Nanoplasmonics
&
NanoOptics

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FESTA
The Femtosecond Technology Research Association

AMOLF FOM

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Outline

- Subwavelength imaging

    phase-sensitive NSOM in collection mode

    examples: speeds of light

    tracking eigenstates in k-space

    “weird” evanescent fields

    polarization singularities

- Coupling to plasmonic nanowires

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NanoOptics: the problem

$$\Delta x \, \Delta k \geq 2\pi$$

$\Rightarrow$ Can’t resolve optical information smaller than $1/2\lambda$,

this information is evanescent

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Evanescent field

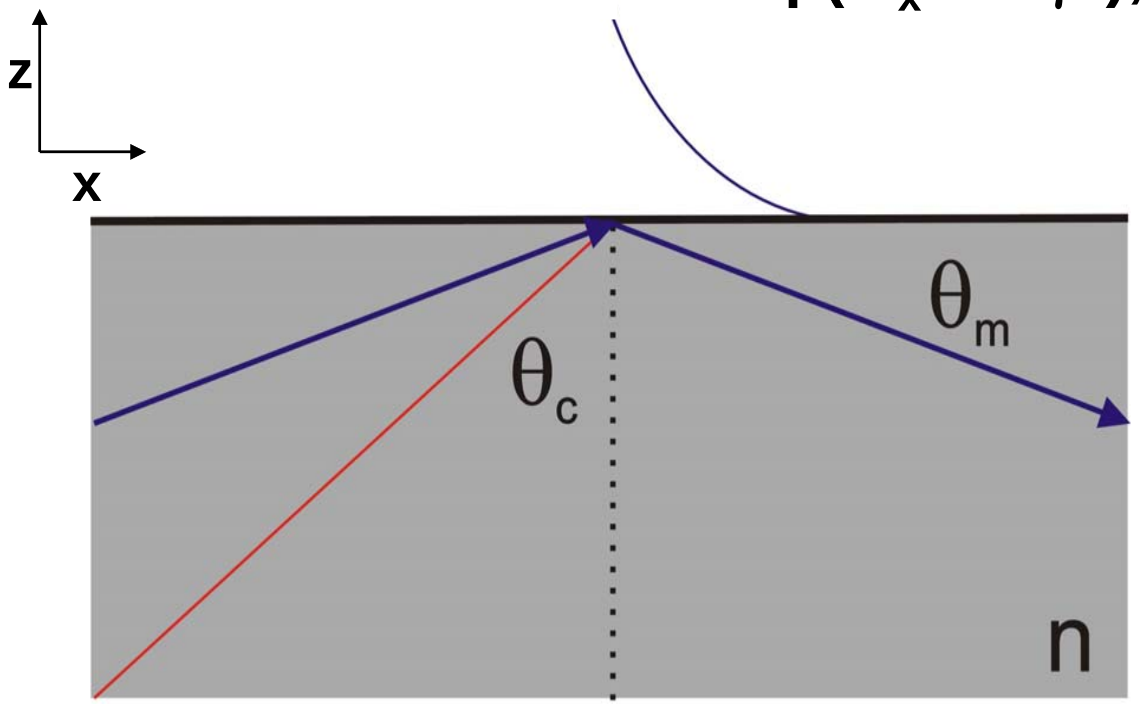
hundred thouſandth Part of an Inch, will go through that Surface, and through the Air or *Vacuum* between the Glaſſes, and enter into the ſecond Glaſs, as was explain'd in the firſt, fourth,

$$E(z) = E(0)\mathrm{e}^{iz\sqrt{k_0^2 - k_\parallel^2}}, \text{ with } k_0^2 = \epsilon_{low}\frac{\omega^2}{c^2}$$

I. Newton, Opticks (William Innys, London, 1730), Book III, Qu. 29, 4th ed., p. 346-347.

Total internal reflection

Evanescent field $\propto \exp(ik_x x + i\gamma z)$, $\gamma = i\sqrt{(k_x^2 - \omega^2/c^2)}$

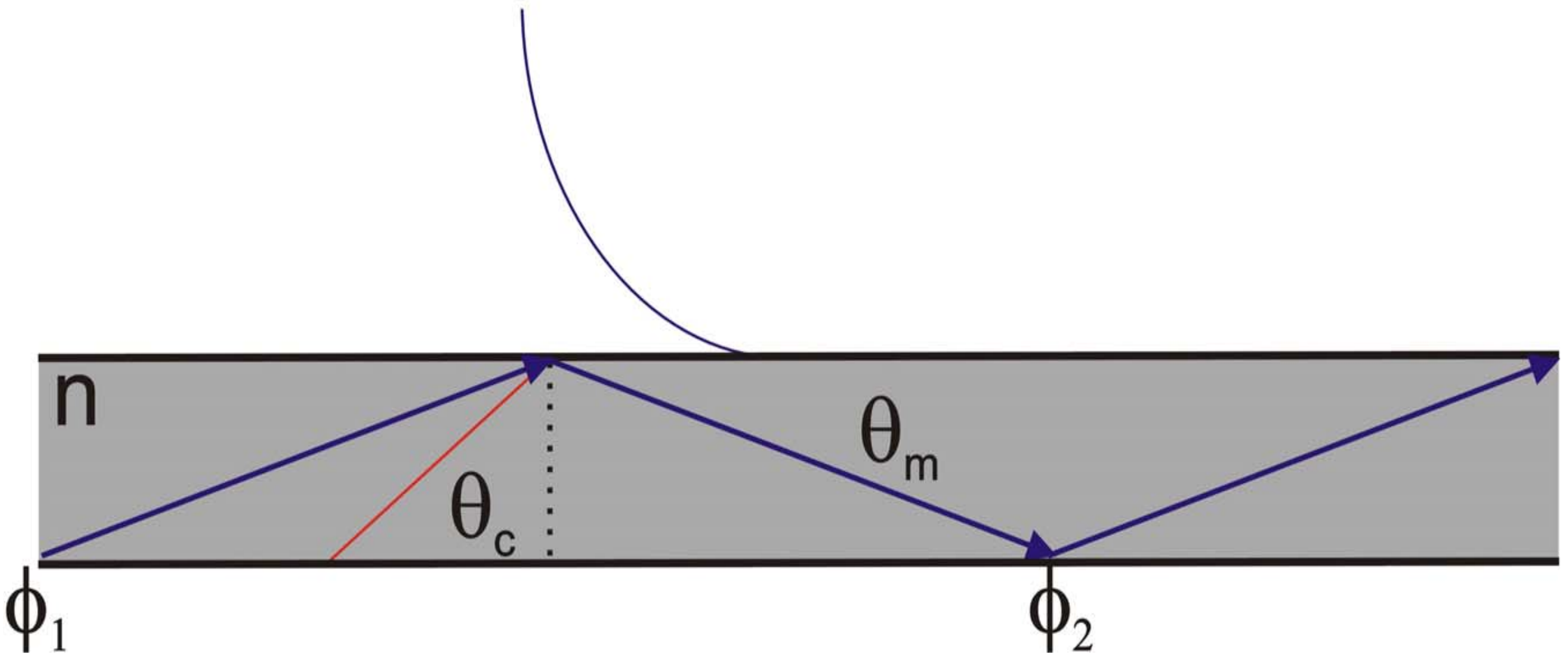


$k_x = n\cos\theta_m \, 2\pi/\lambda$
$(> \sqrt{(\omega^2/c^2)})$

k too large: light becomes evanescent

($\Rightarrow$ sub-λ info always evanescent!)

Guided Mode



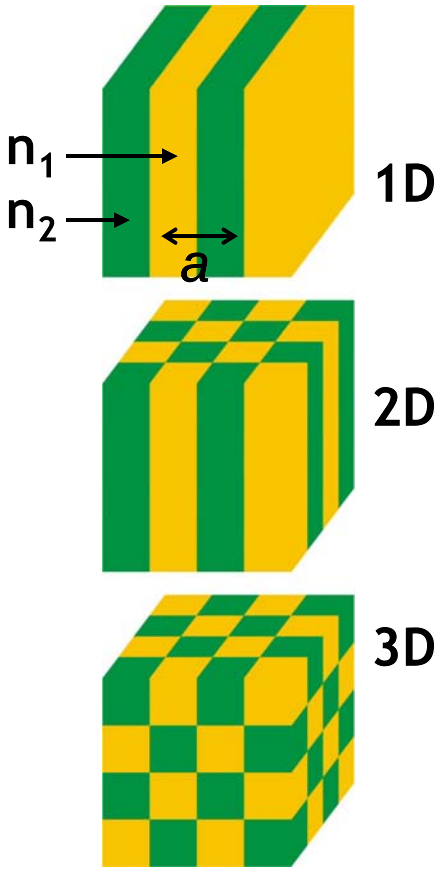
Light is trapped by total internal reflection

For all θ_m for which $\phi_1 - \phi_2 = N\,2\pi$ there is a guided mode if the "ray" stays under the critical angle

Intermezzo:
photonic crystals

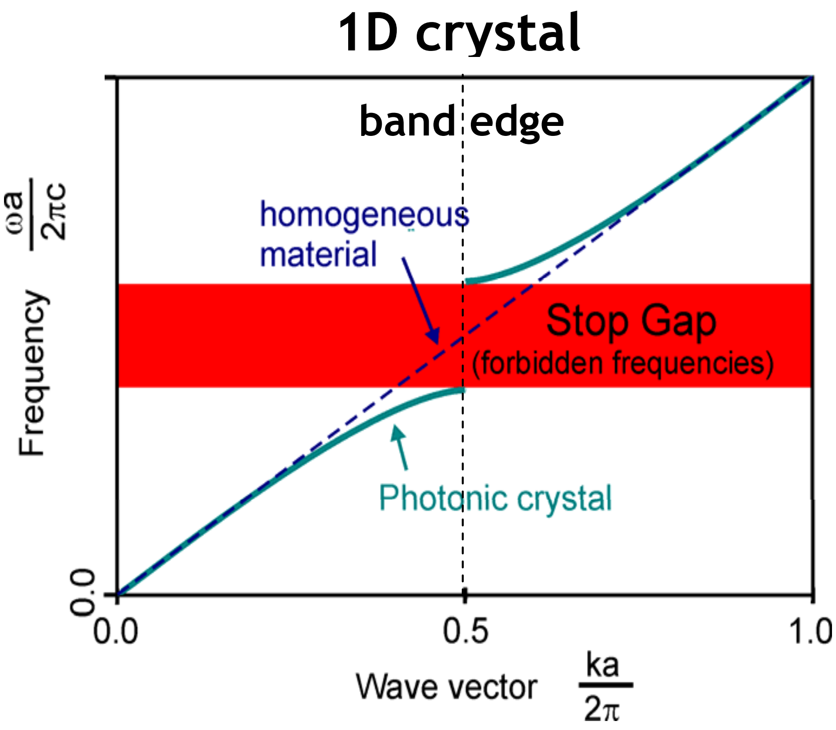
Photonic crystals

periodic composites with $n_2 > n_1$



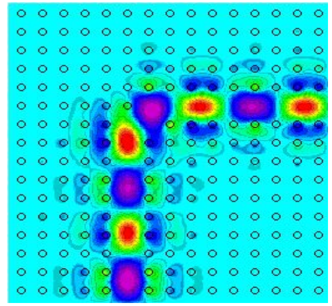
- a ~ 0.5 l
- n_2 / n_1 large

Photonic band structure



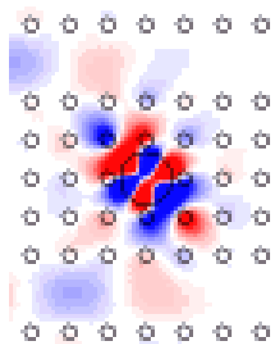
Miniaturization of integrated optics

defect waveguides

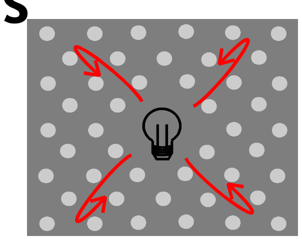


sharp turns (~λ)

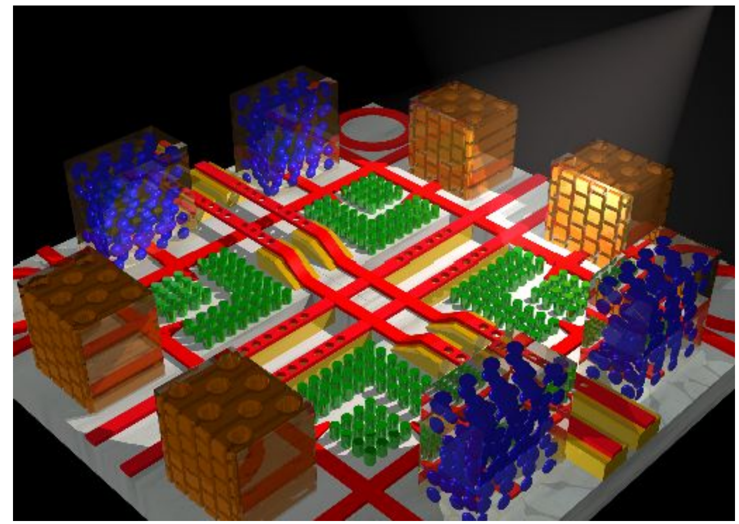
filters



zero threshold lasers
coherent LED's
photons on demand
photovoltaics



Vision of the future



MIT: "Micropolis" 1997

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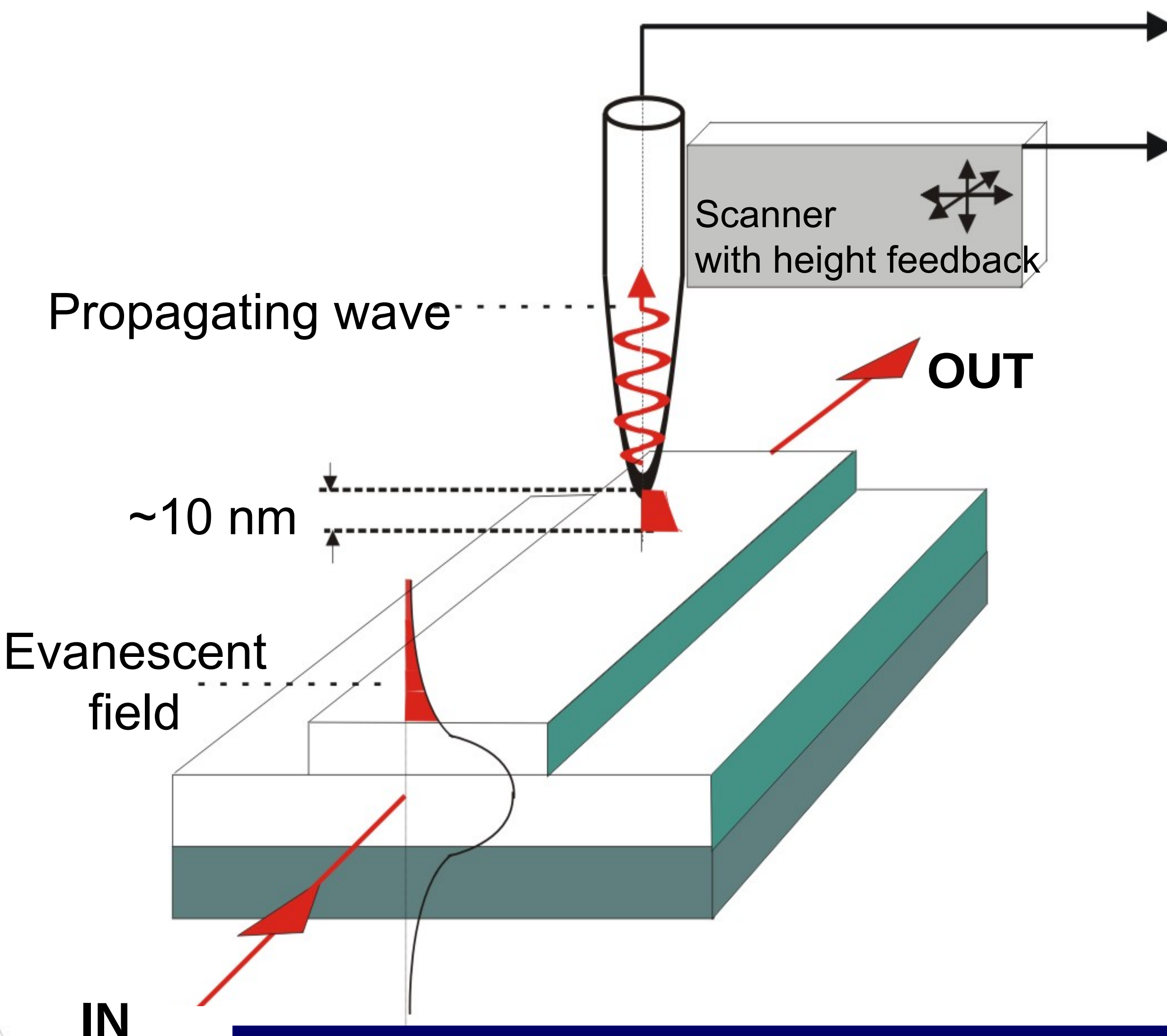
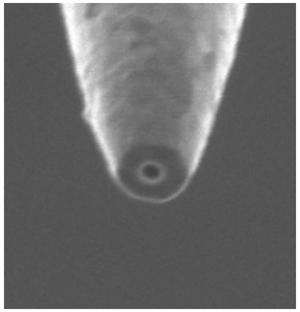
NanoOptics

collection mode NSOM (SNOM, PSTM, STOM)

Photon Scanning Tunneling Microscopy



Fiber probe



optical resolution determined by the aperture of the probe (~80 nm)

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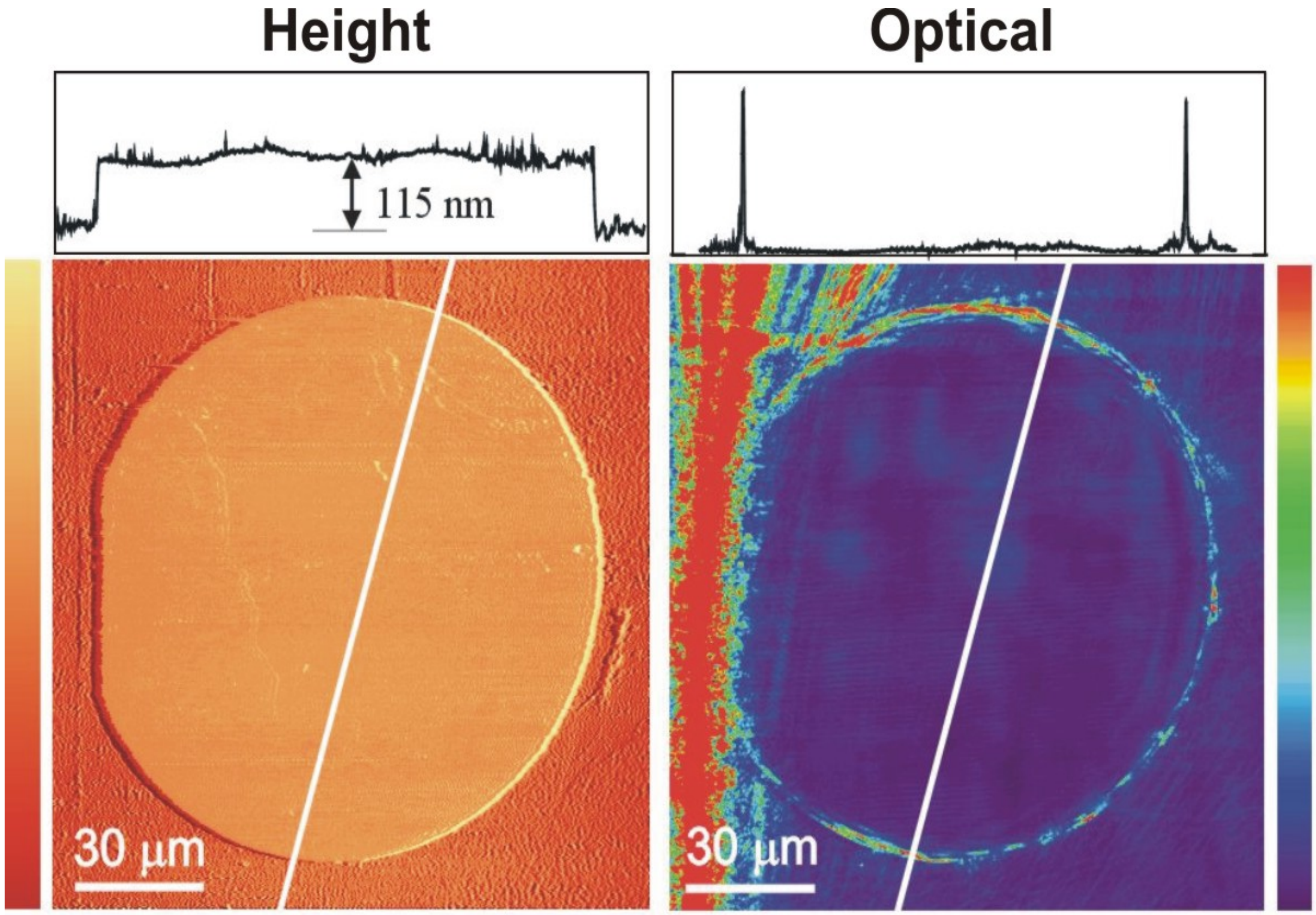
Whispering gallery modes

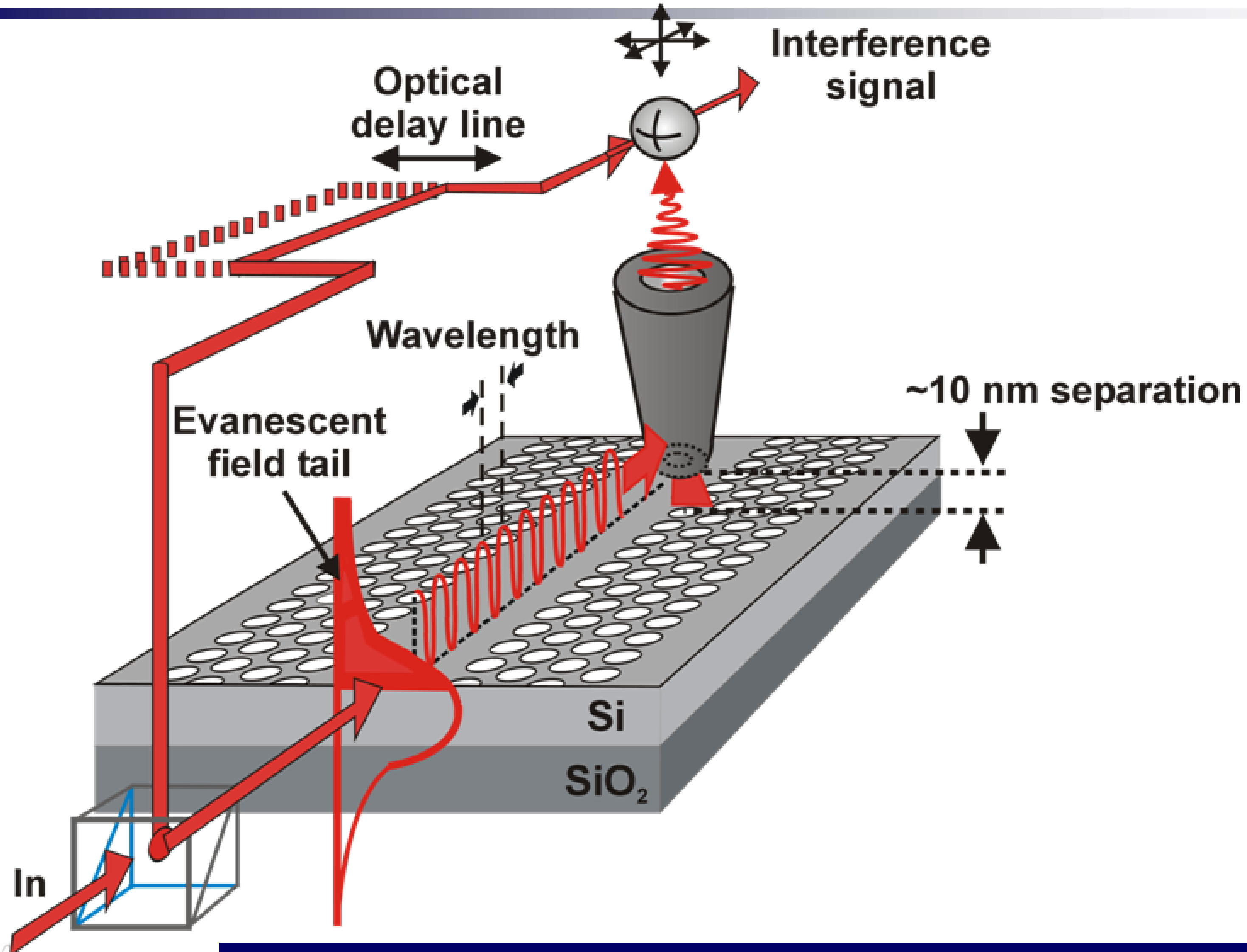


Light confined to the rim: WGM

Opt.Lett. 1999

Work performed with Dion Klunder and Alfred Driessen (MESA+)

Local phase-sensitive probing of light



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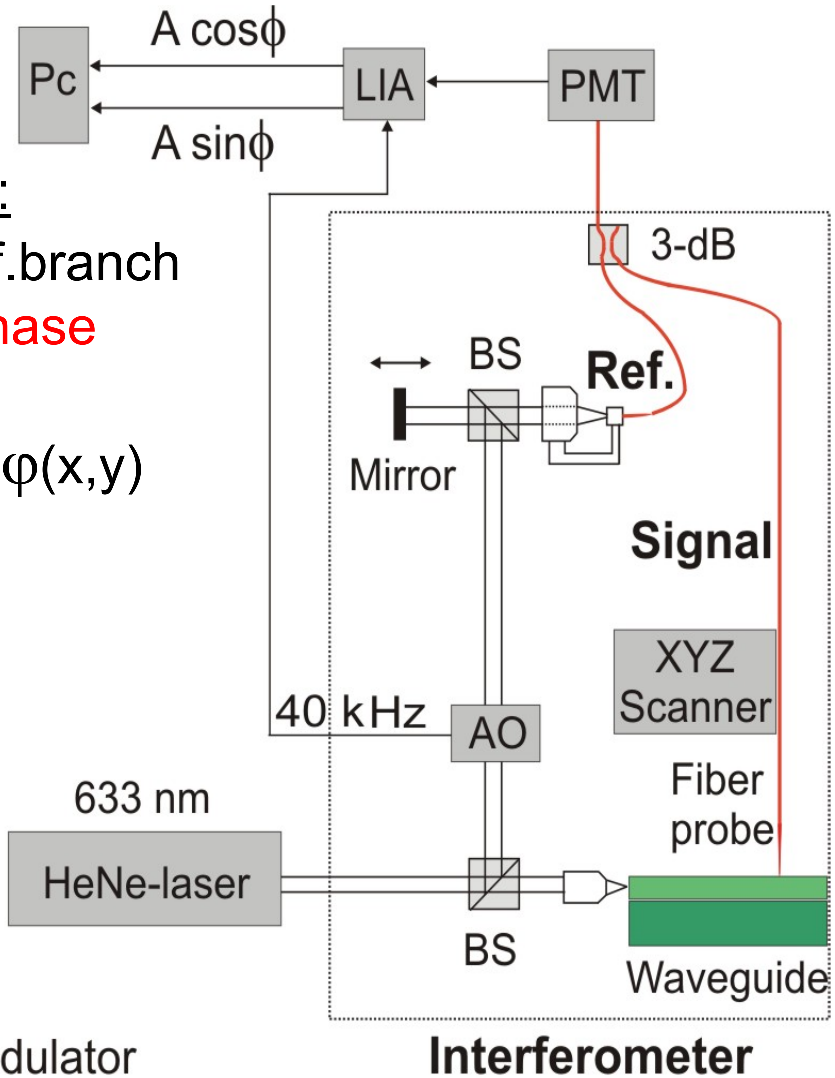
Heterodyne detection



