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SAND2013-4569C

Ultra-Strong Light-Matter Interaction with Mid-Infrared Metamaterials

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[3] University of California, Irvine, CA

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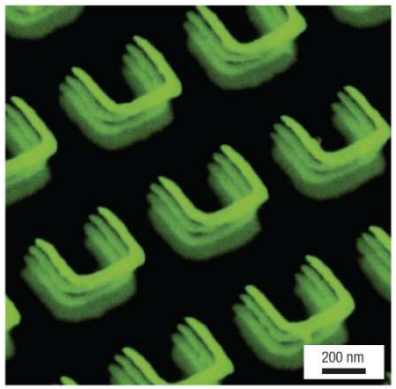
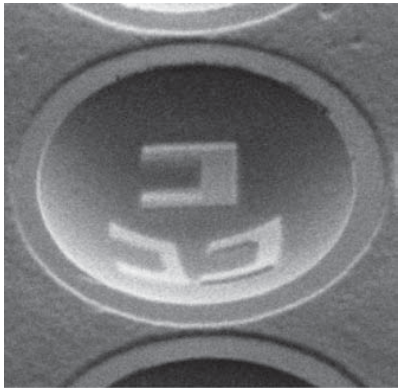
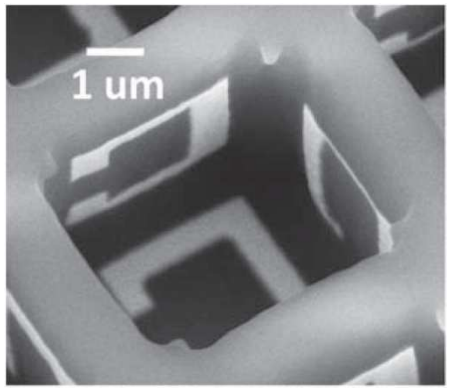
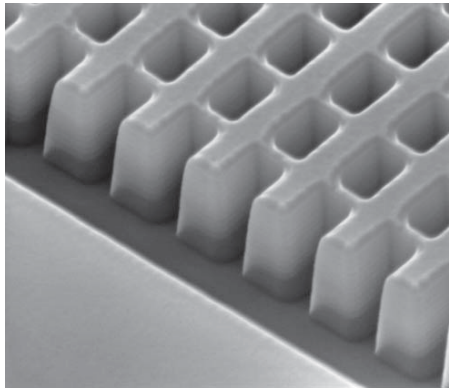
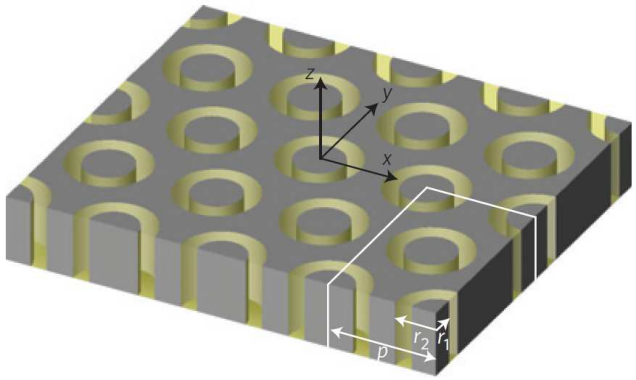
Metamaterial overview

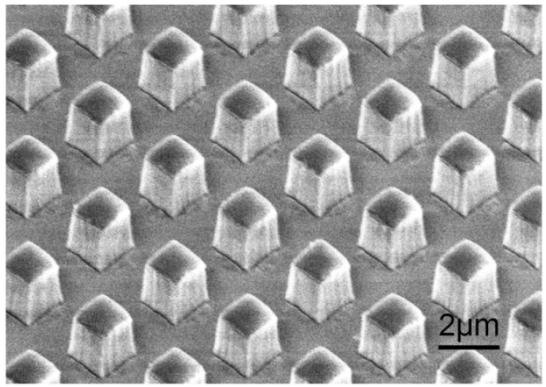


3D SRRs[1,2,3]

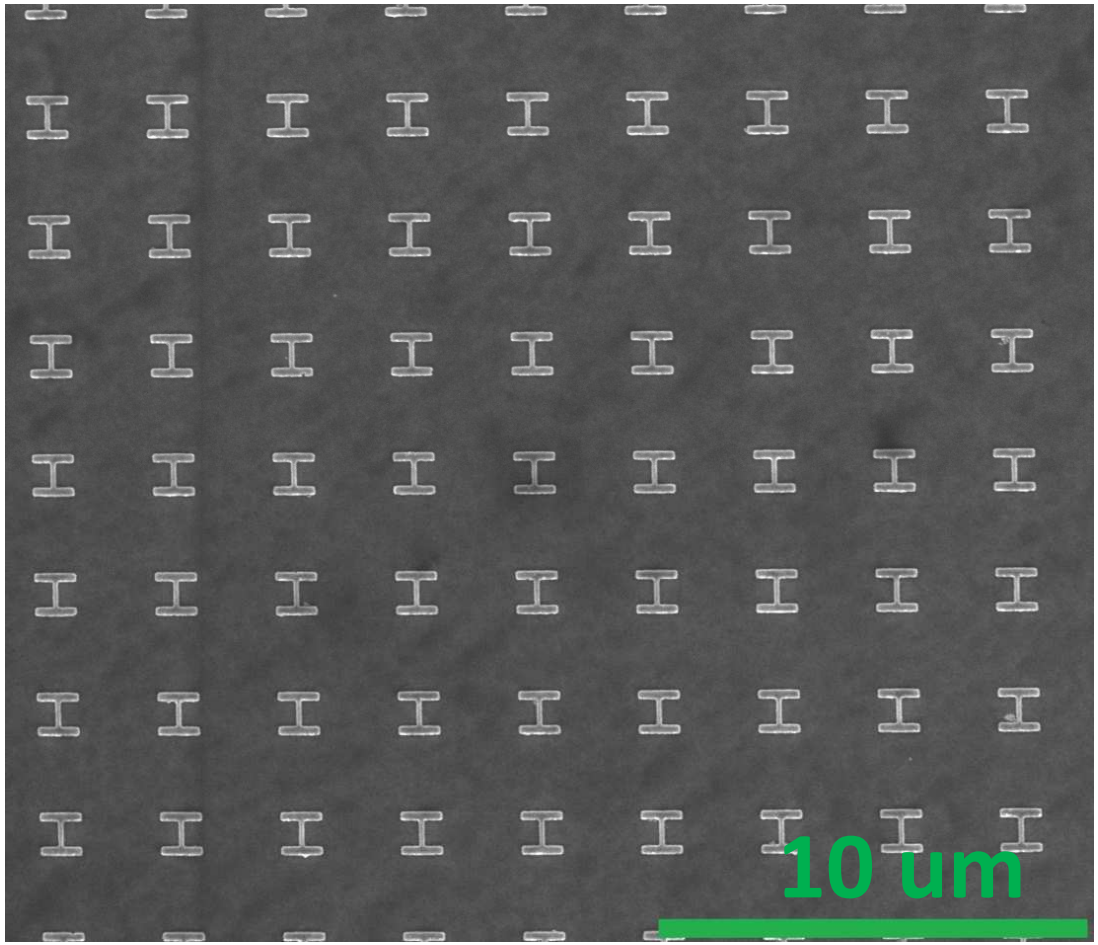
Negative index[1,2]



Magnetic mirrors[3]

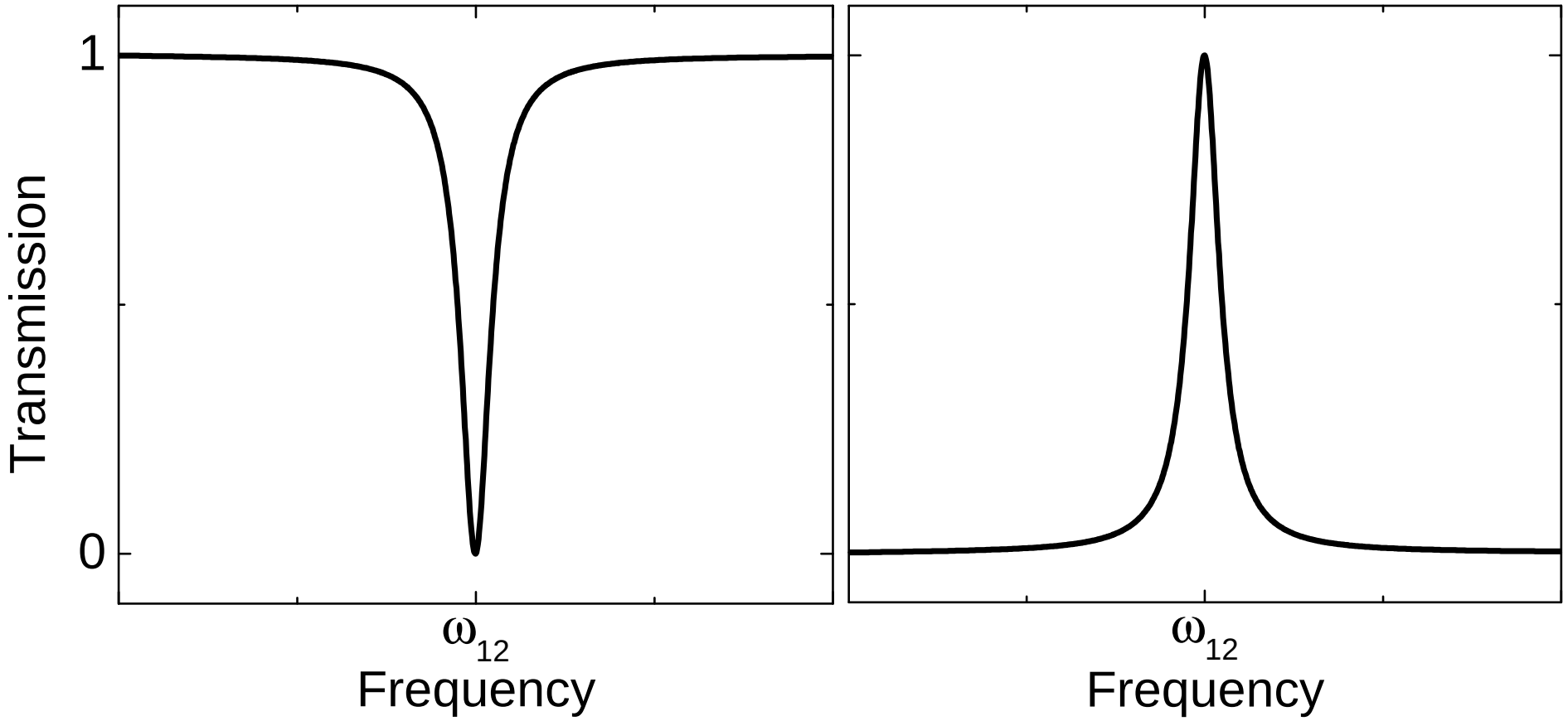
[1] N. Liu et al. Nature Materials **7**, 31 (2008)
[2] D. Burckel et al., Adv. Mater. **2010**, 22, 3171
[3] D. Burckel et al., Adv. Mater. **2010**, 22, 5053
[4] J. Valentine et al., Nature **455**, 376 (2008)
[5] S. Burgos et al., Nature Materials **9**, 407 (2010)
[6] J. Ginn et al., Phys. Rev. Lett.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

