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Metamaterials in applications: tunable filters and resonant detectors

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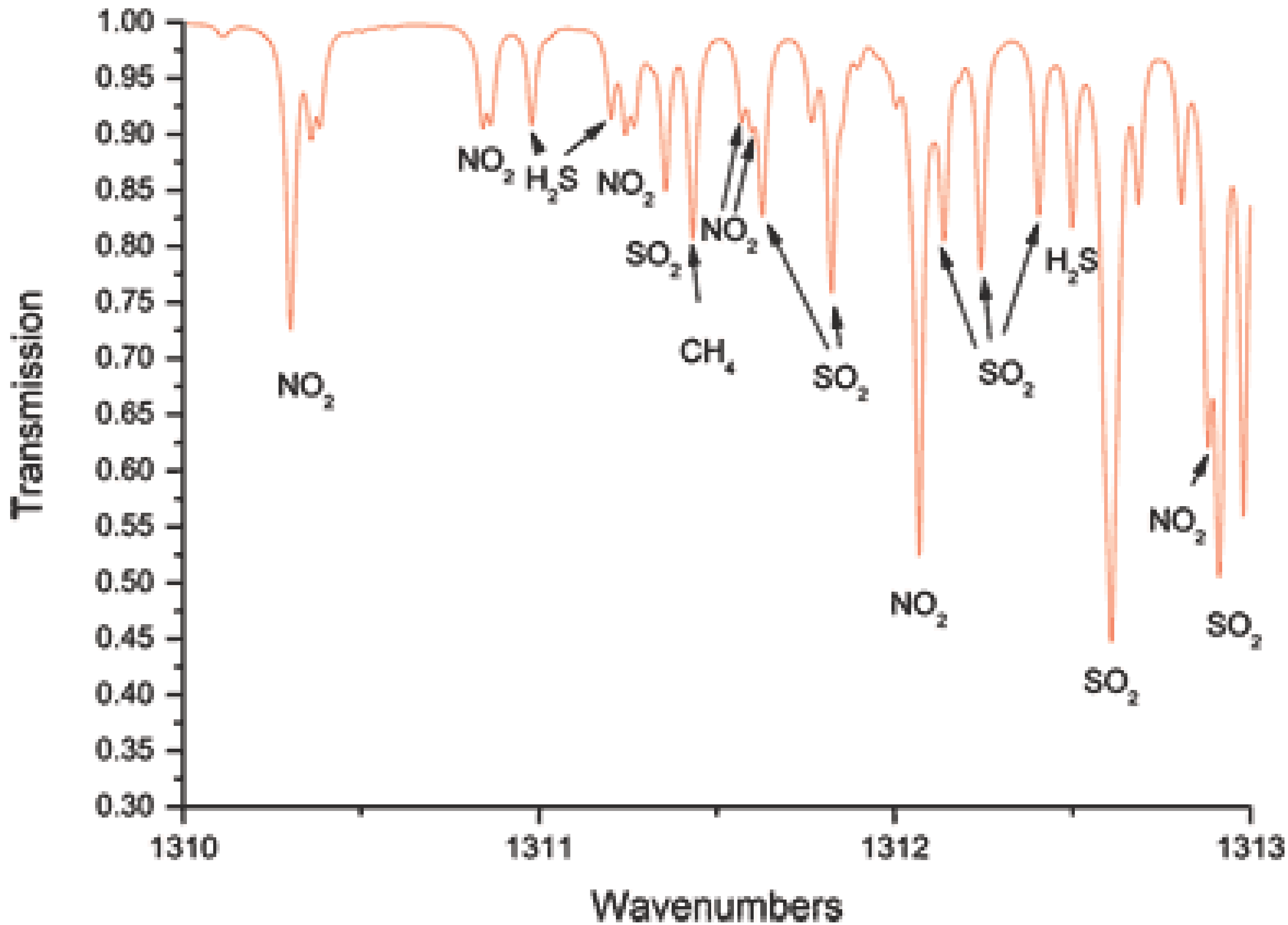
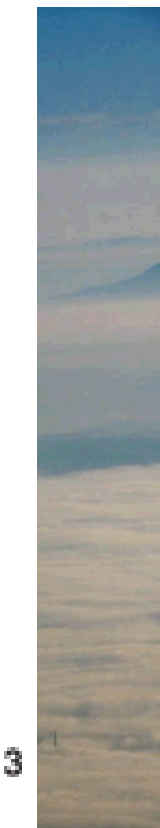
Overview

- Introduction
  - Motivation
  - Metamaterial ⇔ Intersubband transitions
- Tunable filters
  - Ultra-strong light-matter interaction
- Resonant detectors
  - Source ⇔ Detector

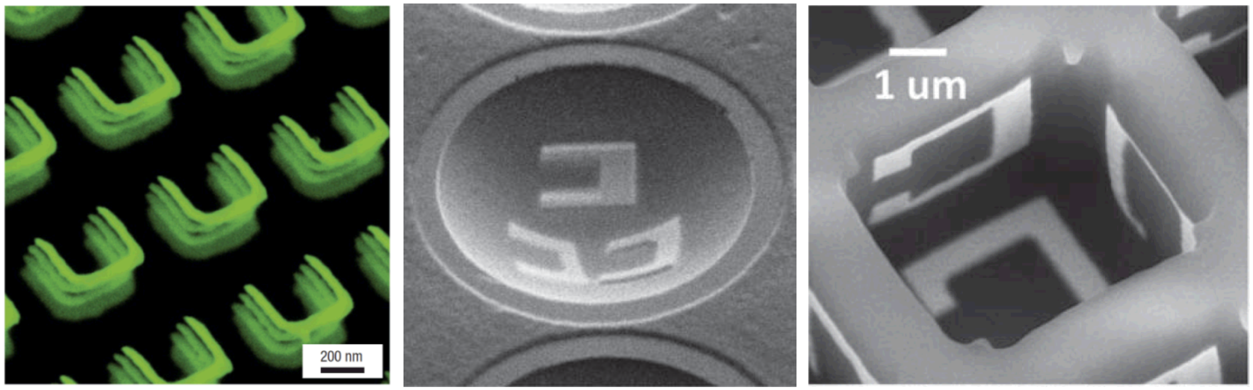
Why mid- and far-IR?

- La

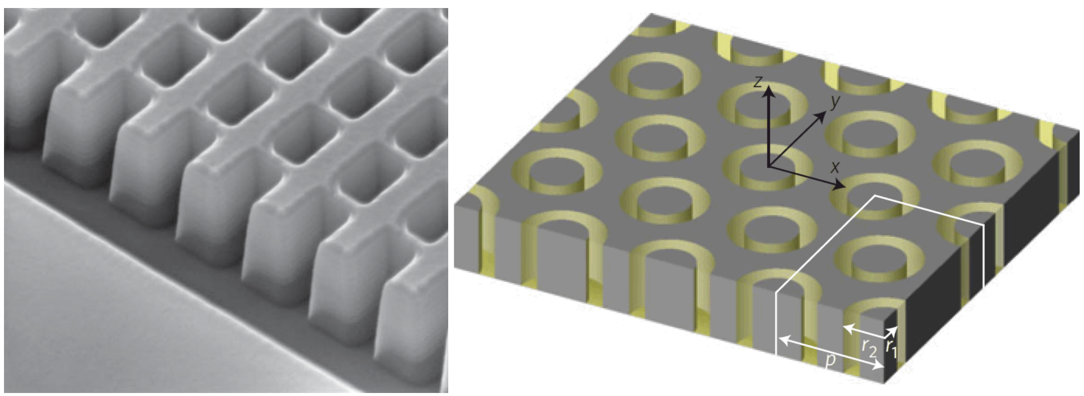




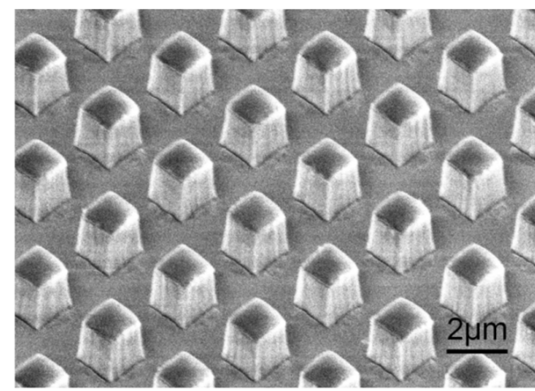
Metamaterial overview



3D SRRs[1,2,3]



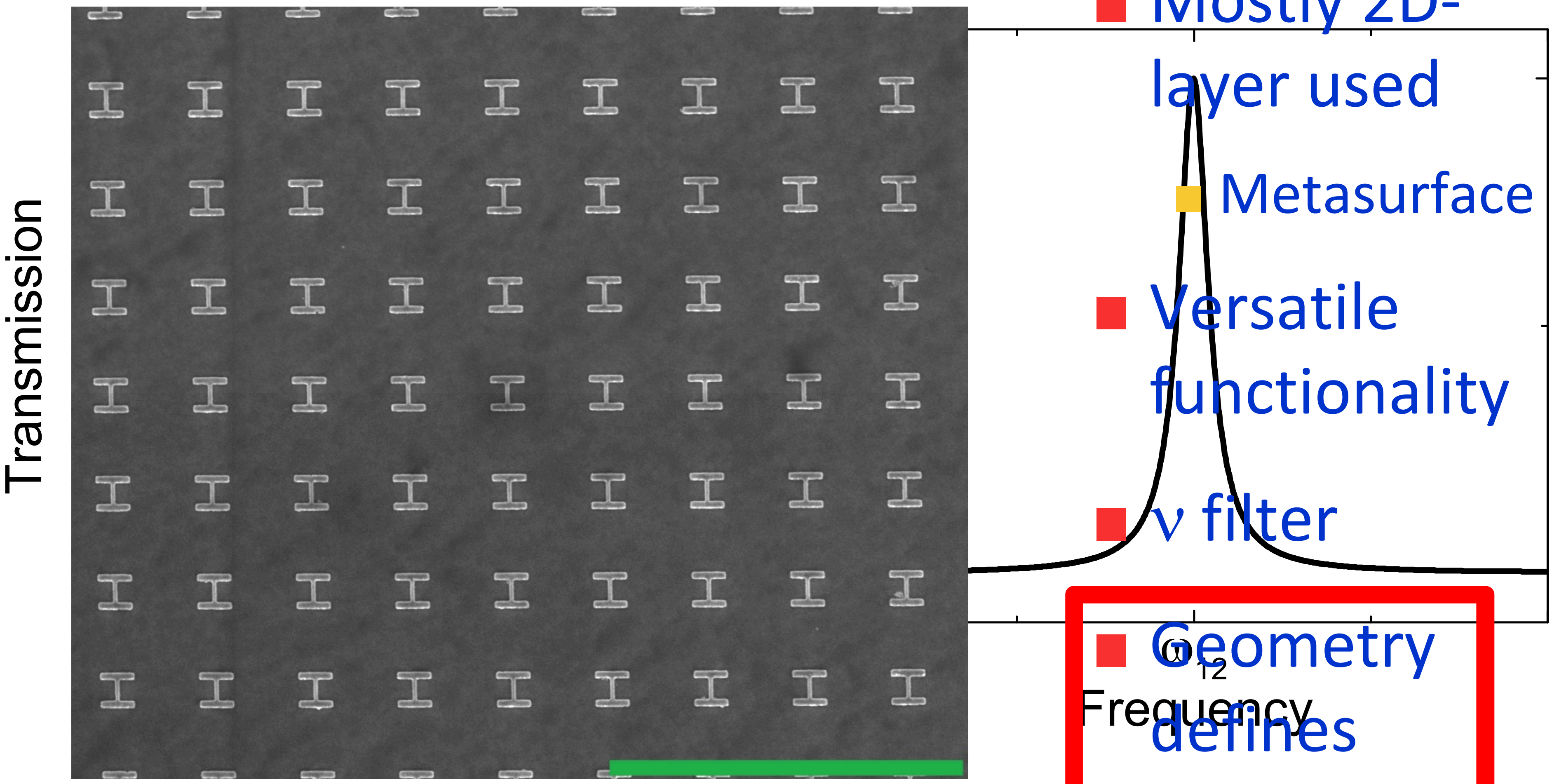
Negative index[1,2]



Magnetic mirrors[3]

