Sandia National Laboratories

SAND2013-6955C

Ultra-strong light-matter interaction with mid-infrared metamaterials

A. Benz[1,2], S. Campione[3], S. Liu[1,2], I. Montano[2], J. F. Klem[2], A. Allerman[2], M. B. Sinclair[2], F. Capolino[3], and I. Brener[1,2]

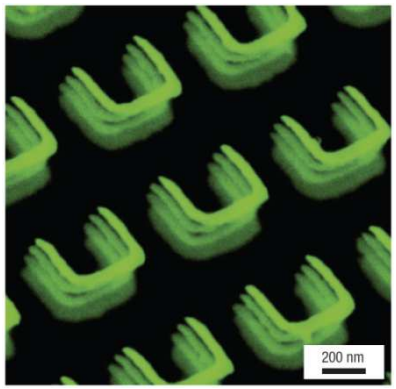
[1] Center for Integrated Nanotechnologies (CINT), Sandia National Laboratories, Albuquerque, NM

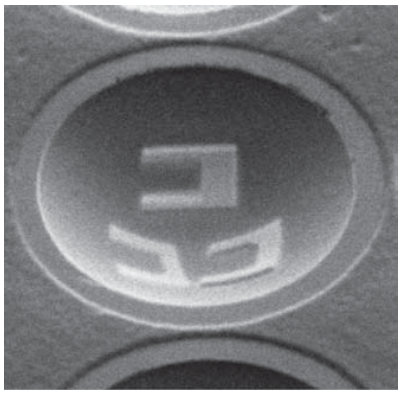
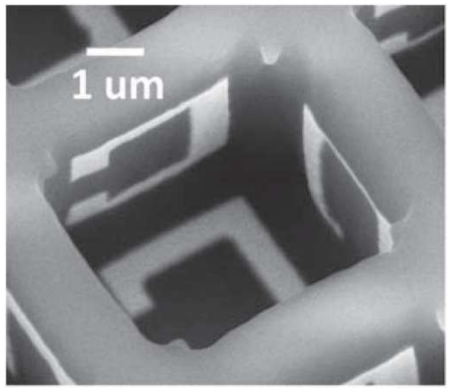
[2] Sandia National Laboratories, Albuquerque, NM

[3] University of California, Irvine, CA

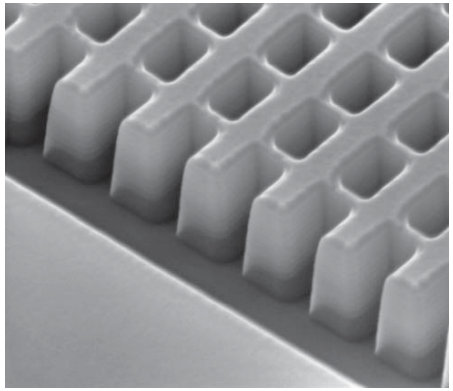
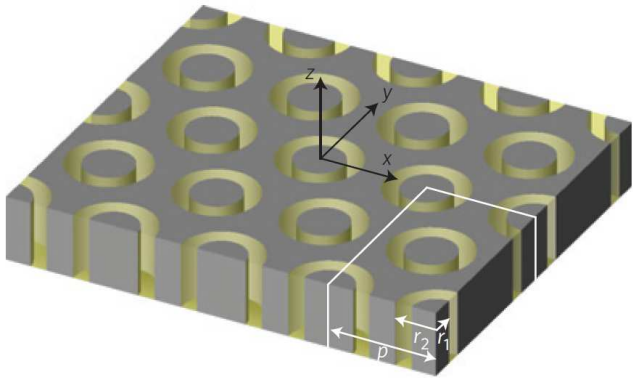
This work was performed, in part, at the Center for Integrated Nanotechnologies, a U.S. Department of Energy, Office of Basic Energy Sciences user facility. Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Metamaterial overview

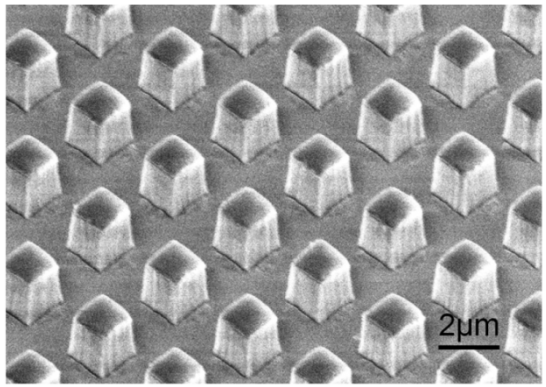


3D SRRs[1,2,3]

Negative index[4,5]

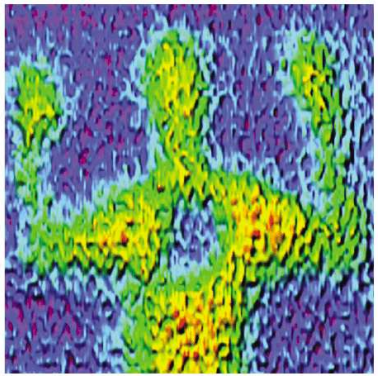


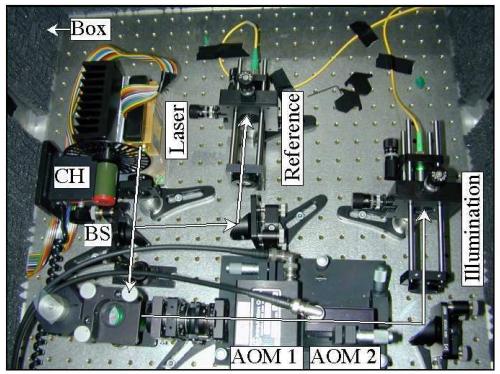
Magnetic mirrors[6]

[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)

Why mid-IR?

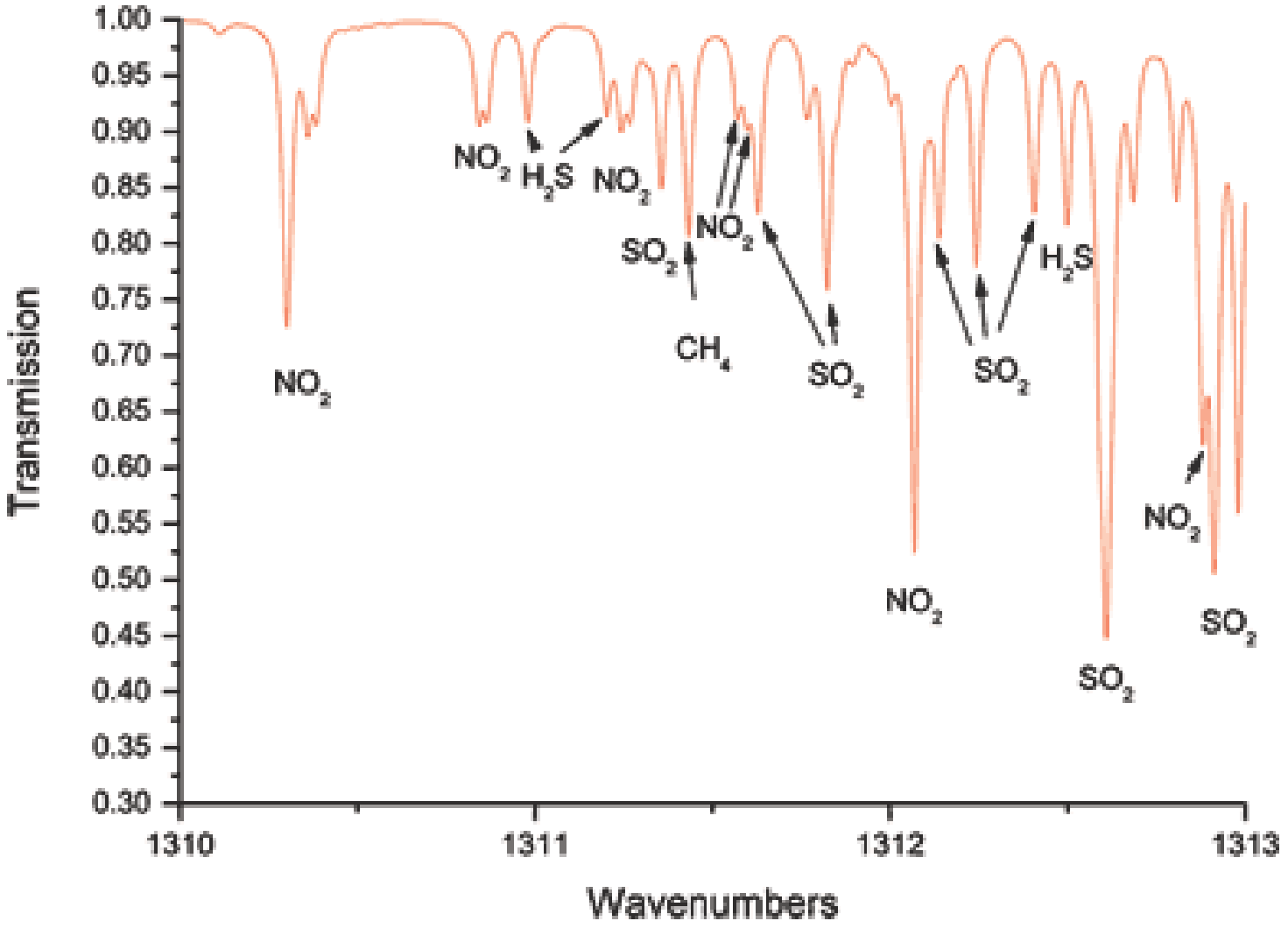
- Large number of possible applications
  - Spectroscopy
  - Heterodyne detection
  - Process controll
  - Security systems
  - Imaging



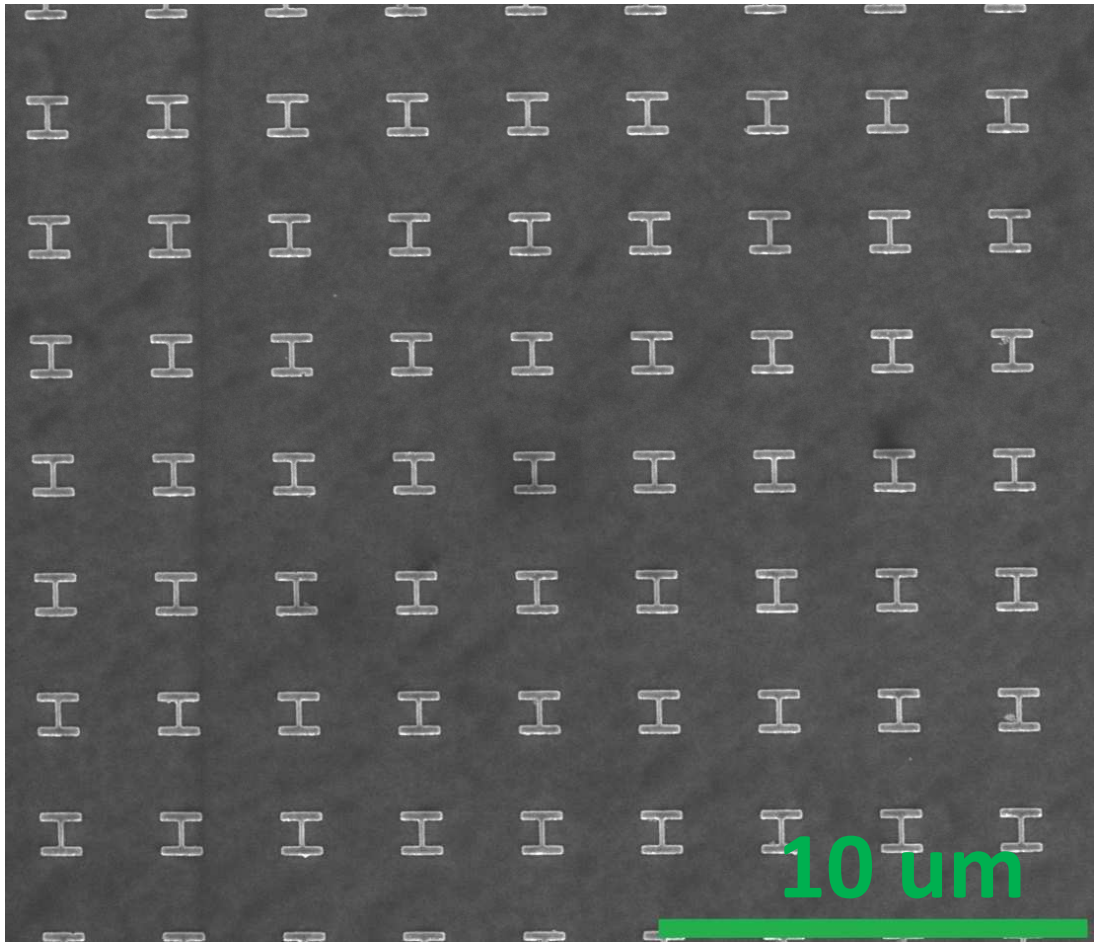


Why mid-IR?

- La

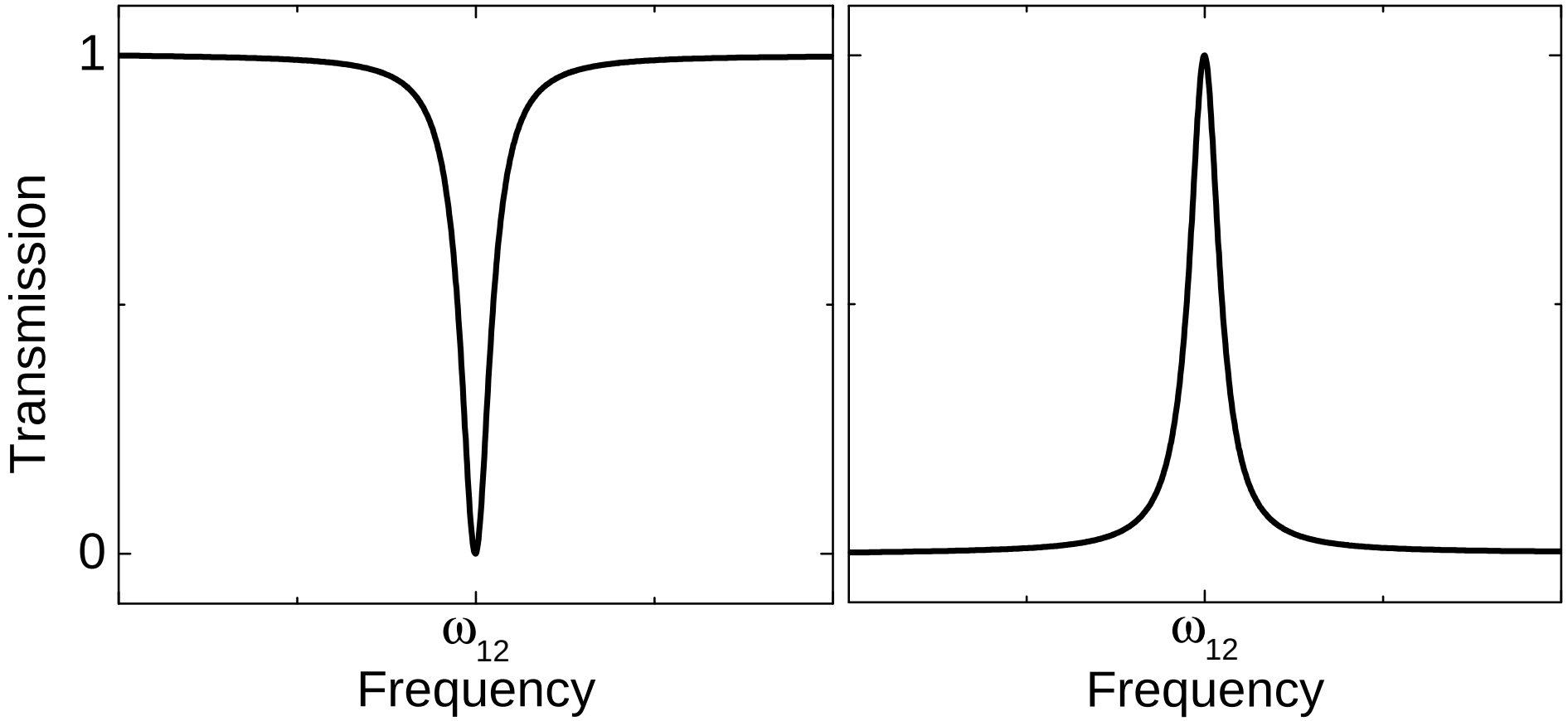

Transmission
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
1310
1311
1312
1313
Wavenumbers
NO2
NO2
H2S
NO2
SO2
NO2
CH4
SO2
NO2
SO2
H2S
NO2
SO2
SO2

