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Title: Response of High-Tc Superconductor Metamaterials to High Intensity THz Radiation

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Response of High-T_c Superconductor Metamaterials to High Intensity THz Radiation

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Massachusetts Institute of Technology

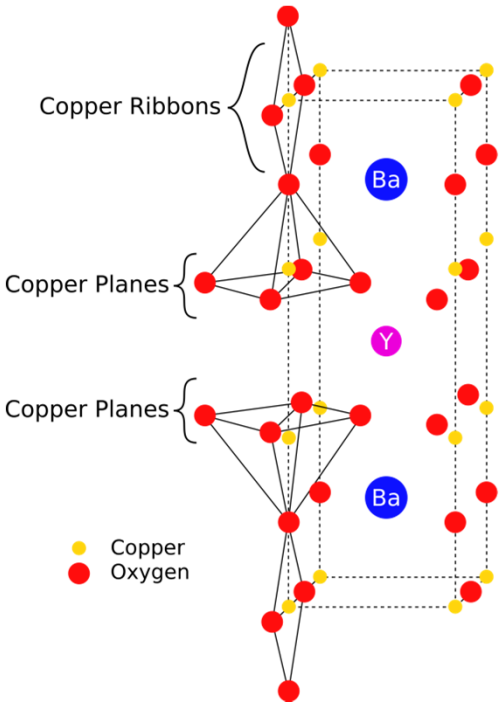
Introduction

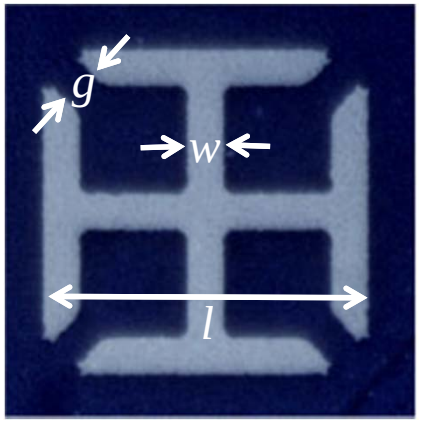
YBCO

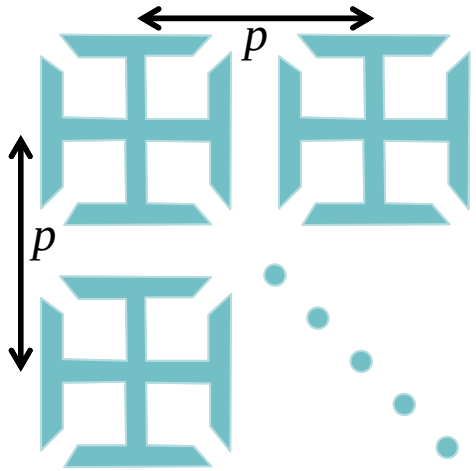
- High T_c superconductor
- Epitaxially grown on 0.5 mm thick $LaAlO_3$ substrates by pulsed laser deposition
- $T_c \approx 91$ K

High intensity THz-pump THz-probe spectroscopy

- Metamaterials:
  - Active devices
- Thin Films:
  - Mechanism of nonlinearity

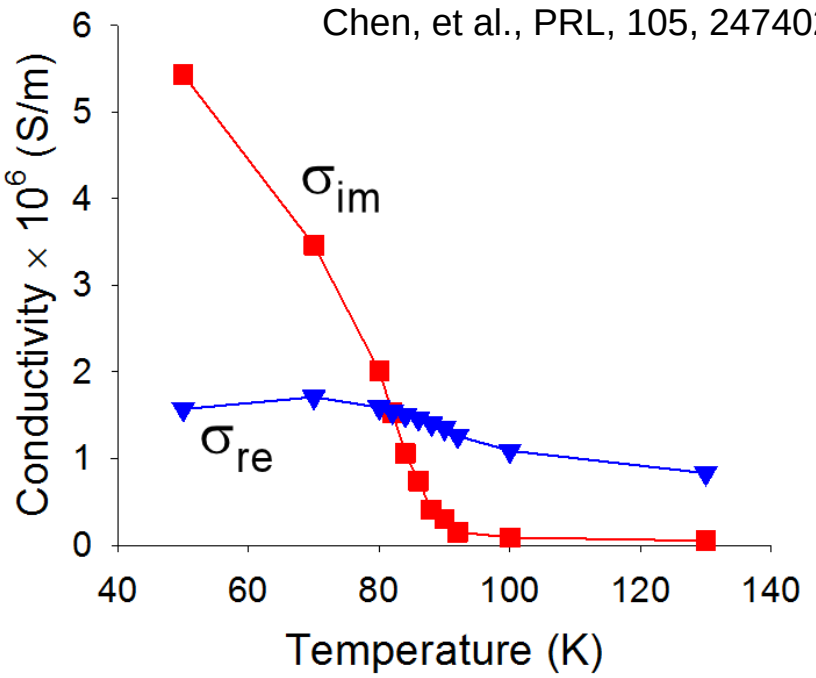






Spectroscopic Characterization of YBCO

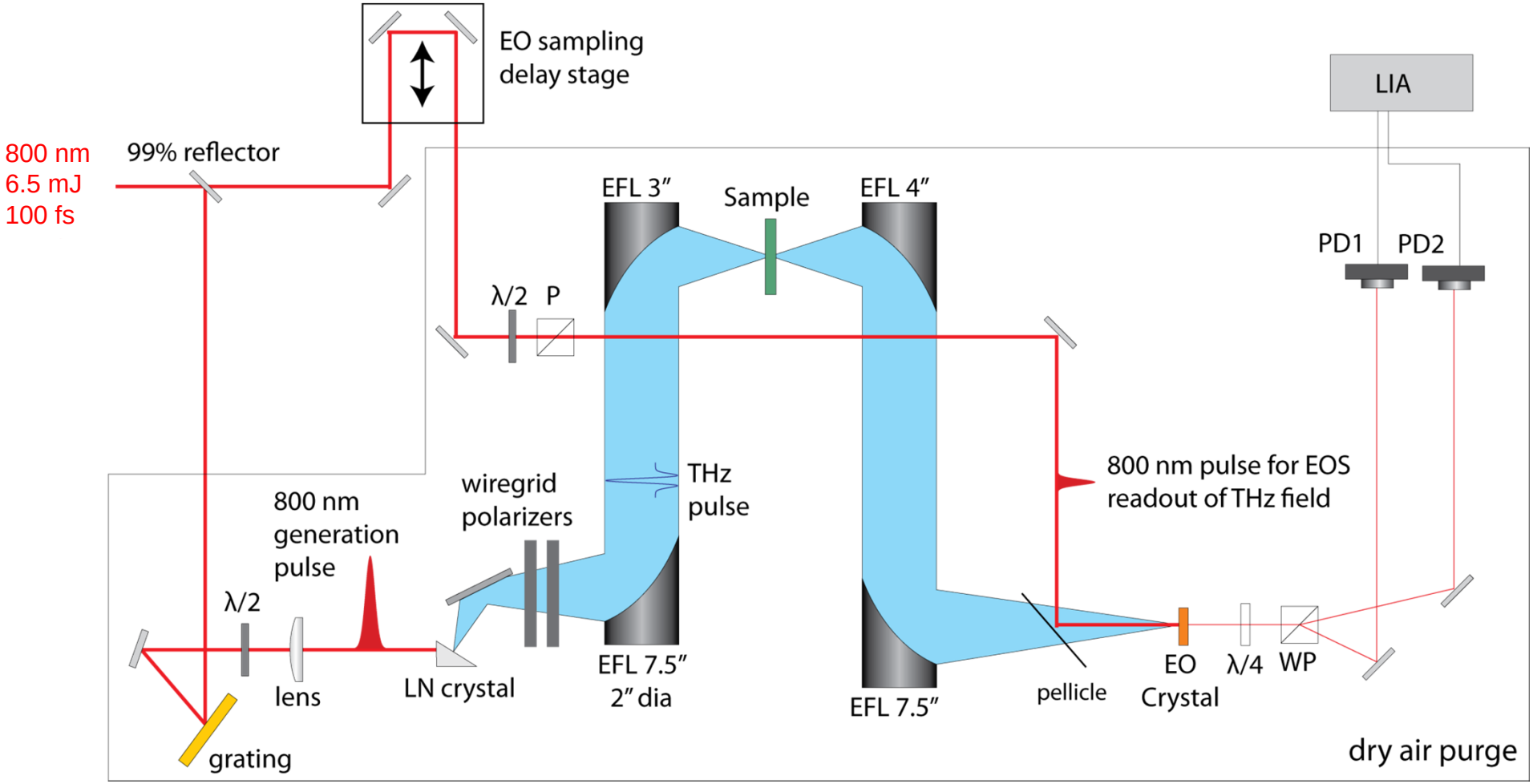
- THz Time-Domain Spectroscopy
  - Amplitude and phase
  - Complex conductivity at 0.6 THz
- Conductivity above T_c
  - Real conductivity – normal carrier population
- Superconductivity
  - Transition temperature ~ 90 K
  - Imaginary conductivity grows as temperature drops
- Two-fluid model
  - Normal carrier fraction: $f_n(T)$
  - Superfluid fraction: $f_s(T)$



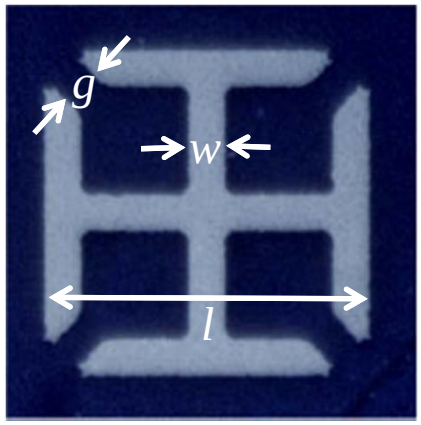
$$\sigma_{re} = \frac{ne^2}{m^*} \cdot \frac{f_n(T) \cdot \tau}{1+\omega^2\tau^2}$$

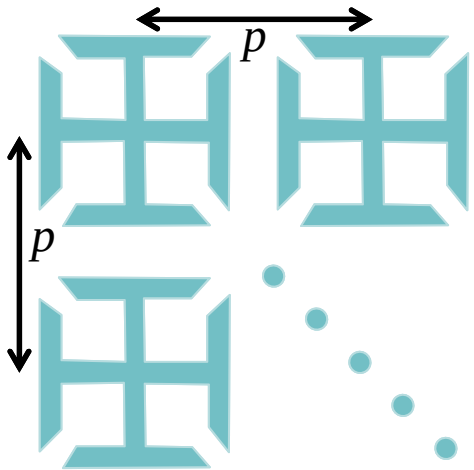
$$\sigma_{im} = \frac{ne^2}{m^*} \cdot \left[\frac{f_n(T) \cdot \tau}{1+\omega^2\tau^2} + \frac{f_s(T)}{\omega} \right]$$

