Chiral interaction of light and matter in confined geometries

8th International Summer School of the SFB/TRR21
"Control of Quantum Correlations in Tailored Matter"
Heinrich-Fabri-Haus, Blaubeuren, Germany
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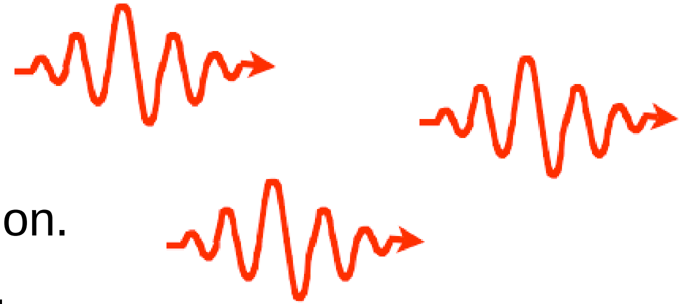
Vienna Center for Quantum Science and Technology,
Atominstitut, TU Wien, Austria

Introduction – Hybrid (Quantum) Systems

Introduction – Atom–Light Interfaces

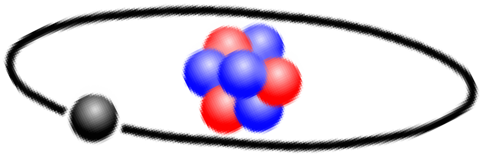
- Optical photons



  - Propagate at speed of light.
  - Easy state manipulation and detection.
  - Weakly coupled to the environment.

  ➔ Ideal carriers for transmitting (quantum) information.

- Atoms



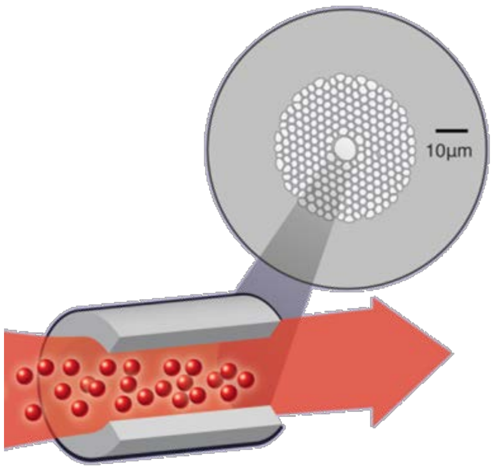
  - Identical quantum systems (~10^{21} Rb atoms per $).
  - Well-known level structure and optical transitions.
  - Laser control of internal & external degrees of freedom.
  - Excellent ground state coherence properties.
  - Nonlinear response and controlled interactions.

  ➔ Ideal for storing and processing quantum information.

➔ Realize quantum interface between atoms and <u>propagating</u> optical photons.

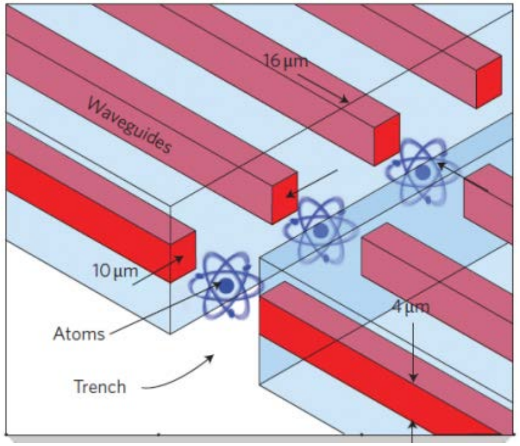
Introduction – Atom–Light Interfaces

- Challenge:
  - Interaction cross section between atoms and light is small.
  - ➔ Strong transversal confinement of light.

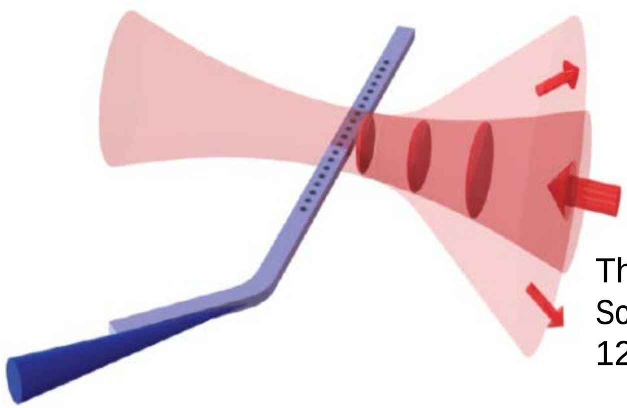


Christensen et al., PRA **78**, 033429 (2008)

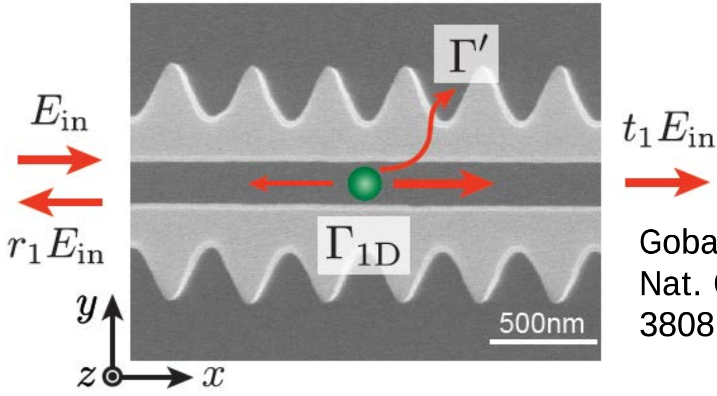
Bajcsy et al., PRL **102**, 203902 (2009)



Kohnen et al., Nat. Phot. **5**, 35 (2010)



Thompson et al., Science **340**, 1202 (2013)



Goban et al., Nat. Comm. **5**, 3808 (2014)

Introduction – Atom–Light Interfaces

- Challenge:
  - Interaction cross section between atoms a...
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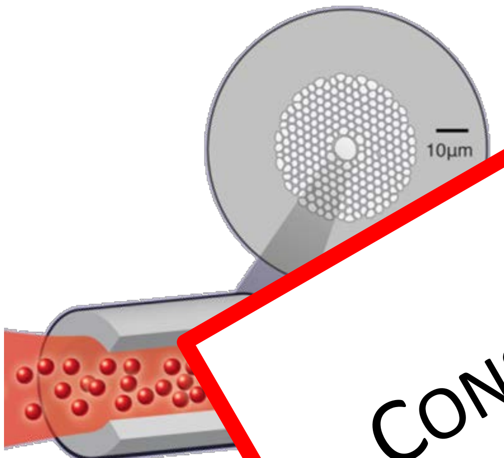
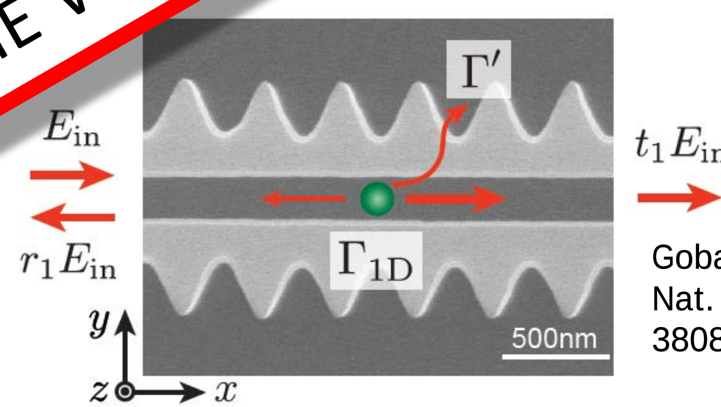


Chr...

...nen et al., ...Phot. **5**, 35

DISCLAIMER:
CONSULT MAXWELL'S EQUATIONS BEFORE COUPLING EMITTERS TO A LIGHT FIELD THAT IS TRANSVERSALLY CONFINED AT THE WAVELENGTH SCALE.

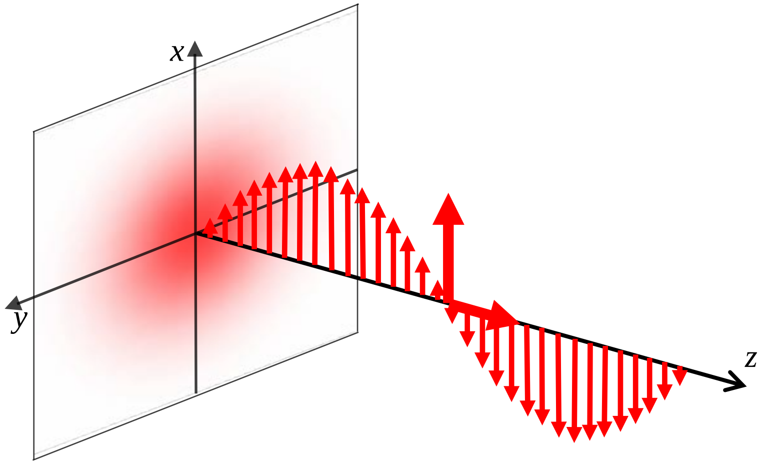
...mpson et al., Science **340**, 1202 (2013)



Goban et al., Nat. Comm. **5**, 3808 (2014)

Introduction – Non-transversal Polarization

- Non-transversal polarization
  - Electric field oscillating in direction of propagation



$$\vec{\nabla} \cdot \vec{E} = 0$$

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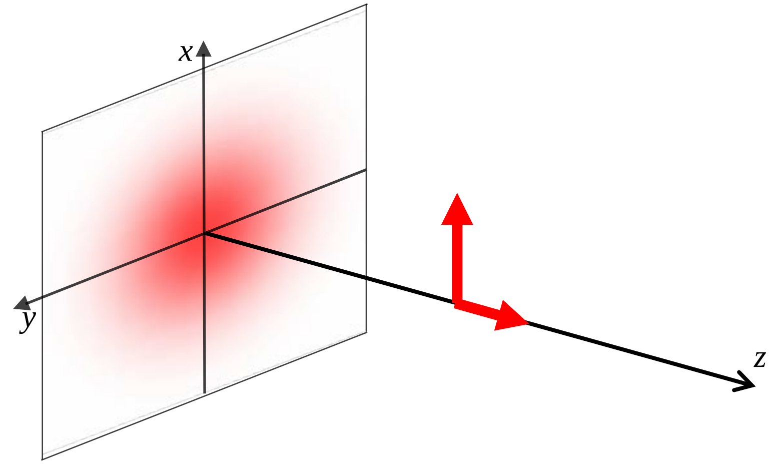

- Origin of longitudinal field
  - Non-zero transversal divergence
  - E. g., if transversal E-field points along the field gradient

  ➔ Longitudinal field component

$$\underbrace{\partial_x E_x + \partial_y E_y}_{\vec{\nabla}_{trans} \cdot \vec{E}_{trans}} + \underbrace{\partial_z E_z}_{\approx i\frac{2\pi}{\lambda} E_z} = 0$$

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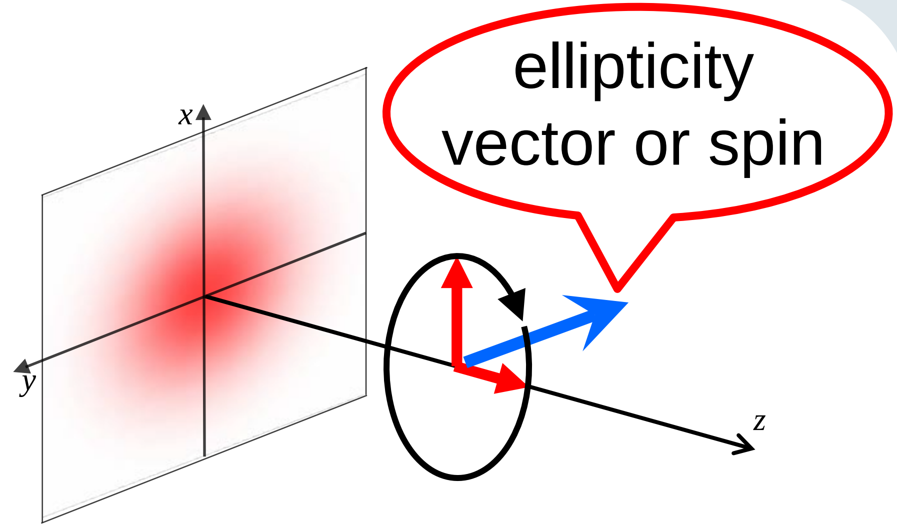

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  - Non-zero transversal divergence
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  ➔ Longitudinal field component

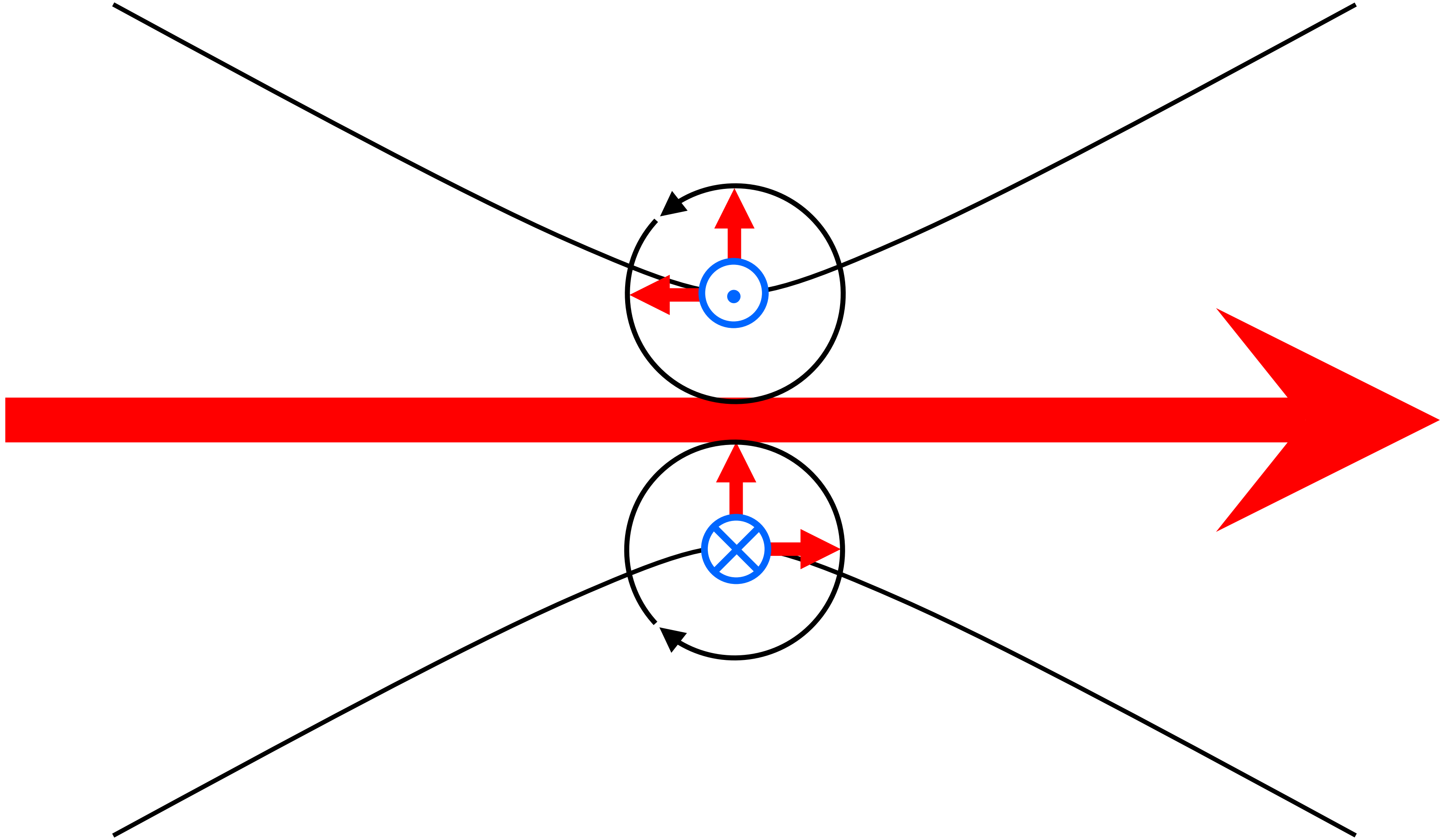
$$E_z = i\frac{\lambda}{2\pi}\left(\vec{\nabla}_{trans}\cdot\vec{E}_{trans}\right)$$

oscillates 90° out of phase!!

➔ Significant longitudinal field if gradient is significant on wavelength scale

Introduction – Spin-Orbit Interaction of Light

- Linearly polarized propagating focused Gaussian mode



⇒ Local ellipticity (or spin) depends on transverse position

Introduction – Spin-Orbit Interaction of Light

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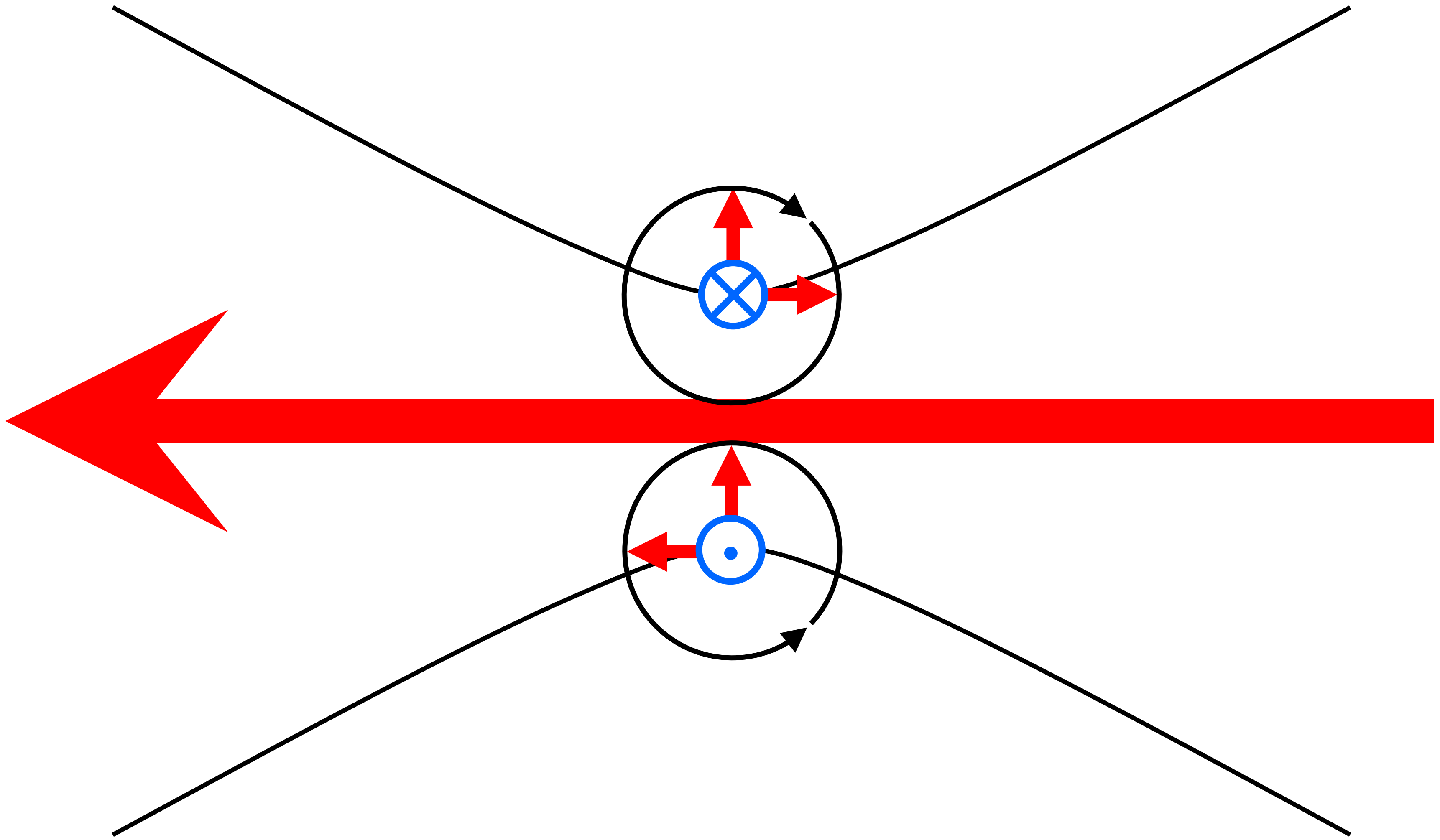
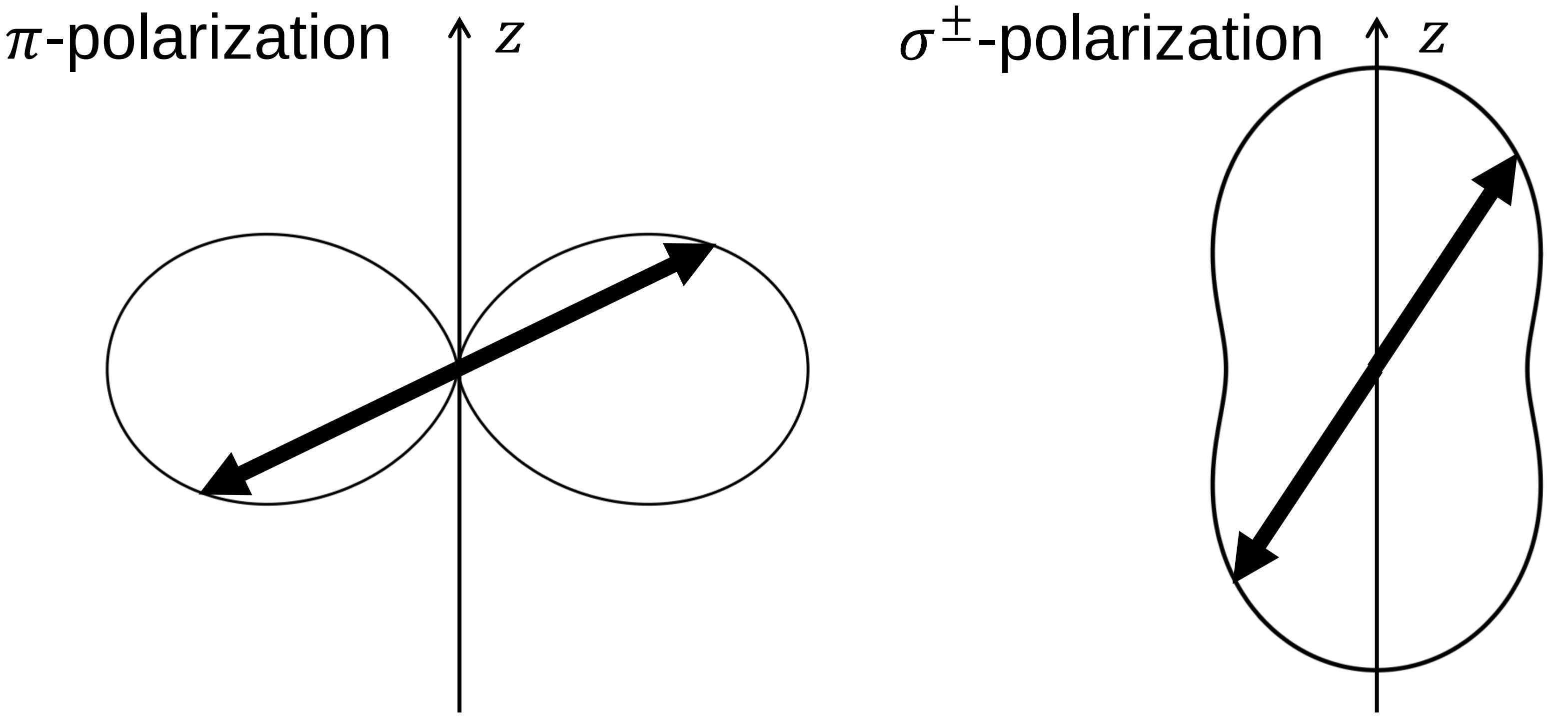


