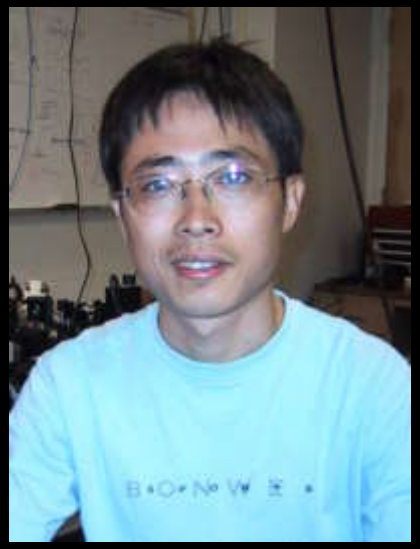
Nonlinear optics at the nanoscale

Ultrafast Optics 2007
Santa Fe, 5 September 2007

Rafael Gattass

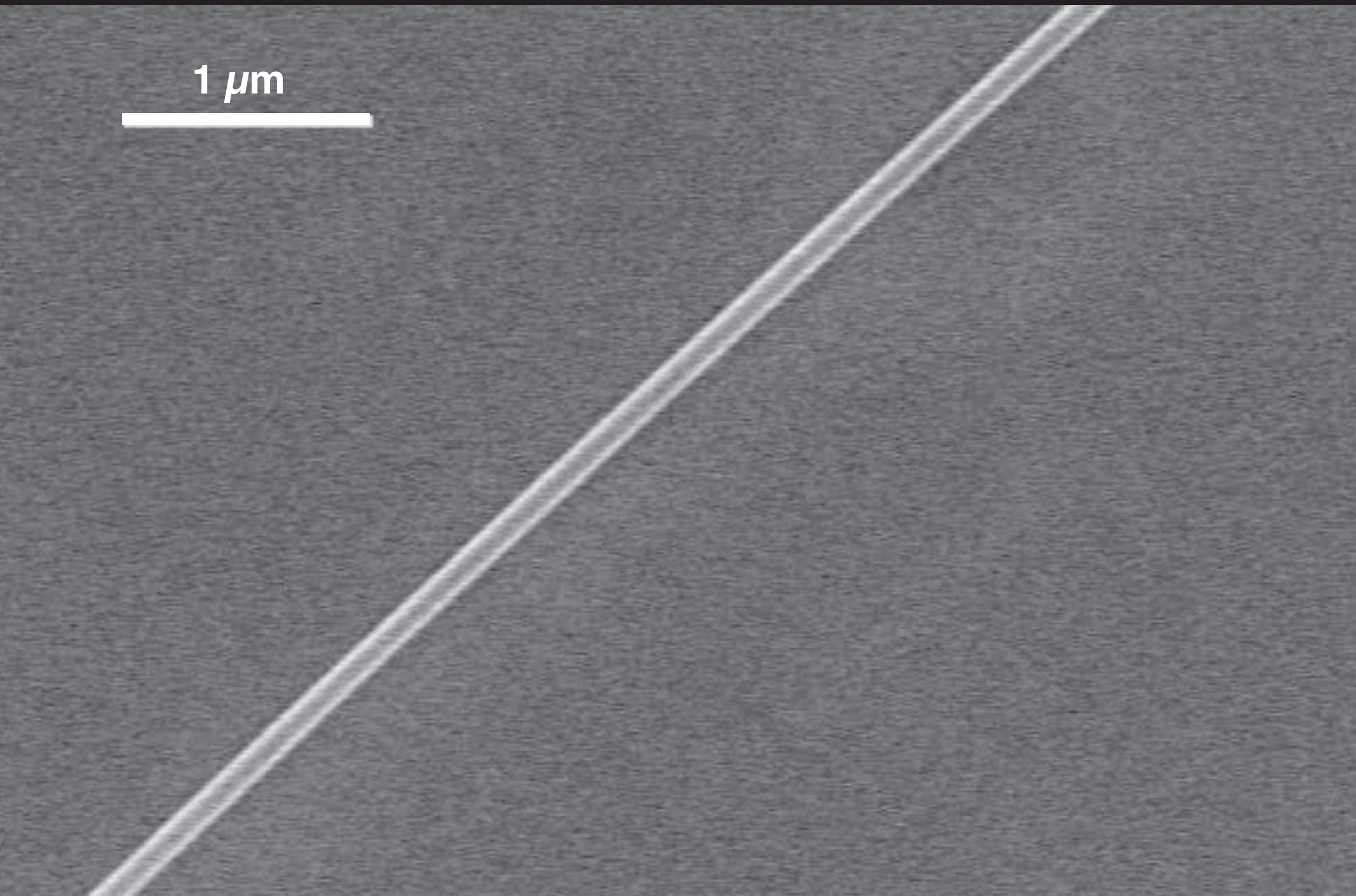
Geoff Svacha



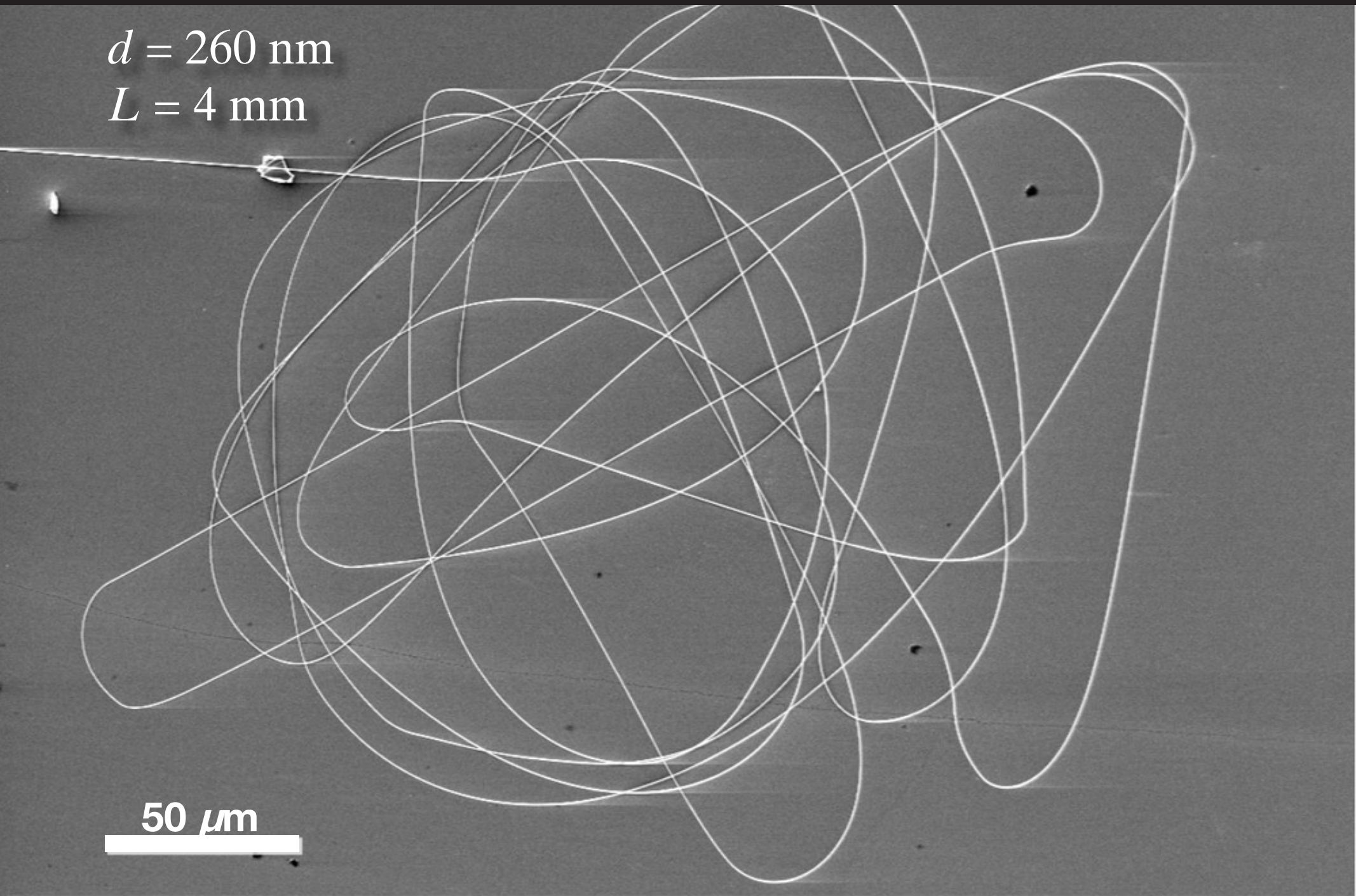
Limin Tong

Tobias Voss

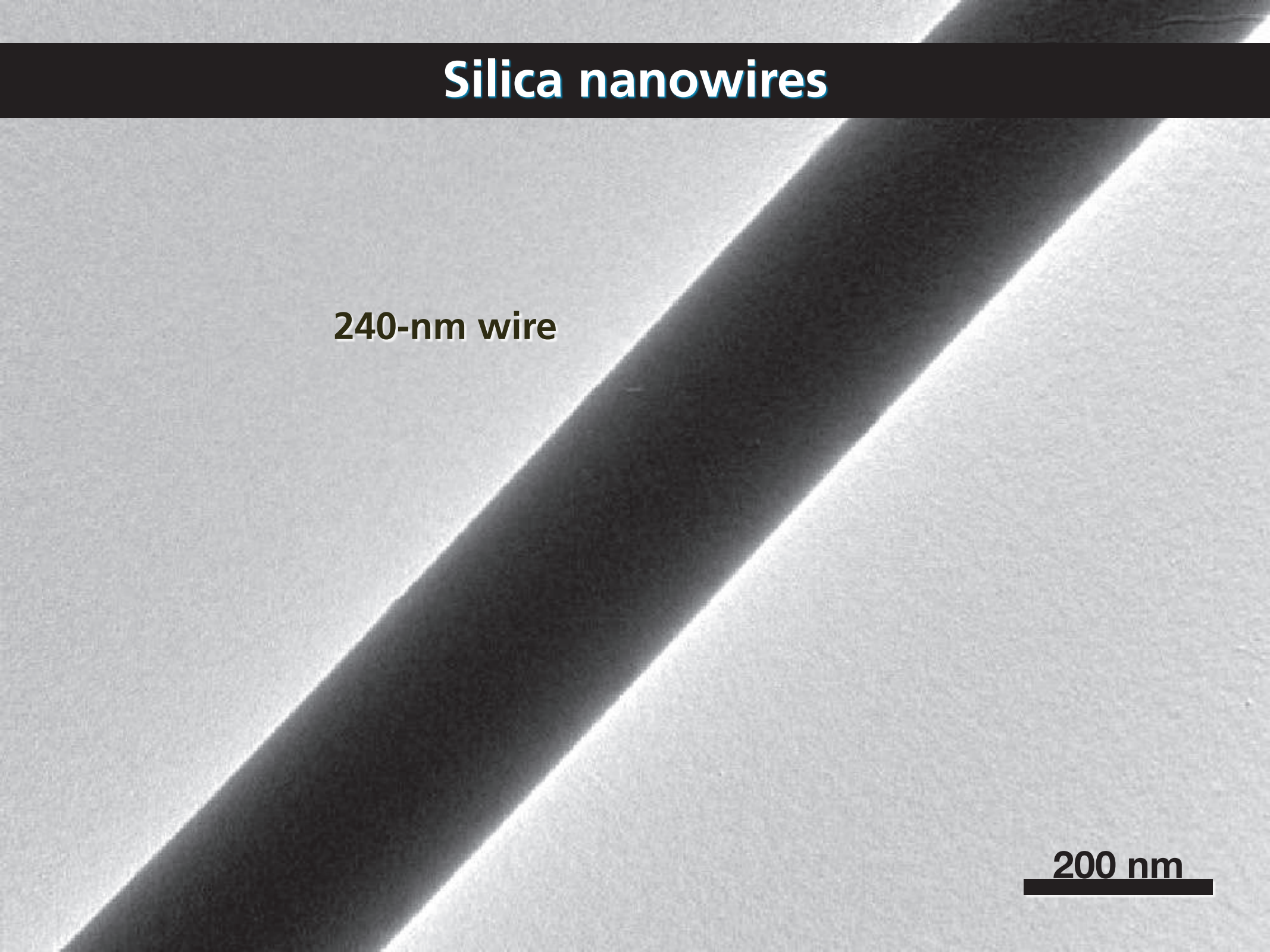
Silica nanowires



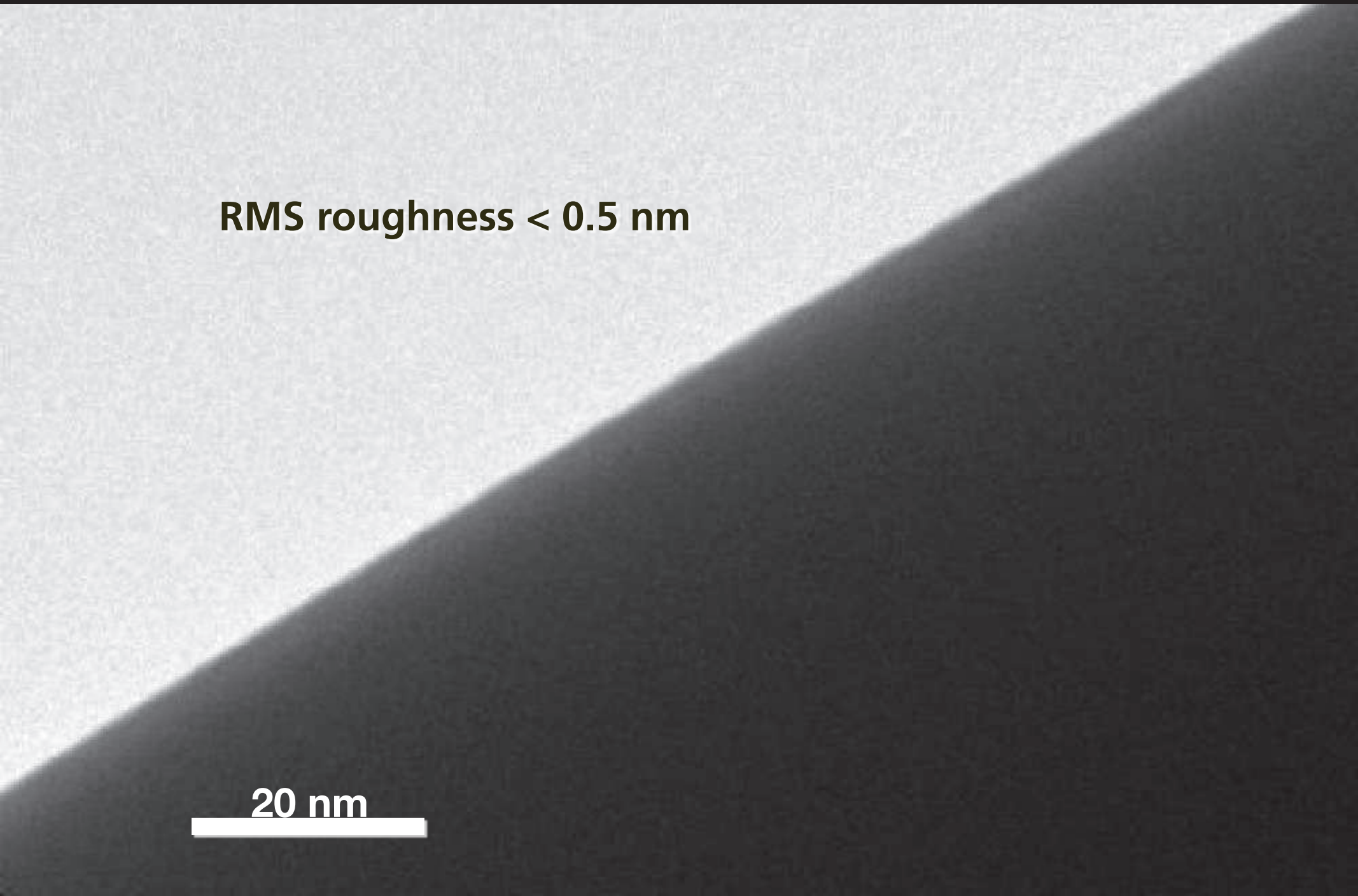
Silica nanowires



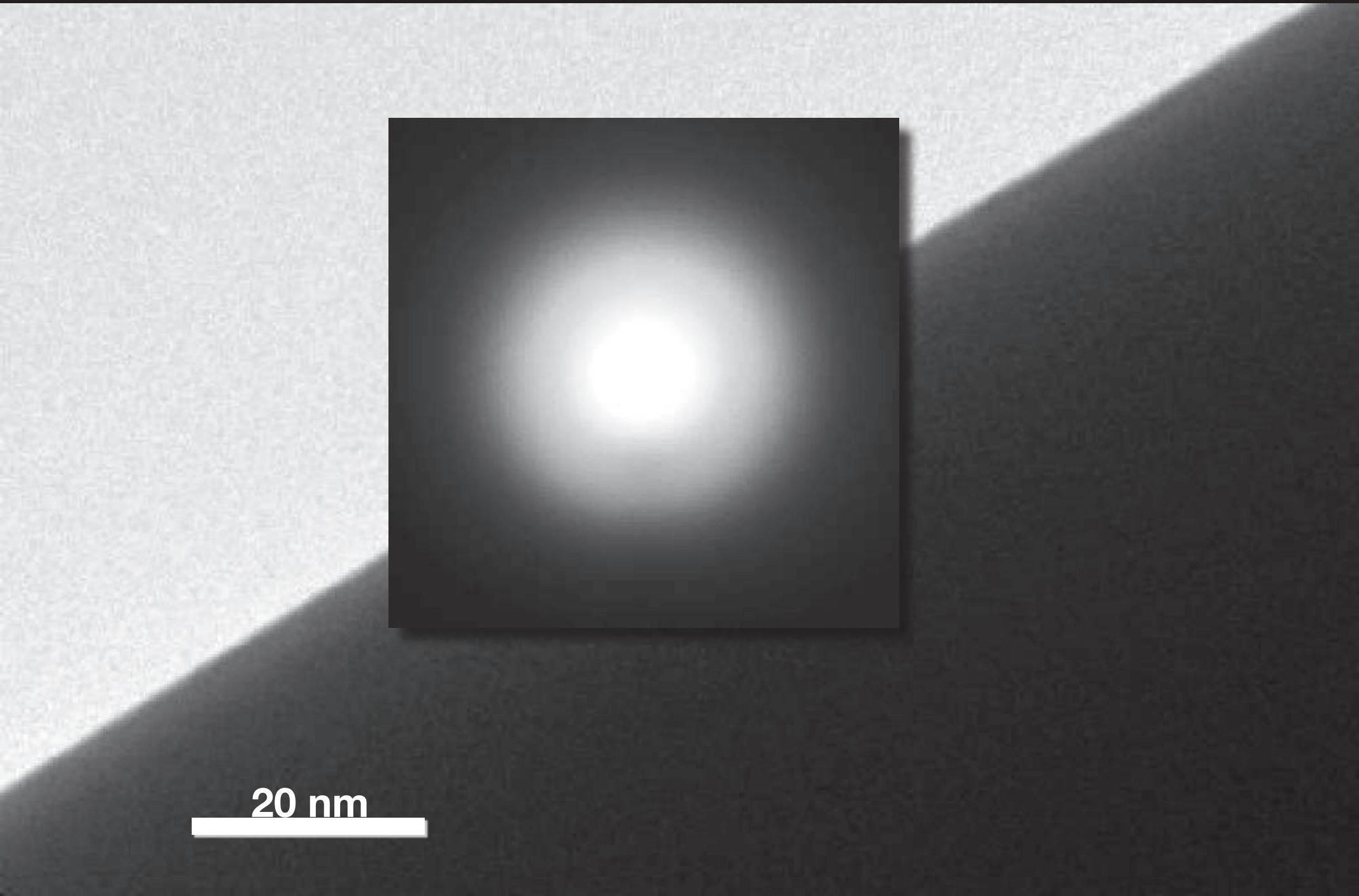
Silica nanowires



Silica nanowires



Silica nanowires



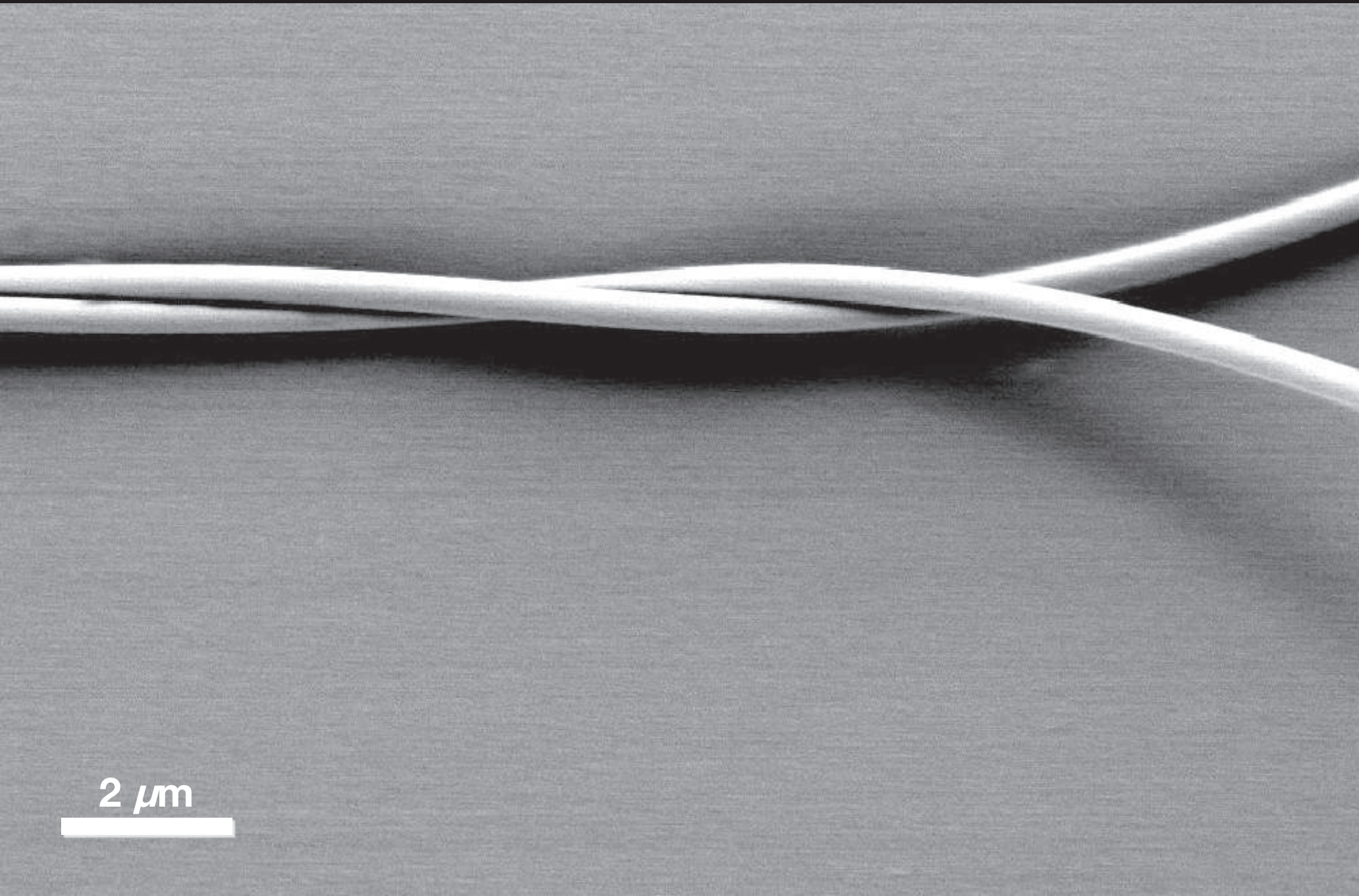
Silica nanowires

Specifications

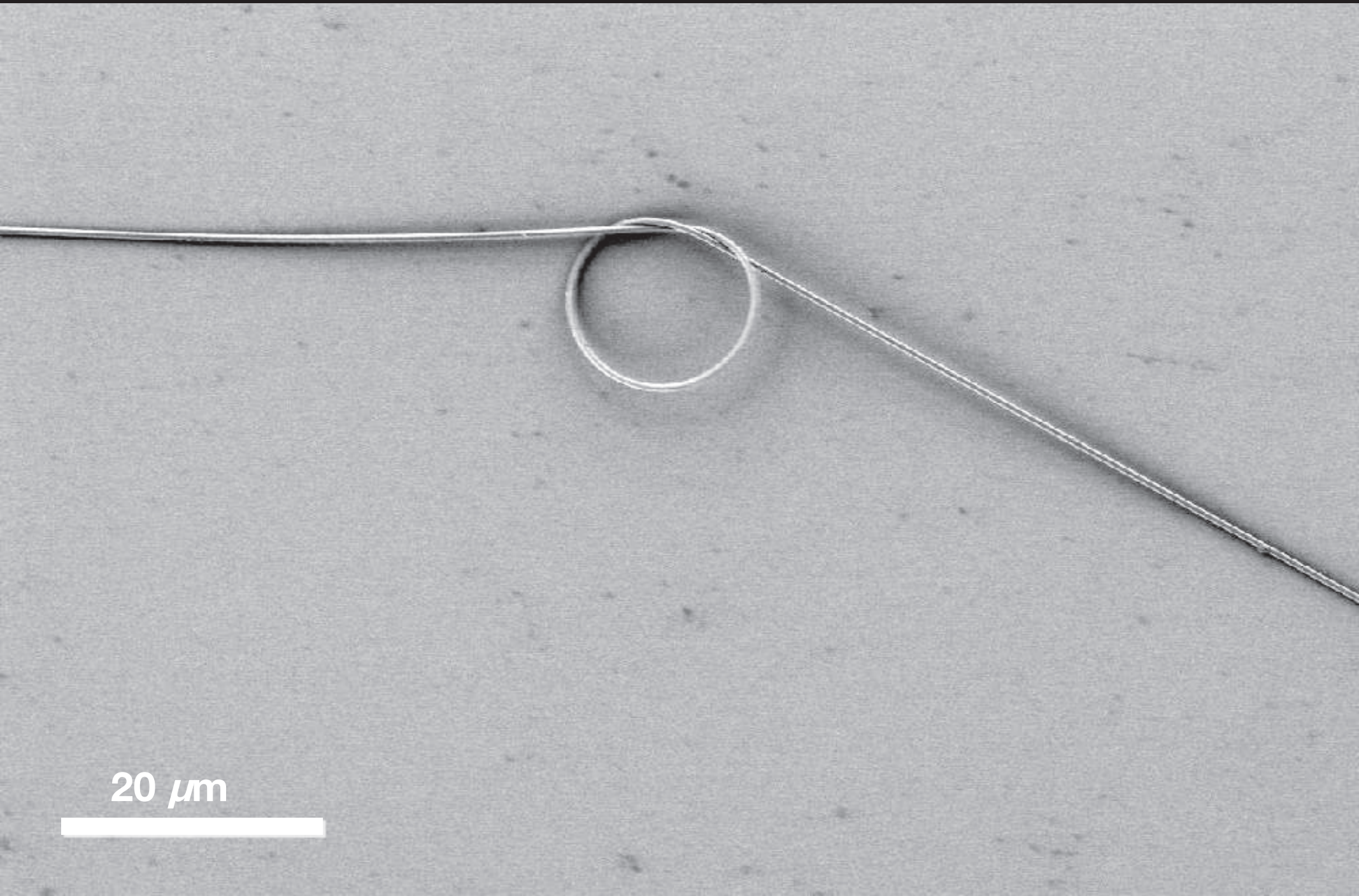
diameter D:	down to 20 nm
length L:	up to 90 mm
aspect ratio D/L:	up to 10^6
diameter uniformity $\Delta D/L$:	2×10^{-6}