High Intensity THz Source:
Tilted Pulse Front Optical Rectification

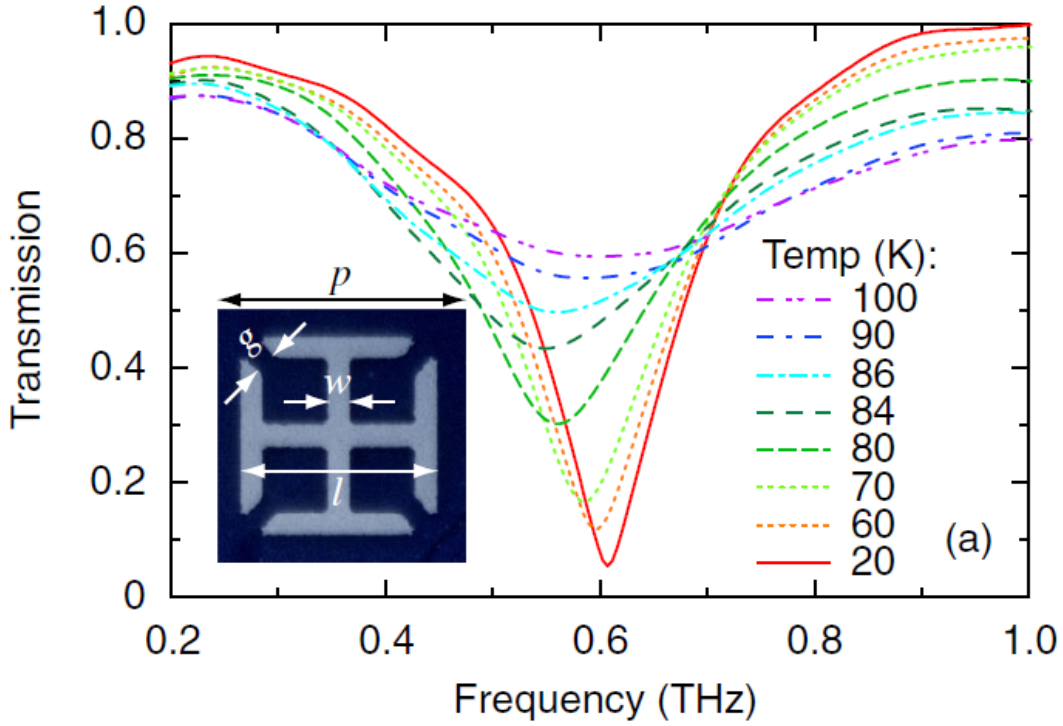


YBCO Metamaterials



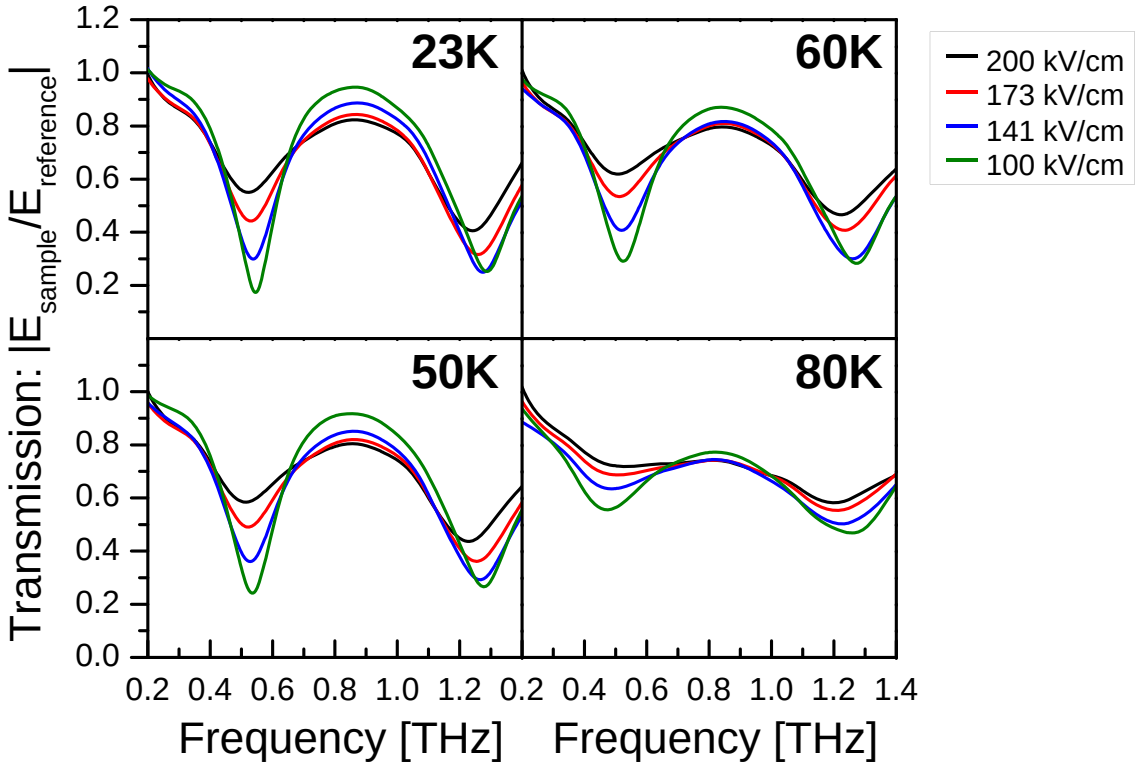


- Metamaterial fabricated from 100 nm thick YBCO film: g = 4 μm, w = 4 μm, l = 46 μm, p = 46 μm



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

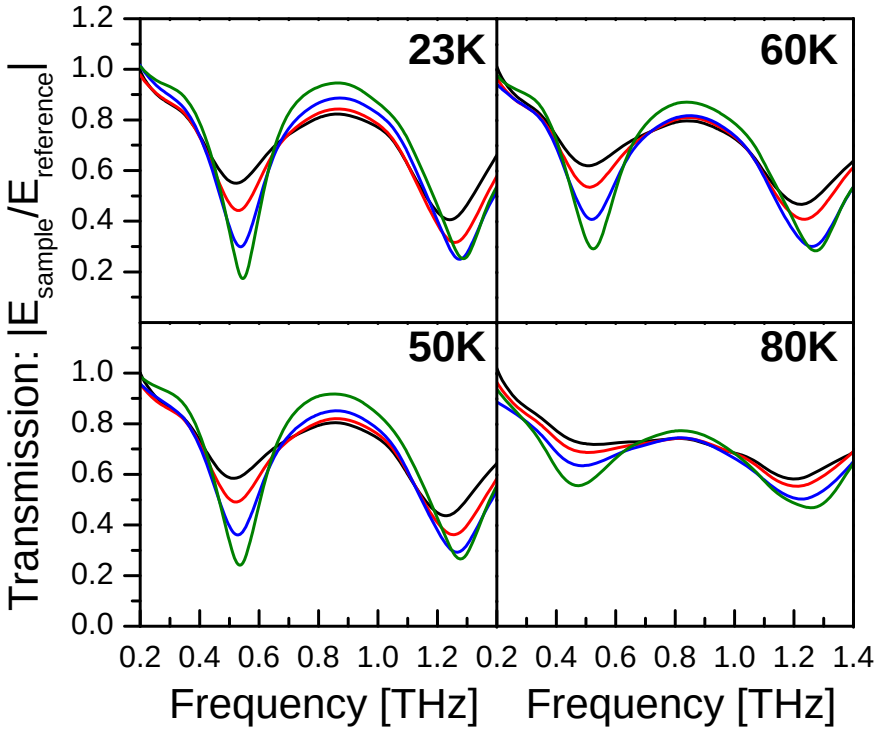
Intensity-Dependent Transmission: Metamaterial

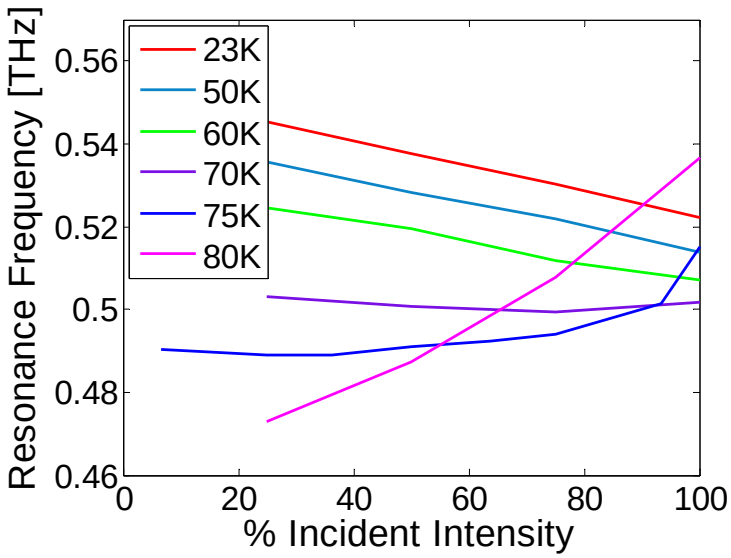


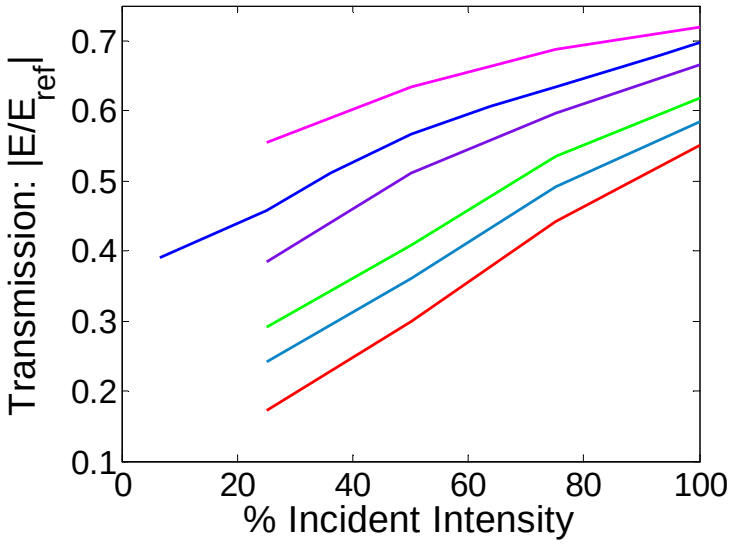
Increase incident intensity:

- Transmission increases: turning off resonance
- Resonance frequency shifts

Intensity-Dependent Transmission: Metamaterial



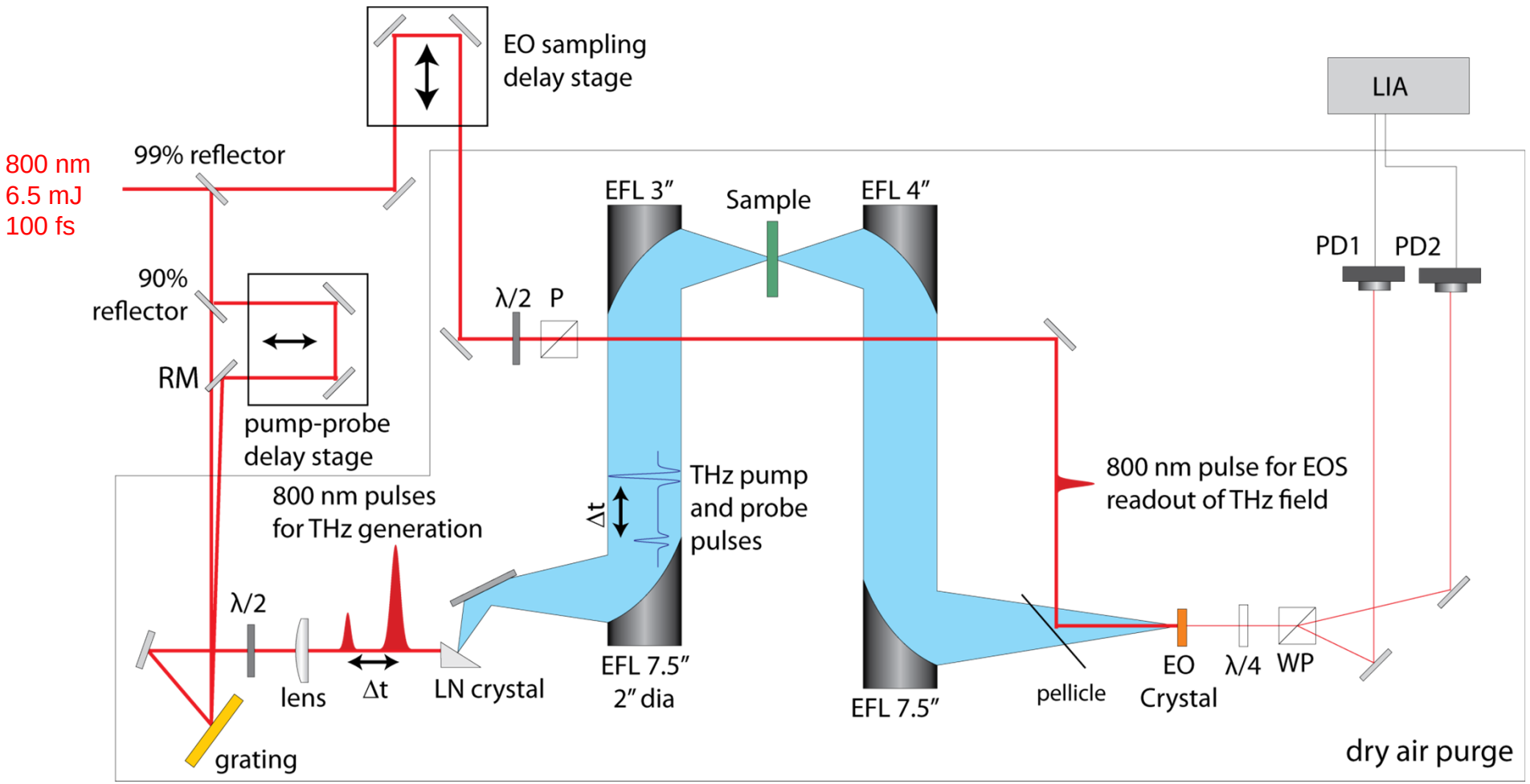




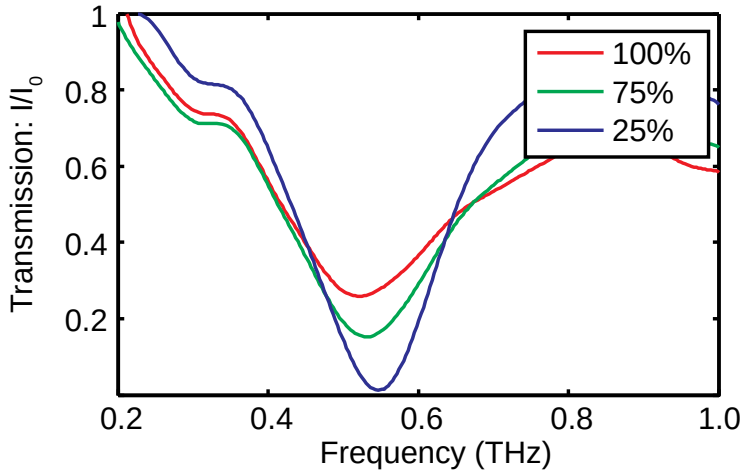
Increase incident intensity:

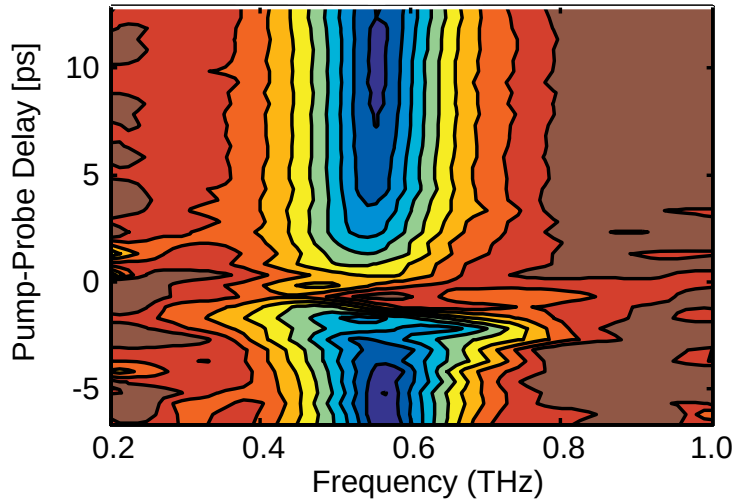
- Red-shift at low temperature
- Blue-shift at high temperature
- Transmission increases

High Intensity THz Source:
Tilted Pulse Front Optical Rectification

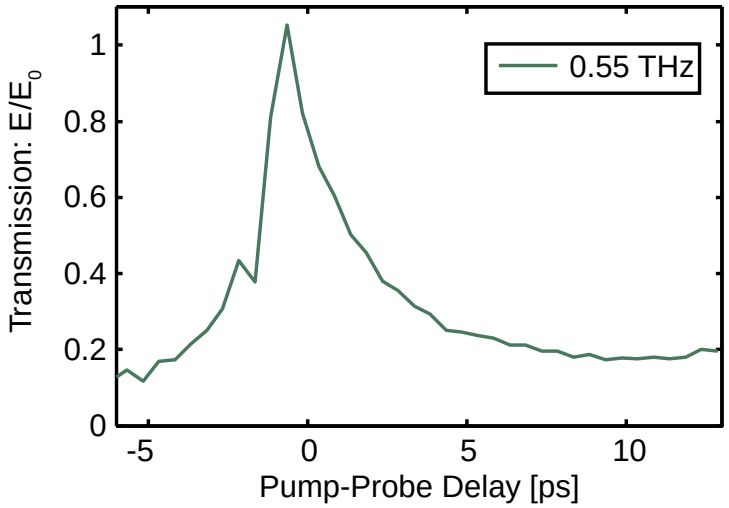


Dynamics: Metamaterial

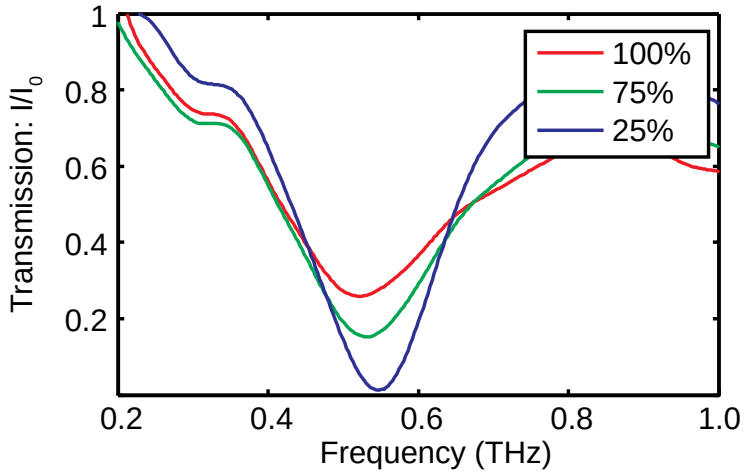


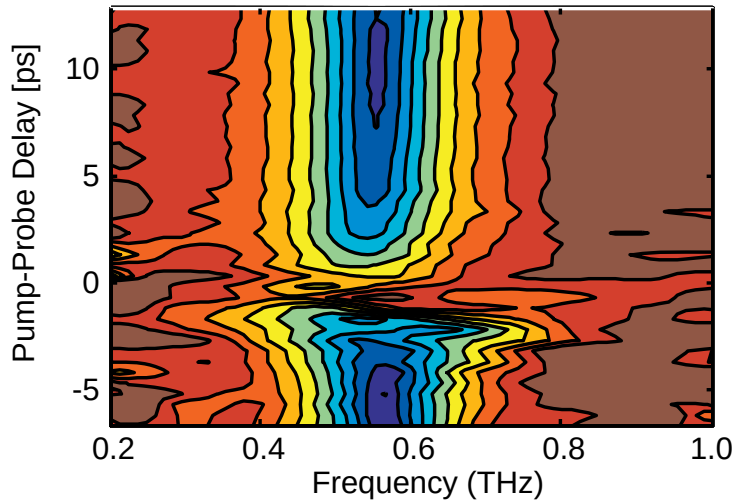


- Measure THz-TDS trace at every pump-probe delay
- Transmission shifts to higher energy and increases in strength with increasing pump-probe delay

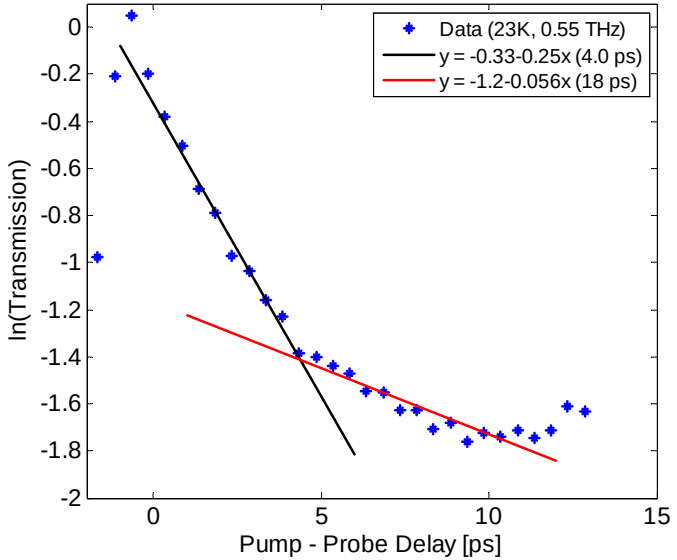


Dynamics: Metamaterial

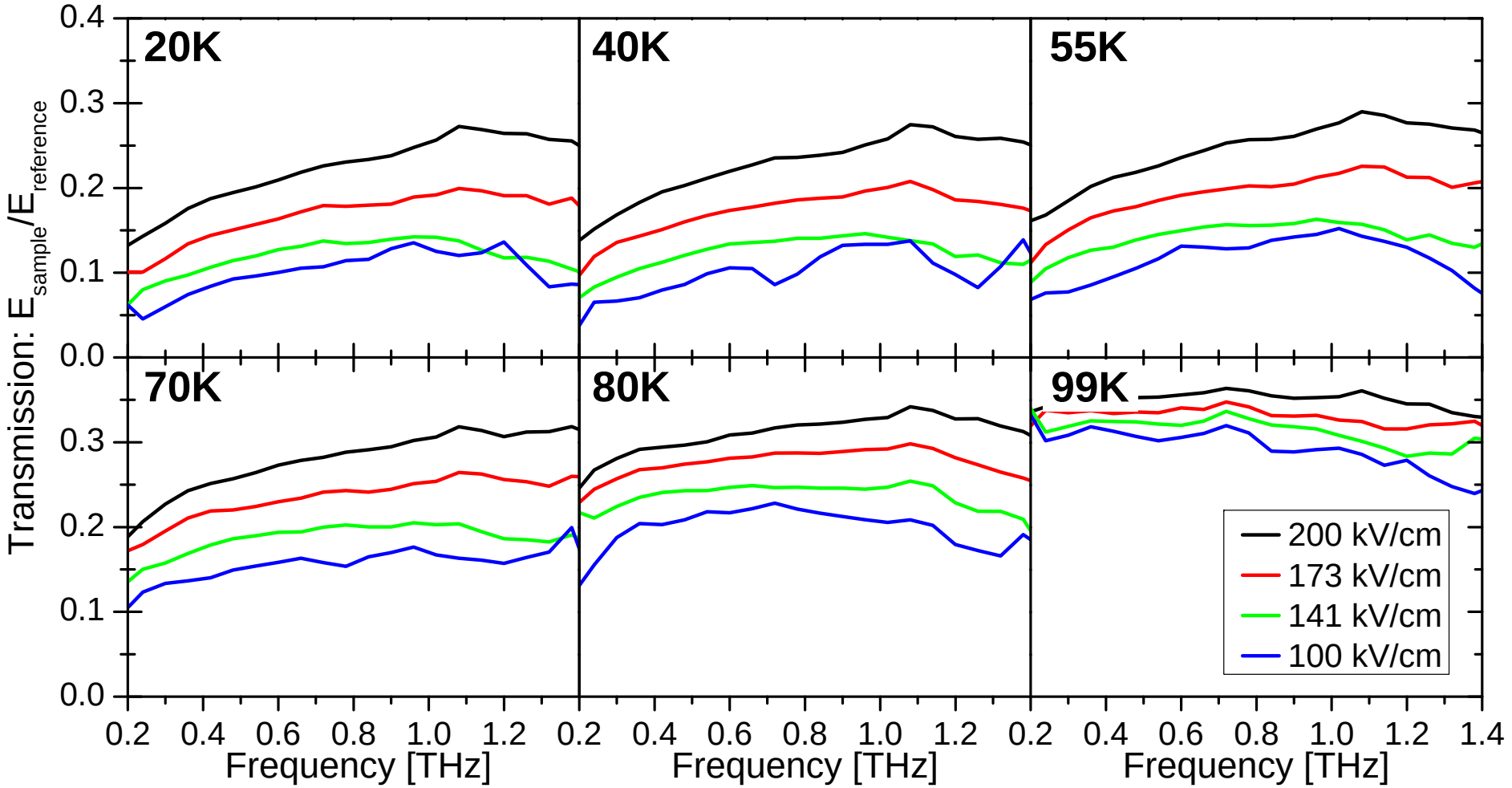




- Measure THz-TDS trace at every pump-probe delay
- Transmission shifts to higher energy and increases in strength with increasing pump-probe delay
- Two component decay