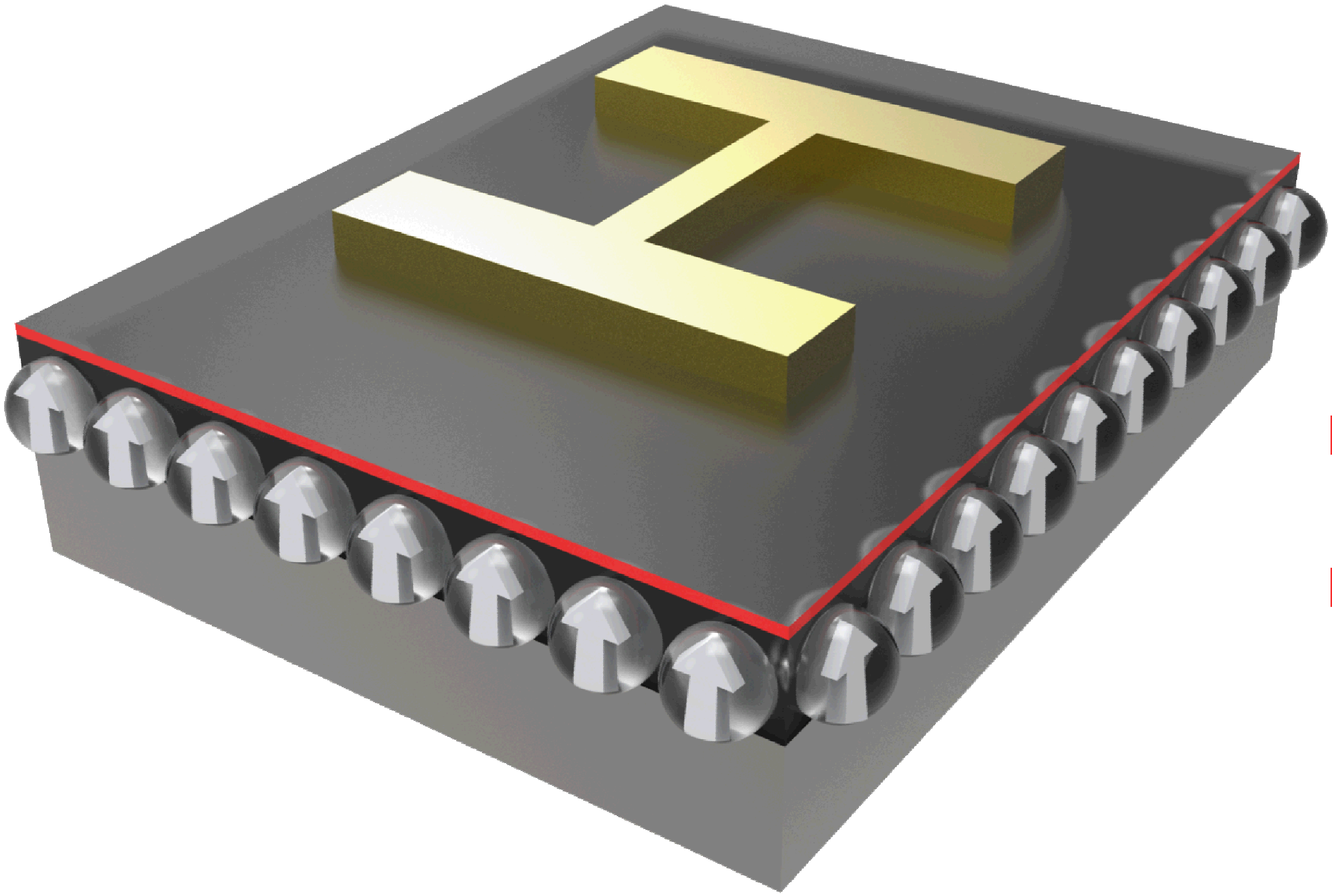
[1] N. Liu et al. Nature Materials **7**, 31 (2008)
[2] D. Burckel et al., Adv. Mater. **2010**, 22, 3171
[3] D. Burckel et al., Adv. Mater. **2010**, 22, 5053
[4] J. Valentine et al., Nature **455**, 376 (2008)
[5] S. Burgos et al., Nature Materials **9**, 407 (2010)
[6] J. Ginn et al., Phys. Rev. Lett. **108**, 097402 (2012)

Metasurface



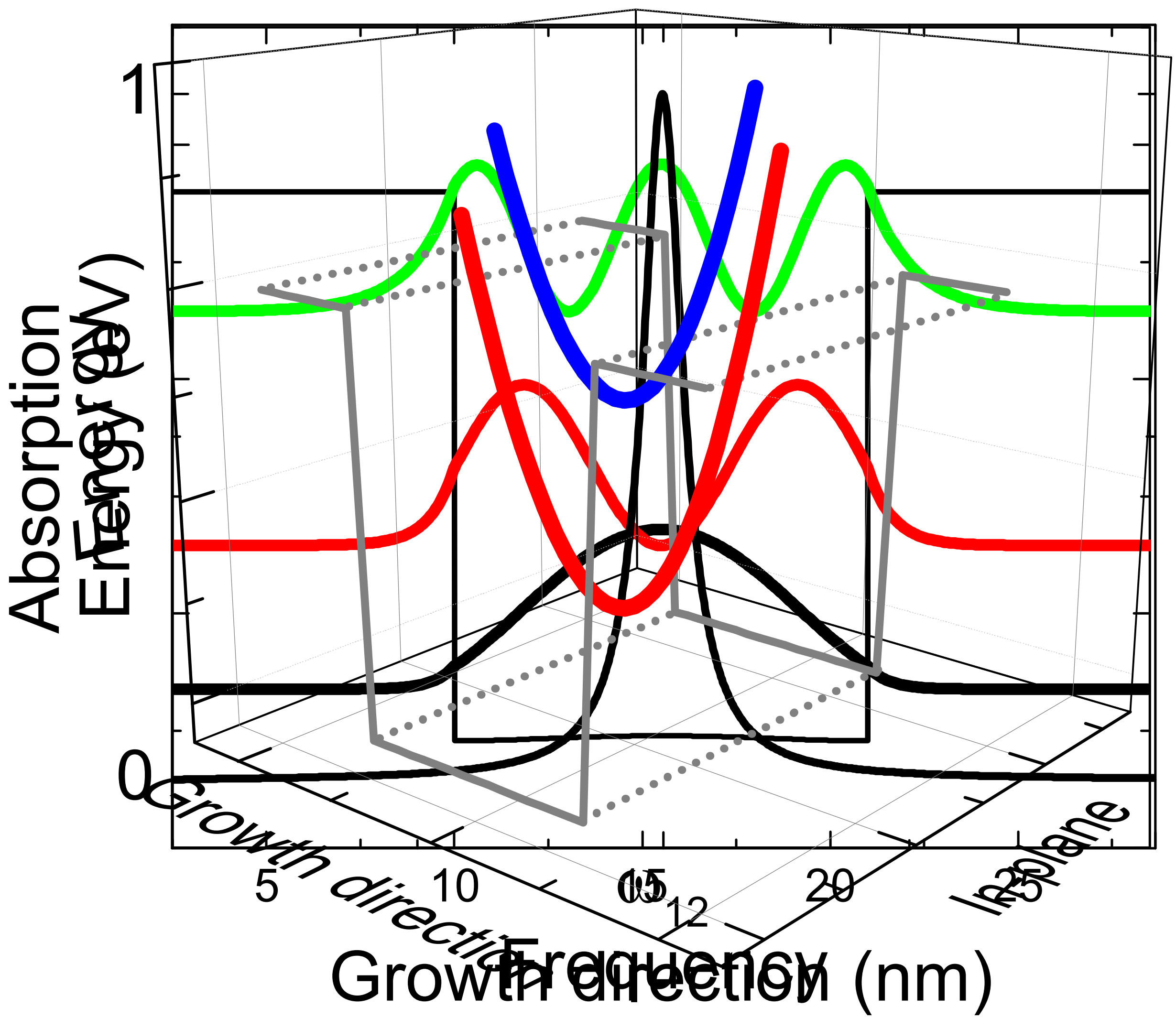
- Mostly 2D-layer used
  - Metasurface
- Versatile functionality
- ν filter
- Geometry defines properties

Additional functionality



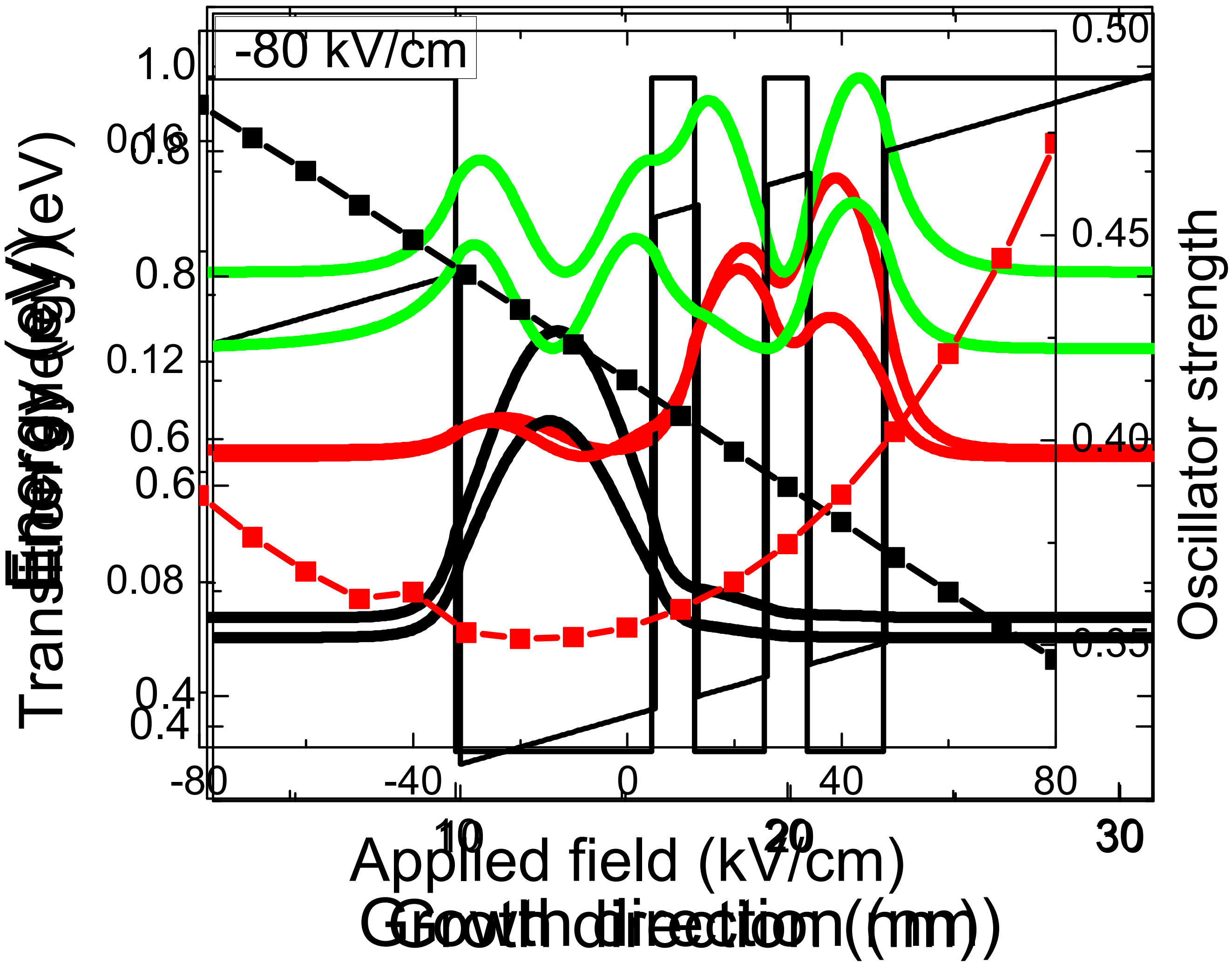
- Combine metamaterial with semi-conductor
- Coupling
- Alter properties
  - Geometry vs. bias

Intersubband transitions



- Energy levels designed
  - Quantized
- Narrow absorption
  - Parabolic bands
- Tuning
  - Depletion

Intersubband tuning



- Intersubband resonance tuned
  - Stark effect
  - Scales linearly
- Oscillator strength constant

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Ultra-strong coupling physics

- Splitting Ω_R similar to system resonance
  - Anti-resonant terms in equilibrium
- Squeezed vacuum as ground state
  - Release correlated photon pairs
- Light-matter superposition = Polaritons

