SAND2013-4753C

CLEO: 2013 in San Jose
Pres. number: QF2A.2
Session: Nano-antennas, Coupling & Absorbers

Merging Magnetic and Electric Resonances for All-Dielectric Nanoantenna Arrays

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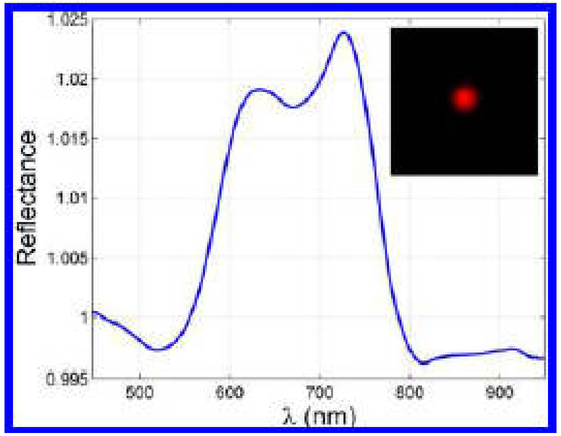
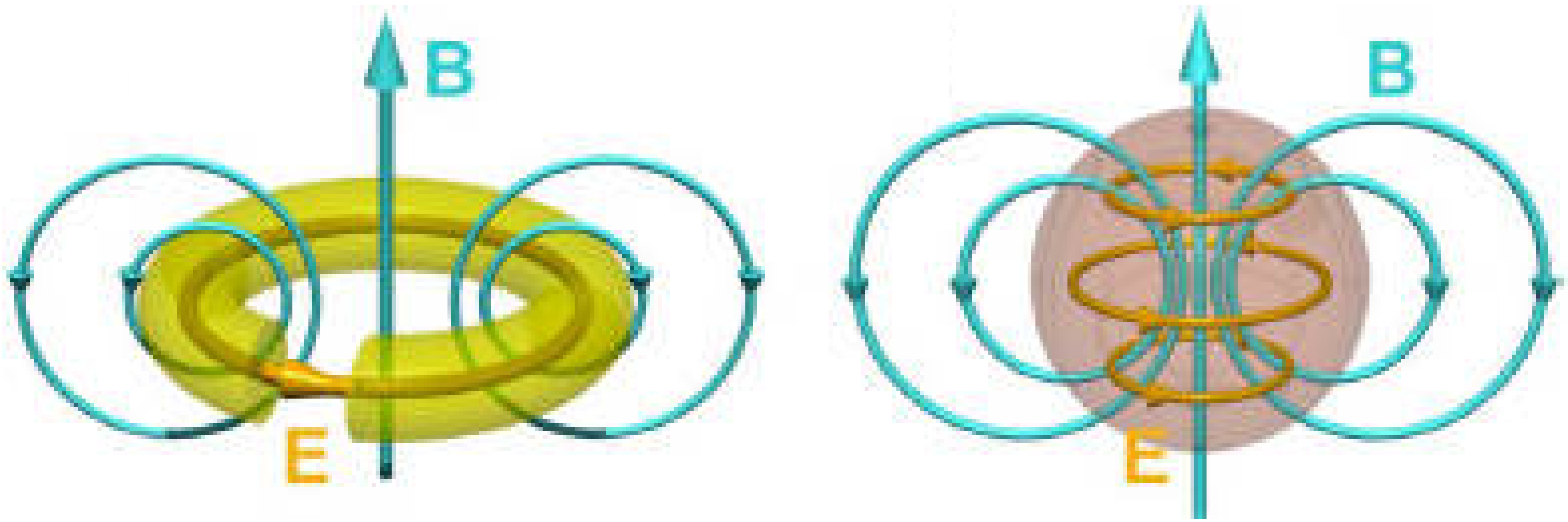
High-Index All-Dielectric Nanoparticles

- Low non-radiative losses at optical frequencies
- Strong resonances
- Both *electric* and *magnetic* modes in high-symmetry high-refractive index all-dielectric nanoparticles



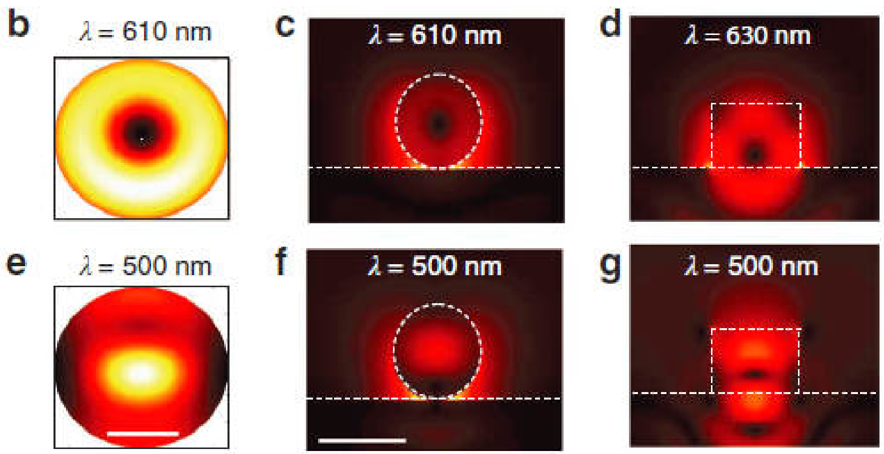
A. Evlyukhin et al., *Nano Lett.* **12**, 3749, 2012.



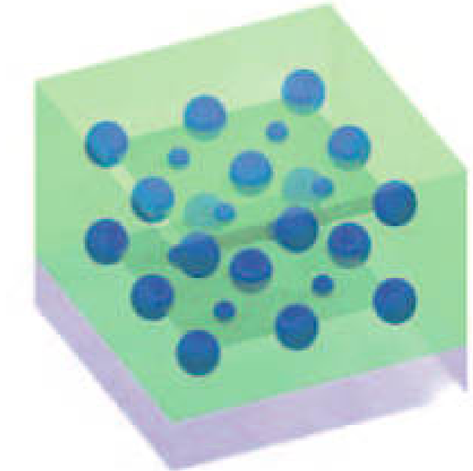
A. Kuznetsov *et al.*,*Sci. Rep.* **2**, 492, 2012.

Potential Fields of Application

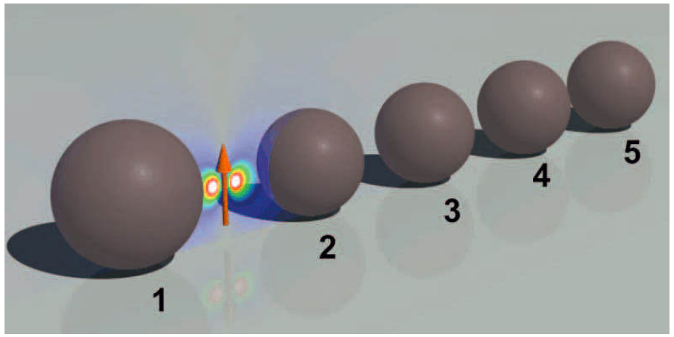
- Solar energy applications
- All-dielectric metamaterials
- All-dielectric nanoantennas
- Novel manifestation of Fano resonances (sensing)



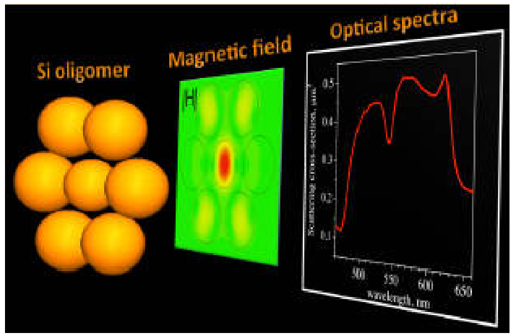
P. Spinelli *et al*. *Nat. Commun.* **3**, 692, 2012.



C. M. Soukoulis *et al*., *Nature Photon.* **5**, 523, 2011.



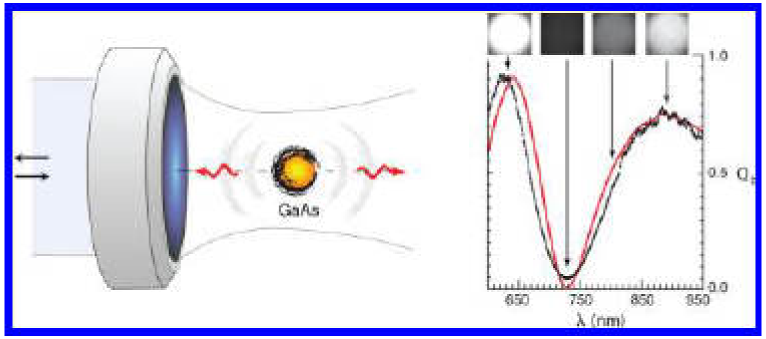
A. E. Krasnok *et al*., *Opt. Exp.* **20**, 20599, 2012.



