Sub-wavelength optical mode volumes for THz quantum cascade lasers

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Motivations

- Guide the optical mode with the sole patterning of the metal.

- Lowering the injected electrical power:

  Vertically → Reduction of the applied bias.

  Laterally → Reduction of the threshold current.

- Sub-wavelength cavity volume THz QCL.

Outline

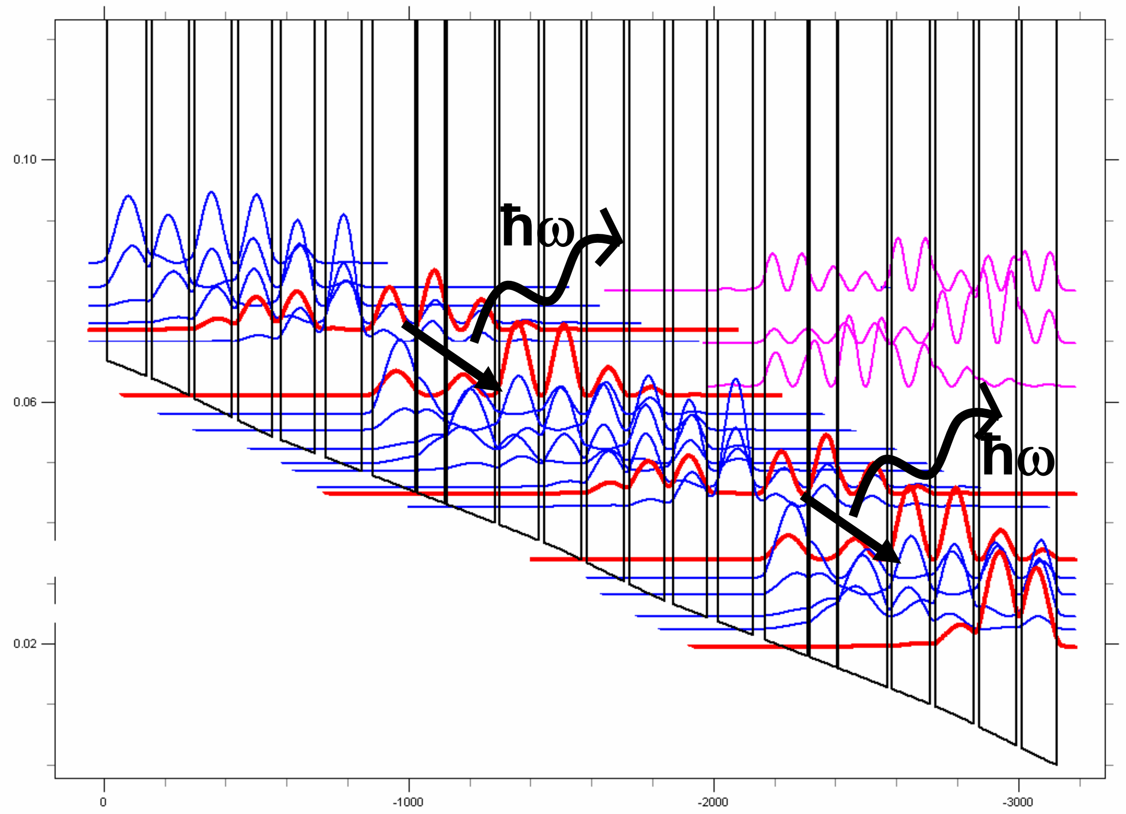
I. Thickness reduction using a Double Metal waveguide

II. Circular resonator using the guiding properties of metal
   a) measurements
   b) simulations

III. Preliminary results on photonic crystals

The quantum cascade laser structure

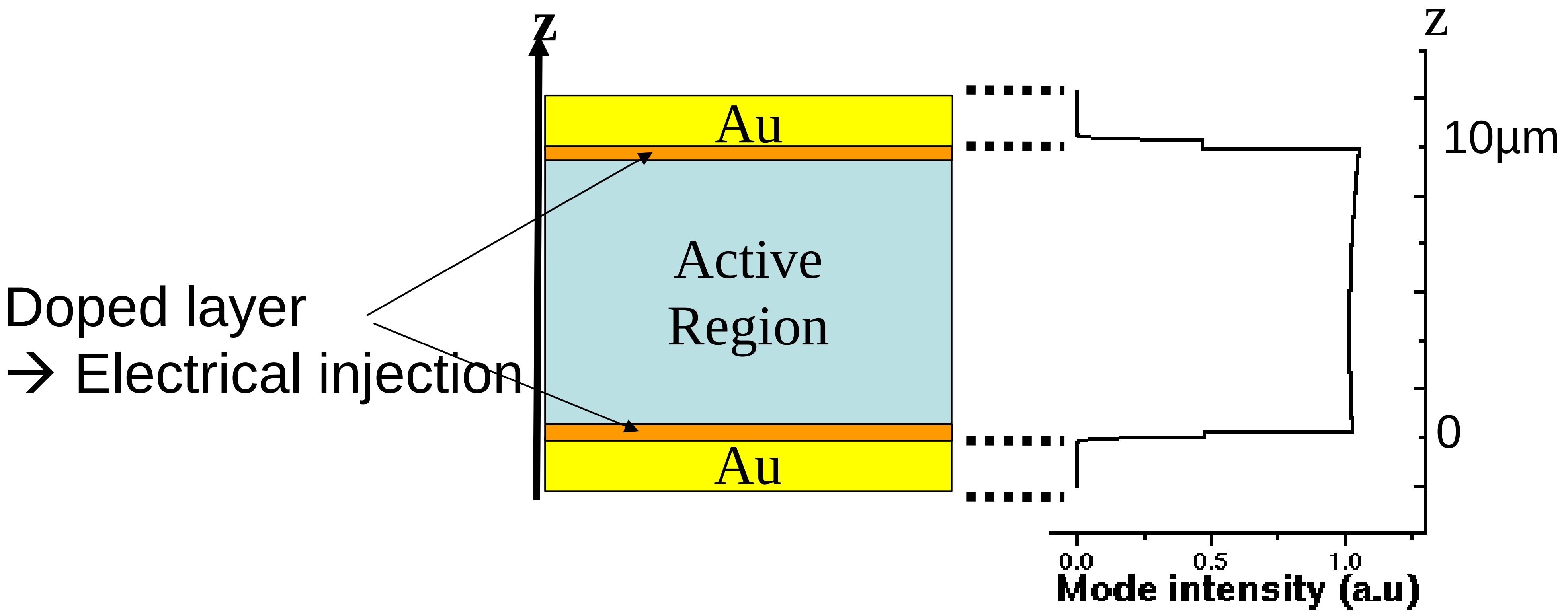
- Emission: 2.9 THz
- Electrical injection



Bound to continuum QC structure

S. Barbieri et al, Appl. Phys. Lett., ***85****, 1674 (2004)*

Vertical confinement: metal-metal waveguide

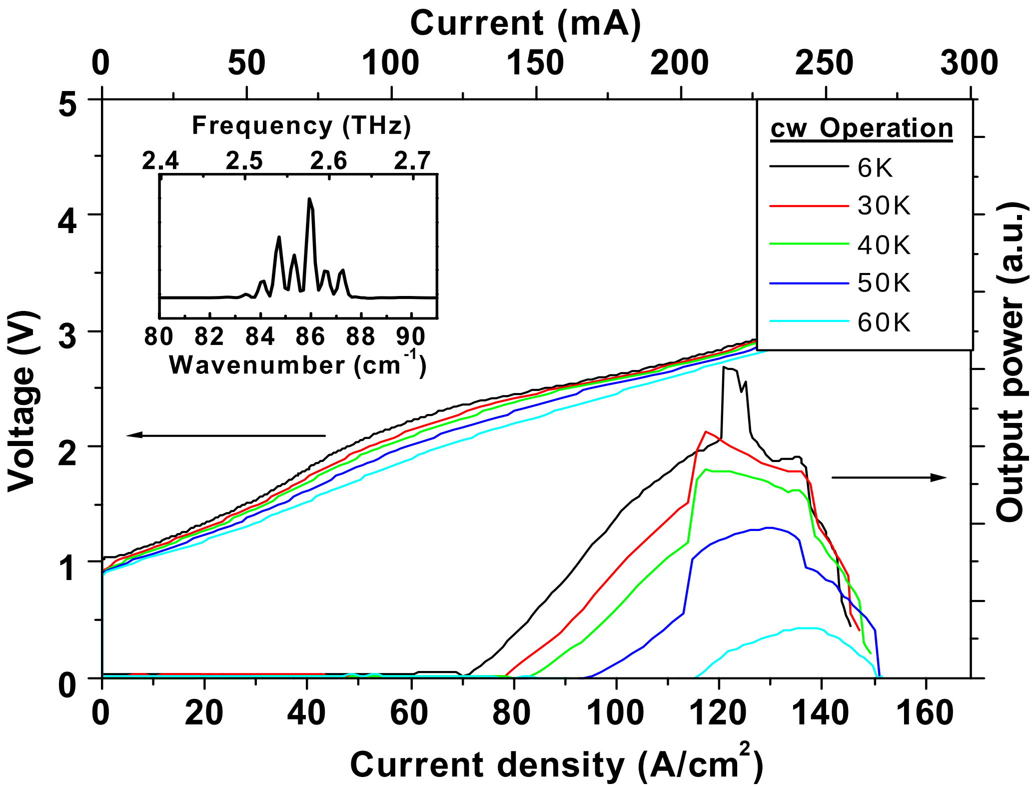


- Double-Metal geometry
- Typical active region thickness: 10-15 µm
- λ ~ 115 µm (2.6 THz)
- Electric field in the e_z direction
- Confinement: Γ=1

