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Mid-infrared metamaterials strongly coupled to intersubband transition

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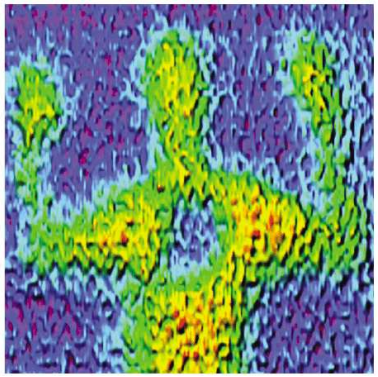
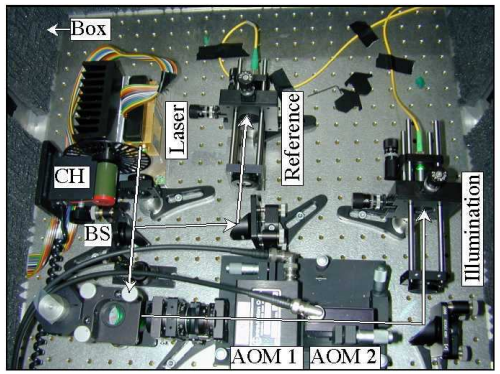
Why mid-IR?

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





Why mid-IR?

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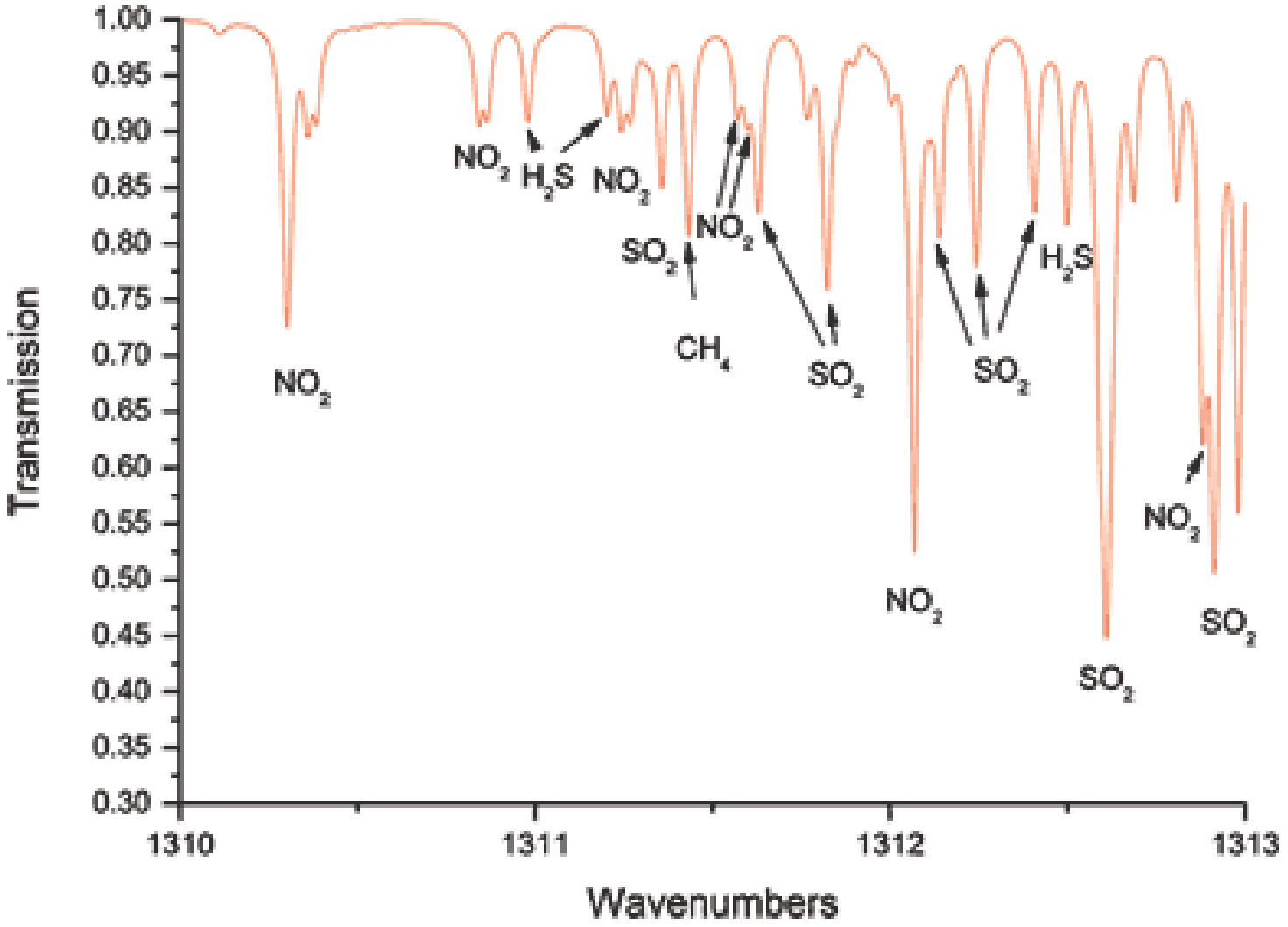
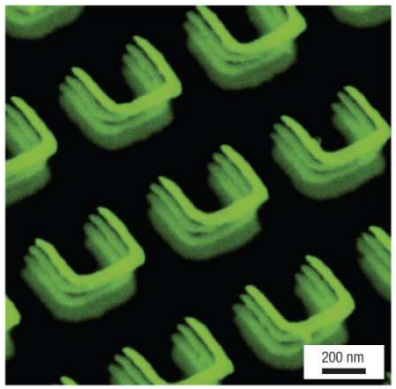
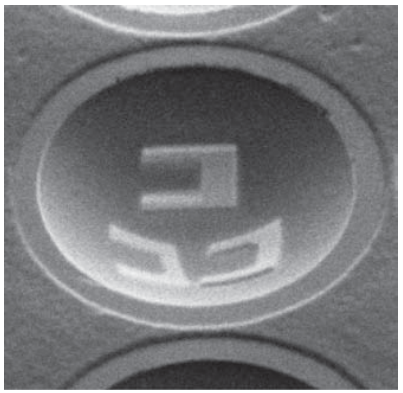
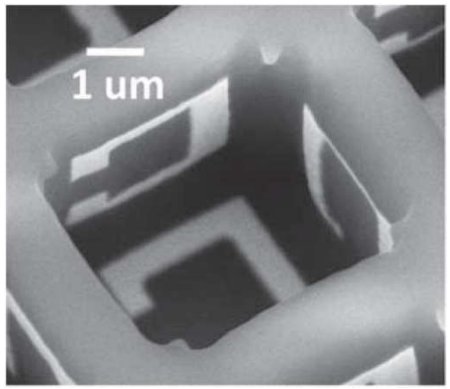
- La

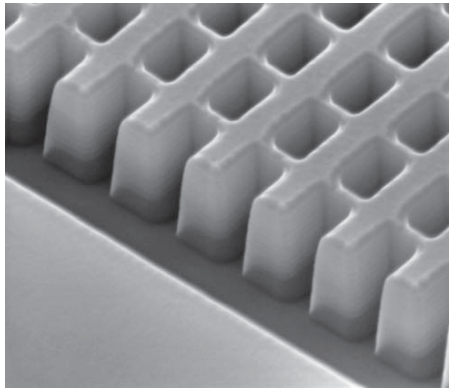
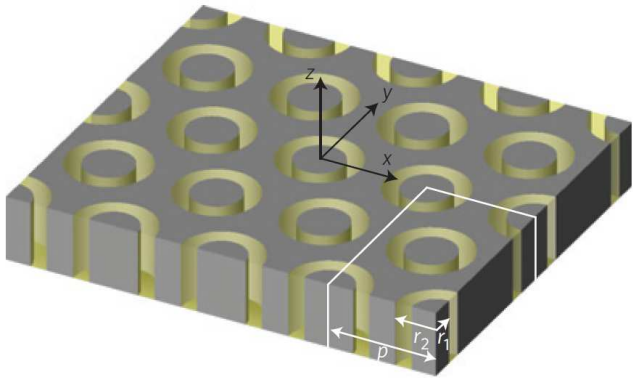


Metamaterial overview

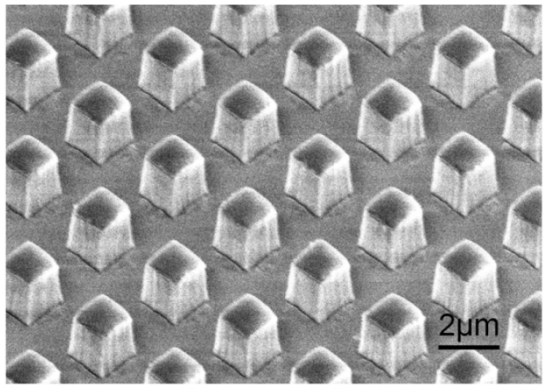


3D SRRs[1,2,3]

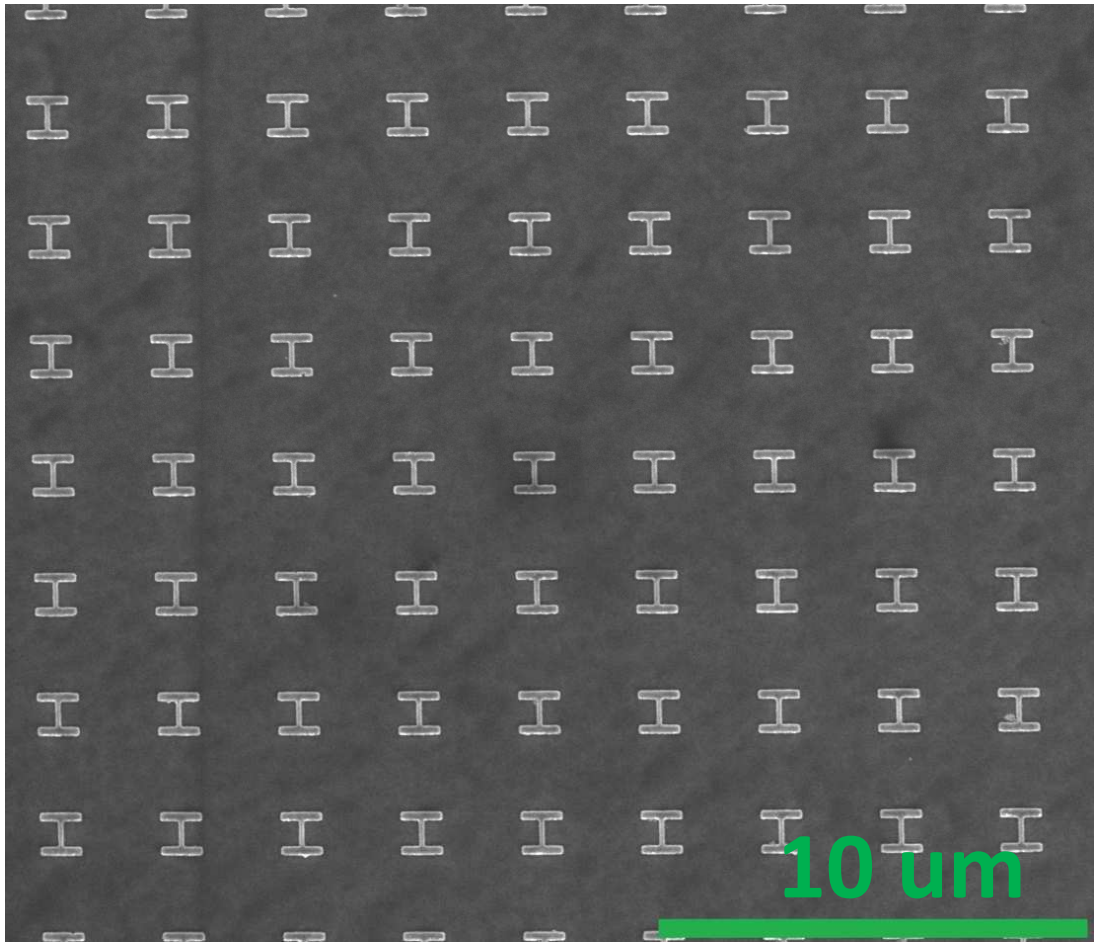
Negative index[1,2]