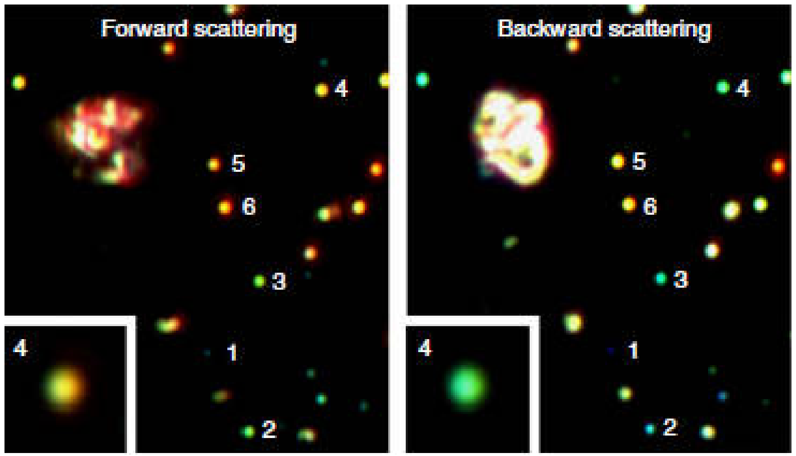
A. M. Miroshnichenko *et al.* *Nano Lett.* **12**, 6459, 2012.

Resonance Interplay

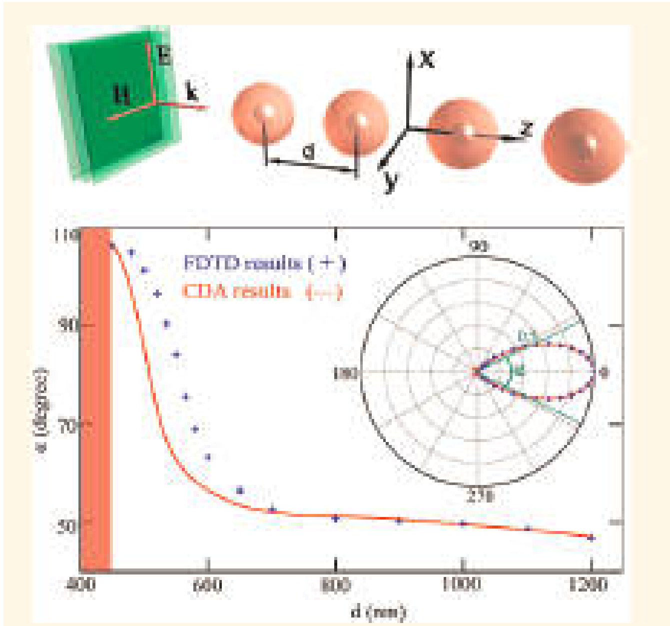
- Strong effects on scattering pattern
- Kerker-conditions for hypothetic magneto-electric spheres (M. Kerker *et al.*, *J. Opt. Soc. Am.* **73**, 765.)
- Larger scattering cross-sections for resonant scattering



S. Person *et al.*, *Nano Lett.* **13**, 1806, 2013.



Y.-H. Fu *et al.*, *Nat. Commun.* **4**, 1527, 2013.



W. Liu *et al.*, *ACS Nano* **6**, 5489, 2012.

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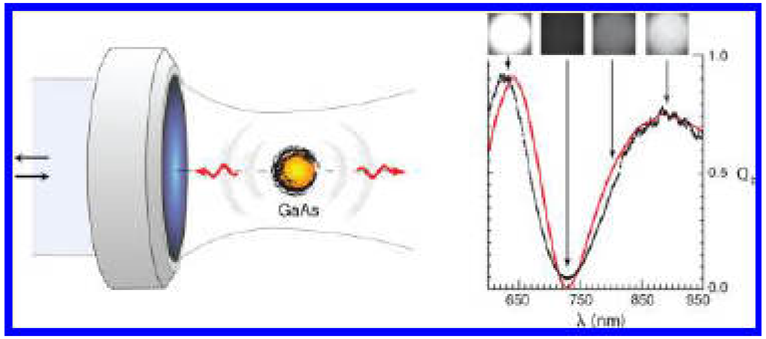
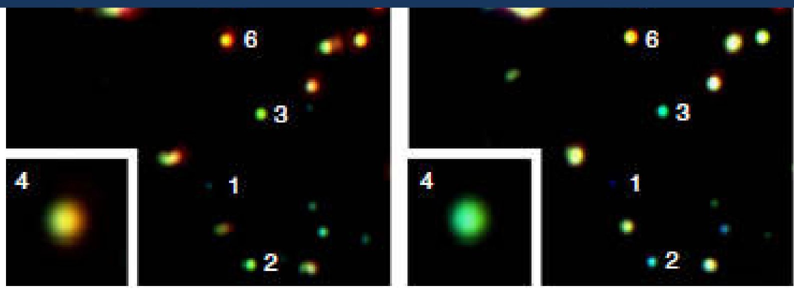


S. Person *et al.*, *Nano Lett.* **13**, 1806, 2013.

Can we design all-dielectric subwavelength particles with overlapping electric and magnetic resonances?



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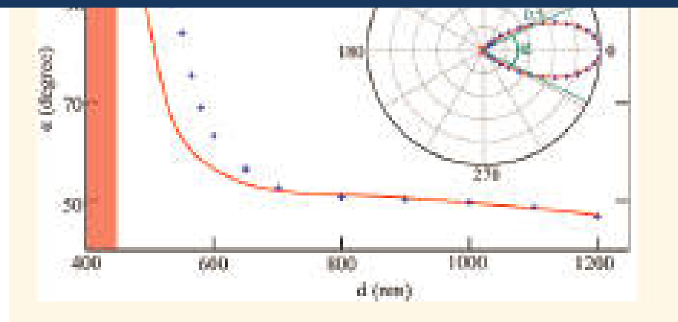


W. Liu *et al.*, *ACS Nano* **6**, 5489, 2012.

Discrete Dipole Model

- Multipole light scattering by nonspherical nanoparticles in the discrete dipole approximation

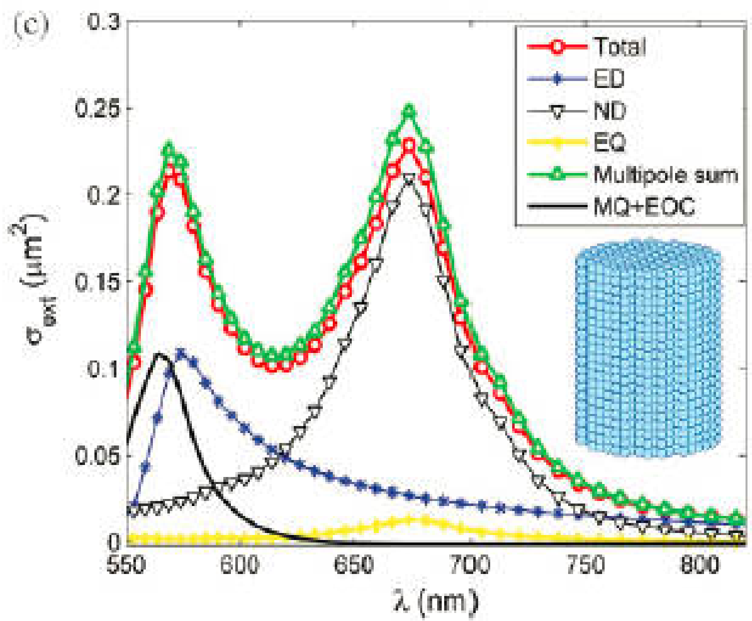
$$\sigma_{\text{ext}} \approx \sigma_{\text{ext}}^{p} + \sigma_{\text{ext}}^{m}$$

$$\sigma_{\text{ext}}^{p} = \frac{k_b}{\varepsilon_0 \varepsilon_b |\mathbf{E}_0|^2} \,\text{Im}\left(\mathbf{E}_0^*(\mathbf{r}_0)\cdot\mathbf{p}\right), \qquad \sigma_{\text{ext}}^{m} = \frac{k_b}{\varepsilon_b |\mathbf{H}_0|^2} \,\text{Im}\left(\mathbf{H}_0^*(\mathbf{r}_0)\cdot\mathbf{m}\right)$$

$$\mathbf{p}_j = \alpha_p \mathbf{E}_0(\mathbf{r}_j) + \alpha_p \frac{k_0^2}{\varepsilon_0}\sum_{l\neq j}^{N} \hat{G}(\mathbf{r}_j,\mathbf{r}_l)\,\mathbf{p}_l$$

$$\mathbf{m}_j(\mathbf{r}_0) = \frac{\omega}{2i}(\mathbf{r}_j - \mathbf{r}_0)\times\mathbf{p}_j$$