⇒ Local ellipticity (or spin) changes sign with direction of propagation

Introduction – Spontaneous Emission

In free space, dipolar emission exhibits cylindrical symmetry w. r. t. quantization axis (z-axis) and is mirror-symmetric w. r. t. z=0 plane:

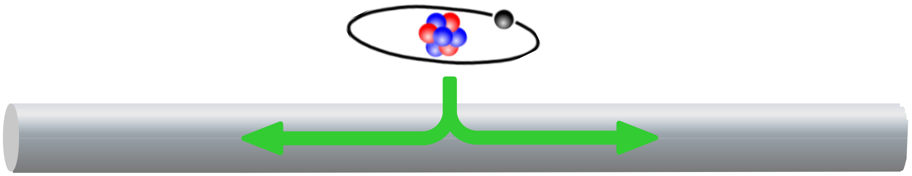


⇒ Emission in any given direction is the same as for opposite direction

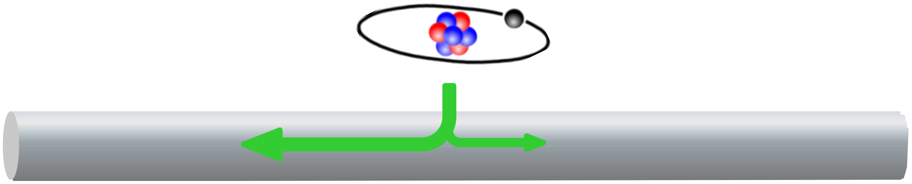
Intro: Directional Spontaneous Emission

Emitters coupled to a nanophotonic waveguide

- Symmetric:



- Asymmetric:



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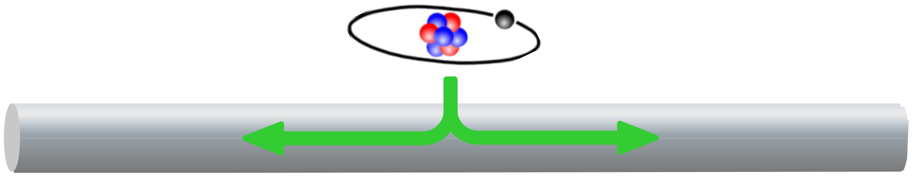

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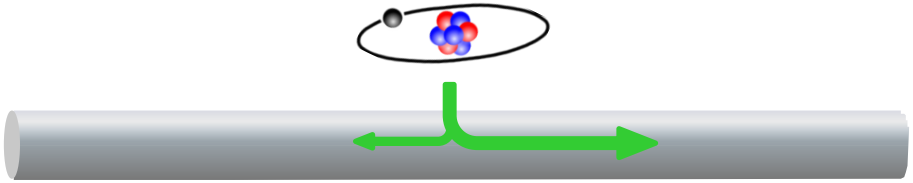
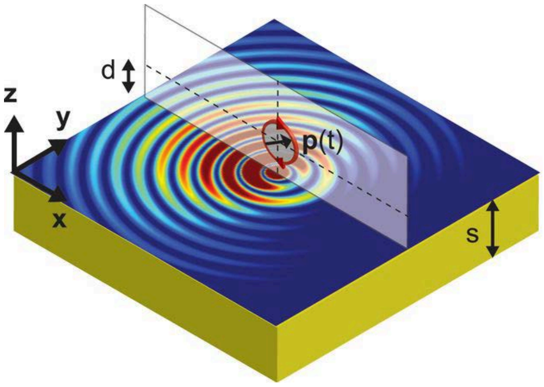


Intro: Directional Spontaneous Emission

- Directional spontaneous emission in different physical situations.
  - Surface-plasmons:



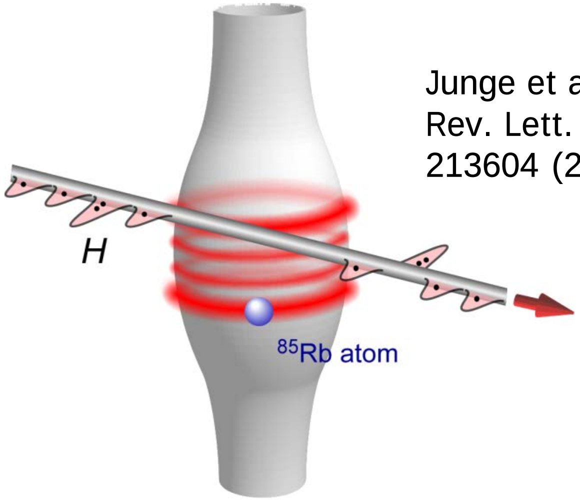
Rodríguez-Fortuño et al., Science **340**, 328 (2013)

J. Lin, et al., Science **340**, 331 (2013)

Intro: Directional Spontaneous Emission

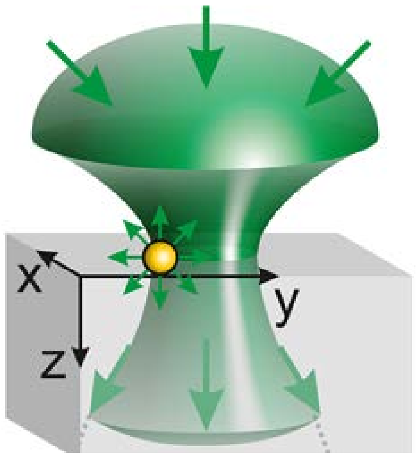
- Directional spontaneous emission in different physical situations.

- Cavity QED with WGMs:



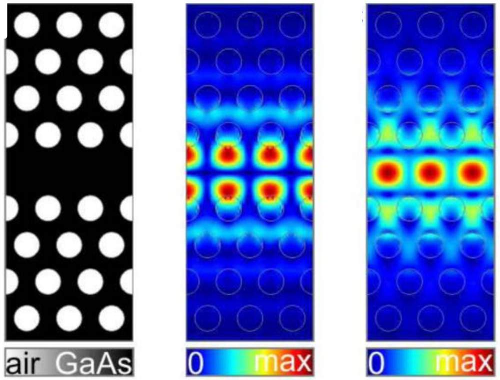
Junge et al., Phys. Rev. Lett. **110**, 213604 (2013)

- Dielectric interface & 2d waveguides



Neugebauer et al., Nano Lett. **14**, 2546 (2014)

- Photonic crystal waveguides:

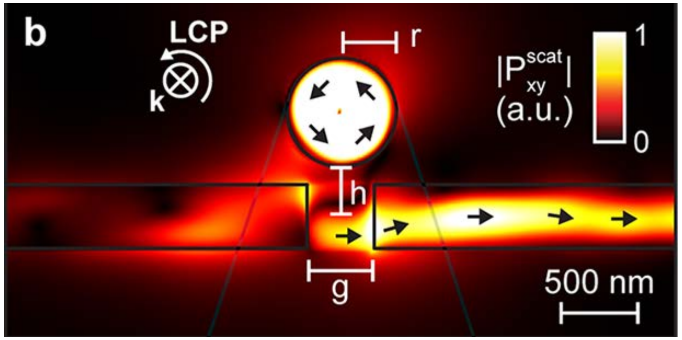


Young et al., arXiv:1406.0714

Söllner et al., arXiv:1406.4295

le Feber et al., arXiv:1406.7741

- Dielectric 1d waveguides:

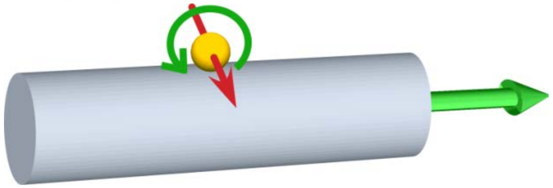


Rodríguez-Fortuño et al., ACS Photonics (2014)
DOI: 10.1021/ph500084b

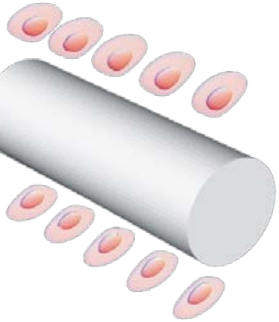
Overview

- Guided modes in optical nanofibers

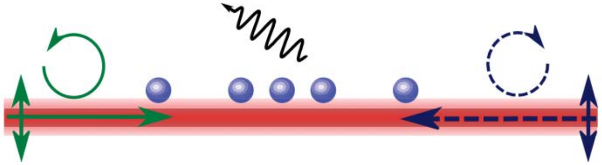
- Directional emission of a gold nanoparticle



- Directional atom-waveguide interface

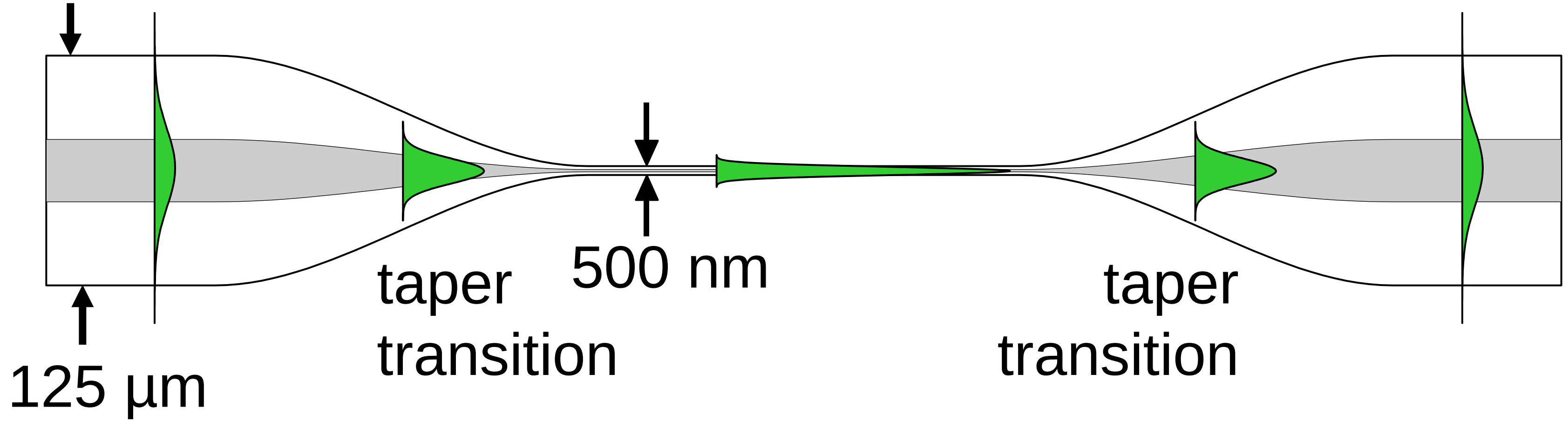


- Nonreciprocal nanophotonic waveguide



Nanofibers as the Waist of a Tapered Fiber

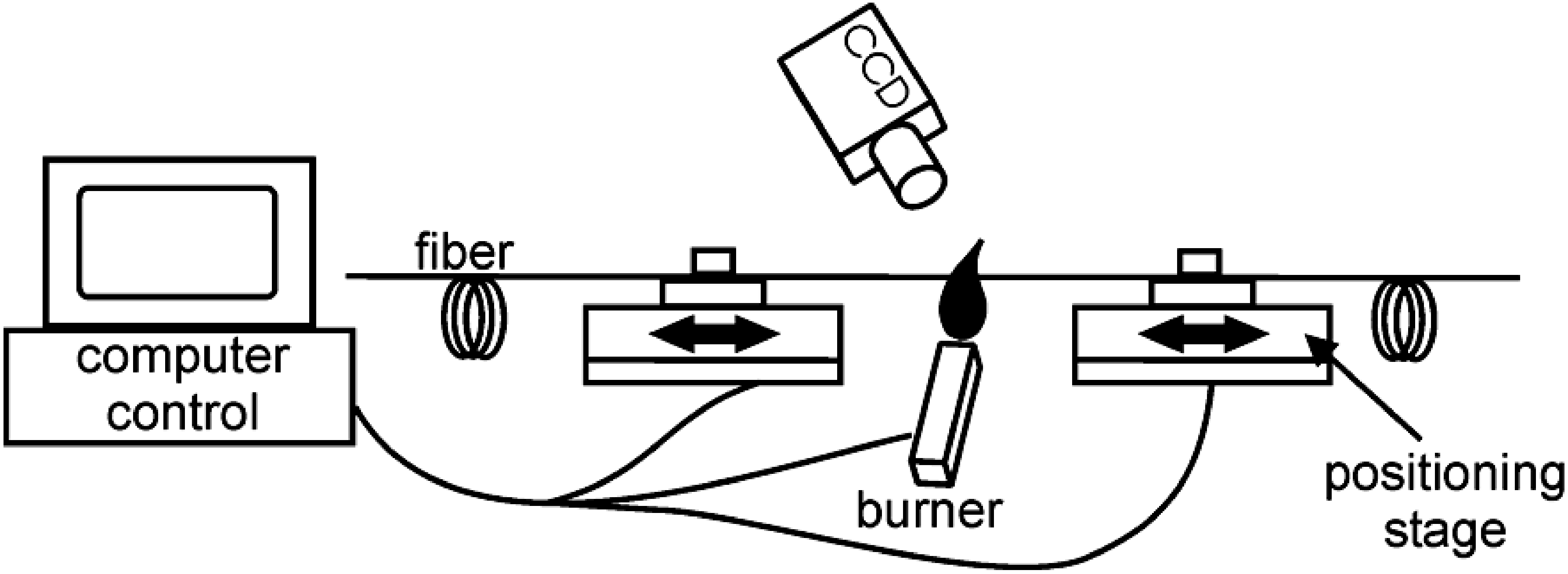
Efficient coupling of light into and out of the nanofiber



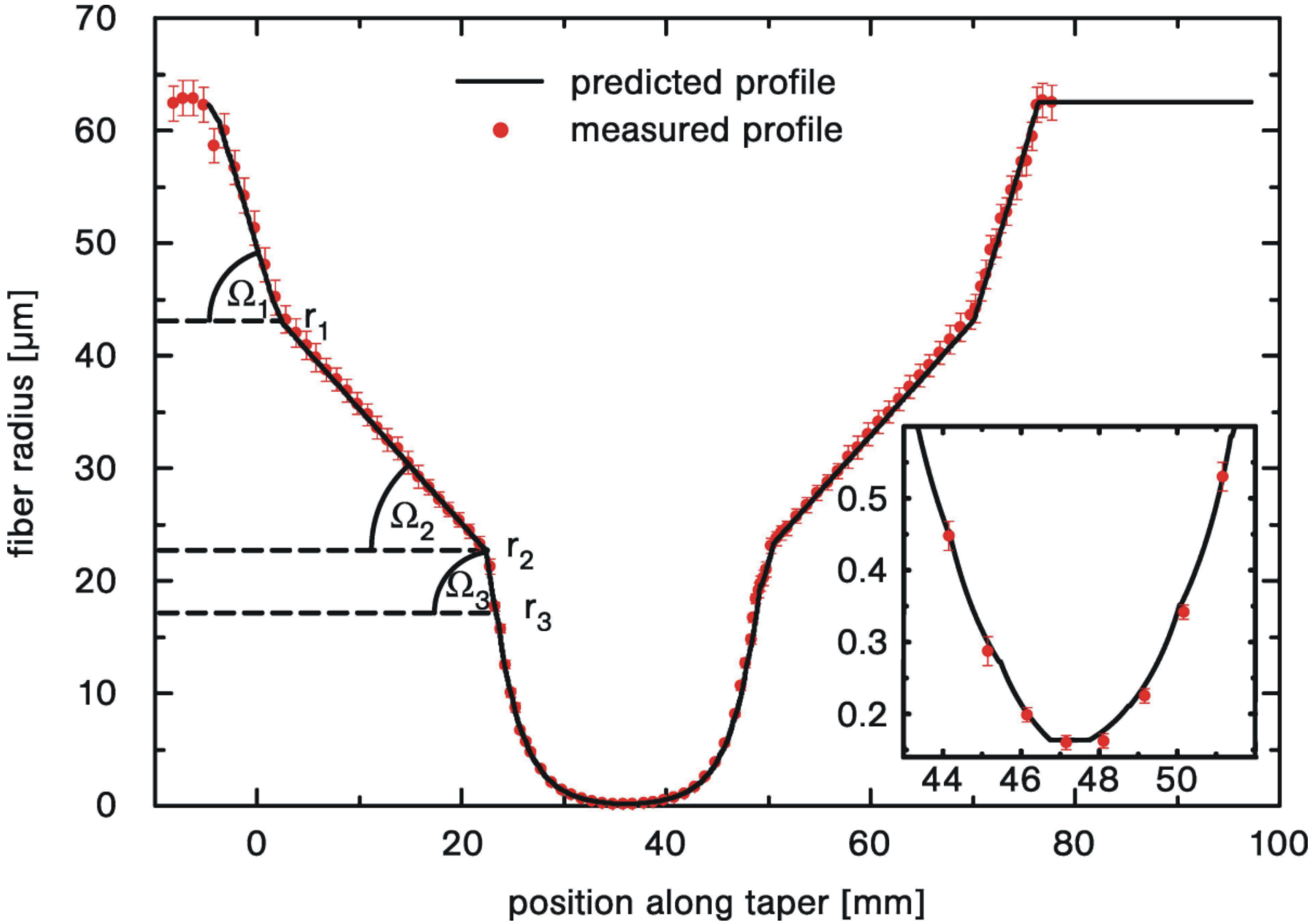
- Adiabatic mode transformation ⇒ up to 99% transmission
- Withstands >100 mW of transmitted optical power in vacuum