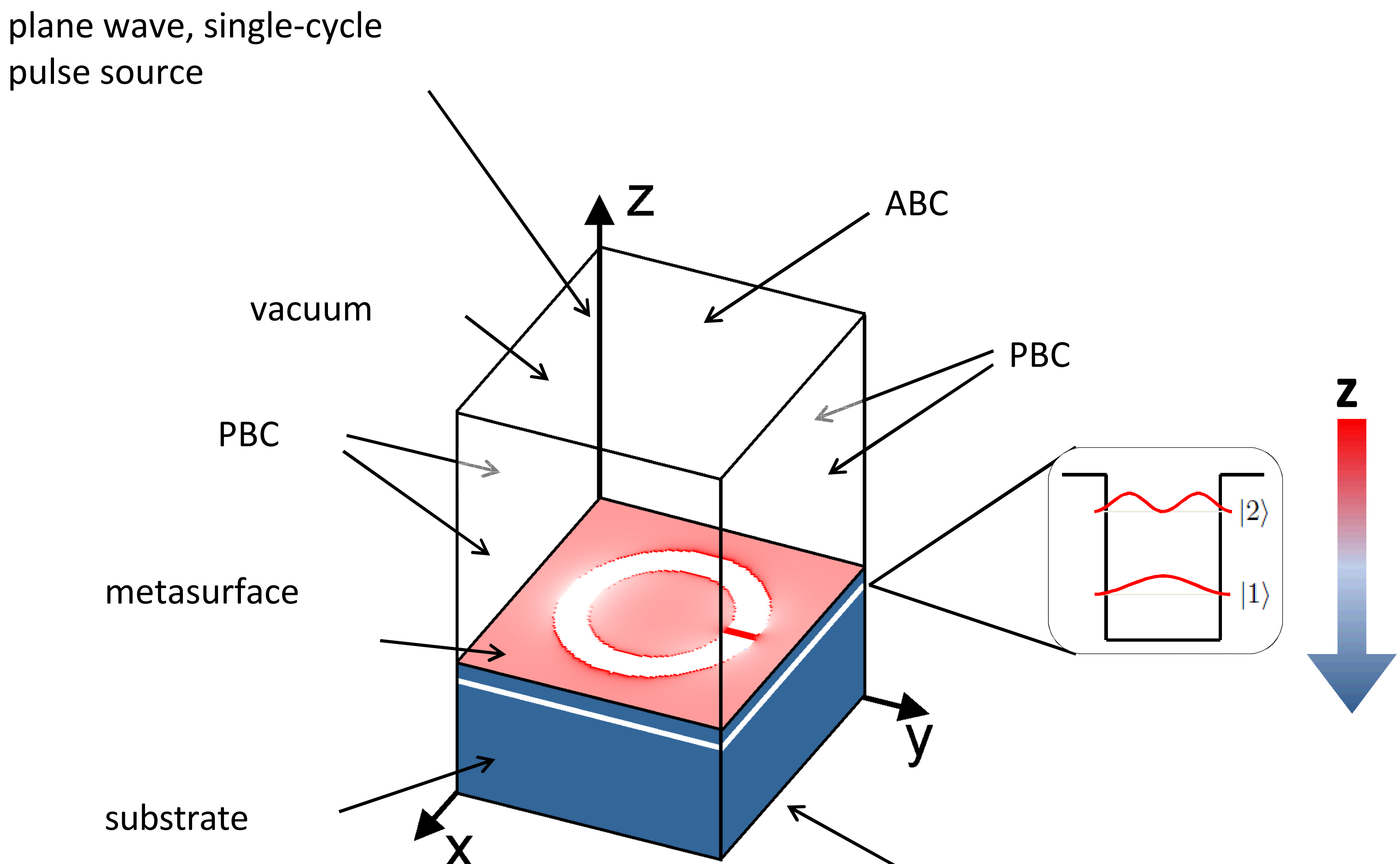
$$\Omega_R = \sqrt{f_W}\,\omega_p/2$$

Geometry factor

Plasma frequency

C. Ciutu et al., Phys. Rev. B **72**, 115303 (2005)   S. DeLiberato et al., Phys. Rev. Lett. **98**, 103602 (2007)

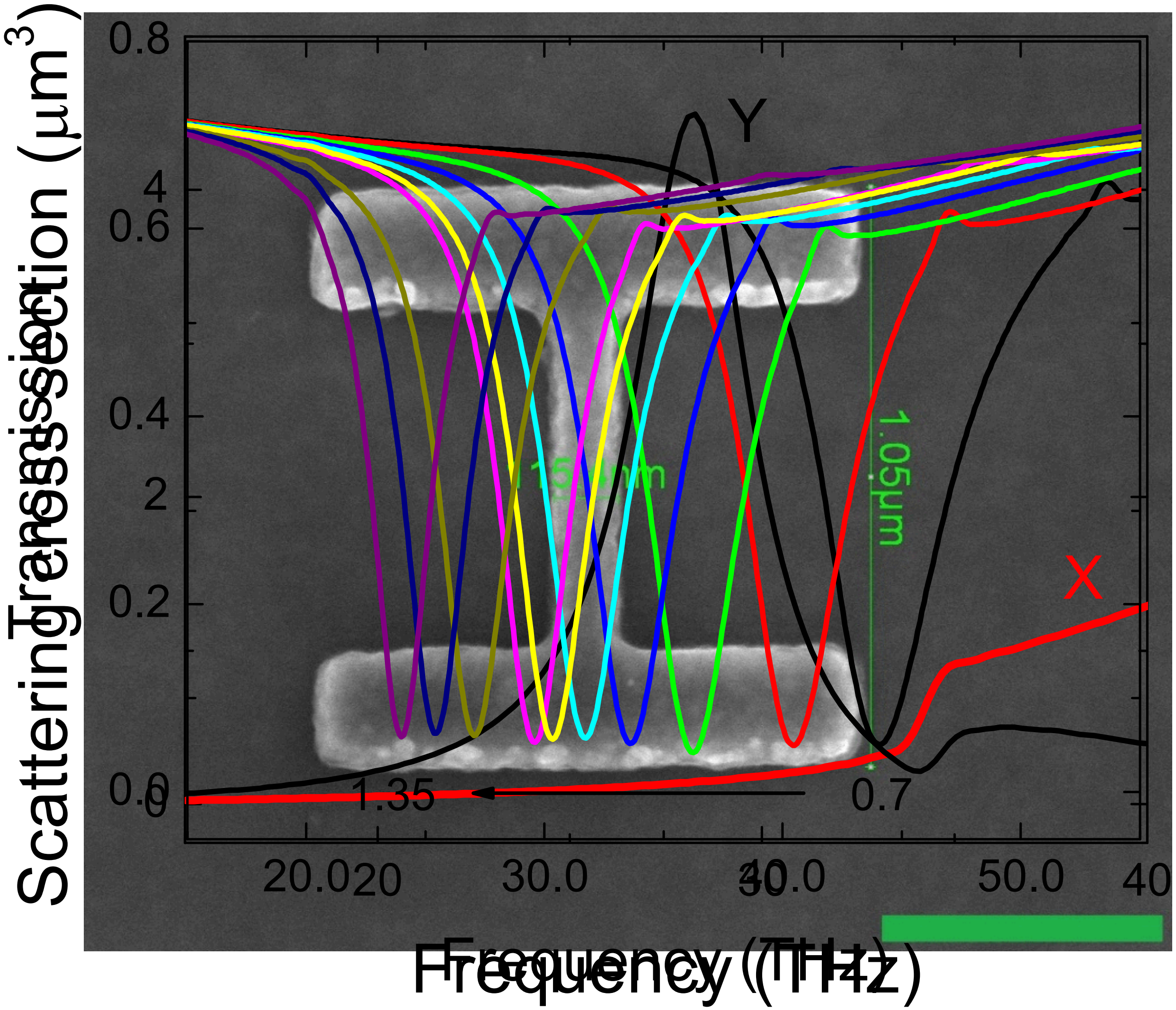
FDTD resonator design



Courtesy of D. Dietze

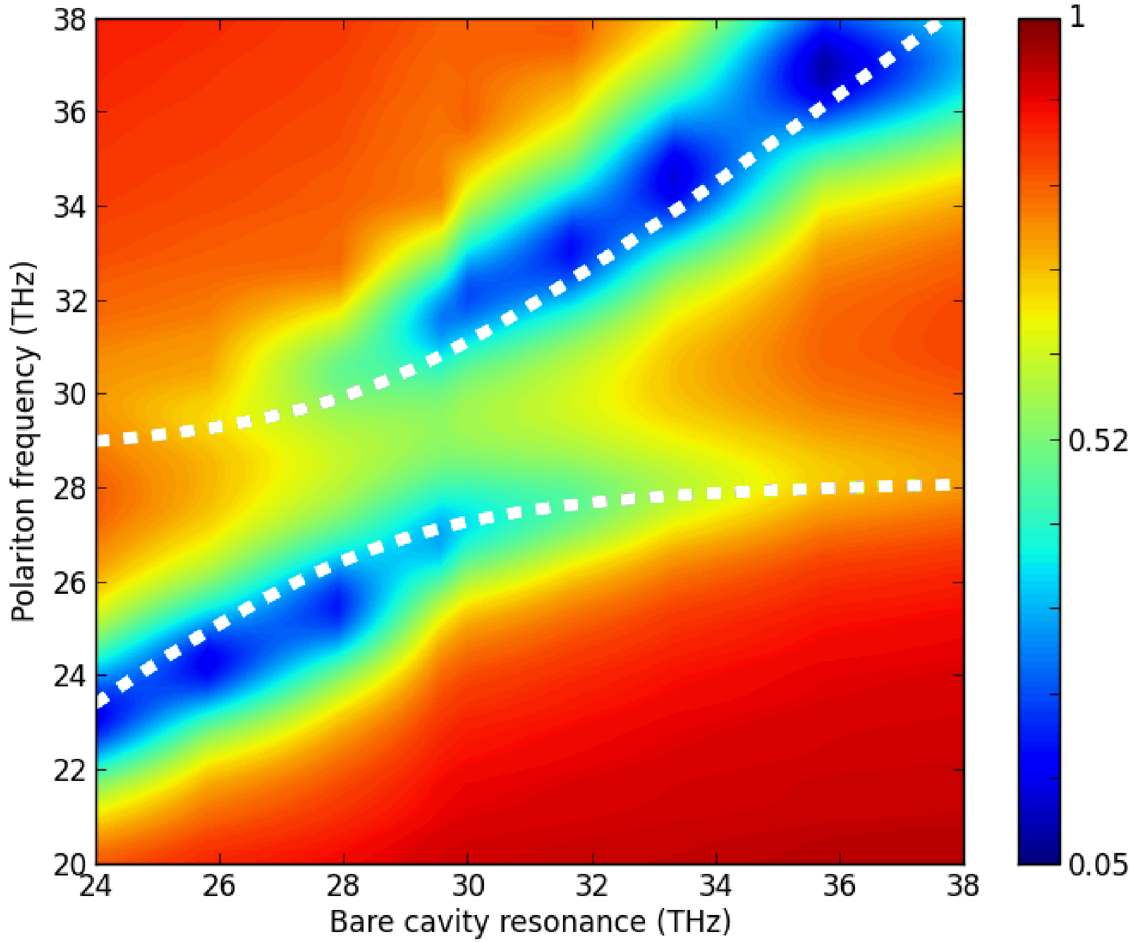
Sandia National Laboratories

Metamaterial fabrication



- Processing
  - Ebeam litho
  - 100 nm gold
- Easily adjustable
- Virtual ground
- Anisotropic scattering

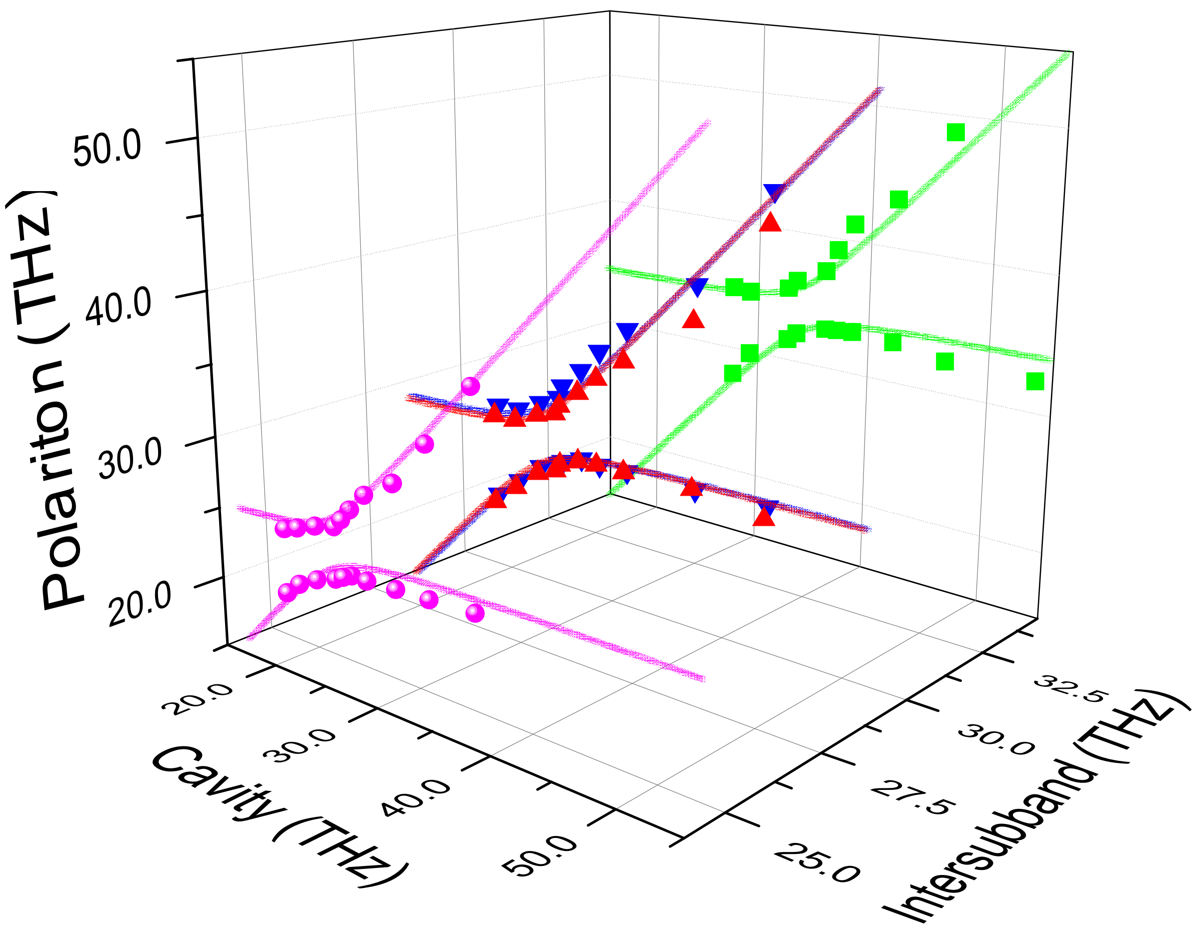
Strong coupling theory vs. experiment



- FDTD simulations
- Anti-crossing
- Polariton picture[1,2]