Nature, 426, 816 (2003)

Silica nanowires



Silica nanowires



Silica nanowires

Points to keep in mind:

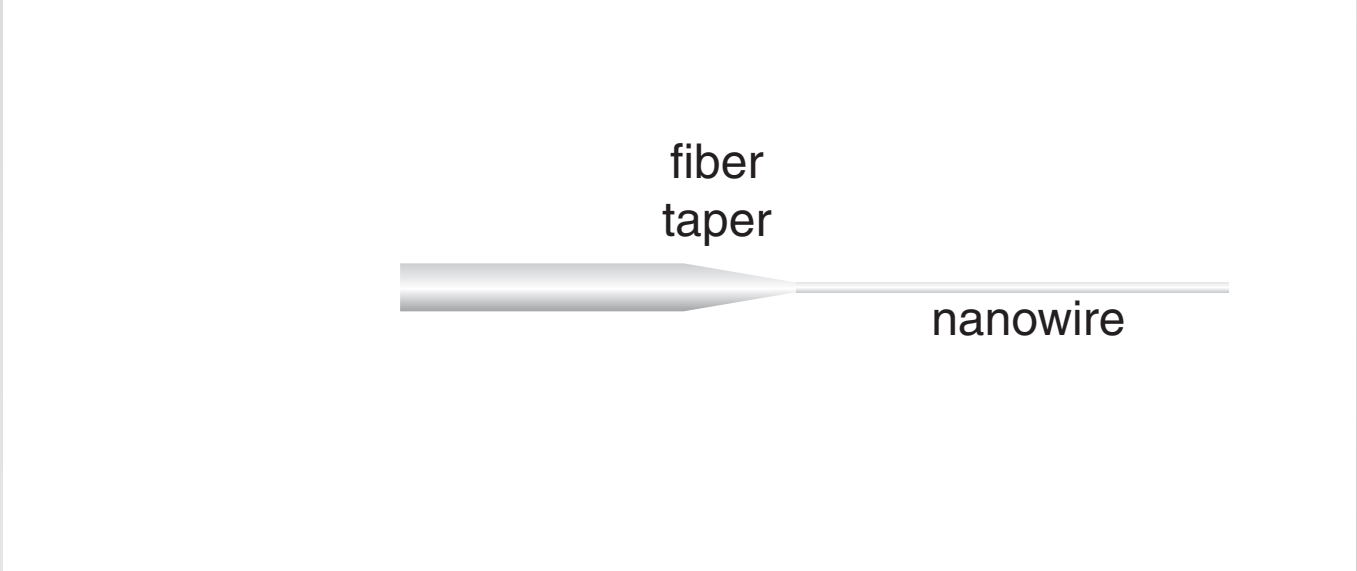
- easy fabrication
- atomic level smoothness
- malleable

Outline

- silica nanowires
- **manipulating light at the nanoscale**
- nanoscale nonlinear optics

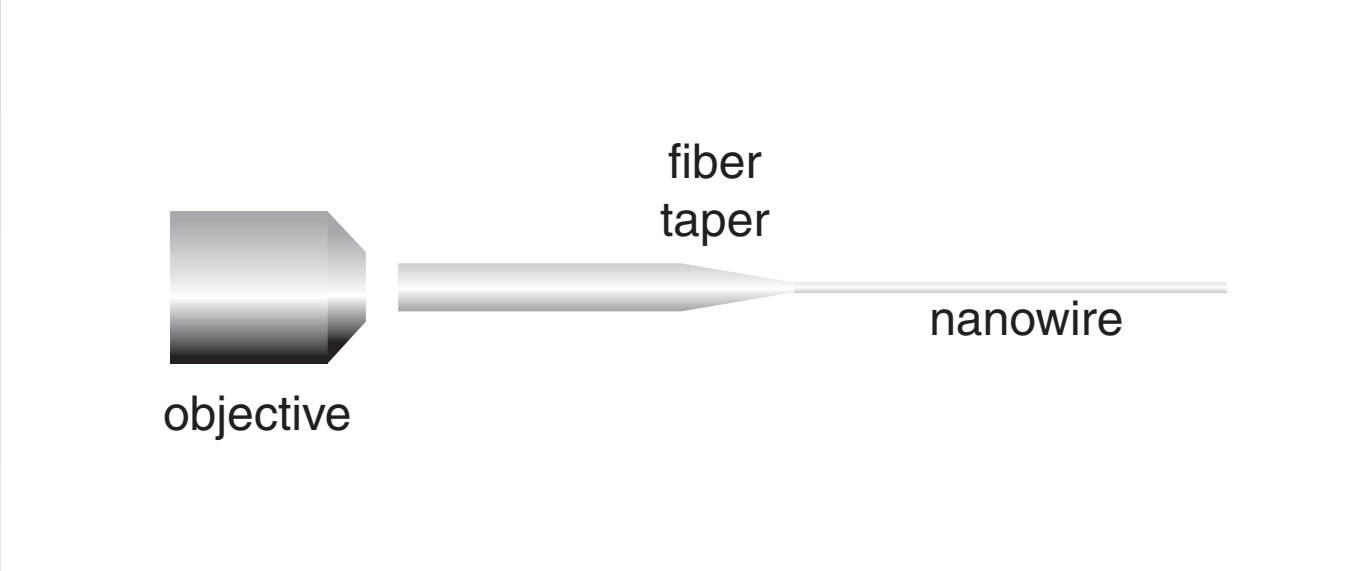
Manipulating light at the nanoscale

coupling light into nanowires



Manipulating light at the nanoscale

coupling light into nanowires



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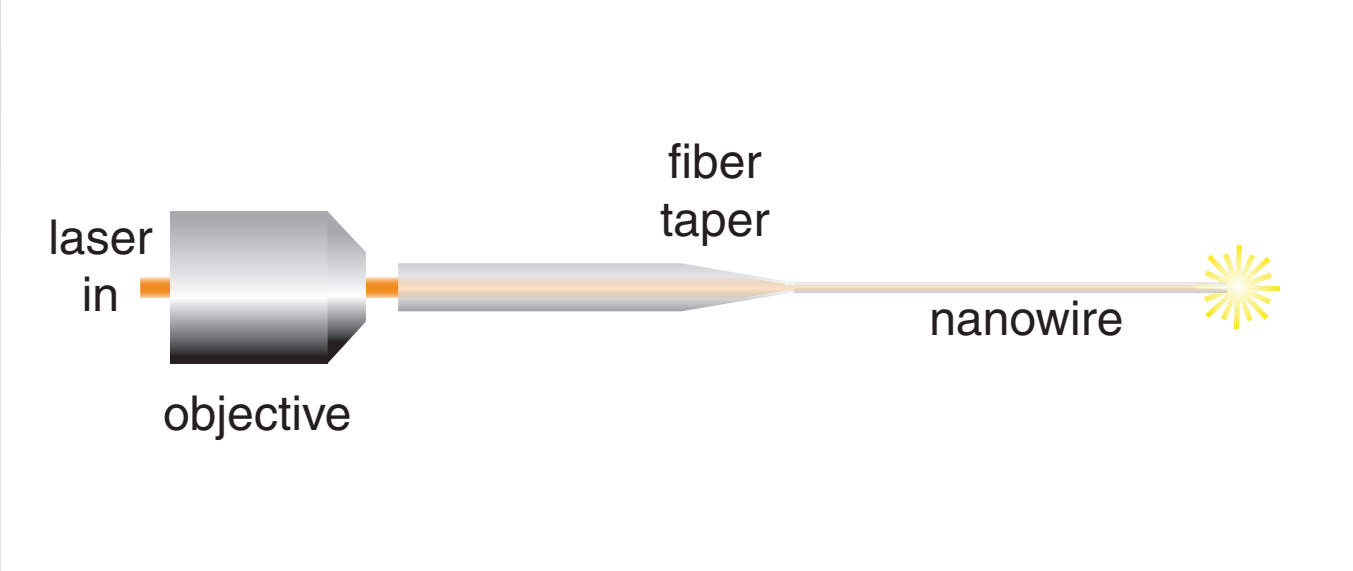
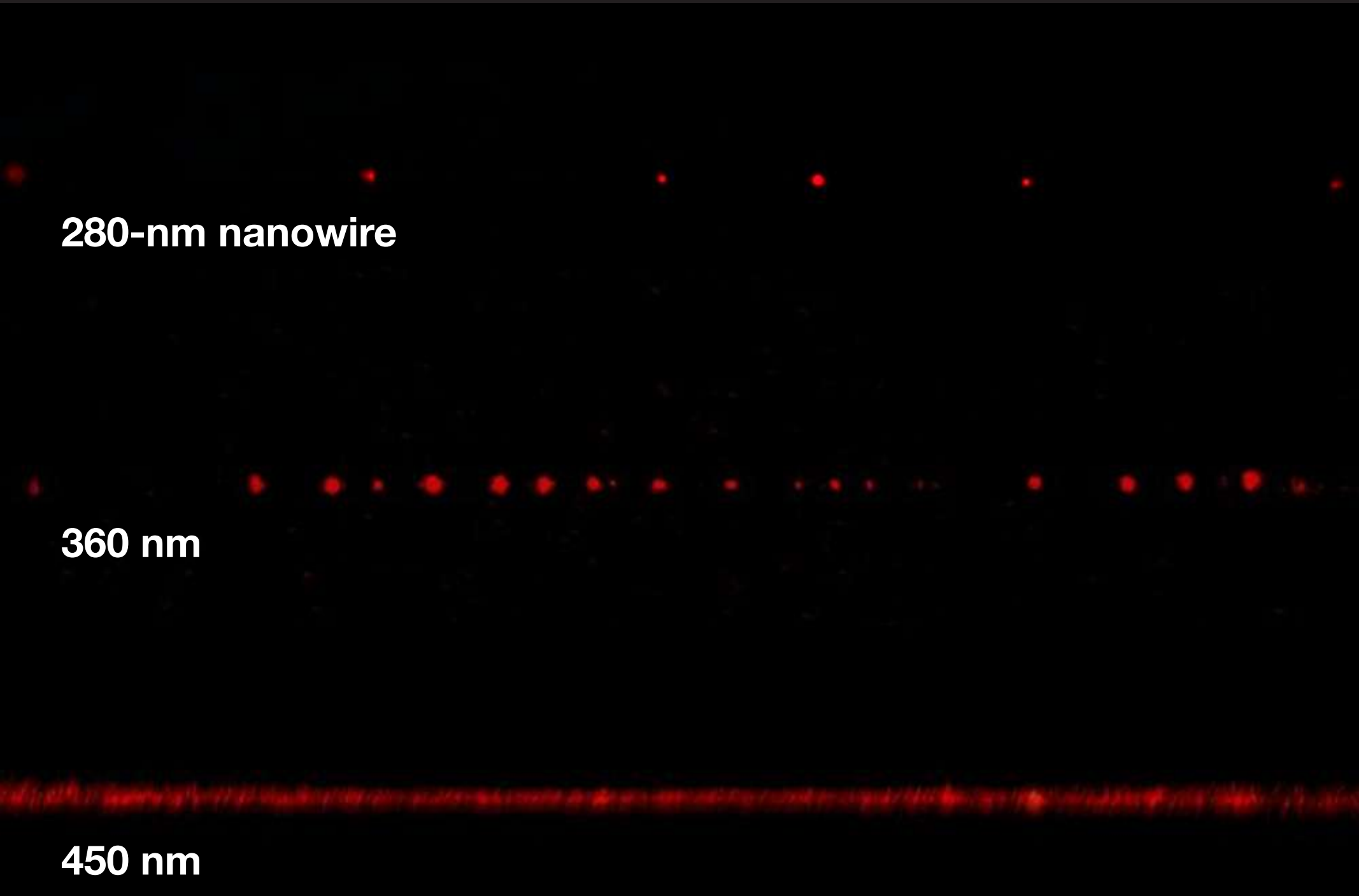
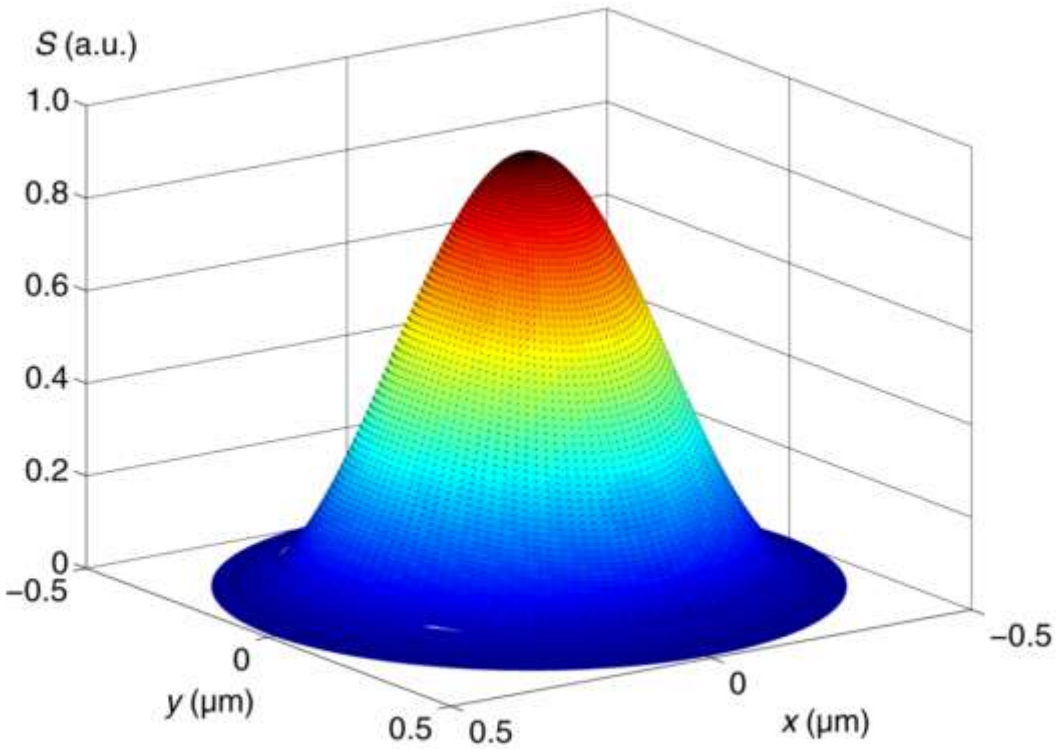


Manipulating light at the nanoscale



Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



Manipulating light at the nanoscale

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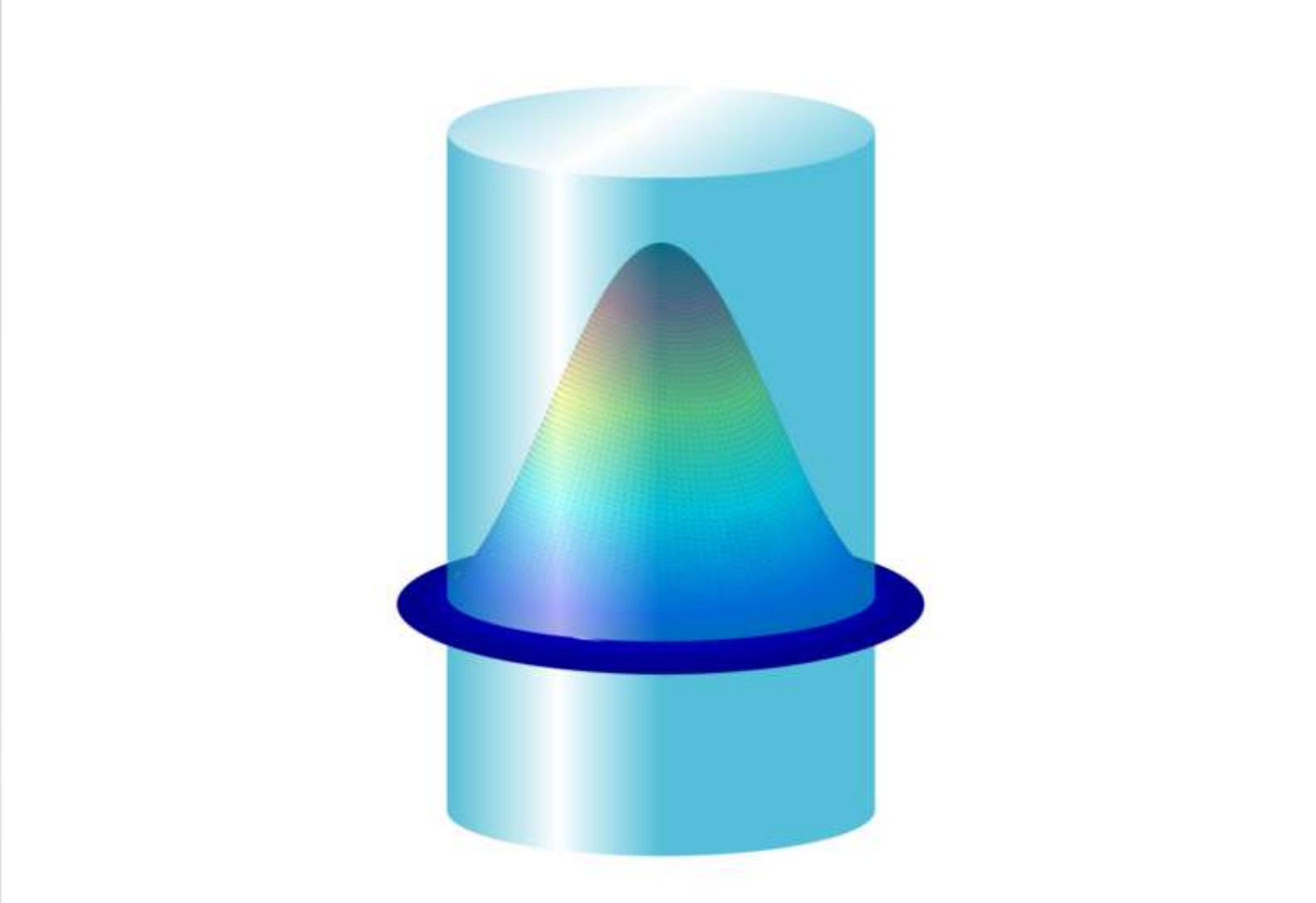

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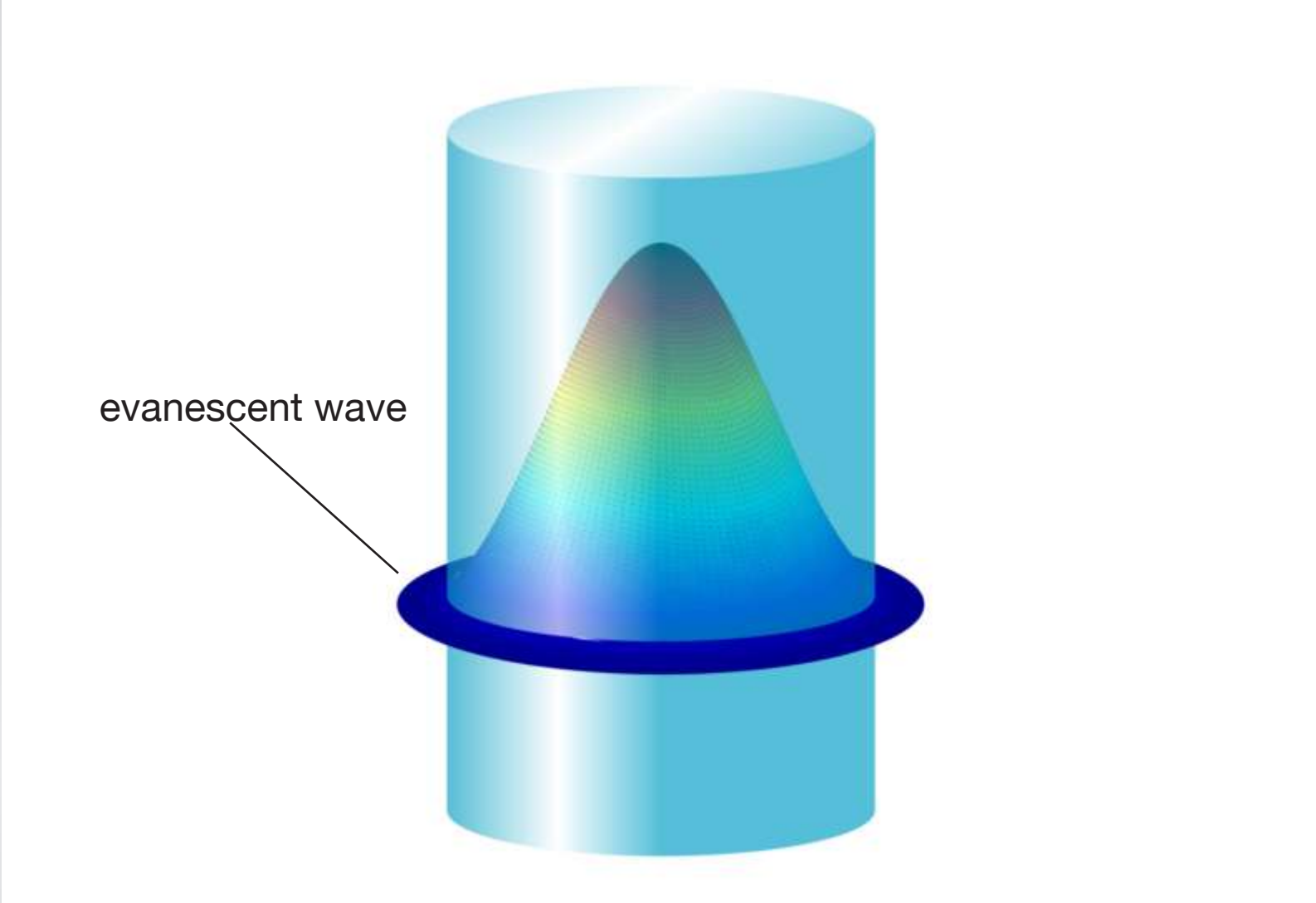
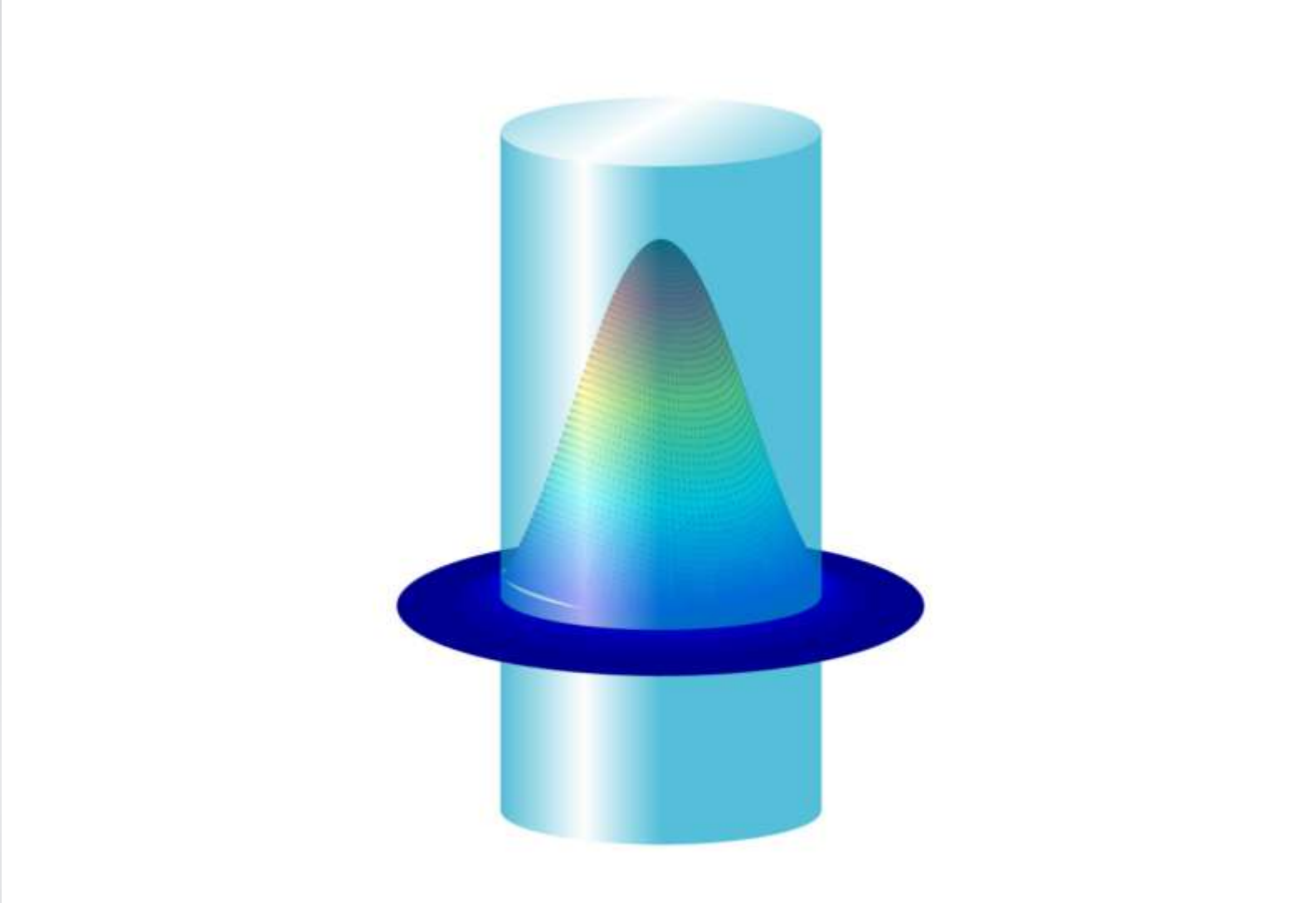


