



# FIB-Milling of Photonic Nanostructures

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# Outline

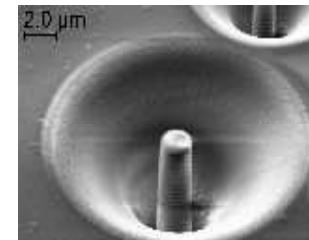
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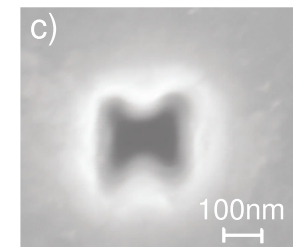
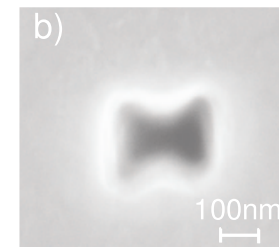
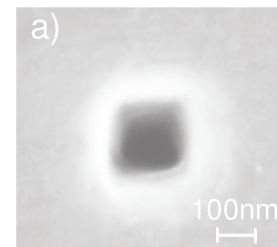
1. Fabrication of dielectric pillar microcavities with embedded colloidal semiconductor quantum dots
2. Nanoapertures in thin Metal Films



# Dielectric Micropillar Cavities

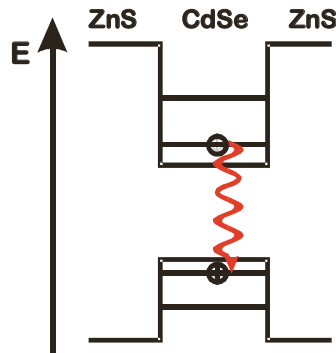


## Nanoapertures



# Photon Emission from a one-exciton System

## one-exciton system



-> spontaneous emission  
of a photon

goal:

- control spontaneous emission
- short radiative lifetime

Possible Applications:

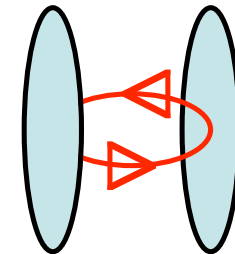
single photon sources for  
quantum optics:

- quantum cryptography
- quantum information processing
- fundamental processes in a few electron and photon quantum system

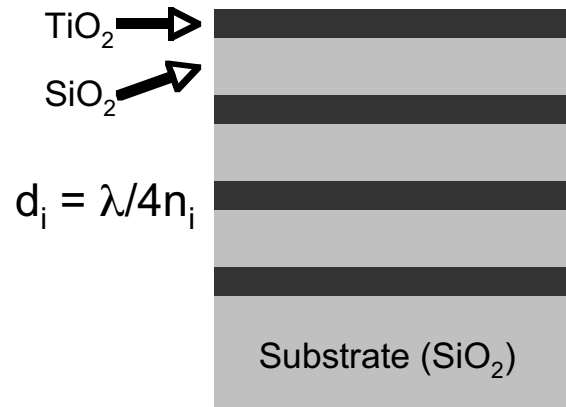
=> optical cavity (Purcell Effect)

$$1/\tau_{\text{rad}} \approx \frac{Q}{V_{\text{Mod}}} \cdot \left(\frac{\lambda}{n}\right)^3$$

Q: Quality factor  
Q <-> value for the  
average dwell time of a  
photon in the resonator



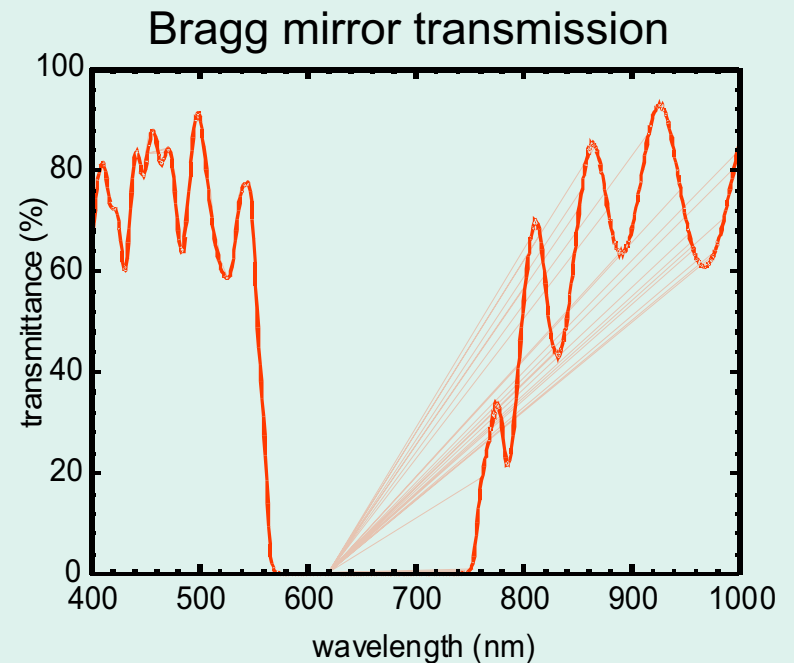
# Dielectric Bragg Mirror



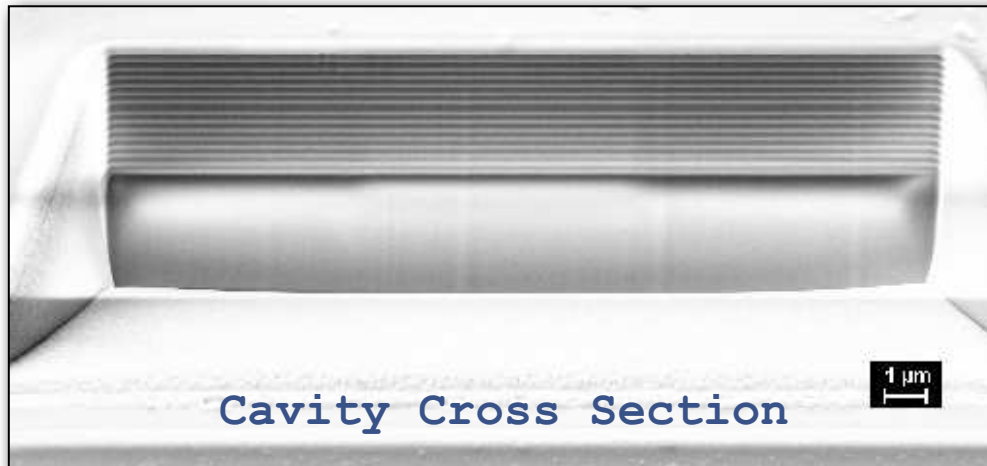
- Fabrication via RF sputtering
- Reflectivity (yields **high Q**) depends on the number of layers
- Width of the stopband depends on the refractive index contrast ( $n_1/n_2$ )
- Spectral position depends on layer thickness ( $1/4$ )

