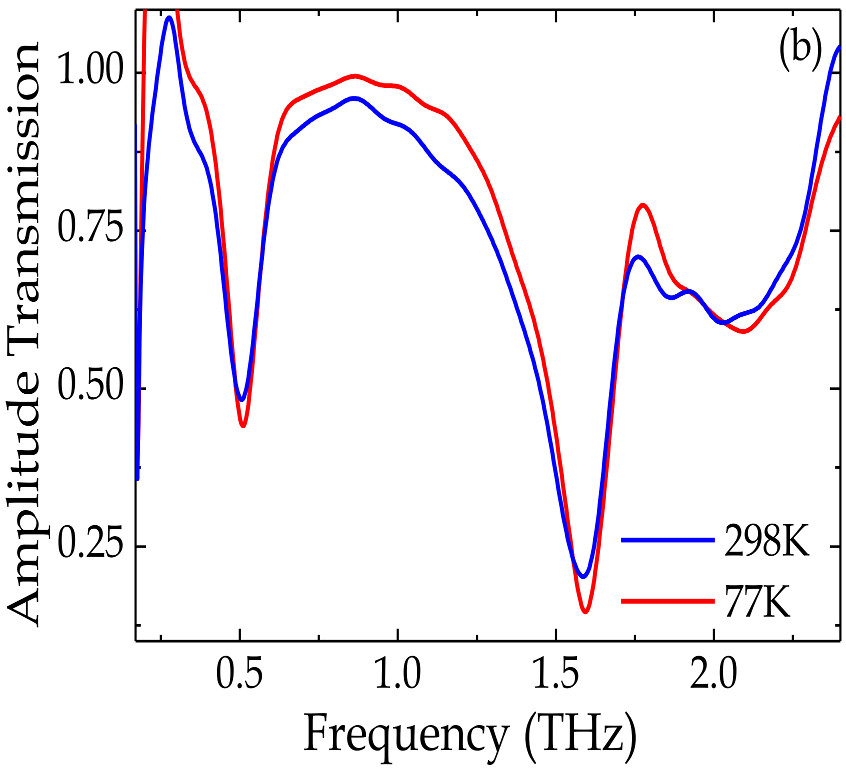
R. Singh et al., Opt. Lett. **33**, 1506 (2008)

Metal SRRs at cryogenic temperatures

Al SRR with metafilm thickness of 150 nm

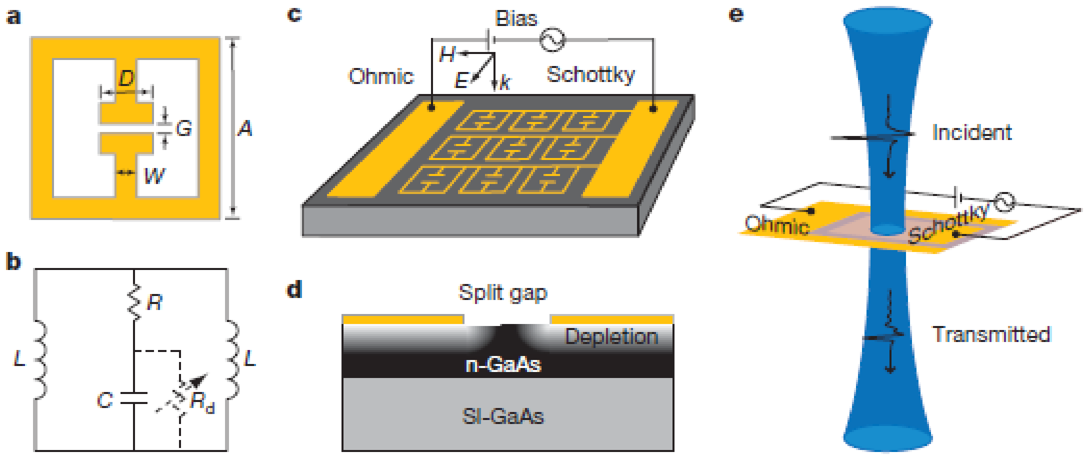
Only 13% enhancement in *Q* factor of LC resonance

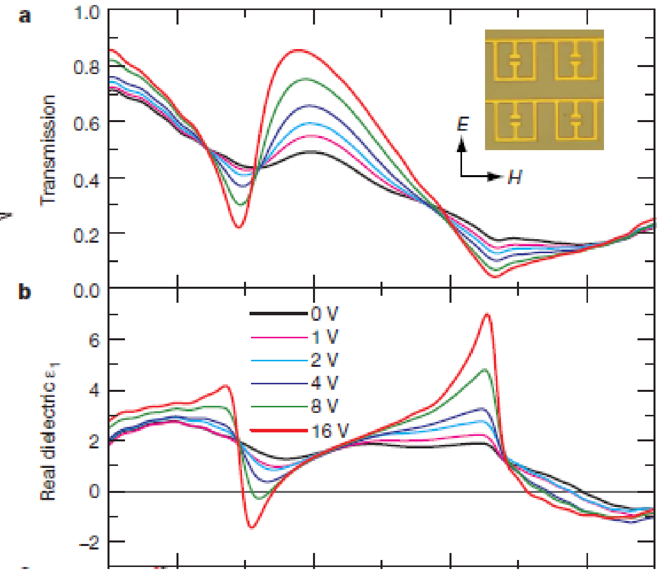




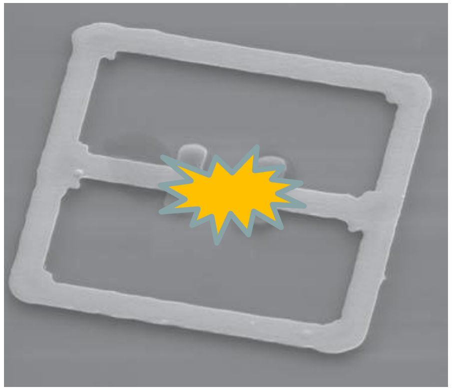
R. Singh et al., Appl. Phys. Lett. **96**, 071114 (2010)

