On-Chip Quantum Optics using Electrically Driven Quantum Dot - Micropillar Cavities

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Acknowledgement

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Technische Physik, Universität Würzburg, Germany

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Universität Magdeburg, Germany

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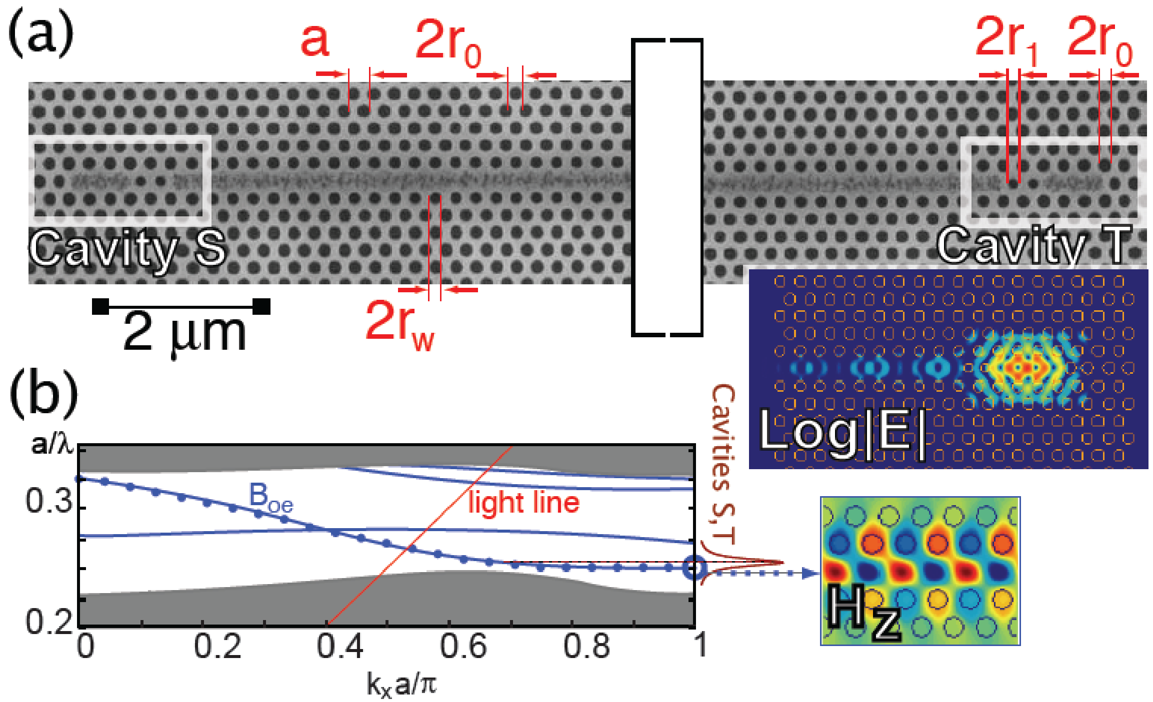
SEVENTH FRAMEWORK PROGRAMME

Motivation

- On-chip photonic networks: central topic in modern nanotechnology
- Goal: On-chip integration of linear elements, non-linear elements, detectors, light sources …

On-chip transfer of single photons in photonic crystals



D. Englund, et al., Opt. Express 15, 5550 (2007)

Motivation

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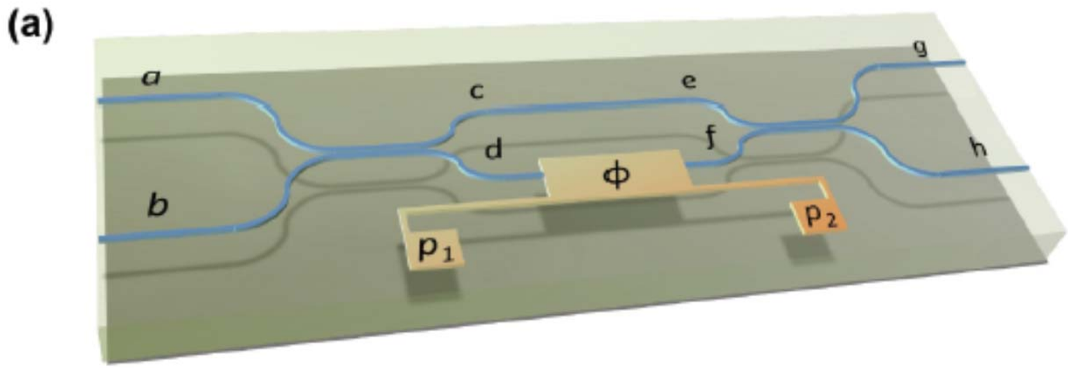
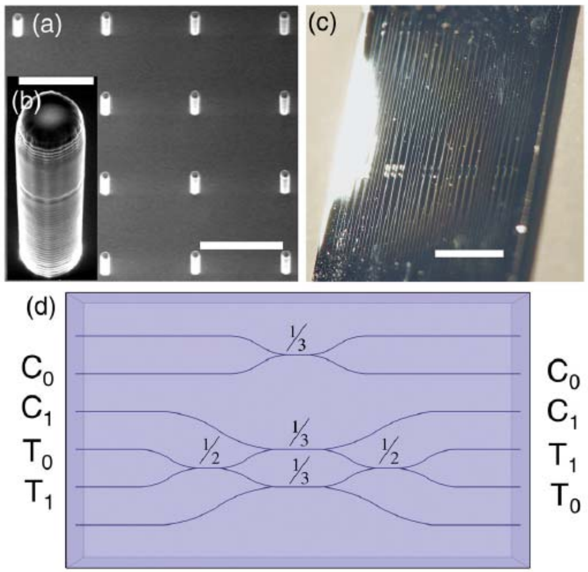
Implementation of quantum operations using coupled waveguides

Multi-photon entanglement



J. C. F. Matthews et al., Nat. Phot. 3, 346 (2009)

CNOT gate



M. A. Pooley et al, APL 100, 211103 (2012)

Motivation

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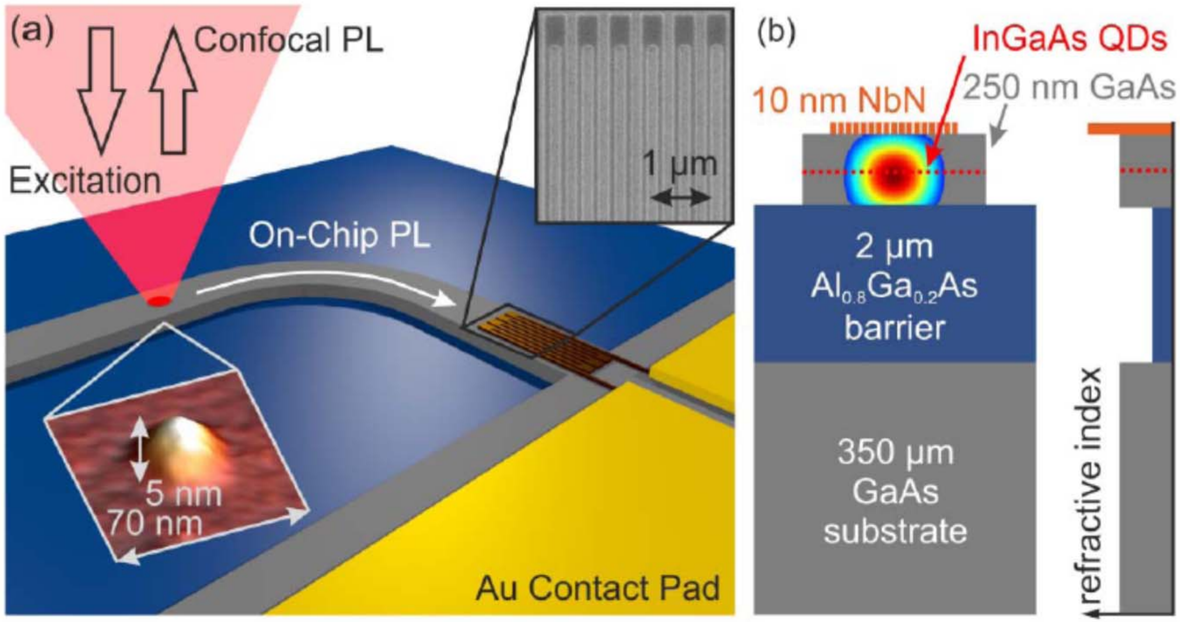
Monolithically integrated photon detector



G. Reithmaier et al., Scienitific Reports 3, 1901 (2013), see **ThOM3**

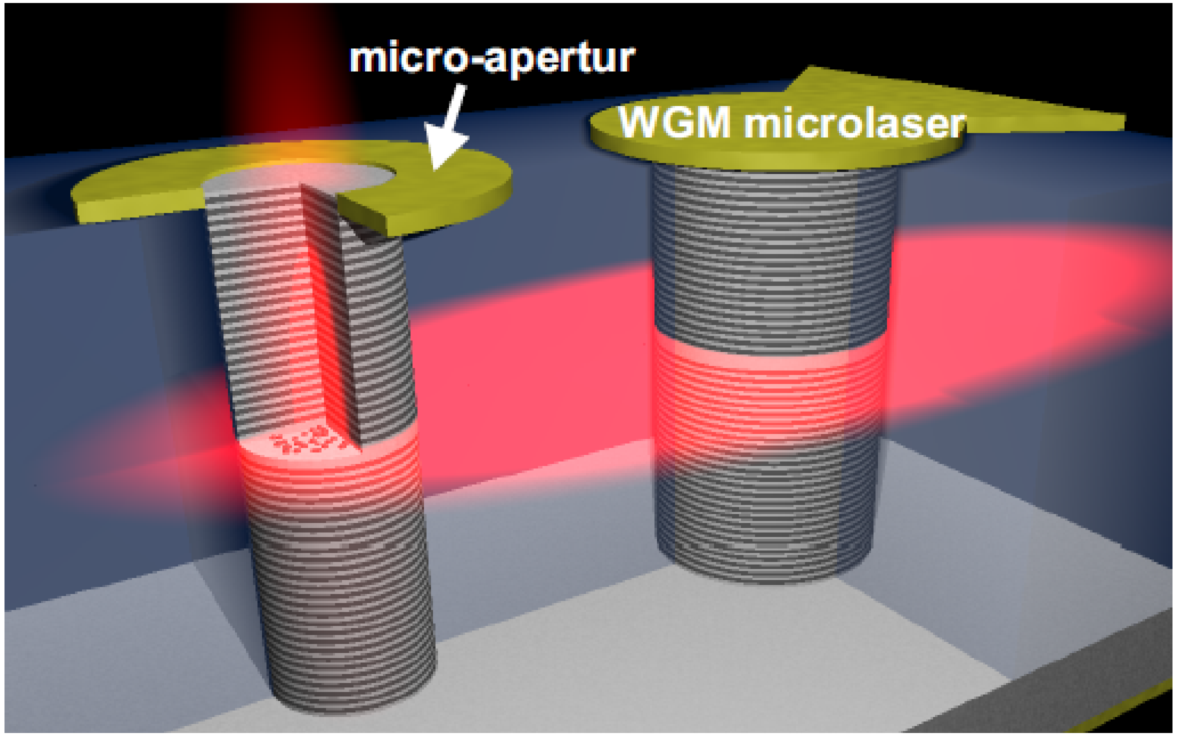
Motivation

- On-chip photonic networks: central topic in modern nanotechnology
- Goal: On-chip integration of linear elements, non-linear elements, detectors, light sources …
- So far: lack of suitable monolithically integrated, electrically driven light sources

Our approach:

On-chip quantum optics experiments and non-classical light sources using integrated electrically driven micropillar lasers for resonant excitation of coupled QD - microcavities