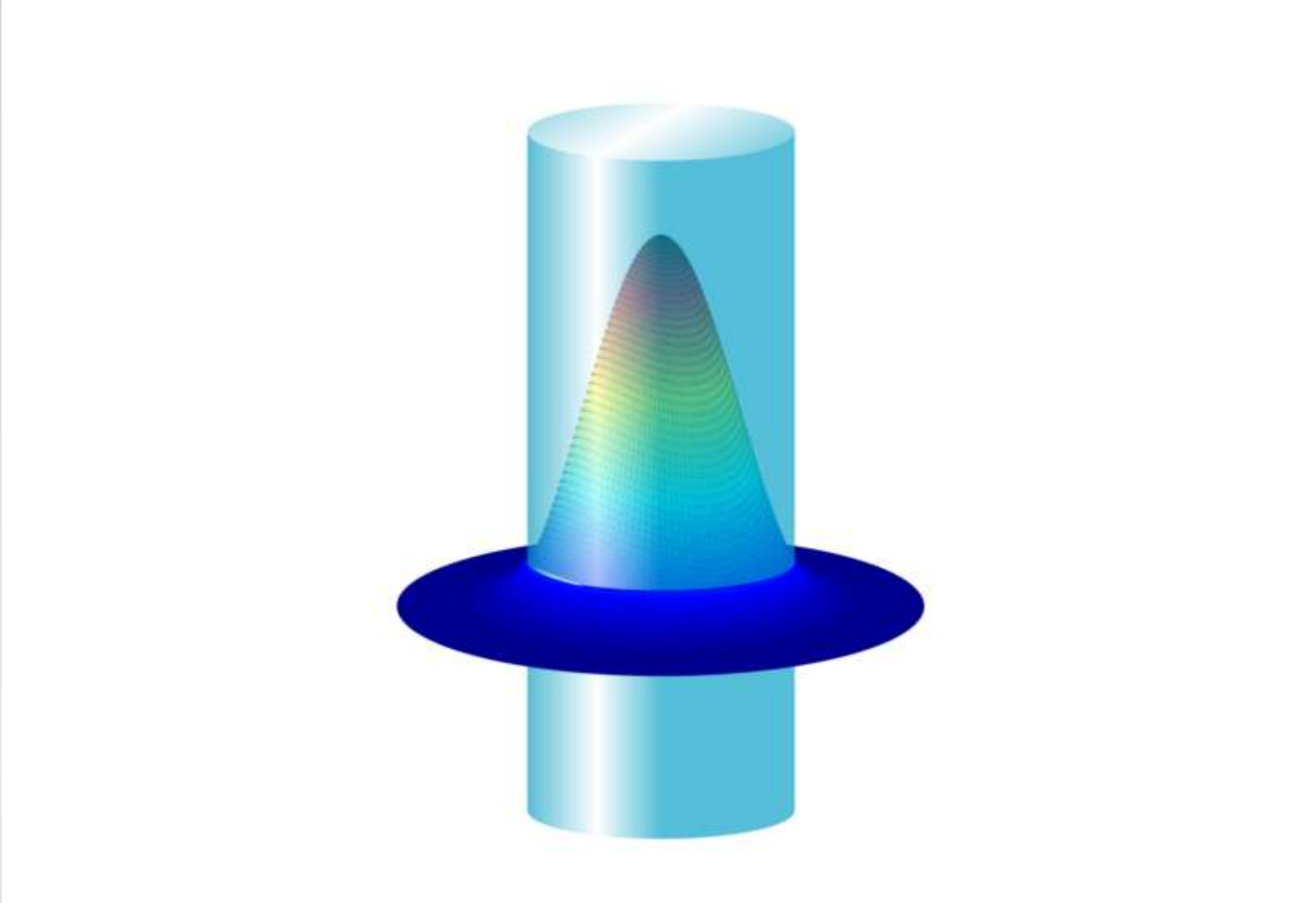
Manipulating light at the nanoscale

Poynting vector profile for 600-nm nanowire



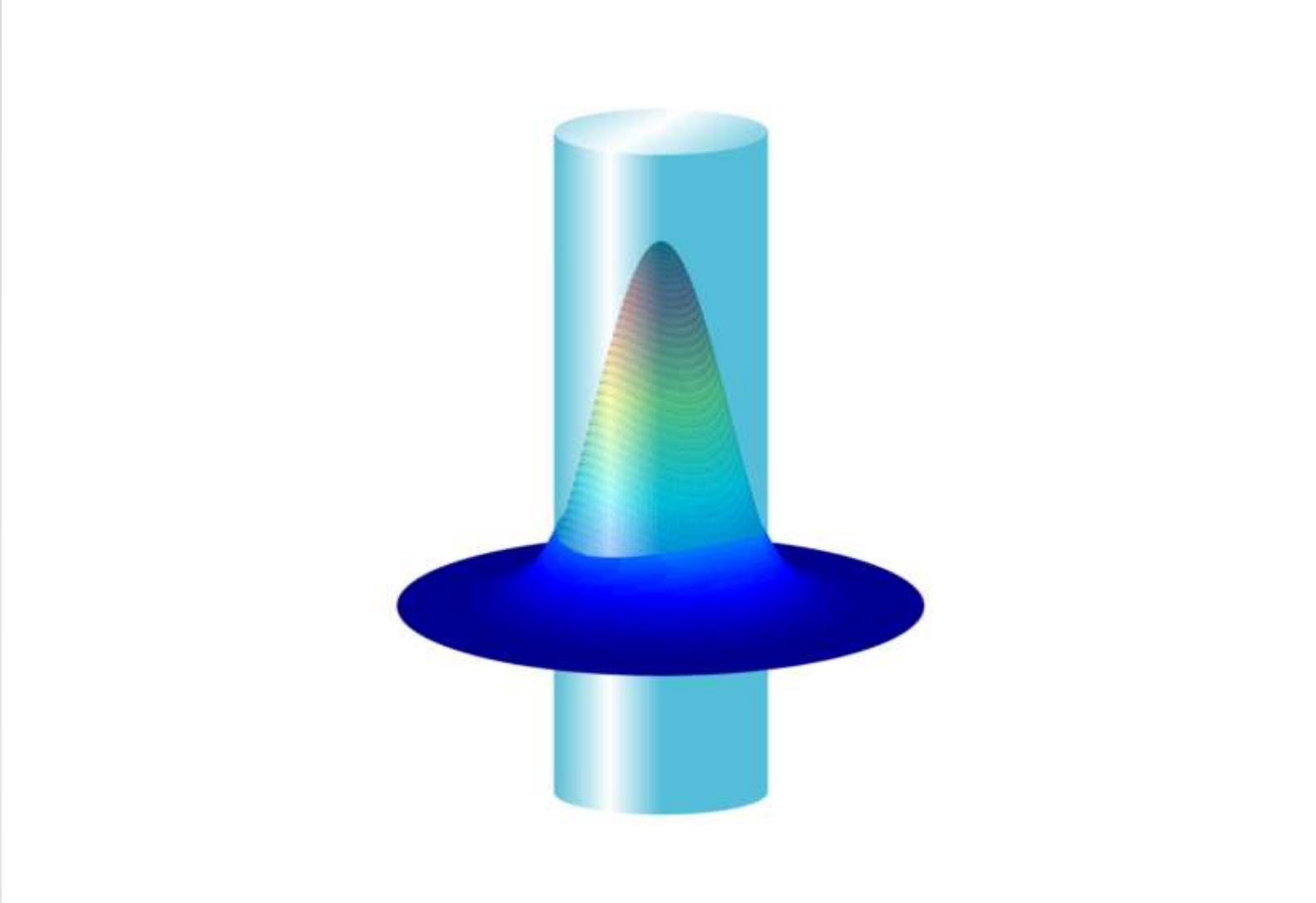
Manipulating light at the nanoscale

Poynting vector profile for 500-nm nanowire



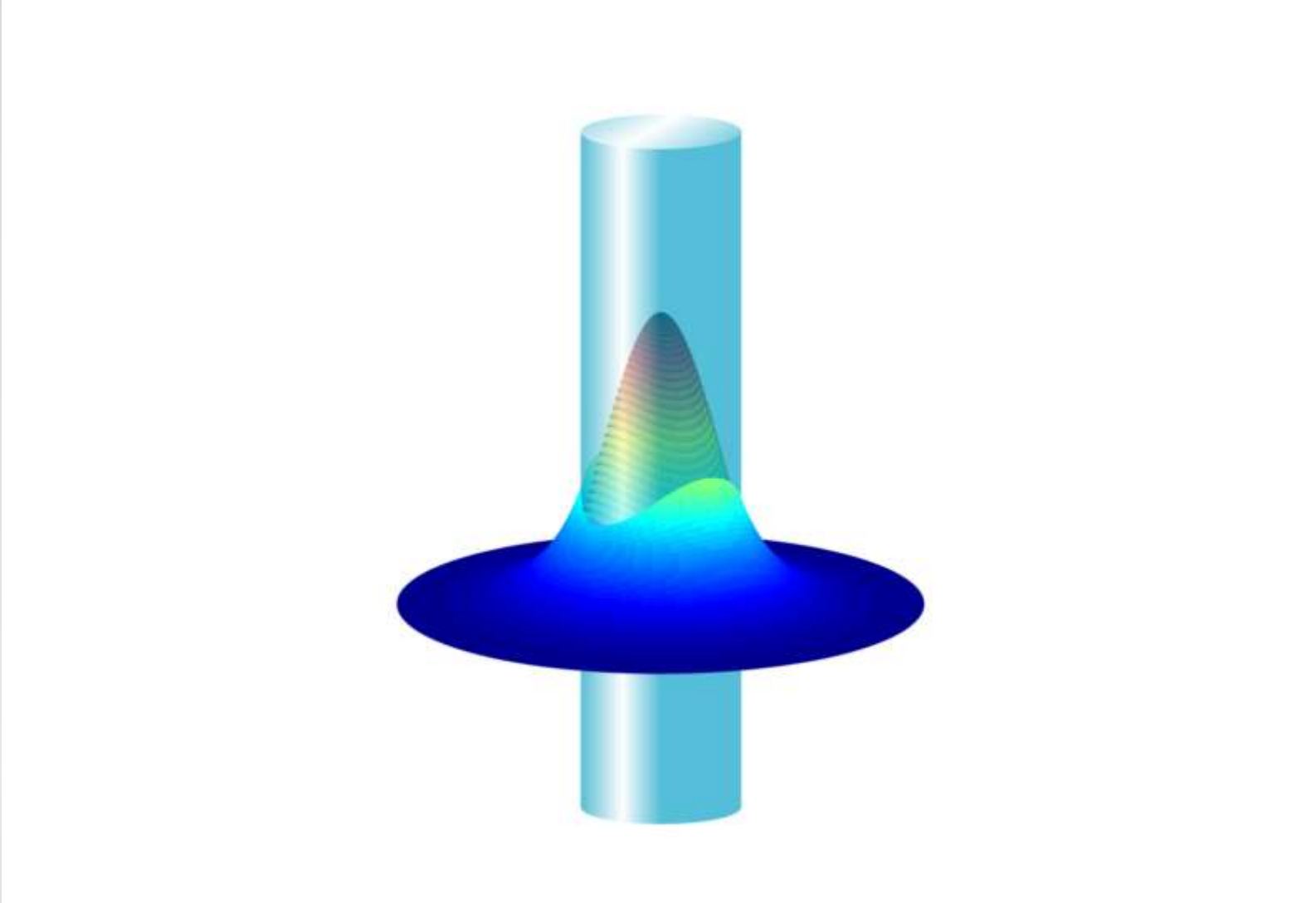
Manipulating light at the nanoscale

Poynting vector profile for 400-nm nanowire



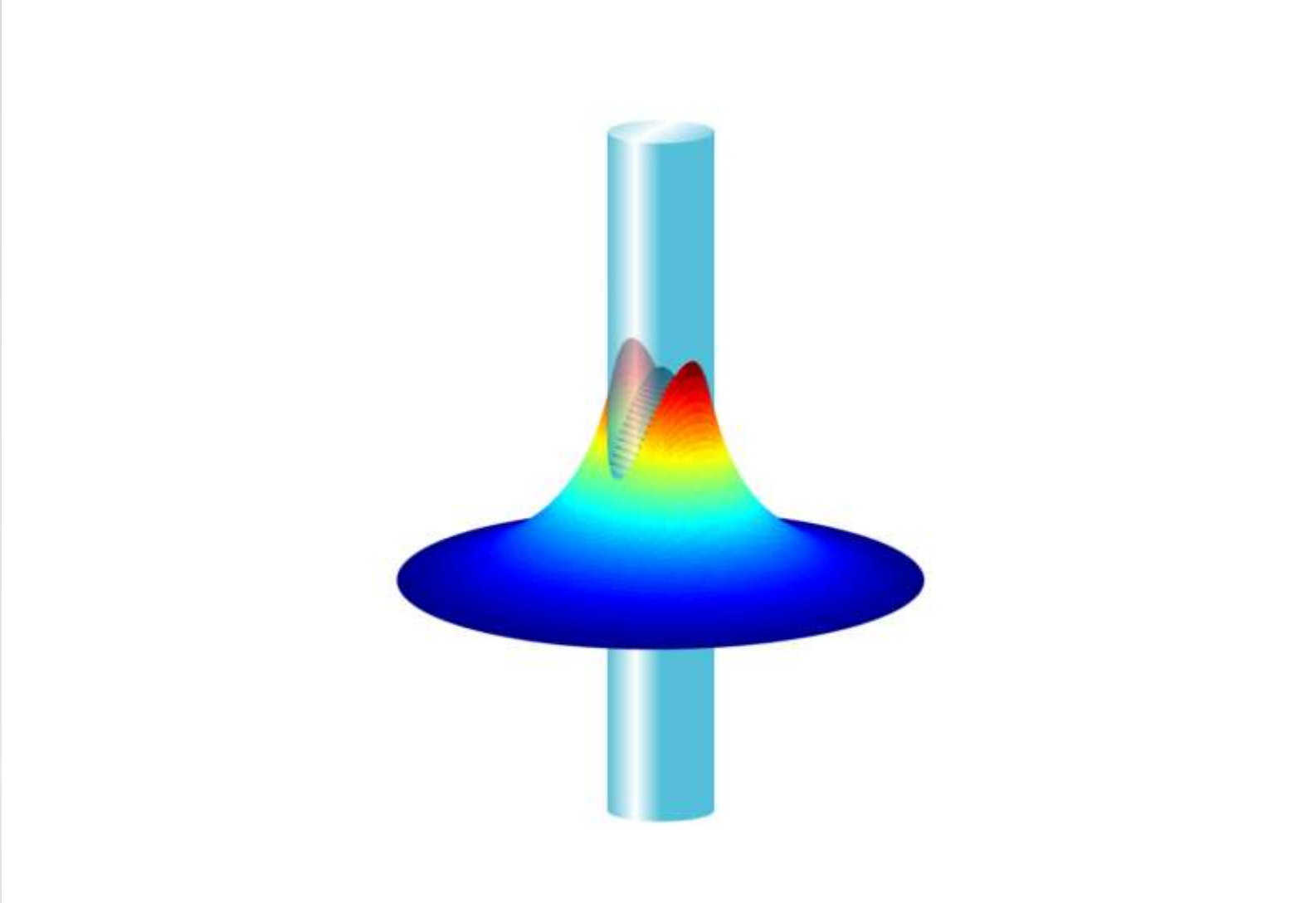
Manipulating light at the nanoscale

Poynting vector profile for 300-nm nanowire



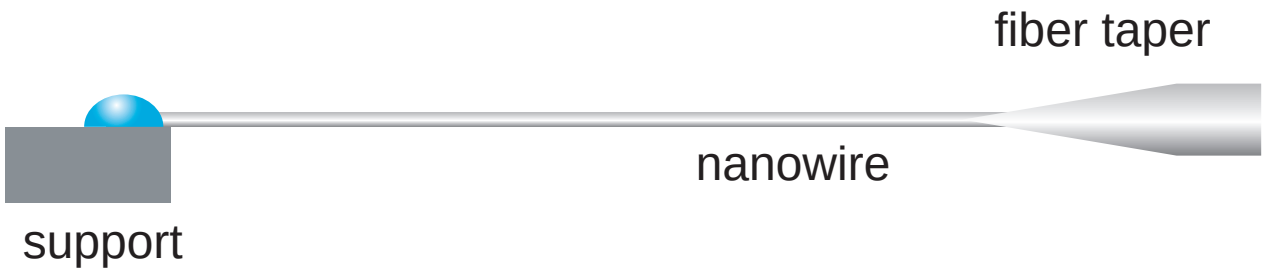
Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