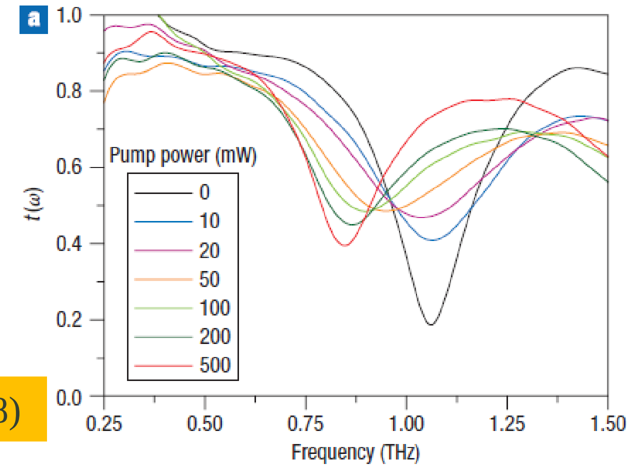
Tunable THz metamaterial-Semiconductors





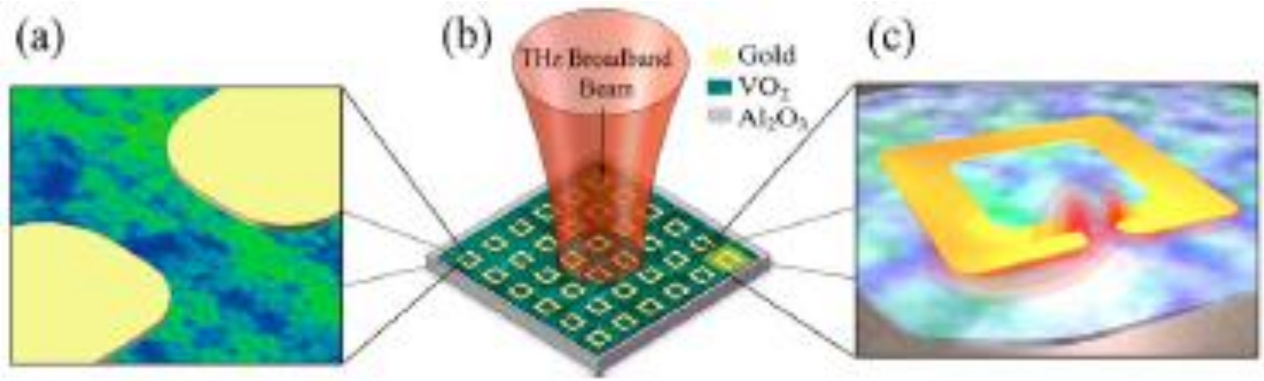
H.T Chen et al., Nature **444**, 597 (2006)

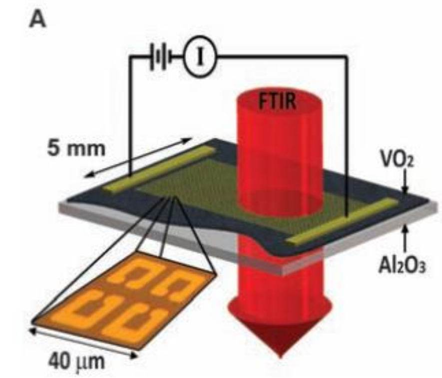




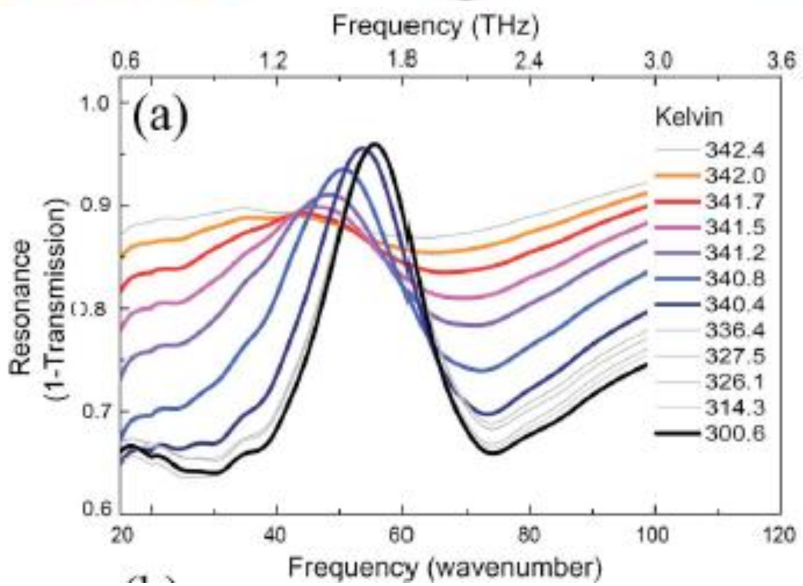
H.T Chen et al., Nature Photon. **2**, 295 (2008)

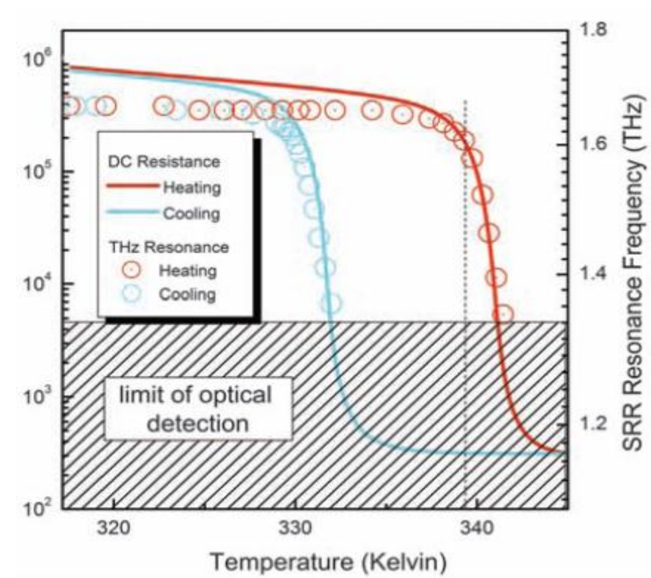
Tunable hybrid metamaterial using VO_2





Driscoll et al., Science **325**, 1519 (2009)





Driscoll et al., APL **93**, 024101 (2008)