<u>Heterodyne detection:</u>

By changing frequency of ref.branch both amplitude and the phase of light are retrieved

$A(x,y)\cos\varphi(x,y)$ & $A(x,y)\sin\varphi(x,y)$ measured

$A(x,y)e^{i\varphi(x,y)}$

can be constructred

ϕ = Phase

A = Amplitude

LIA = Lock-In Amplifier

AO = Acousto-Optic Modulator

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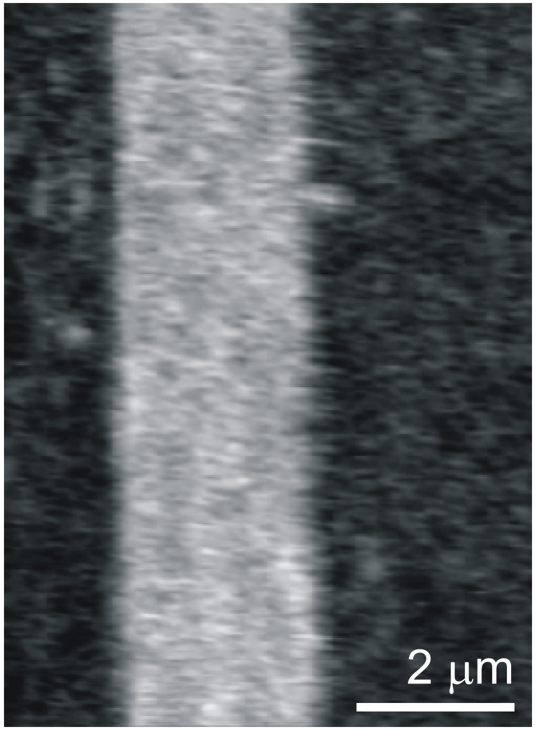
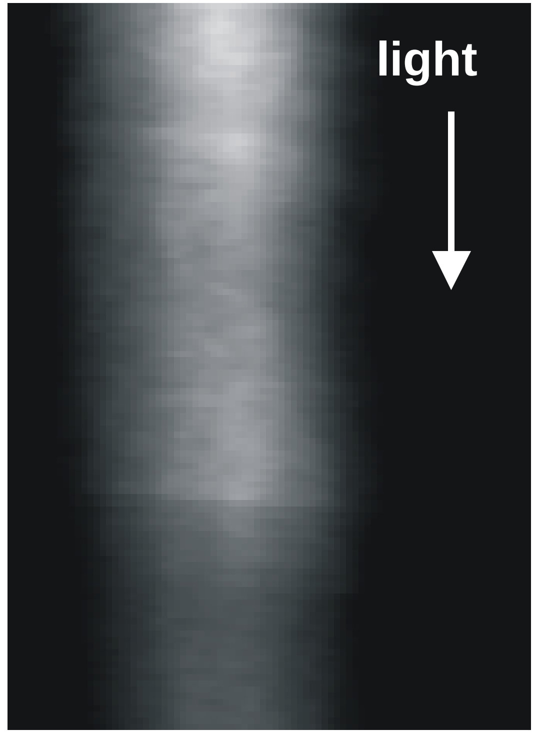
Single mode in channel waveguide

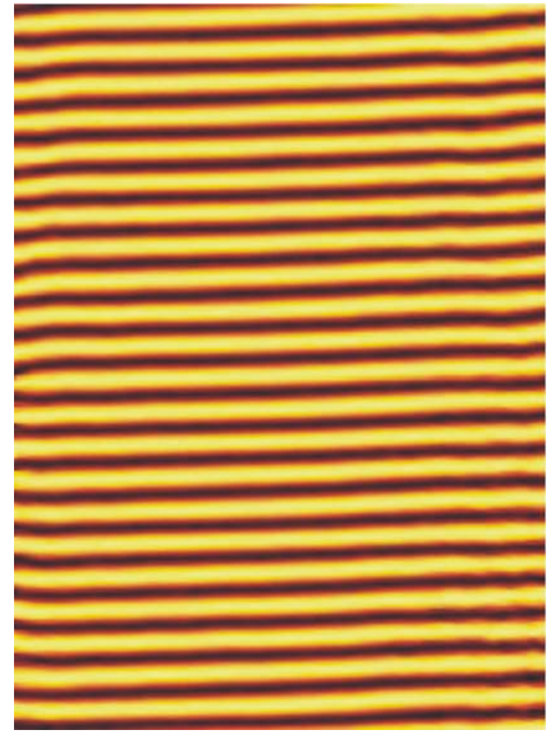
Topography



Amplitude



cosφ



Measurement yields: **modeprofile** **wavelength (refractive index)**

Propagation of a plane wave

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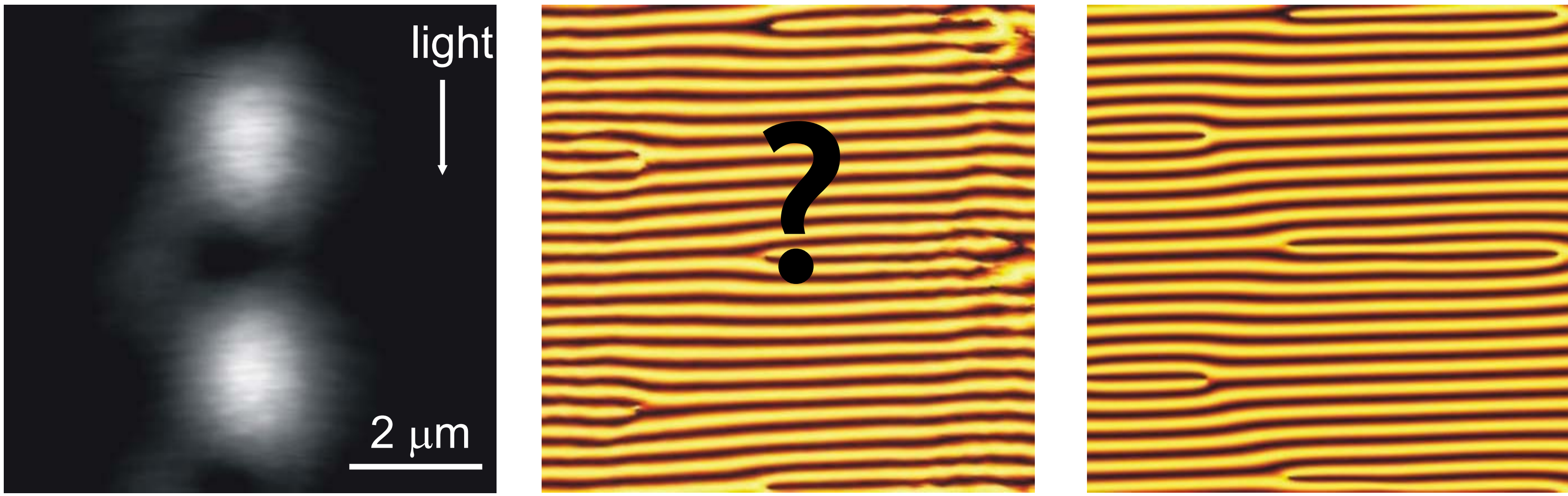
Phase singularities

Three modes co-propagating (same ω, different k (or n_{eff}))

Amplitude | **cosφ (experiment)** | **cosφ (calculation)**



- **Local observation of mode beating**
- **Observation of phase singularities (topological charge ± 1)**

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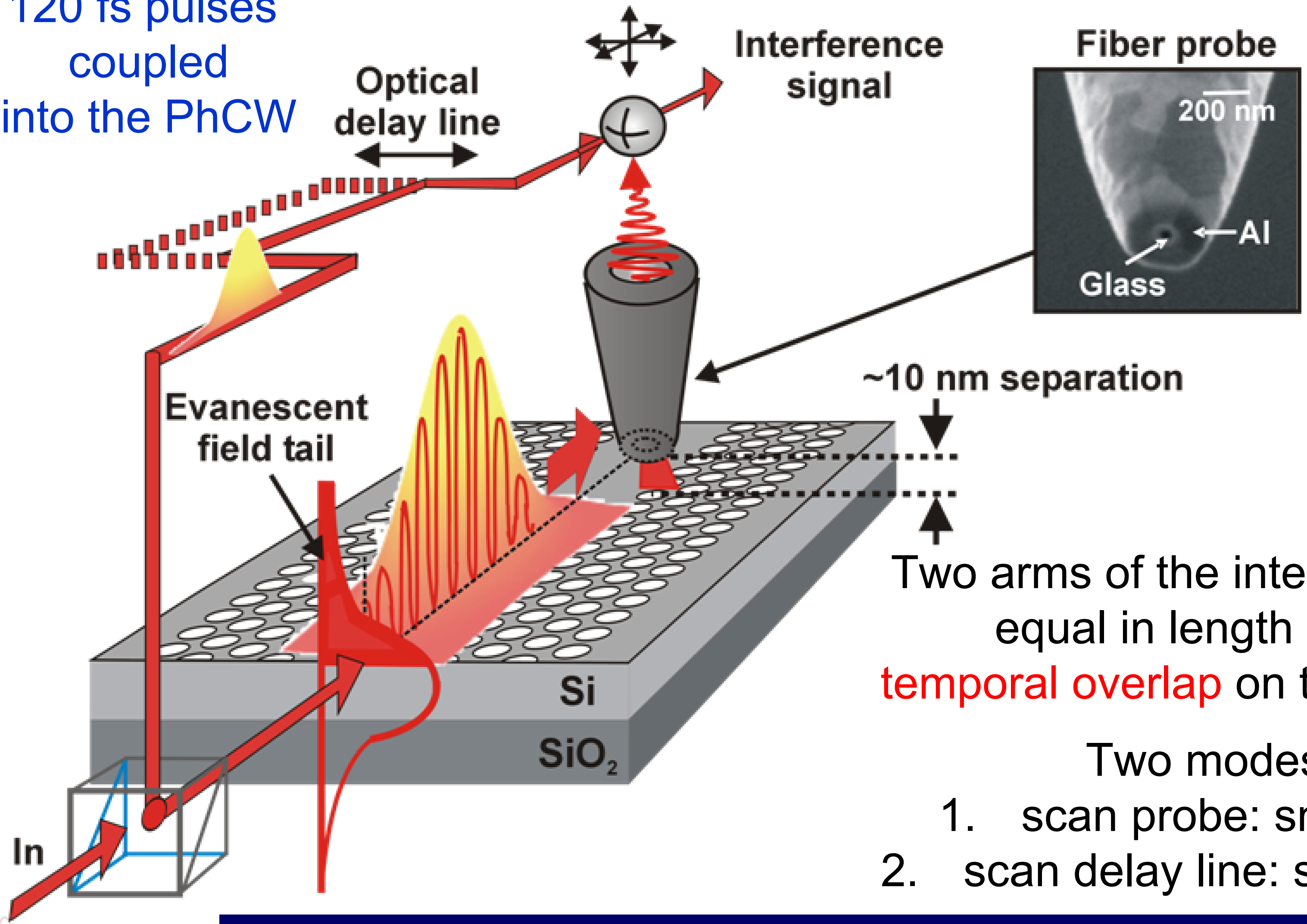
M.L.M. Balistreri, et al., PRL 2000

Pulse tracking PSTM

120 fs pulses coupled into the PhCW



Two arms of the interferometer equal in length gives temporal overlap on the detector

Two modes:

1. scan probe: snapshots
2. scan delay line: spectral info

Mode 1
Snapshots

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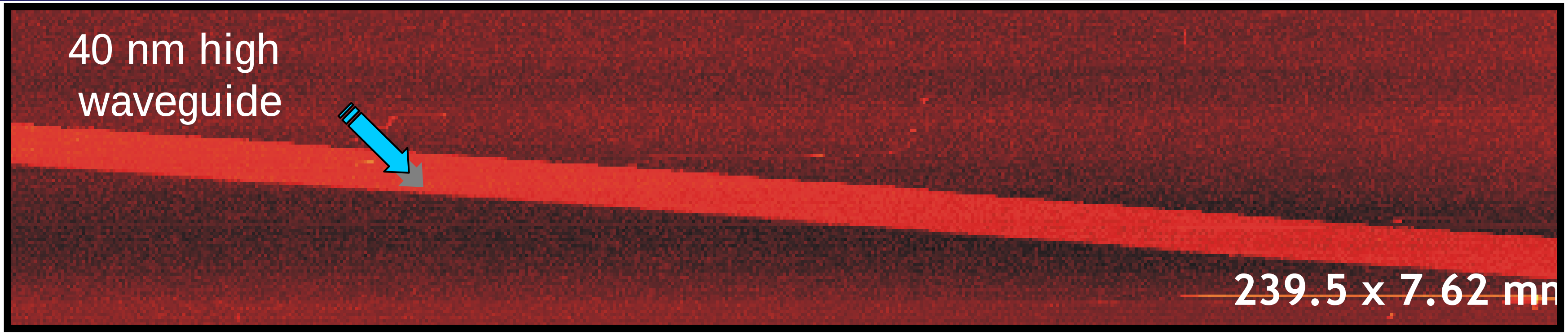
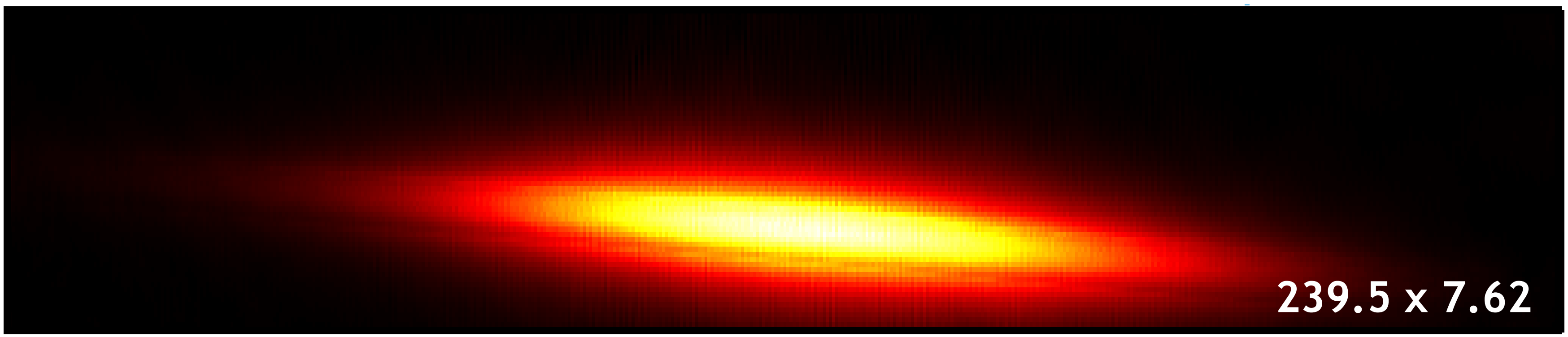
"snapshot" of pulse





TE_{00} pulse, l =1300 nm
pulse duration : 120 fs

Fixed reference branch

"snapshot" of pulse

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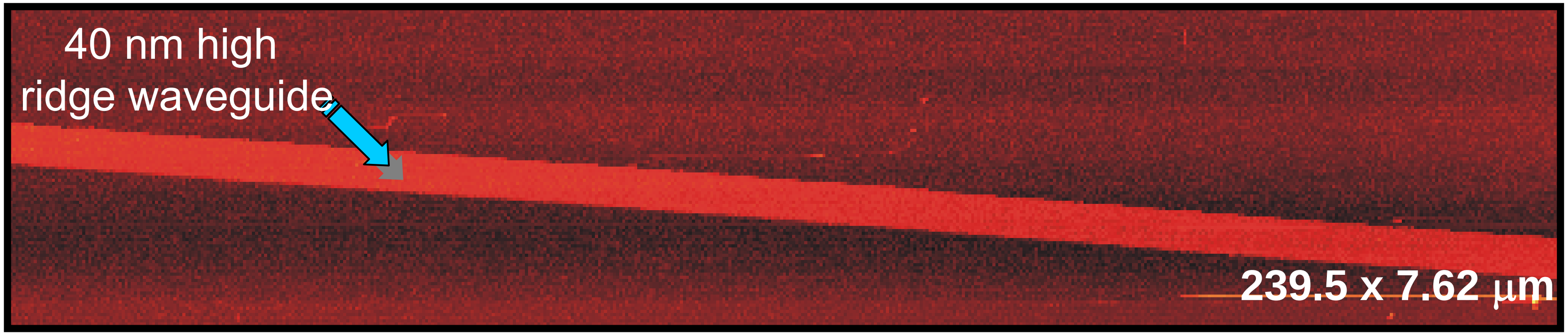
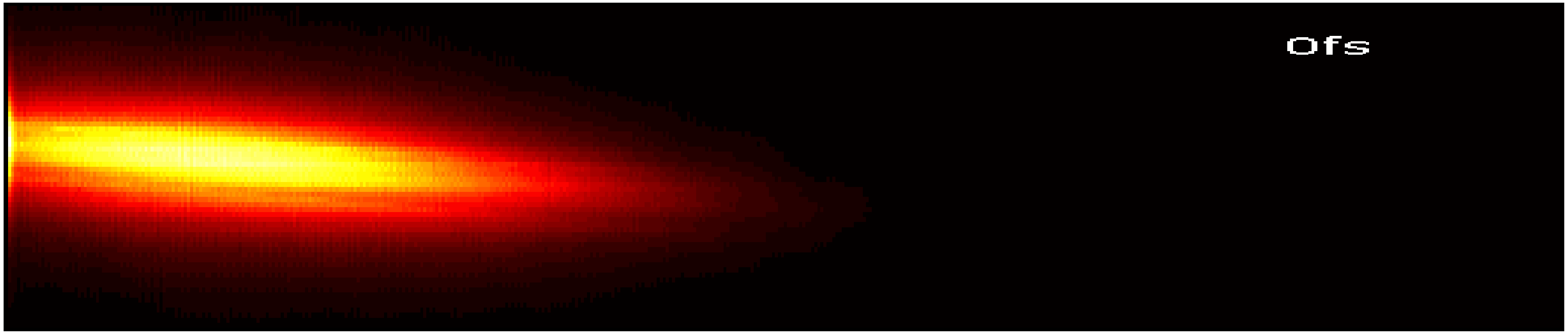
Pulse tracking





TE$_{00}$ pulse, λ =1300 nm
duration : 120 fs

Stepping optical delay

Pulse propagation visualized

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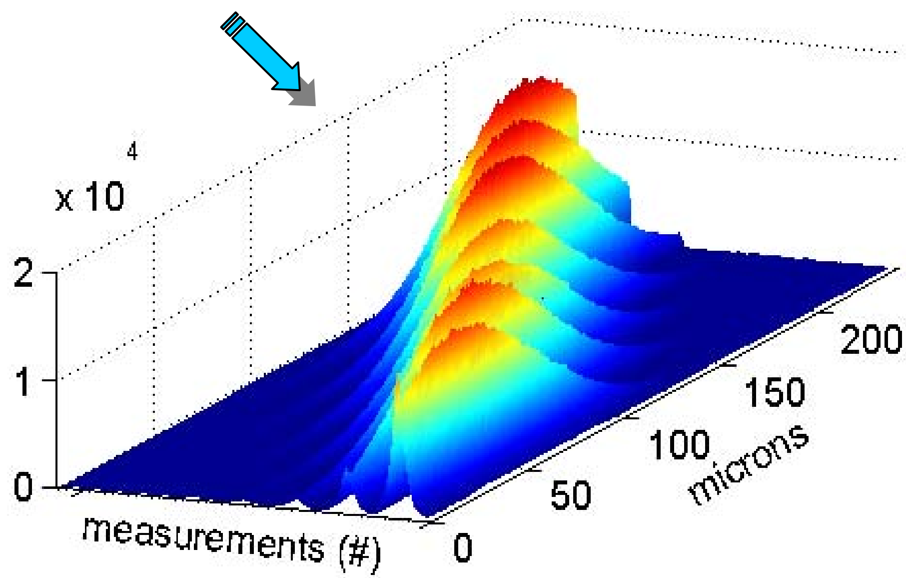
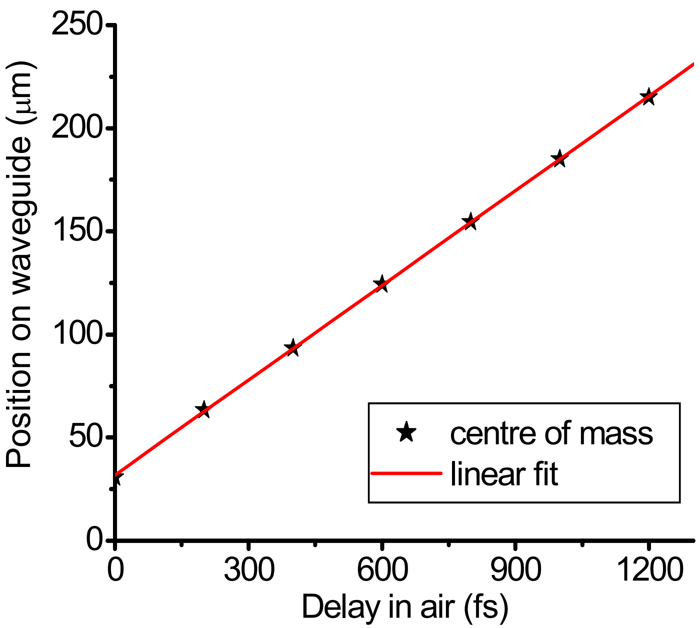
Group velocity

Positional change of the "centre of mass" gives the _roup velocity





Local probing of the group velocity

A constant group velocity is found:

$$v_g = 1.532 \pm 0.007 \times 10^8 \text{ m/s}$$

*M.L.M. Balistreri, H. Gersen et al. Science **294**, 1080 (2001)*

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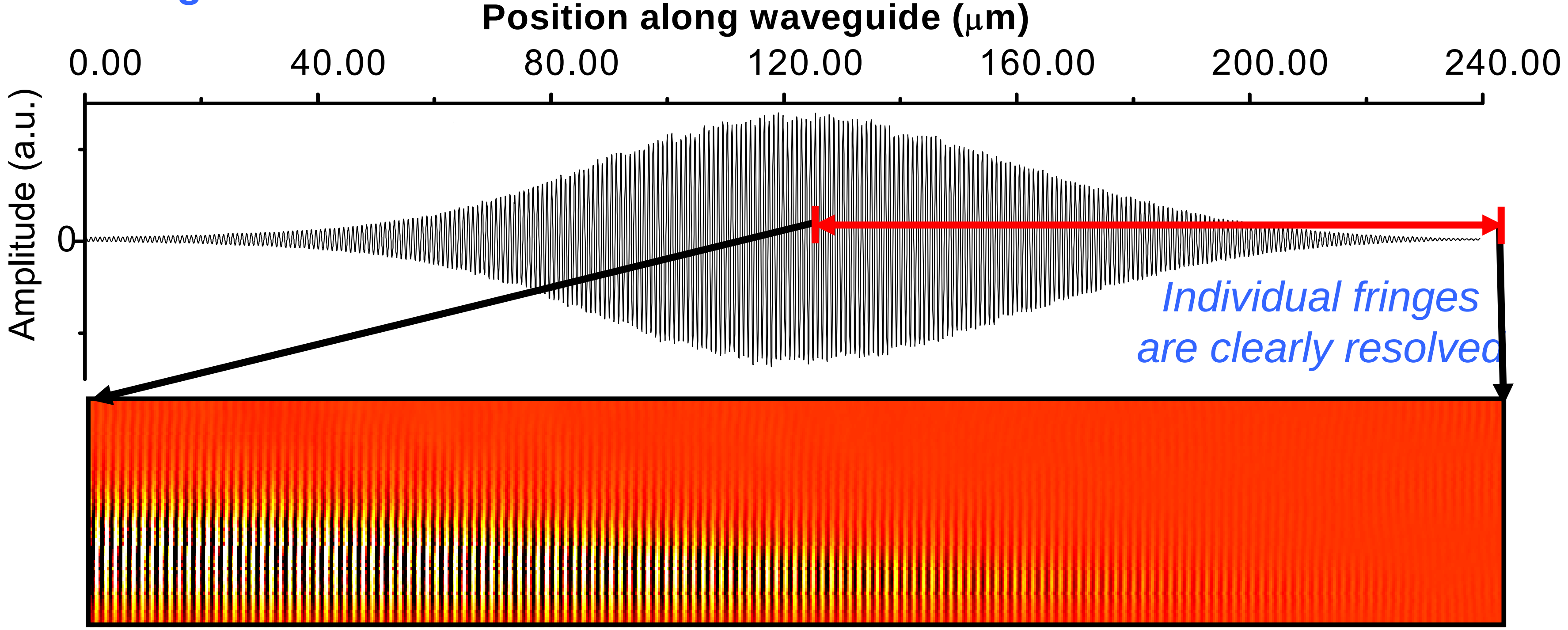
Phase velocity

Full interferometric signal for a single scan line



TE_{00} pulse, λ =1300 nm
pulse duration : 120 fs

Central wavelength is 796 ± 2 nm, so phase velocity: $v_{ph} = 1.84 \pm 0.03 \times 10^8$ m/s