Metasurface

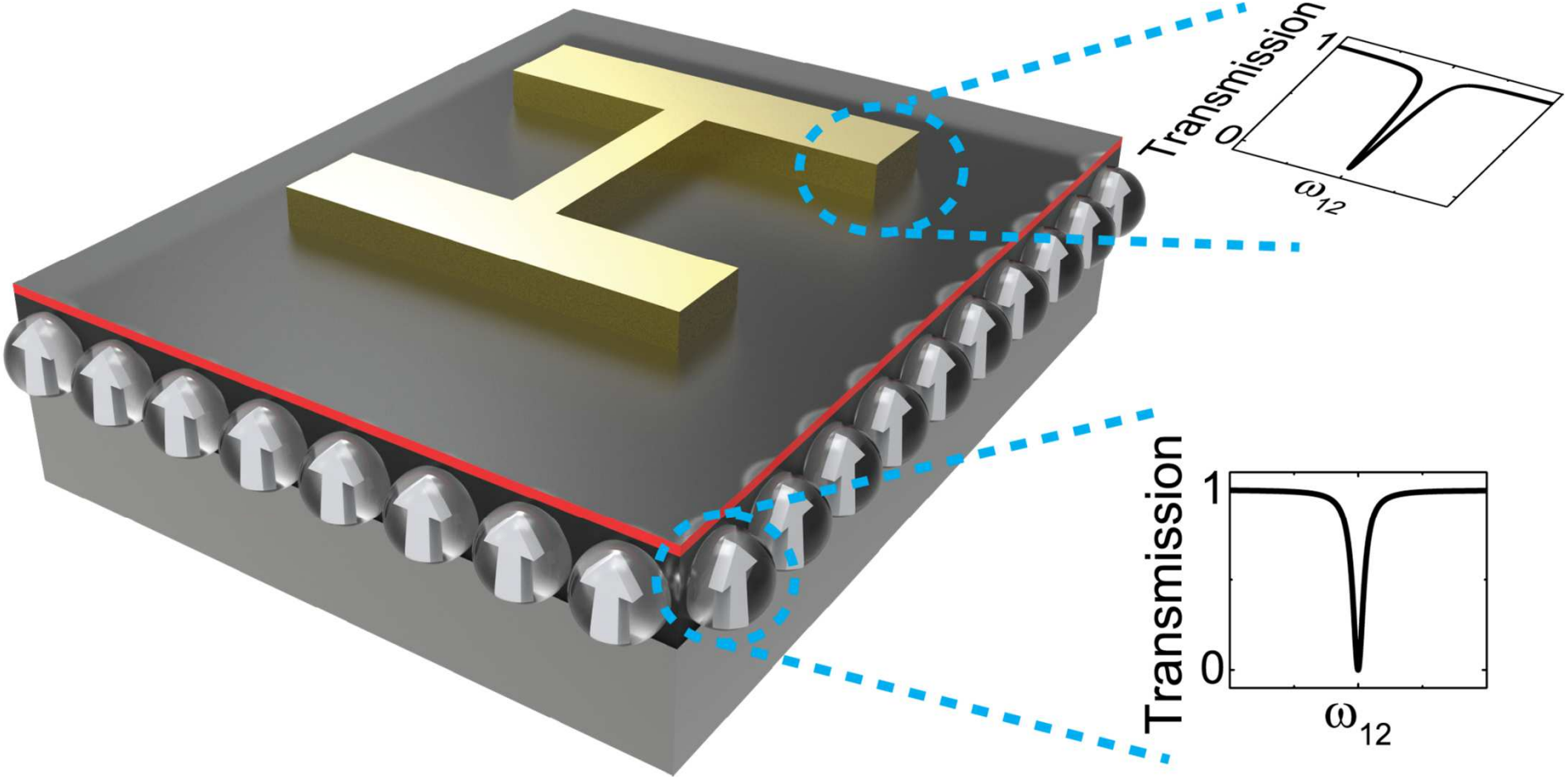


- Mostly 2D-layer used
  - Metasurface
- Versatile functionality
- ν filter
- Geometry defines properties

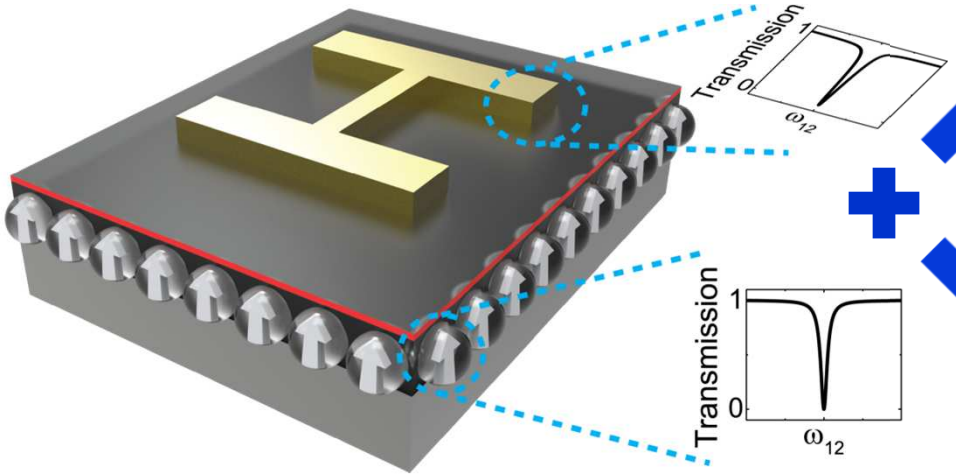
Metasurface



Light-matter coupling



Light-matter coupling



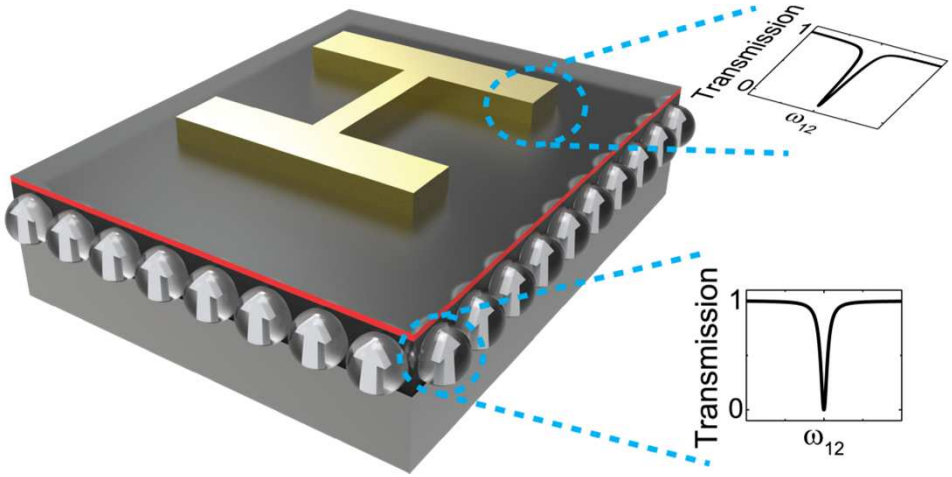
Weak coupling

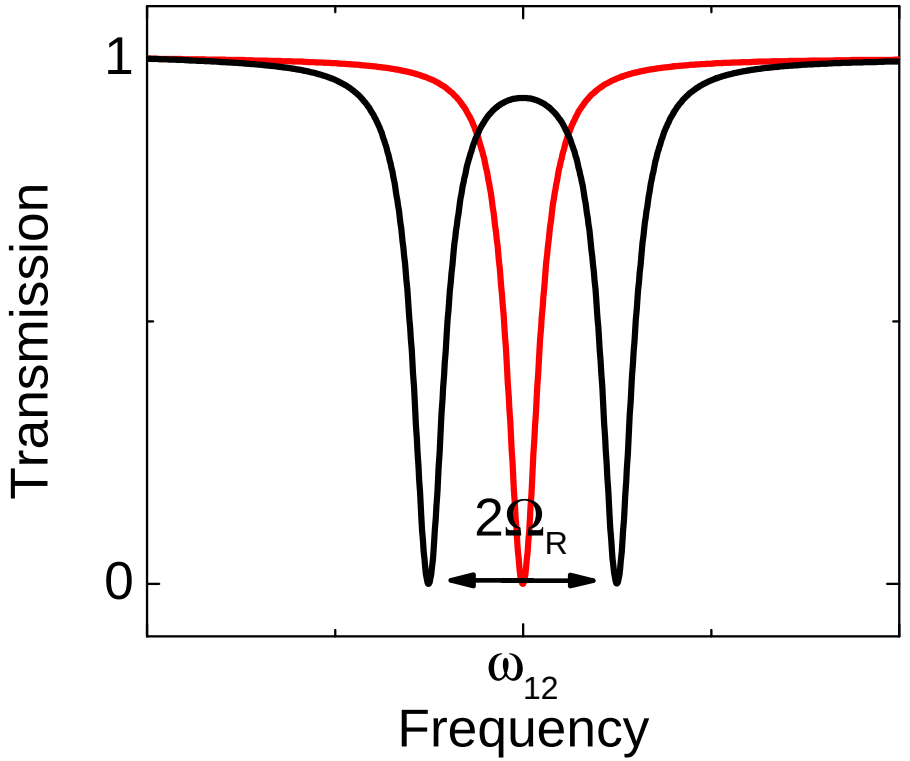
- Losses > Coupling
- Purcell regime

Strong coupling

- Coupling > Losses
- Energy exchange
- Rabi frequency

Light-matter coupling





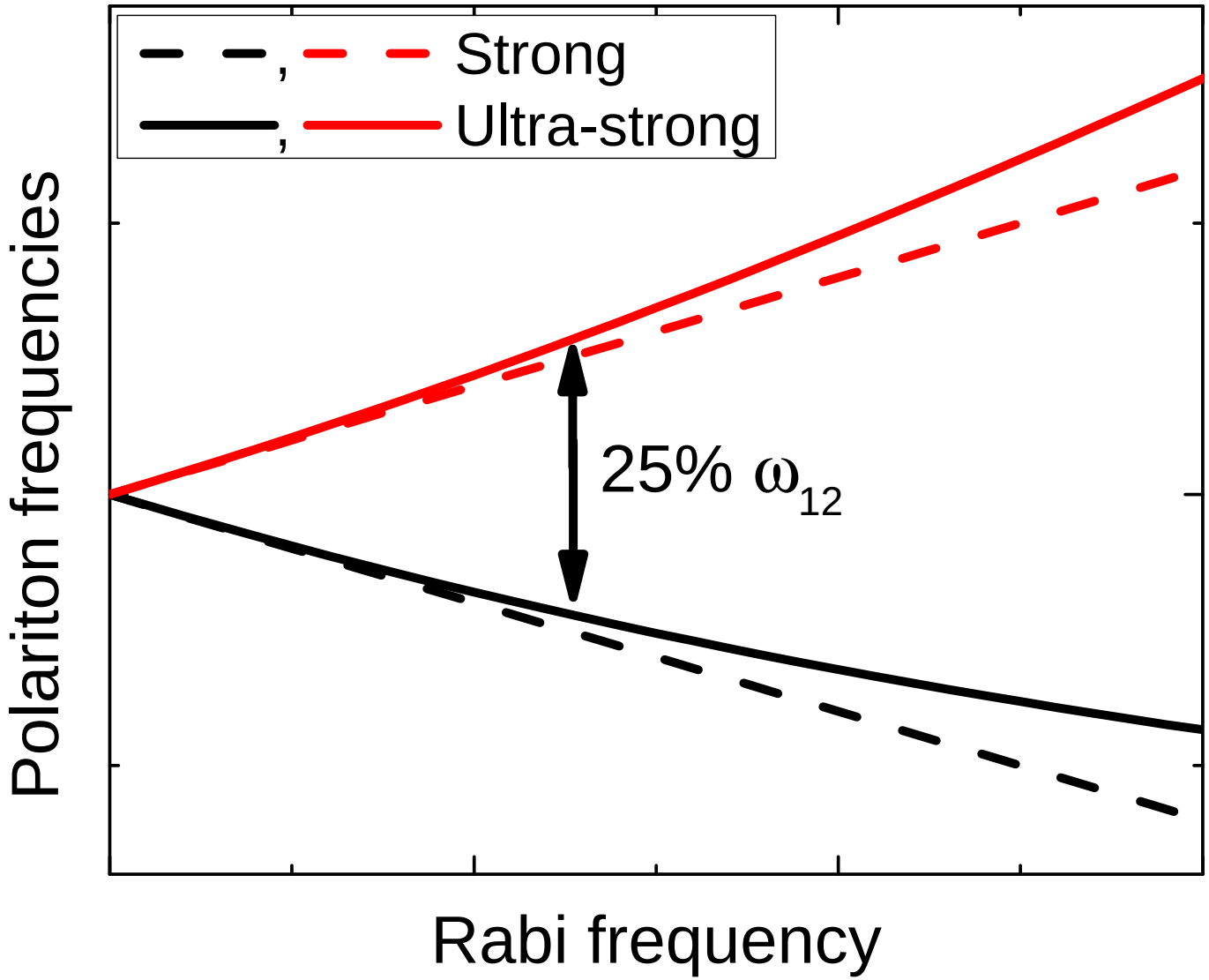
Ultra-strong coupling physics

Sandia National Laboratories

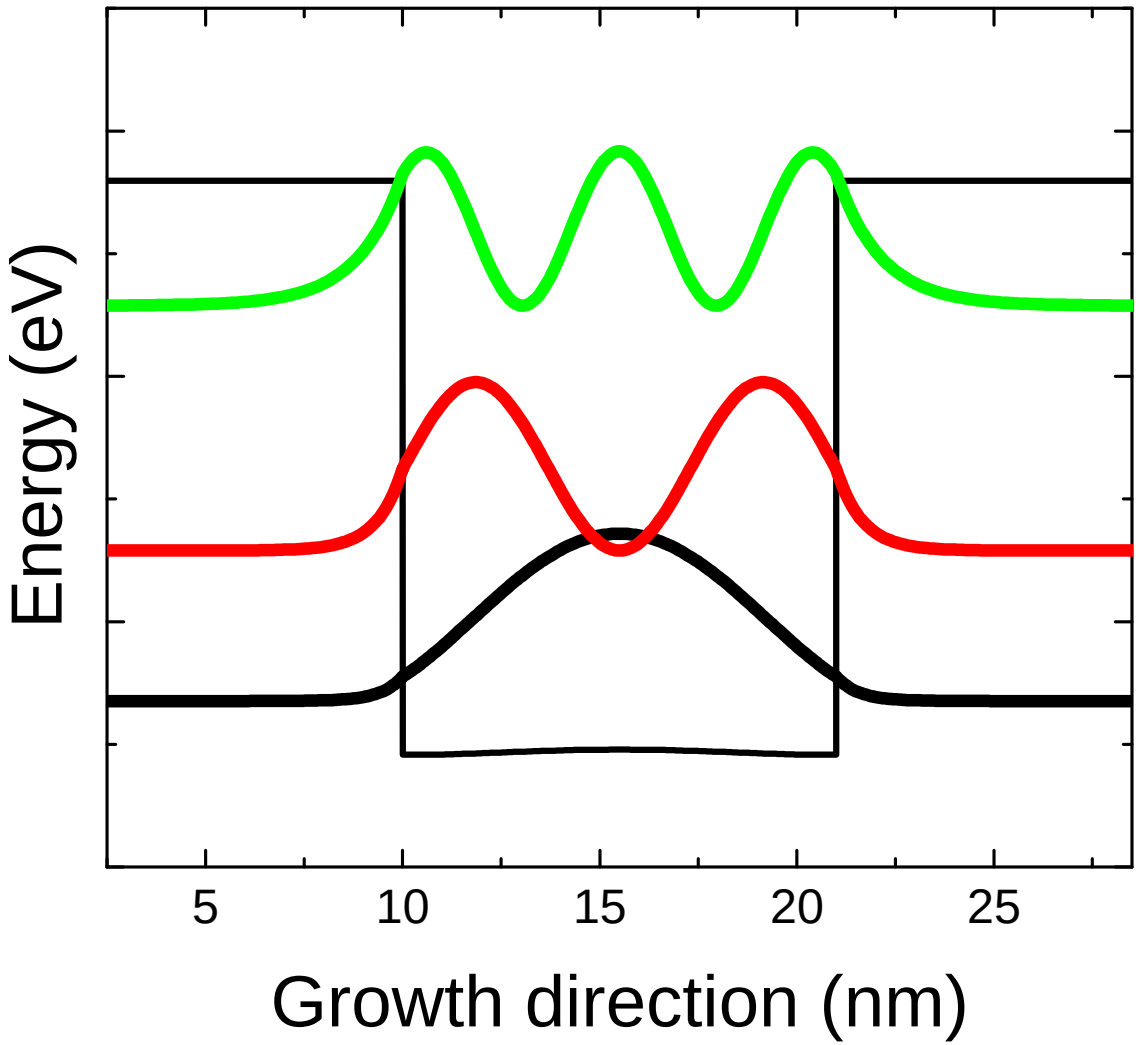
- Two resonators anti-cross
- Light-matter superposition = Polaritons
- Splitting Ω_R similar to system resonance
  - Energy exchange ≈ Fundamental system oscillation
  - Anti-resonant terms in equilibrium
- Squeezed vacuum as ground state
  - Release correlated photon pairs