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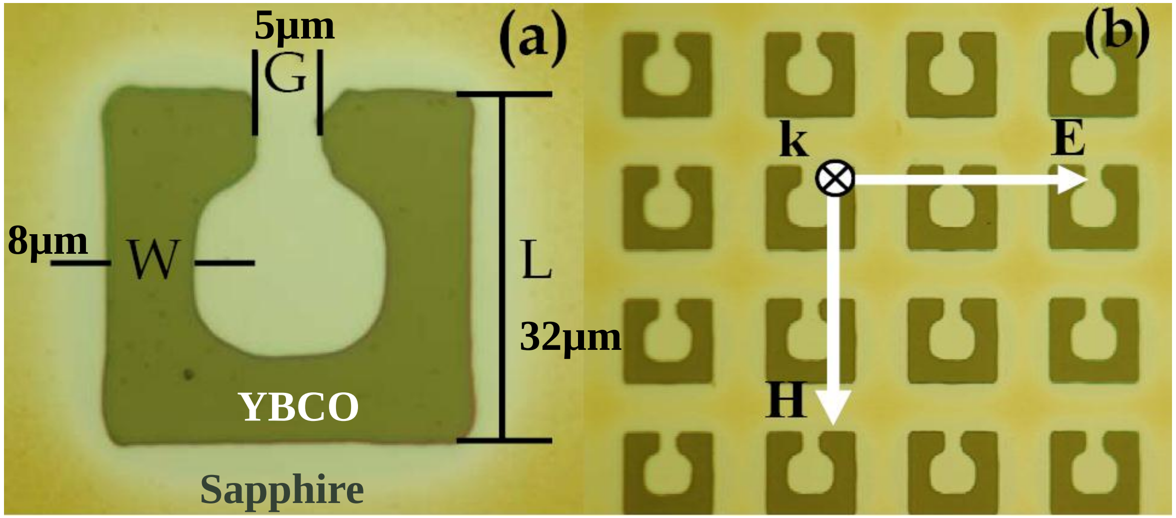
High Tc superconducting metamaterial



J. Gu et al., APL **97**, 071102 (2010)

$$\sigma_{re} = \frac{ne^2}{m^*}\frac{f_n(T)\tau}{1+\omega^2\tau^2}$$

$$\sigma_{im} = \frac{ne^2}{m^*}\left(\frac{f_n(T)\omega\tau^2}{1+\omega^2\tau^2} + \boxed{\frac{f_s(T)}{\omega}}\right)$$

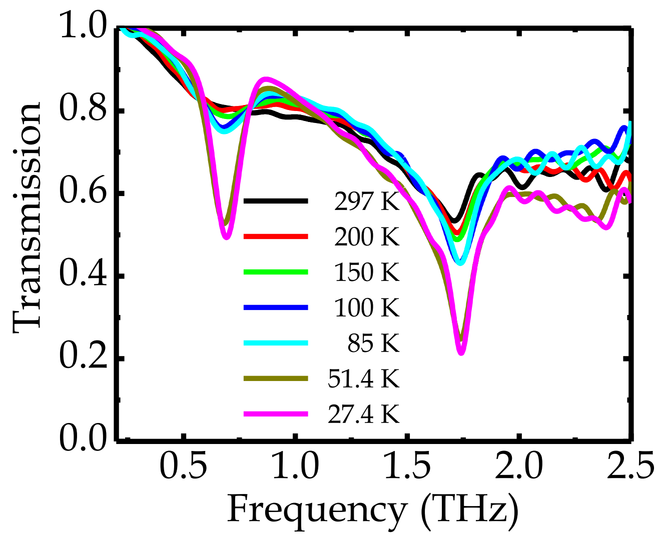
Cooper pairs!

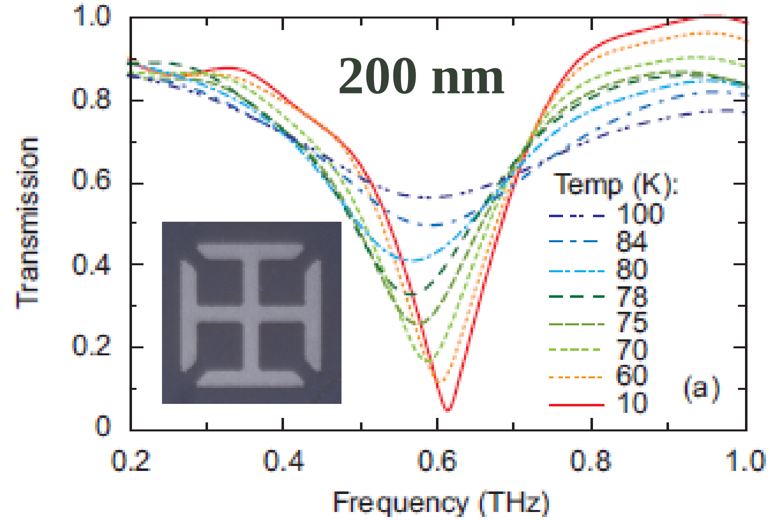
Provides an extra tuning Knob!

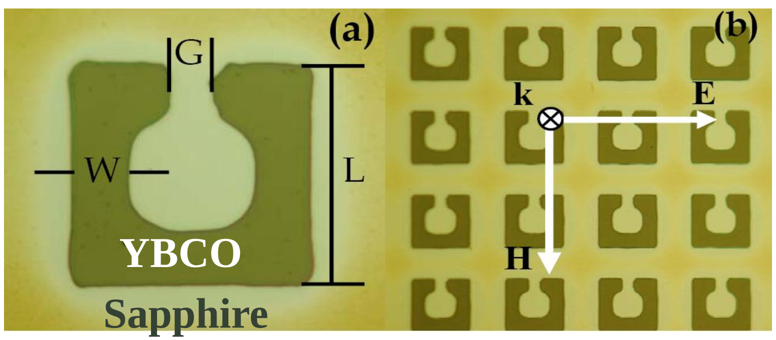
M. Ricci et al., Appl. Phys. Lett. **87**, 034102 (2005)