Fabrication of Tapered Optical Fibers

- Tapering standard optical fibers by flame pulling:

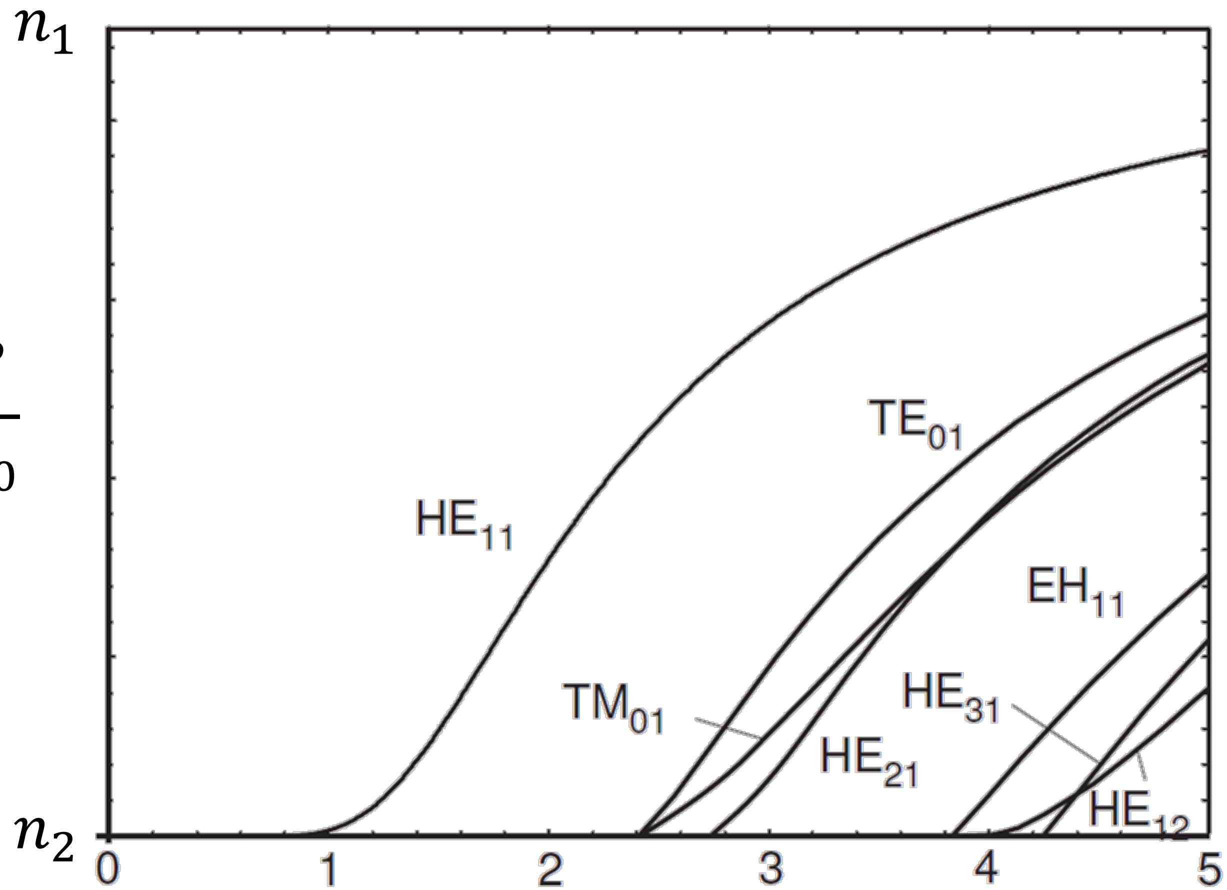


Tapered Fibers of Predetermined Shape



A. Stiebeiner *et al.*, Opt. Express, **18**, 22677 (2010)

Normalized Propagation Constant

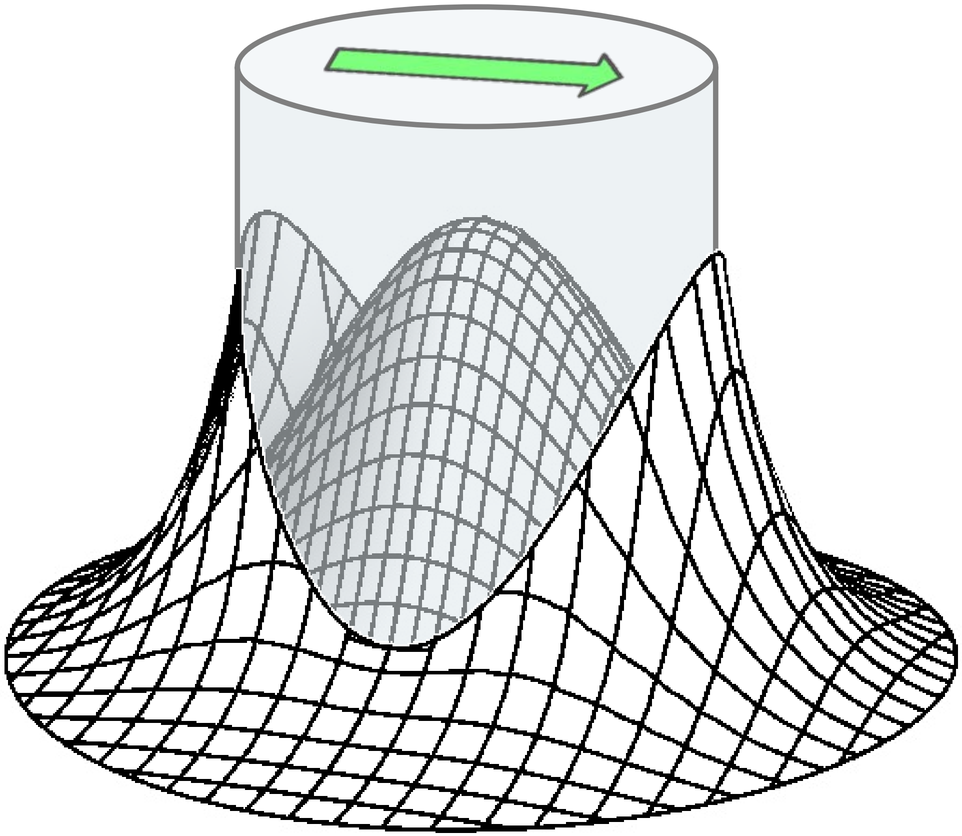


$$n_{\mathrm{eff}} = \frac{\beta}{k_0}$$

$$V = \frac{2\pi a}{\lambda}\sqrt{n_1^2 - n_2^2}$$

HE_{11} Mode: Intensity Distribution

- Quasi linearly polarized HE_{11} mode.
- Parameters: $a = 250$ nm, $n_1 = 1.46$ (silica), $n_2 = 1$ (vacuum / air), and $\lambda = 852$ nm.



HE_{11} Mode: Evanescent Field Decay Length

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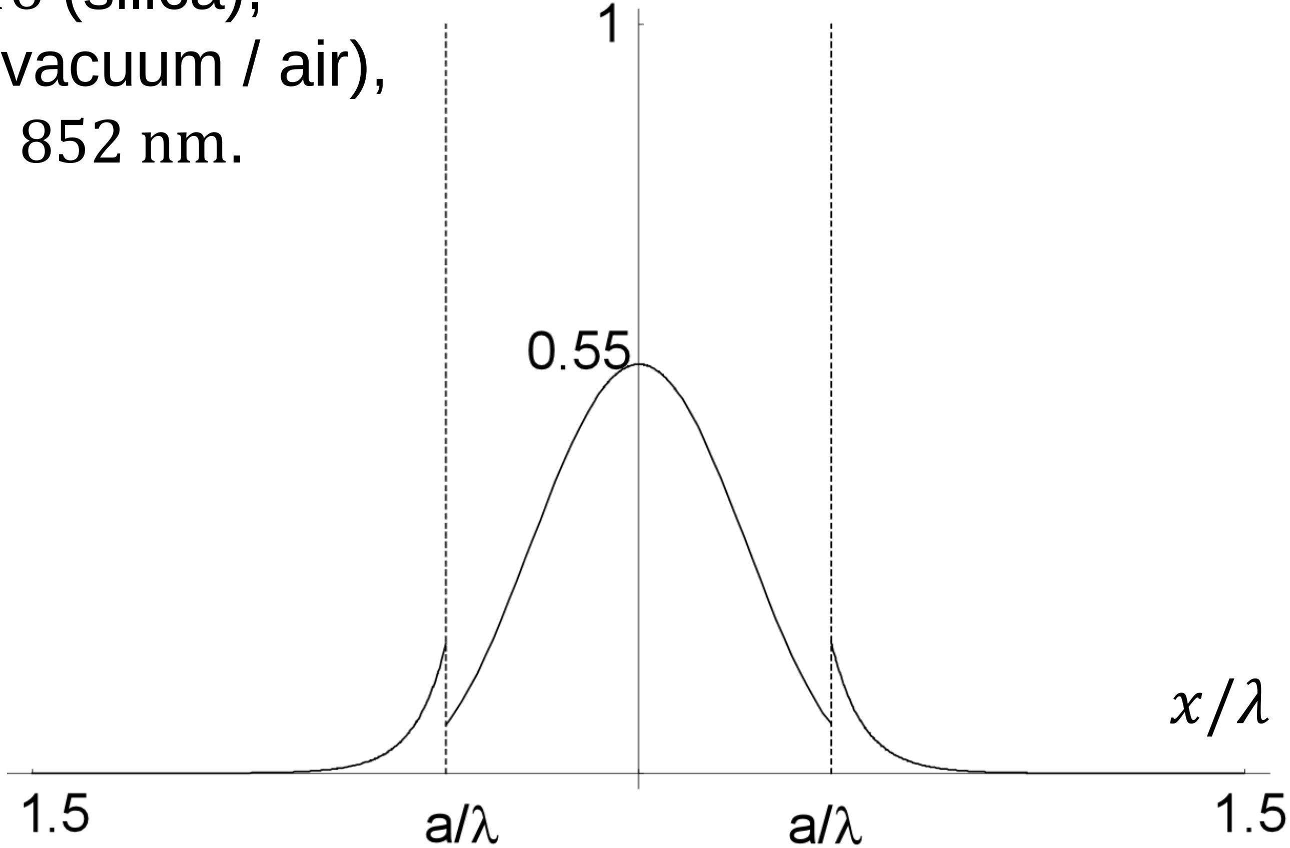
$$\frac{\left|\vec{E}(x, y = 0)\right|^2}{\left|\vec{E}(x = a, y = 0)\right|^2_{a=0.23\lambda}}$$



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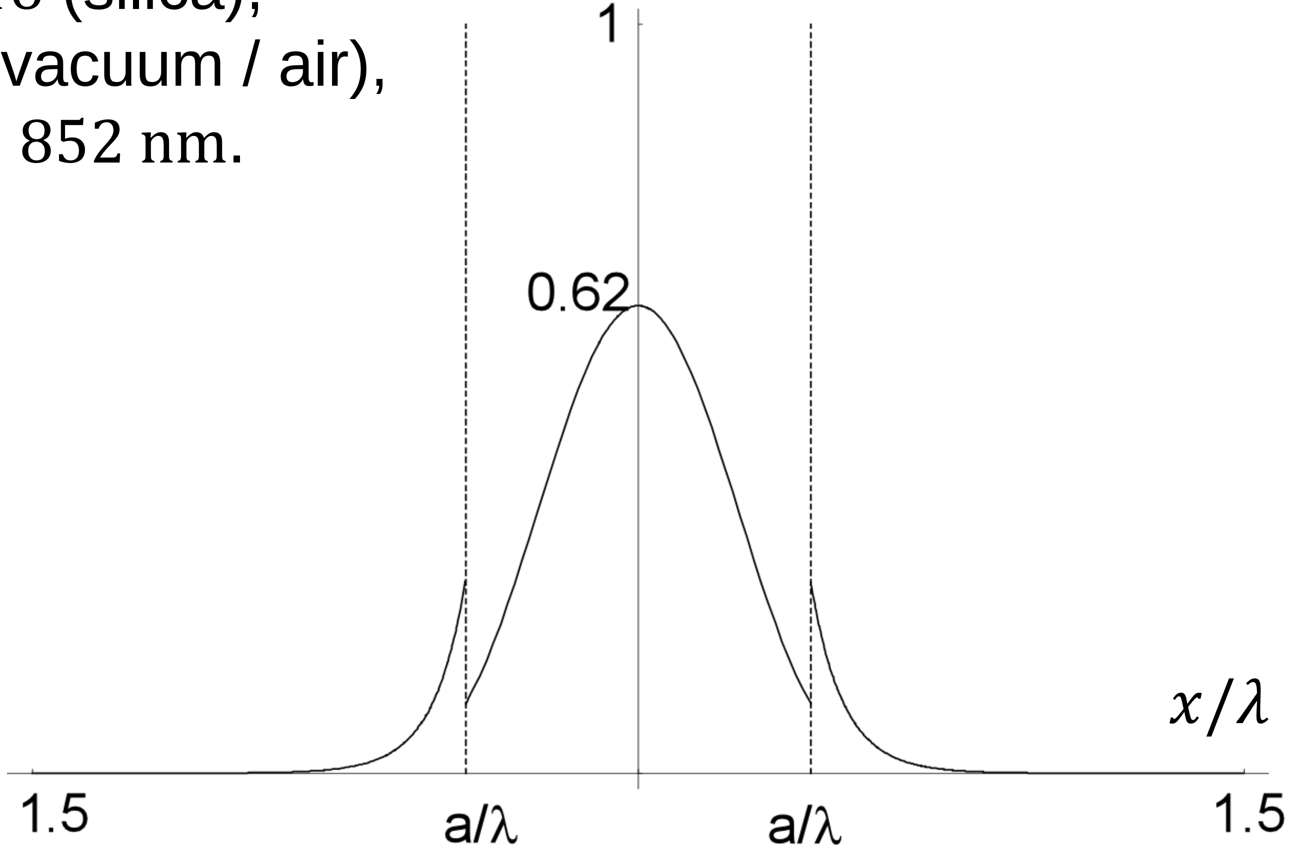

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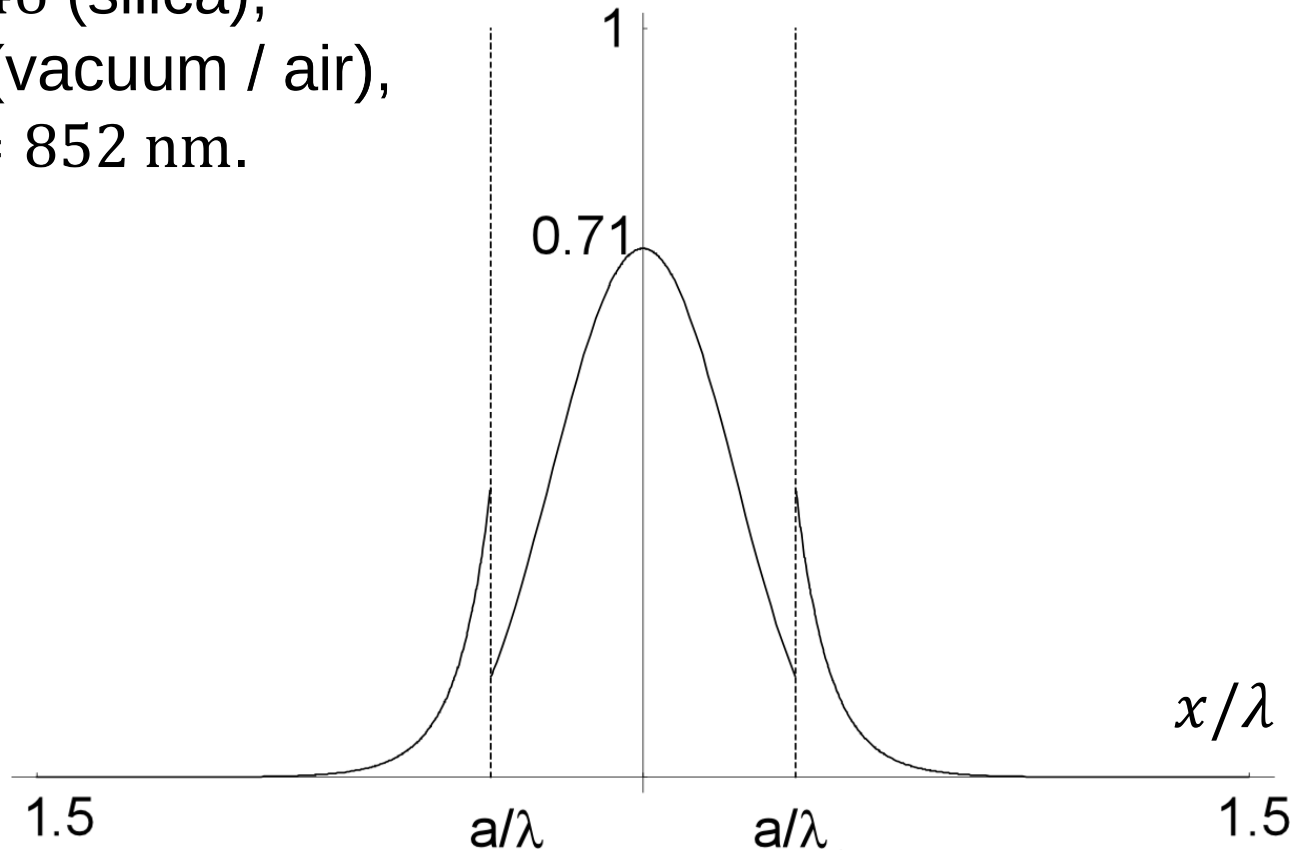

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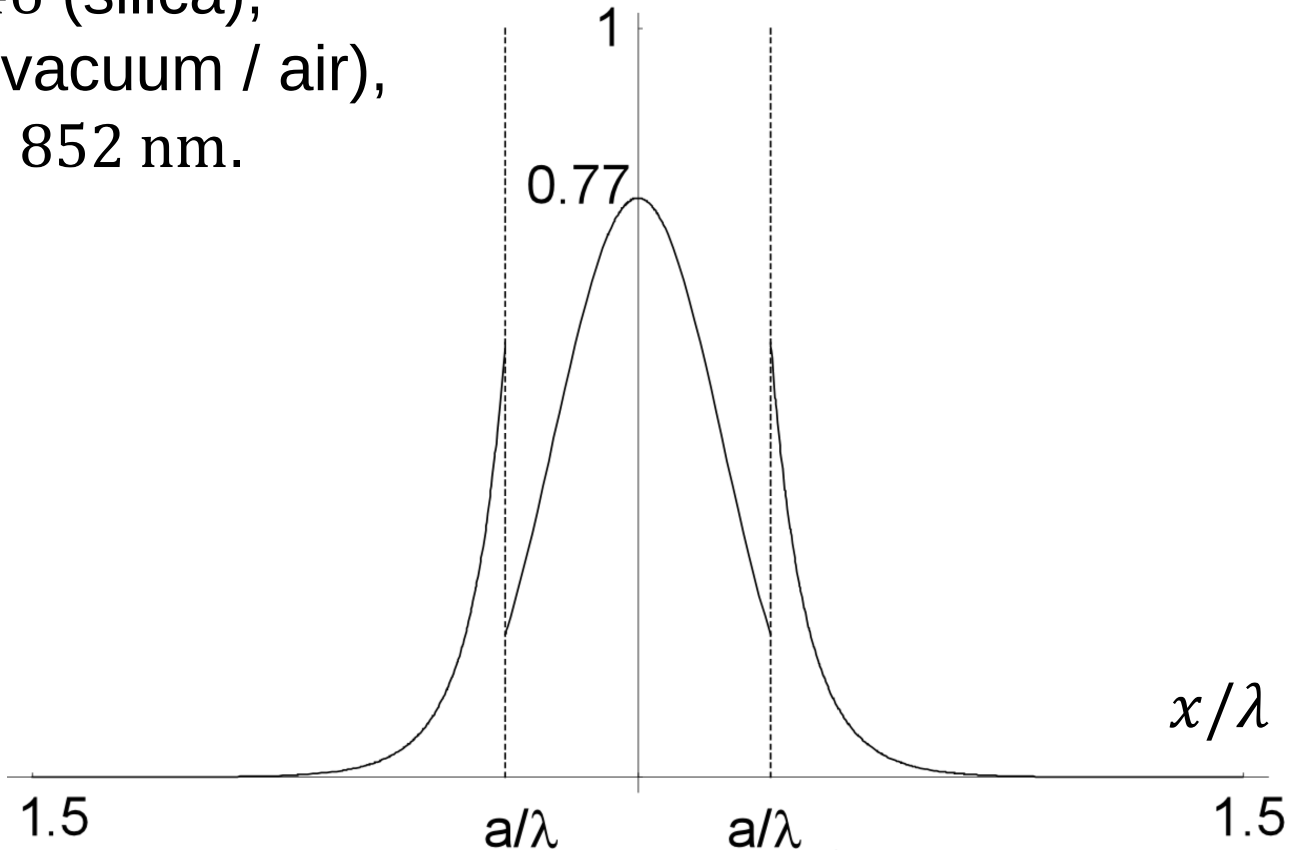

