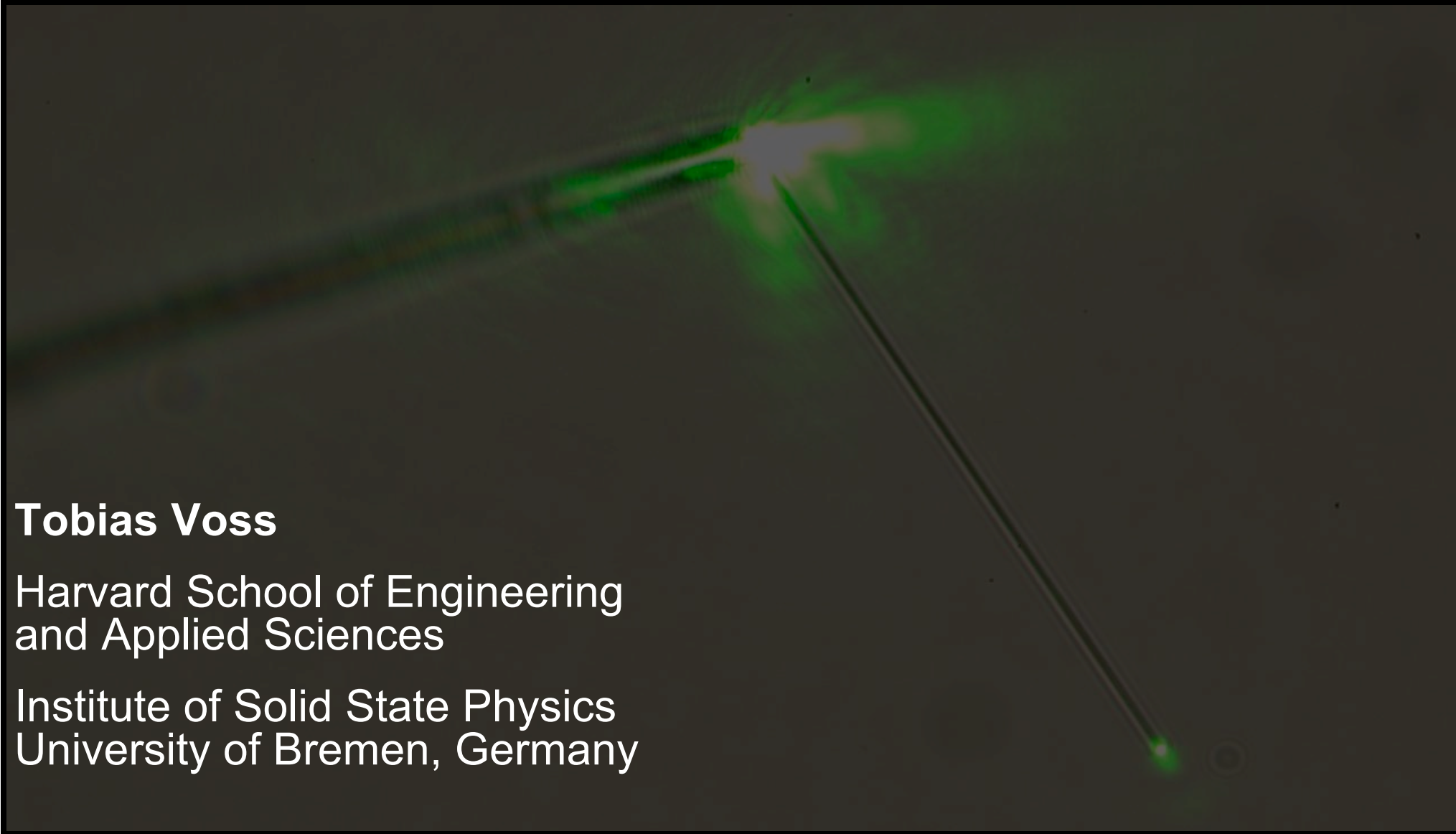
Combining top-down and bottom-up: Nanophotonics with silica and ZnO nanowires



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ZnO nanowires:
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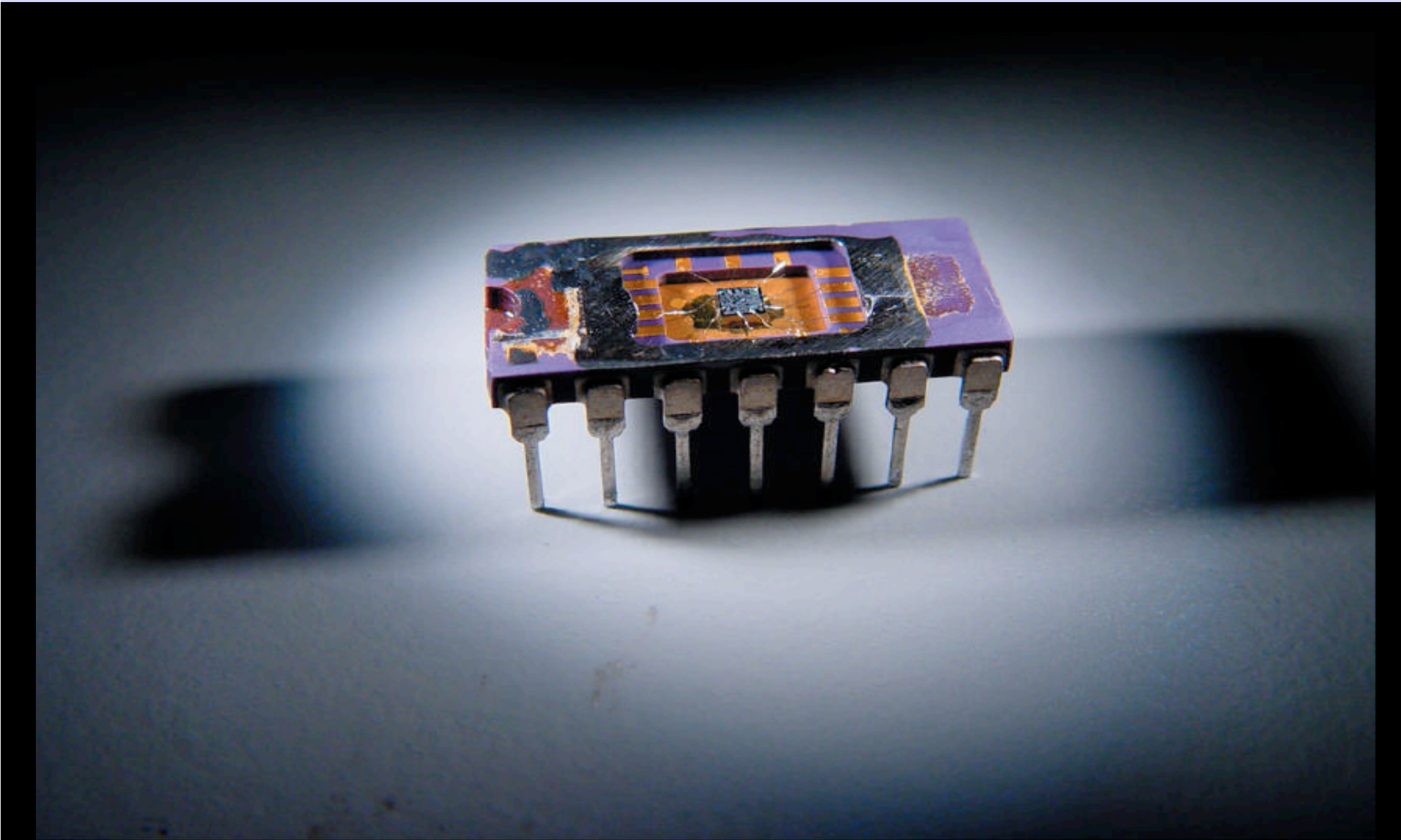
Introduction



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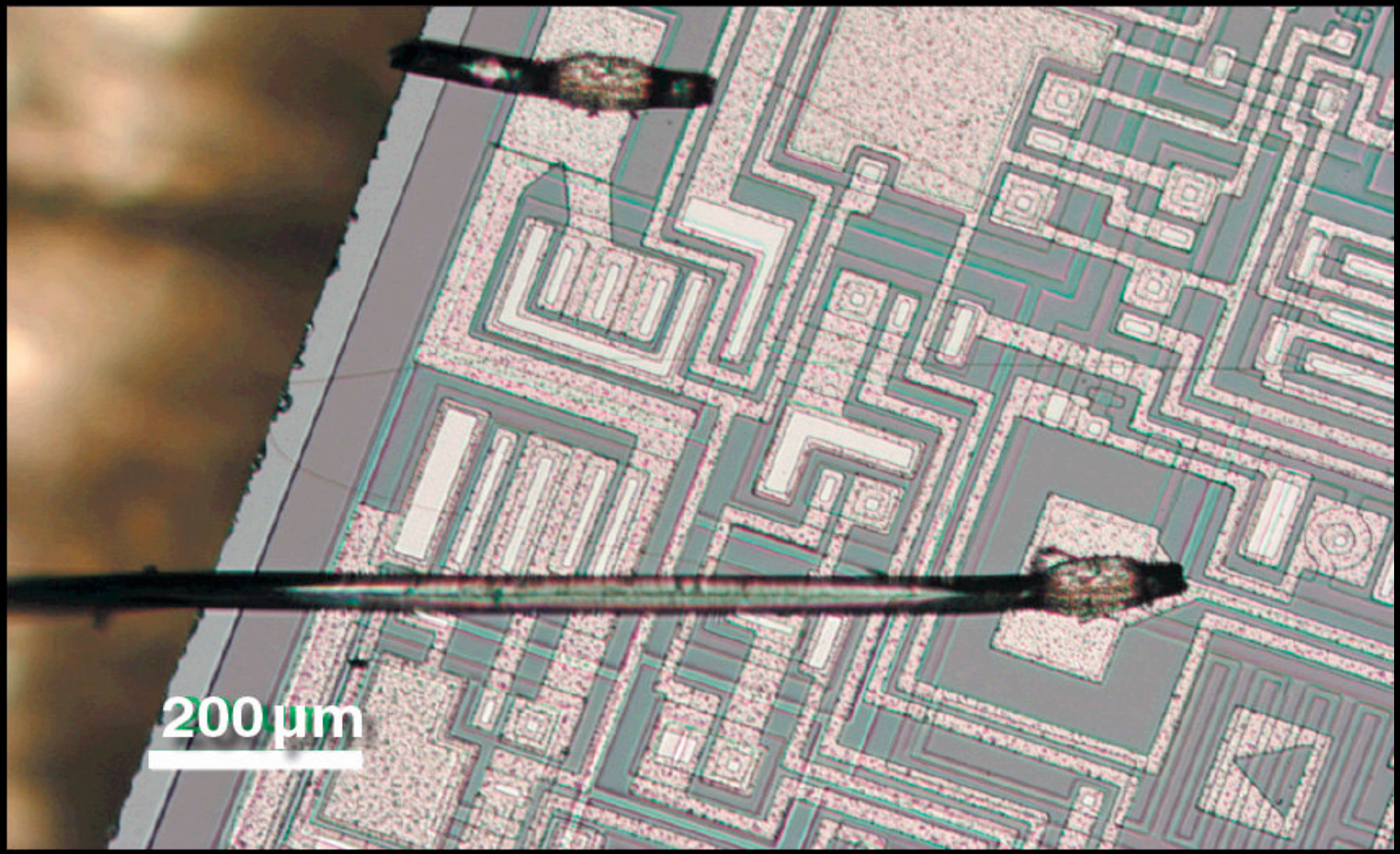

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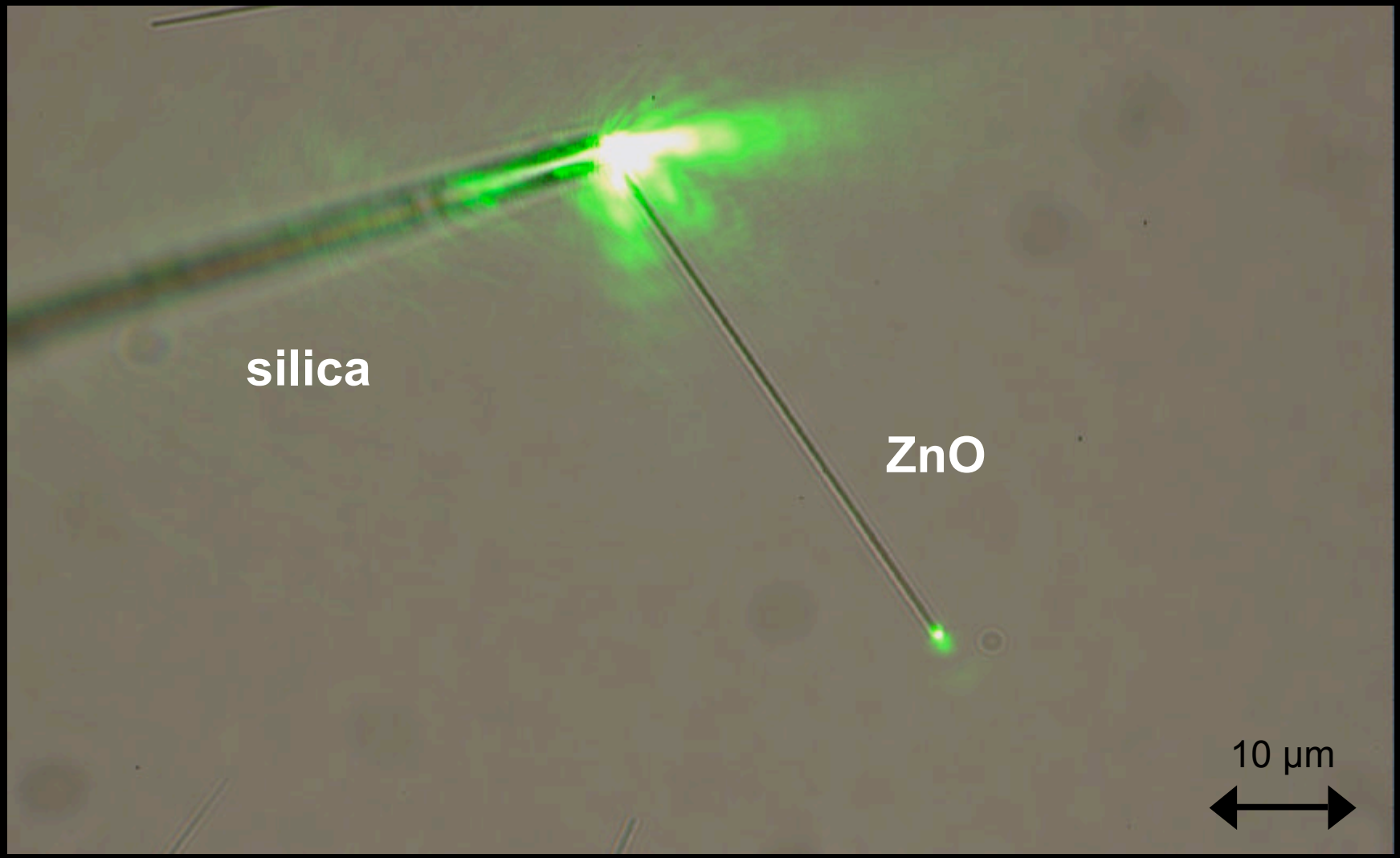
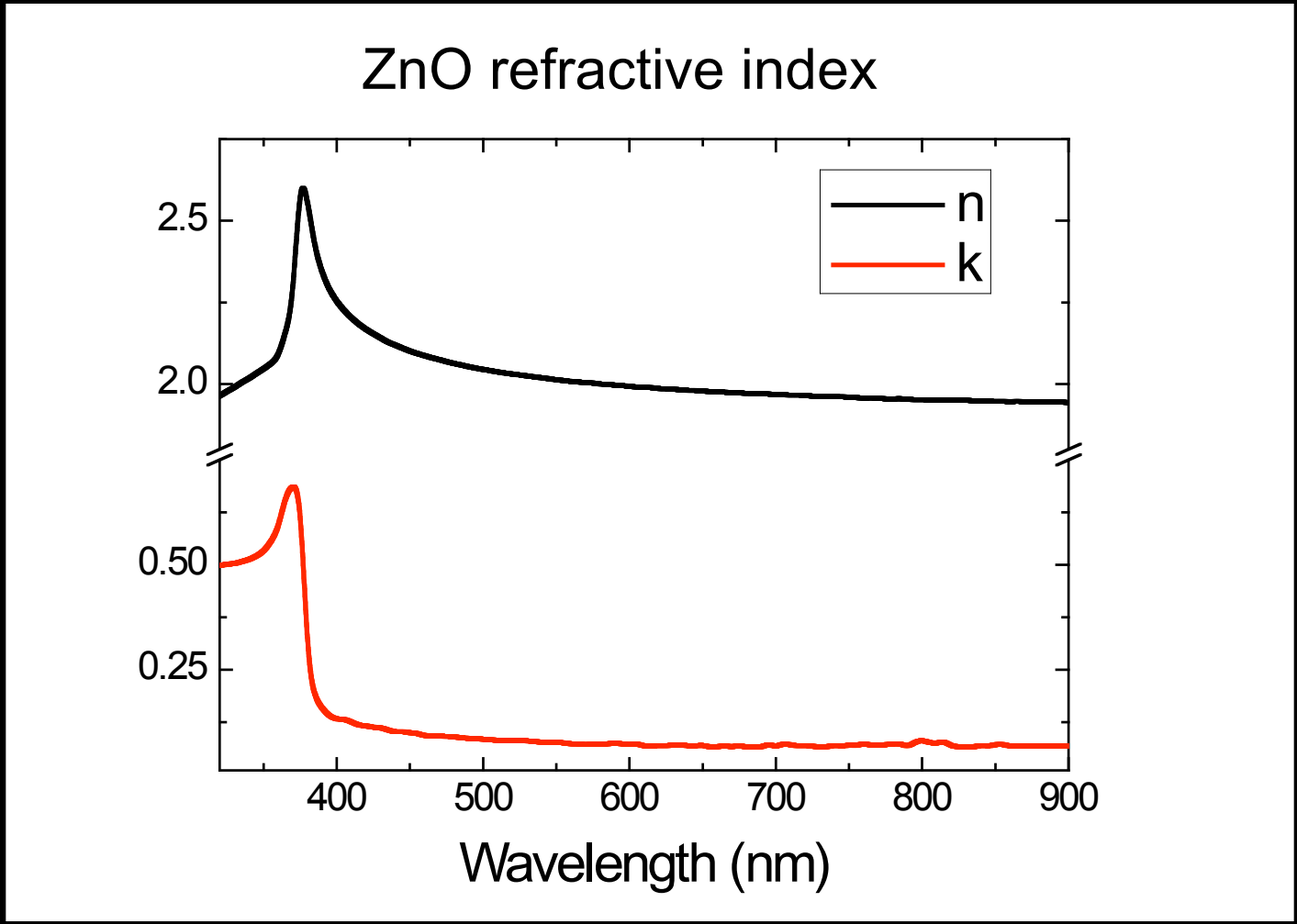


Introduction

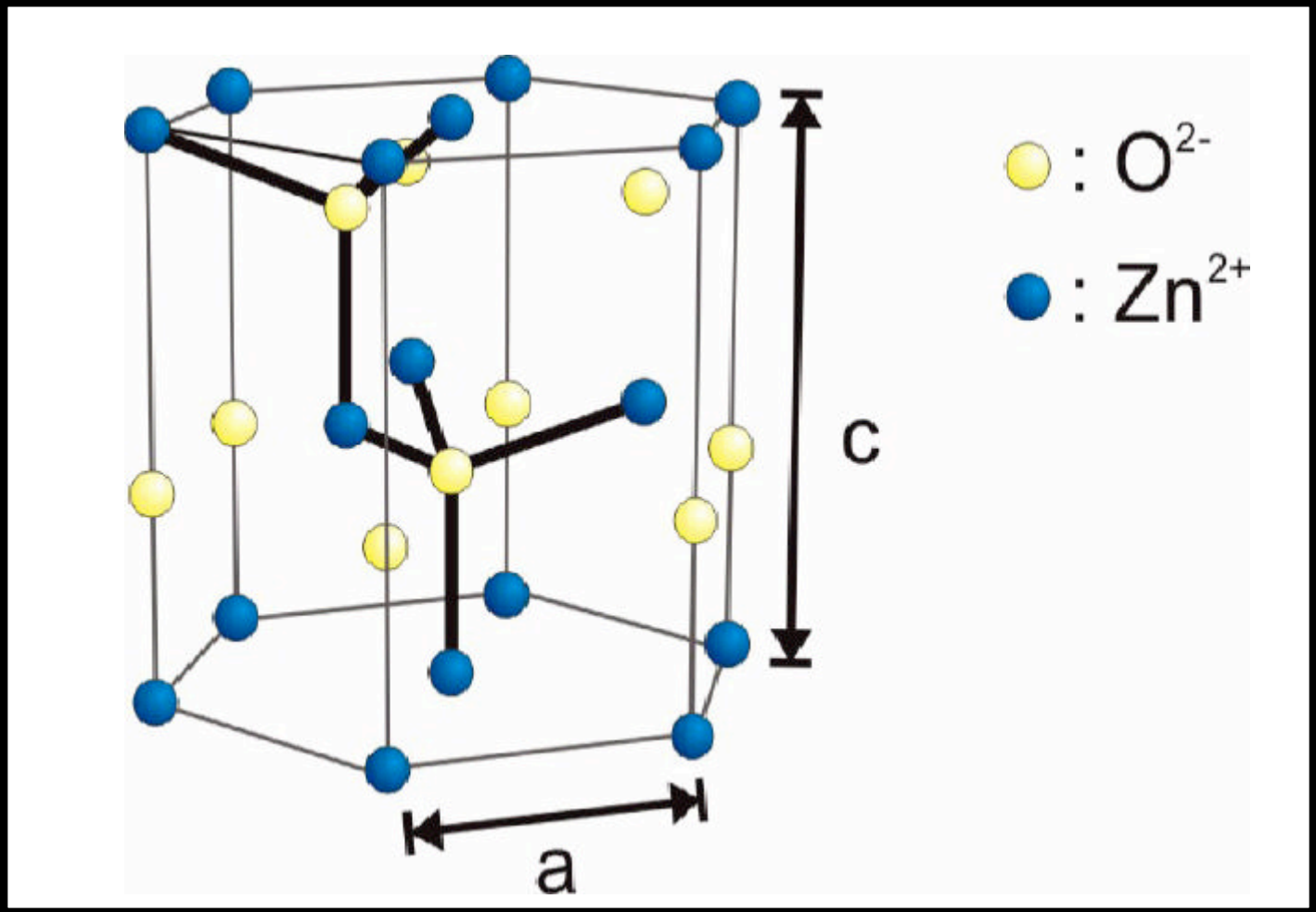
Zincoxide: non-toxic wide-bandgap semiconductor

