Laboratoire Kastler Brossel
Physique quantique et applications

ED 564

A new photonic crystal platform for interfacing slow light and trapped cold atoms

Adrien Bouscal

Rencontres des Jeunes Physicien·ne·s
02/11/22

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Quantum Networks Team

Alban Urvoy

Jérémy Berroir

Anaïs Chochon

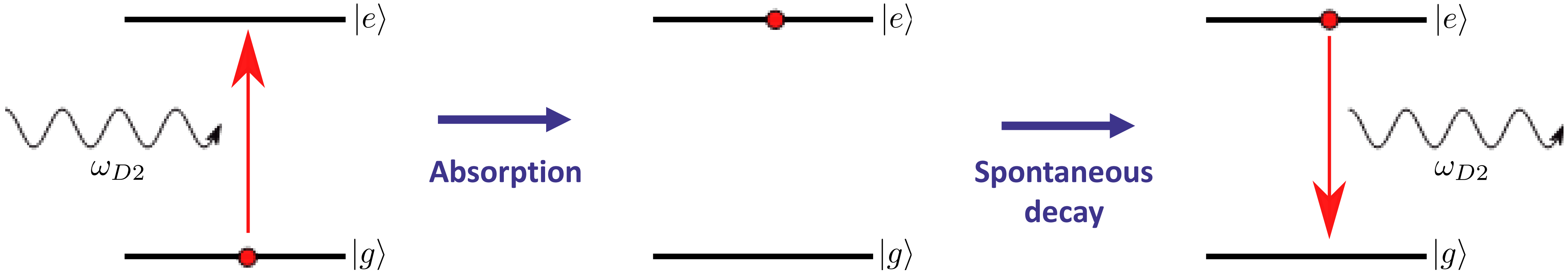
Research interests :

Quantum optics

Atom-light interactions
Quantum memories
Collective effects

Non-gaussian states of light
Hybrid entanglement
Quantum teleportation

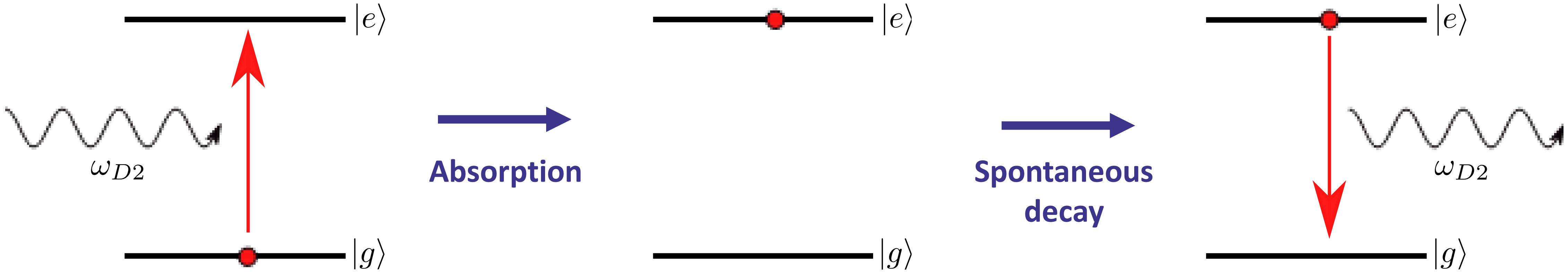
Push light-matter interaction to new highs



Absorption

Spontaneous decay

Push light-matter interaction to new highs



Absorption

Spontaneous decay

But what is the efficiency of the absorption process in real life, for a single atom and photon ?

Push light-matter interaction to new highs

Probability of interaction between light and atoms

$$\boxed{P \propto \lambda^2/d^2}$$

Mode area of incoming light

Limited by diffraction

→ How to maximise this coupling ?

Push light-matter interaction to new highs

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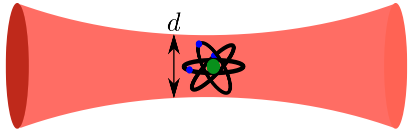
Strong focusing

$P \propto \lambda^2/d^2$ Decrease d, P ≈ few %



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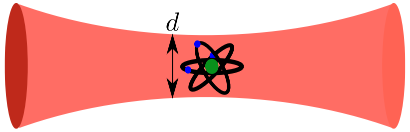

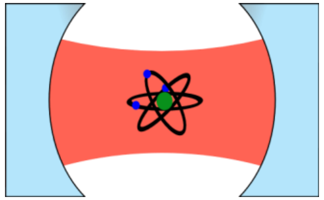

Cavity QED

$$\mathcal{F}\cdot(\lambda^2/d^2) \gg 1$$

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Push light-matter interaction to new highs

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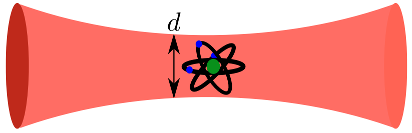

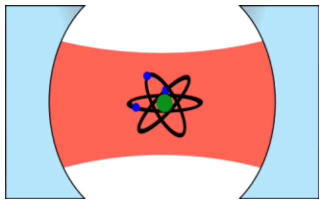

Cavity QED

$$\mathcal{F} \cdot (\lambda^2/d^2) \gg 1$$

Hard to integrate

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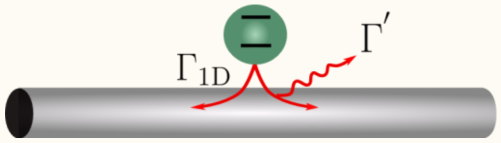
Waveguide QED

$$P \propto n_g \frac{\lambda^2}{S}$$



S can be very small over long distances

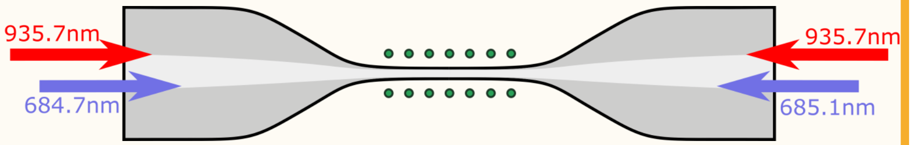
Push light-matter interaction to new highs

Probability of interaction between light and atoms is very small

$$P \propto \lambda^2/d^2$$

How to maximise this coupling ?

Waveguide QED



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N. Corzo *et al.*, "Waveguide-coupled single collective excitation of atomic arrays" Nature, **566** 359 (2019)

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Waveguide QED

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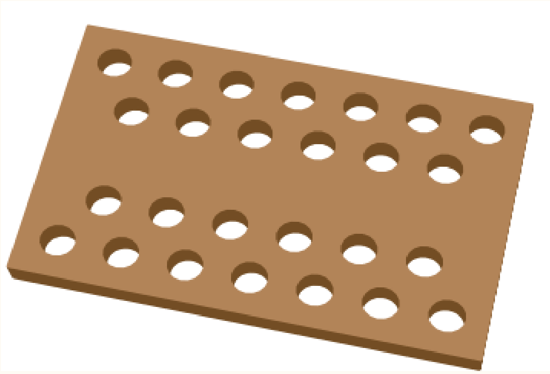


S can be very small over long distances

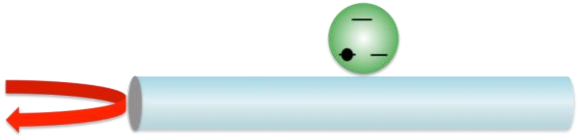
+ n_g can be engineered for photonic crystal waveguides → ***slow light***

N. Corzo *et al.*, "Waveguide-coupled single collective excitation of atomic arrays" Nature, **566** 359 (2019)

Push light-matter interaction to new highs

→ If P = 100%

Single atom mirror

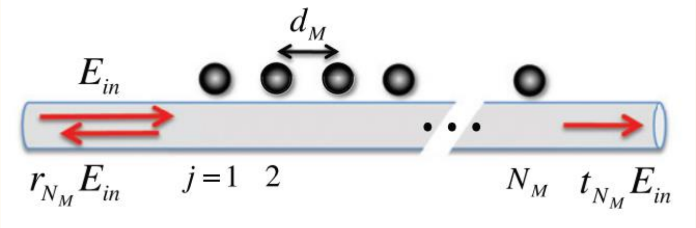


D. Chang et al., *Nature Photon.* **8**, 685 (2014)

→ With P ≈ few %

Use collective effects :

Controlable Bragg mirrors



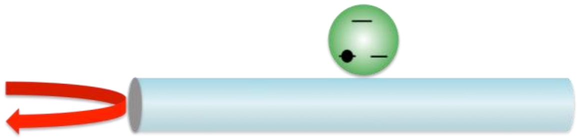
D. Chang et al., *Nat. Phys.* **3** 807 (2007)
D. Chang et al., *New. J. Phys.* **14** 063003 (2012)

Quantum communications or computing

Push light-matter interaction to new highs

→ If P = 100%

Single atom mirror



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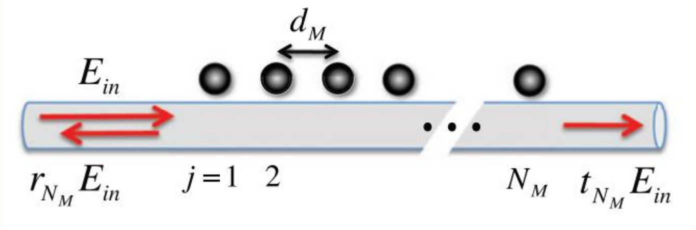
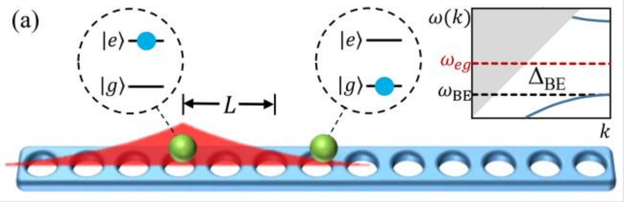


D. Chang et al., *Nat. Phys.* **3** 807 (2007)
D. Chang et al., *New. J. Phys.* **14** 063003 (2012)

→ With P ≈ few % + Photonic crystals

Bandgap physics with long range interactions



J. S. Douglas et al., *Nat. Phys.* **9** 326 (2015)

Quantum communications or computing

Quantum simulation

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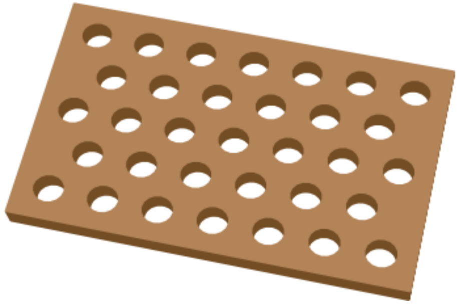
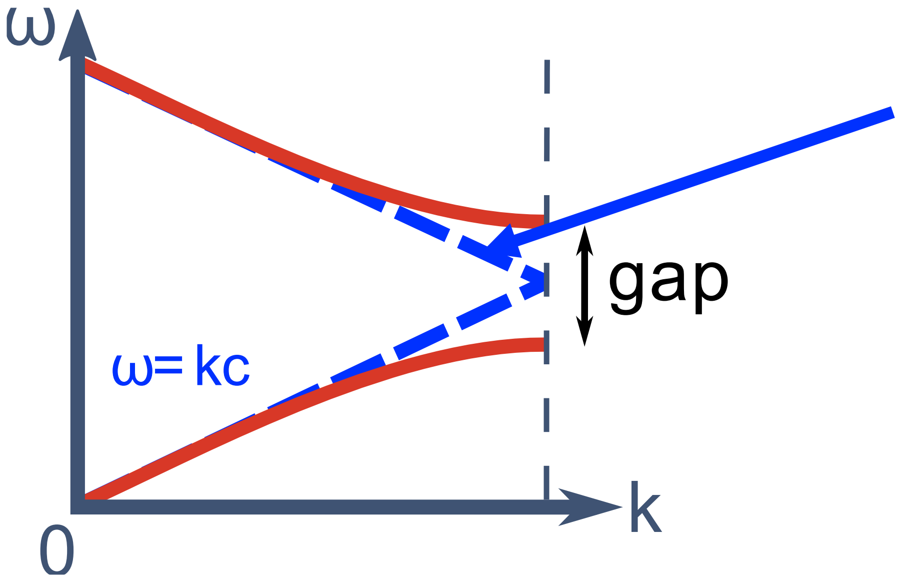
Controlling the speed of light