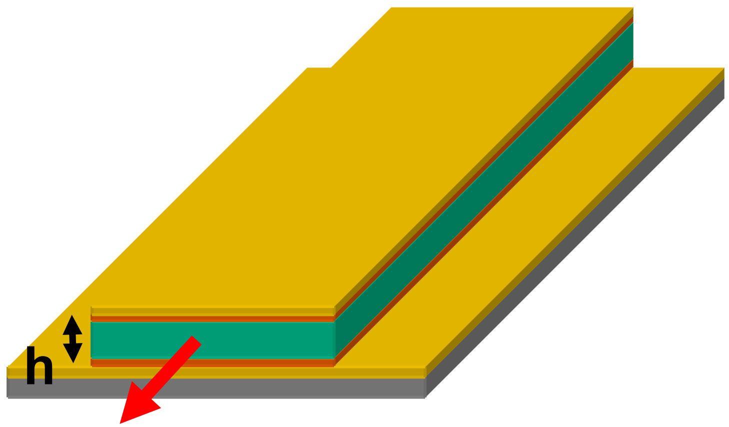
6-µm-thick QC active core: results

Typical structure: **h = 12 µm (90 periods)**

Thin structure: **h = 6 µm (45 periods)**



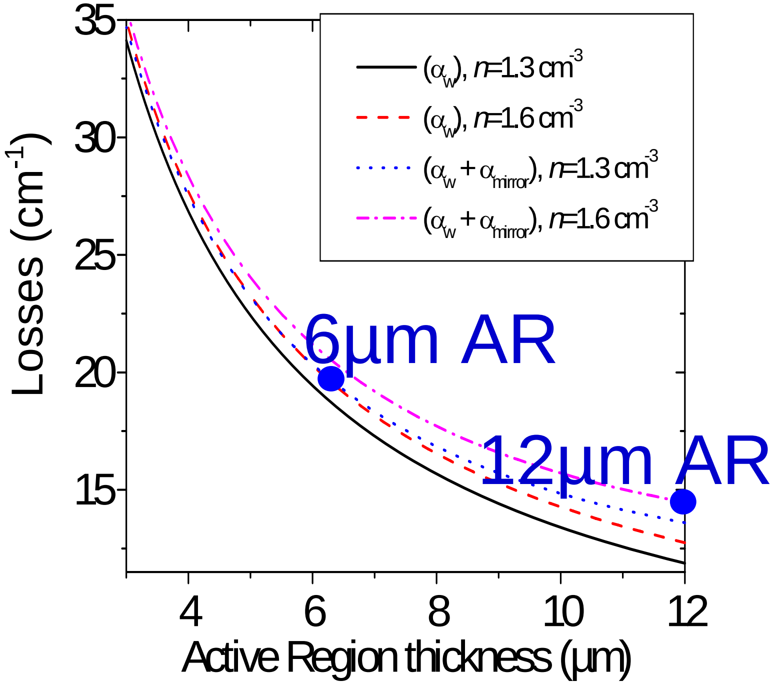
*LIV curves for the **6µm** AR structure*



Double metal ridge

*Y. Chassagneux et al, El. Lett., **43**, 285 (2007)*

Unexpected "low" current threshold



h=6µm (45 periods)

Expected losses: 20 cm-1
Jth = 71A/cm^2
Jmax/Jth ~2

Tmax (pulsed) = 75K
Tmax (cw) = 60 K

Unexpected results: similar performance for the thin active region structure
Possible hypothesis:

→The active region is less doped
→The thin structure might have a narrower gain spectrum?

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- a) measure
- b) simulations

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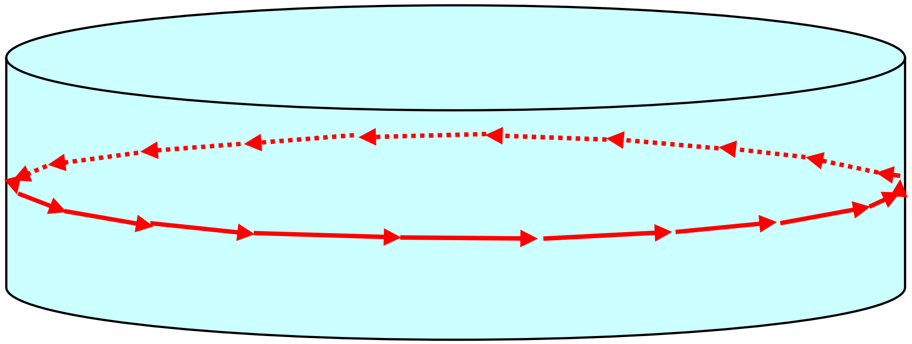
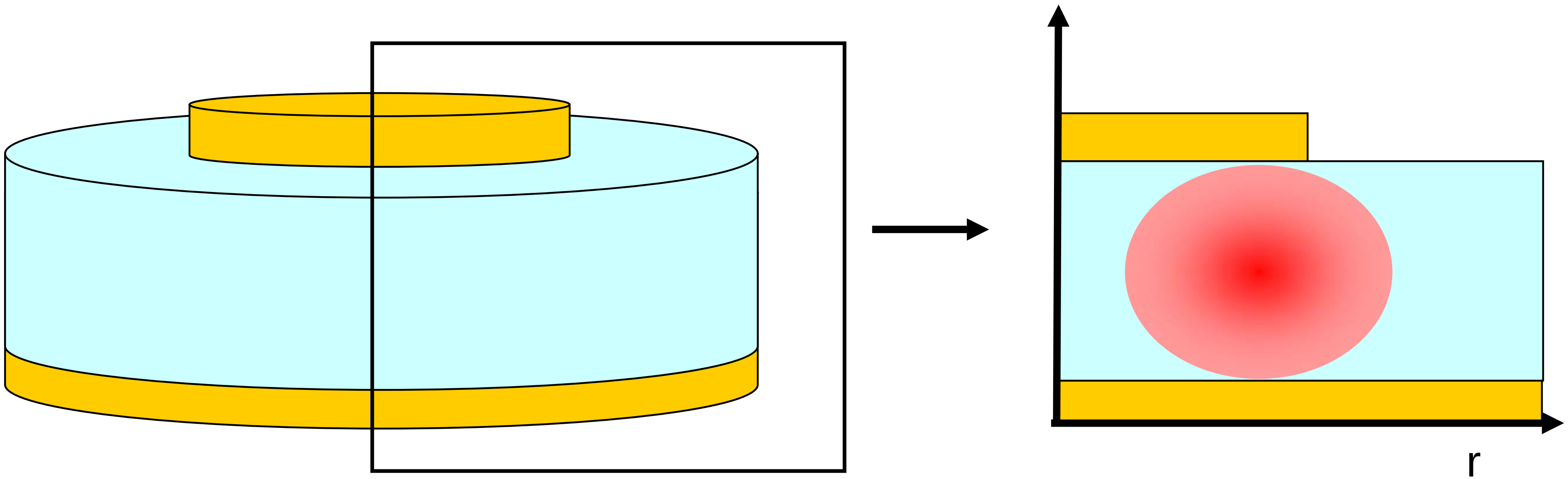
Lateral confinement *via* metal patterning



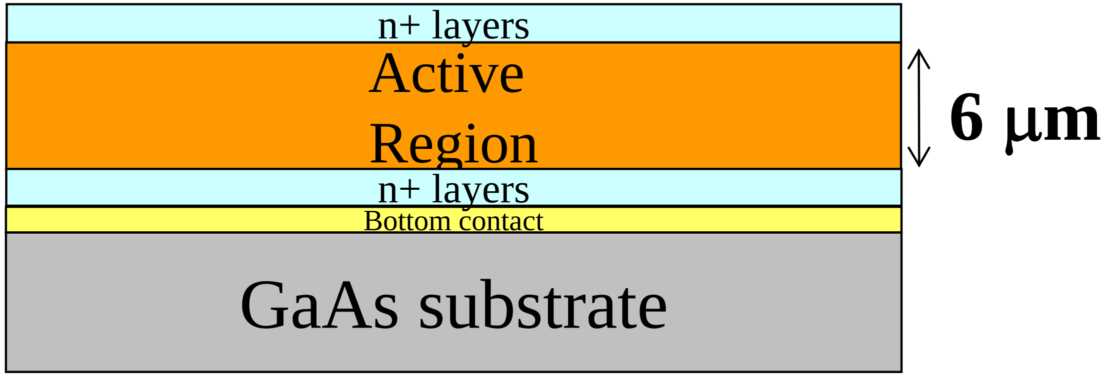
Usual configuration:

Confinement since n>1 .
Total internal reflection on the circular boundary.