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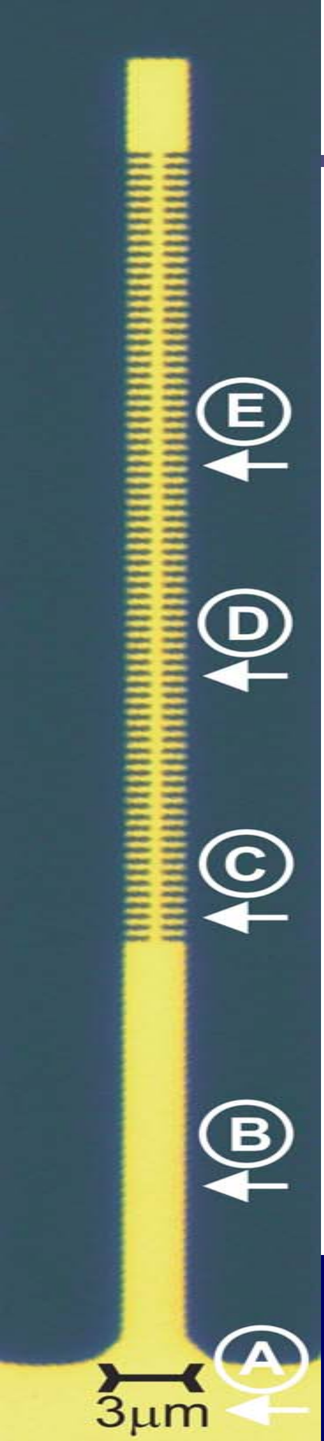
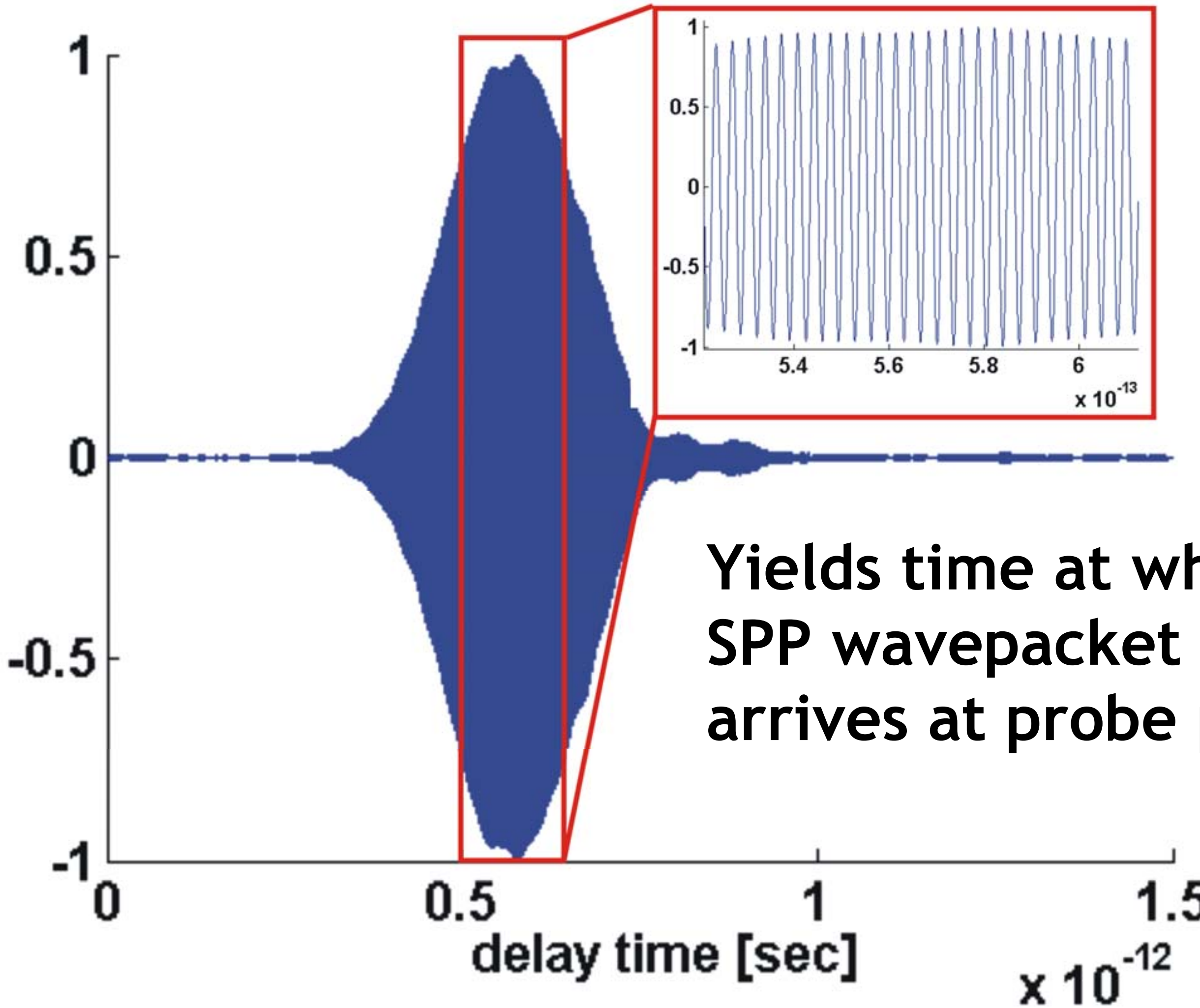
Mode 2
Spectral information

Delay scan @ fixed probe position

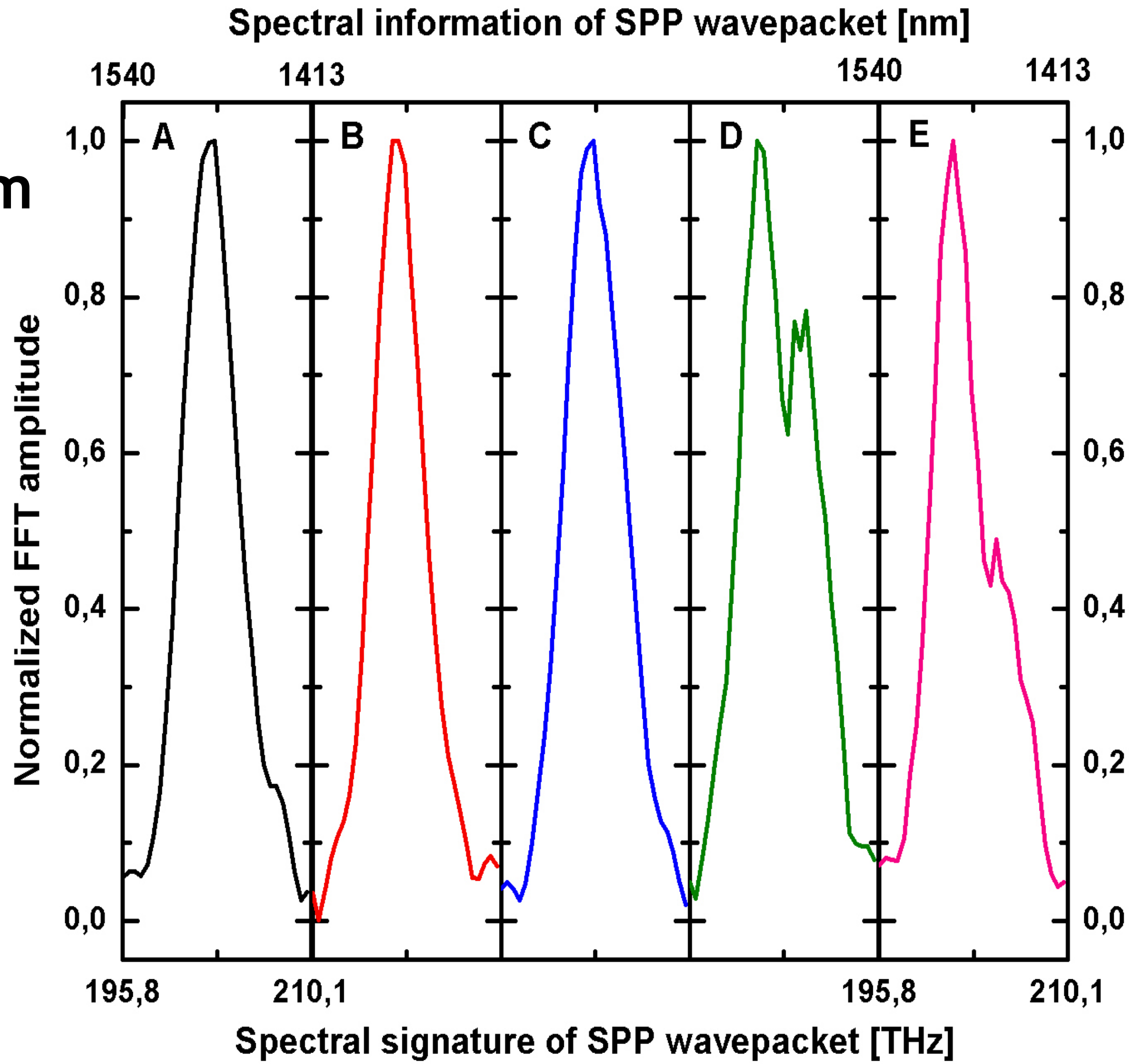




Yields time at which SPP wavepacket arrives at probe position

Observation of plasmonic stop gap

Fourier transform yields spectral information



M. Sandtke, et al., *Nature Photonics* 1, 573 - 576 (2007)

M. Sandtke, et al., Phys Rev B, 2008

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Real space
vs.
Reciprocal space (k-space)

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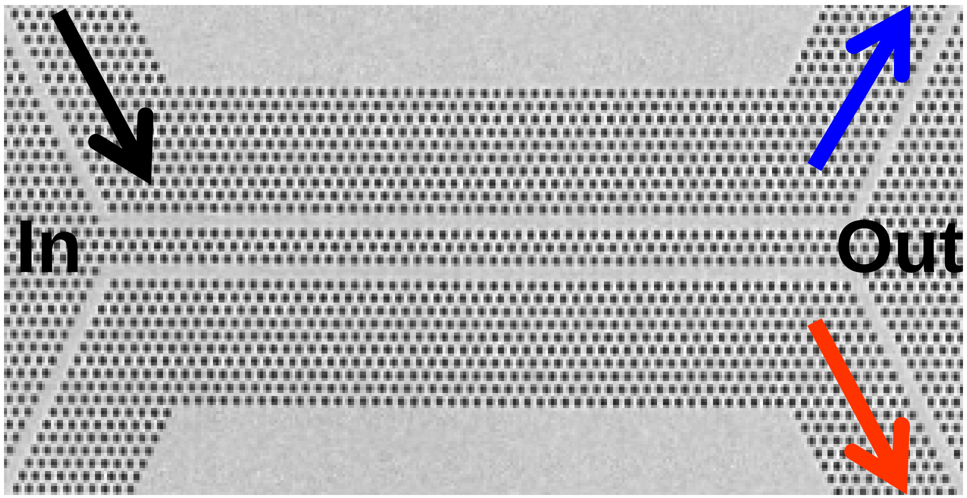
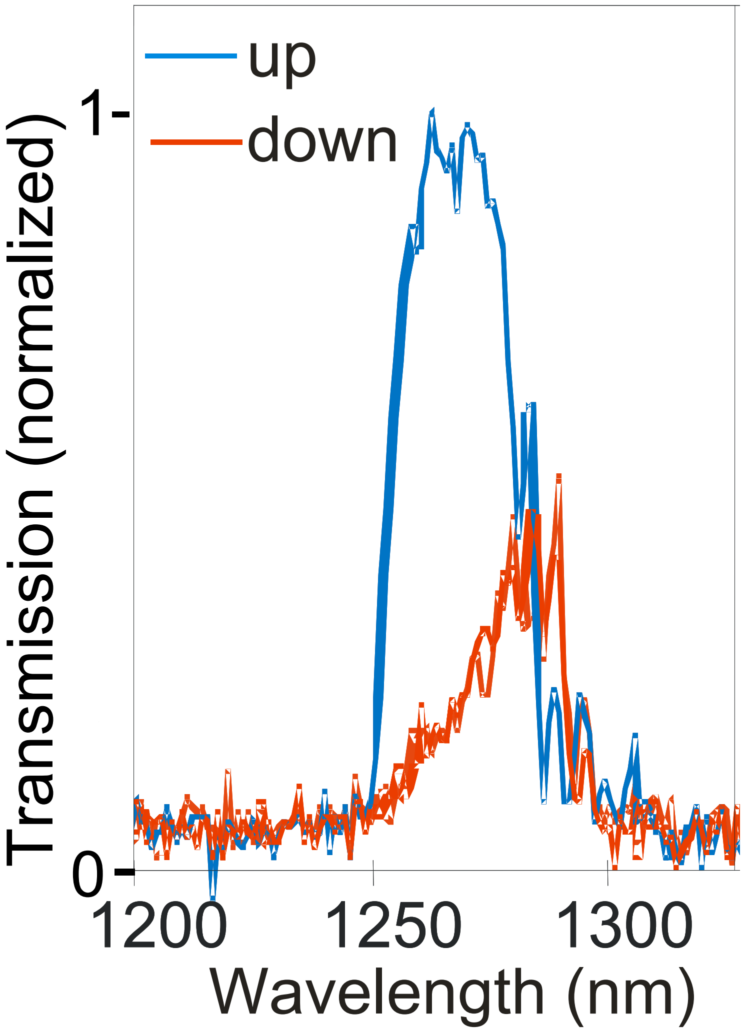
Transmission directional coupler



Two photonic crystal waveguides form a coupling structure



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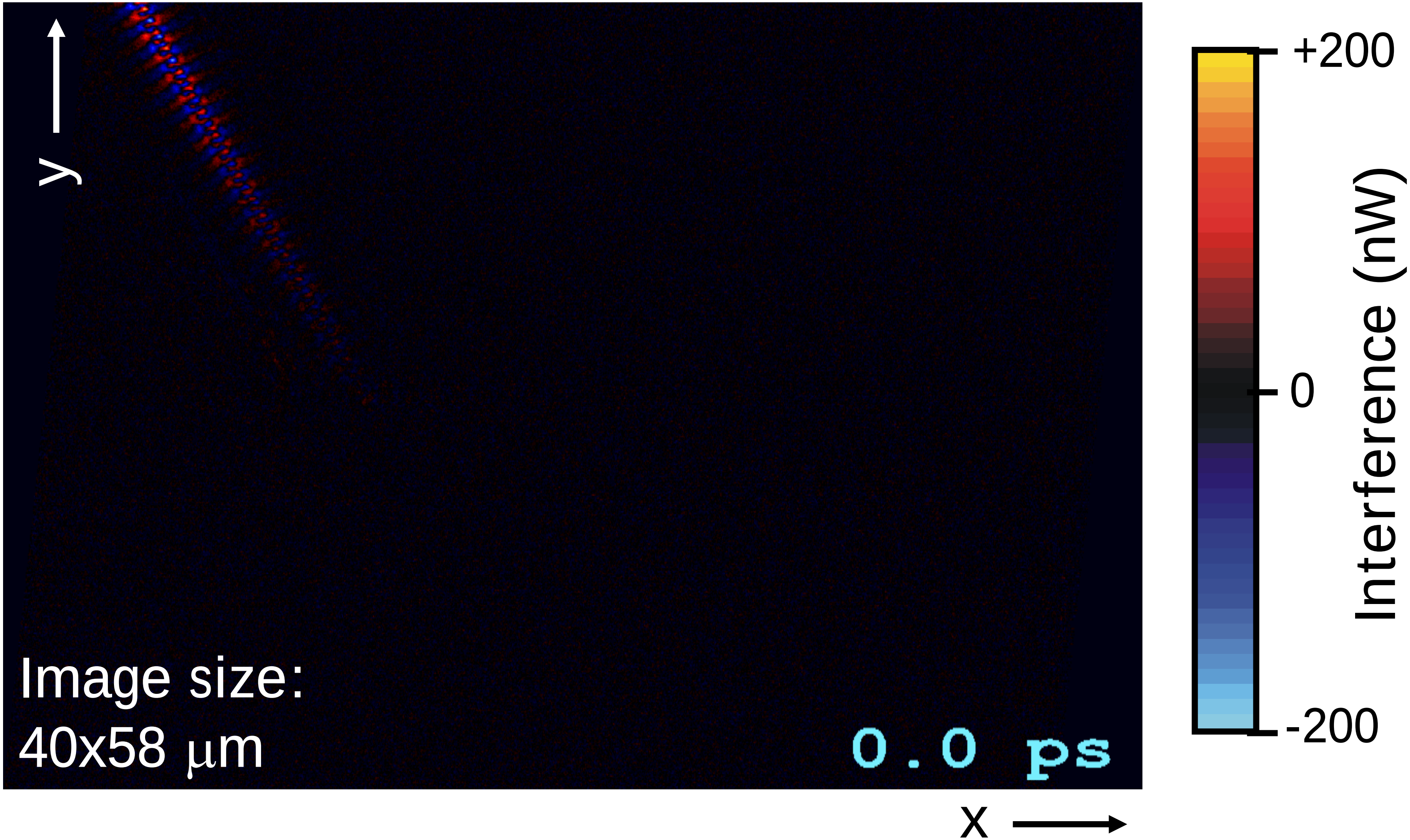
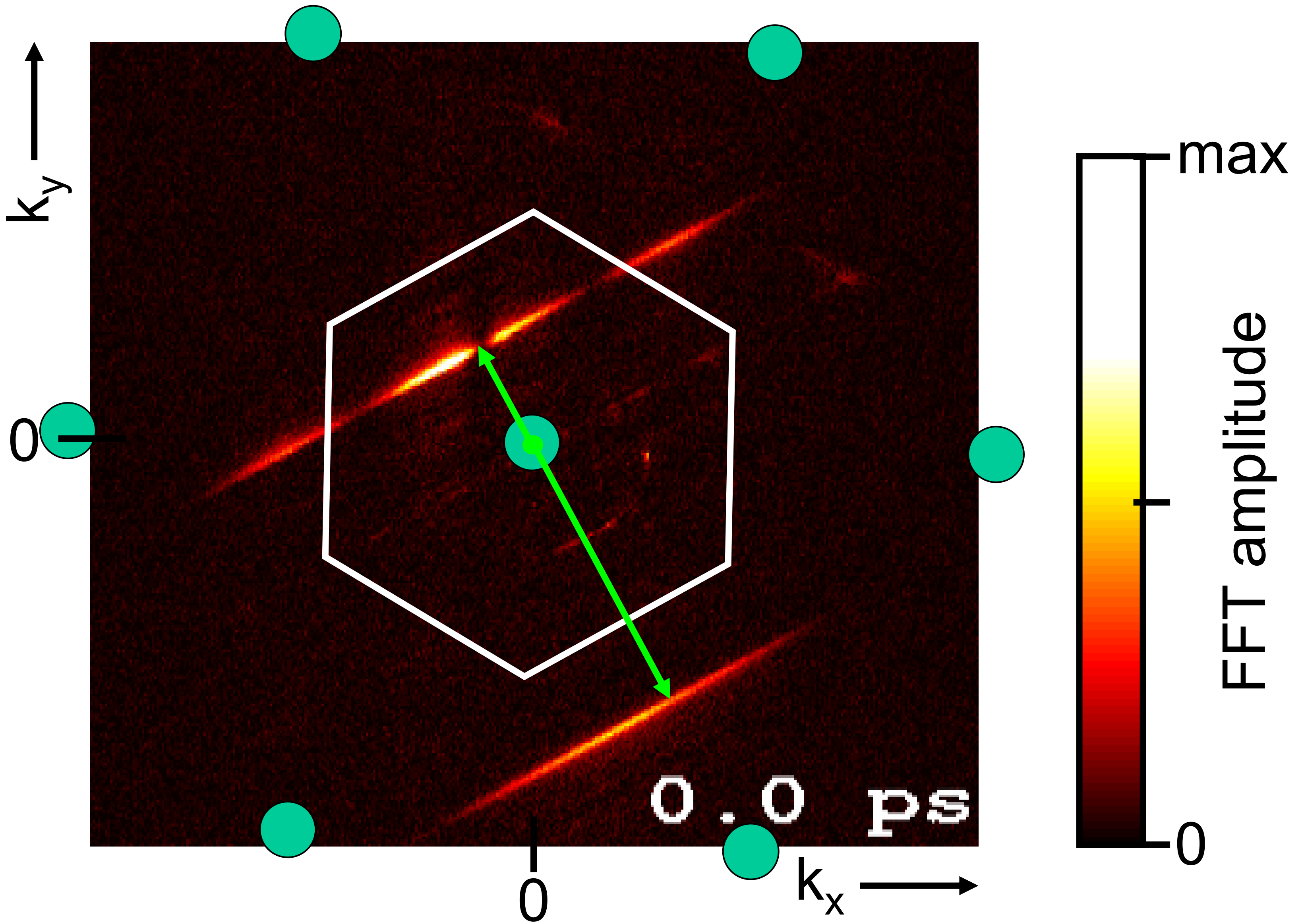
Real-space tracking



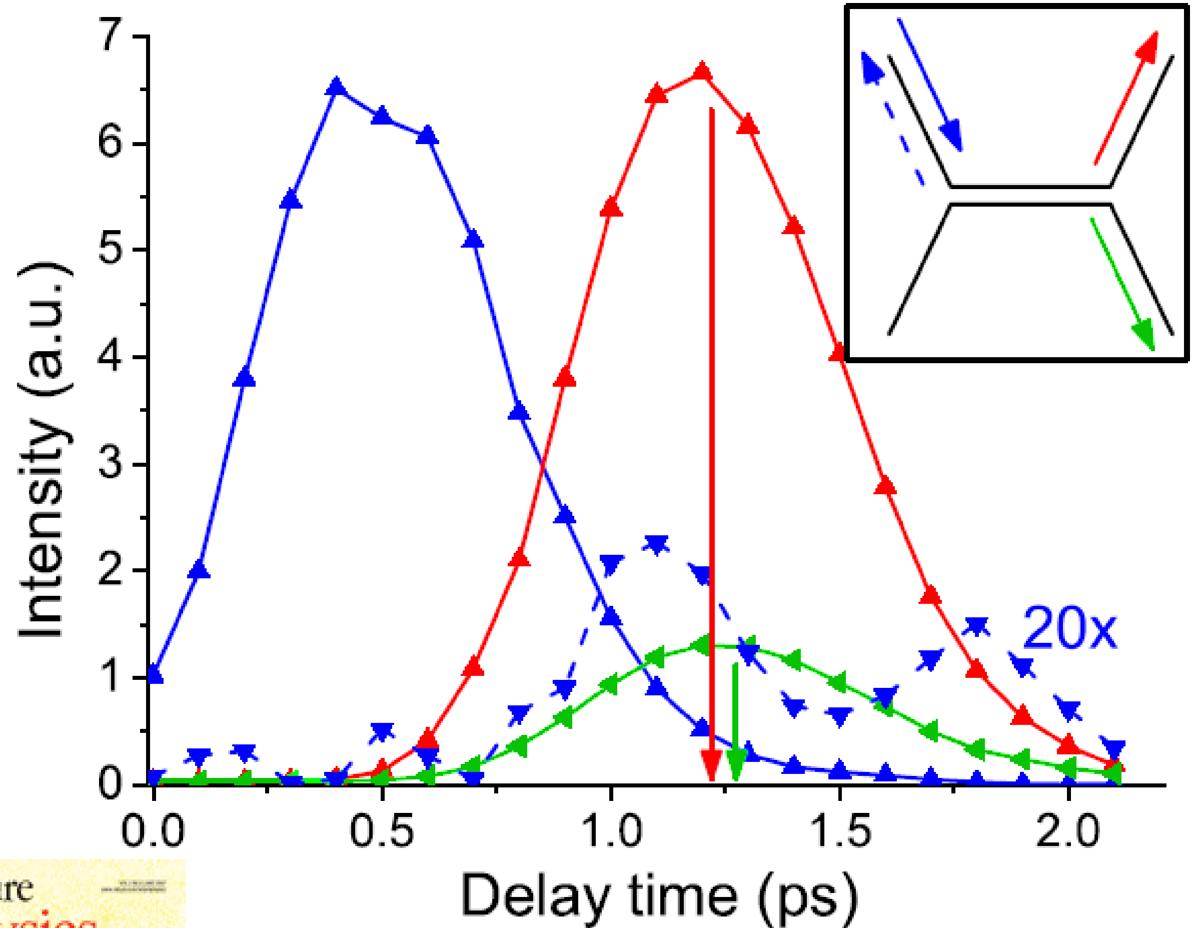
Wavepacket propagation vizualized in real space

k-space tracking



Evolution wavepackets visualized in reciprocal space

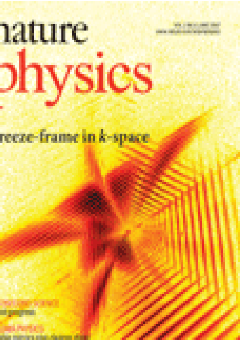
Time-dependence eigenstate amplitudes



Spliting ratio output waveguides: 1:5

Output pulses: 50±10 fs difference

Reflection into input waveguide: ~2%



Passive filter analyzed using real and reciprocal space

R.J.P. Engelen, et al., Nature Physics **3**, 401 (2007)

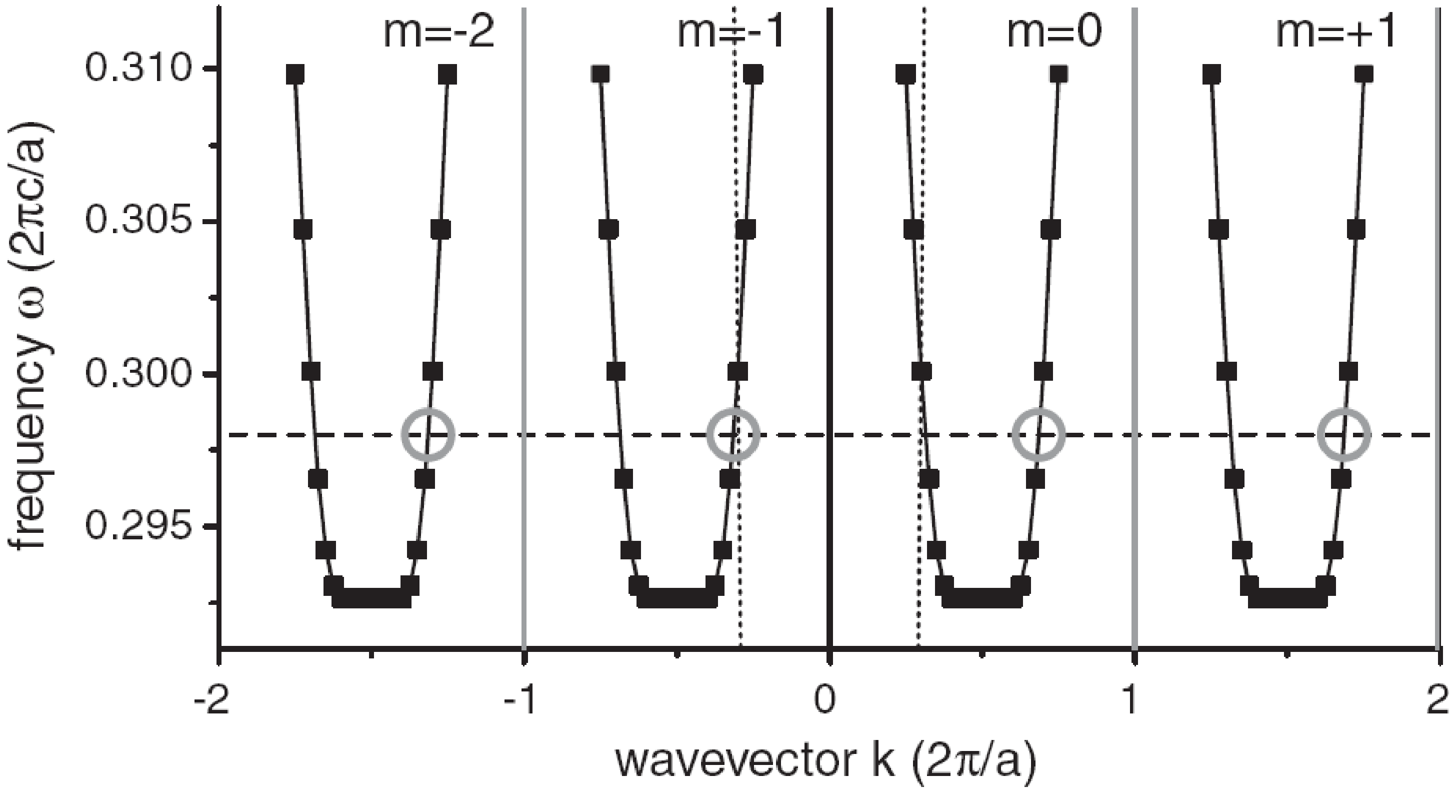
Evanescent field of a photonic Bloch mode