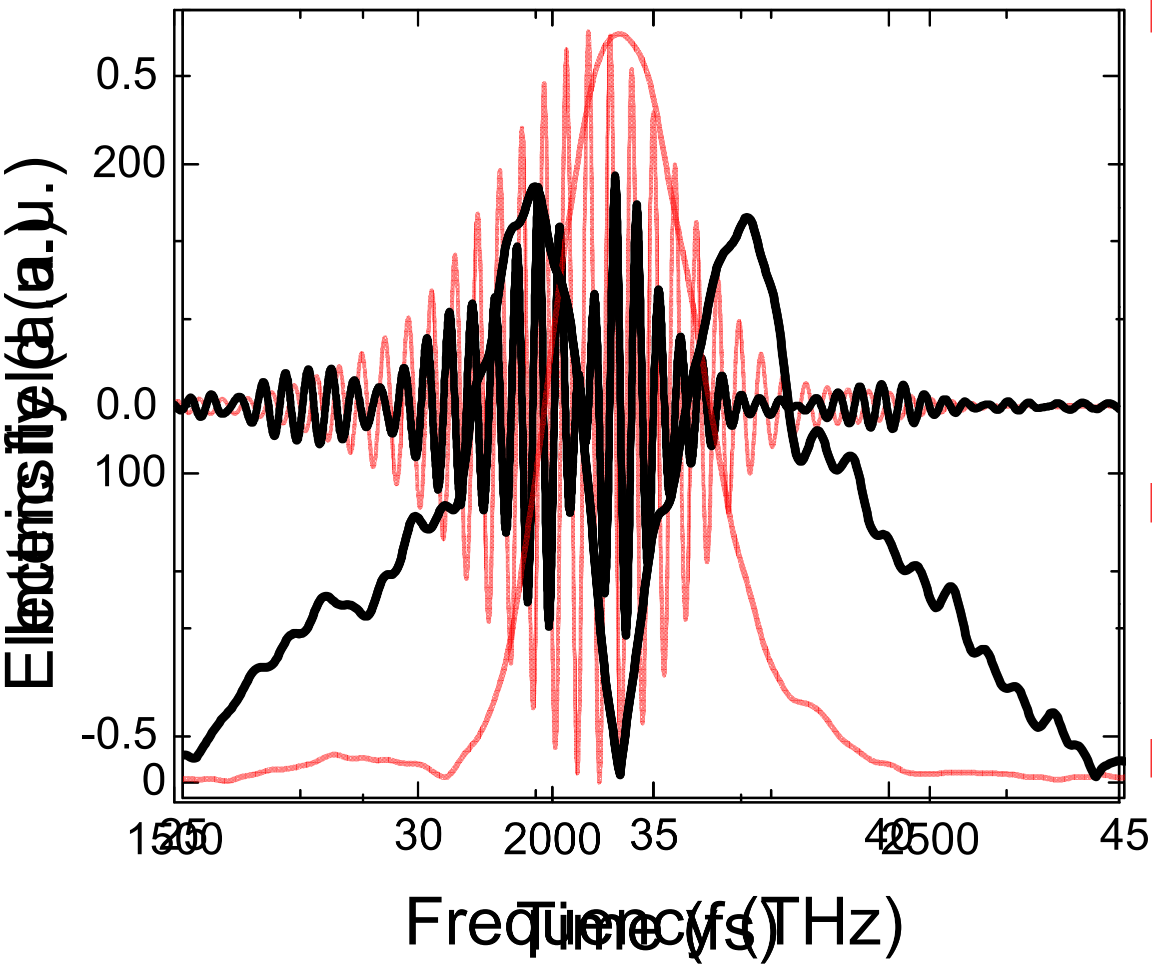
[1] C. Ciutu et al., Phys. Rev. B **72**, 115303 (2005)   [2] Y. Todorov et al., Phys. Rev. Lett. **105**, 196402 (2010)

Intersubband flexibility



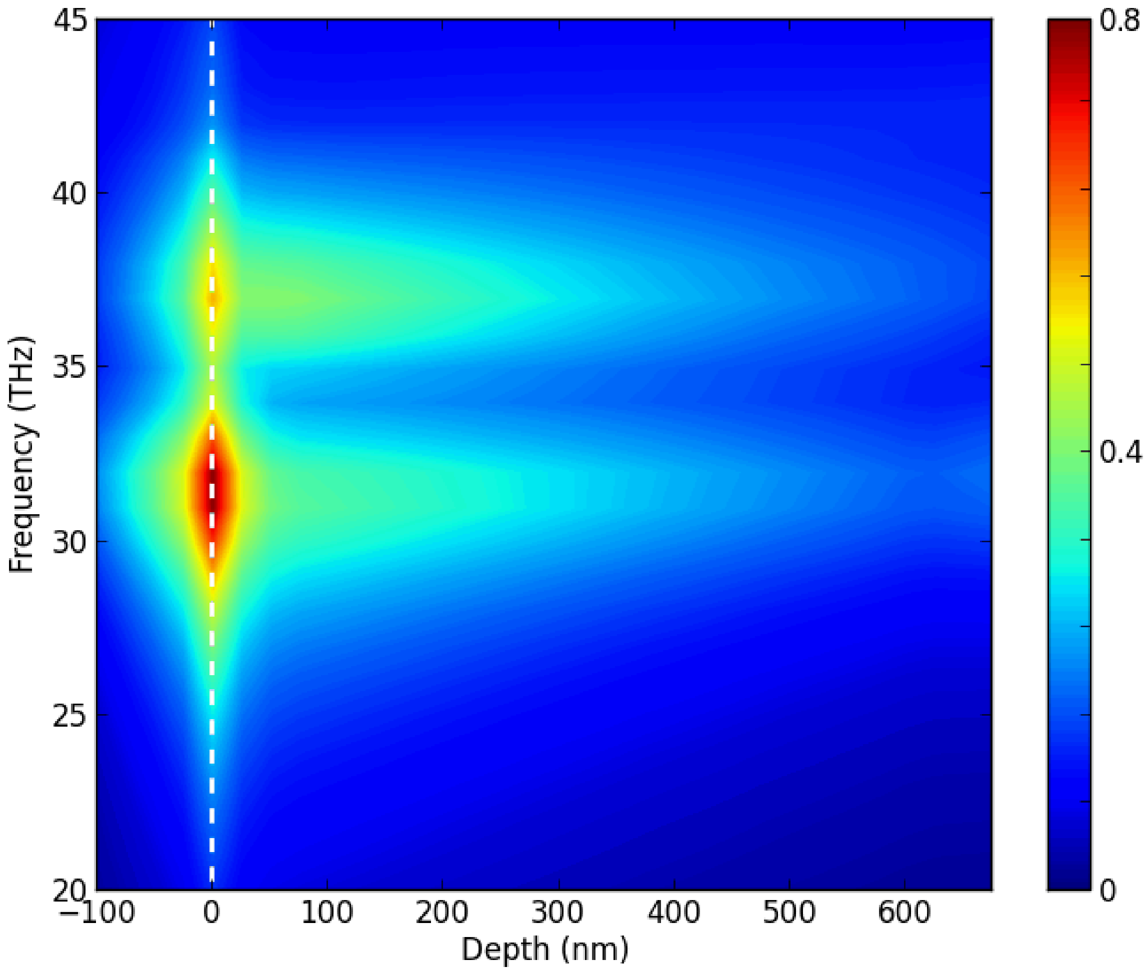
- Cover entire thermal IR
- Quantum-well transitions
  - 8, 10, 12 μm
- Model explains experiment
  - No free fitting parameters

Experimental Rabi oscillations



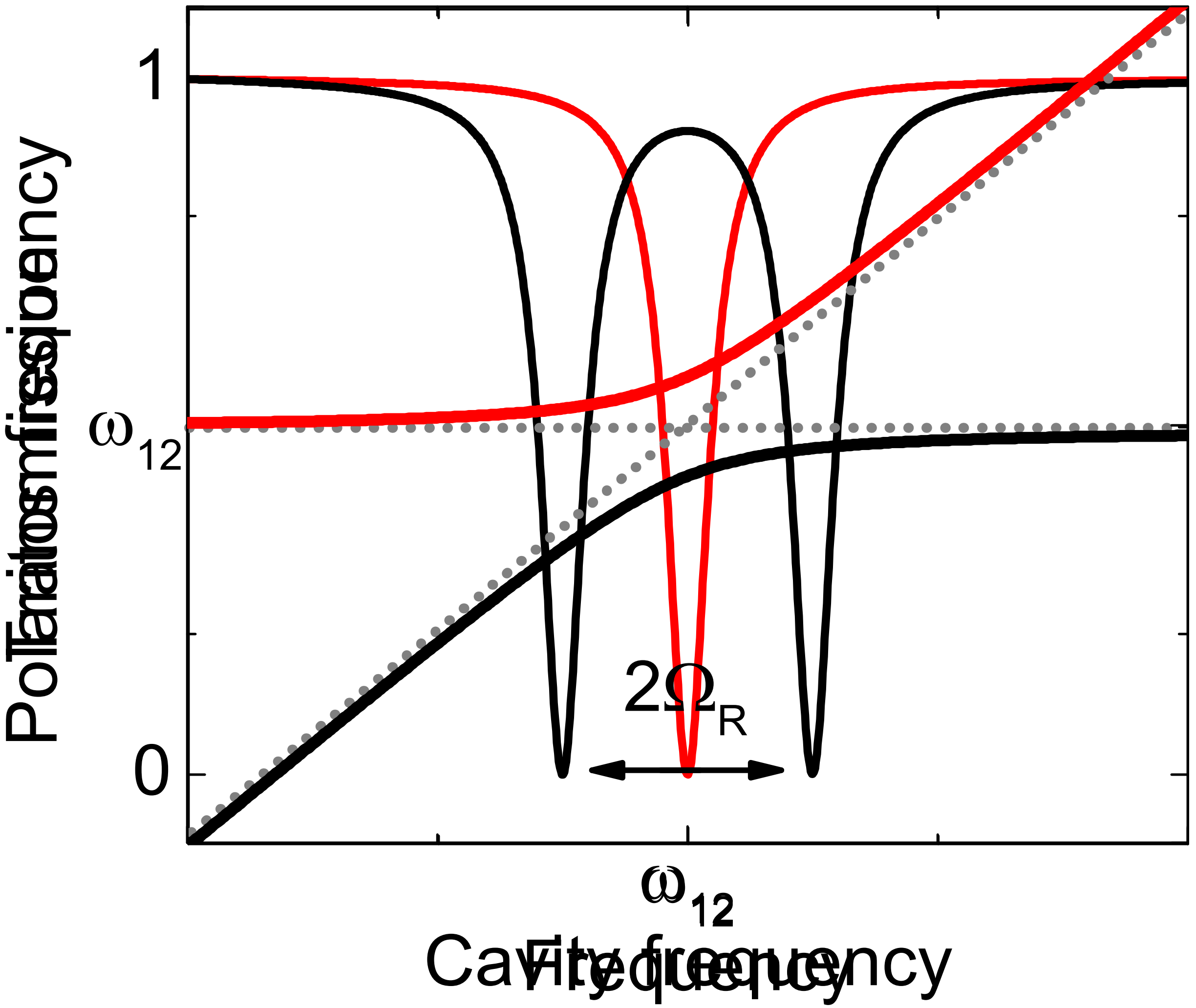
- Energy exchange probed in time
  - 33 fs oscillation
  - 480 fs beating
- System strongly coupled
- Splitting of 4.2 THz measured
  - 15 % of ω_{12}

E_z near-field profiles



- Only E_z couples
  - Near-field
- Exponentially decaying
  - Integrated over xy-plane
- Transmission at cavity res.

Application vs. physics



- Transmission from 0 to 1
  - Electrically switchable
- Works at room temperature
- Resonances anti-cross
  - $\Omega_R \approx \omega_{12}$