Metasurface

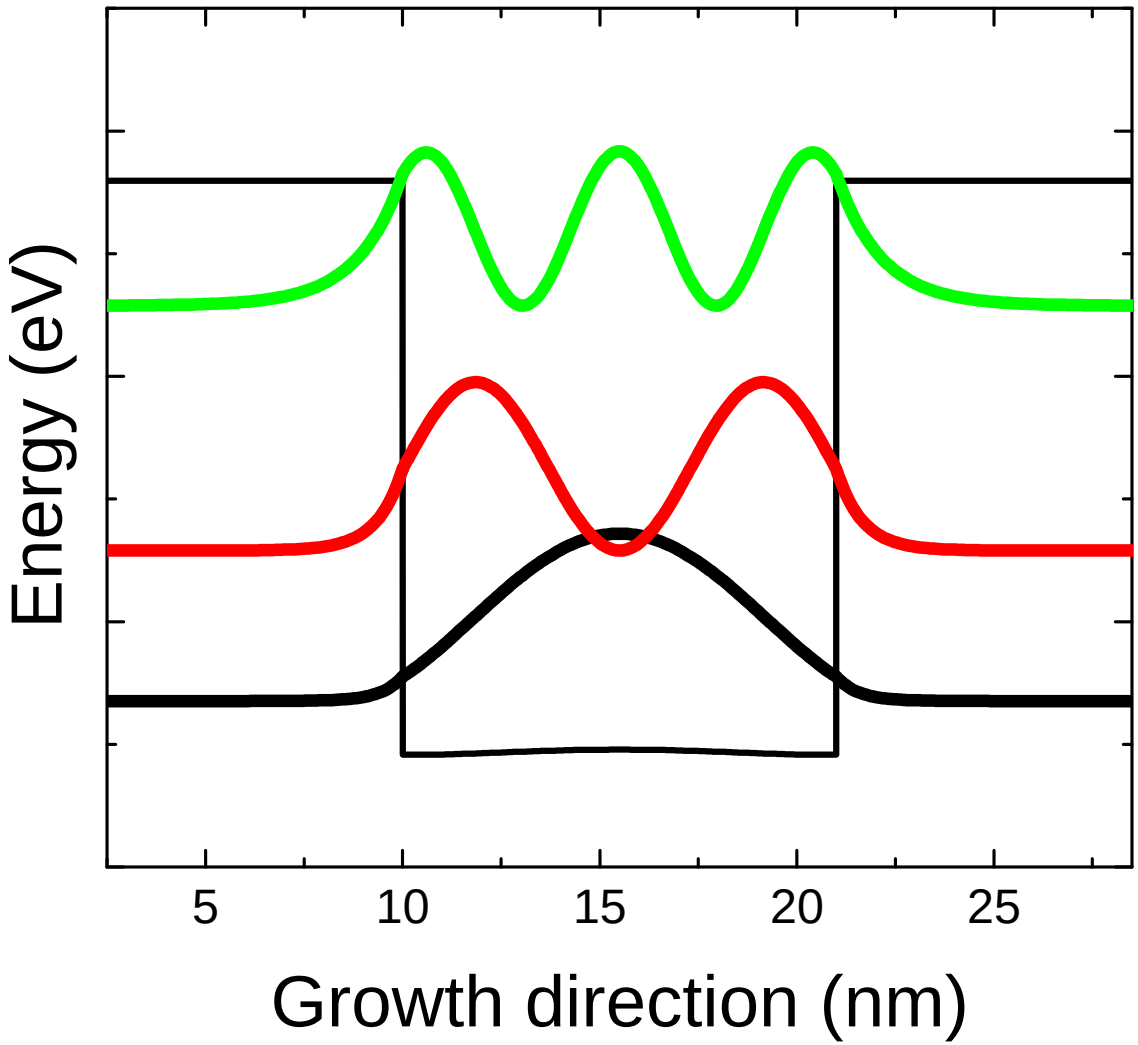


- Mostly 2D-layer used
  - Metasurface
- Versatile functionality
- ν filter
- Geometry defines properties

Metasurface

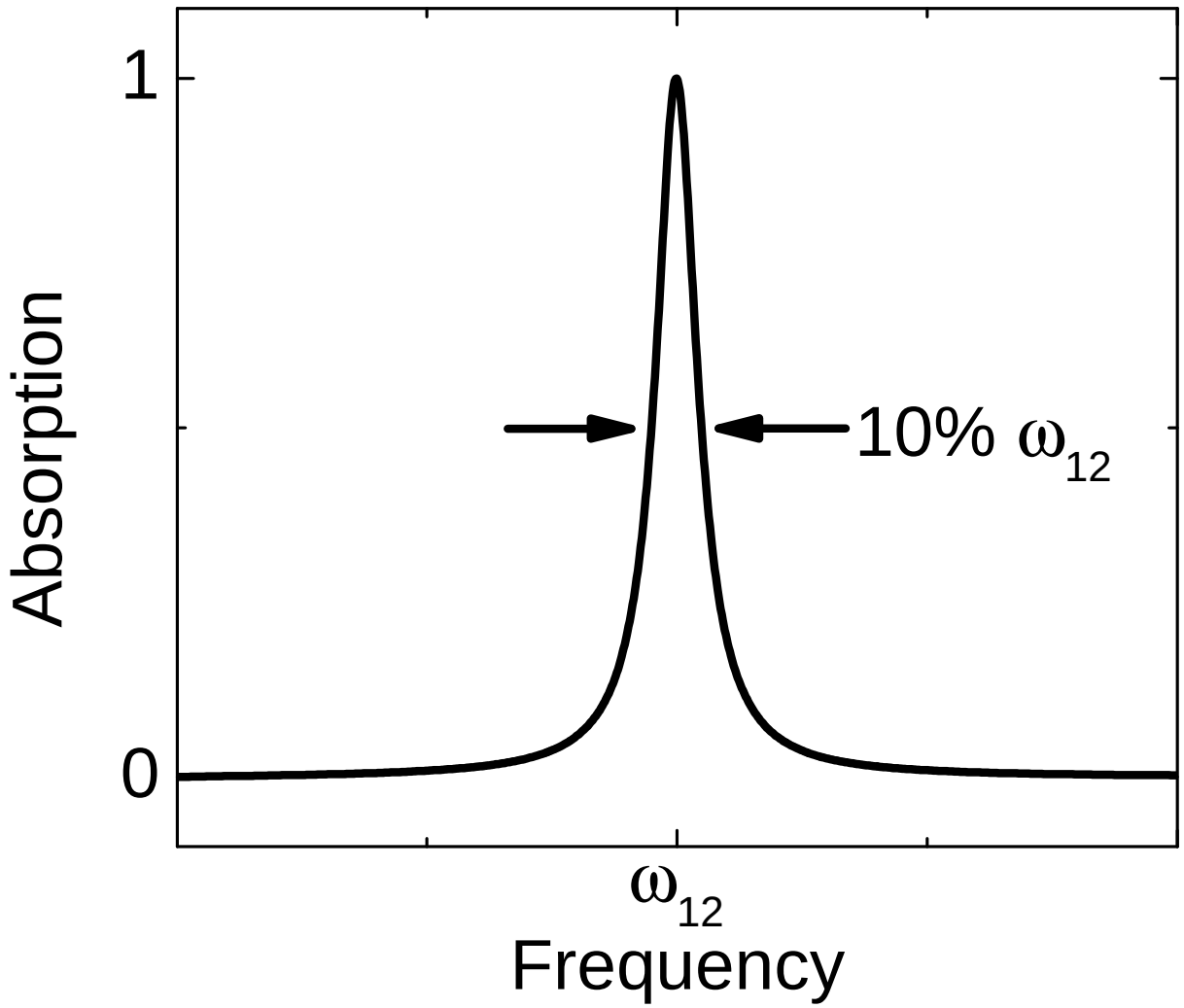


Intersubband transitions



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

Intersubband transitions



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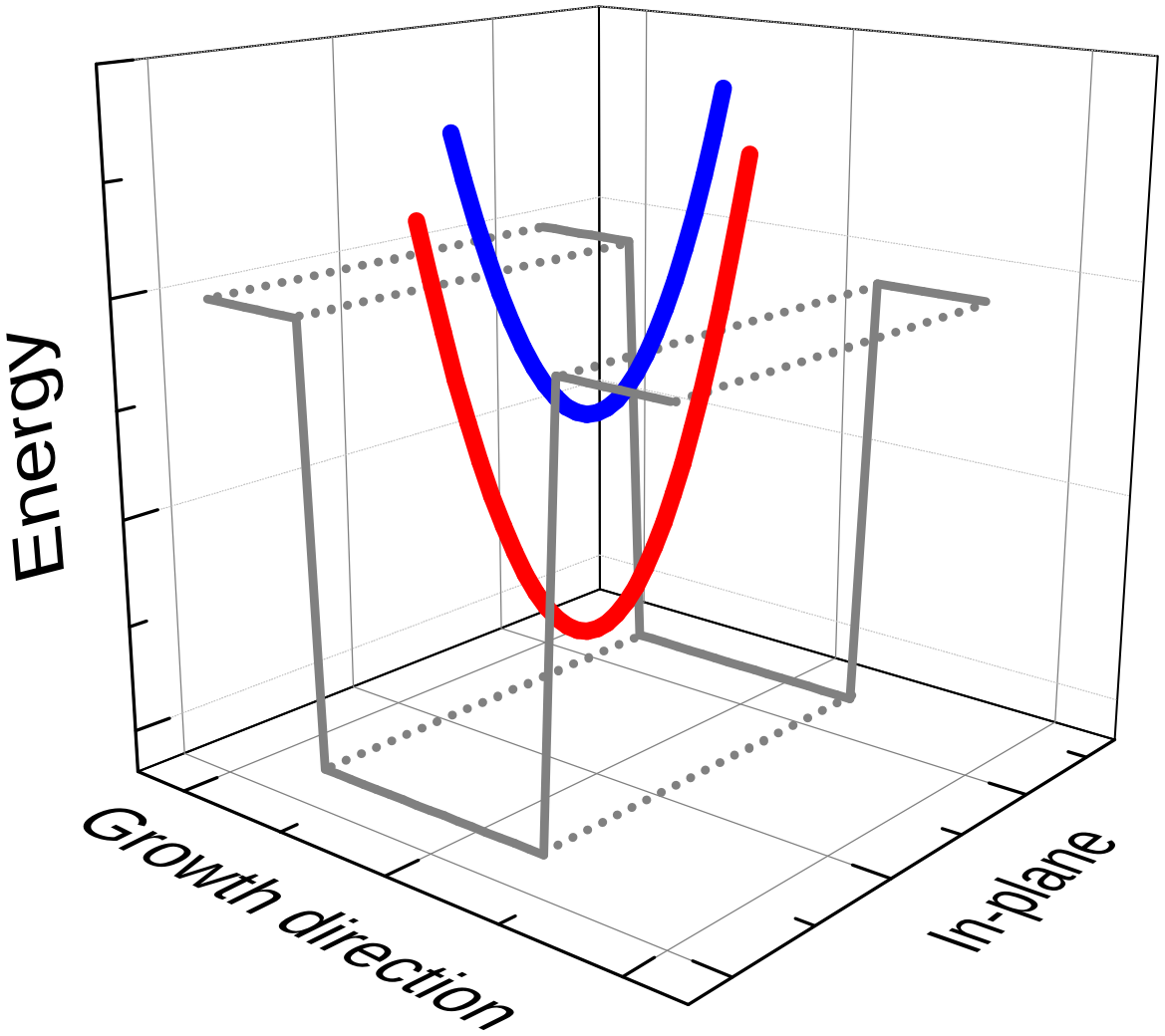

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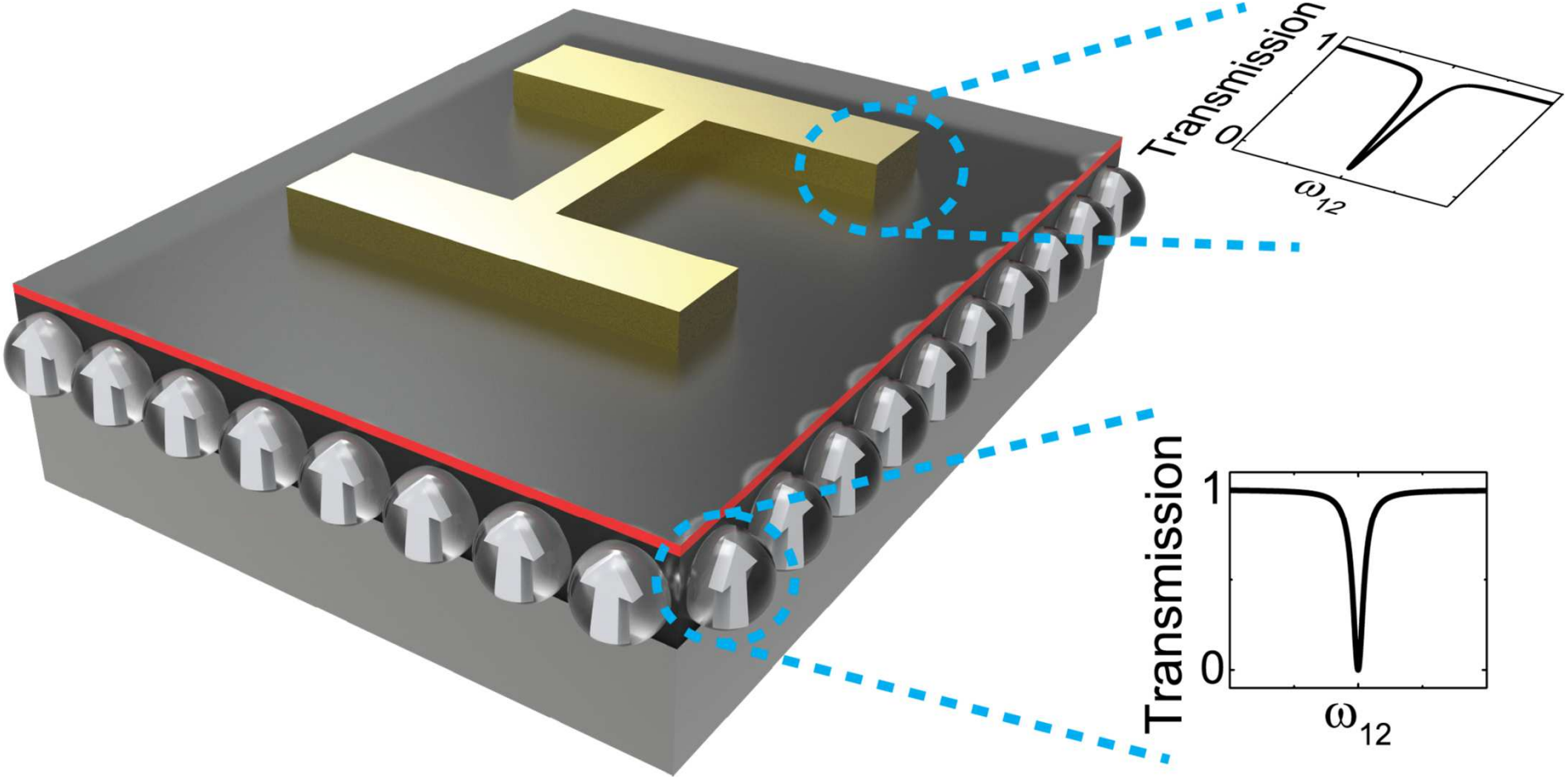
Light-matter coupling