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

Strong vs. ultra-strong coupling

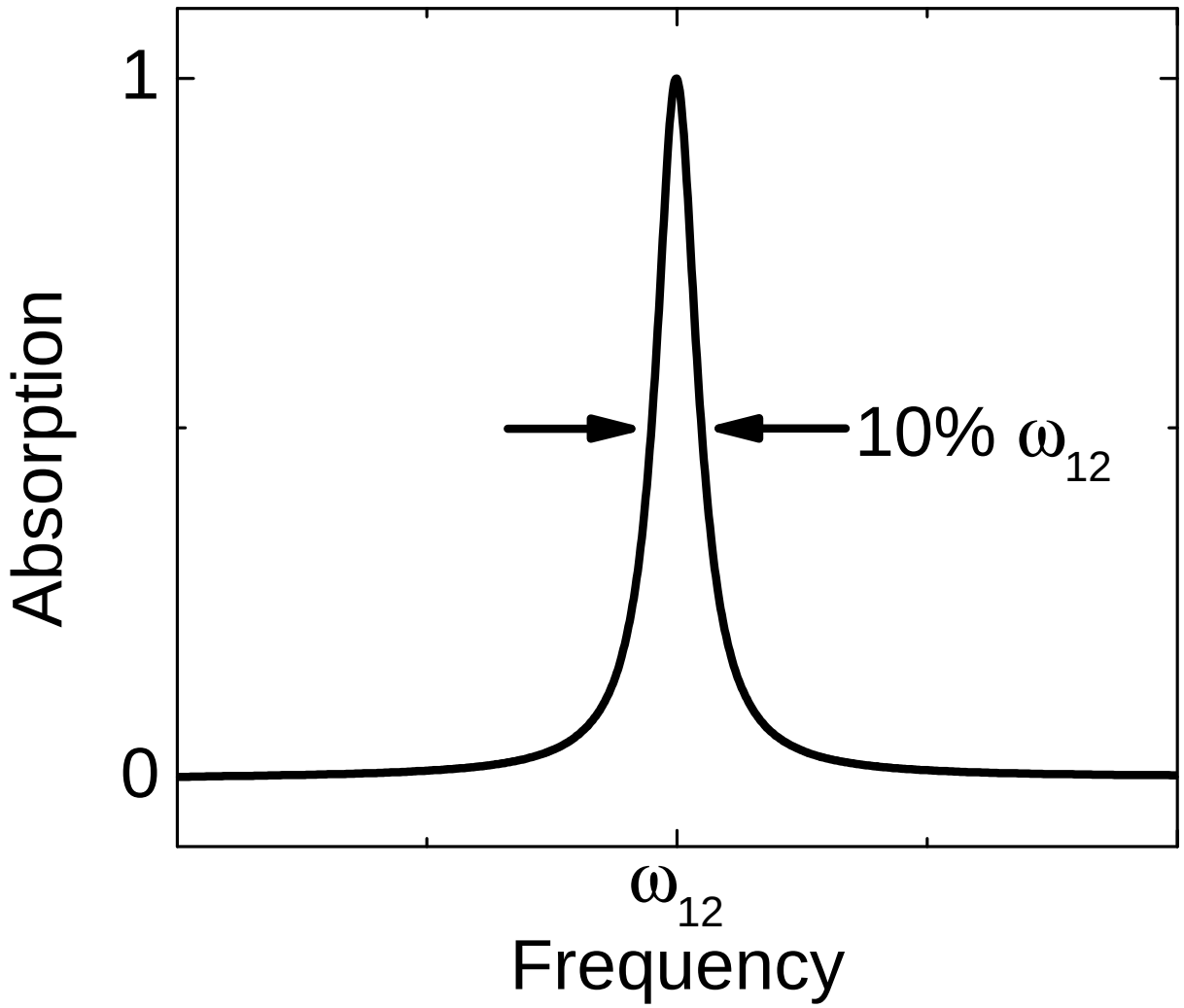


Intersubband transitions



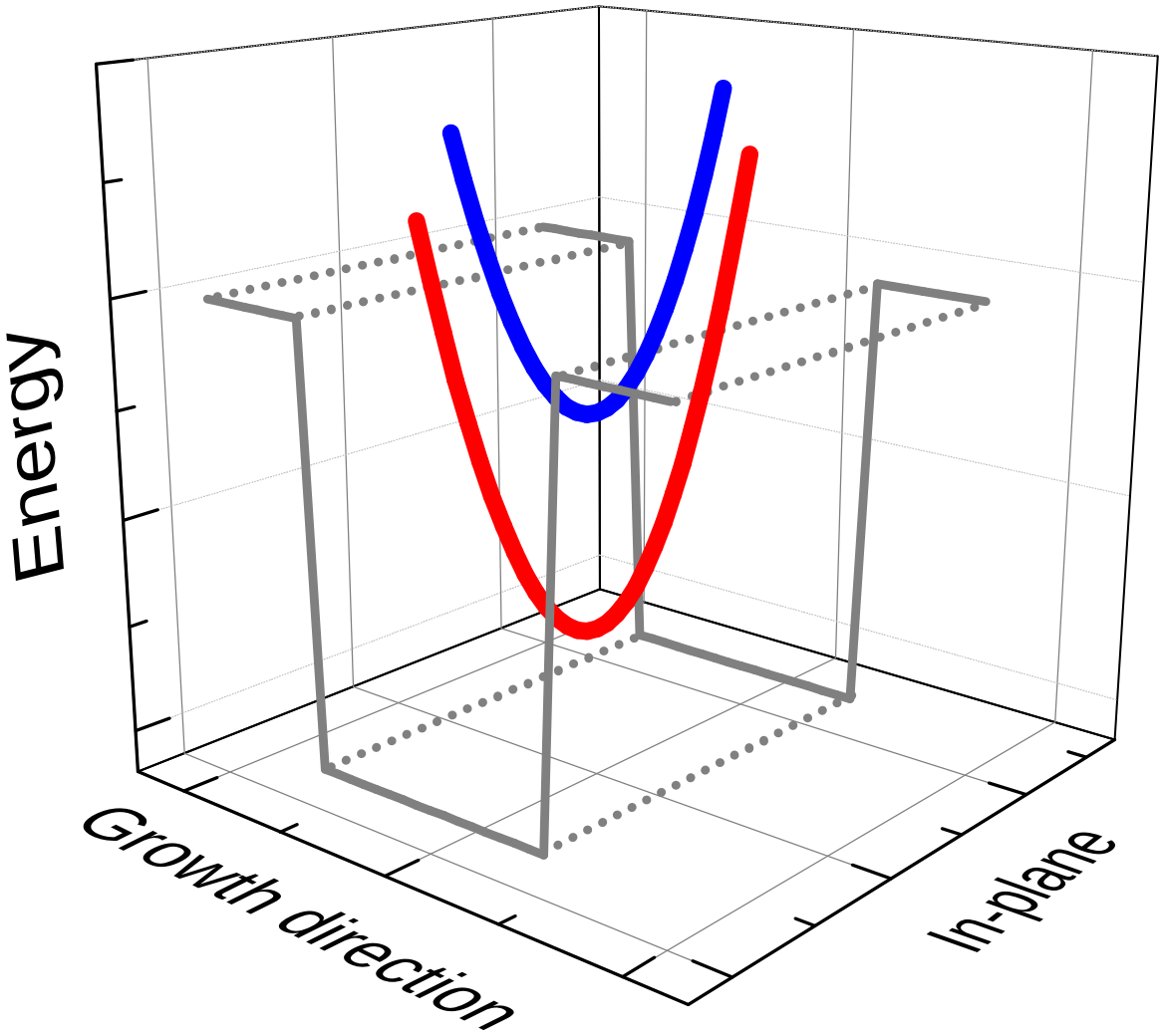
- Energy levels designed
  - Quantized
- Narrow absorption
  - Parabolic bands
- Tuning
  - Depletion

Intersubband transitions



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

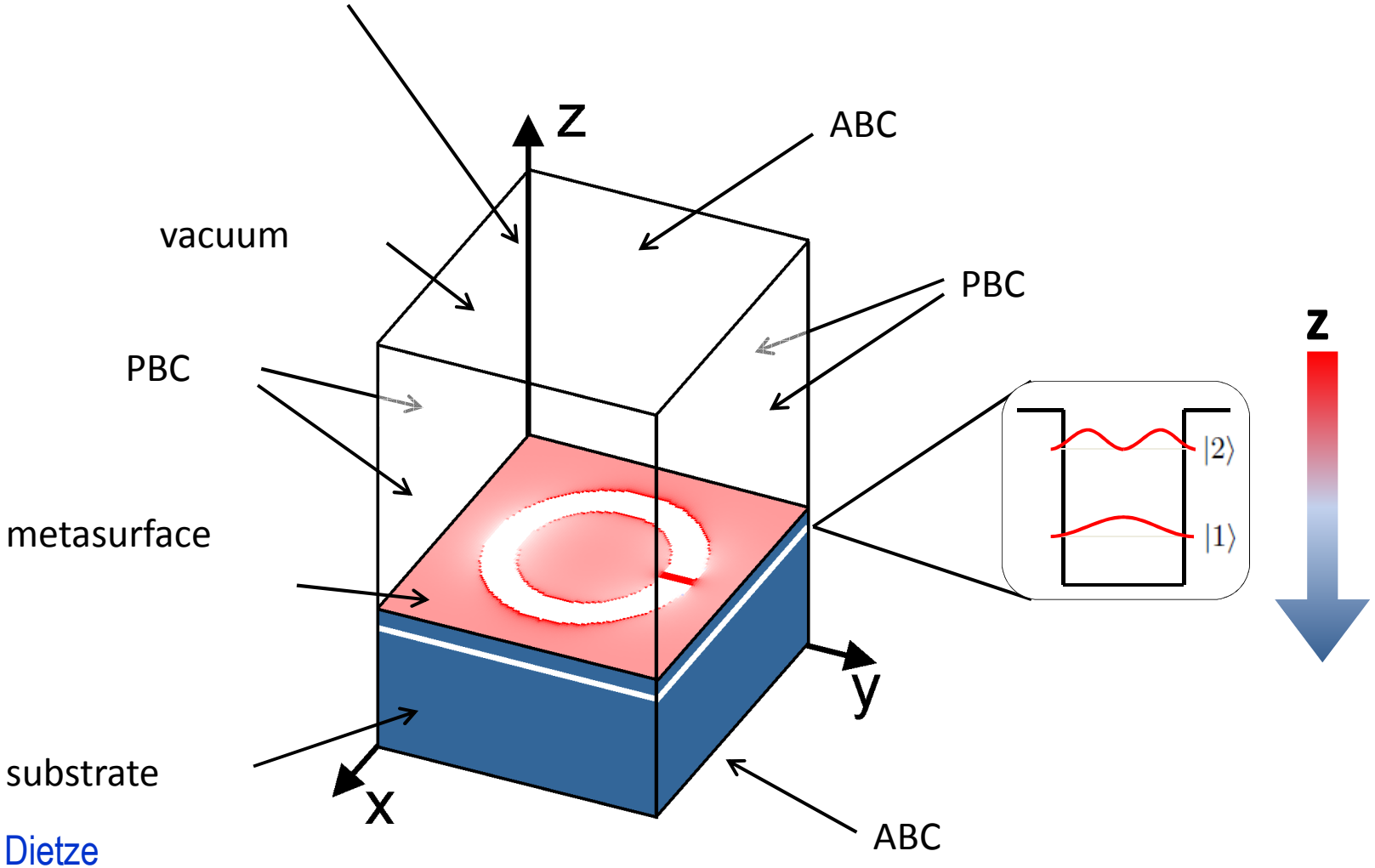
Intersubband transitions



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

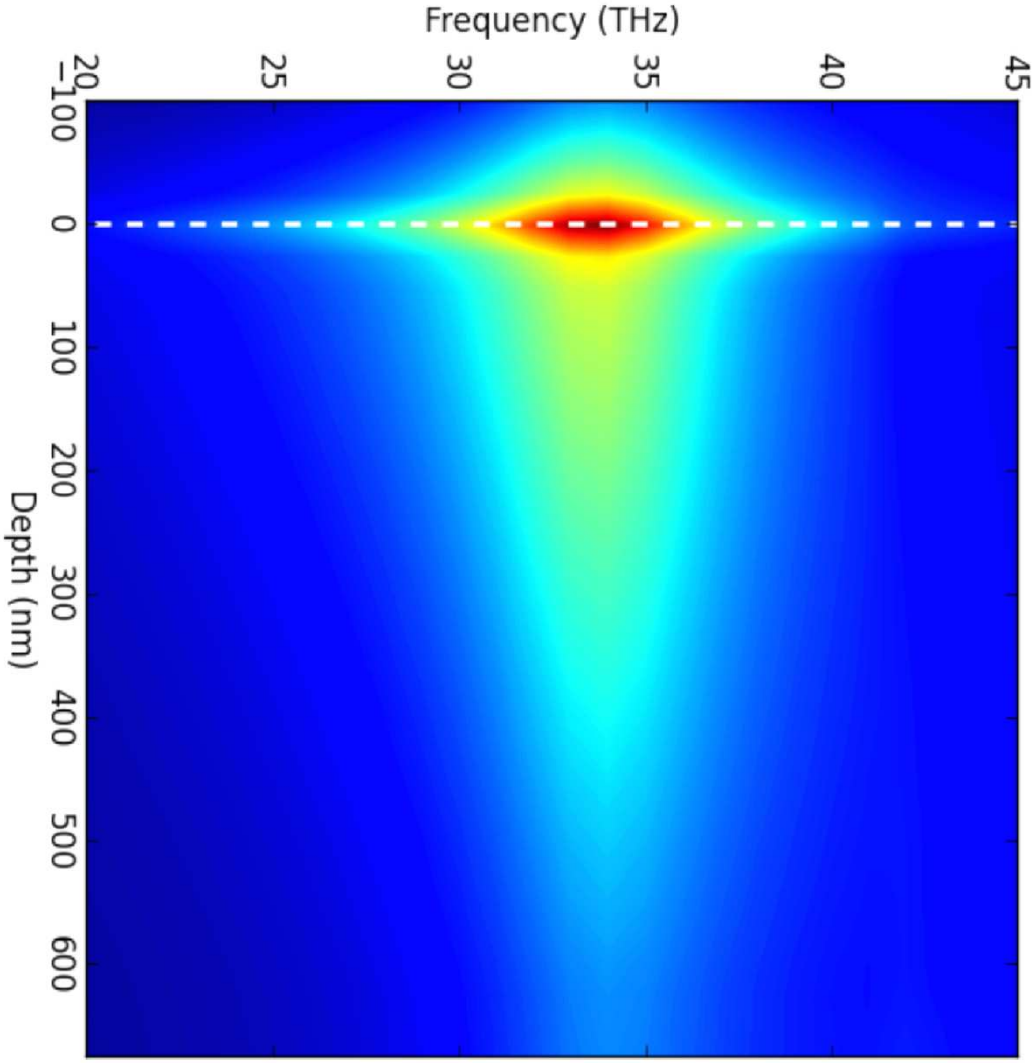
FDTD resonator design

plane wave, single-cycle pulse source



Courtesy of D. Dietze

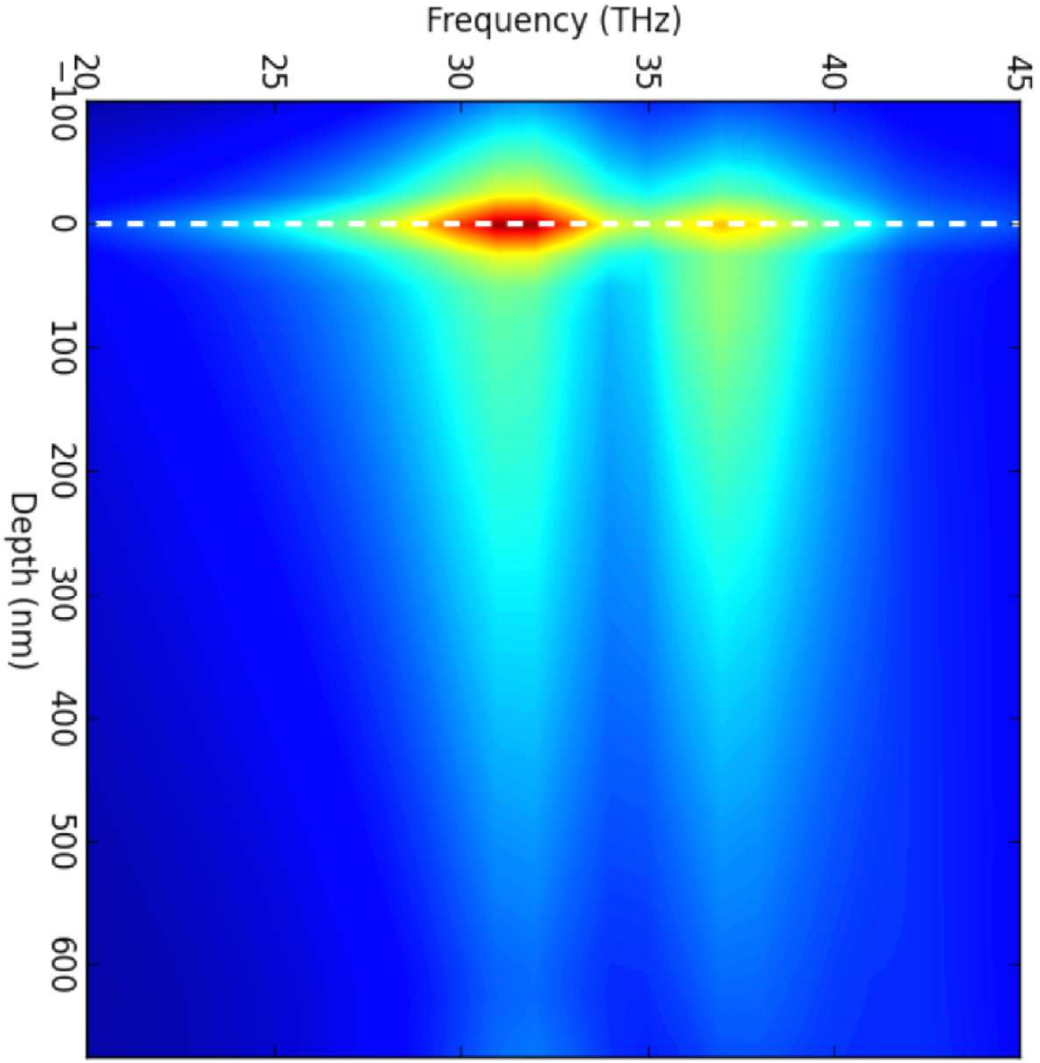
E_z near-field profiles



- Only E_z couples
  - Near-field
- Quickly decaying
- Transmission at cavity resonance
- $\Omega_R = \sqrt{f_W}\upsilon_p/2$