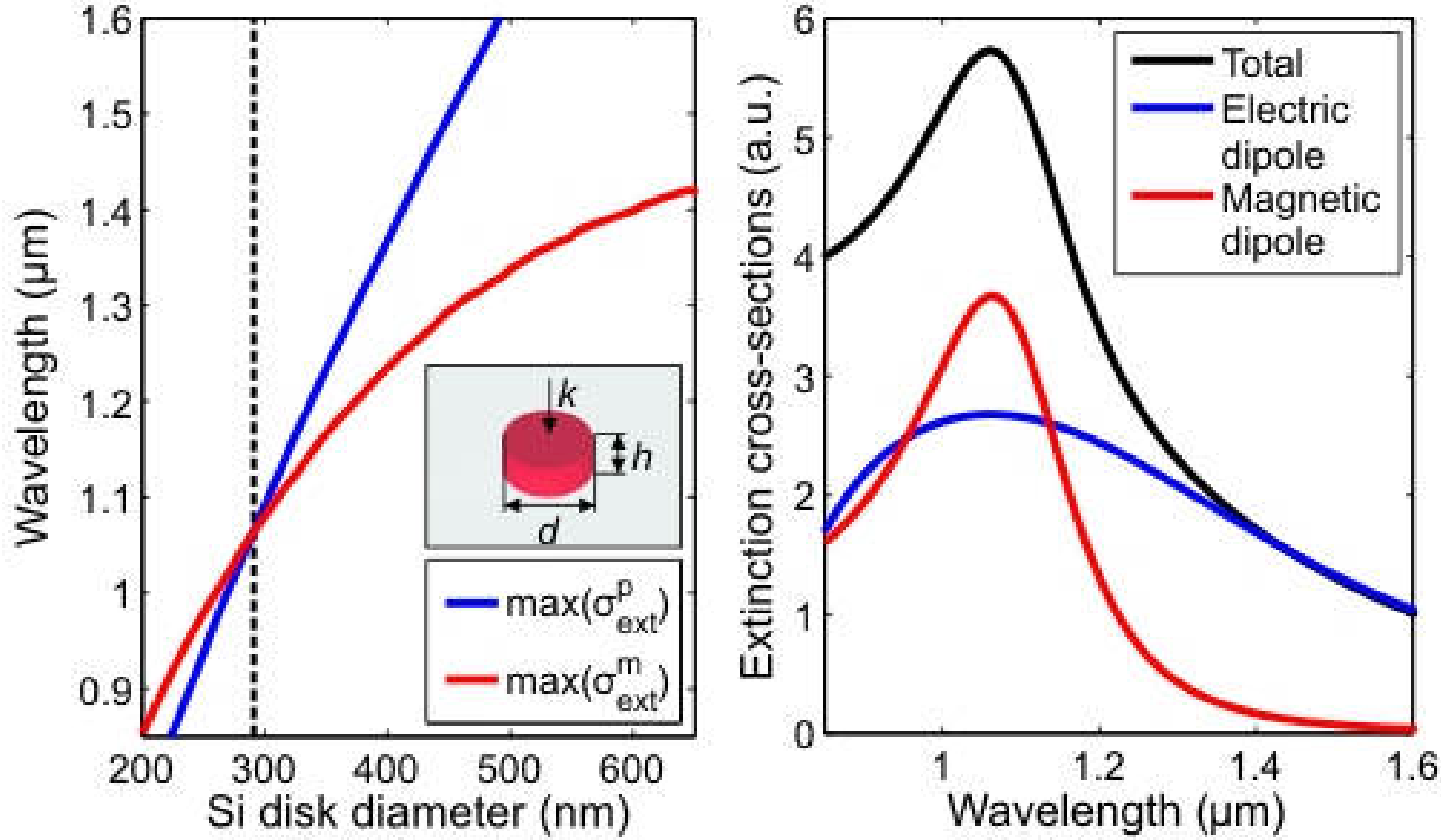
$$\mathbf{p} = \sum_{j=1}^{N}\mathbf{p}_j, \qquad \mathbf{m} = \sum_{j=1}^{N}\mathbf{m}_j(\mathbf{r}_0).$$



A. Evlyukhin et al., *Phys. Rev. B* **84**, 235429, 2011.

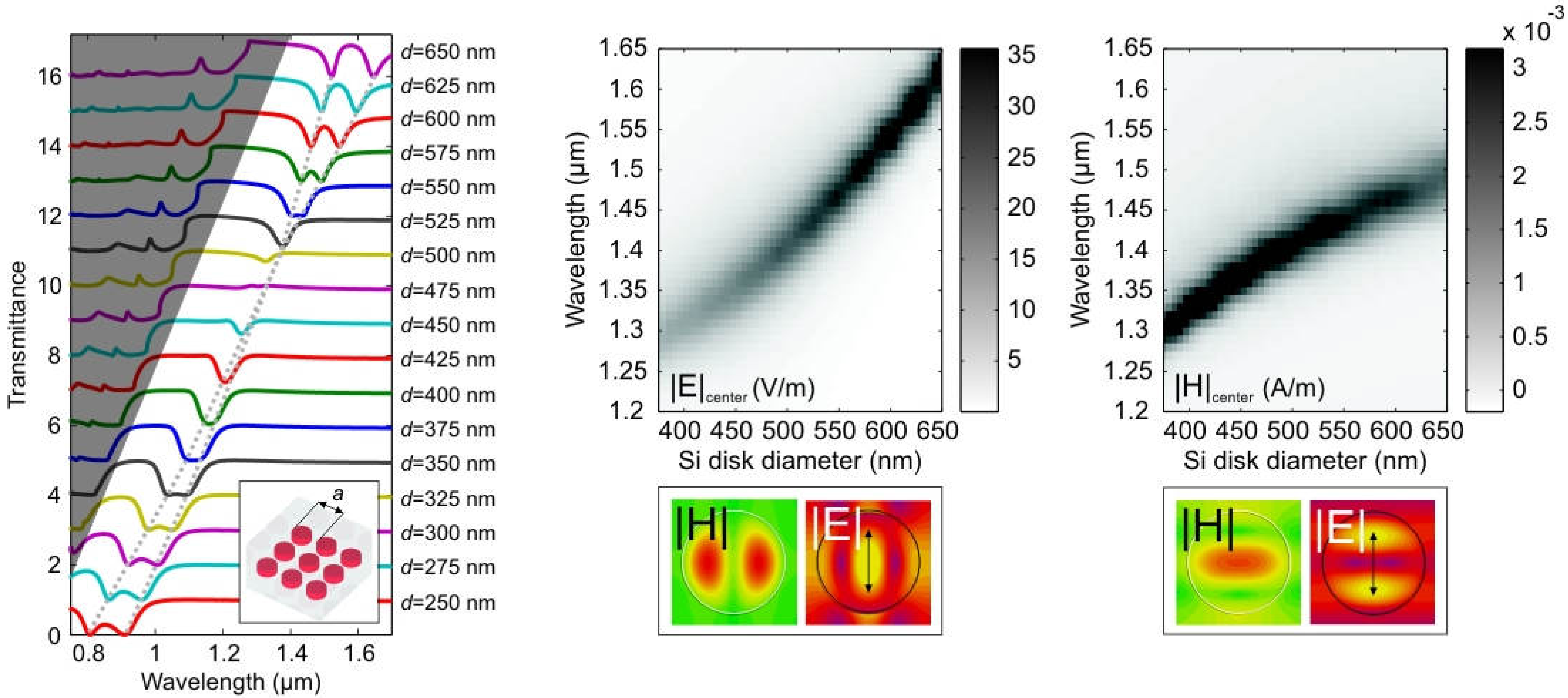
Discrete Dipole Model

- Multipole light scattering by silicon nanodisks embedded into n = 1.5 medium for systematic variation of the disk aspect ratio (h = 220 nm)