On-Chip Quantum Optics Approach Using Micropillar Cavities

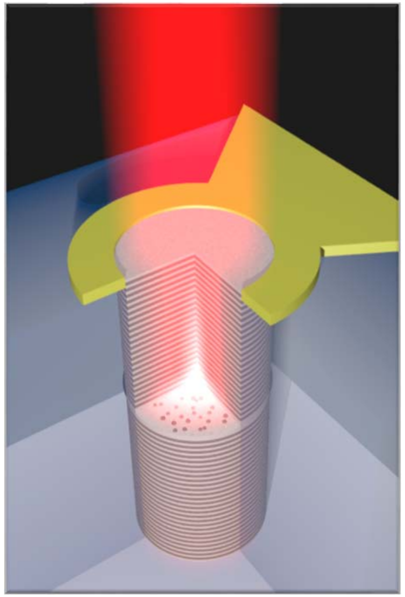


Outline

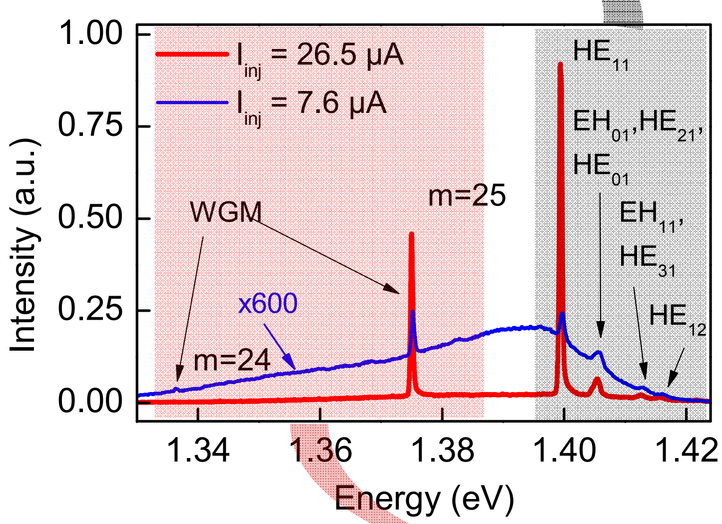
- Motivation
- Introduction & Technology
- On-chip quantum optic experiments using an integrated WGM laser
- Directional lateral emission from Limaçon microlasers
- Deterministic in-situ electron-beam lithography
- Outlook & Summary

Vertical & Lateral Emission from QD – Micropillar Cavities

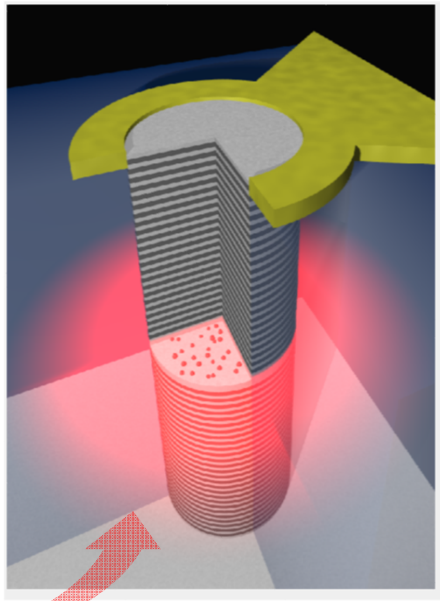
Vertical (HE_{11}, …) – emission from micropillar lasers



Co-existence of HE11- and WGM-Lasing:



Lateral WGM – emission from micropillar lasers



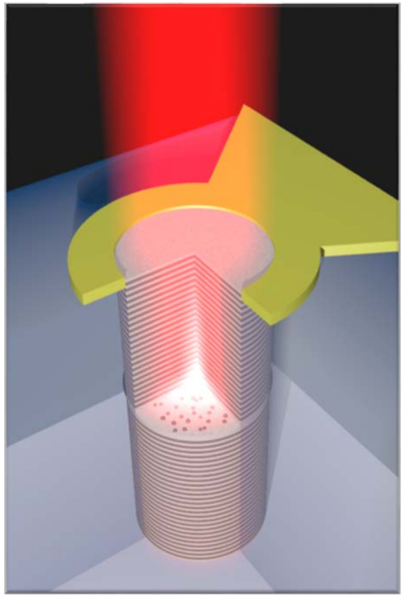
Low-threshold (few µA), high-β (~0.1) via HE11 AND WGM modes!

S. Reitzenstein et al., APL 93, 061104 (2008)
Efficient SPS: T. Heindel et al., APL 96, 011107 (2010)

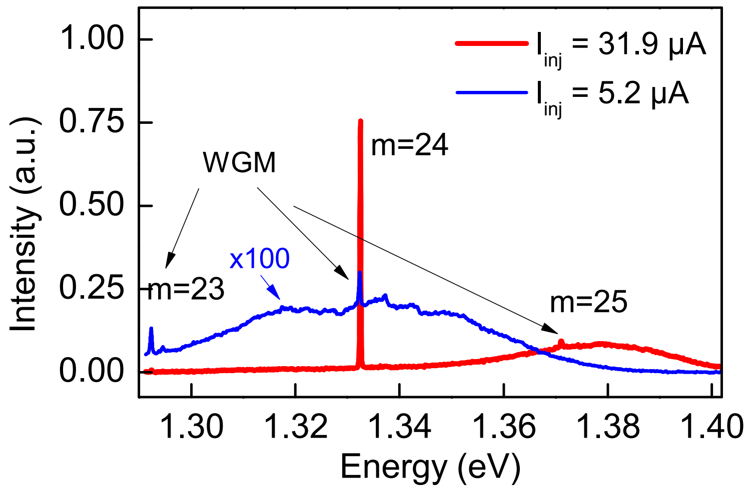
F. Albert et al., APL 97, 101108 (2010)

Vertical & Lateral Emission from QD – Micropillar Cavities

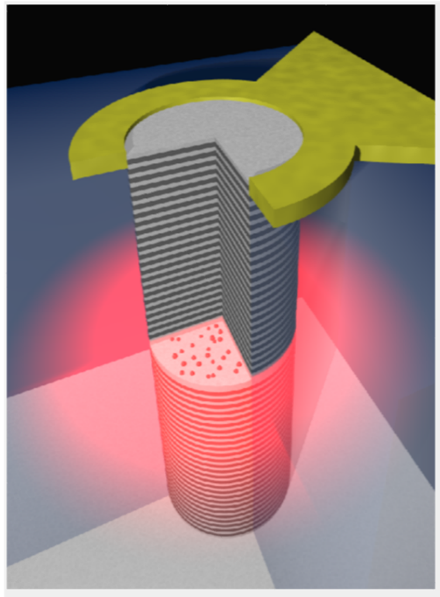
Vertical (HE_{11}, …) – emission from micropillar lasers



Pure WGM-Lasing:



Lateral WGM – emission from micropillar lasers



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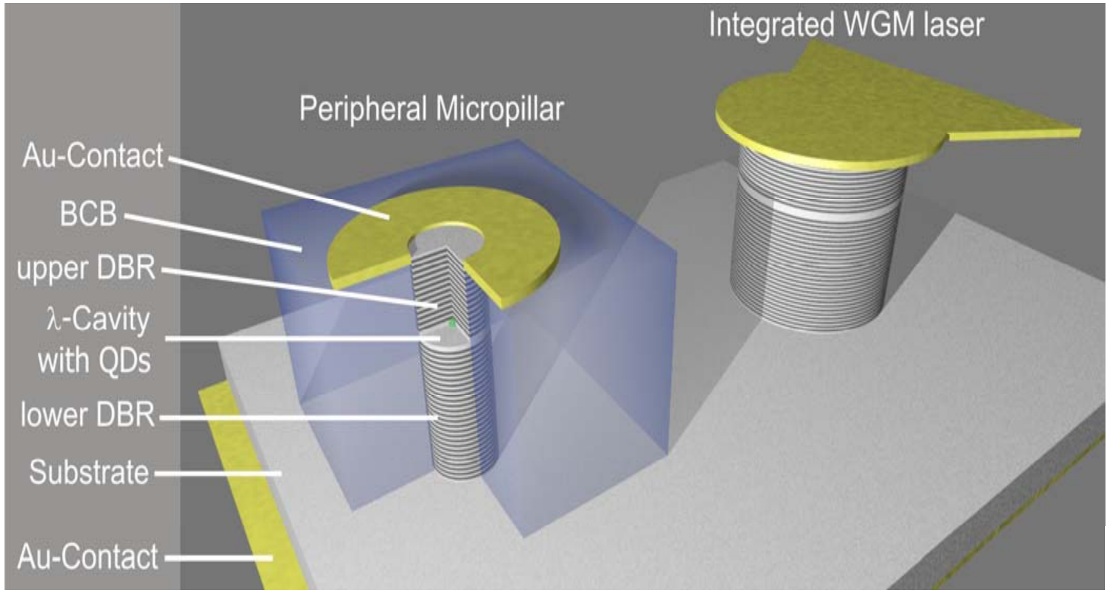
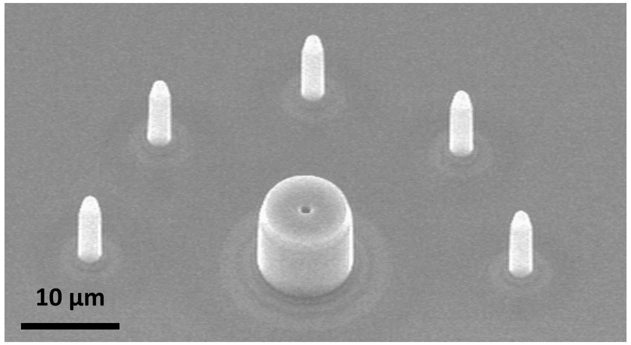
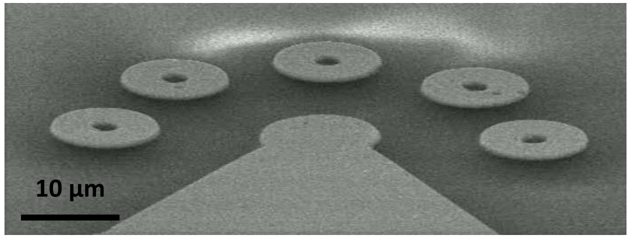
F. Albert et al., APL 97, 101108 (2010)