## Advantages

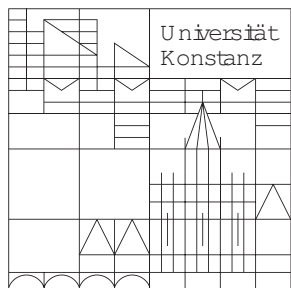
- no absorption
- high reflectivity due to multipath interferences
- high flexibility in target wavelength design



# Dielectric Bragg Mirror

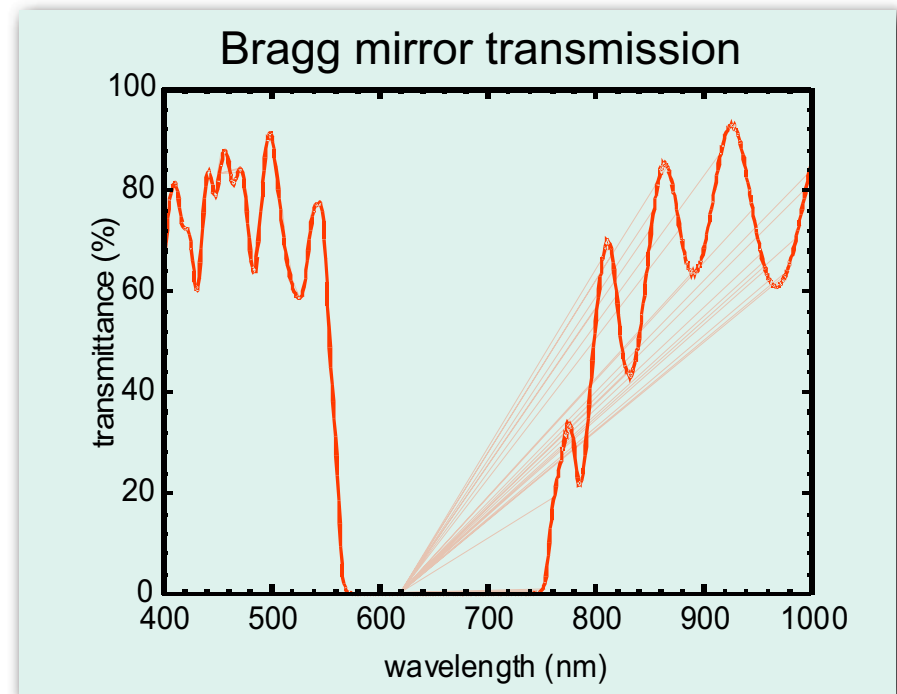


- Fabrication via RF sputtering
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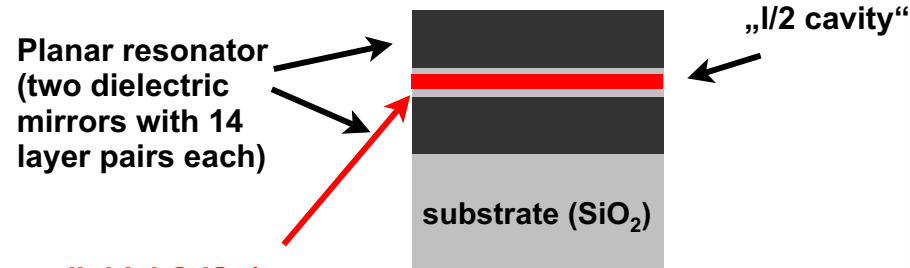


## Advantages

- no absorption
- high reflectivity due to multipath interferences
- high flexibility in target wavelength design



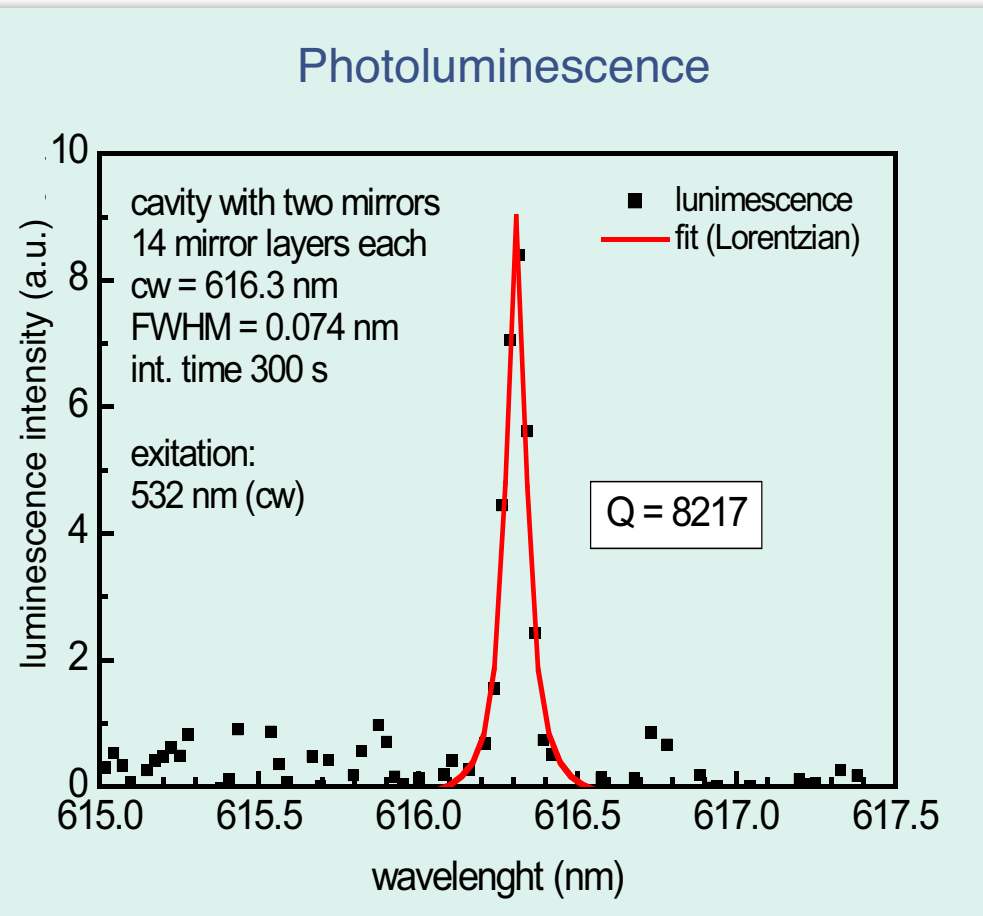
# Planar Dielectric Cavity with CdSe/ZnSe QDs



colloidal CdSe/  
 ZnS  
 quantum dots as  
 internal  
 lightsource



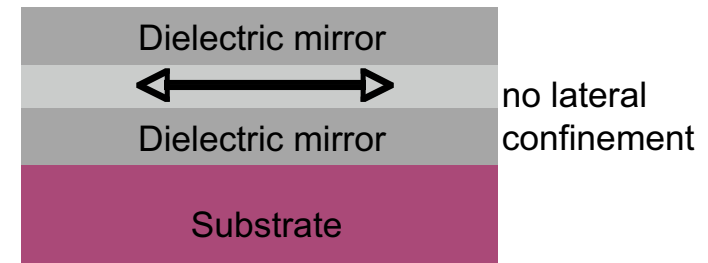
- width of resonance:  
 $\Delta\lambda = 0,074 \text{ nm}$
- resonator quality:  
 „Q - factor“:  
 $Q = \Delta\lambda/\lambda = 8200$