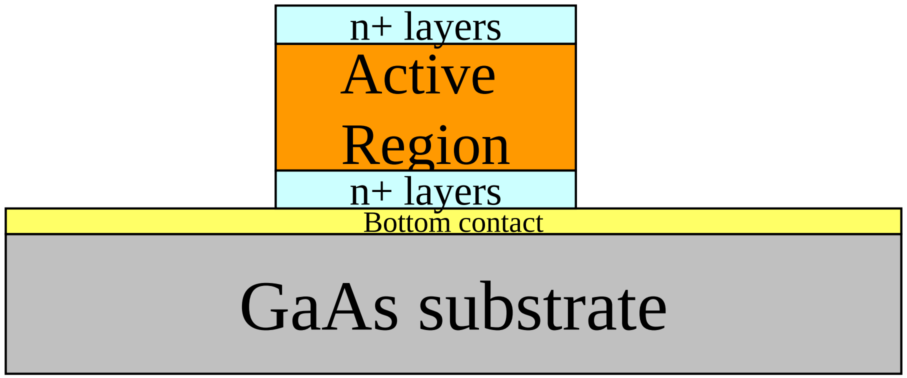
A metal can induce lateral confinement (mode mismatch)



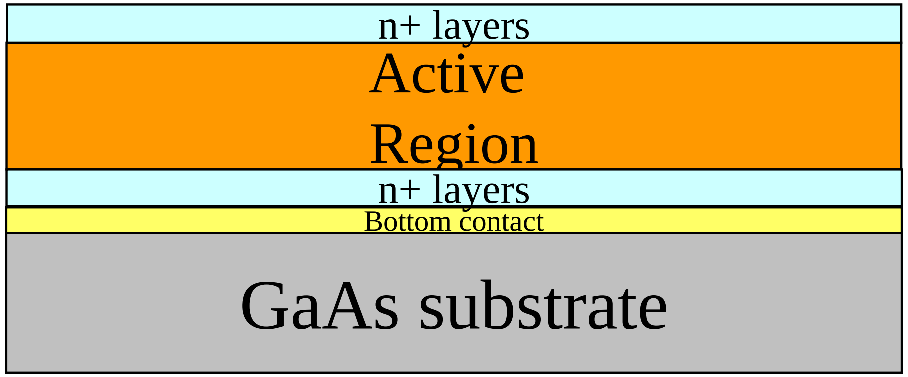
Device Processing



a) Wet etch
cylindrical mesa
R=32, 45, 95 μm



Effect of the n+ contact layer



a) Wet etch
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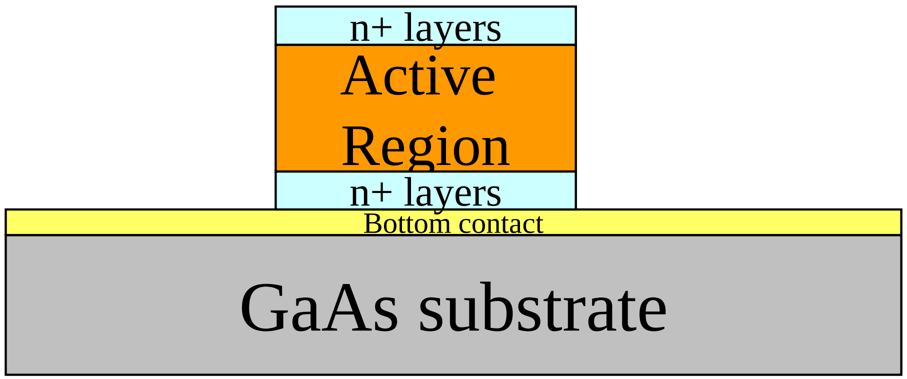
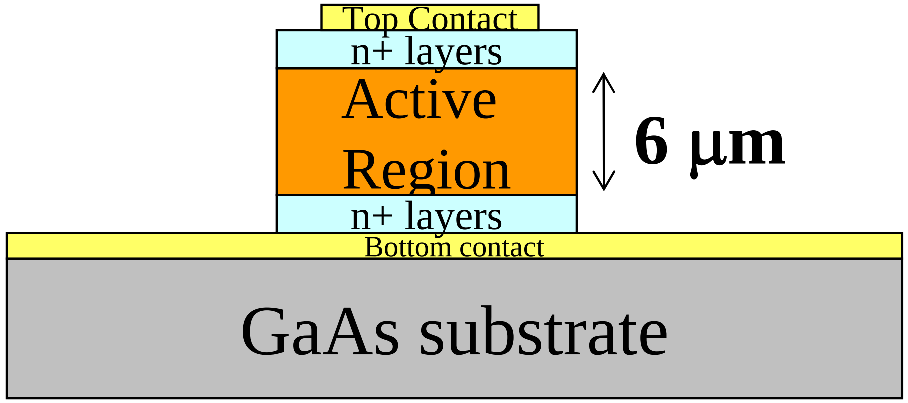
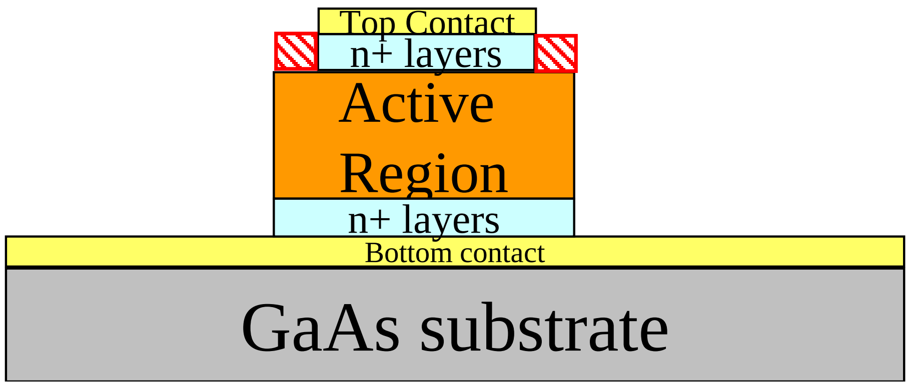


b) Metallization
R_{metal}=25, 37.5, 87.5 µm



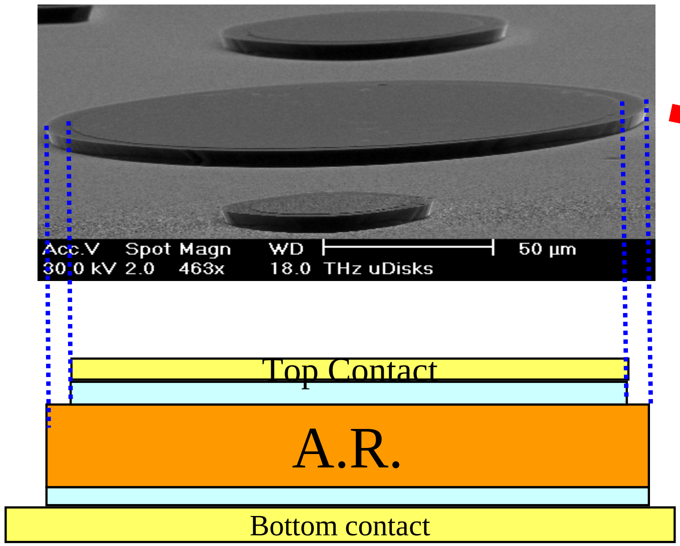
No lasing due to high losses in the top doped layer

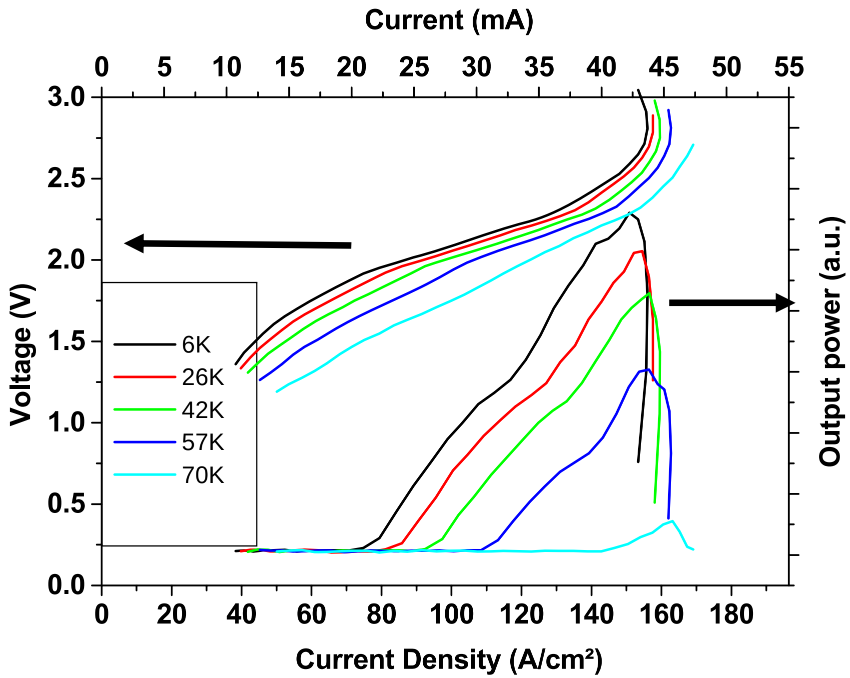
c) Wet etch
Remove a part of the doped layer



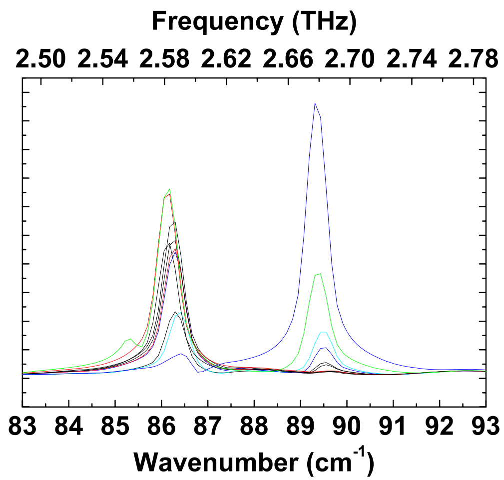
LIV characteristics (R=95μm)