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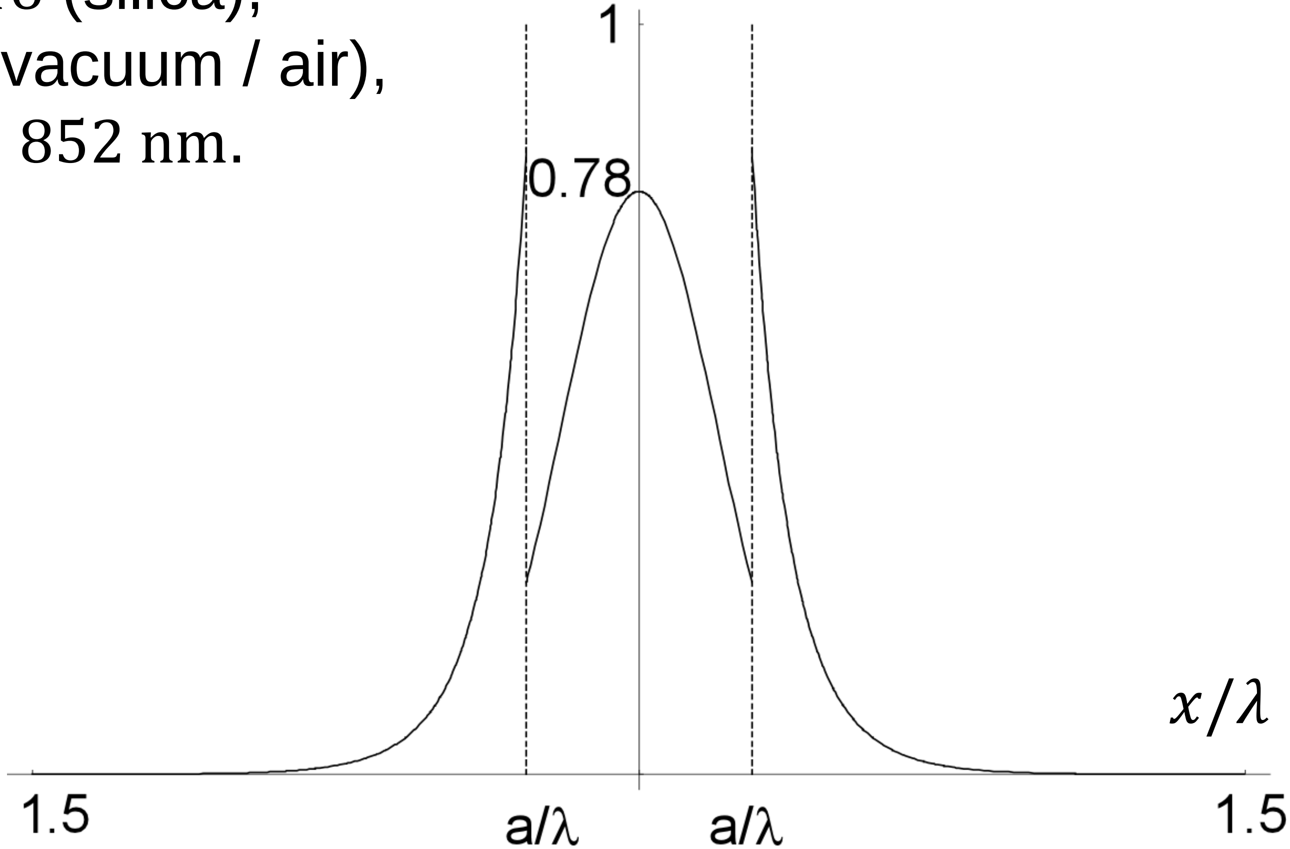

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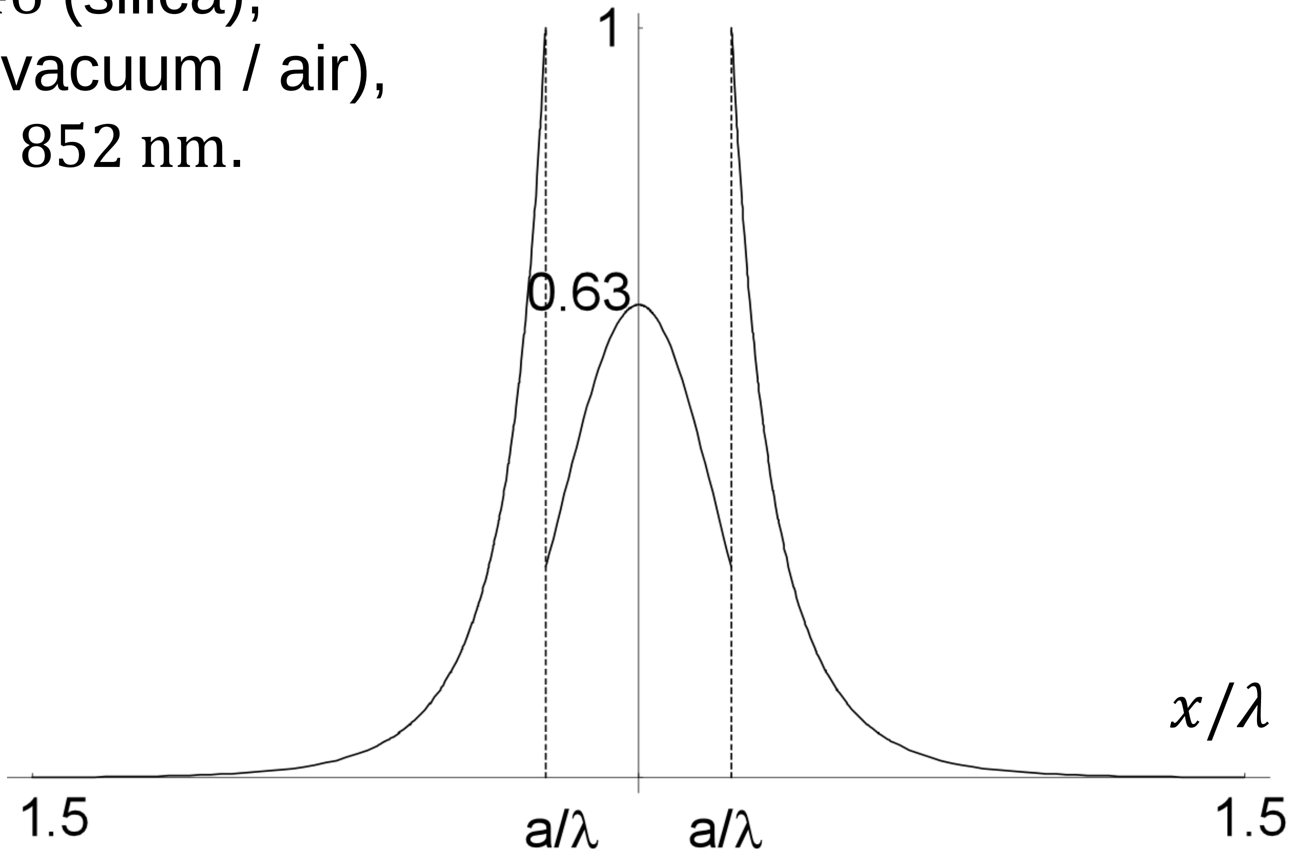

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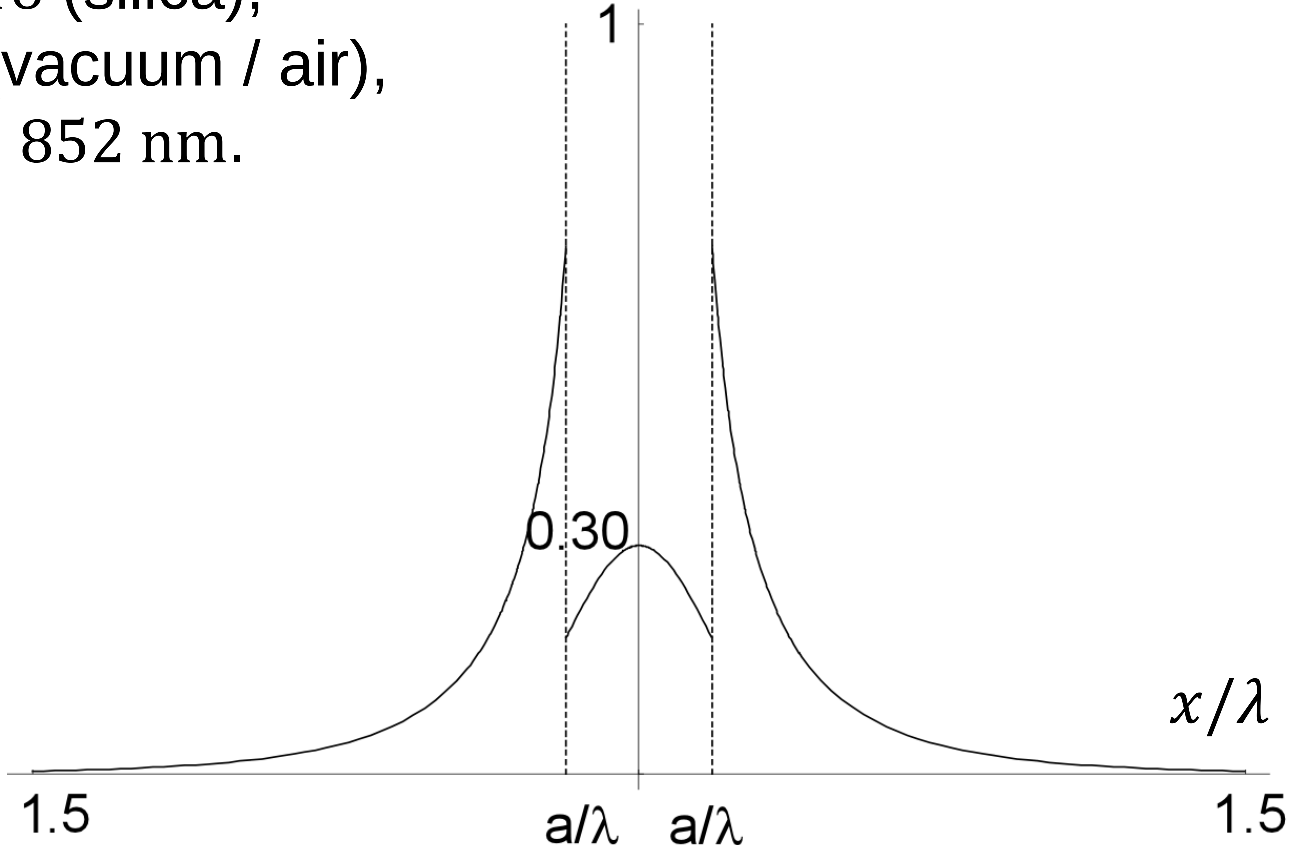

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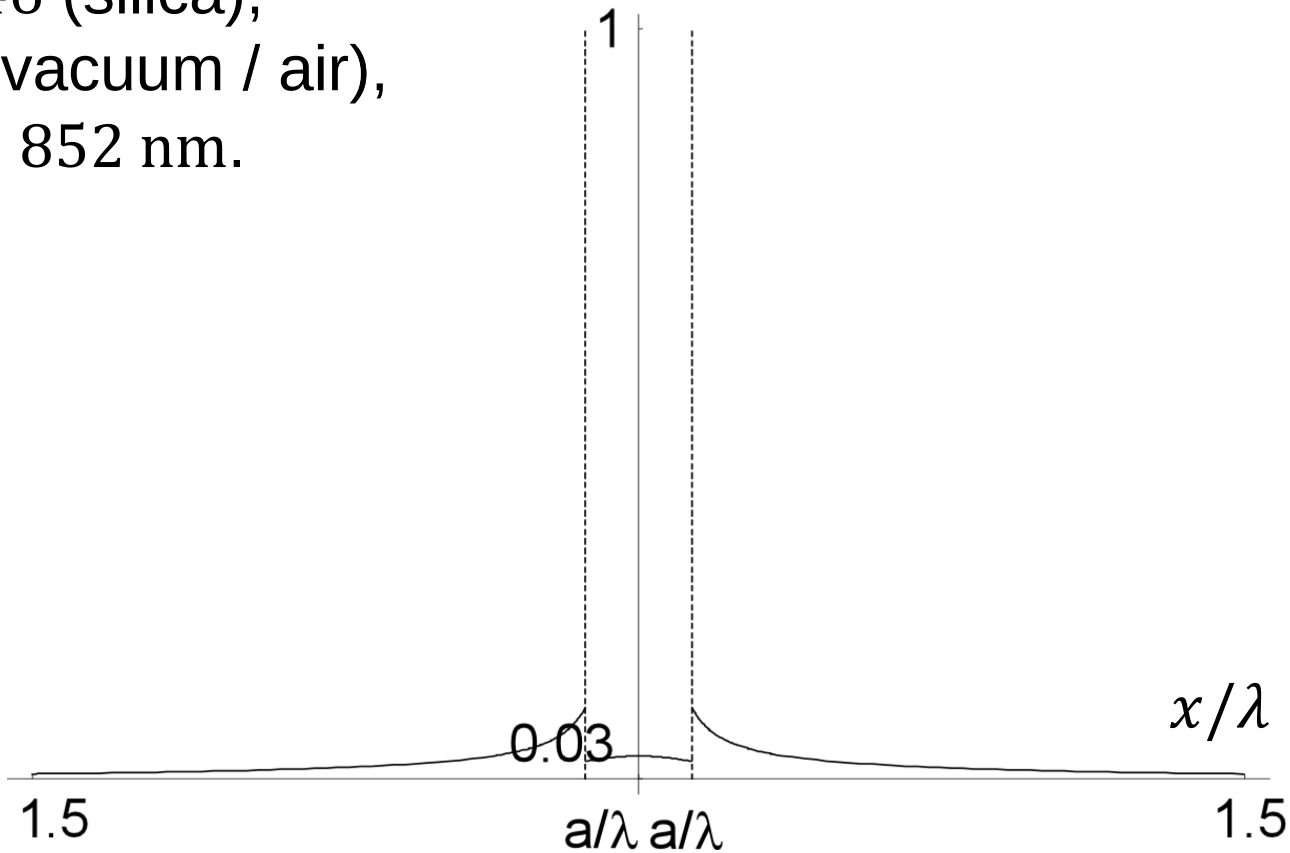
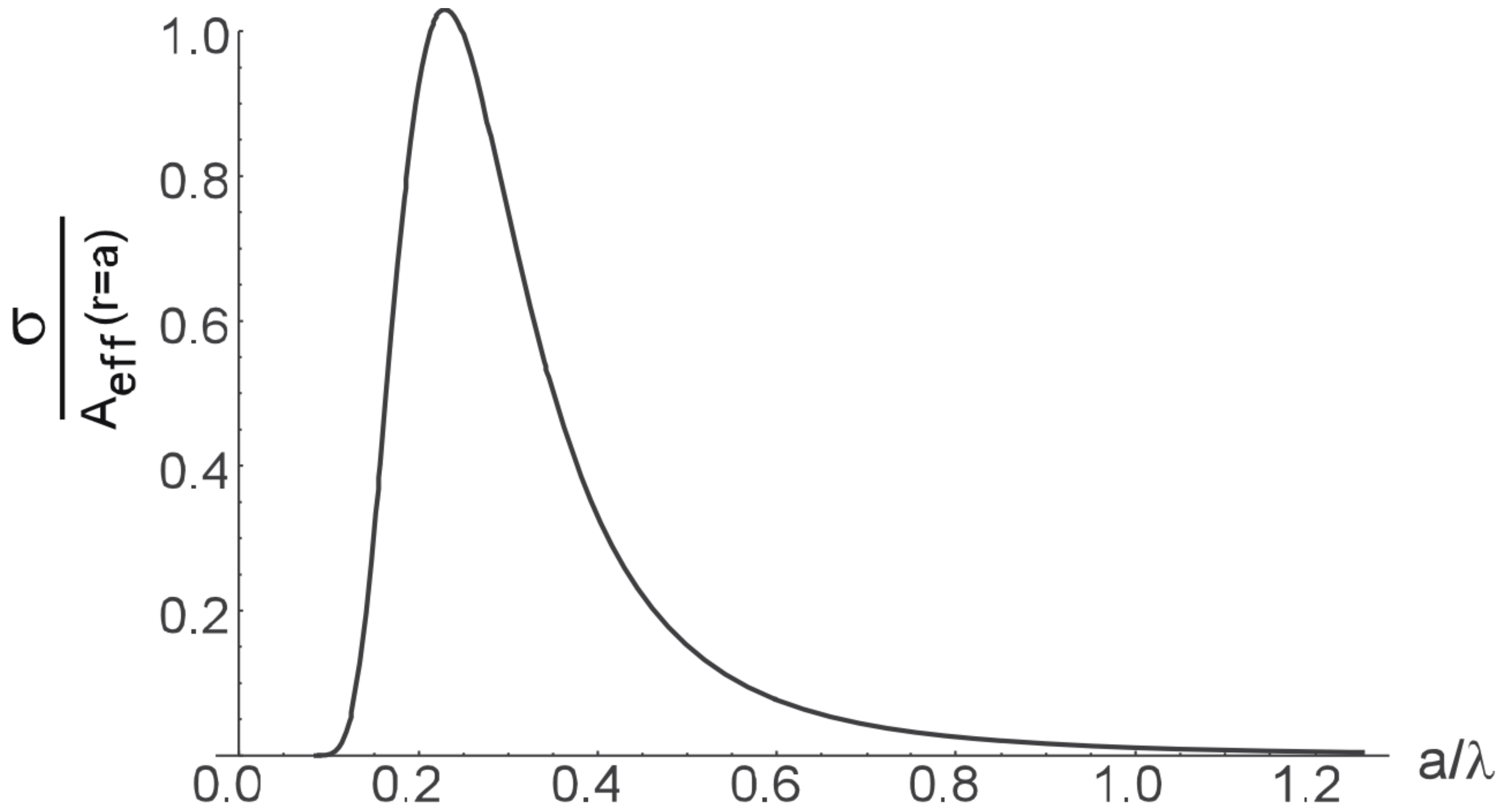


HE_{11} Mode: Effective Mode Area

- Quasi circularly polarized HE_{11} mode.
- Parameters: $a = 250\ \mathrm{nm}$, $n_1 = 1.46$ (silica), $n_2 = 1$ (vacuum / air), and $\lambda = 852\ \mathrm{nm}$.