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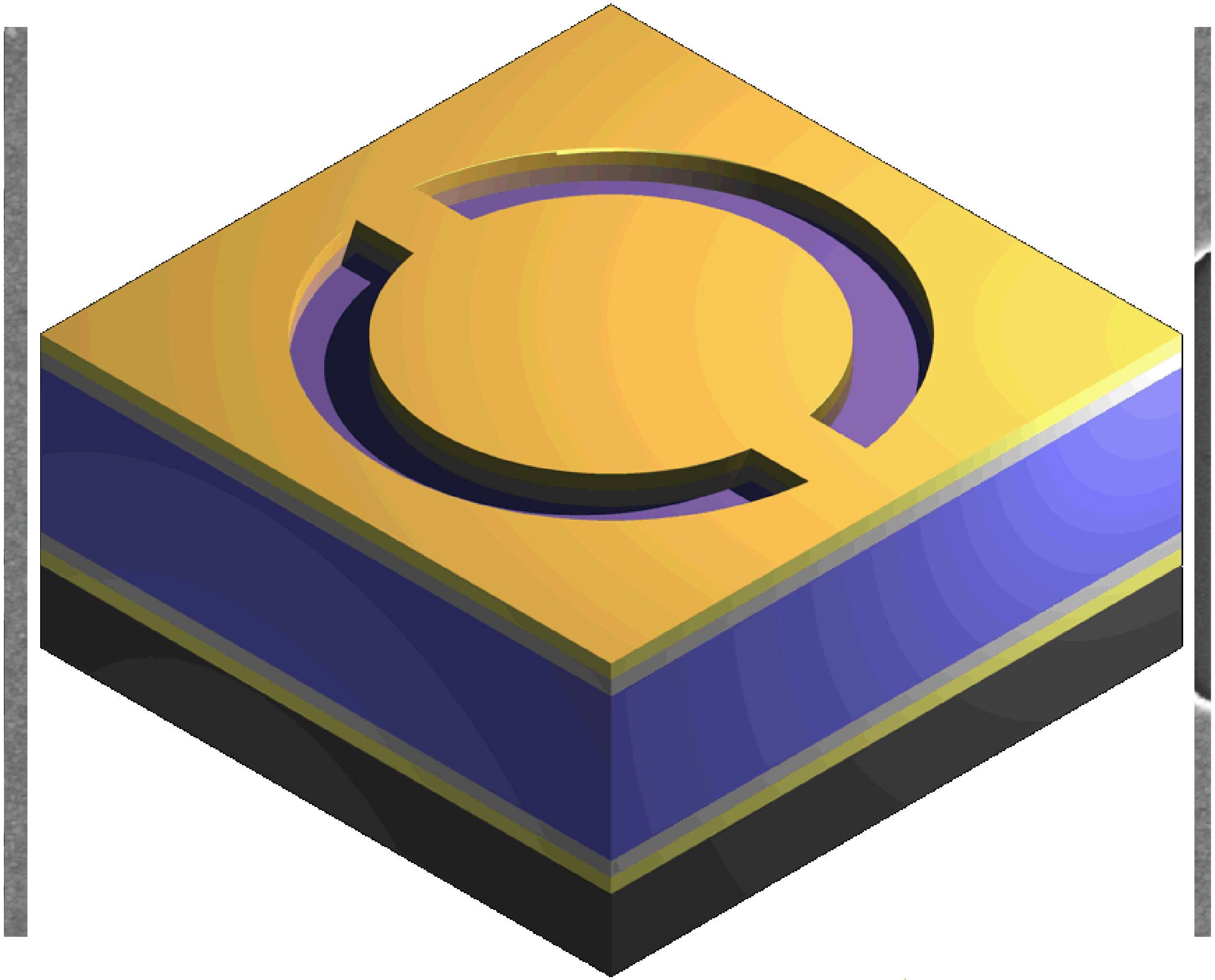
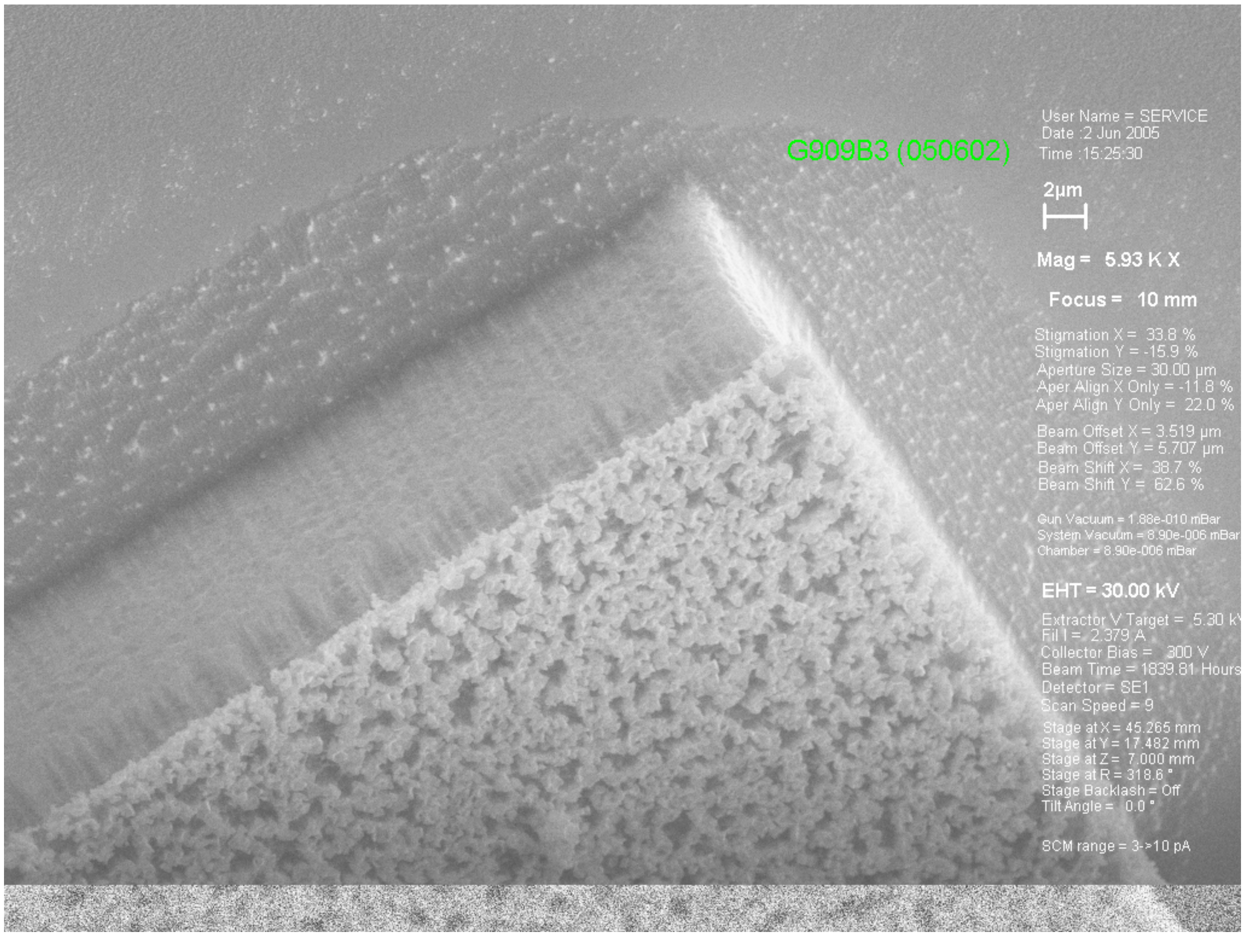
Metamaterial detector



Courtesy of S. Schwarz

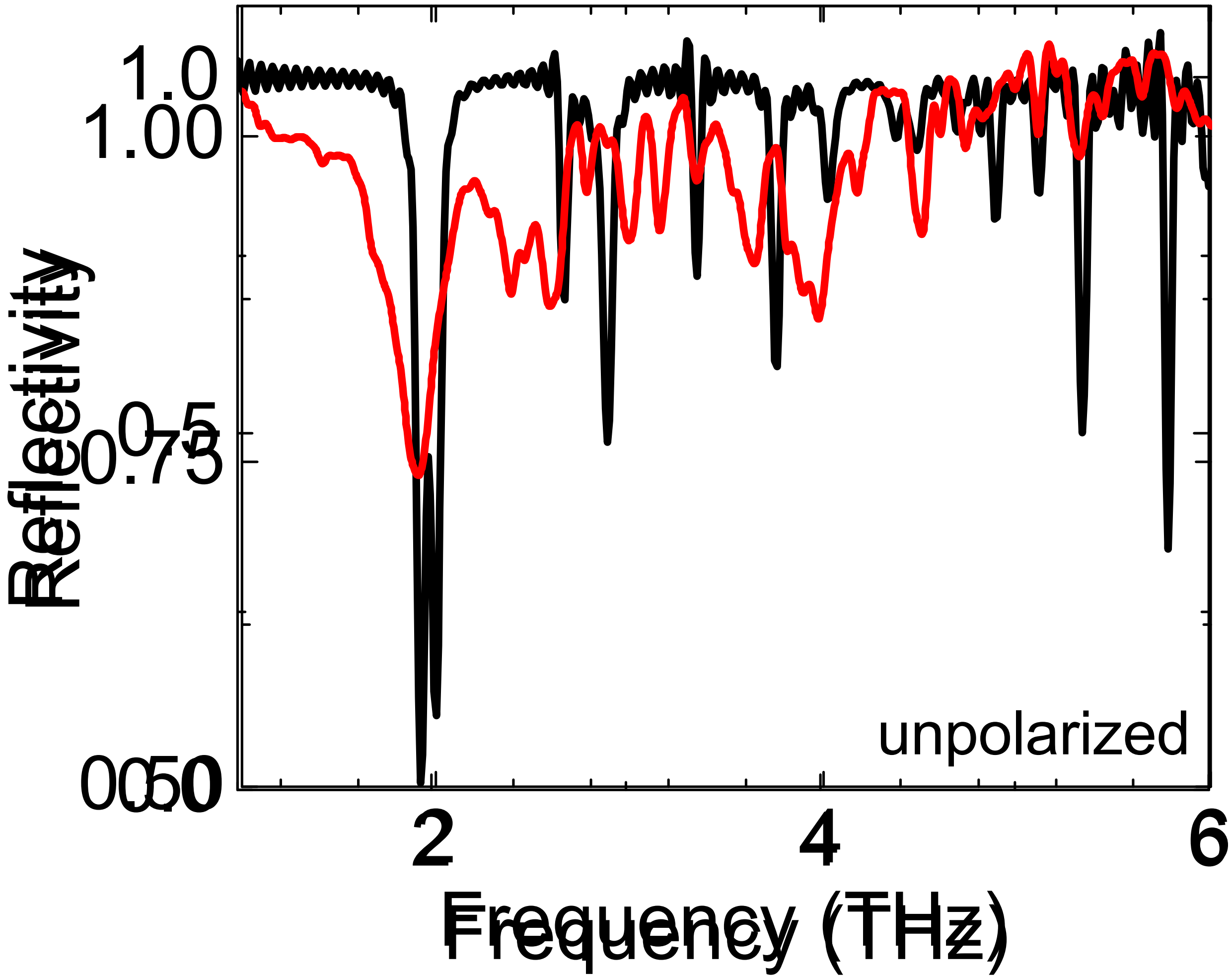
- Inverted metamaterial
- Double-metal cavity =>high-Q
  - Processing
- Mesa structure
- Couple normal incidence light quantum-well

Waveguide



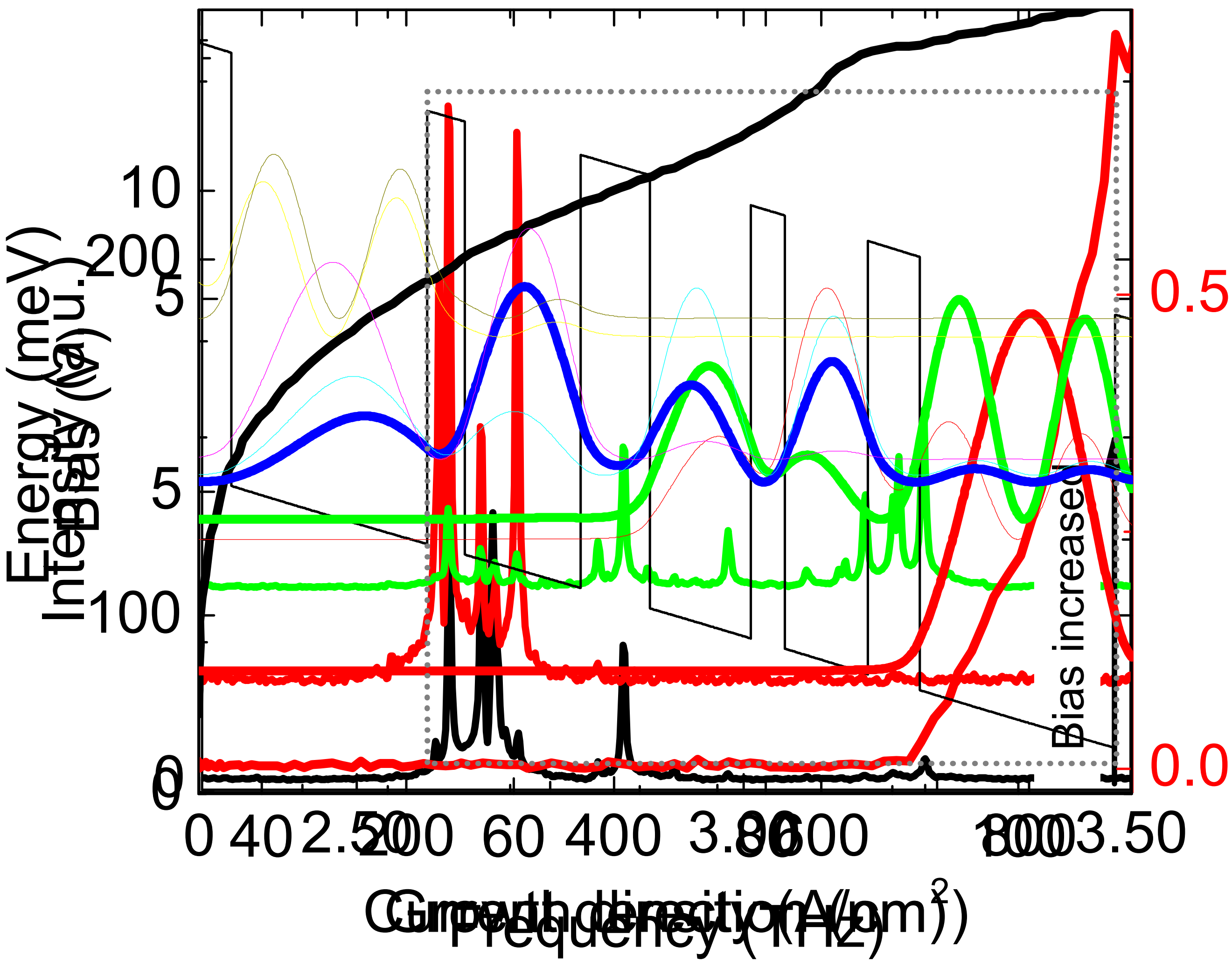
- Plasmonic waveguide
- Losses α=5 cm^{-1}
- Confinement 100 %
- Constant mode profile
- No leakage

Reflection measurements



- Similar behavior as conventional metamaterial
- Reflection and transmission exchanged
- Simulation and experiment agree well

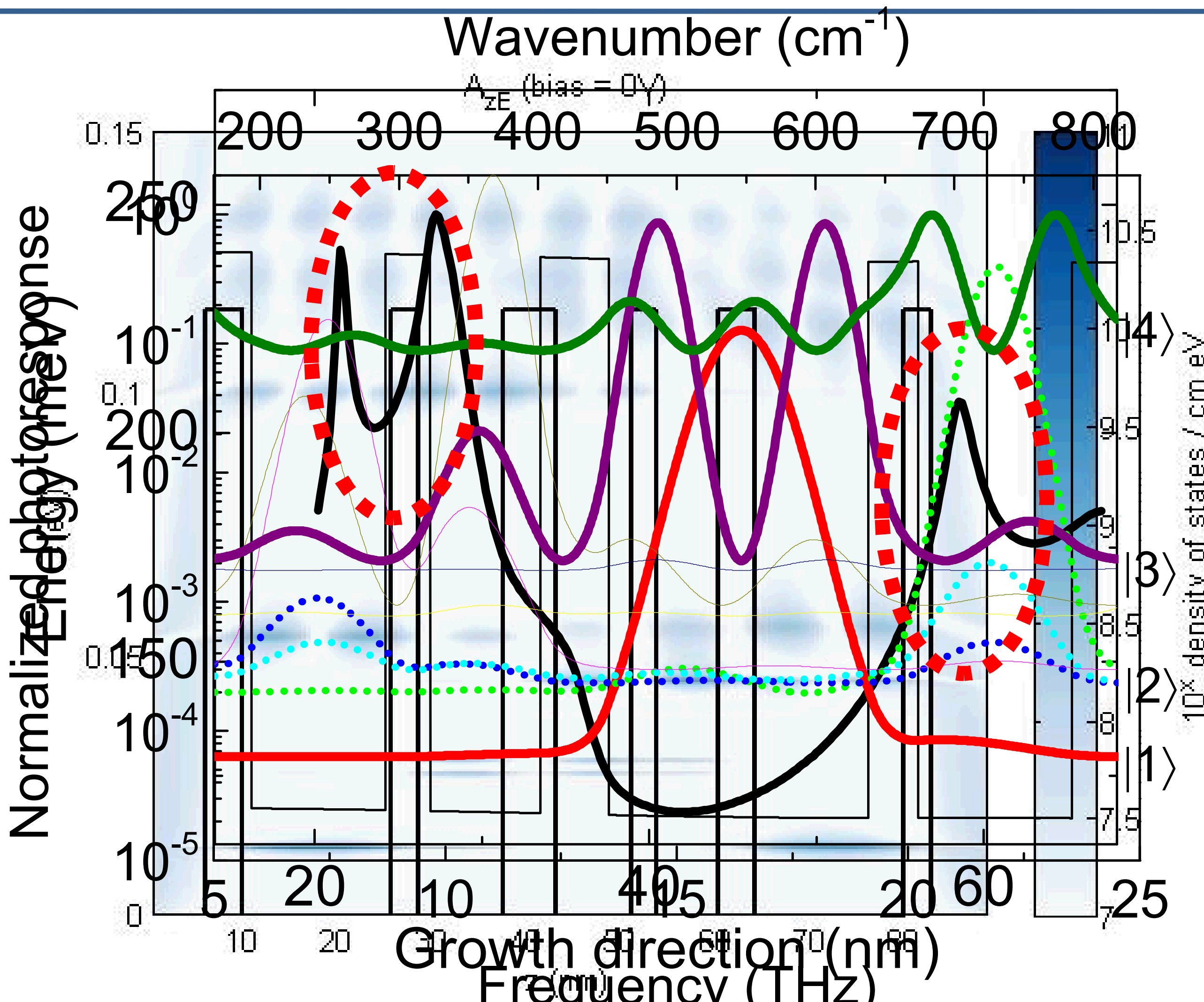
THz-QCL characterization



- Same active region
  - Integration
- LO-phonon scheme[1, 2]
- T_{max} 150 K
- Emission 2.6 to 3.2 THz