Photonic Bloch mode

Bloch mode:

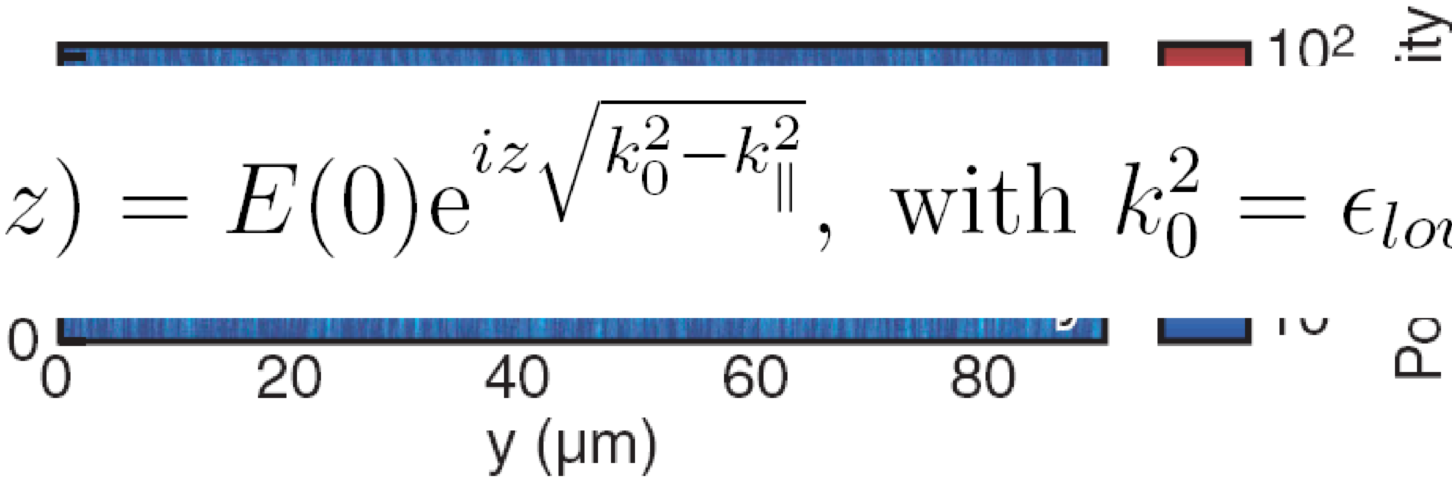
$$\psi(x, y, z) = u_k(x, y, z) \exp(iky)$$

$$u_k(x, y, z) = u_k(x, y + a, z)$$

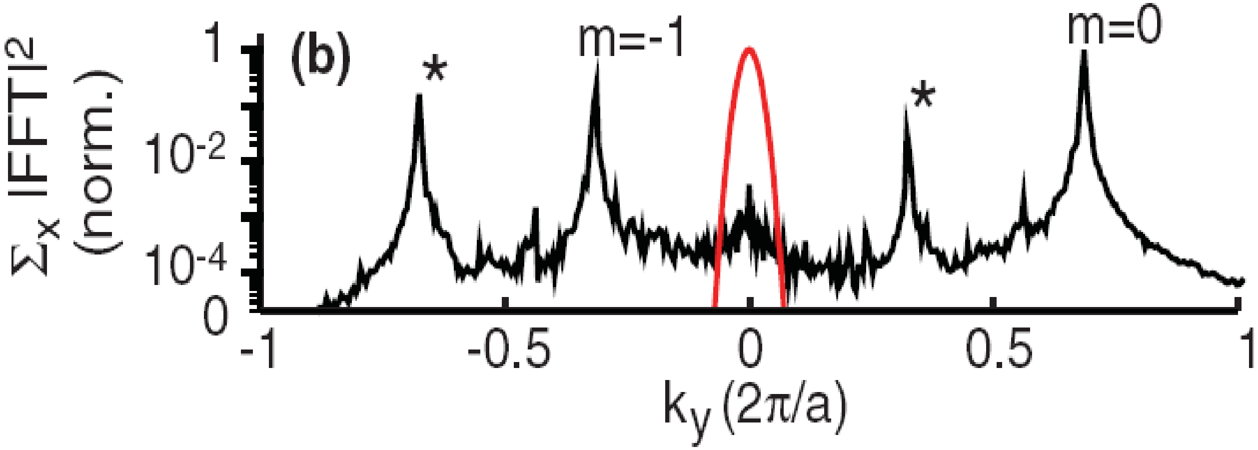


Separating Bloch harmonics

Light in a photonic crystal waveguide

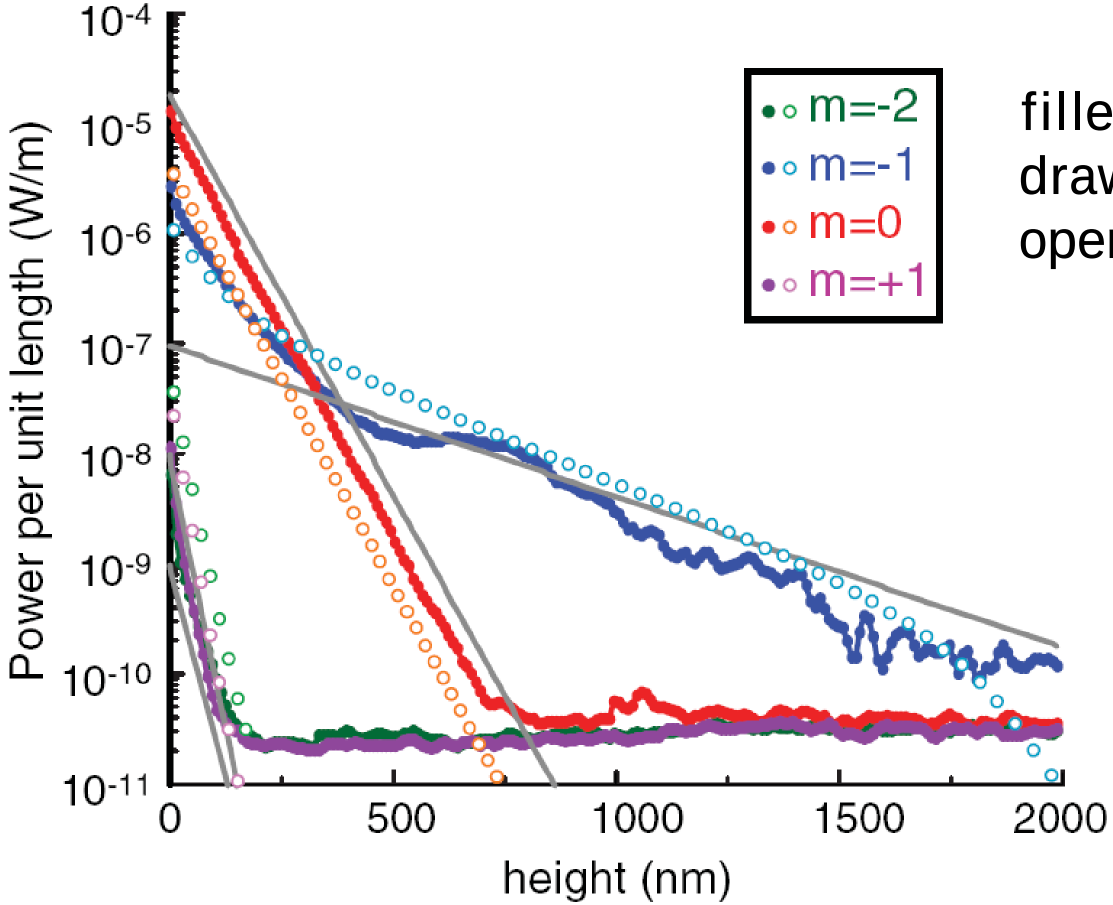


$$E(z) = E(0)\mathrm{e}^{iz\sqrt{k_0^2 - k_\parallel^2}}, \text{ with } k_0^2 = \epsilon_{low}\frac{\omega^2}{c^2}$$



See also: S.I. Bozhevolnyi, *et al*., *Phys.Rev.B* **66**, 235204 (2002).

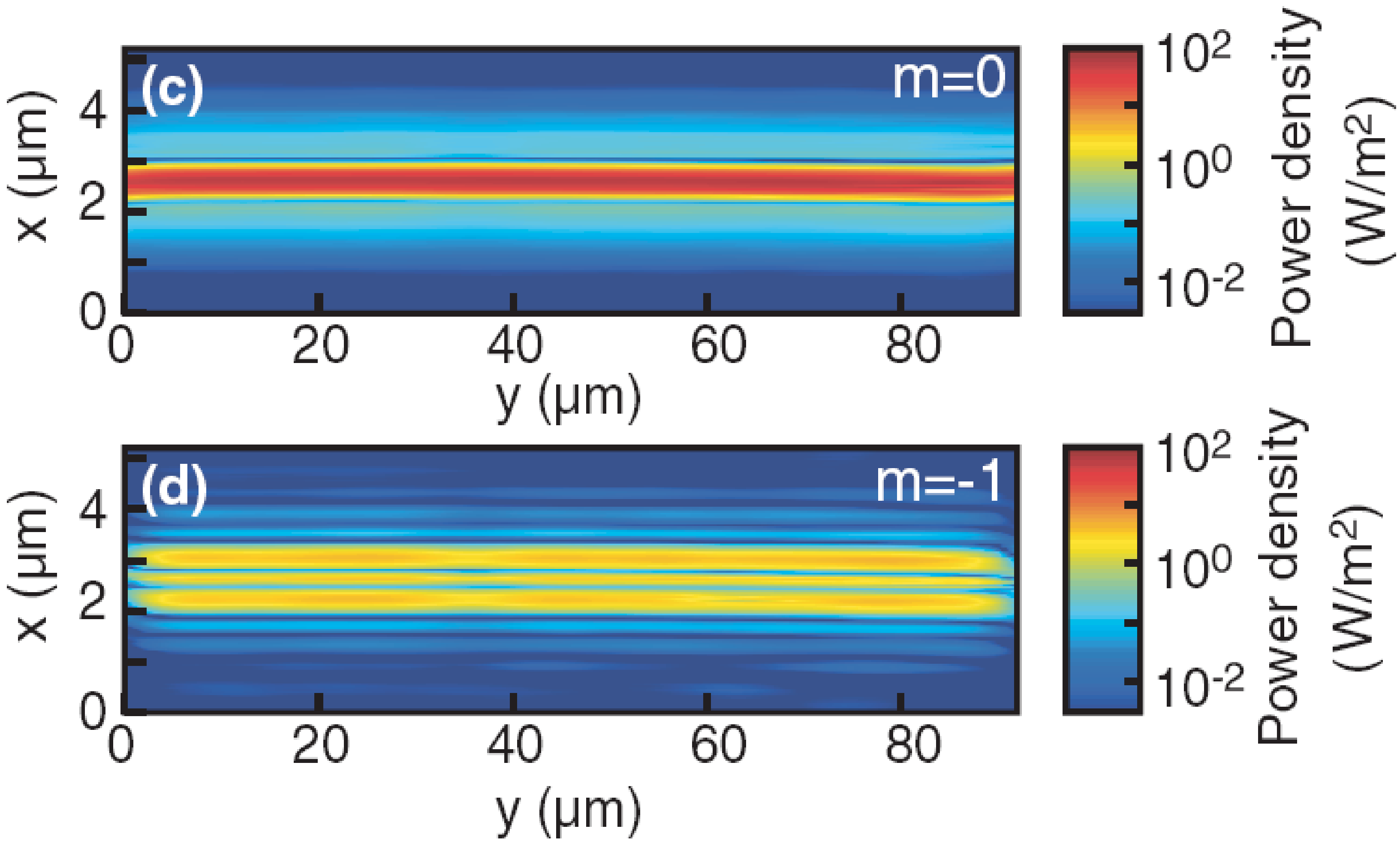
Evanescent decay Bloch harmonics



filled symbols: exp.
drawn lines: ´normal´ decay
open symbols: 3D FDTD calc.

Each Bloch harmonic has own exponential decay, but not quite

Lateral mode profiles Bloch harmonics



Each Bloch harmonic has own lateral profile: non-exp. decay

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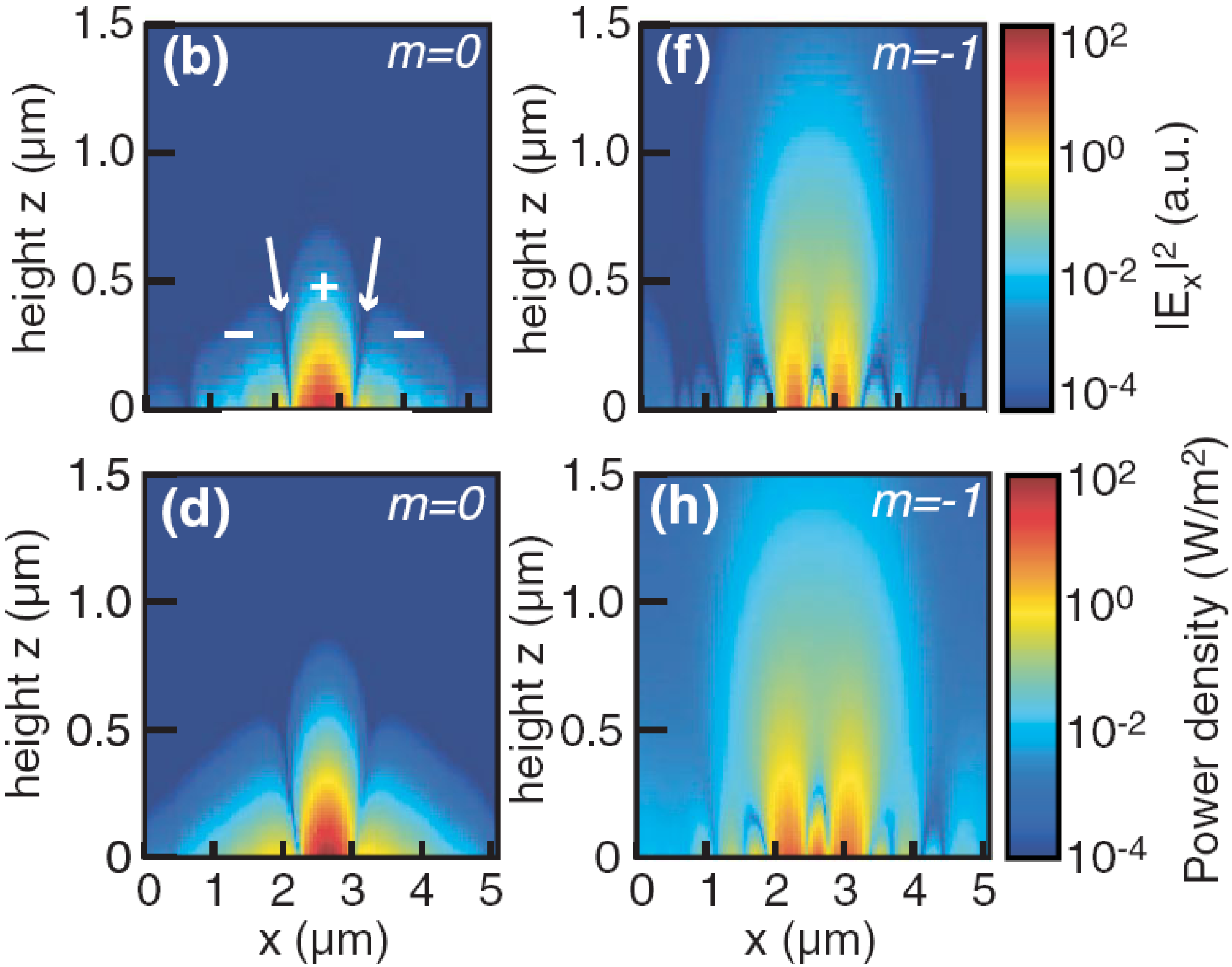
See also: H.Gersen *et al.*, *Phys.Rev.Lett* **94**, 123901 (2005)

Complex field of Bloch mode

Exp.

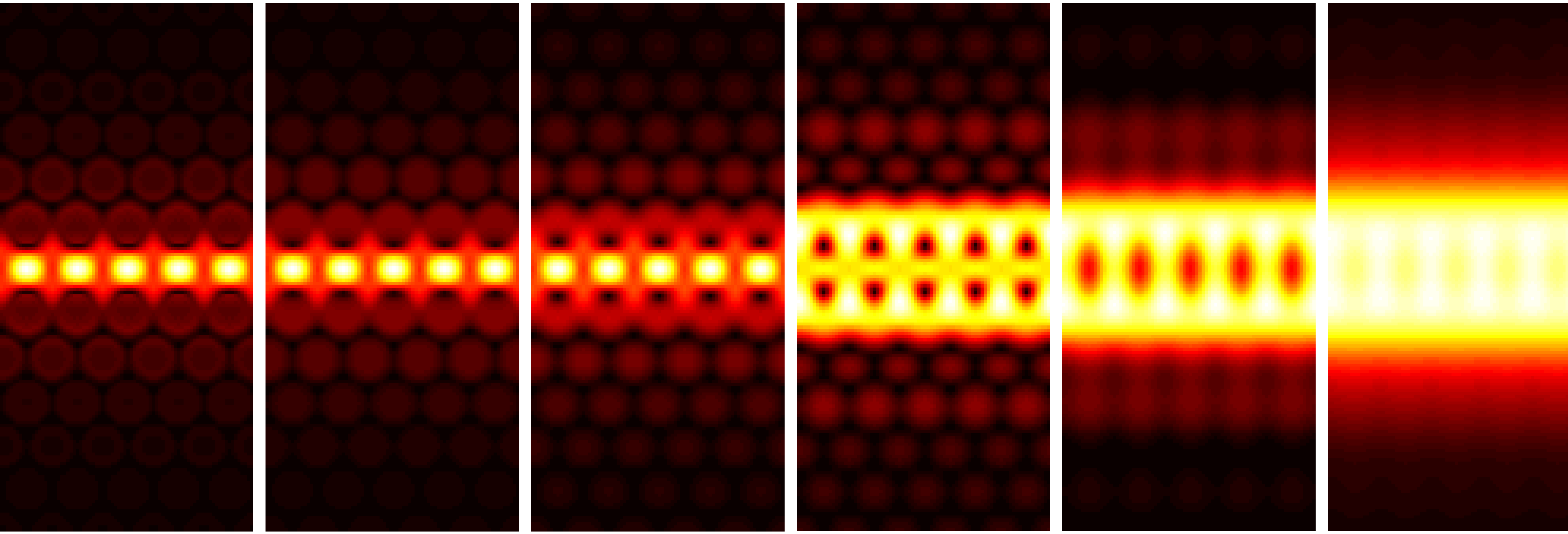
Calc.



R.J.P. Engelen, *et al.*, *Phys.Rev.Lett*. **102**, 023902 (2009)

Height evolution light field

center	10nm	100nm	330nm	560nm	790nm



2	1.1	0.45	0.045	0.002	0.001

maximum H_z Field strength

The amplitude pattern changes as a function of height

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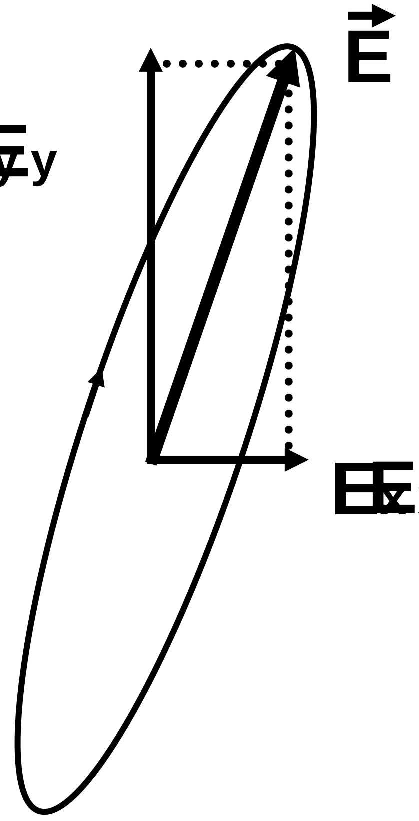
Polarization singularities

Polarization

$|E_y|\exp(i\phi_y) = E_y$

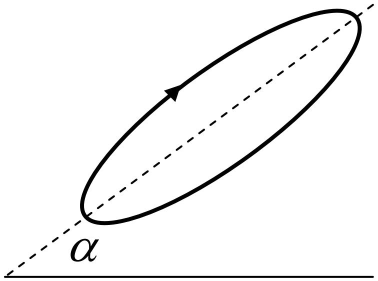


$E_x = |E_x|\exp(i\phi_x)$

The polarization state depends on the relative phase and amplitude of the 2 components

On the concept of imaging nanoscale vector fields:
K.G. Lee, *et al*., *Nature Photon*. **1**, 53 (2007)
& H. Gersen, *et al*., *ibid*, 242 (2007)

Polarization singularities



Three parameters describe the polarization ellipse:

1. Handedness
2. Eccentricity
3. Orientation angle α

If one of these parameters in undetermined we have a polarization singularity. Two types of polarization singularities:

• Handedness undetermined $\longrightarrow$ (Linear polarization) $\longrightarrow$ *L*–lines.

• α undetermined $\longrightarrow$ (Circular polarization) $\longrightarrow$ C-point.

N.B. at a polarization singularity, the state of polarization is well defined!

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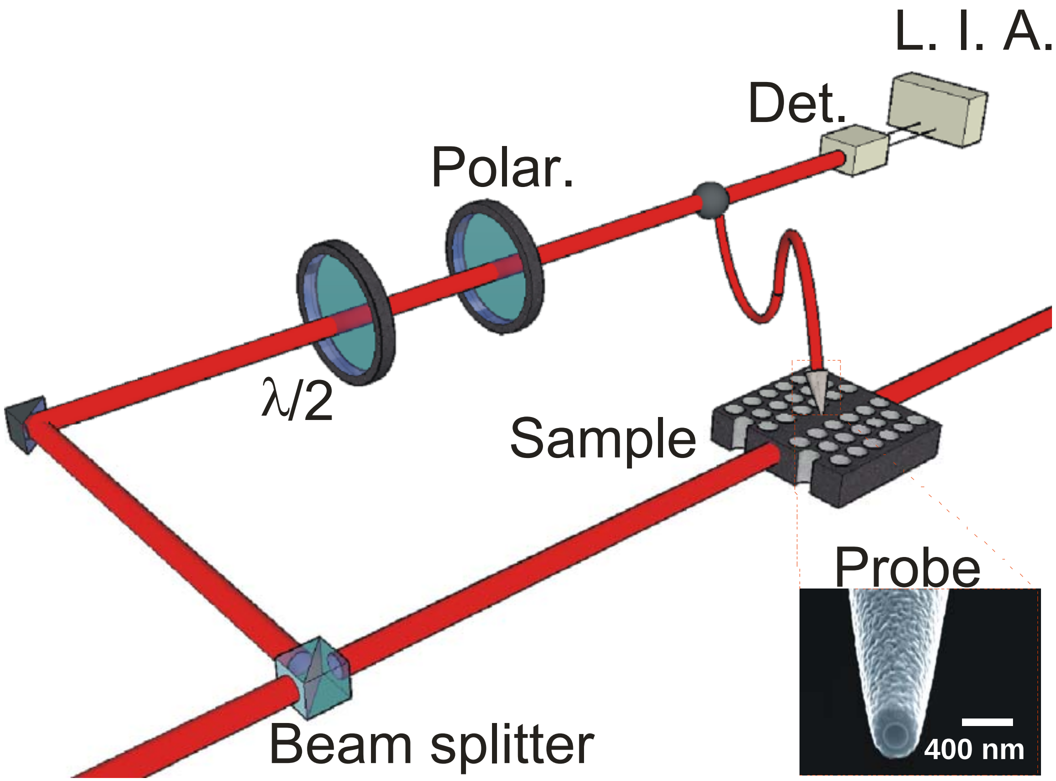
J. F. Nye and M. V. Berry, *Proc. R. Soc. A* 336, 165 (1974)

Separating in-plane field components



Control of polarization in reference branch yields sensitivity to field components of near field