HE_{11} Mode: Intensity Distribution

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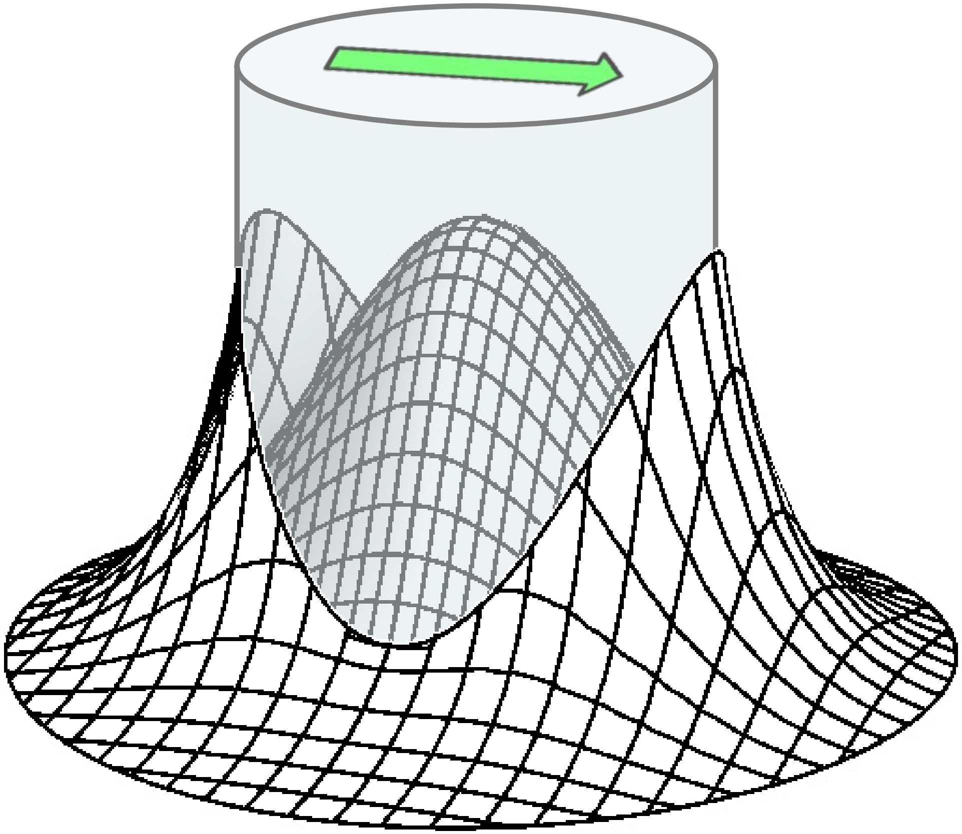

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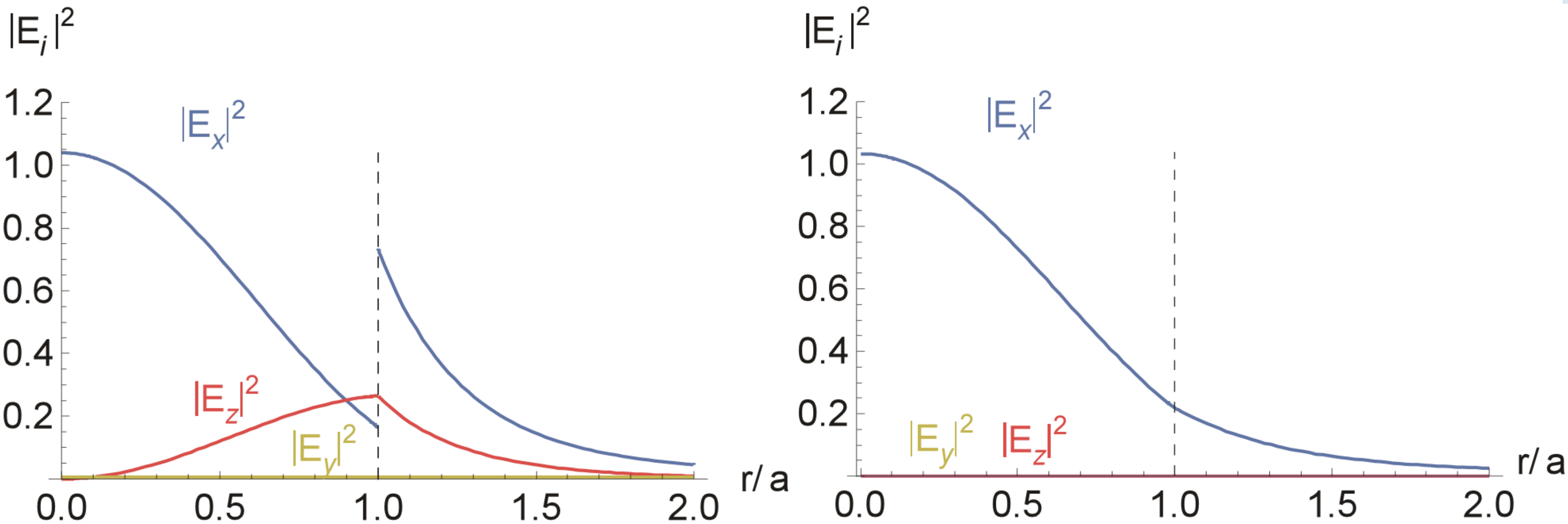

along $(x, y = 0)$ along $(x = 0, y)$

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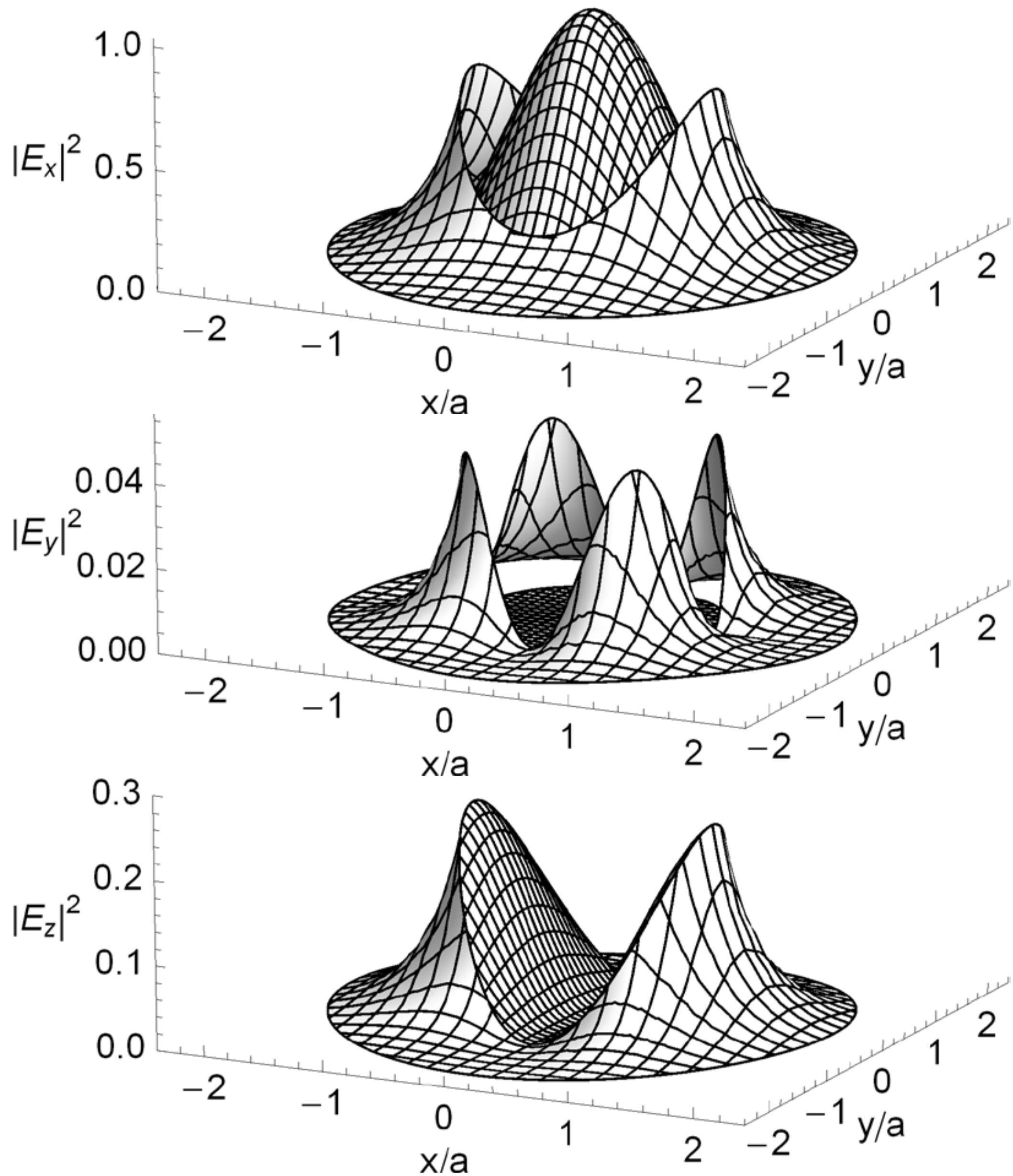
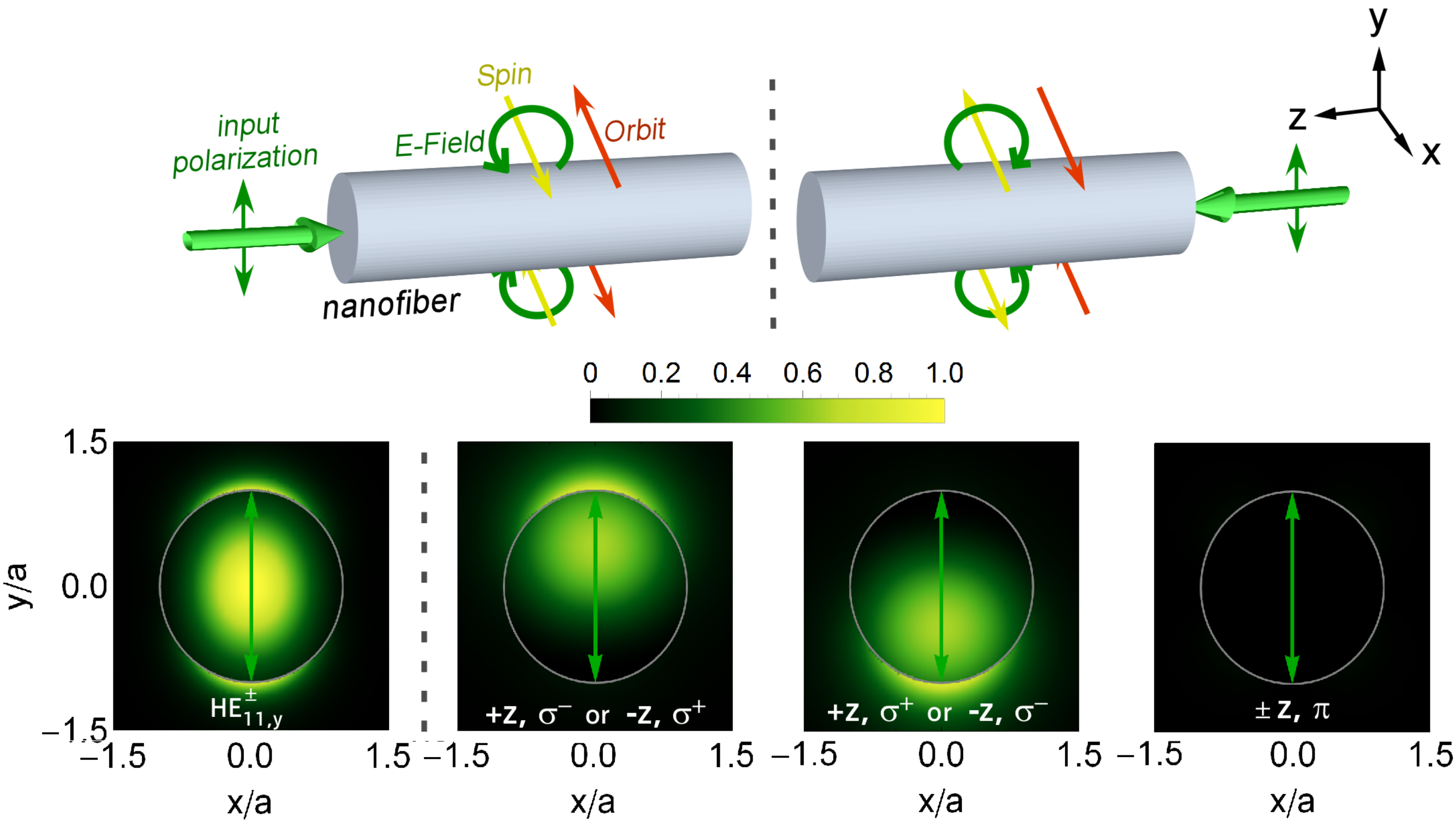


HE_{11} Mode: Polarization Properties

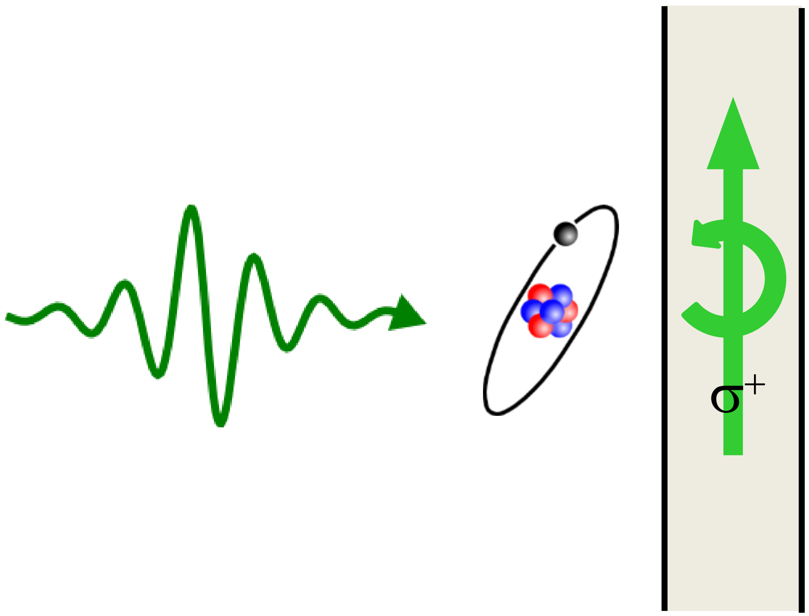


Directional Spontaneous Emission

Recipe

- Locate emitter on one side of the nanofiber
- Optical excitation...

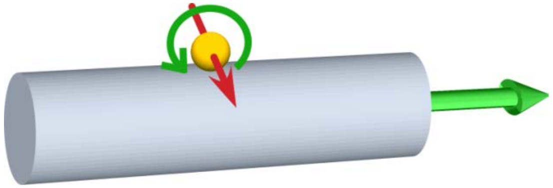
  ... emission of a σ^+-photon



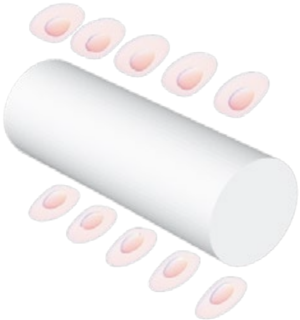
Overview

- Guided modes in optical nanofibers

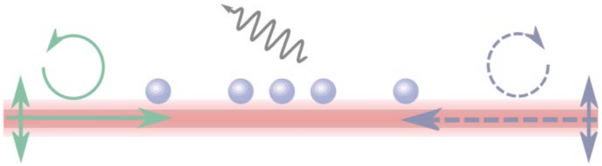
- Directional emission of a gold nanoparticle



- Directional atom-waveguide interface



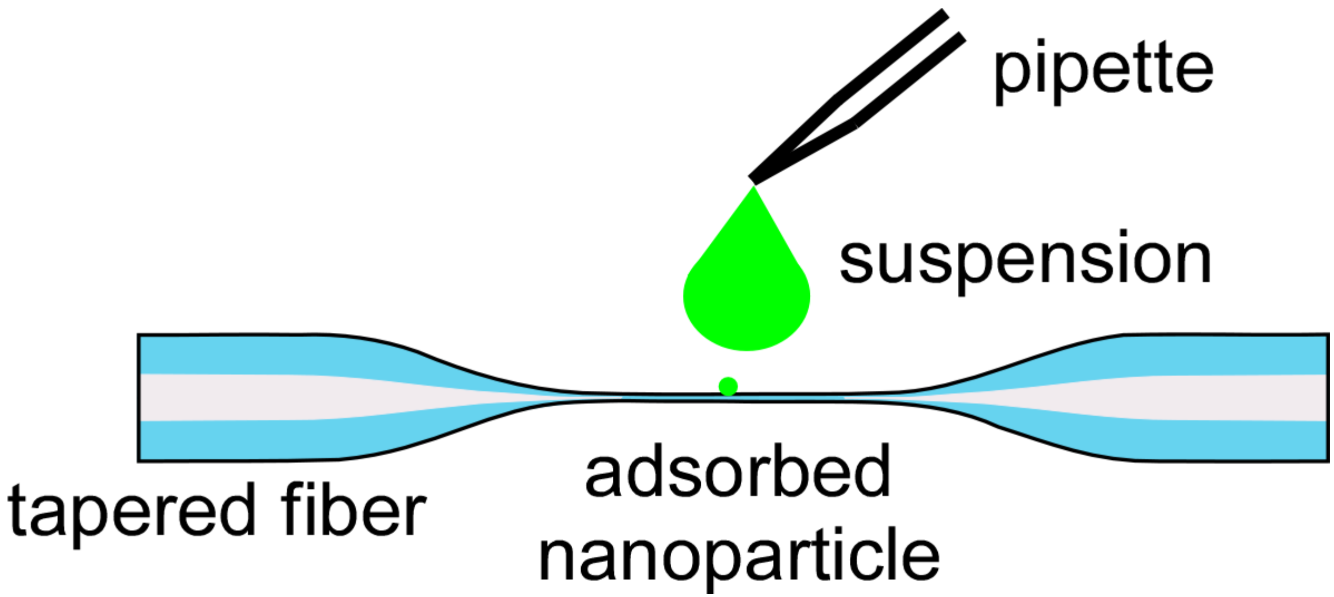
- Nonreciprocal nanophotonic waveguide



Sample Preparation

Touch nanofiber with drop of suspension of gold nanoparticles

- Presence of single gold nanoparticle detected via absorption spectroscopy



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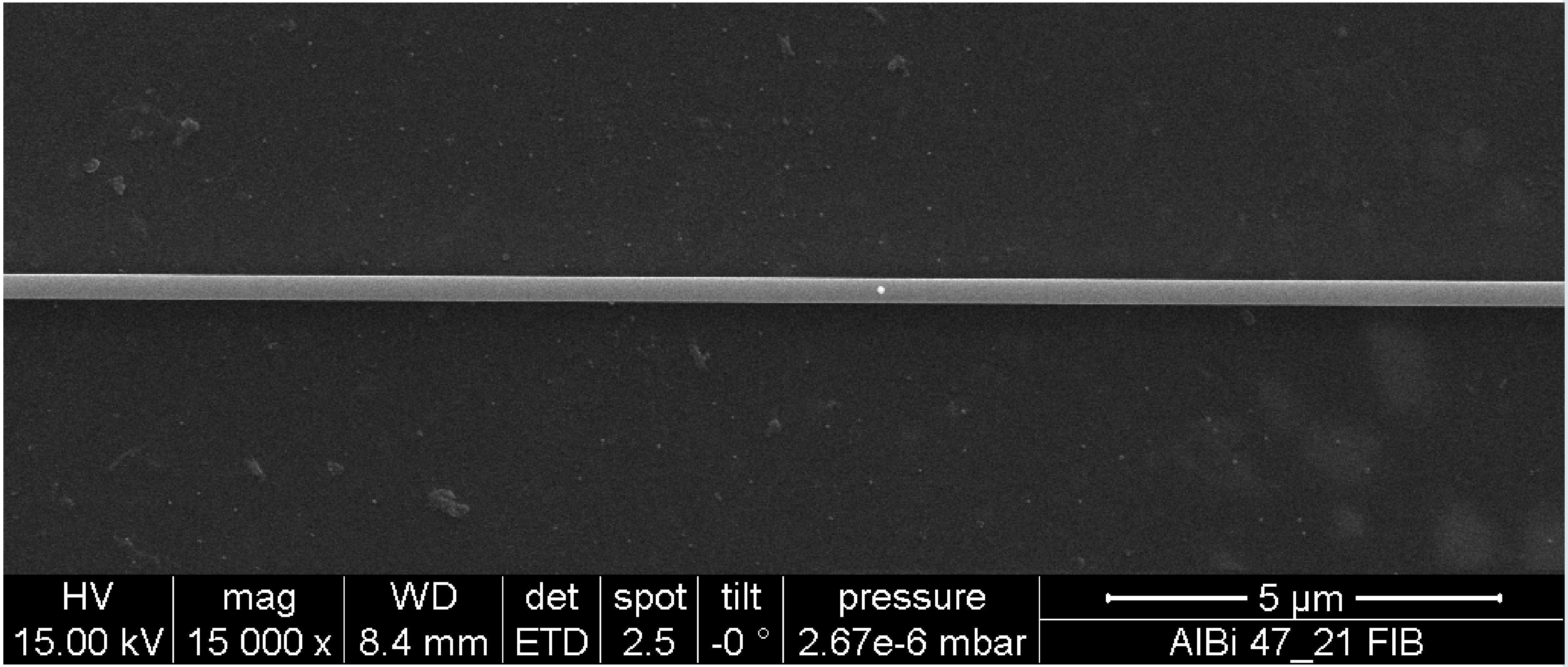
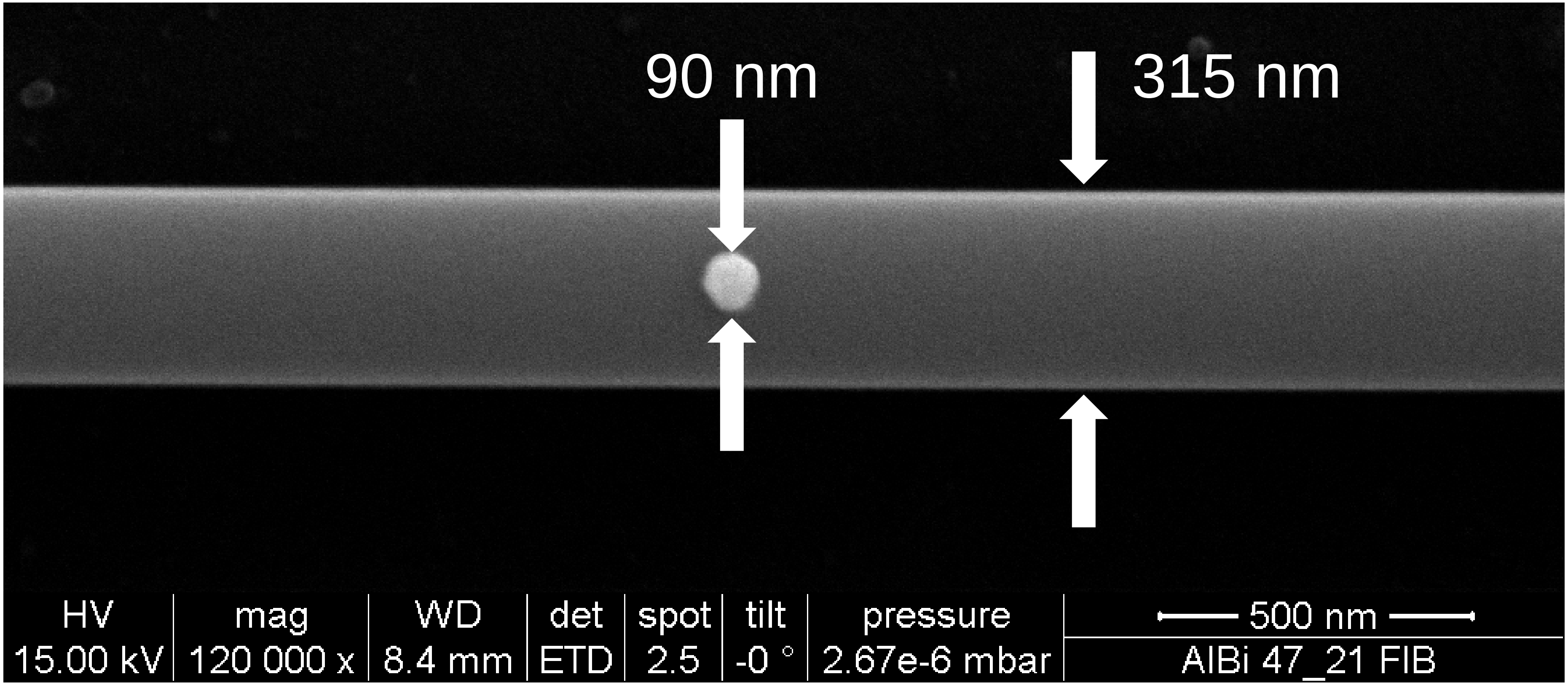
- Presence and diameter of particle checked with SEM after experiment