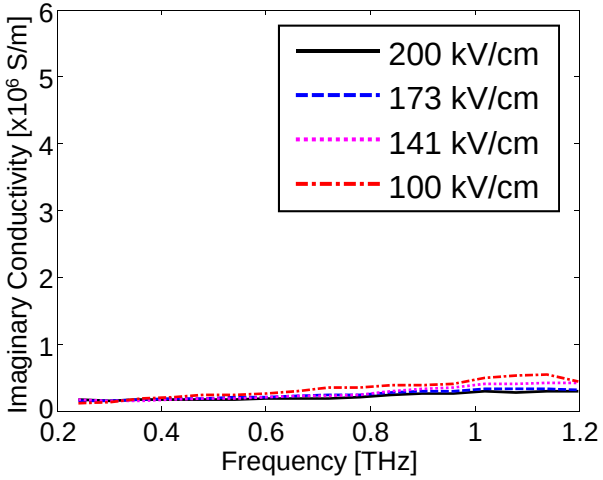


THz Field Dependent Transmission Spectra: 50 nm thick film

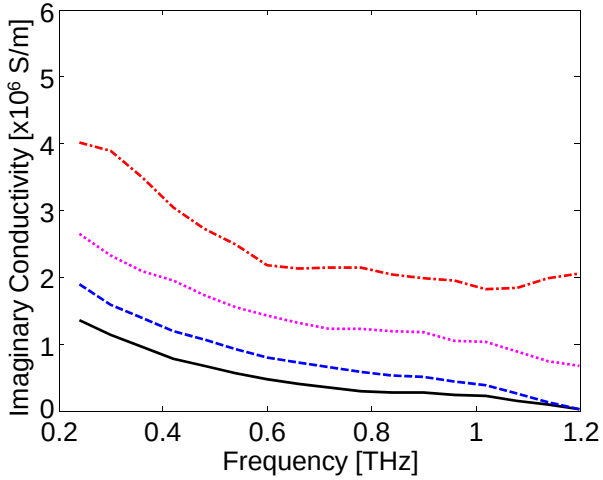


50 nm YBCO Film Conductivity

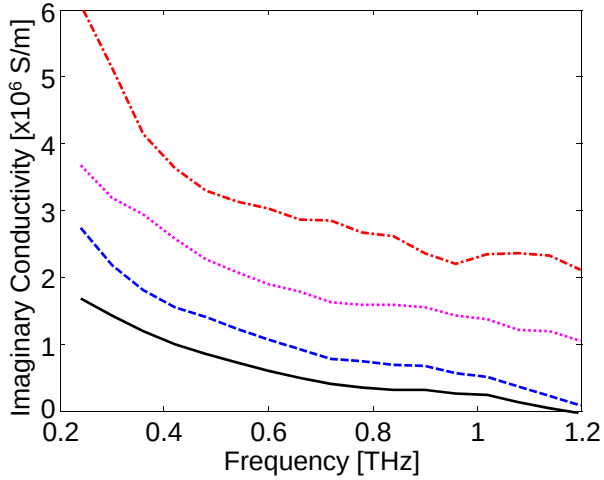
Temperature = 99K



Temperature = 55K

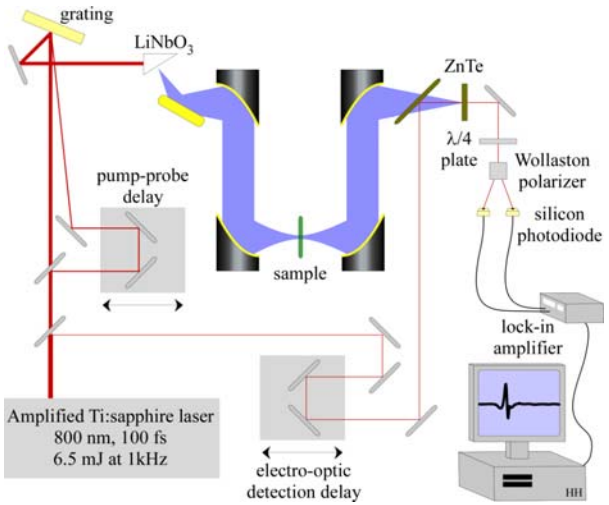


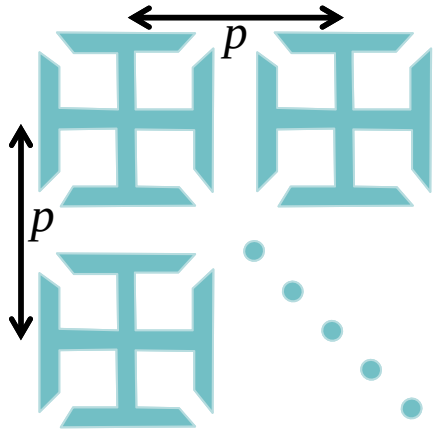
Temperature = 20K

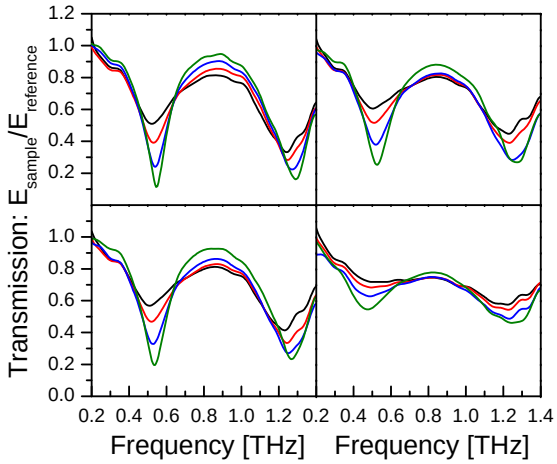


- THz-TDS: both magnitude and phase of electric field measured ∴ can extract complex refractive index
- Two Fluid Model:
  - Residual normal carrier Drude response + Superconducting Cooper pairs: $\tilde{\sigma} = \tilde{\sigma}_n + \tilde{\sigma}_s$
  - $\sigma_{im} = \frac{ne^2}{m}\left[\frac{\boldsymbol{f_n}\,\omega\,\tau^2}{1+\omega^2\,\tau^2} + \frac{\boldsymbol{f_s}}{\boldsymbol{\omega}}\right]$
- Superconductivity decreases with increasing THz field strength
- Breaking cooper pairs: Impact ionization? Ballistic acceleration of supercurrent?
- Change in conductivity → Shift in metamaterial resonance

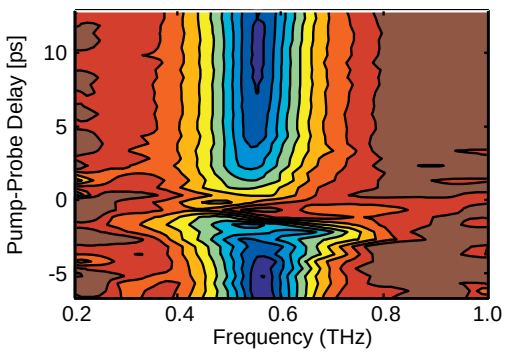
Conclusions

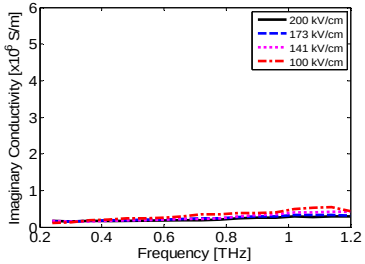


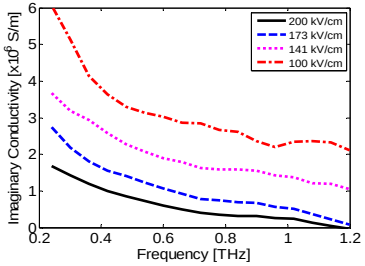




Investigated the spectral and dynamic response of YBCO films and metamaterials to high intensity THz radiation







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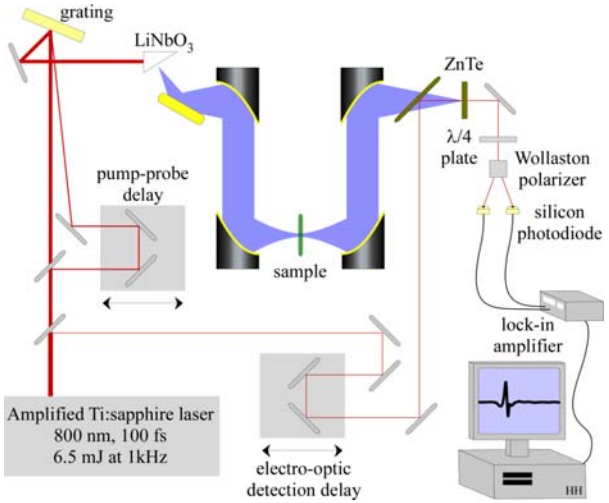
Conclusions



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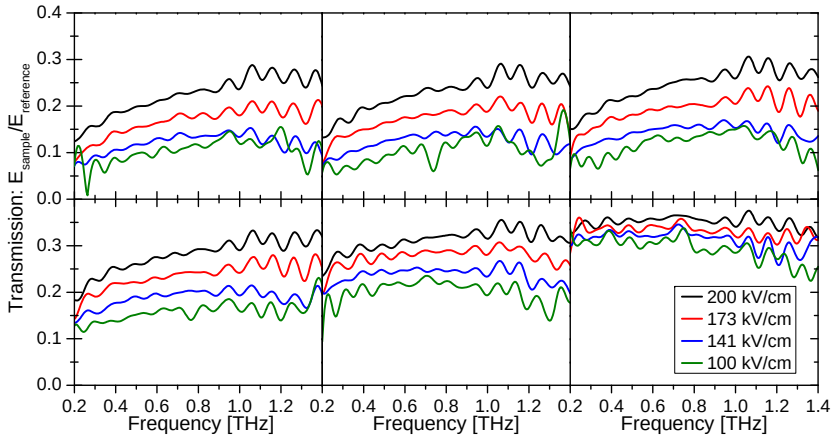

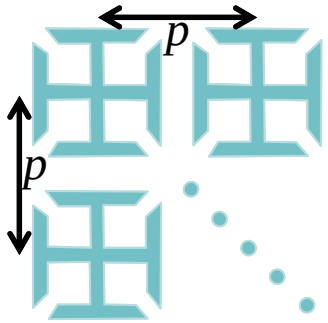

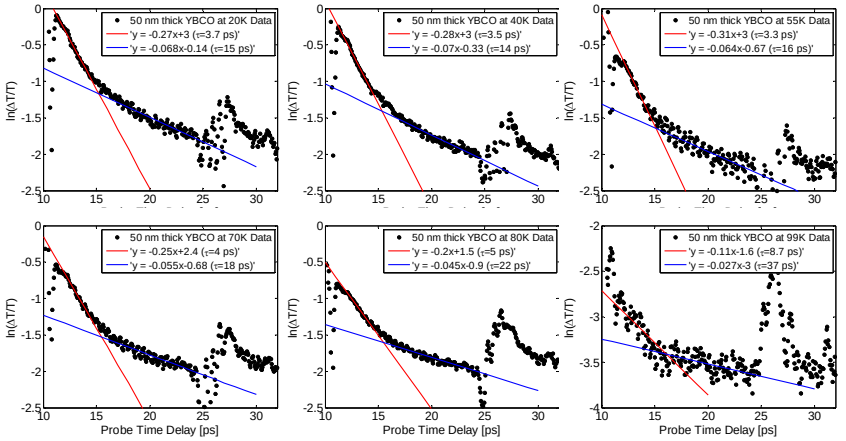

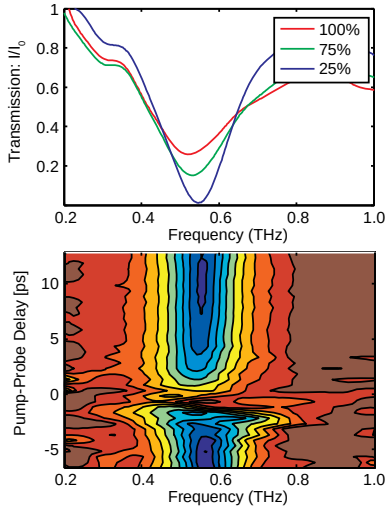

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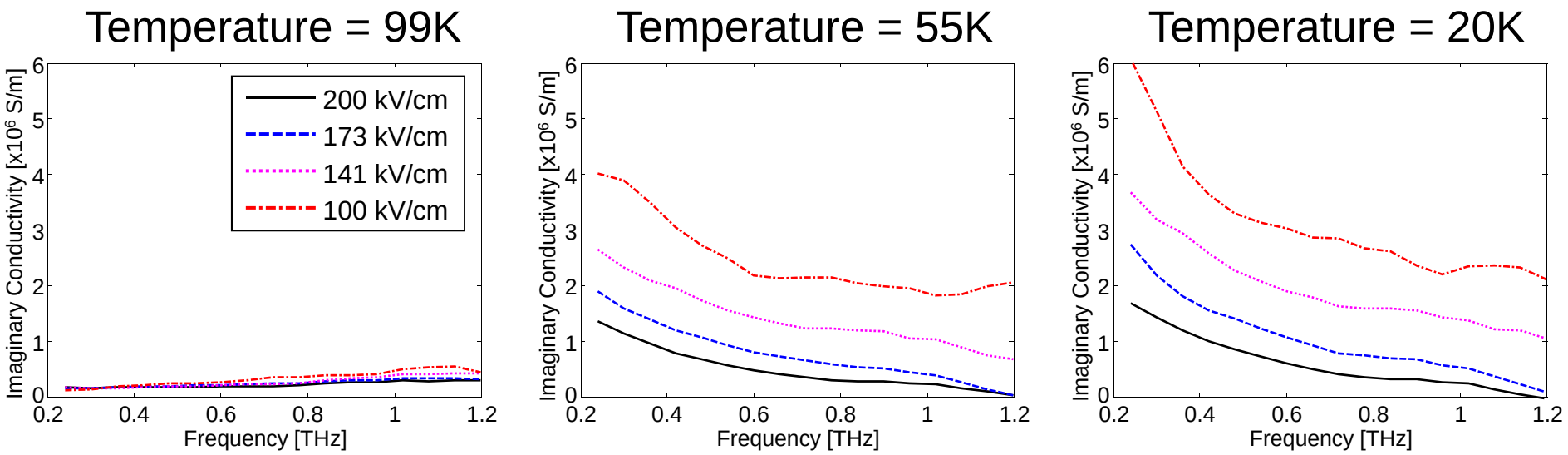
50 nm YBCO Film Conductivity