I. Staude *et al.*, submitted (2013).

Numerical Calculation

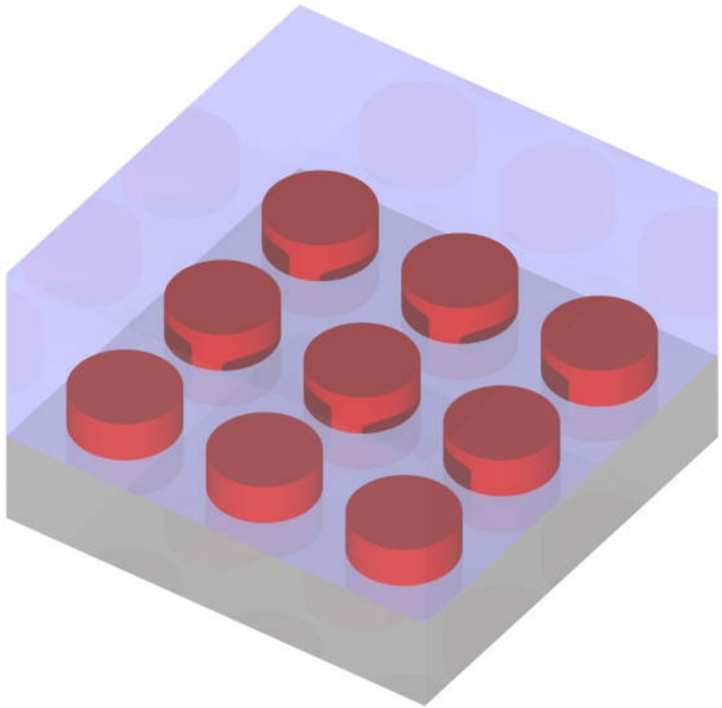


- Complete crossing of electric and magnetic resonances can be achieved
- Transmittance approaches unity for resonance overlap

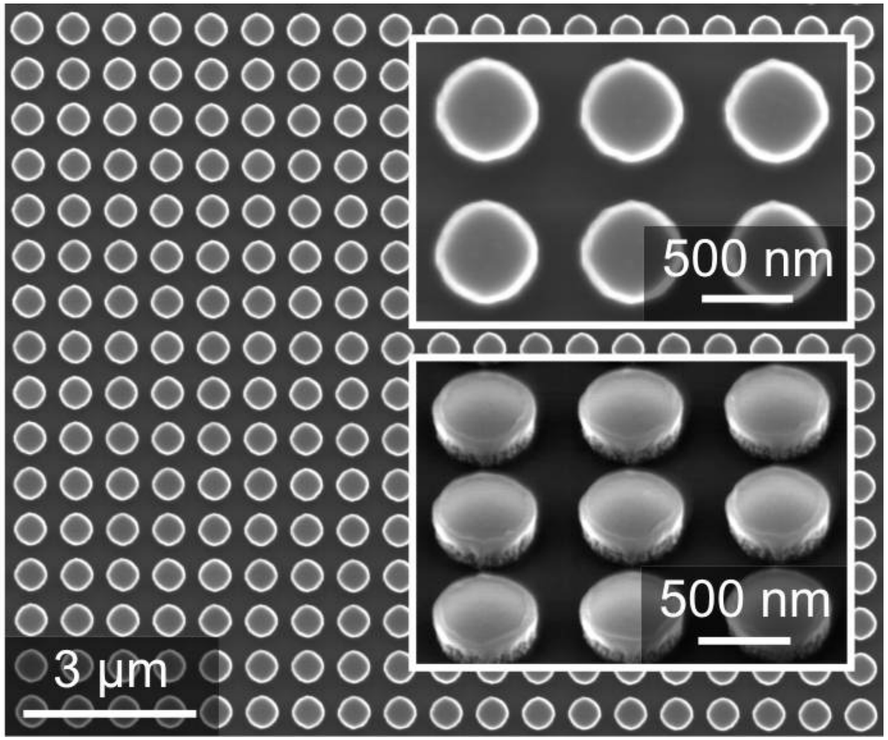
I. Staude *et al.*, submitted (2013).

Fabrication

Sketch of the experimental geometry



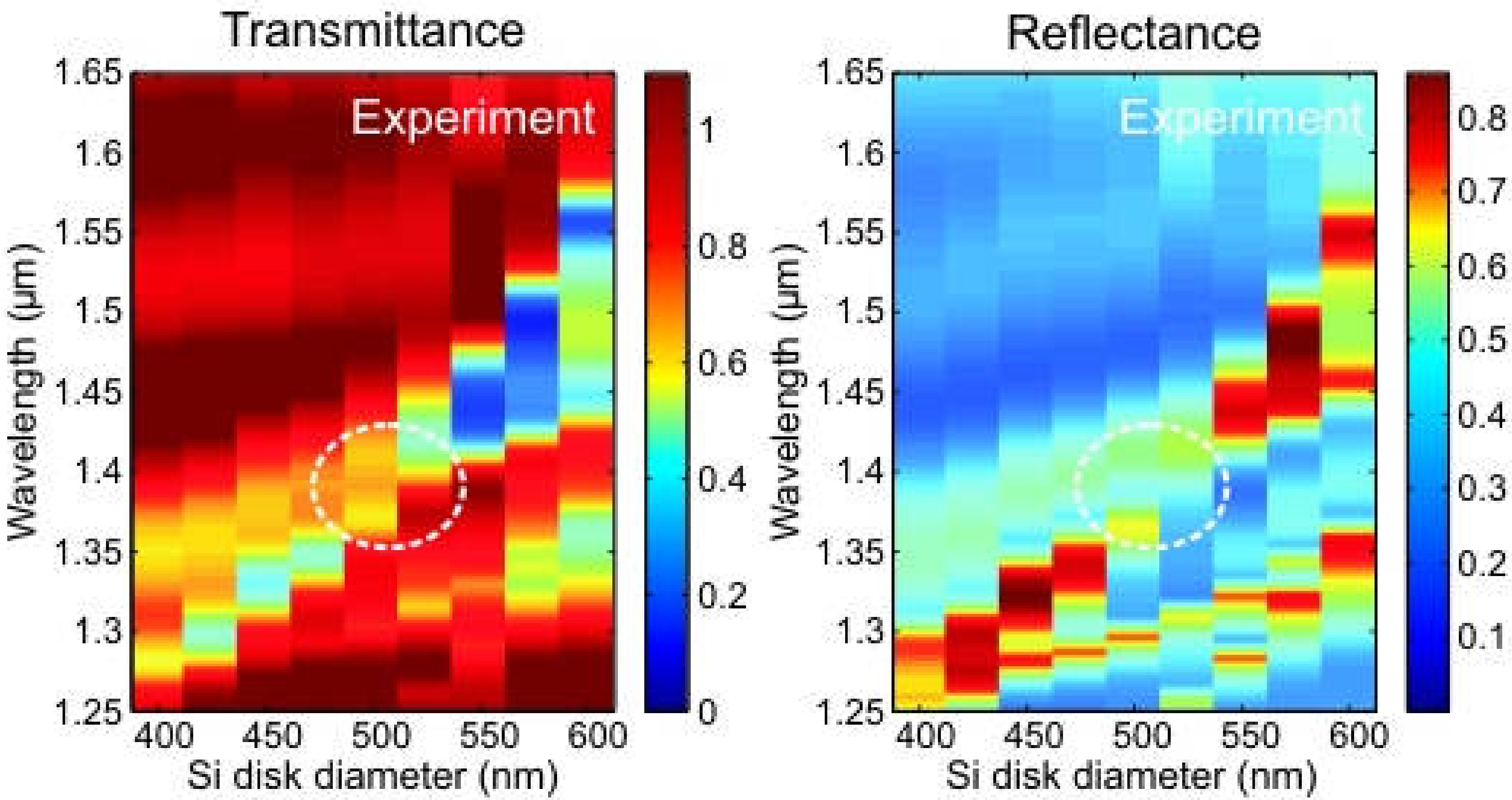
Electron-micrograph of fabricated silicon nanodisk array