**Q-factor 50x higher than previously reported values.**

# Cavity with 3D Light Confinement

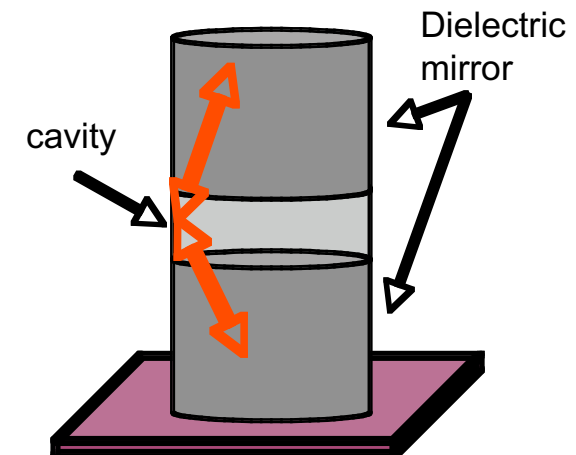
Planar Resonator:  
Light confinement only  
perpendicular to the mirrors  
-> mode volume not optimized



goal: 3D light confinement

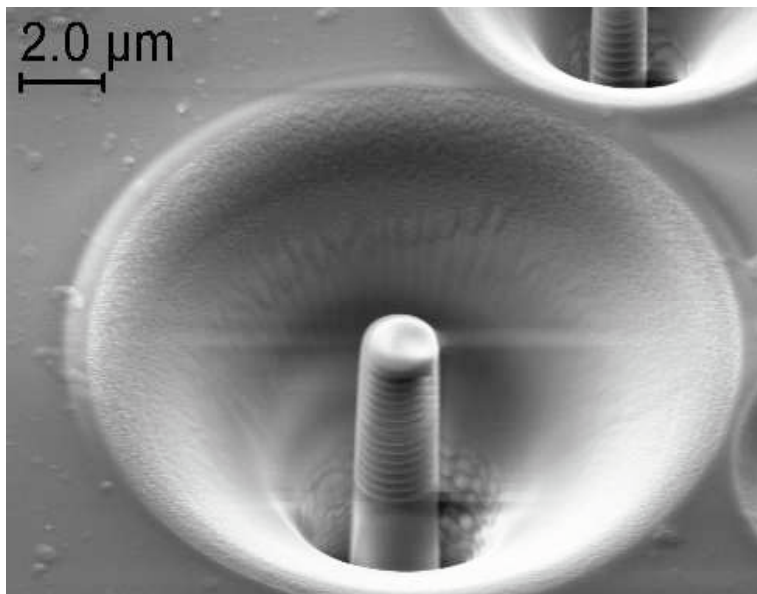
solution:

cylindrical waveguiding structure  
cut into planar cavity  
-> lateral mode guiding by total  
internal reflection at the walls

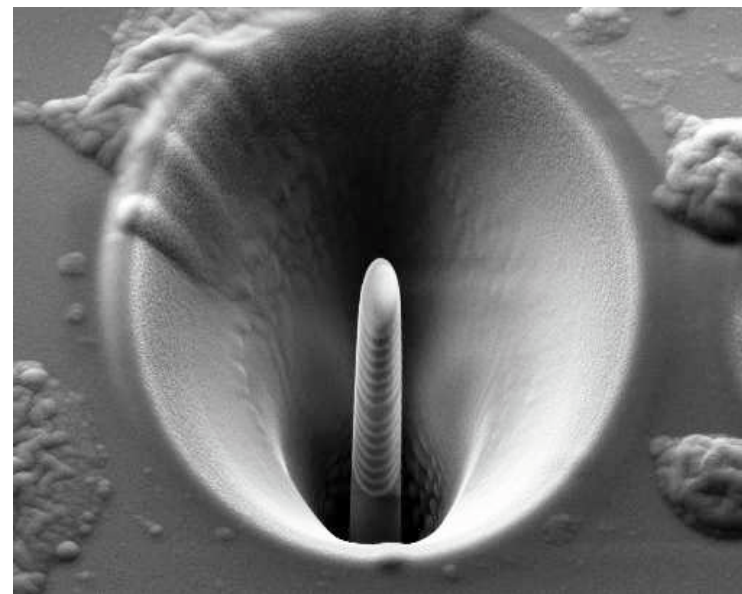


# Fabrication of Micropillars with FIB\*

circular pillar resonator



elliptical pillar resonator



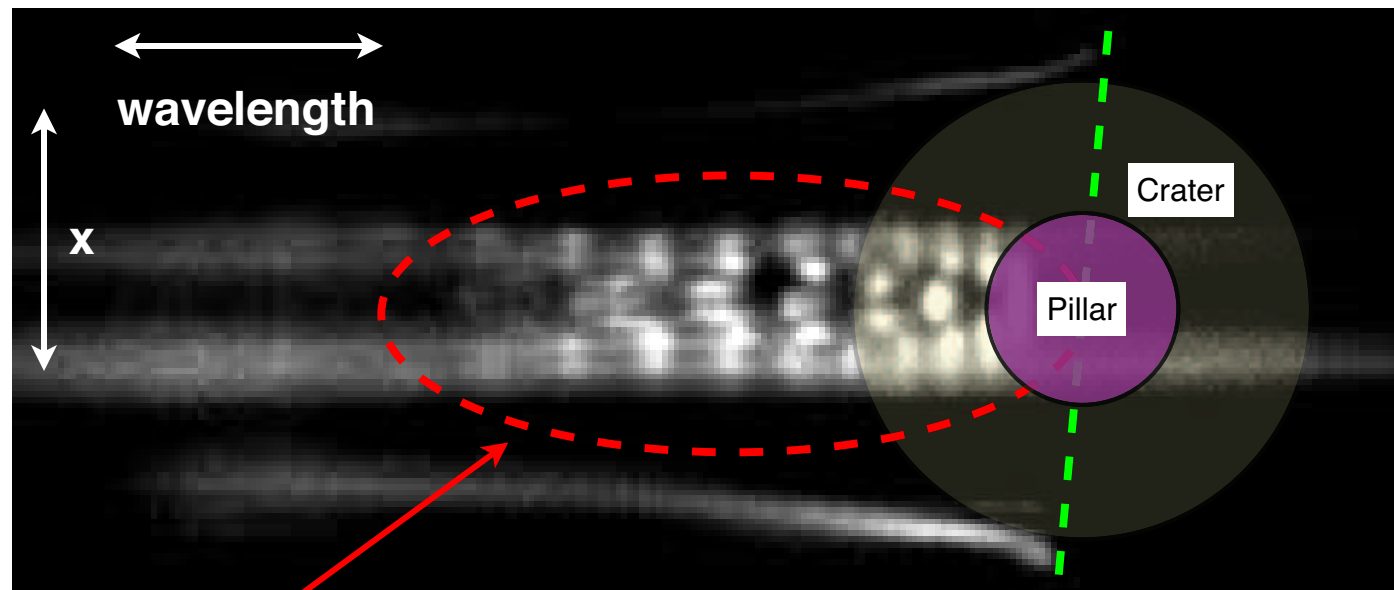
M. Kahl et al, Nano Lett. 7(9), 2897 (2007)