Geometry factor

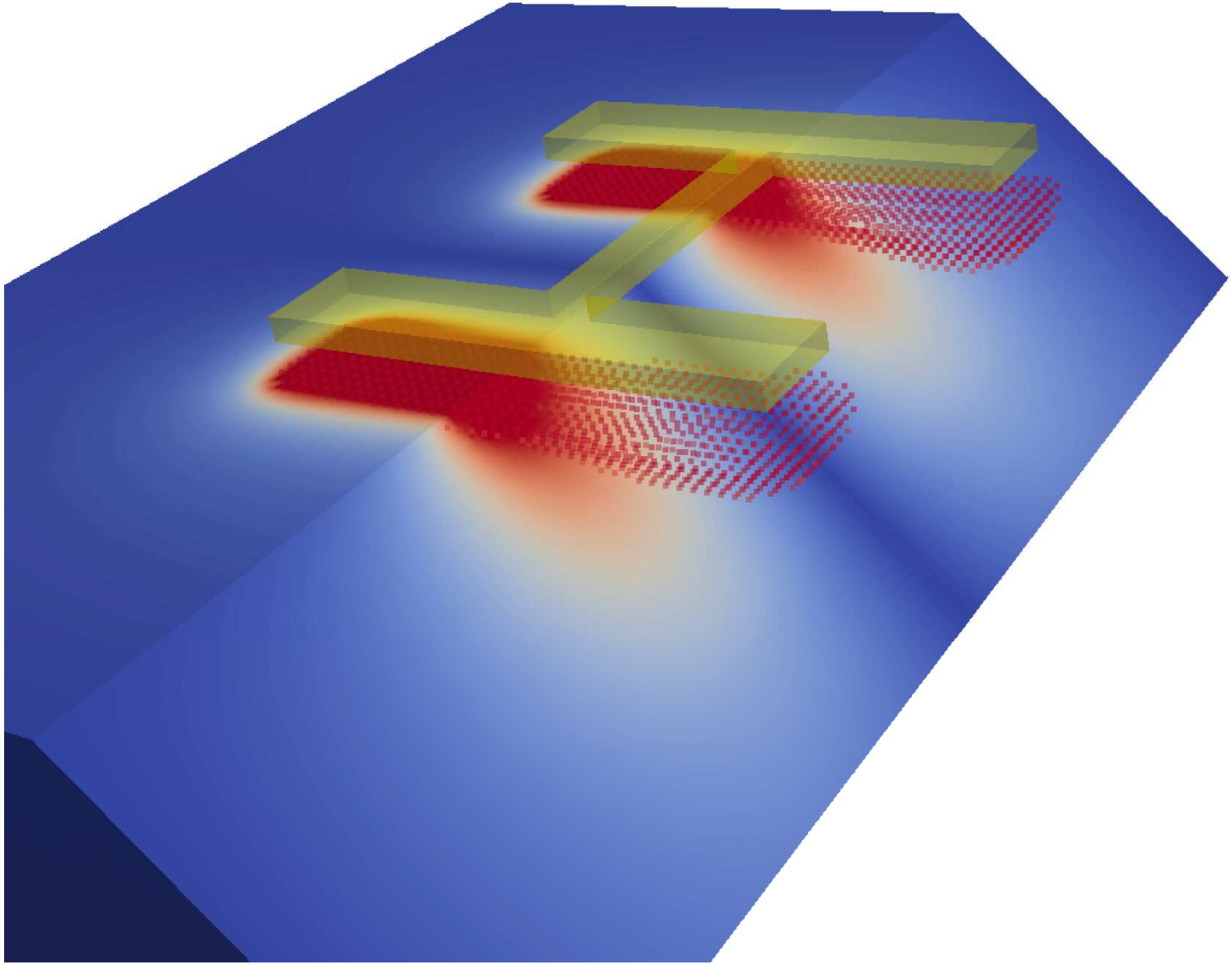
E_z near-field profiles



- Only E_z couples
  - Near-field
- Quickly decaying
- Transmission at cavity resonance
- $\Omega_R = \sqrt{f_W \omega_p}/2$

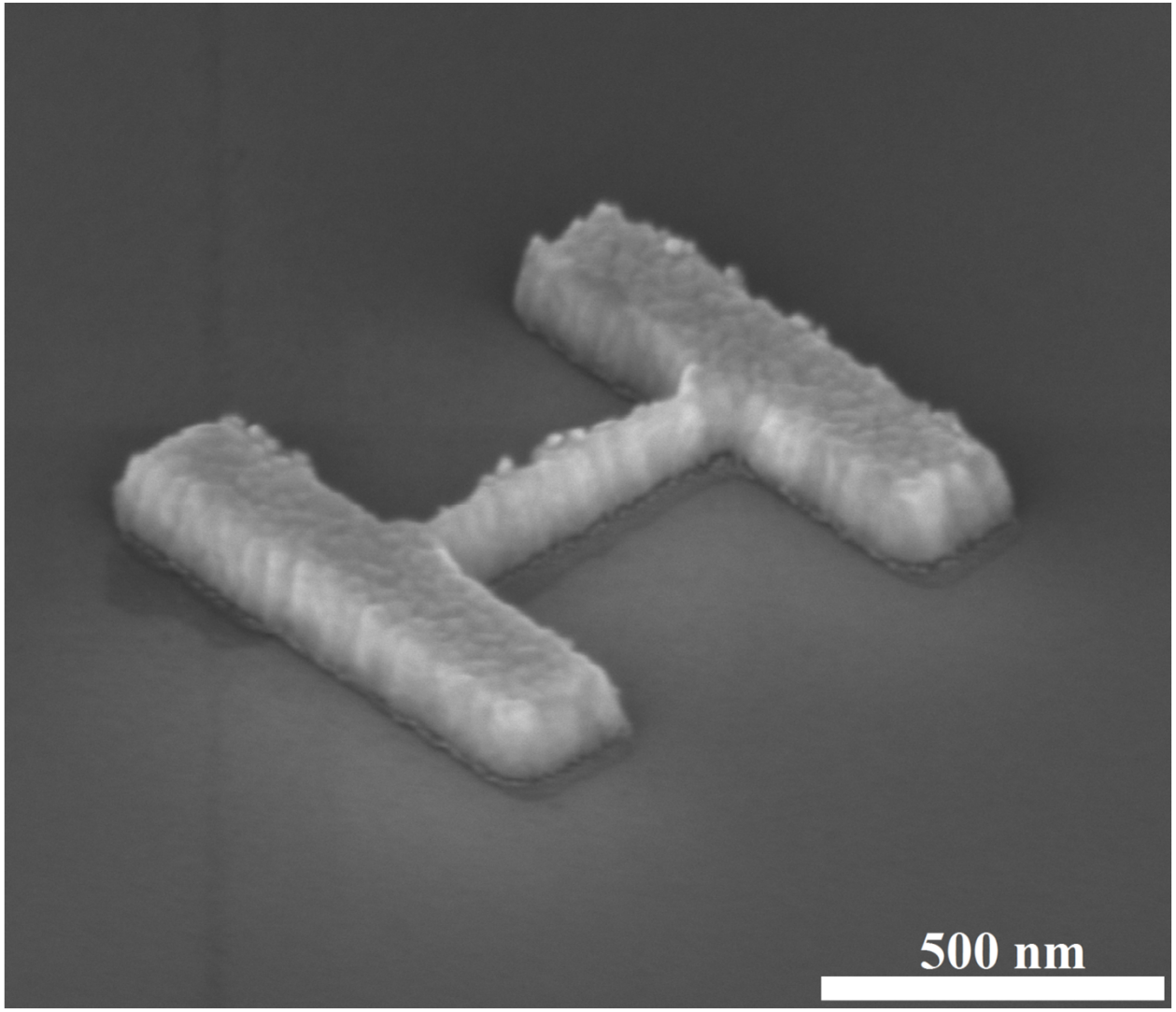
Plasma frequency

Mode profile



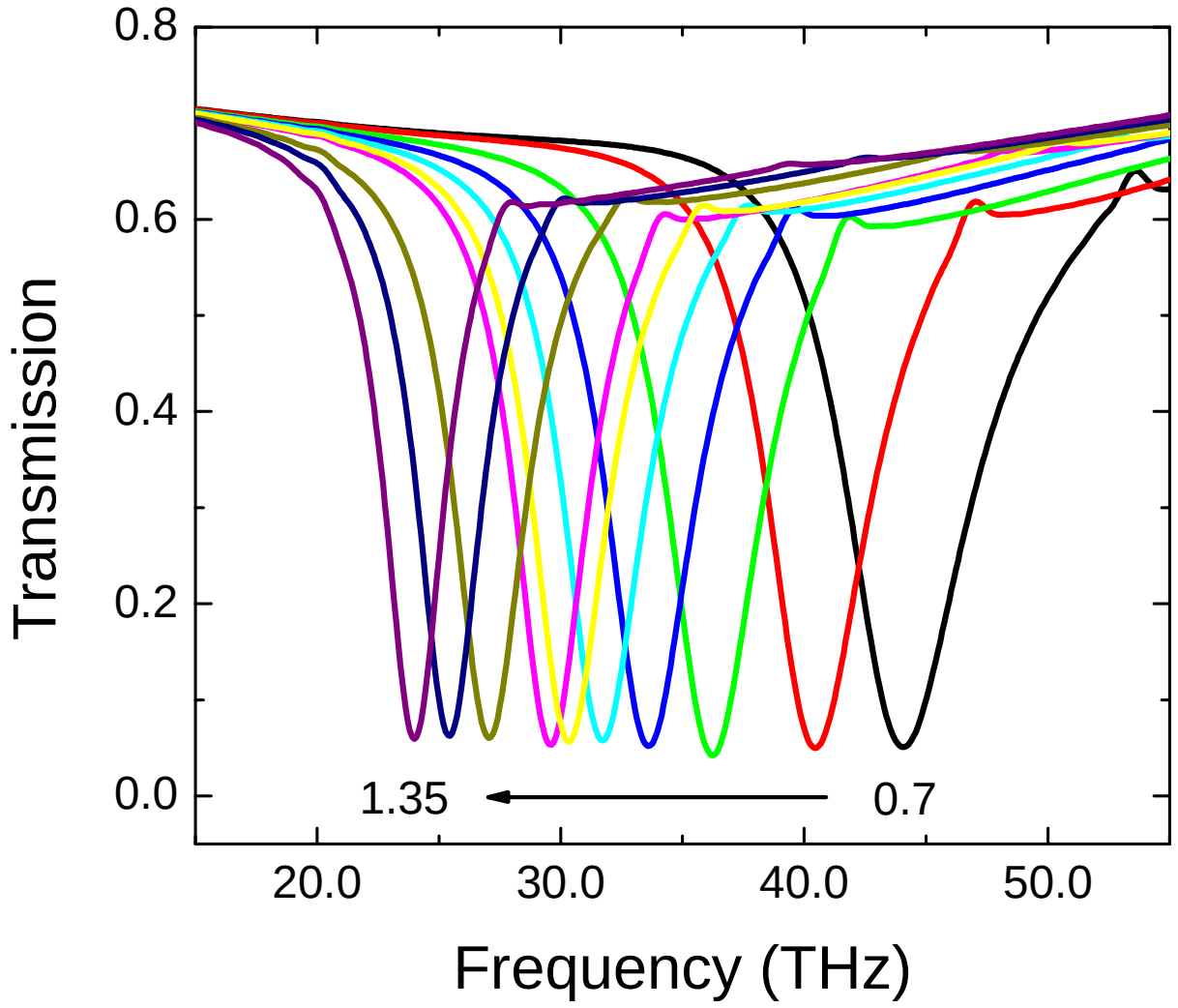
- Coupling defined in near-field
- Mode volume 5e(-4) λ_{eff}^3
- Less than 2400 electrons

Metamaterial fabrication



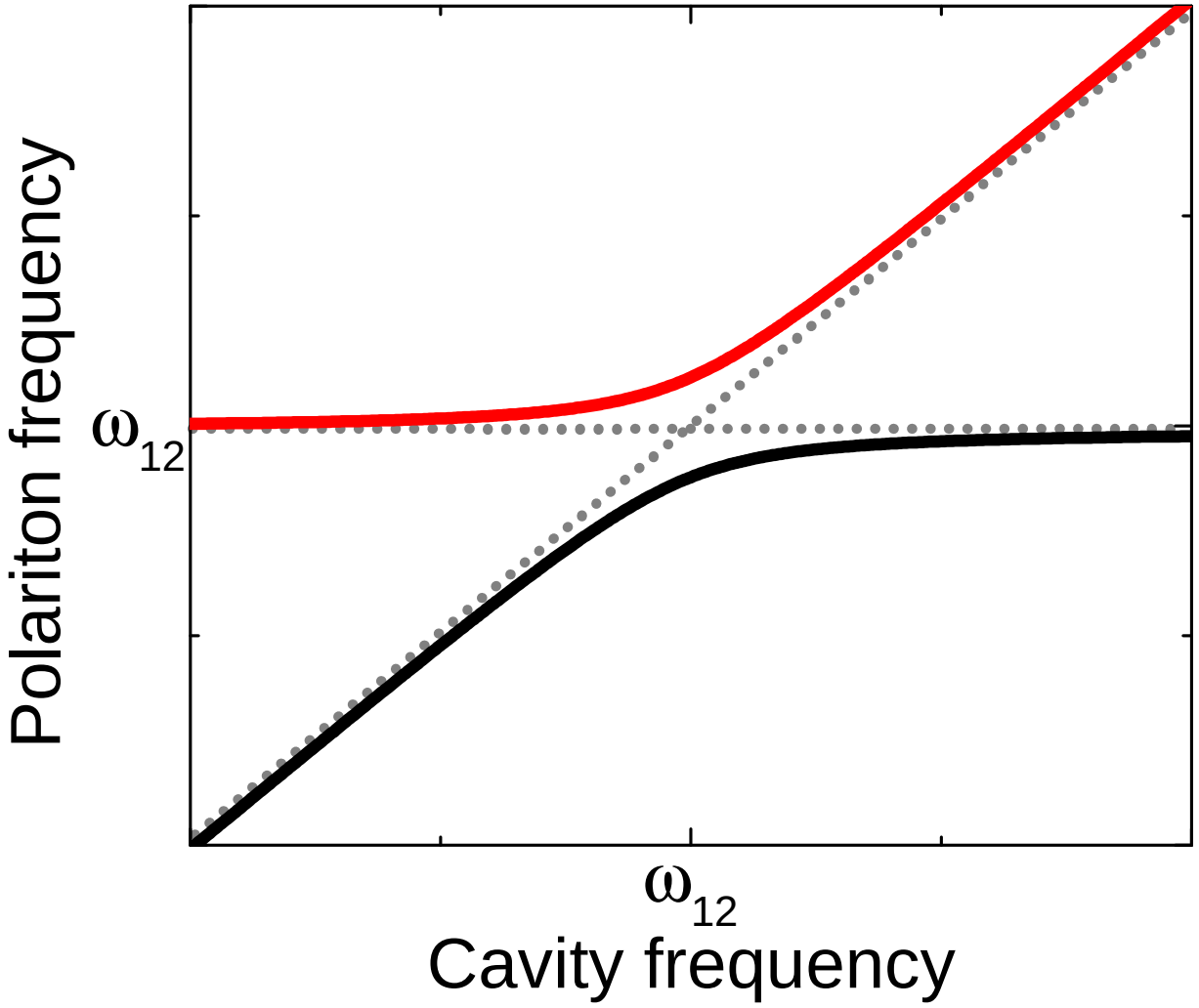
- Processing
  - Ebeam litho
  - 100 nm gold
- Easily adjustable
- Virtual ground
- Anisotropic scattering