Periodic modulation of refractive index



Bloch theorem

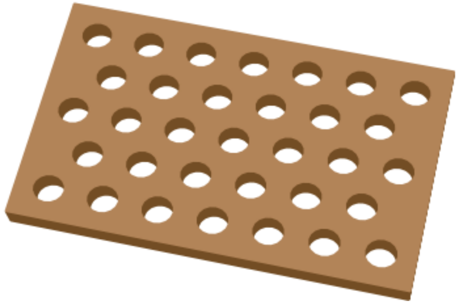
2D Photonic crystals



Dispersion relation of light in vacuum

Controlling the speed of light

Periodic modulation of refractive index



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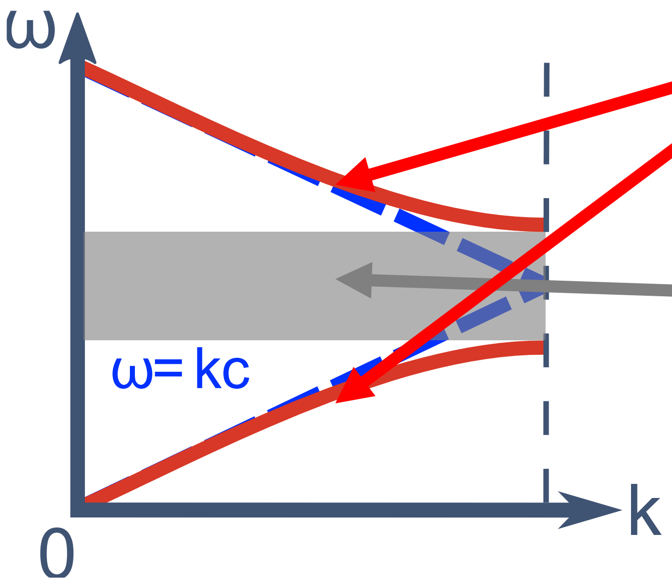
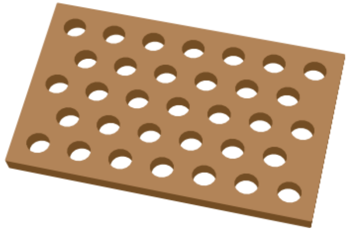


Band diagram of the infinite 2D PhC

Frequency range where no mode of the crystal exists

Controlling the speed of light

Periodic modulation of refractive index



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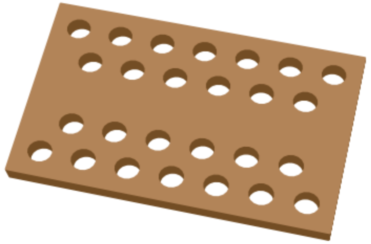
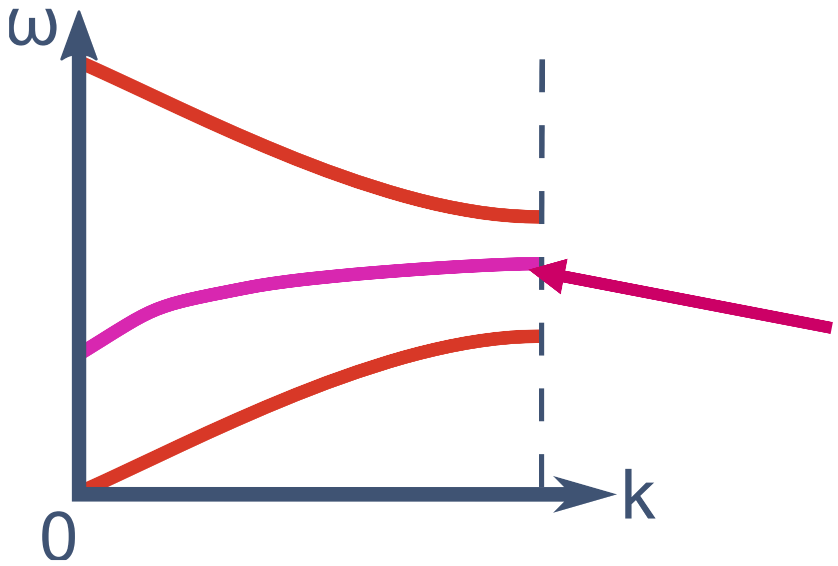
Introduction of a defect



2D Photonic crystals **waveguides**



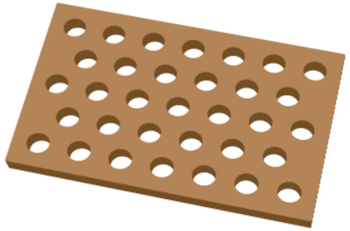
New band due to the defect → **guided mode**

Defect row → guided mode in the band gap of the 2D PhC

Tunable dispersion curve by **changing the geometry**

Controlling the speed of light

Periodic modulation of refractive index



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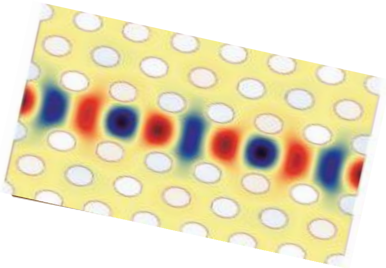

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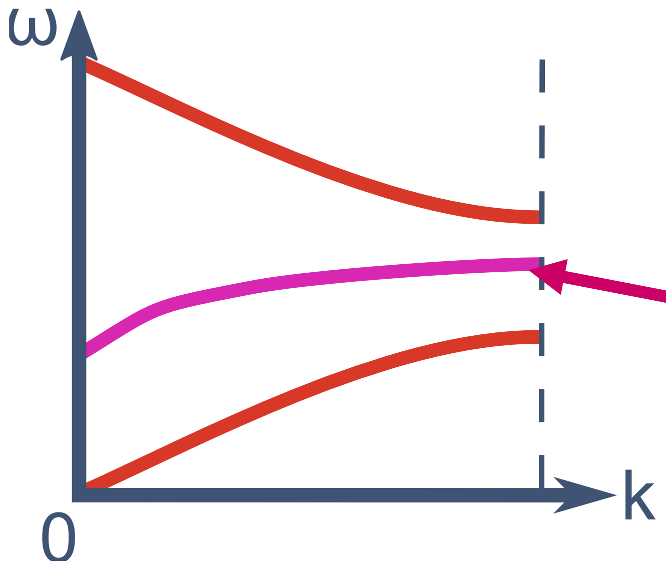

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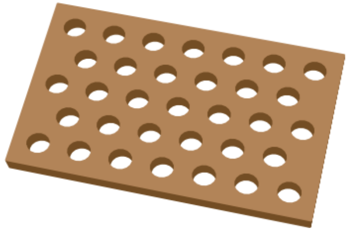

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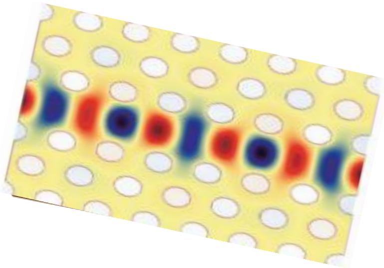

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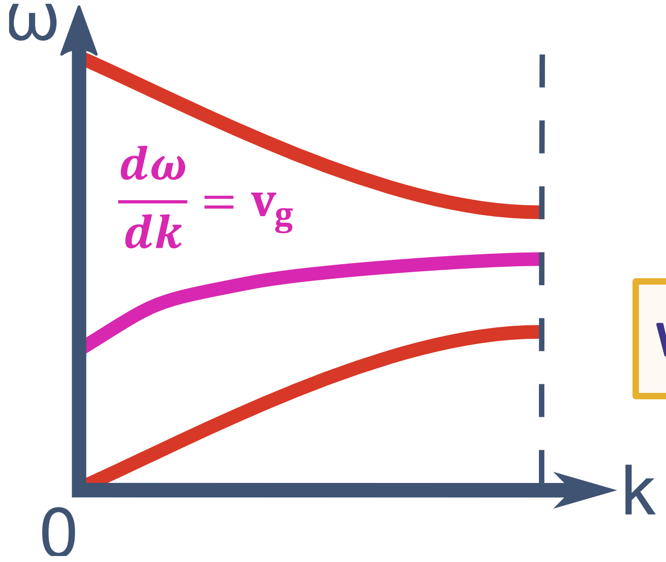

Can flatten the band

$v_g \sim \frac{c}{100}$ possible

Why do slow modes increase interaction ?