\* Zeiss Crossbeam XB 1540

# Mode Spectrum of a Micropillar cavity

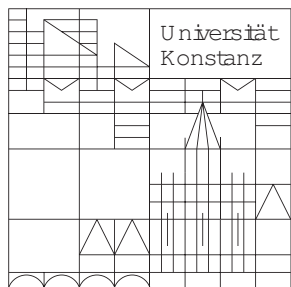
- micropillar with 5.1  $\mu\text{m}$  diameter
- CdSe/ZnS dots, emission @ 600 nm
- high density of dots ( $>1000 / \mu\text{m}^2$ )  $\rightarrow$  ensemble measurement
- excitation with 532 nm cw-laser

spatially and spectrally resolved CCD image

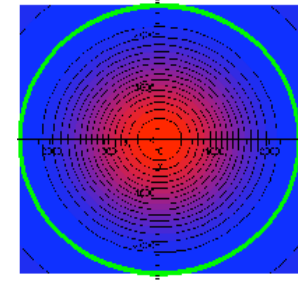
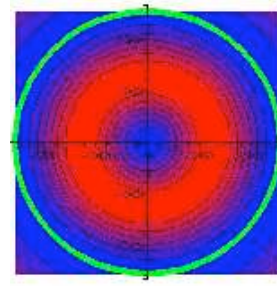
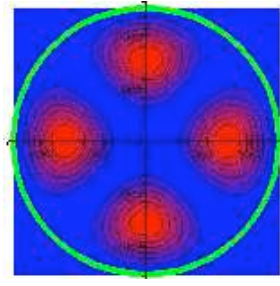
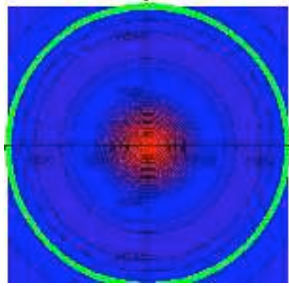


mode structure

resonance of planar cavity

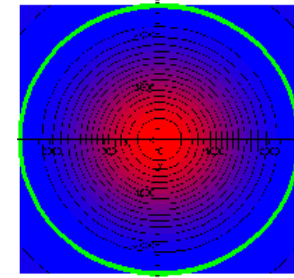
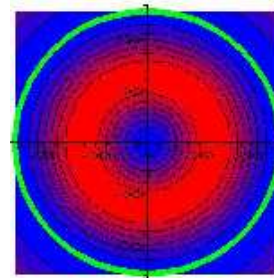
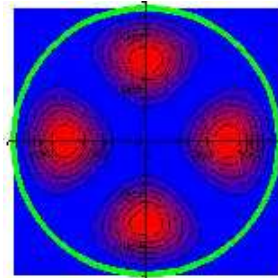
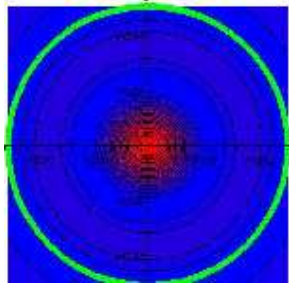