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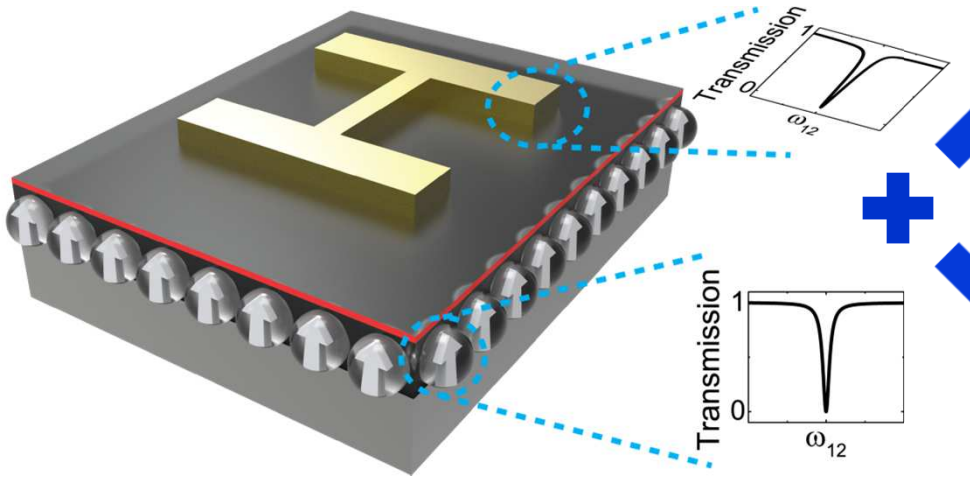


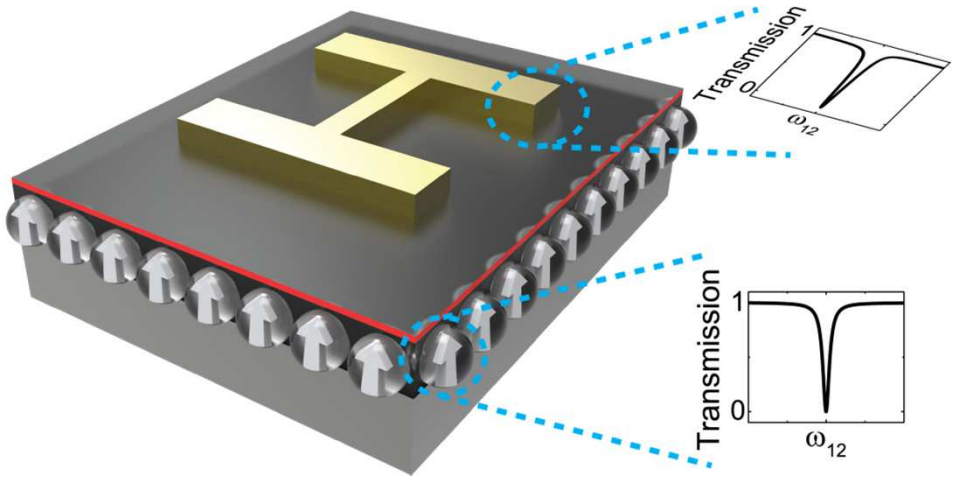
Weak coupling

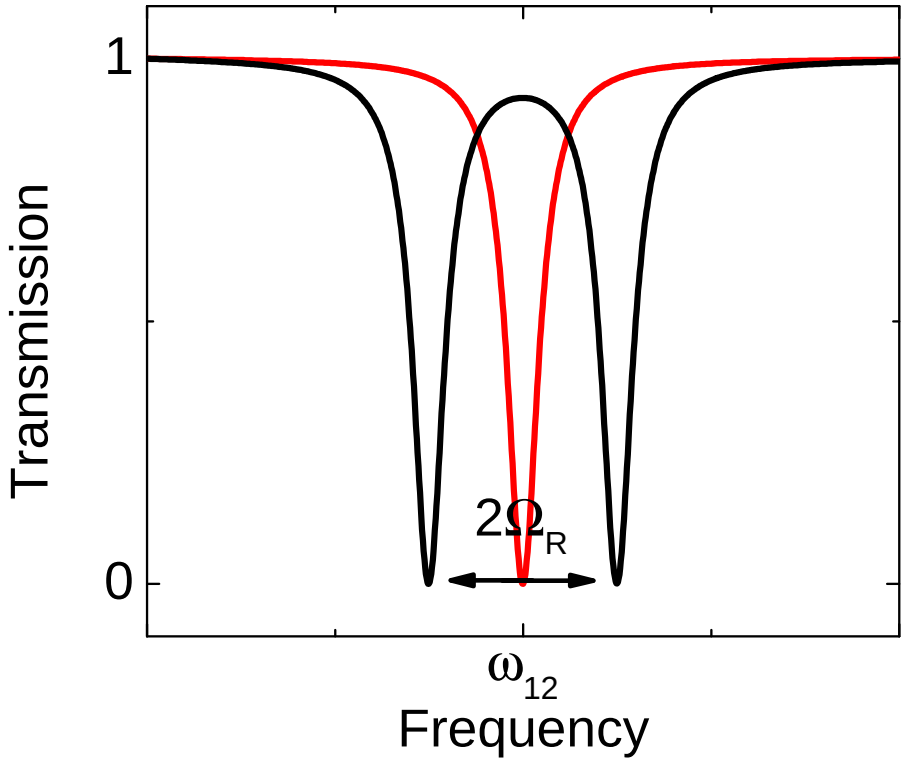
- Losses > Coupling
- Purcell regime

Strong coupling

- Coupling > Losses
- Energy exchange
- Rabi frequency

Light-matter coupling





Ultra-strong coupling physics

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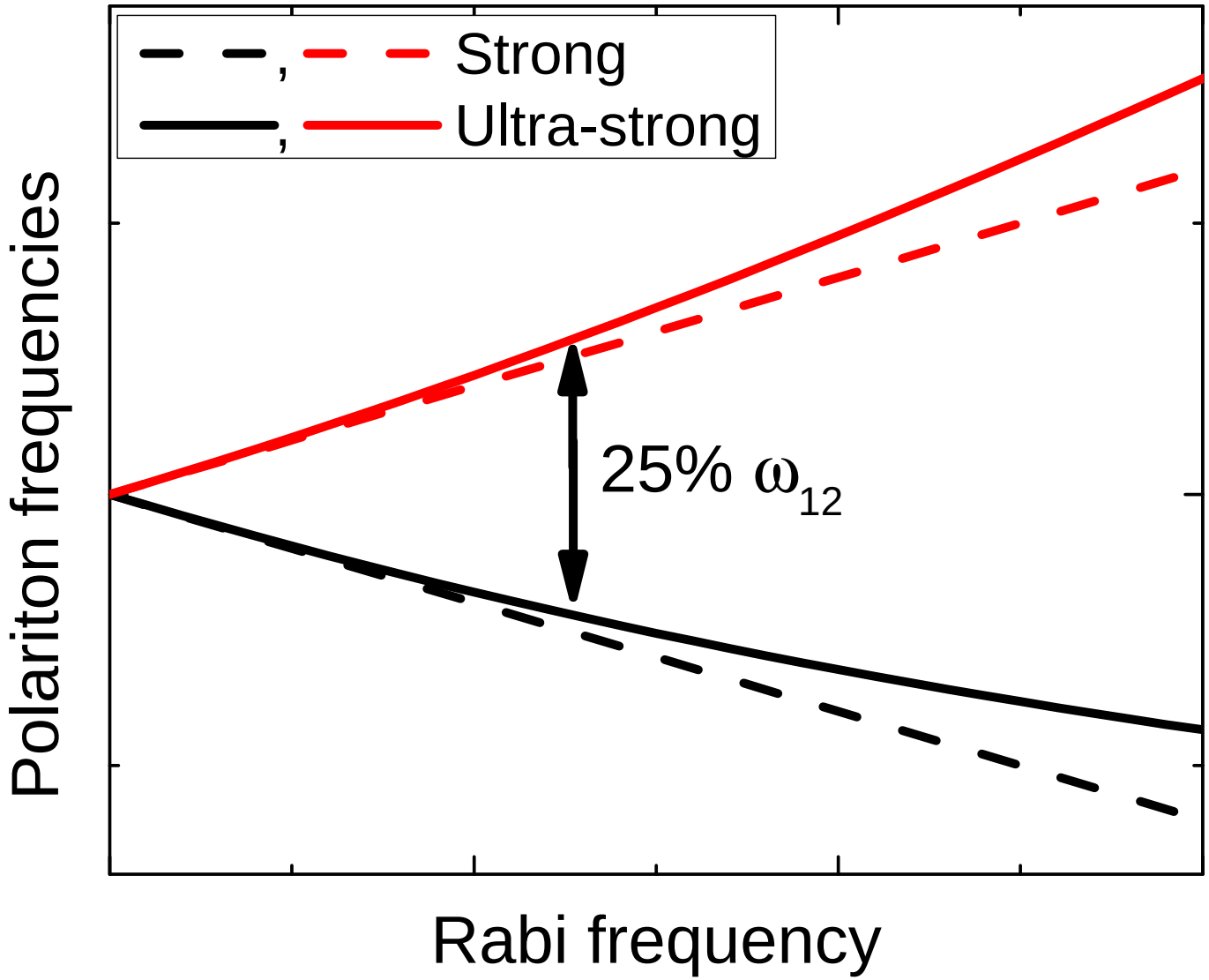
- Two resonators anti-cross
- Splitting Ω_R similar to system resonance
  - Energy exchange ≈ Fundamental system oscillation
  - Anti-resonant terms in equilibrium
- Squeezed vacuum as ground state
  - Release correlated photon pairs
- Light-matter superposition = Polaritons

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

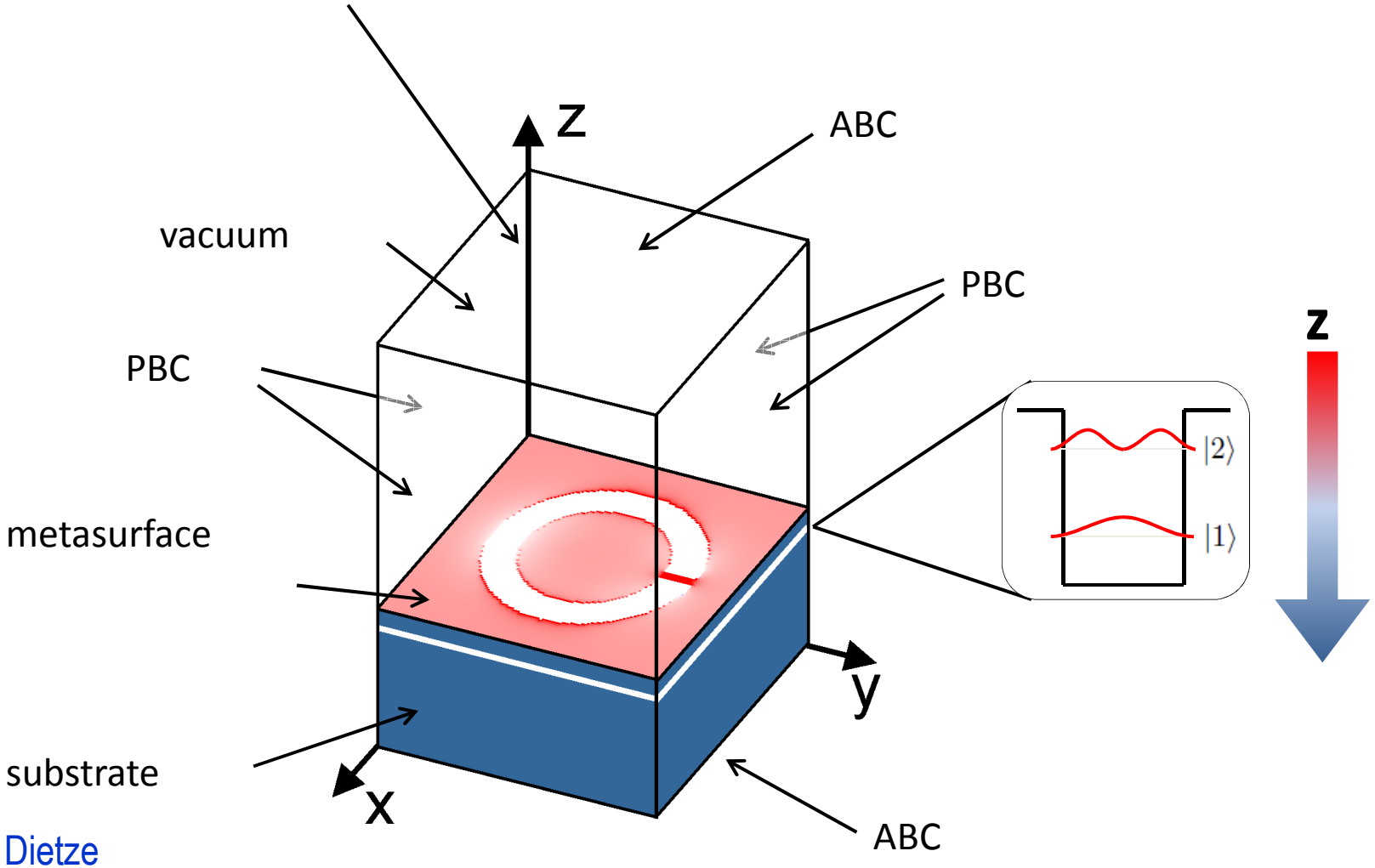
S. DeLiberato et al., Phys. Rev. Lett. **98**, 103602 (2007)