Magnetic mirrors[3]

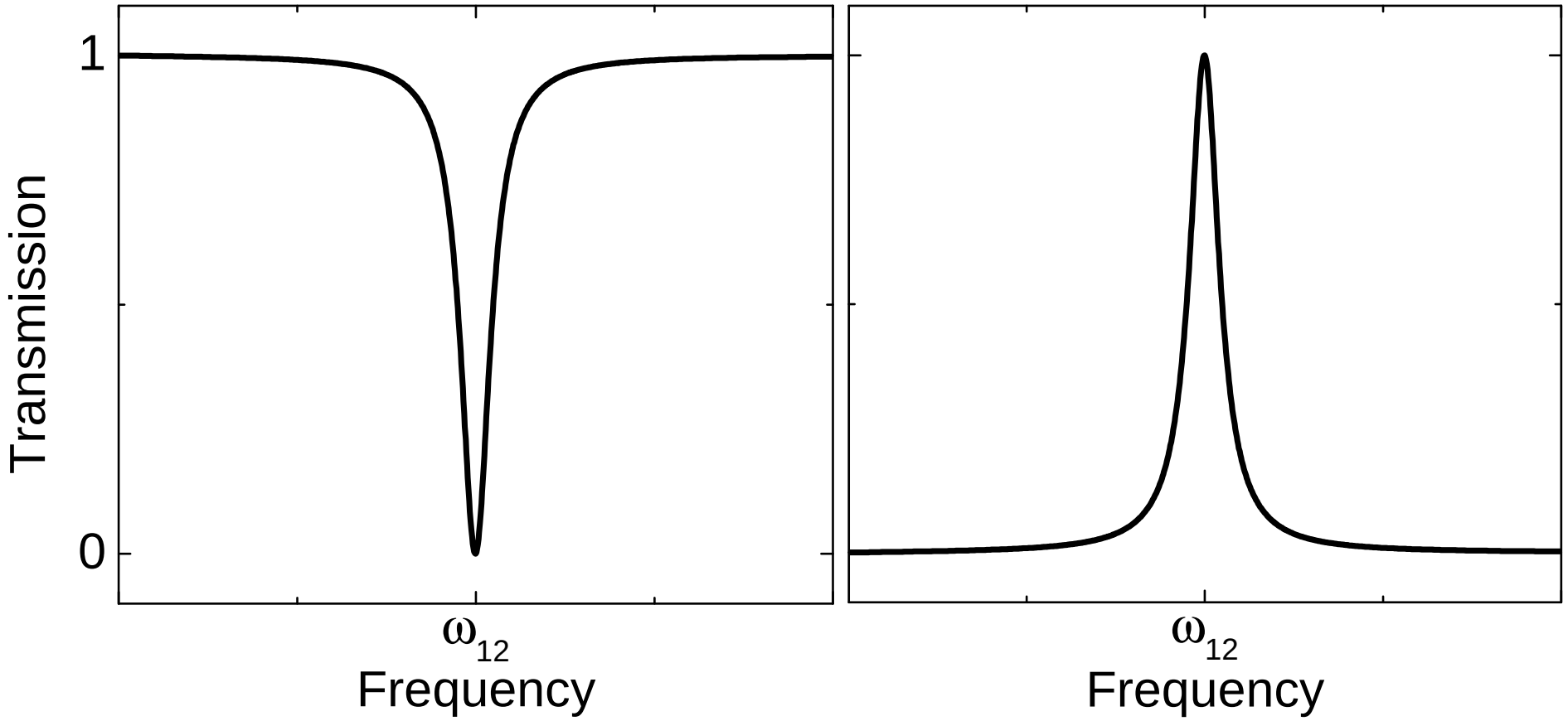
[1] N. Liu et al. Nature Materials **7**, 31 (2008)
[2] D. Burckel et al., Adv. Mater. **2010**, 22, 3171
[3] D. Burckel et al., Adv. Mater. **2010**, 22, 5053
[4] J. Valentine et al., Nature **455**, 376 (2008)
[5] S. Burgos et al., Nature Materials **9**, 407 (2010)
[6] J. Ginn et al., Phys. Rev. Lett.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

Metasurface

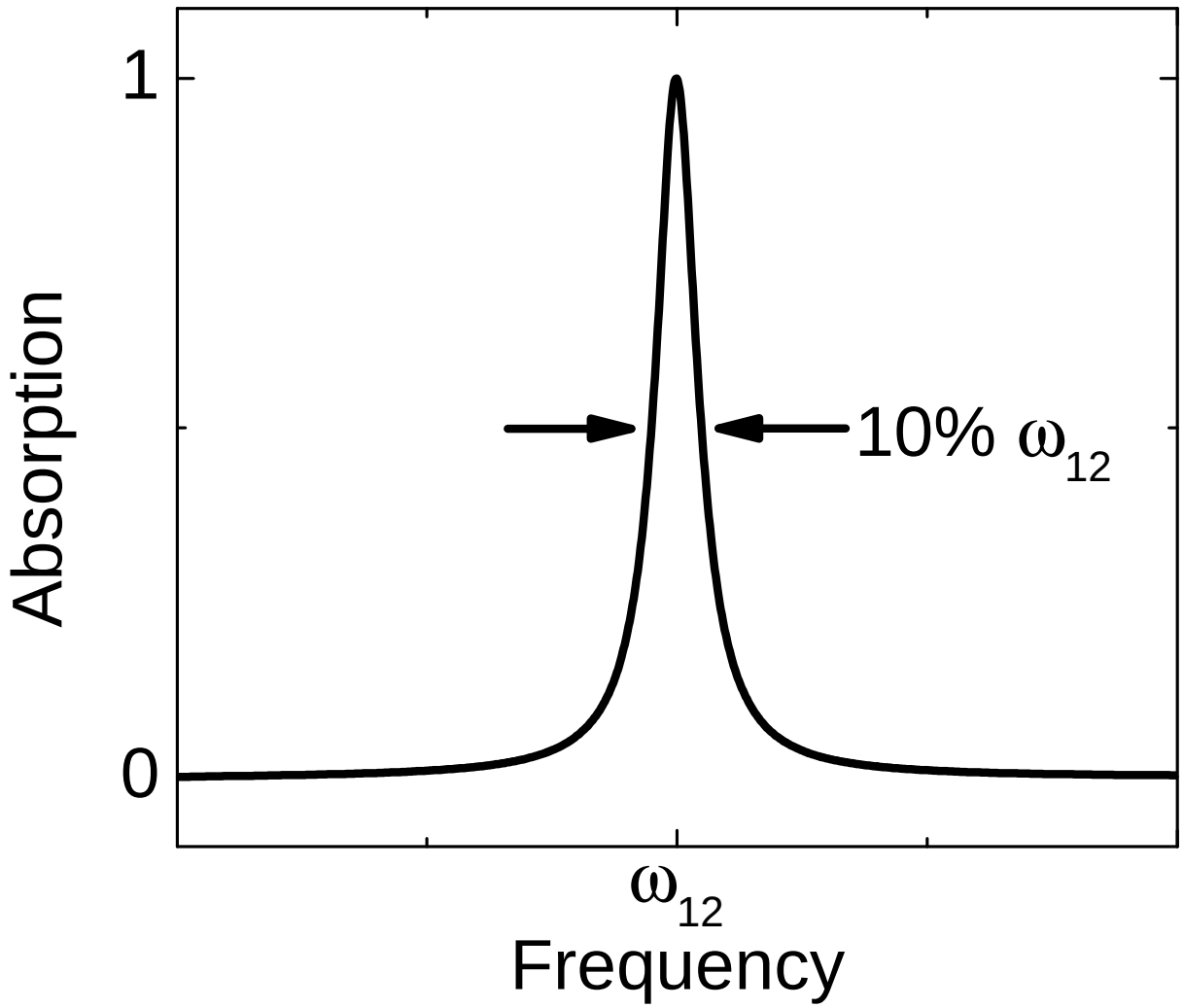


- Mostly 2D-layer used
  - Metasurface
- Versatile functionality
- ν filter
- Geometry defines properties