Sample Fabrication



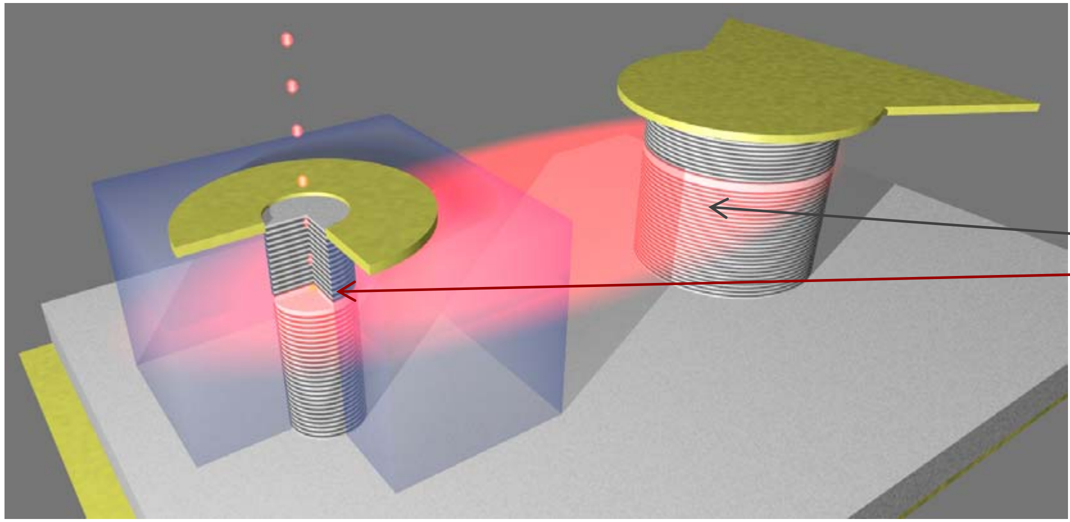


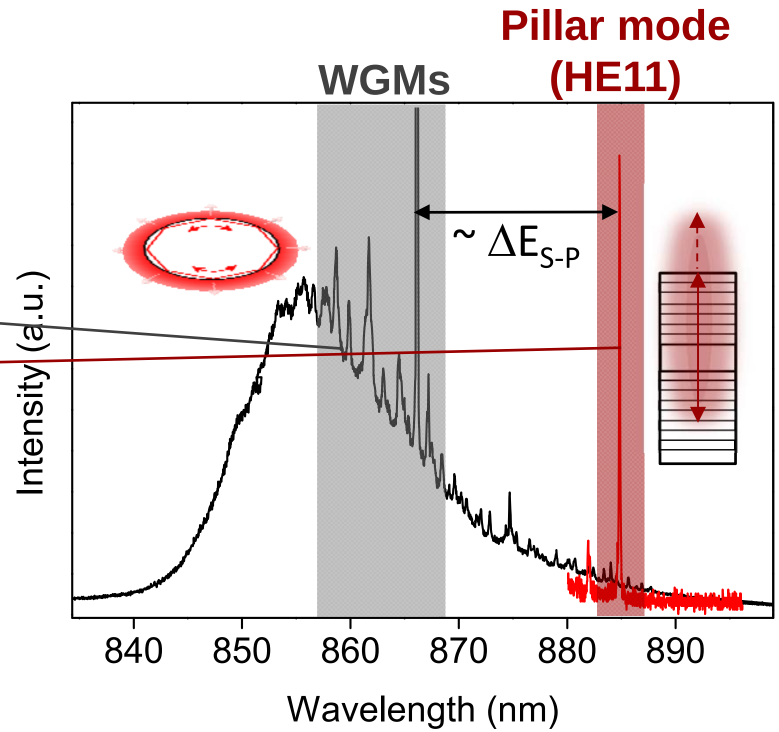


- High-Q, doped planar AlAs/GaAs-microcavity structure
- Single layer of self-assembled InGaAs QDs
- Electrically driven WGM microlaser at the center (6.0 µm diameter)
- In-plane excitation of five peripheral “target” micropillar cavities (1.6 - 2.5 µm diameter)

Sample growth and processing: Technische Physik, Universität Würzburg, Germany

Optical Mode Design & QD Gain Characteristics



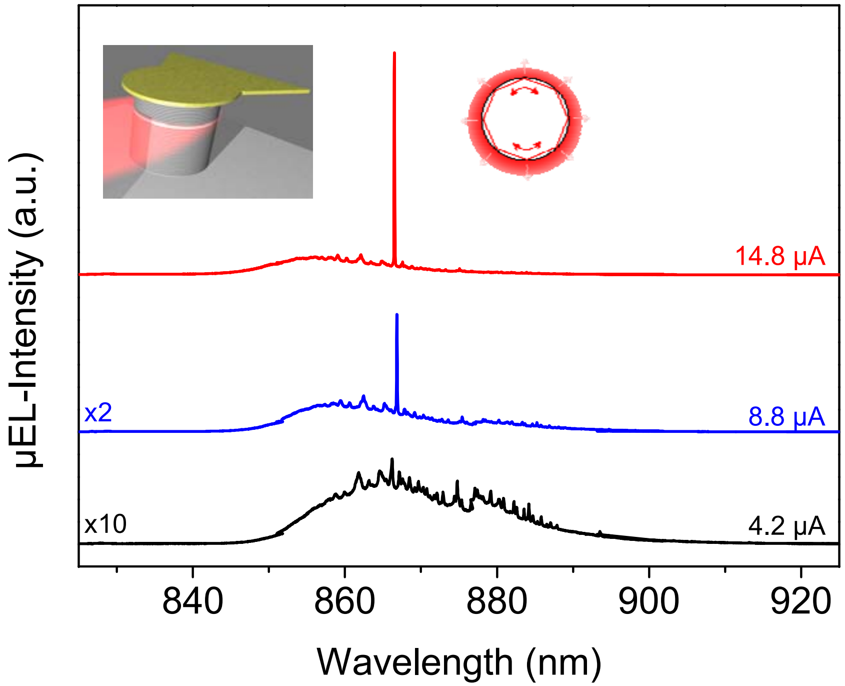


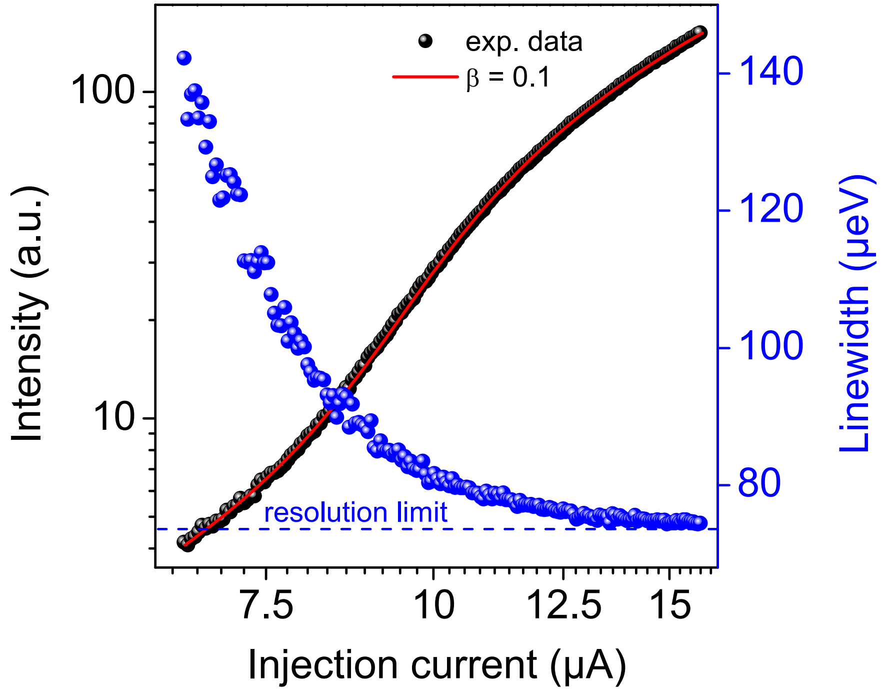
Technological Challenges:

- Design planar microcavity and active QD medium to provide sufficient gain for WGM lasing AND the possibility of single-QD cQED experiments
- Ensure that WGM microlaser emits at p-shell energy of single QDs

  (p-shell excitation: beneficial for the generation of indistinguishable photons)
- State-of-the-art processing with very high yield

Integrated Electrically Driven WGM-Microlaser



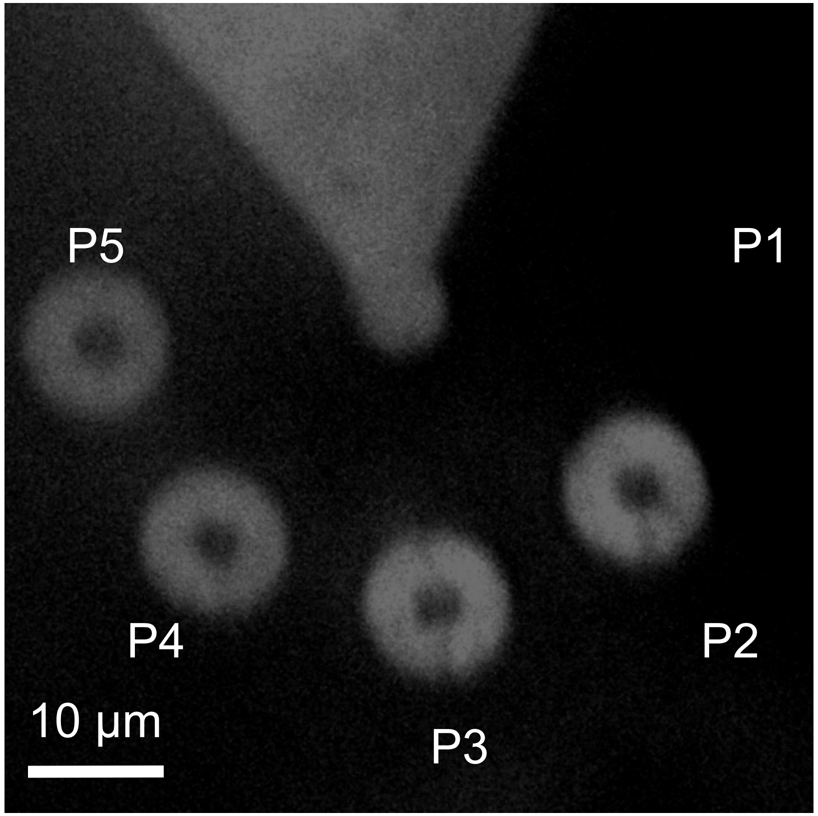


Electrically pumped central micropillar (T = 15K):

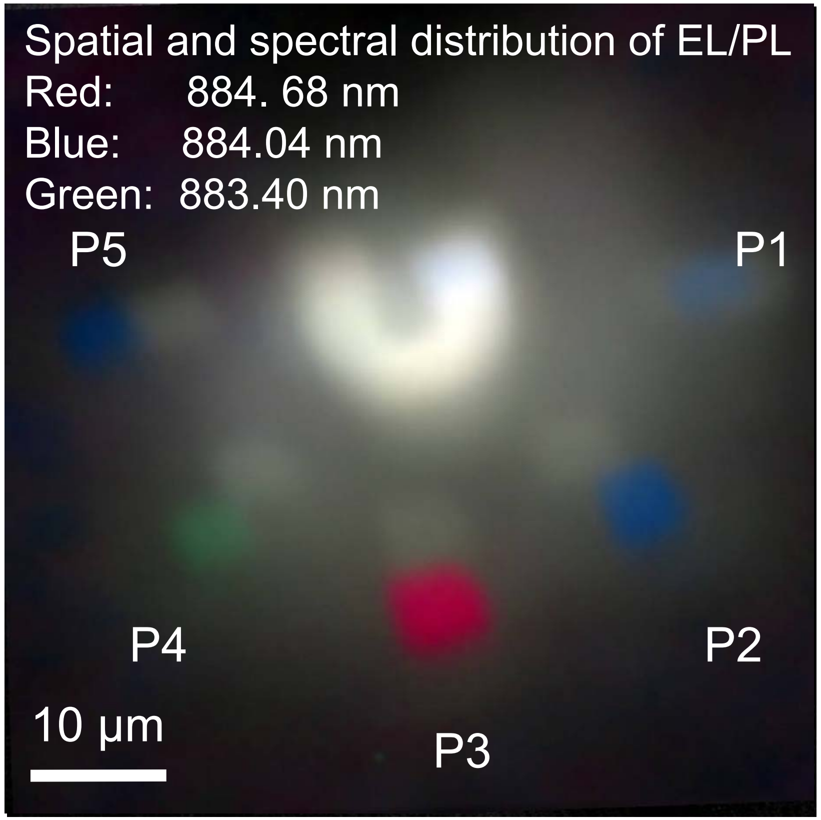
- μEL features WGM-lasing with ultralow threshold current of $I_{th} \approx 8$ μA and $\beta = 0.1$
- Single mode WGM lasing at $\lambda = 866.5$ nm