Metamaterial fabrication



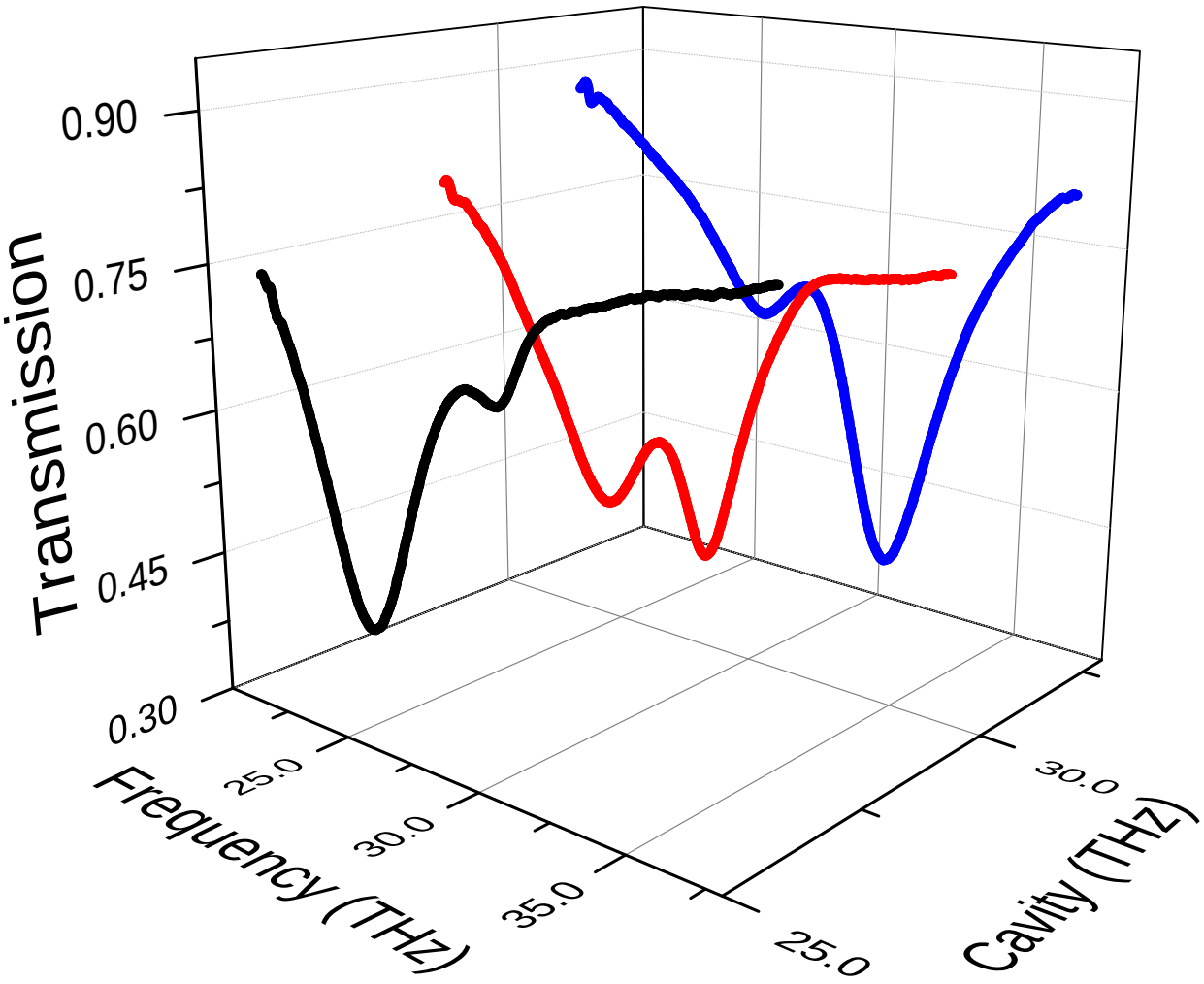
- Processing
  - Ebeam litho
  - 100 nm gold
- Easily adjustable
- Virtual ground
- Anisotropic scattering

Metamaterial fabrication



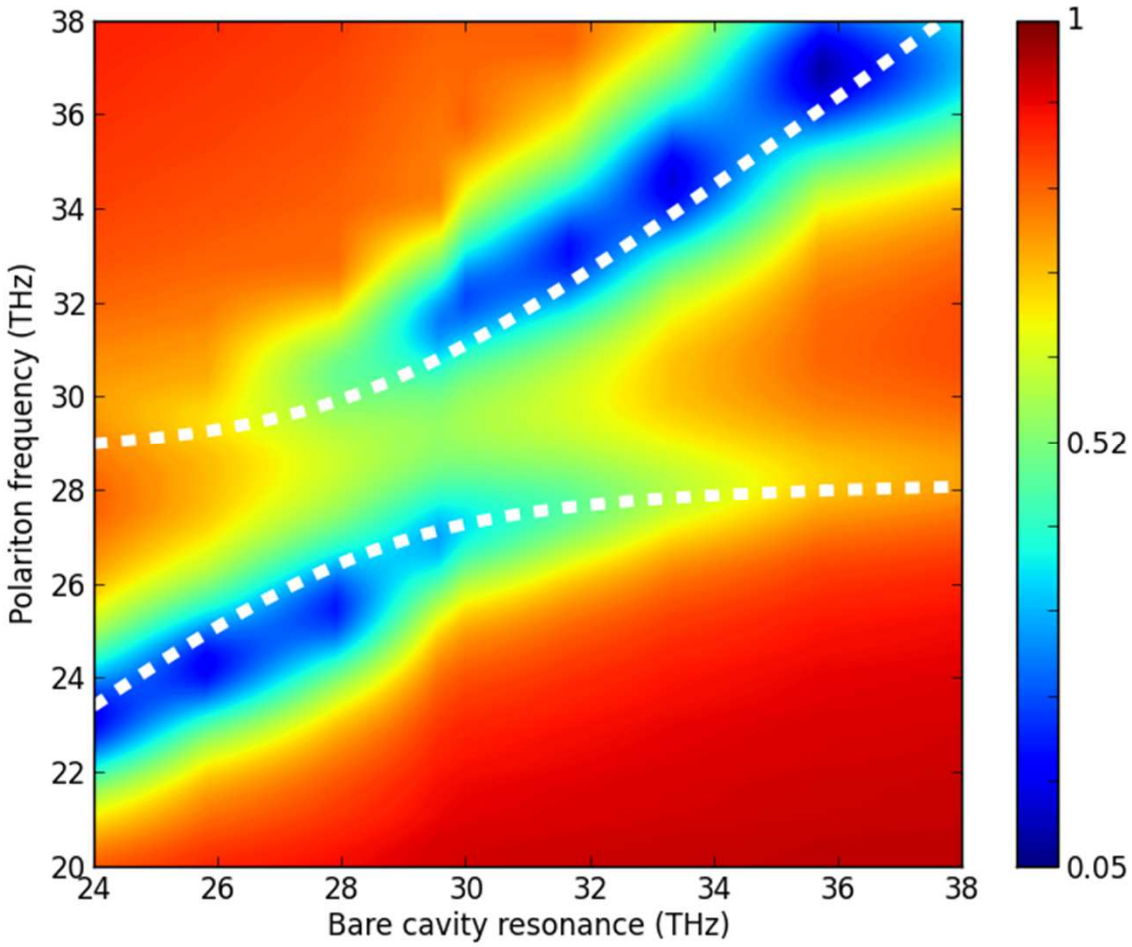
- Processing
  - Ebeam litho
  - 100 nm gold
- Easily adjustable
- Virtual ground
- Anisotropic scattering

Experimental anti-crossing



- Optical transmission for different metamaterials
- On-resonance two peaks visible
- Interaction sets splitting

Strong coupling theory vs. experiment

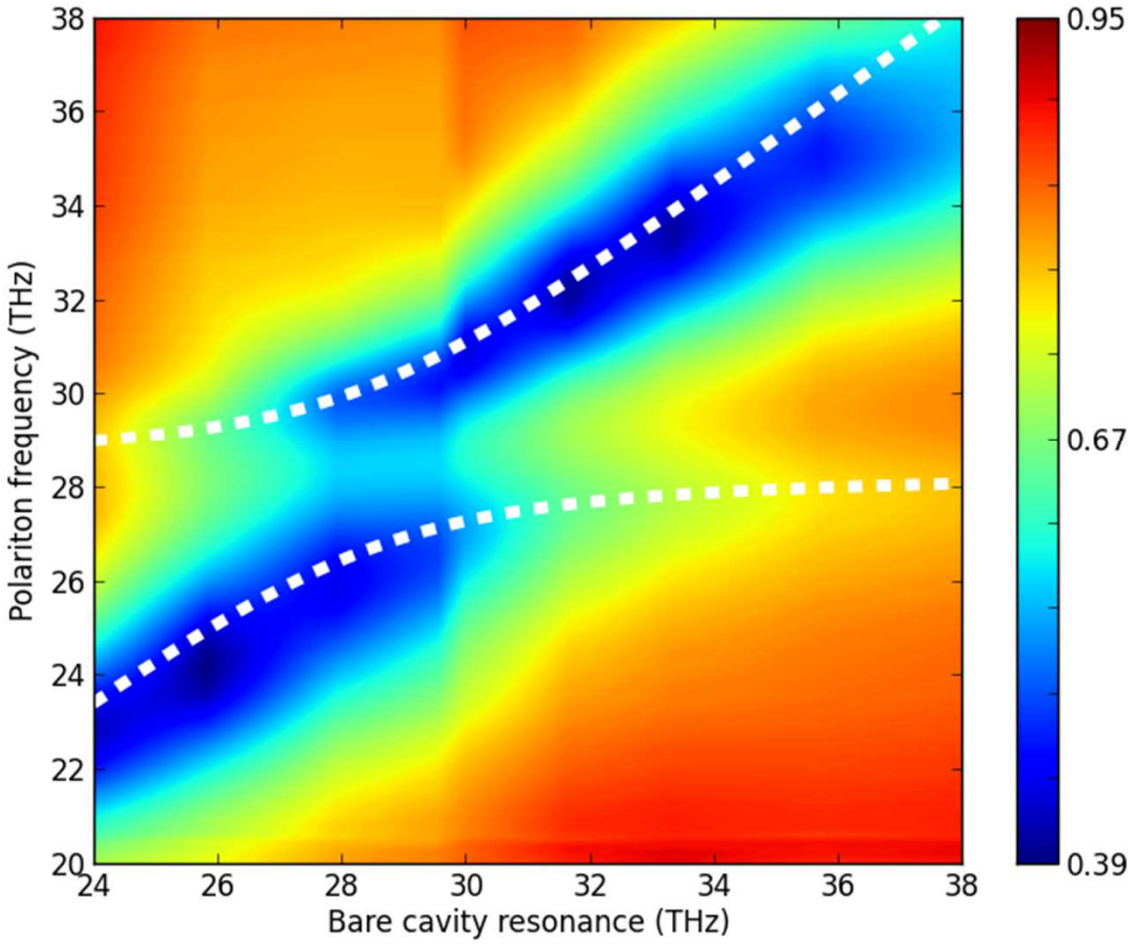


- FDTD simulations
- Anti-crossing
- Polariton picture[1,2]

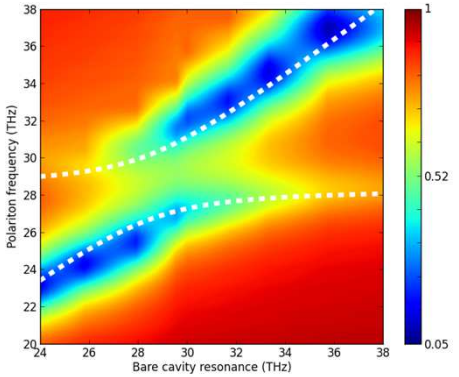
[1] A. Gabbay et al., Appl. Phys. Lett. **98**, 203103 (2011)

[2] A. Gabbay et al., Opt. Exp. **20**, 6584 (2012)

Strong coupling theory vs. experiment



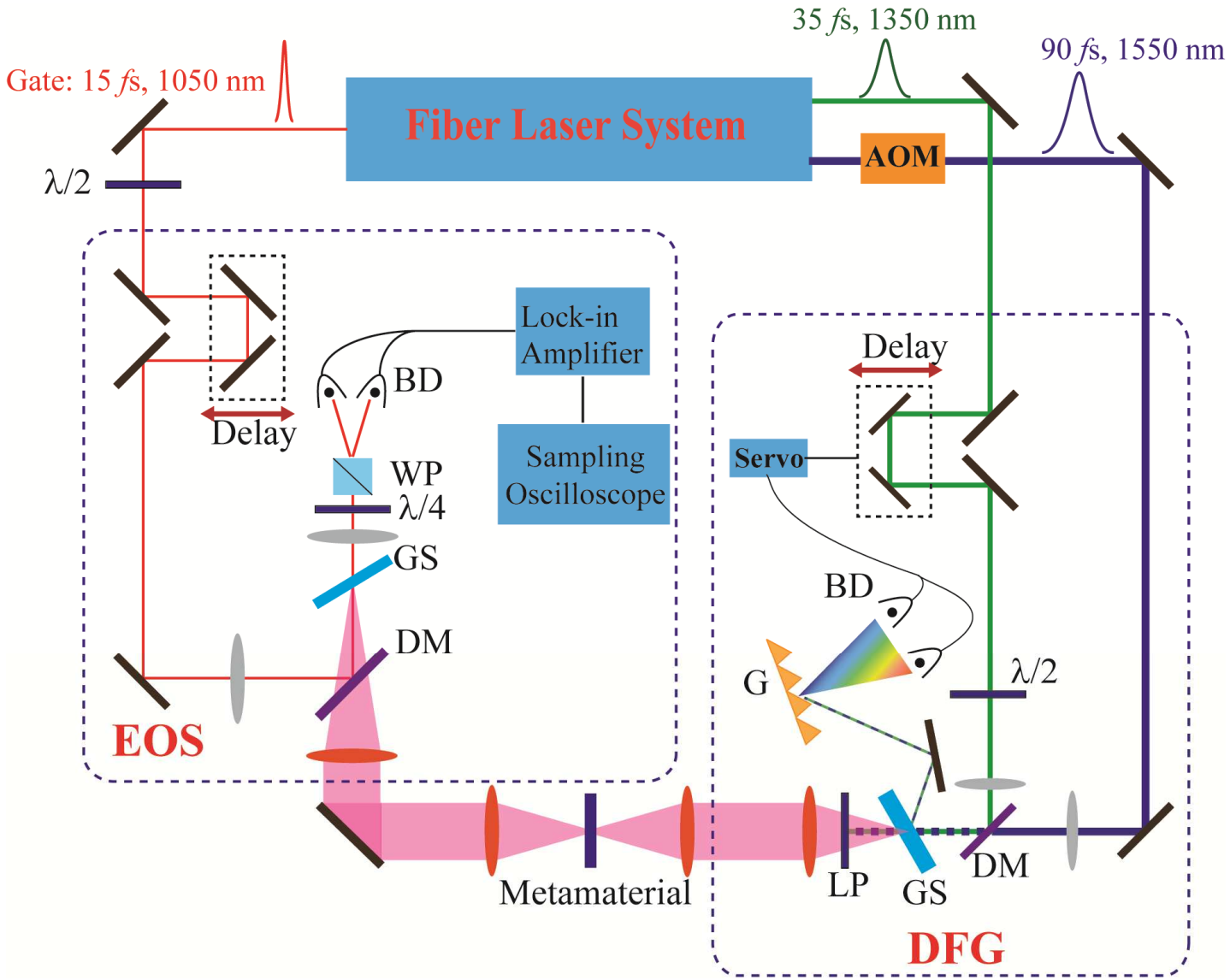
- FDTD simulations
- Anti-crossing
- Polariton picture[1,2]