Metasurface

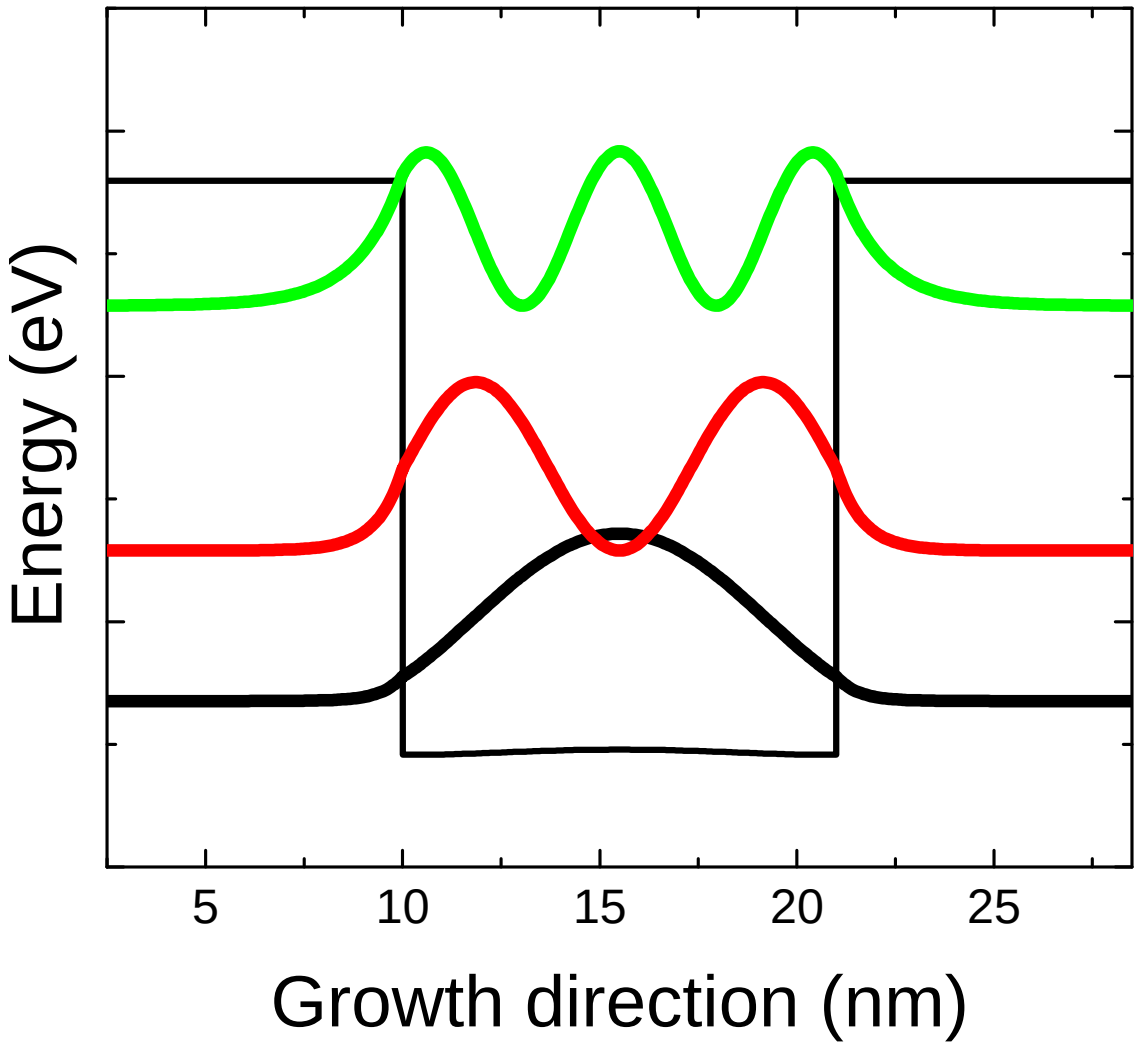


Intersubband transitions



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

Intersubband transitions



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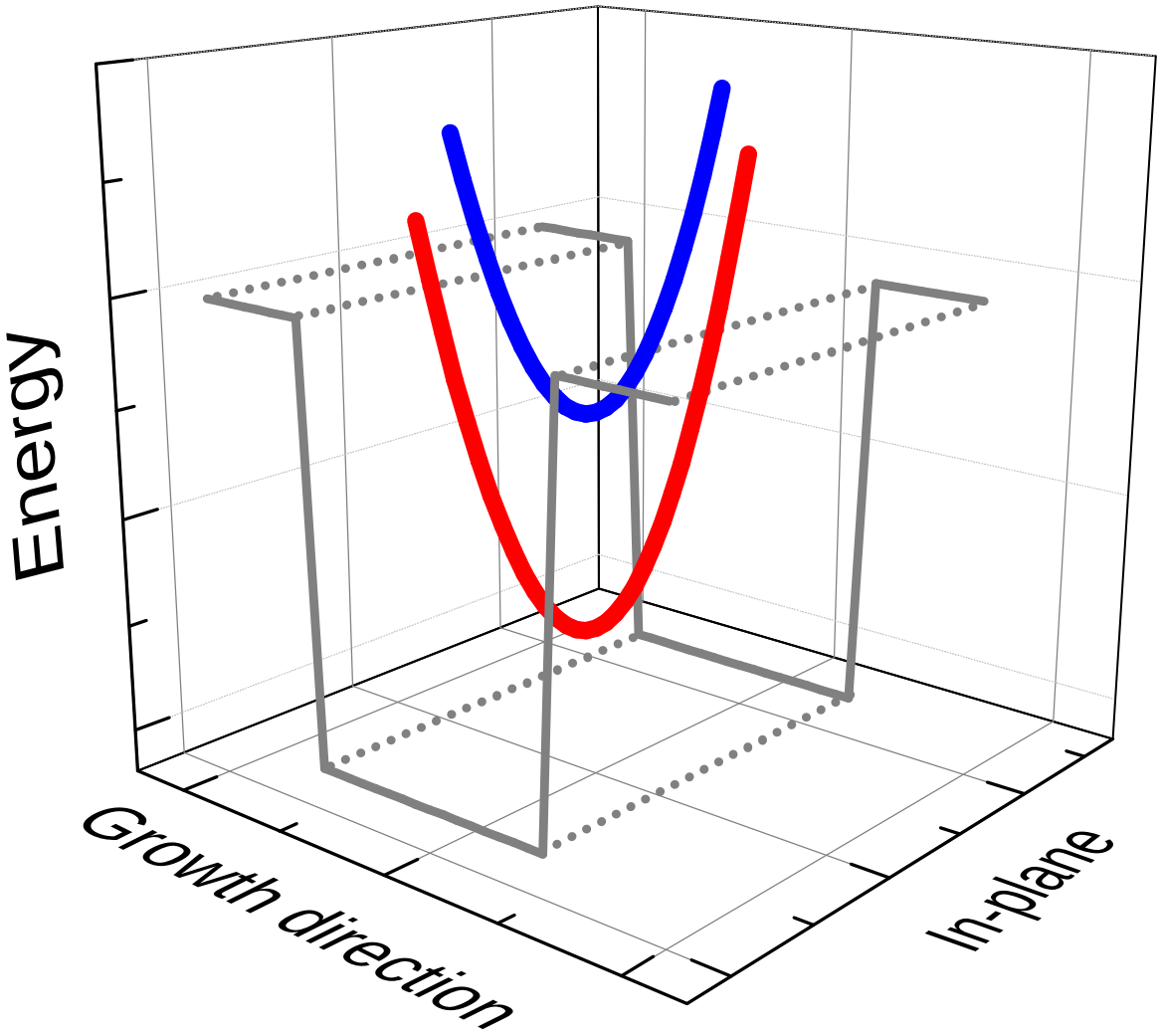

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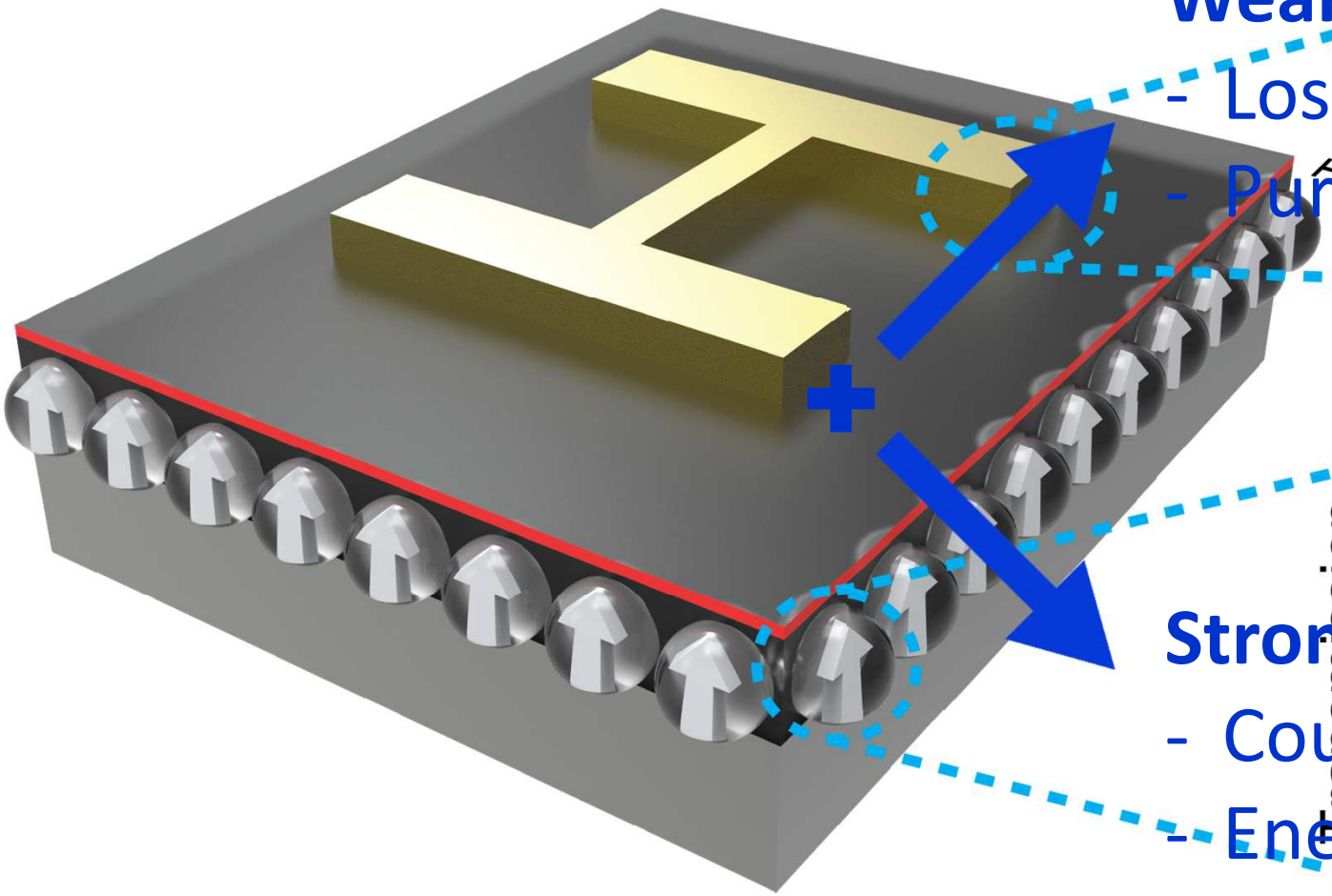
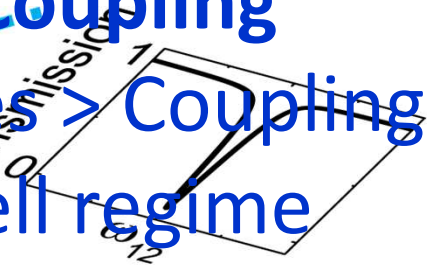
Light-matter coupling