BIG SIZE



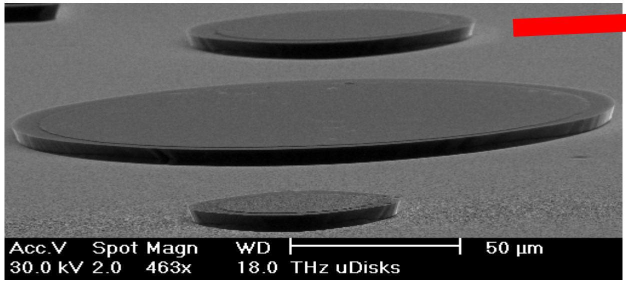


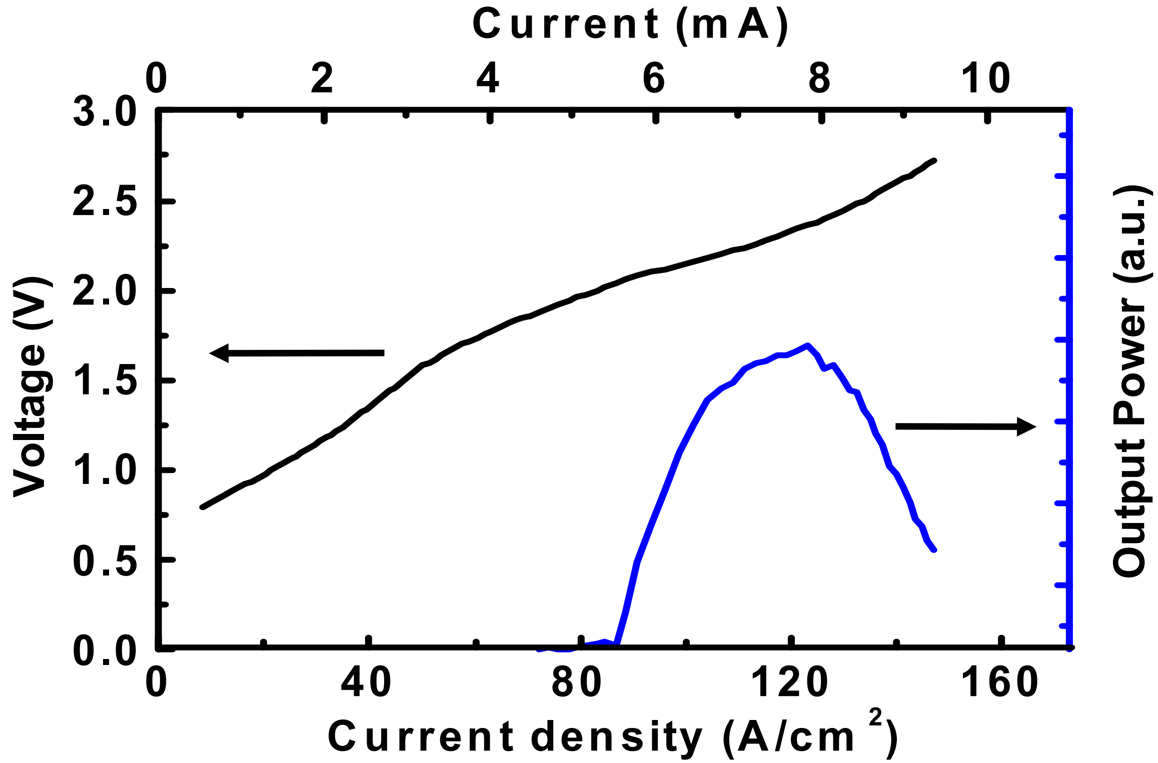
- Tmax ≈ 70K in pulsed mode
  ≈ 65K en continuous wave
- Threshold: 21mA
- Two laser frequencies:
  2.58 & 2.68 THz



LIV characteristics (R=45µm)

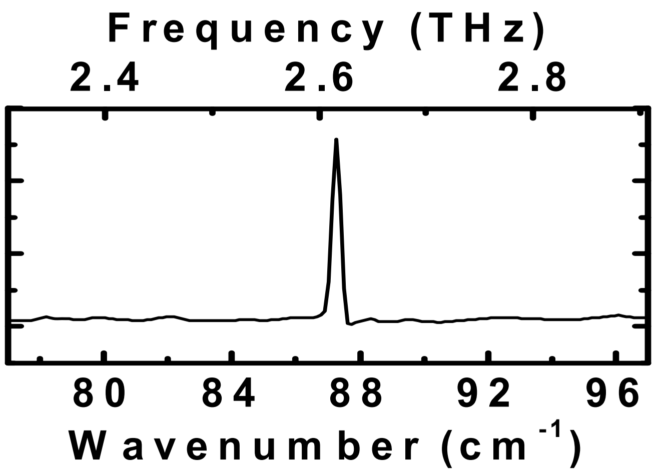
MEDIUM SIZE





- Threshold: 5.5 mA

- **Single mode emission**: 2.61THz

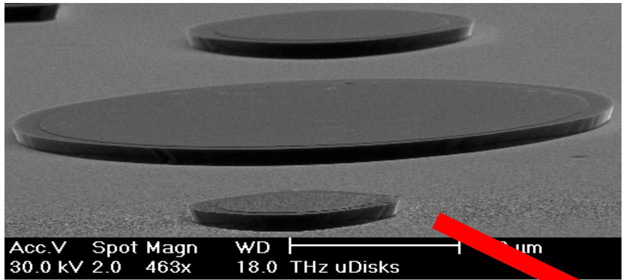


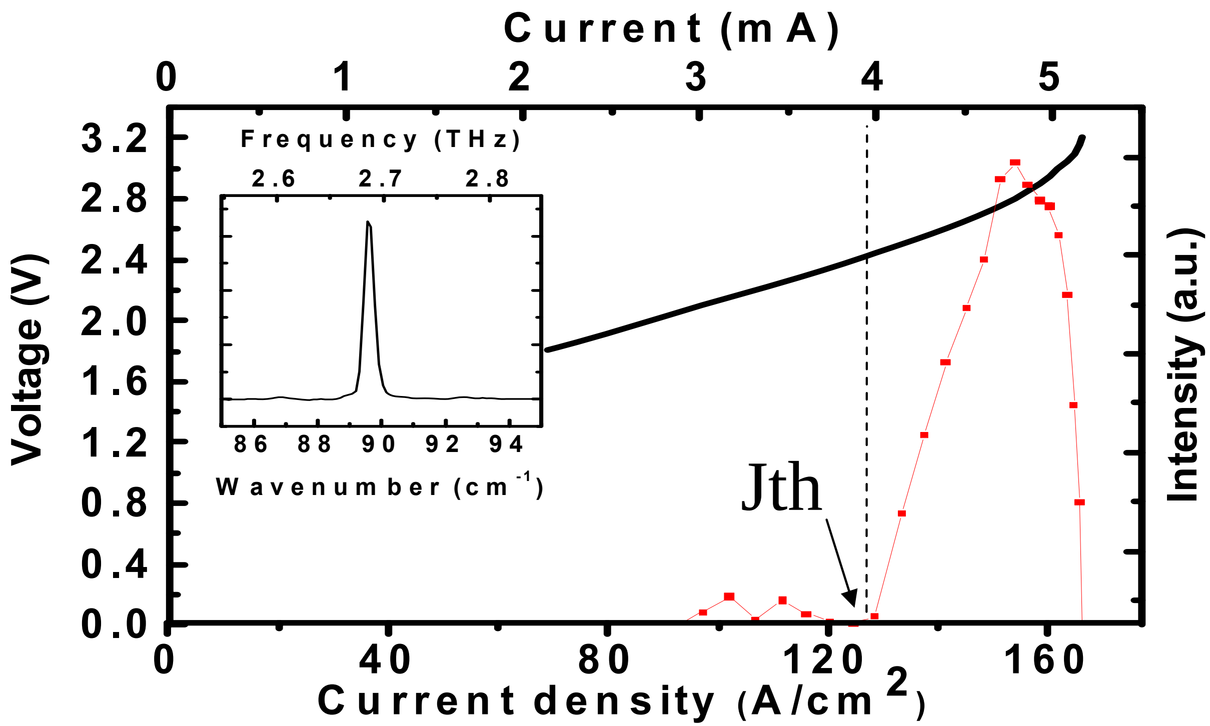
LIV characteristics (R=32µm)