Strong vs. ultra-strong coupling



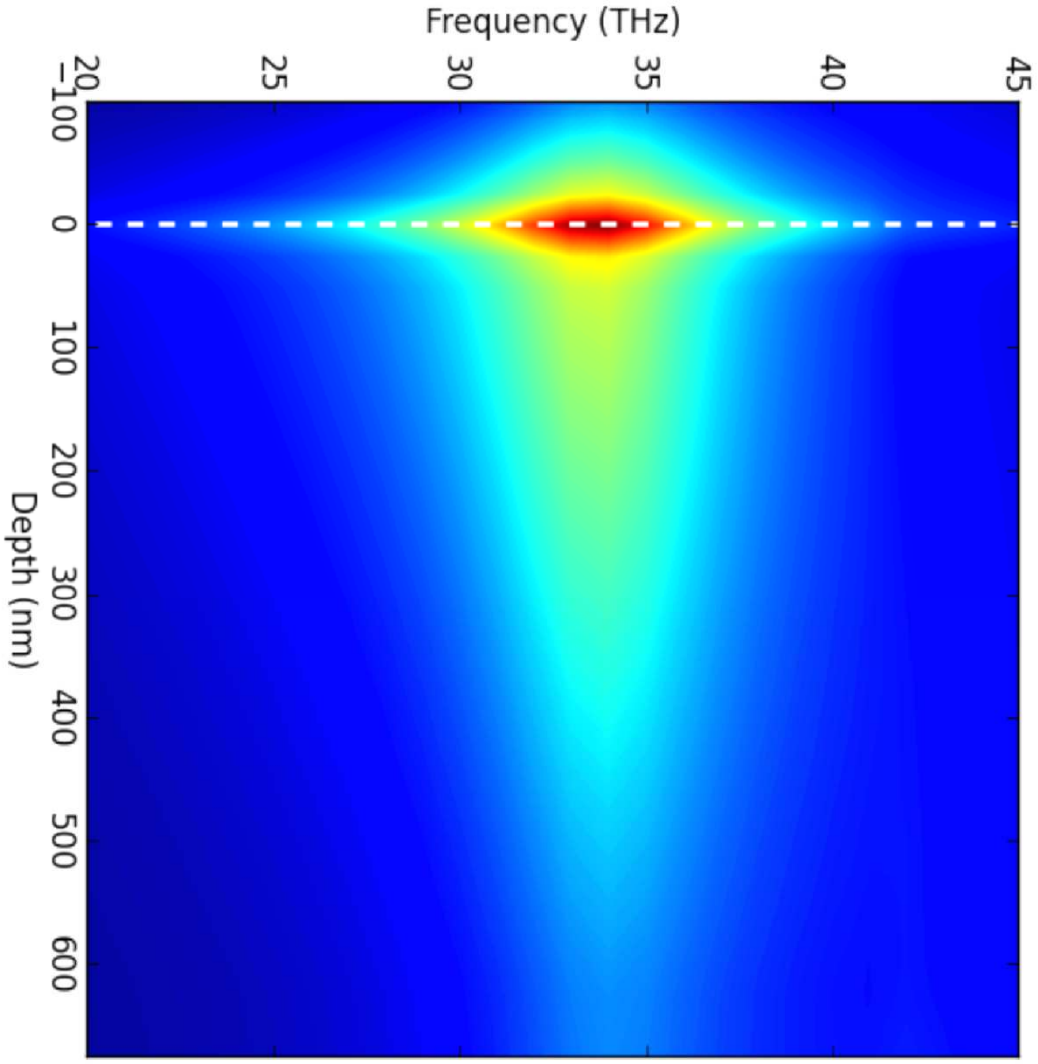
FDTD resonator design

plane wave, single-cycle pulse source



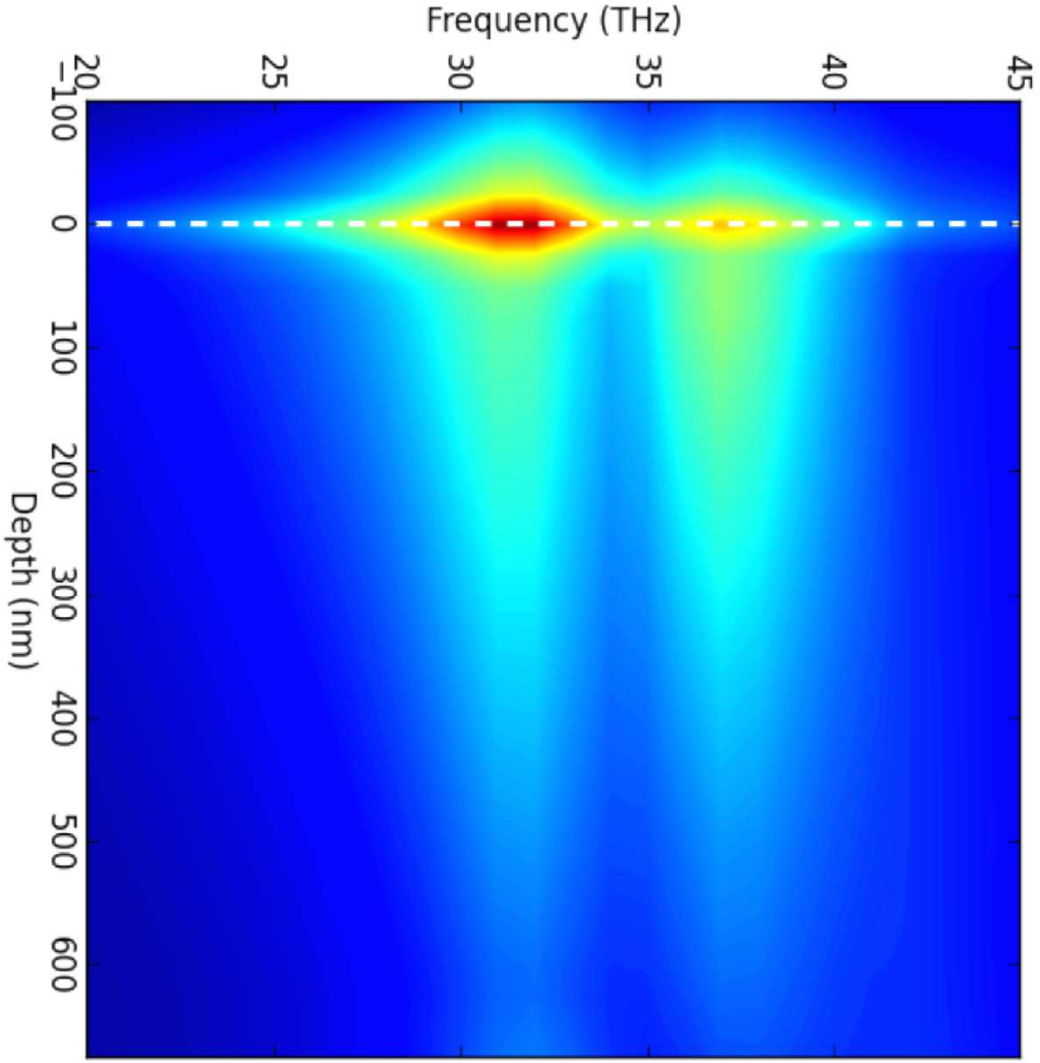
Courtesy of D. Dietze

E_z near-field profiles



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

E_z near-field profiles



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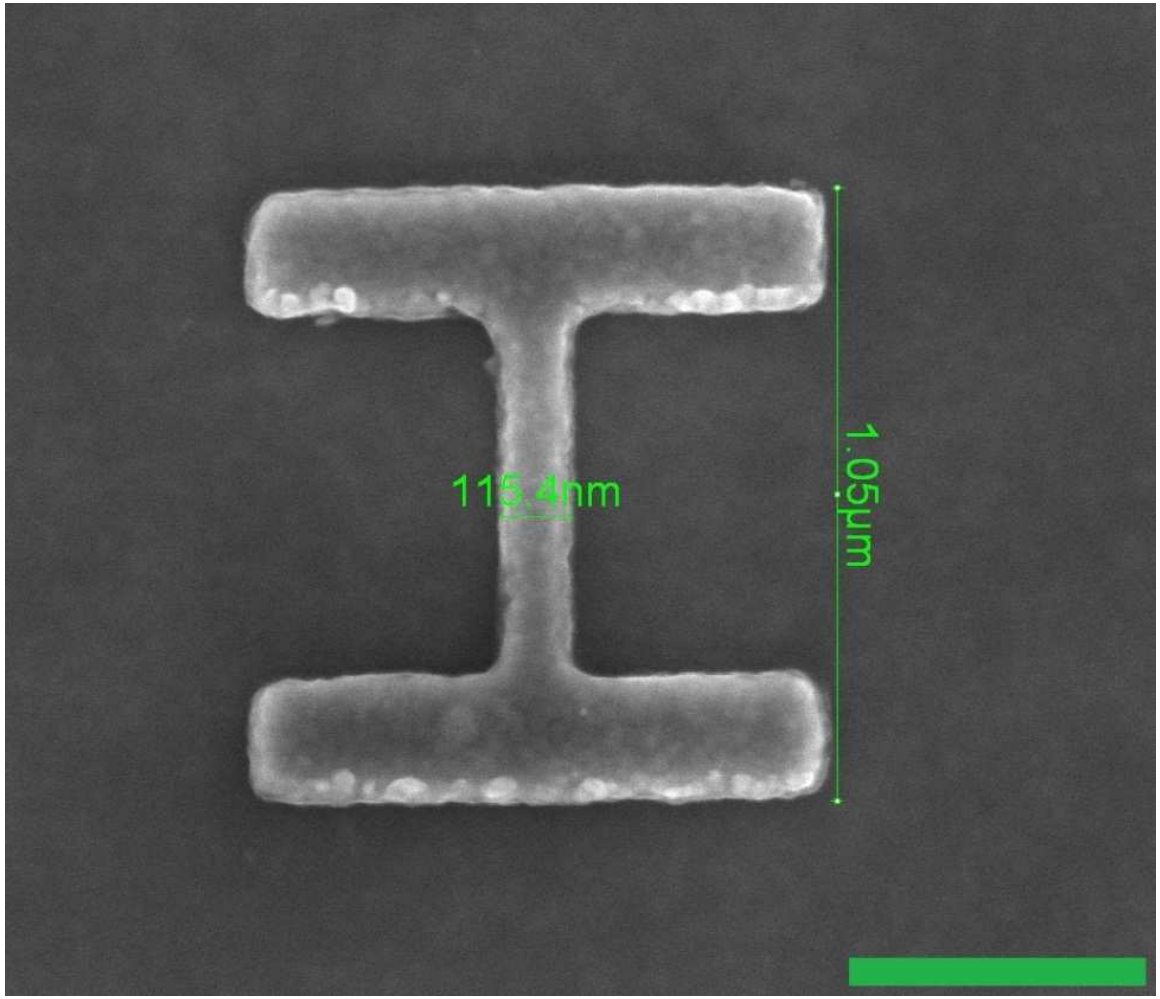
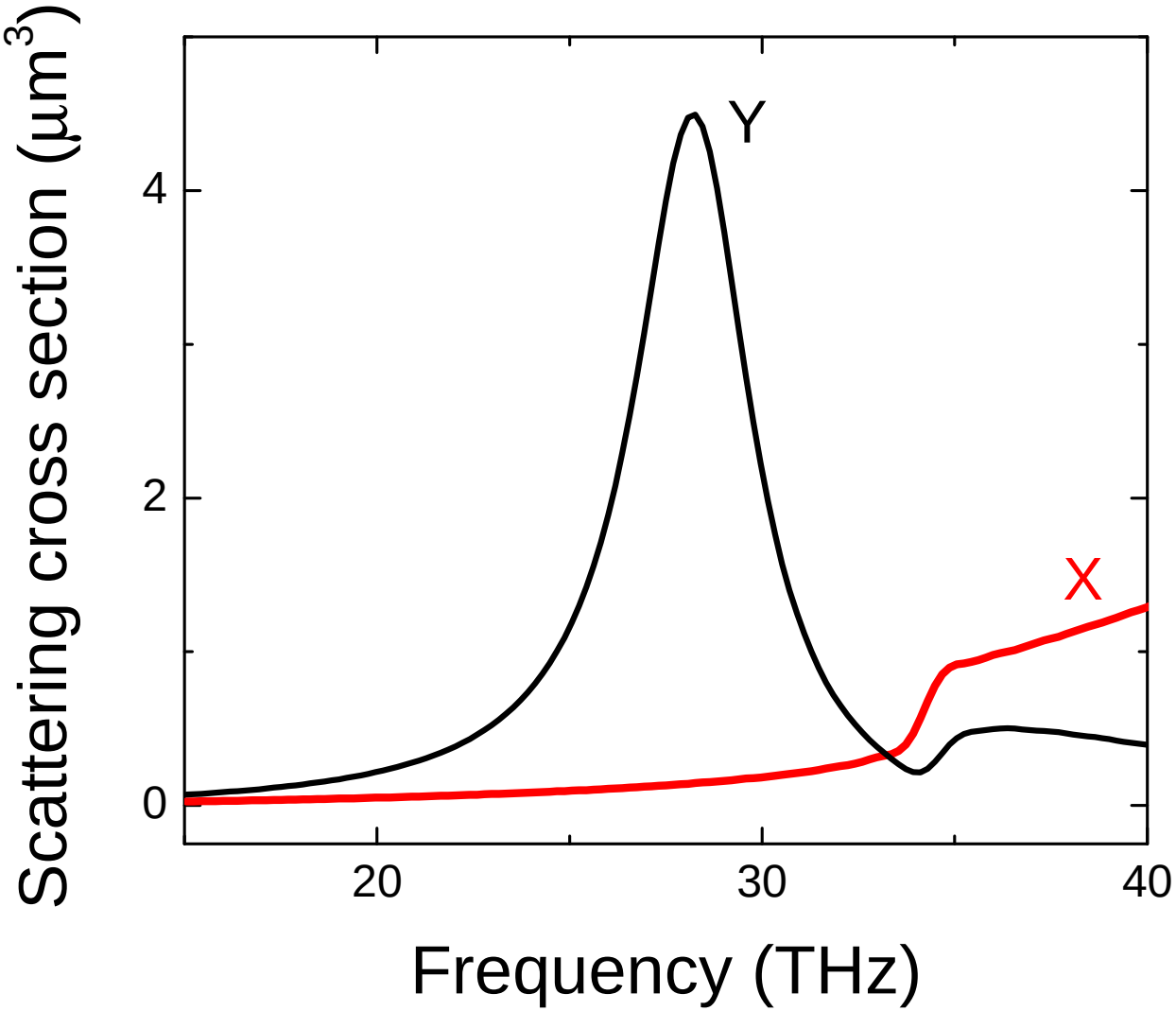
Metamaterial fabrication