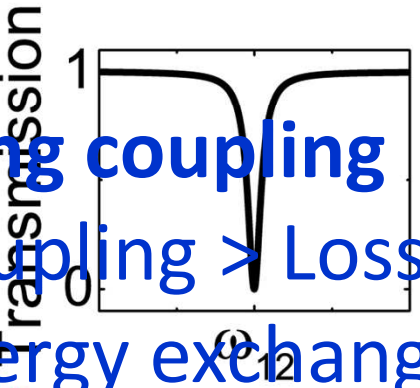
Weak coupling

- Losses > Coupling
- Purcell regime

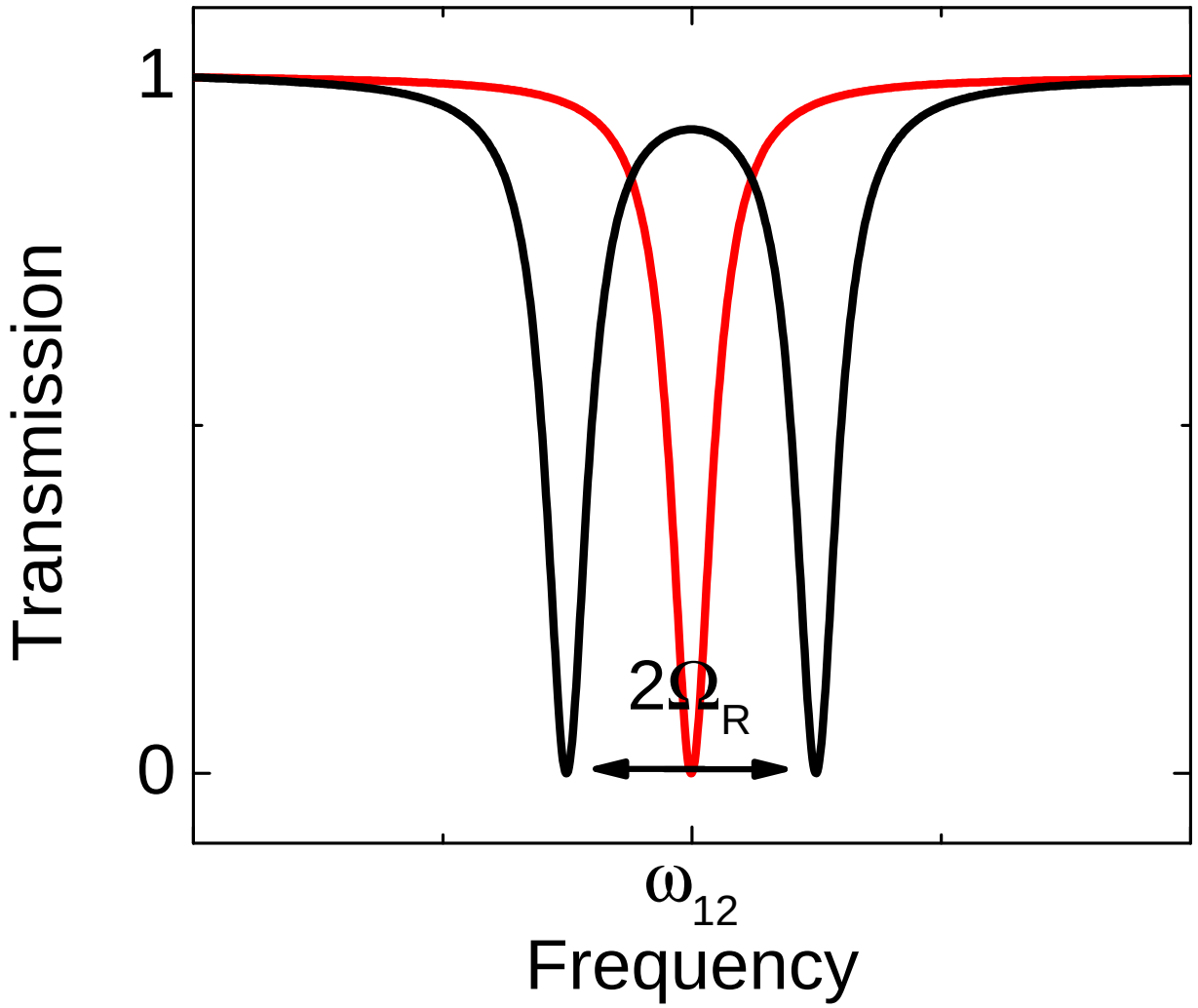


Strong coupling

- Coupling > Losses
- Energy exchange
- Rabi frequency

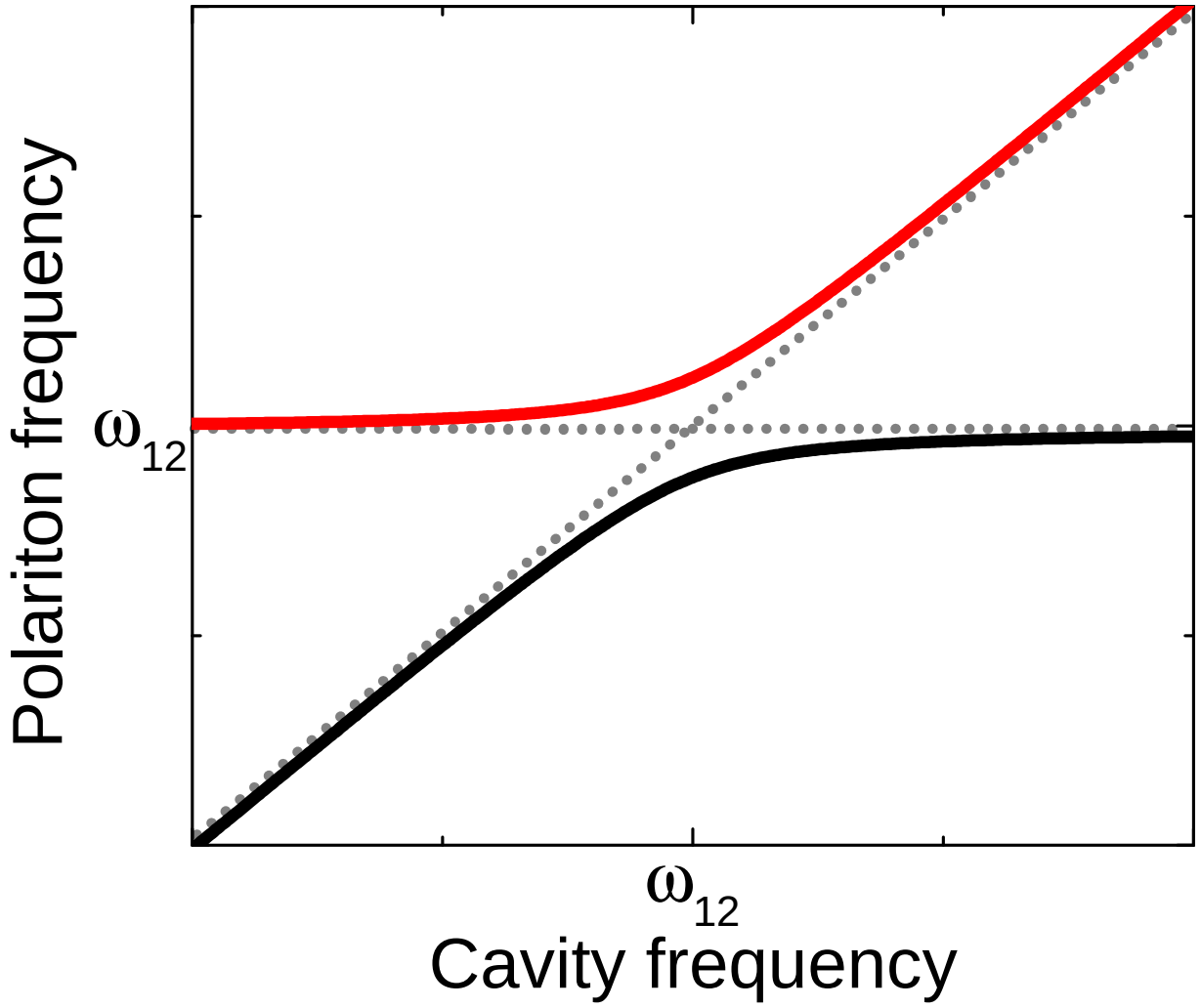


Strong coupling



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

Strong coupling



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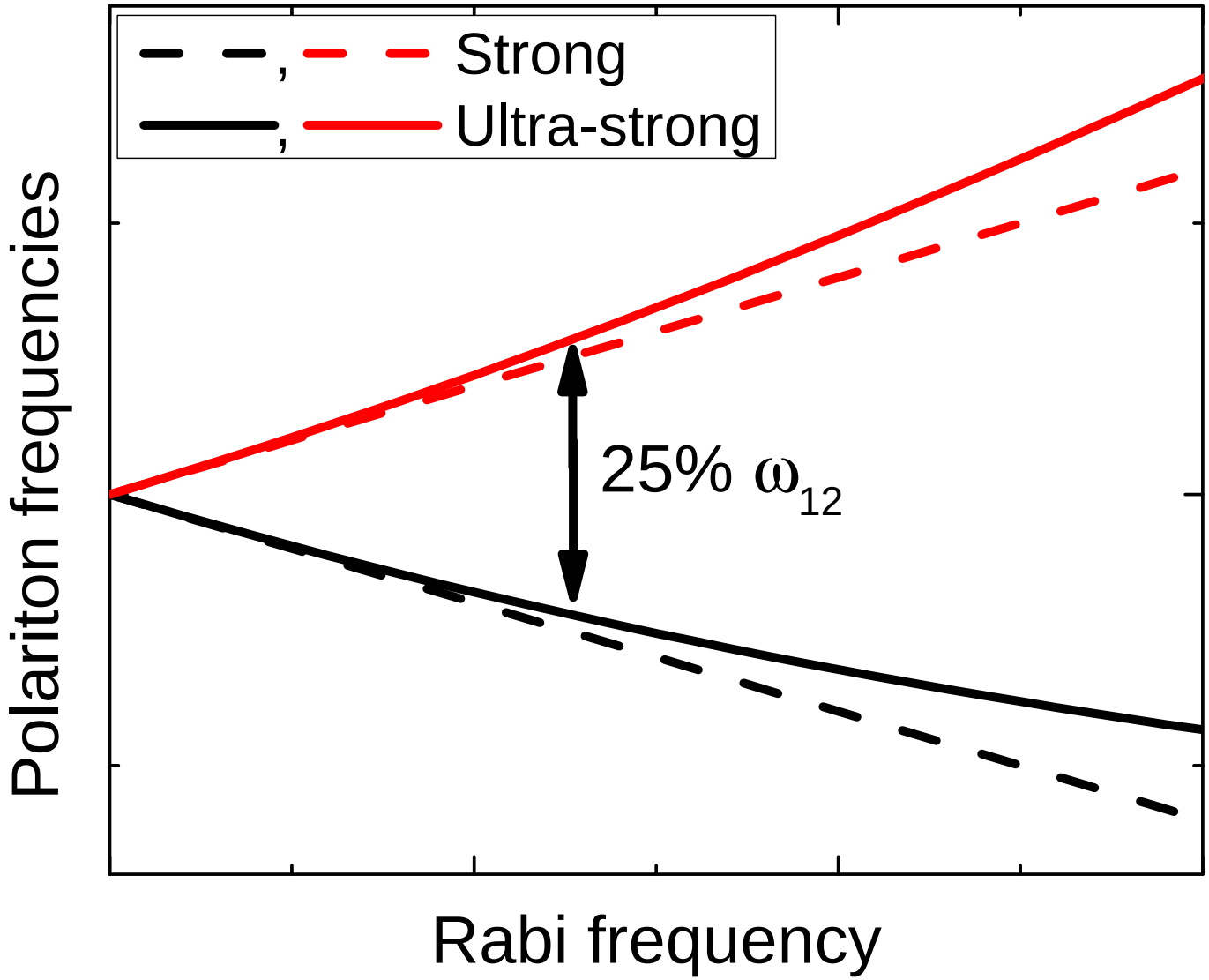
Strong vs. ultra-strong coupling