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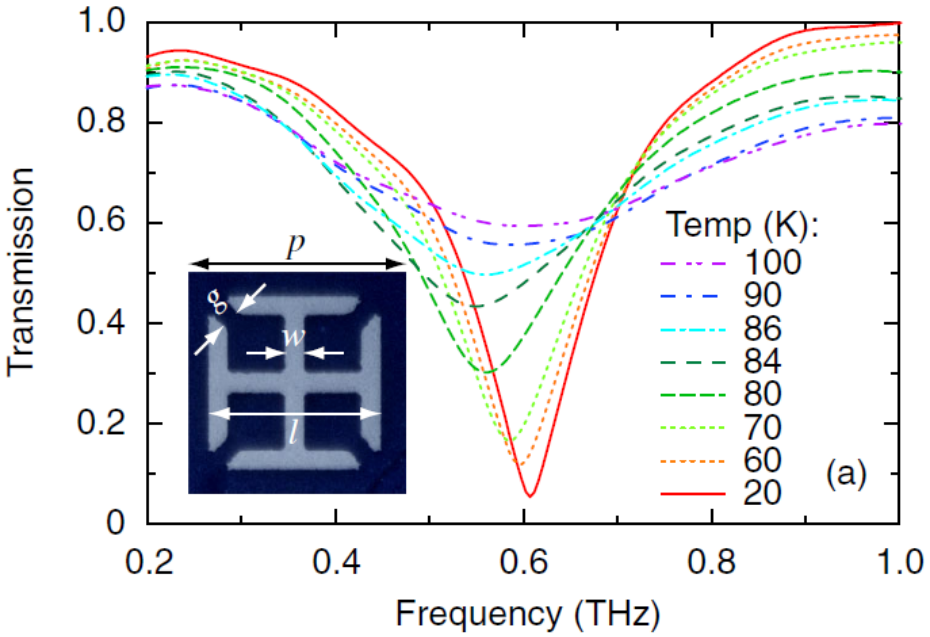
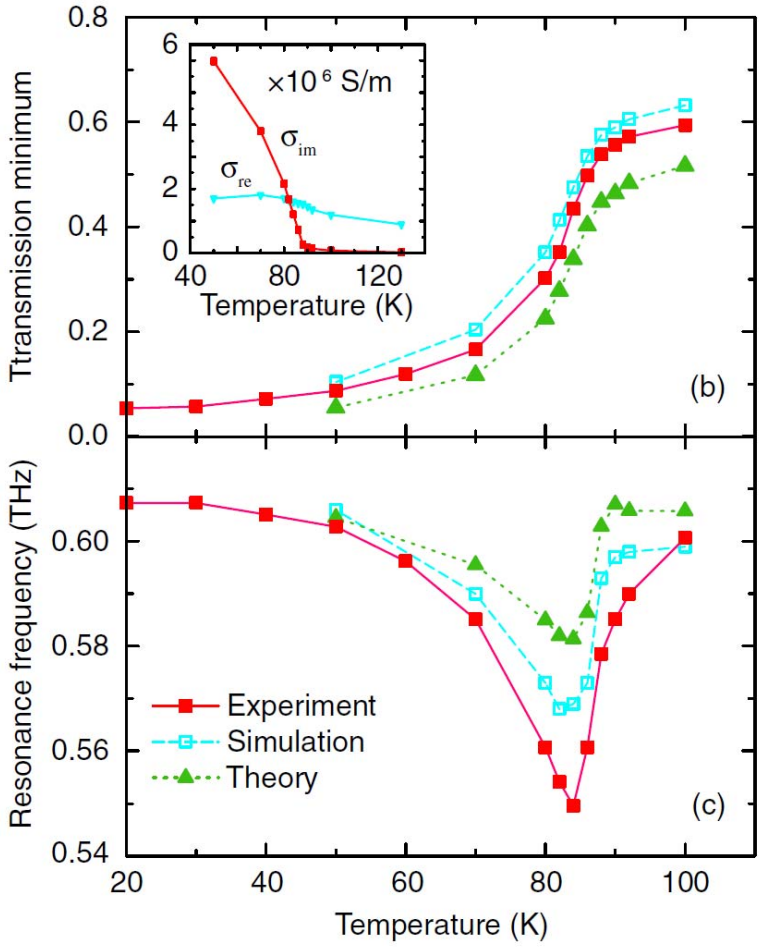
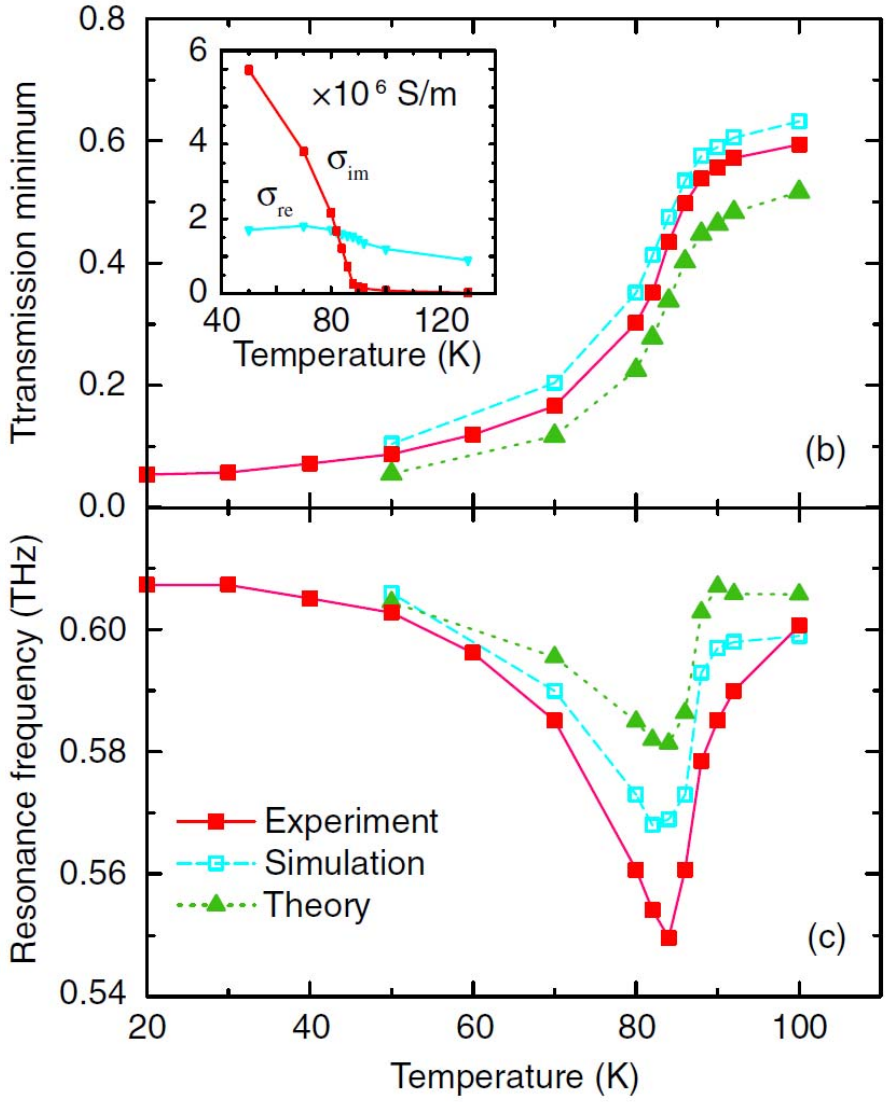
YBCO Metamaterials





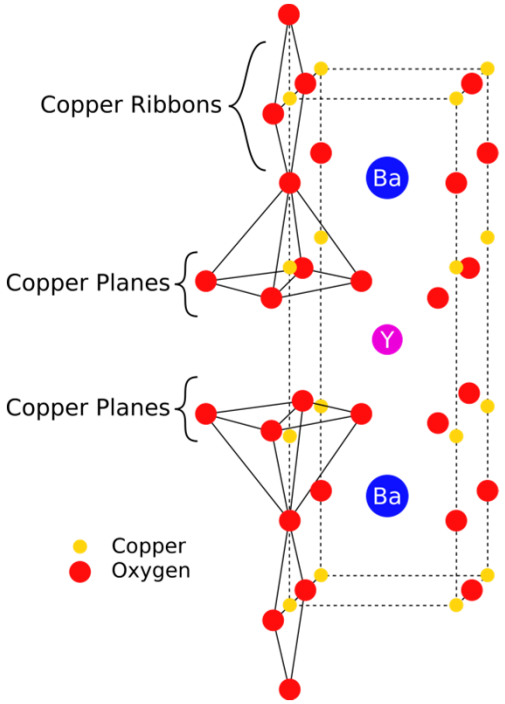
- Metamaterial fabricated from 100 nm thick YBCO film: g = 4 μm, w = 4 μm, l = 46 μm, p = 46 μm
- Resonance frequency shifts with temperature

- ds


Ttransmission minimum
0.8
0.6
0.4
0.2
0.0
6
4
2
0
×10 6 S/m
σ im
σ re
40
80
120
Temperature (K)
(b)
Resonance frequency (THz)
0.60
0.58
0.56
0.54
Experiment
Simulation
Theory
(c)
20
40
60
80
100
Temperature (K)