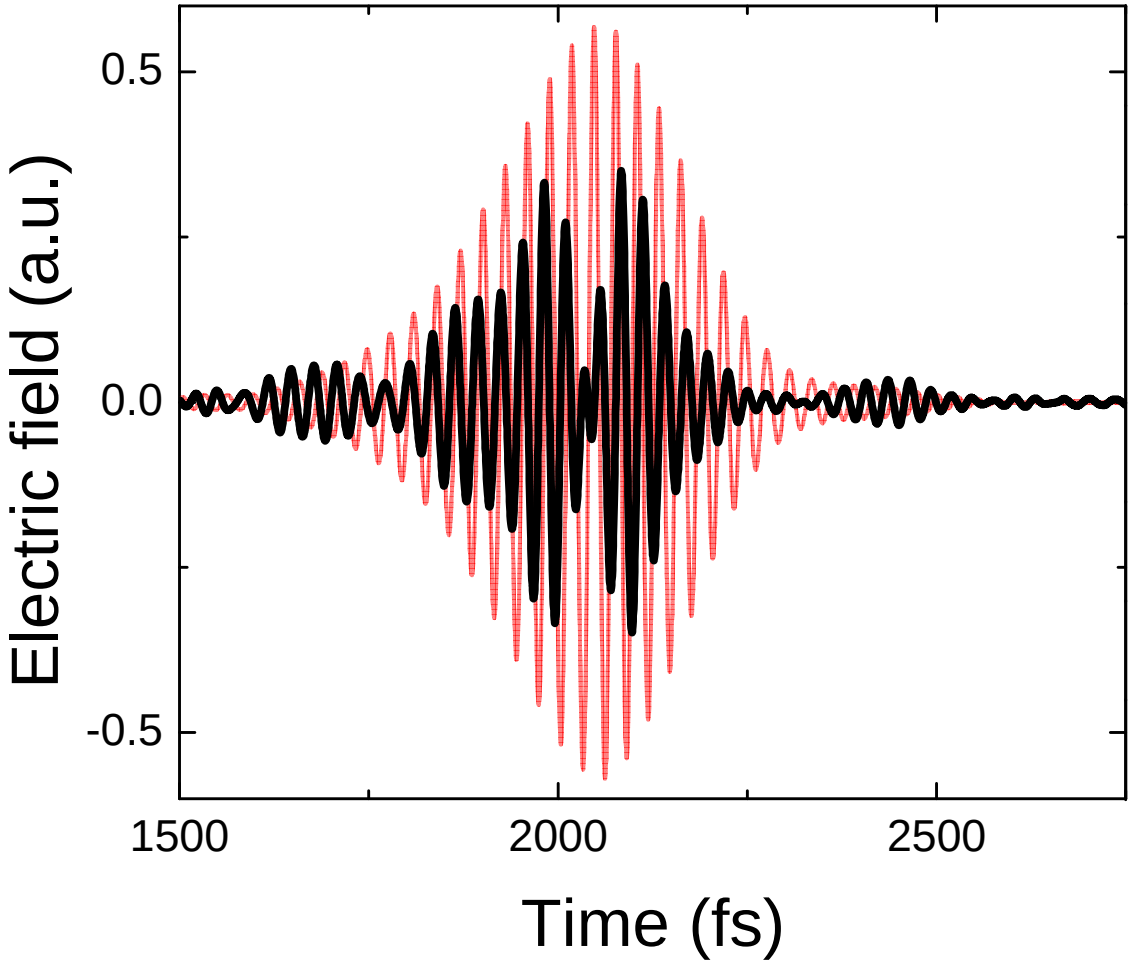
[1] A. Gabbay et al., Appl. Phys. Lett. **98**, 203103 (2011)

[2] A. Gabbay et al., Opt. Exp. **20**, 6584 (2012)

Experimental Rabi oscillations

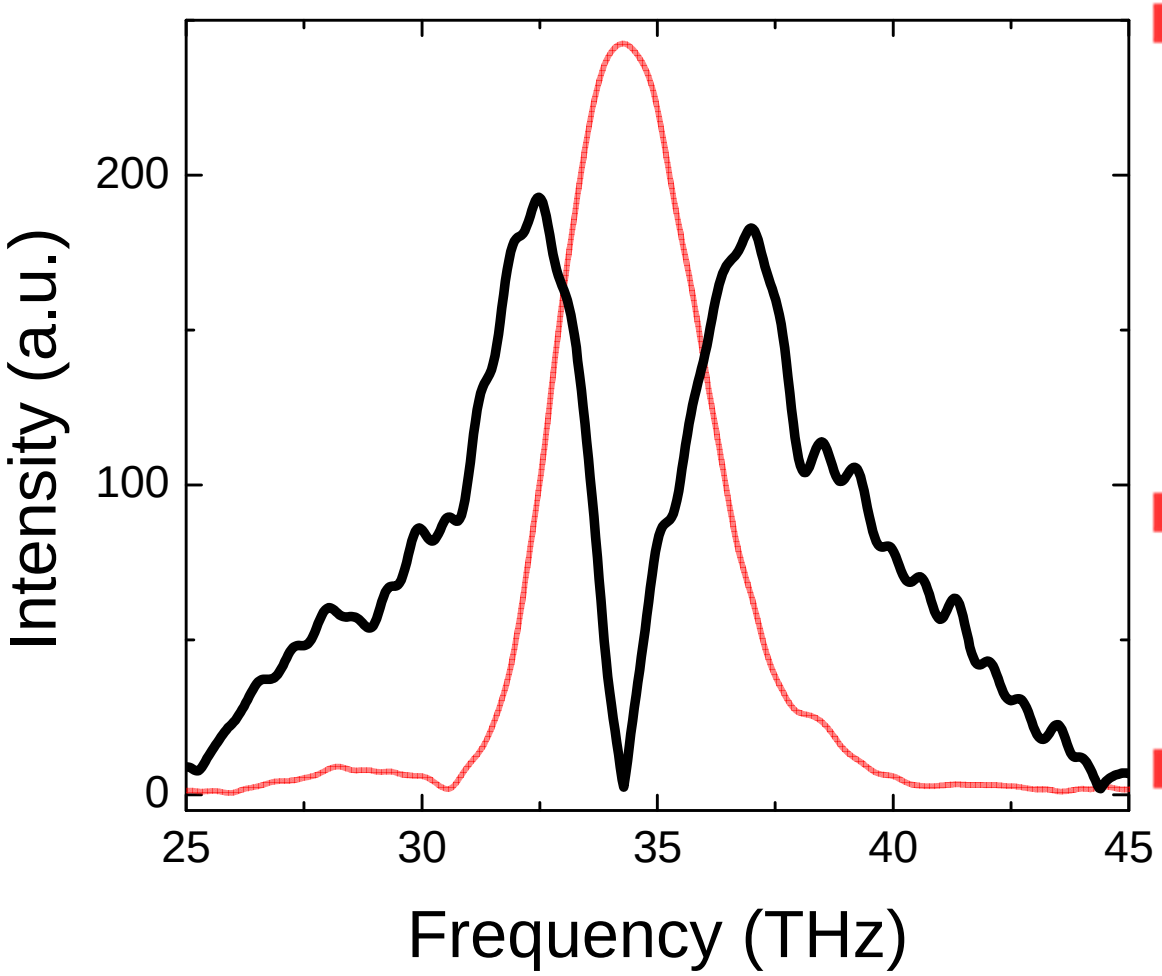


Experimental Rabi oscillations



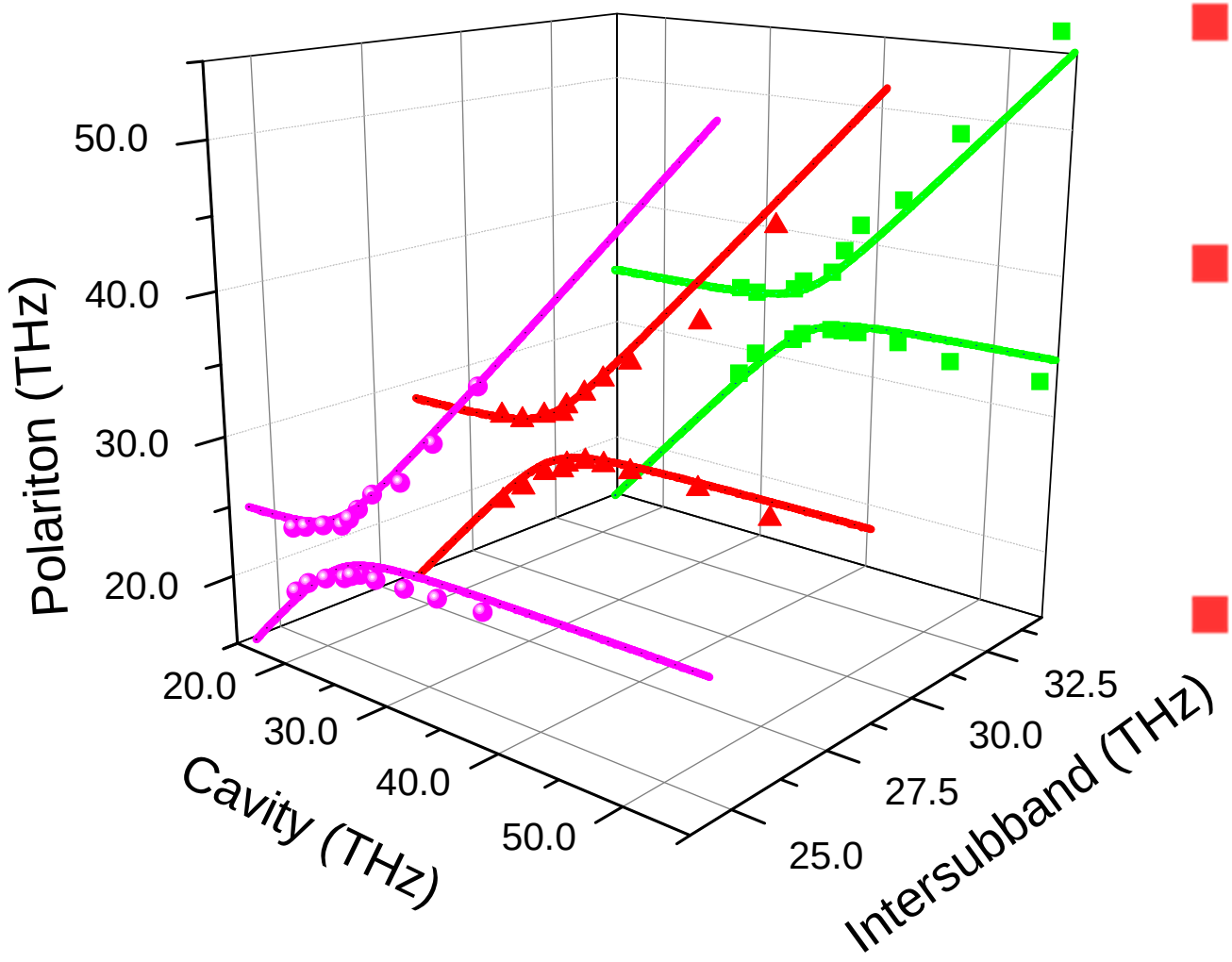
- Energy exchange probed in time
  - 33 fs oscillation
  - 480 fs beating
- System strongly coupled
- Splitting of 4.2 THz measured
  - 15 % of ω_{12}

Experimental Rabi oscillations



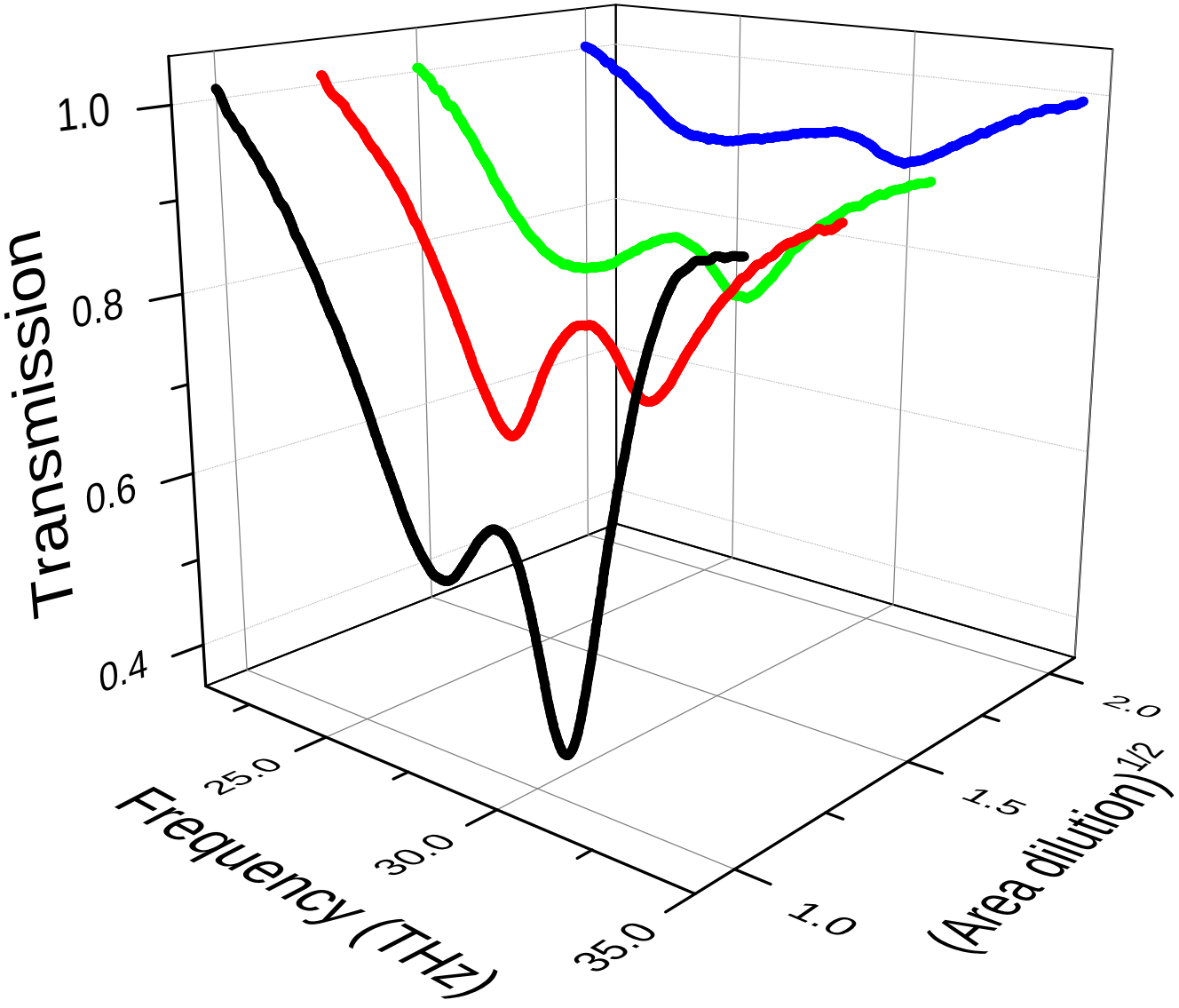
- Energy exchange probed in time
  - 33 fs oscillation
  - 480 fs beating
- System strongly coupled
- Splitting of 4.2 THz measured
  - 15 % of ω_{12}

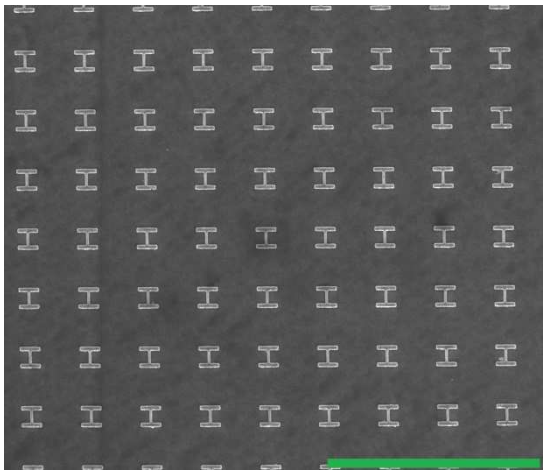
Intersubband flexibility

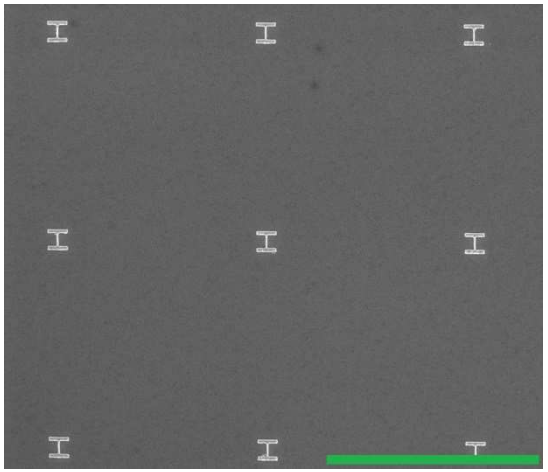


- Cover entire thermal IR
- Quantum-well transitions
  - 8, 10, 12 µm
- Model explains experiment
  - No free fitting parameters