Defect row → guided mode in the band gap of the 2D PhC

Tunable dispersion curve by **changing the geometry**

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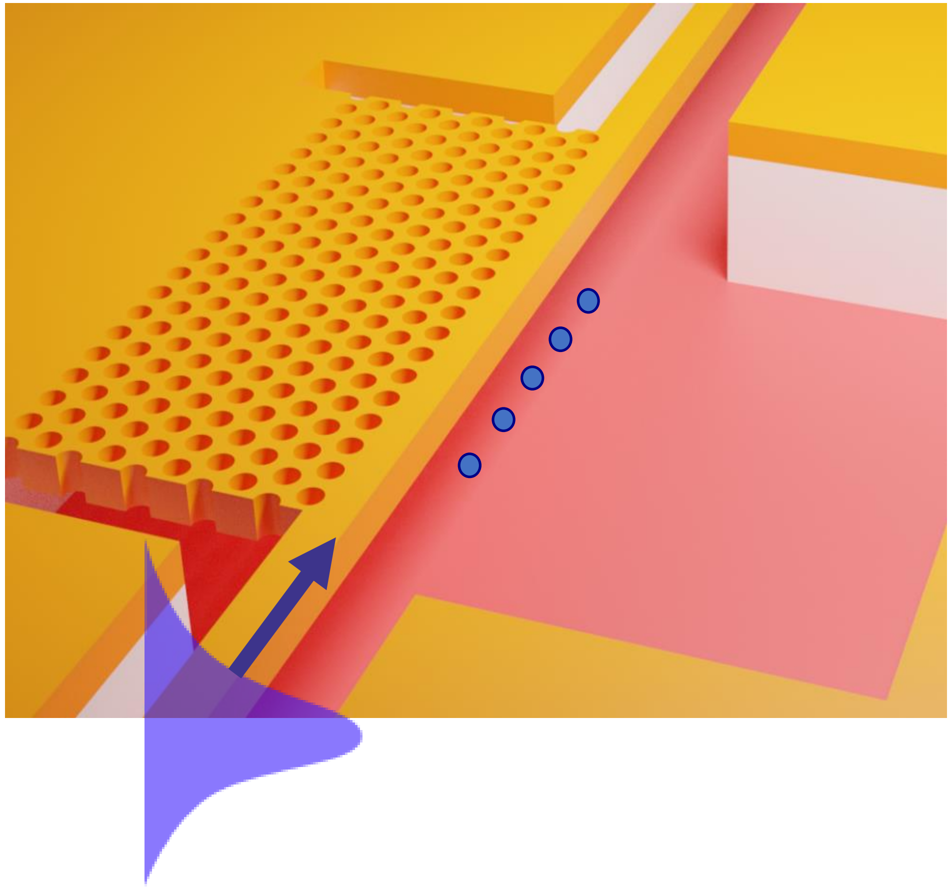
Slow light for increased interactions



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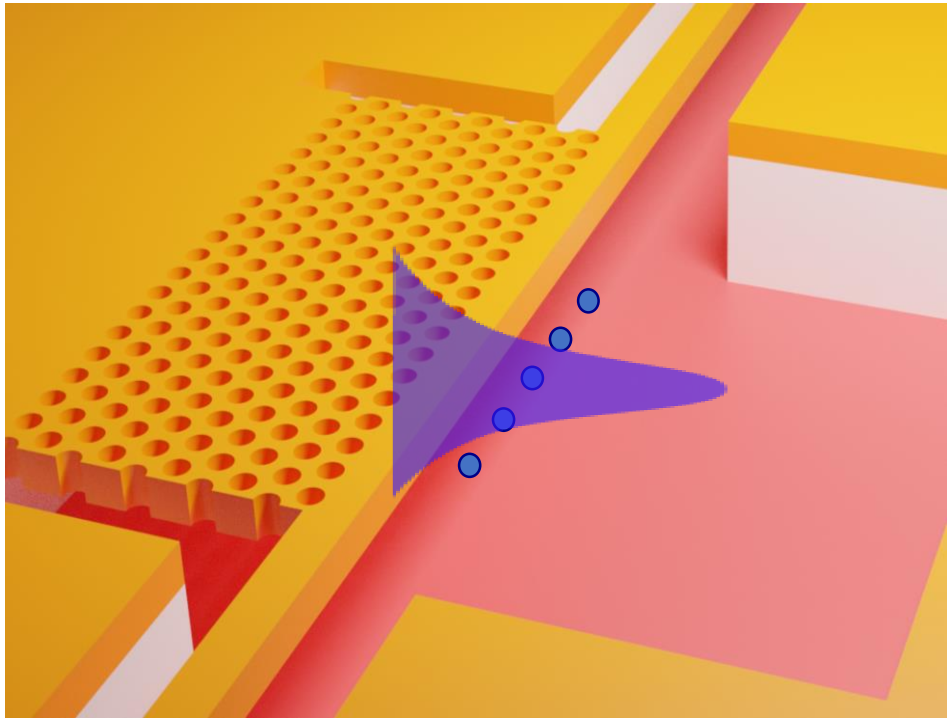

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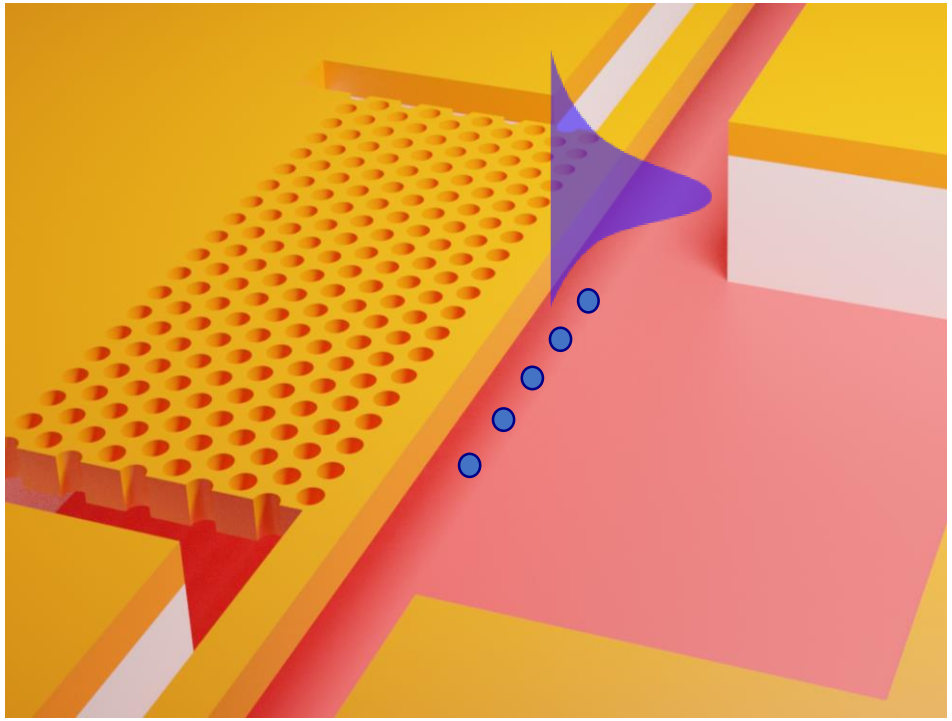
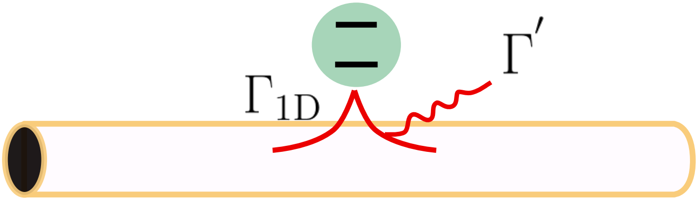


Mathematically interaction quantified by Purcell factor

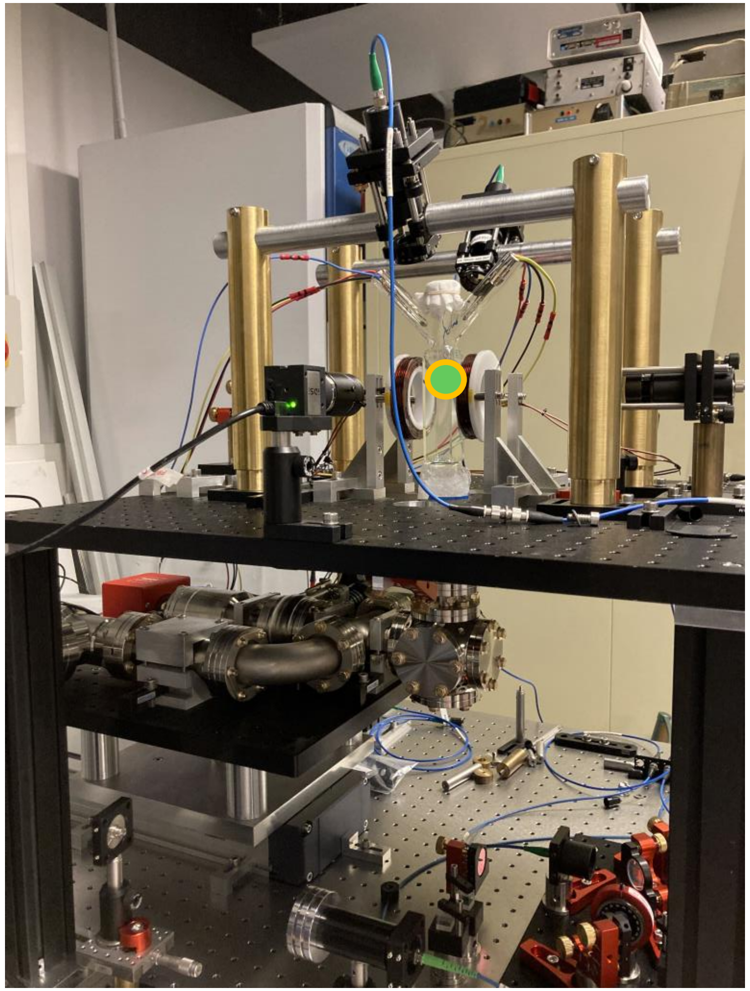


$$\frac{\Gamma_{1D}}{\Gamma_0} = \frac{1}{2}\frac{c}{v_g}\frac{\sigma_0}{S}\,|E_{mode}|^2$$