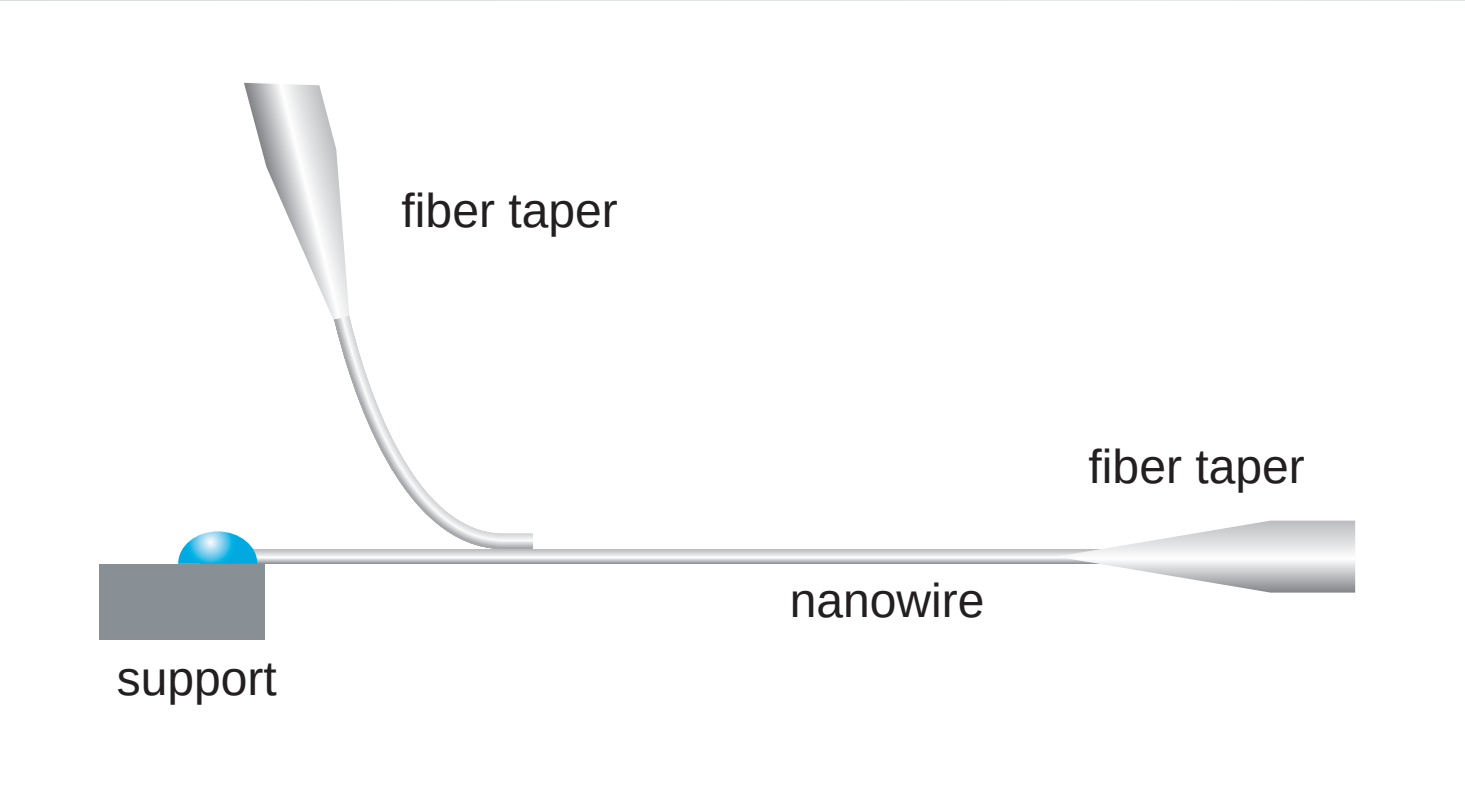
Manipulating light at the nanoscale

coupling light between nanowires



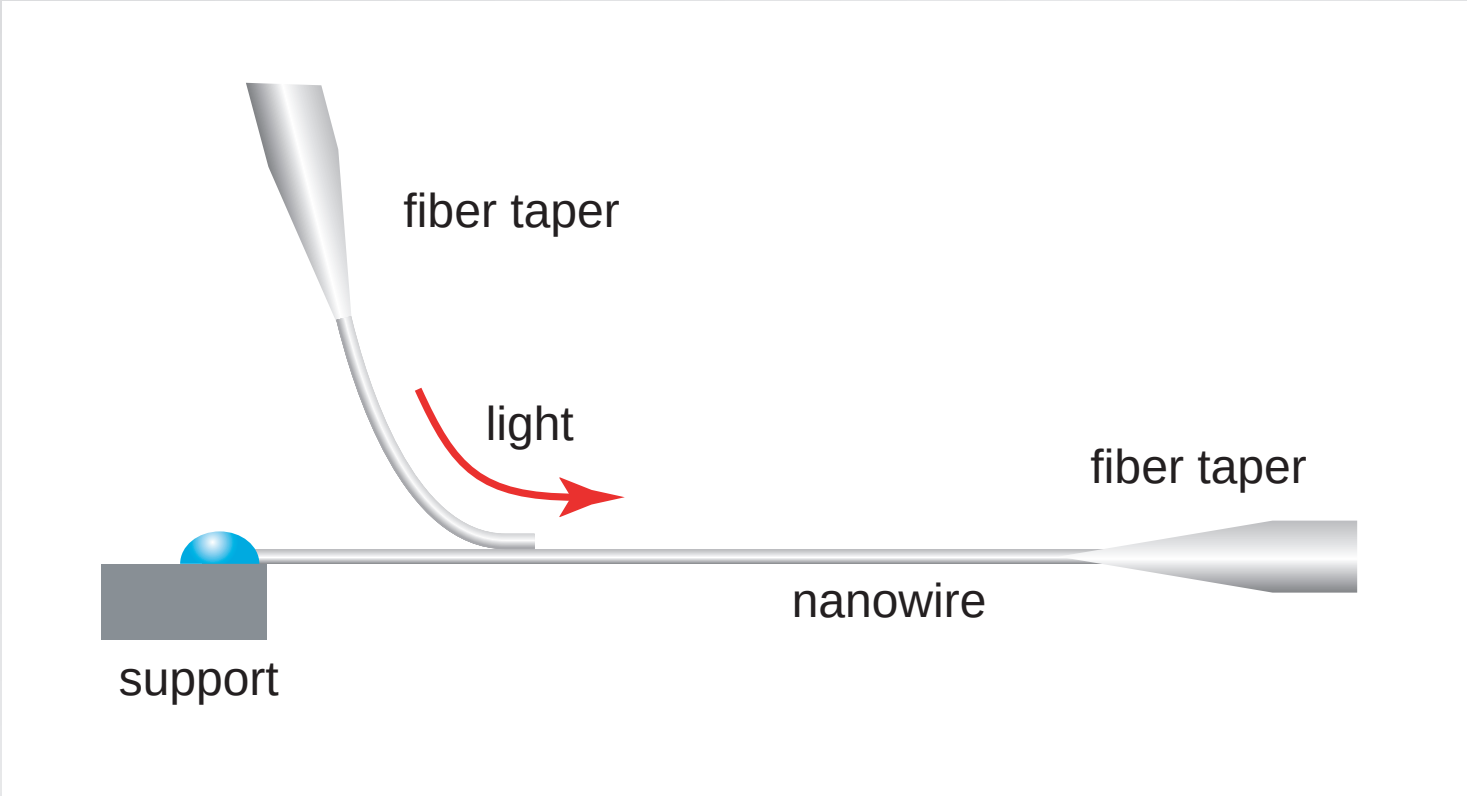
Manipulating light at the nanoscale

coupling light between nanowires



Manipulating light at the nanoscale

coupling light between nanowires



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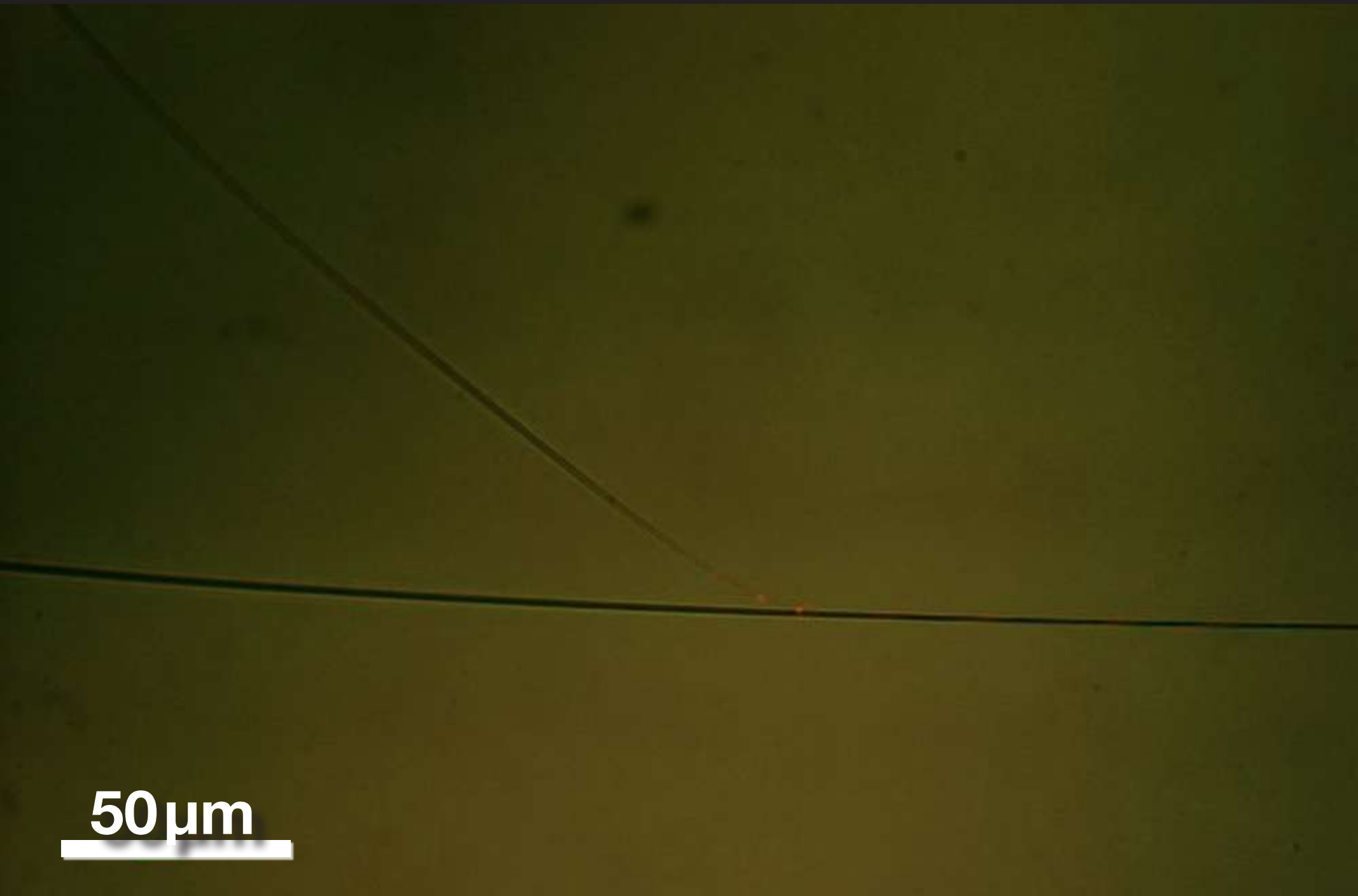
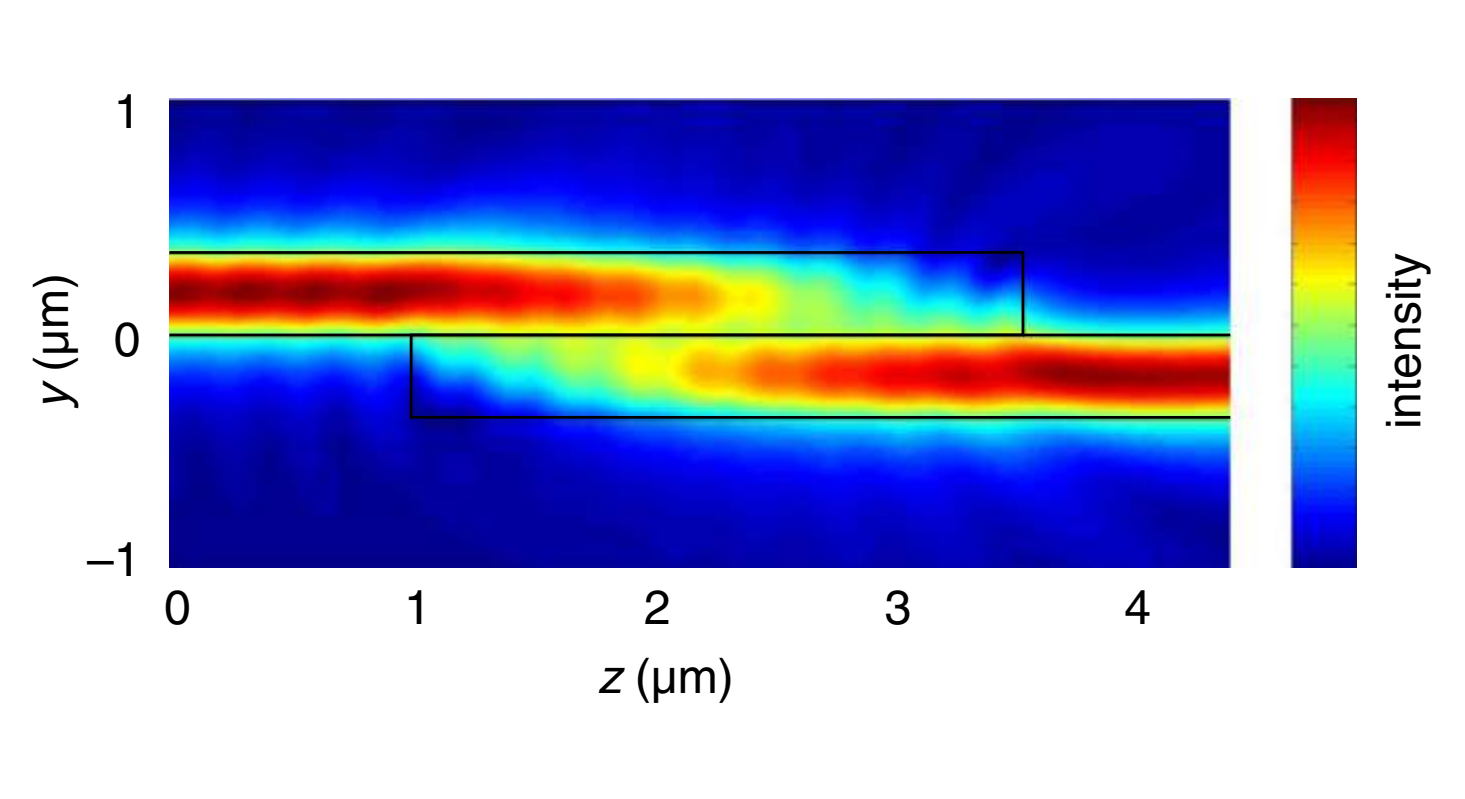


Manipulating light at the nanoscale

Manipulating light at the nanoscale

intensity distribution



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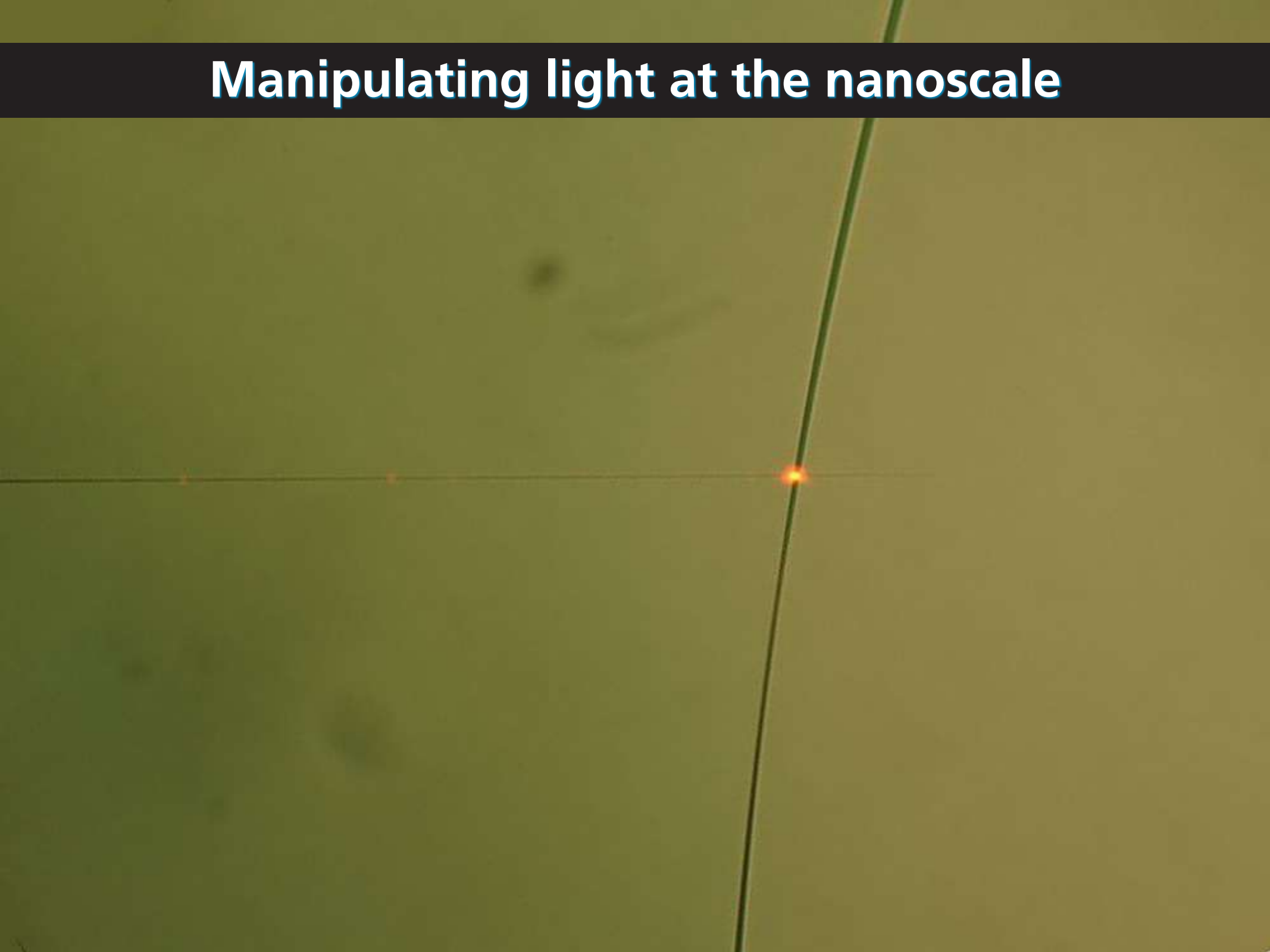

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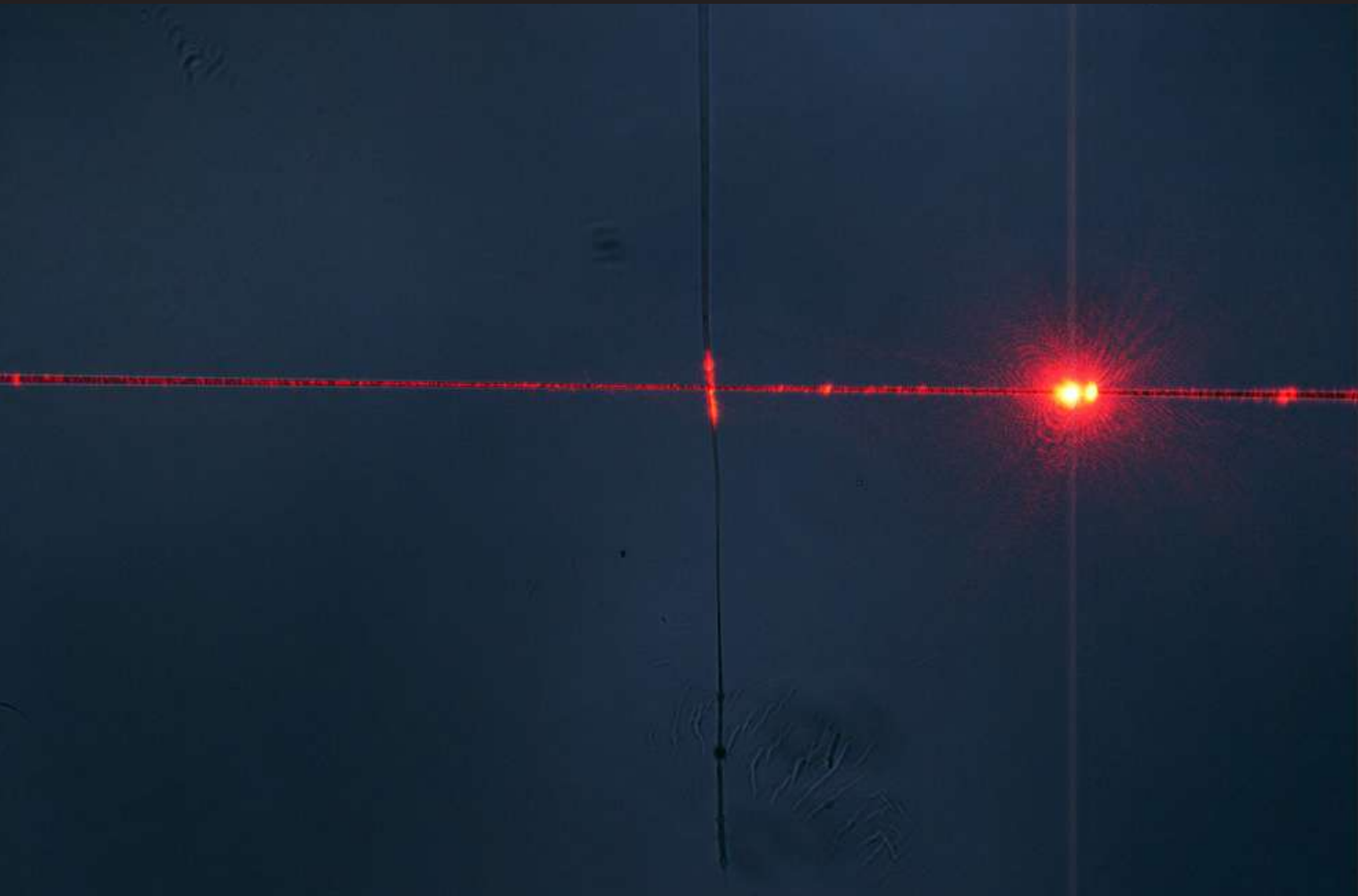

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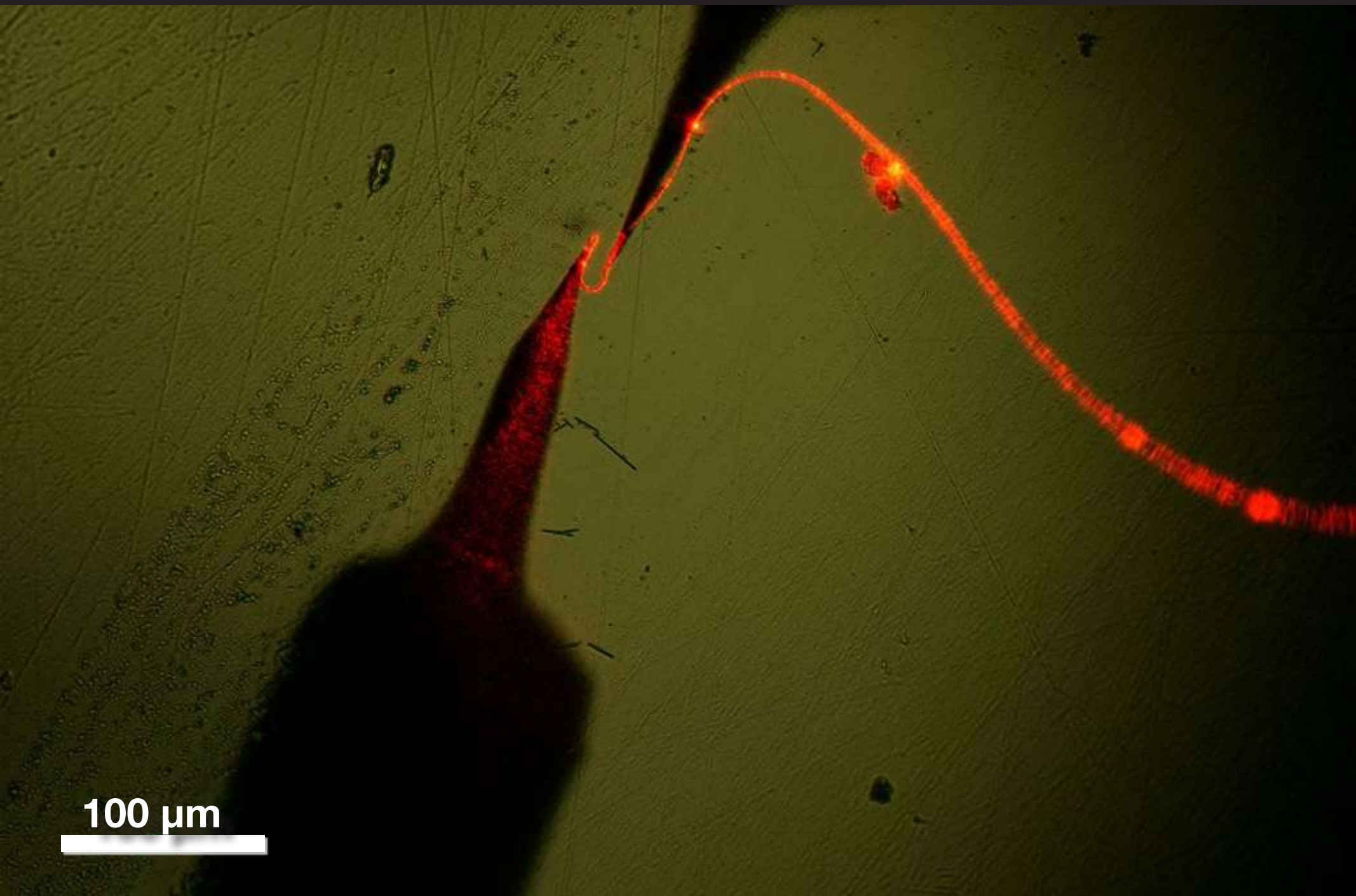

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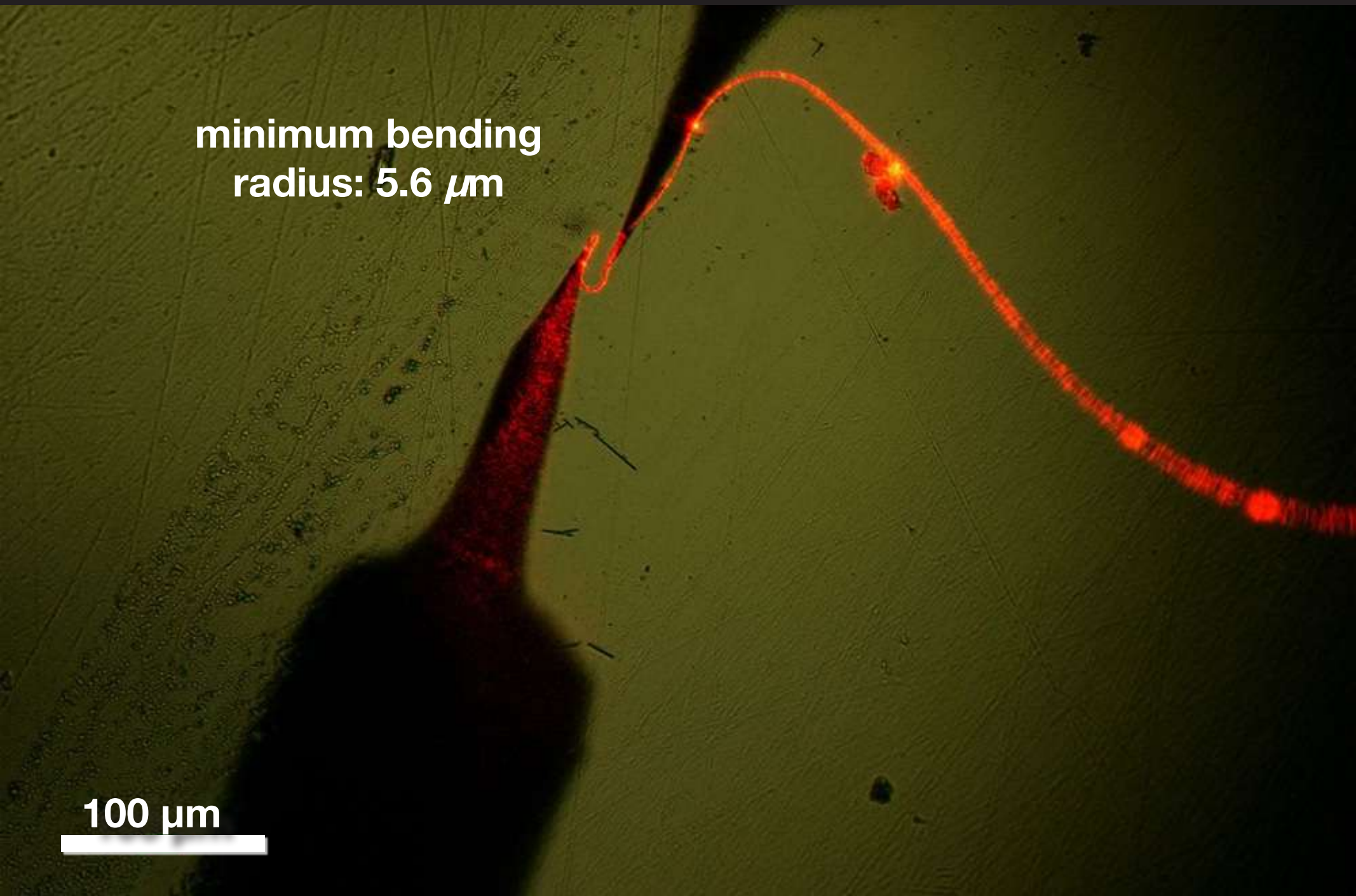
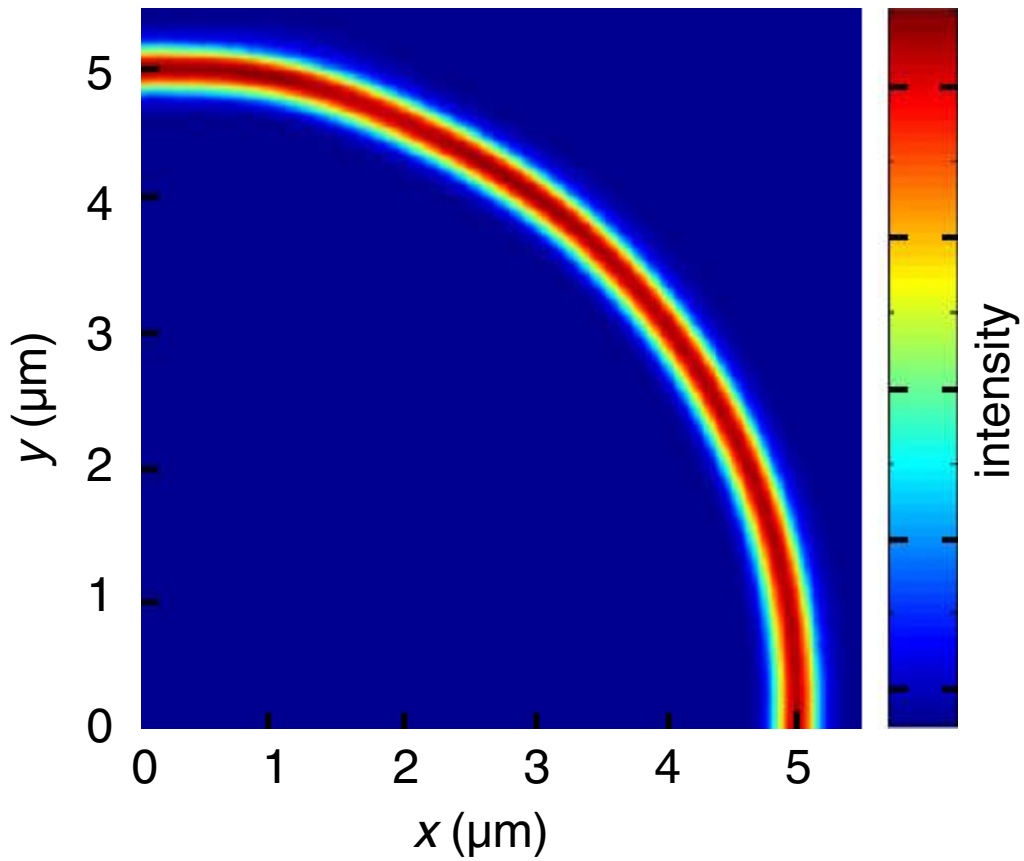


Manipulating light at the nanoscale

virtually no loss through 5 μm corner!