[1] B. S. Williams, et al., Appl. Phys. Lett. **82**, 1015–1017 (2002).
[2] A. Benz et al., Appl. Phys. Lett. **90**,101107:1–101107:3 (2007).

Detector operation

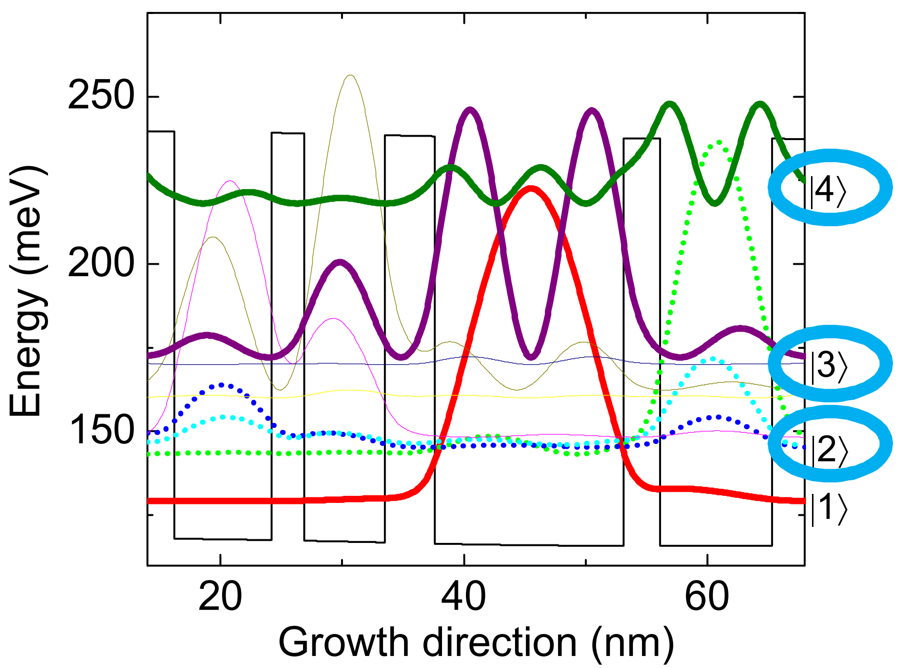


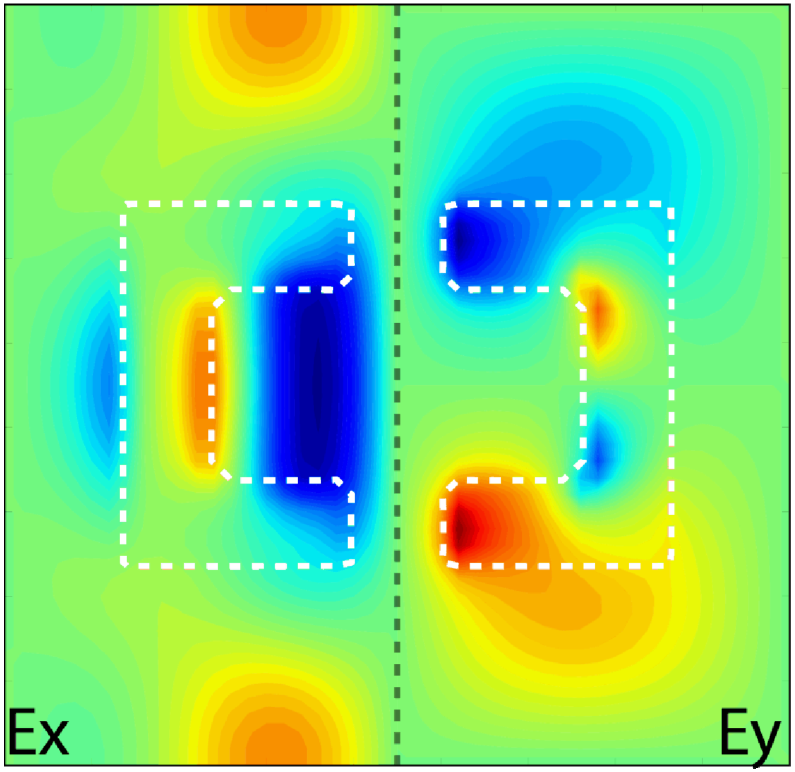
- Zero bias
- Three transitions
- NEGF transport [1]
  - Light field included
  - Ballistic tunneling[2]

[1] L. E. Henrickson, J. Appl. Phys. **91**, 6273–6281 (202).

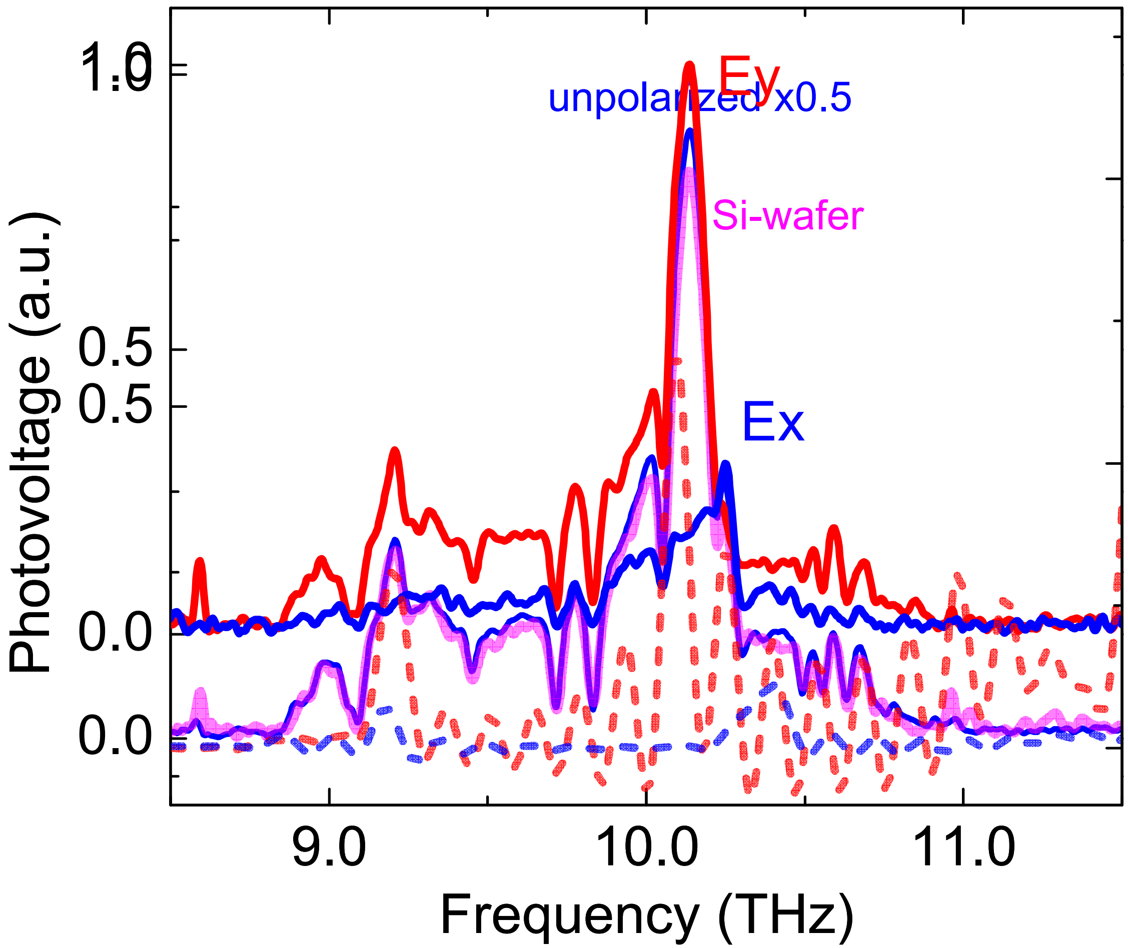
[2] T. Kubis, et al., phys. stat. sol. (c) **5**, 232–235 (2008).

Field distribution





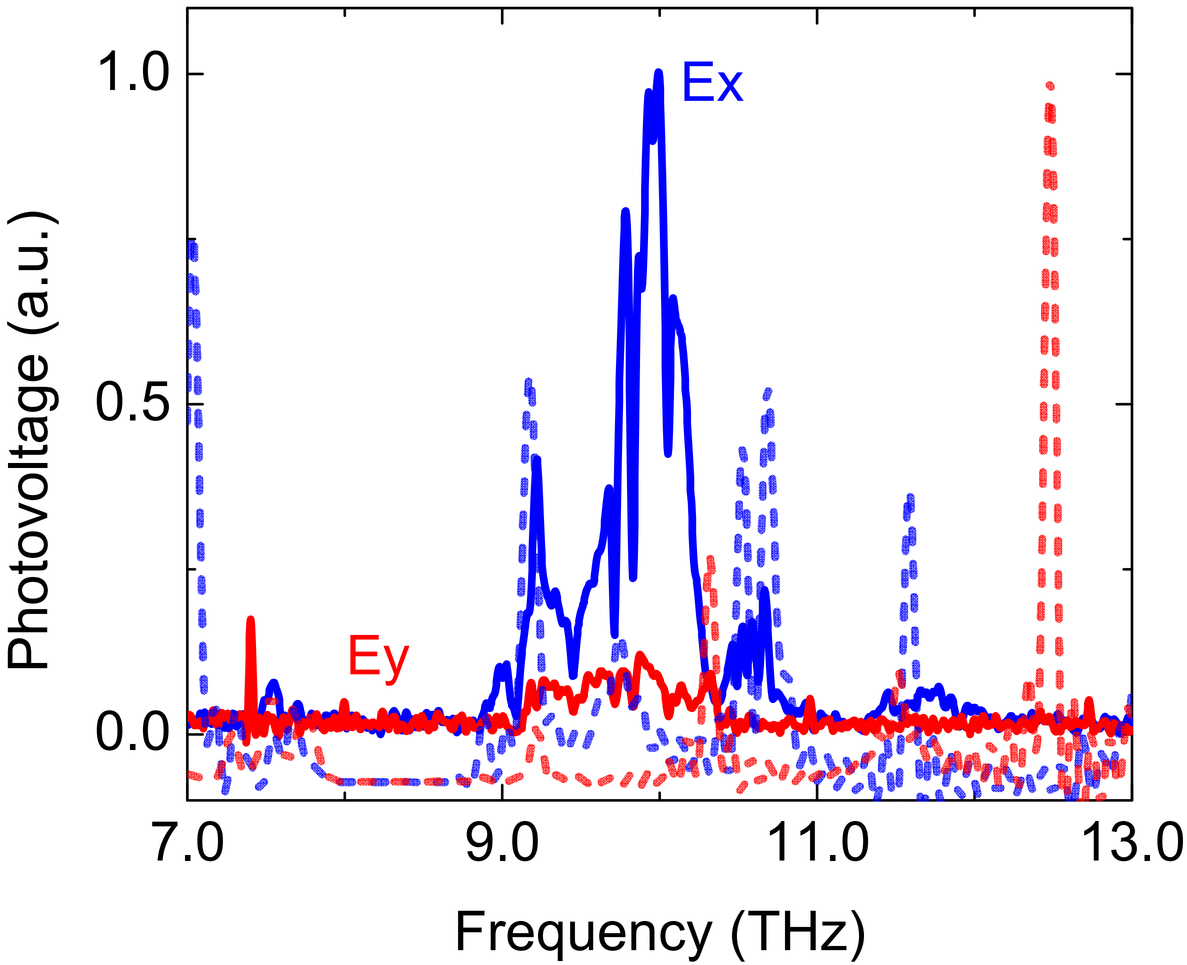
Detector a=9.15 μm



- Globar as source
  - Linear regime
  - FTIR
- No bandgap components
- Overlap of quantum-well and metamat.