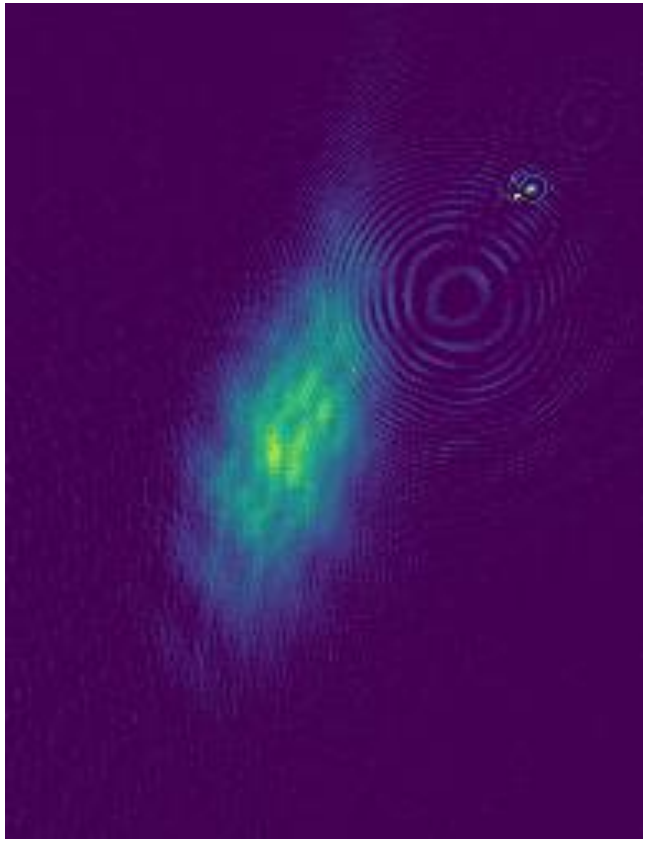
Purcell Factor proportional to n_g

T. Krauss *et al.*, "Slow light in photonic crystal waveguides" J. Phys. D, **40** 2666 (2007)

Actually bringing the atoms there



MOT



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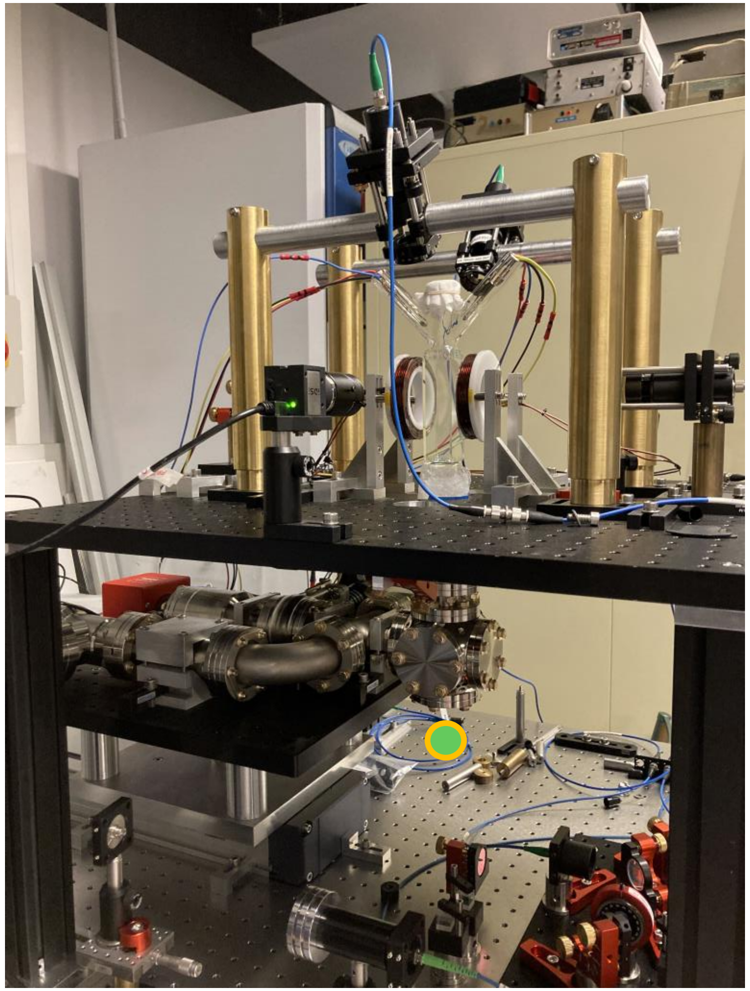

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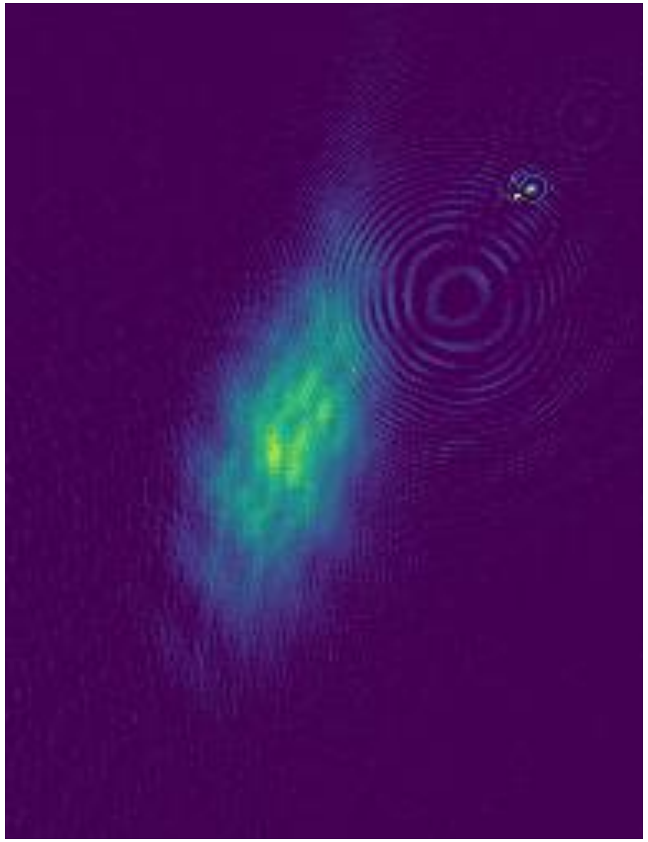

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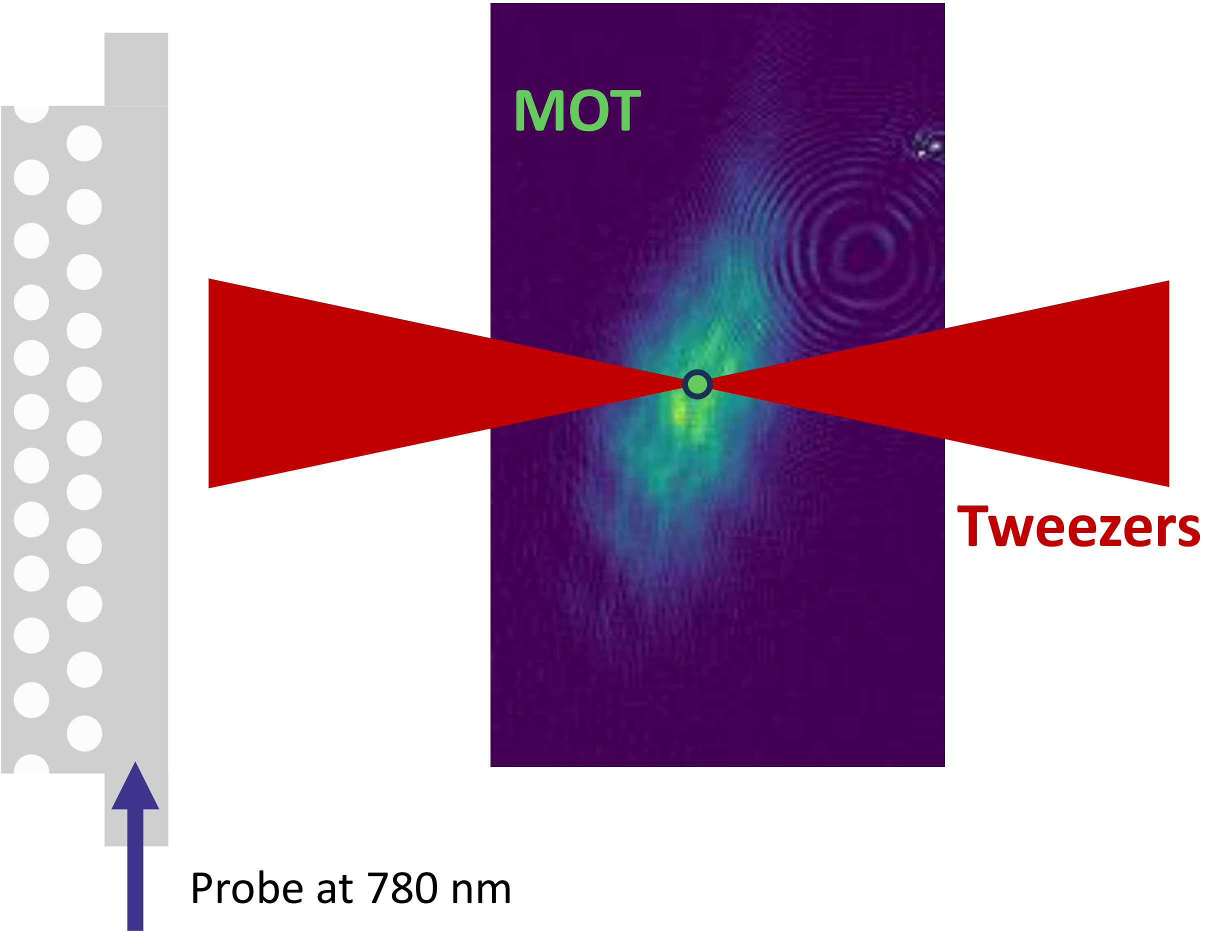

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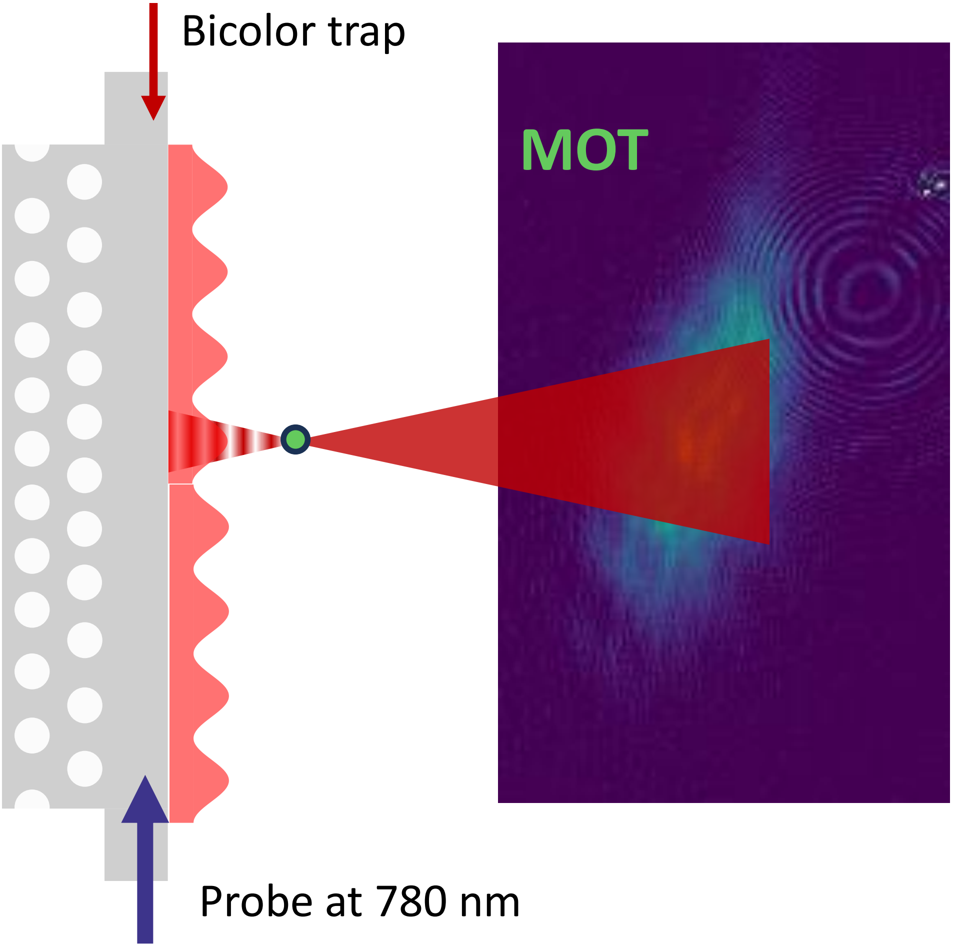
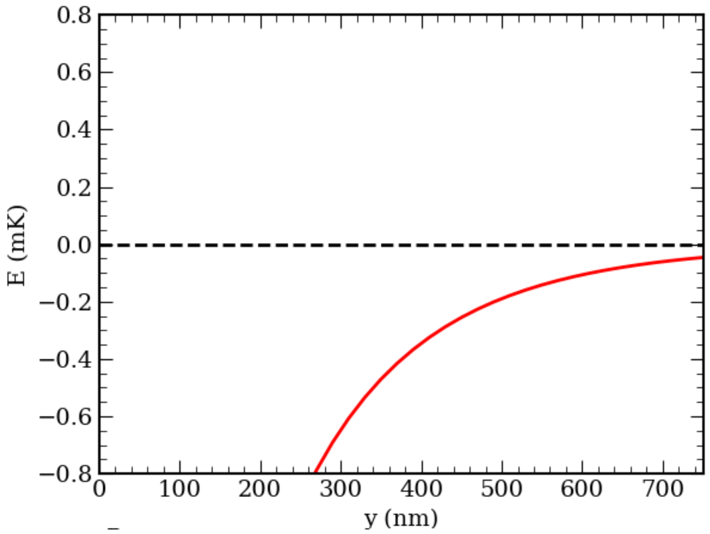