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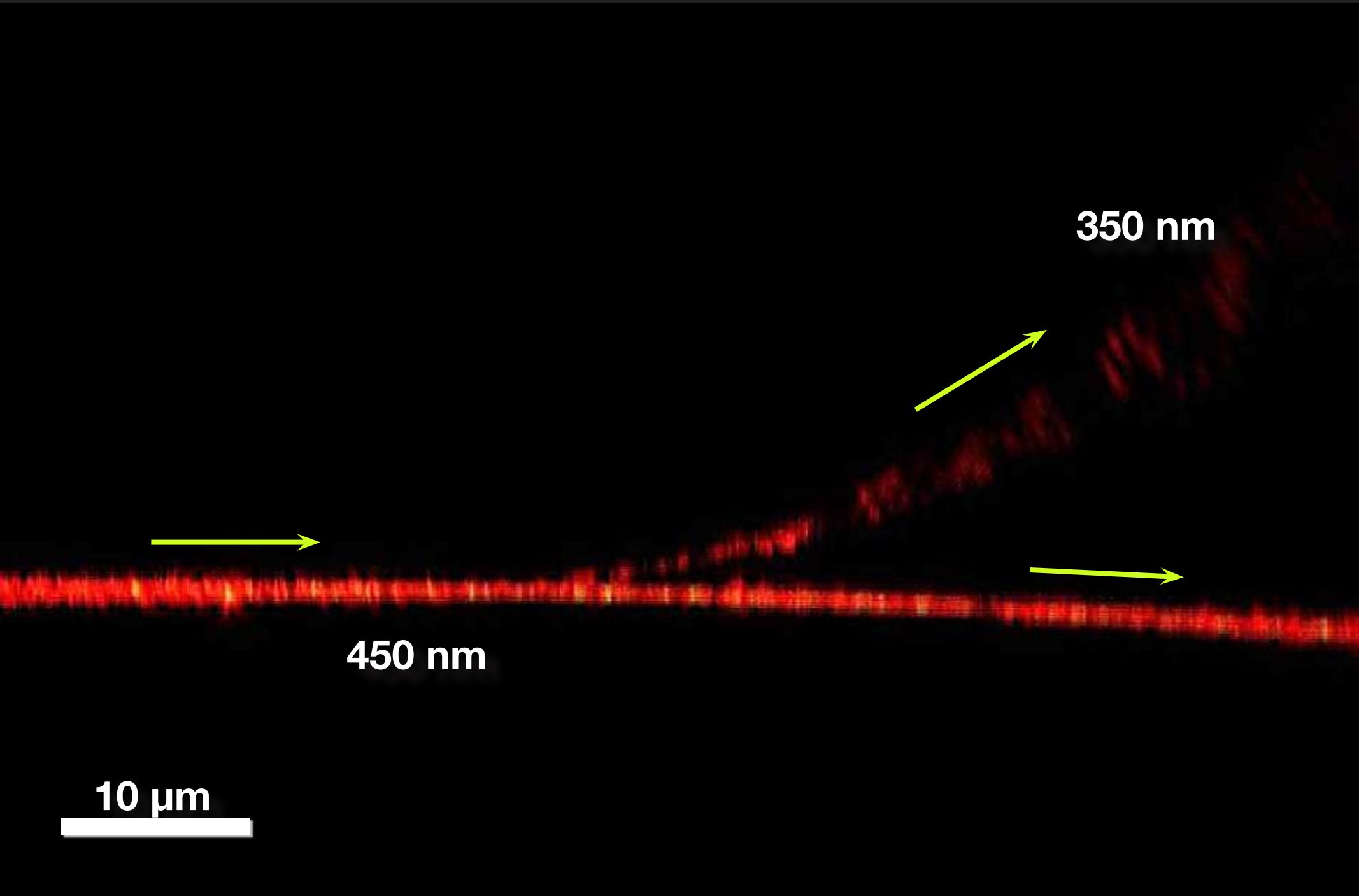

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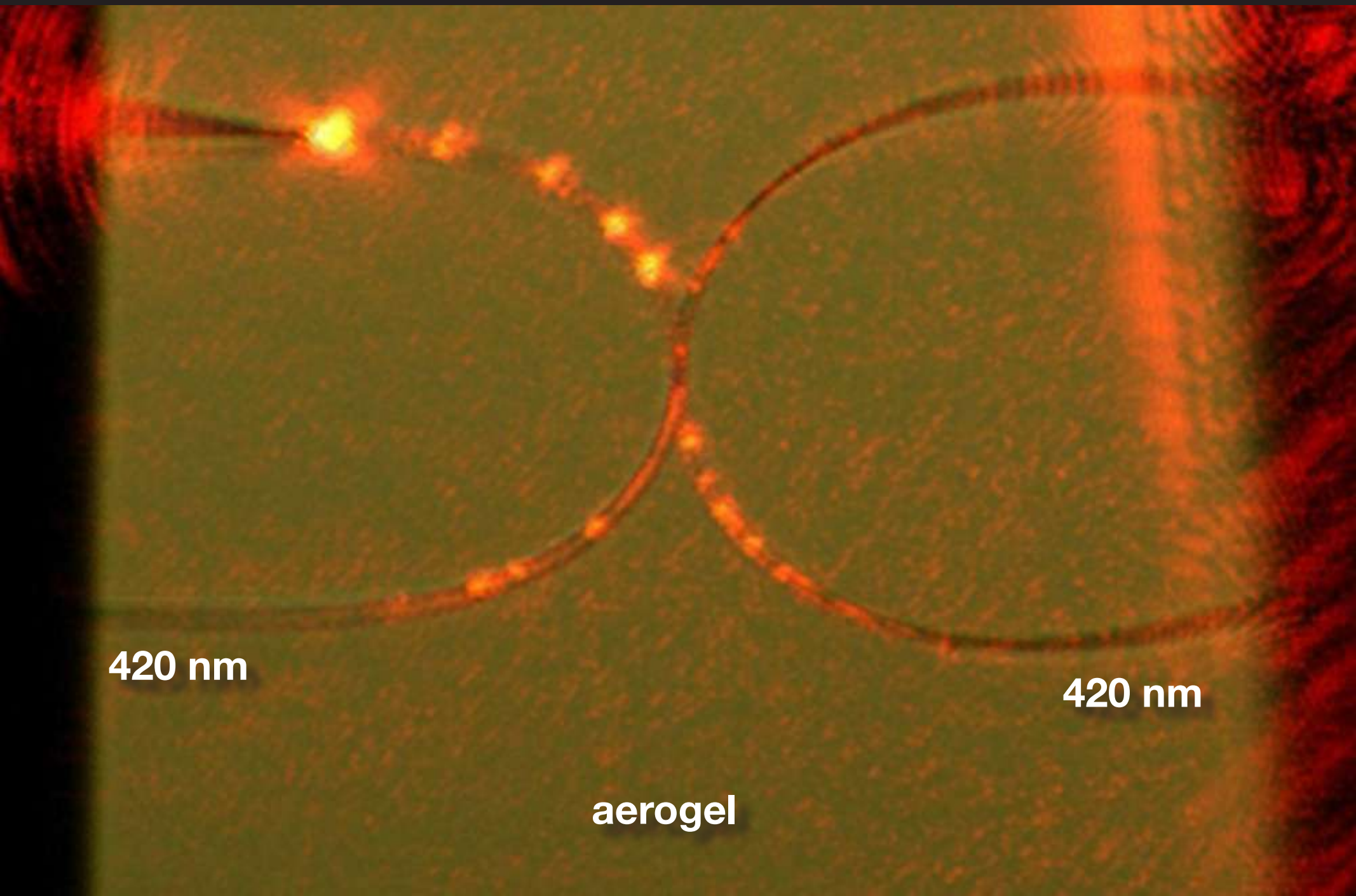

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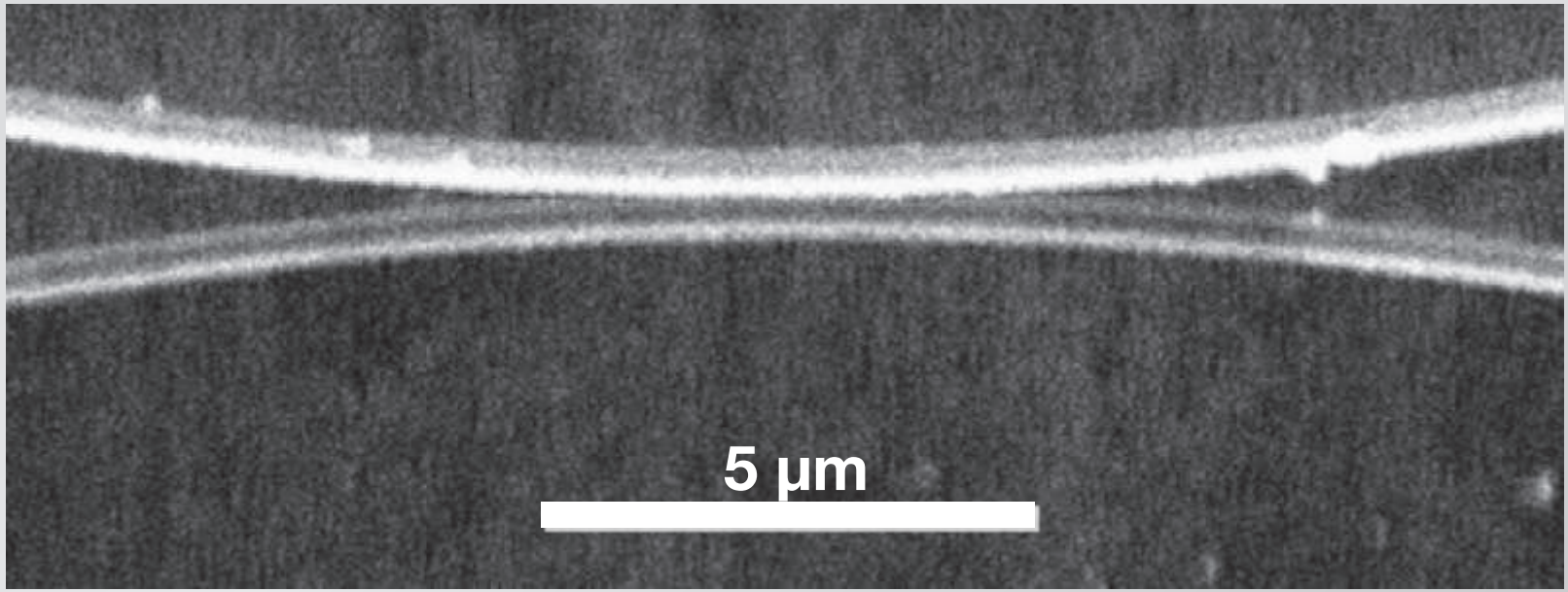

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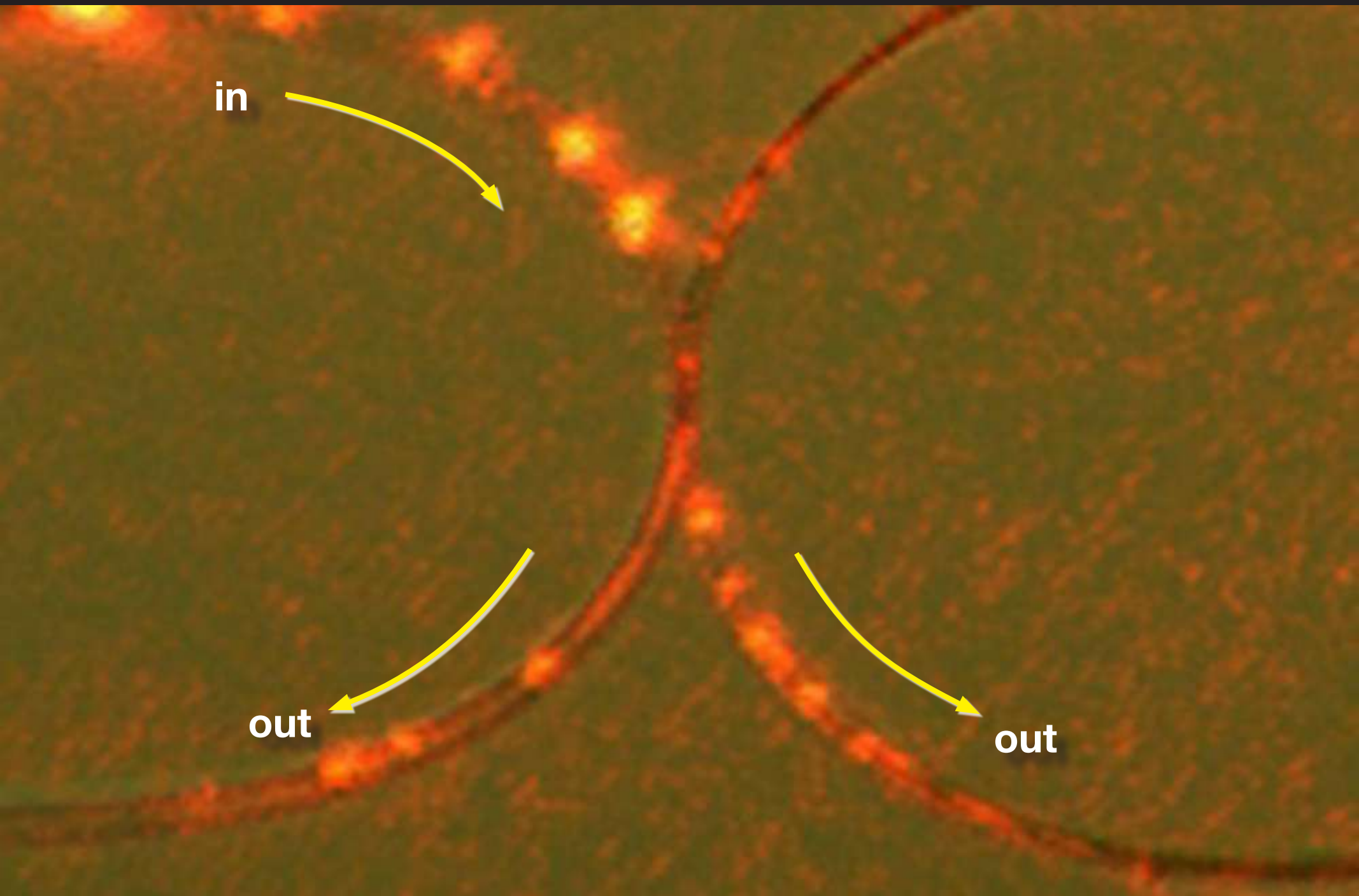


Manipulating light at the nanoscale

use tapered fibers to couple light to nanoscale objects

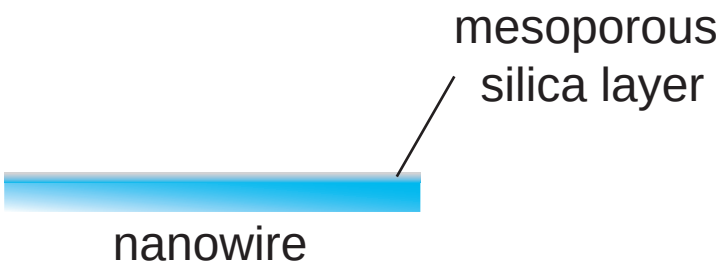
Manipulating light at the nanoscale

ZnO nanowire specifications

diameter	80 — 400 nm
length	up to 80 μm
aspect ratio	$5\ 10^2$

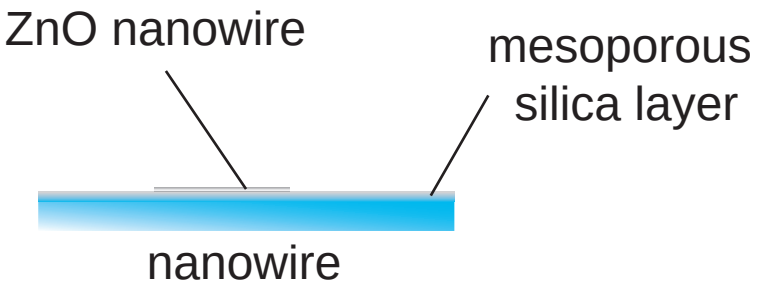
Manipulating light at the nanoscale

coupling to ZnO nanowires



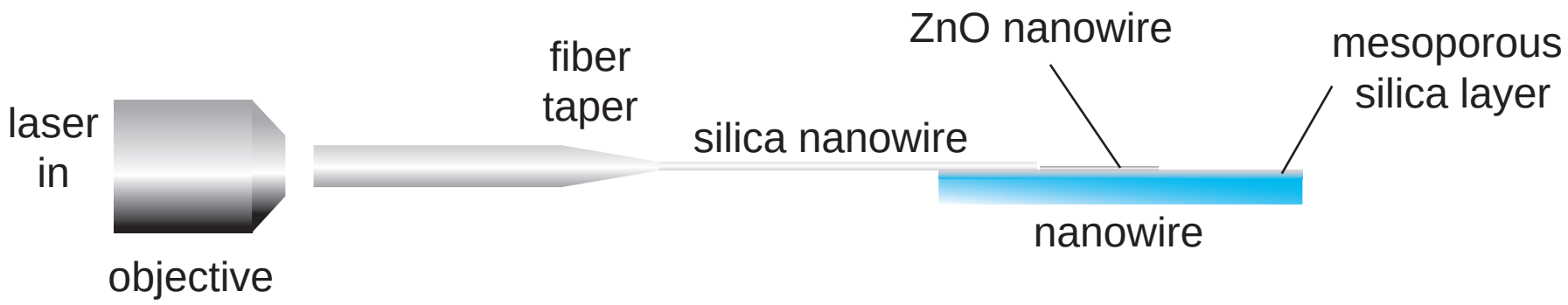
Manipulating light at the nanoscale

coupling to ZnO nanowires



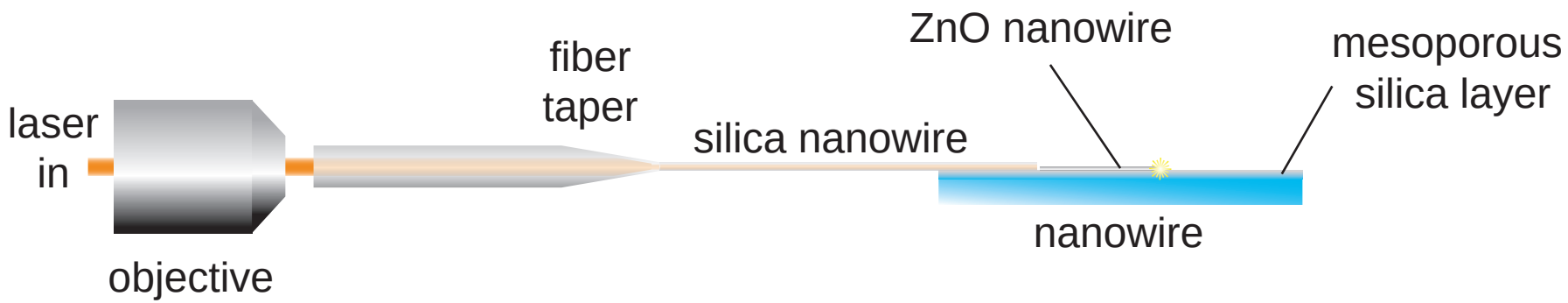
Manipulating light at the nanoscale

coupling to ZnO nanowires



Manipulating light at the nanoscale

coupling to ZnO nanowires



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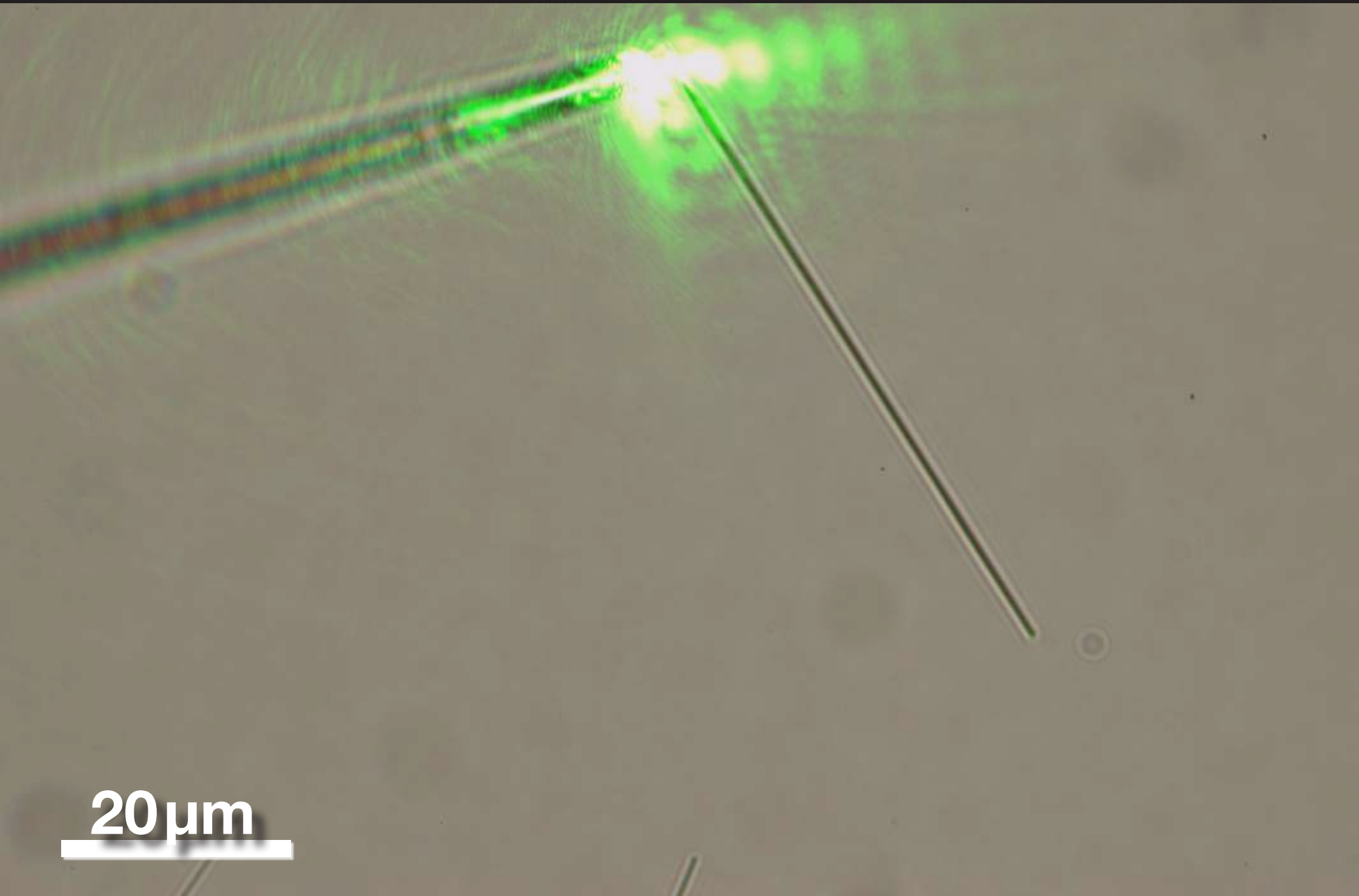

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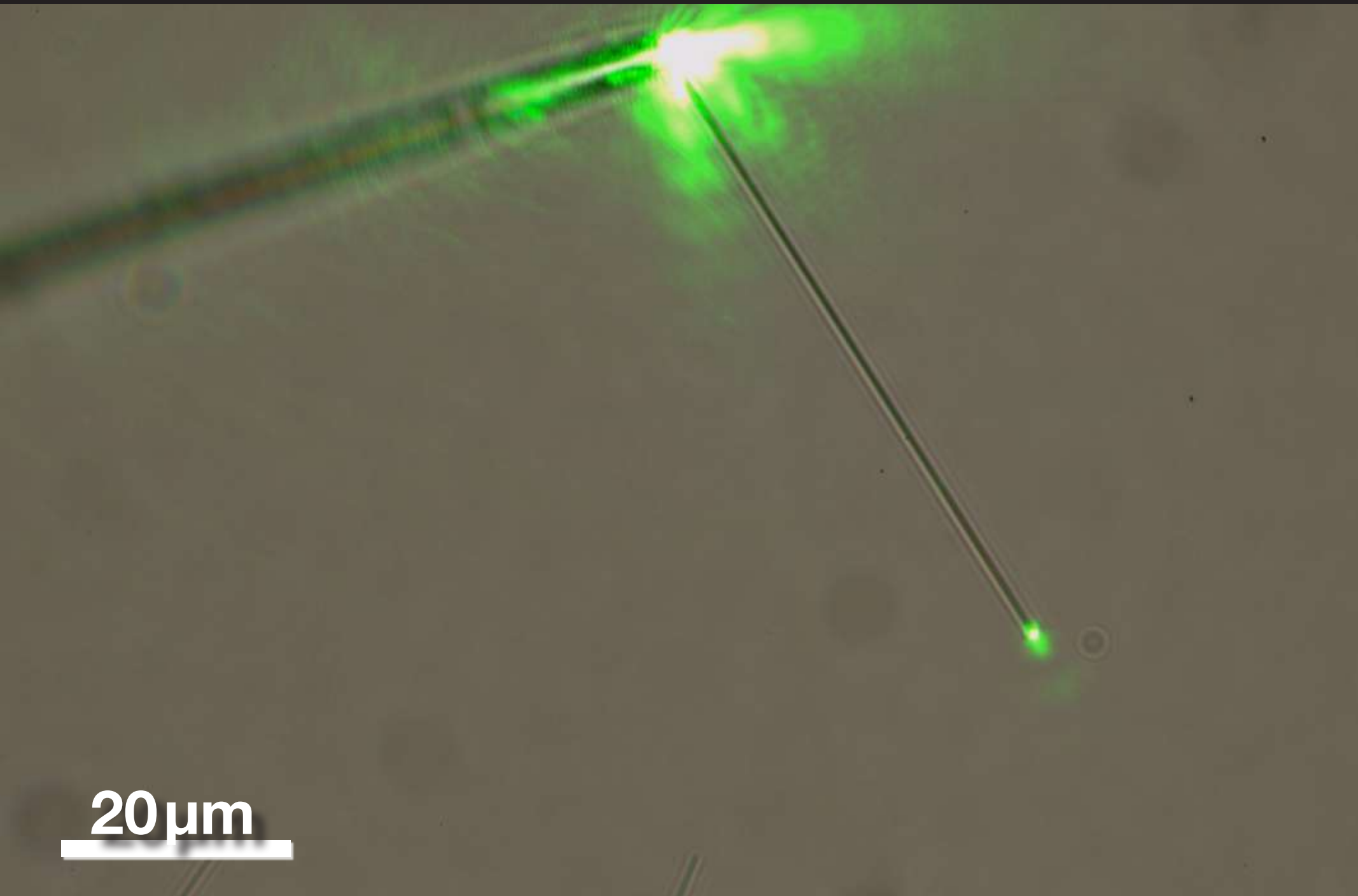