# Mode spectrum: Theory and Experiment

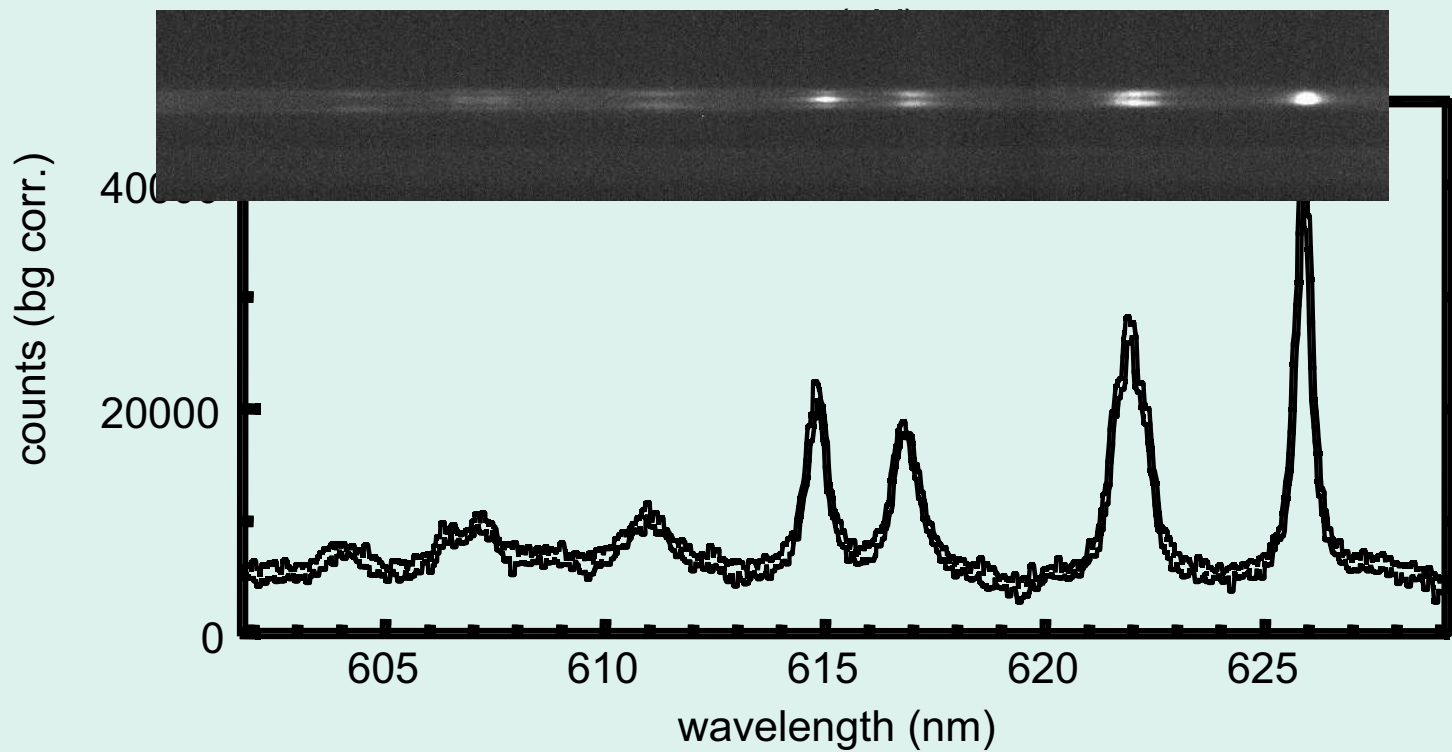


Theory

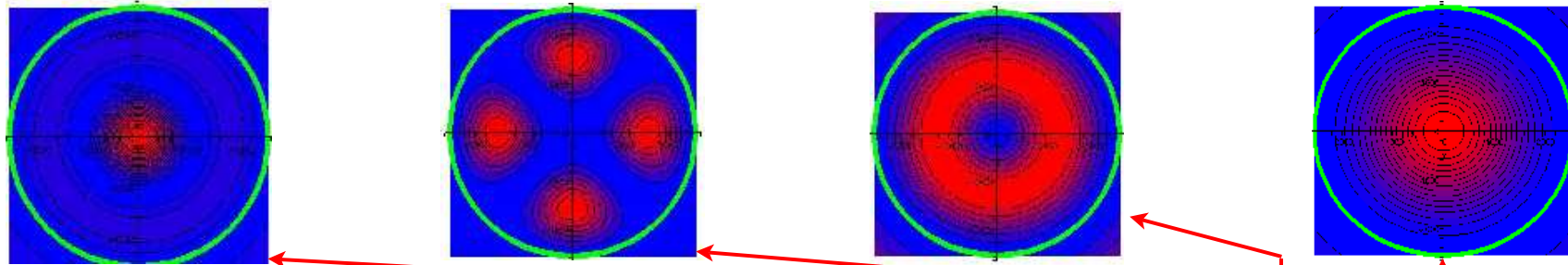
# Mode spectrum: Theory and Experiment



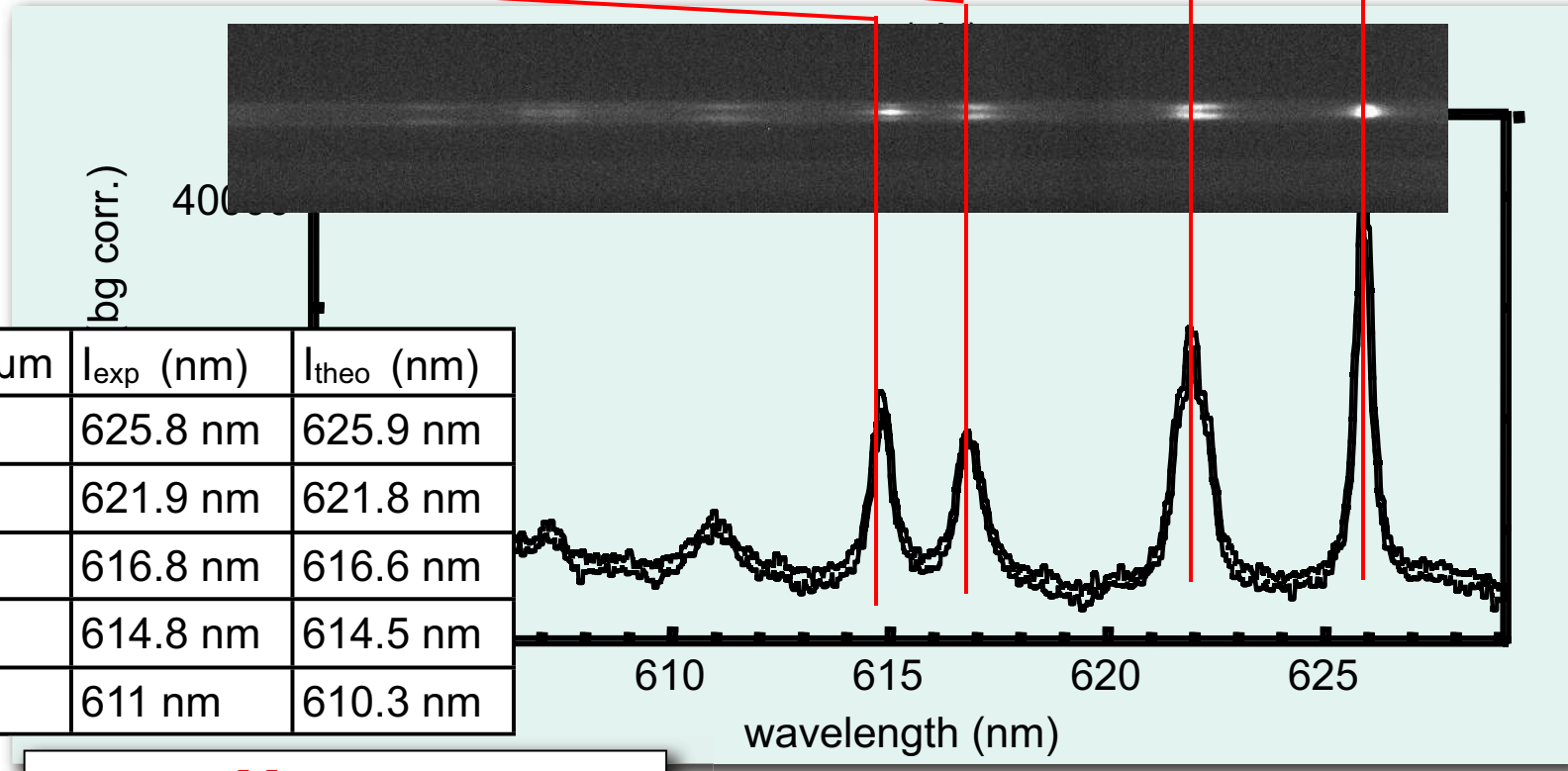
## Experiment



# Mode spectrum: Theory and Experiment

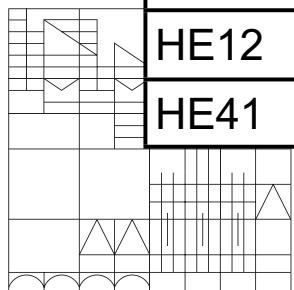


Experiment

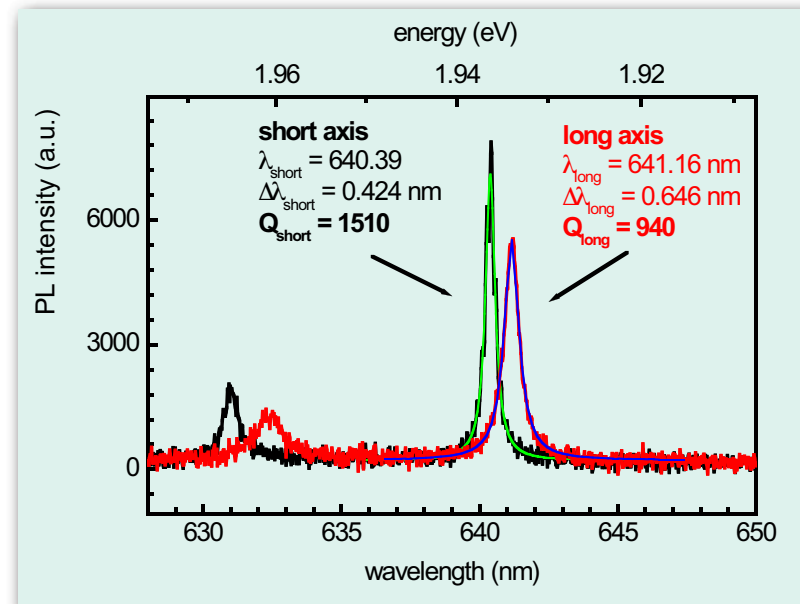
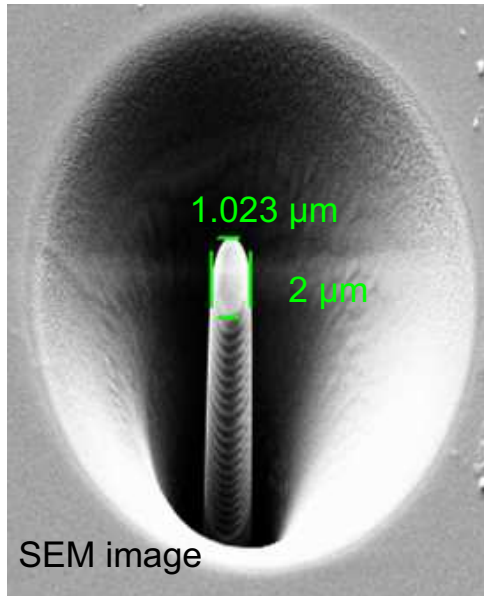