YBCO

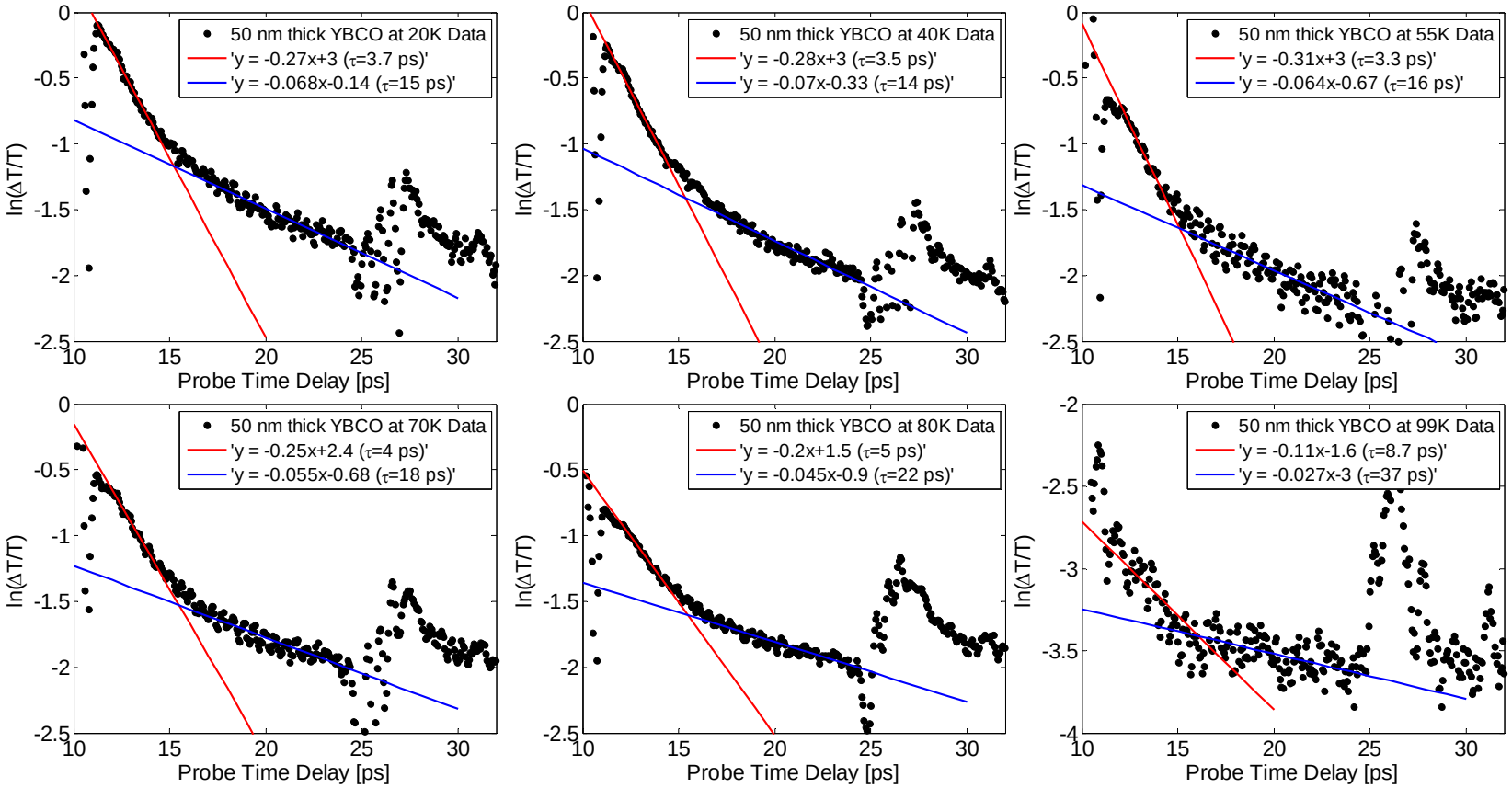
- High-T_c Superconductor



YBCO Crystal Structure

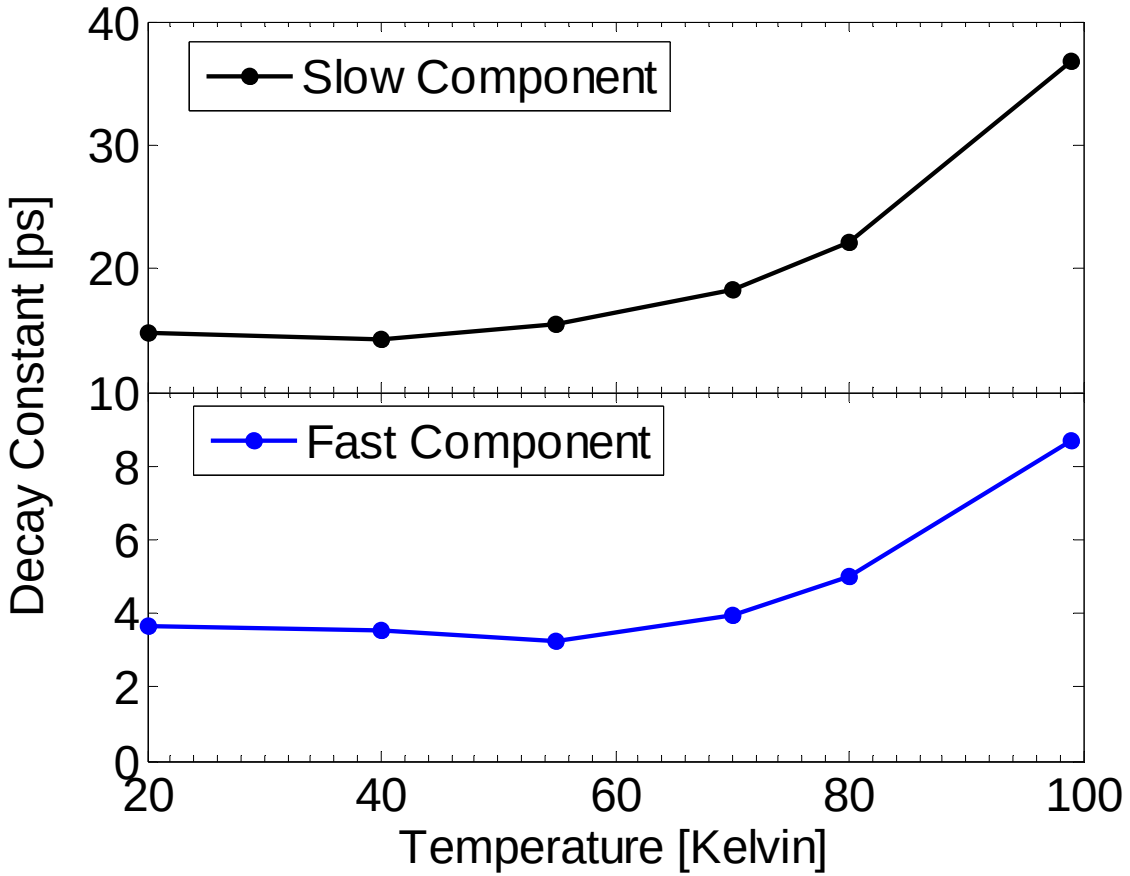
- (source: Wikipedia)

Dynamics: THz-Pump / THz-Probe



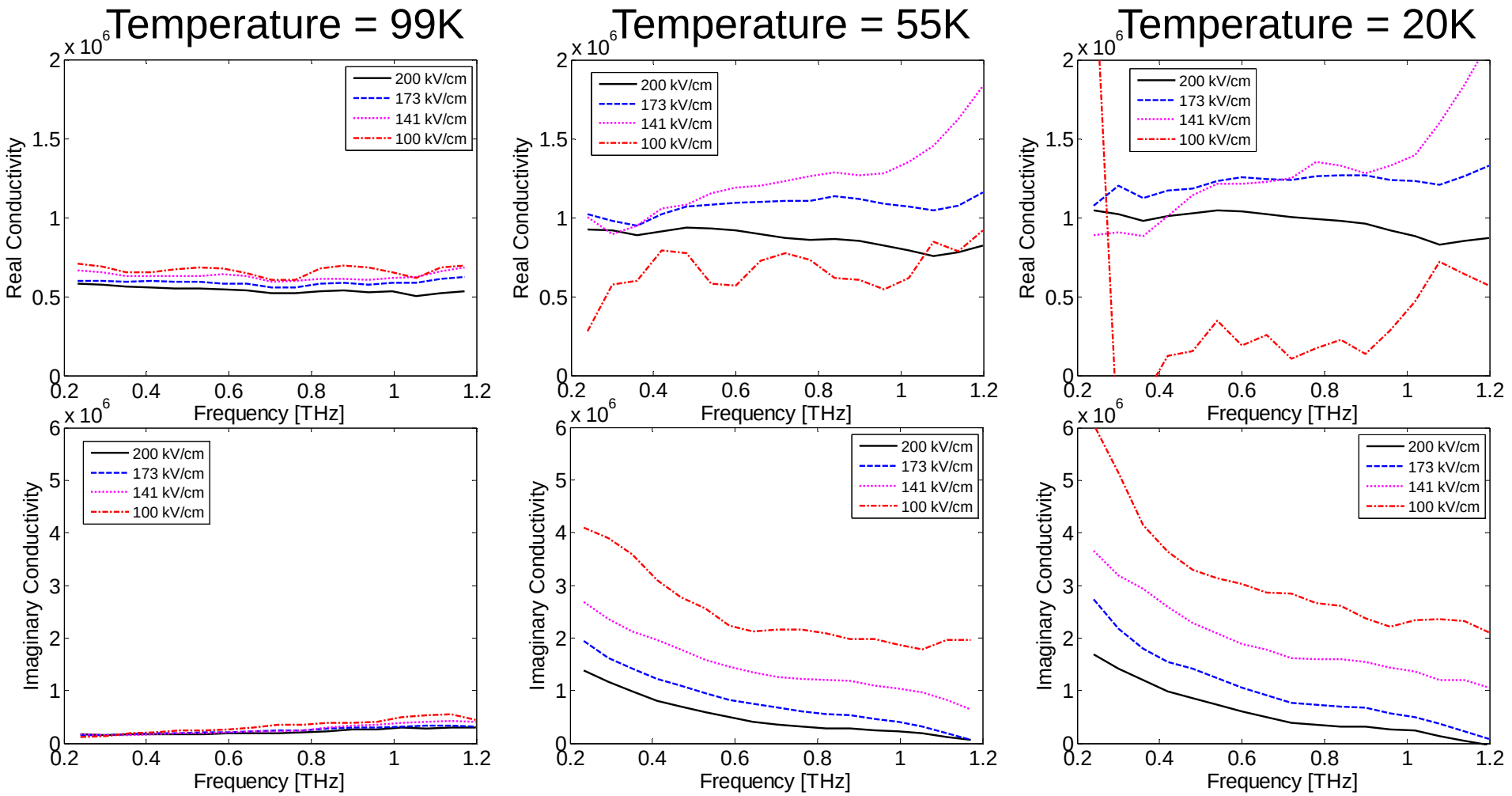
- Peak Scan: set electro-optic sampling delay to measure peak probe electric field, scan pump-probe delay
- Decay constant consistent with optical-pump / THz-probe measurements

Dynamics: Temperature Dependence



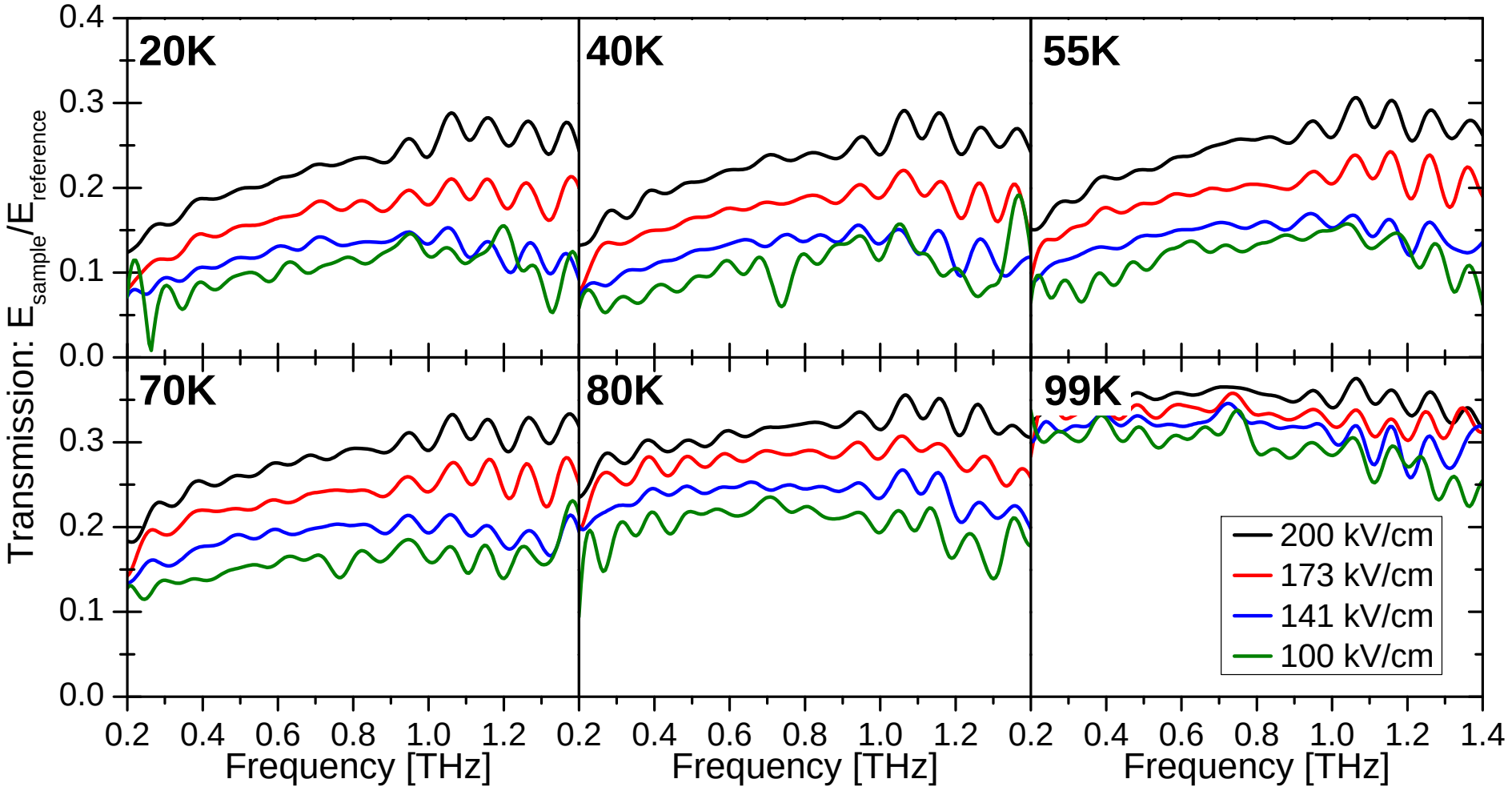
- Decay constant increases with temperature

50 nm YBCO Film Conductivity



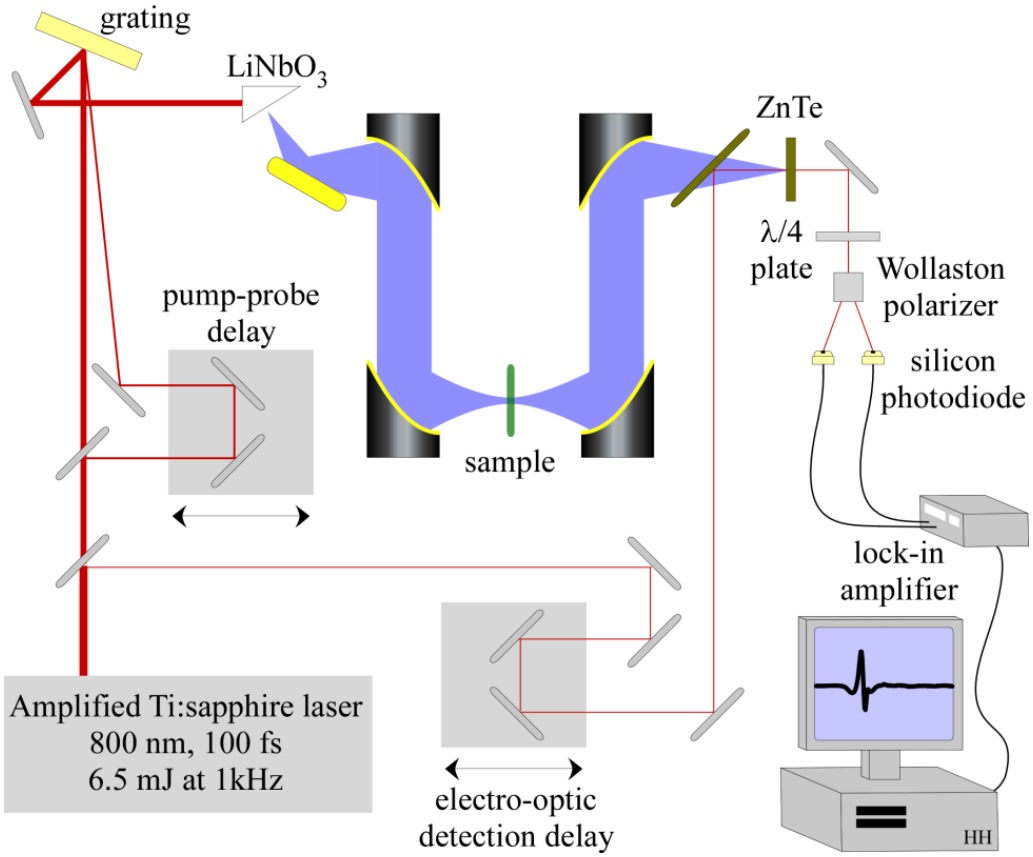
- Change in conductivity → Shift in metamaterial resonance