Introduction



Introduction

wurtzite crystal structure



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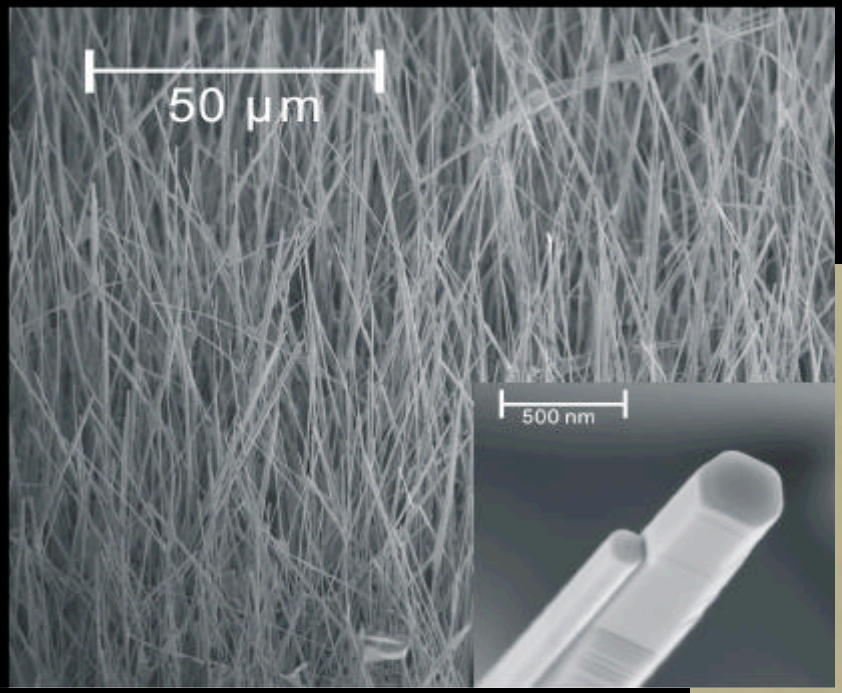
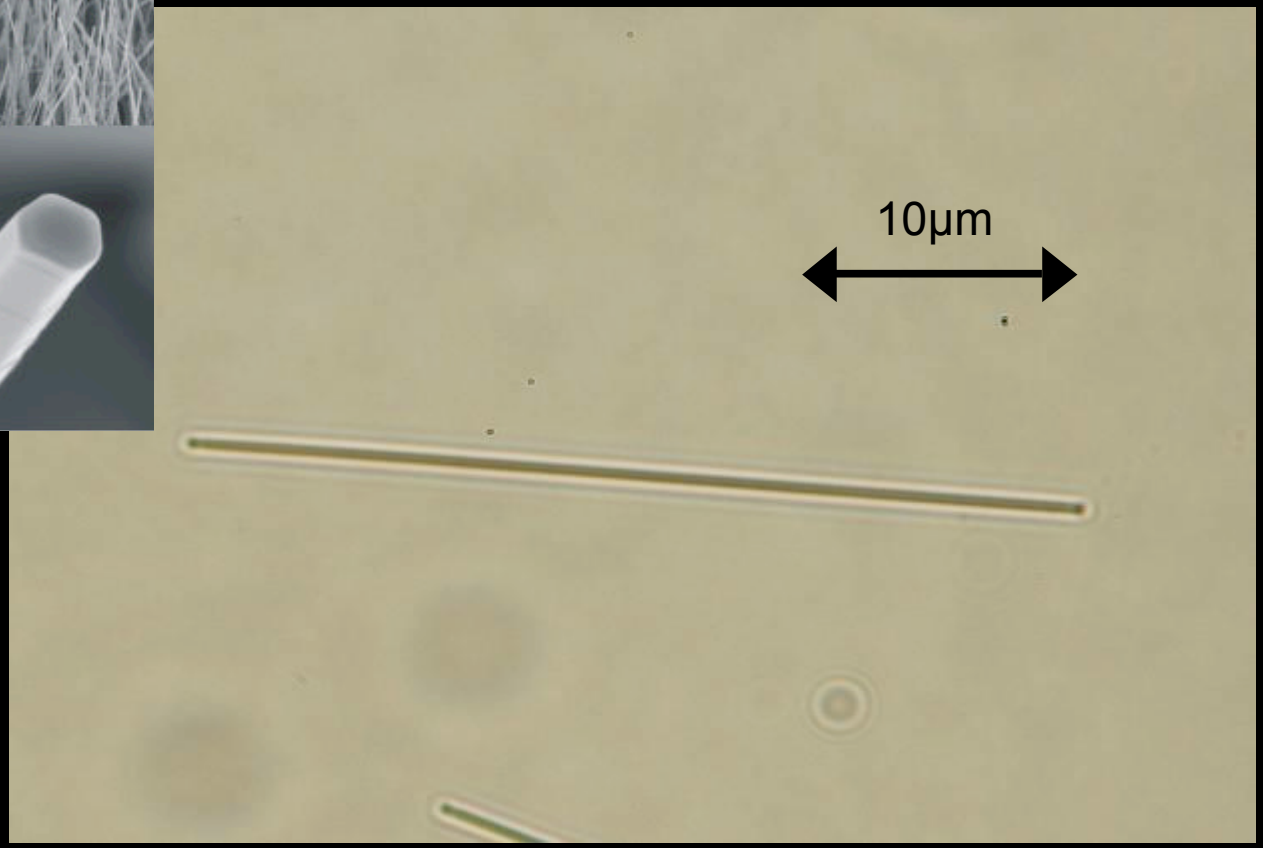


ZnO nanowires
electron microscope



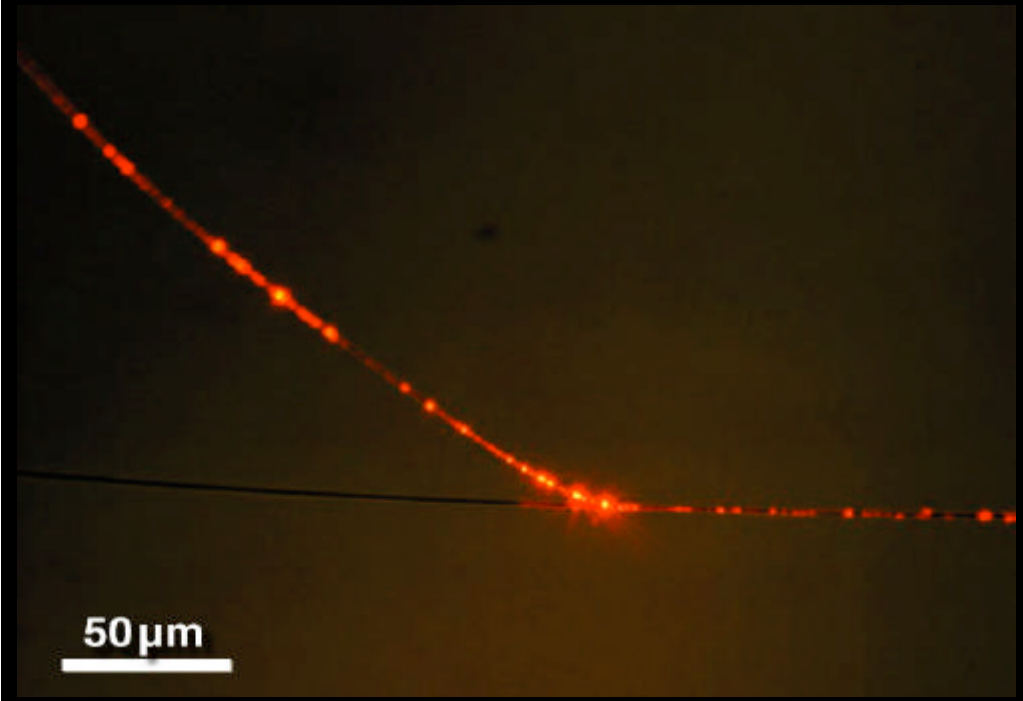
optical microscope

Introduction

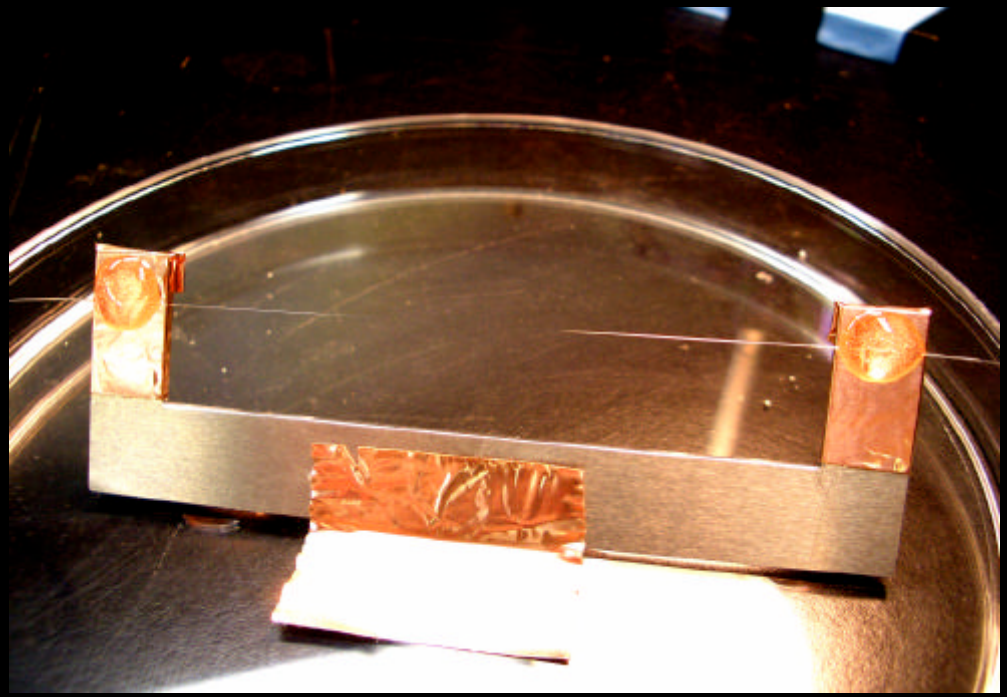
ZnO nanowire specifications

diameter	80 – 400 nm typical: 250 nm
length	up to 80 µm
aspect ratio	up to 5×10^2

Introduction

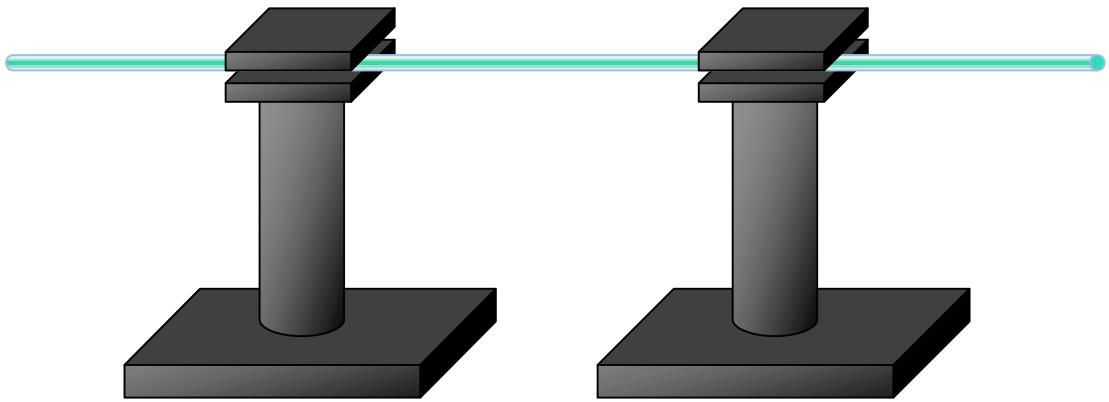


silica nanowires



Introduction

Pulling of silica nanowires/tapered fibers



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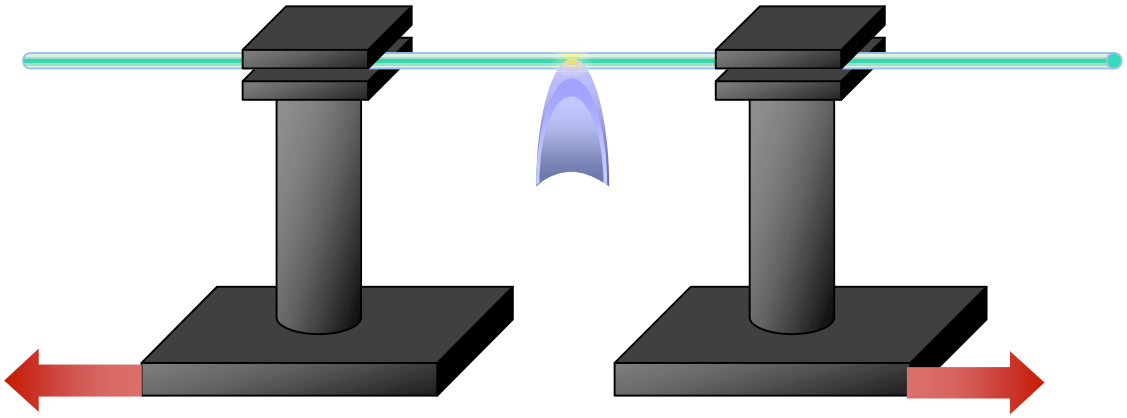

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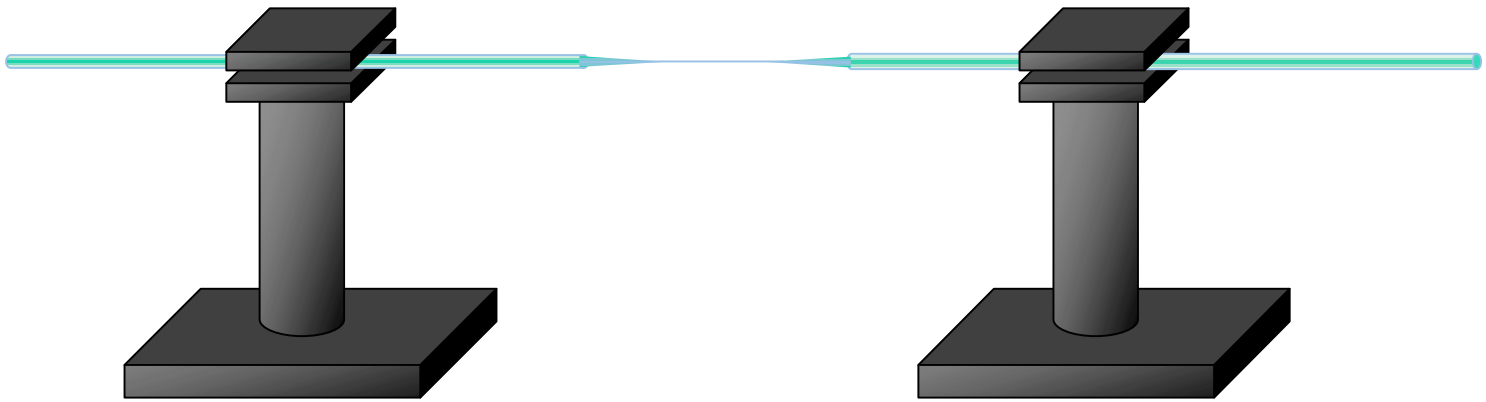
Pulling of silica nanowires/tapered fibers



Introduction

Silica nanowire specifications

diameter	down to 20 nm
length	up to 20 mm
aspect ratio	up to 10^6

Motivation

Combine two different worlds of nanowires

semiconductor NWs (ZnO)	**glass NWs (silica)**
bottom-up	top-down
active photonic devices	passive waveguides
electrical operation	link to macroscopic light sources

Motivation

- waveguiding
- optical coupling

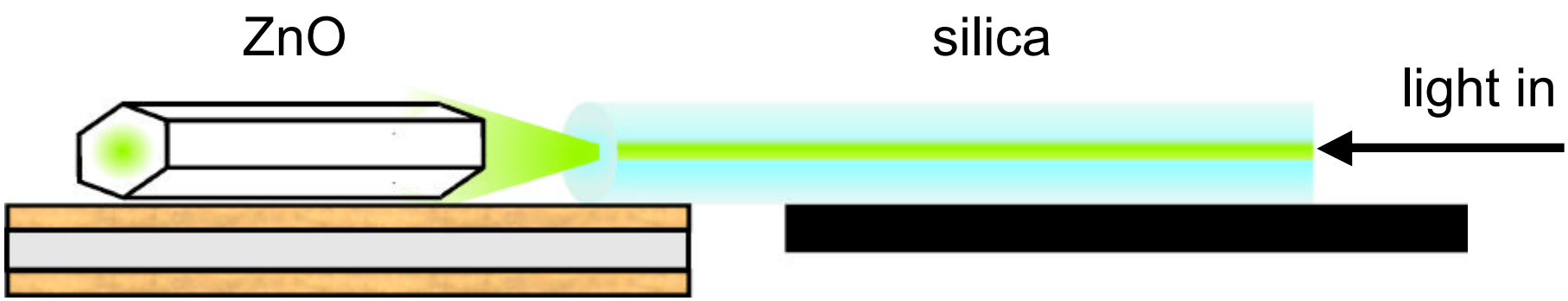
Outline

- Optical coupling to the nanoscale
- High-order mode contributions
- Nonlinear optics in ZnO nanowires

Outline

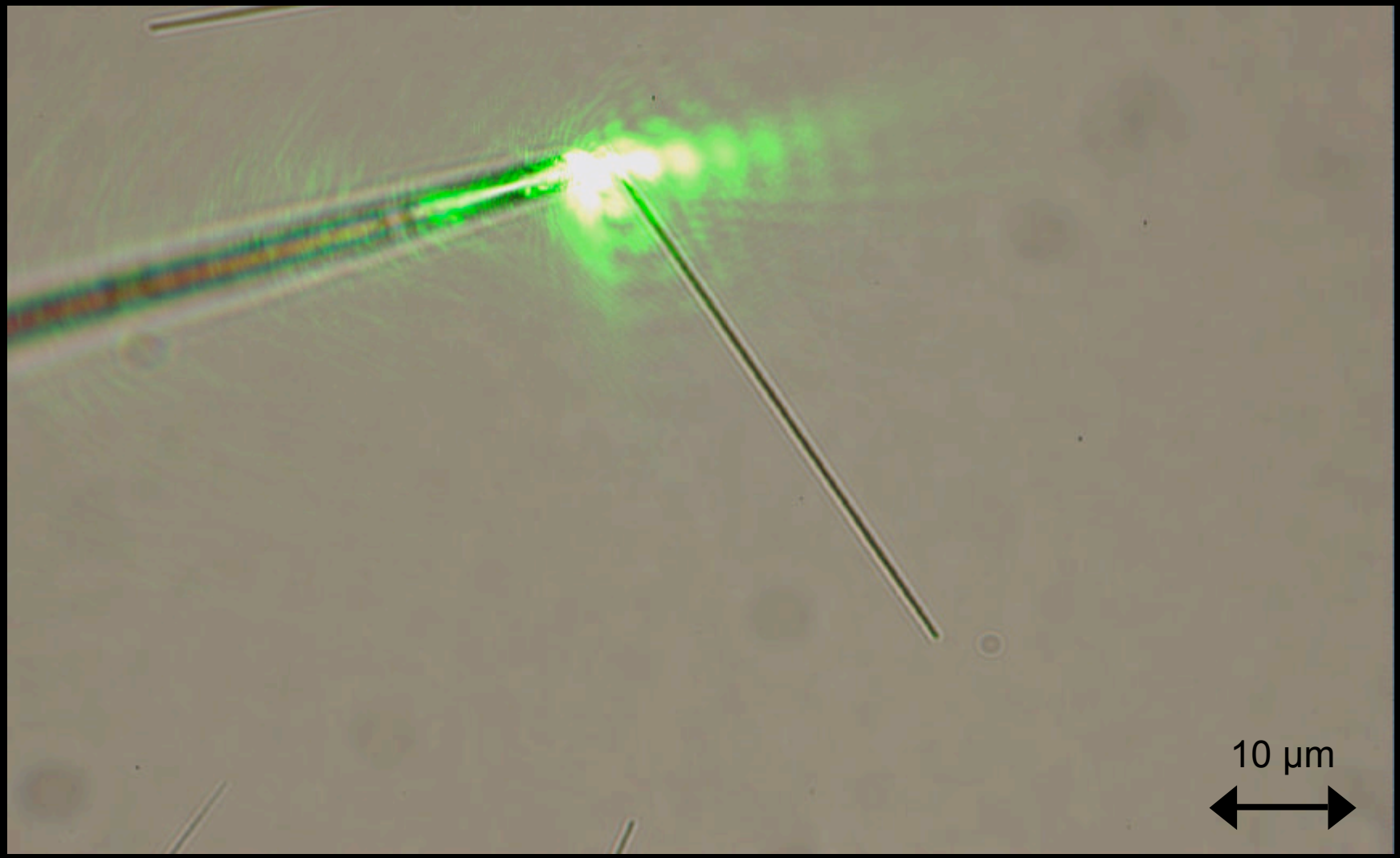
- Optical coupling to the nanoscale
- High-order mode contributions
- Nonlinear optics in ZnO nanowires