Tweezers



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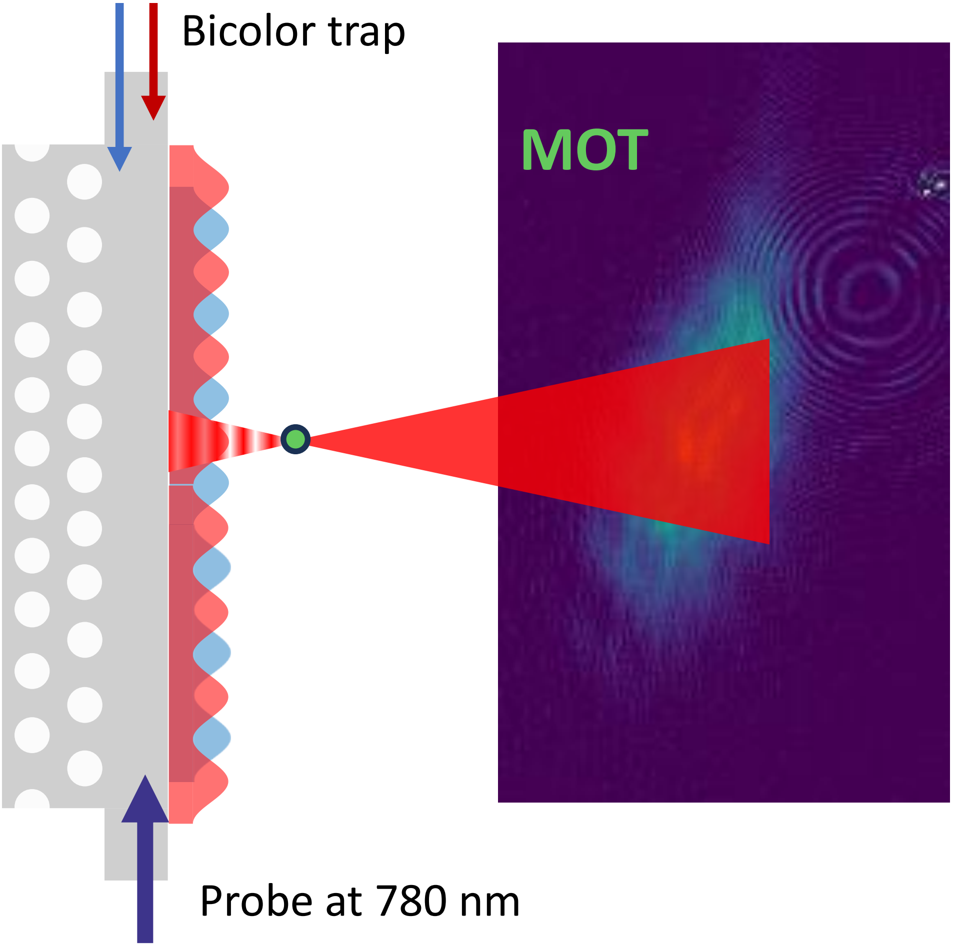
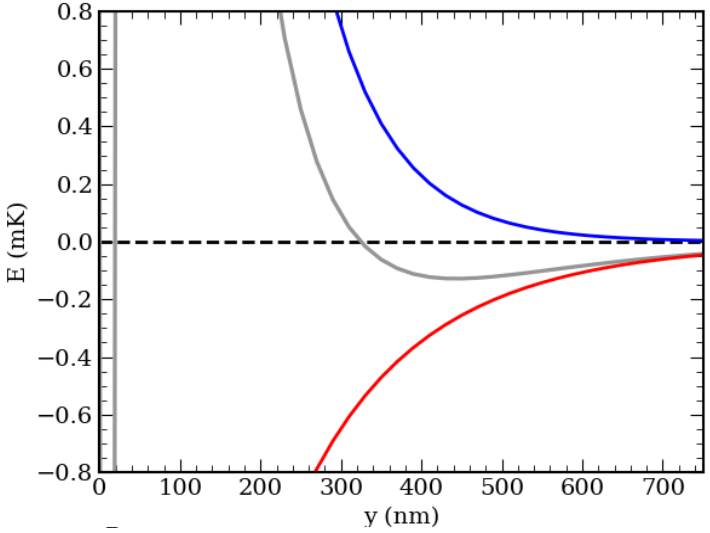


Bicolor trap

MOT

Probe at 780 nm

Tweezers



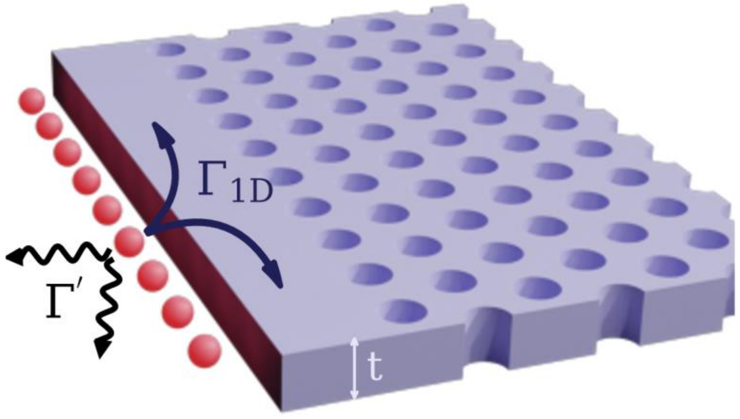
J. Berroir*, A. Bouscal* *et al.*, " Nanotrappy: An open-source versatile package for cold-atom trapping close to nanostructures" PRR, **4** 013079 (2022)

Design and fabrication

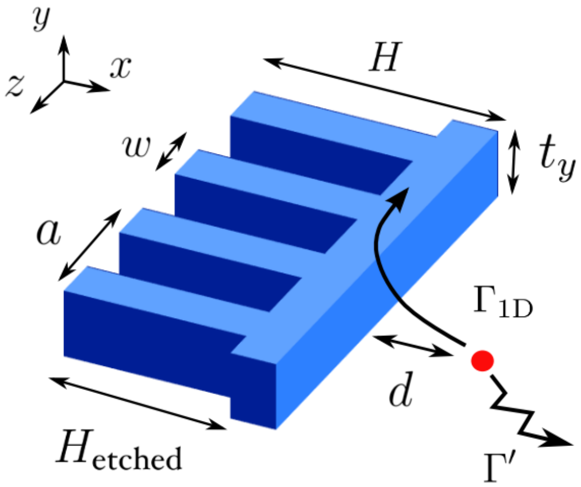
Focus on two structures (both for design and fabrication)

Asymmetric → optical access
High refractive index → Small mode area

Aim group index of 30-50



Half-W1 waveguide



Comb waveguide

A. Bouscal *et al.*, " Systematic design of a new photonic crystal platform for interfacing slow light and trapped cold atoms" under preparation
N. Fayard, A. Bouscal *et al.*, "Asymmetric comb waveguide for strong interactions between atoms and light" arXiv:2201.02507, accepted in Optics Express

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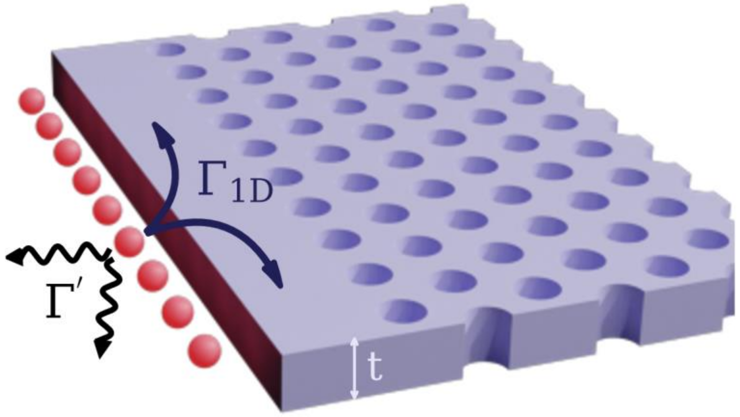
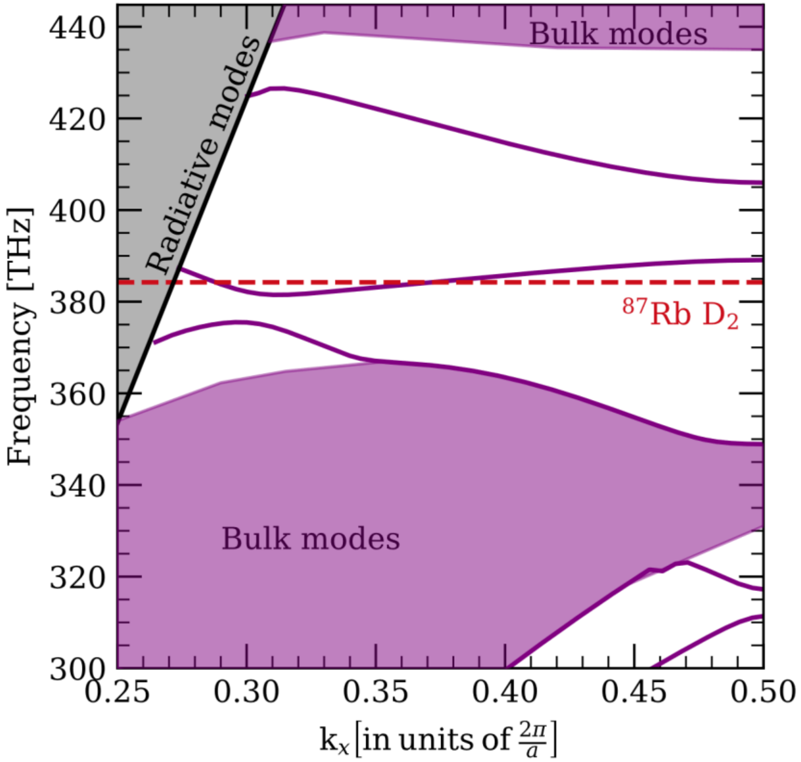
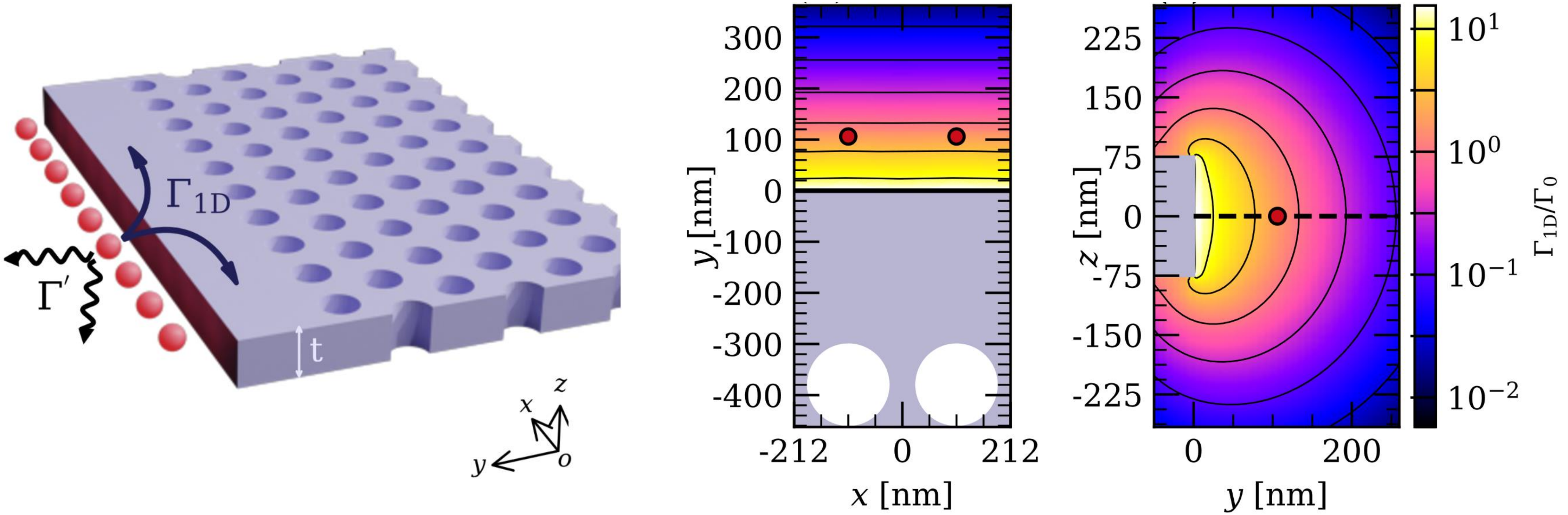