I. Staude *et al.*, submitted (2013).

Optical Measurement

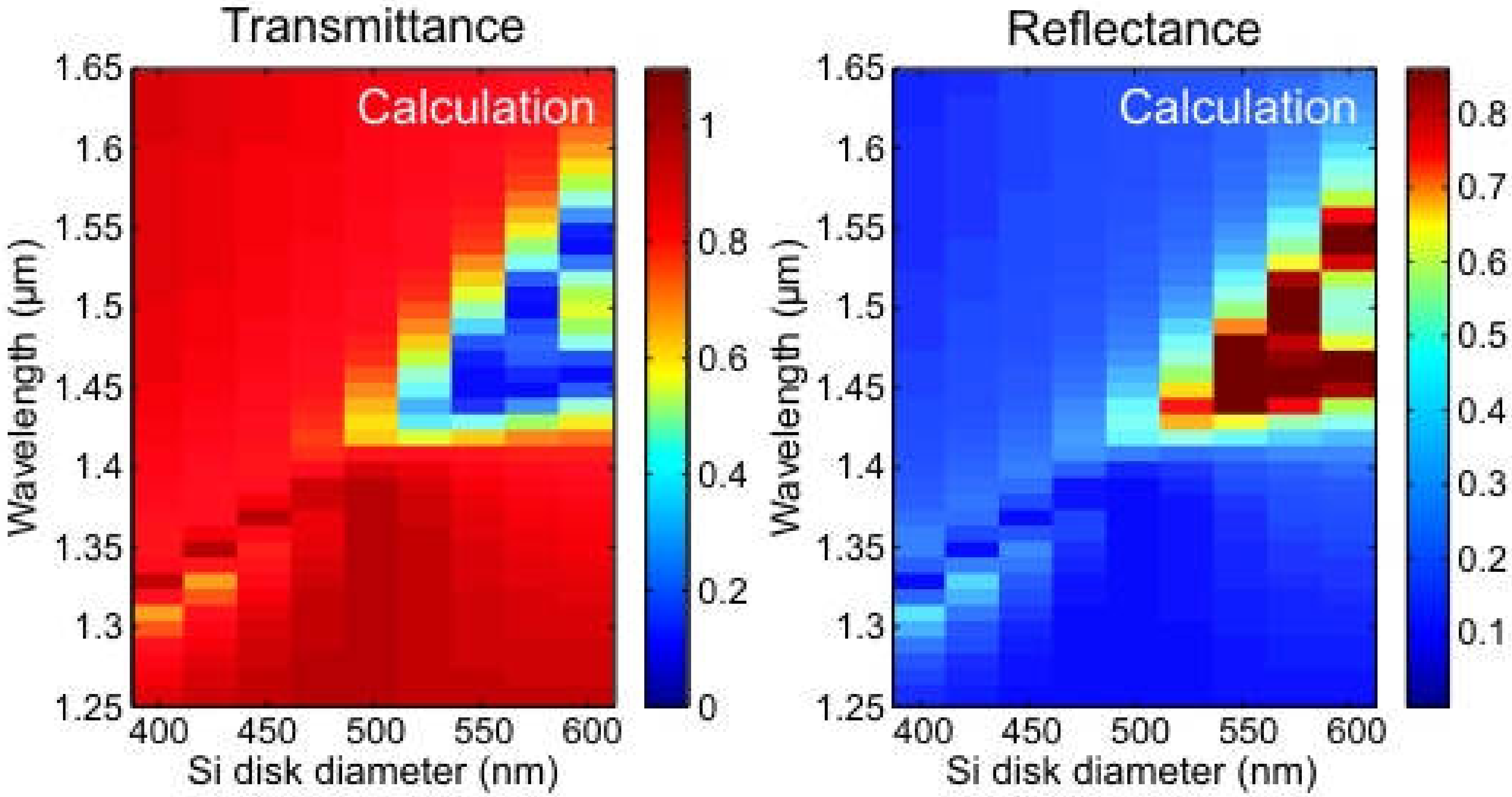
- Embedded disks



I. Staude *et al*., submitted (2013).

Comparison with Theory

- Embedded disks



I. Staude *et al*., submitted (2013).

Comparison with Theory

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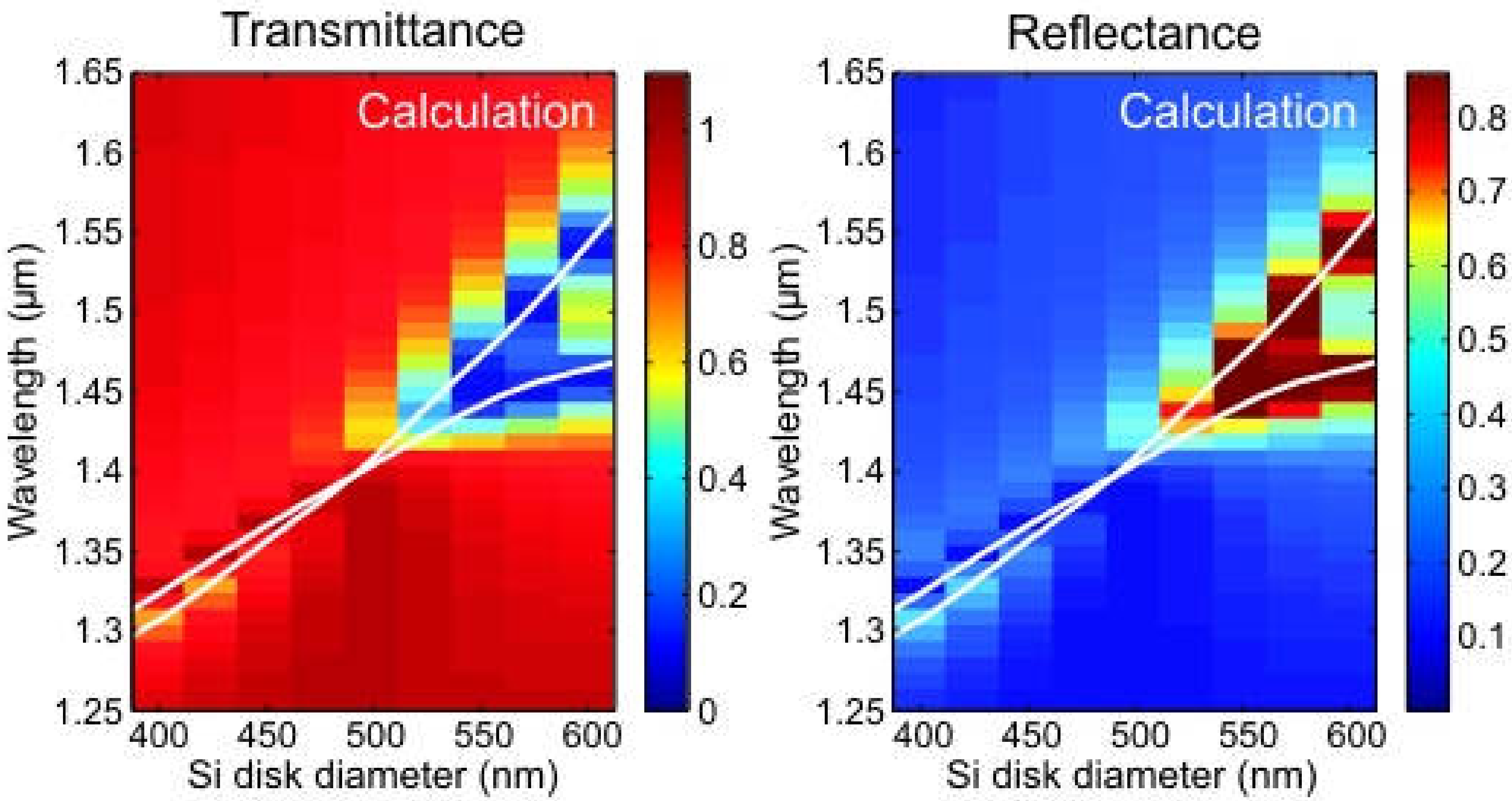
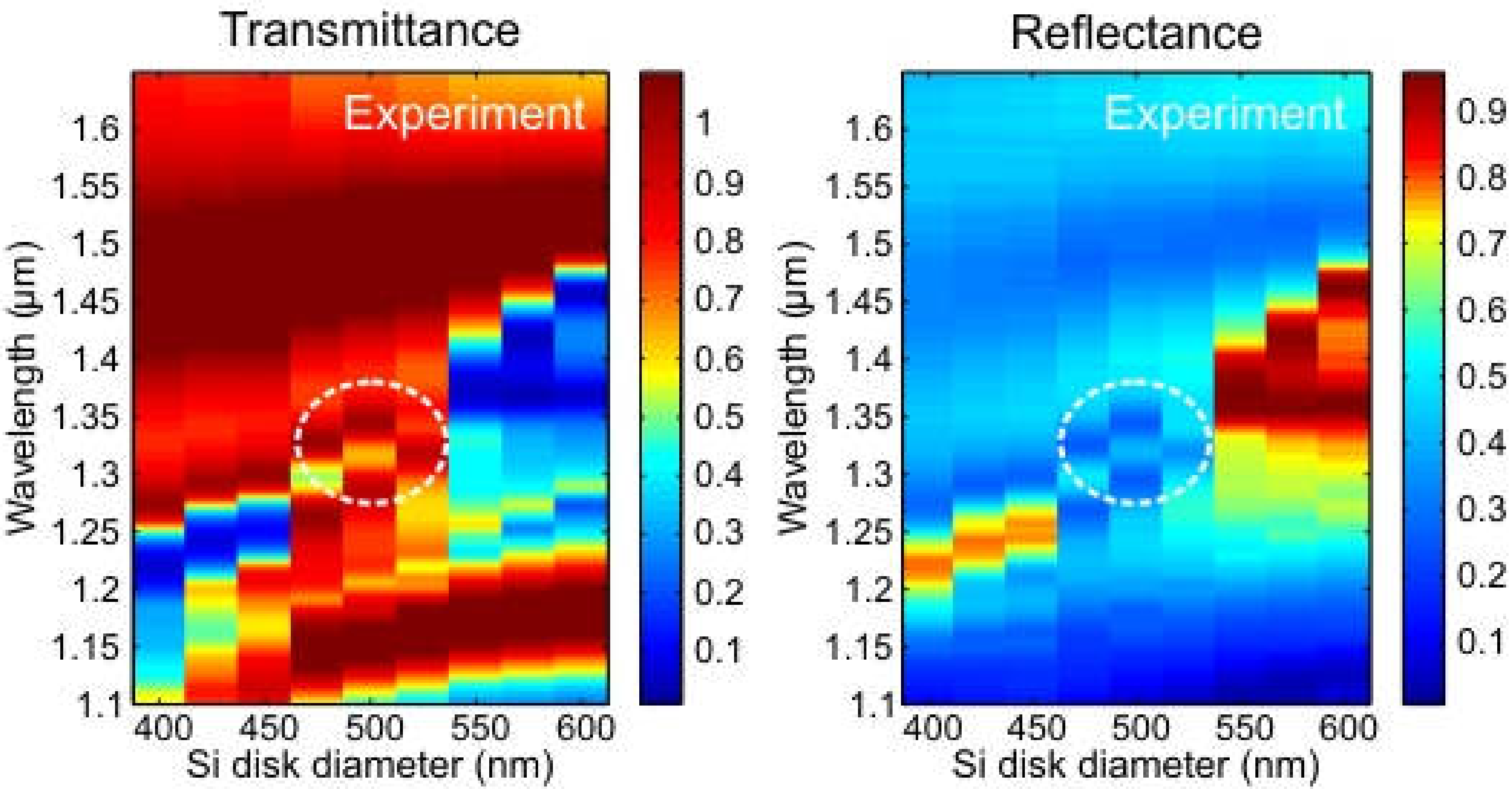