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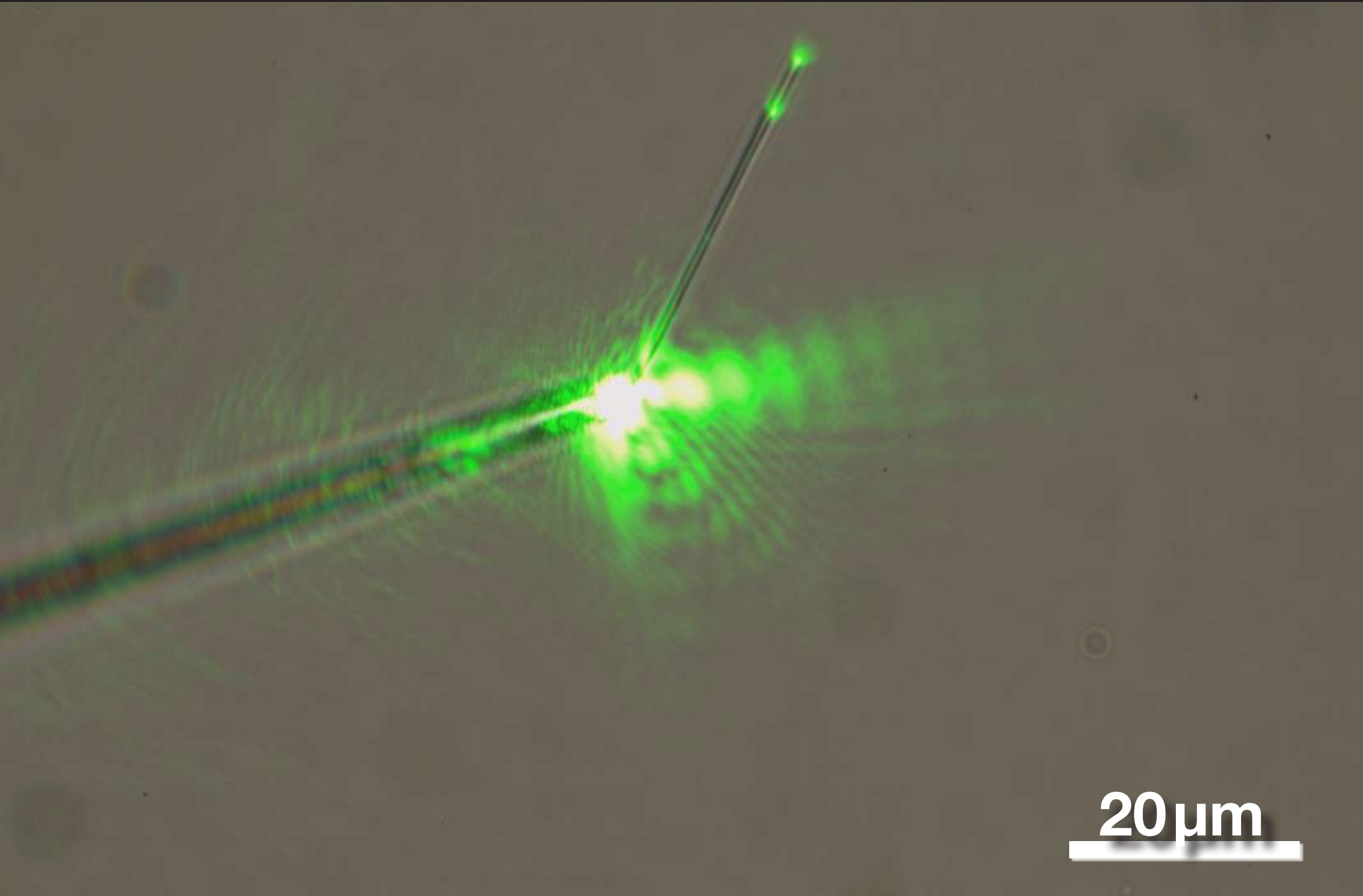

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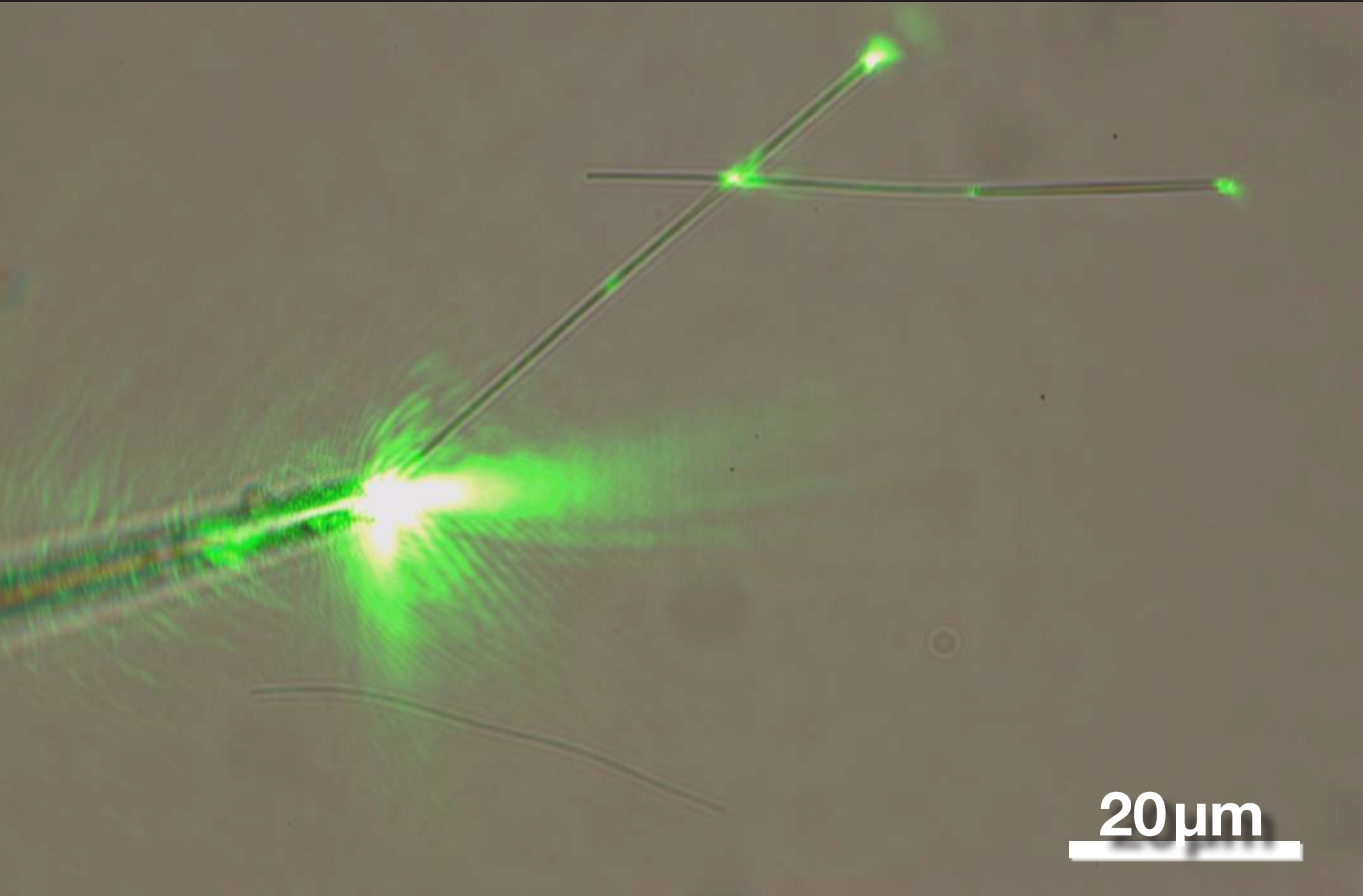

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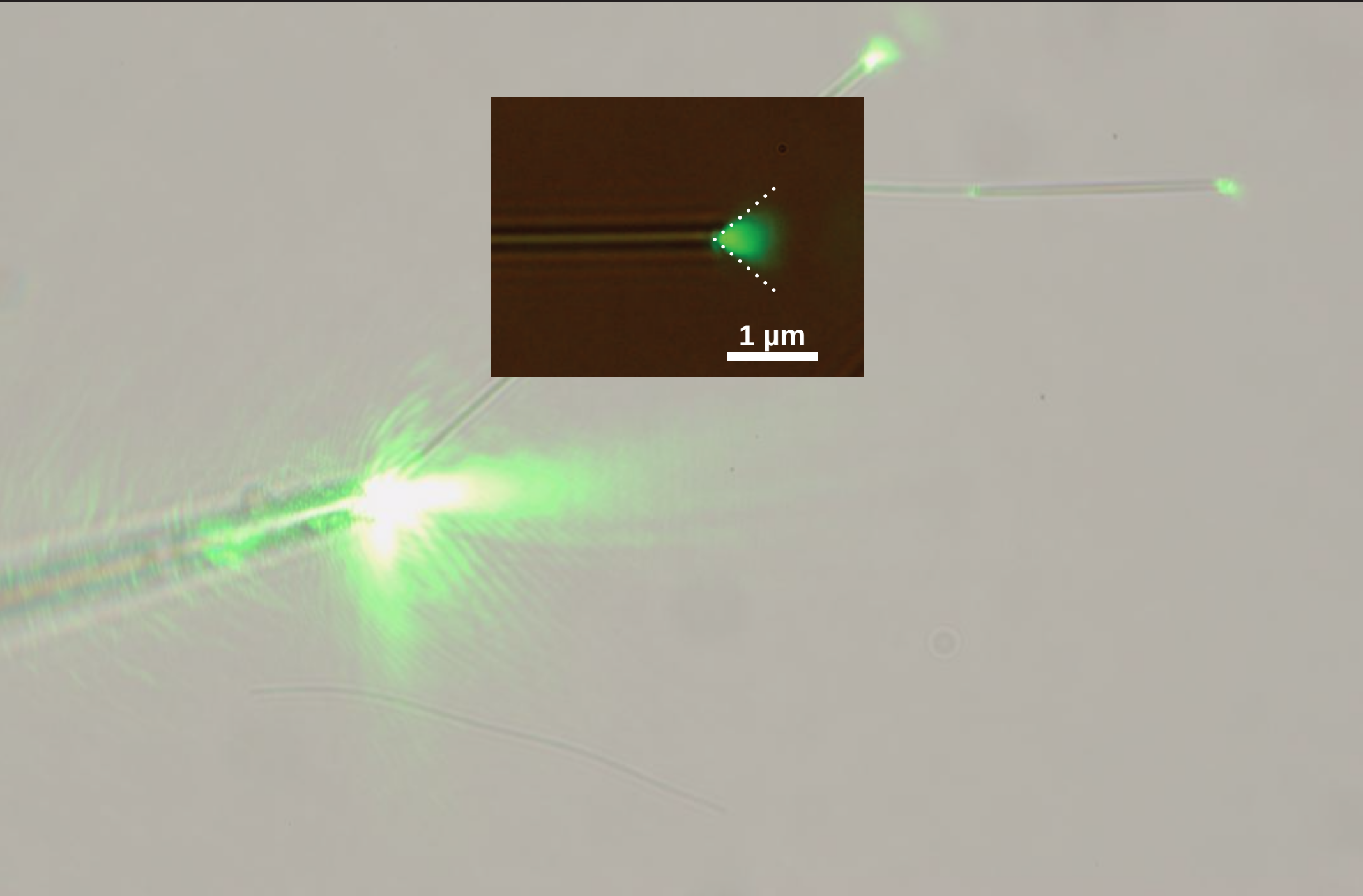

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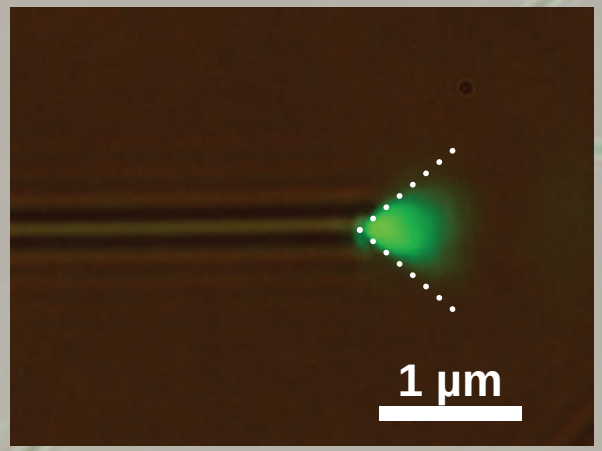
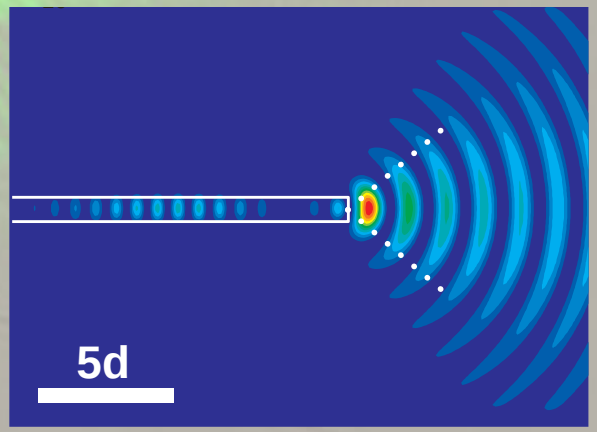


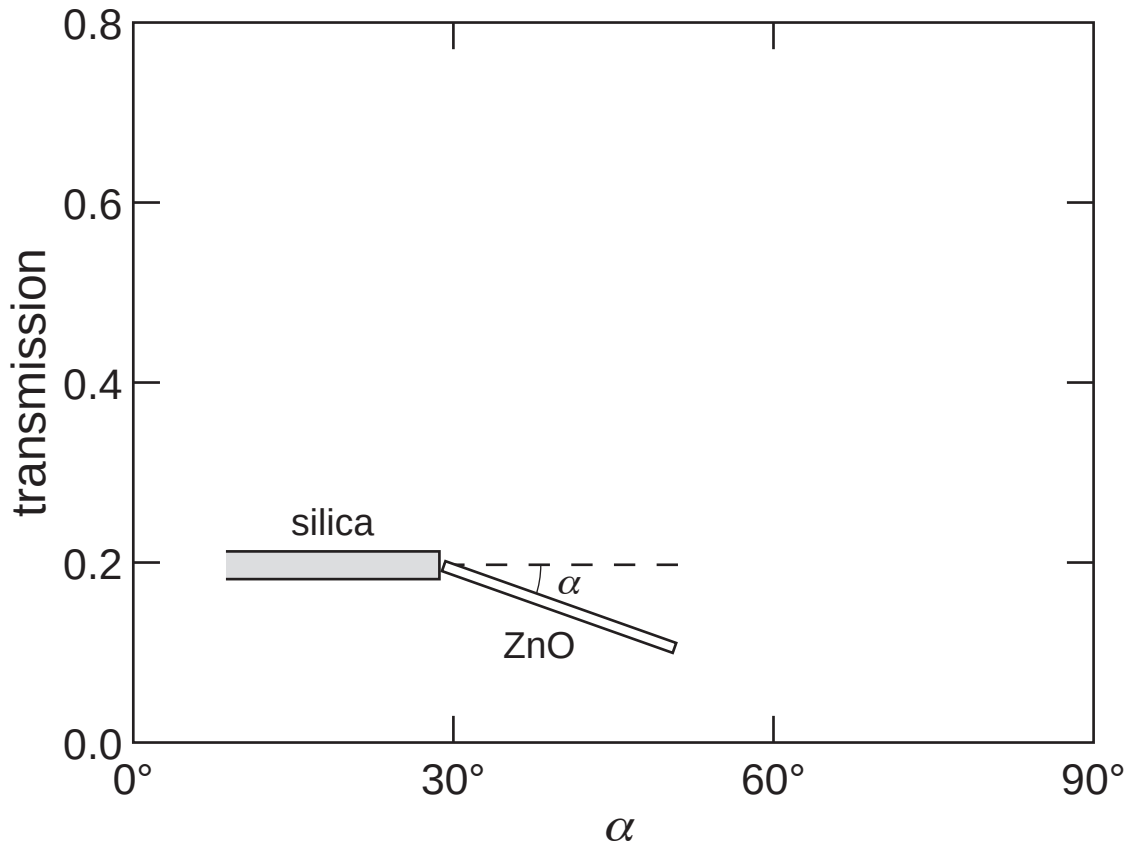
FDTD simulation



ab-initio.mit.edu/wiki/index/Meep

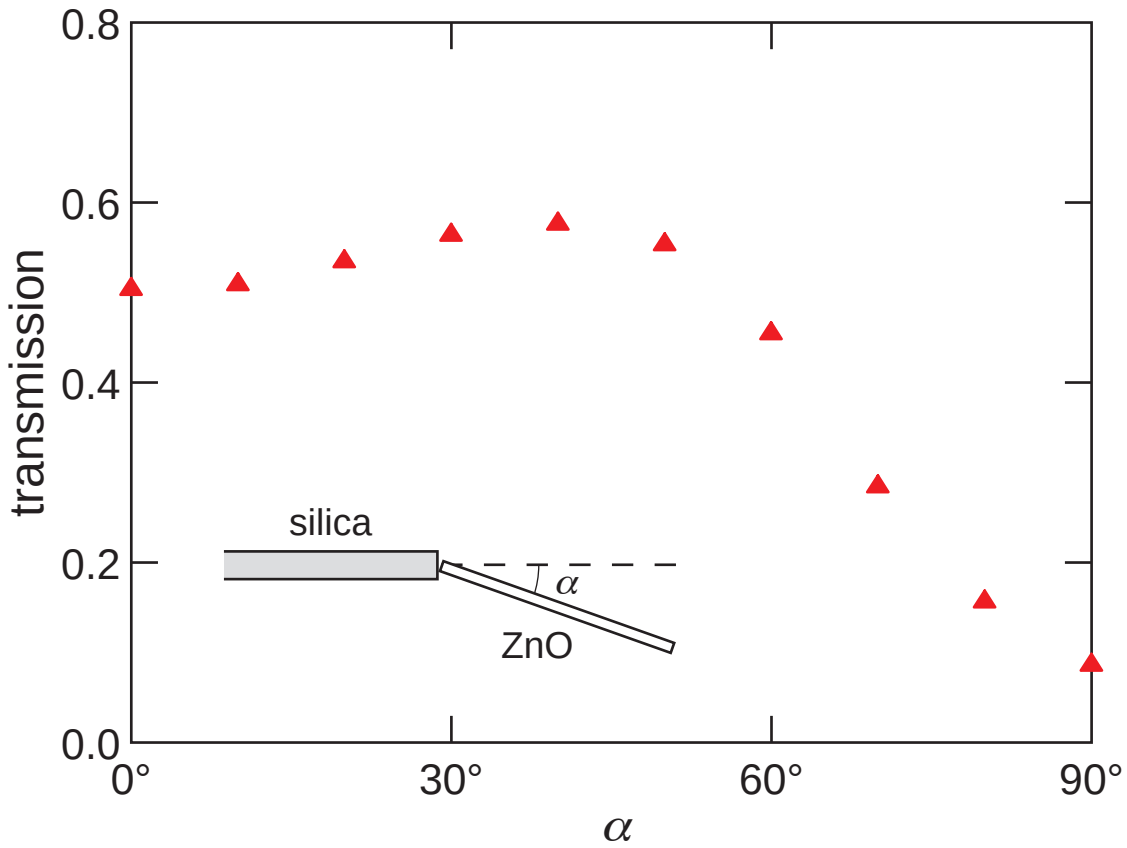
Manipulating light at the nanoscale

coupling efficiency



Manipulating light at the nanoscale

coupling efficiency



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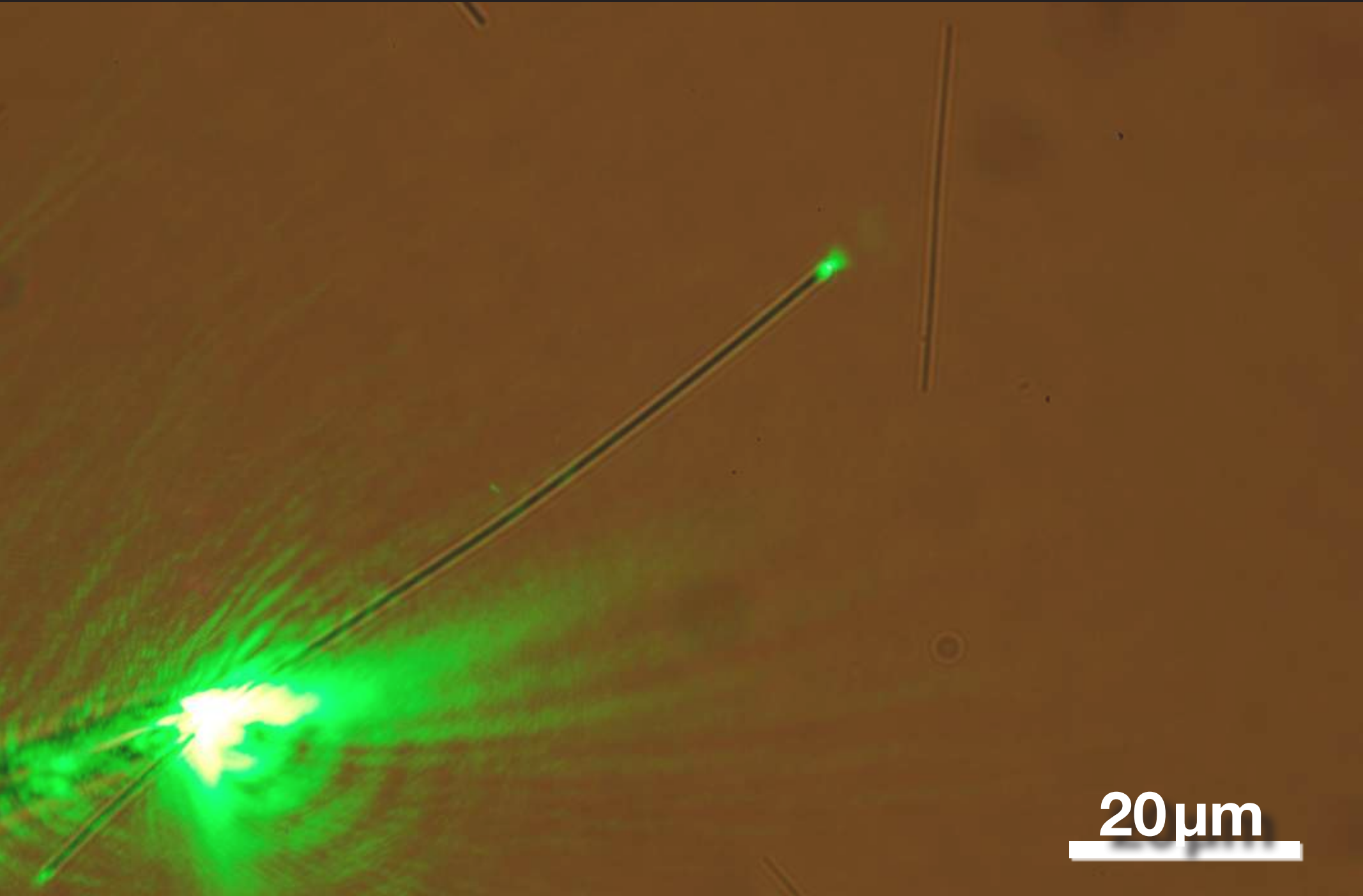
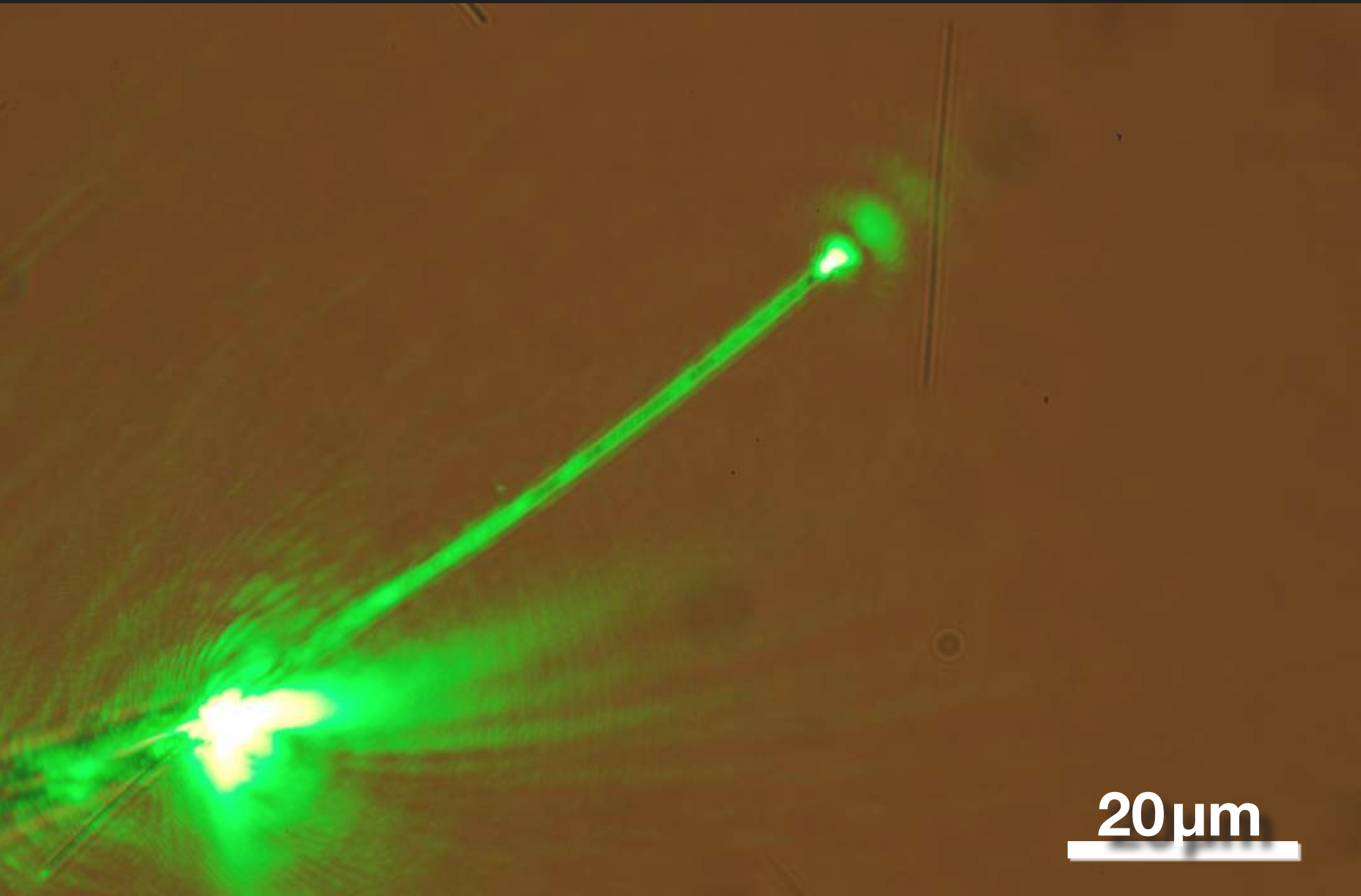
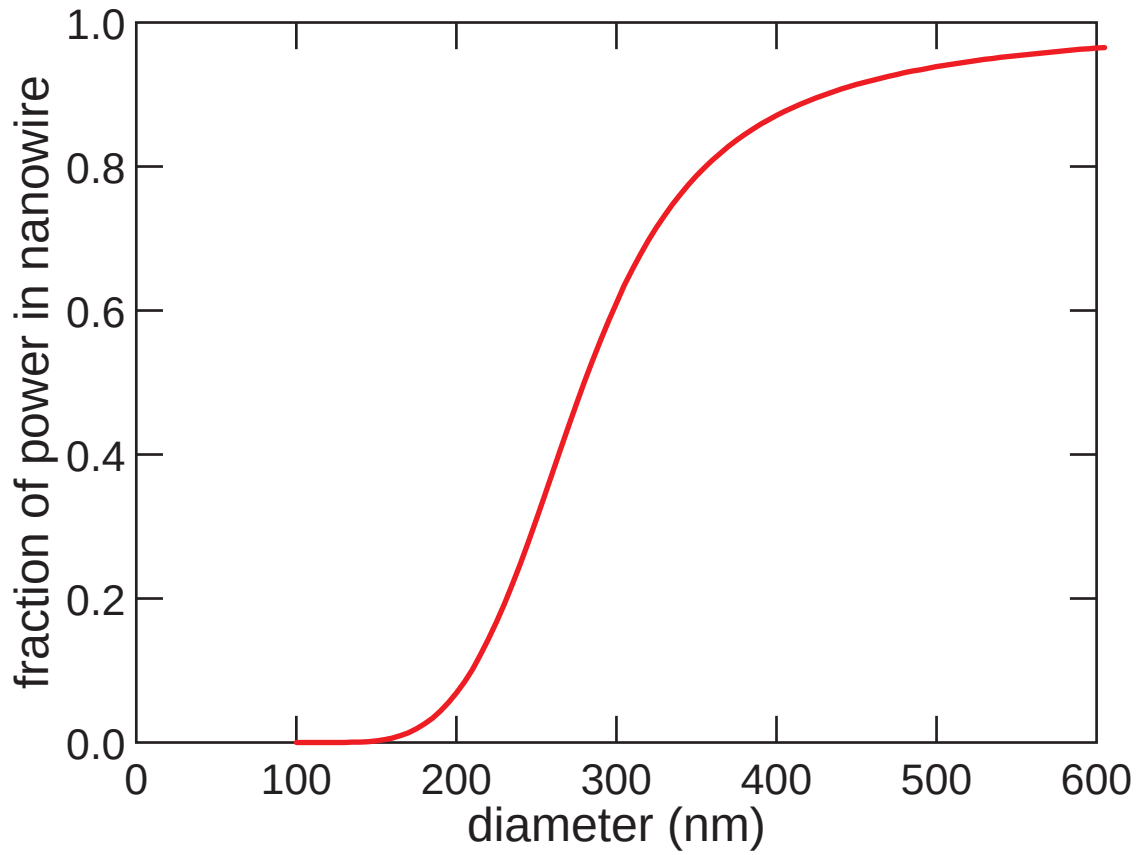