THz Field Dependent Transmission Spectra: 50 nm thick film



High Intensity THz Source: Tilted Pulse Front Optical Rectification

- Generate THz fields up to 200 kV / cm at the sample
- Tilted pulse front allows “velocity matching” between the THz and optical pulses in $LiNbO_3$
- Use diffraction grating to tilt the pulse front
- Measurements performed in Keith Nelson’s lab at MIT



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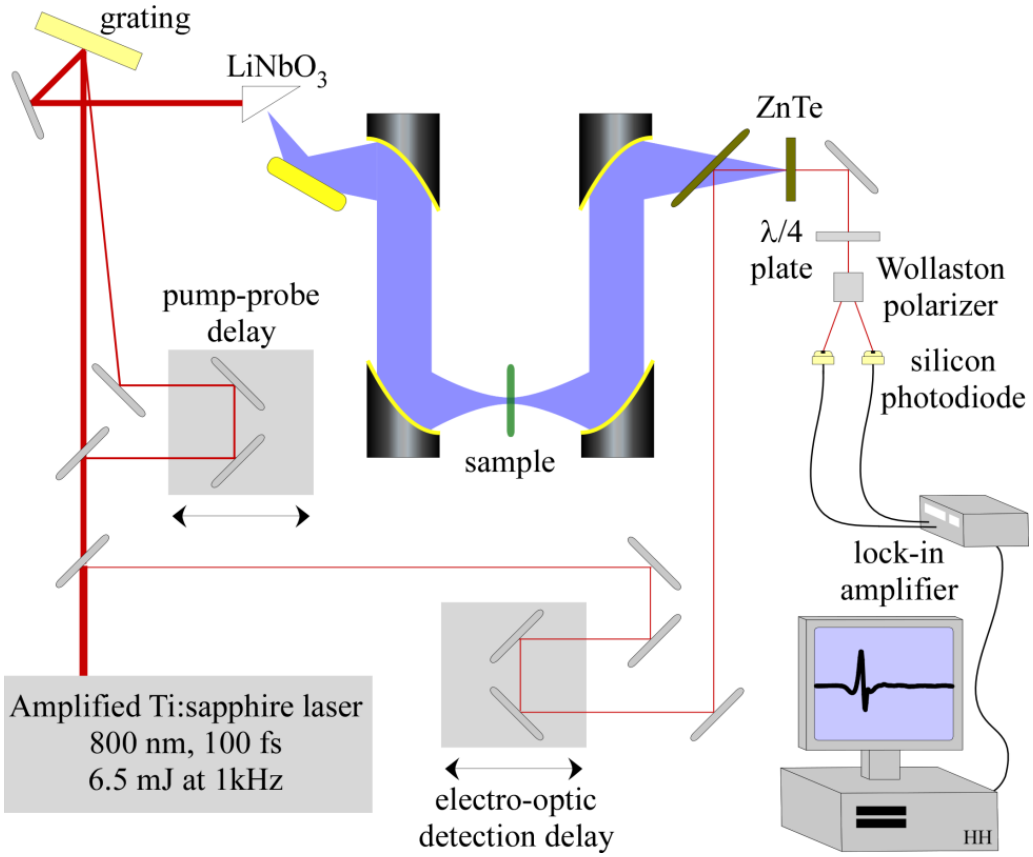
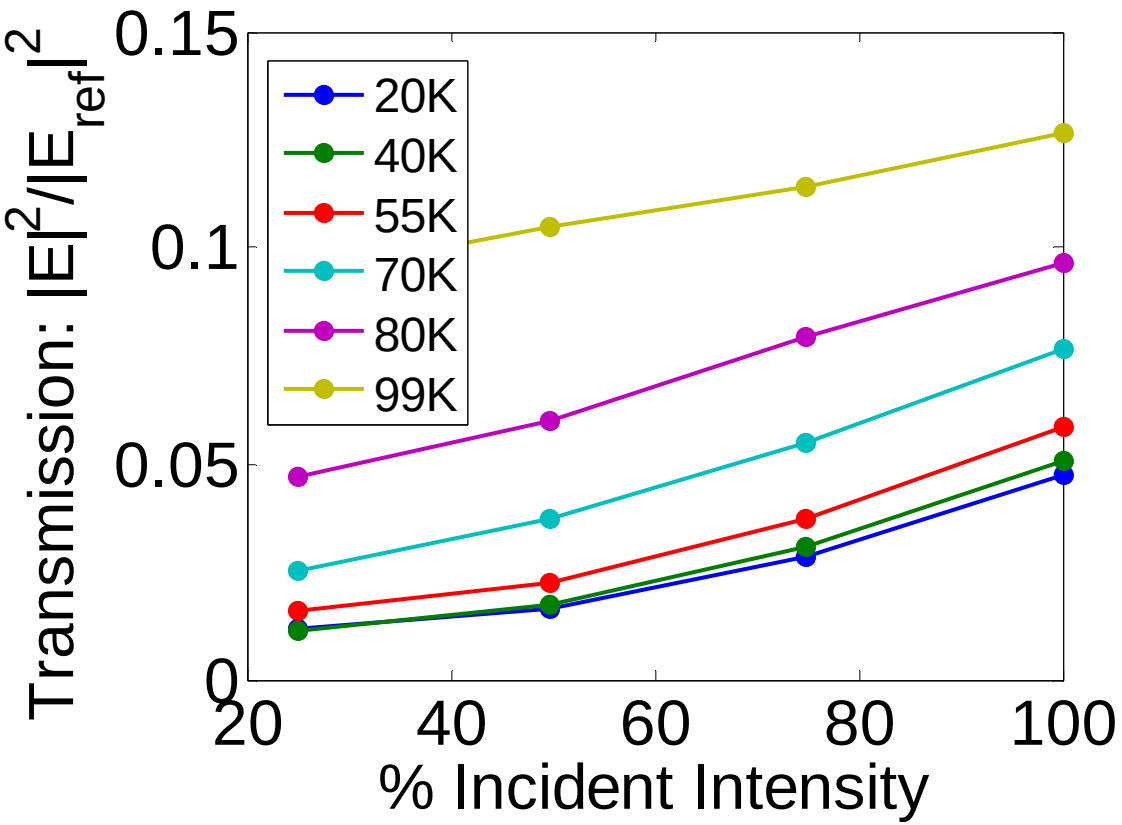
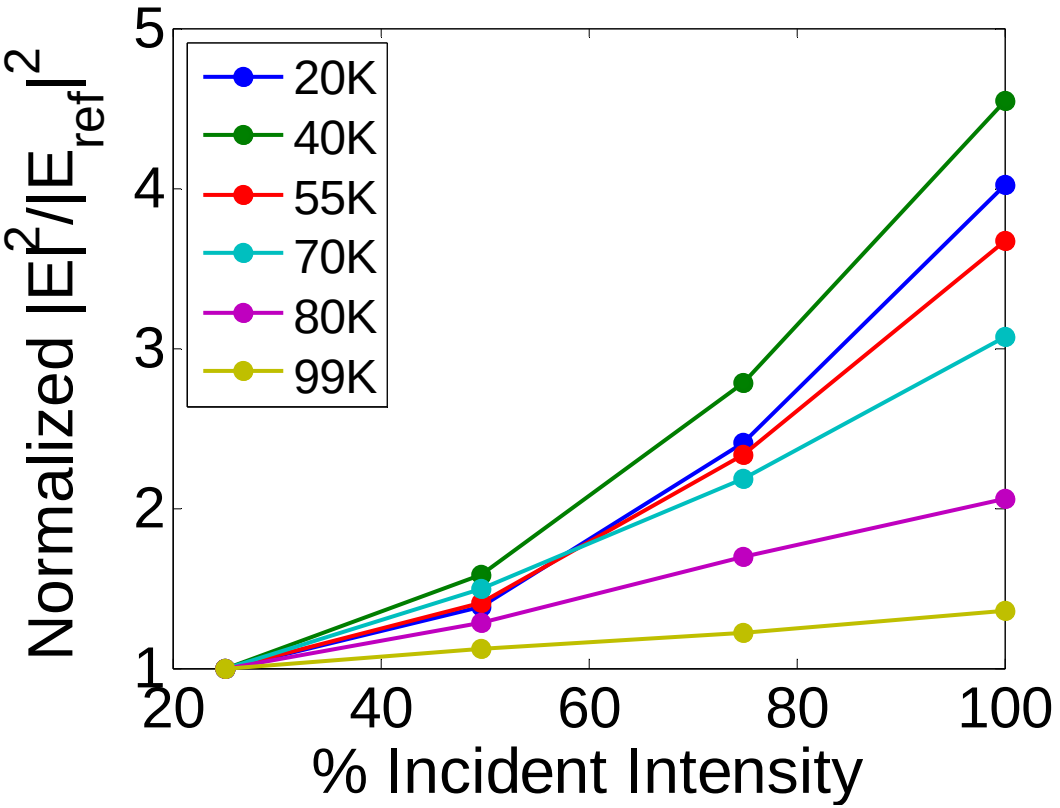


THz Intensity Dependent Transmission



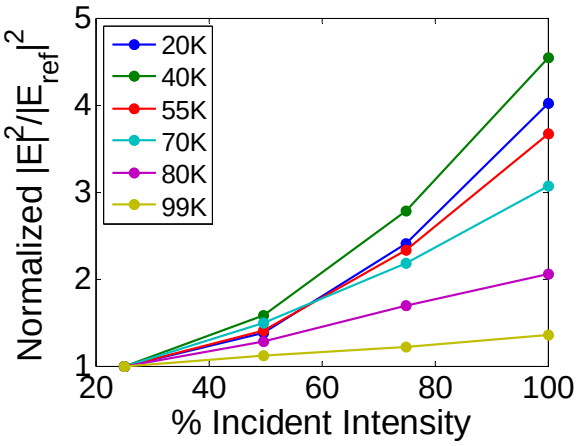
- Integrated THz waveform intensity: $T = \int|E_{samp}|^2dt/\int|E_{ref}|^2dt$
- Both axes now in intensity

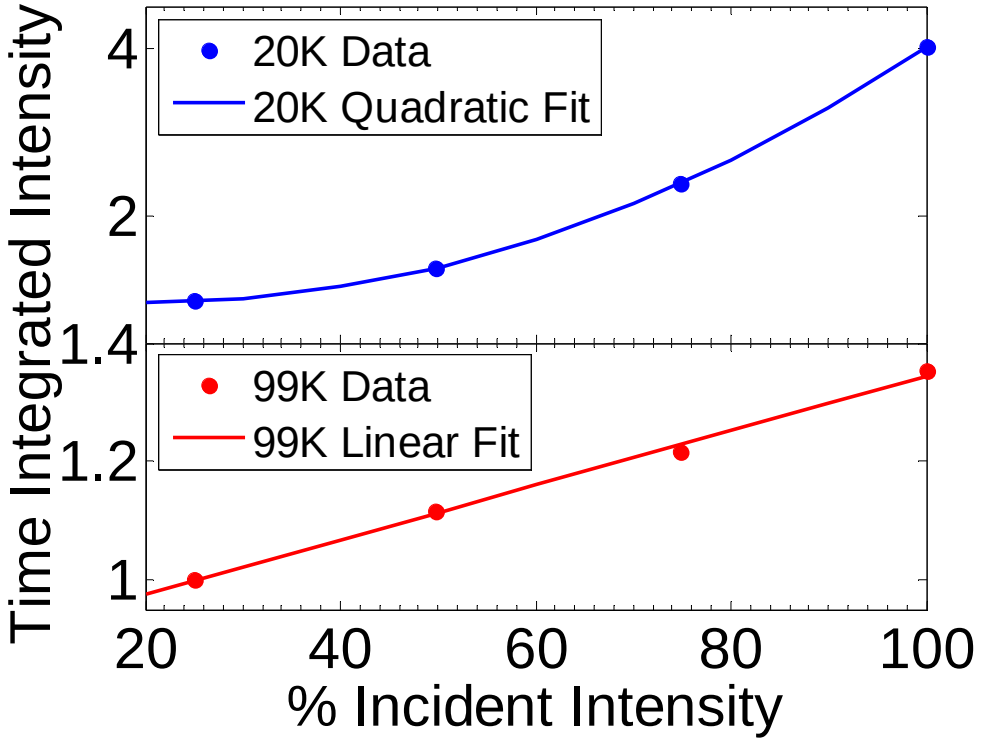
THz Intensity Dependent Transmission



- Normalize: divide by transmission at lowest intensity
- Relative change in transmission largest at 40 K