$d=3.02\mu\text{m}$	$I_{\text{exp}}$ (nm)	$I_{\text{theo}}$ (nm)
HE11	625.8 nm	625.9 nm
HE21	621.9 nm	621.8 nm
HE31	616.8 nm	616.6 nm
HE12	614.8 nm	614.5 nm
HE41	611 nm	610.3 nm

**-> excellent agreement**



# Pillar Shapes: Elliptical

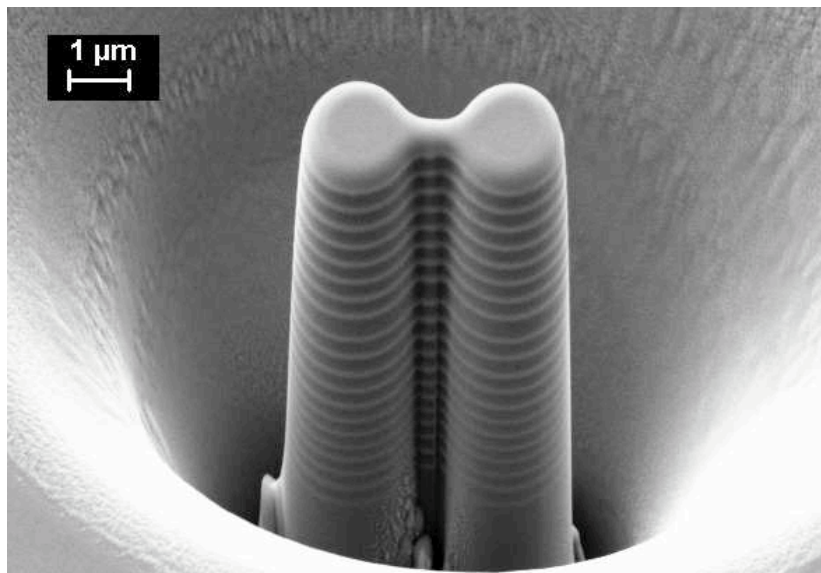


Fundamental mode split into two modes with crossed linear polarisation

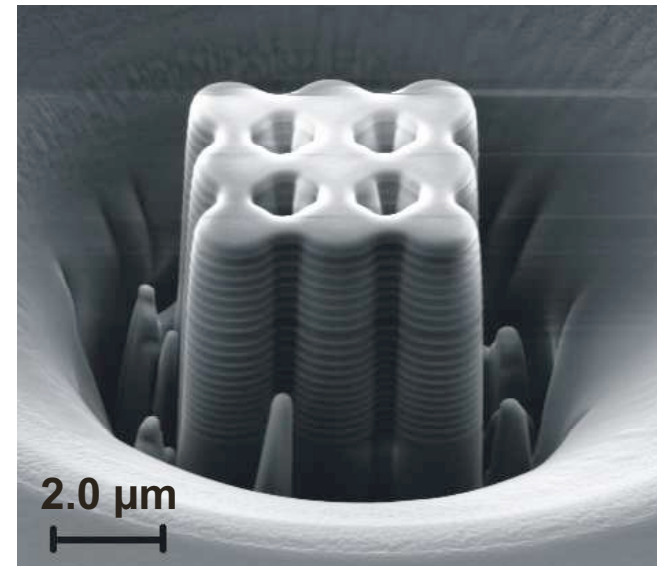
=> may provide source for linear polarized single photons