SMALL SIZE

➢ **VERY LOW THRESHOLD:**
I_{th}=4mA

➢ **SUB-WAVELENGTH CAVITY VOLUME:**
$V \approx 0.7*(\lambda/n_{GaAs})^3$





Y. Chassagneux et al, Appl. Phys. Lett., ***90****, 091113 (2007)*

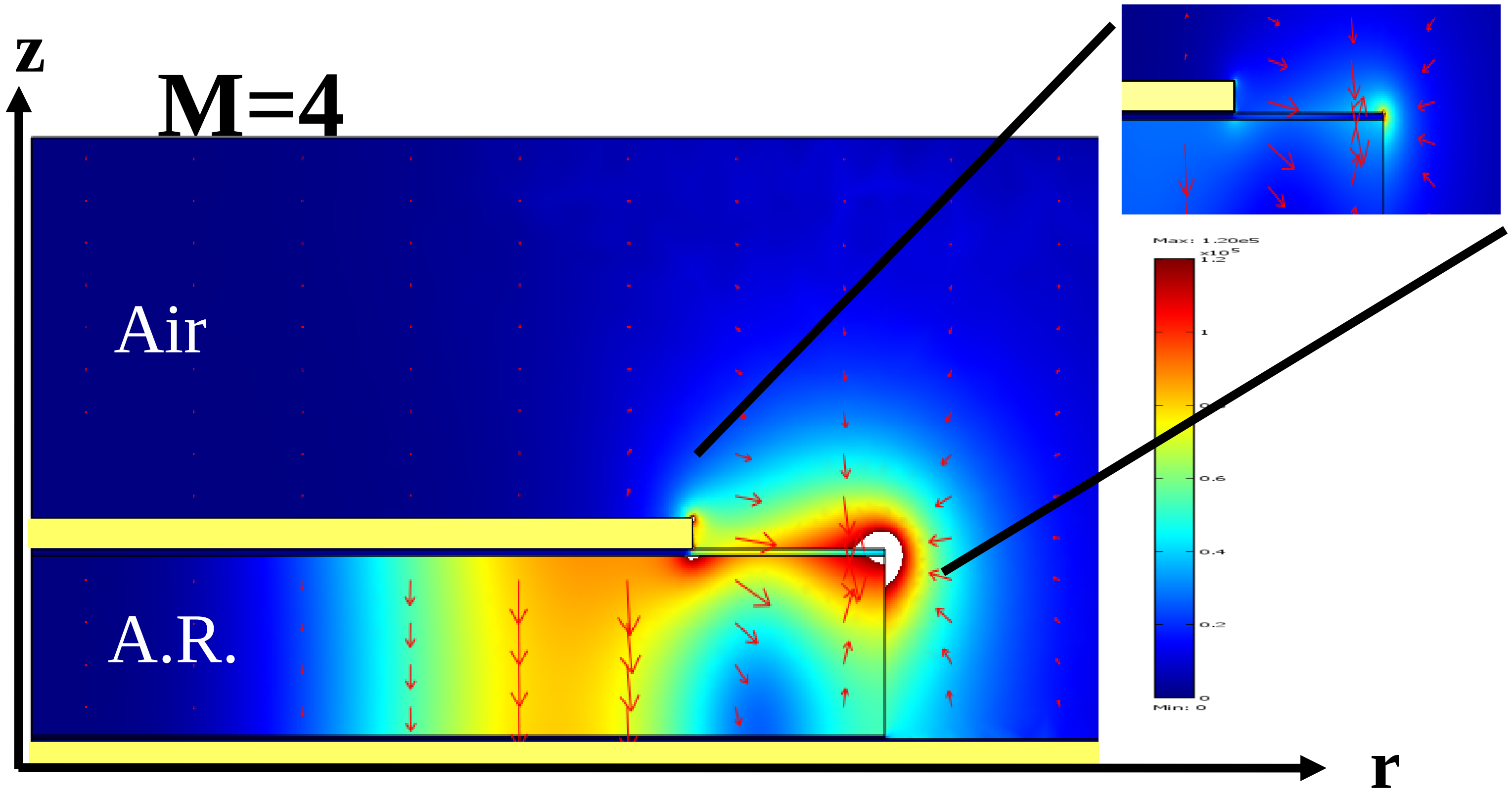
Simulations

- Finite element simulation

- 3D simulation (x,y,z) → requires a high computational power.

- 2D simulation (r,z) using the axial symetry+ 1 parameter integer M: azimuthal order

The mode is guided by the doped layer



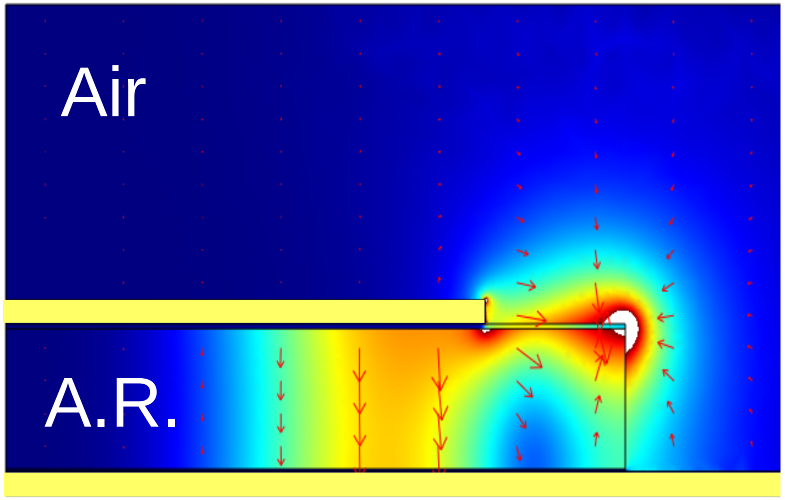
Color scale: x3

The optical mode is guided partially by the metal and partially by the doped layer:

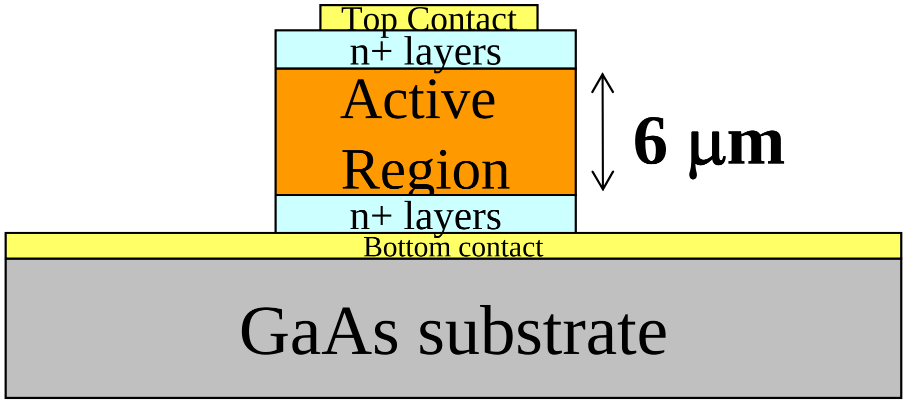
→ high losses

The removal of the n+ layer reduces the losses

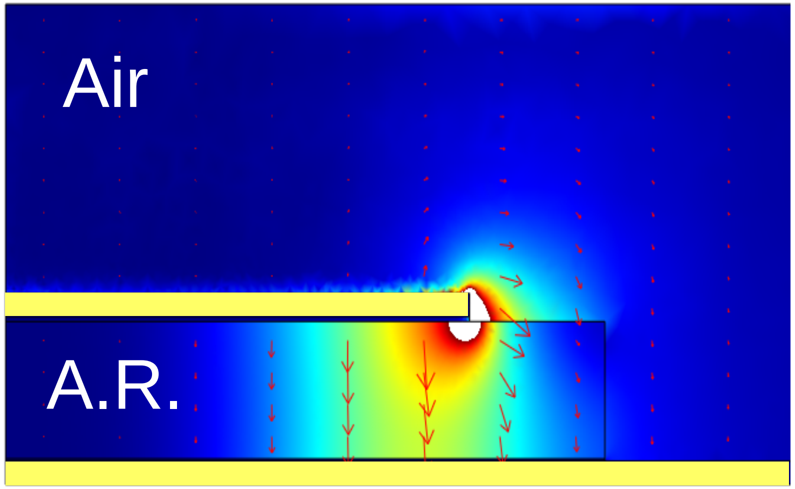
With the doped layer



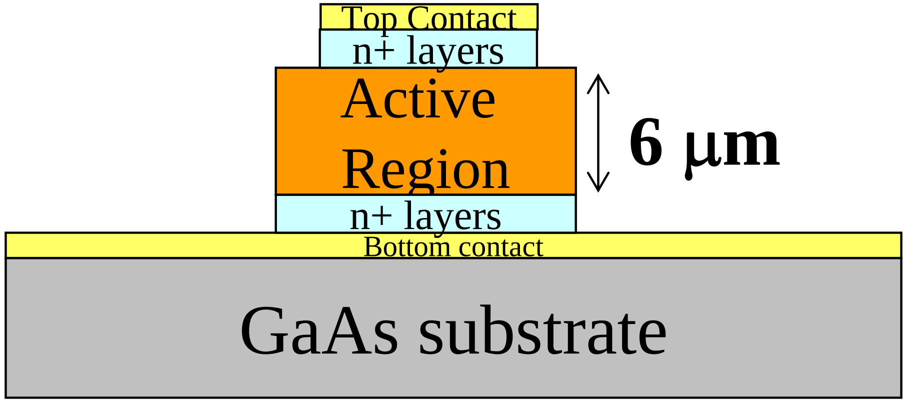
Q=4.3



Without the doped layer

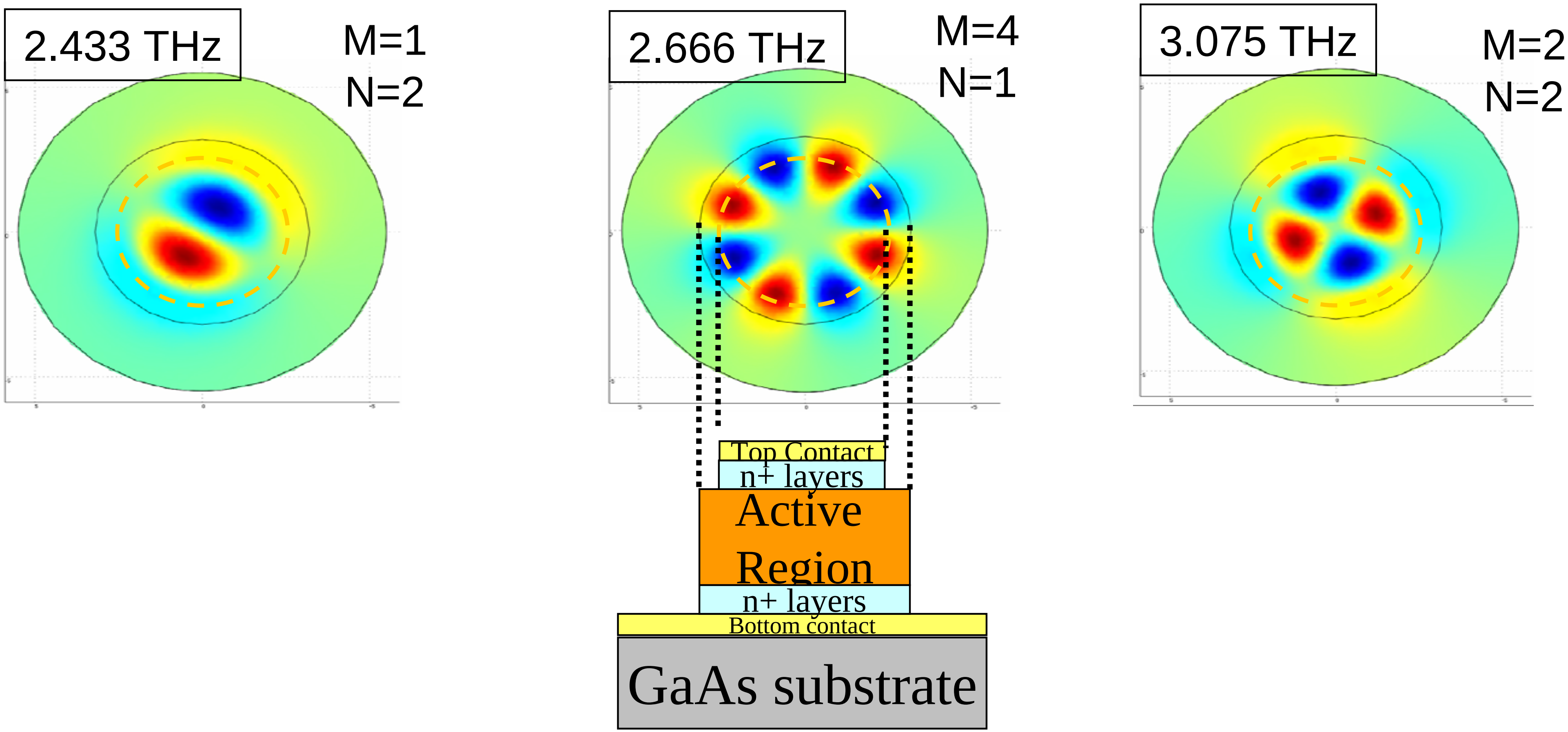


Q=90



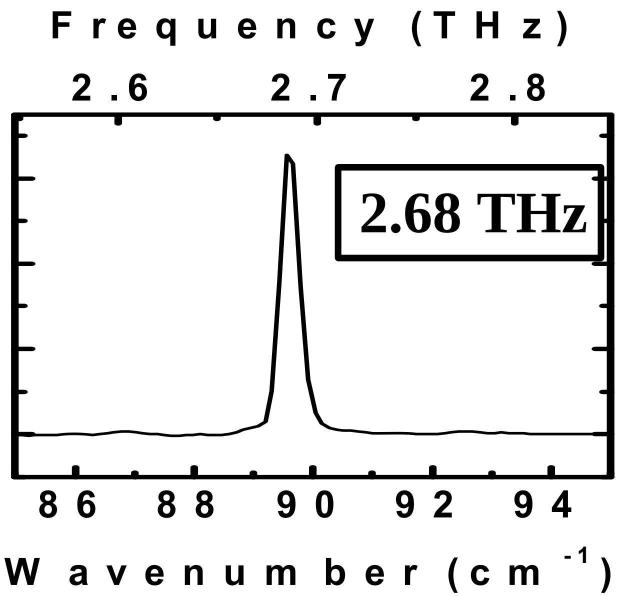
The mode is guided by the metal

Why the small disks are single-mode?

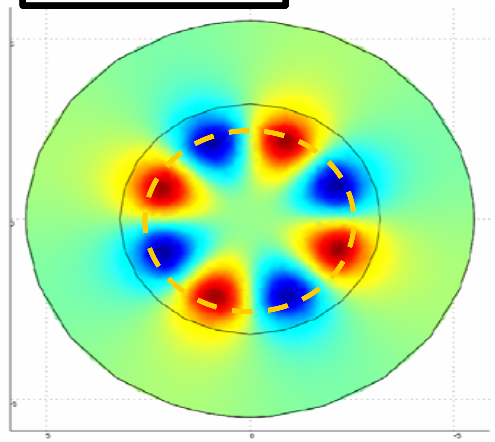


Typical gain peak at ≈2.6 ± 0.15 THz

Mode identification

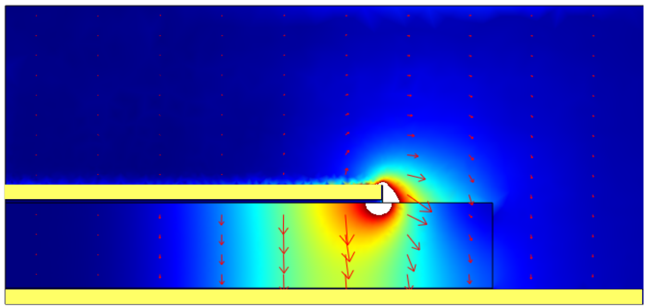


2.67 THz



3D simulation

2.70 THz



2D Simulation (M=4)

Good agreement between simulations and experiment

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   a) measure
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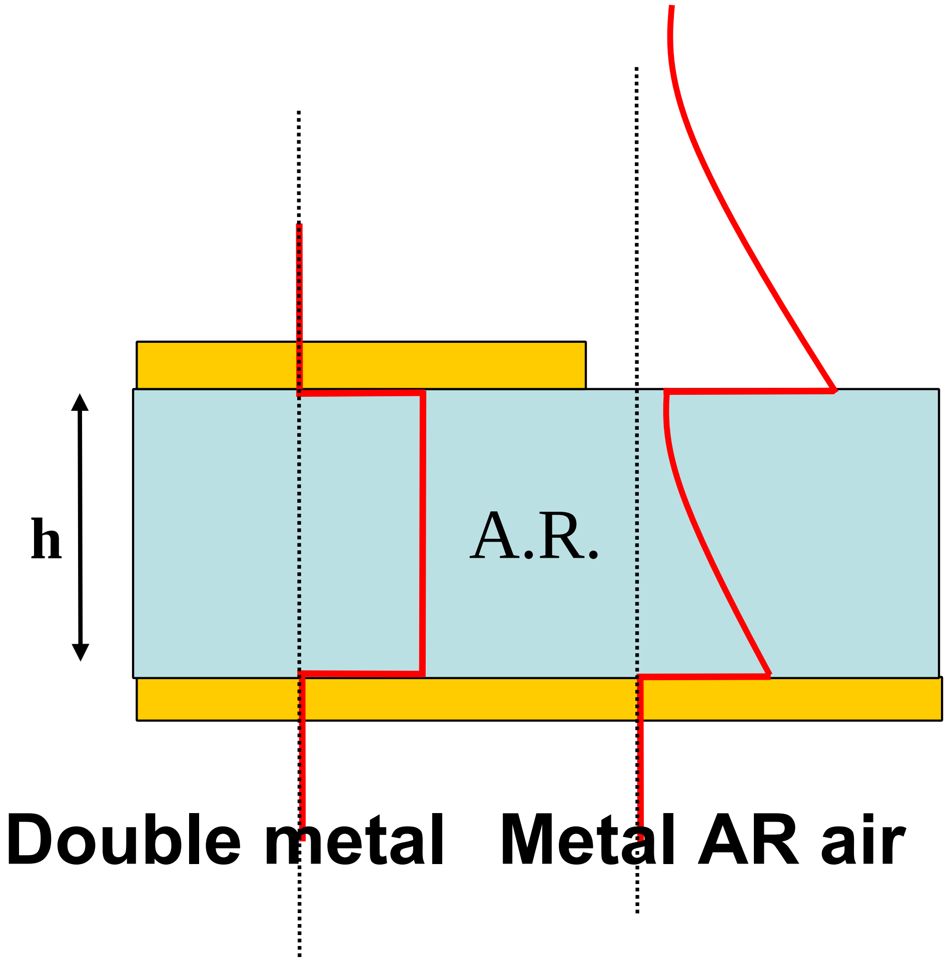
Additional reason to reduce AR thickness



- Mode mismatch

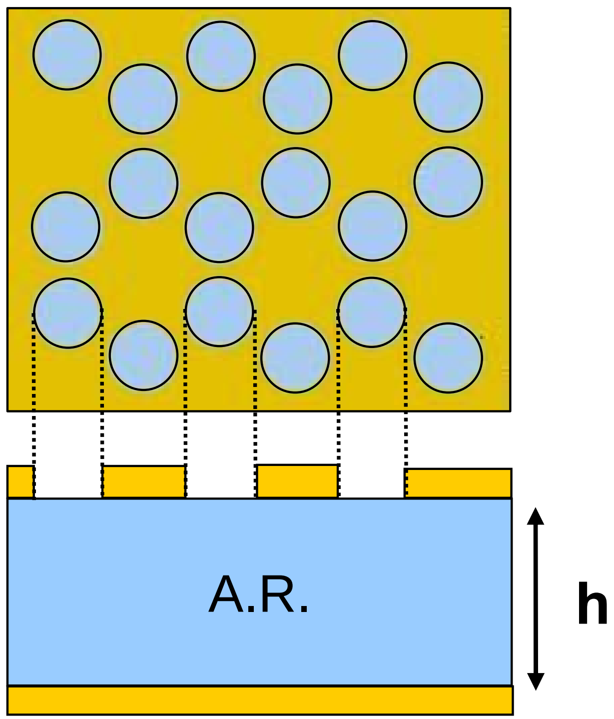
Mismatch Double Metal mode & mode metal-AR-air

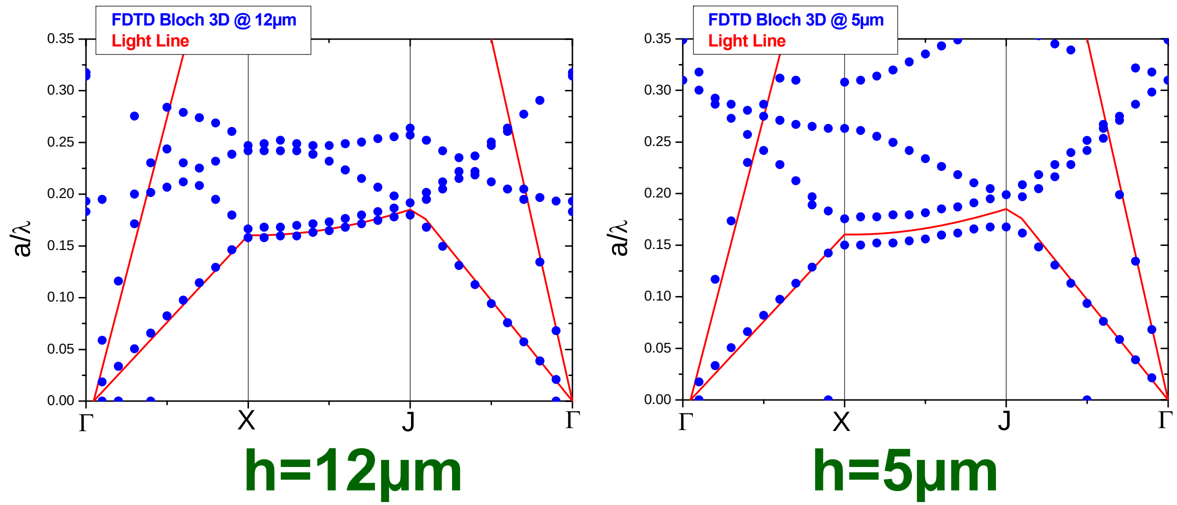
→Origin: extreme confinement of metal-metal waveguides