Half-W1 waveguide



Group index of 30

Design and fabrication

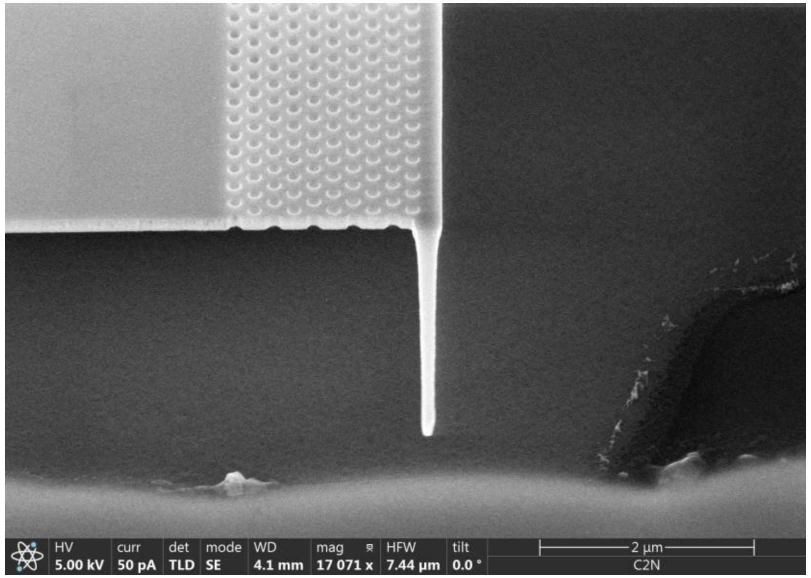


→ At the trap minimum, **probability around 70%** can be achieved

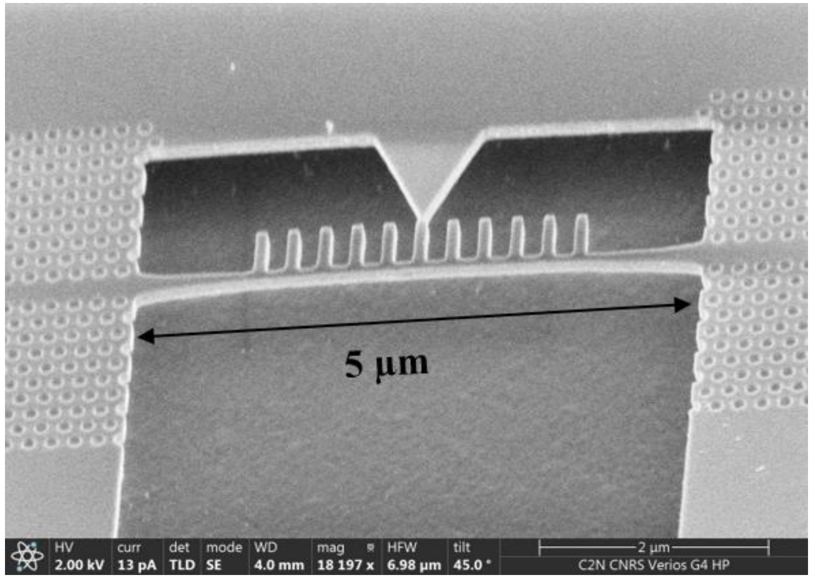
Design and fabrication

C2N had to train working on GaInP

1st generation Half-W1



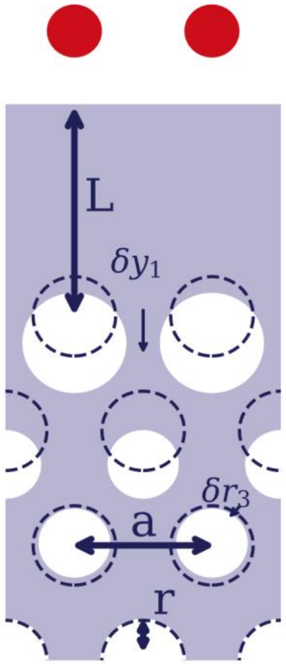
Comb waveguide

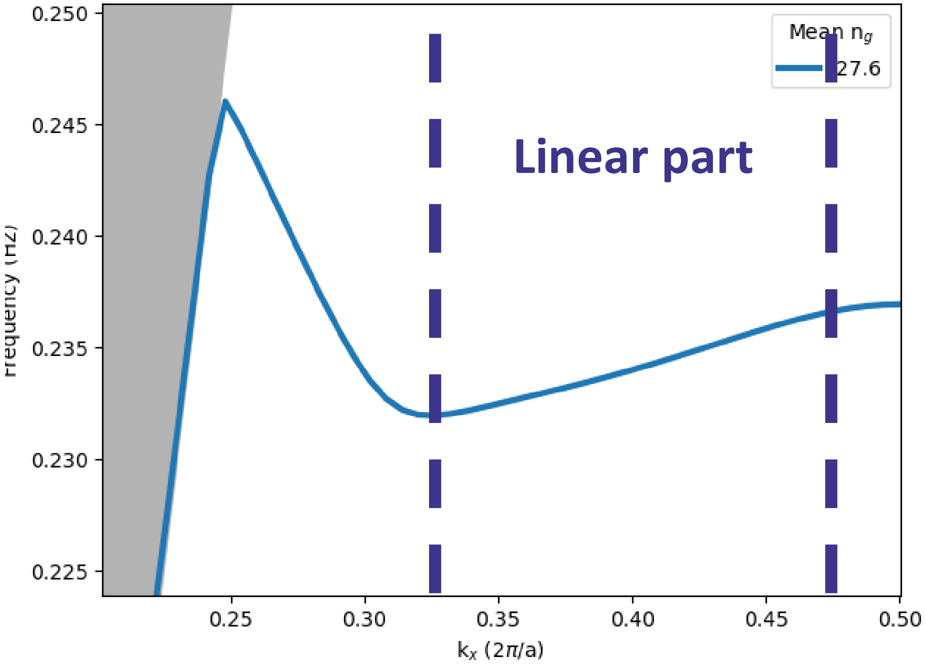


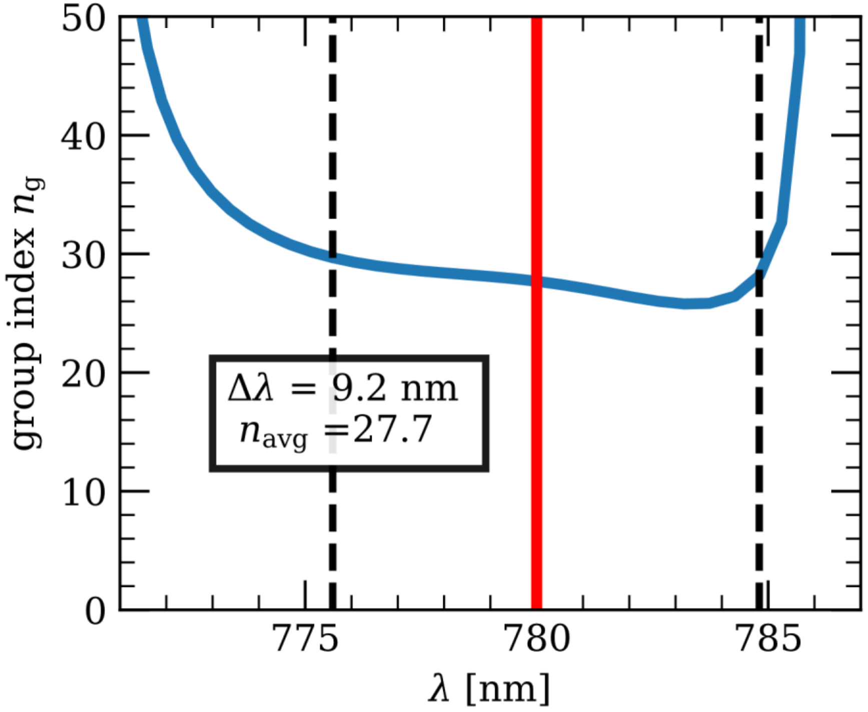
Characterization ongoing…

Appendix : robustness to fabrication imperfections

Shifting first rows positions and radiuses, we can make the bands more linear







To see the increased interaction you have to keep the atoms still close to the waveguide → trapping

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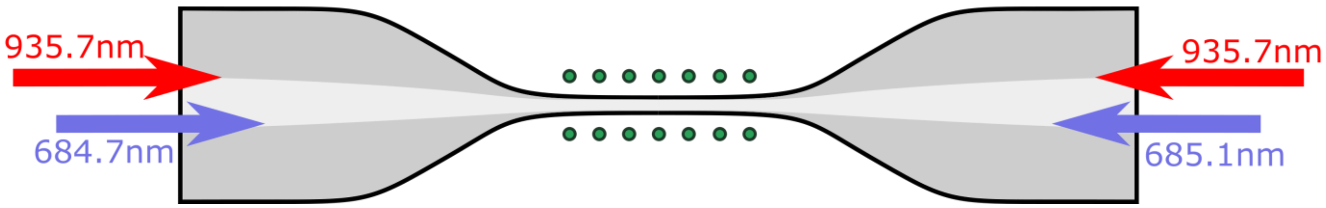
Appendix : two-color dipole trap