Optical coupling to the nanoscale

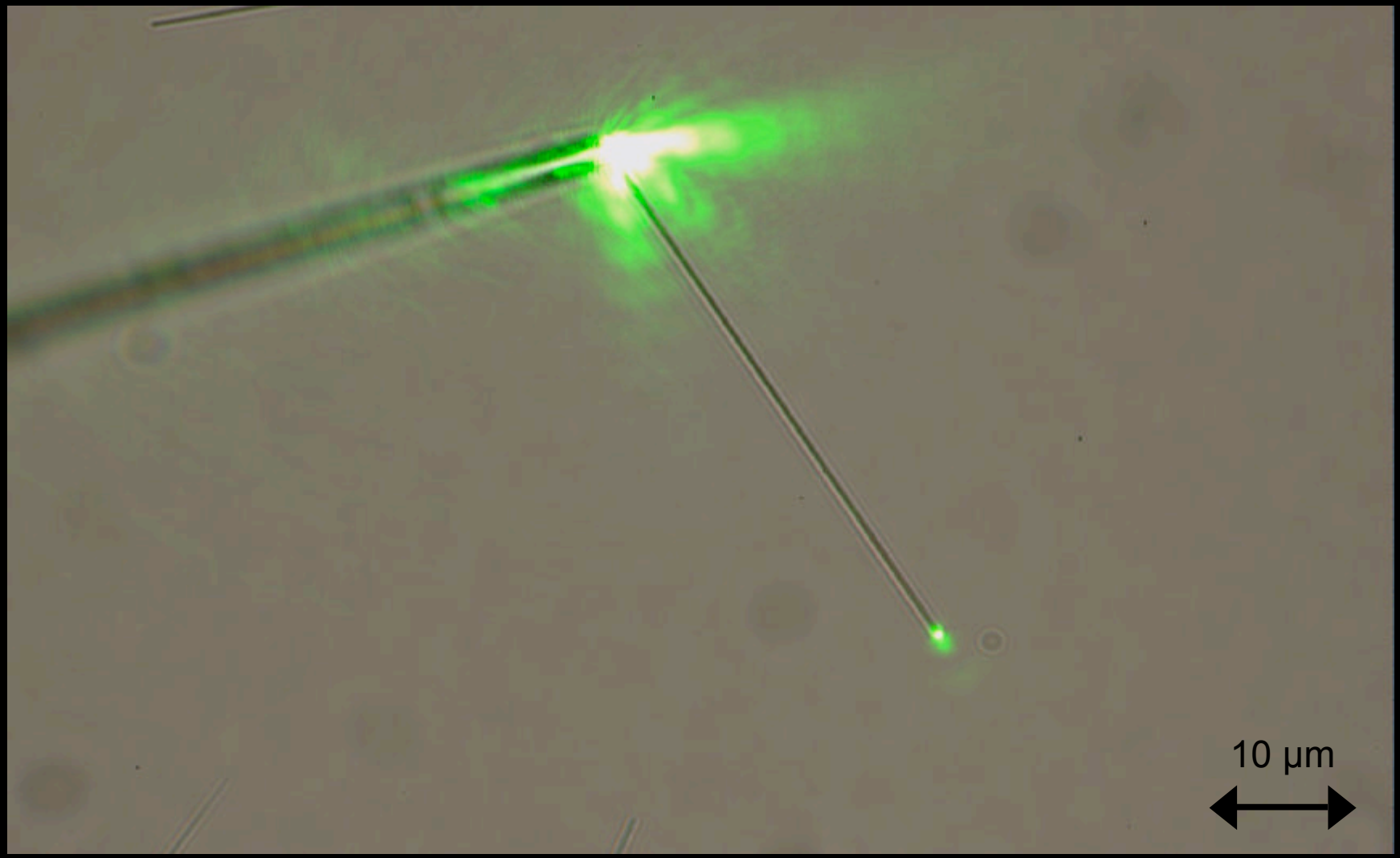


substrates covered with
mesoporous silica (n = 1.18)

Optical coupling to the nanoscale



Optical coupling to the nanoscale



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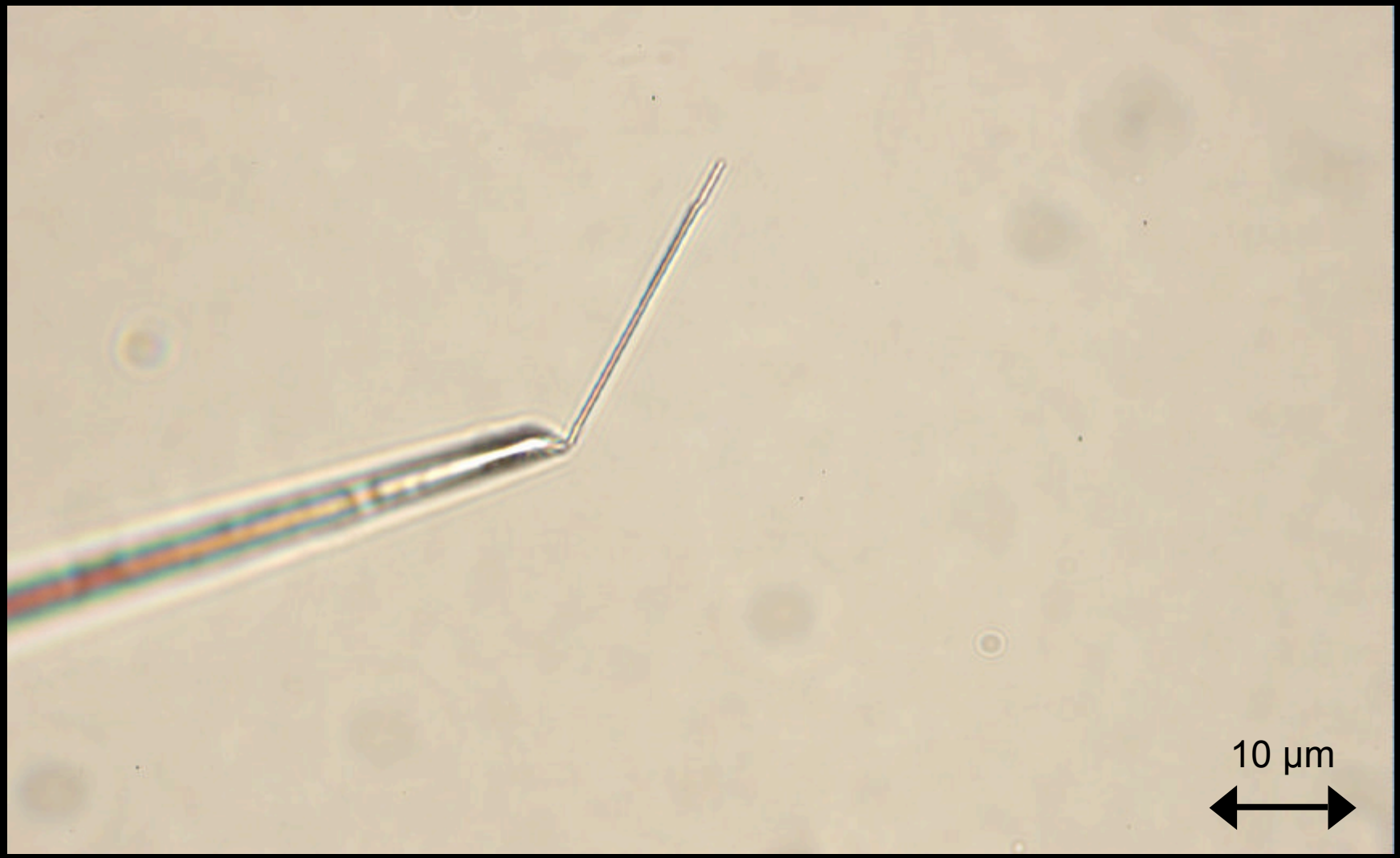

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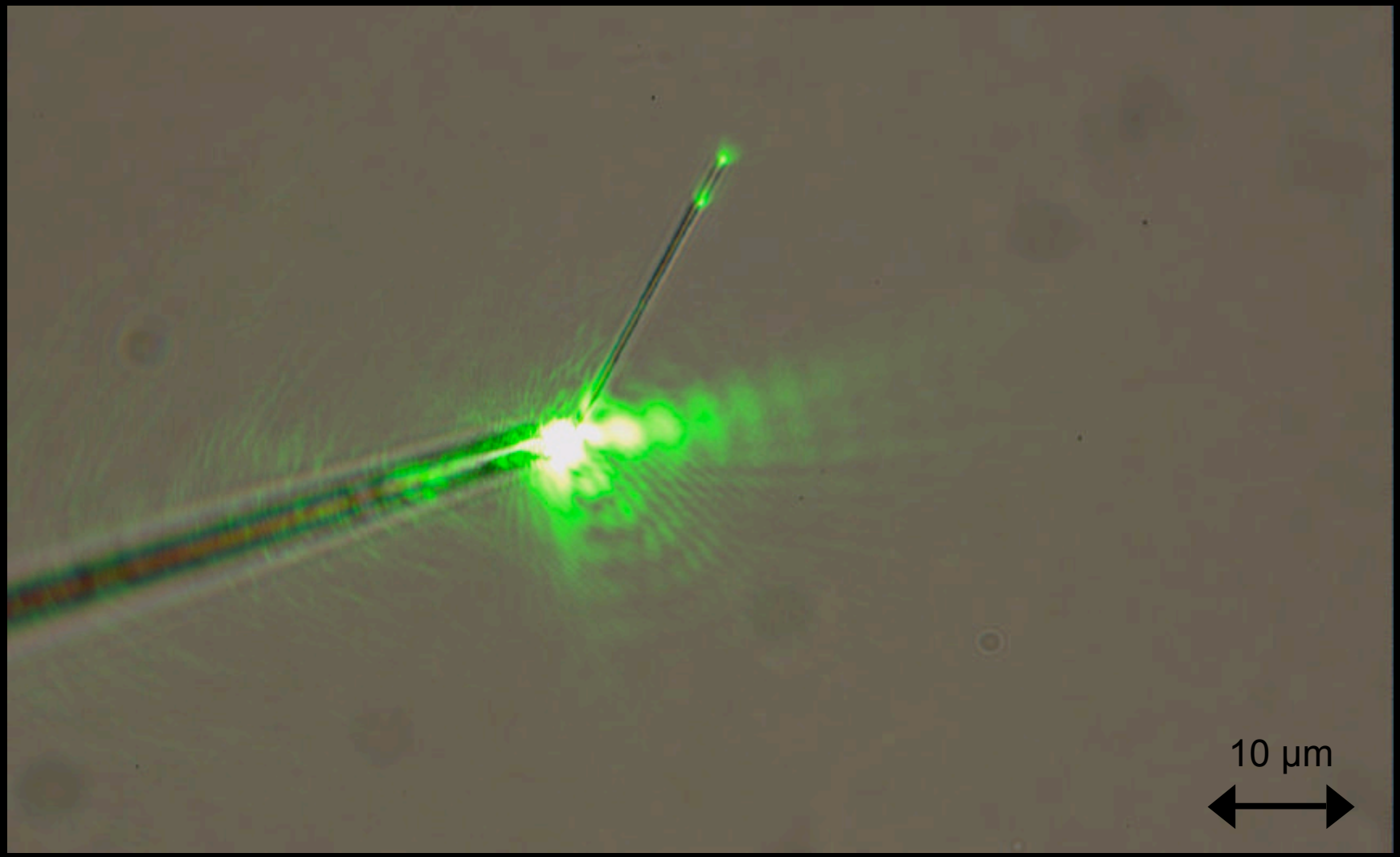
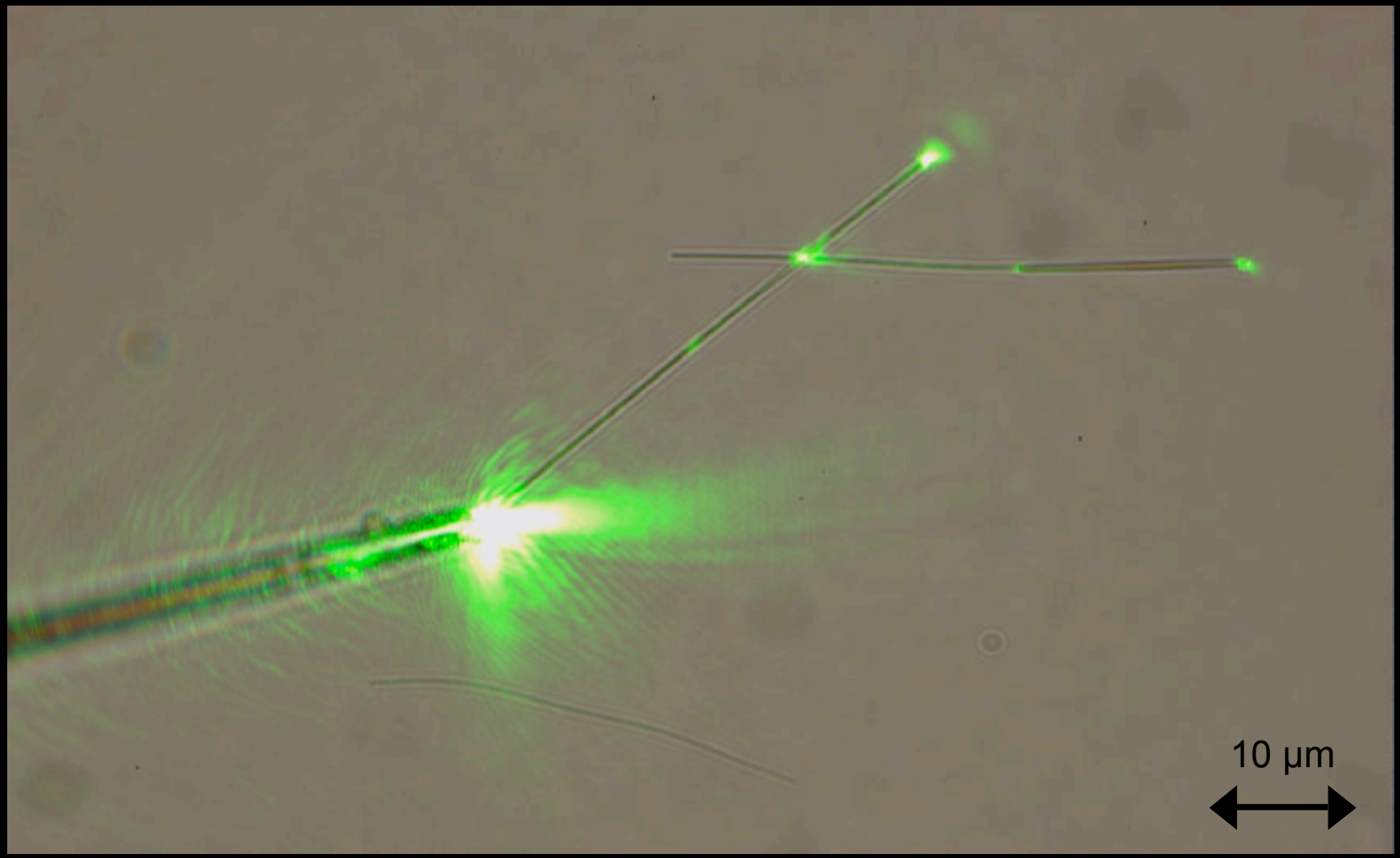
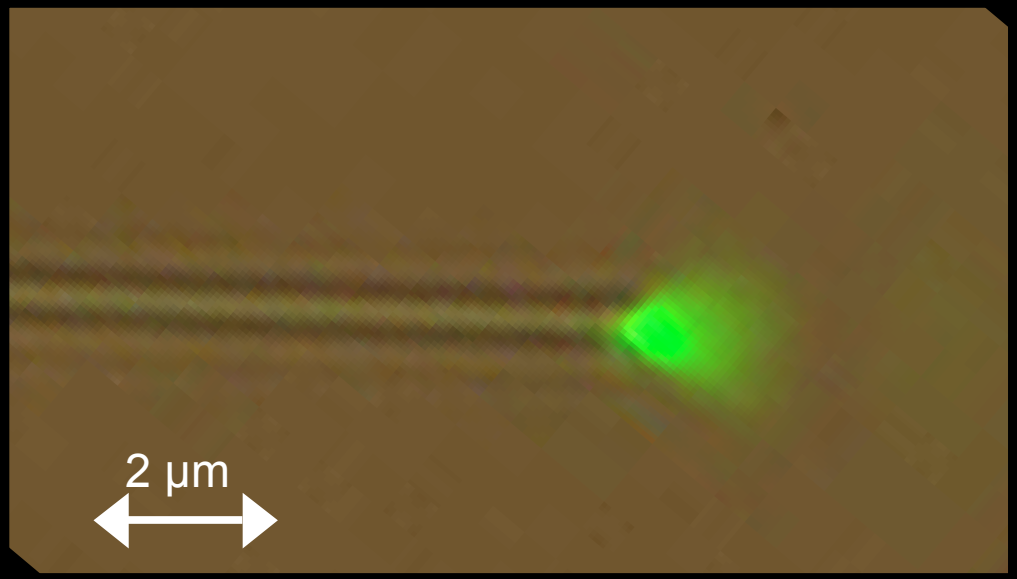


Optical coupling to the nanoscale



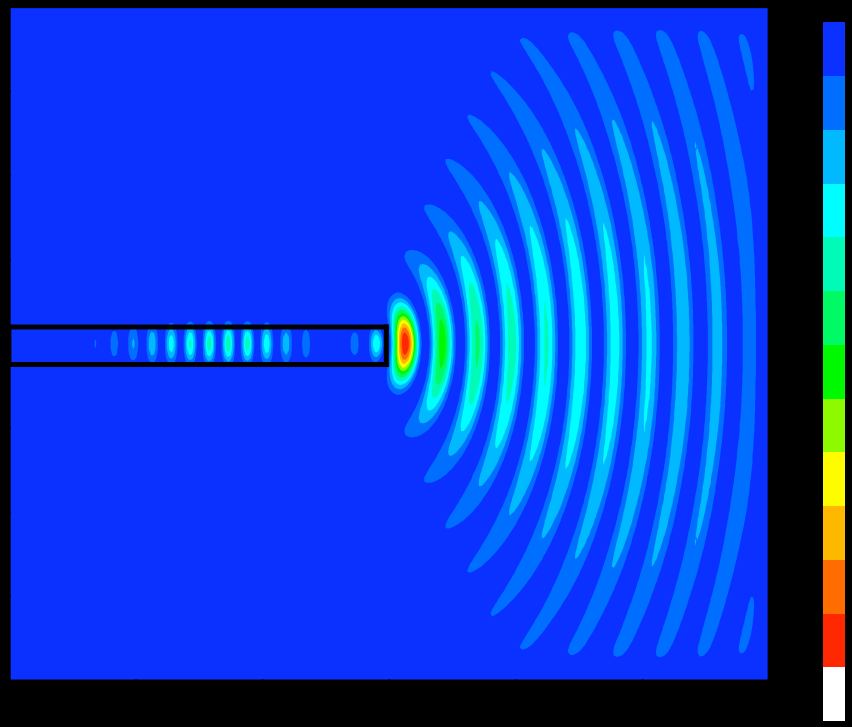
Optical coupling to the nanoscale

emission from a ZnO nanowire



Optical coupling to the nanoscale

FDTD simulation



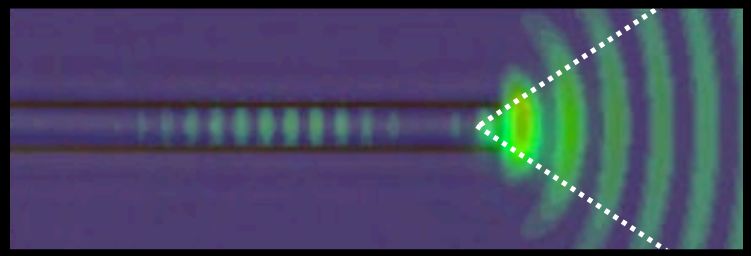
square of electric field in z direction

d_{wire} = 200 nm, l_{vacuum} = 532 nm, n = 2

software:http://ab-initio.mit.edu/wiki/index.php/Meep

Optical coupling to the nanoscale

emission from a ZnO nanowire



emission angle 80°

Optical coupling to the nanoscale

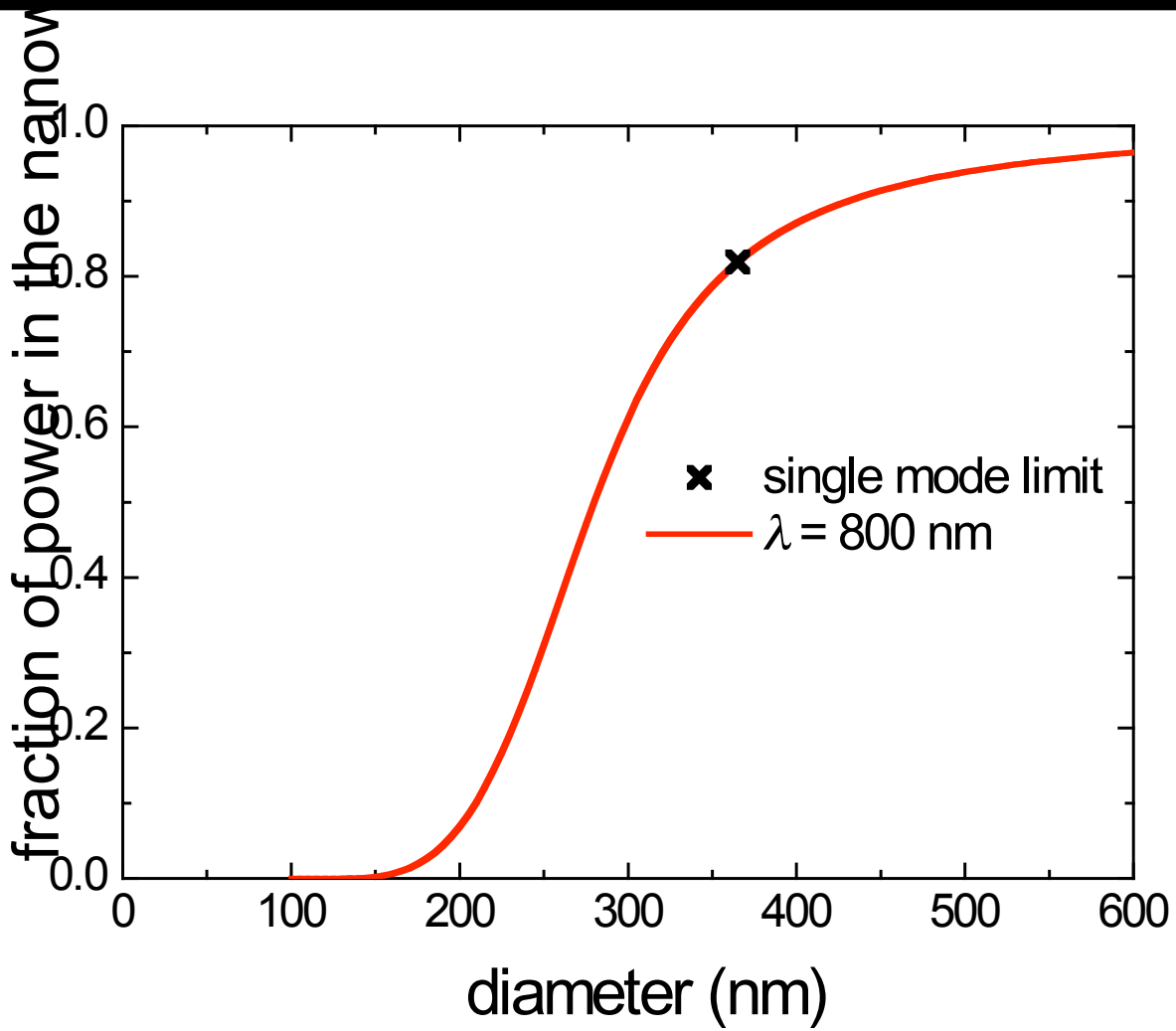
Things to keep in mind:

- link between macro and nano world
- directed emission
- large index contrast

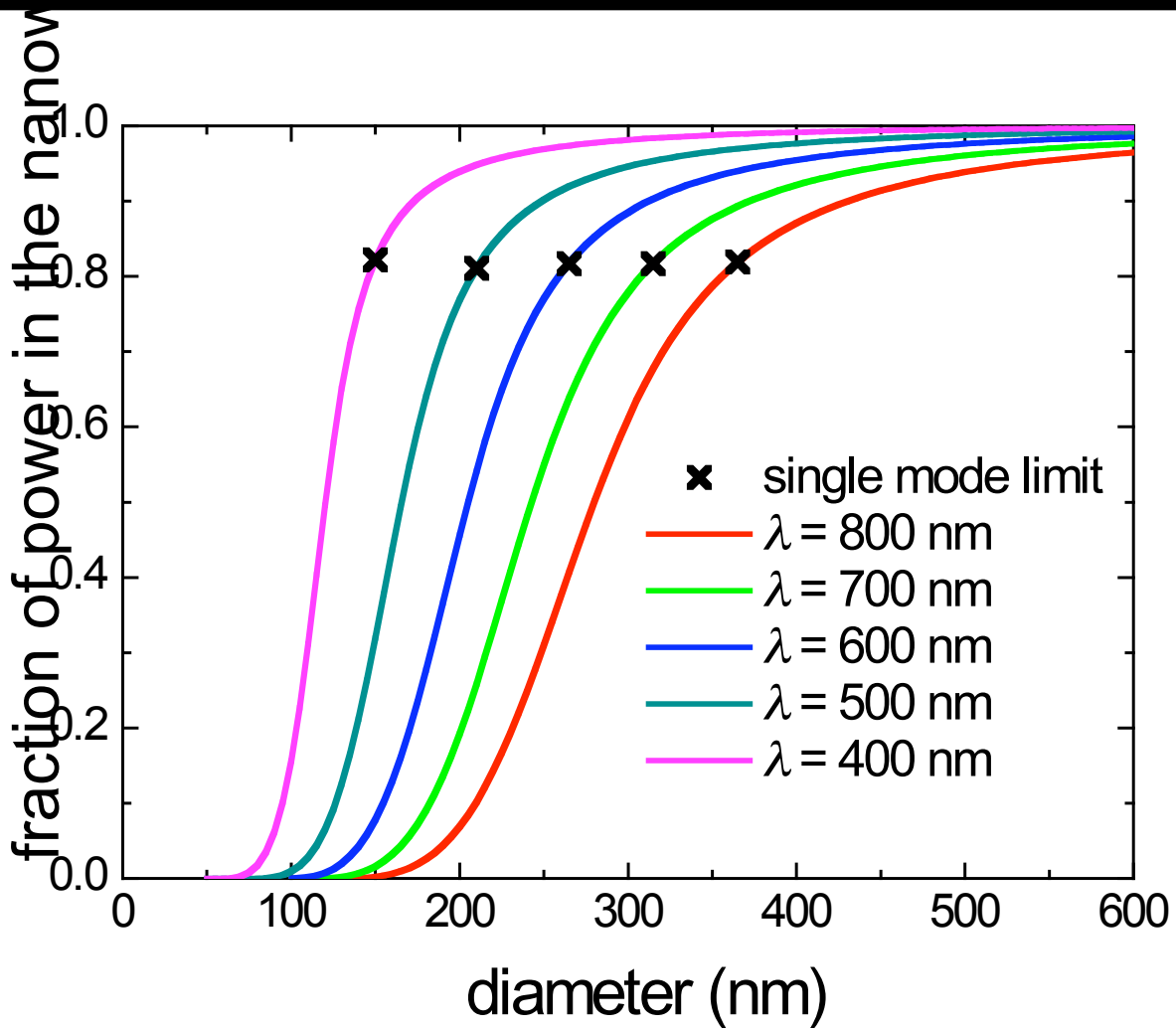
Outline

- Optical coupling to the nanoscale
- High-order mode contributions
- Nonlinear optics in ZnO nanowires

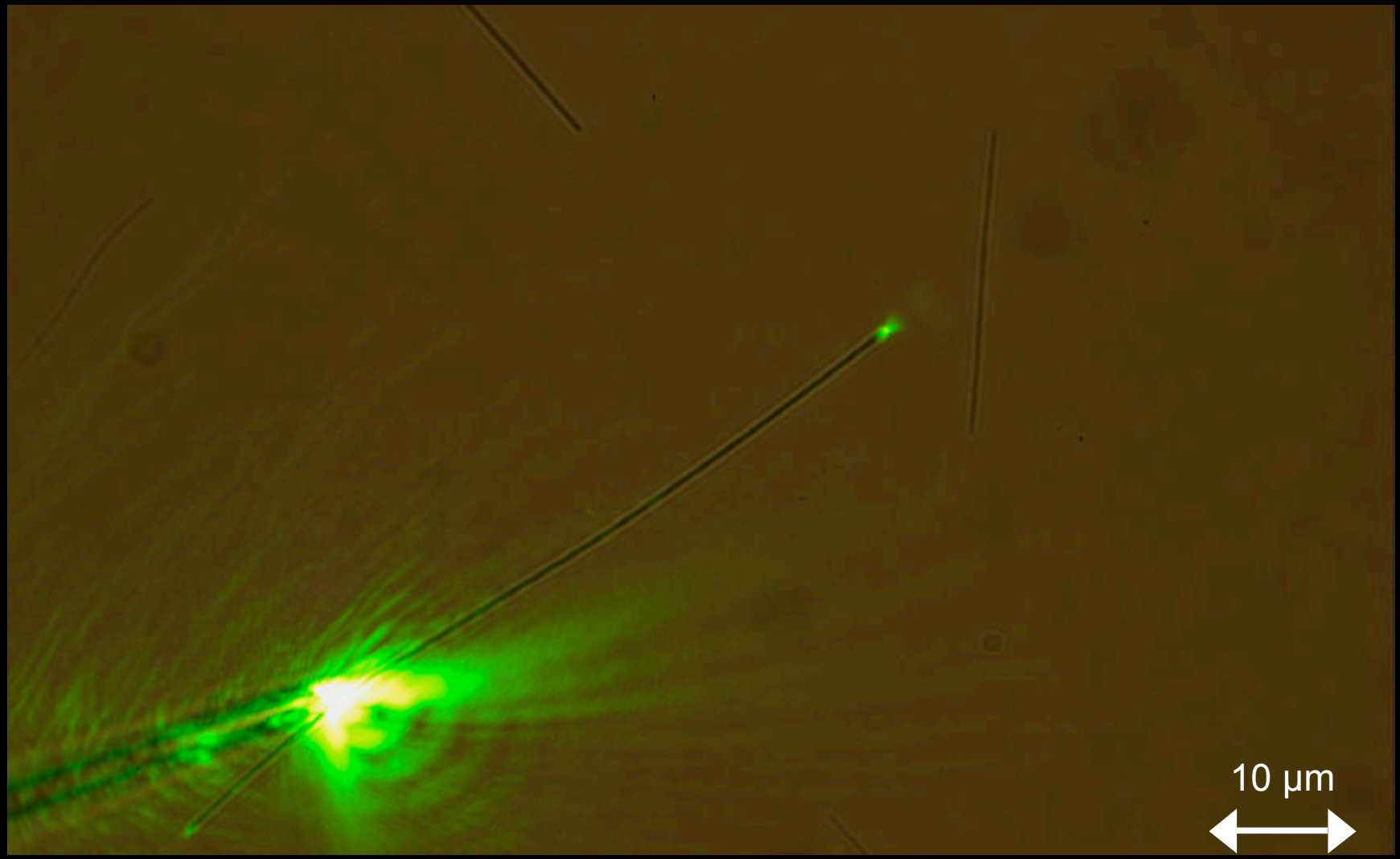
Optical coupling to the nanoscale



Optical coupling to the nanoscale



High-order mode contributions



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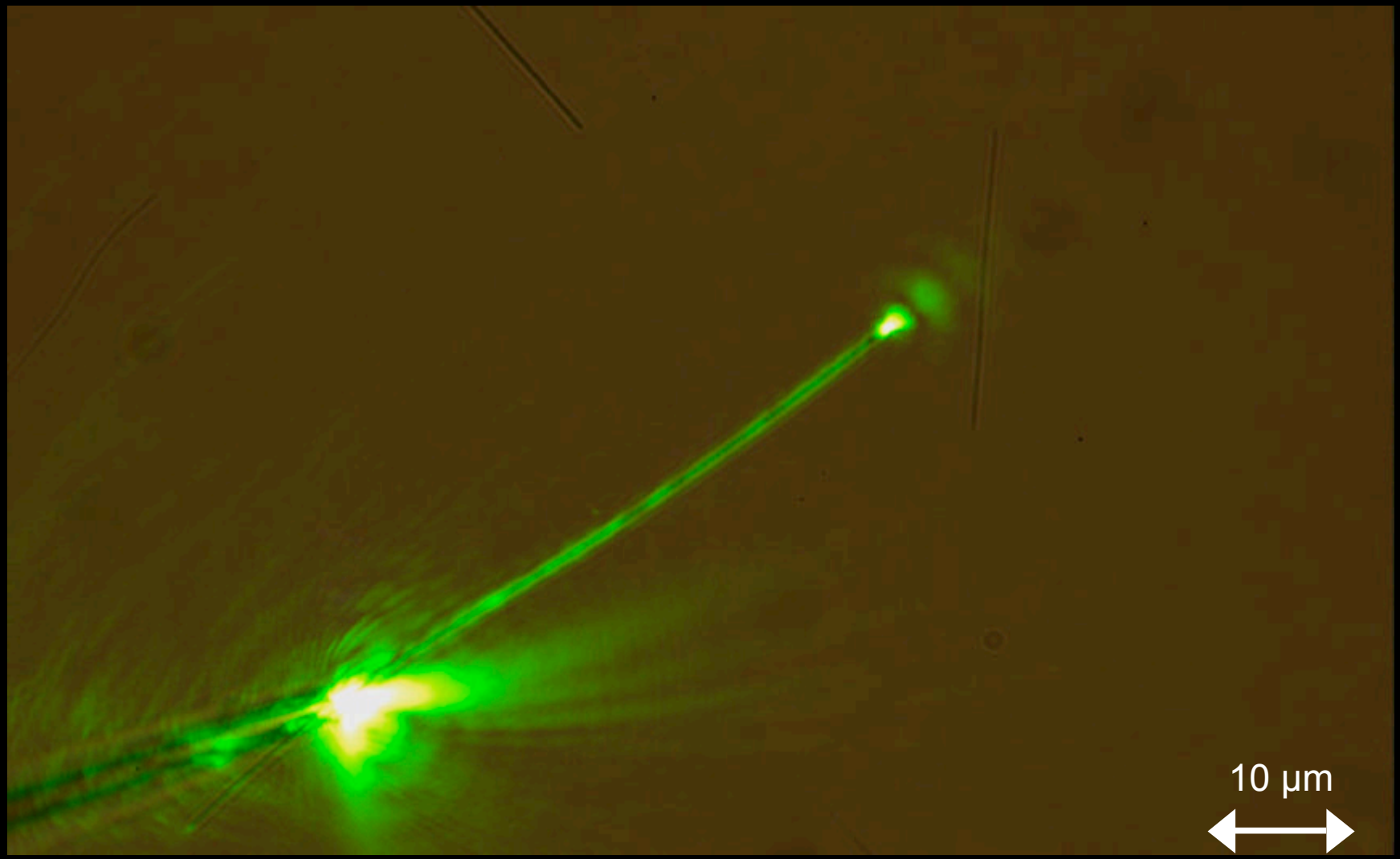
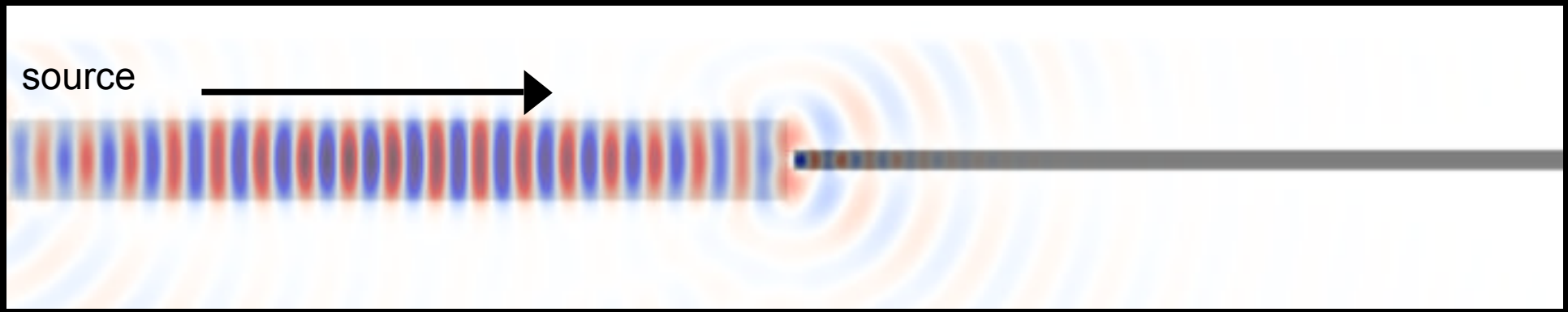


High-order mode contributions

FDTD simulations

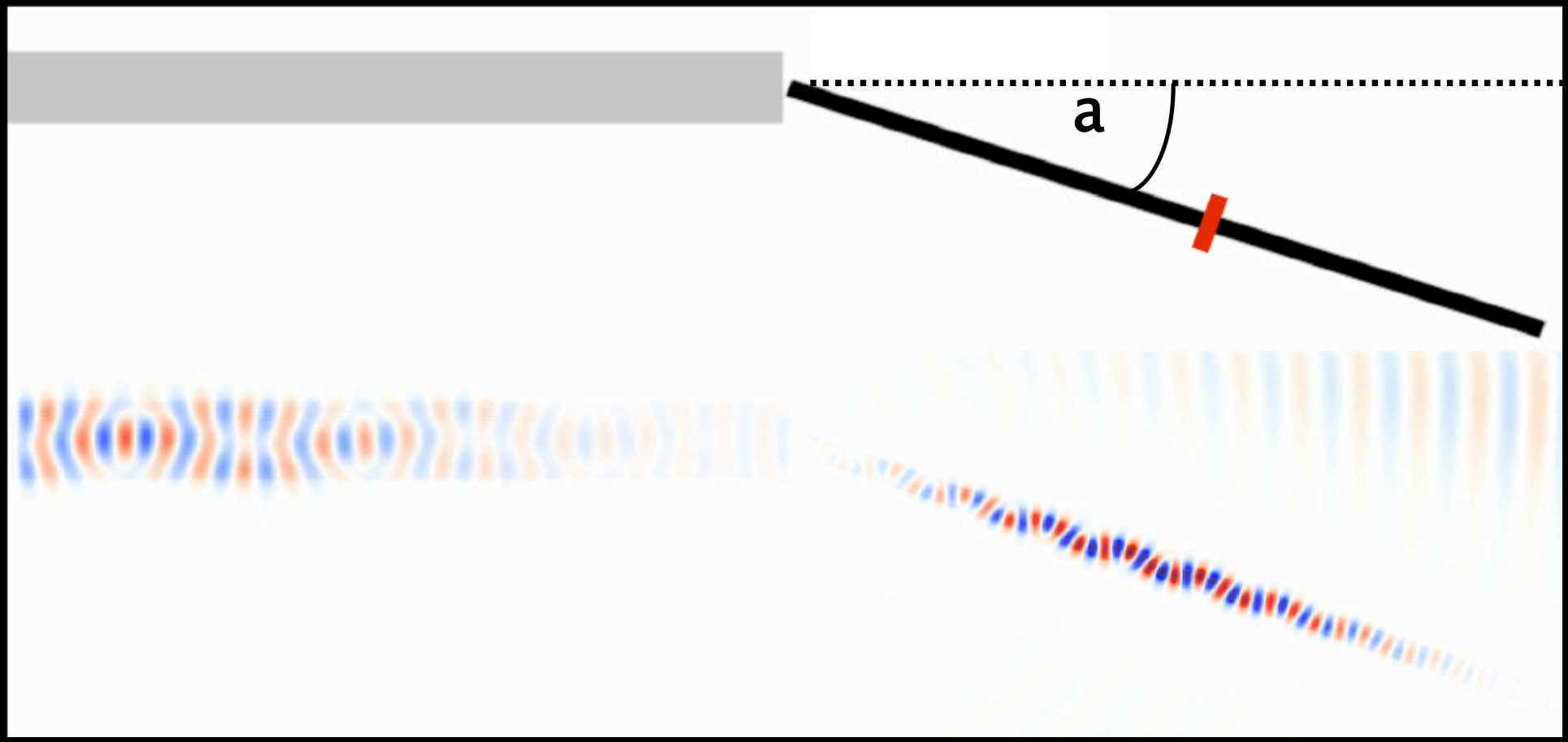
z component of electric field



(negative – zero – positive)