V. A. Fedotov et al., Opt. Express. **18**, 9015 (2010)

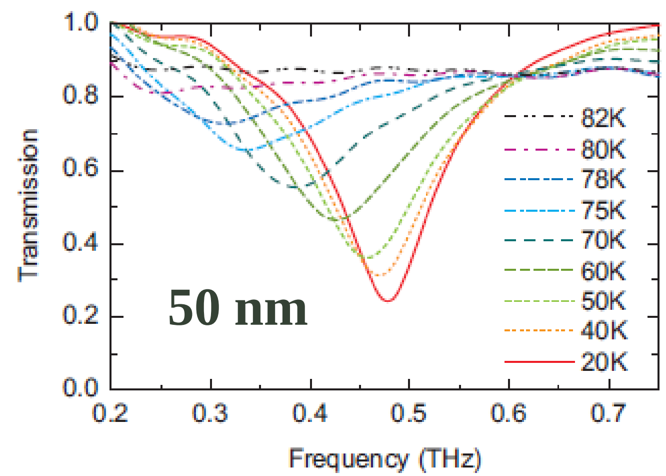
Temperature tuning in THz YBCO SRRs





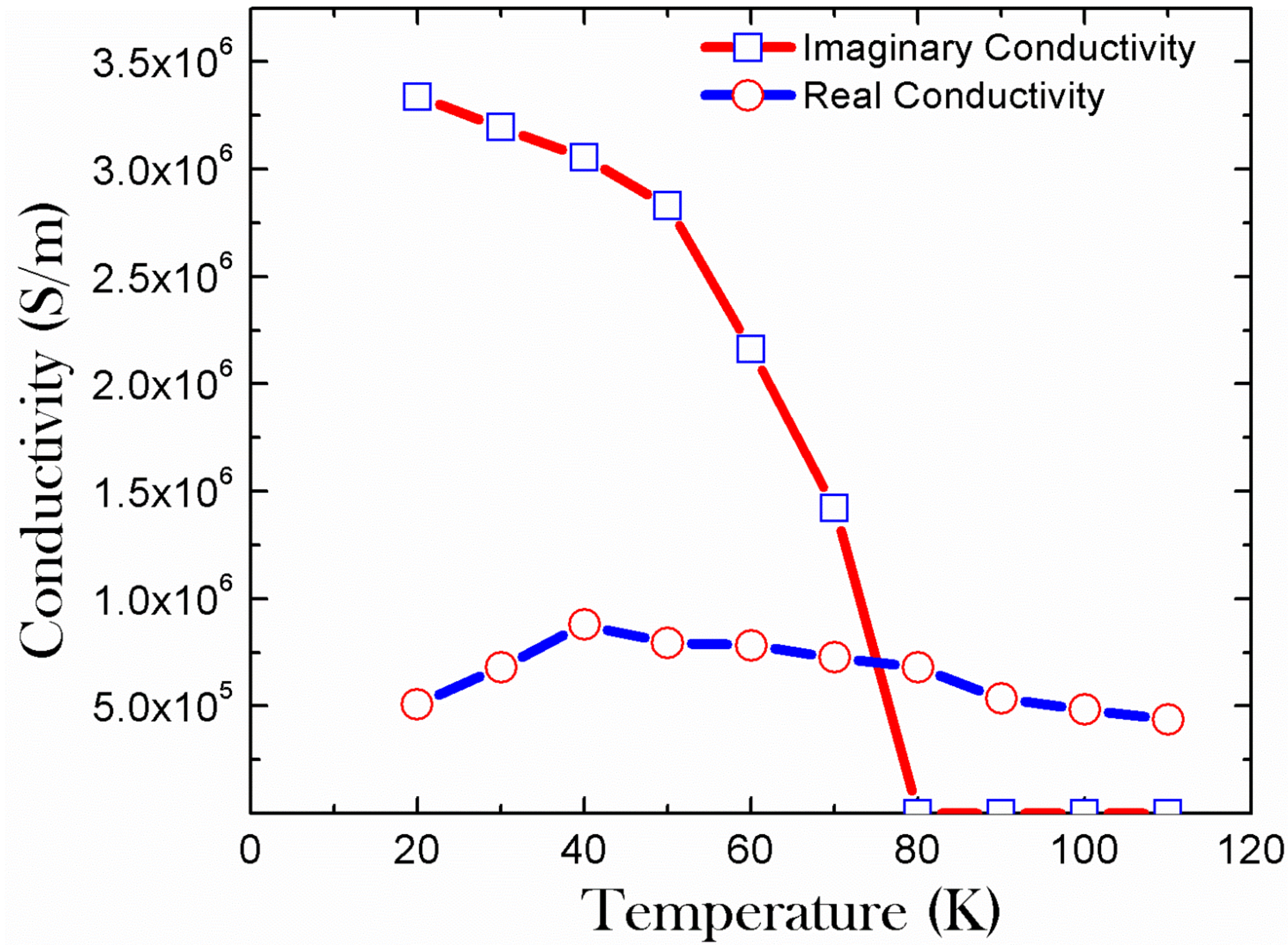


J. Gu et al., Appl. Phys. Lett. **97**, 071102 (2010)

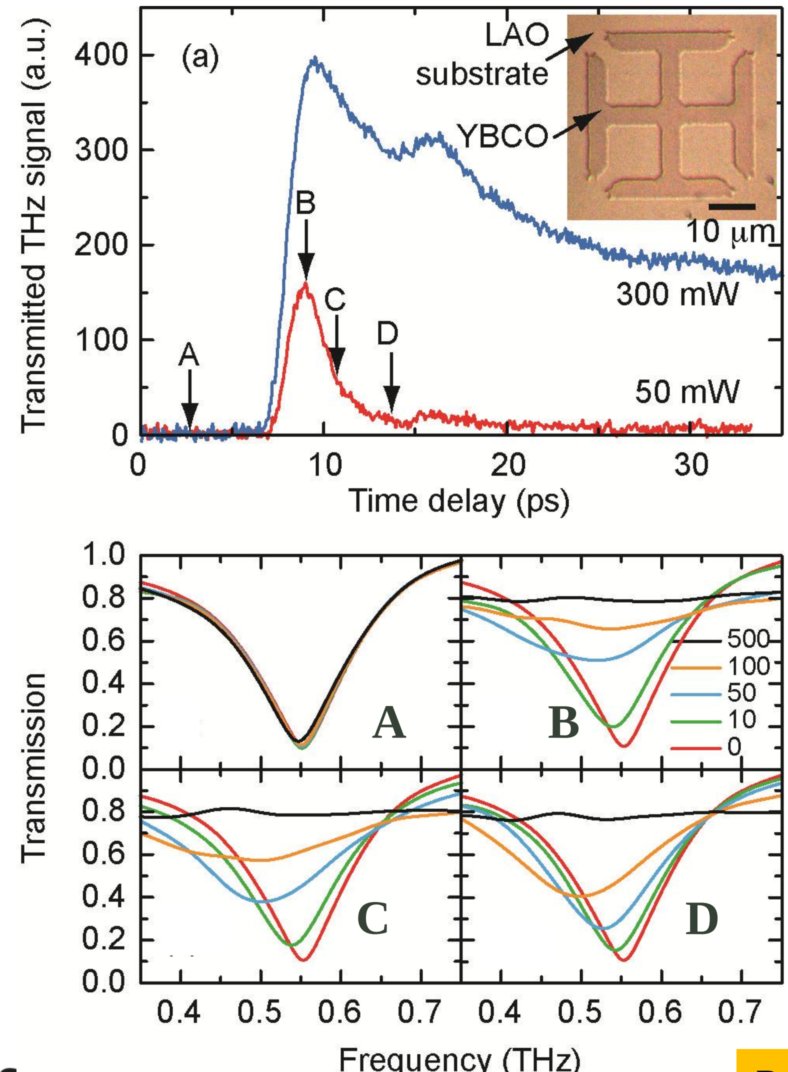


H. T. Chen et al., PRL **105**, 247402 (2010)

Measured conductivity of 100 nm YBCO film



Ultrafast Optical switching of YBCO MMs



Pump probe measurements

Pump = 800 nm light

Probe = THz

Laser beam: 50 fs, 3.2 mJ/ pulse
1 KHz repetition rate