Ultra-strong coupling physics

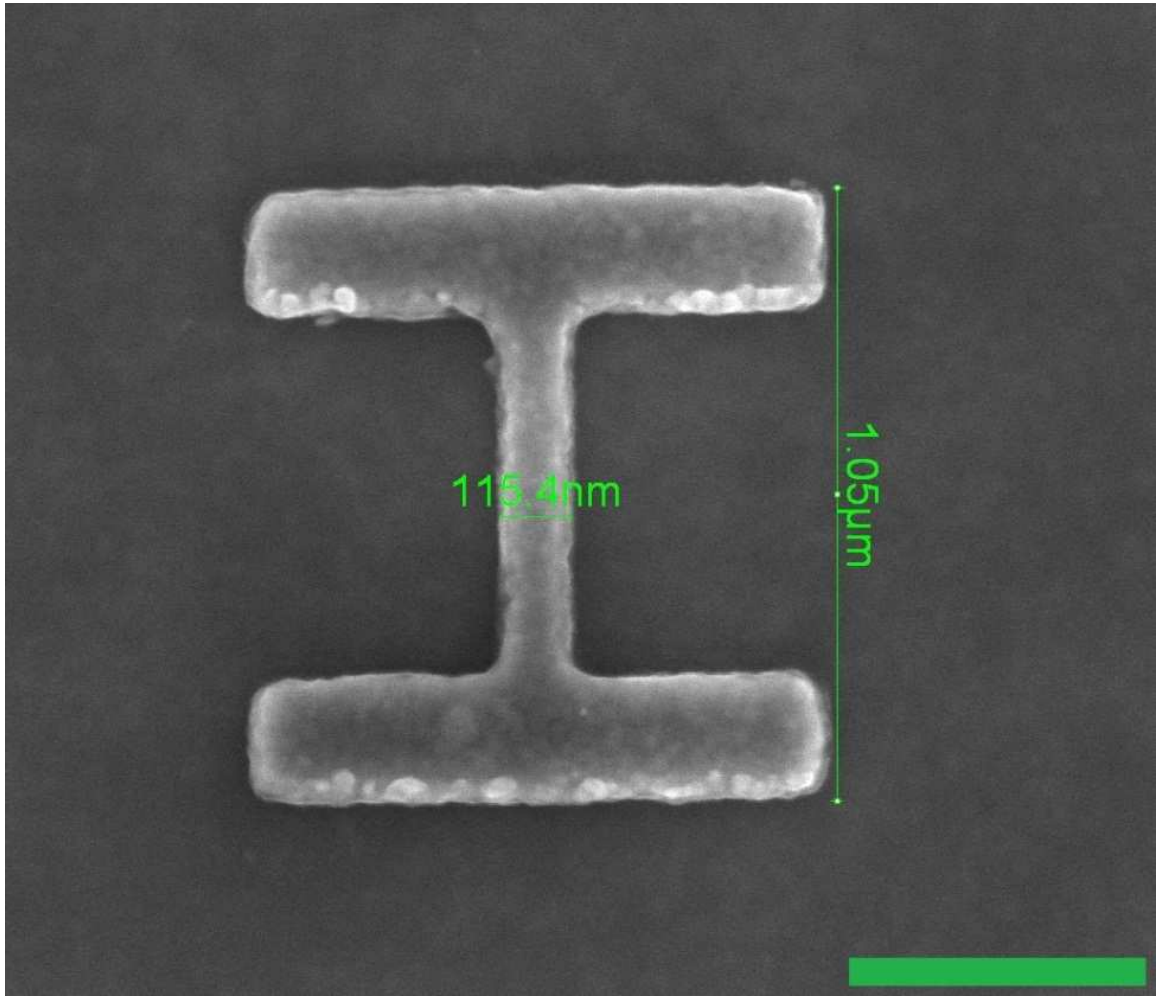
- Splitting Ω_R similar to system resonance
  - Anti-resonant terms in equilibrium
- Squeezed vacuum as ground state
  - Release correlated photon pairs
- Light-matter superposition = Polaritons

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

Geometry factor Plasma frequency

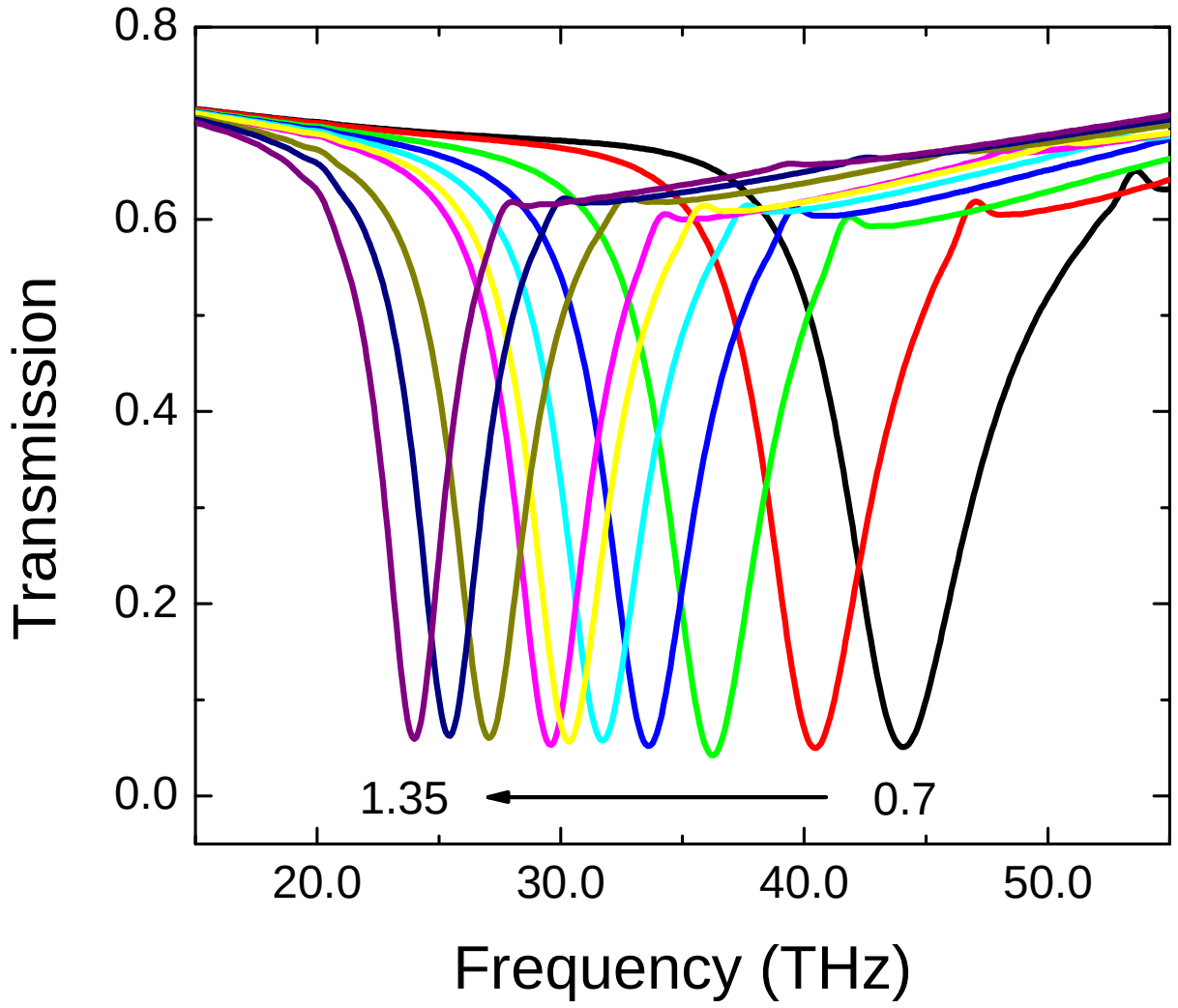
C. Ciutu et al., Phys. Rev. B **72**, 115303 (2005) S. DeLiberato et al., Phys. Rev. Lett. **98**, 103602 (2007)

Metamaterial fabrication



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

Metamaterial fabrication



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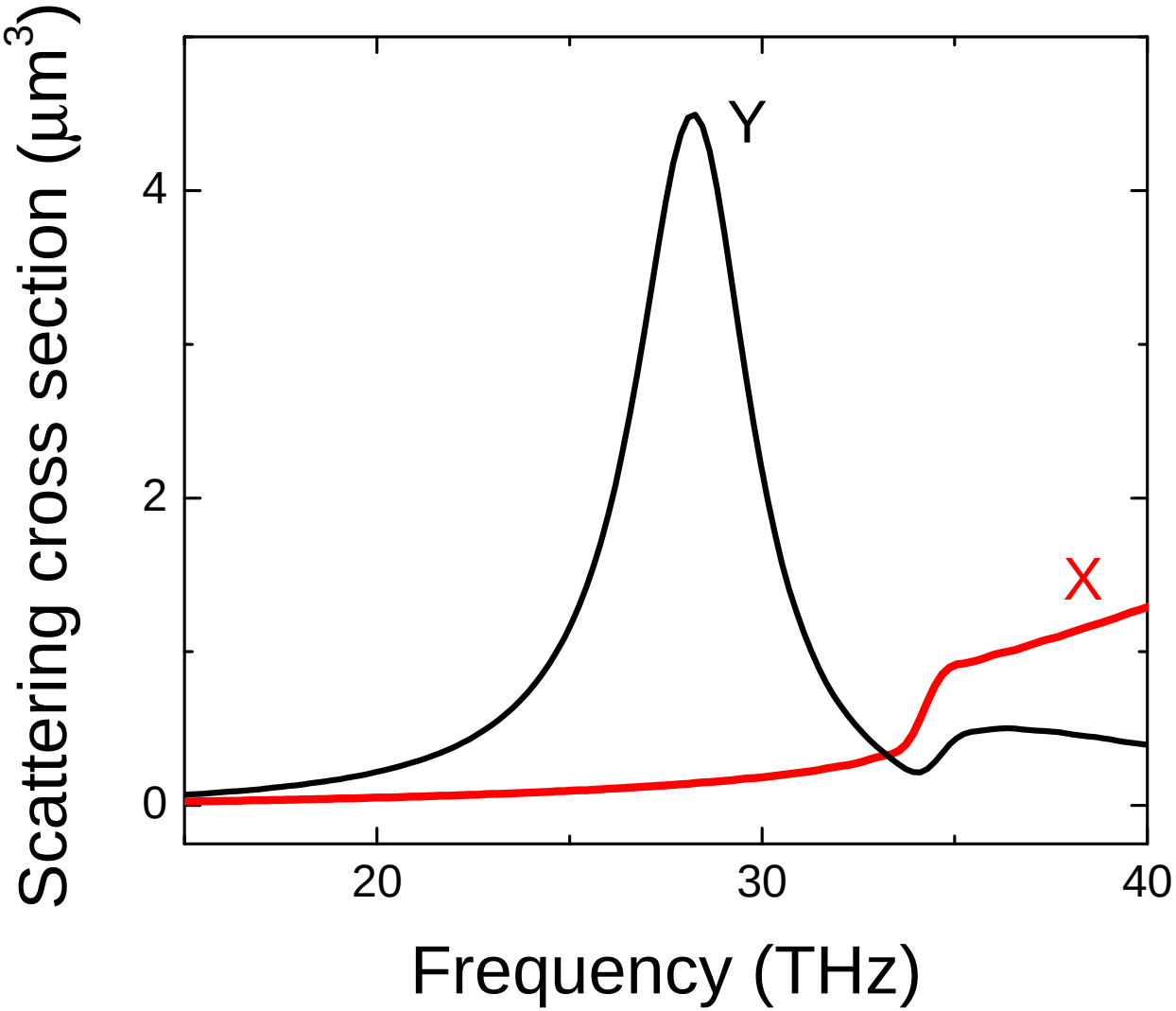