A. Benz et al., (in preparation)

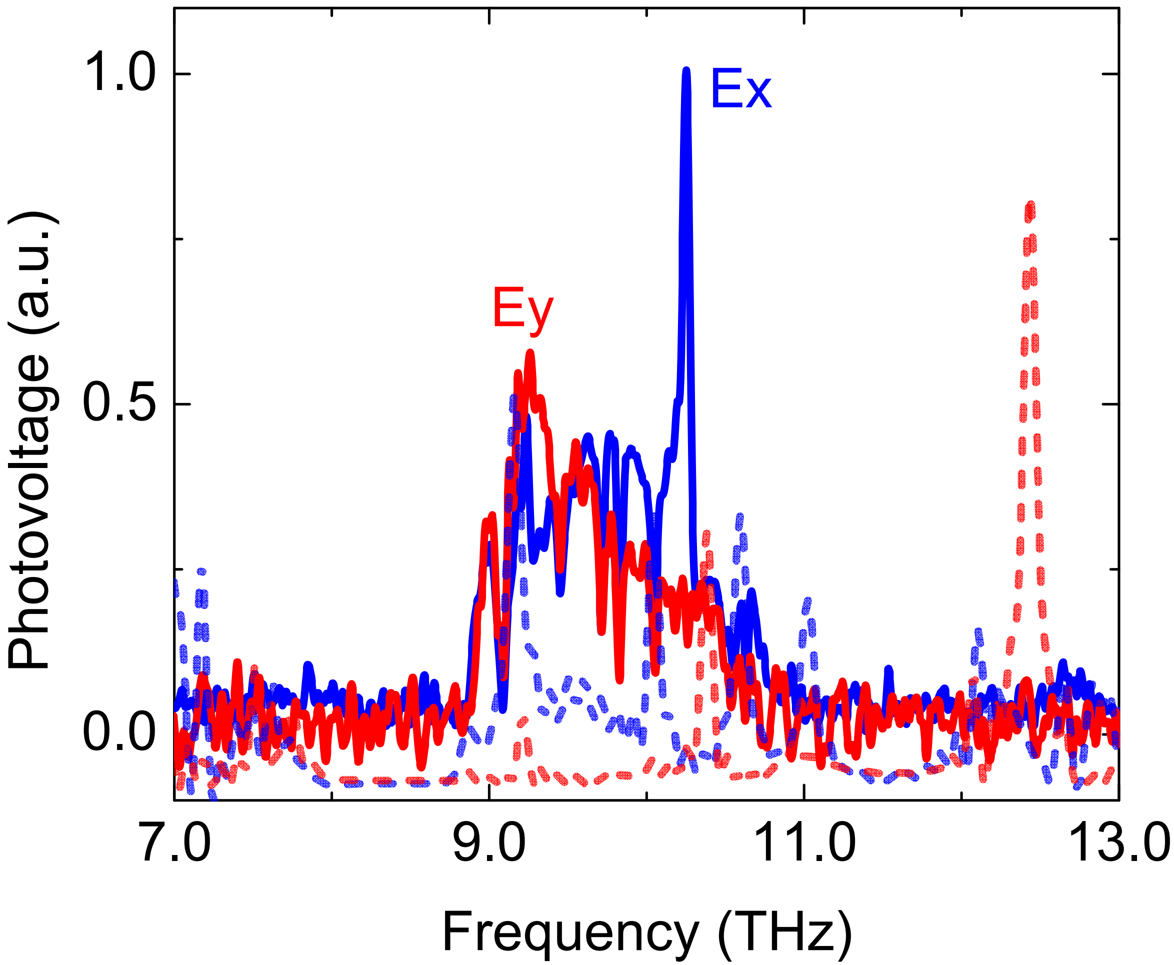
Detector a=10.56 μm



- Almost no response for Ey polarized light
- Ex shows sharp features
- Broadband by quantum-well

A. Benz et al., (in preparation)

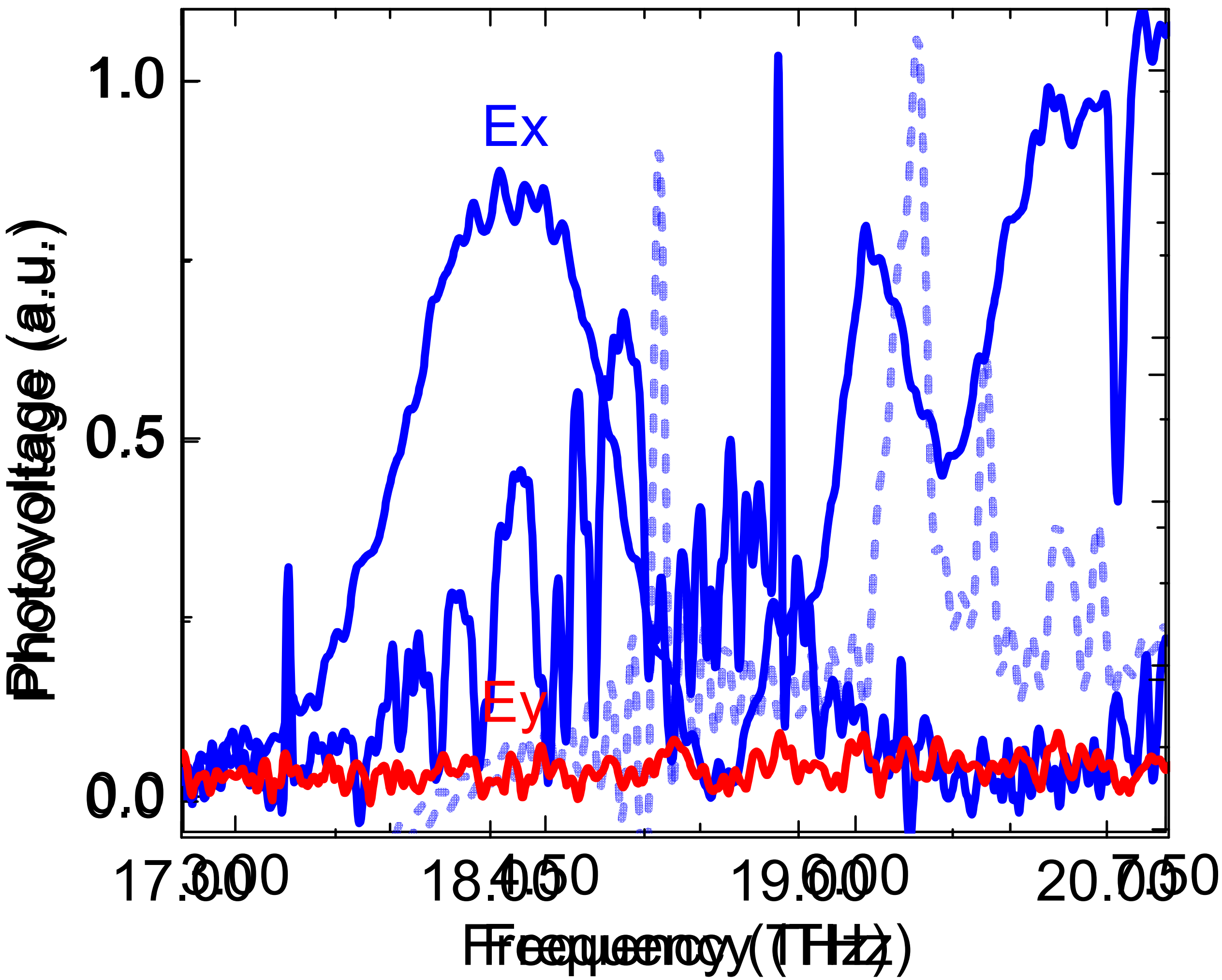
Detector a=11.97 μm



- Ex and Ey peaks re-produced by the simulation
- No response above 11 THz or below 9 THz
- Broadband again the QW

A. Benz et al., (in preparation)

Low / high frequency response



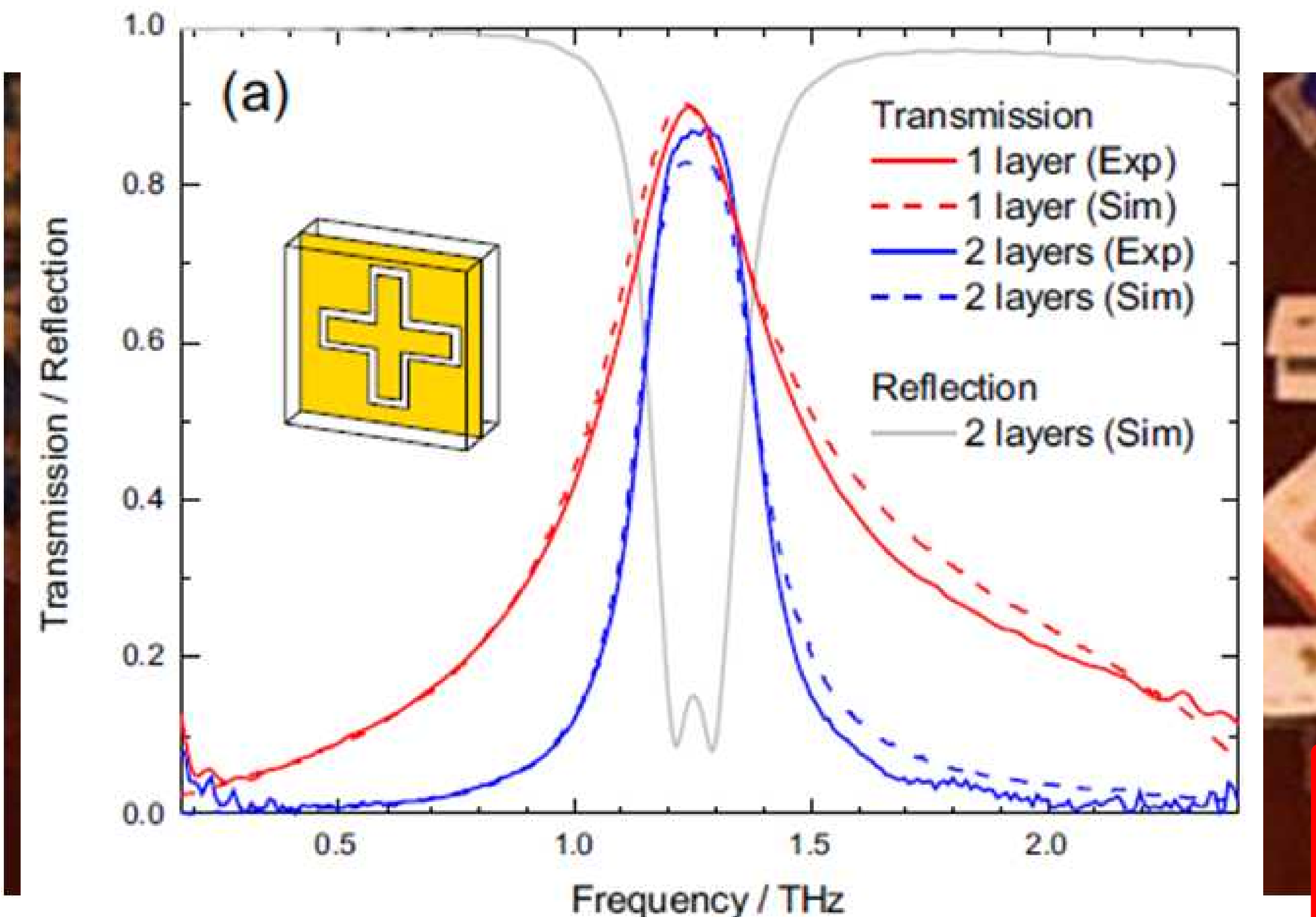
- Low frequency weak & broad
  - Miniband of states
  - Predictable
- High freq. suppresses Ey
  - Double-lobes

A. Benz et al., (in preparation)

Conclusion & Outlook

- Tunable filter
  - Operating in the ultra-strong coupling limit
  - Splitting can be turned on / off
  - Rich physics
- Metamaterial detector
  - Normal incidence radiation
  - Integrated source-detector solution
  - Active region generates and detects light