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

Metamaterial fabrication



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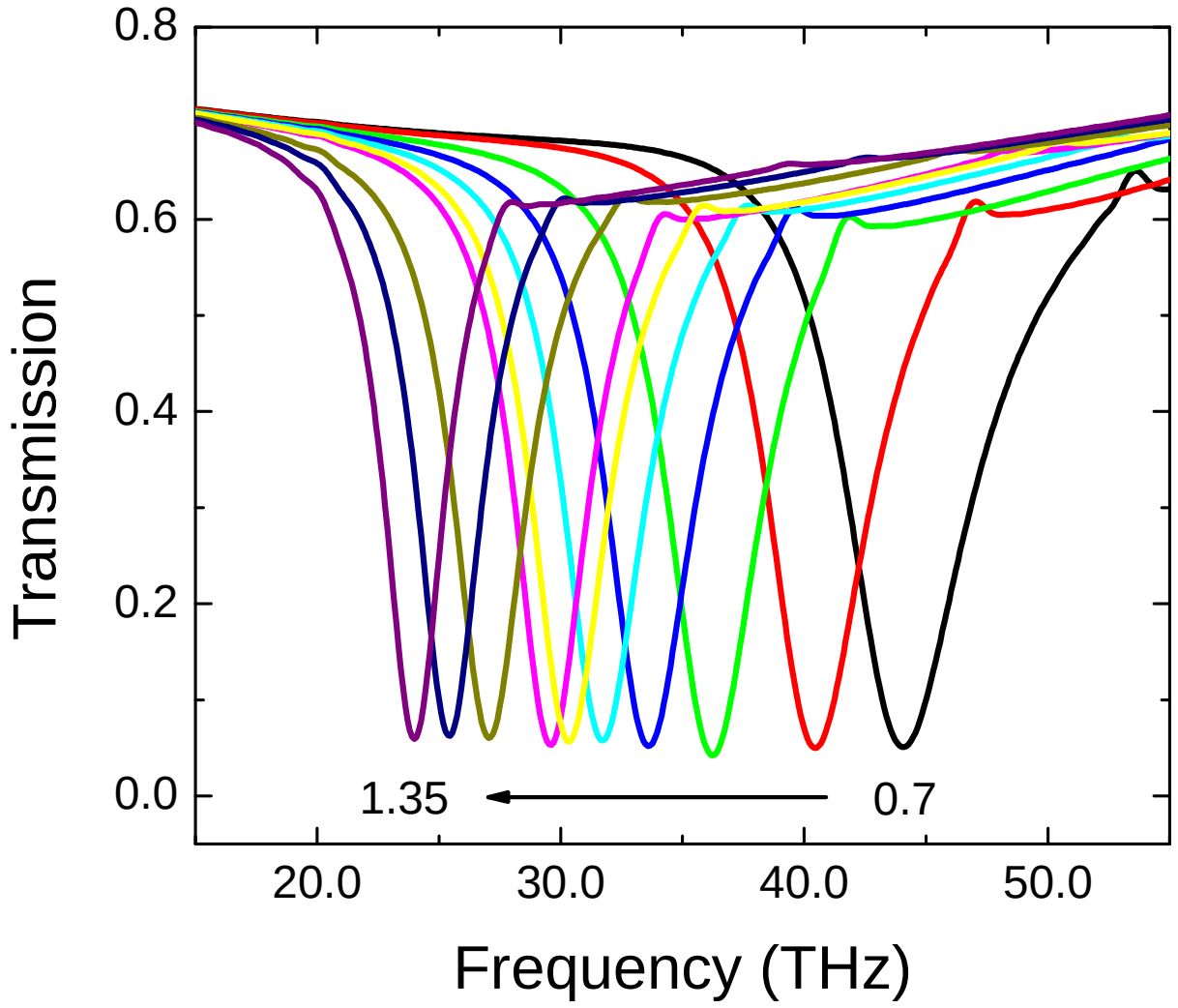

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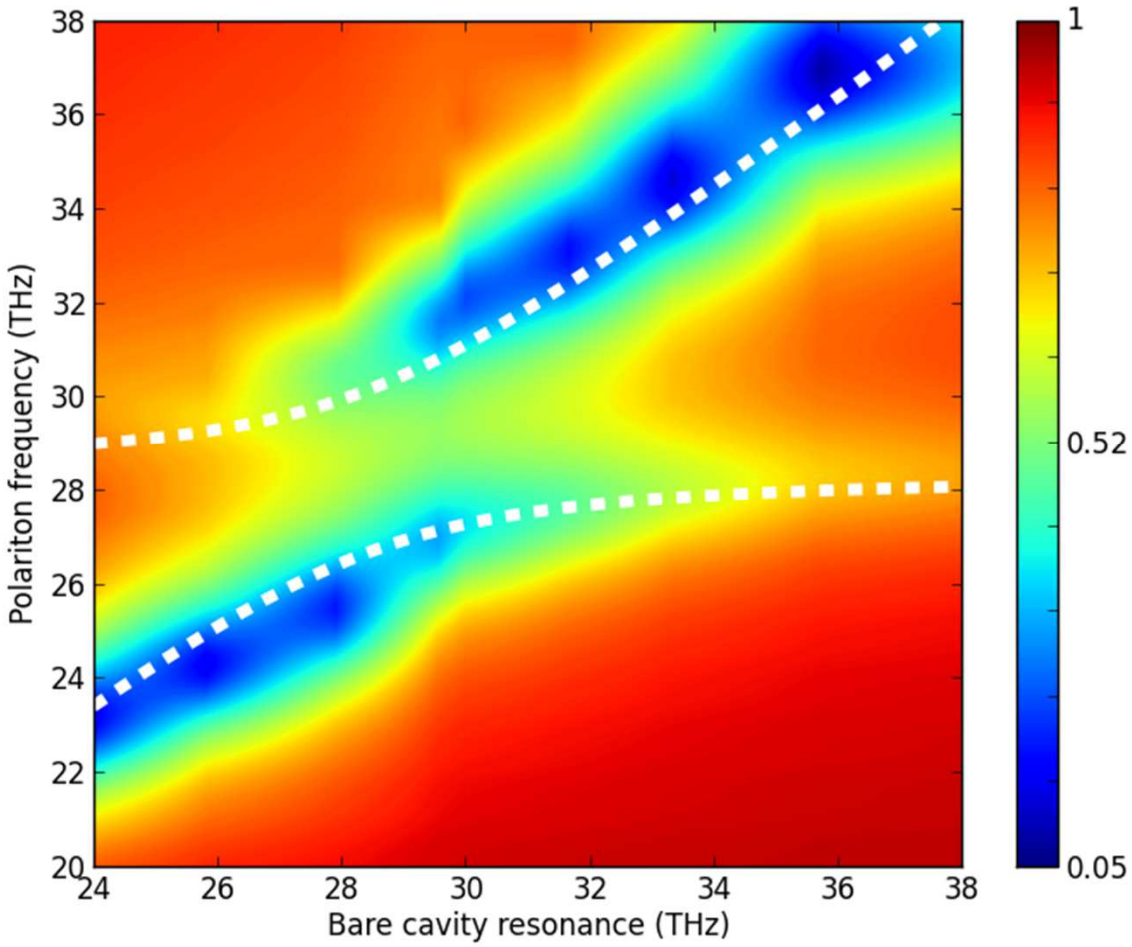
Strong coupling theory vs. experiment

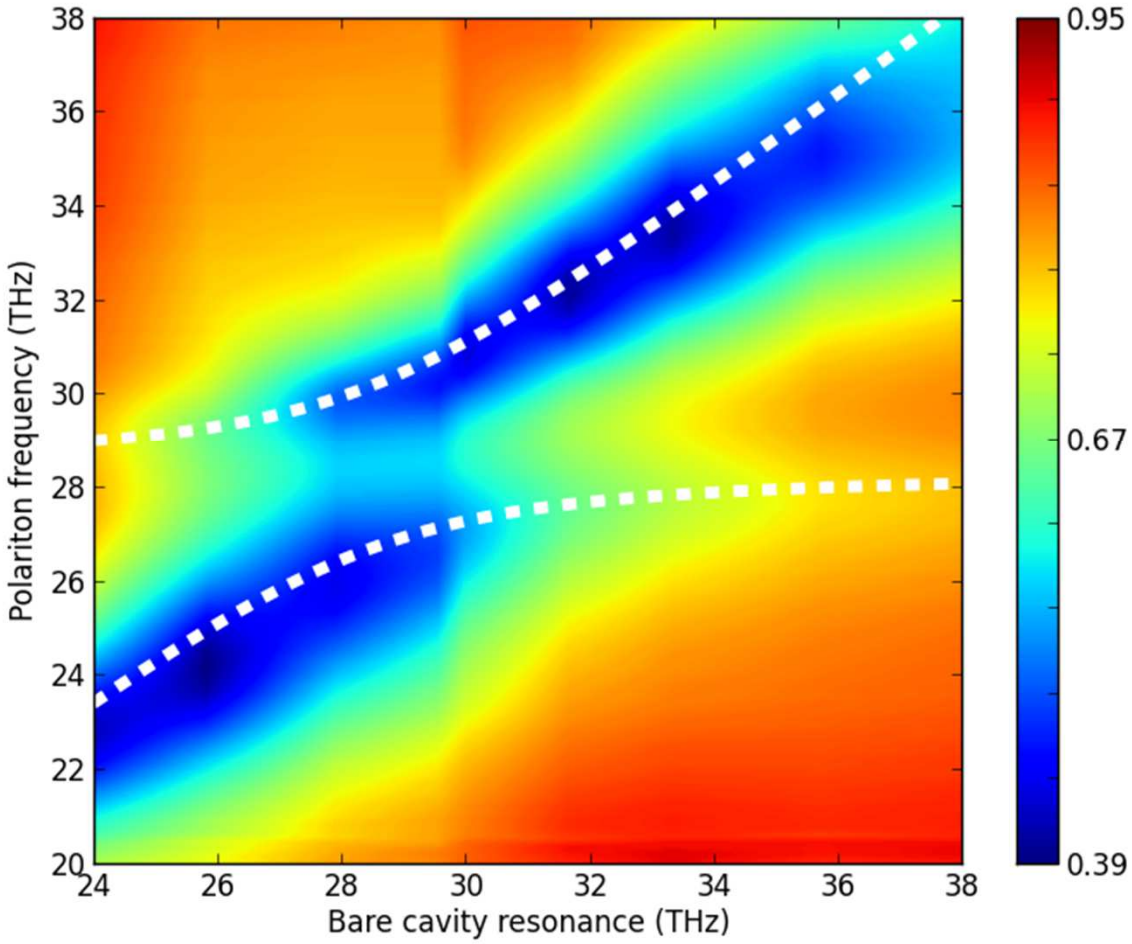


- FDTD simulations
- Anti-crossing
- Polariton picture[1,2]