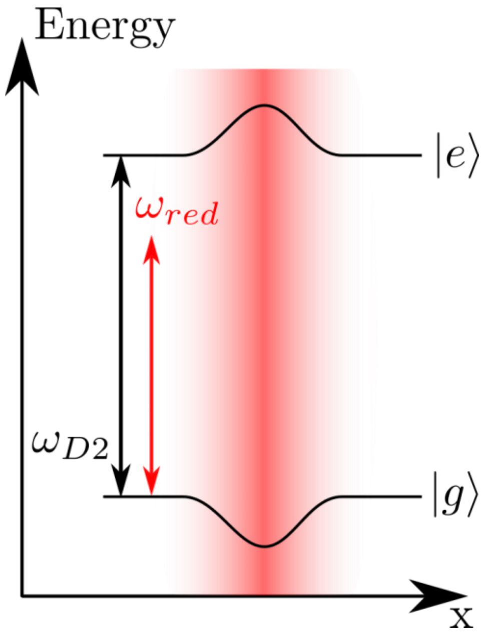
Example of a nanofiber

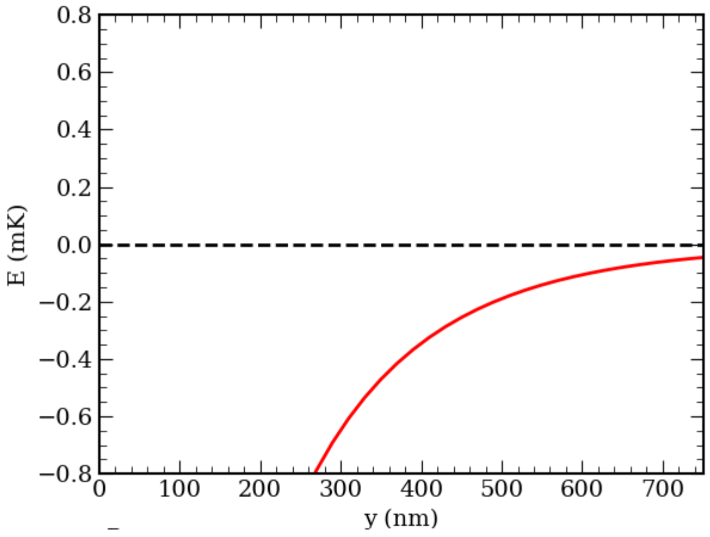
Two-color guided evanescent trap:

- **Red attracts**
- Blue repels

Contrapropagating the red to have a standing wave







F. Le Kien *et al.*, " Atom Trap and Waveguide Using a Two-Color Evanescent Light Field Around a Subwavelength-diameter Optical Fiber" Phys. Rev. A, **70** 063403 (2004)

E. Vetsch *et al.*, "Optical Interface Created by Laser-Cooled Atoms Trapped in the Evanescent Field Surrounding an Optical Nanofiber" Phys. Rev. Lett., **104** 203603 (2010)

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Example of a nanofiber

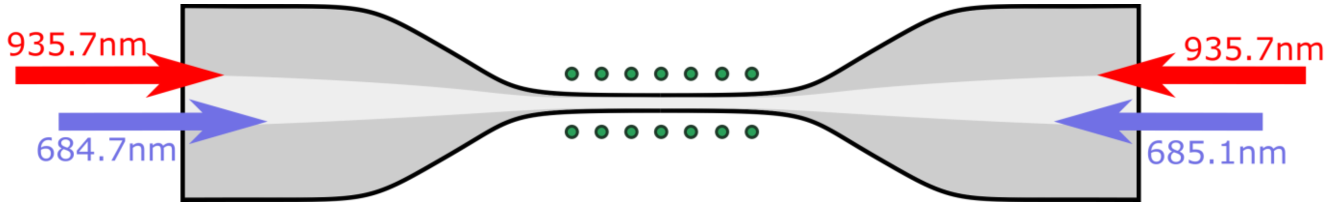
Two-color guided evanescent trap:

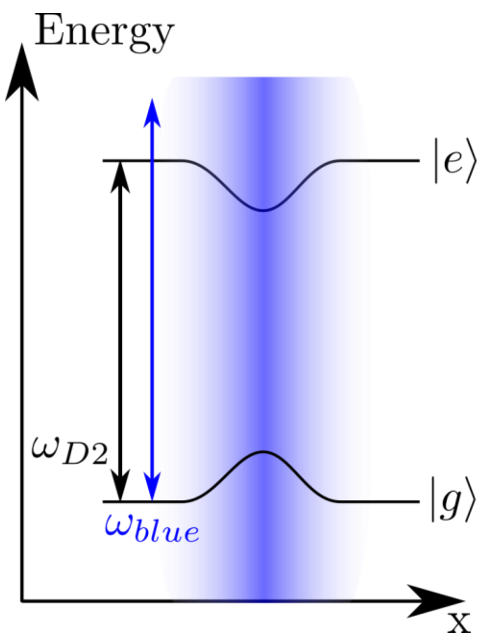
- Red attracts
- Blue repels

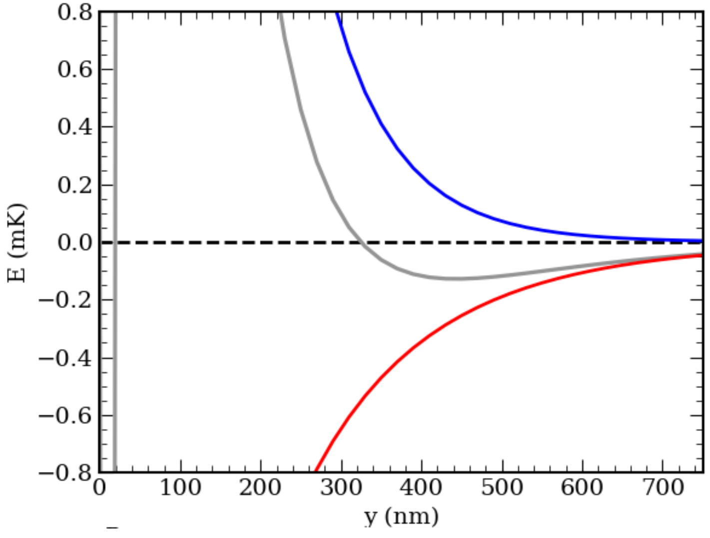
Contrapropagating the red to have a standing wave

To be able to follow the same idea with our PCW, we need guided modes for trapping

New constraint on design





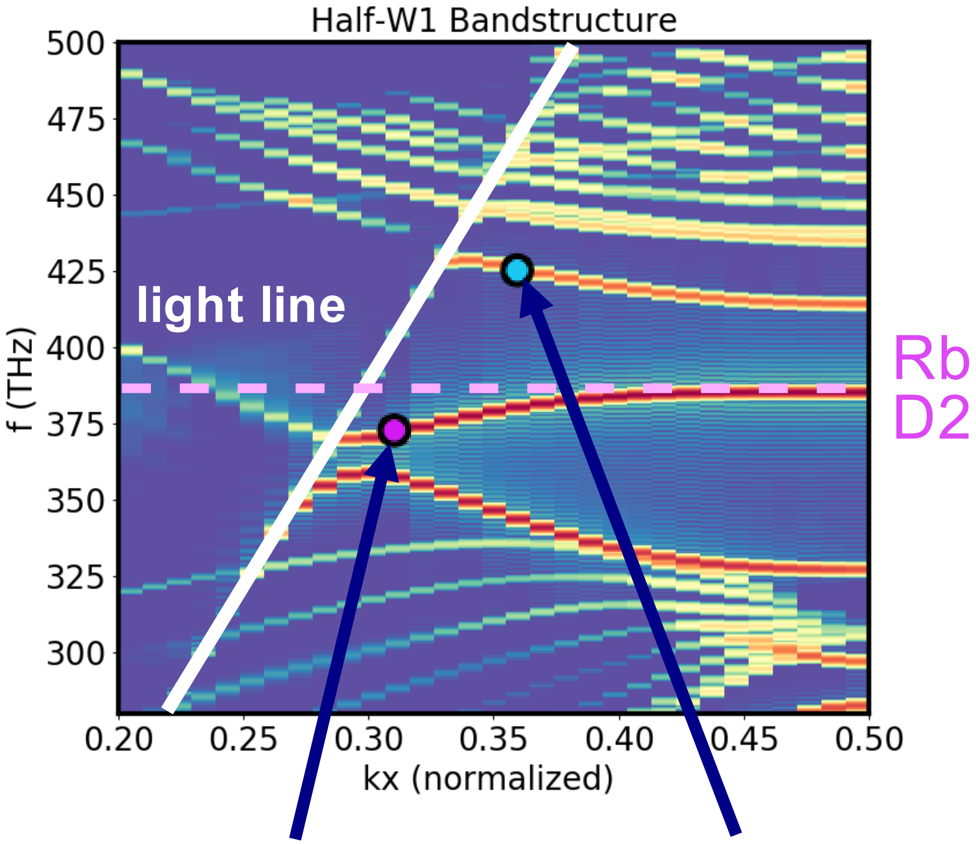


F. Le Kien *et al.*, " Atom Trap and Waveguide Using a Two-Color Evanescent Light Field Around a Subwavelength-diameter Optical Fiber" Phys. Rev. A, **70** 063403 (2004)
E. Vetsch *et al.*, "Optical Interface Created by Laser-Cooled Atoms Trapped in the Evanescent Field Surrounding an Optical Nanofiber" Phys. Rev. Lett., **104** 203603 (2010)

Appendix : two-color dipole trap

More difficult with photonic crystal waveguides !