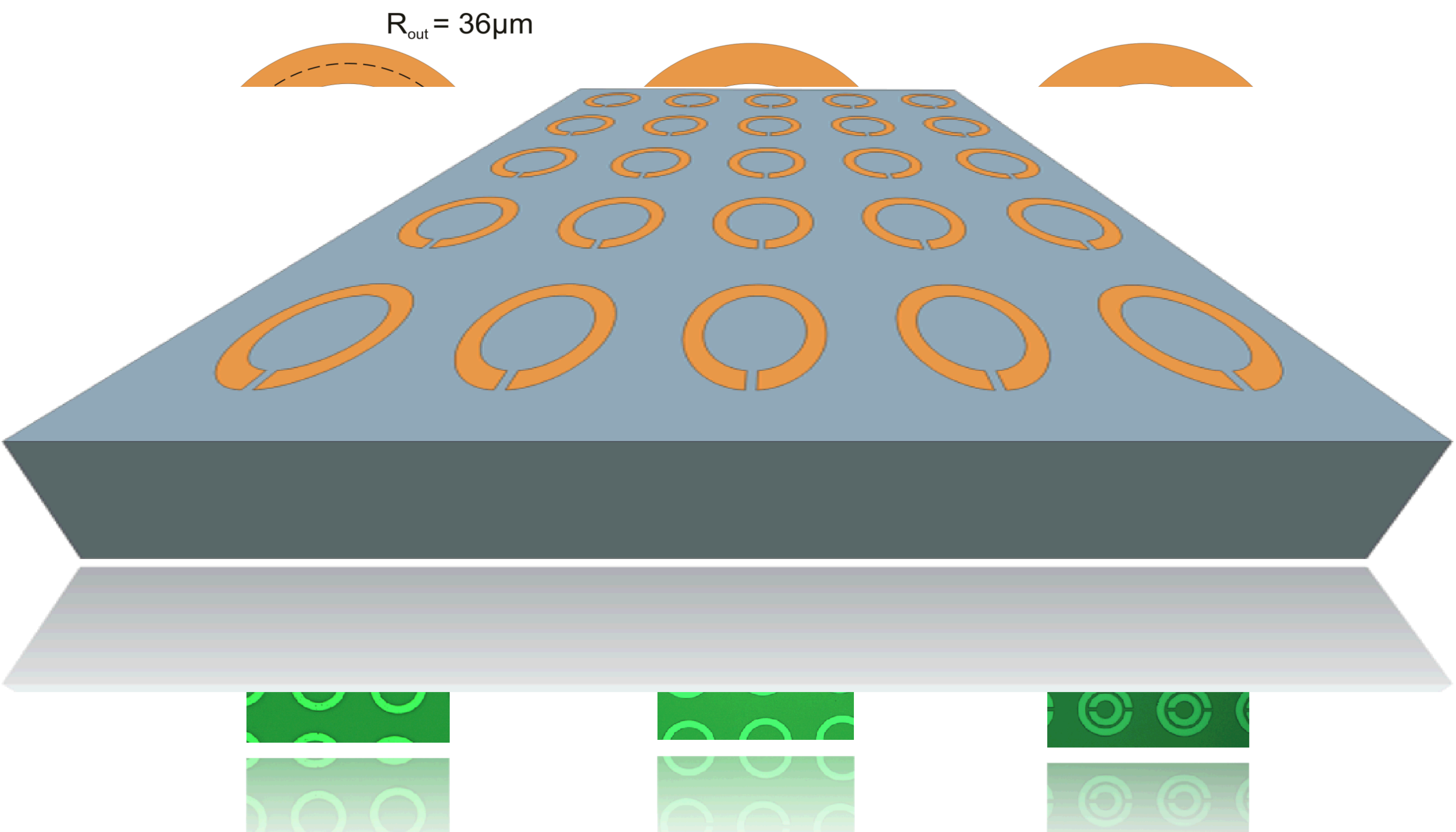
Metamaterial



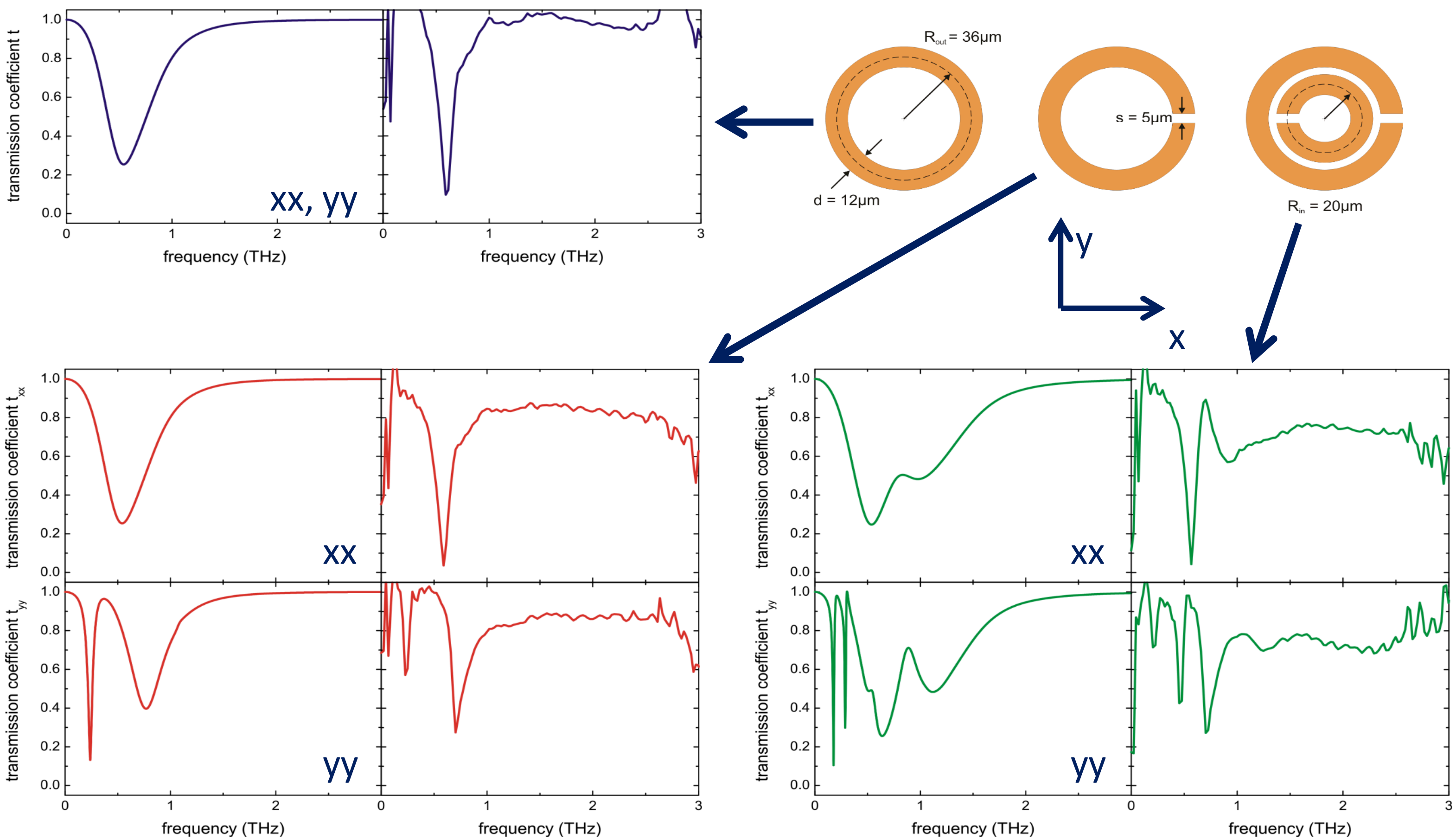
Paul, Opt. Express 17, 819 (2009)
Fang, Science 308, 534 (2005)

- Resonant subwave-length str.
- ν filters
- Superlense
- Cloaking
- Geometry defines properties

Metamaterial (2)

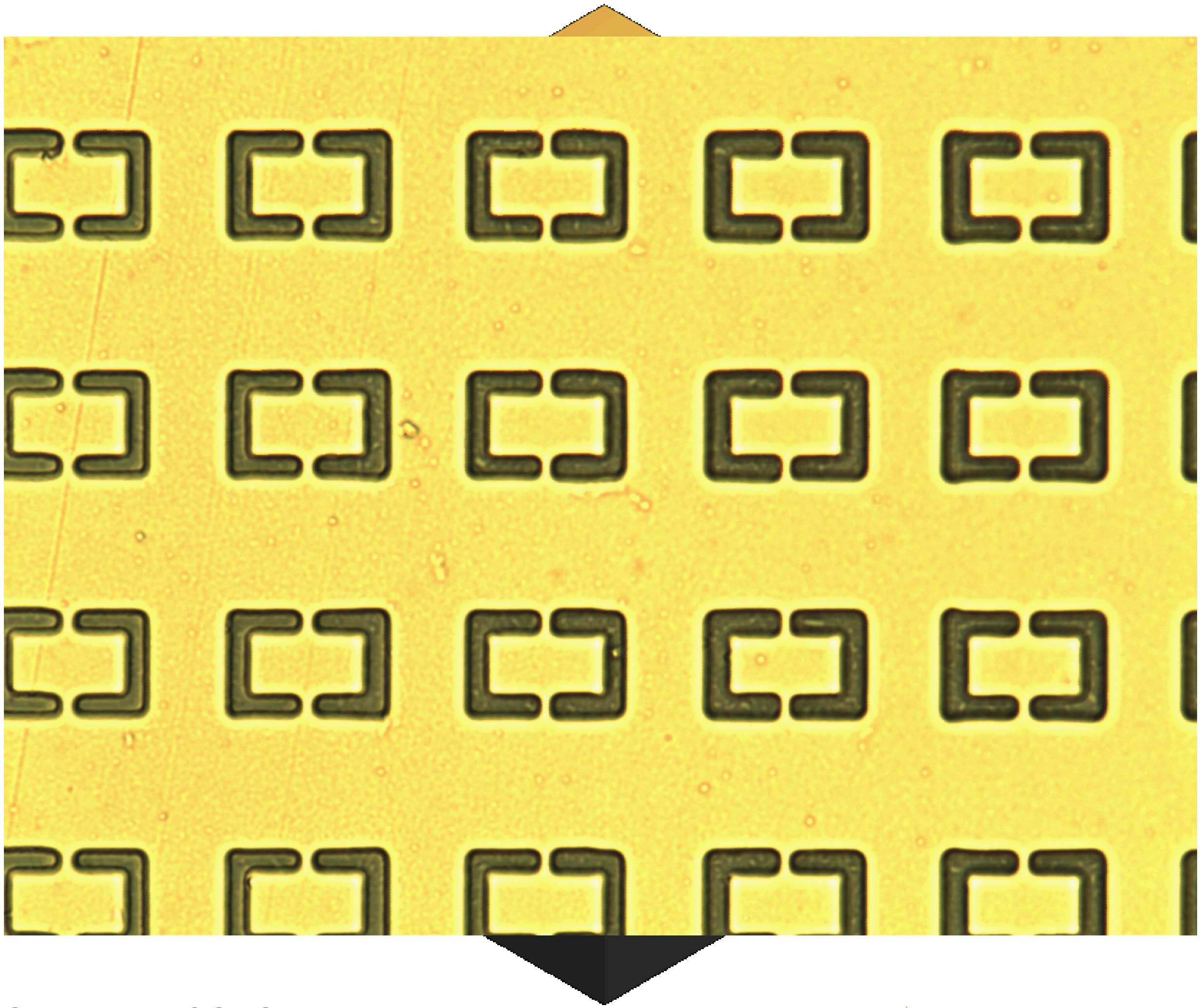


Metamaterial simulation



- Control near-field precisely, field-enhancement

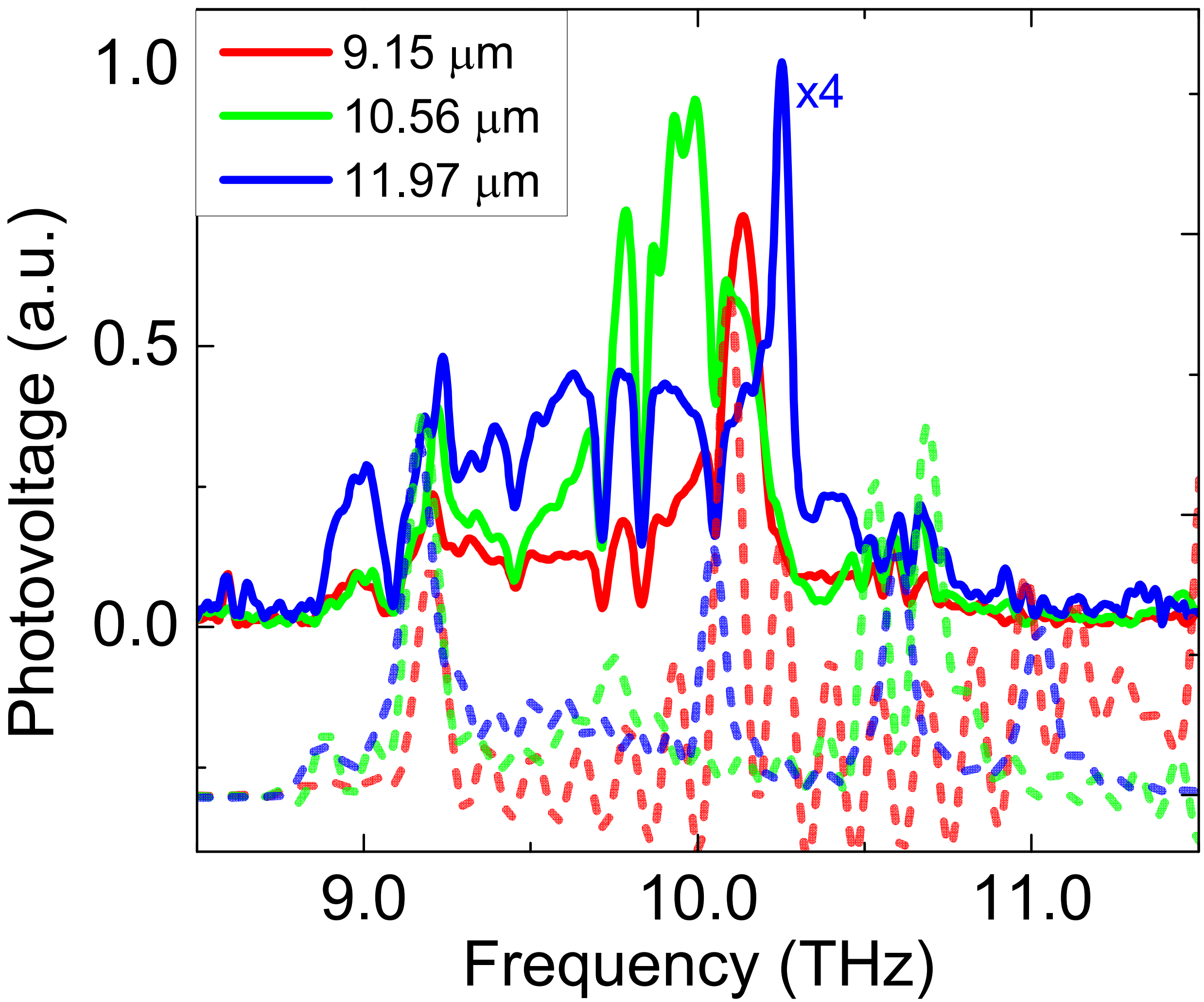
Resonant detector



Courtesy of S. Schwarz

- Inverted metamaterial
- Double-metal cavity =>high-Q
- Mesa structure
- Couple normal incidence light to quantum well

Detector overview



- Incident Ex-polarization
- Sharp features metamaterial
- Broadband from QW-transition

A. Benz et al., (in preparation)

Motivation, applications

- Why filters
- MIR / THz very rich for applications
- No components
- Some products already there