- Processing
  - Ebeam litho
  - 100 nm gold
- Easily adjustable
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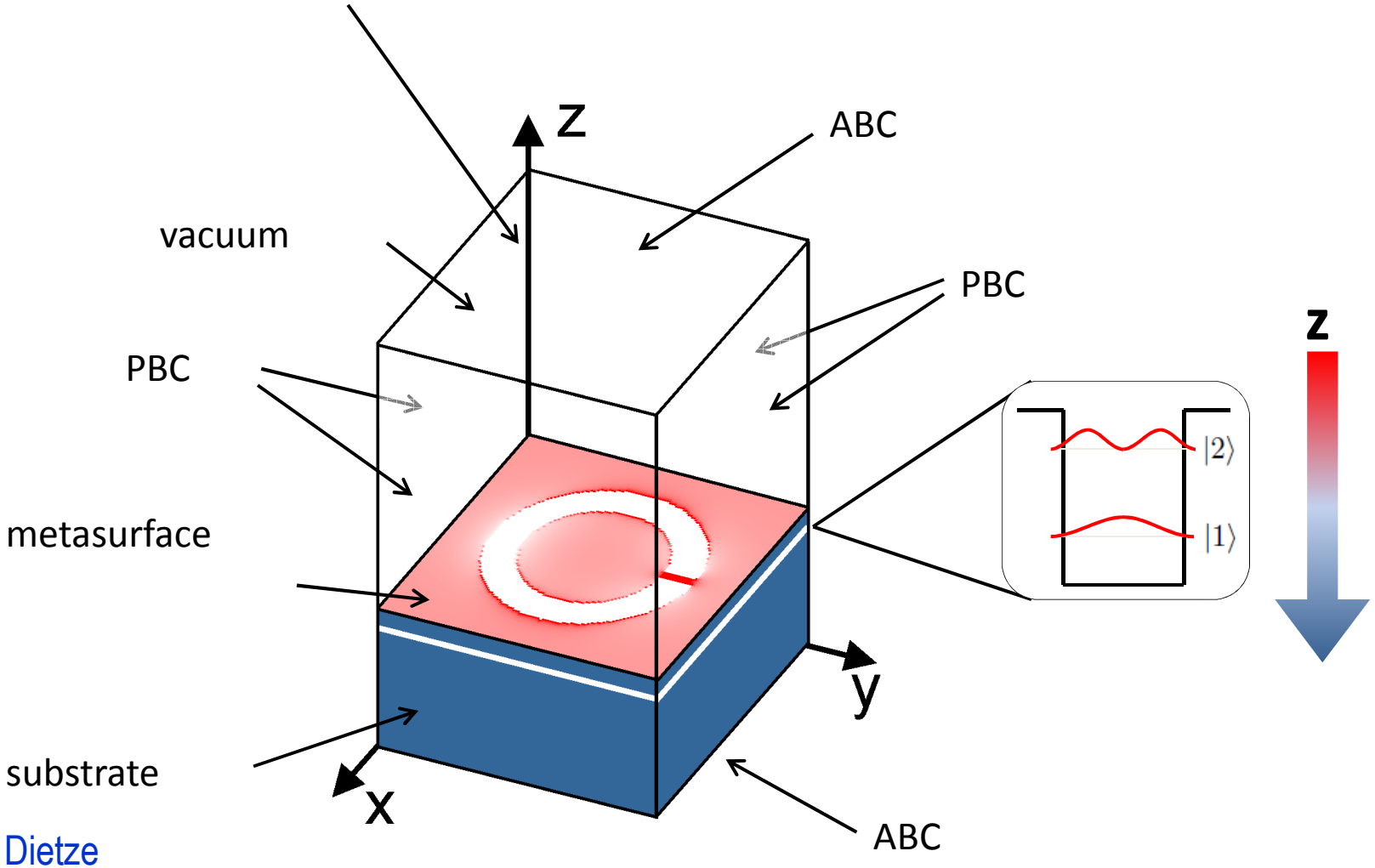
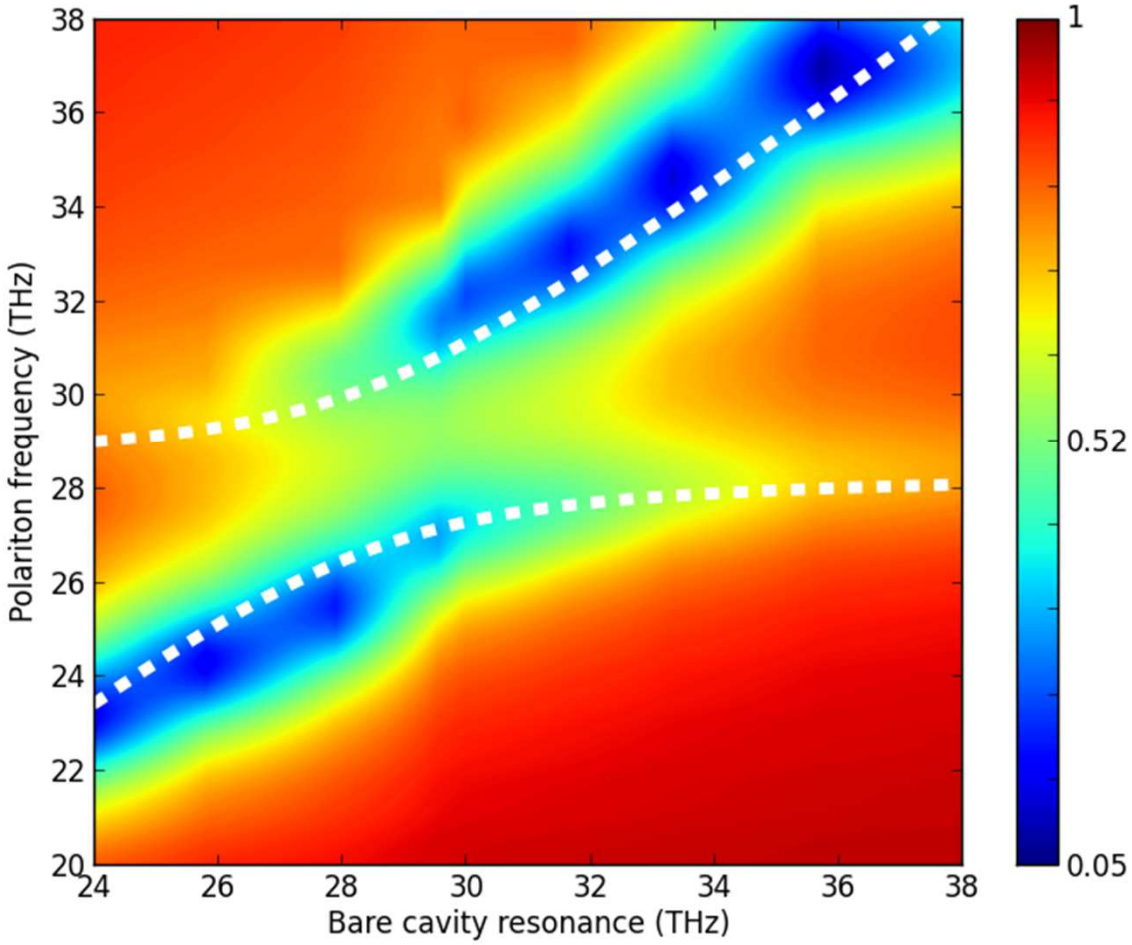
FDTD resonator design

plane wave, single-cycle pulse source



Courtesy of D. Dietze

Strong coupling theory vs. experiment

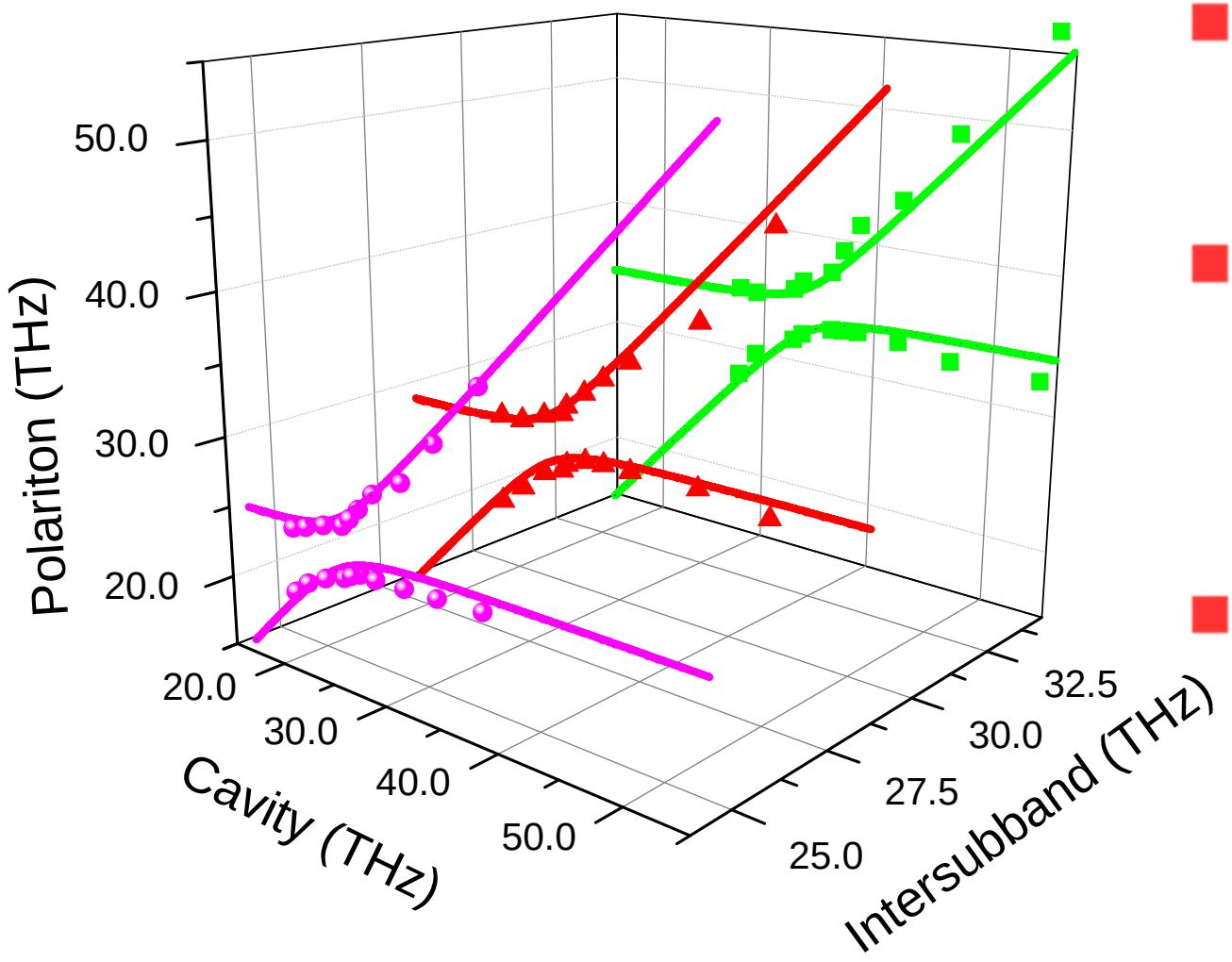


- FDTD simulations
- Anti-crossing
- Polariton picture[1,2]