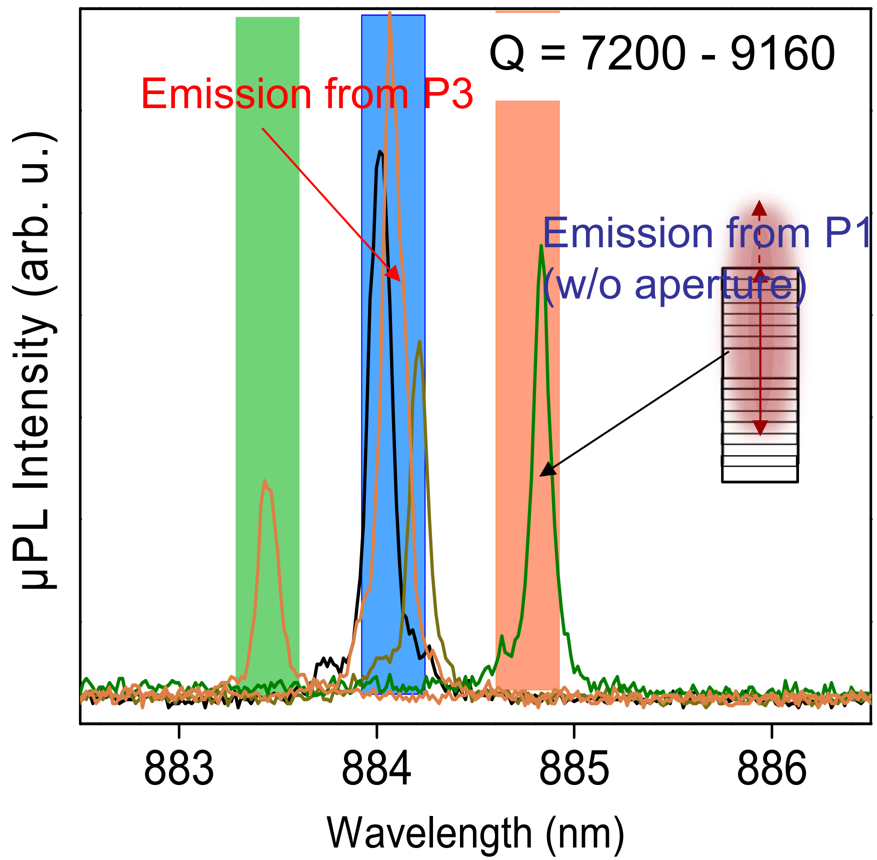
Central micropillar:
High-β WGM microlaser acts as low-threshold on-chip microlaser

In-plane Excitation of Peripheral Micropillars



In-plane Excitation of Peripheral Micropillars

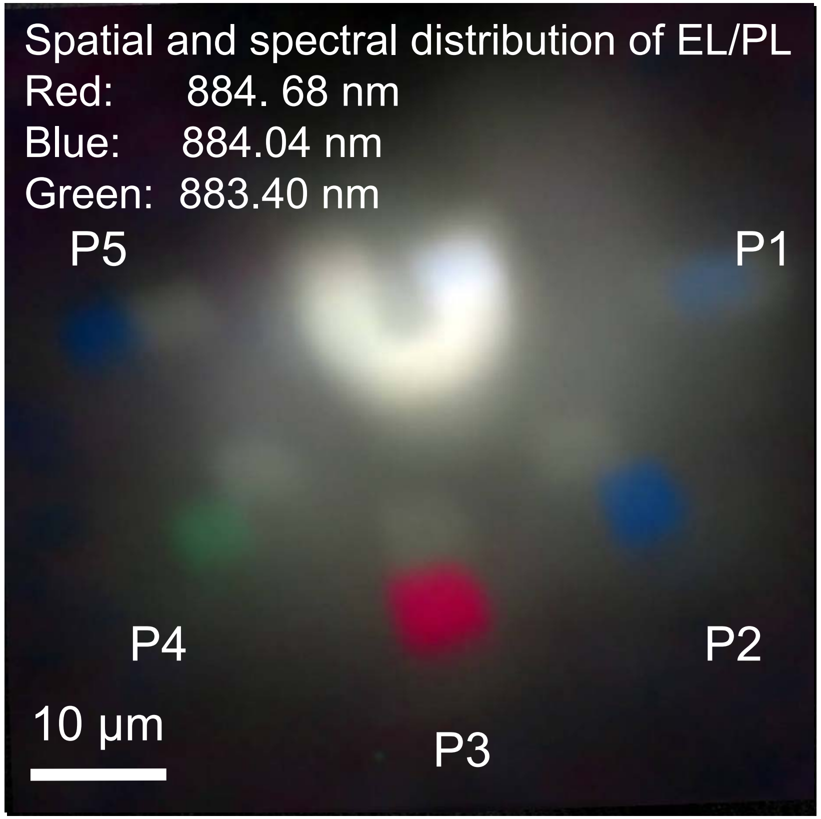


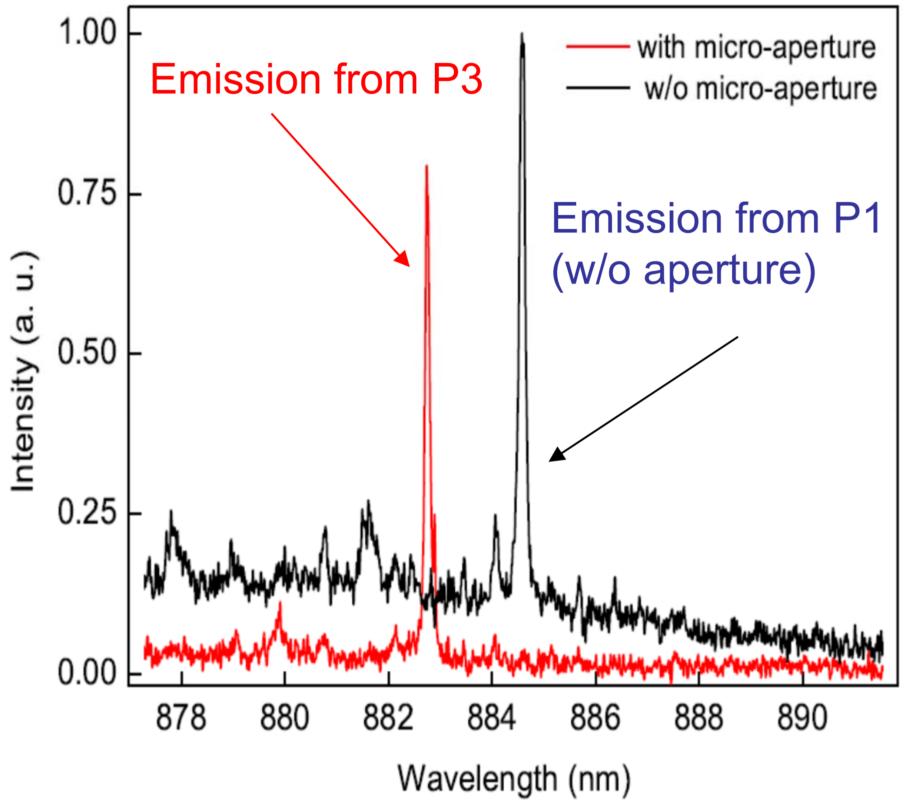


Peripheral micropillars (d_C = 2.5 µm):

- µPL of peripheral micropillars under WGM-microlaser excitation @ 867 nm
- Absorption limited Q-factors close to 10.000

In-plane Excitation of Peripheral Micropillars

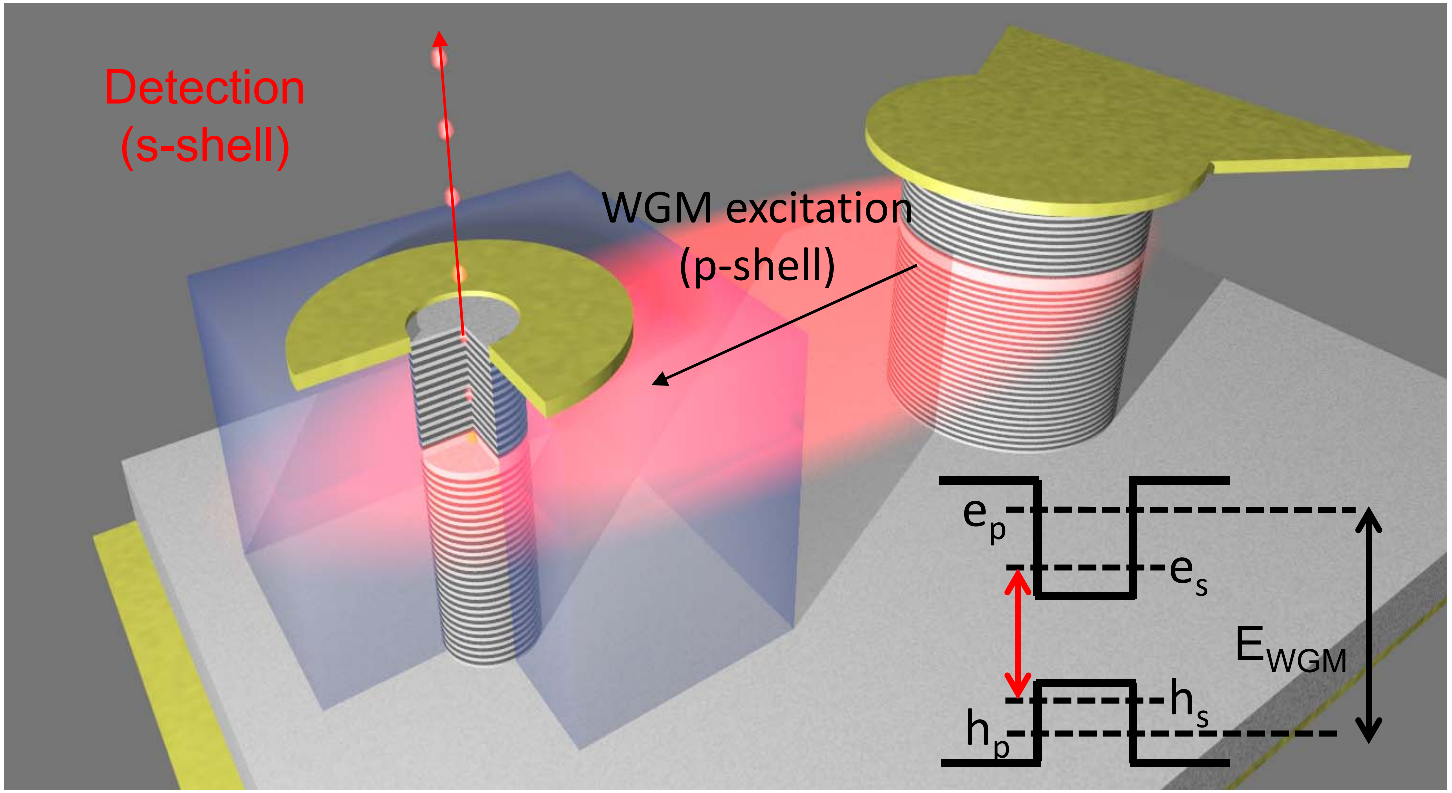




Peripheral micropillars (d_C = 2.5 µm):

- µPL of peripheral micropillars under WGM-microlaser excitation @ 867 nm
- Absorption limited Q-factors close to 10.000
- Supression of stray light from WGM laser by microaperture