Manipulating light at the nanoscale



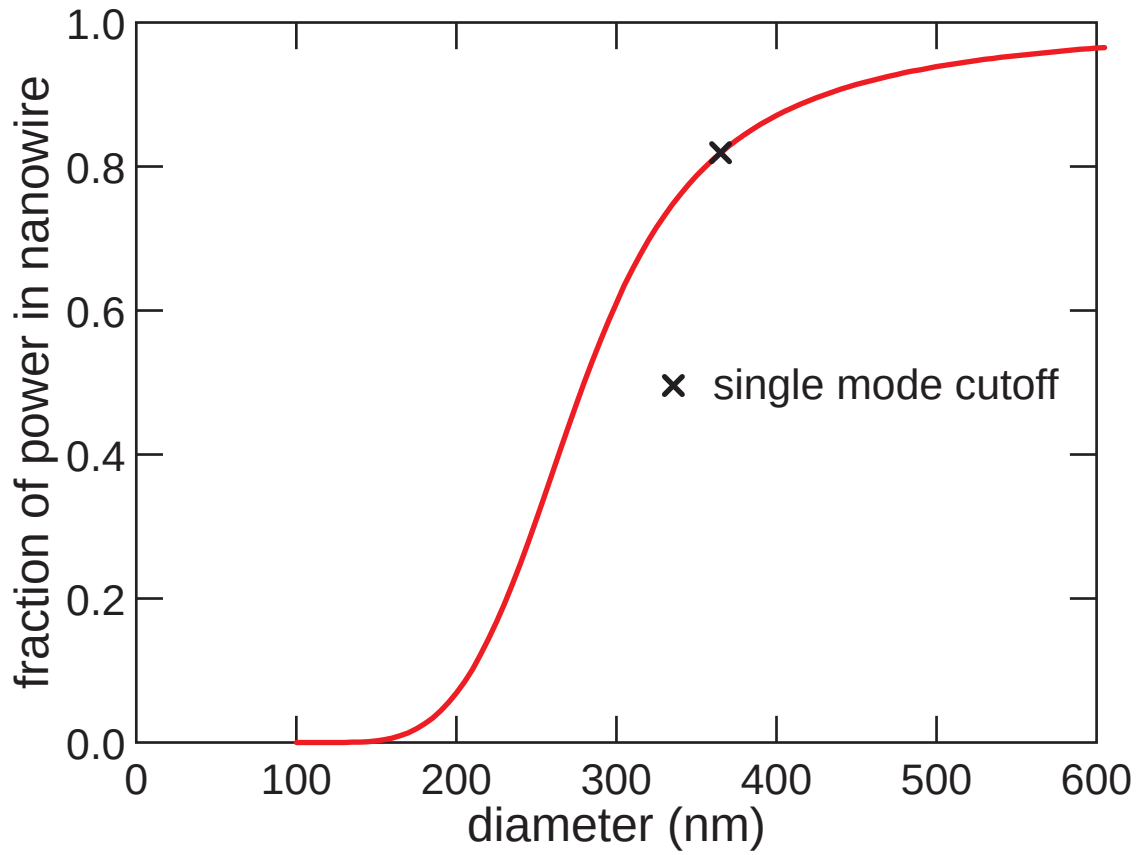
Manipulating light at the nanoscale

single-mode cutoff



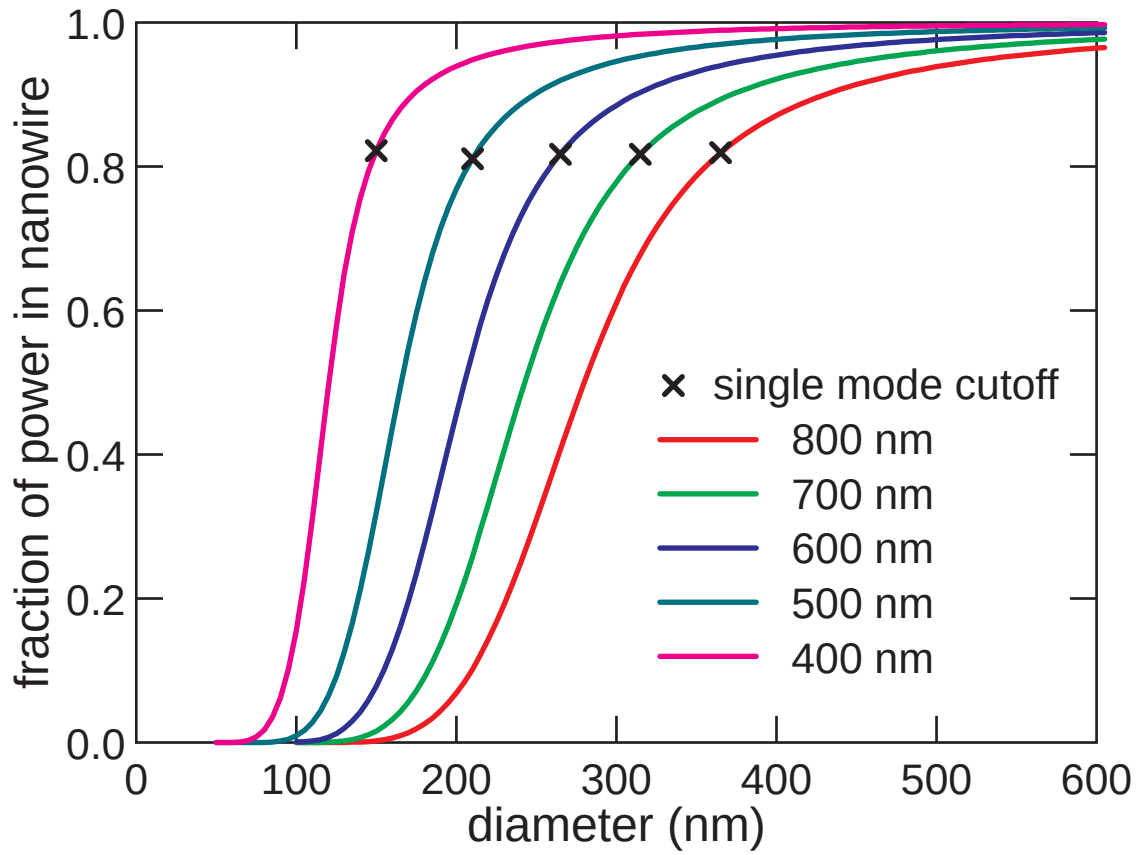
Manipulating light at the nanoscale

single-mode cutoff



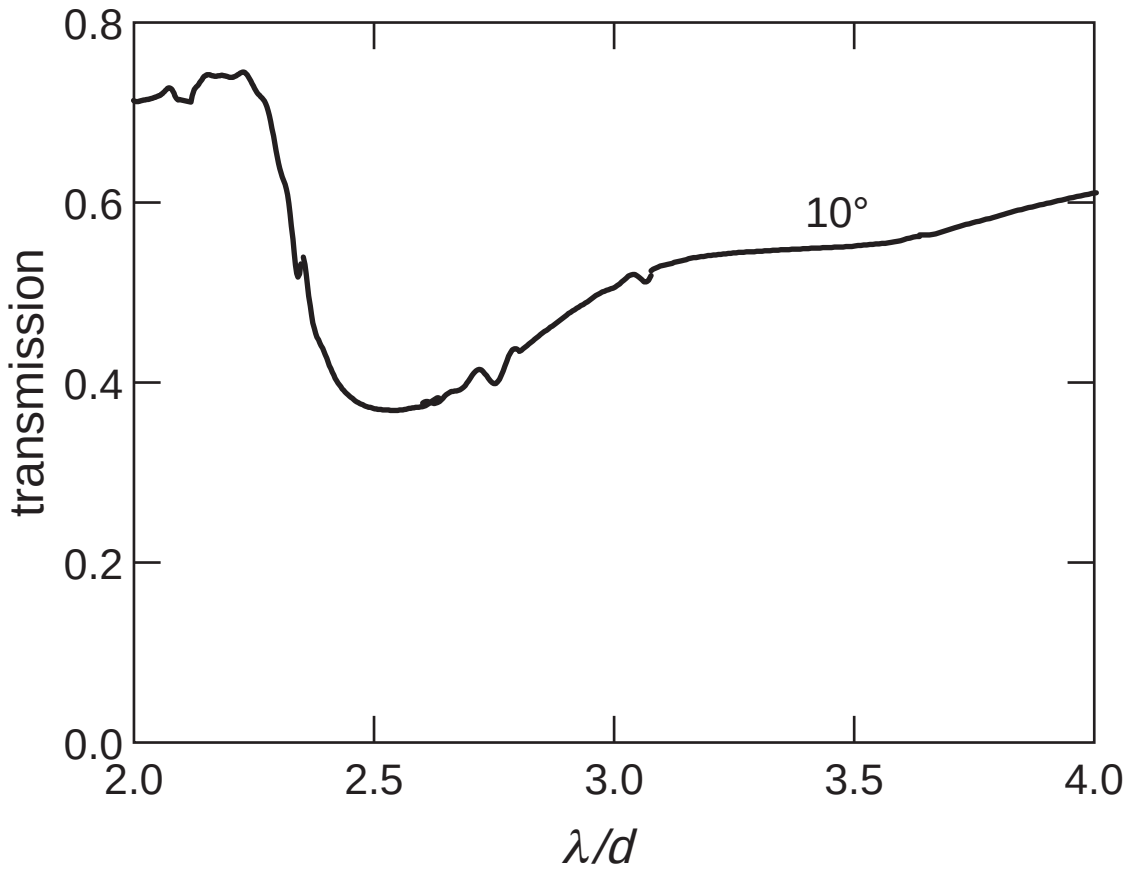
Manipulating light at the nanoscale

single-mode cutoff



Manipulating light at the nanoscale

transmission spectrum



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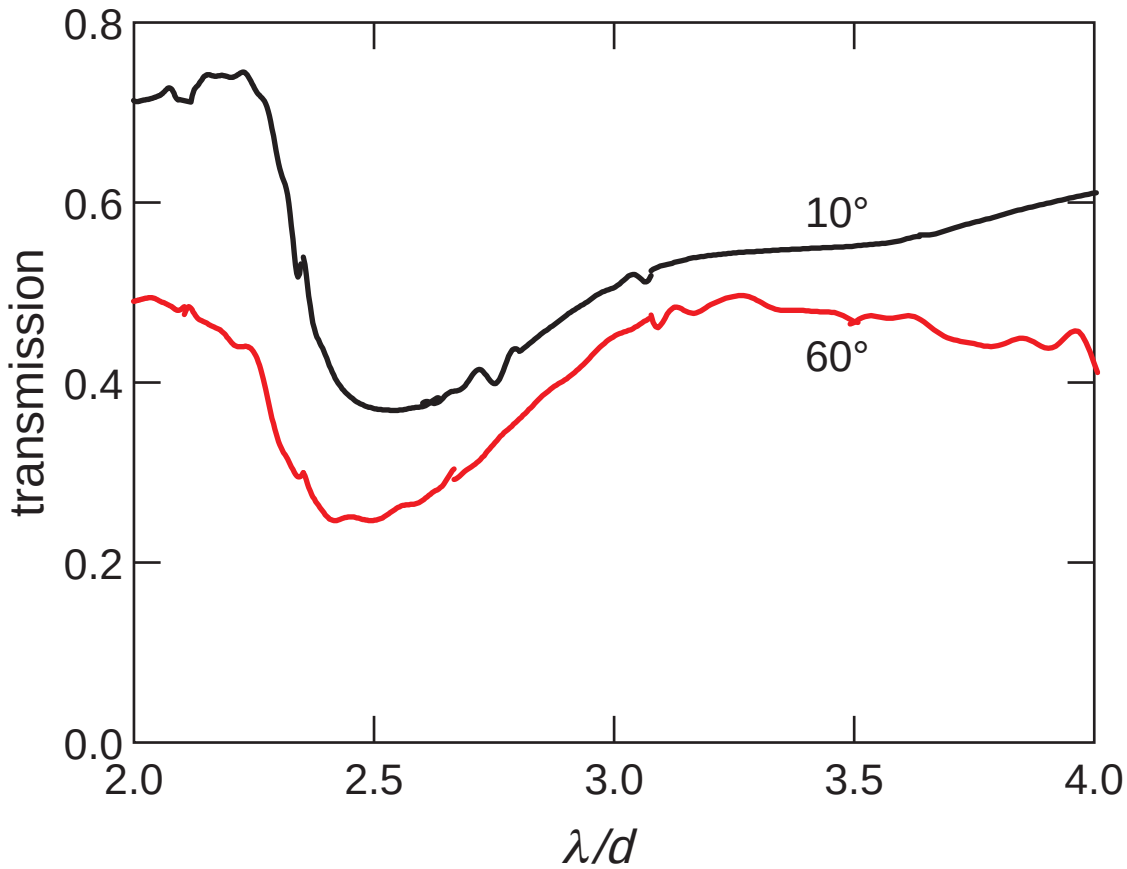

Manipulating light at the nanoscale

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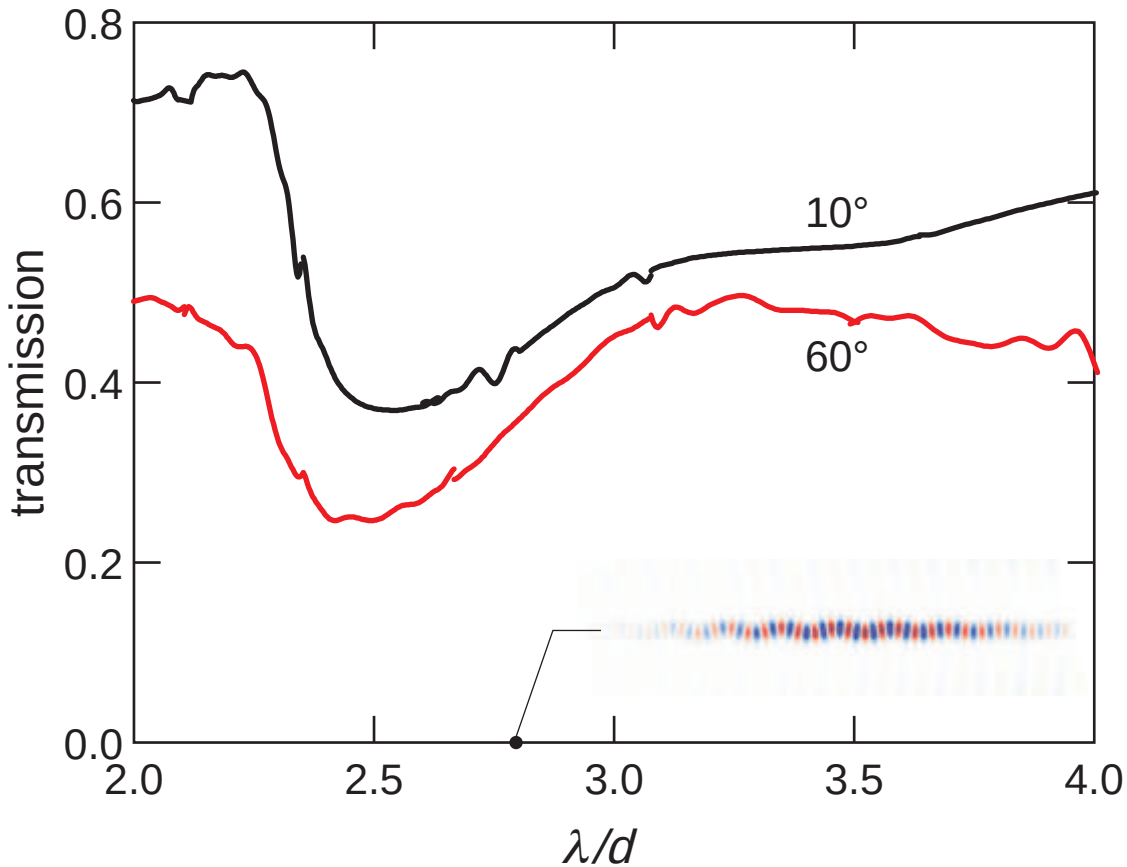
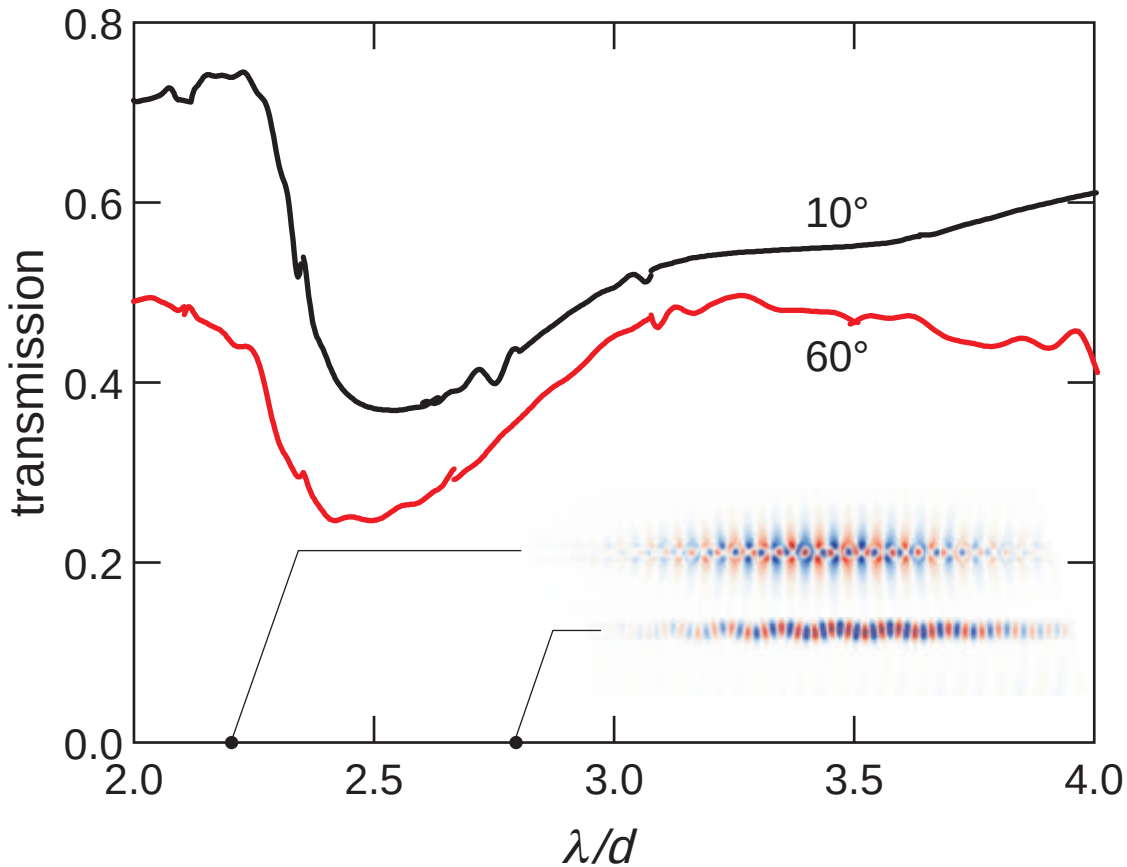
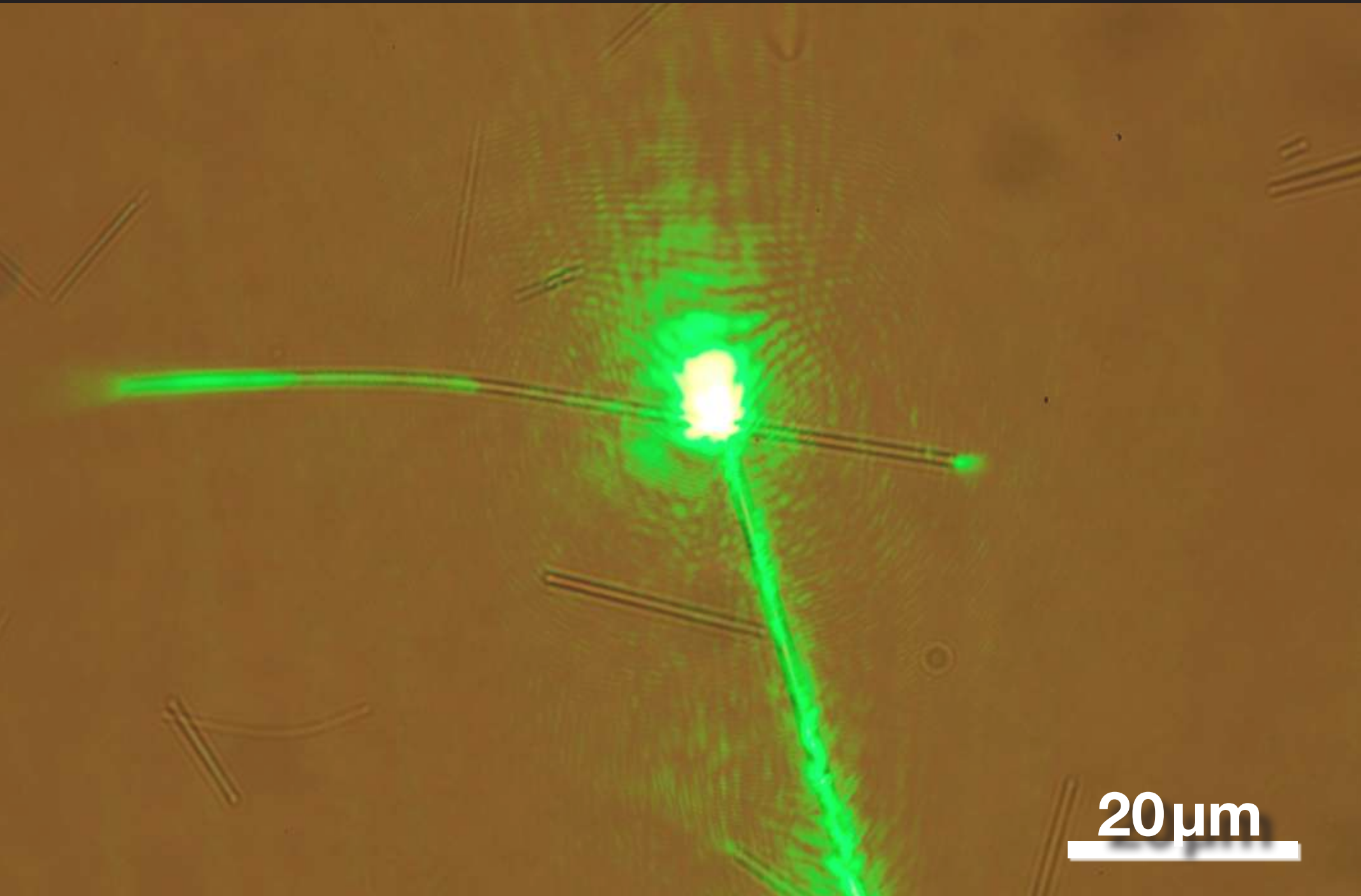