I. Staude *et al*., submitted (2013).

Optical Measurement

- Free standing (not embedded) disks



I. Staude *et al*., submitted (2013).

Comparison with Theory

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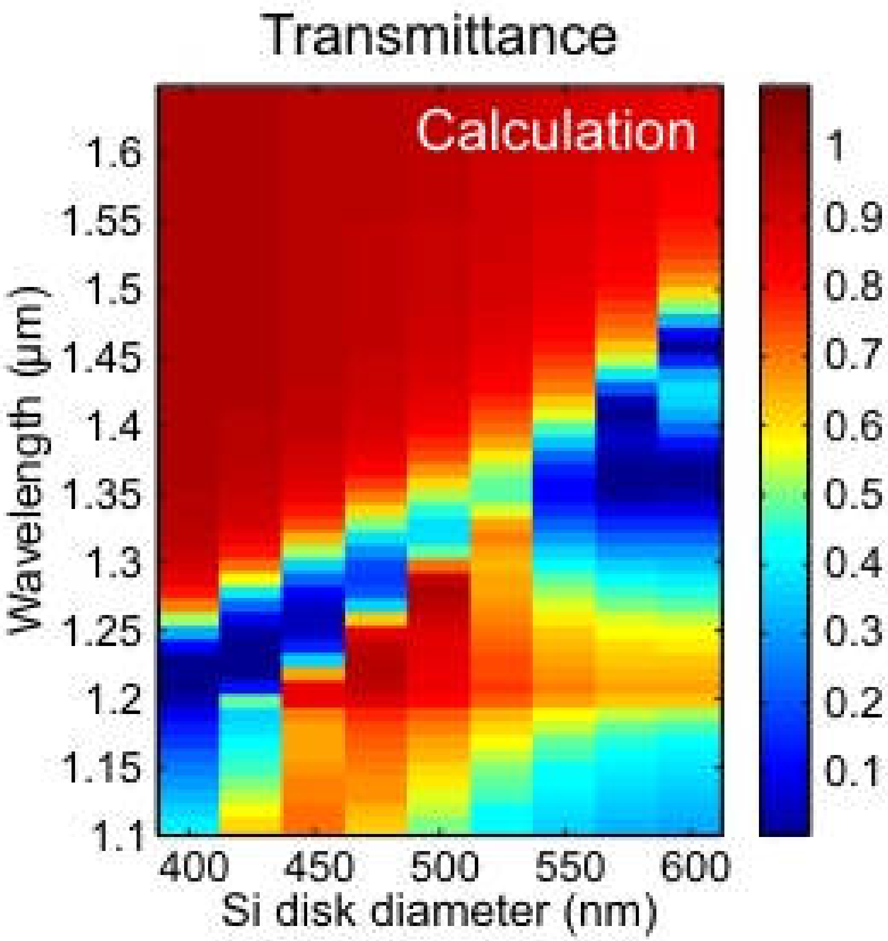
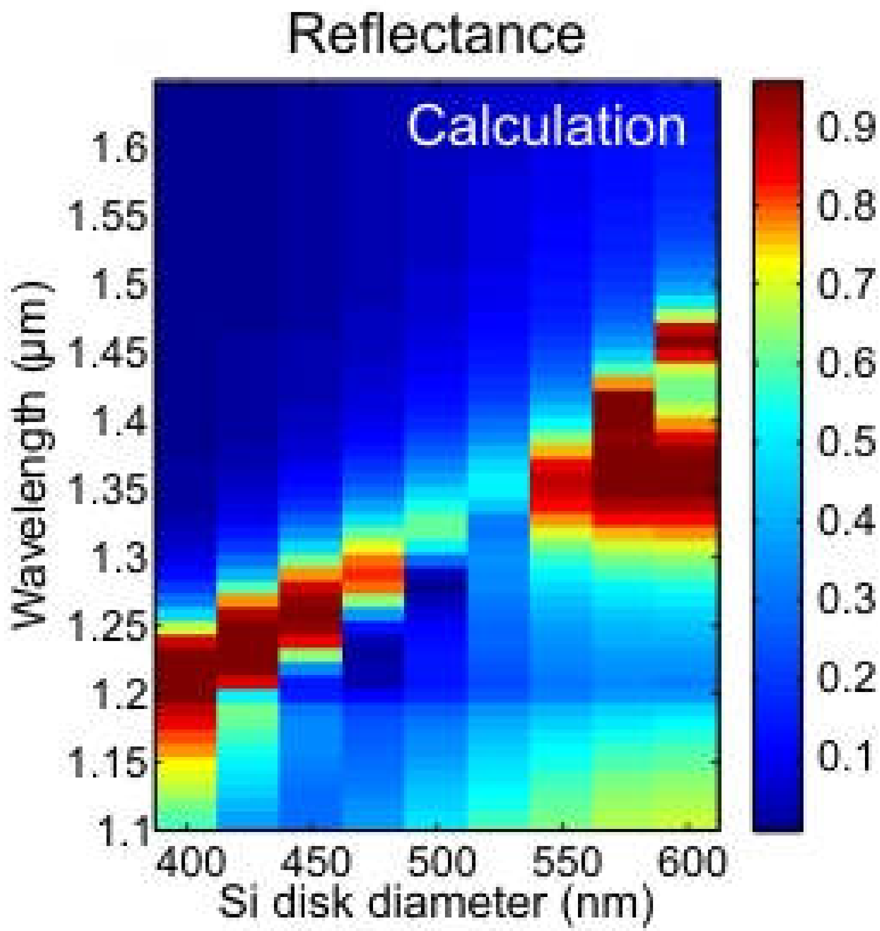