→Useful for photonic structure using the only patterning of the metal

An additional reason to reduce AR thickness

Traditional P.C. → Localization, diffraction, reflection given by the highest $\Delta \mathbf{n}_{\mathbf{eff}}$
For D.M. structure those features highly depend on the active region thickness





FDTD simulation of the honey-comb band structure

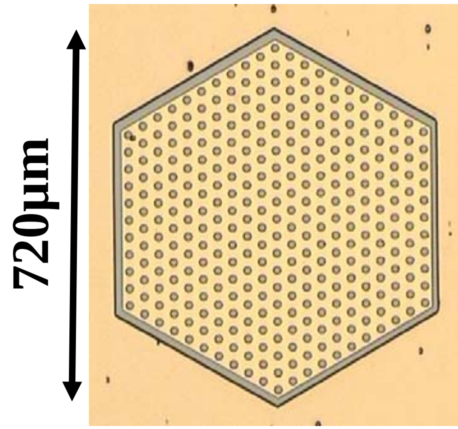
For thinner structures the sole metal patterning is more effective in controlling light propagation

M. Bahriz et al.,Opt. Expr., ***58****, 5948 (2007)*

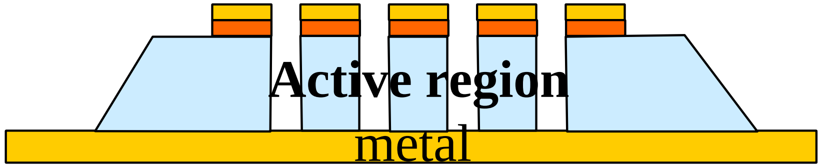
Motivations for photonic crystal development

GOAL:

- Single-mode laser
- Surface emission
- Tunability with the photonic crystal period
- No semiconductor etch (use metal patterning)
- Far-field control

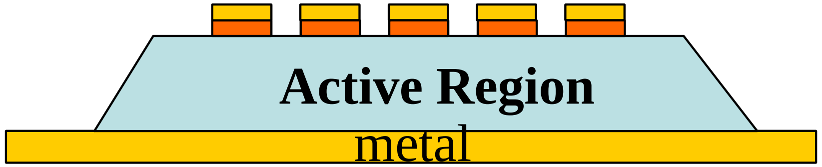


Standard PC structure
hole etched



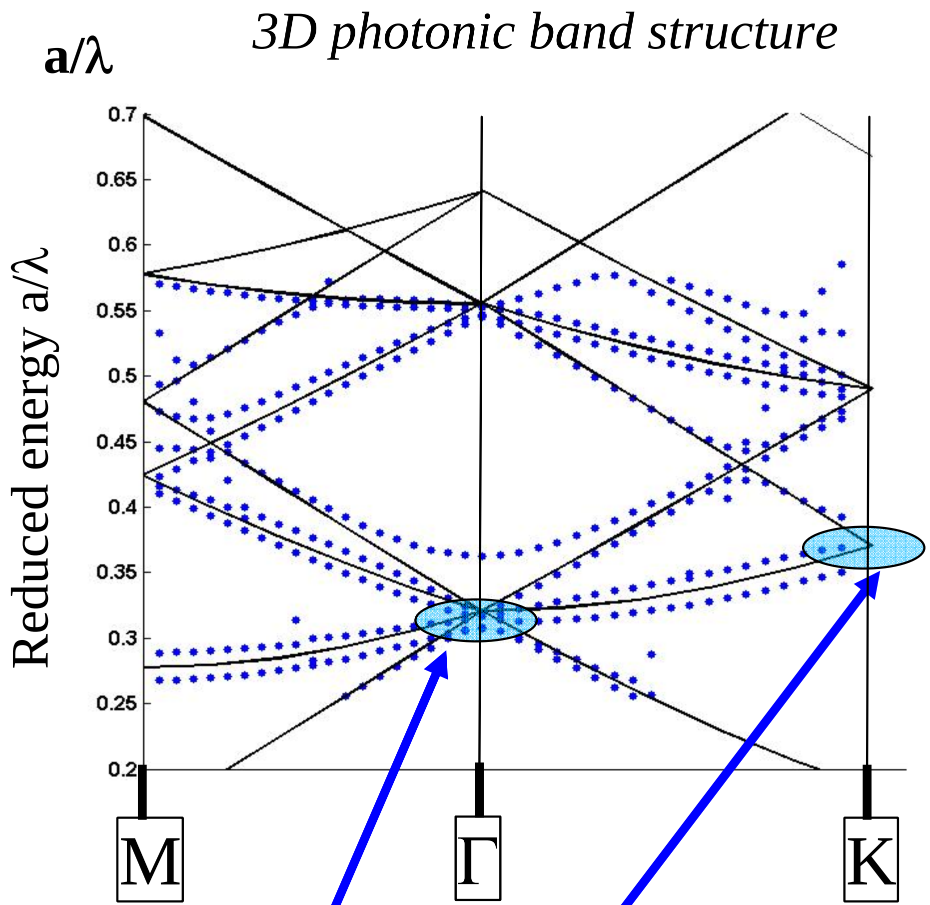
Feedback given by Δn_{eff}

Double metal structure: only the metal and the doped layer are etched



Feedback given by the mode mismatch

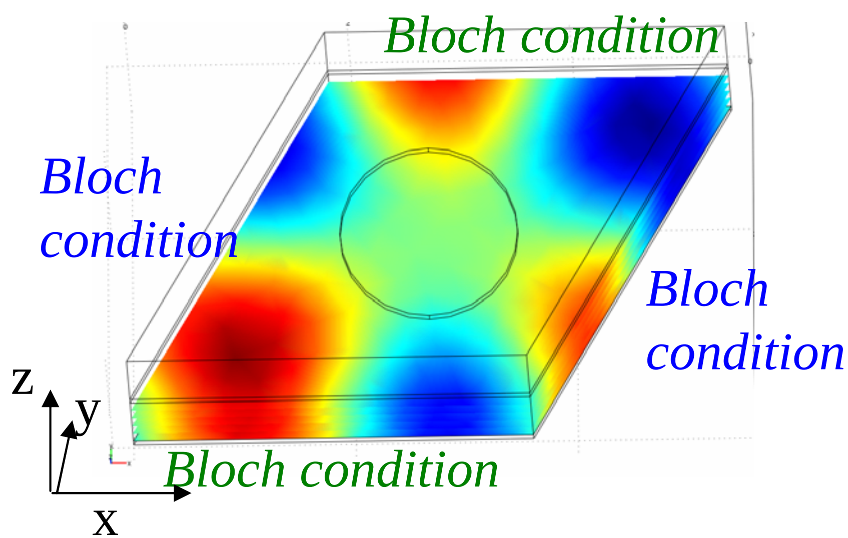
Infinite structure: 3D photonic band diagram



Lasing expected at band-edge
(lowest group velocity)

Bloch Simulation

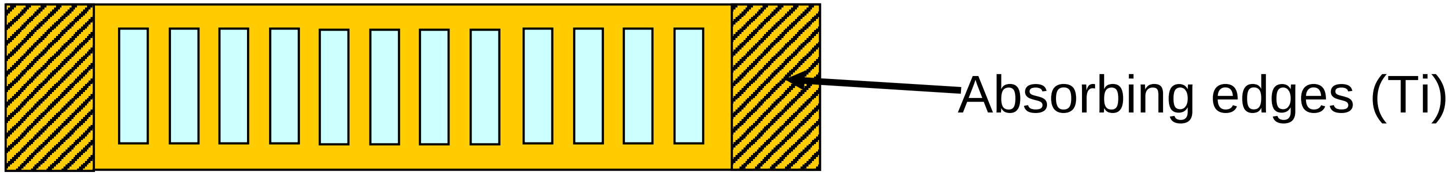
Double metal structure
→ 3D simulation needed



3D unit cell

Finite structure: boundary conditions

1D DFB, Double Metal waveguide

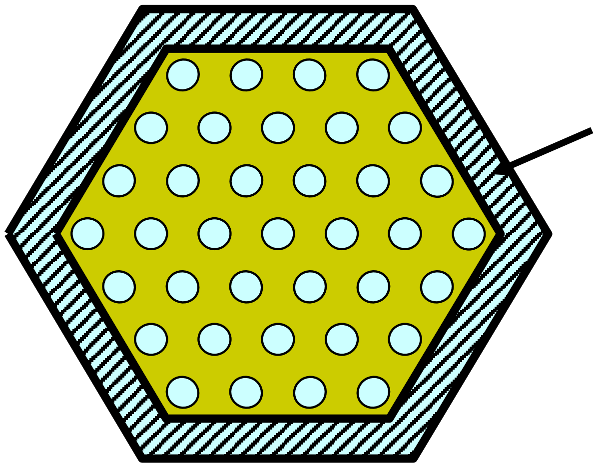


Top view

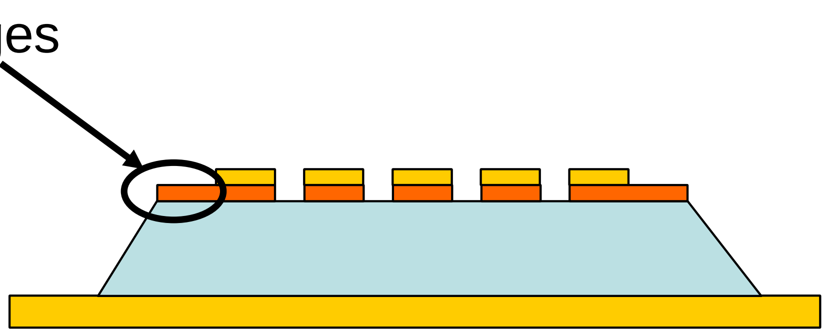
"Absorbing edge structures […] ensure distributed feedback in the cavity"