# Coupled Microcavities

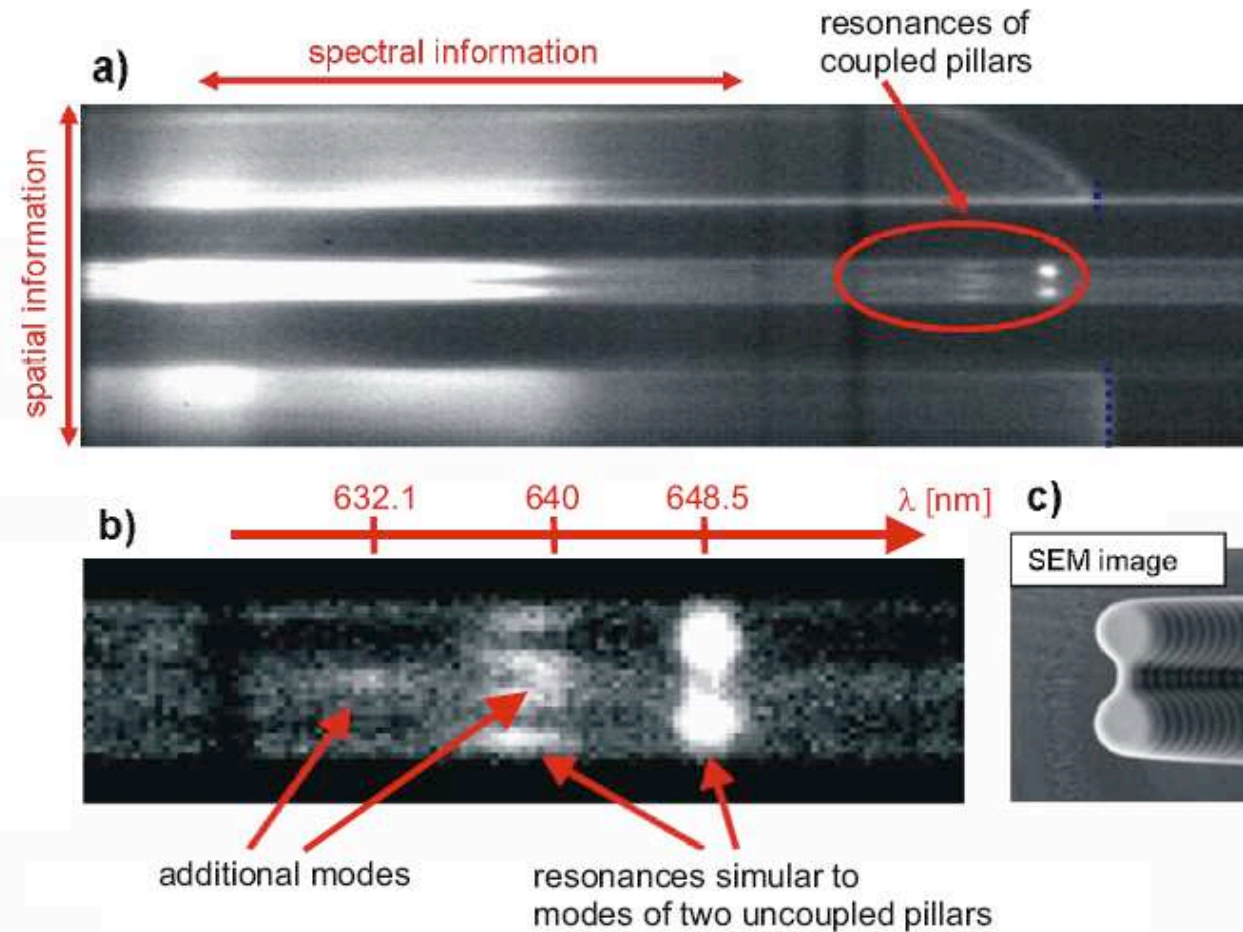
photonic molecule



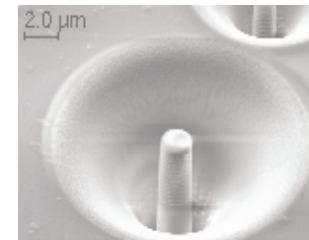
resonator array



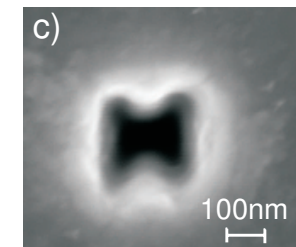
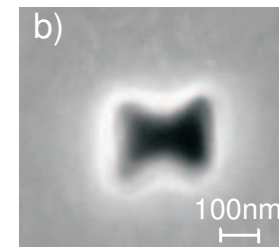
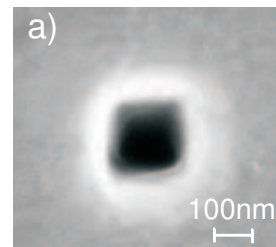
# Mode Spectrum of a „Photonic Molecule“



# Dielectric Micropillar Cavities



## Nanoapertures

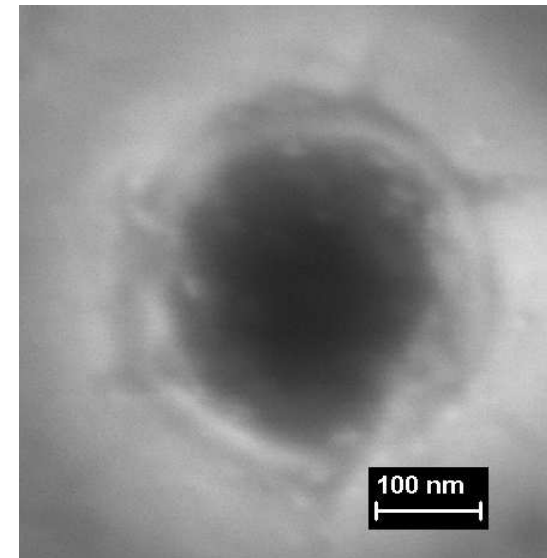
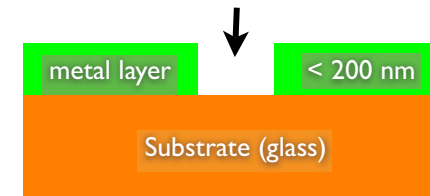


## Motivation:

### Nanoapertures for:

- **field enhancement inside the nano aperture** (PRL 95, 117401 (2005) H Rigneault et al.)
- **enhanced transmission through subwavelength holes** (JJAP 44, L364 (2005) T. Ishi)

subwavelength nanoaperture

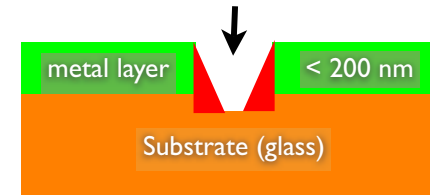


# Cone-shaped Circular Nanoaperture

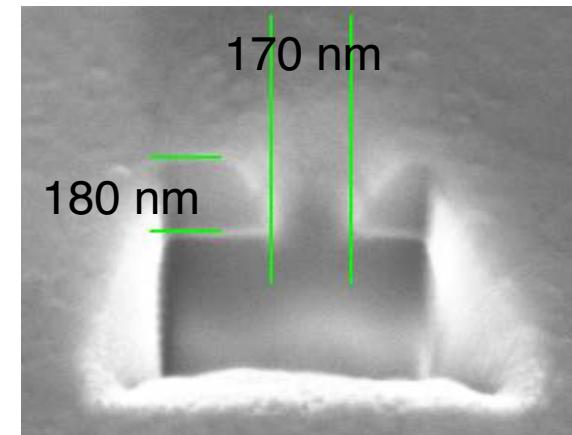
## Fabricating Nanoapertures using FIB

- Cone-shaped cross section
  - Difficult to control milling depth
- > Control by End Point  
Detection

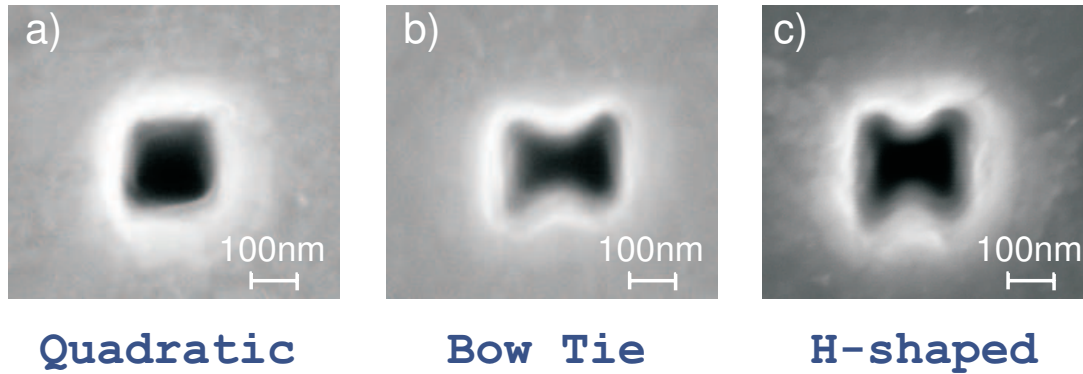
cone shaped aperture with  
diameter 50 - 300 nm