- Mode intensity shapes change from one band to another but also inside a given band
- Complex polarisation structure $H_{AF} = -\vec{d}.\vec{E}$



Red detuned mode

Blue detuned mode

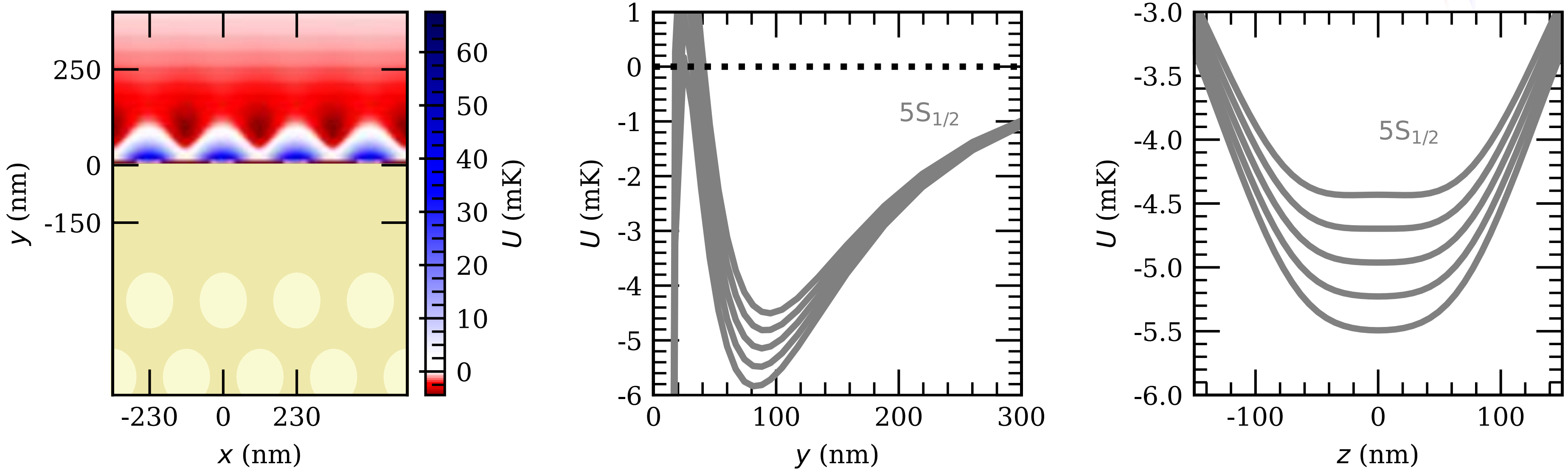
Tuning the band diagram to have sufficient modes available

We need **1** mode for slow light → probe
+ **2** modes for dipole trapping (similar to nanofiber)

Appendix : two-color dipole trap

Stable trapping scheme around our Half-W1

nanotrappy

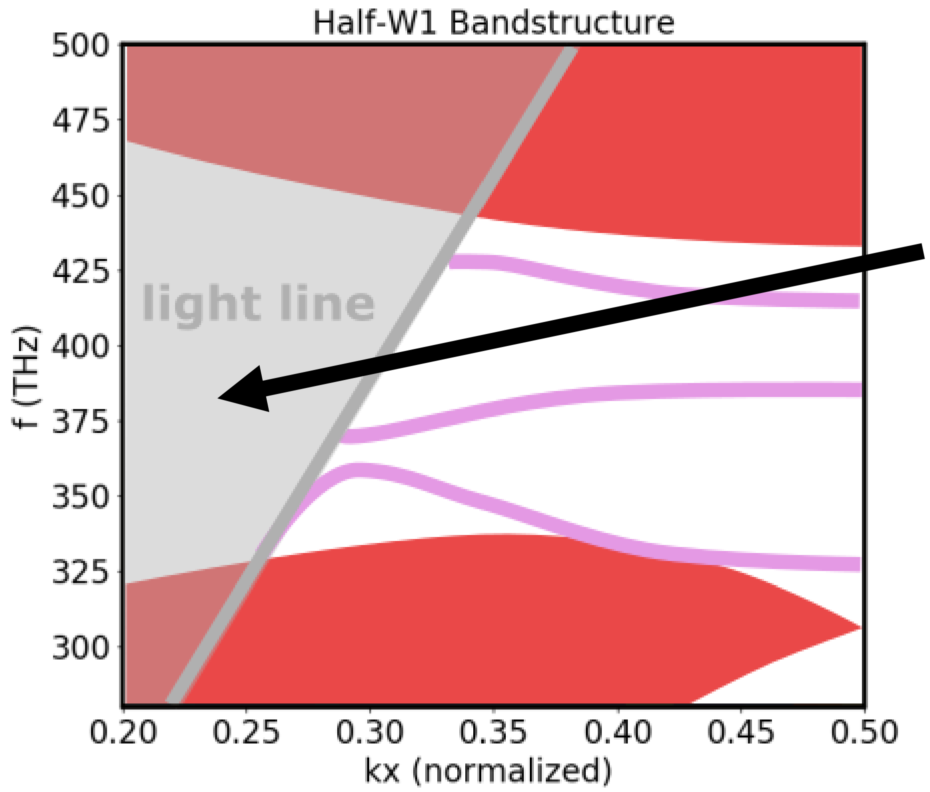


- Stable trap in all 3 directions
- Traps computed with nanotrappy in a few seconds
- Small splitting of the m_f states

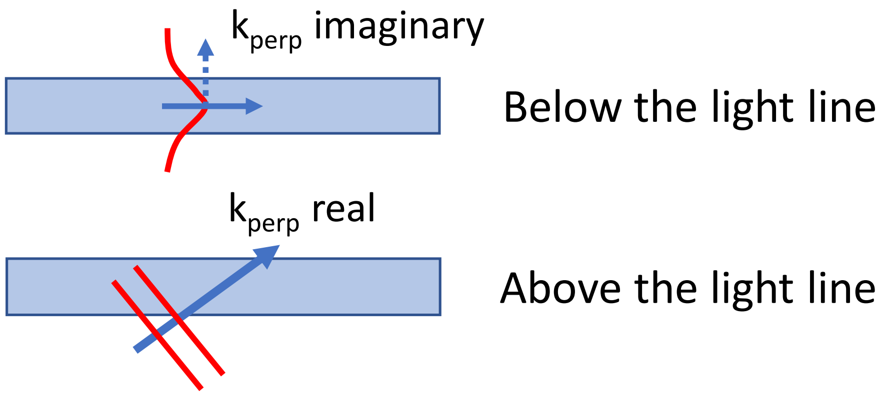
J. Berroir*, A. Bouscal* *et al.*, " Nanotrappy: An open-source versatile package for cold-atom trapping close to nanostructures" PRR, **4** 013079 (2022)

Appendix : Propagation above the light line

Construction step by step of the diagram



Delocalized modes
not guided in the slab

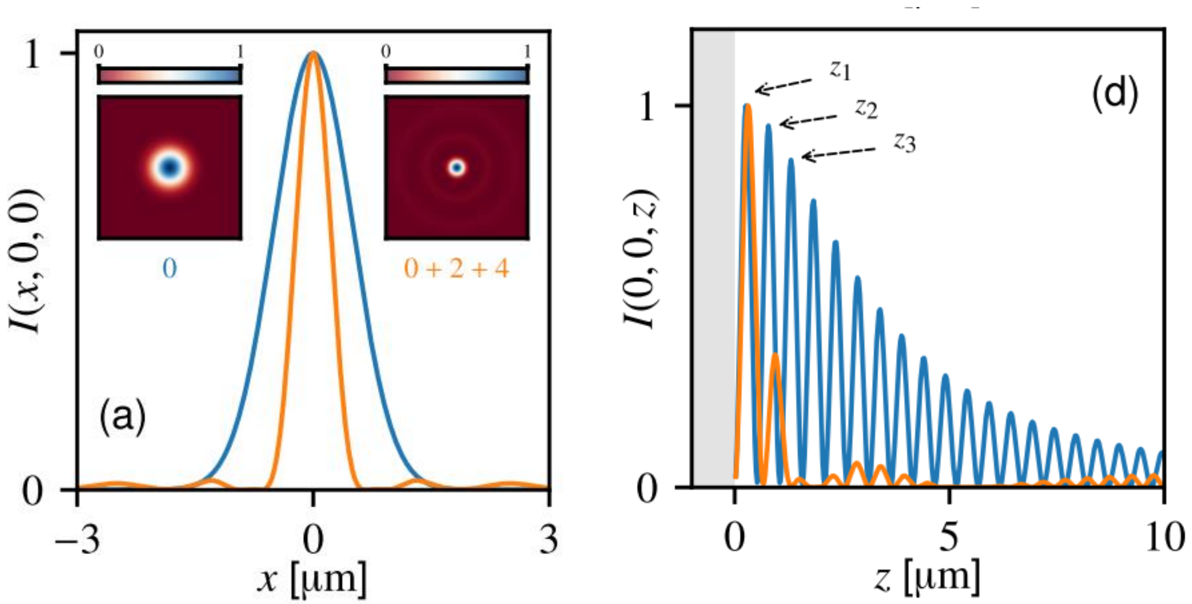


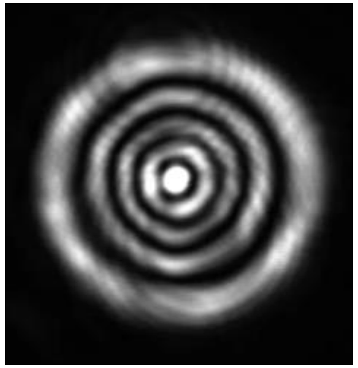
Appendix : Tweezers with LG beams

Prelimary work on tweezers :

- Tweezer arrays
- Laguerre Gaussian tweezers

Goal : Trap the atoms with a superposition of LG beams to reduce mode volume and reflections on the surface





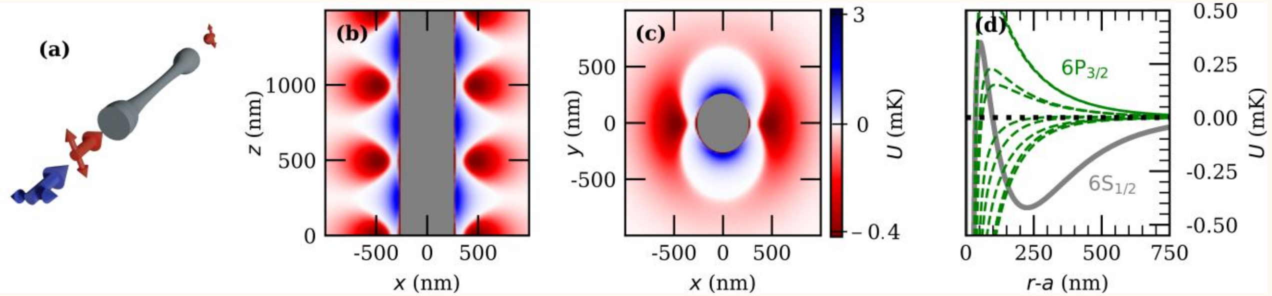
JB. Béguin *et al.*, "Reduced volume and reflection for bright optical tweezers with radial Laguerre–Gauss beams" PNAS (2020)

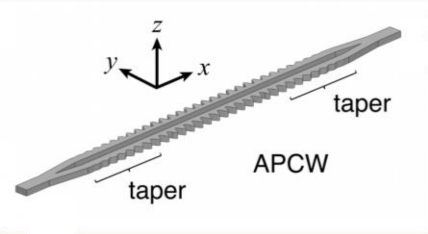
Appendix : Python package for dipole trapping aroung structures

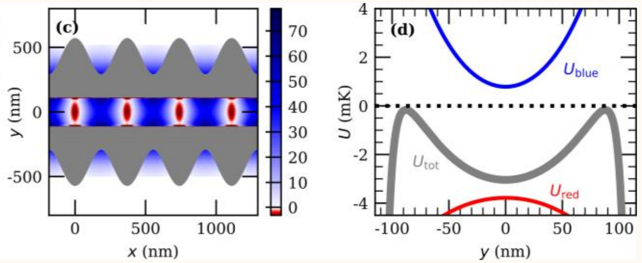
nanotrappy **for computing traps**

Tool for easing dipole trap and structure design

- For all alkali atoms and any structure
- Down to hyperfine splitting (accounts for vector and tensor shifts)
- Interactive control and GUI (no need to know Python)
- Systematic optimization via parameter sweeps







Simple installation from GitHub

J. Berroir*, A. Bouscal* *et al.*, ” Nanotrappy: An open-source versatile package for cold-atom trapping close to nanostructures” PRR, **4** 013079 (2022)