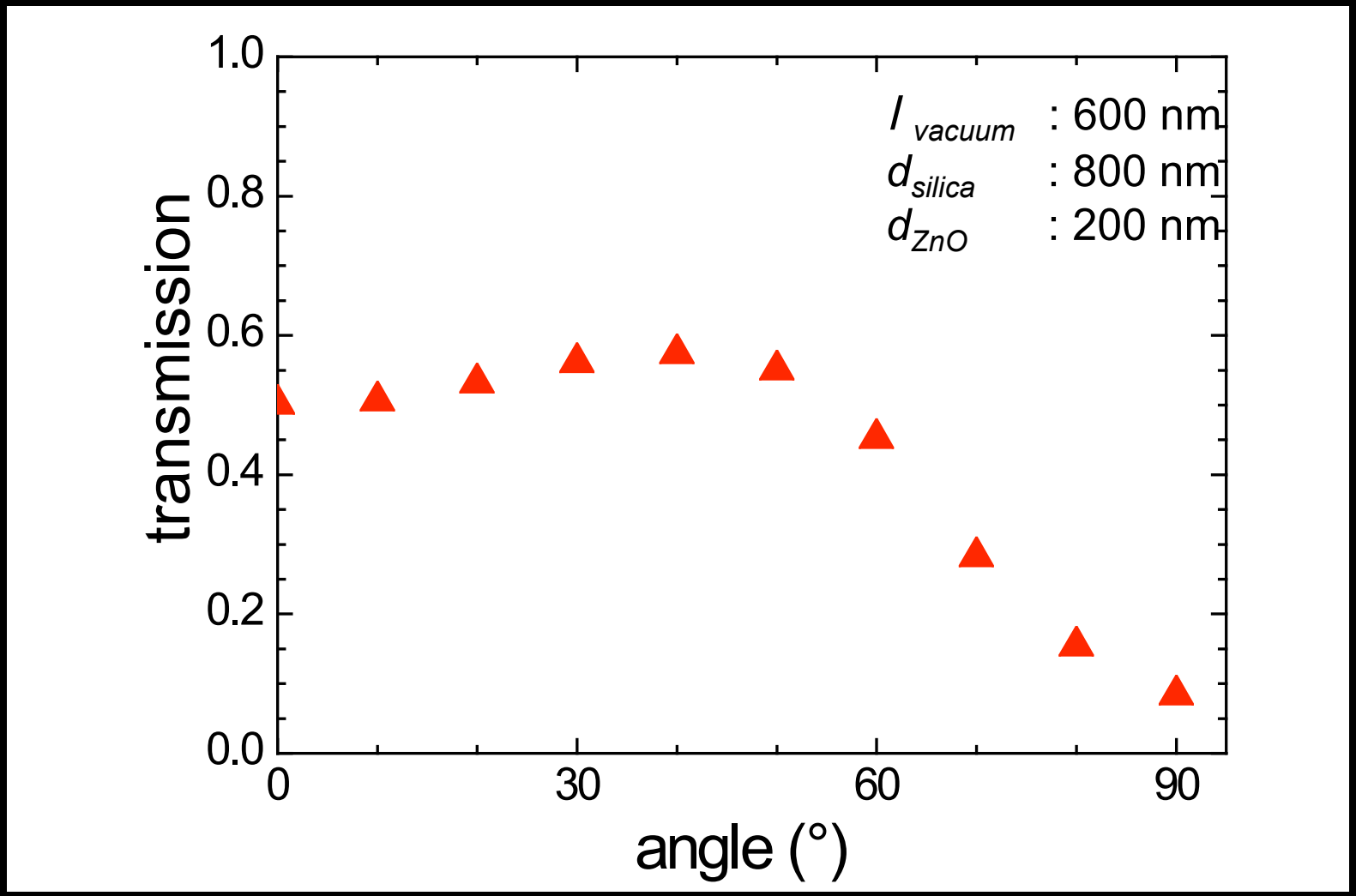
High-order mode contributions

FDTD simulations



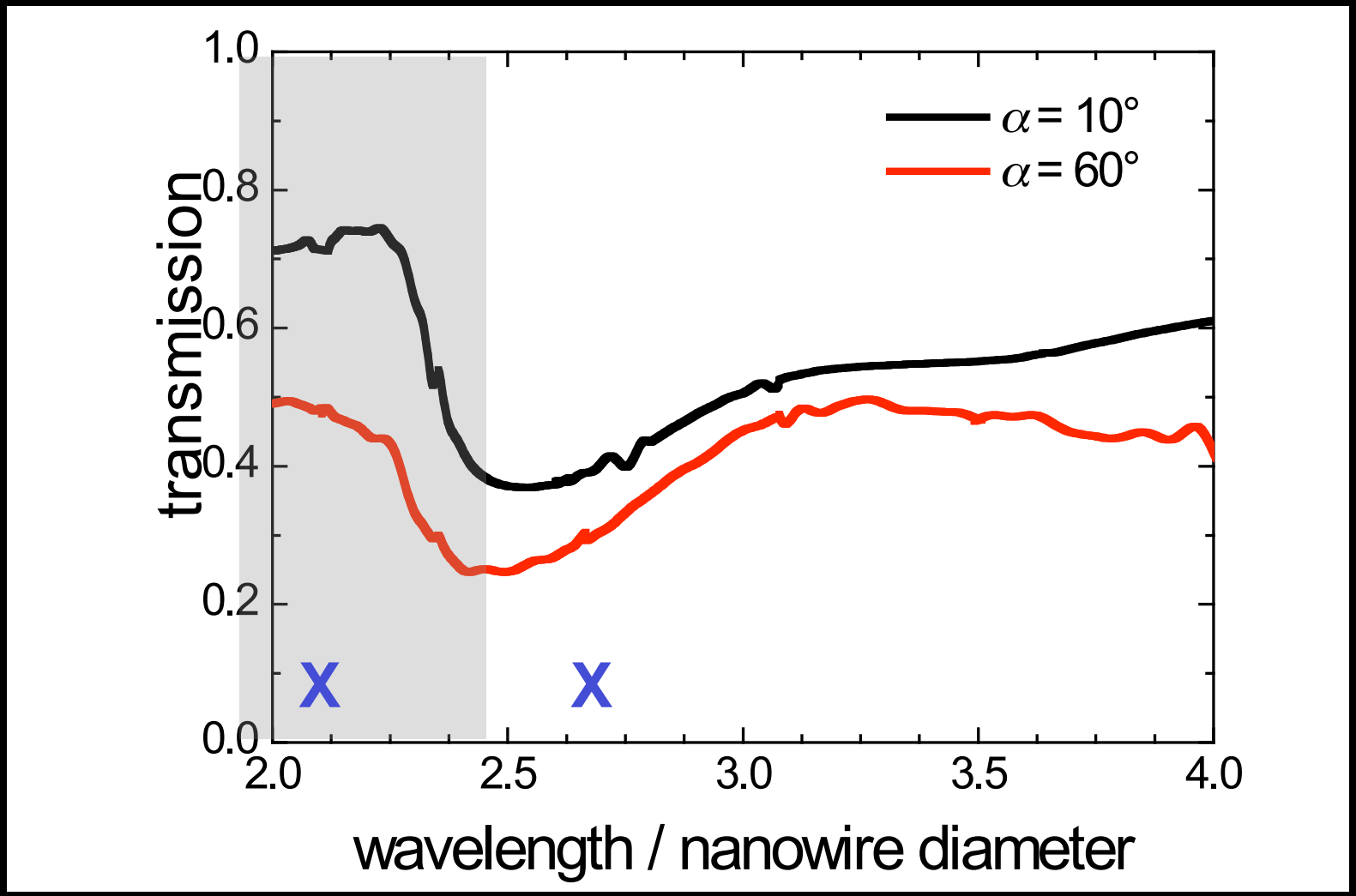
High-order mode contributions

coupling efficiency



High-order mode contributions

transmission spectrum

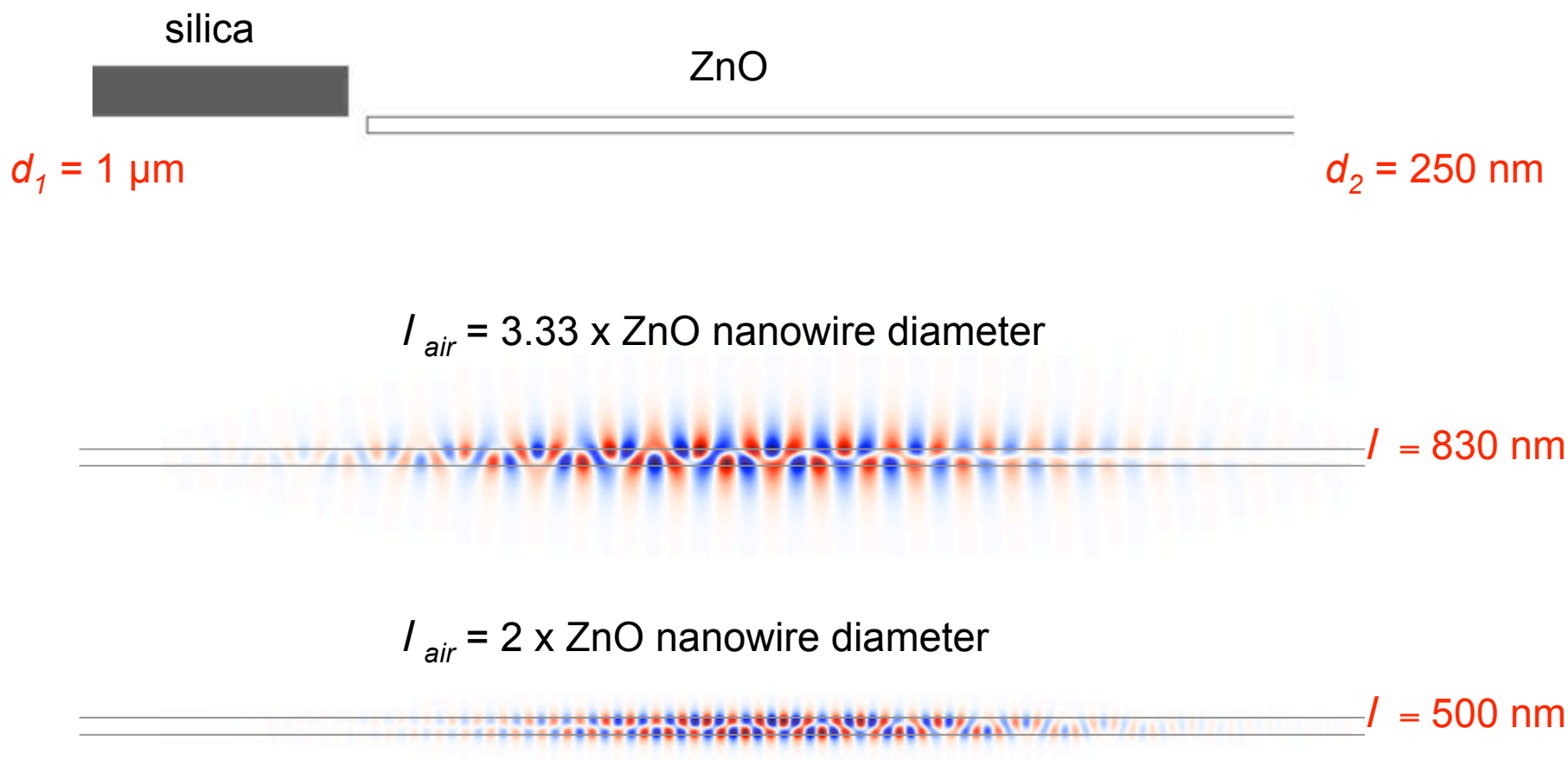


High-order mode contributions

l_{air} = 2.8 x wire diameter

l_{air} = 2.2 x wire diameter

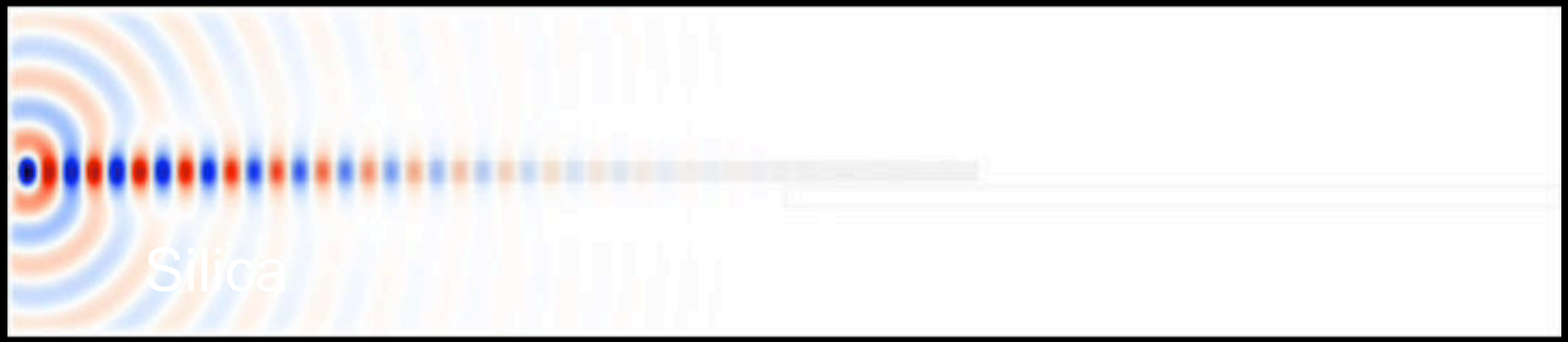
High-order mode contributions



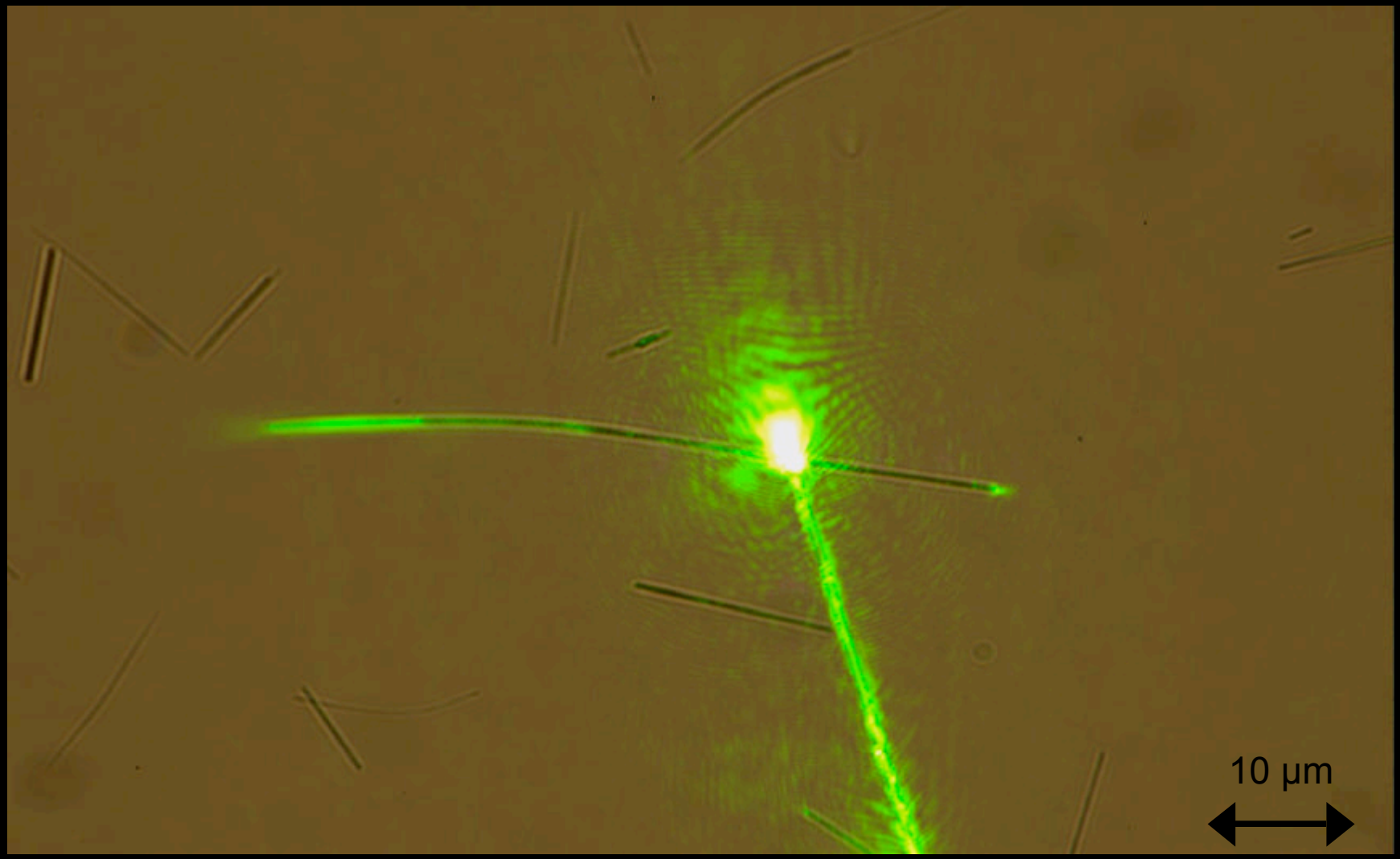
High-order mode contributions

evanescent coupling from silica to ZnO

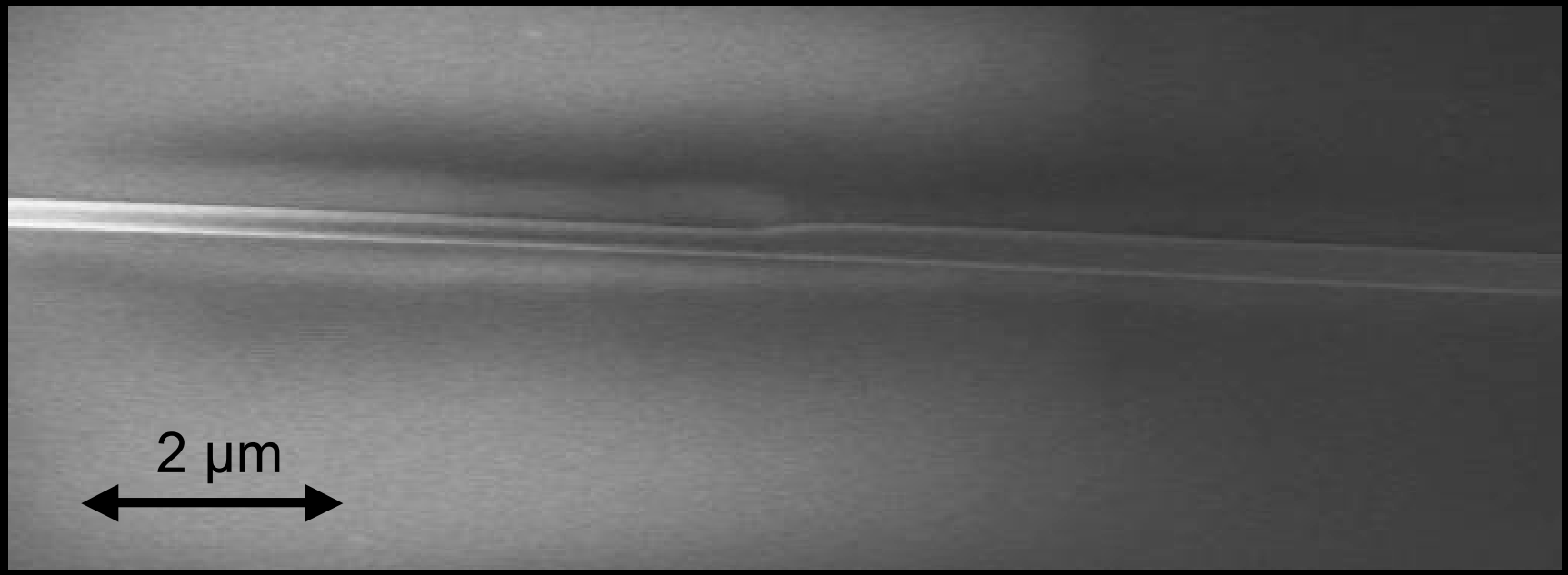
wire diameters: 1 a.u. separation: 0.2 a.u. wavelength: 3 a.u.