Resonant Excitation – On-Chip μPLE



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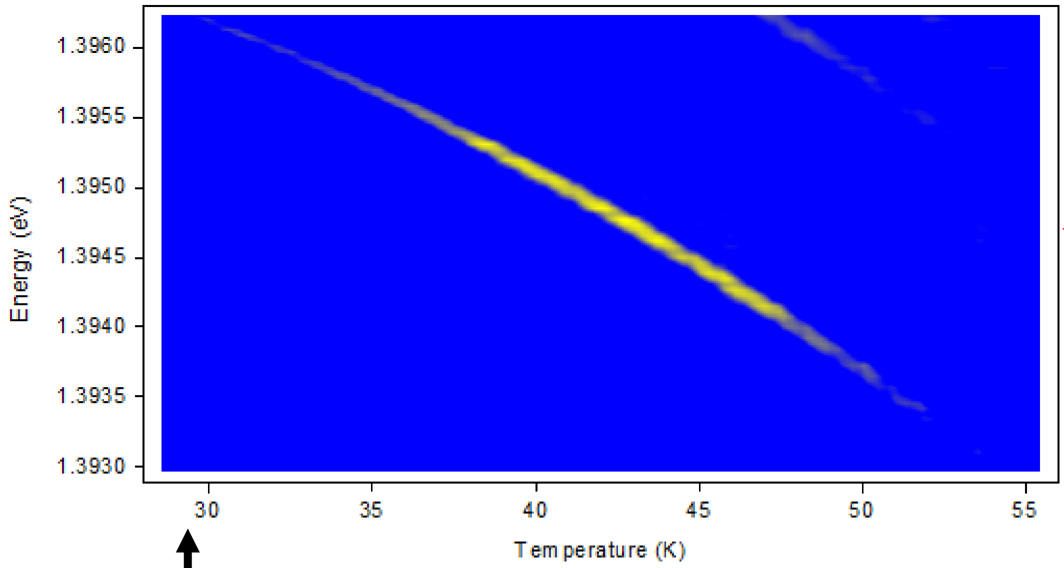
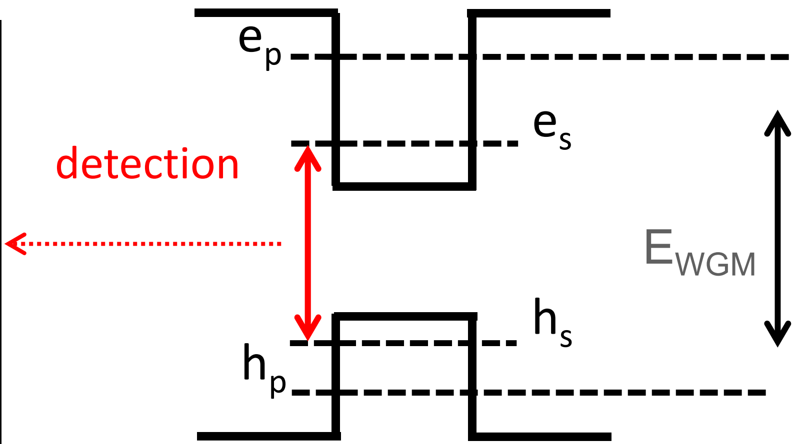
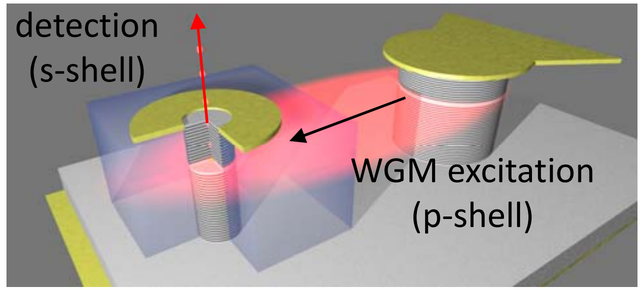






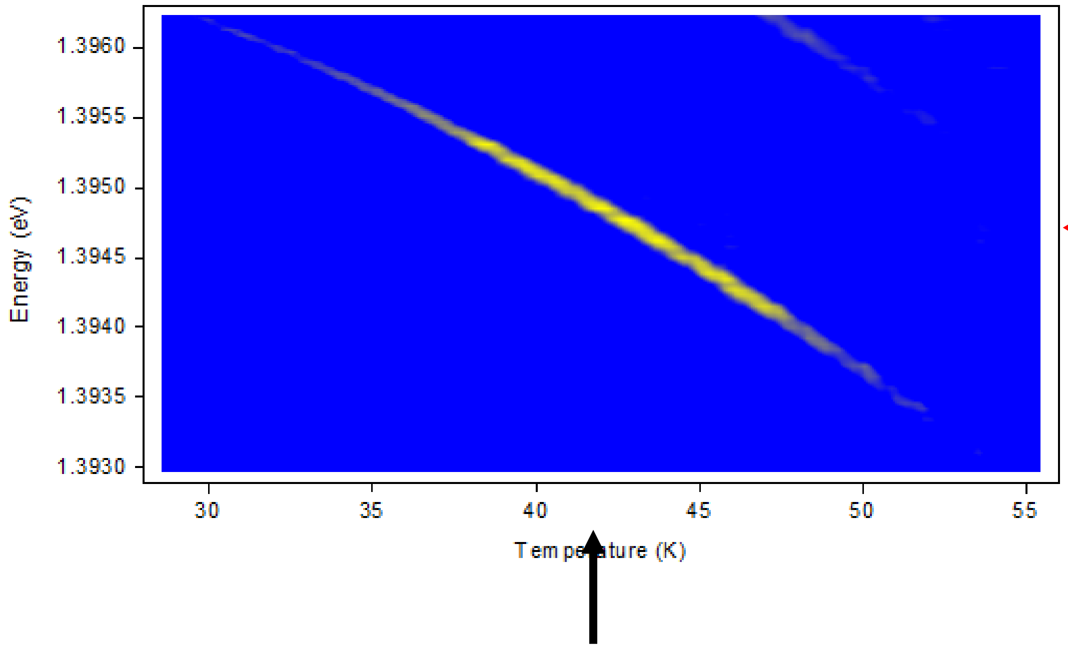
µPL of peripheral micropillar:

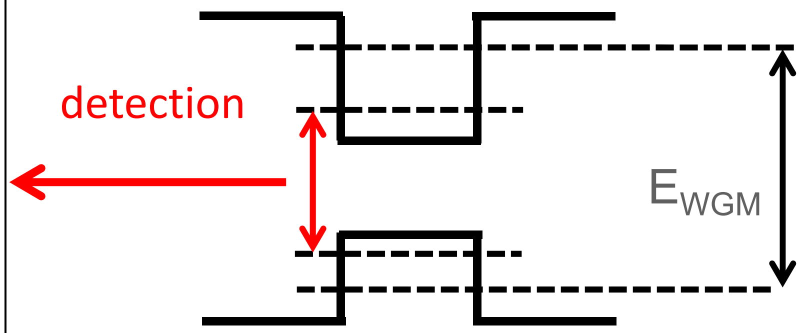
- Excitation by fixed WGM mode at E_{WGM} =1.426 eV
- Temperature variation → resonant s-shell emission when $E_{p\text{-shell}} = E_{WGM}$

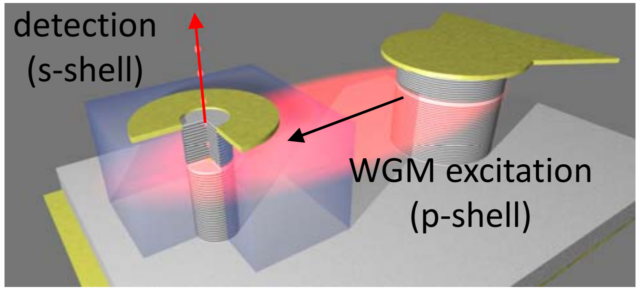
⇒ Resonant excitation of QD when WGM laser-mode hits p-shell of QD in micropillar at T_{res} ≈ (40 - 45) K (s-p-splitting: ≈ 20 nm, 31 meV)

E. Stock et al., Adv. Materials **25**, 707–710 (2013)

Resonant Excitation – On-Chip μPLE







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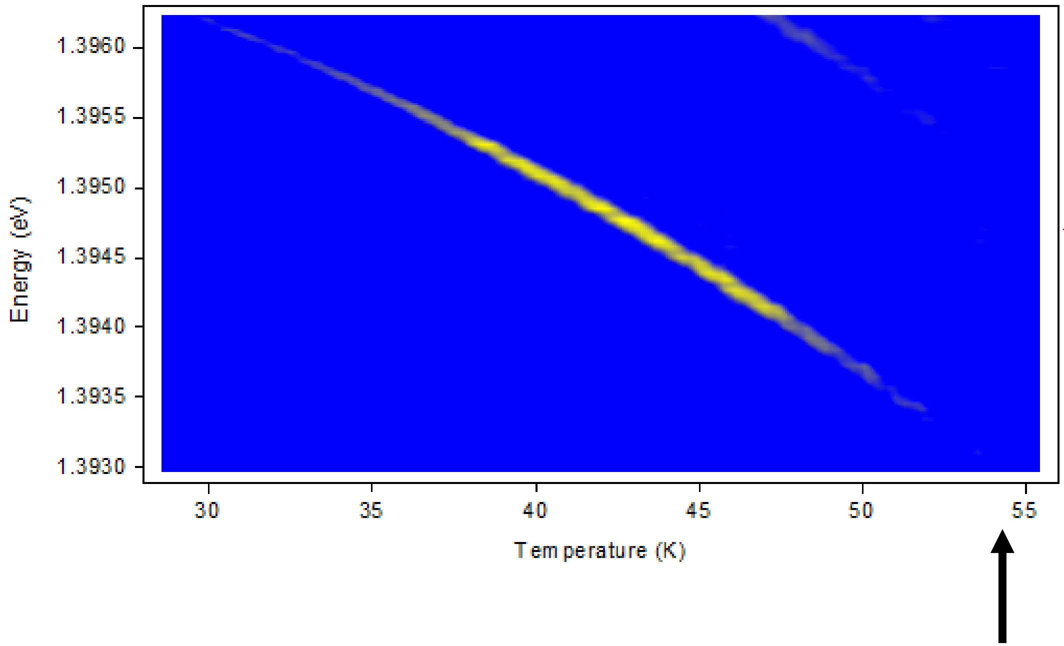
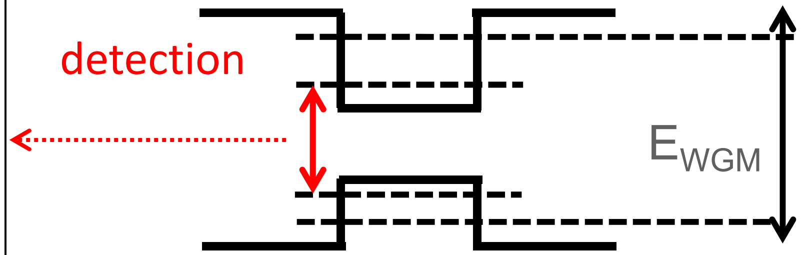
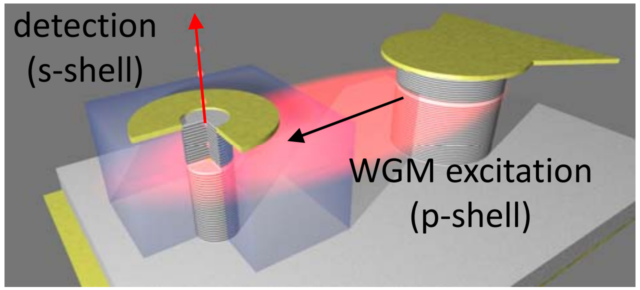
Resonant Excitation – On-Chip μPLE