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

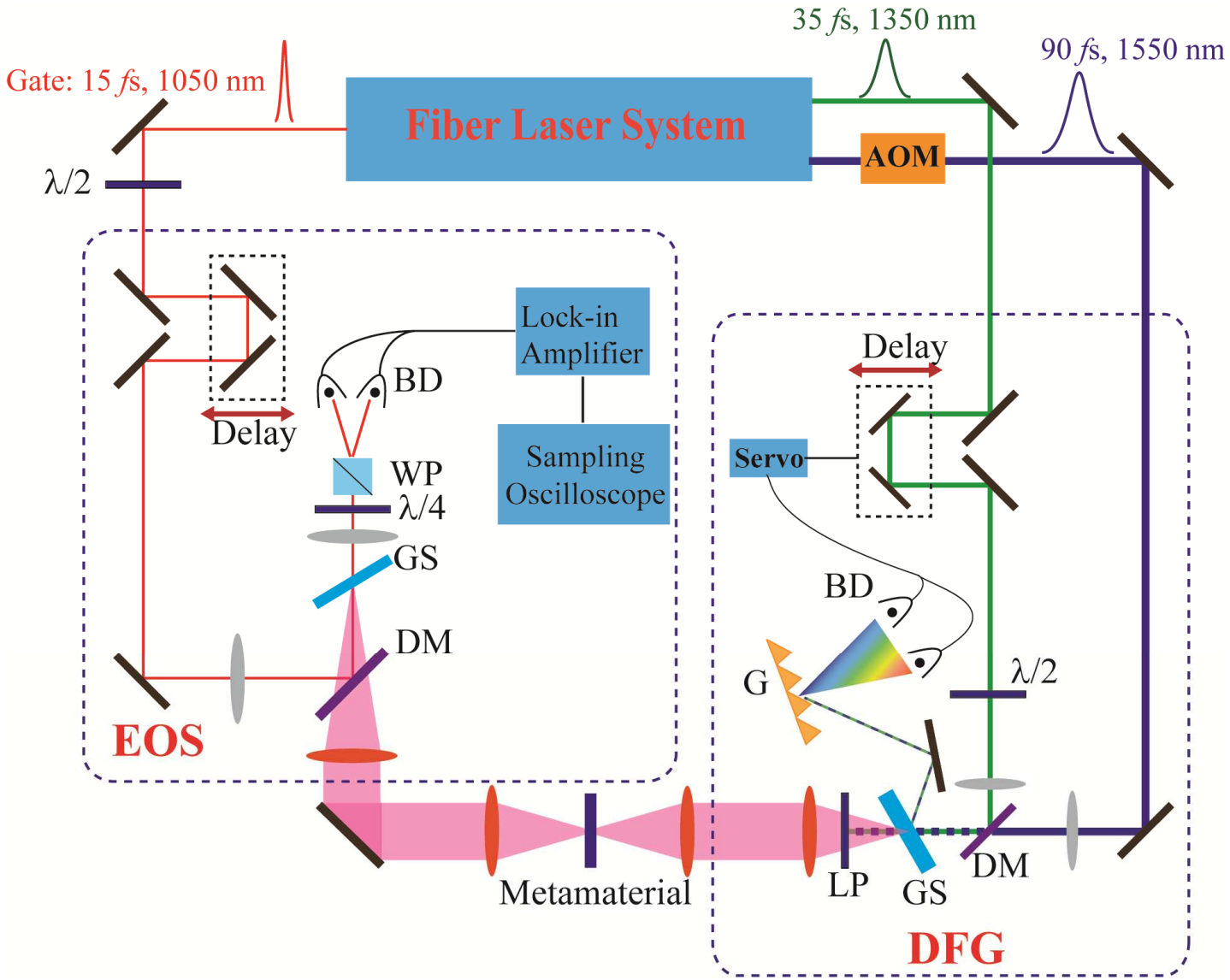
[2] A. Gabbay et al., Opt. Exp. **20**, 6584 (2012)

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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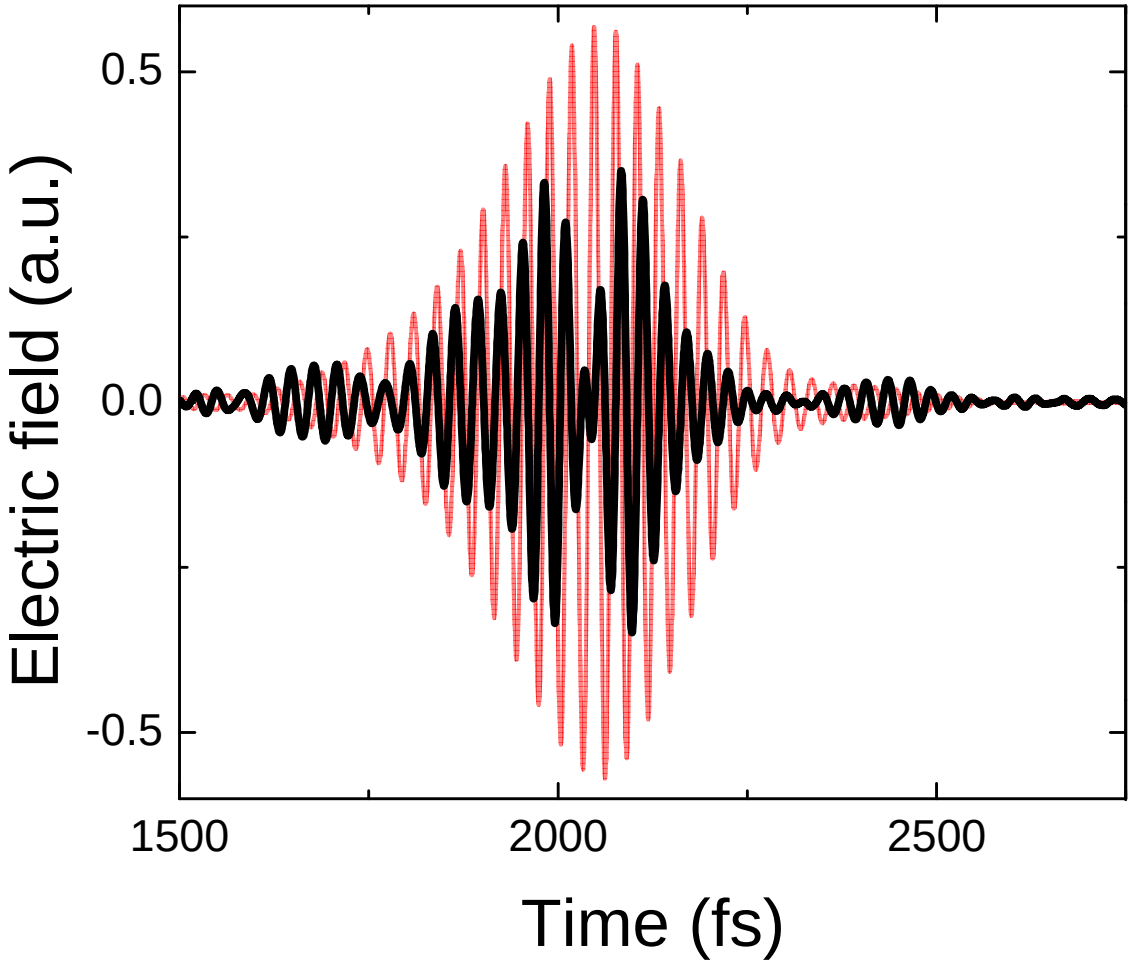
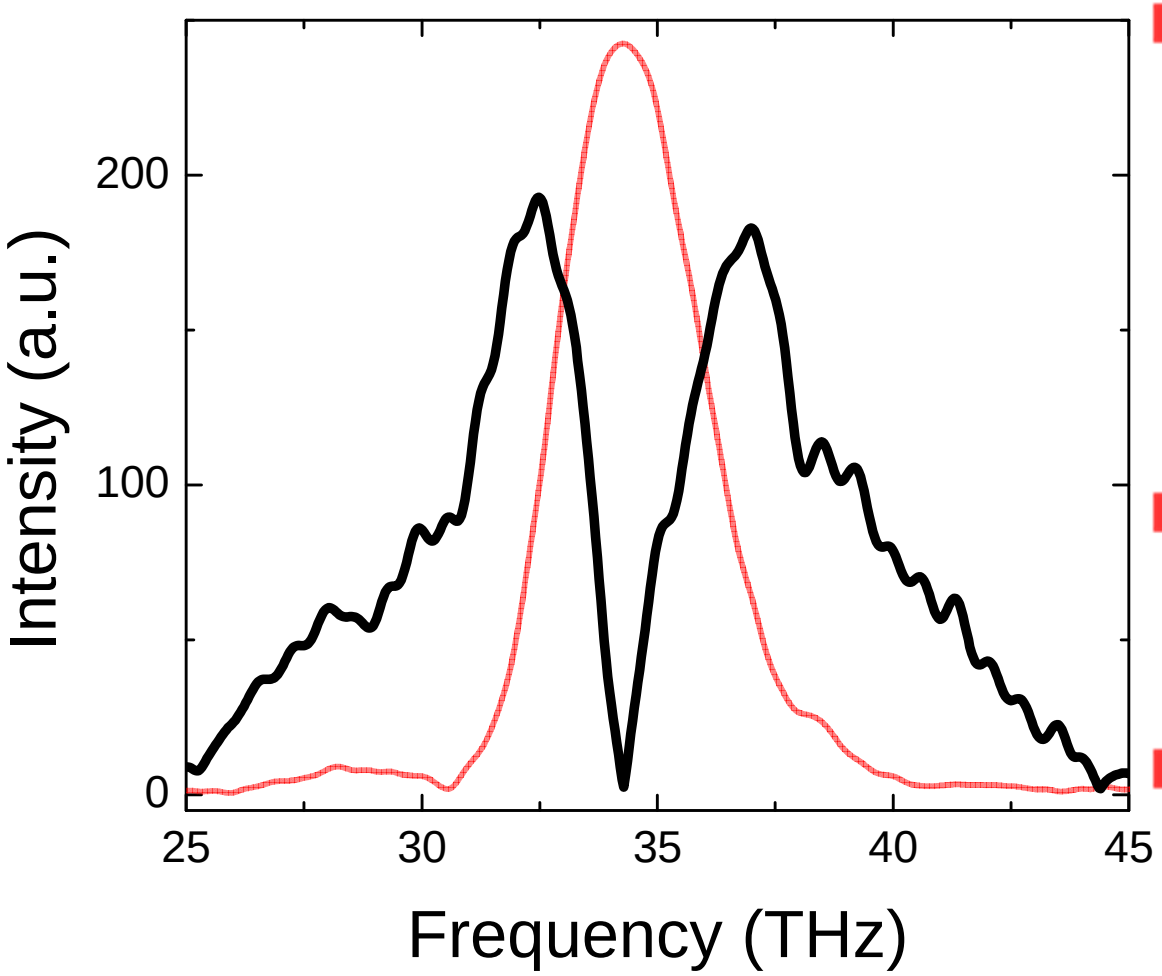


- Energy exchange probed in time
  - 33 fs oscillation
  - 480 fs beating
- System strongly coupled
- Splitting of 4.2 THz measured
  - 15 % of ω_{12}