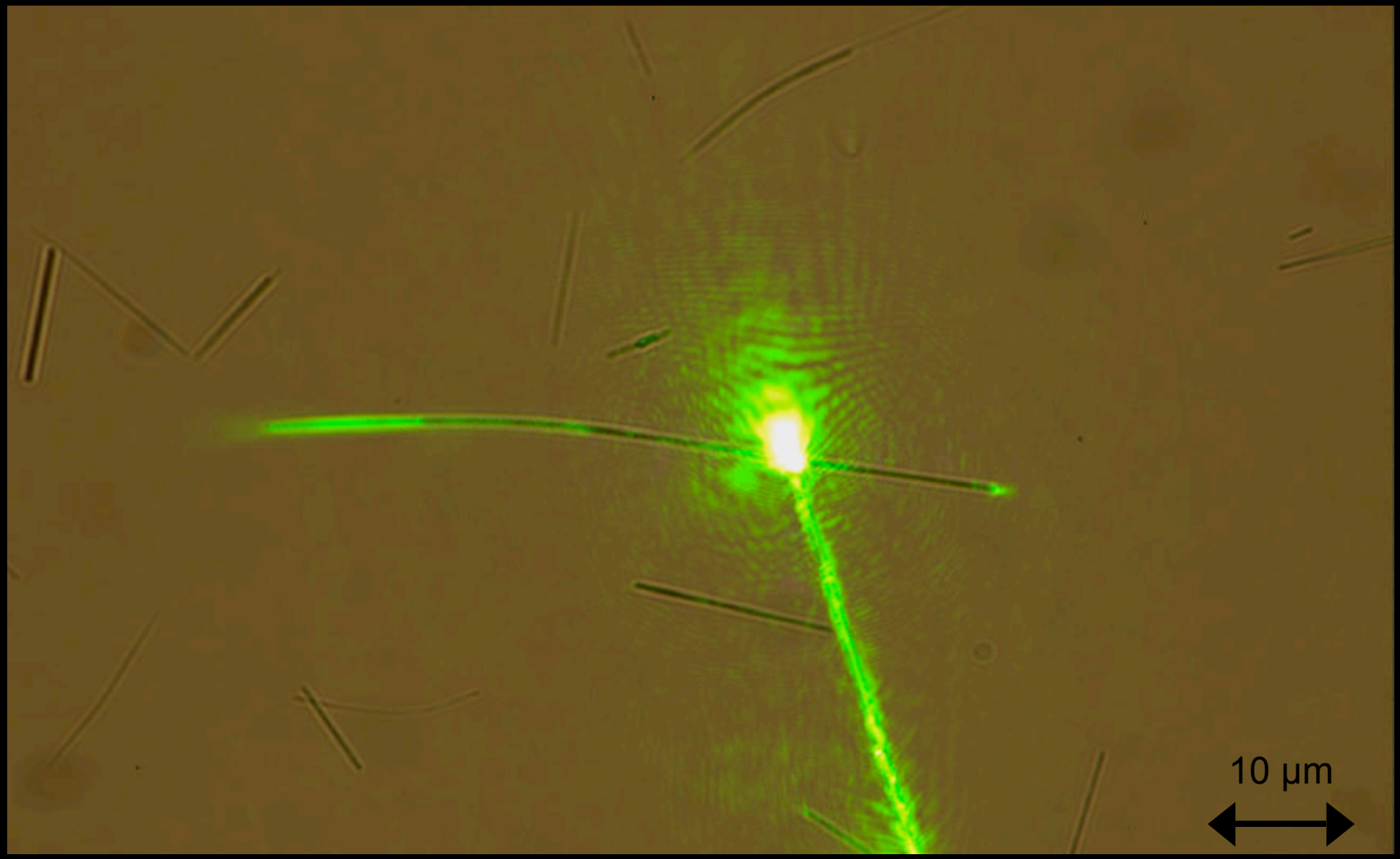
High-order mode contributions



High-order mode contributions



High-order mode contributions



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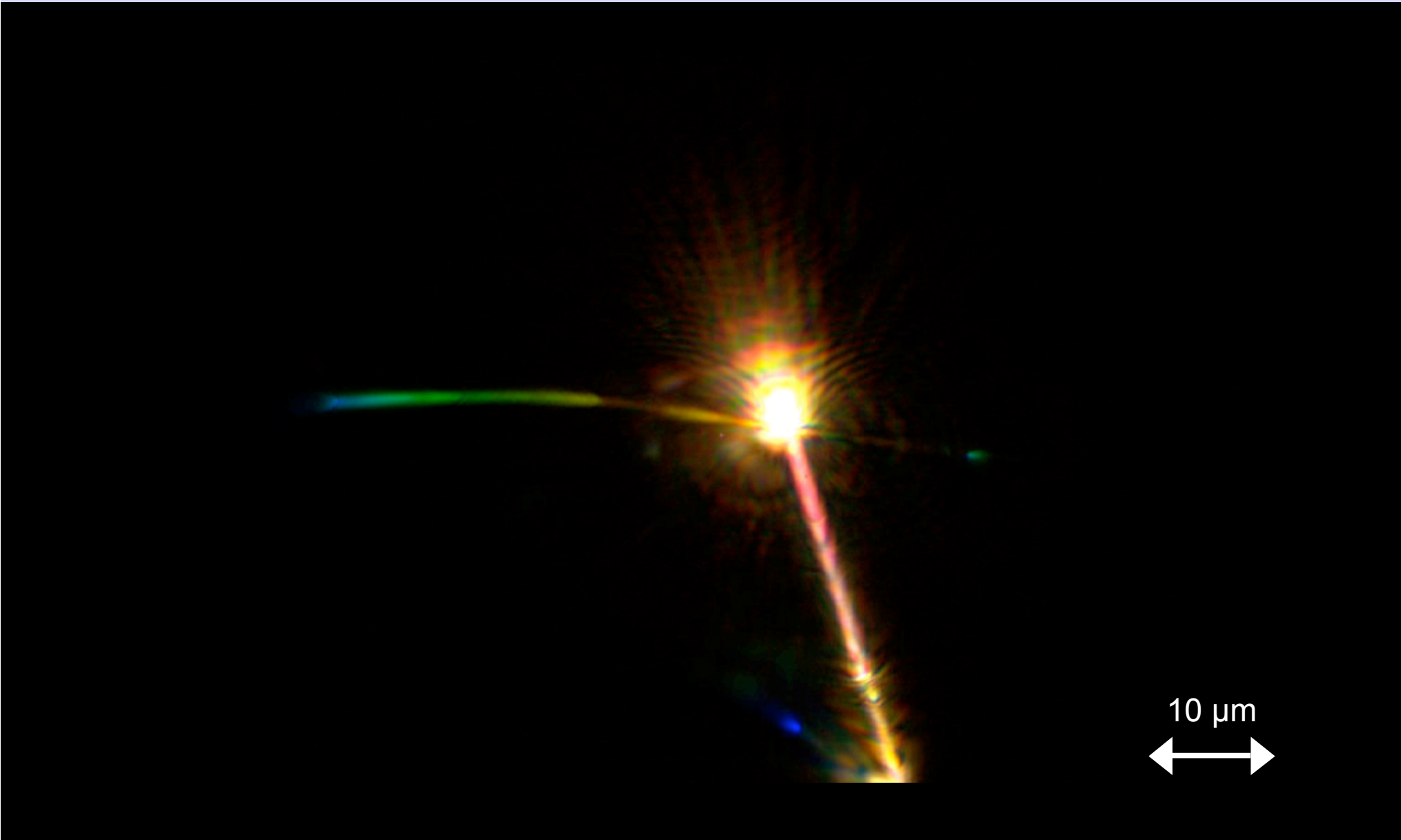


High-order mode contributions

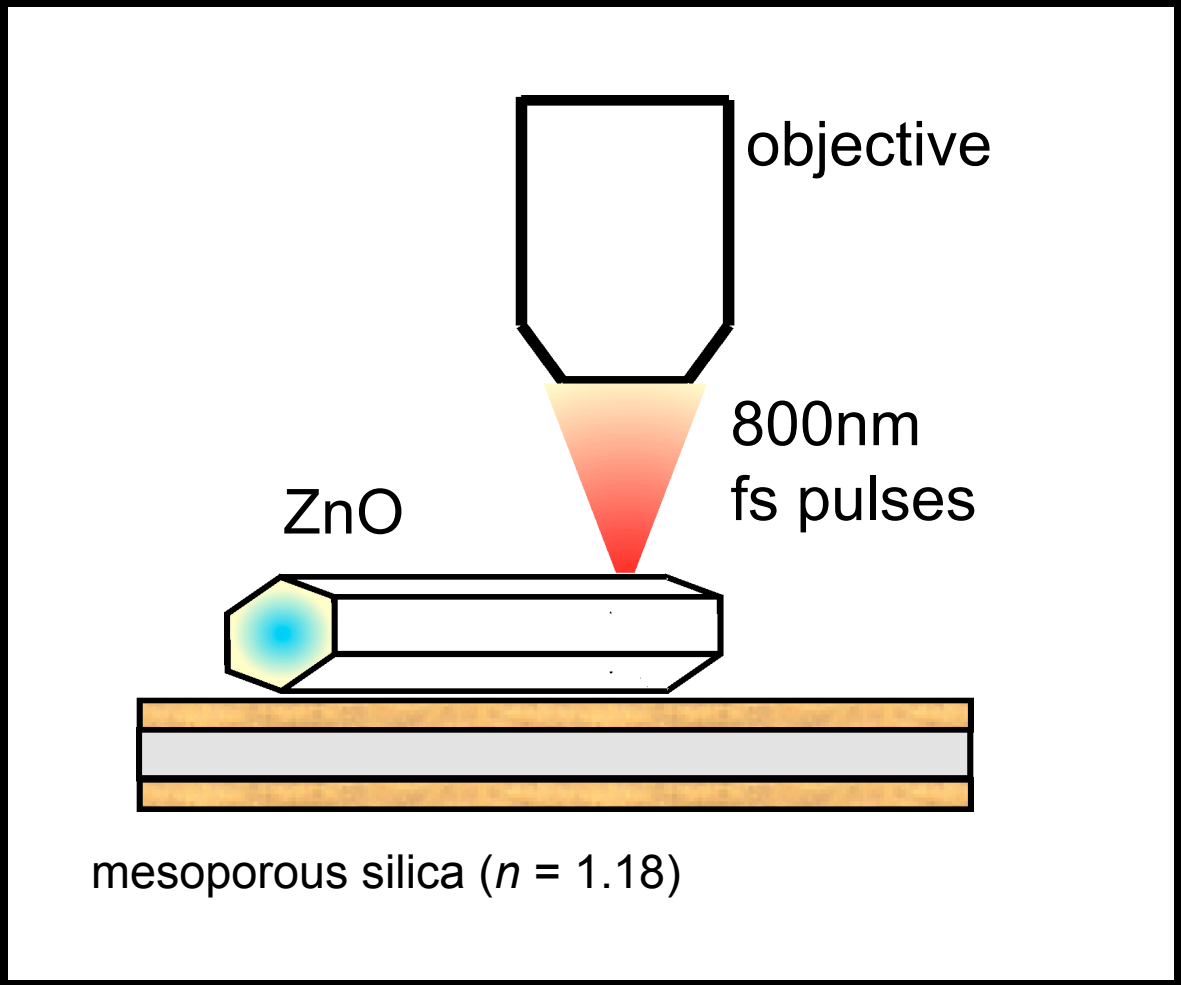
Things to keep in mind:

- single or multi-mode waveguiding
- wavelength-dependent losses

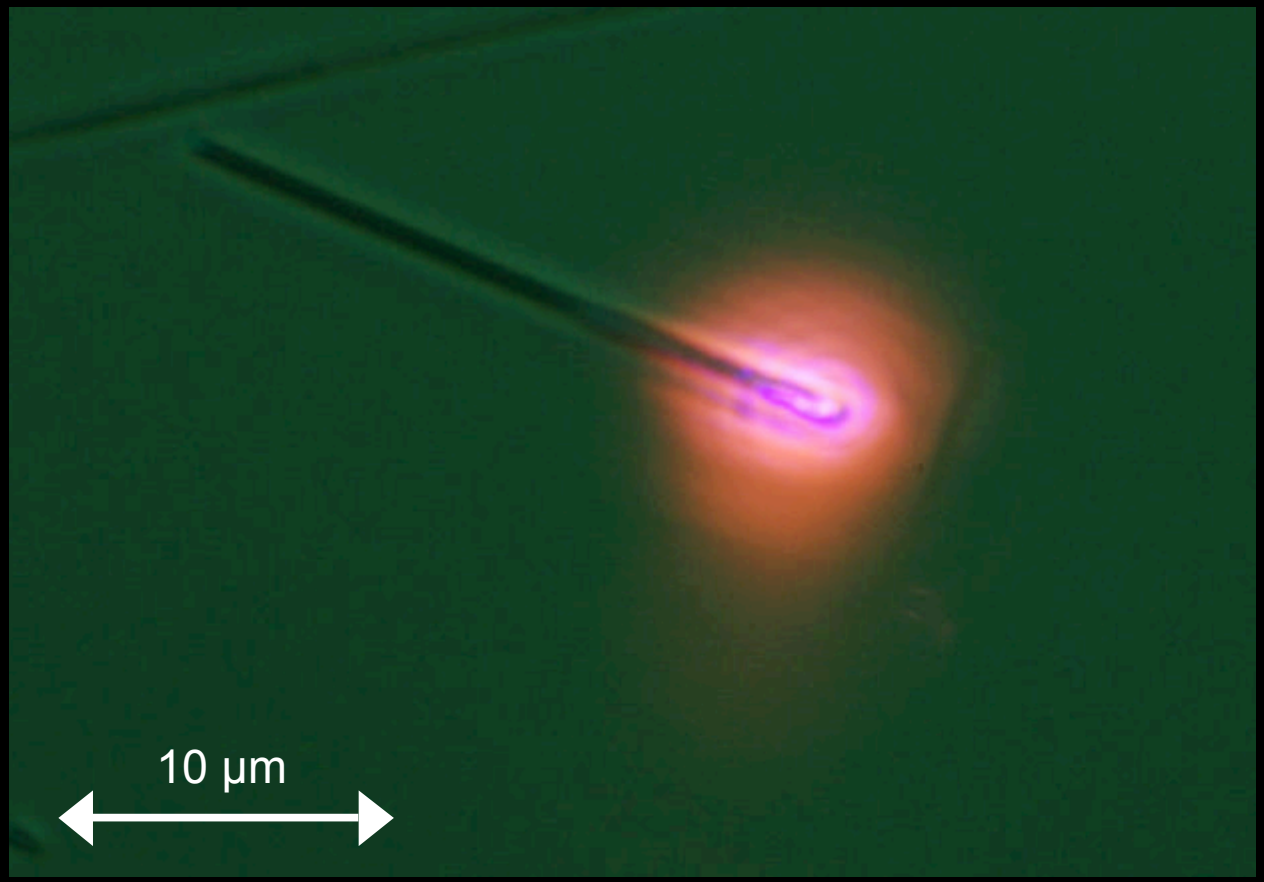
Outline

- Optical coupling to the nanoscale
- High-order mode contributions
- Nonlinear optics in ZnO nanowires

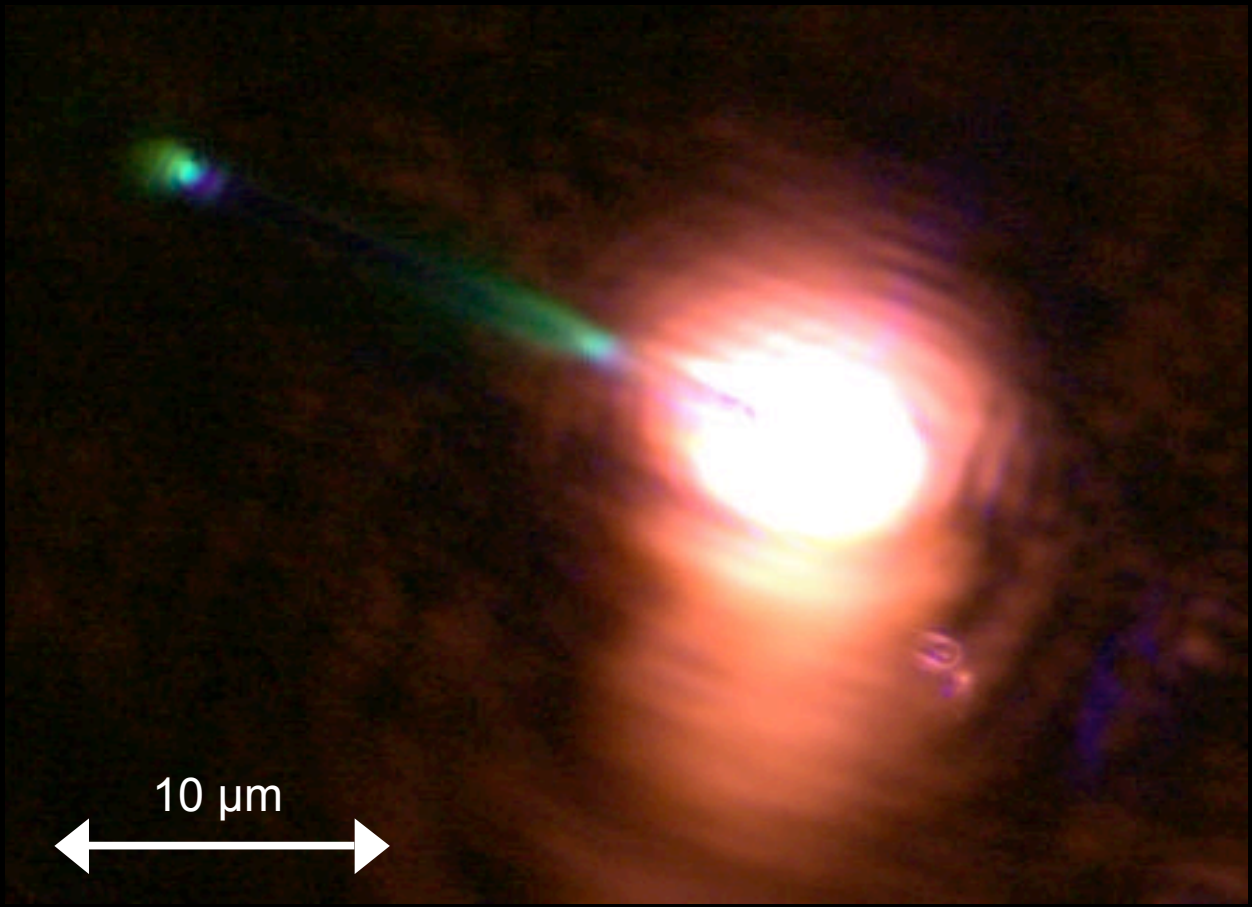
Non-linear optics in ZnO nanowires



Non-linear optics in ZnO nanowires



Non-linear optics in ZnO nanowires



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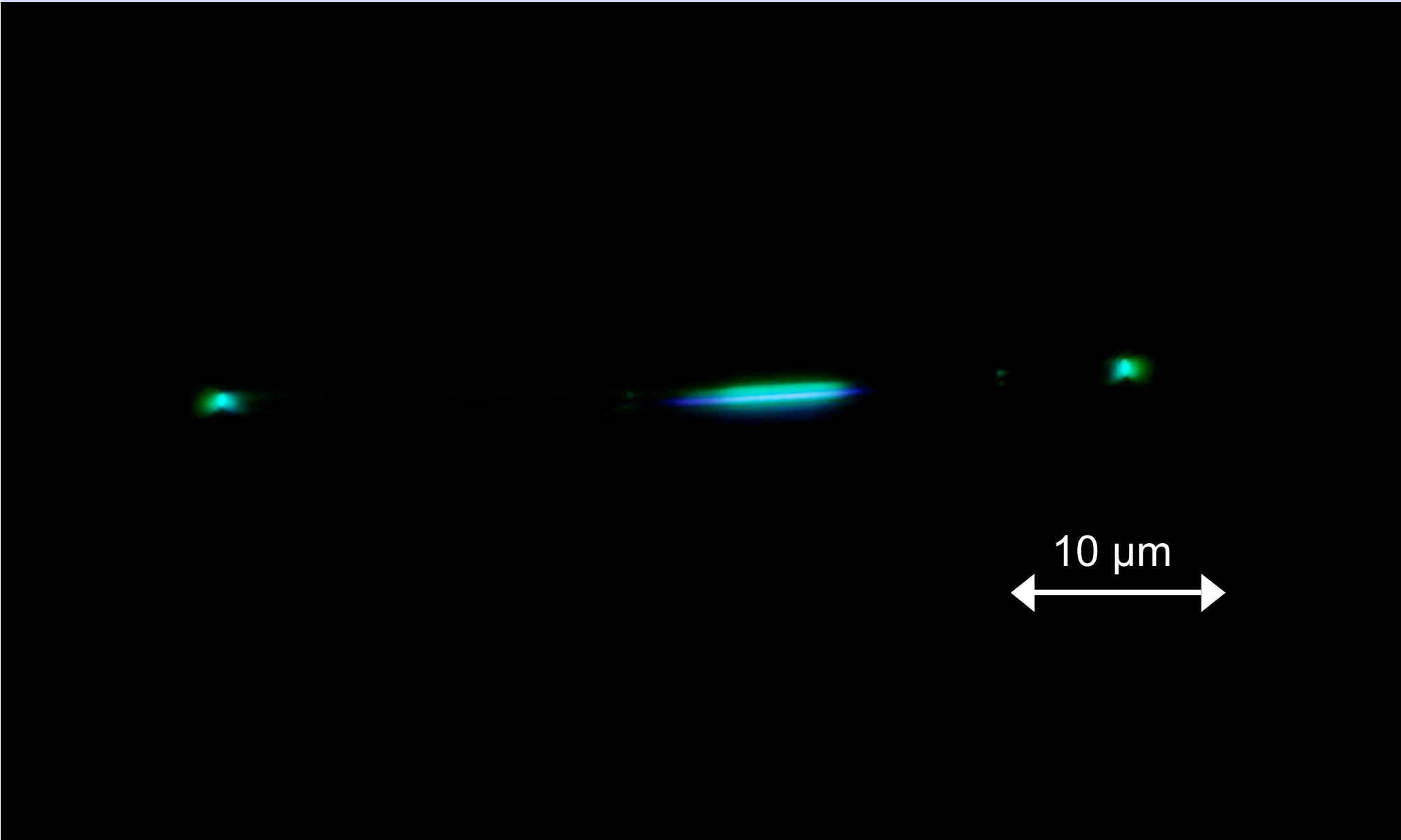
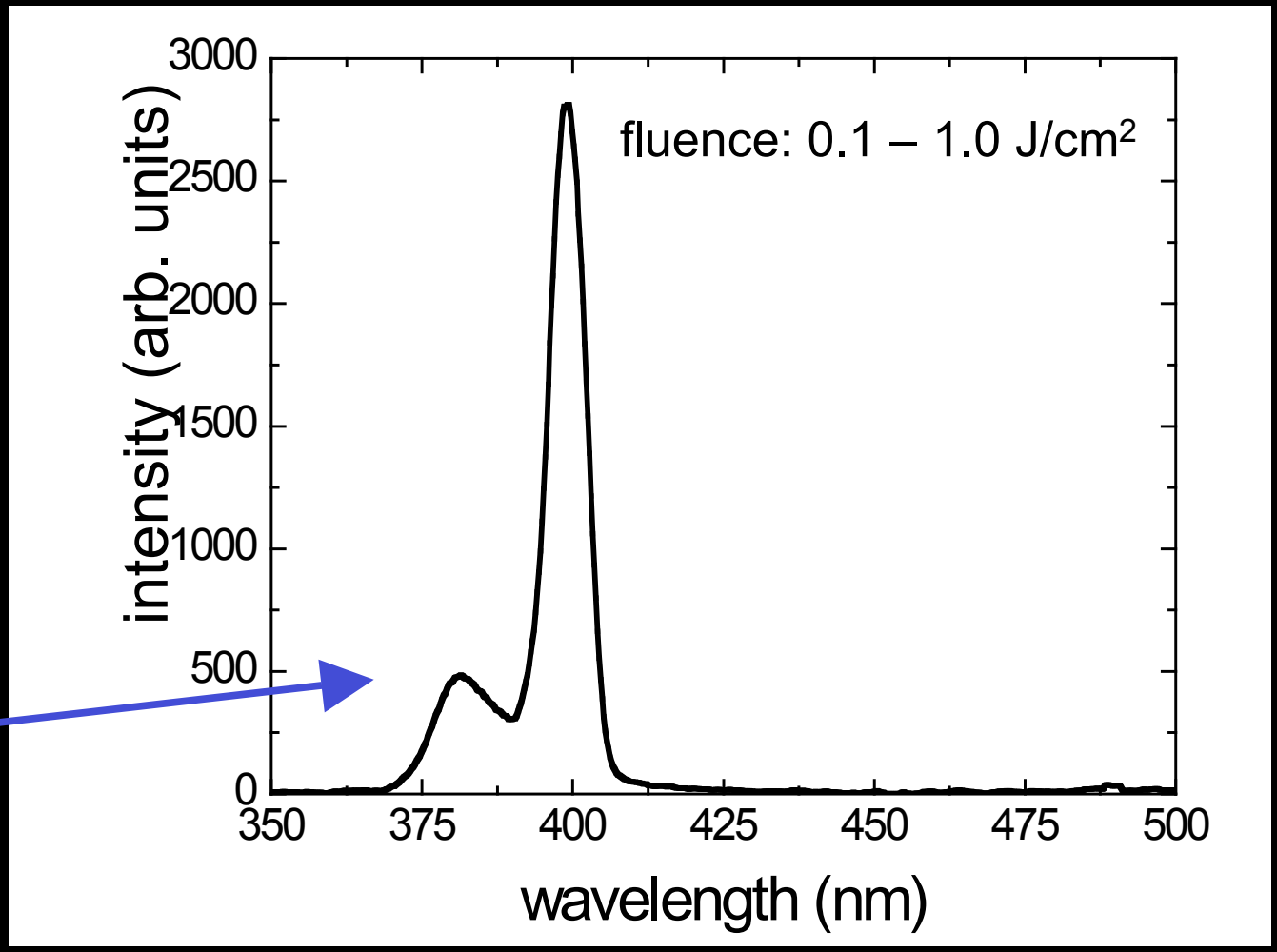
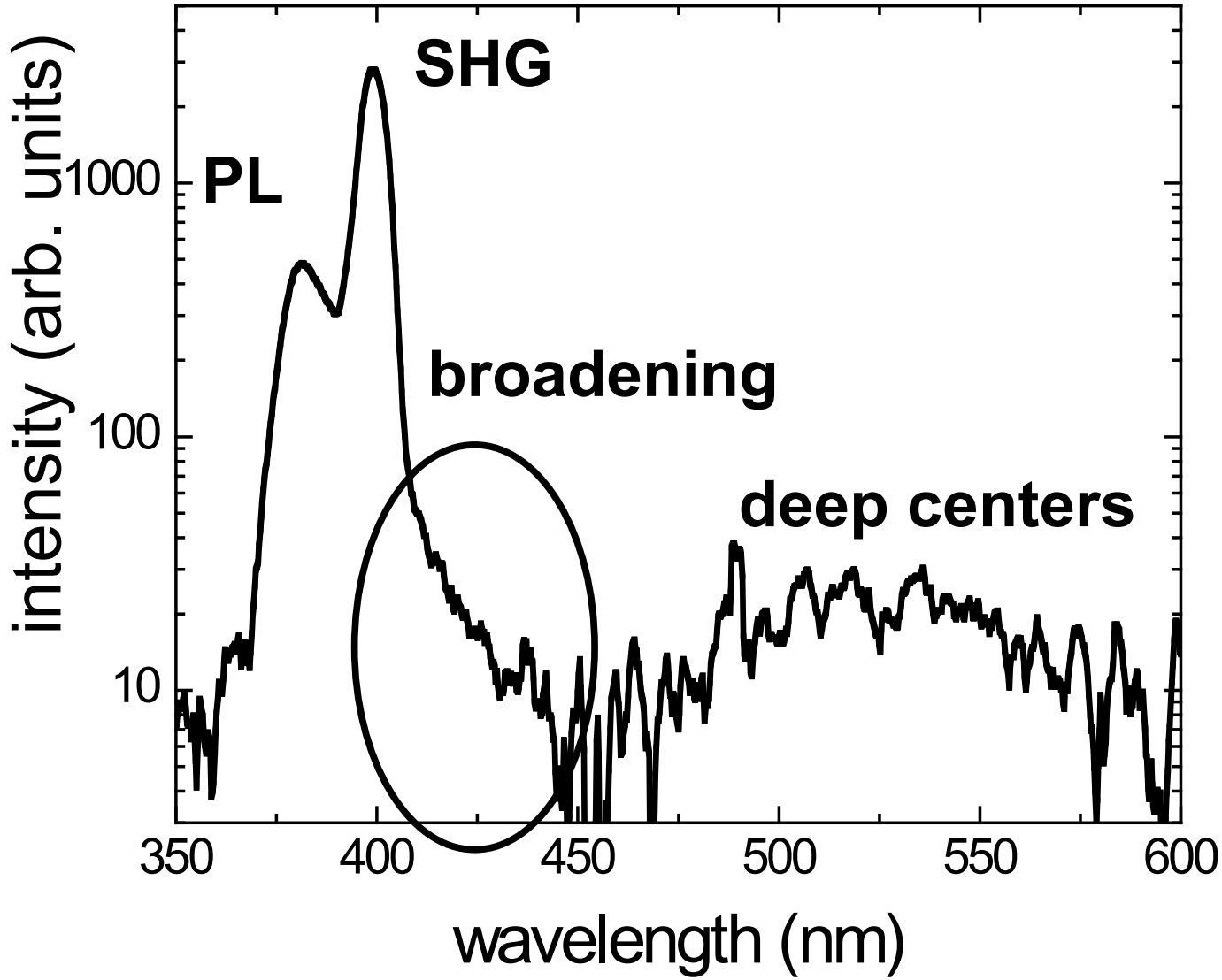