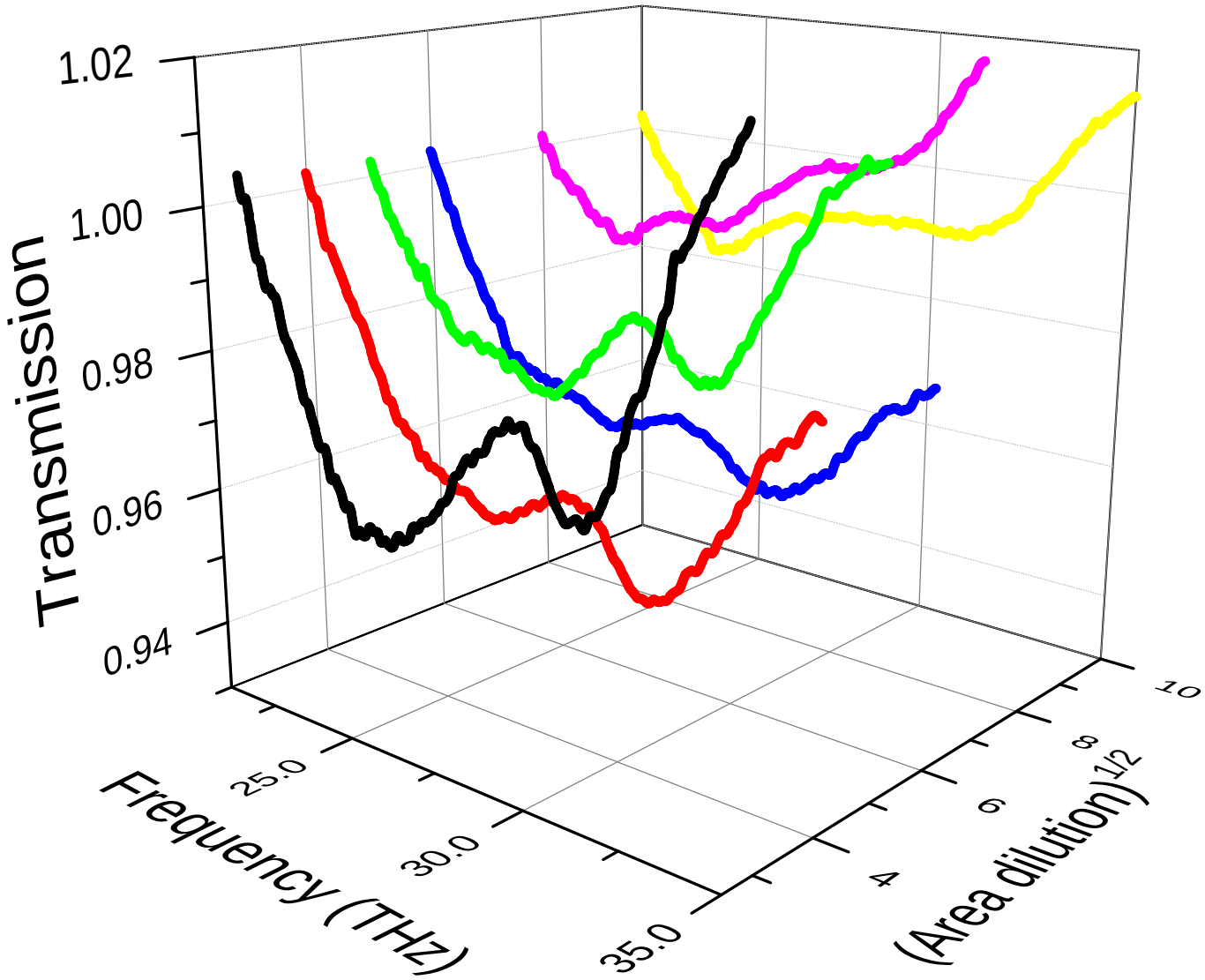
Single metamaterial cavities

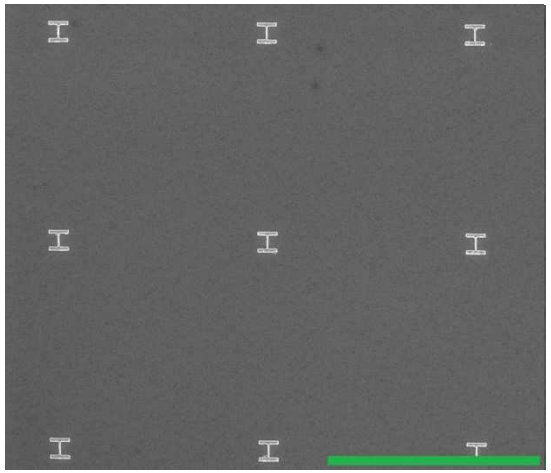


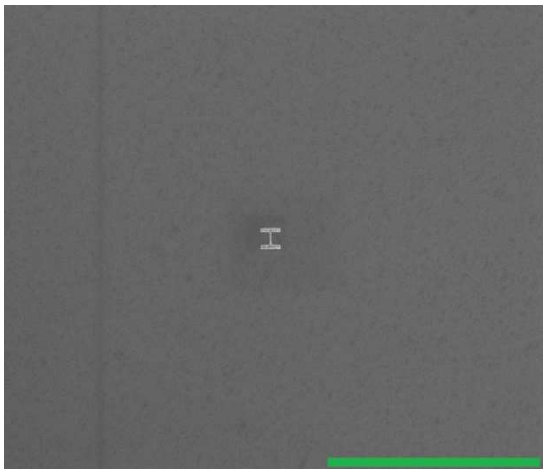




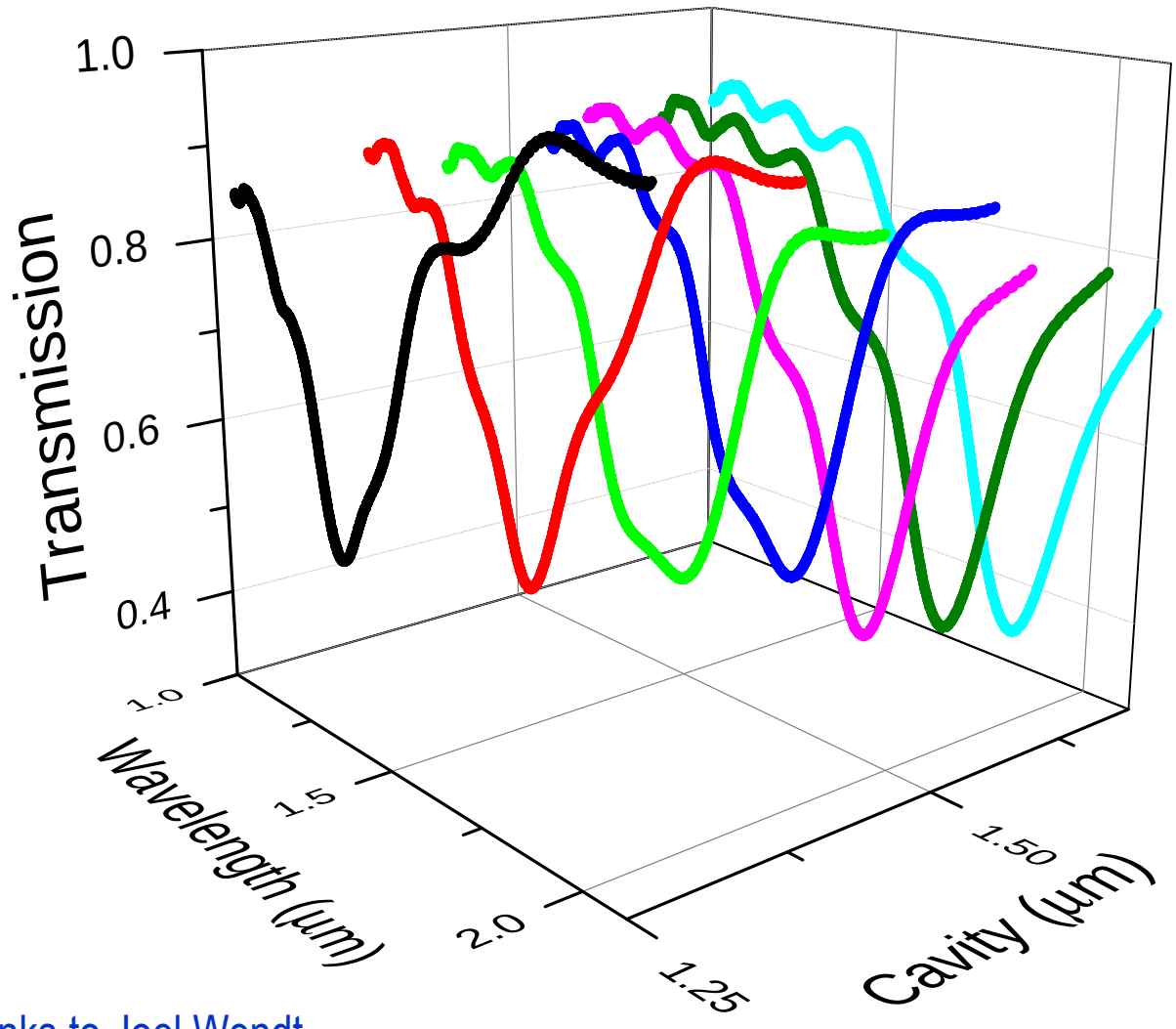
Single metamaterial cavities







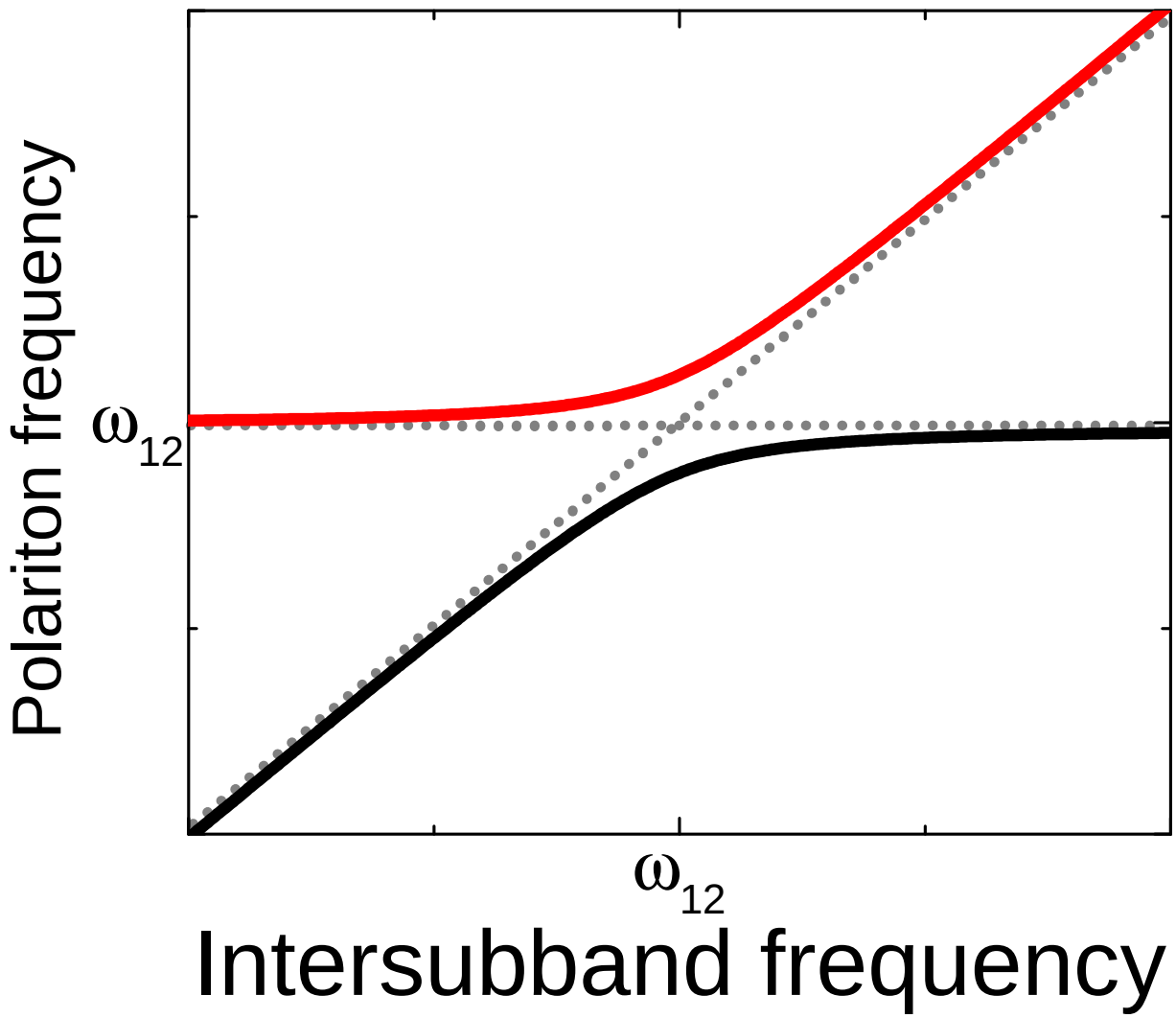
Telecomm range



- GaN/AlN quantum-well
- Splitting 10%
- Fully scalable concept
- Telecomm
- Photon statistic

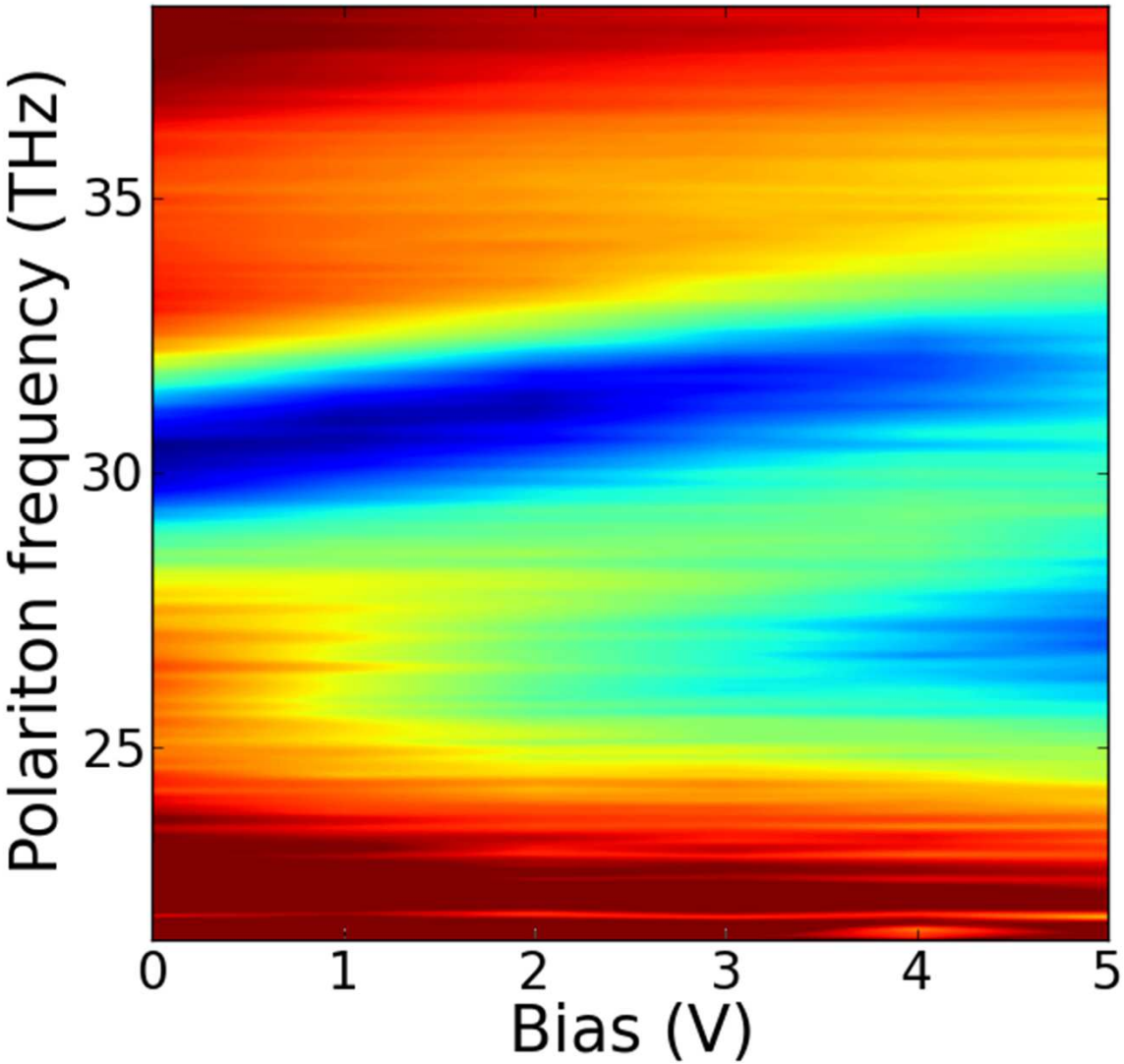
Thanks to Joel Wendt

Tunable filters



- Transmission electrically switchable
  - Stark tuning
  - Low voltages
- No deformation
- No heating
- Works at room temperature

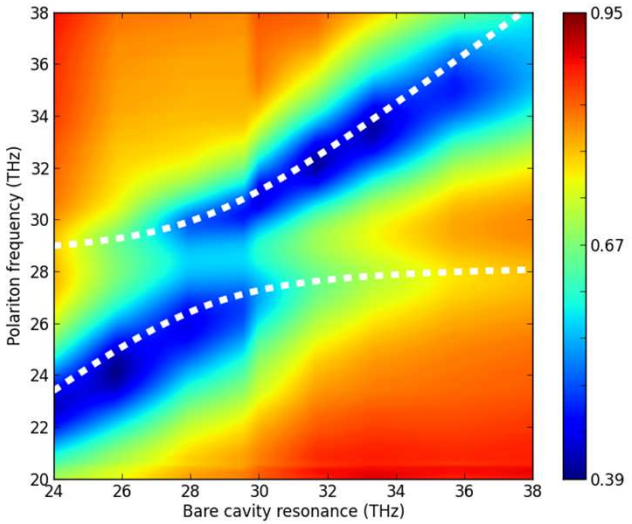
Tunable filters

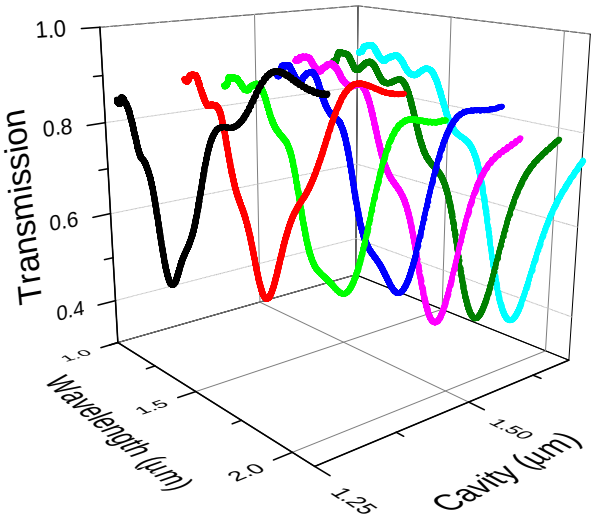


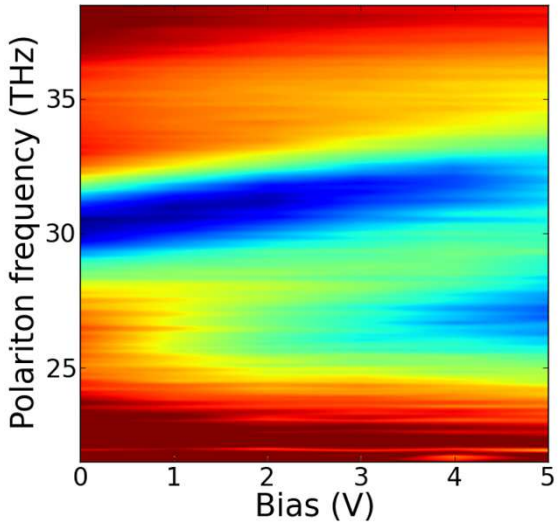
- Transmission electrically switchable
  - Stark tuning
  - Low voltages
- No deformation
- No heating
- Works at room temperature