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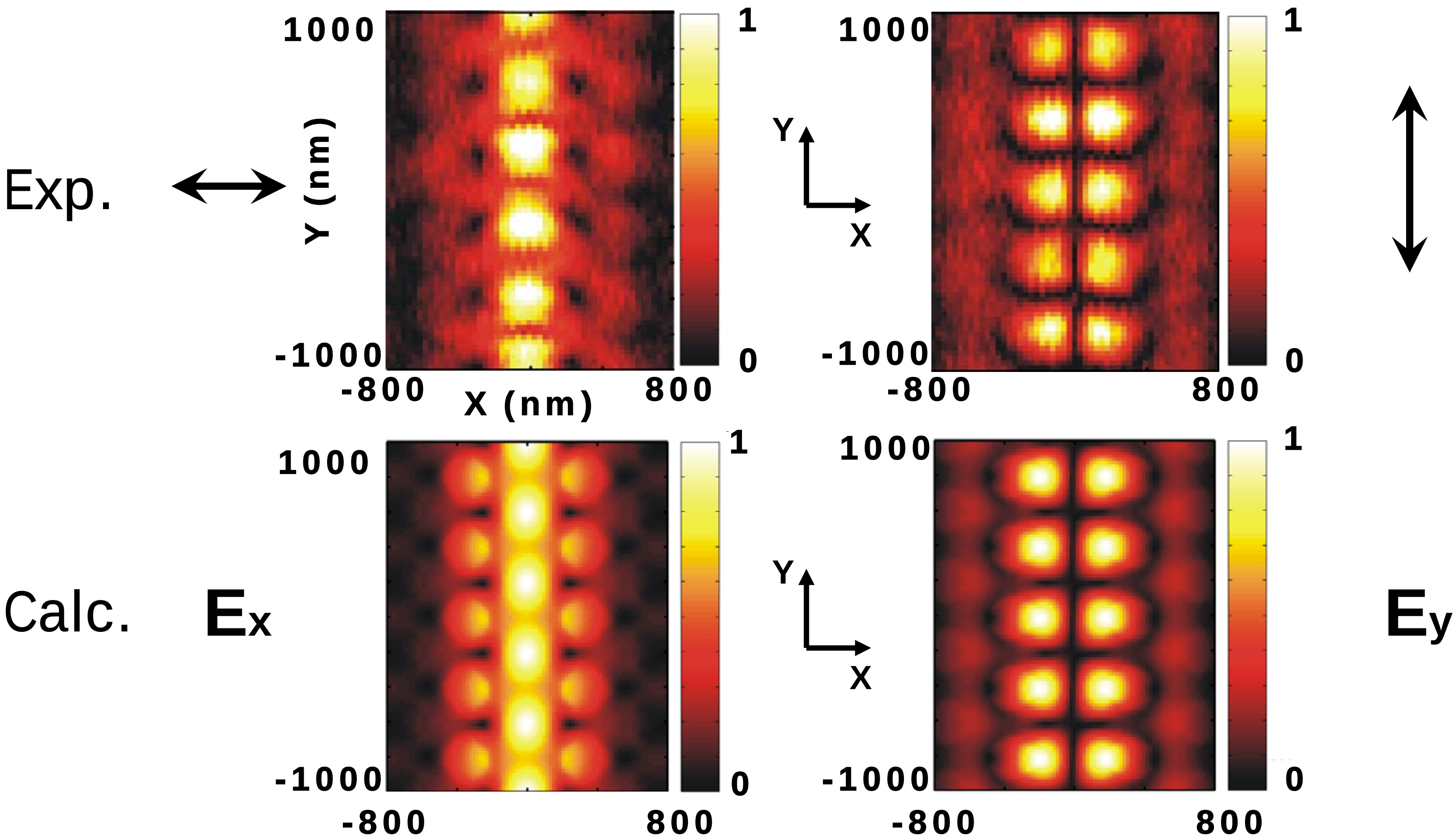
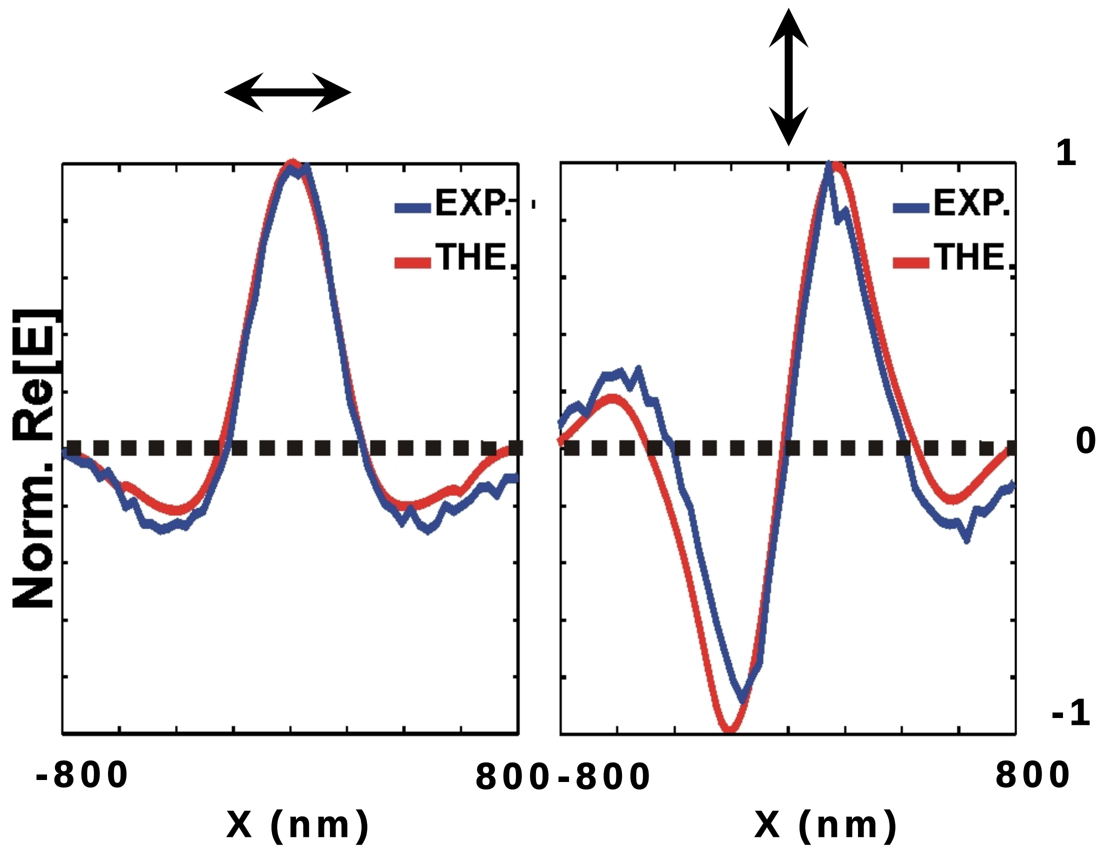
Orthogonal polarizations



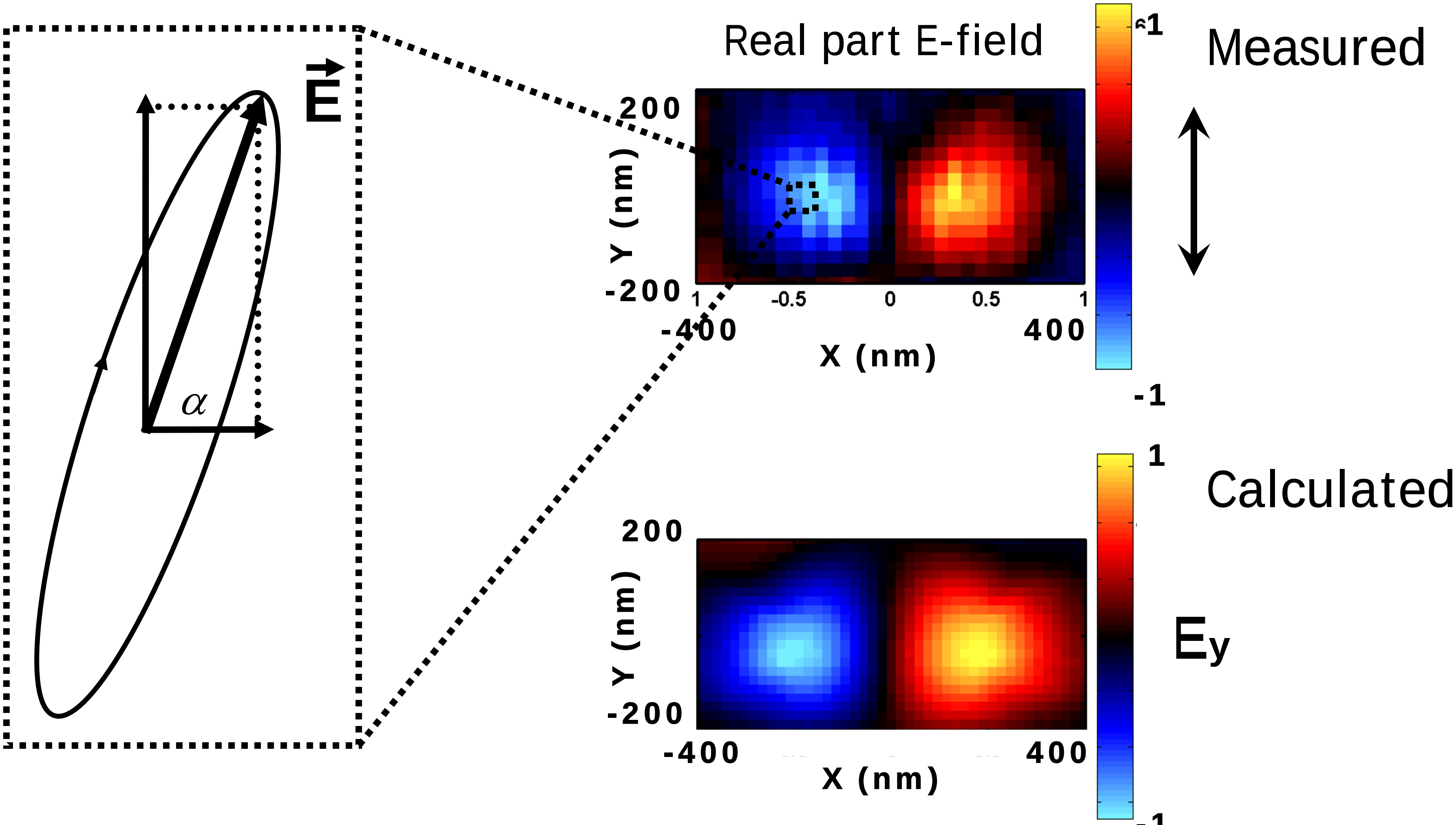
Vector field sensitivity

Cross section of real part of E



Symmetric and anti-symmetric pattern

Reconstructing the ellipse



Ellipse can be reconstructed for every position above structure

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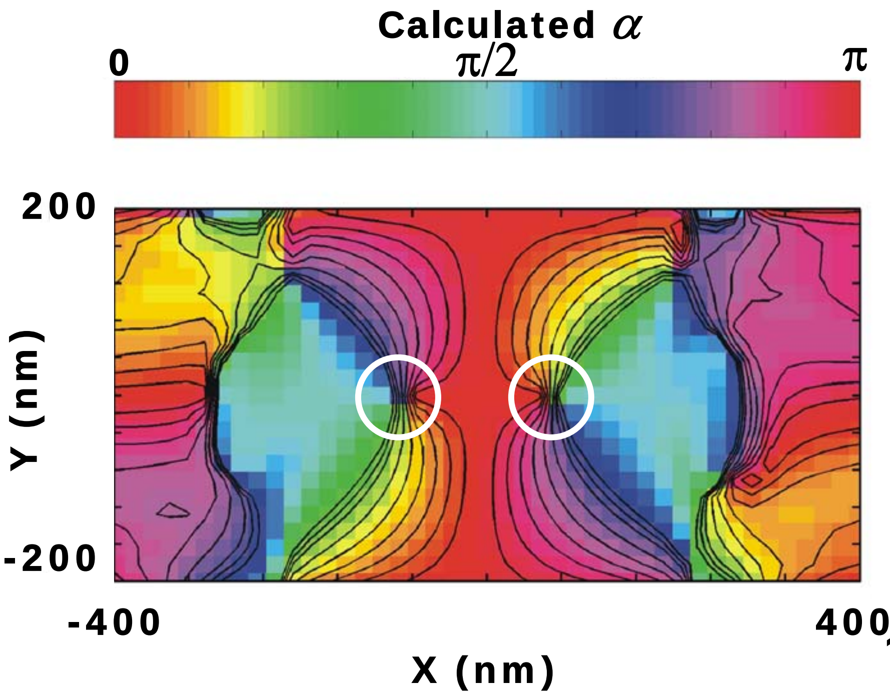
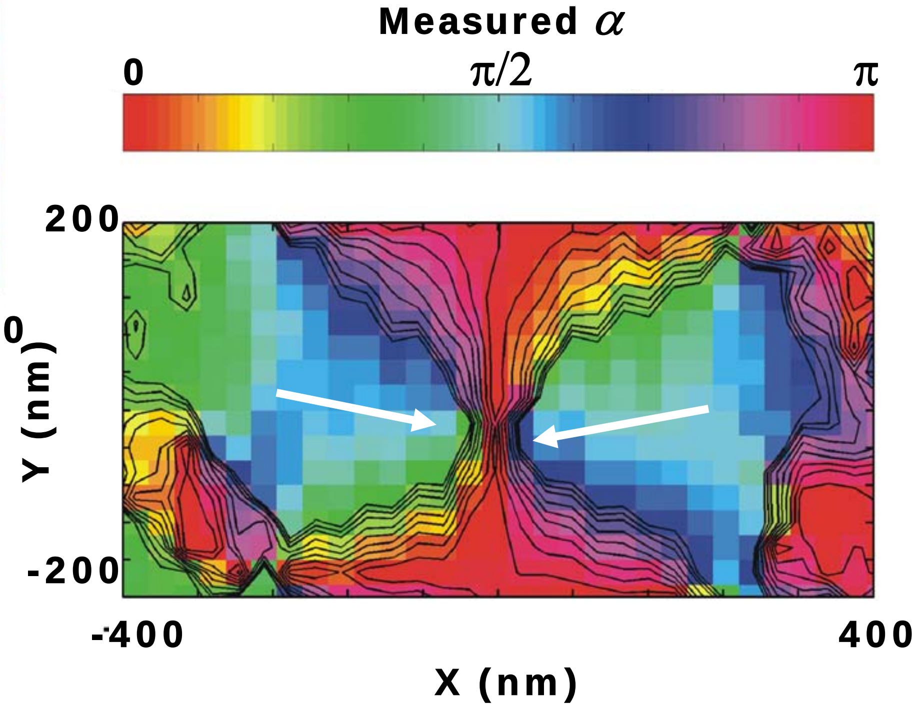
C-points at the nanoscale



Isogyres (lines with the same α)

Calculation: C-points separation ~150 nm



Left-hand C-point and Right-hand C-point

Measurement: C-points separation <200 nm

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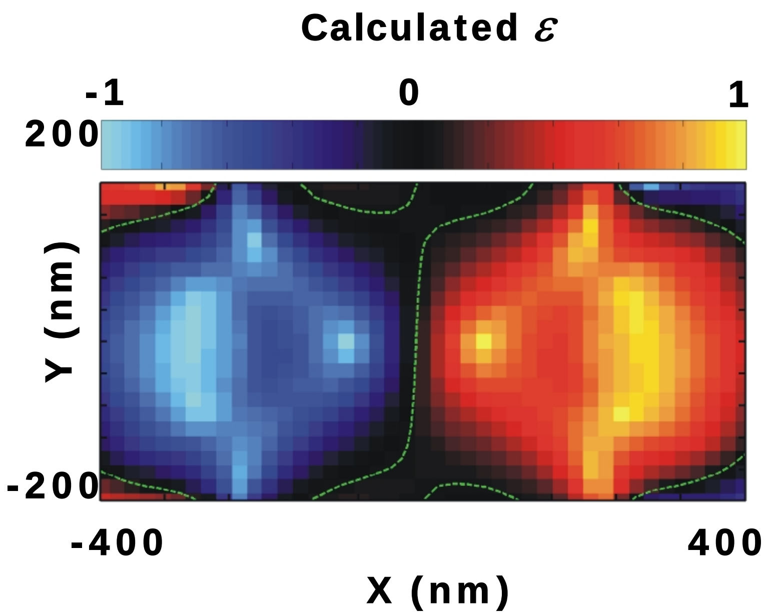
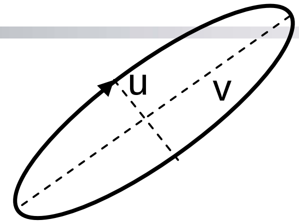
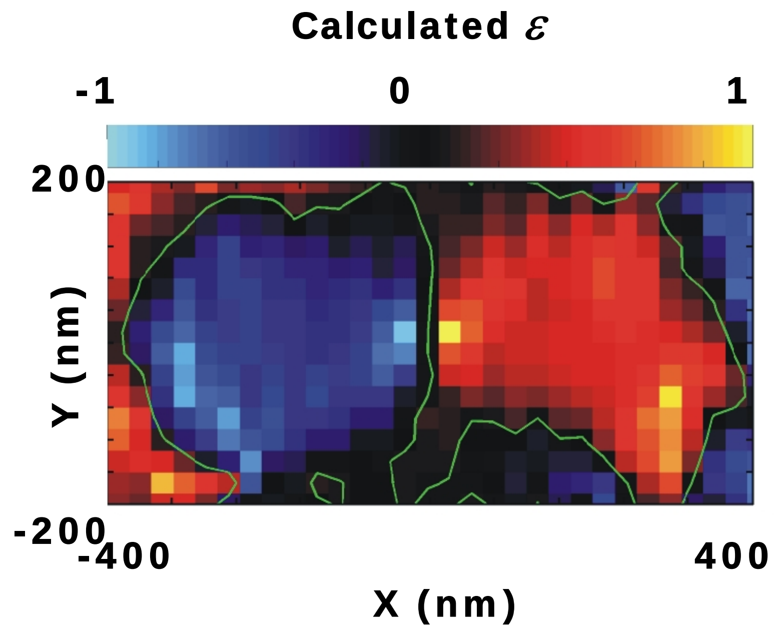
M. Burresi, *et al.*, *Phys.Rev.Lett.* **102**, 033902 (2009)

L-lines





$\varepsilon = \mp u/v$



Green lines show the positions where the eccentricity is 0 => handedness is not defined=> L-lines

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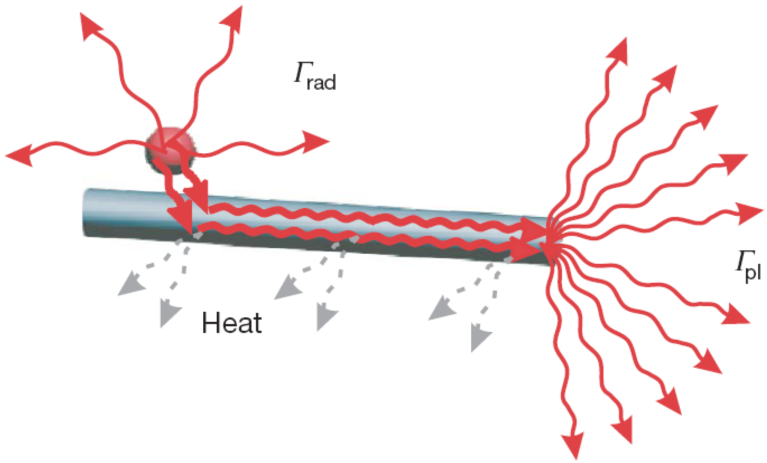
Adiabatic coupling to plasmonic nanowires

Plasmonics: confining light @ nanoscale

Elements of plasmonics



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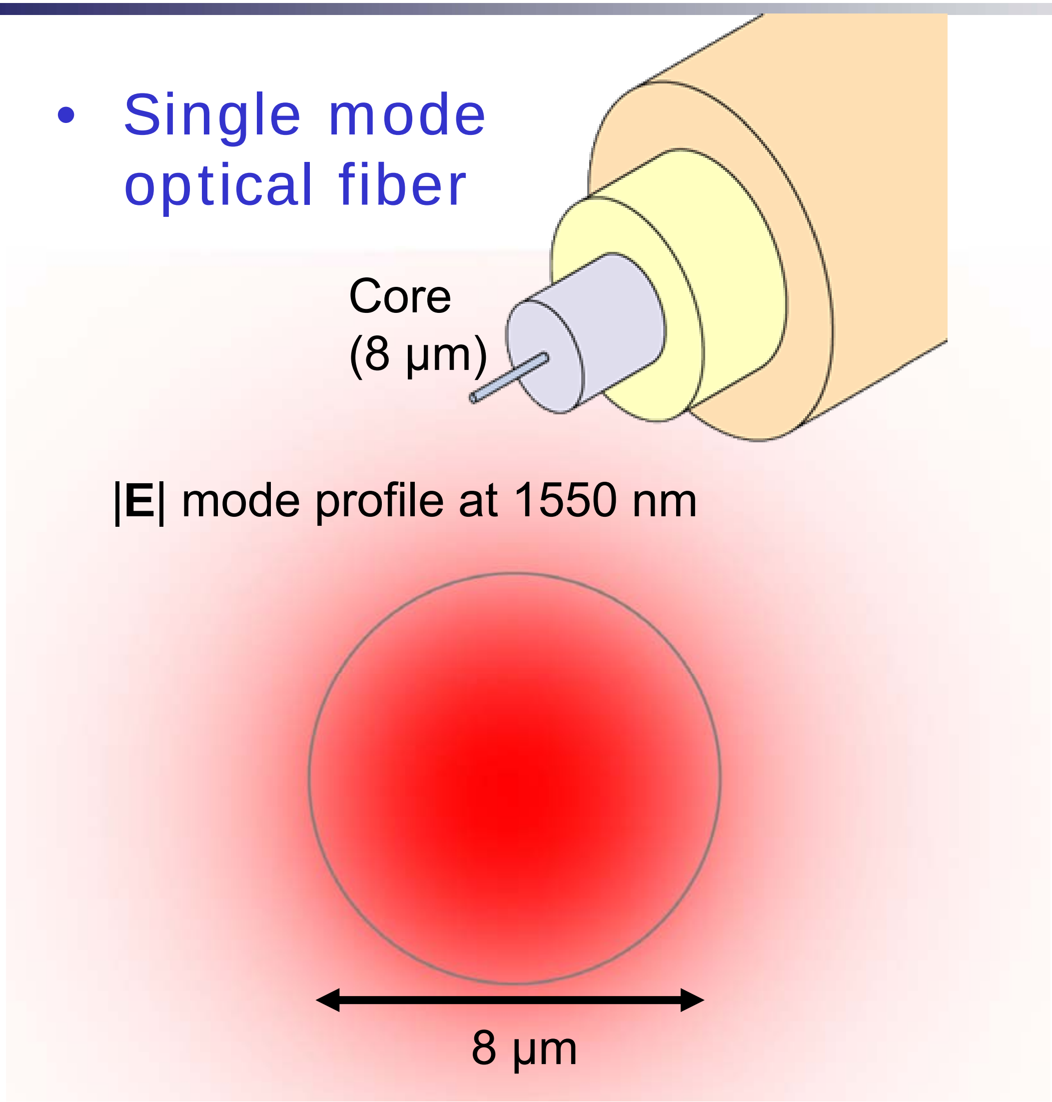
*Ebbesen et al., Physics Today **44** (2008)*
*Akimov et al., Nature **450** (2007)*

Coupling problem in plasmonics

- Single mode optical fiber



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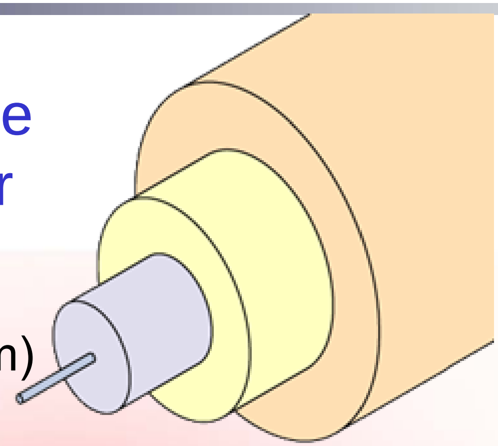
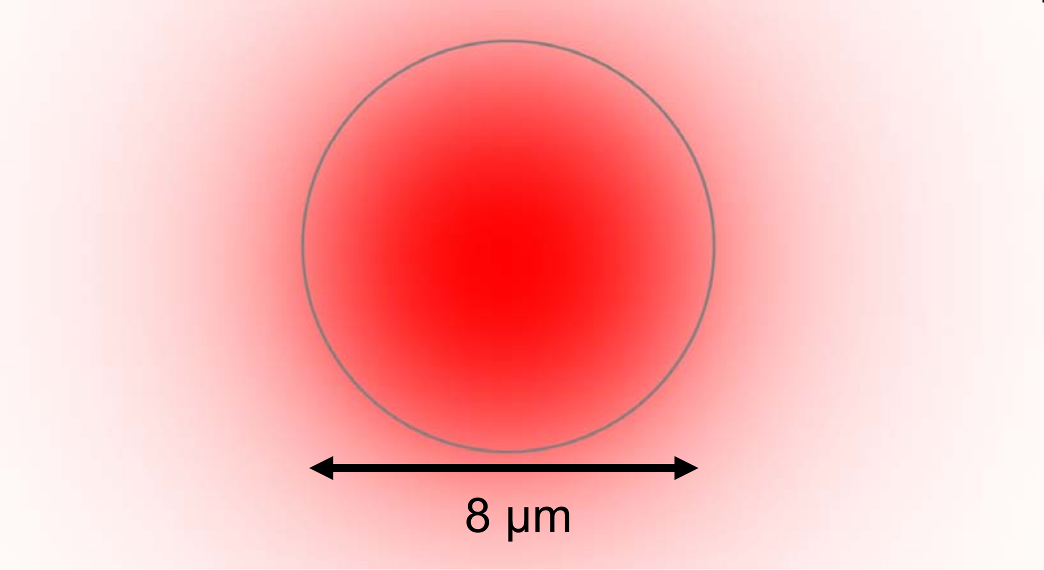
Coupling problem in plasmonics

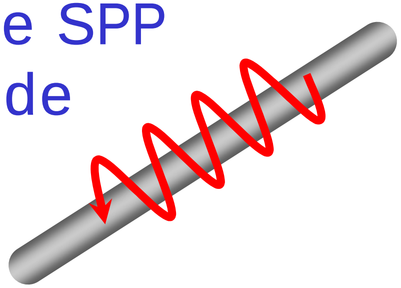
- Single mode optical fiber



|**E**| mode profile at 1550 nm



- Nanowire SPP waveguide



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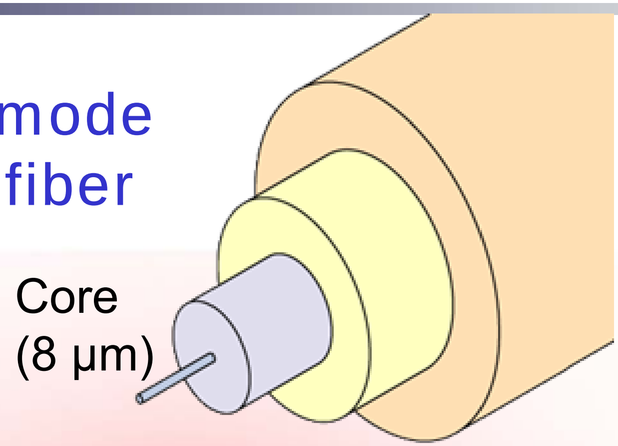
Coupling problem in plasmonics

- Single mode optical fiber



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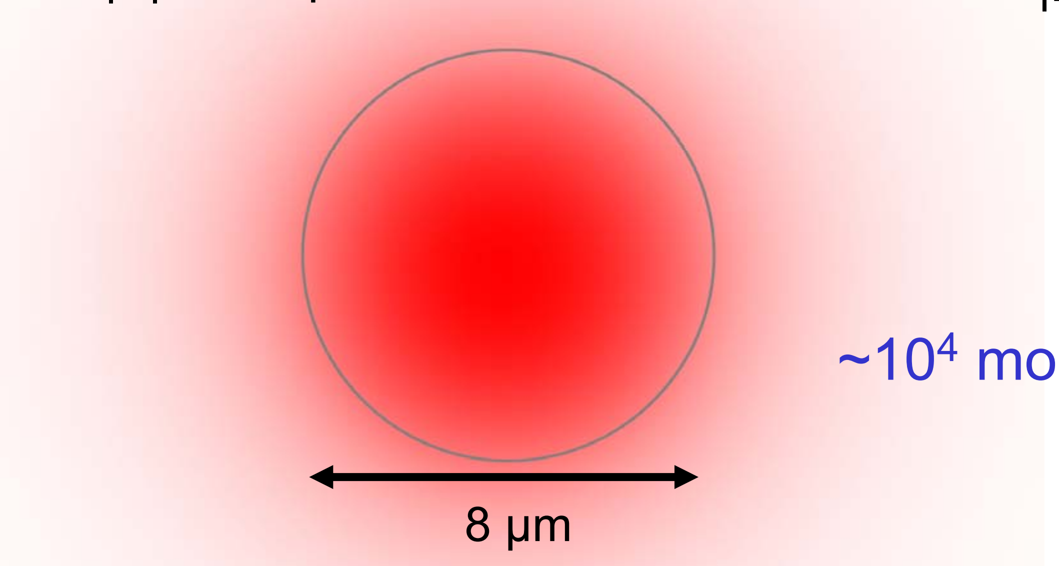
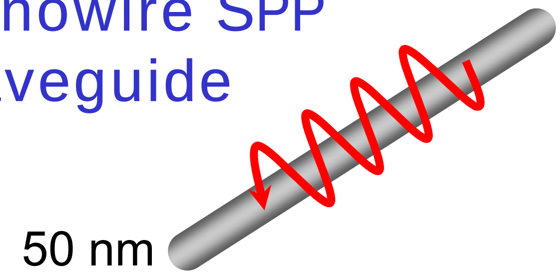