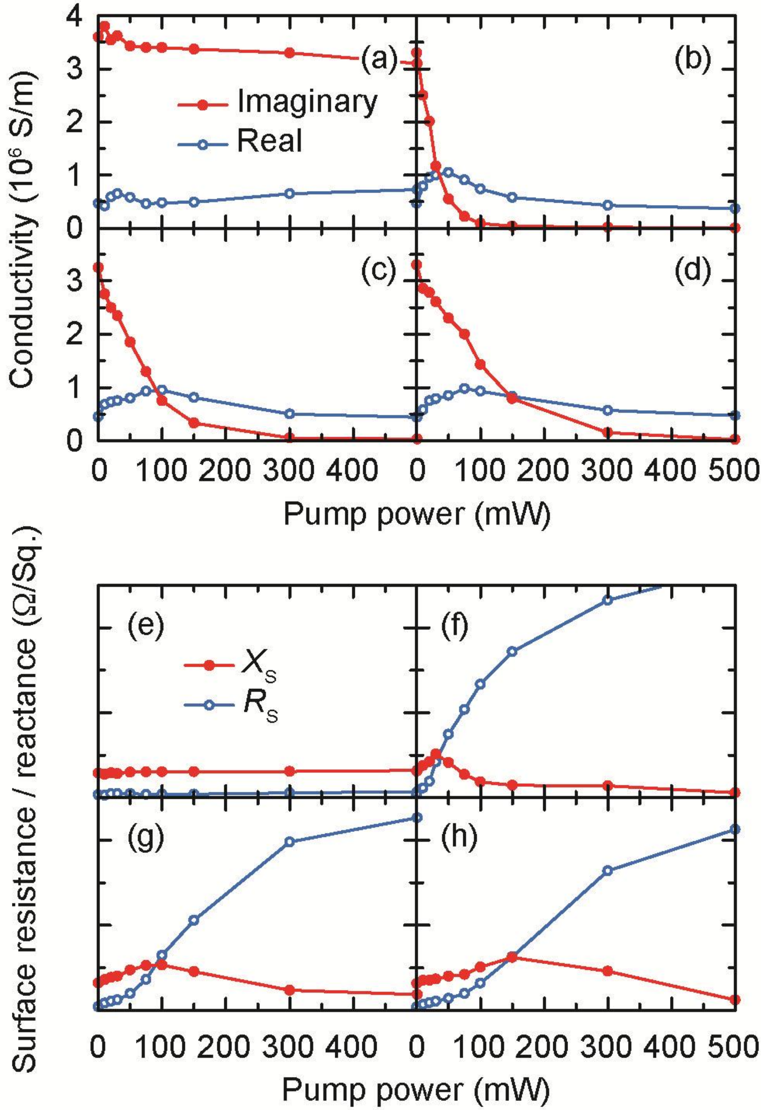
<u>All measurements done at 20 K</u>

Cooper pairs recombine in ~ 5 ps

Measurements at different dynamic points A, B, C, and D and different pump power

R. Singh et al., Nanophotonics (in press, 2012)

Tuned conductivity and surface impedance



Surface Impedance of YBCO film

$$Z_s = R_s + iX_s = Z_0 \frac{n_3 + i n_2 \cot(\beta d)}{n_2^2 - n_3^2}$$

$$n_2 = \sqrt{\frac{i\sigma}{\varepsilon_0 \omega}}$$ *Index of YBCO*

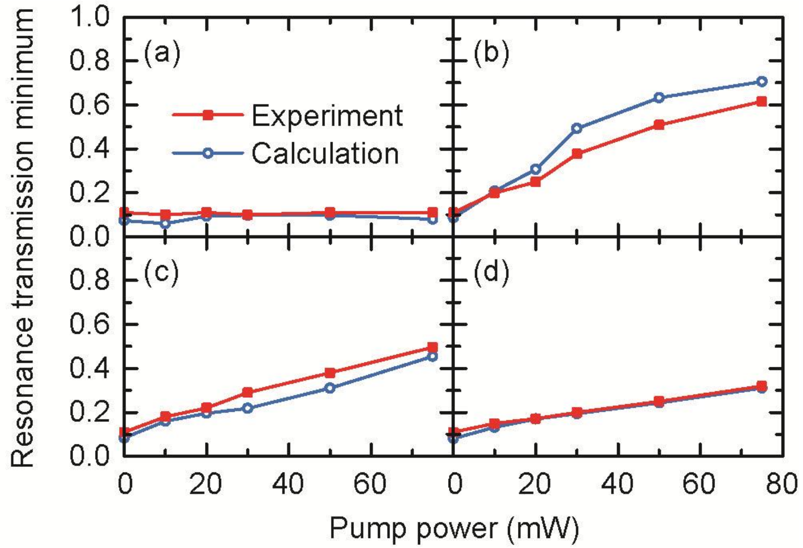
$$\beta = \frac{n_2 \omega}{c_0}$$ *Propagation constant*