THz Intensity Dependent Transmission

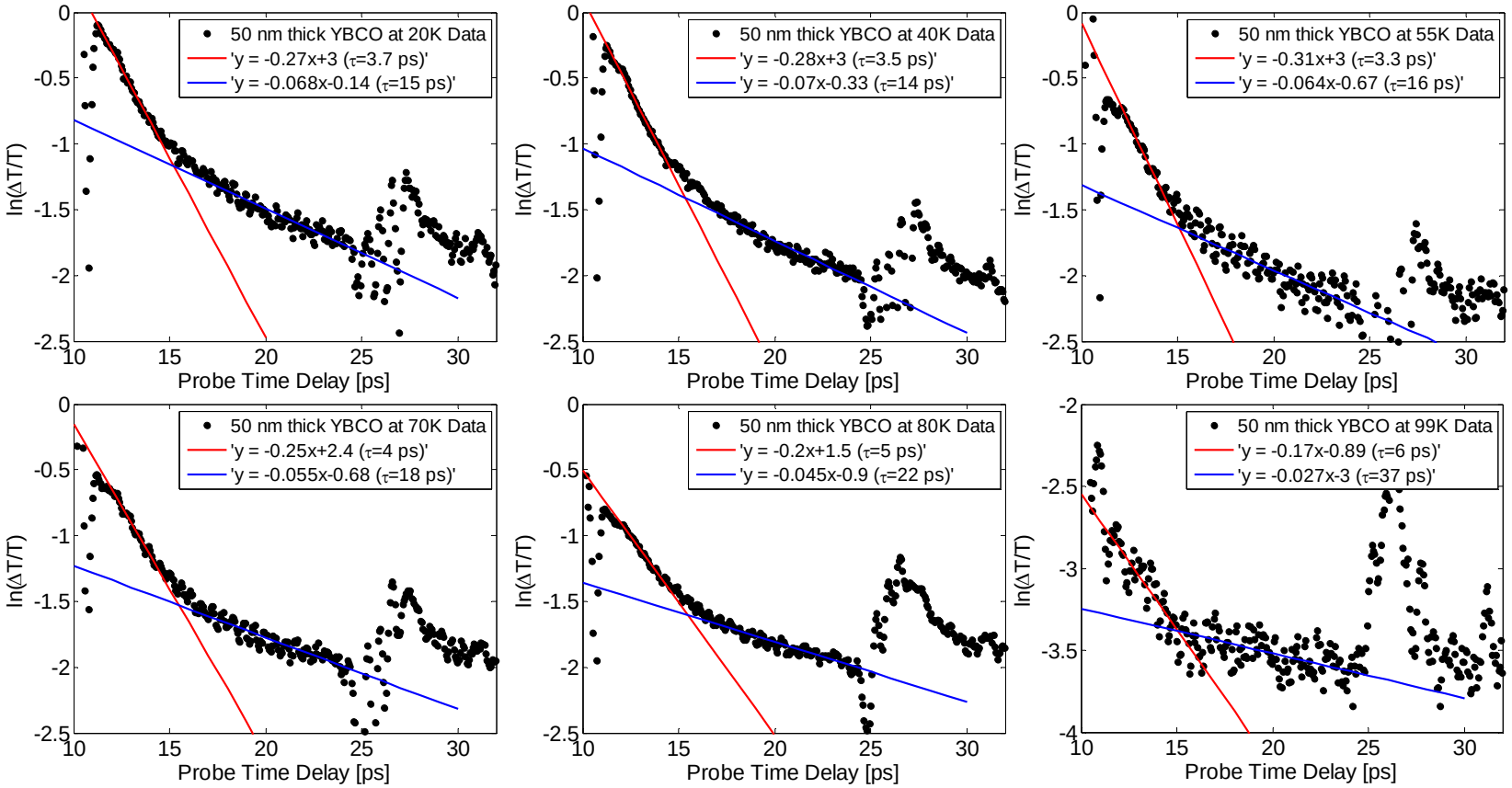




Fit 20K and 99K transmission to polynomial:

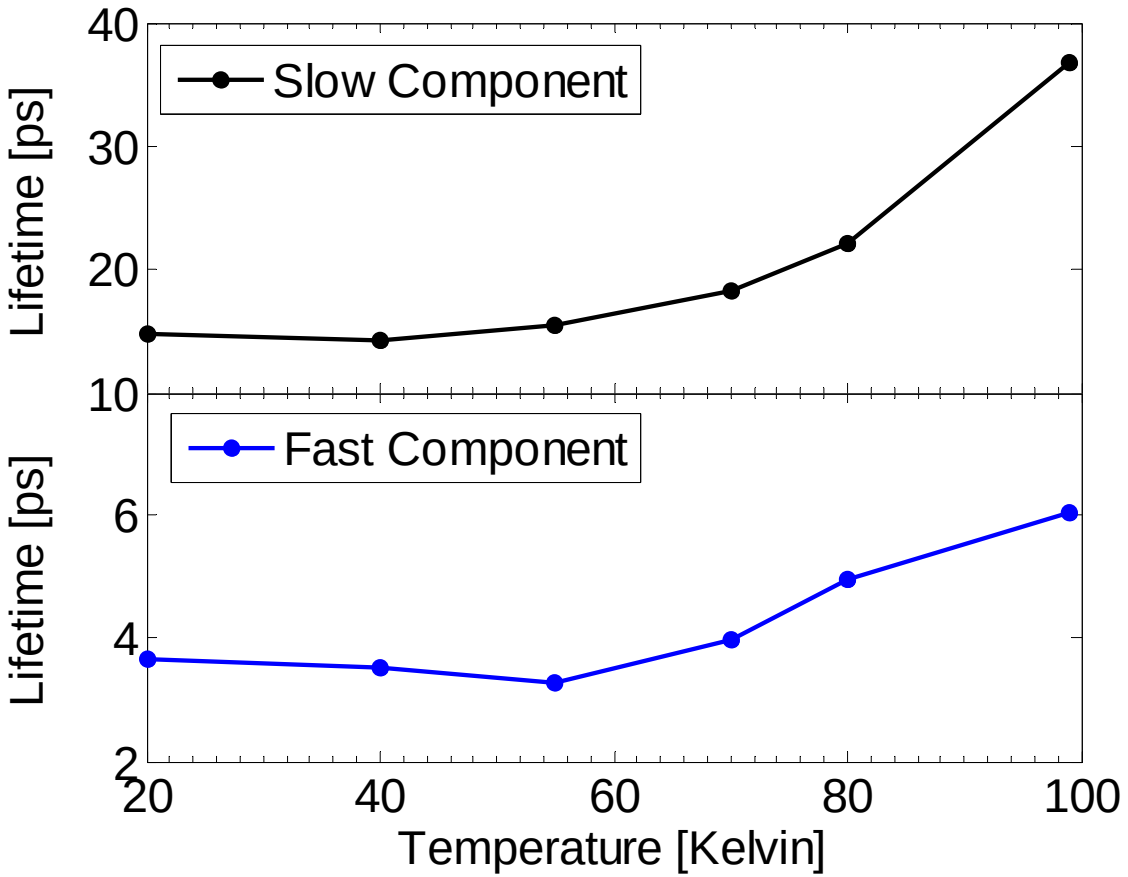
- 20K: Quadratic
- 99K: Linear

Dynamics: THz-Pump / THz-Probe



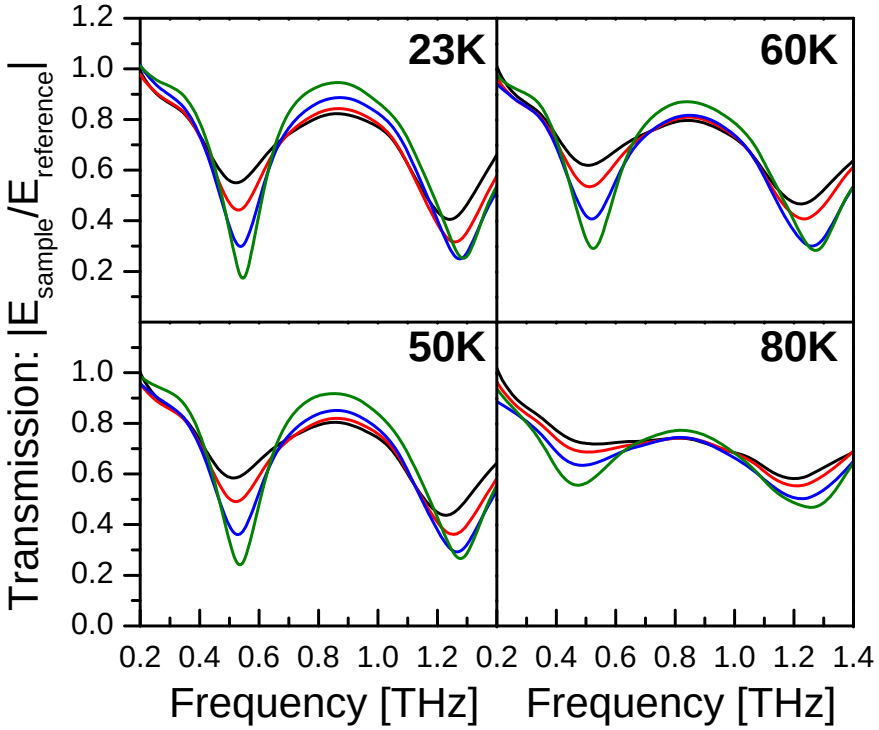
- Peak Scan: set electro-optic sampling delay to measure peak probe electric field, scan pump-probe delay
- Decay constant consistent with optical-pump / THz-probe measurements

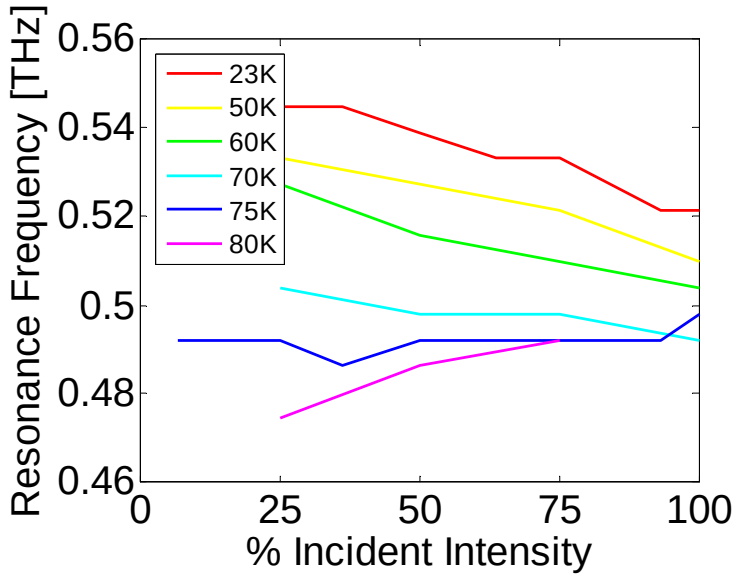
Dynamics: Temperature Dependence

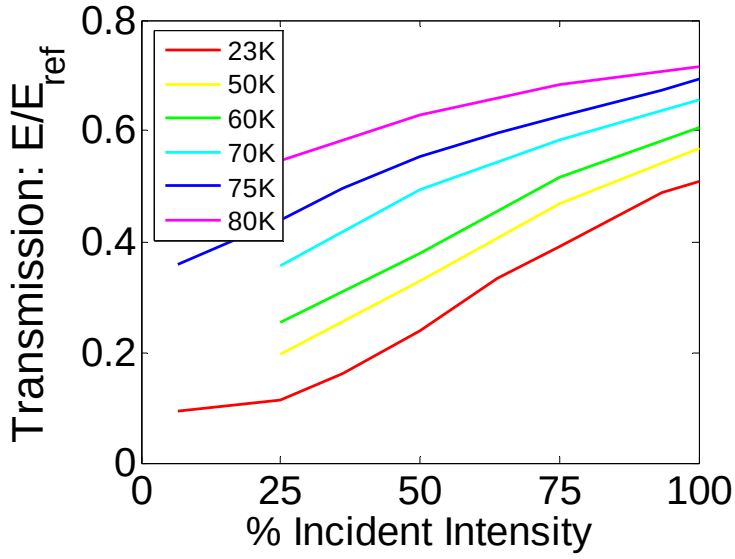


- Decay constant increases with temperature

Intensity-Dependent Transmission: Metamaterial







- Resonance red-shifts at low temperature, blue-shifts at high temperature