[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



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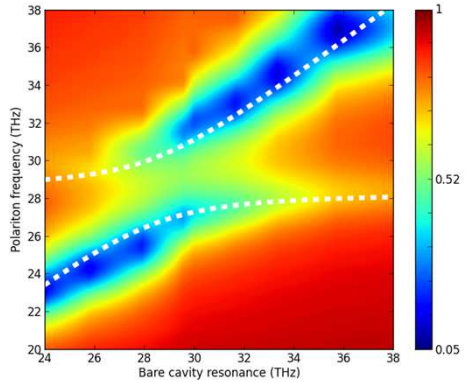
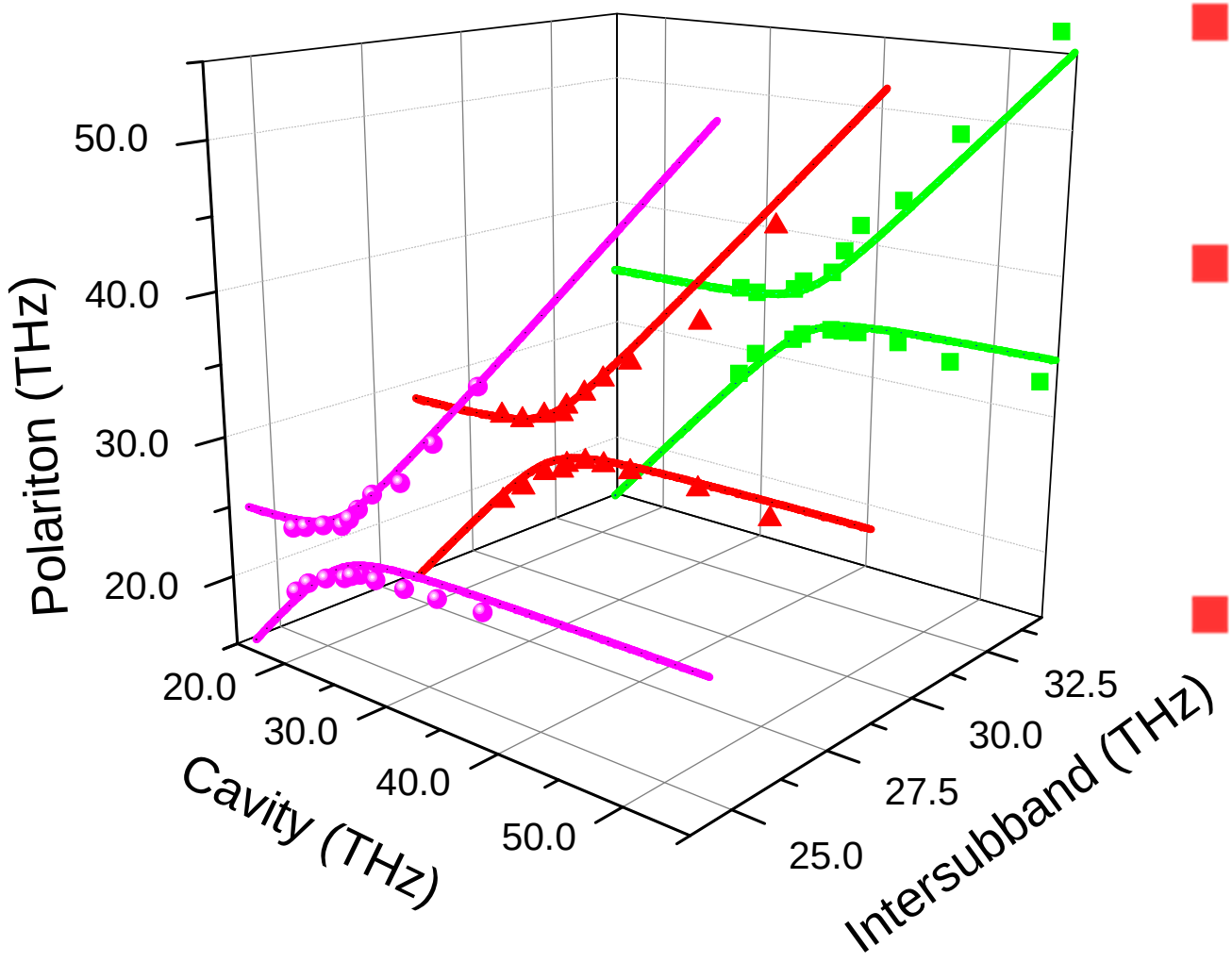


[1] A. Gabbay et al., Appl. Phys. Lett. **98**, 203103 (2011)

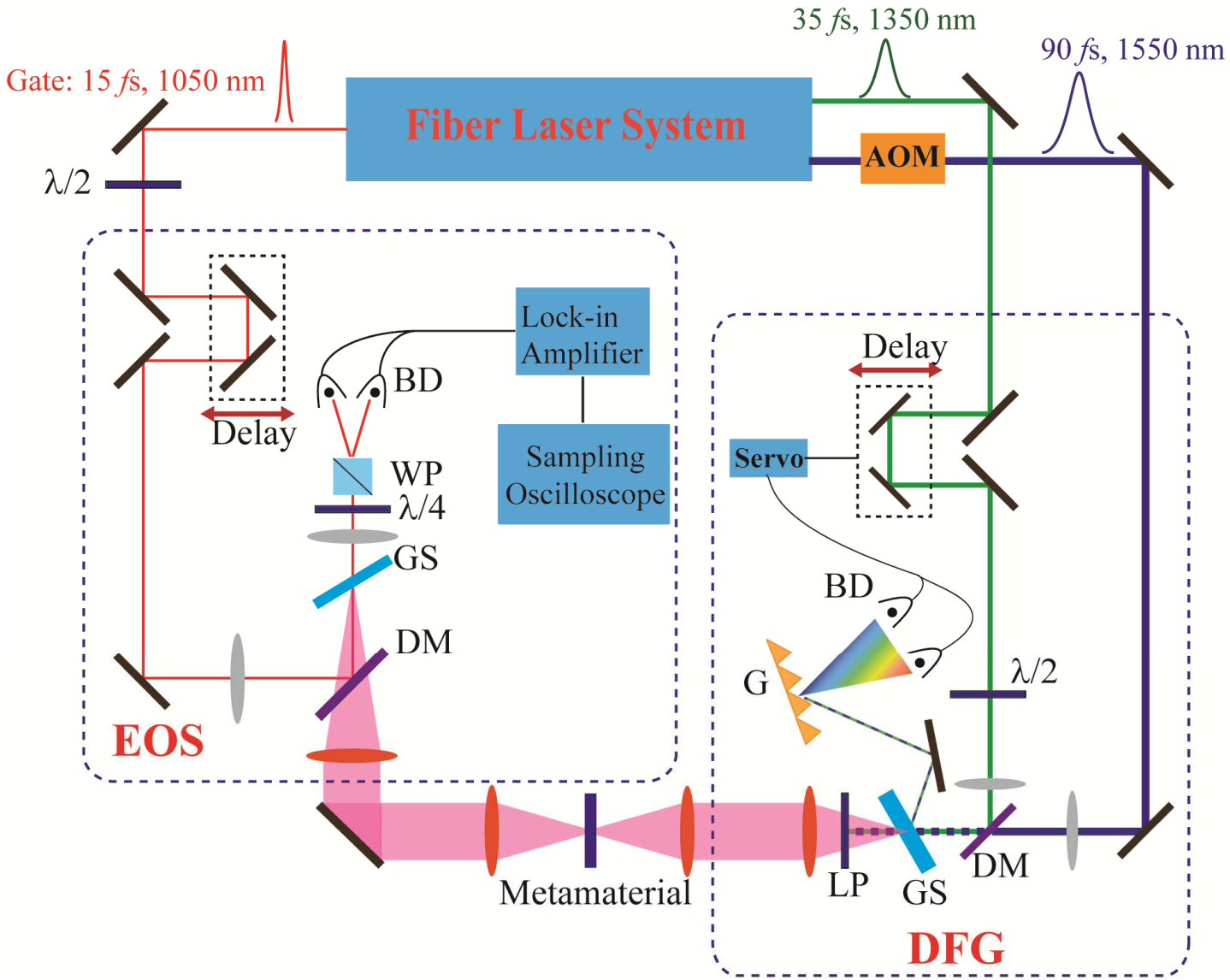
[2] A. Gabbay et al., Opt. Exp. **20**, 6584 (2012)

Intersubband flexibility



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

Experimental Rabi oscillations



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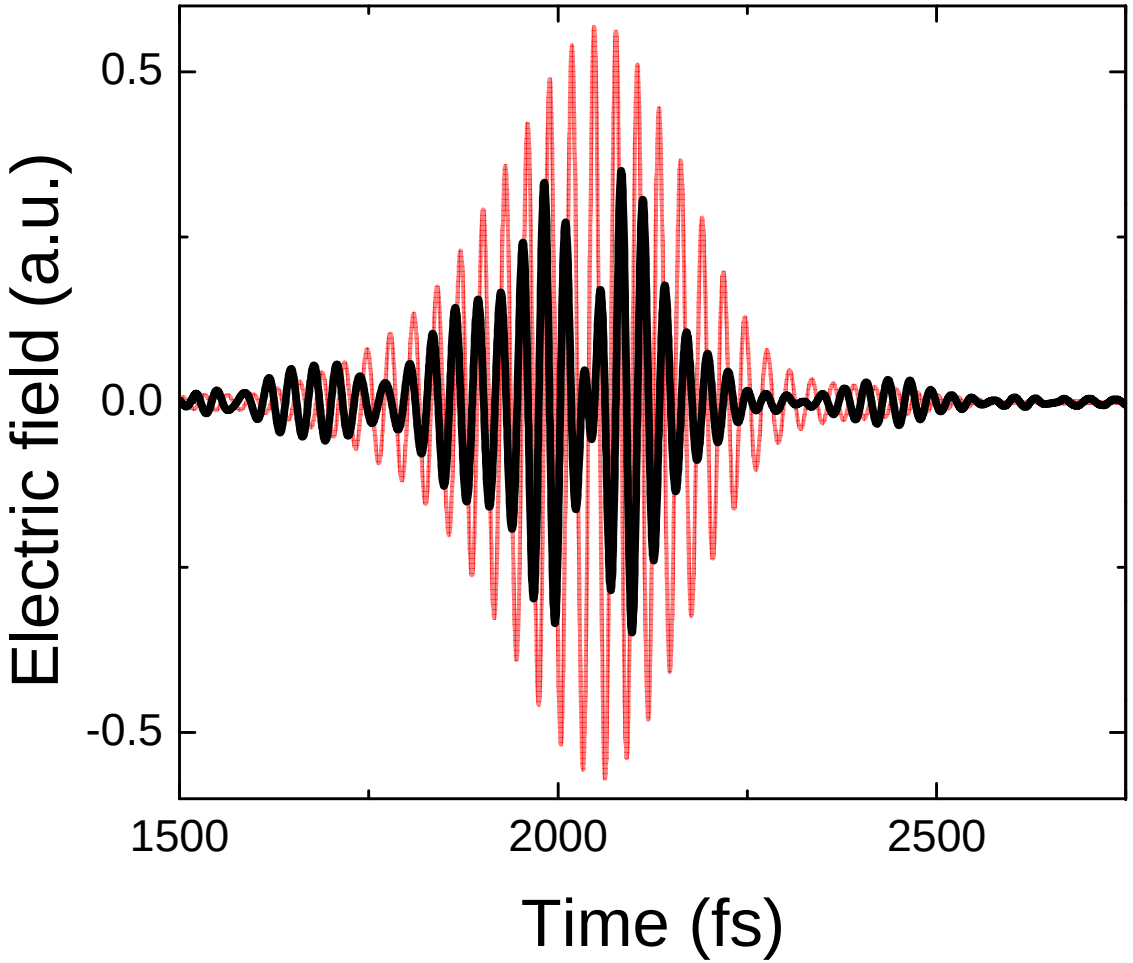
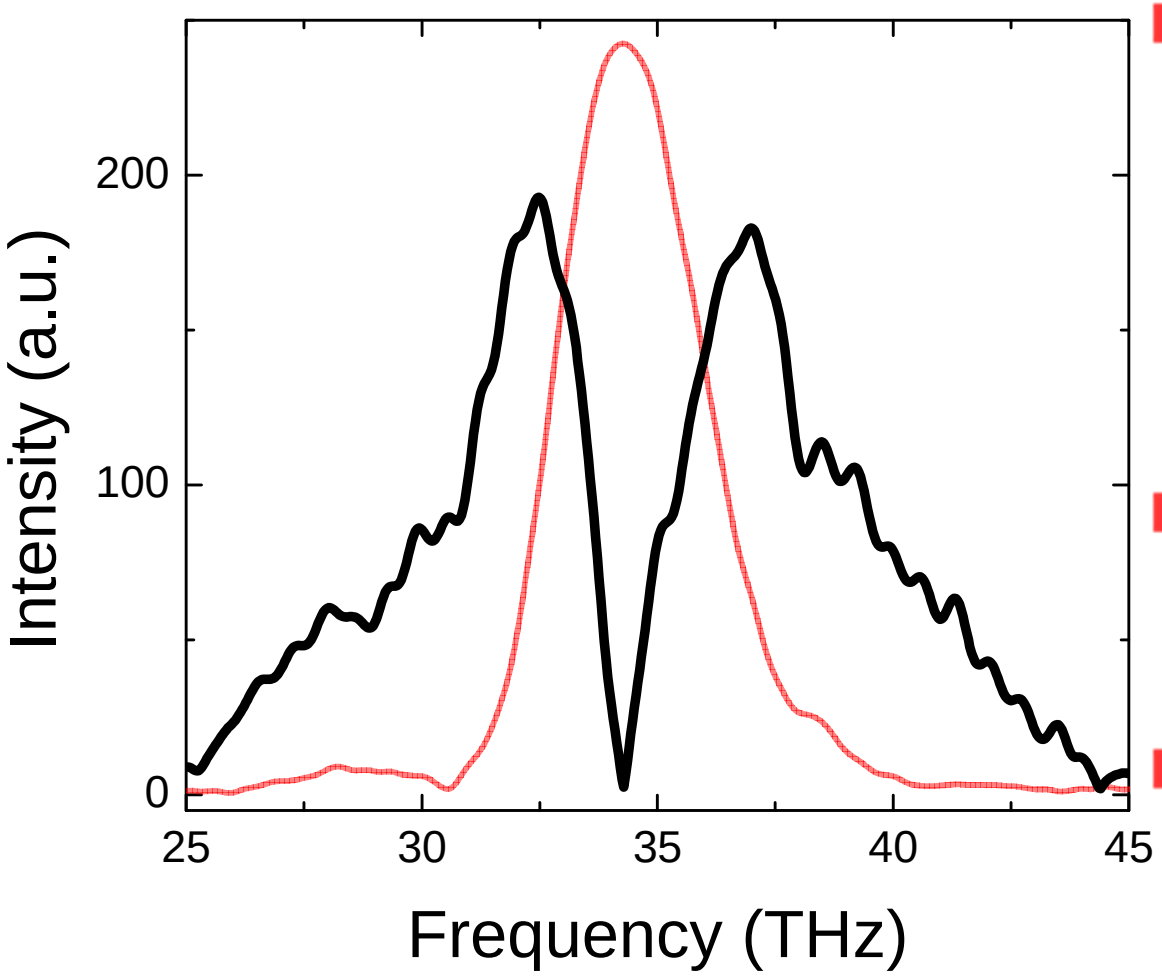