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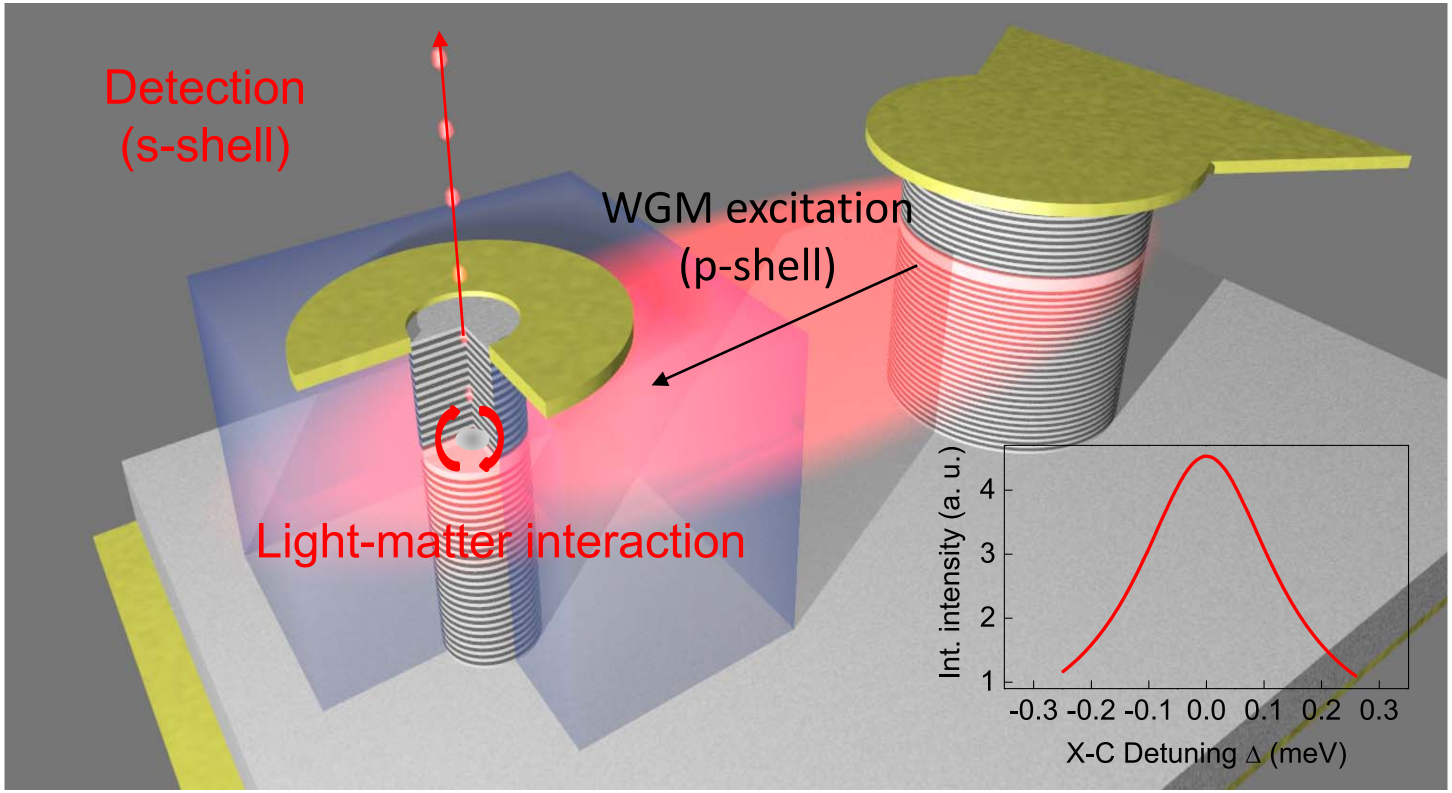
⇒ Resonant excitation of QD when WGM laser-mode hits p-shell
of QD in micropillar at $T_{res} \approx$ (40 - 45) K (s-p-splitting: ≈ 20 nm, 31 meV)

E. Stock et al., Adv. Materials **25**, 707–710 (2013)

On-chip cQED - Weak Coupling Regime



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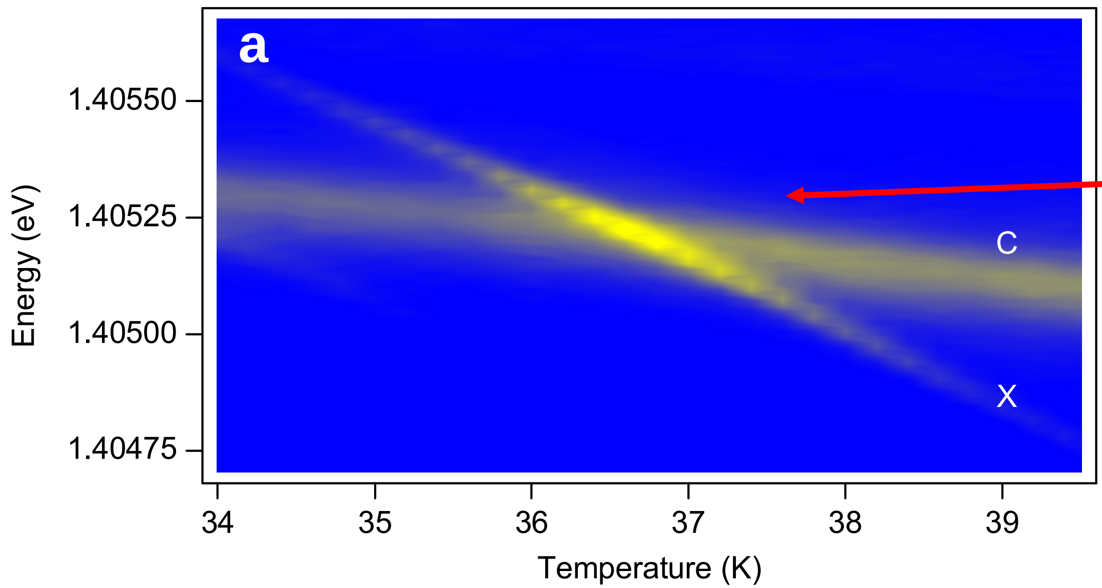
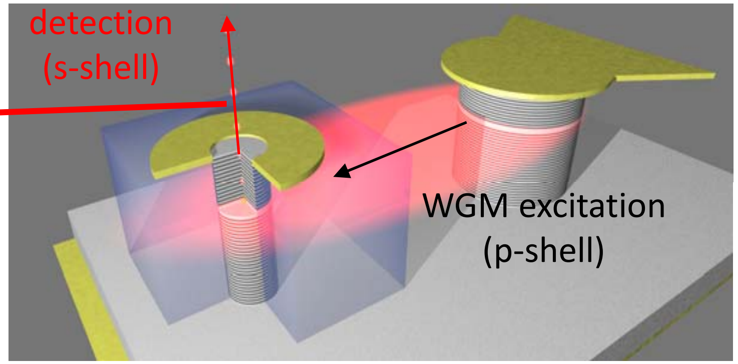


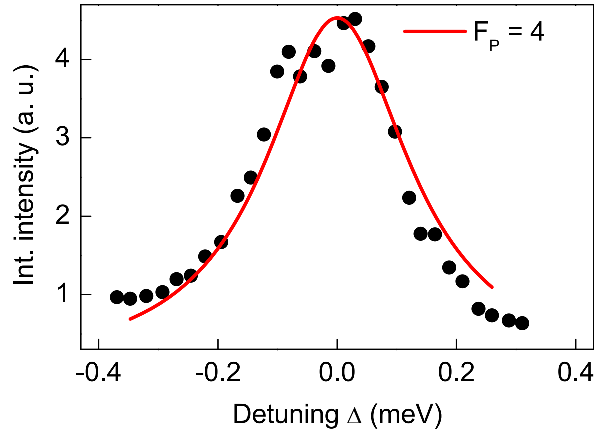


El. pumping of micropillar by WGM laser-mode at 1.431 eV

⇒ In-plane p-resonant excitation of QD in micropillar

⇒ Strong enhancement of X-emission at T_{res} = 36.5 K

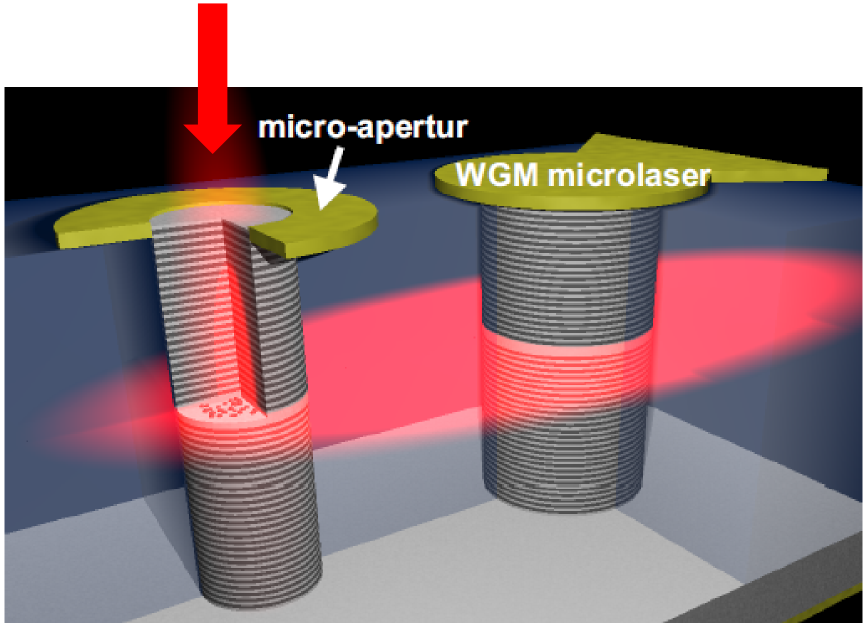
⇒ Purcell factor: F_P = 4

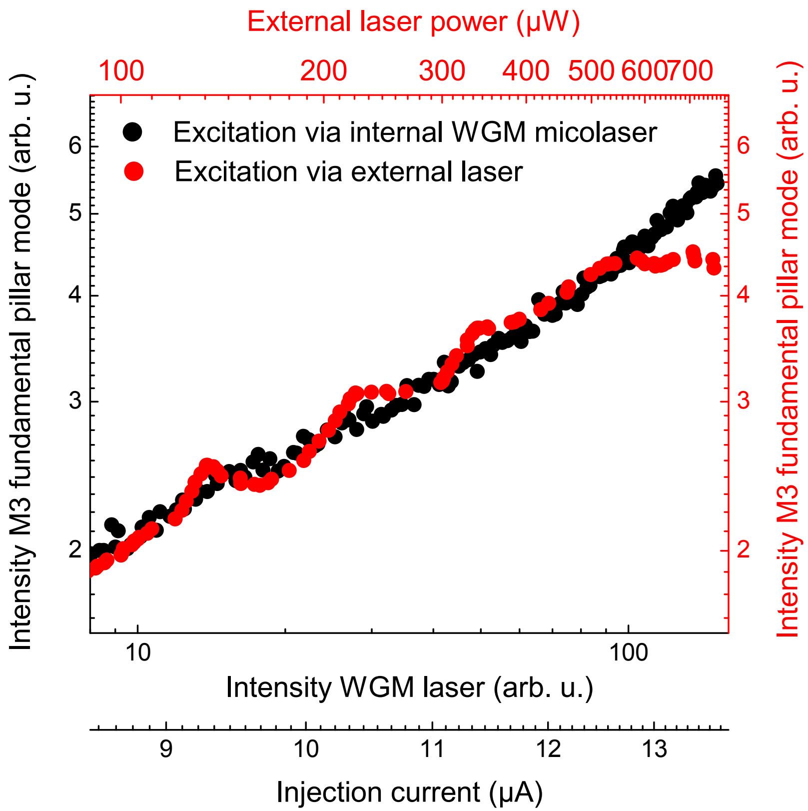


E. Stock et al., Adv. Materials **25**, 707–710 (2013)

About Excitation Efficiency

External laser



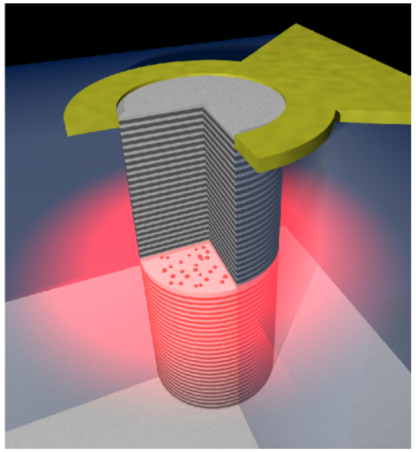


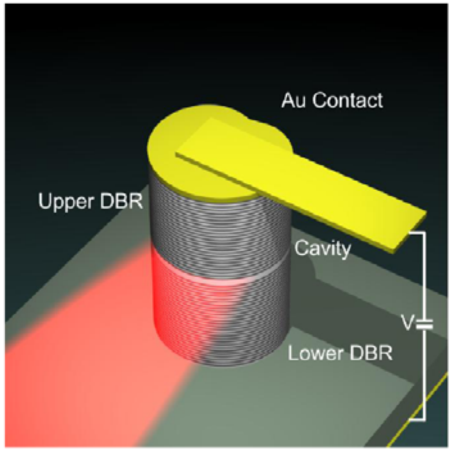
Comparison: Excitation of peripheral micropillar

via external laser vs. internal WGM microlaser, both at 867 nm

External powers between 100 and 700 μW ↔ injection currents between 9 – 13 μA

A Way to Enhance Excitation Efficiency: Directional Lateral WGM Lasing via Limaçon Cross-Section