I. Staude *et al.*, submitted (2013).

Discussion

- Beer-Lambert law

$$T \approx exp(-\sigma_{ext}/a^2)$$

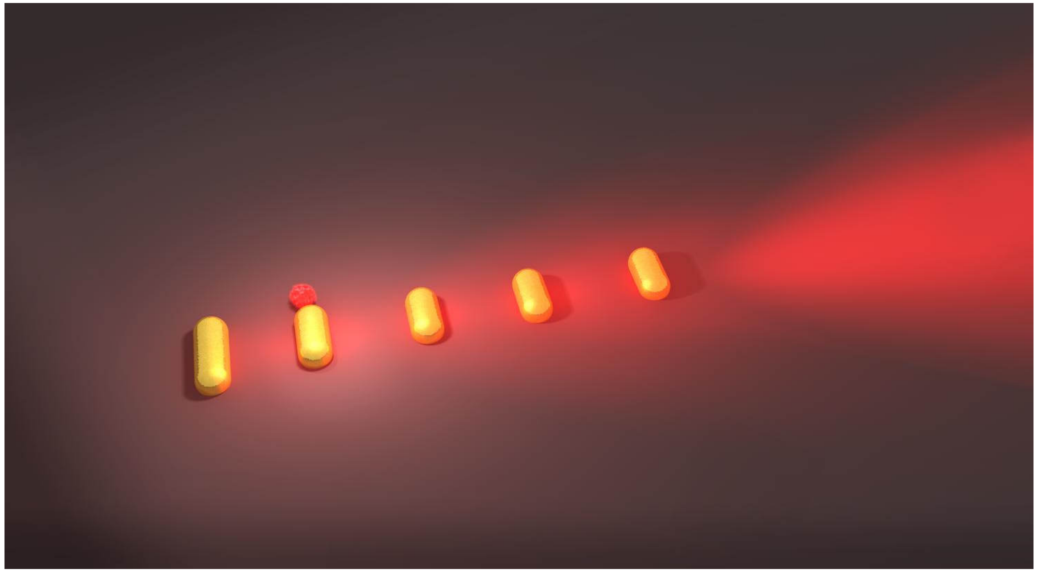
- For a single resonance:
  - T min, σ_{ext} max
  - Destructive interference of the incident wave and the scattered wave in forward direction
- Resonance overlap:
  - $T \approx 1$ despite a maximum in σ_{ext}
  - Destructive interference of the incident wave and the scattered waves in backward direction
  - Strong resonance in phase

- Alternative point of view: Impedance matching ($\varepsilon \approx \mu$)

Tailoring Mode Interference

- How about other cases?
  - Non-overlap
  - Off-resonance

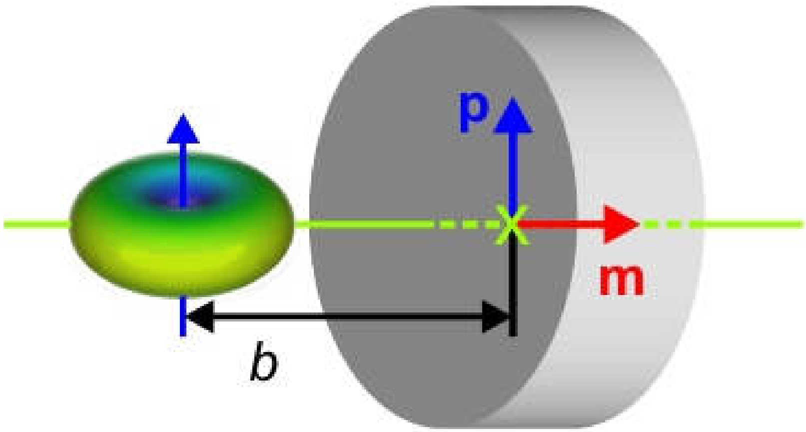
- Is it possible to tailor mode interplay to achieve highly directional emission from a dipole source?

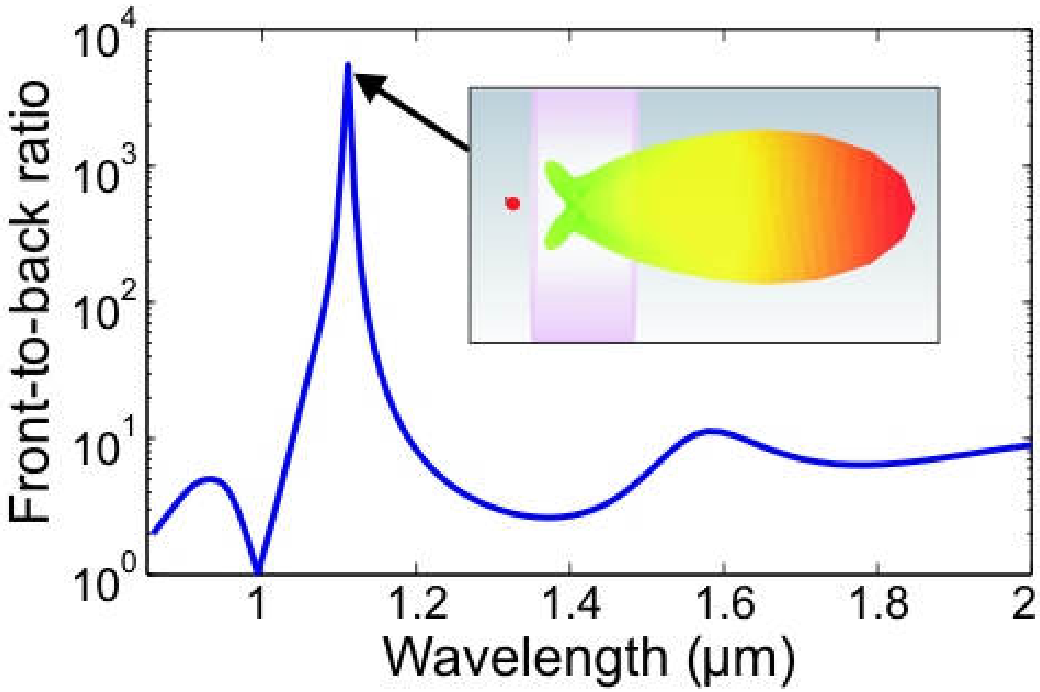


A. G. Curto *et al.*, *Science* **329**, 930 (2010).

Silicon Disk Nanoantennas

- Silicon nanodisk with *d* = 620 nm
- Dipole emitter located 45 nm away from the disk surface
- Embedded into *n* = 1.5 medium





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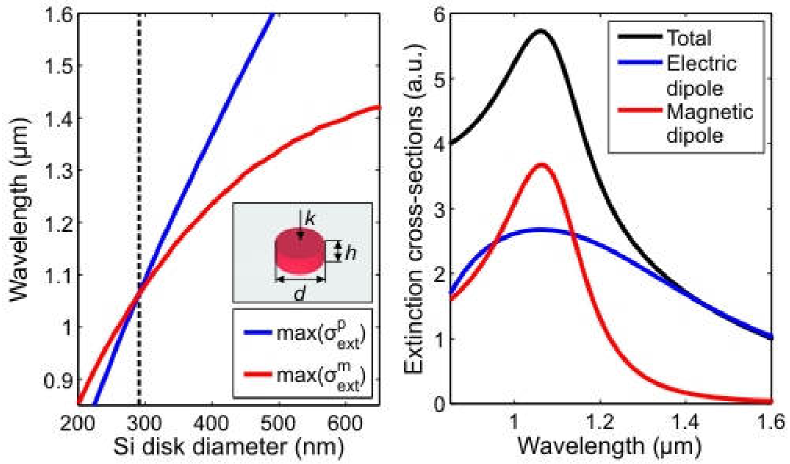
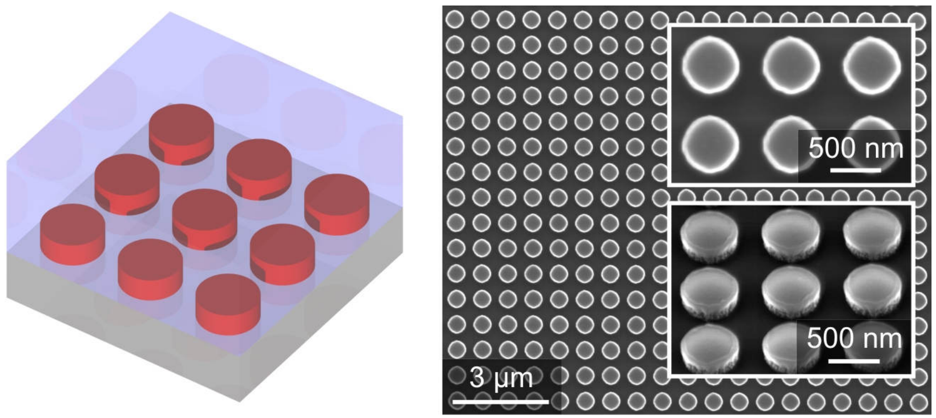
Conclusions