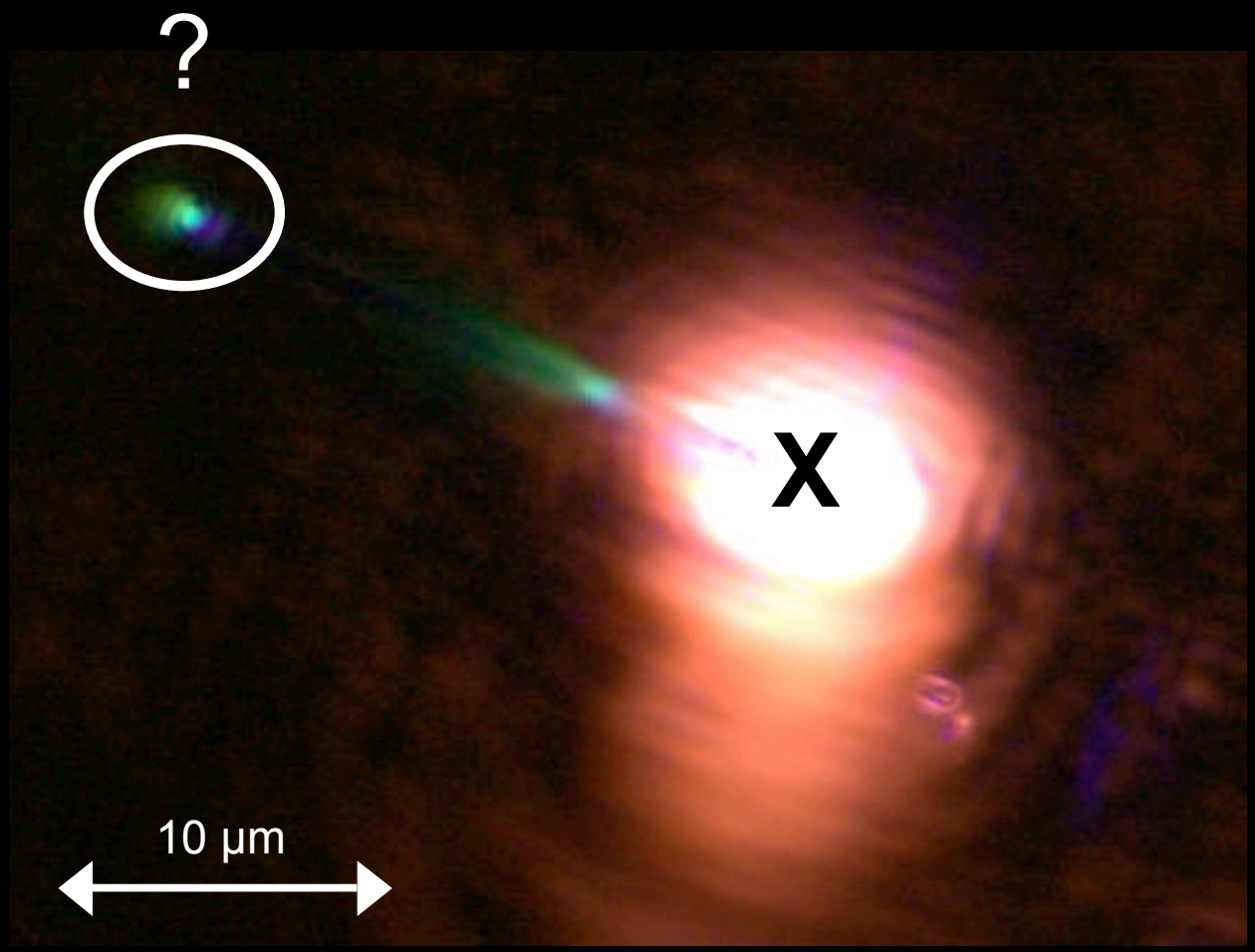
Non-linear optics in ZnO nanowires



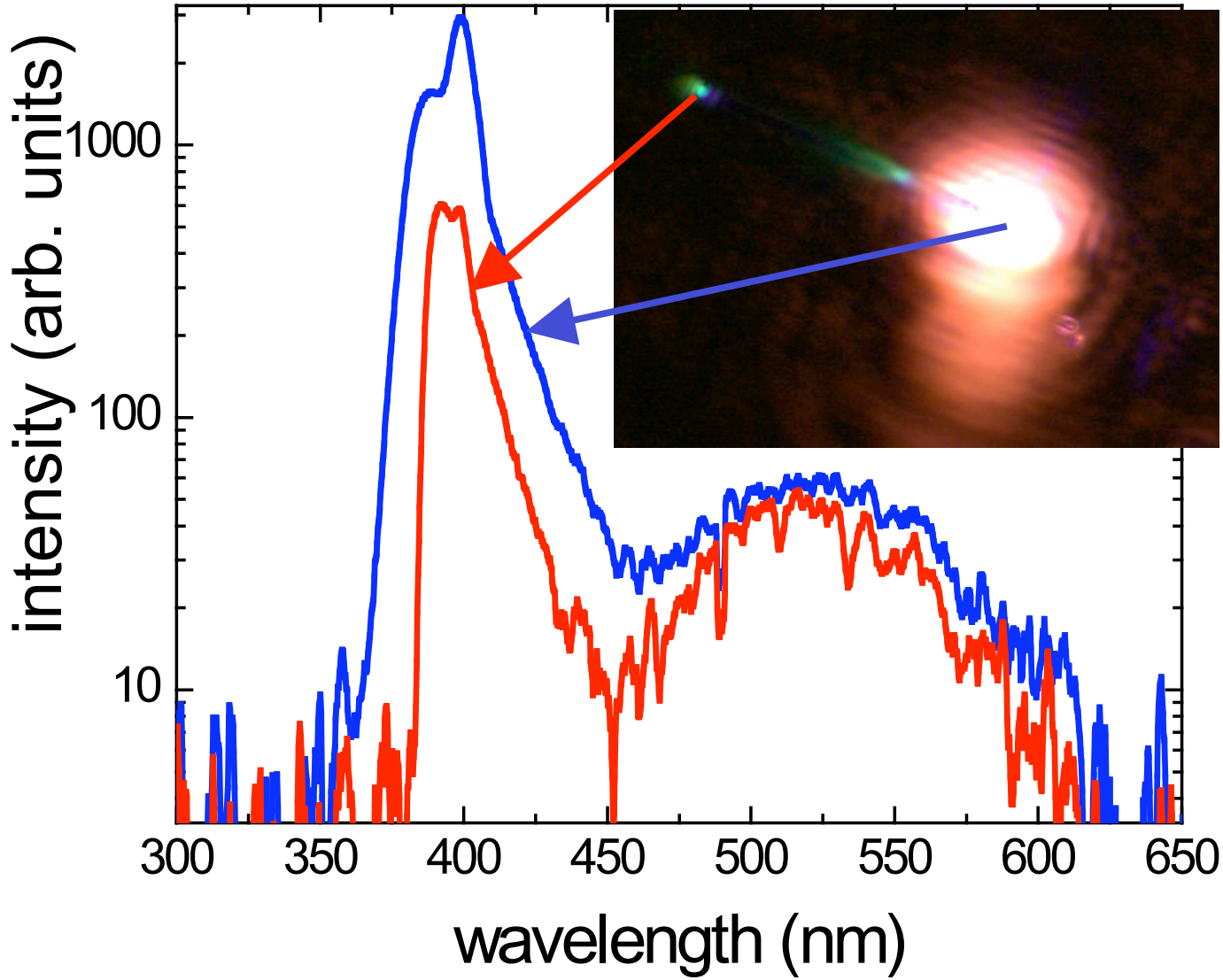
Non-linear optics in ZnO nanowires



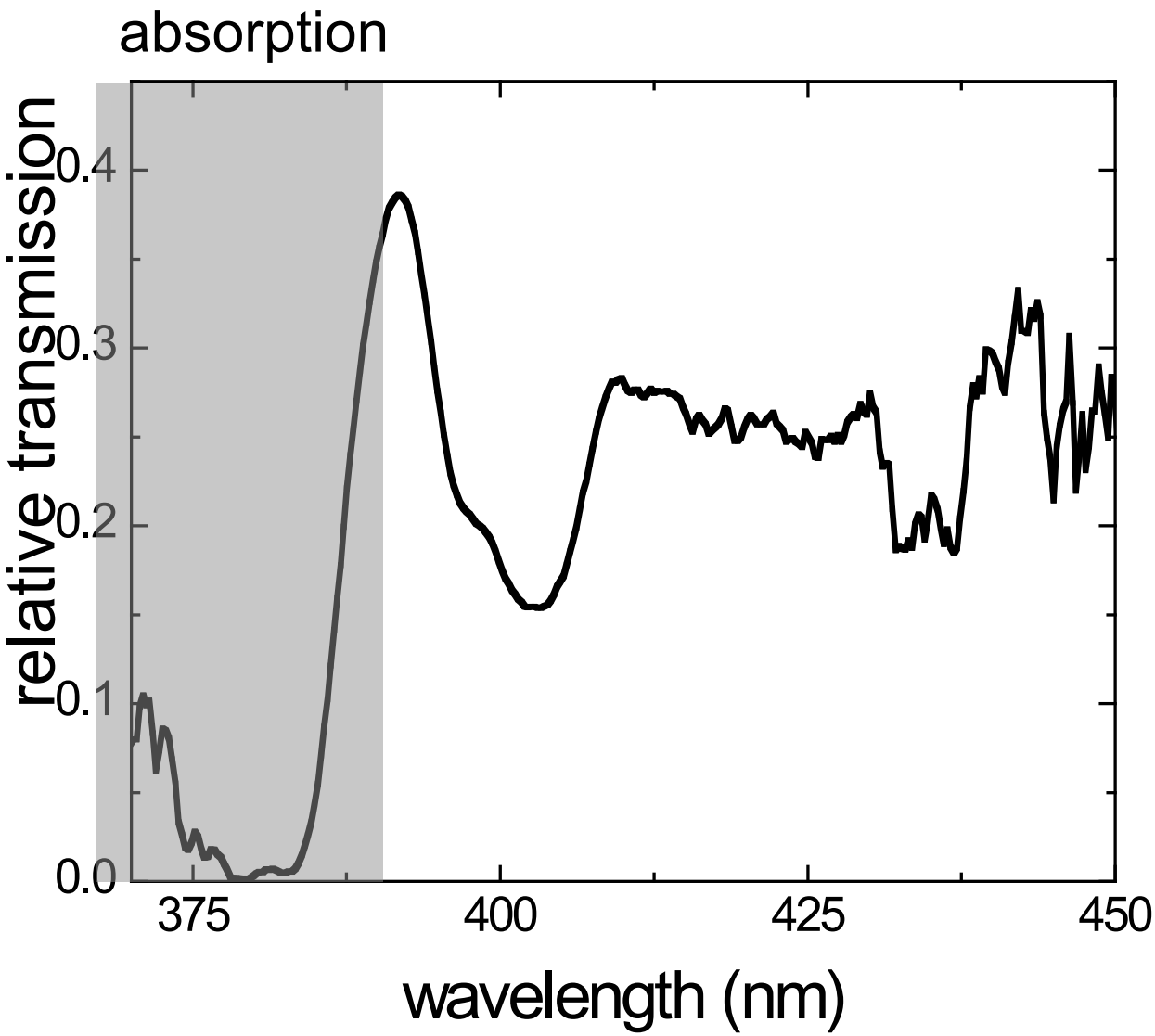
Non-linear optics in ZnO nanowires



Non-linear optics in ZnO nanowires



Non-linear optics in ZnO nanowires



Non-linear optics in ZnO nanowires

Band gap at room temperature (literature)

E_{gap} = 3.370 eV

Non-linear optics in ZnO nanowires

Band gap at room temperature (literature)

E_{gap} = 3.370 eV

Band gap from transmission spectrum

E_{gap} = (3.205 ± 0.025) eV

Band gap shift

DE = (165 ± 25) meV

Non-linear optics in ZnO nanowires

Effective temperature of the ZnO nanowire

$T = (550 \pm 50)$ K

Non-linear optics in ZnO nanowires

Things to keep in mind:

- non-linear excitation of waveguide modes
- absorption measurement indicates band-gap shift

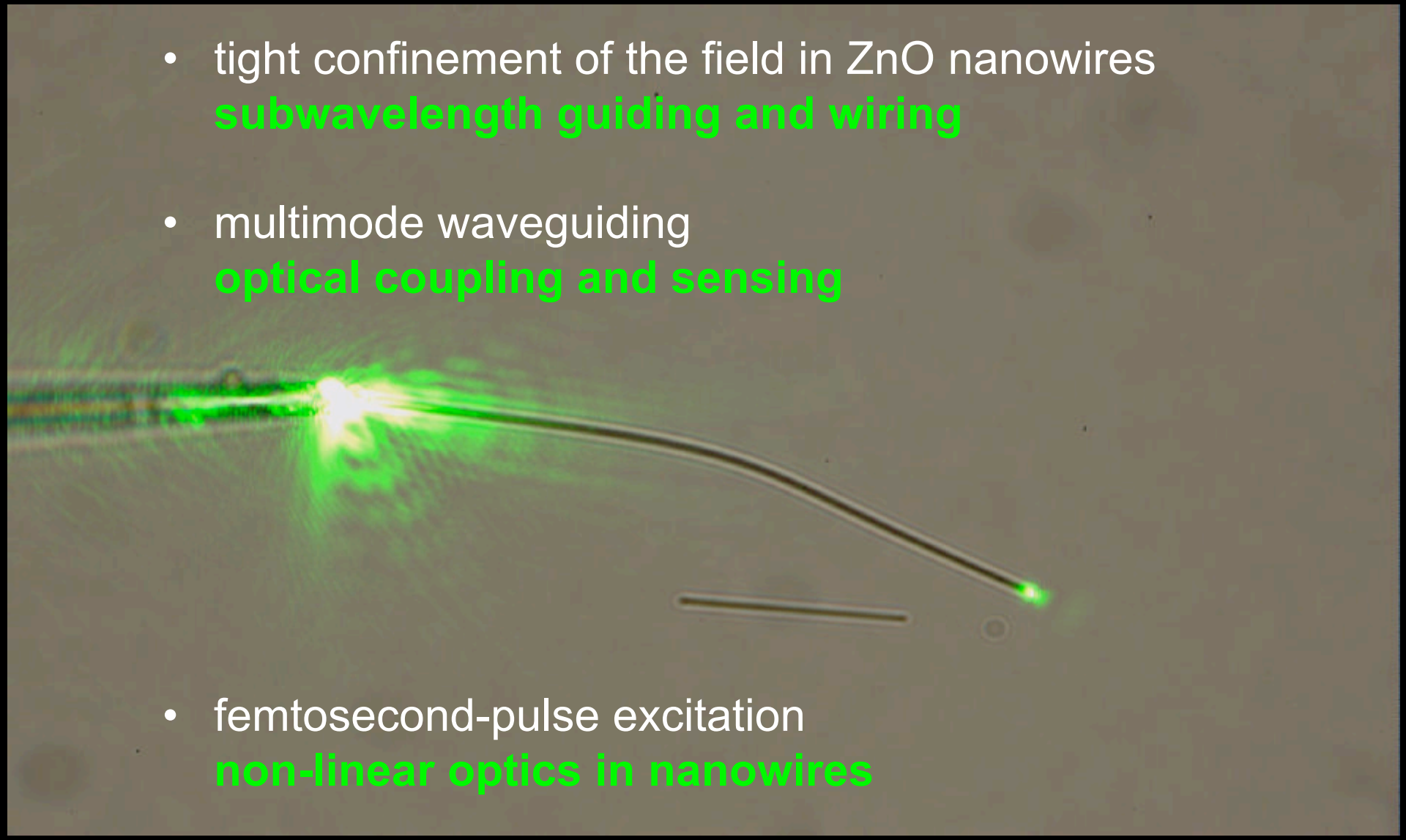
Summary and Conclusions

- Efficient coupling from silica to ZnO nanowires
- High-order waveguide modes
- Absorption measurement of band-gap shift

Outlook

- tight confinement of the field in ZnO nanowires
  subwavelength guiding and wiring