- Energy exchange probed in time
  - 33 fs oscillation
  - 480 fs beating
- System strongly coupled
- Splitting of 4.2 THz measured
  - 15 % of ω_{12}

Experimental Rabi oscillations



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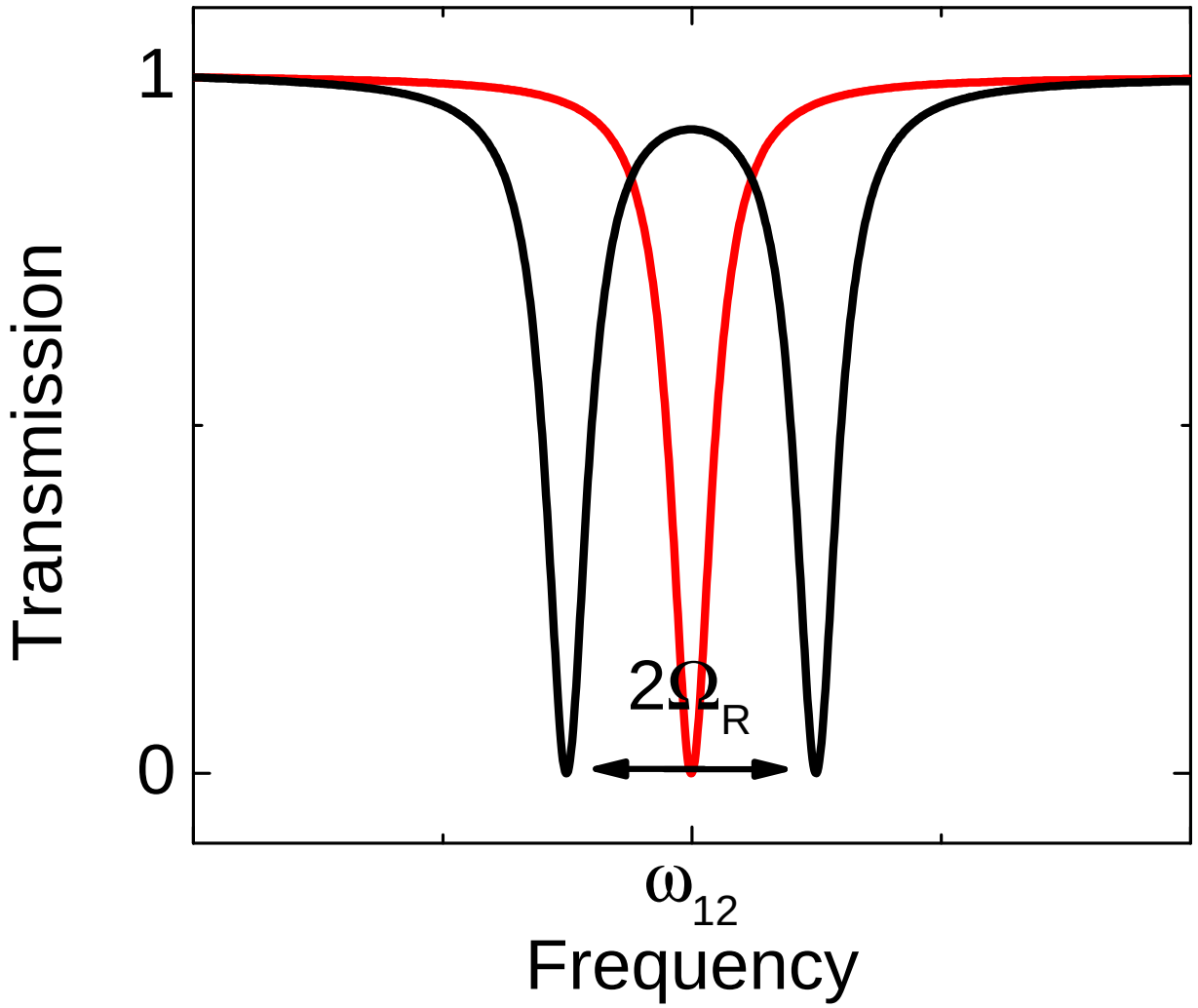
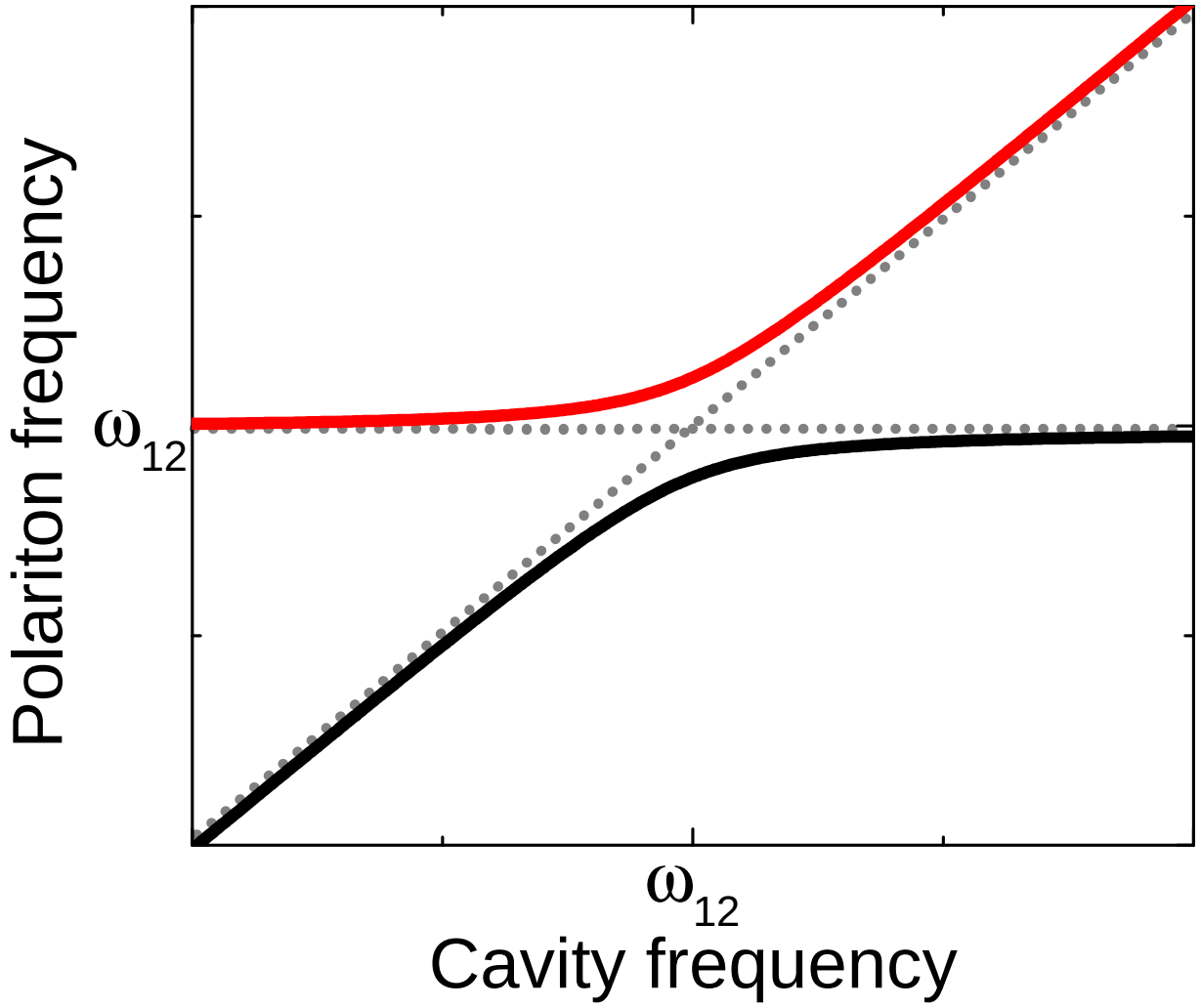
Application vs. physics



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

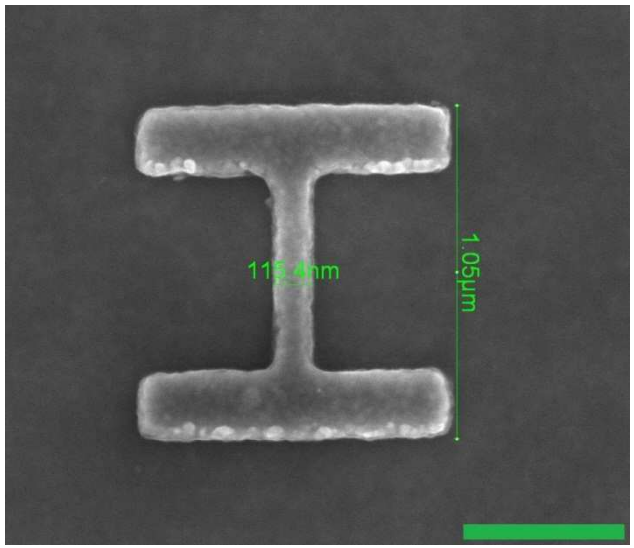
Application vs. physics

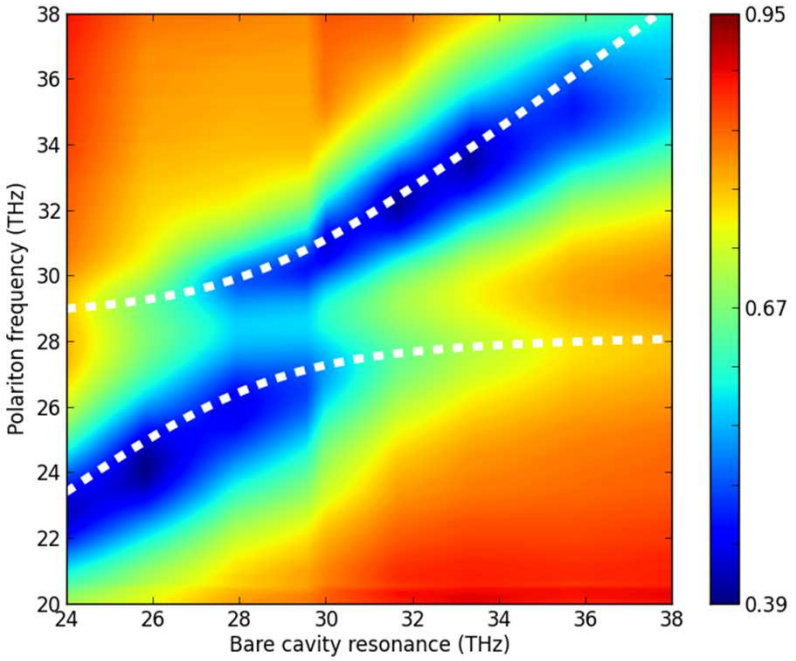


- Transmission from 0 to 1
  - Electrically switchable
- Works at room temperature
- Resonances anti-cross
  - $\Omega_R \approx \omega_{12}$

Conclusion & Outlook

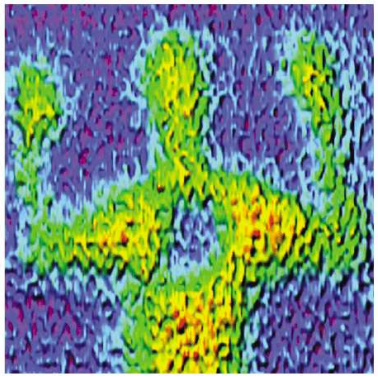
- Ultra-strong light-matter interaction
  - Rabi frequency similar to bare cavity resonance
- Quantum-well controlled electrically
  - Turn coupling on/off

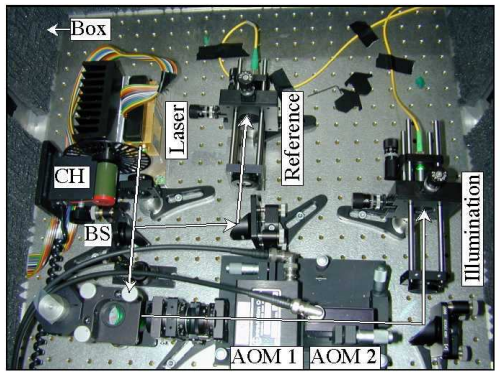




Why mid-IR?