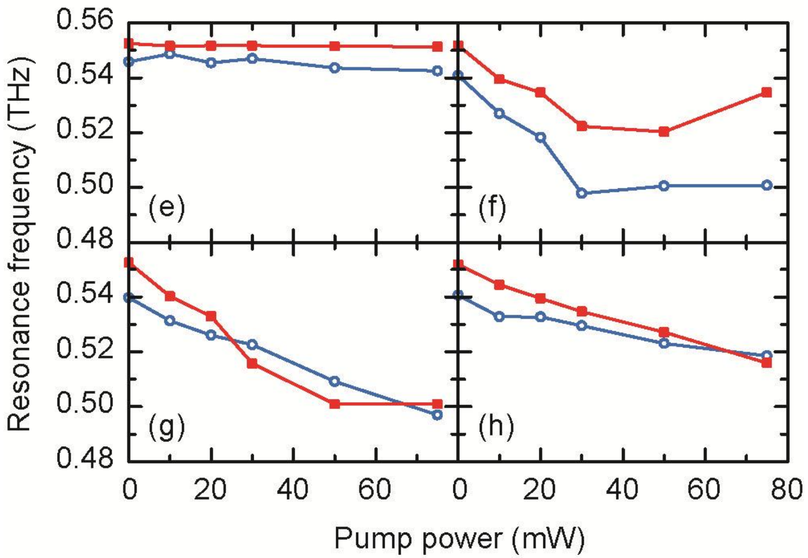
d = *YBCO film thickness*

n_3 = *Substrate Index*

σ = *Measured YBCO conductivity*

Transmission and resonance frequency





$$R = [(A - g)/w]R_s$$

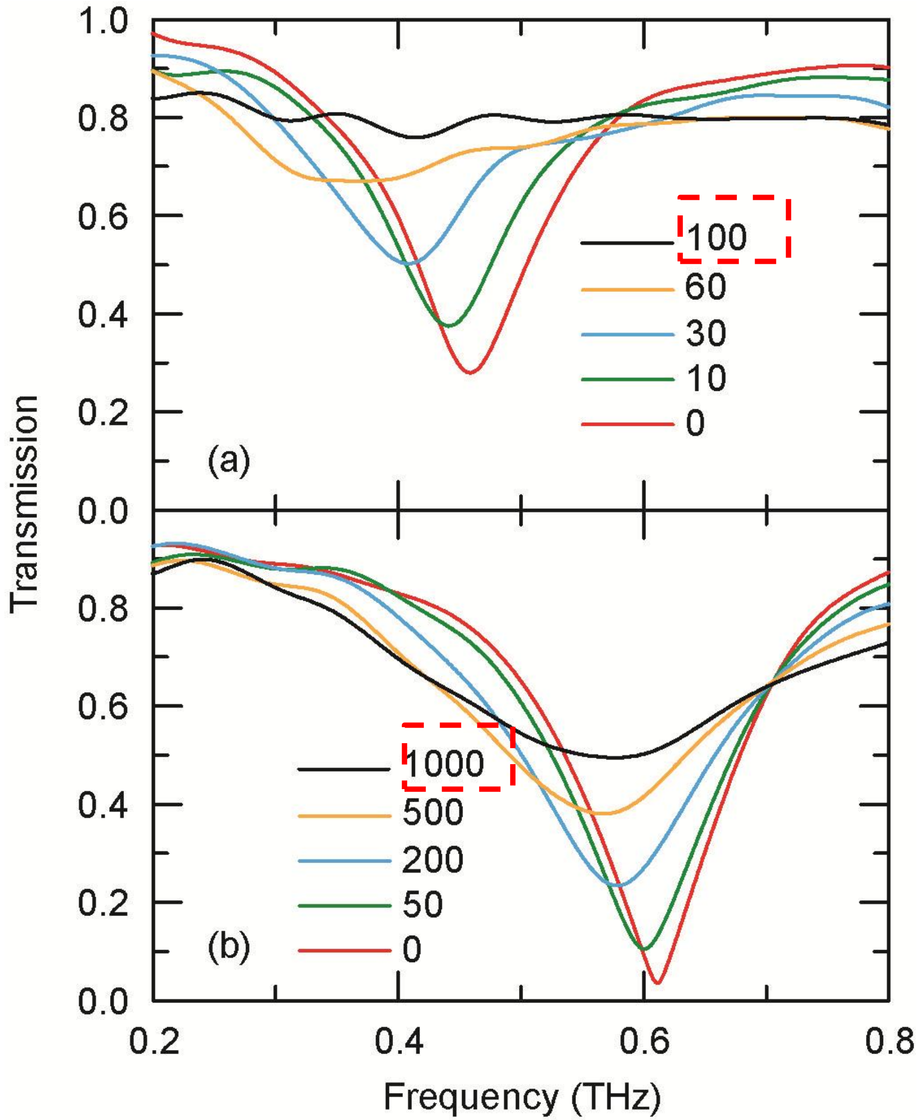
To account for high Ohmic losses

$$\omega_0^2 = \frac{1}{LC} - \boxed{\frac{R^2}{4L^2}}$$

$$L = L_g + L_k$$

$$L_k = [(A - g)/w](X_s/\omega)$$

Different thickness YBCO SRRs

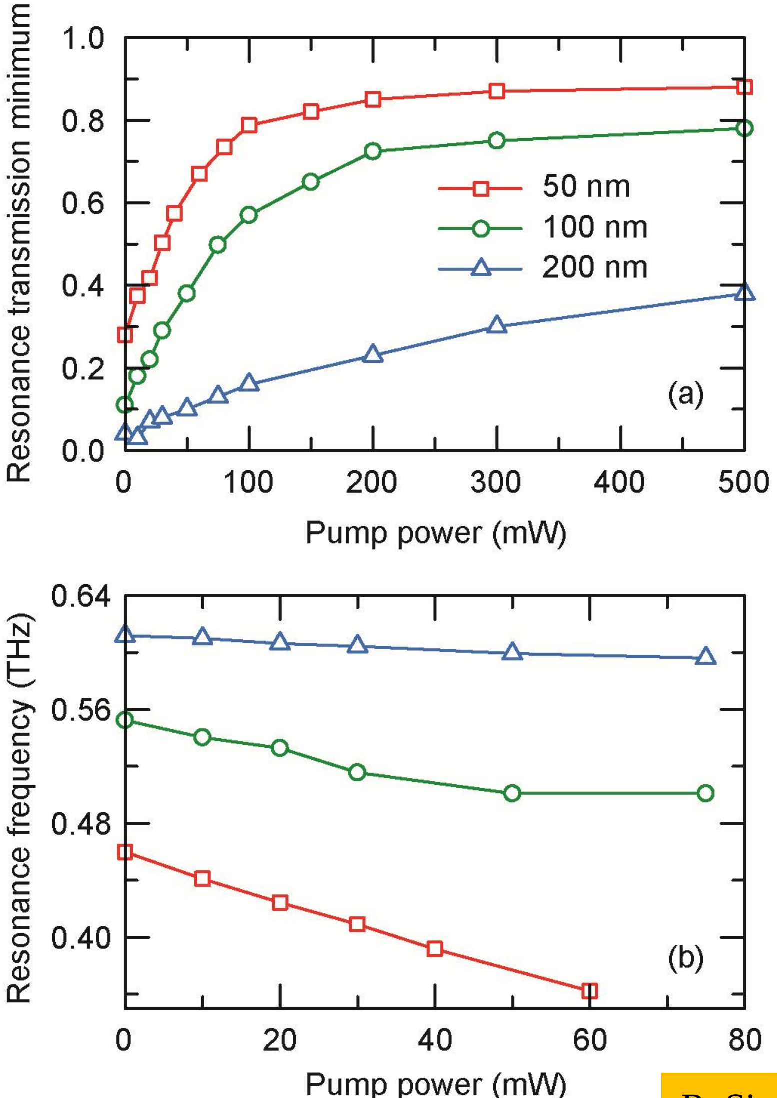


50 nm YBCO SRRs

200 nm YBCO SRRs

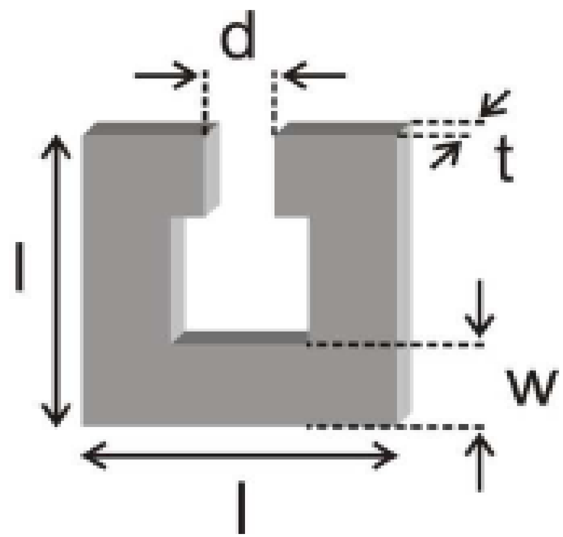
Thinner films require lower pump fluence to switch the resonance!