*J.A. Fan et al, Opt. Exp. **14**, 11672 (2006)*

2D photonic crystal



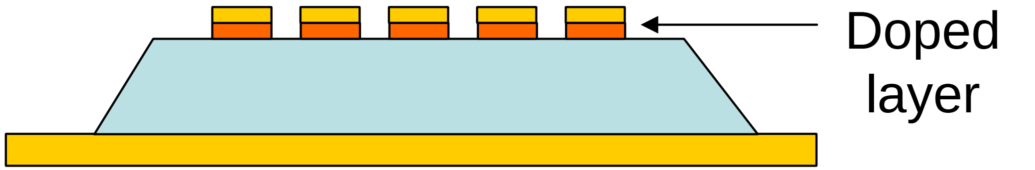
Top view

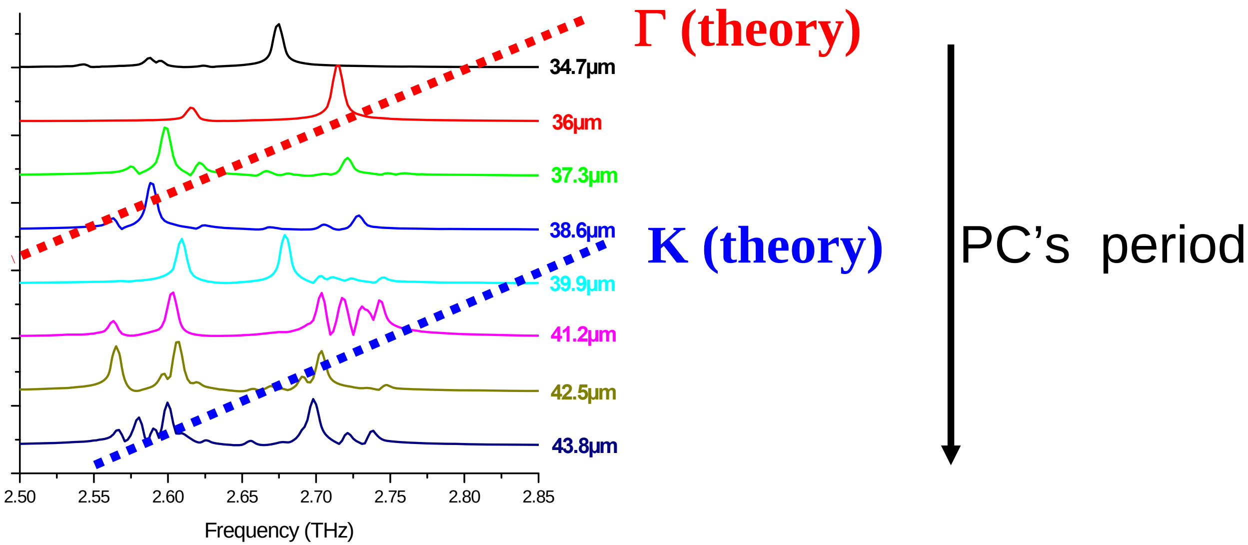


When not covered by the metal
the doped layer induces large losses

Initial experimental results

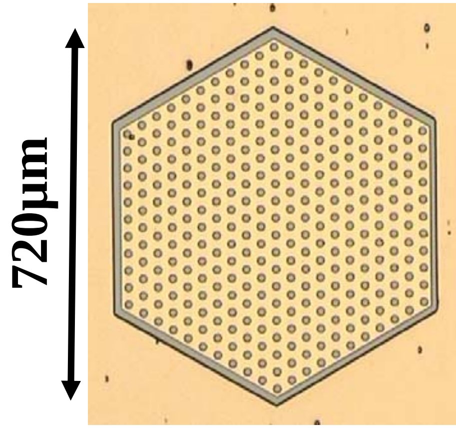
No absorbing edge





→ Each spectrum corresponds to a different Ph.C. lattice spacing

→No evident trend with the photonic crystal characteristics



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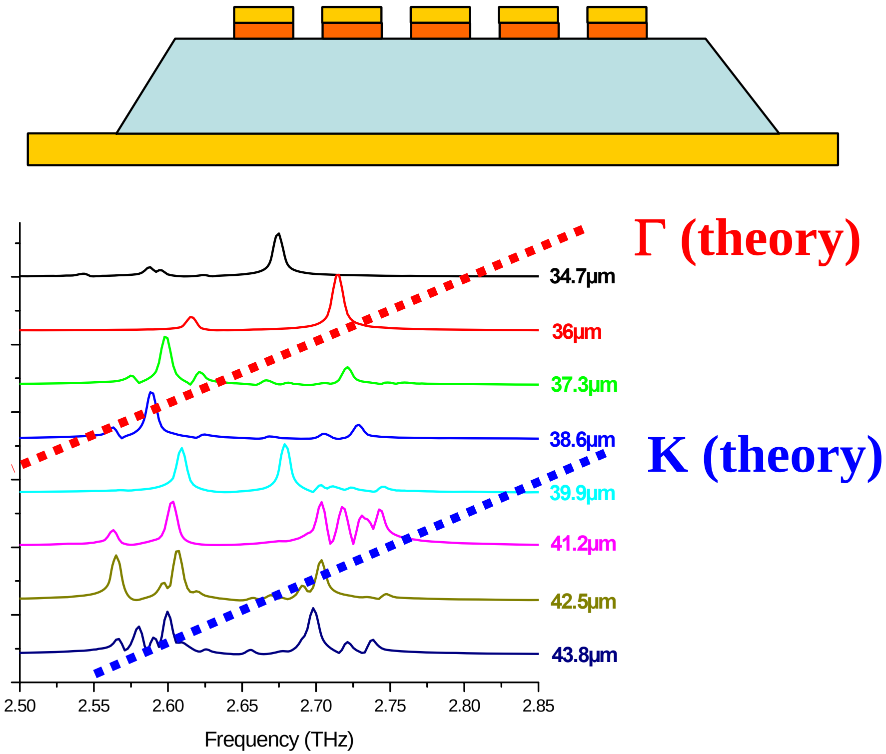
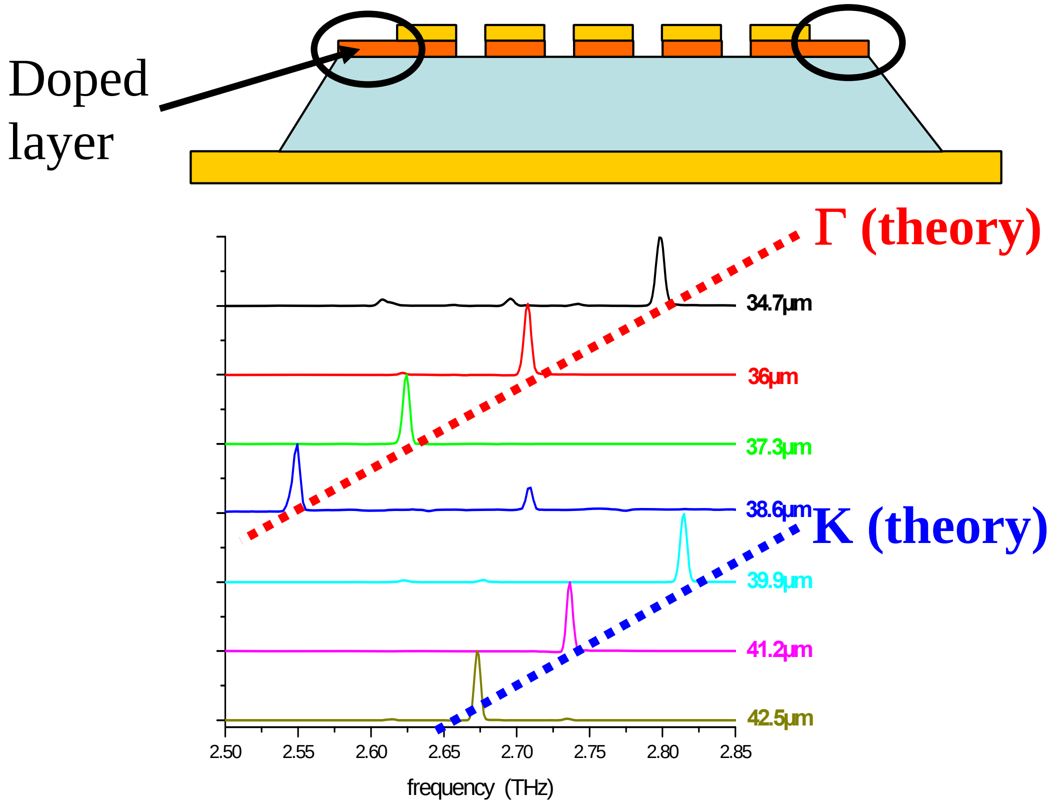


→ No evident trend with the photonic crystal characteristics

Absorbing edge



→ Almost single mode laser shifting according to the photonic crystal period

Conclusions & Perspectives

- We showed that a metal can guide the optical mode
- Low thresholds for micro-cavity lasers: 4mA
- Sub-wavelength cavity volumes
- Preliminary results for 2D photonic crystal

- Pursuing the active-core thickness reduction
- Photonic crystal devices:
  far-field measurements, AR thickness effect, filling factor….

European Science Foundation

European Young Investigator Award