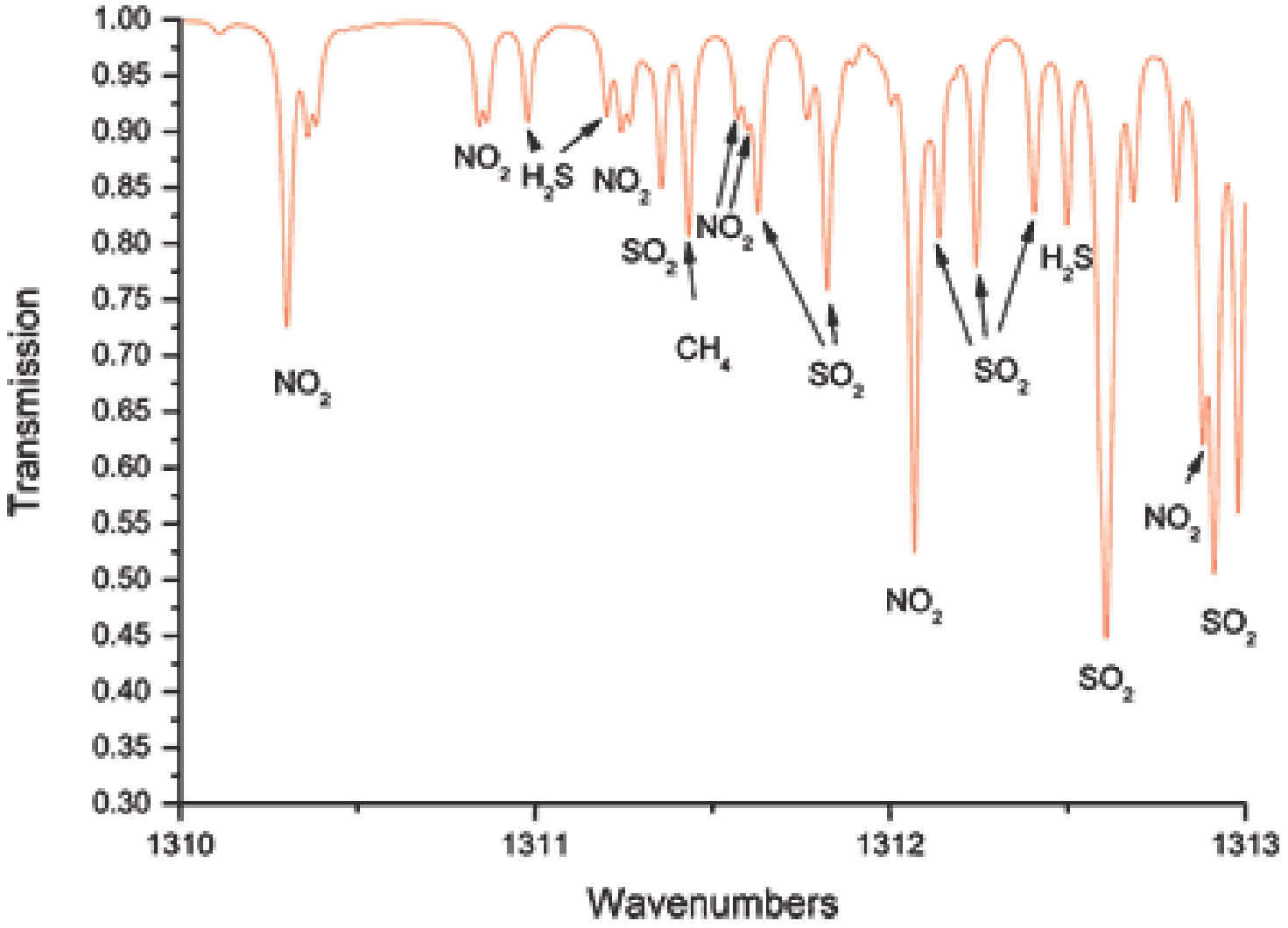
- Large number of possible applications
  - Spectroscopy
  - Heterodyne detection
  - Process controll
  - Security systems
  - Imaging



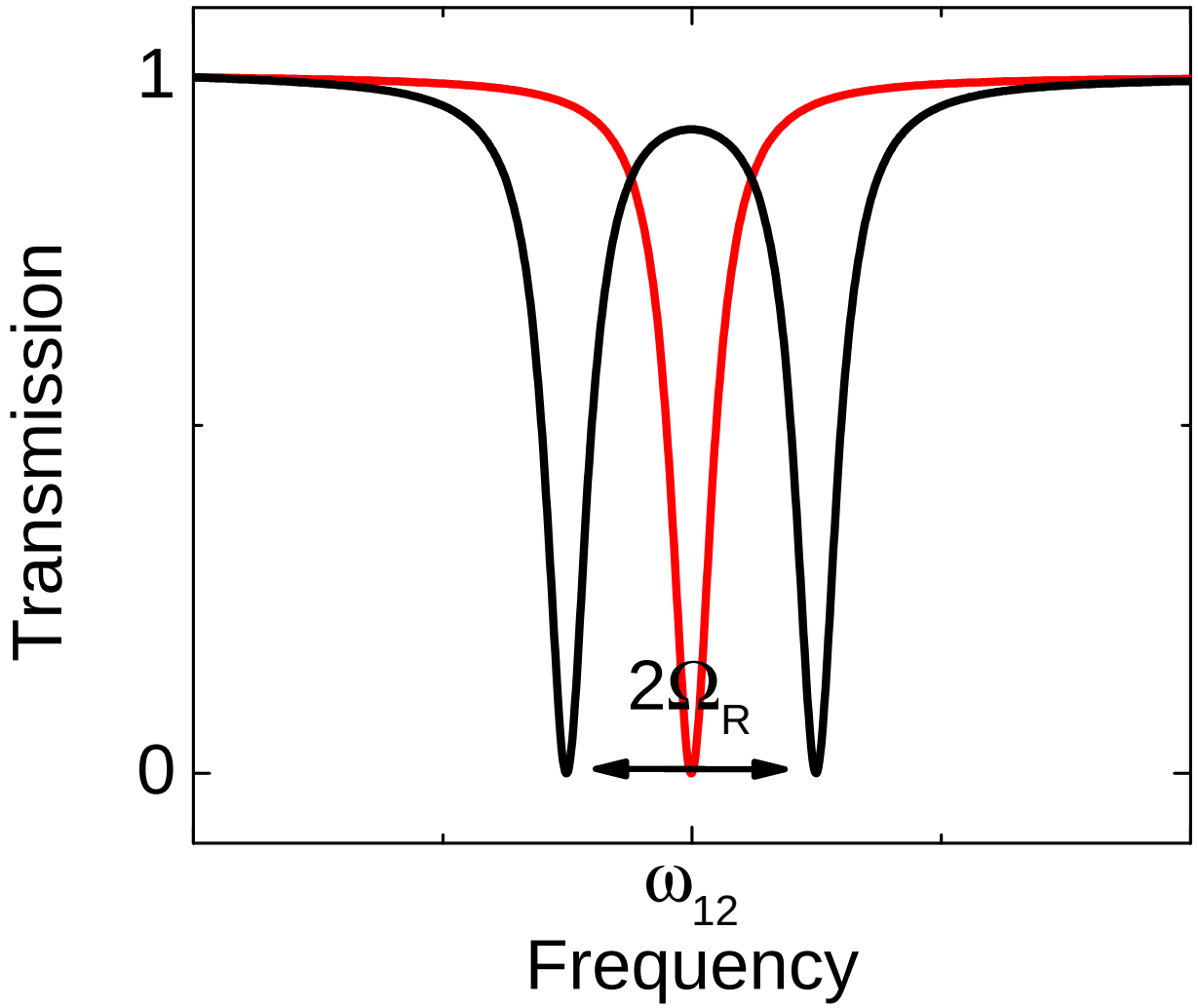


Why mid-IR?

- La

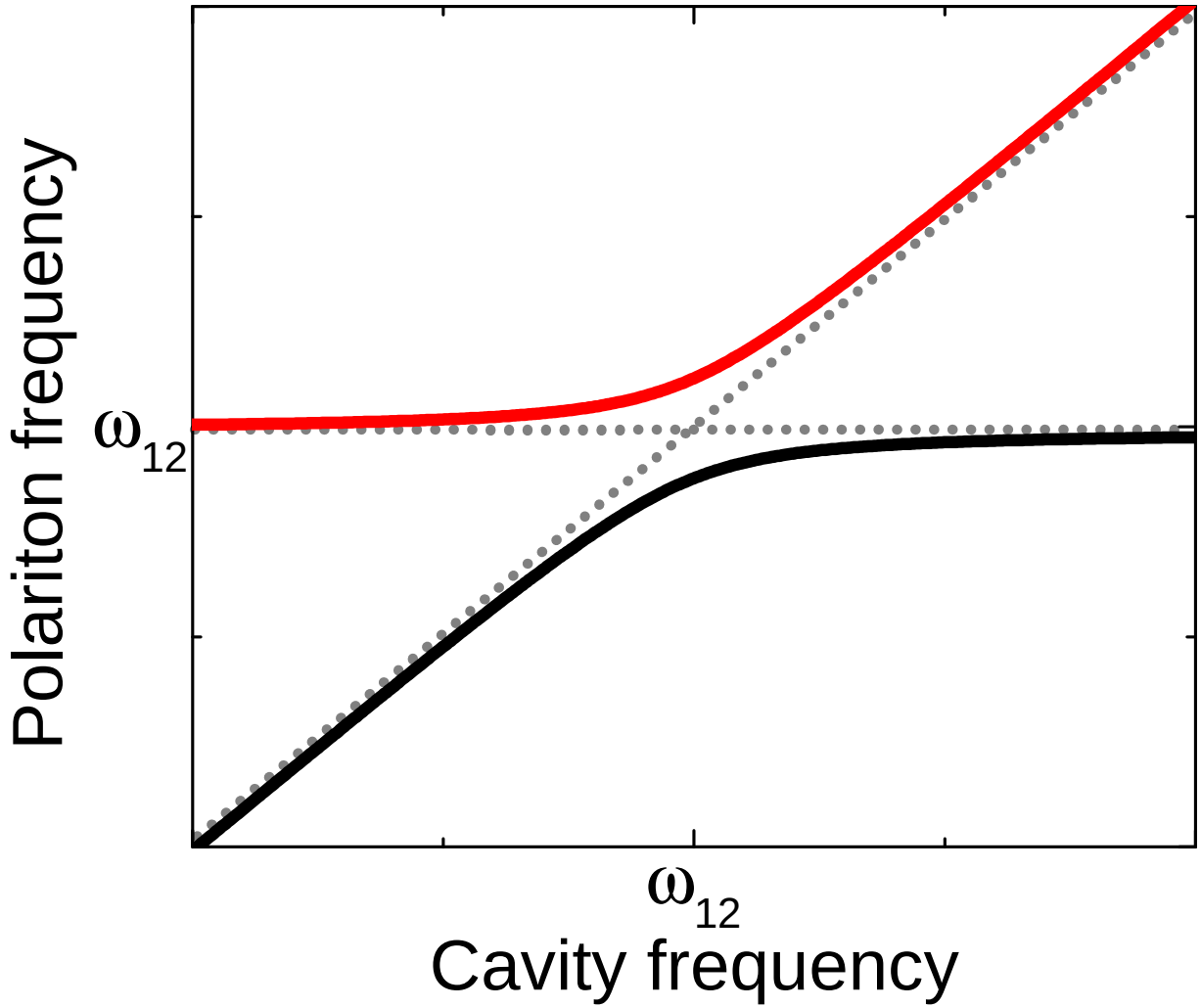

Transmission
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
1310
1311
1312
1313
Wavenumbers
NO2
NO2
H2S
NO2
SO2
NO2
CH4
SO2
NO2
SO2
H2S
NO2
SO2
SO2

Strong coupling



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

Strong coupling



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  - Anti-resonant terms in equilibrium
- Squeezed vacuum as ground state
  - Release correlated photon pairs
- Light-matter superposition = Polaritons

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

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

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Geometry factor

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Plasma frequency

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

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