- Nanowire SPP waveguide



|**E**| mode profile at 1550 nm

~10^4 mode area size mismatch

50 nm

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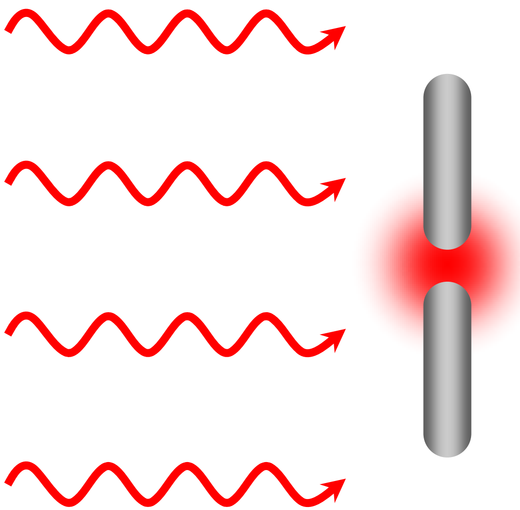
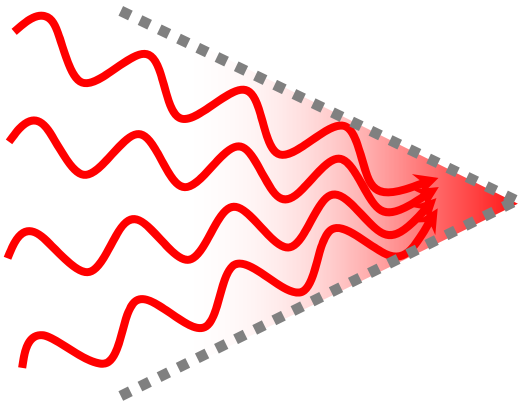
How to bring light to the nanoscale

- Resonant nanoantennas



- Engineering Q, V, σ
- Bandwidth given by Q

- Gradual mode transformation



- Engineering adiabaticity
- Inherently broadband
- Suitable for guided waves

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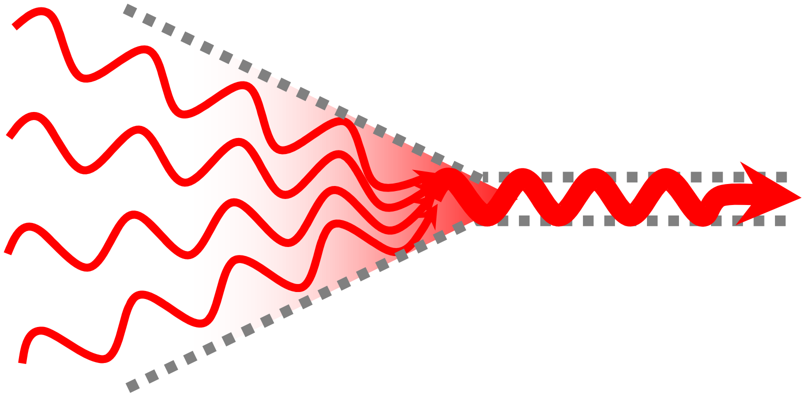
How to bring light to the nanoscale

- Resonant nanoantennas

- Engineering Q, V, α
- Bandwidth given by Q

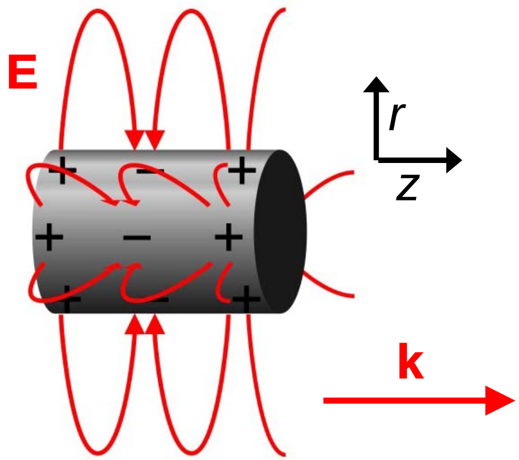
- Gradual mode transformation

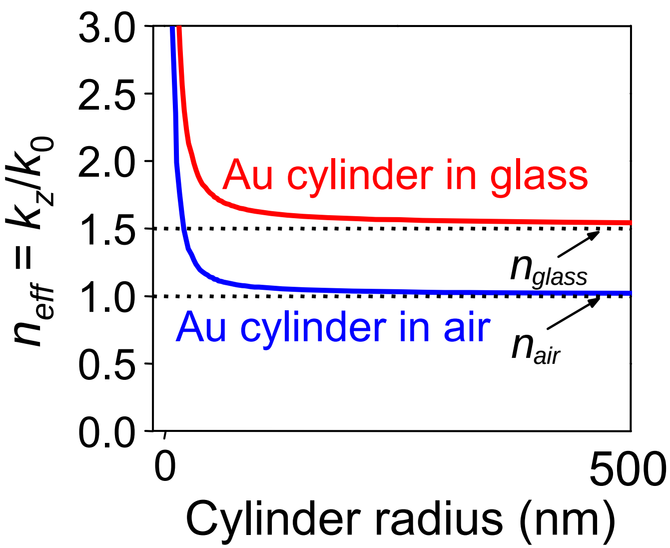


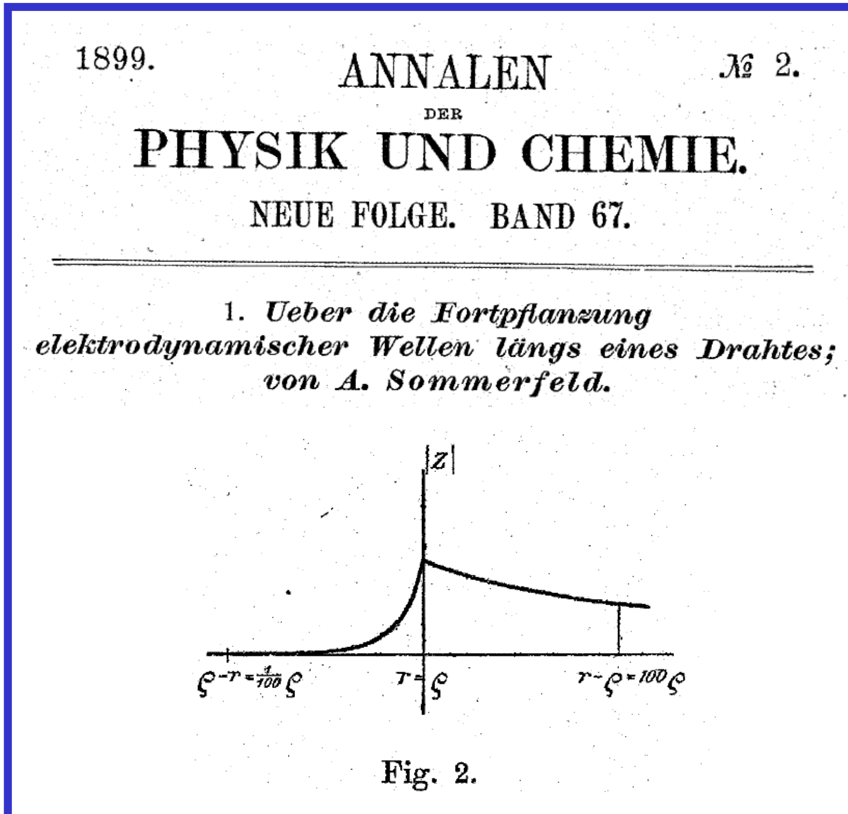
- Engineering adiabaticity
- Inherently broadband
- Suitable for guided waves
- Efficient coupling to highly confined SPPs

Cylindrical metal waveguides

Fundamental SPP mode on cylinder:







1899. ANNALEN № 2.

DER

PHYSIK UND CHEMIE.

NEUE FOLGE. BAND 67.

1. *Ueber die Fortpflanzung elektrodynamischer Wellen längs eines Drahtes; von A. Sommerfeld.*

Fig. 2.

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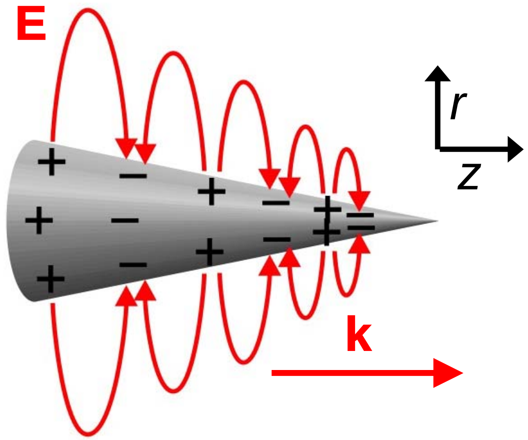
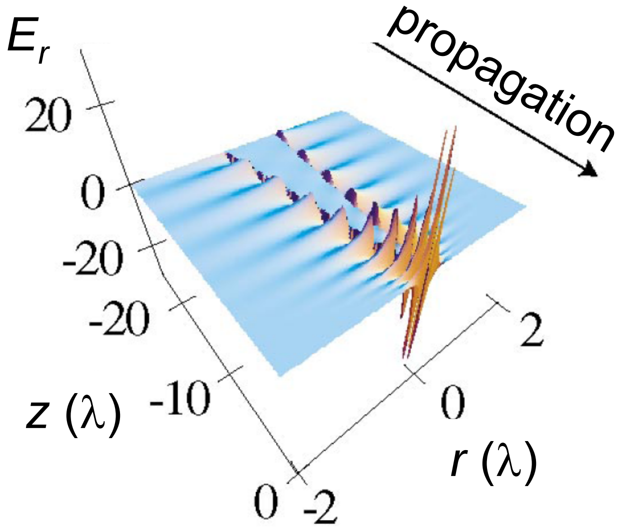
Surface plasmon nanofocusing

- Focusing in tapered metal cylinder



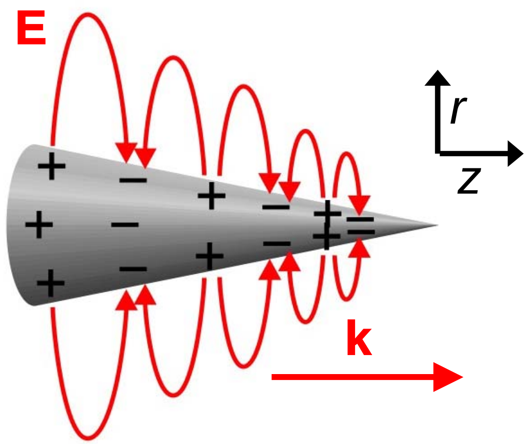


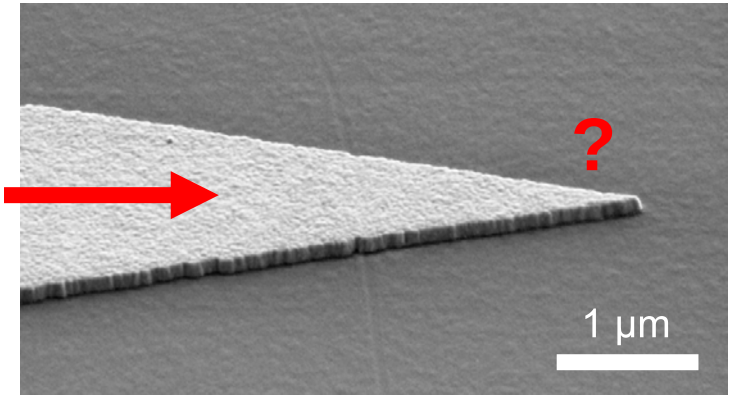
Stockman, PRL ***93****, 137404 (2004)*

- Strong confinement and field enhancement near taper tip
- Focusing of fundamental cylindrical SPP mode

Surface plasmon nanofocusing

- Focusing in tapered metal cylinder





- Same effect in laterally tapered metal film on dielectric substrate?

Weeber et al., PRB 64, 045411 (2001)
Yin et al., Nano Lett. 5, 1399 (2005)
Zia et al., PRB 74, 165415 (2006)
} SPPs at metal/air interface

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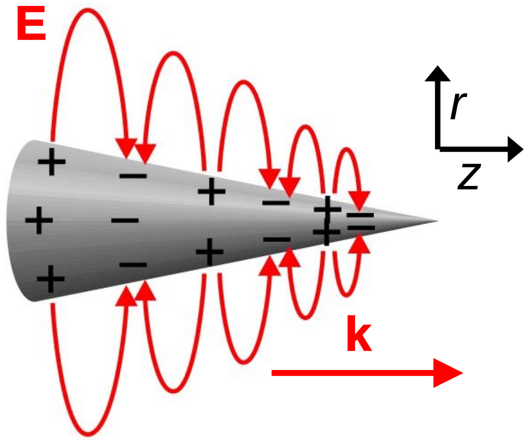
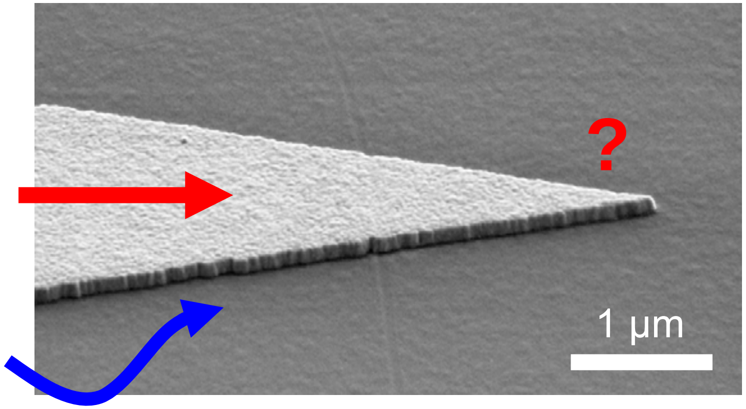
Surface plasmon nanofocusing

- Focusing in tapered metal cylinder





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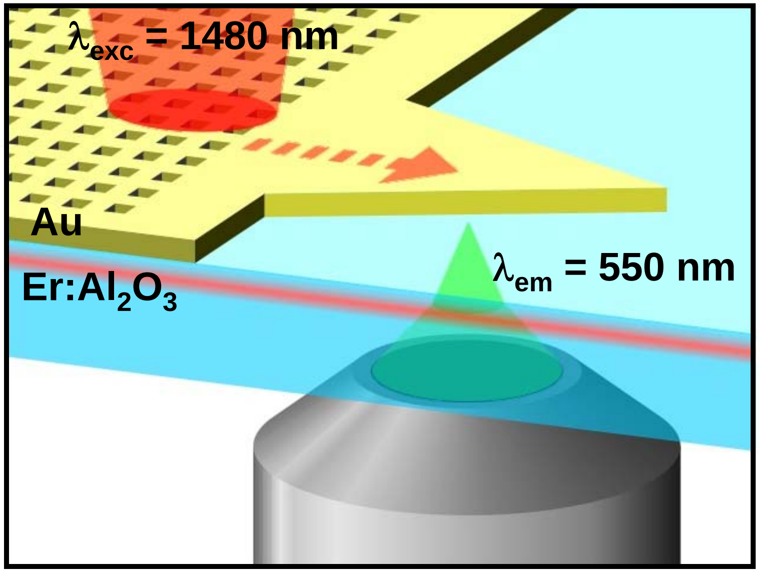
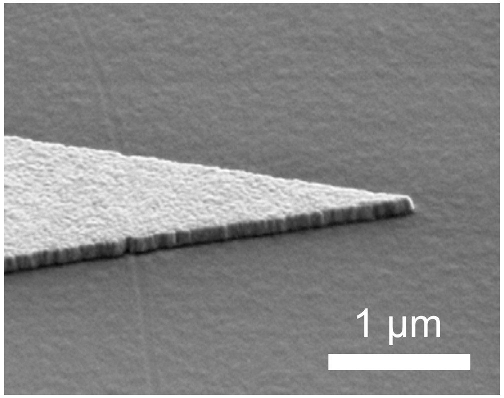
Yin et al., Nano Lett. 5, 1399 (2005)
Zia et al., PRB 74, 165415 (2006)
} SPPs at metal/air interface

Experimental

- **Infrared SPPs** (λ_{exc}=1480 nm) excited **along Au / Al_2O_3 interface**
- ***Geometry:*** Tapered Au waveguide: 12 µm wide, 60 µm long

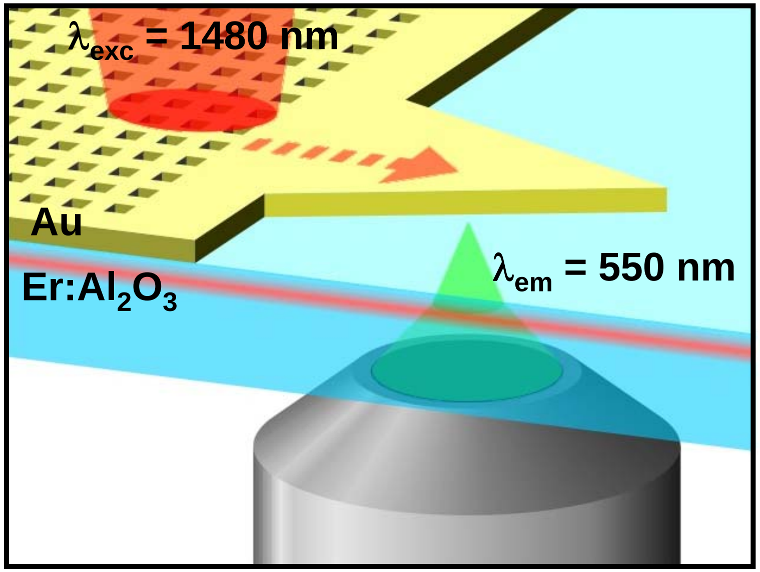


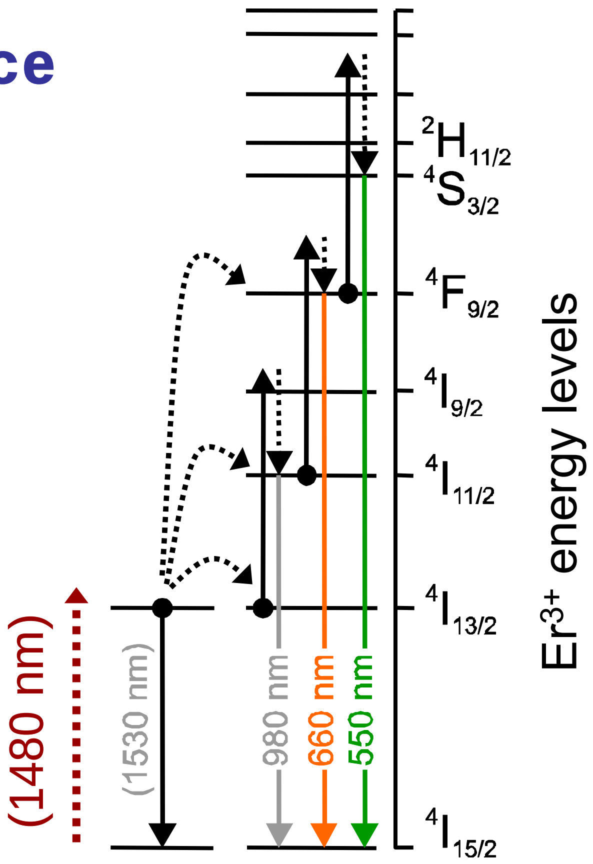
Au film thickness: 100 nm
Apex diameter: ~60 nm



Experimental

- **Infrared SPPs** (λ_{exc}=1480 nm) excited **along Au / Al_2O_3 interface**
- ***Detection:*** Nonlinear upconversion of Er ions implanted at 35 nm from Au





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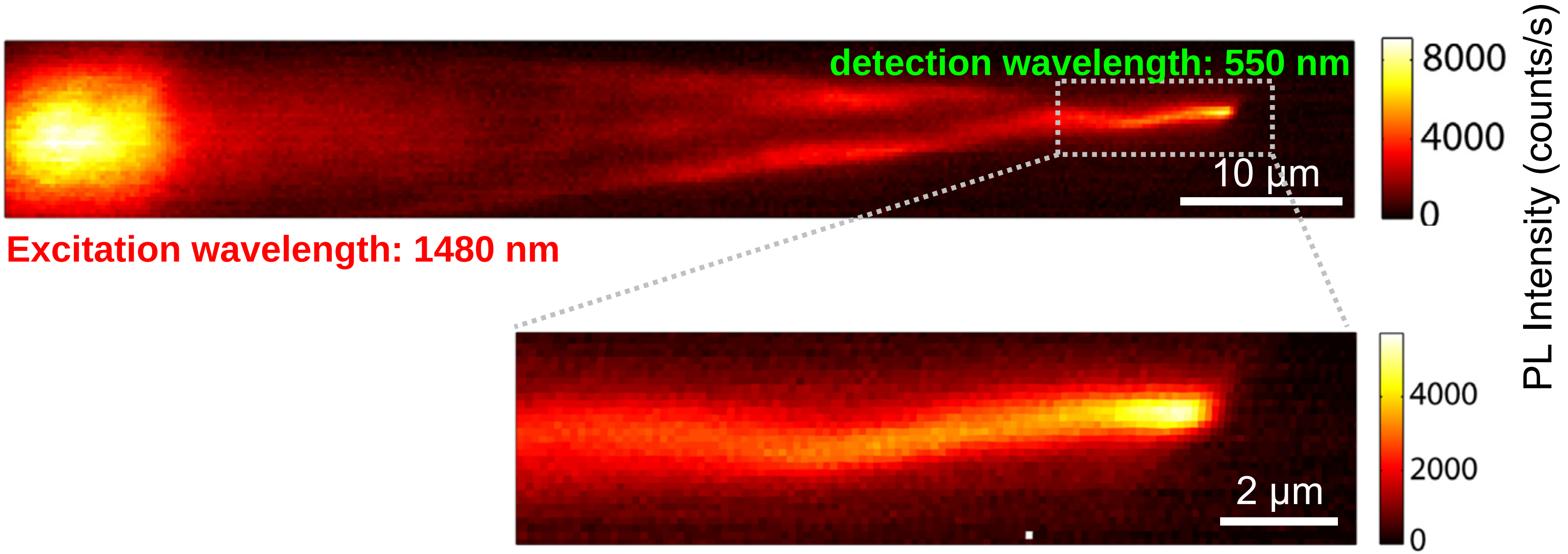
SPP focusing in tapered waveguide



- Concentration to taper tip observed (waveguide width <400 nm)
- No sign of SPP waveguide cutoff

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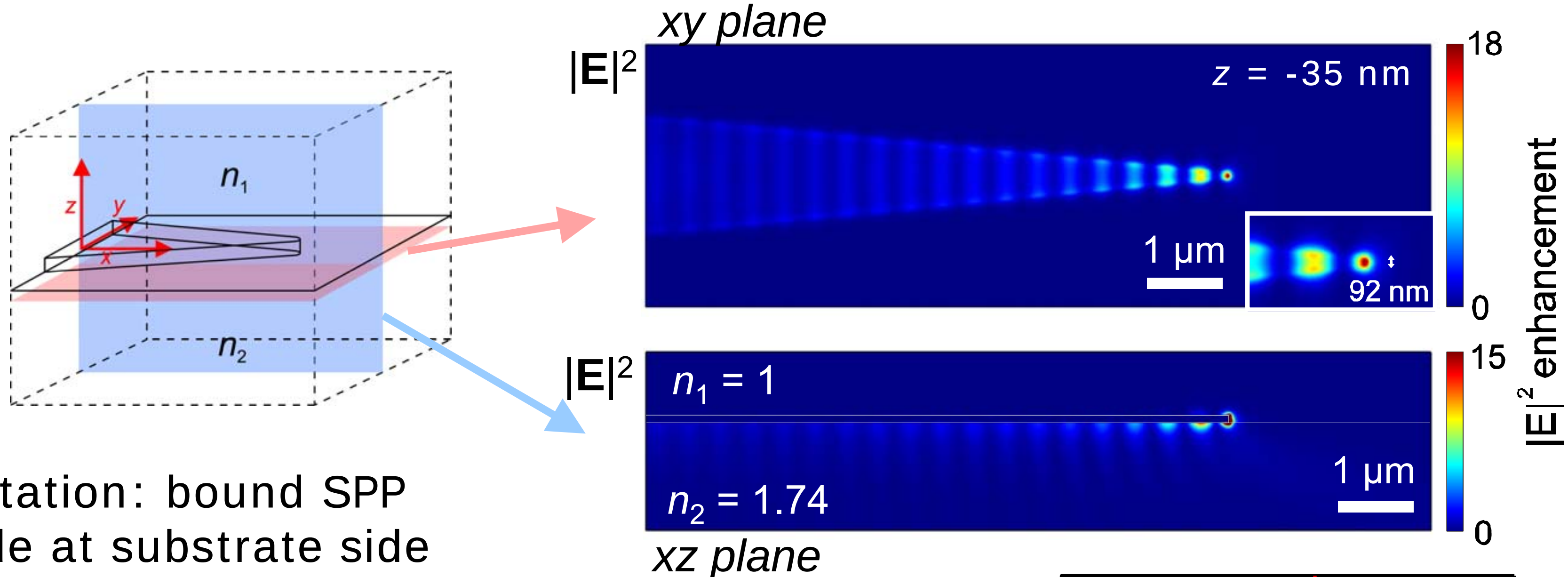
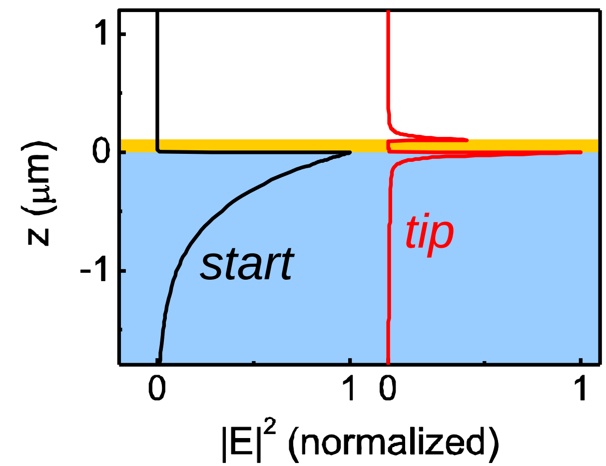
Verhagen et al., Nano Lett. ***7****, 334 (2007)*
Verhagen et al., Opt. Express ***16****, 45 (2008)*