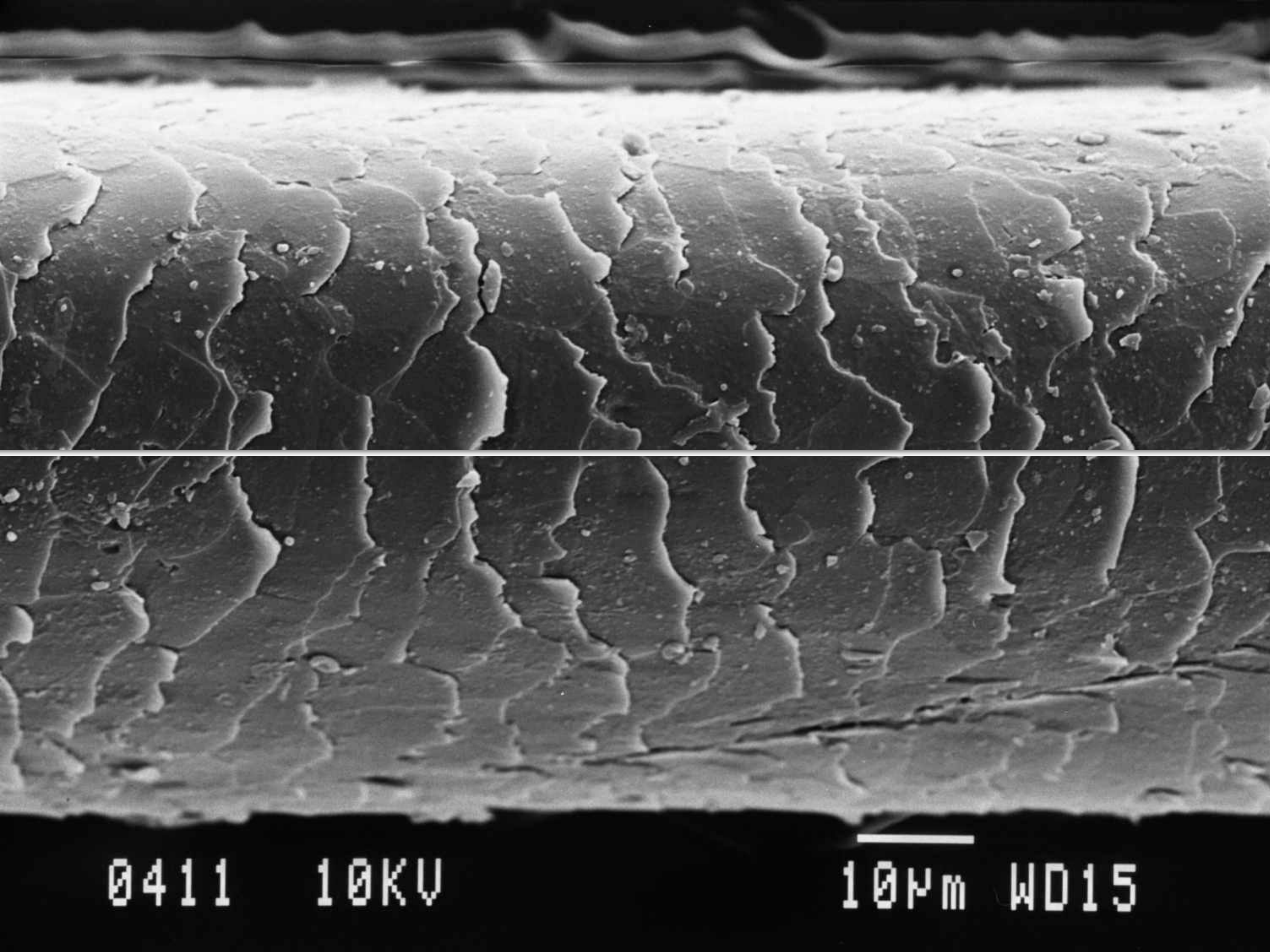


Sample Preparation

Touch nanofiber with drop of suspension of gold nanoparticles

- Presence of single gold nanoparticle detected via absorption spectroscopy
- Presence and diameter of particle checked with SEM after experiment

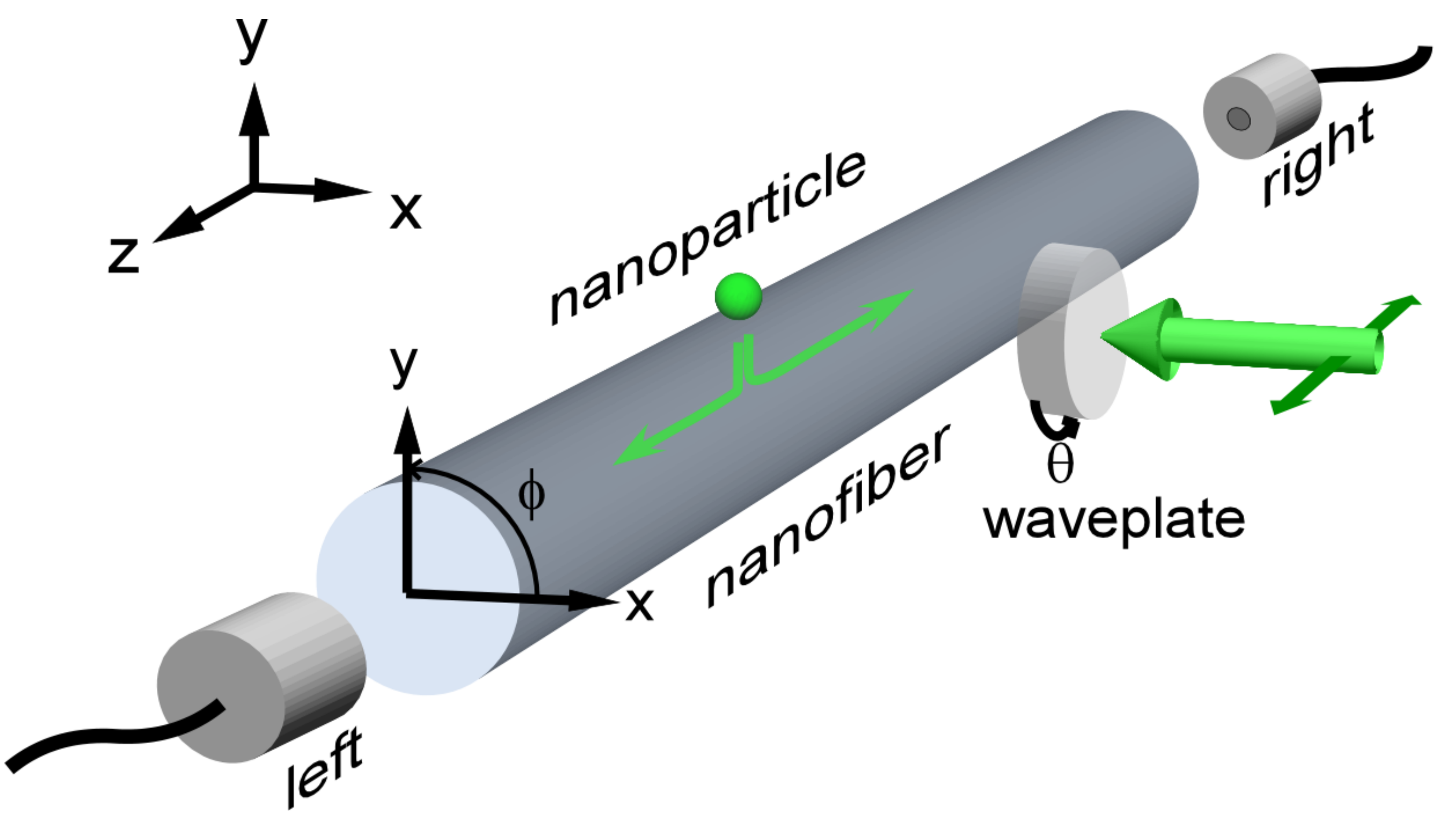



0411 10KV
10μm WD15

Experimental Set-Up

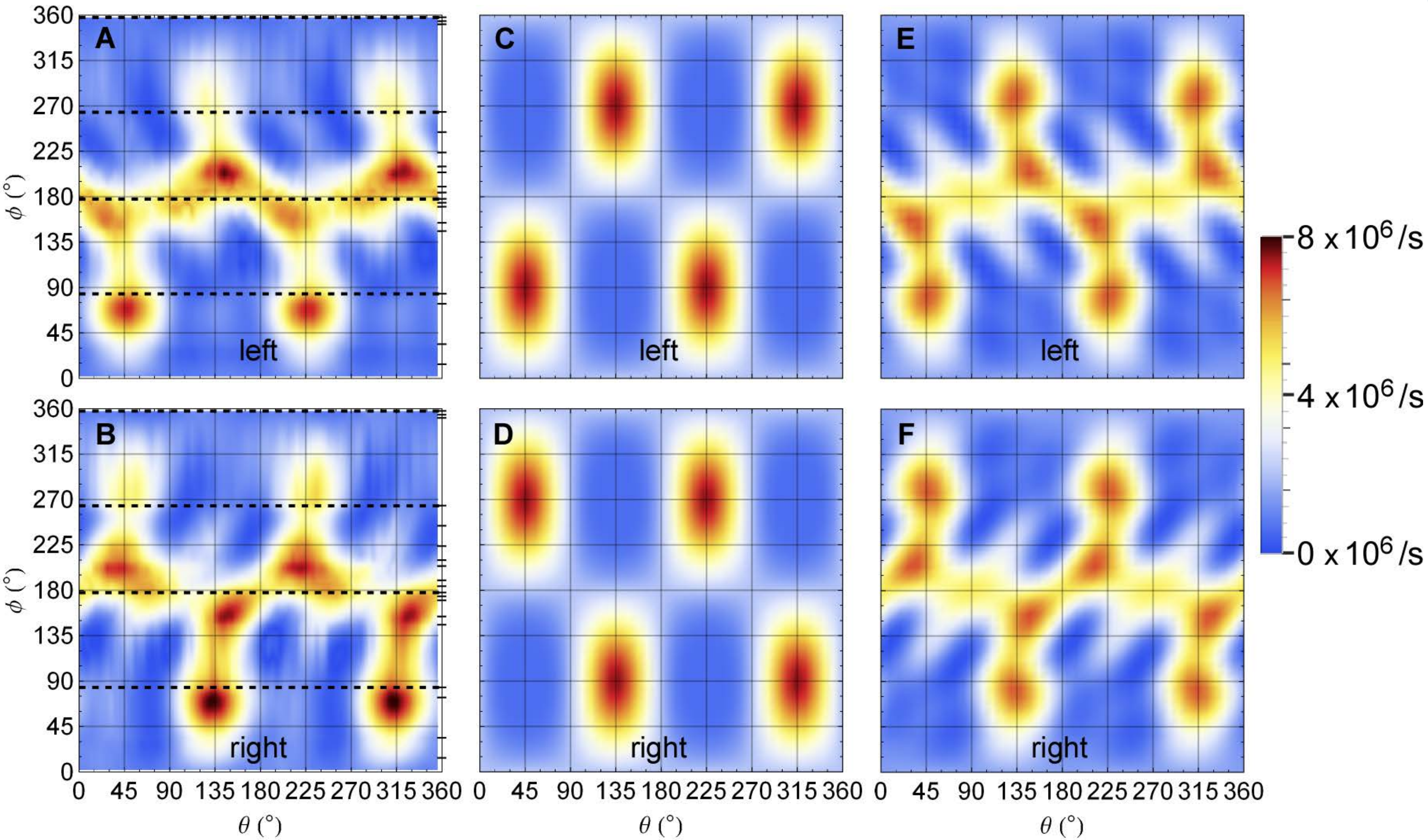
System: Gold nanoparticle (Ø=90 nm) on silica nanofiber (Ø=315 nm)

- Polarization of excitation light (σ^+, σ^-, linear) set by waveplate
- Azimuthal position of gold particle set by rotating nanofiber about axis



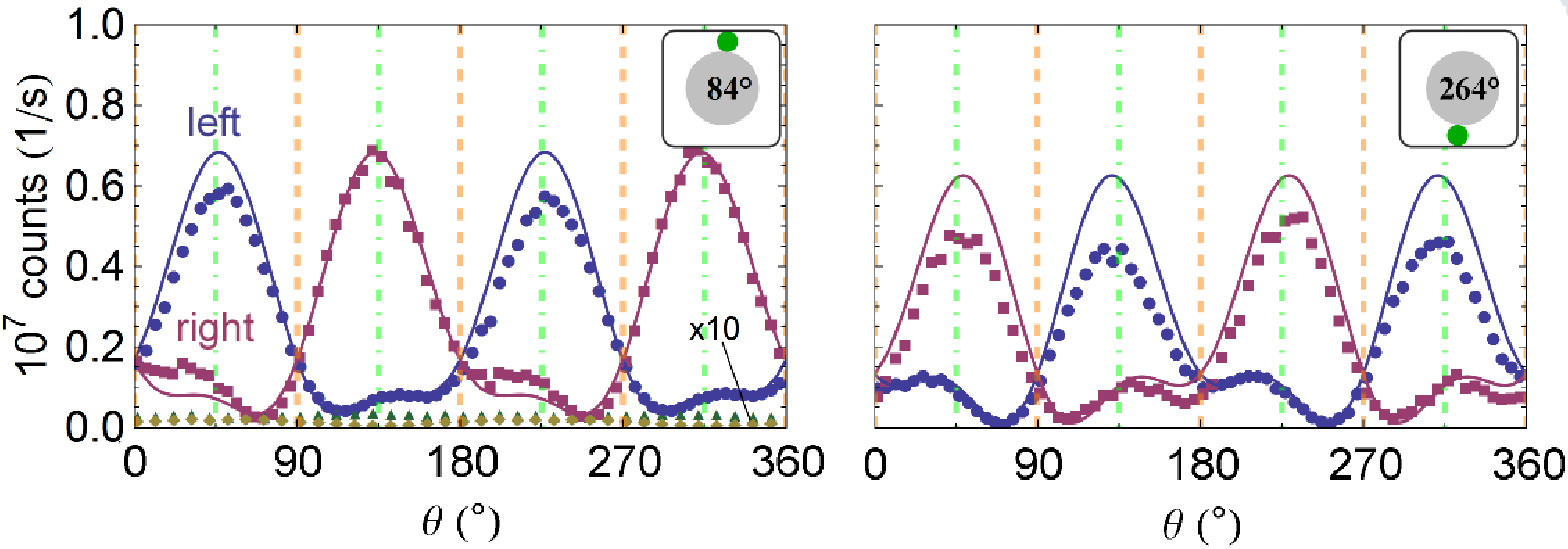
Petersen et al., Science **346**, 67 (2014)

Chiral Waveguide Coupling



Petersen et al., Science **346**, 67 (2014)

Chiral Waveguide Coupling

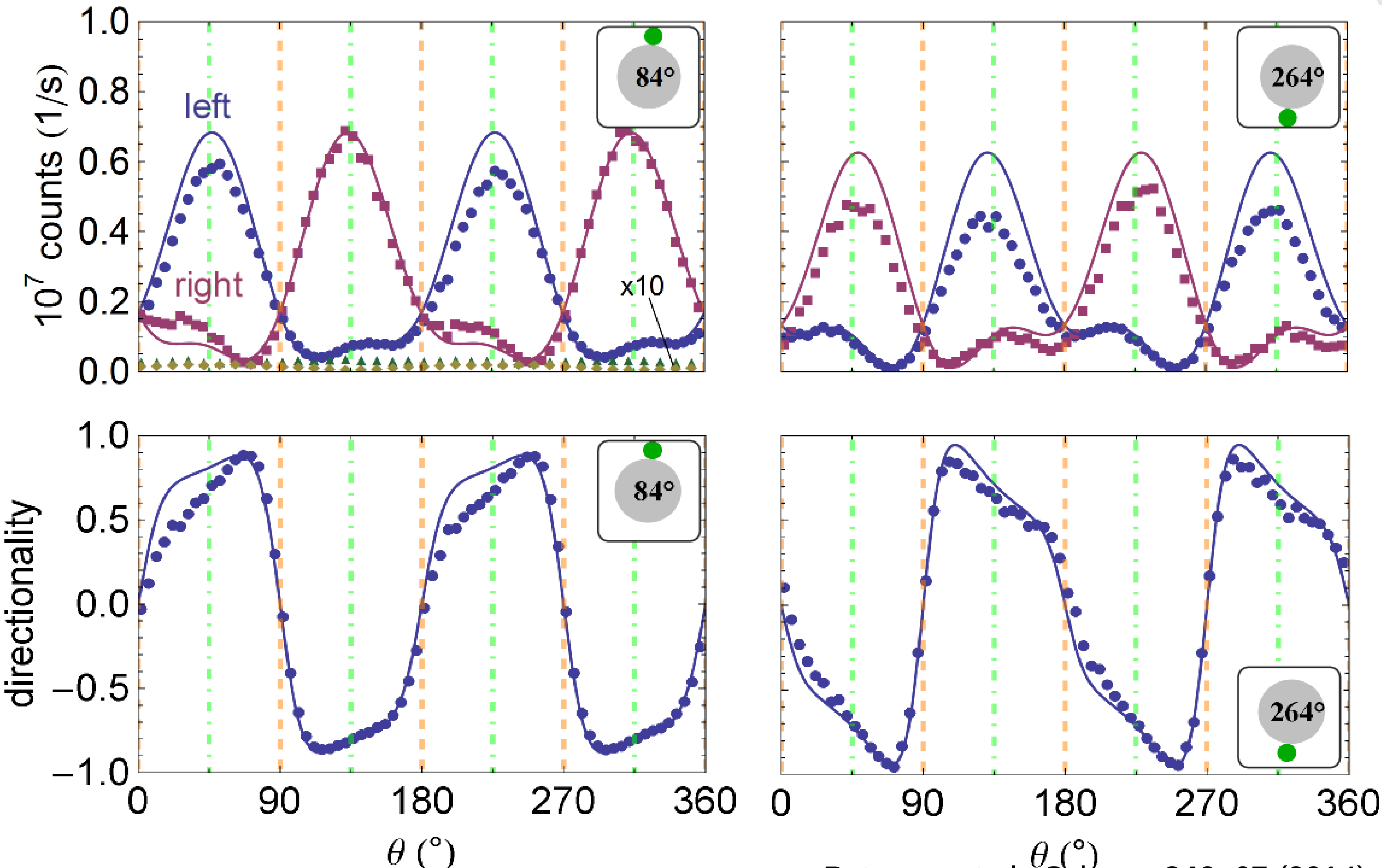


Calculate directionality from above data:

$$D = \frac{c_+ - c_-}{c_+ + c_-}$$

Petersen et al., Science **346**, 67 (2014)