Conclusion & Outlook

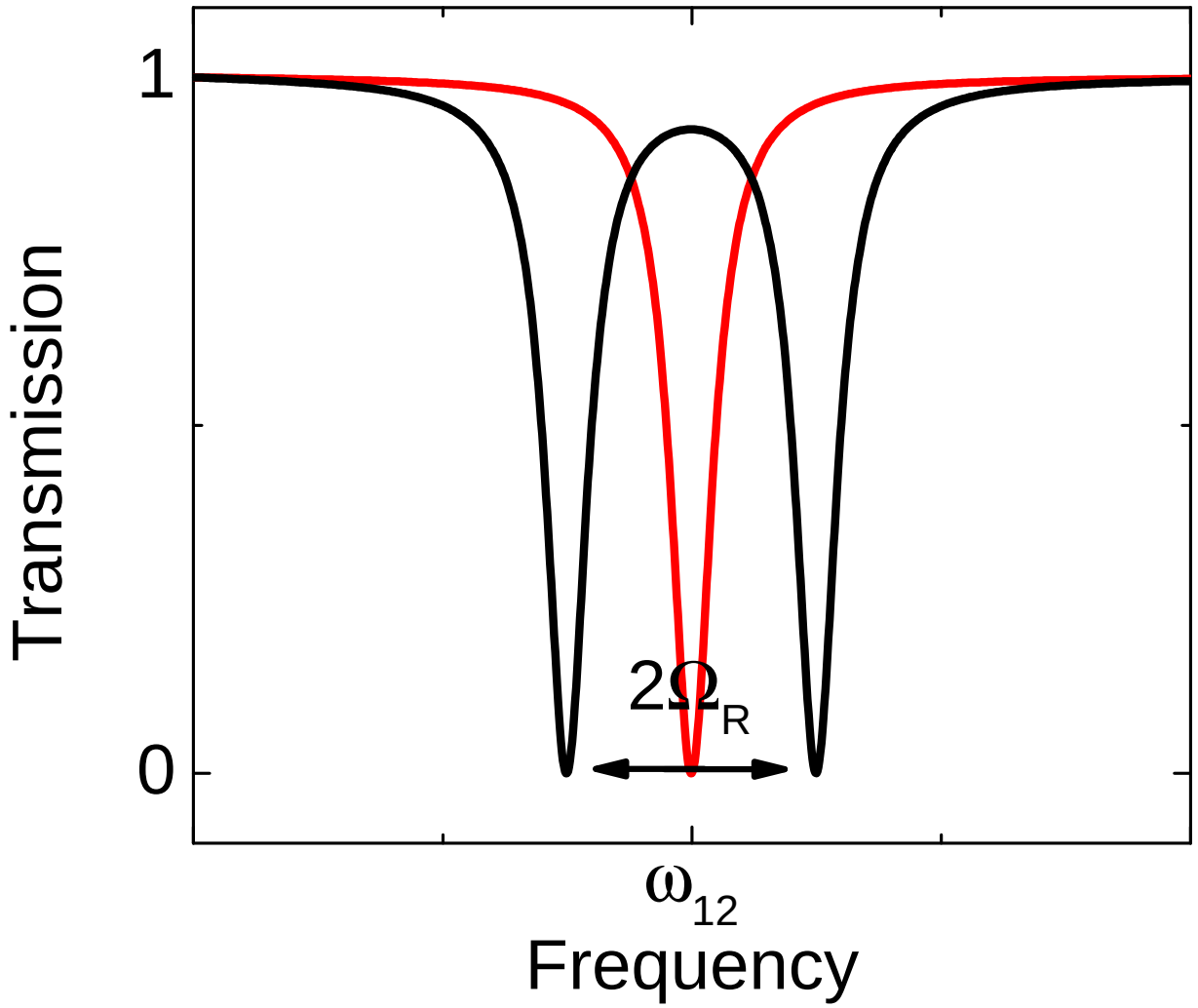
- Ultra-strong light-matter interaction
  - Observed in MIR & NIR
- Quantum-well controlled electrically
  - Turn coupling on/off





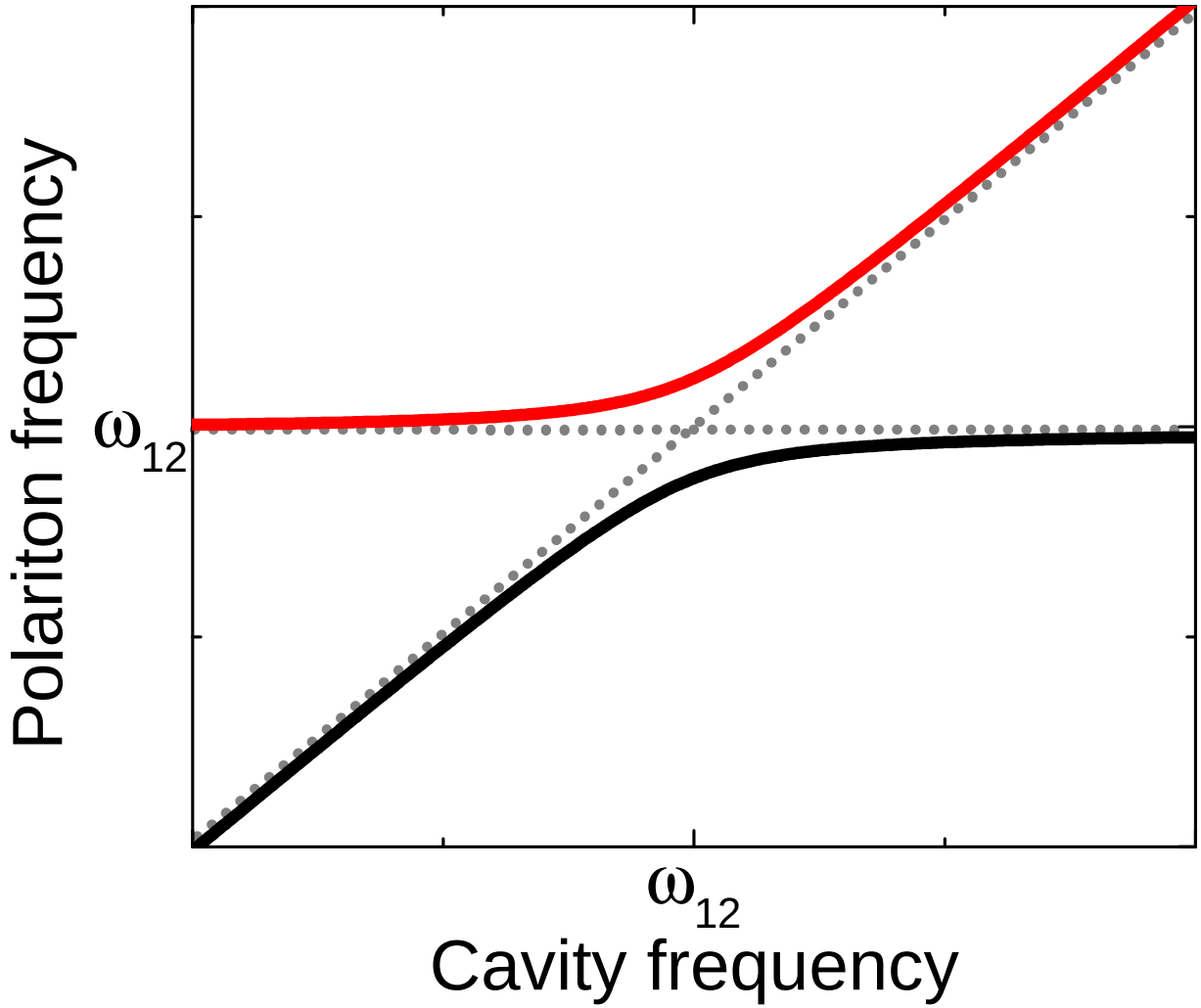


Strong coupling



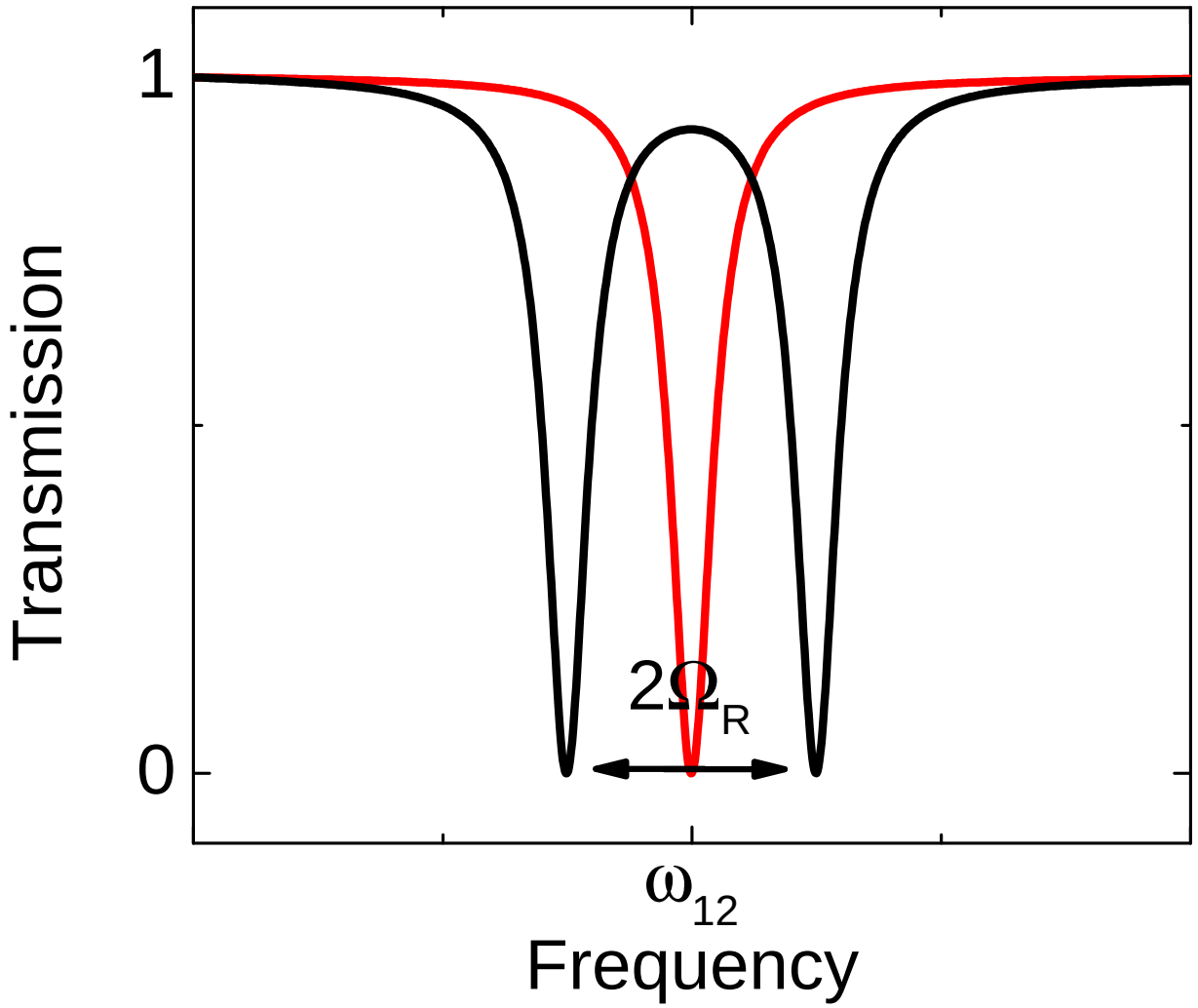
- Bare cavity splits into two polaritons
- On resonance: splitting=$2\Omega_R$
- Two oscillators anti-cross

Strong coupling



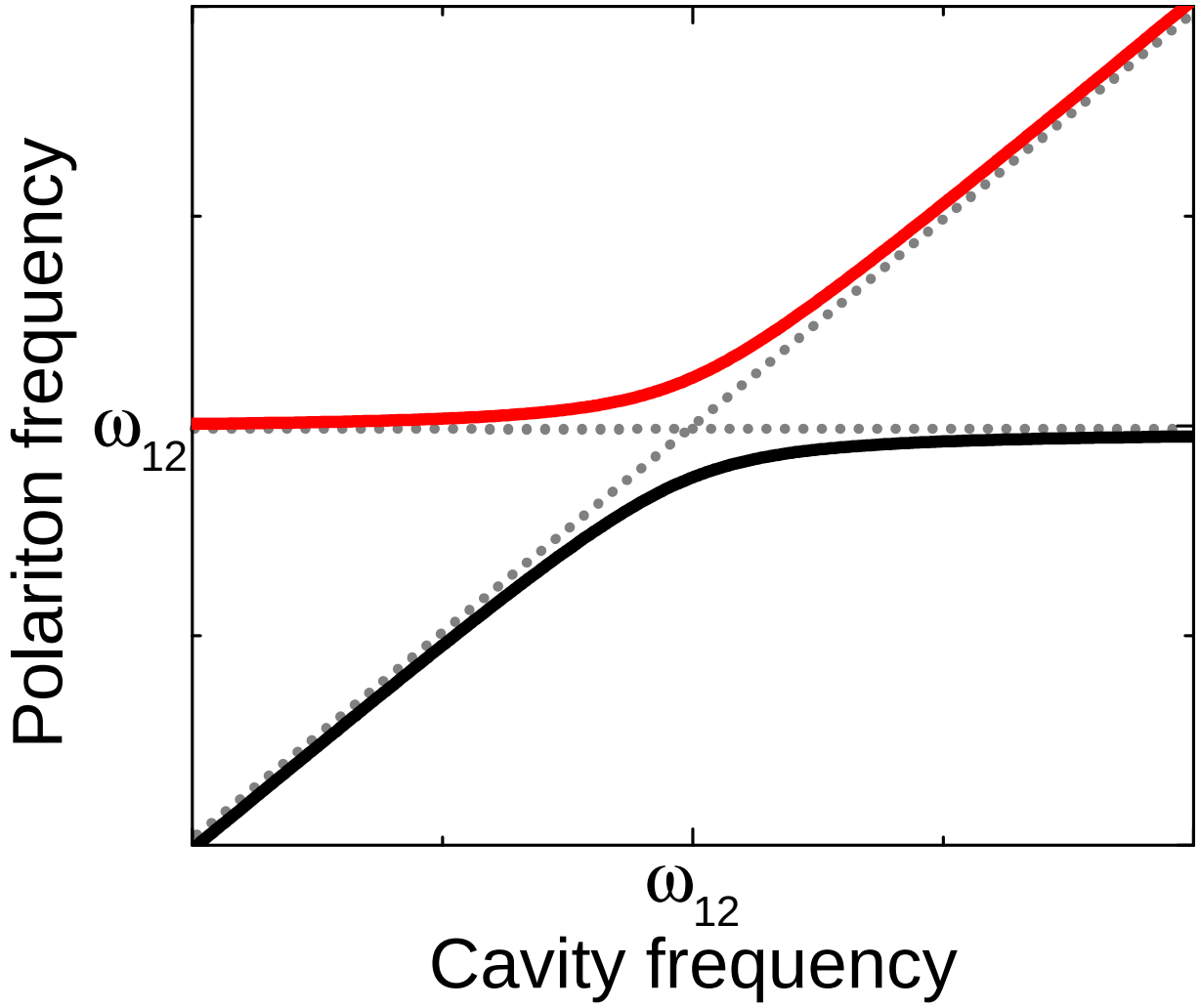
- Bare cavity splits into two polaritons
- On resonance: splitting=$2\Omega_R$
- Two oscillators anti-cross

Application vs. physics



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

Application vs. physics



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

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

C. Ciutu et al., Phys. Rev. B **72**, 115303 (2005)

S. DeLiberato et al., Phys. Rev. Lett. **98**, 103602 (2007)

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

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

Plasma frequency

C. Ciutu et al., Phys. Rev. B **72**, 115303 (2005)

S. DeLiberato et al., Phys. Rev. Lett. **98**, 103602 (2007)