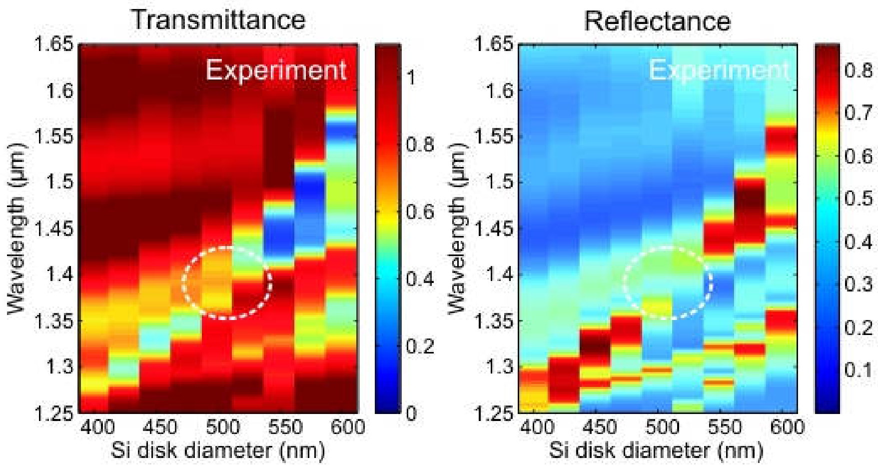
Discrete dipole model



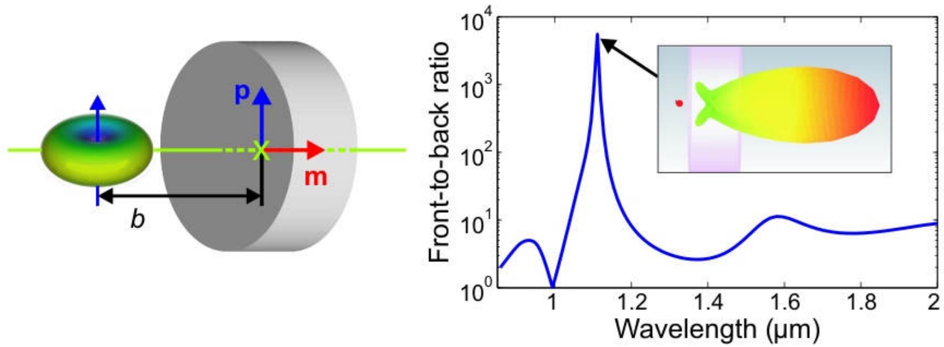
Fabrication in SOI technology



Optical measurements



Giant front-to-back ratio



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Conclusions

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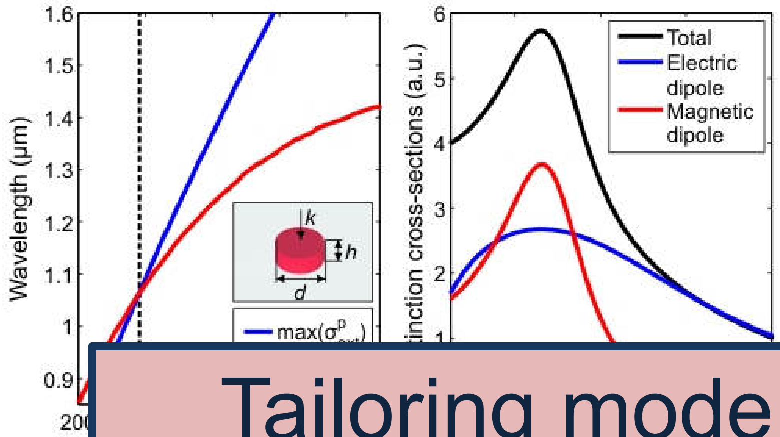
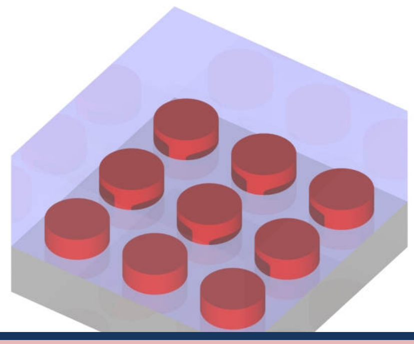
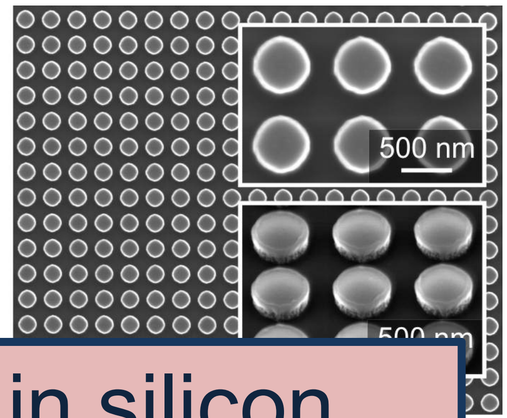
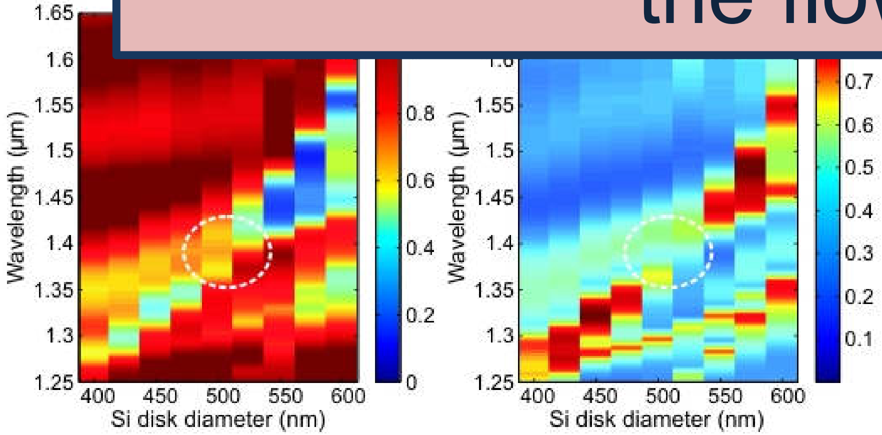


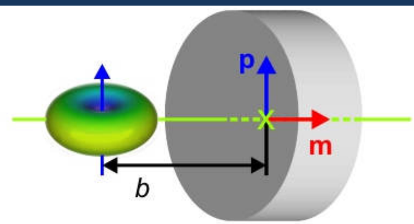
Fabrication in SOI technology

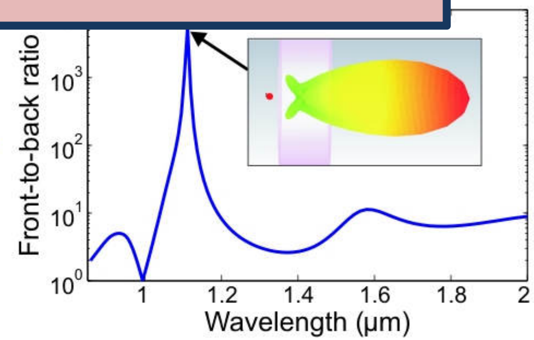




Tailoring mode interference in silicon nanodisks is a powerful tool to engineer the flow of light!







Thank you!

Outline

- **High-index all-dielectric subwavelength particles**
- **Overlapping electric and magnetic resonances for embedded silicon nanodisks:**
  - **Discrete dipole model**
  - **Numerical analysis**
  - **Experiment**
- **Off-resonant effects**
- **Conclusions**