Chiral Waveguide Coupling



Petersen et al., Science **346**, 67 (2014)

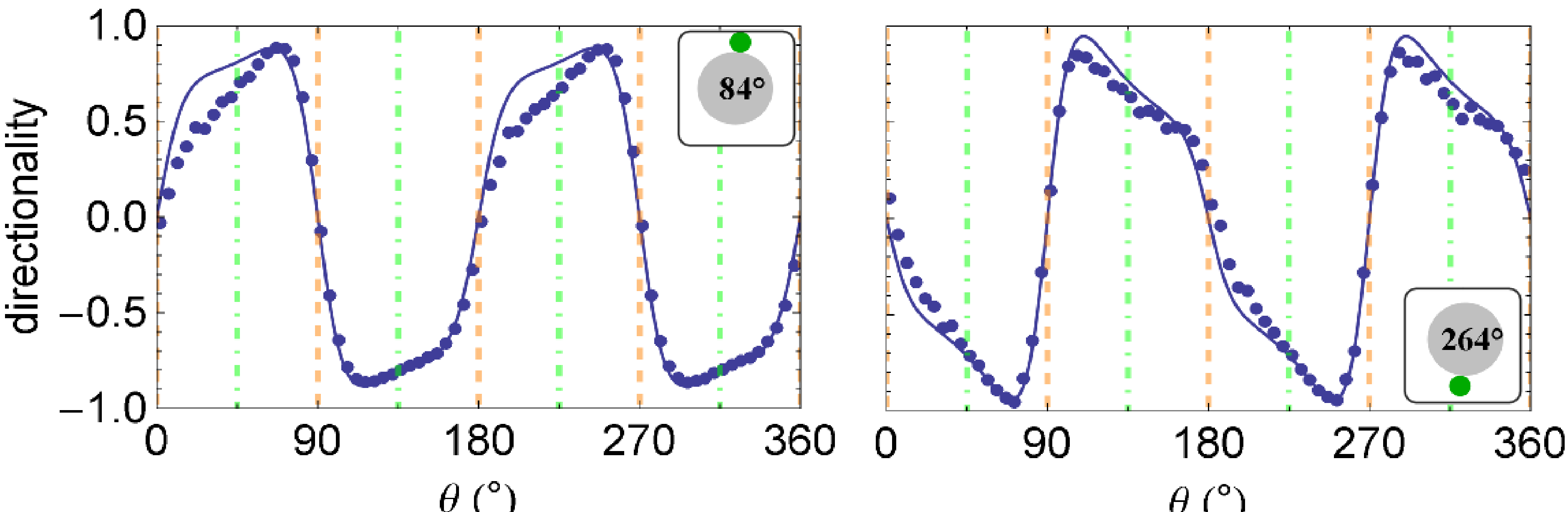
Chiral Waveguide Coupling

- Maximum directionality:

$$D = 0.88 \qquad\qquad D = 0.95$$

- Corresponding ratio of left/right photon fluxes:

$$16 \div 1 \qquad\qquad 40 \div 1$$

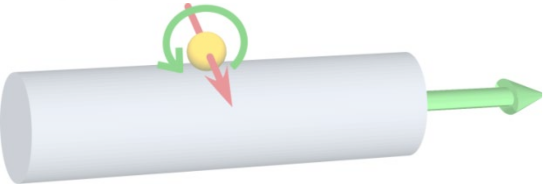


Petersen et al., Science **346**, 67 (2014)

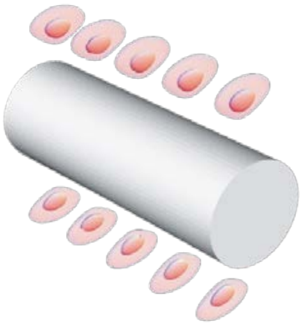
Overview

- Guided modes in optical nanofibers

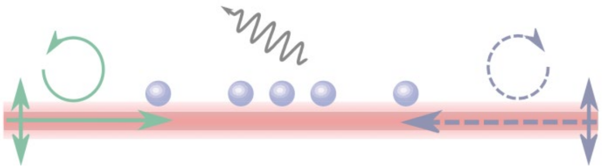
- Directional emission of a gold nanoparticle



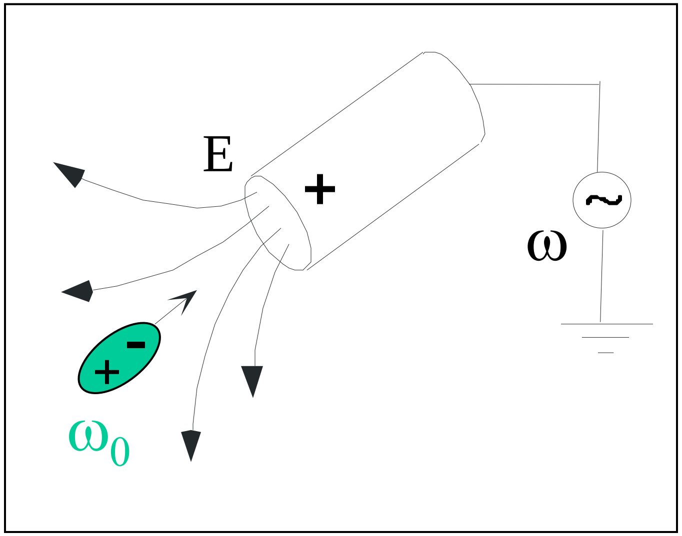
- Directional atom-waveguide interface

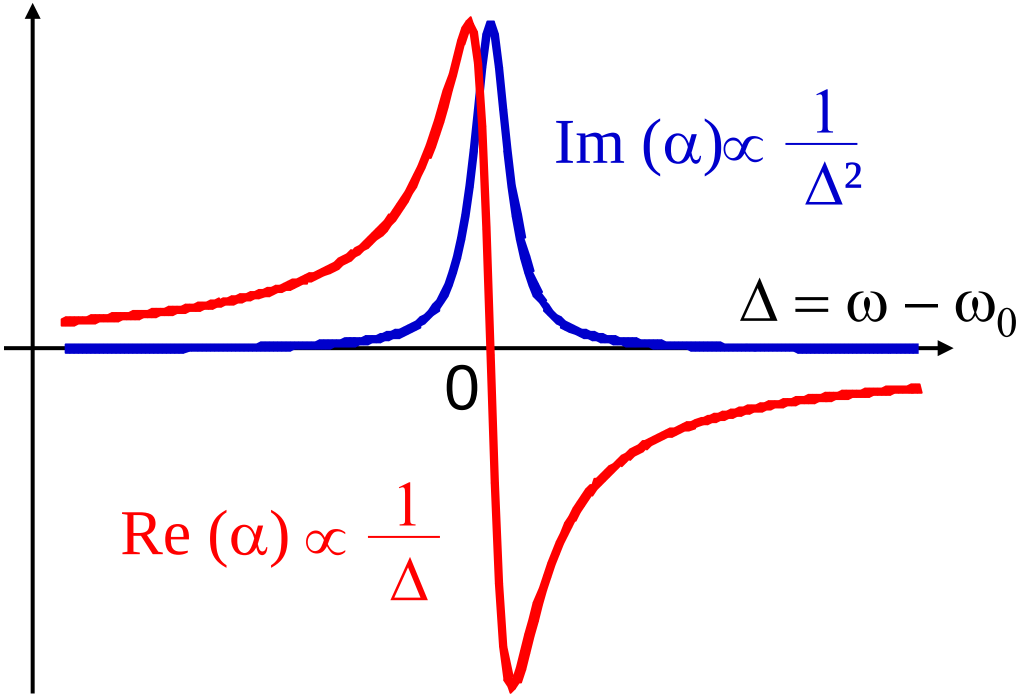


- Nonreciprocal nanophotonic waveguide



Dipole Traps





Induced dipole moment: $\vec{d} = \alpha \vec{E}$ α: Polarizability

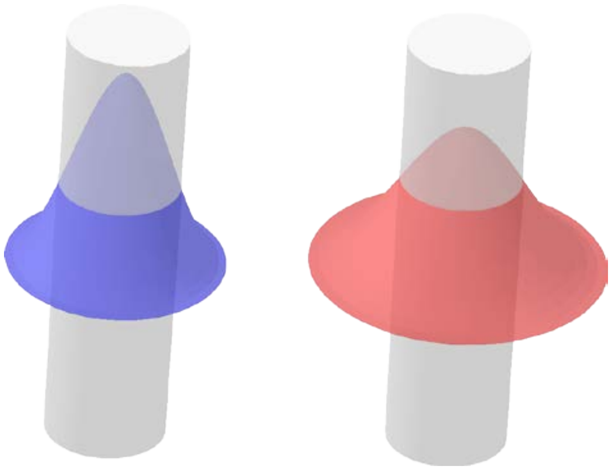
$$U_{dip} = -\frac{1}{2}\langle \vec{d} \cdot \vec{E} \rangle \quad \propto -\mathrm{Re}\,(\alpha) \propto -I/\Delta$$

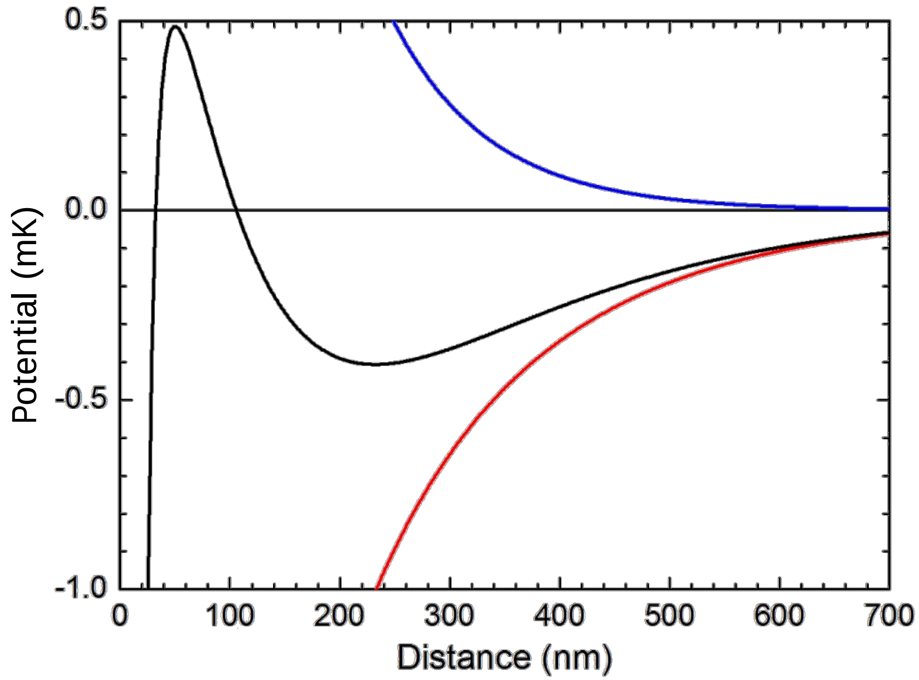
$$\Gamma_{sc} = \langle \dot{\vec{d}} \cdot \vec{E} \rangle / \hbar\omega \quad \propto \mathrm{Im}\,(\alpha) \quad \propto I/\Delta^2$$

Two-Color Nanofiber-Based Atom Trap

Radial confinement

- Evanescent field exerts a dipole force on the atoms
- "Blue light" is more tightly bound to the nanofiber than "red light"





Fam Le Kien et al., PRA **70**, 063403 (2004)

Two-Color Nanofiber-Based Atom Trap

Axial confinement

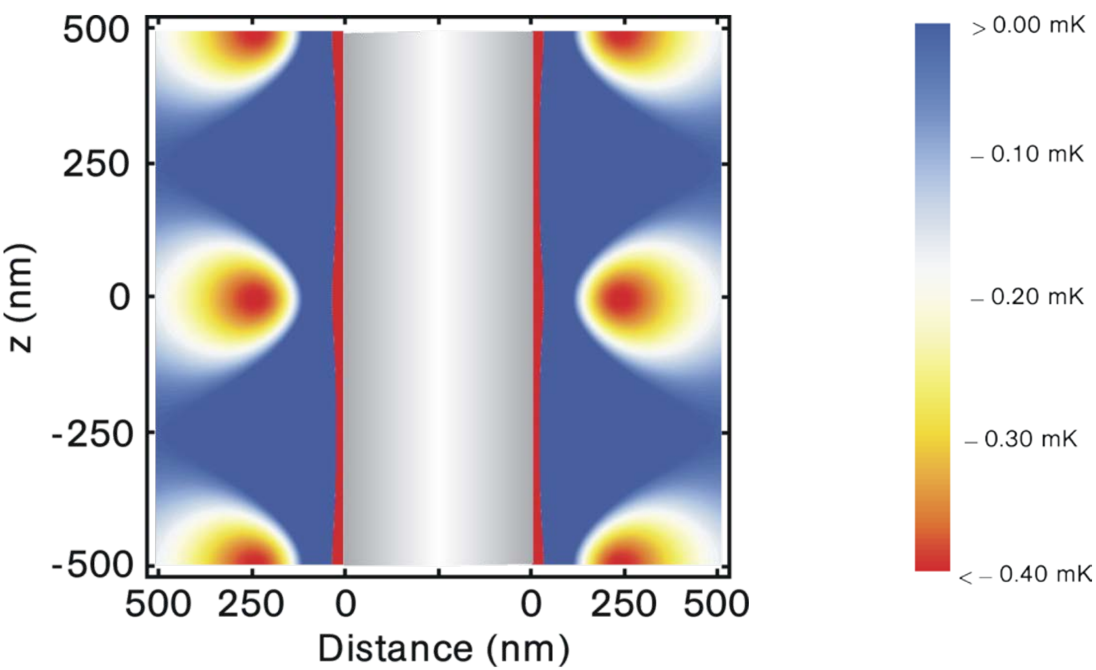
Two counter-propagating red-detuned beams

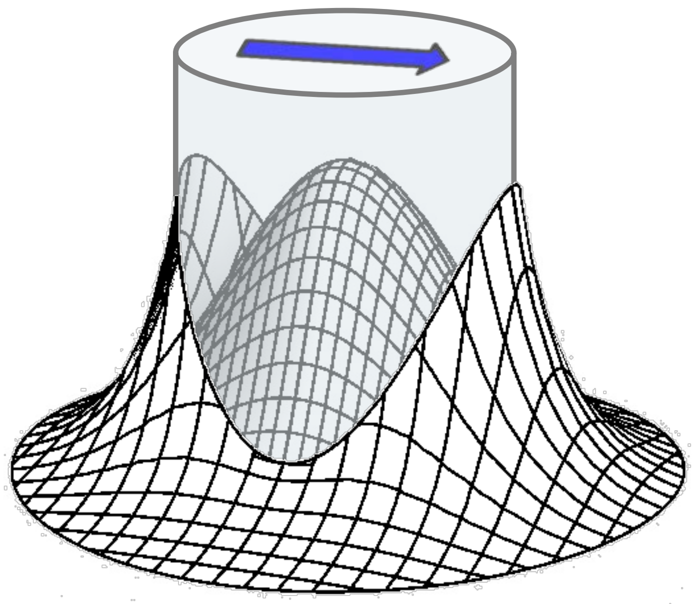
→ standing wave
500 nm between trapping sites

Azimuthal confinement

Linear polarizations

→ breaking of the rotational symmetry





Two-Color Nanofiber-Based Atom Trap

Axial confinement

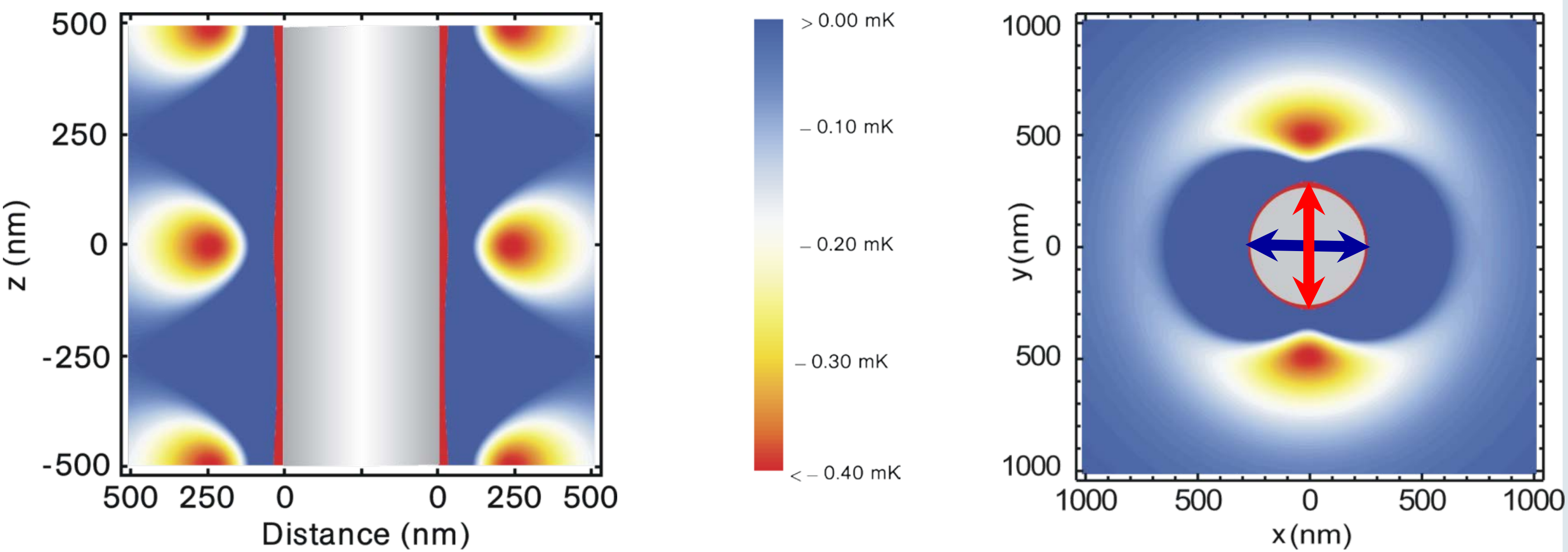
Two counter-propagating red-detuned beams

➡ standing wave
500 nm between trapping sites

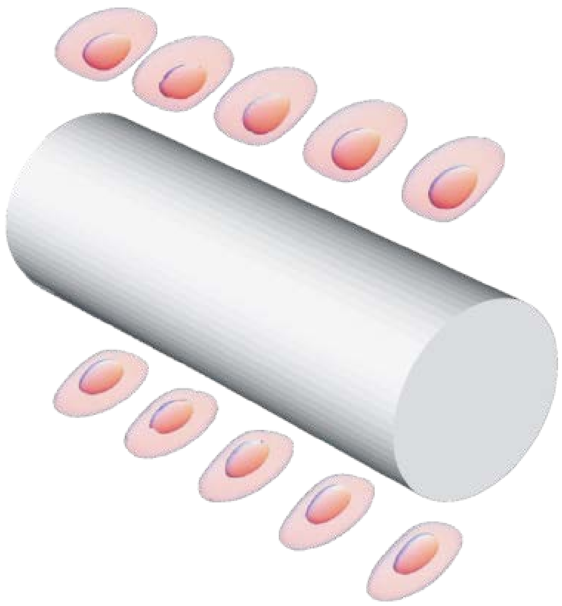
Azimuthal confinement

Linear polarizations

➡ breaking of the rotational symmetry



Two-Color Nanofiber-Based Atom Trap



Two arrays of trapping sites

- Nanofiber diameter: 500 nm
- At most one atom per trapping site
- Filling factor: ~ 0.5