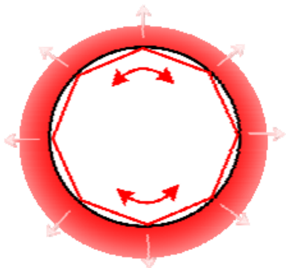


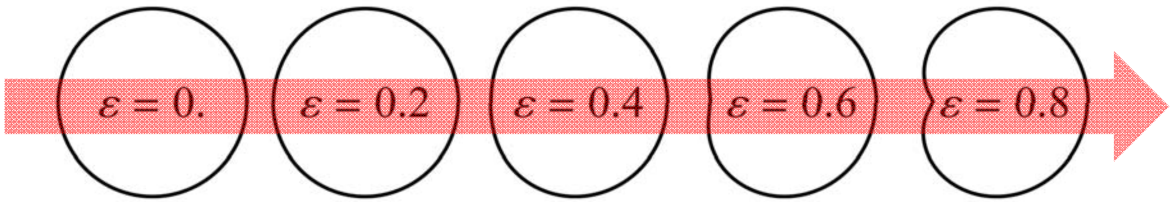


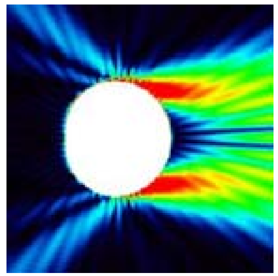
Enhancement of coupling efficiency via directional in-plane emission

→ Deterministic deformation of micropillar cross-section by Limaçon shape:

$$R(\theta) = R_0(1 + \varepsilon\, cos\theta)$$

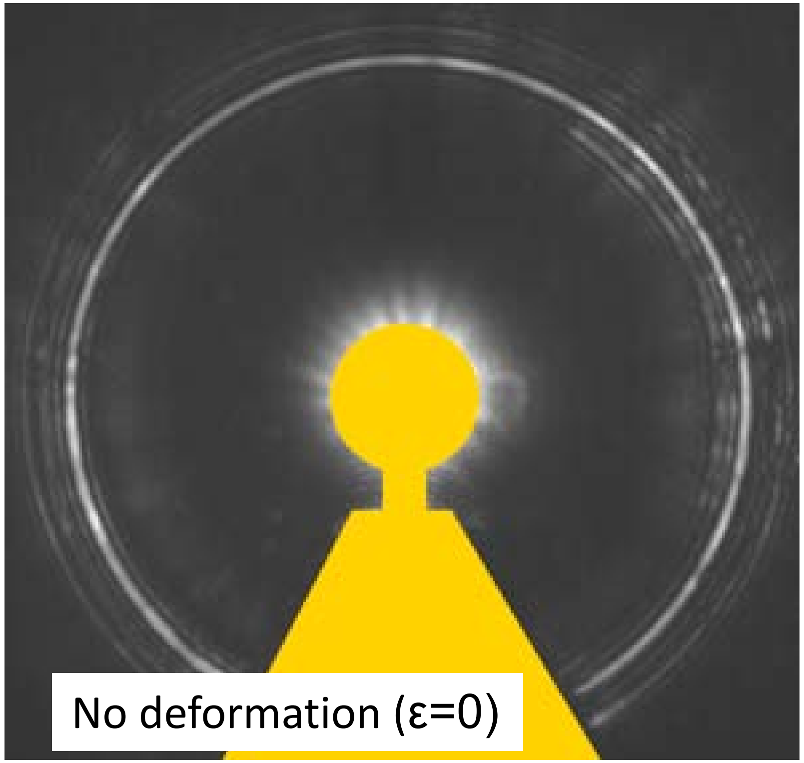


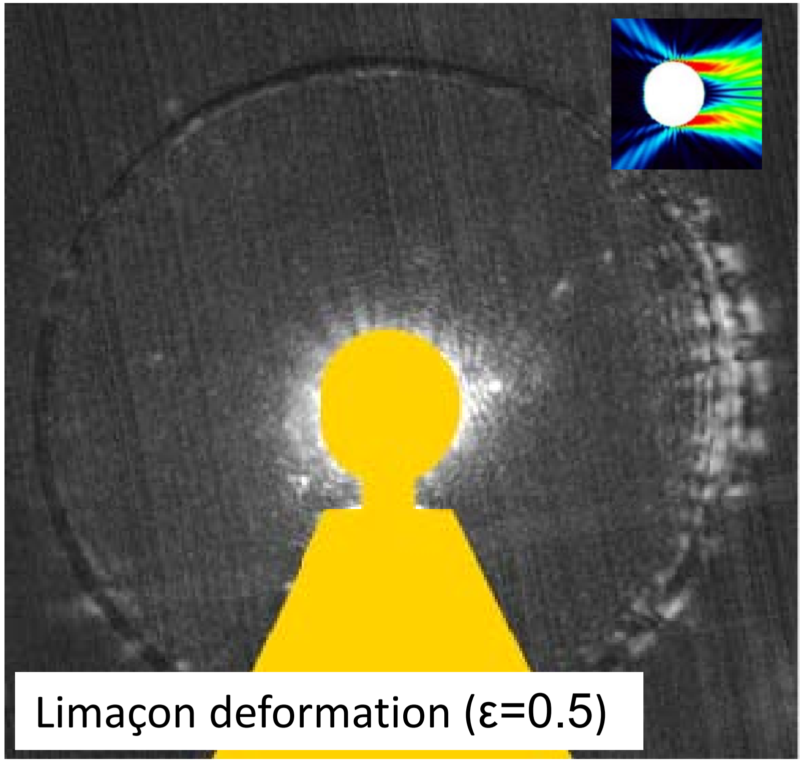




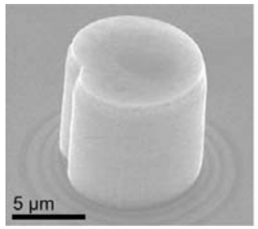
J. Wiersig and M. Hentschel, PRL 100 (2008)

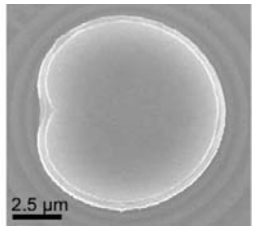
Directional emission from WGM microlasers





Limaçon deformation ($\varepsilon \approx 0.5$) clearly leads to directional in-plane emission!

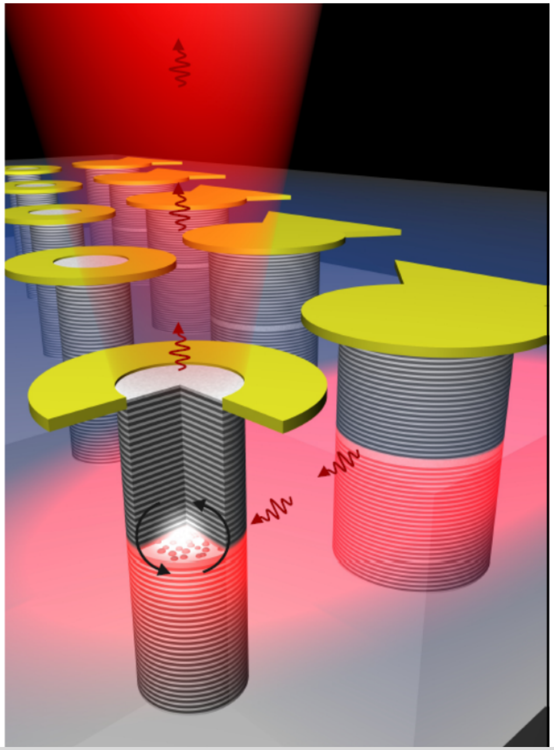




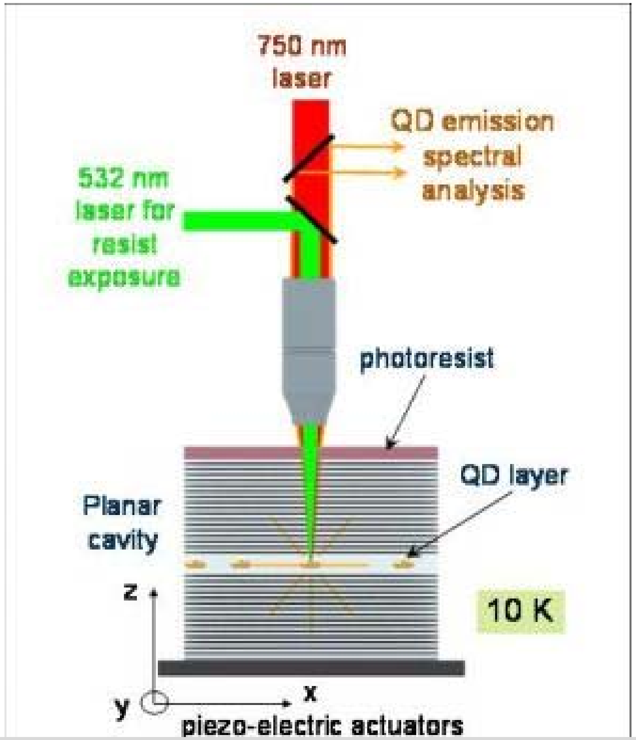
F. Albert et al., Appl. Phys. Lett. 101, 21116 (2012)