FDTD Simulations final 8 μm of taper



excitation: bound SPP mode at substrate side



- Nanofocusing predicted: at 10 nm from tip 100 x $|\mathbf{E}|^2$ enhancement
- 3D Subwavelength confinement: 1.5 μm light focused to 92 nm $\rightarrow$ **(λ/16)**

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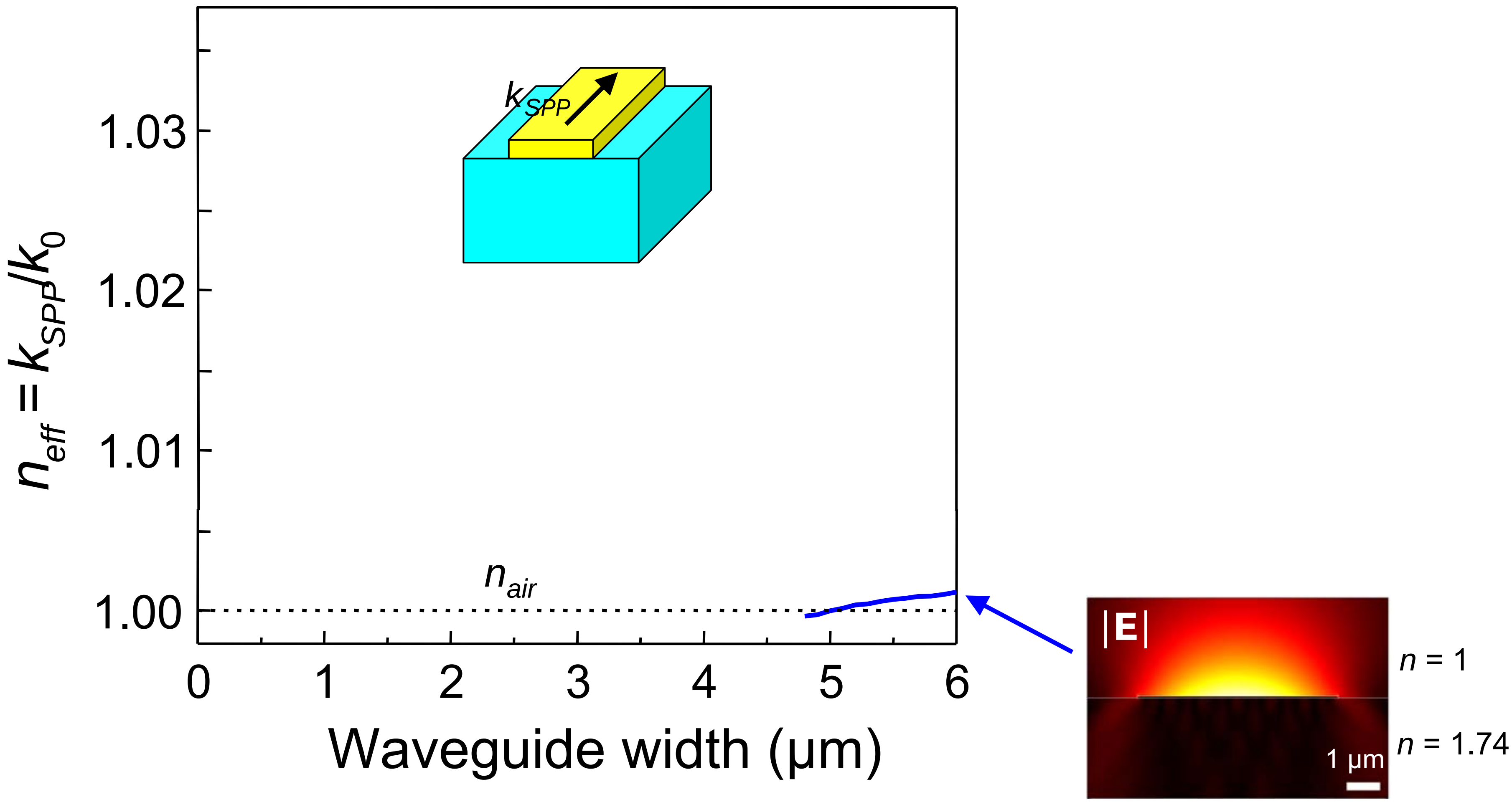
Verhagen et al., Opt. Express ***16****, 45 (2008)*

SPP modes in stripe waveguides



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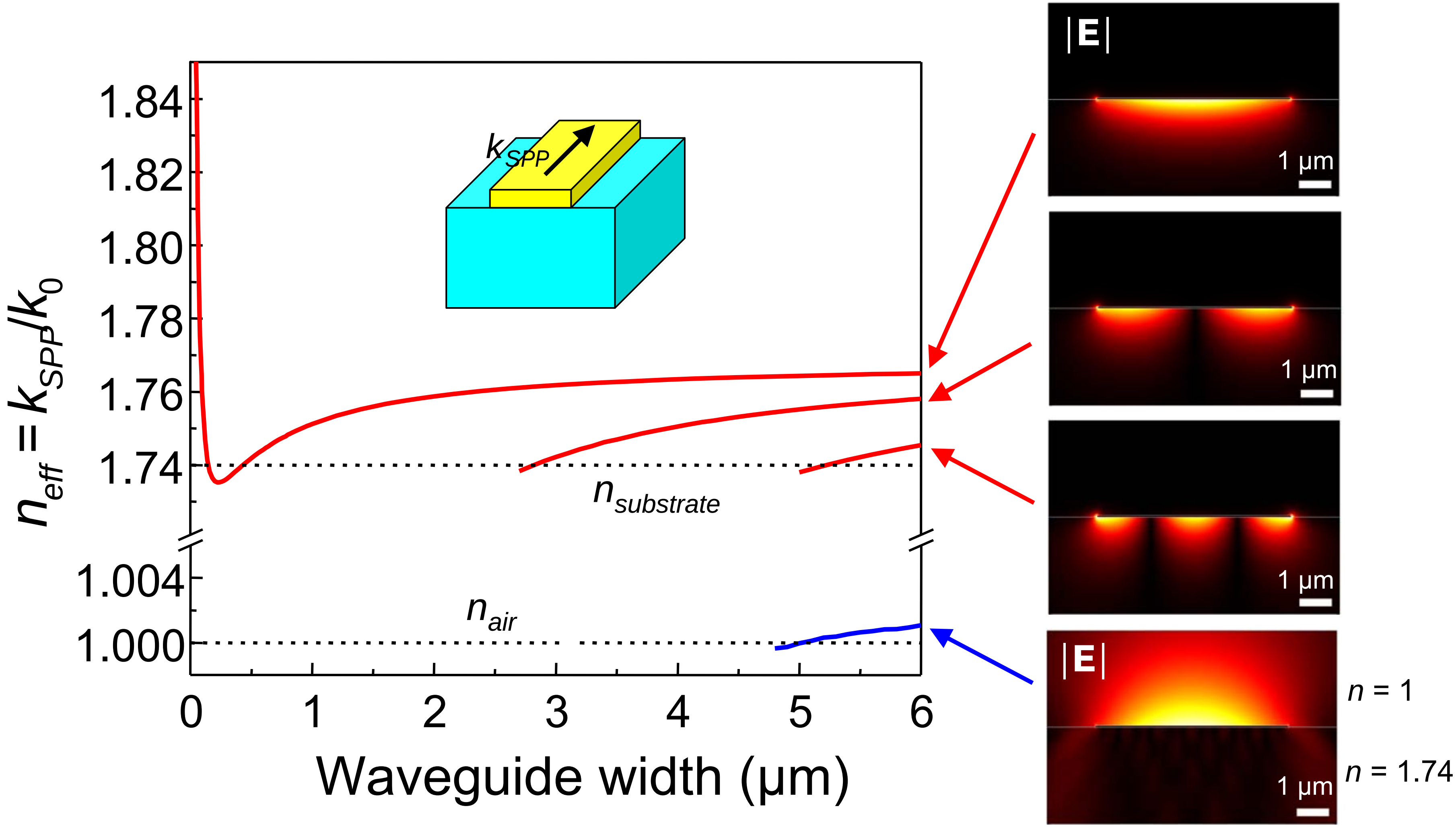
SPP modes in stripe waveguides



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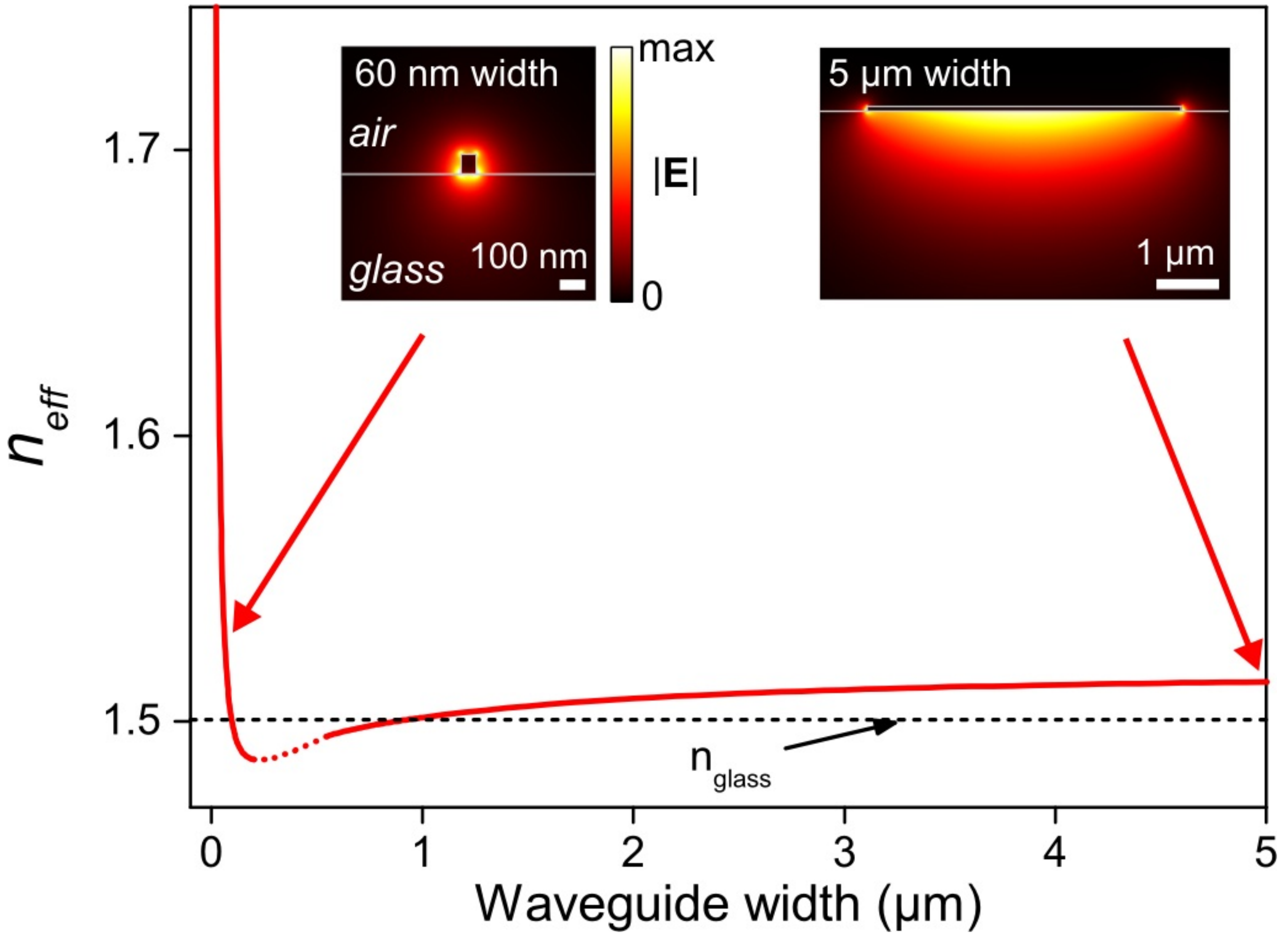
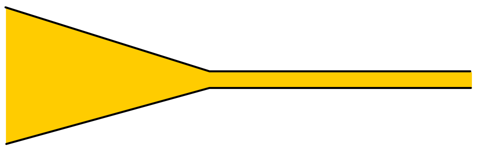
Nanowire coupling



- Mode profile at start of taper ensures good excitability
- Taper can serve as coupling element to excite nanowire SPP



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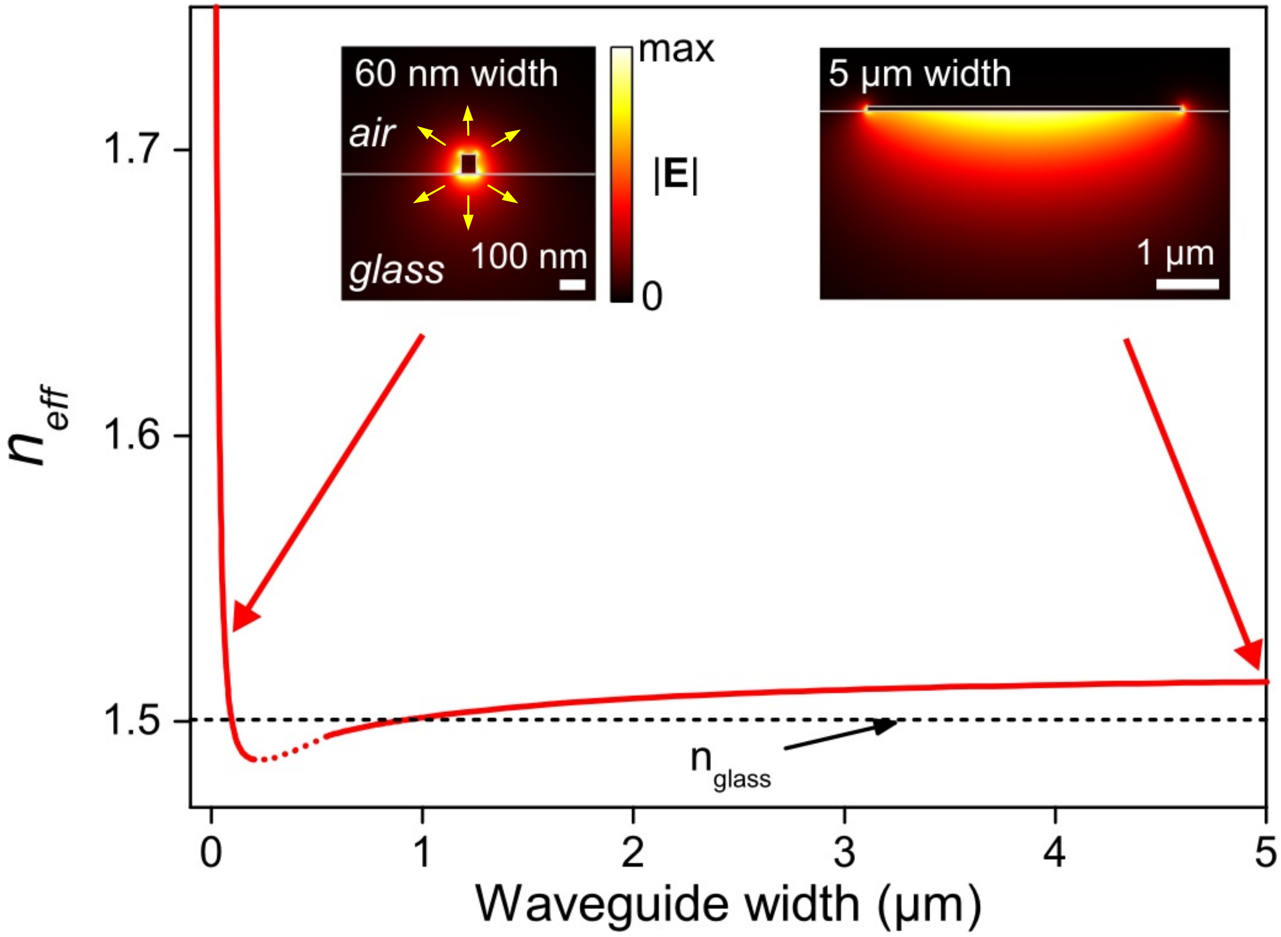
Nanowire coupling



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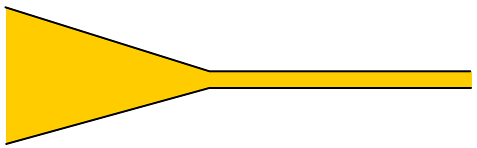
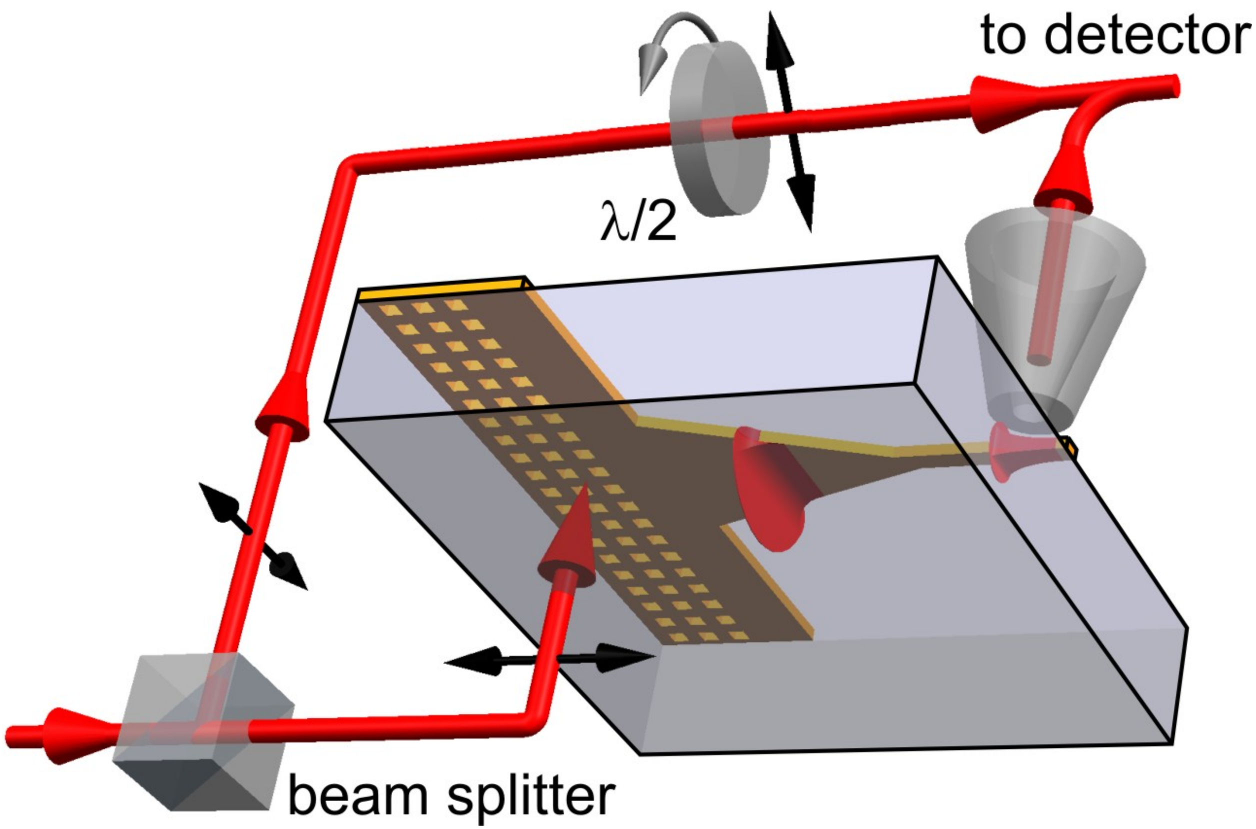


Experiment



Excitation proper SPP mode via subwavelength hole array

Near-field imaging nanowire

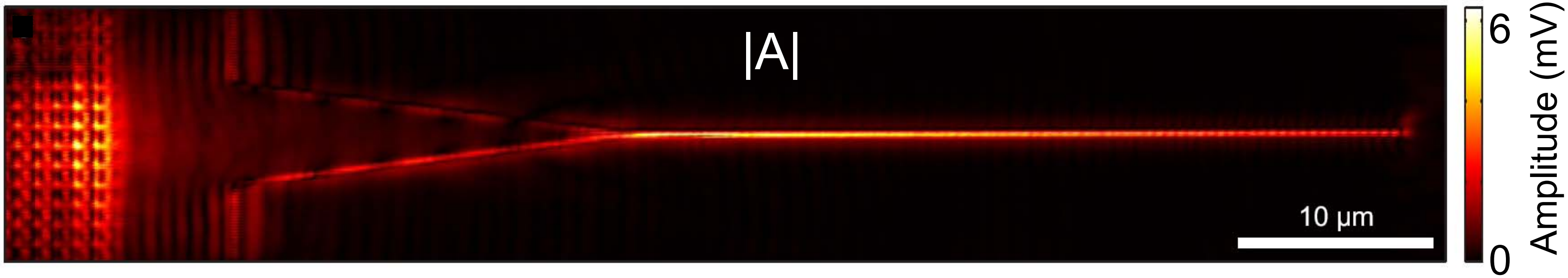
Au film thickness: 77 nm

λ_{exc} = 1550 nm

Near-field imaging nanowire

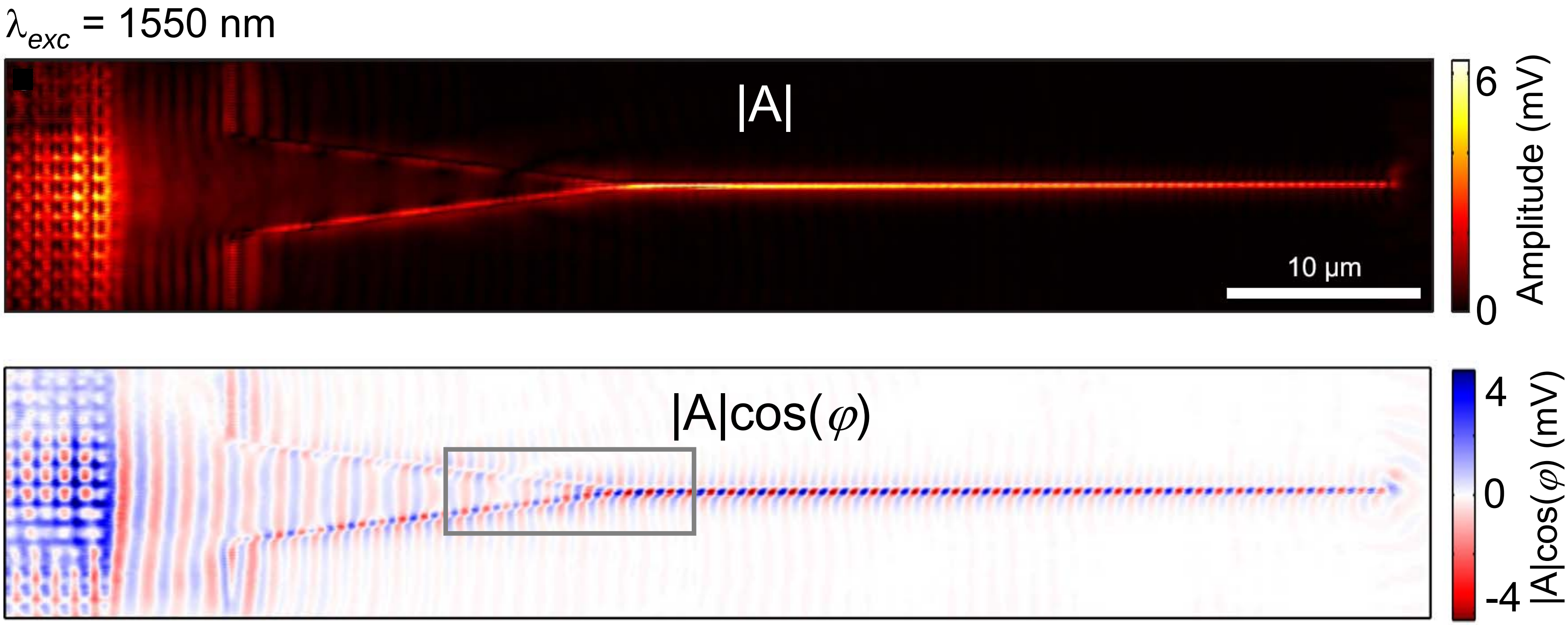
1550 nm excitation light focused to <300 nm (FWHM): **λ / 5**

λ_{exc} = 1550 nm



Near-field imaging nanowire

1550 nm excitation light focused to <300 nm (FWHM): λ / 5



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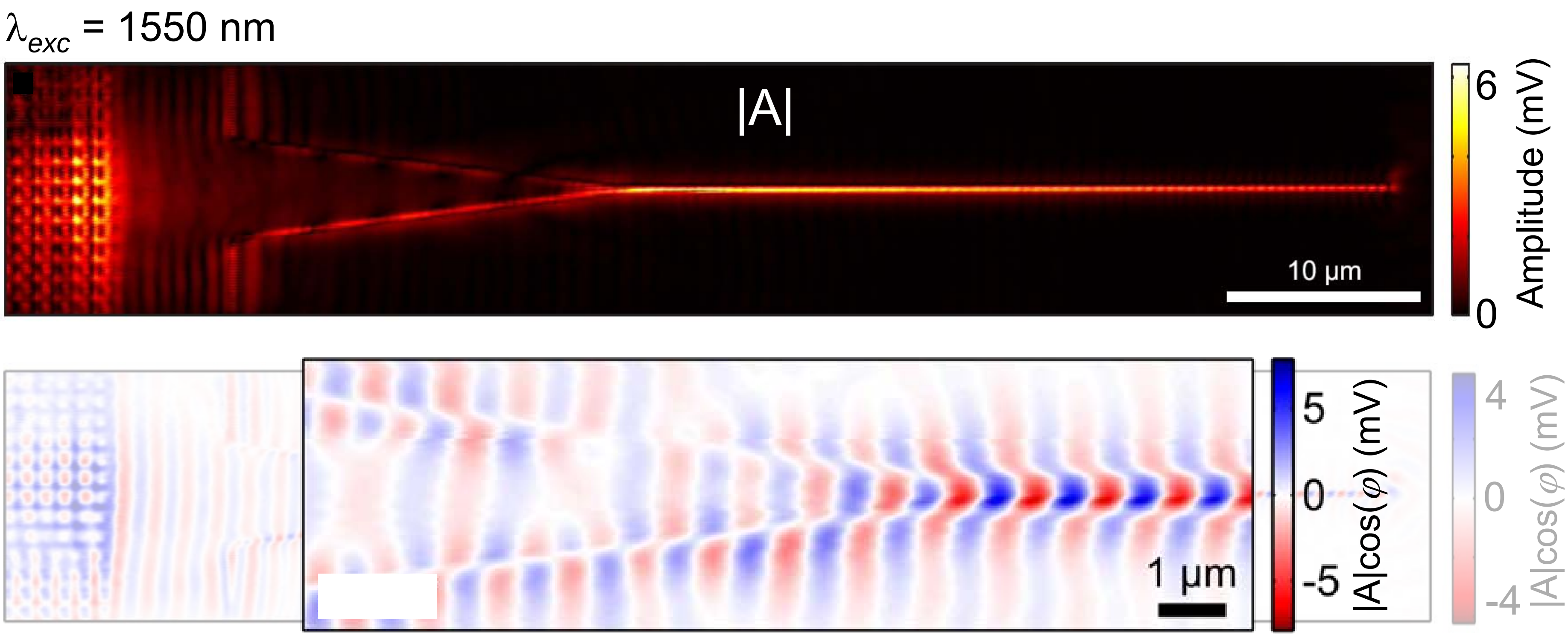