Trap parameters

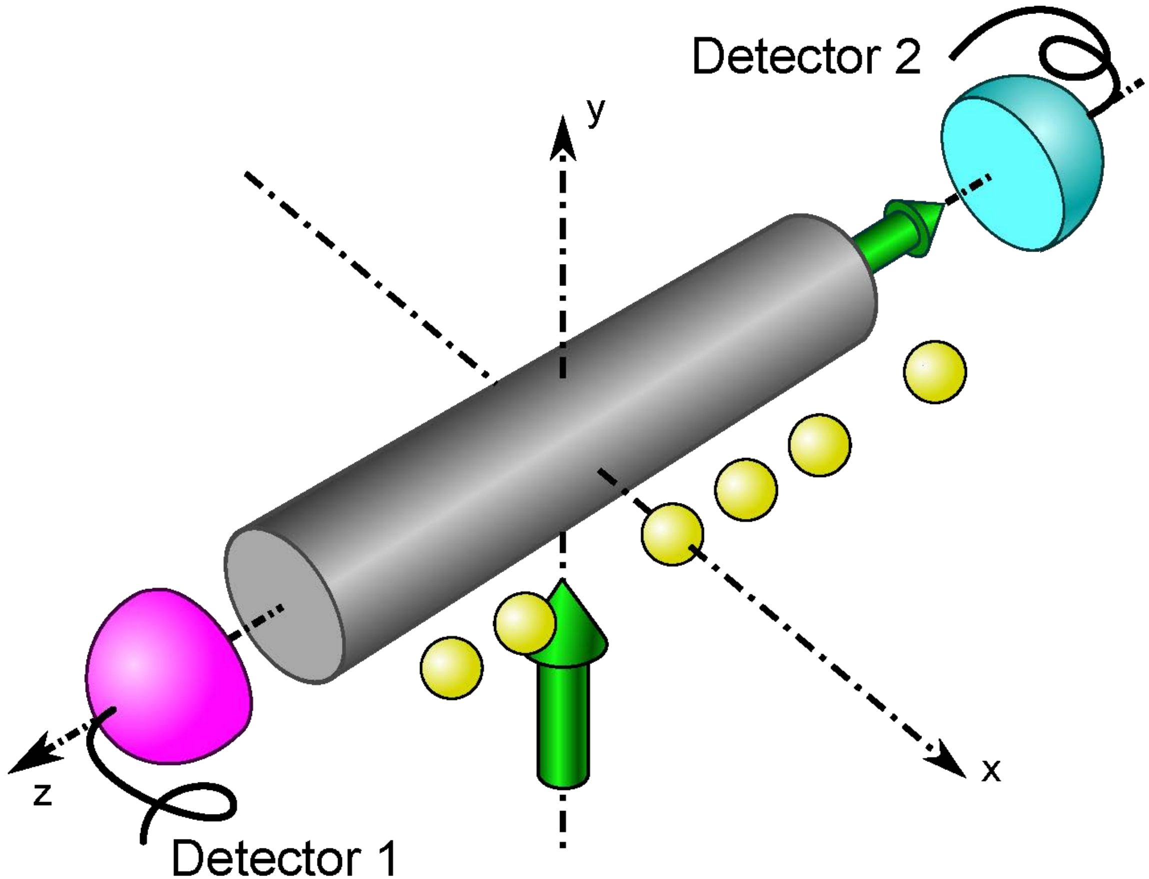
- Atom-surface distance: 230 nm
- Trap frequencies: (200, 315, 140) kHz
- Atoms are localized to a volume $\ll \lambda^3$

More nanofiber-based atom traps (past, present, and future):
Caltech, Niels Bohr Institute, JQI / University of Maryland, LKB Paris, Waseda University, OIST Japan, Univ. of Arizona, Swansea University, Univ. of Queensland, Univ. of Auckland…

E. Vetsch et al., PRL **104**, 203603 (2010)
E. Vetsch et al., IEEE J of Quant Elec. **18**, 1763 (2012)

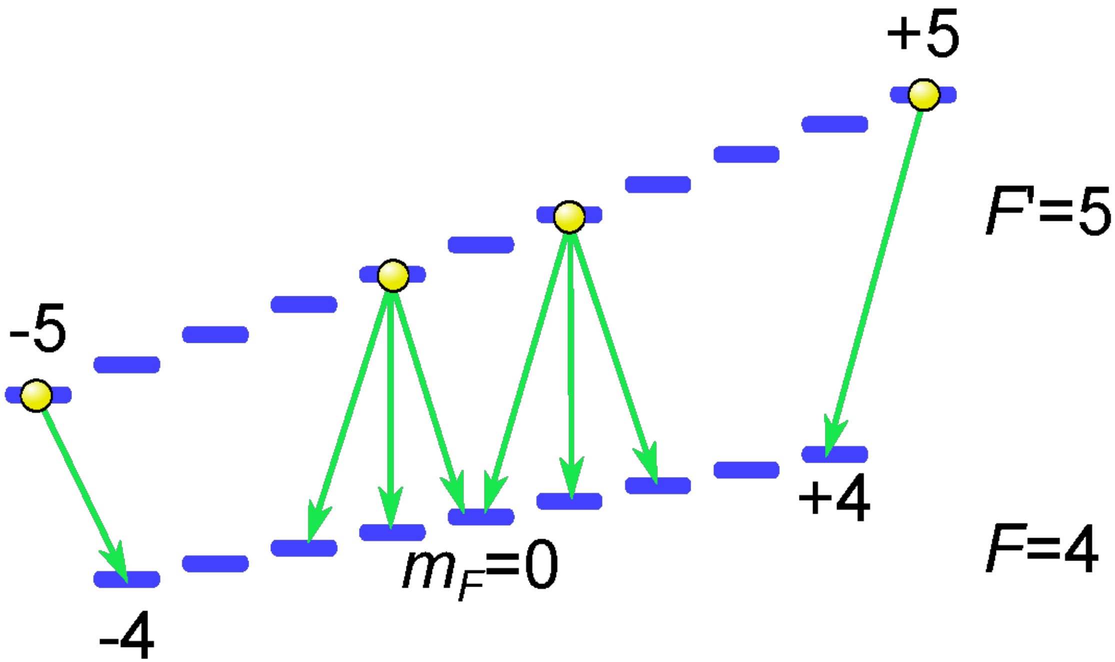
Experimental Set-Up

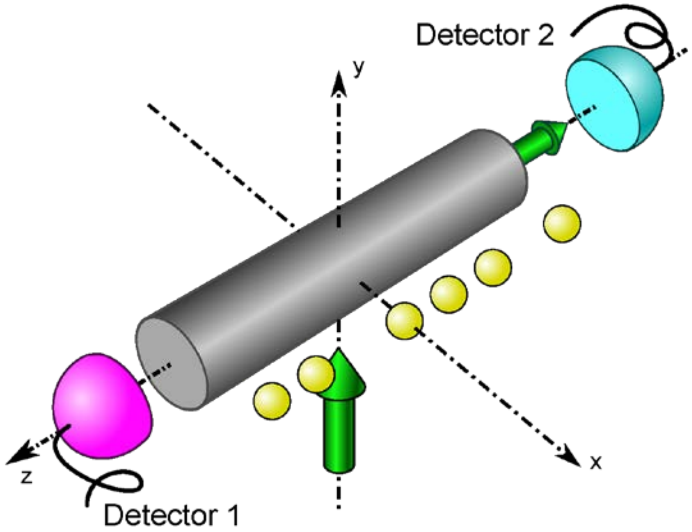
Nanofiber with cesium atoms on one side



R. Mitsch et al., Nat. Commun. **5**, 5713 (2014)

Cesium D2-Line Level Scheme

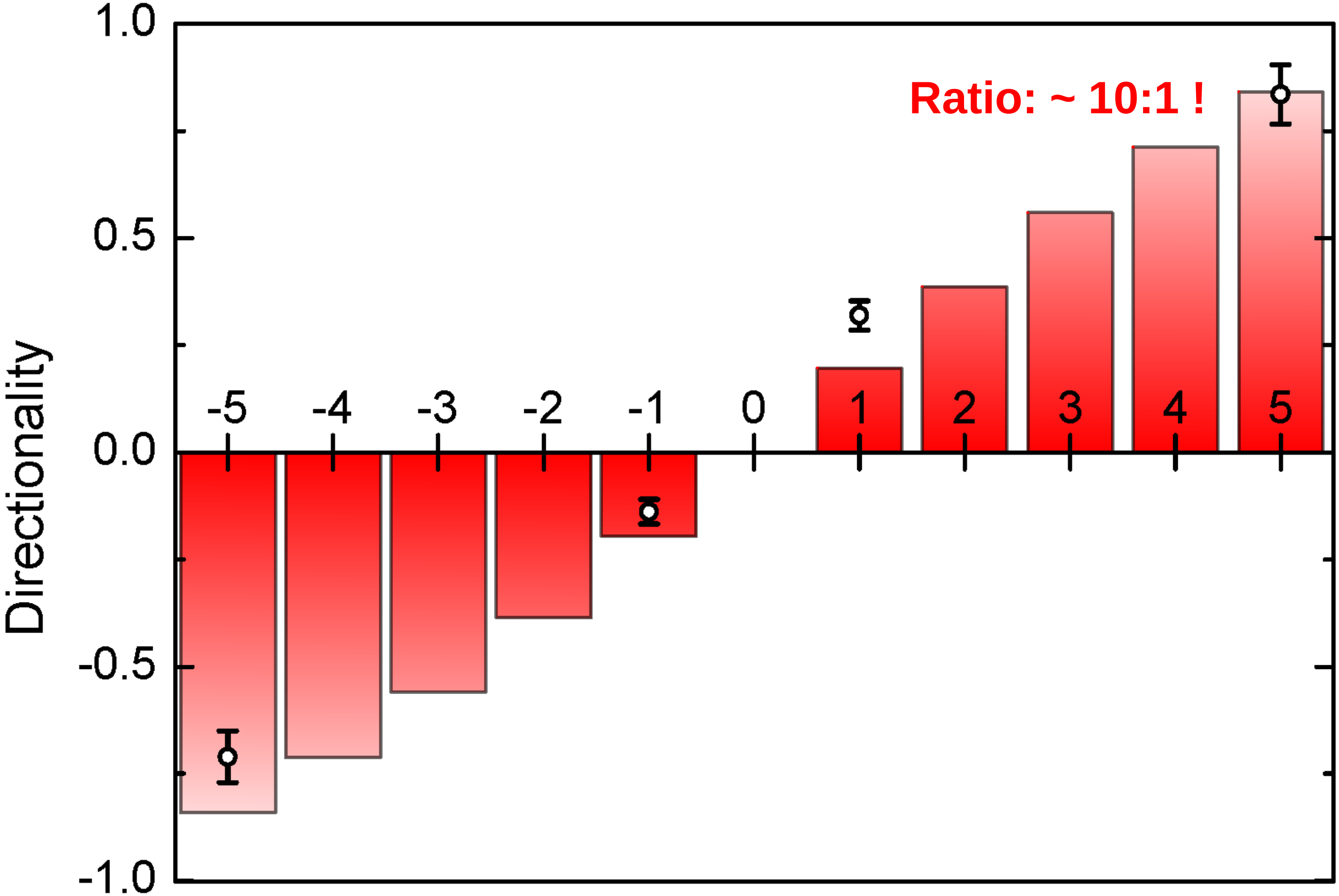




R. Mitsch et al., Nat. Commun. **5**, 5713 (2014)

Directional Atom-Waveguide Interface

Quantum state-controlled directional spontaneous emission



R. Mitsch et al., Nat. Commun. **5**, 5713 (2014)

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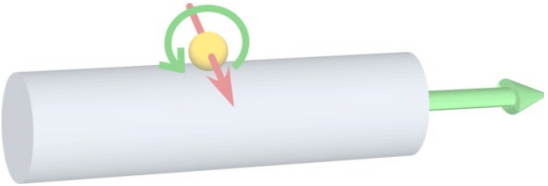
- Directional emission of a gold nanoparticle



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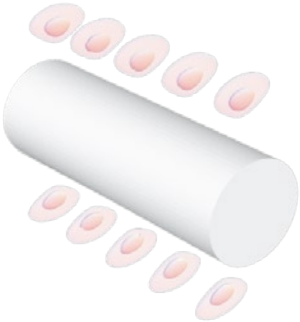
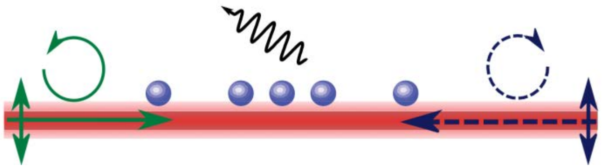
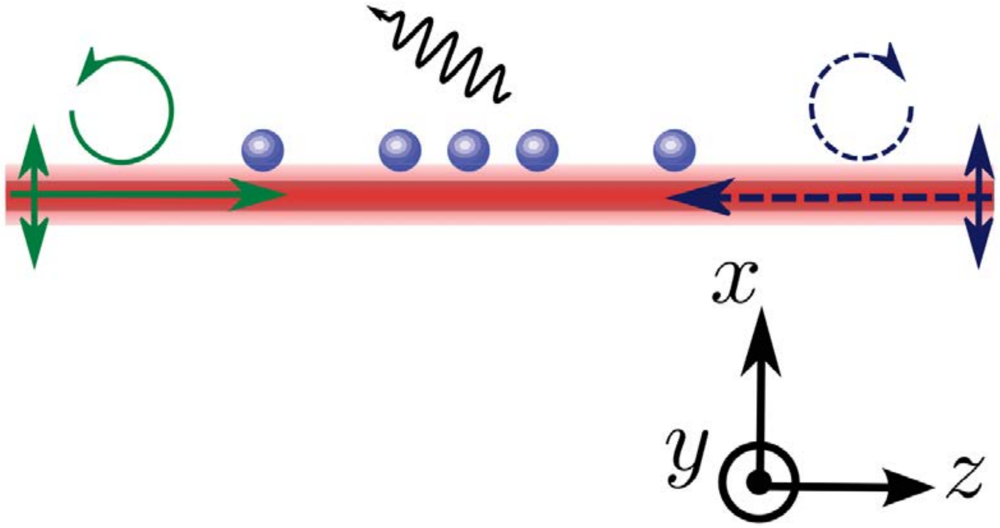


- Nonreciprocal nanophotonic waveguide



Experimental Set-Up

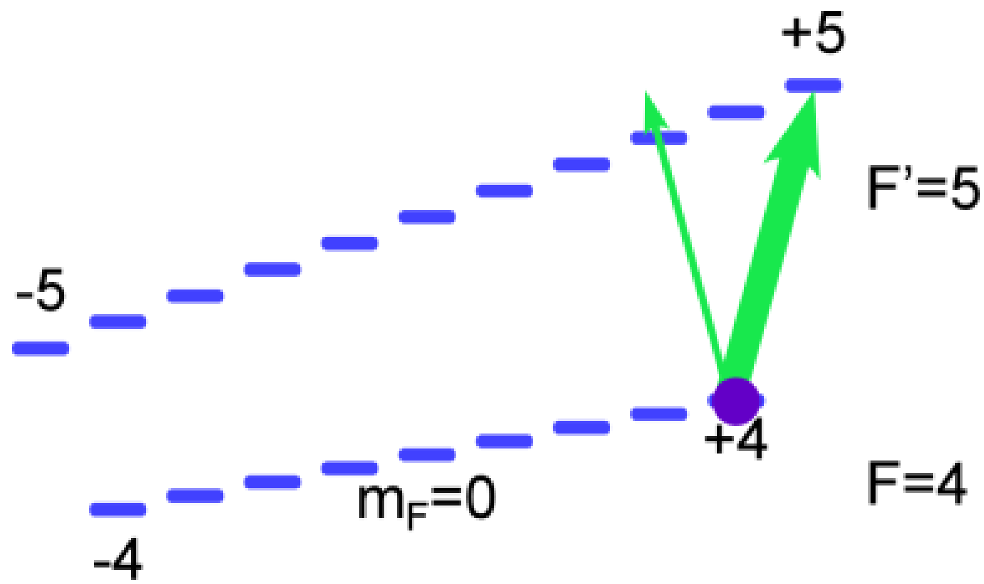
Nanofiber with spin-polarized atoms on one side

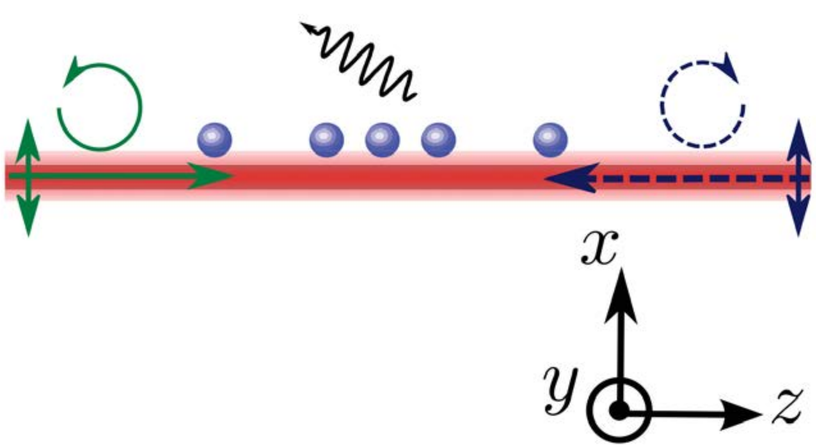


C. Sayrin et al., arXiv:1502.01549 (2015)

Nonreciprocal nanophotonic waveguide

Nanofiber with spin-polarized atoms on one side





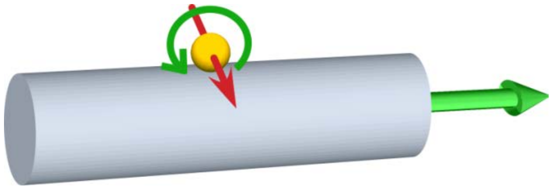
- Forward (backward) transmission of 78 % (13 %).
- Isolation of 8 dB.
- Data agrees with prediction for $\langle N \rangle = 27$ atoms.

C. Sayrin et al., arXiv:1502.01549 (2015)

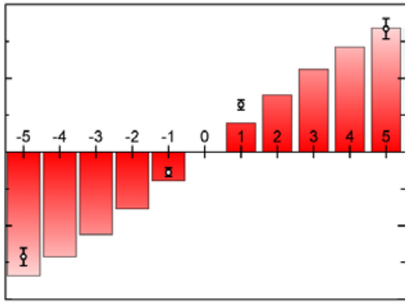
Summary

- Guided modes in optical nanofibers
  - Non-transversal polarization
  - Local polarization ⇔ propagation direction

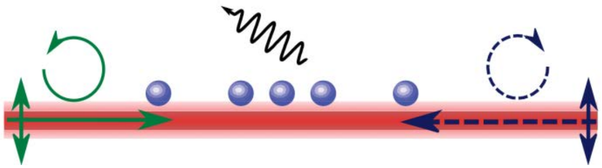
- Directional emission of a gold nanoparticle
  - Waveguide interface for single particle
  - Directionality of up to 95% demonstrated



- Directional atom-waveguide interface
  - Atomic state determines directionality
  - Ratio of ~ 10:1



- Nonreciprocal nanophotonic waveguide
  - Forward transmission of 78 % and isolation of 8 dB for 27 atoms



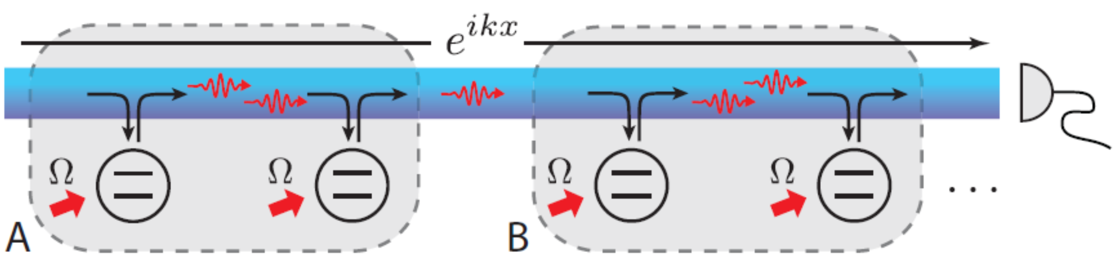
Perspectives

Optical signal processing and routing of light

Nanophotonic sensors for detecting and identifying scatterers with intrinsic polarization asymmetry

Revisit “one-dimensional atom” ⇒ qualitatively new effects

Collective emission creates pure entangled state



Stannigel et al., New. J. Phys. **14**, 063014 (2012)

Thanks…

Students: Bernhard Albrecht, Benjamin Fränkel, Jakob Hinney, Rudolf Mitsch, David Papencordt, Jan Petersen, Adarsh Prasad, Daniel Reitz, Michael Scheucher, Stefan Walser, Daniel Weiss, Elisa Will

Group Technician: Thomas Hoinkes

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Funding

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Thank you for your attention!