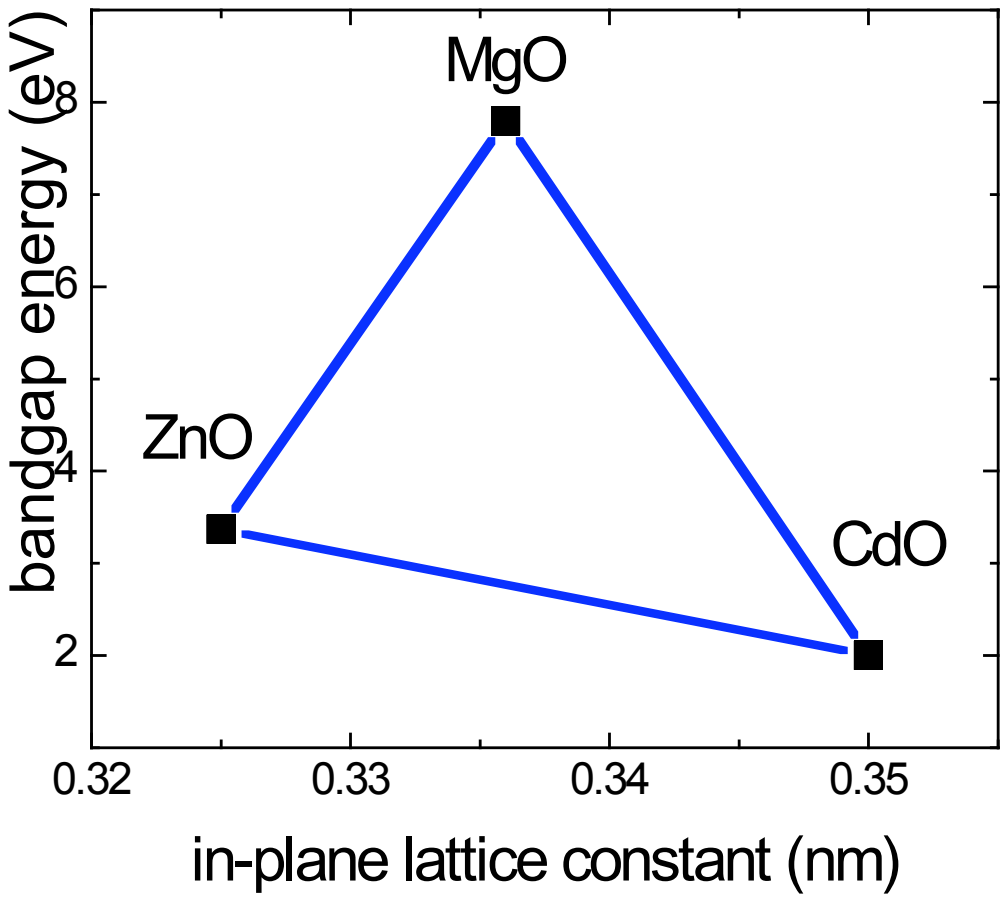
- multimode waveguiding
  optical coupling and sensing



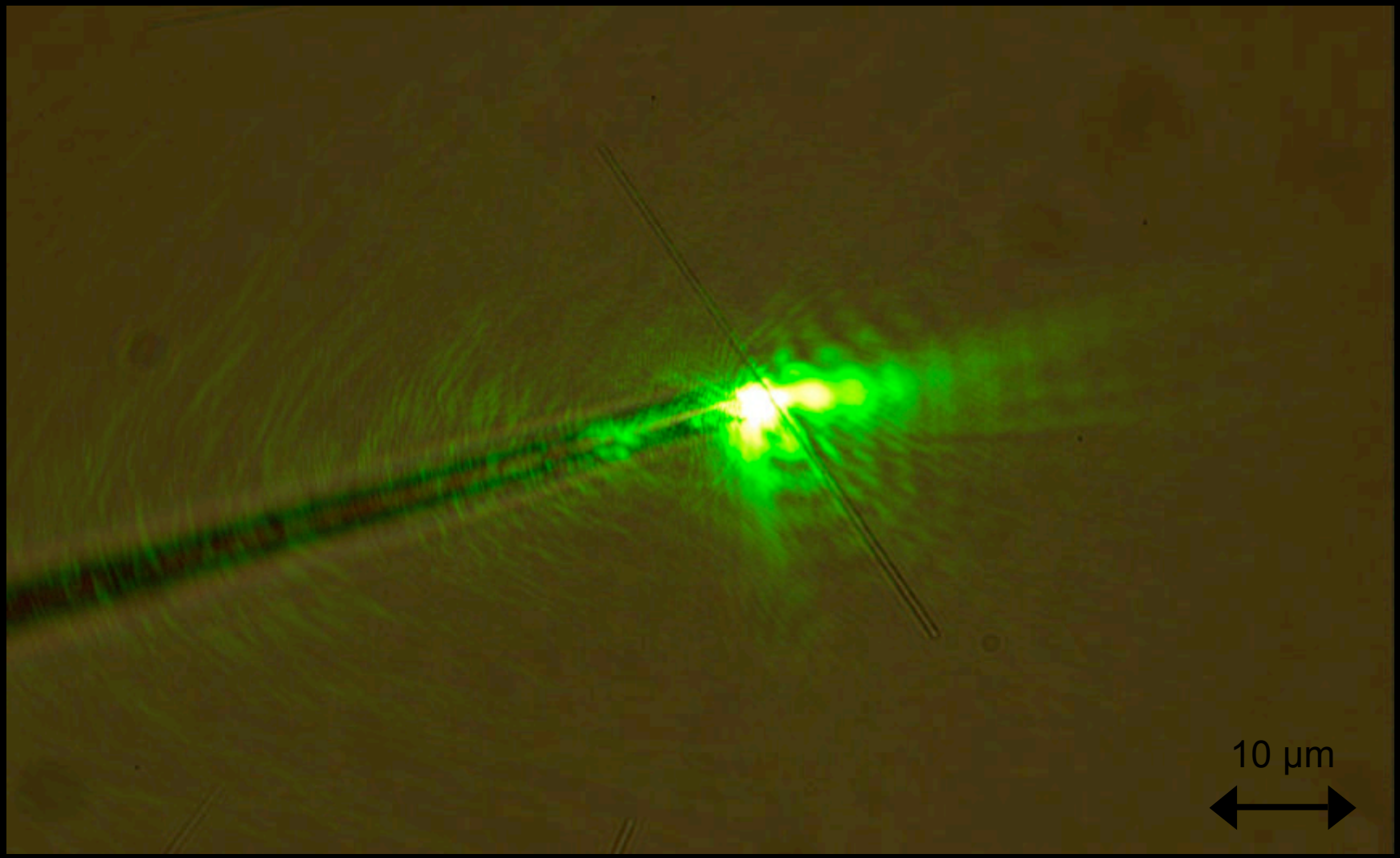
- femtosecond-pulse excitation
  non-linear optics in nanowires

Introduction

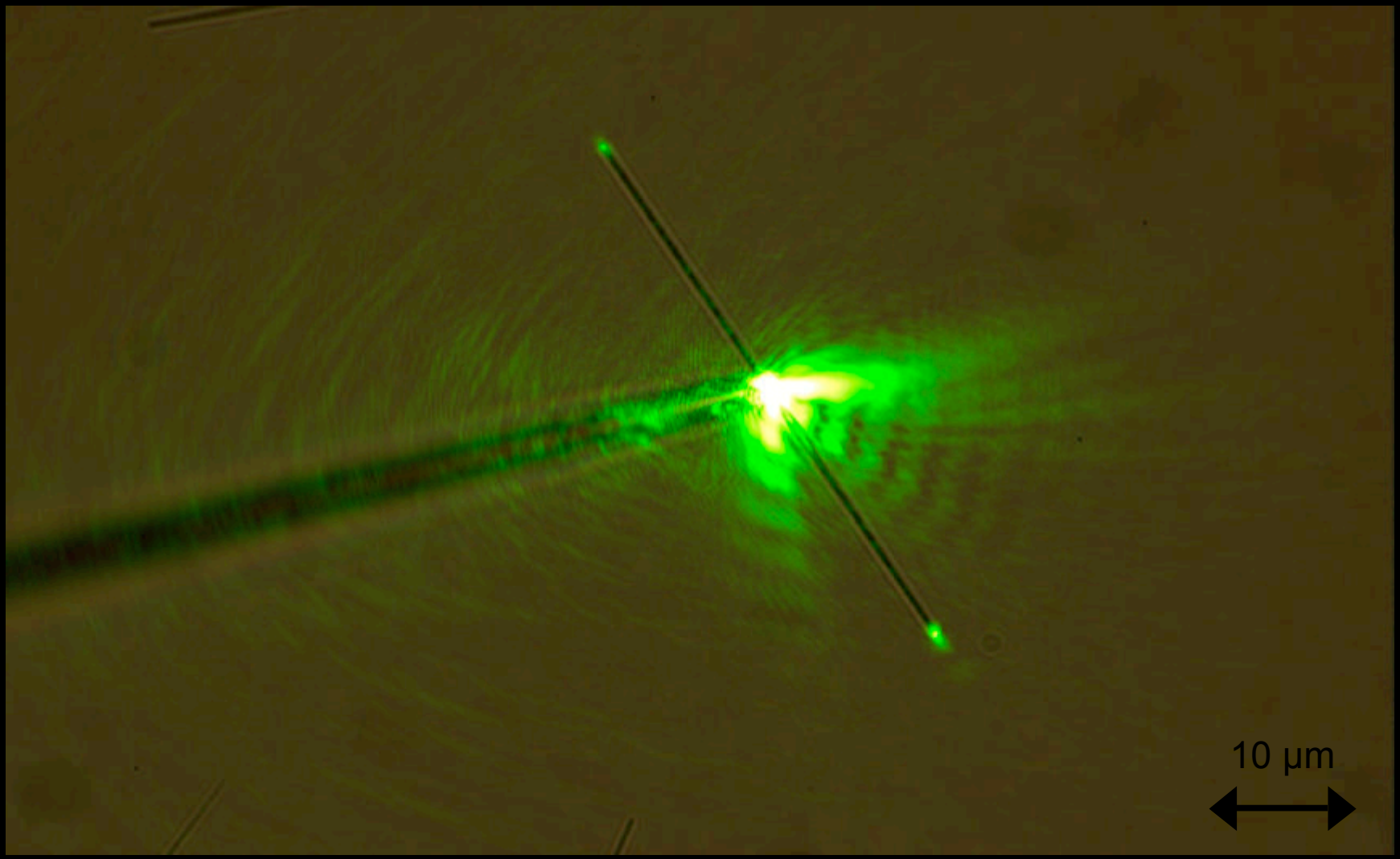
- normally n-type
- limited p-type doping
- large exciton binding energy



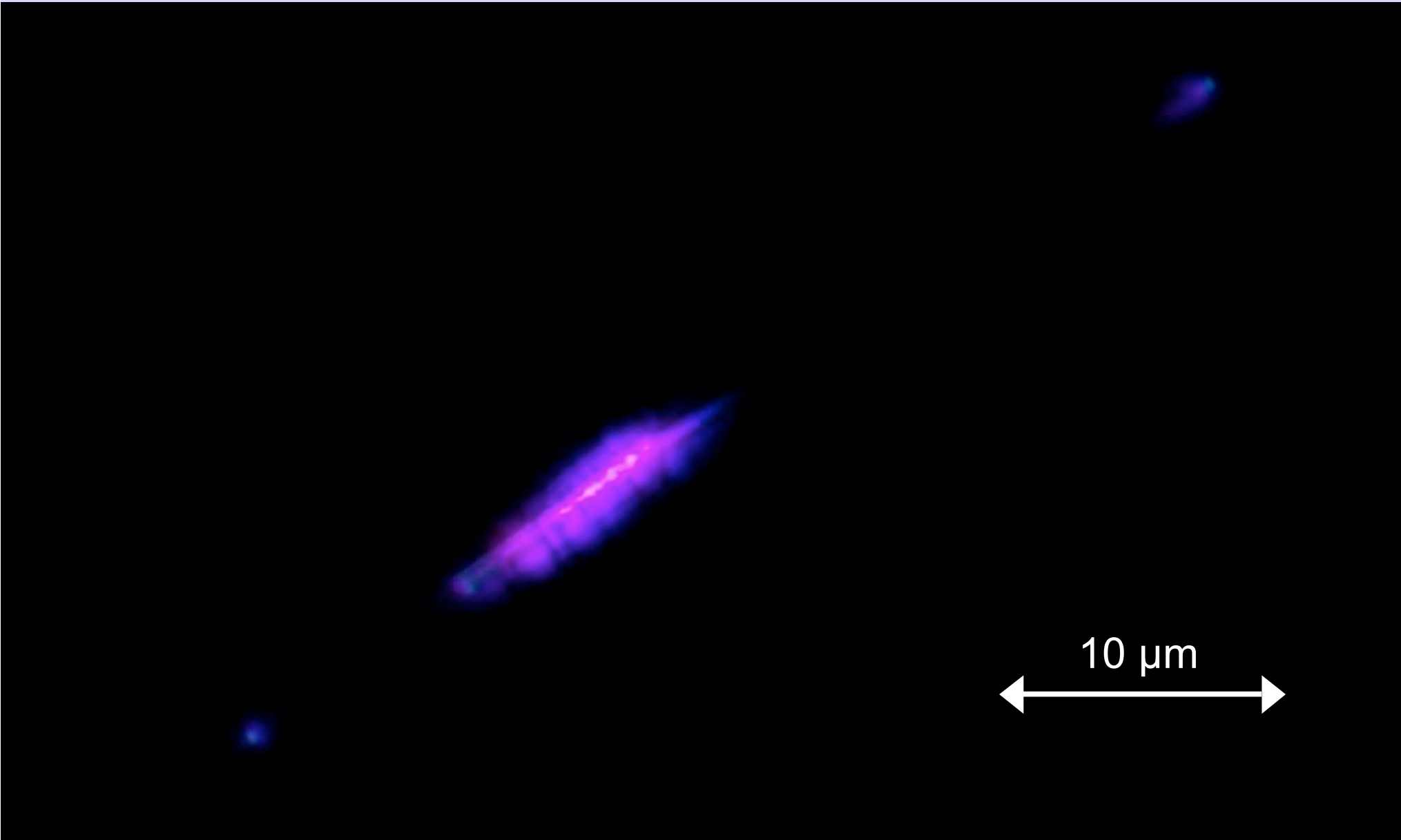
Optical coupling to the nanoscale



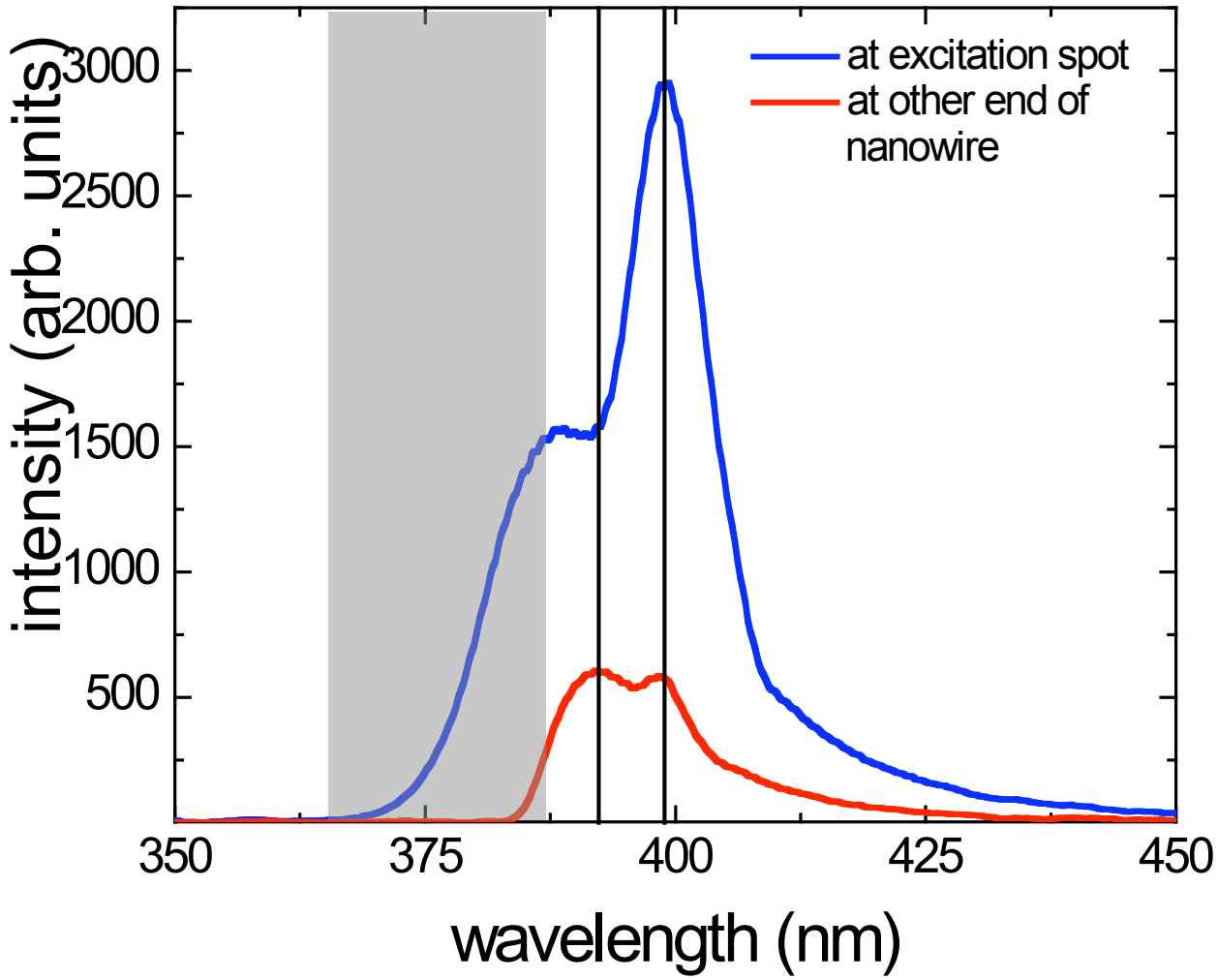
Optical coupling to the nanoscale



Non-linear optics in ZnO nanowires

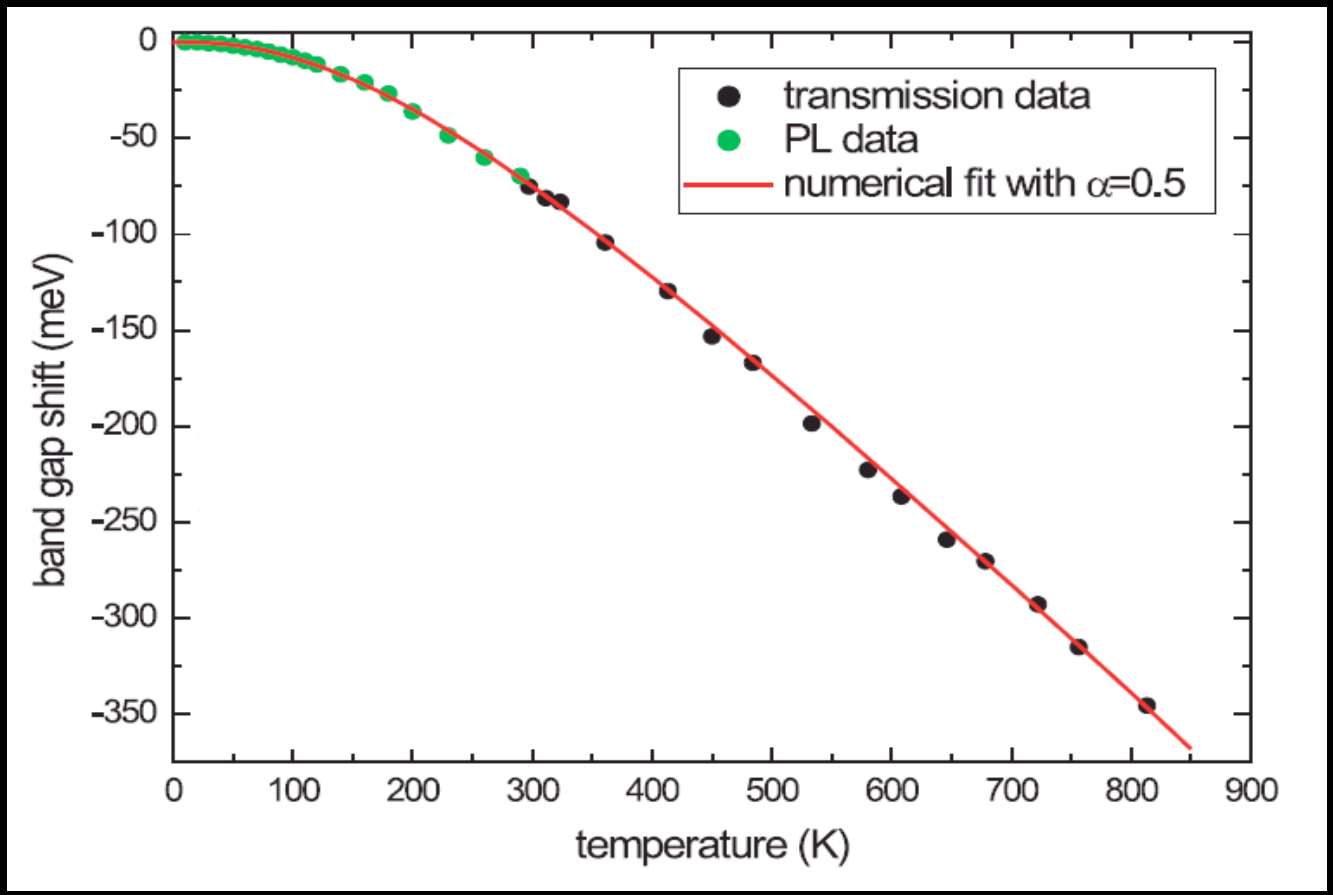


Non-linear optics in ZnO nanowires



Non-linear optics in ZnO nanowires

Literature data (Hauschild et al.)



phys. stat. sol. (c) **3**, No. 4, 976–979 (2006)