Outlook – Deterministic Fabrication Technology

Arrays of quantum light sources
req. spectral and spatial QD-cavity matching



In-situ optical lithography,
A. Dousse et al., PRL 2008

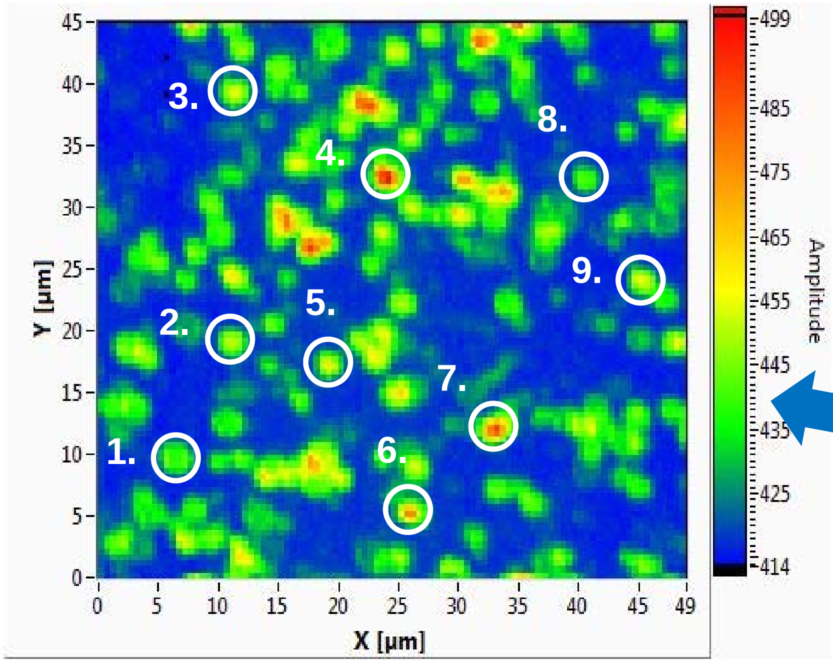


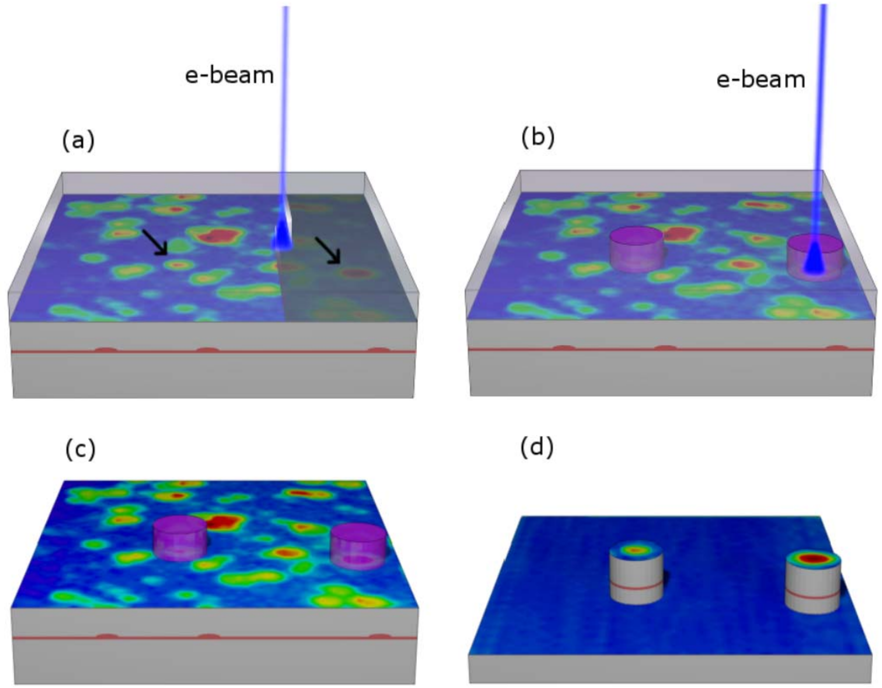
Alternative concept:
Deterministic high-resolution electron beam lithography using low temperature cathodoluminescence

Cf.: In-situ nanowire lithography, F. Donatini & Le Si Dang, Nanotechnology 2010

In-situ, High-Resolution Cathodoluminescence-Lithography

CL-map during CL-lithography





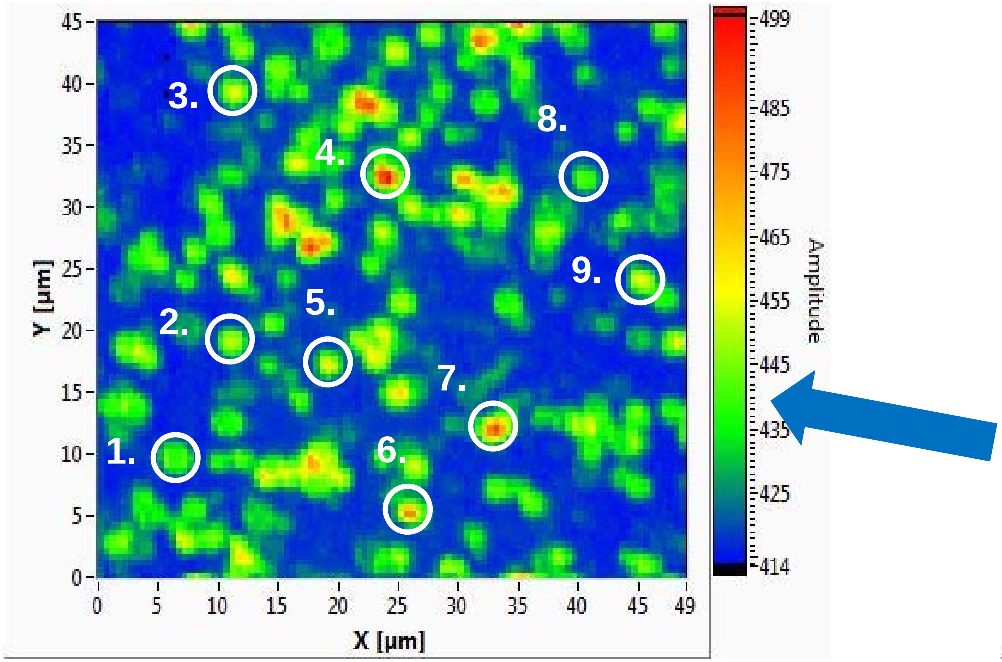
Deterministic fabrication of single QD – structures:

- CL-scanning of InGaAs-QD sample to identify suitable QDs (a)
- In-situ e-beam writing of mesas with < 500 nm diameter (b)
- Development (c)
- CL and µPL to characterize single-QD mesas -> linewidths < 10 µeV, $g^{(2)}(0)<0.05$

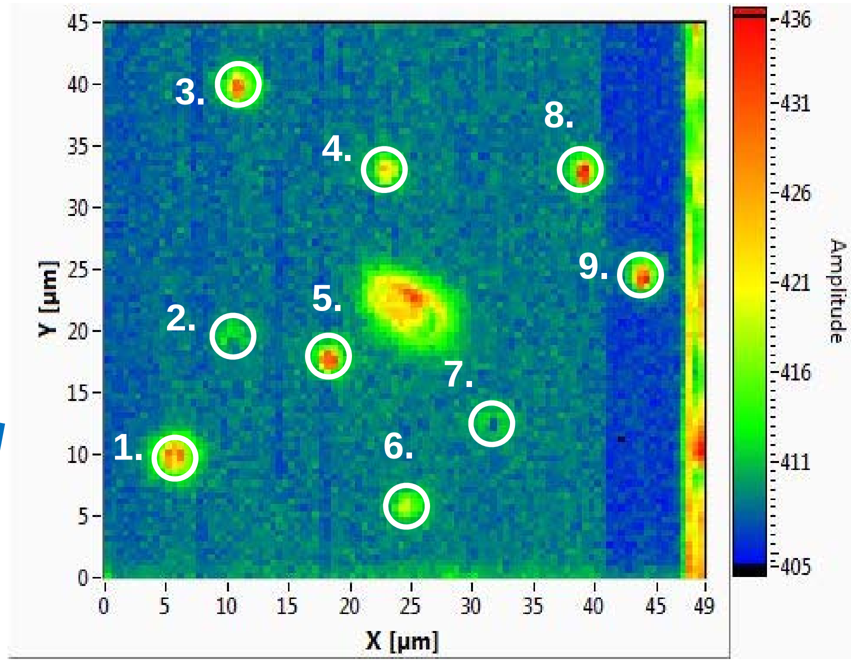
M. Gschrey et al., Appl. Phys. Lett. 102, 251113 (2013), more information: **ThP156**

In-situ, High-Resolution Cathodoluminescence-Lithography

CL-map during CL-lithography



CL-map after CL-lithography



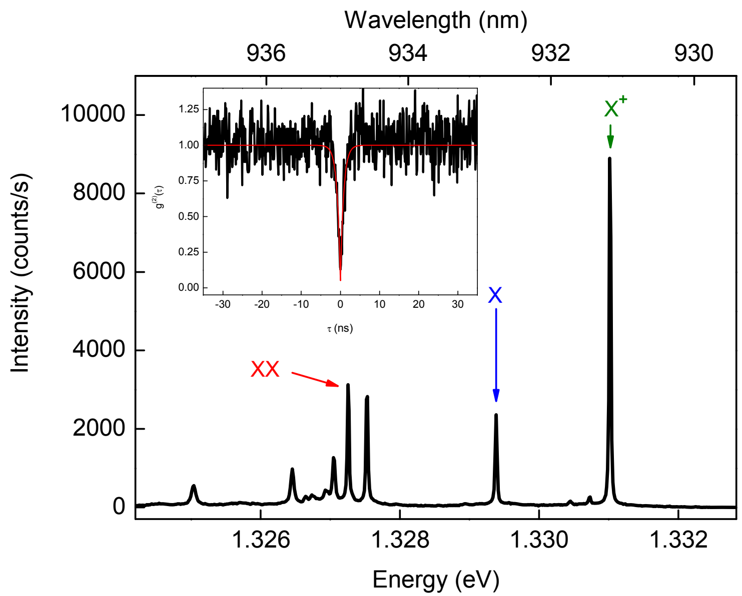
Deterministic fabrication of single QD – structures:

- CL-scanning of InGaAs-QD sample to identify suitable QDs (a)
- In-situ e-beam writing of mesas with < 500 nm diameter (b)
- Development (c)
- CL and µPL to characterize single-QD mesas -> linewidths < 10 µeV, $g^{(2)}(0)<0.05$

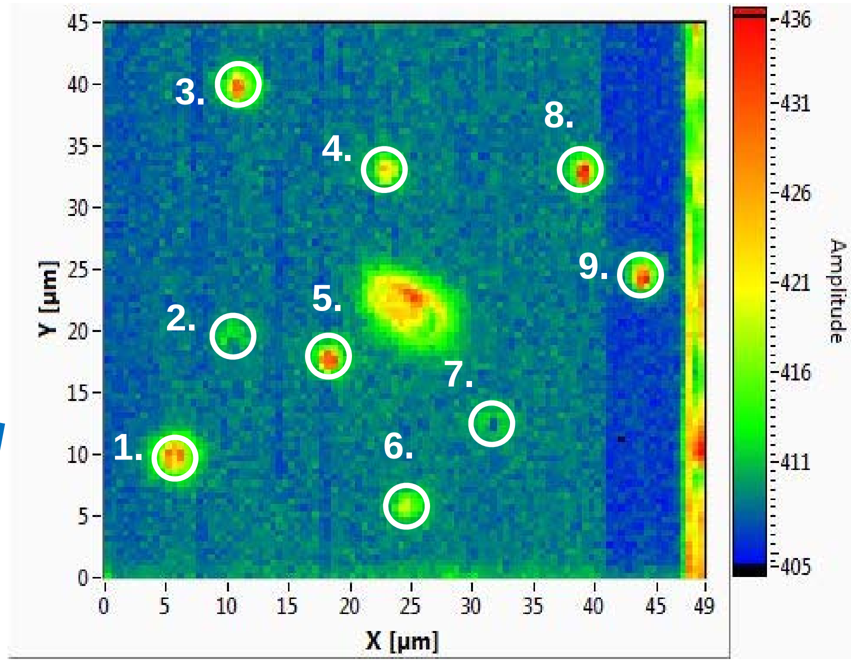
M. Gschrey et al., Appl. Phys. Lett. 102, 251113 (2013), more information: **ThP156**

In-situ, High-Resolution Cathodoluminescence-Lithography

μPL-spectrum after CL-lithography



CL-map after CL-lithography



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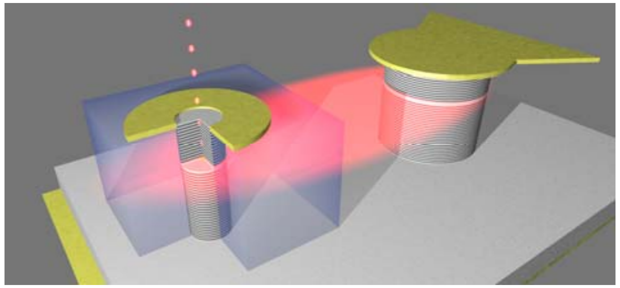
Summary

On-chip quantum optic experiments using integrated WGM lasers:



- Electrically driven WGM microlaser acting as on-chip light source
- In-plane resonant p-shell excitation
- On-chip cQED experiment in the weak coupling regime featuring $F_P = 4$

Outlook:

- Integration of Limaçon-microlasers
- Deterministic fabrication technology (CL-lithography)
- Resonance tuning exploiting the QCSE
- On-chip resonance fluorescence experiments