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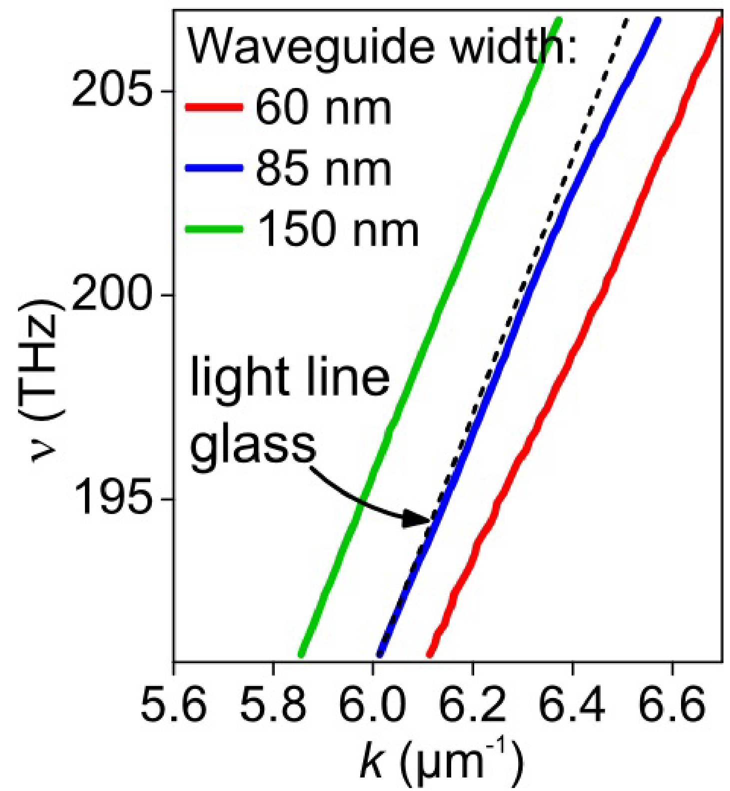
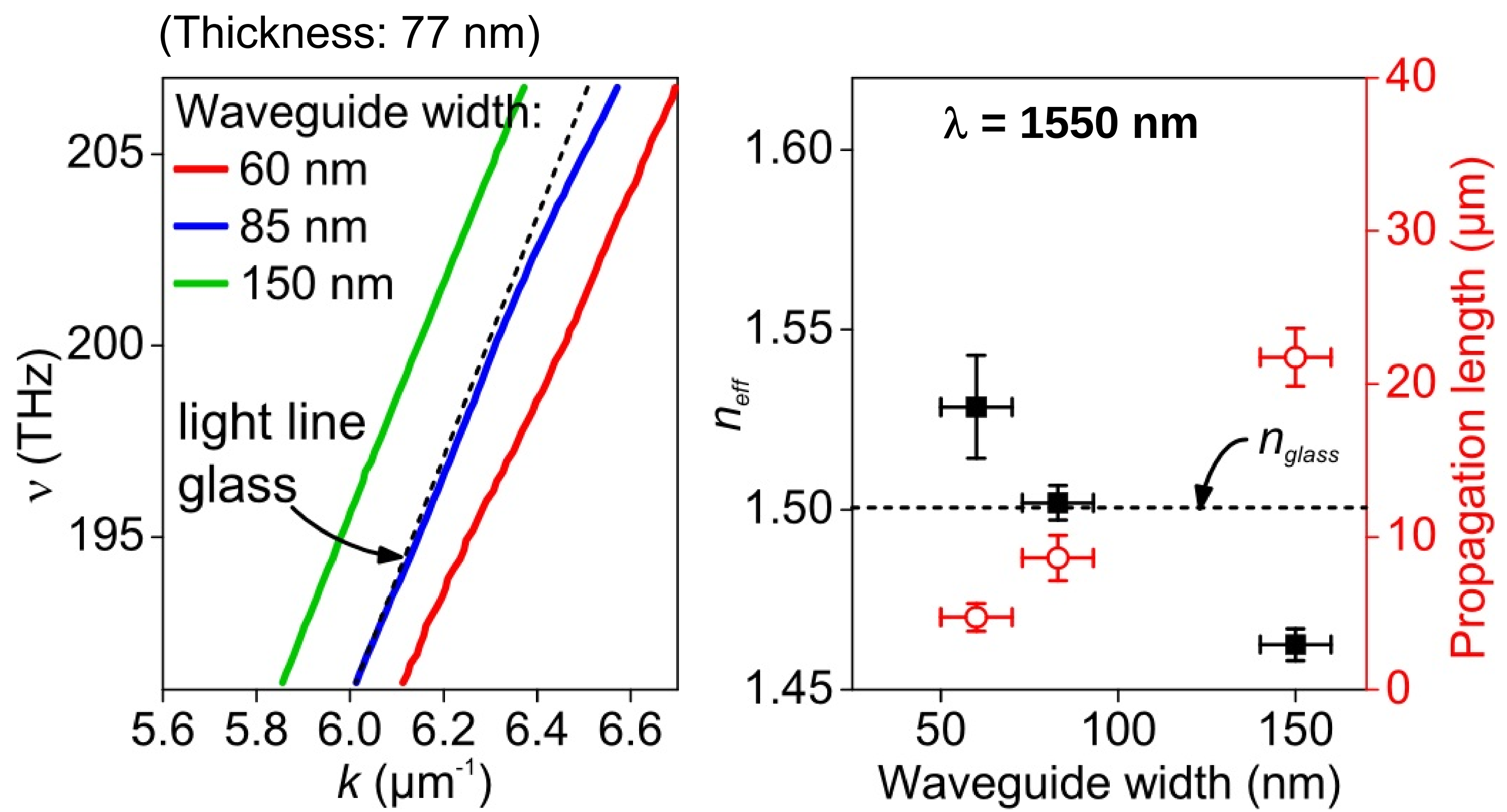
Dispersion and losses in nanowires

(Thickness: 77 nm)



- Dispersion measurements for different nanowire widths confirm calculations

Dispersion and losses in nanowires



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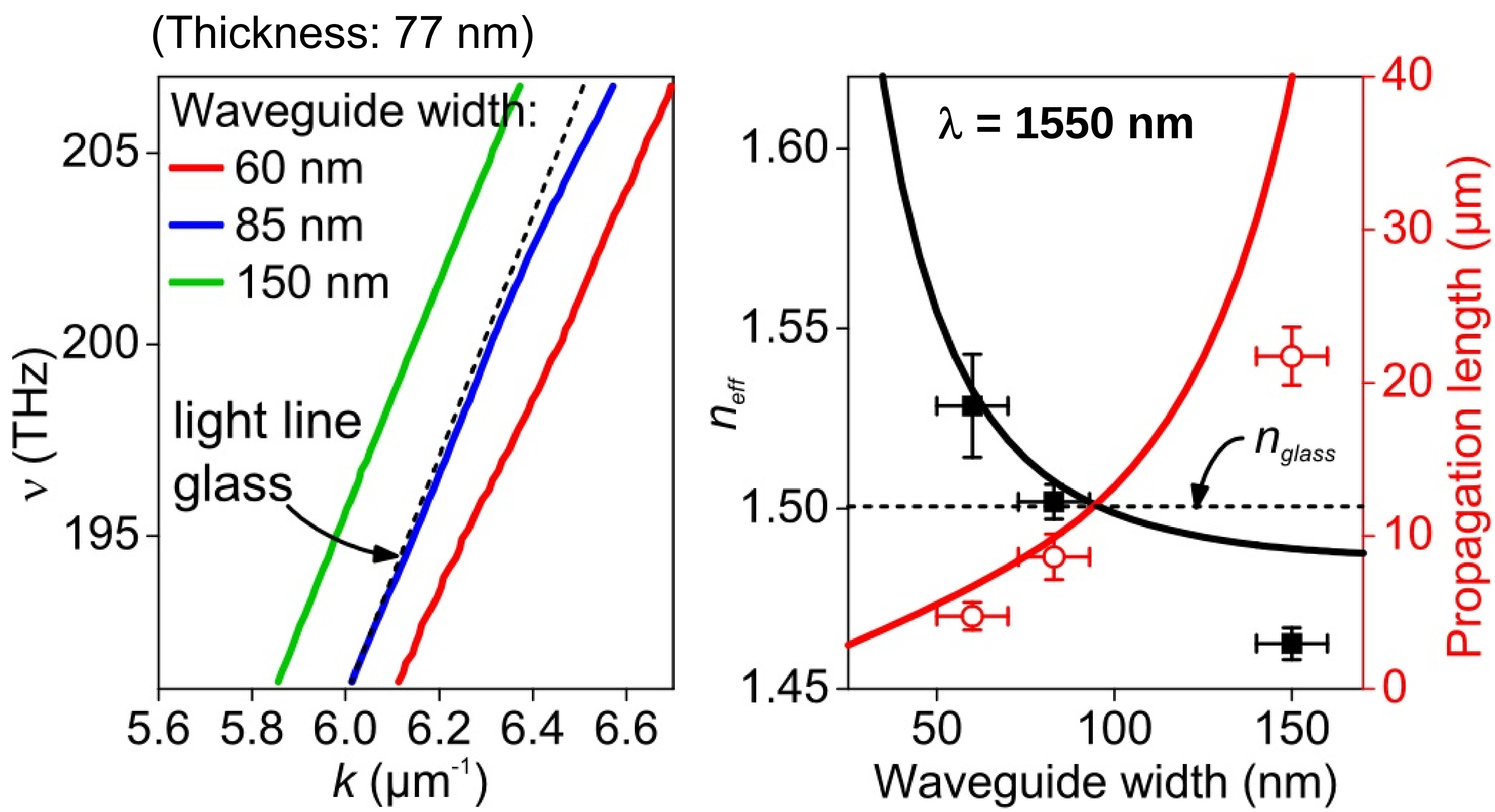
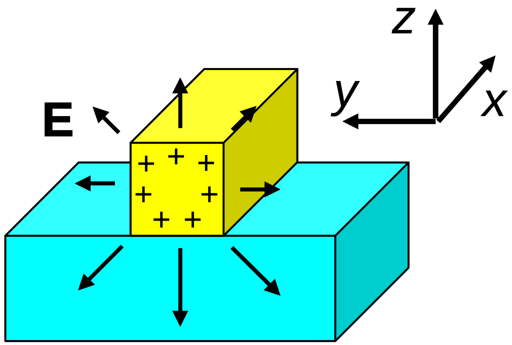
Dispersion and losses in nanowires

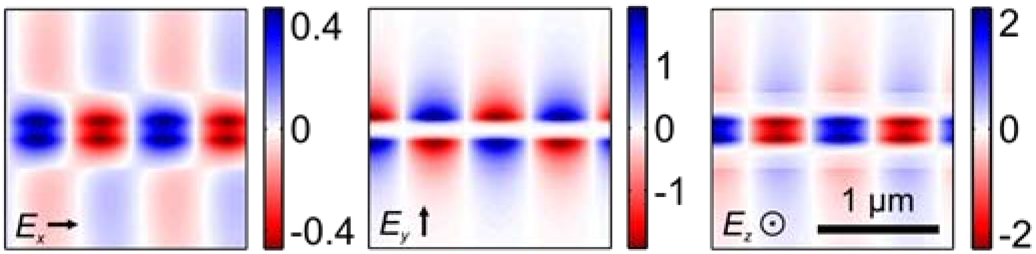


- Dispersion measurements for different nanowire widths confirm calculations

Probing the nanowire SPP polarization



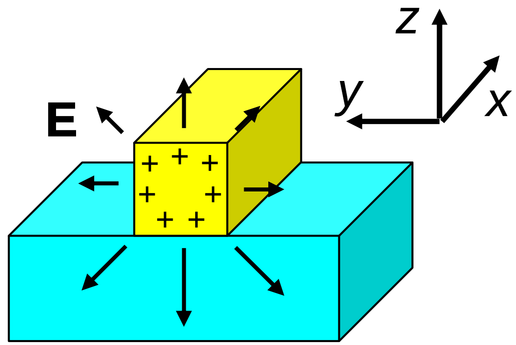
Calculation in scanned plane:



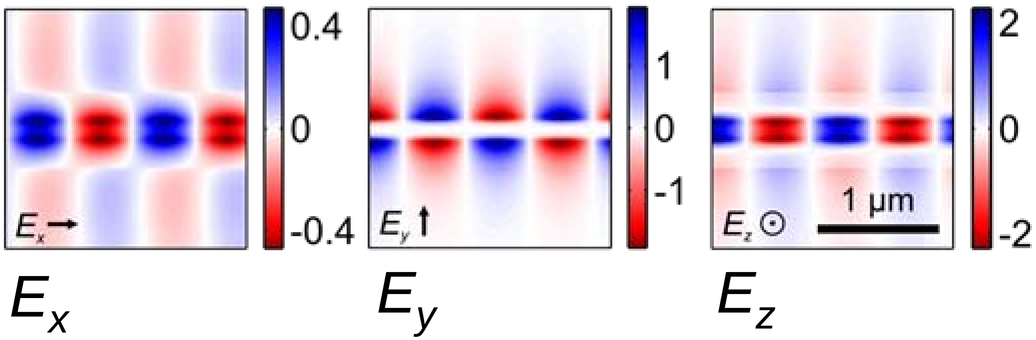
E_x E_y E_z

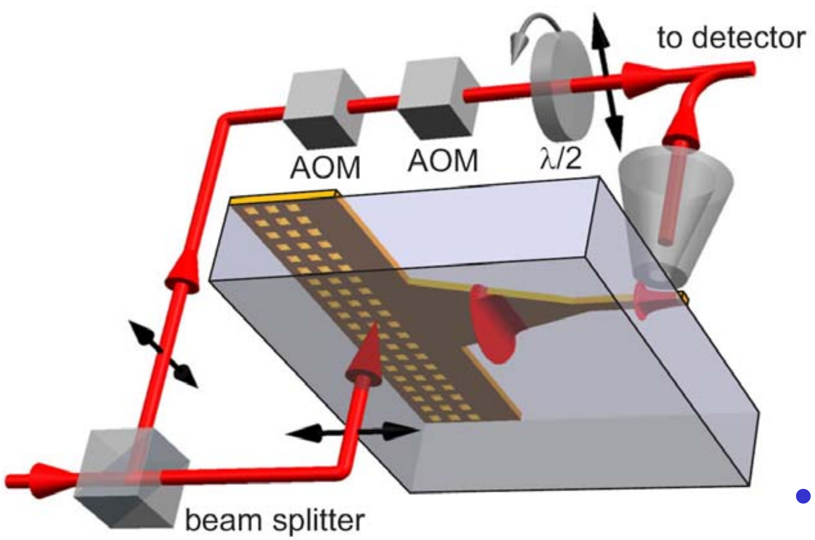
- Can we detect the radially polarized nature of the nanowire SPP mode?

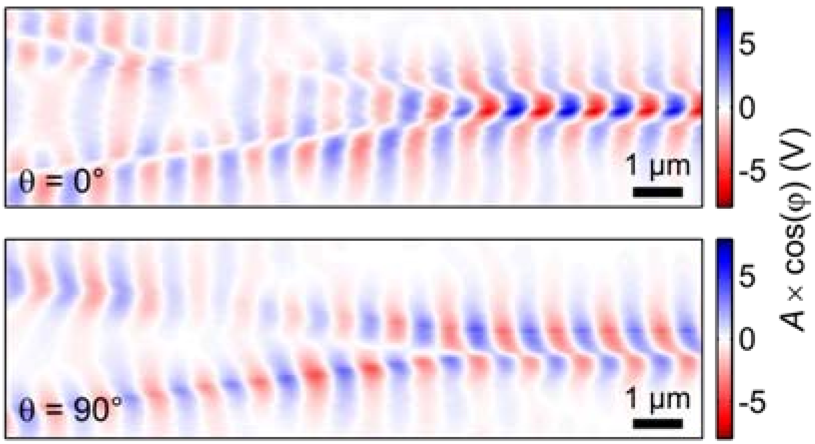
Probing the nanowire SPP polarization



Calculation in scanned plane:

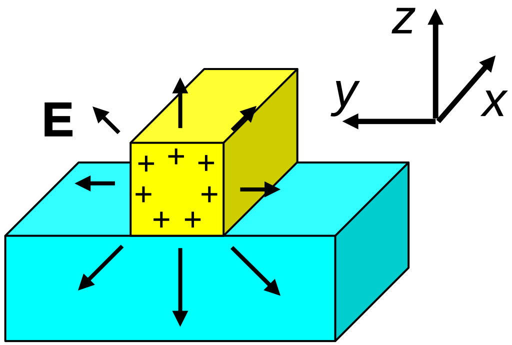




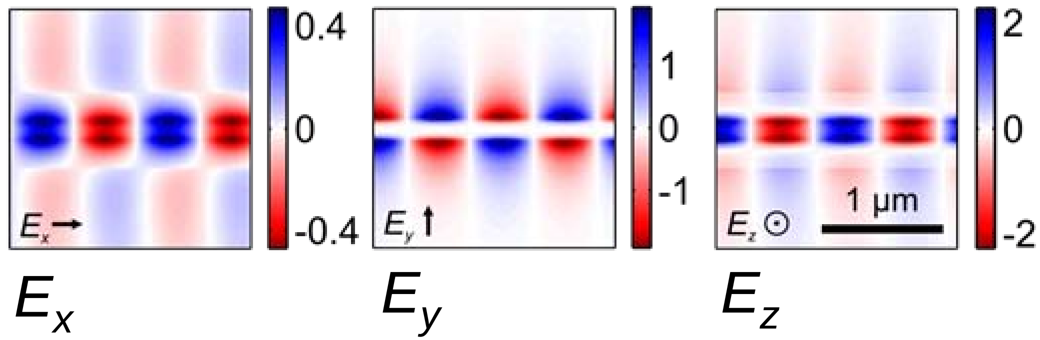


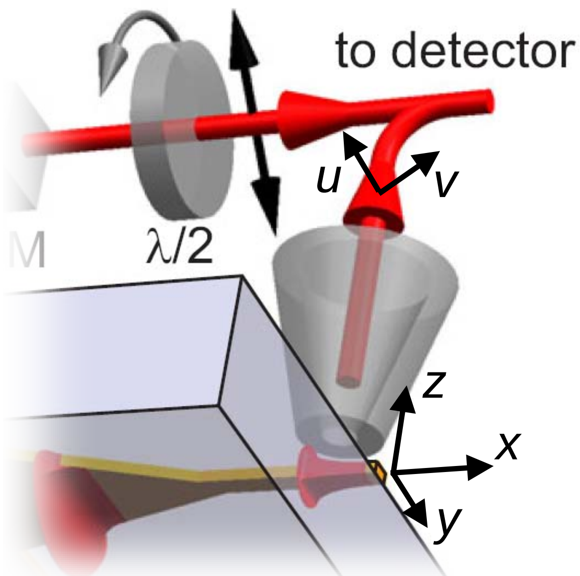
- The reference polarization selects a polarization in the detection fiber

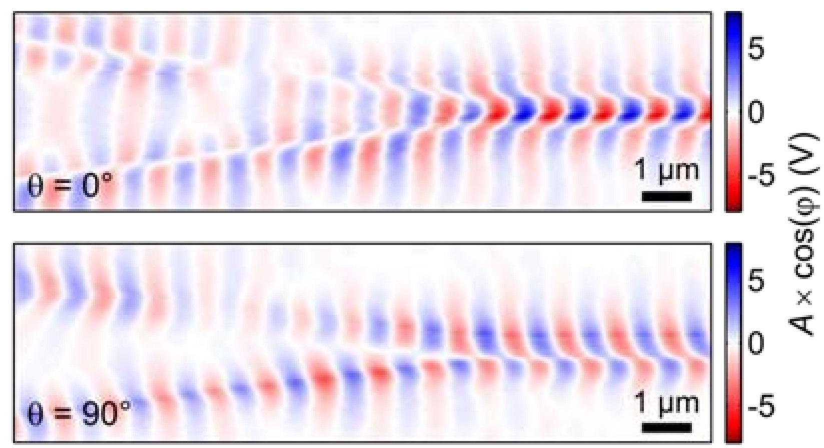
Probing the nanowire SPP polarization



Calculation in scanned plane:







- Collecting different field components

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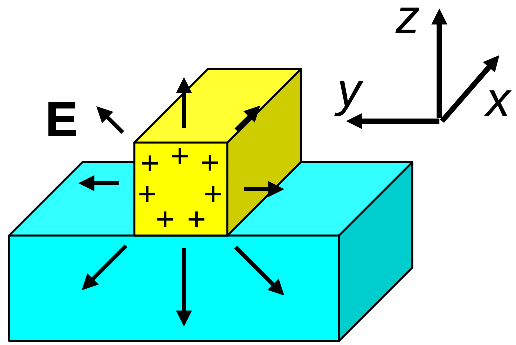
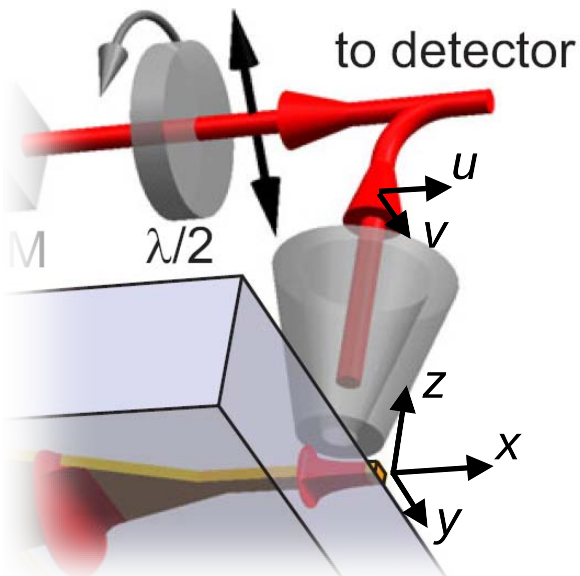
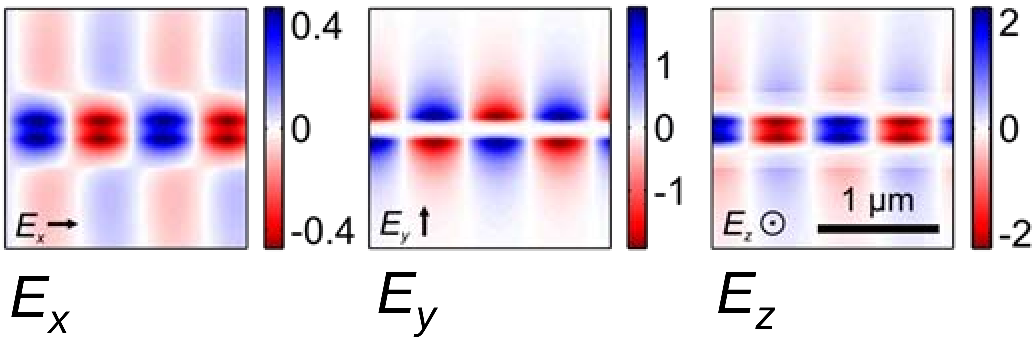
Probing the nanowire SPP polarization

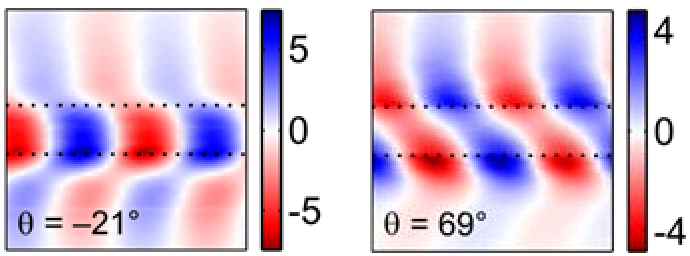




Calculation in scanned plane:



Experiment:

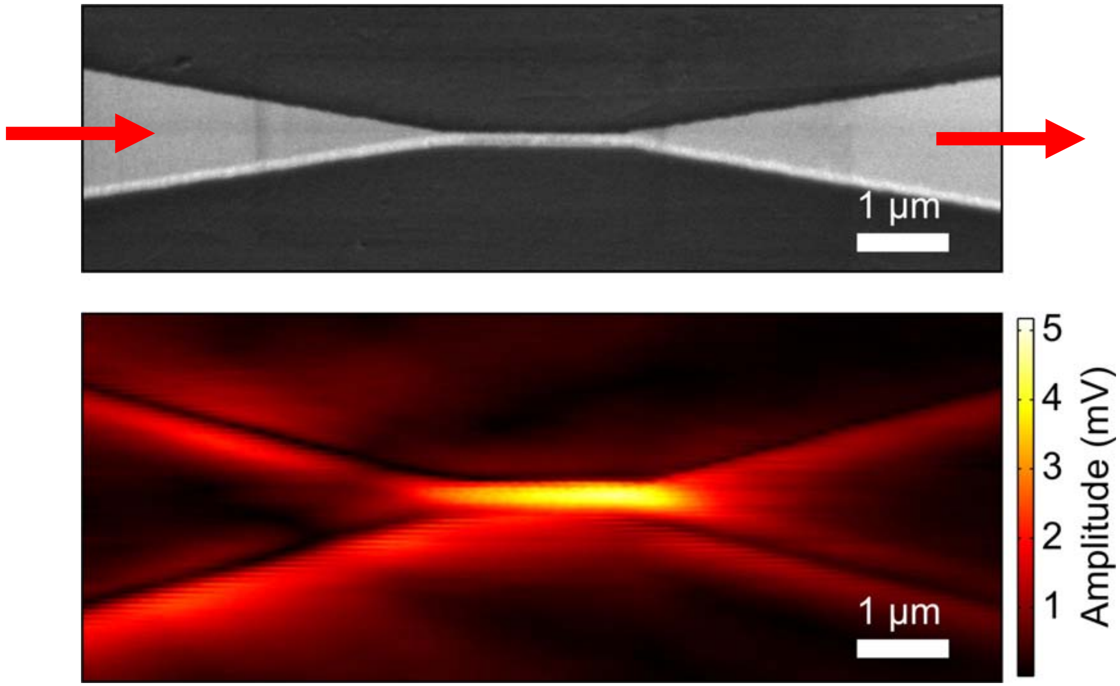


- Strong longitudinal component associated with nanoconfined waves
- Asymmetry reveals radially polarized nature of nanowire SPP mode

Estimating the coupling efficiency

- Coupling from a 2 µm wide taper to a 90 nm wide nanowire and back again

only forward propagating waves:



- *Combined* coupling and decoupling efficiency: 24±7 %
- Taper insertion loss: 3 dB

E. Verhagen, *et al.*, *Phys.Rev.Lett.* **102**, 203904 (2009)

Conclusions

- Highly confined optical info is evanescent
- Near-field microscopy powerful tool to visualize this information
- Efficient coupling to plasmonic nanowires (d = 60 nm) possible through adiabatic mode transformation