Tuning in different thickness YBCO SRRs



R. Singh et al., Nanophotonics (in press, 2012)

Tuning LC resonance through substrate



$$L = \mu_0 \frac{l^2}{t}$$

$$C = \varepsilon_0 \varepsilon_C \frac{wt}{d}$$

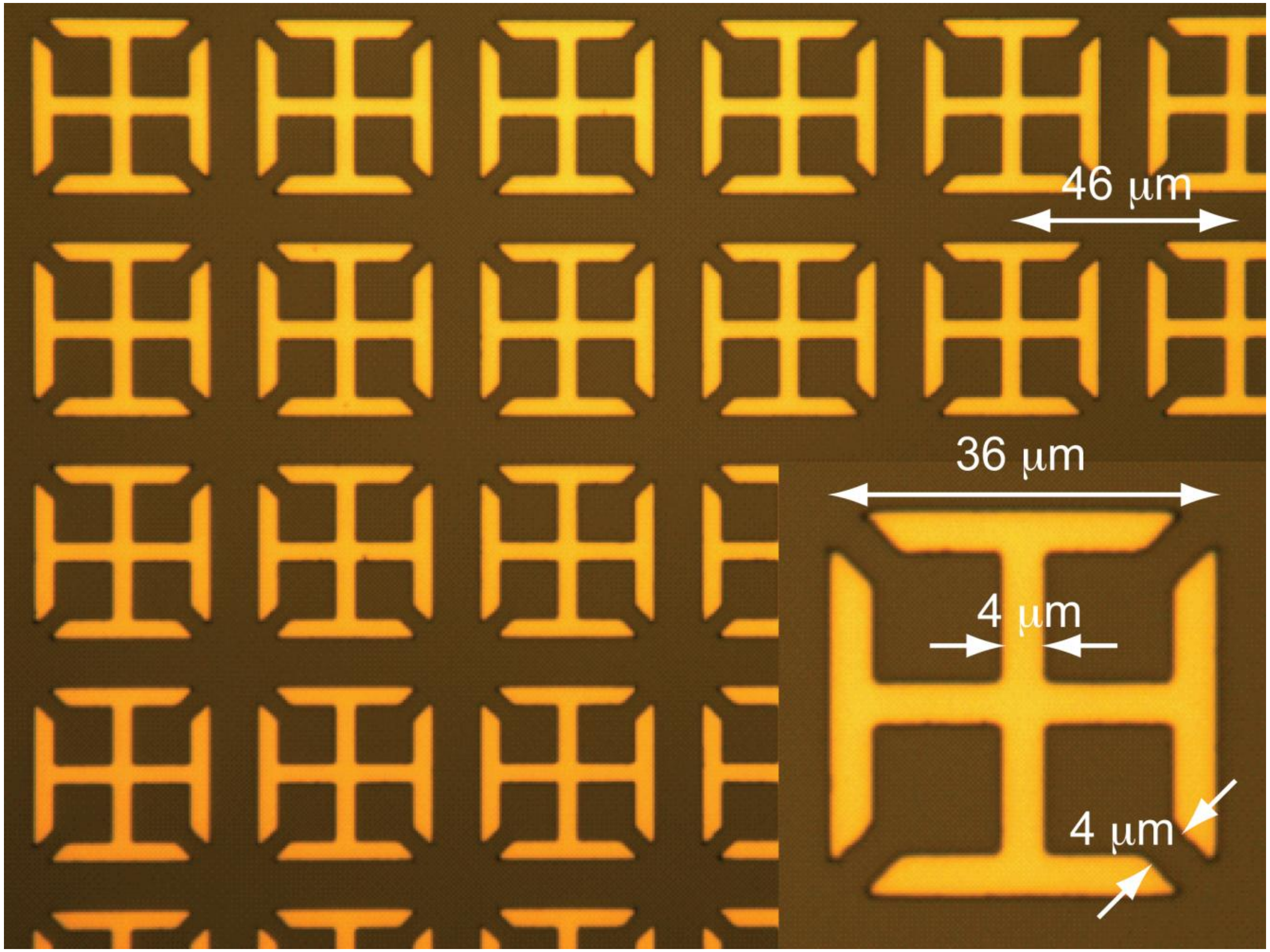
$$\omega_{LC} = \frac{1}{\sqrt{LC}}$$

$$\lambda_{LC} = 2\pi l \sqrt{\varepsilon_C} \sqrt{\frac{w}{d}}$$

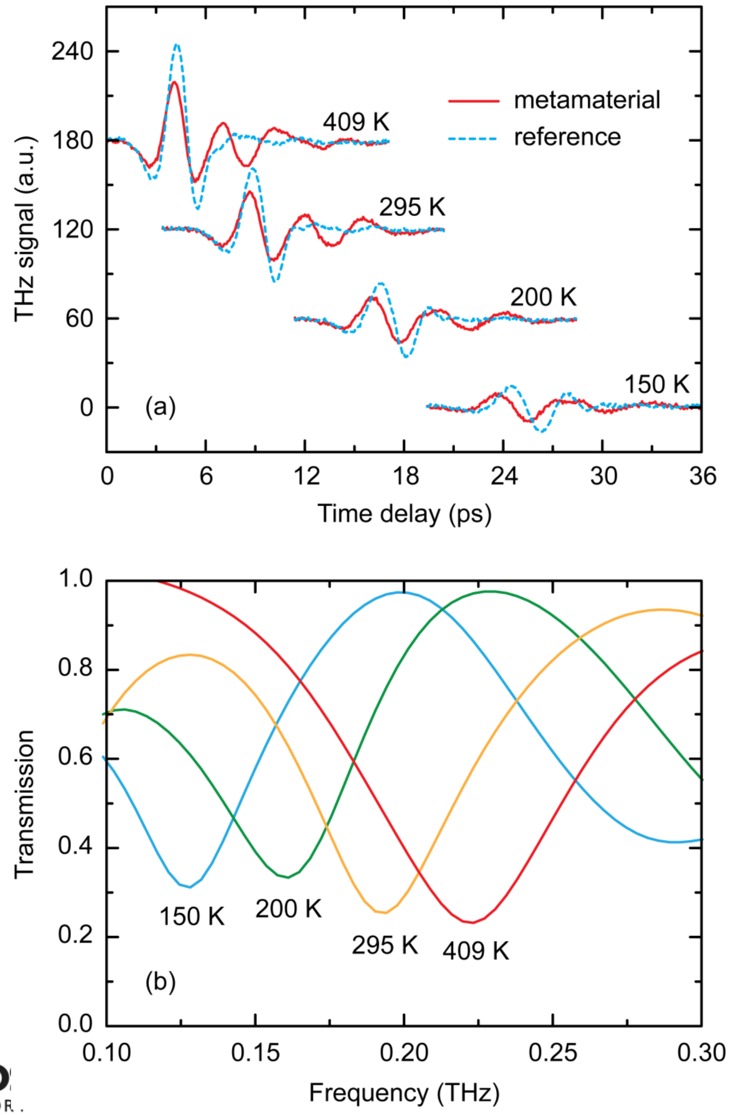
Substrate dielectric

Linden et al., Science **306**, 5514 (2004)

Gold SRRs on bulk STO ($SrTiO_3$) substrate



High Tunability

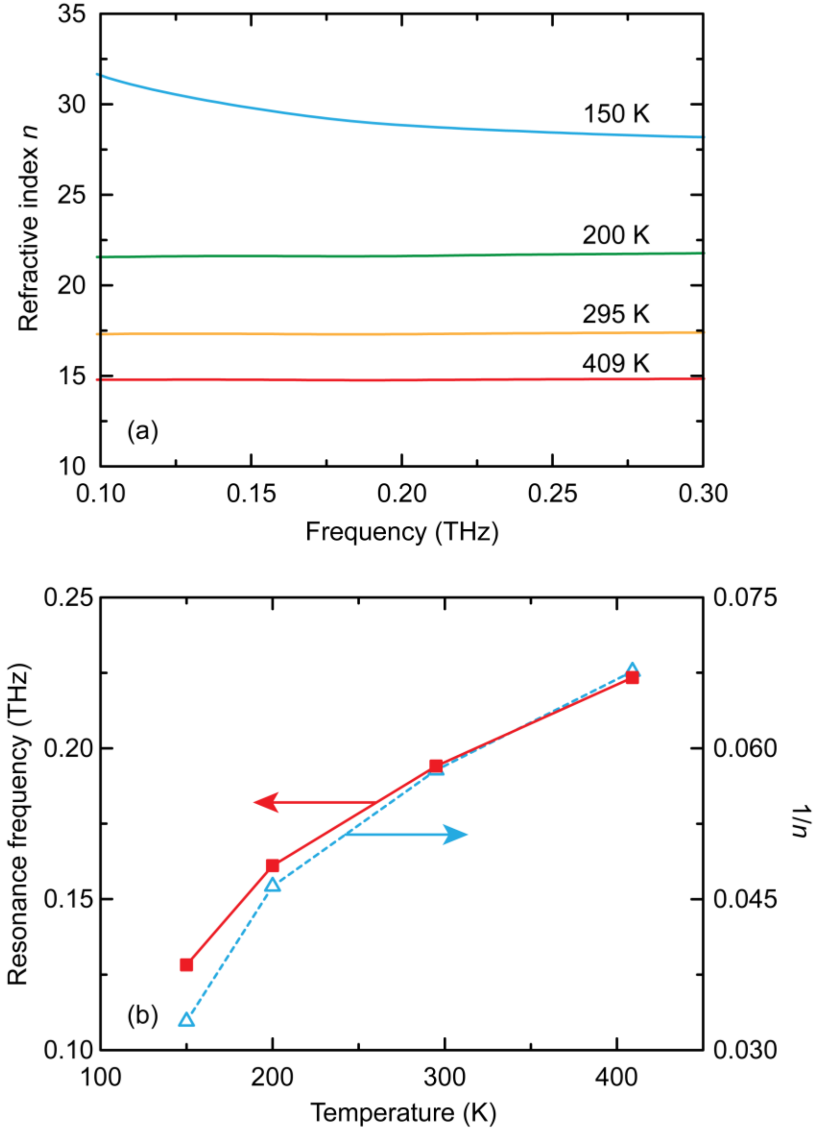


Picosecond pulses arriving later in time due to change in substrate index with decreasing temperature

Resonance tunability is 43%

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

Change in STO dielectric properties



Curie –Weiss law

$$\varepsilon_0 = \frac{C}{T - T_c}$$

$$\omega_{LC} = \frac{1}{\sqrt{LC}} \sim \frac{1}{n}$$

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

Conclusion

- ❖ High Tc superconductors good for tunable and ultrafast metamaterials
- ❖ Large frequency and amplitude tunability in ultrathin superconductor films
- ❖ Such tunable properties cannot be accessed using metals
- ❖ Complex metal oxides can be used as active substrates – large tunability
- ❖ Complex oxides fail to address the issue of radiation losses in THz metamaterials

THANK YOU