Experimental Rabi oscillations



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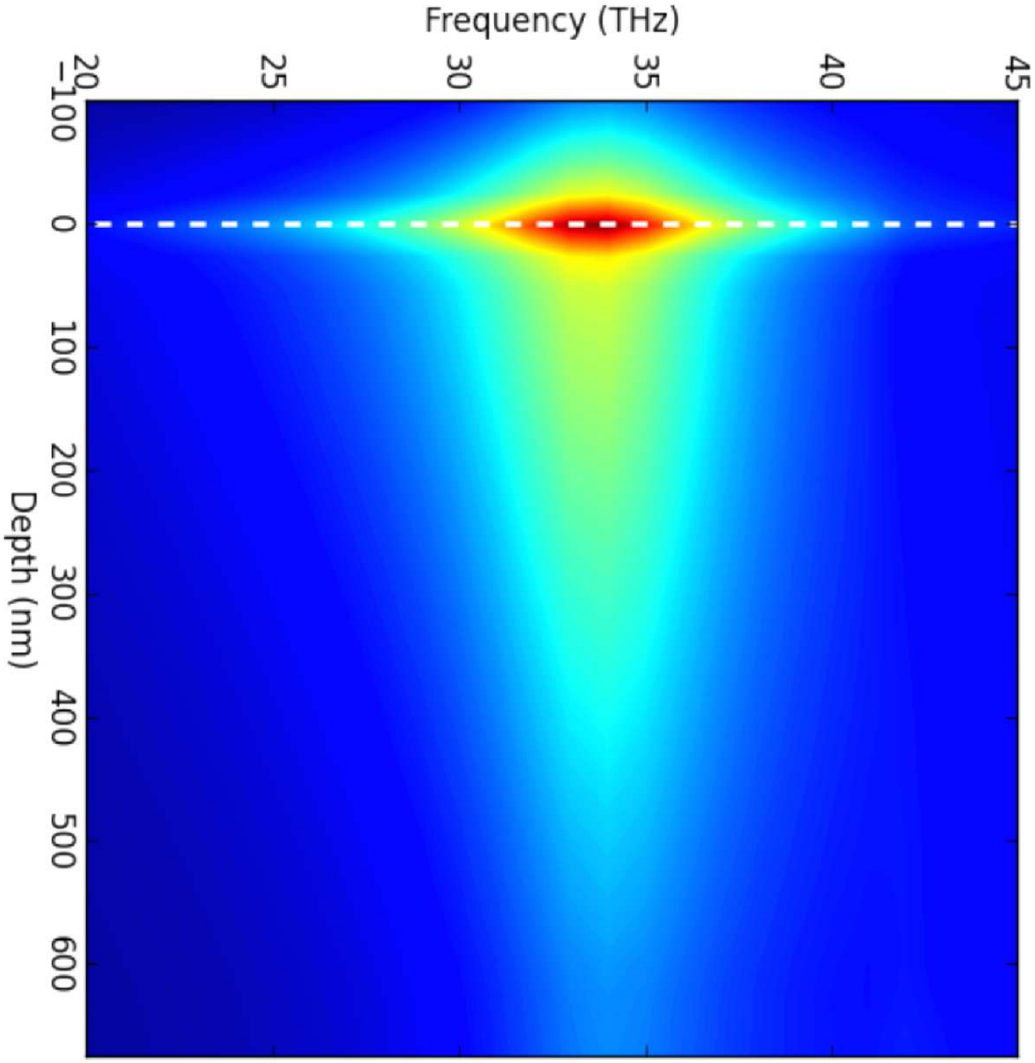
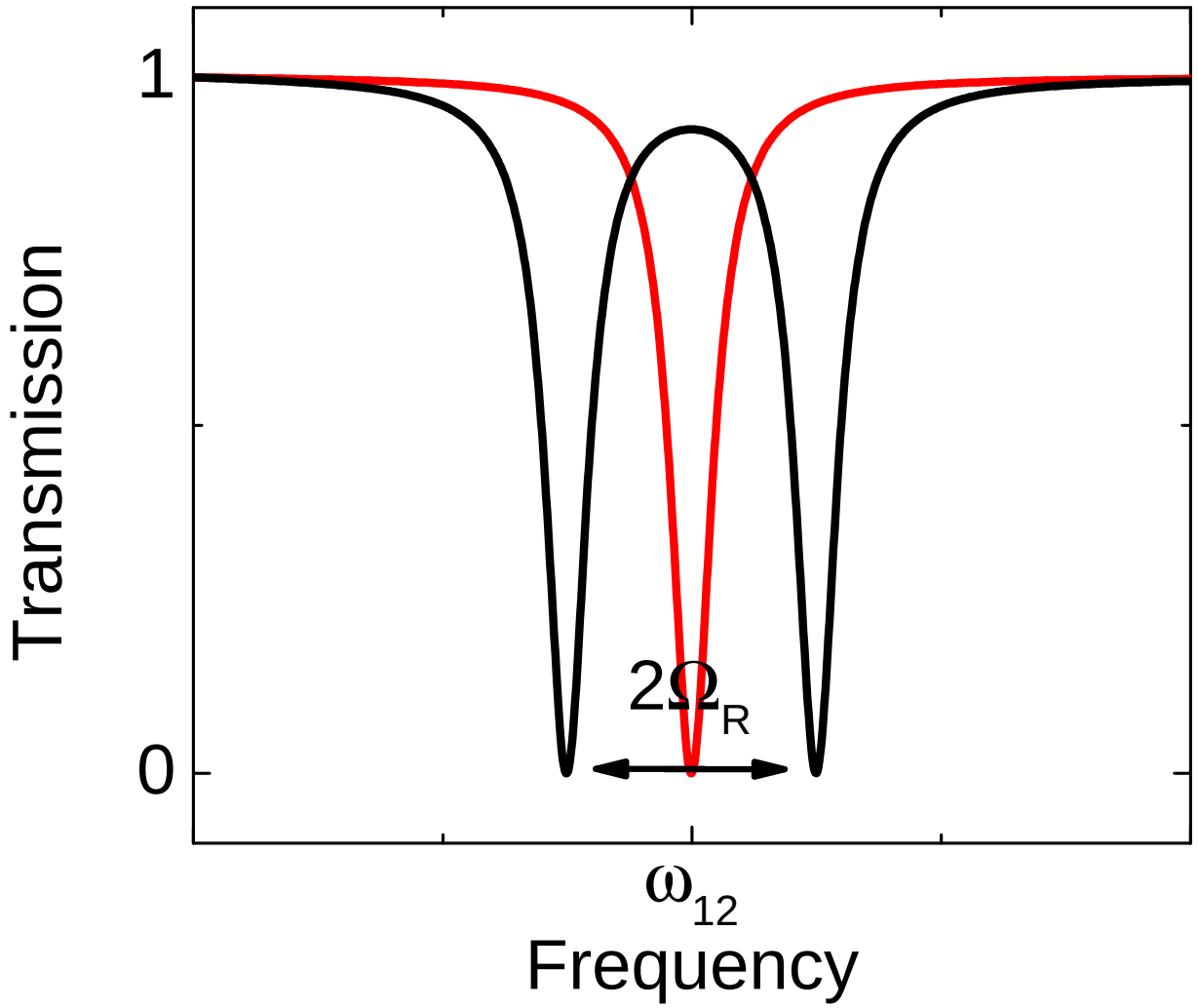
E_z near-field profiles



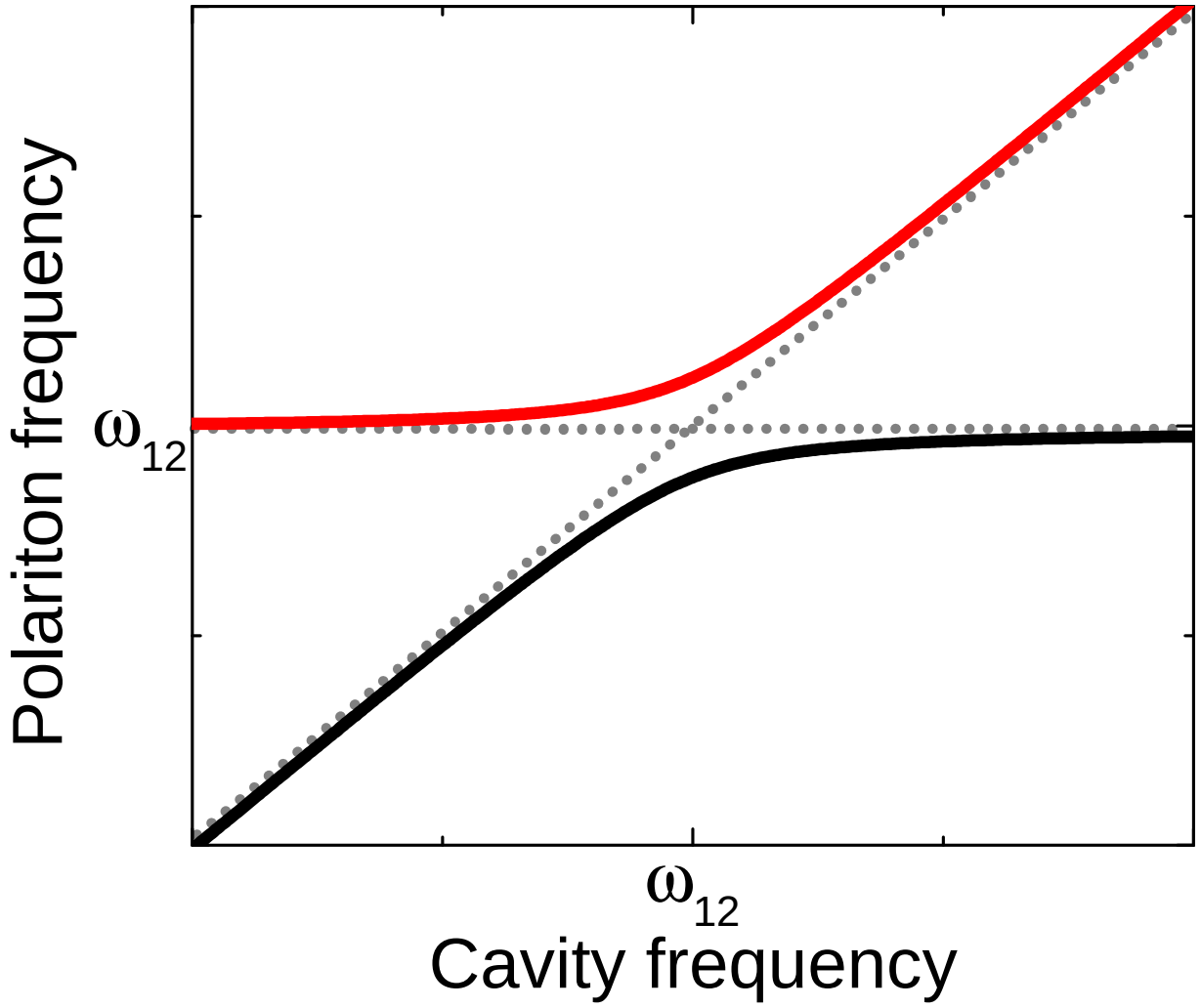
- Only E_z couples
  - Near-field
- Exponentially decaying
  - Integrated over xy-plane
- Transmission at cavity res.

Application vs. physics



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

Application vs. physics



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  - 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