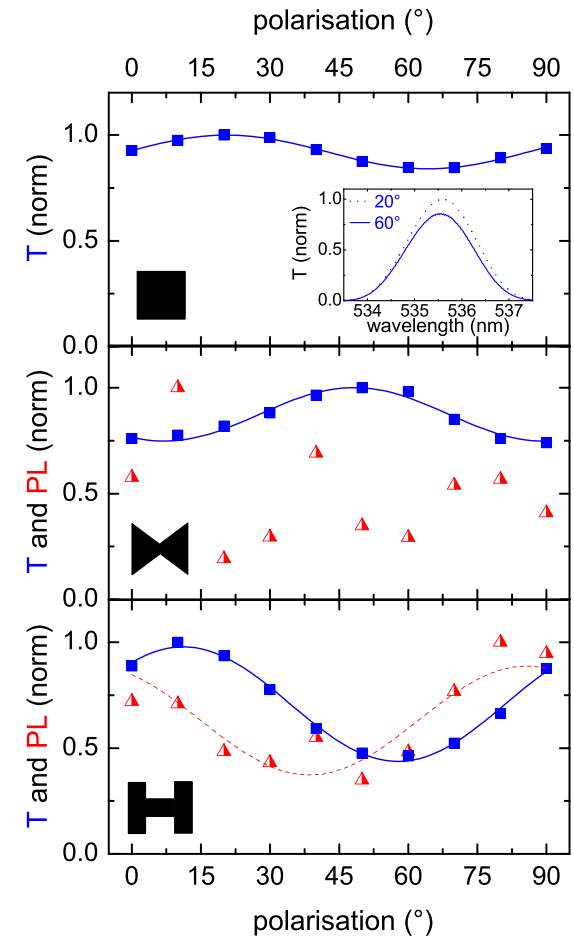
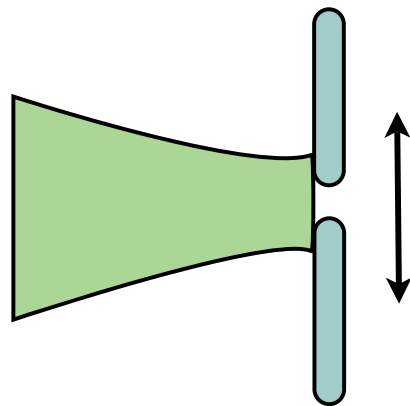
## Cross Section



# Polarisation Dependance of Transmitted Light



Nanoapertures with broken symmetry show polarisation dependent transmission



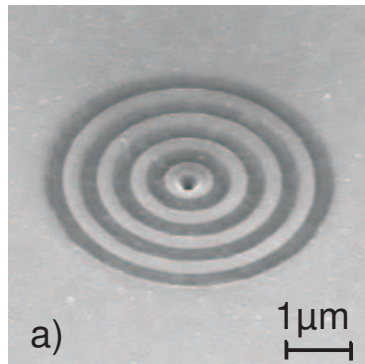
# Collimated Emission through Nanoholes

Nanostructure < light wavelength  
=> point light source ( $4\pi$ )

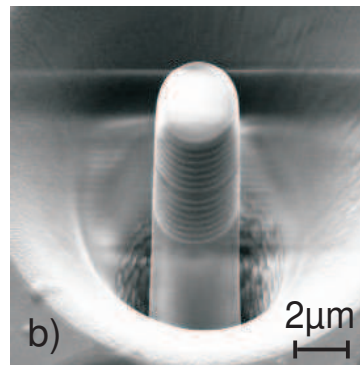
Waveguiding in special „bullseye“ structures  
emit collimated light beam

(PRL 90, 167401 (2003) L. Martin-Moreno)

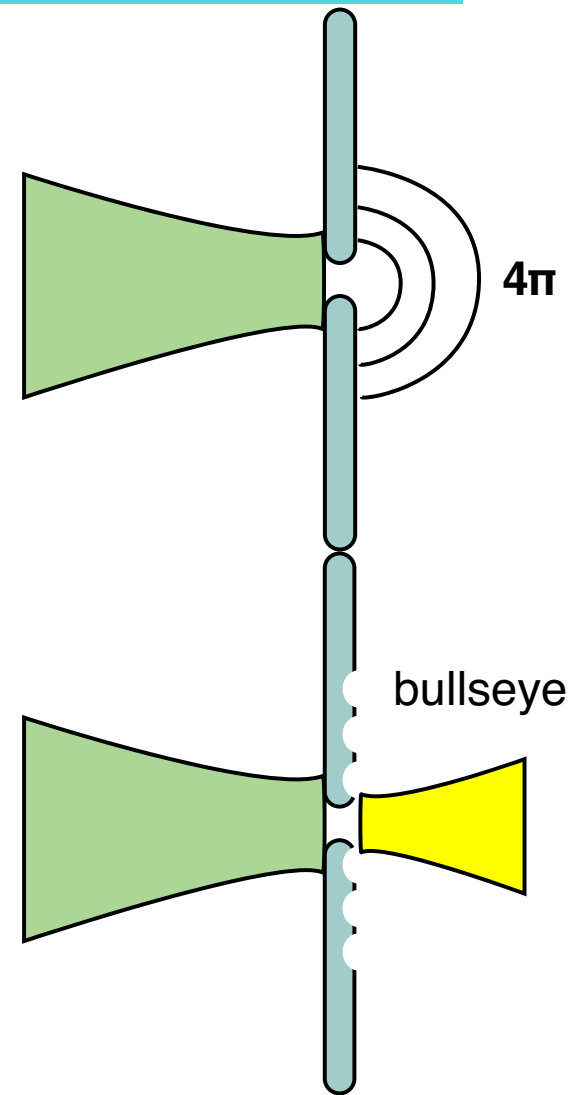
-> higher detection efficiency



**bullseye**



**micropillar**



## 1. Dielectric Microresonator Structures

- **Planar Resonators:**

$Q=8200$

- **Micropillar Resonators:**

detection and calculation of optical modes

- **Coupled Photonic Structures:**

additional modes in mode spectrum

M. Kahl et al, Nano Lett. 7(9), 2897 (2007)

## 2. Metal Nanoapertures

- **Circular Nanoholes:**

diameter 50 - 300 nm, cone-shaped cross section

- **H-shapes Nanoapertures:**

polarisation dependent transmission

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# Thank You!

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*University of Konstanz*

Alfred Leitenstorfer

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