Manipulating light at the nanoscale

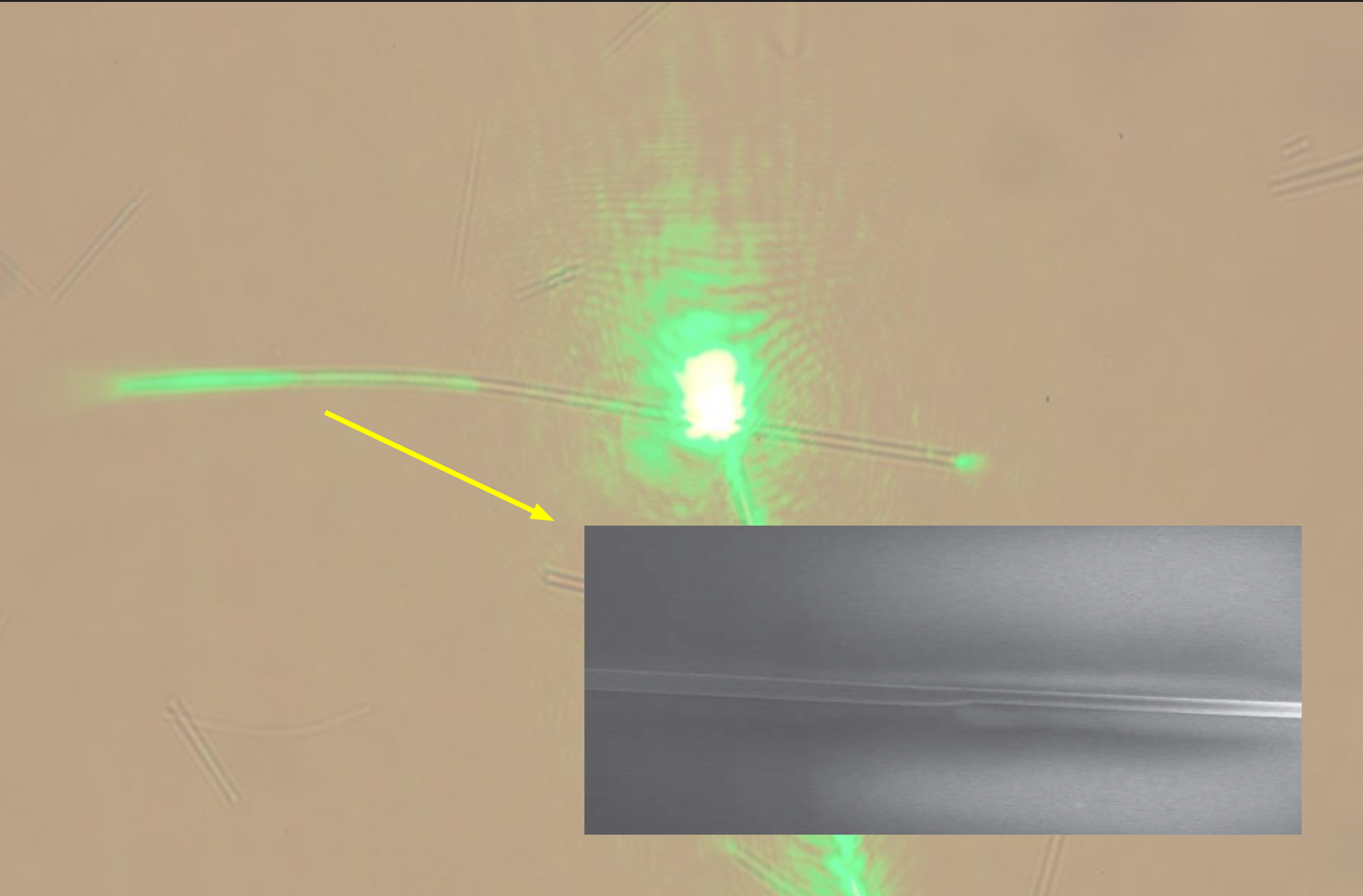
transmission spectrum



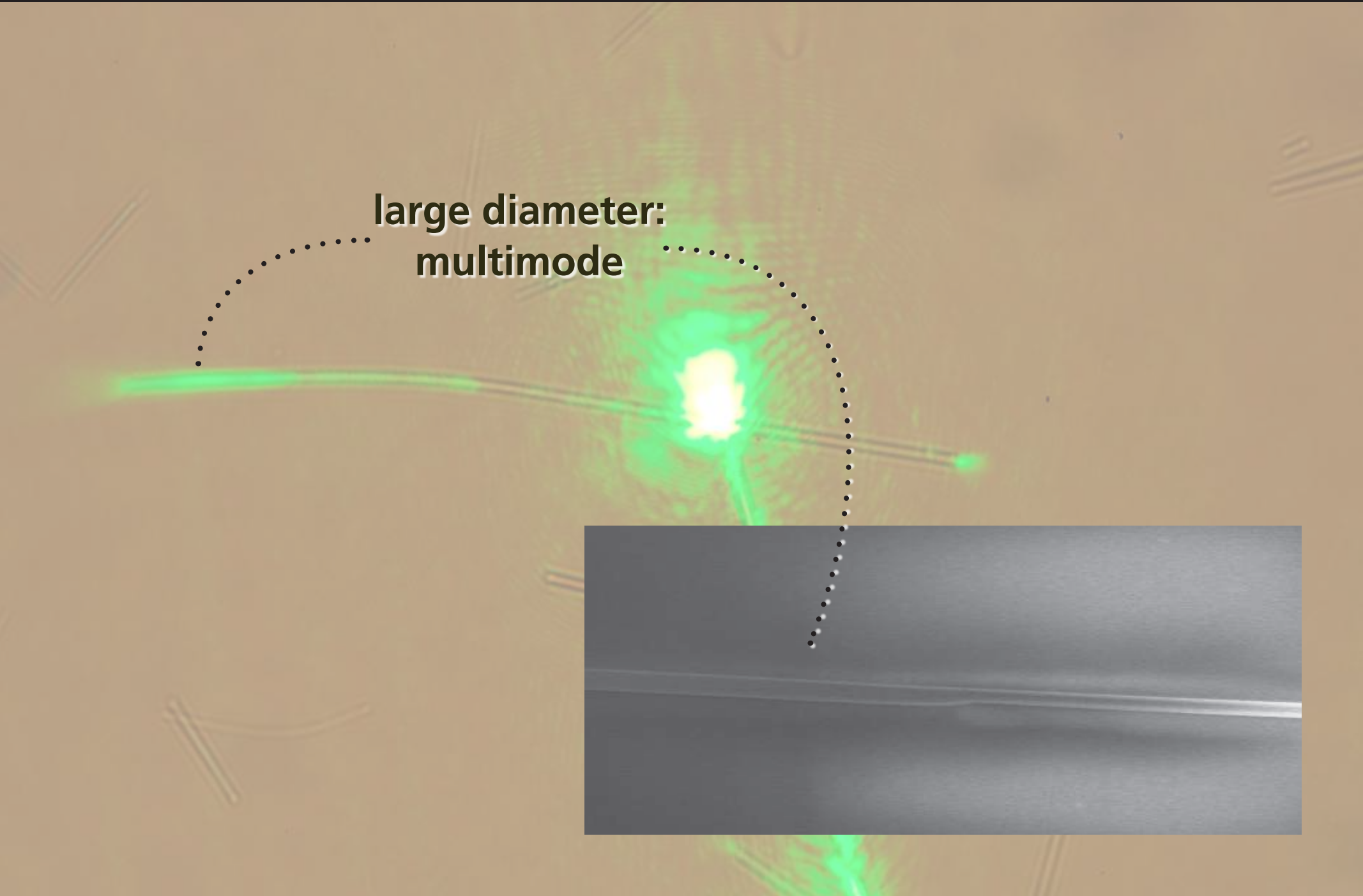
Manipulating light at the nanoscale



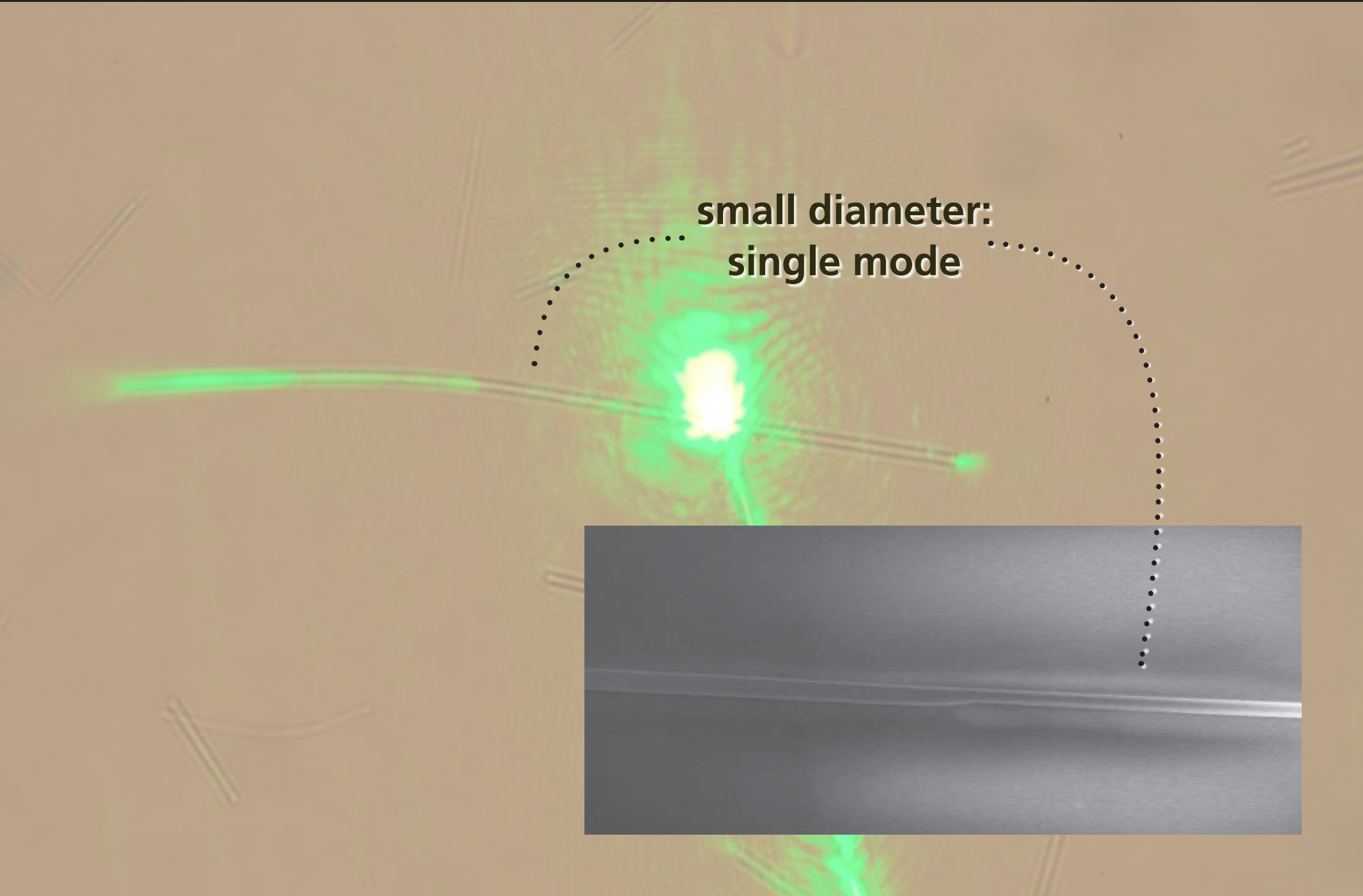
Manipulating light at the nanoscale



Manipulating light at the nanoscale



Manipulating light at the nanoscale



Manipulating light at the nanoscale

Points to keep in mind:

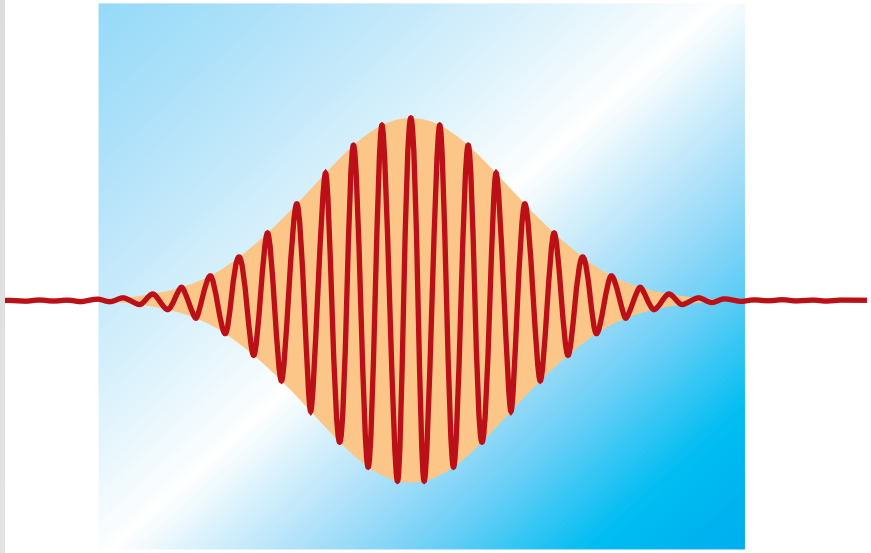
- large evanescent field
- tight confinement
- convenient coupling to nanoscale

Outline

- silica nanowires
- manipulating light at the nanoscale
- nanoscale nonlinear optics

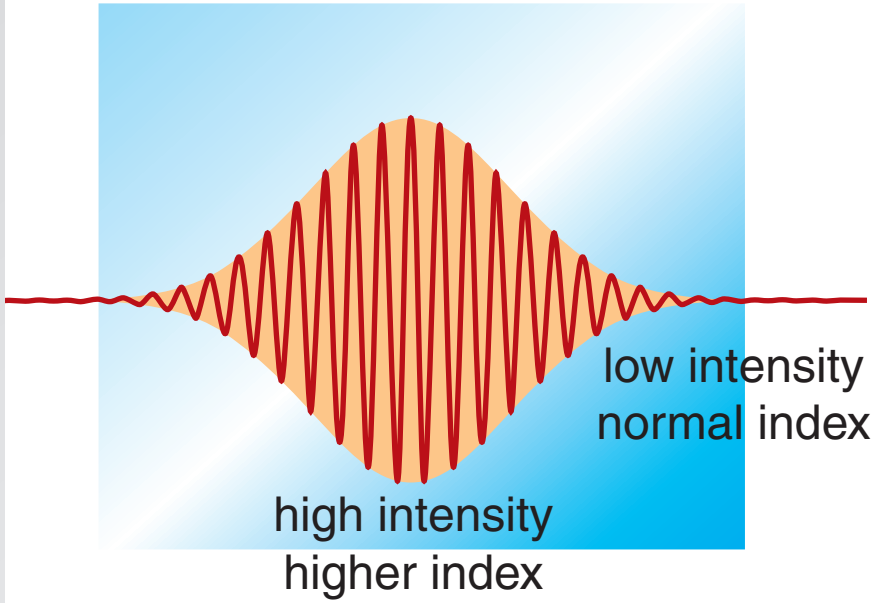
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



Nanoscale nonlinear optics

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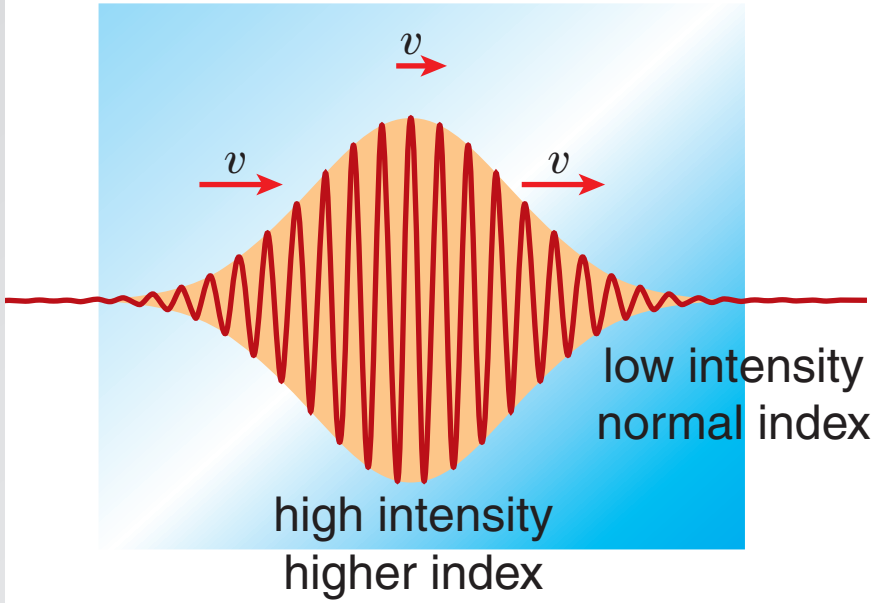
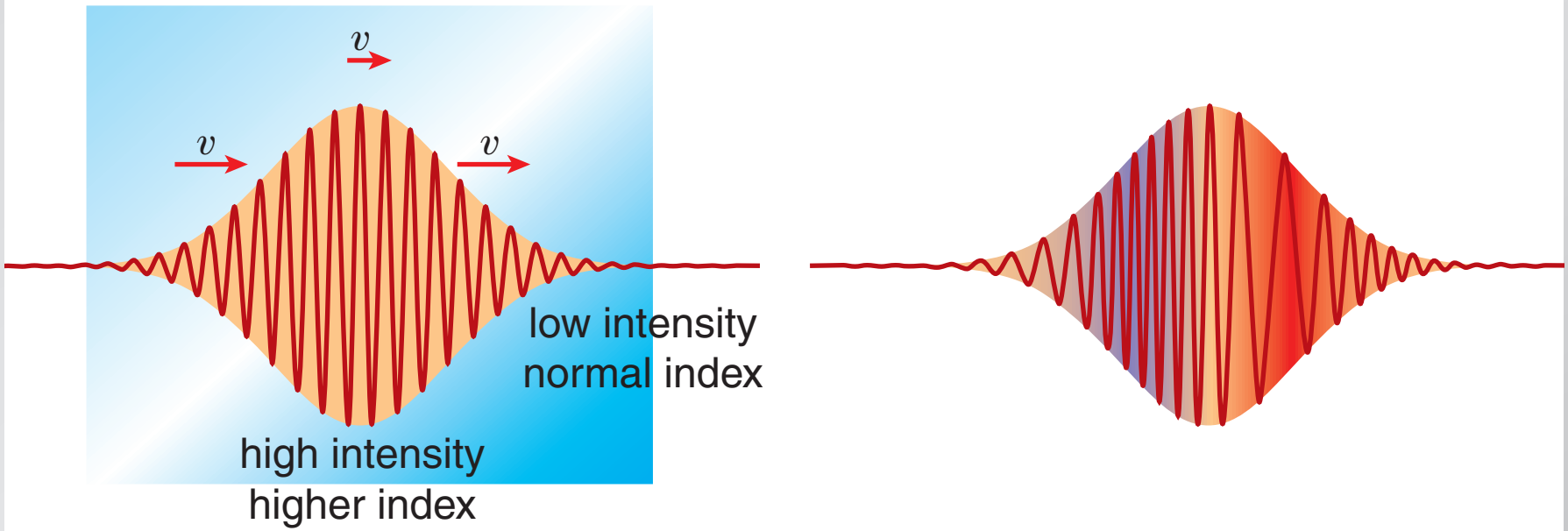


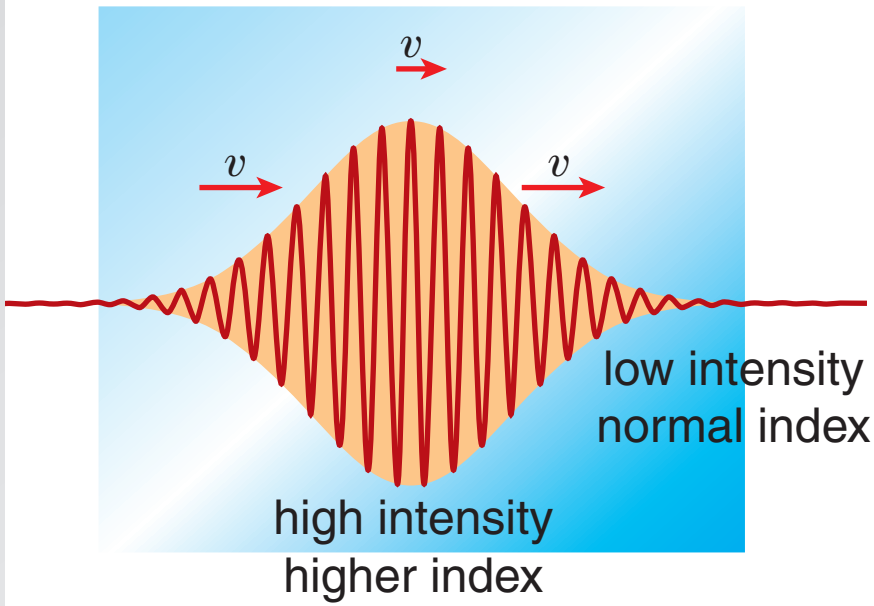
Nanoscale nonlinear optics

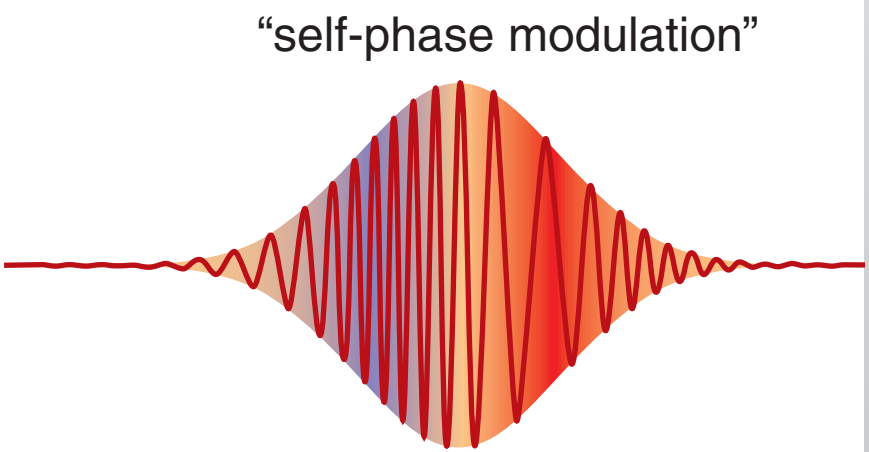
nonlinear dispersion: $n = n_o + n_2 I$



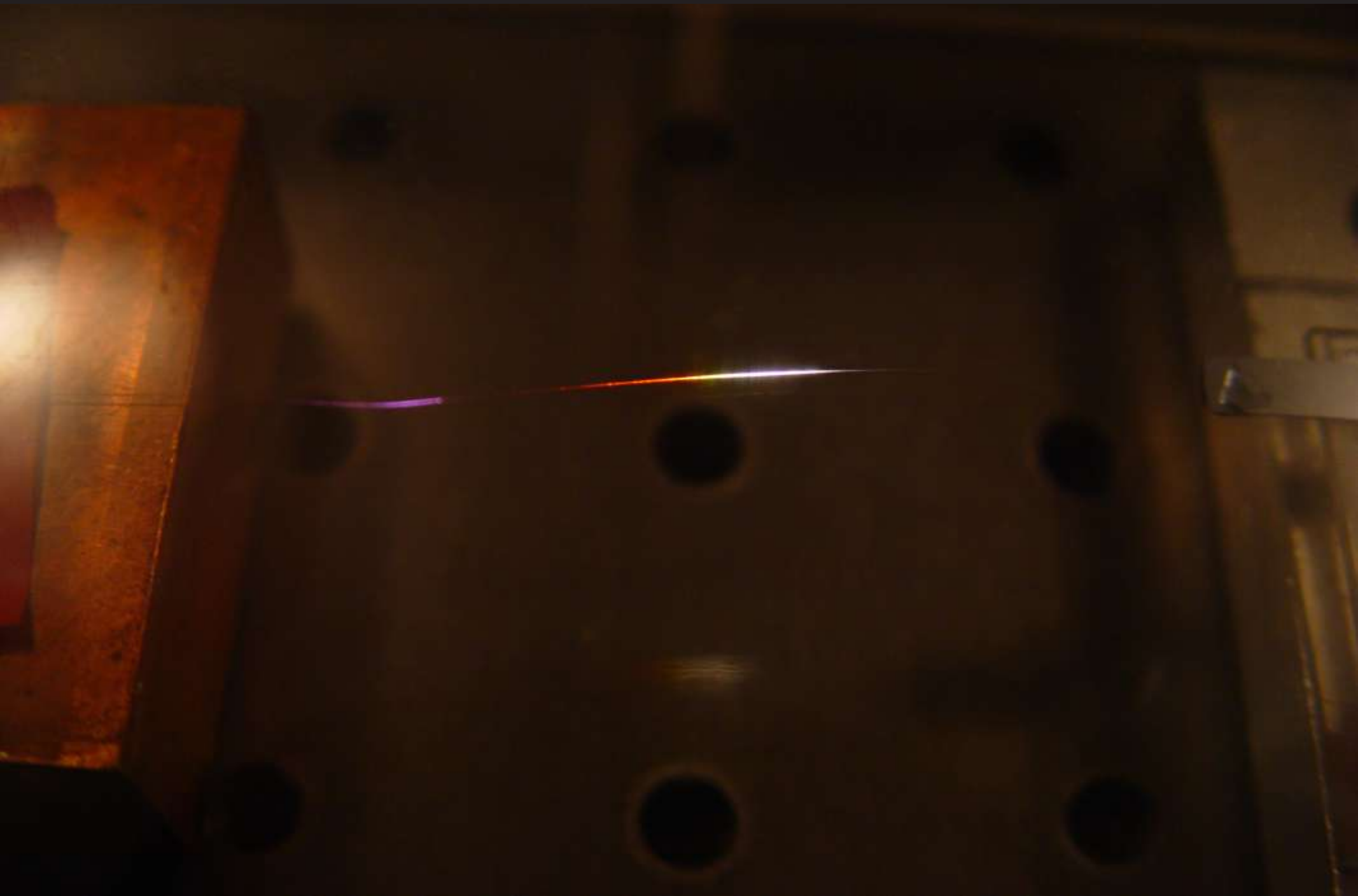
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$





Nanoscale nonlinear optics



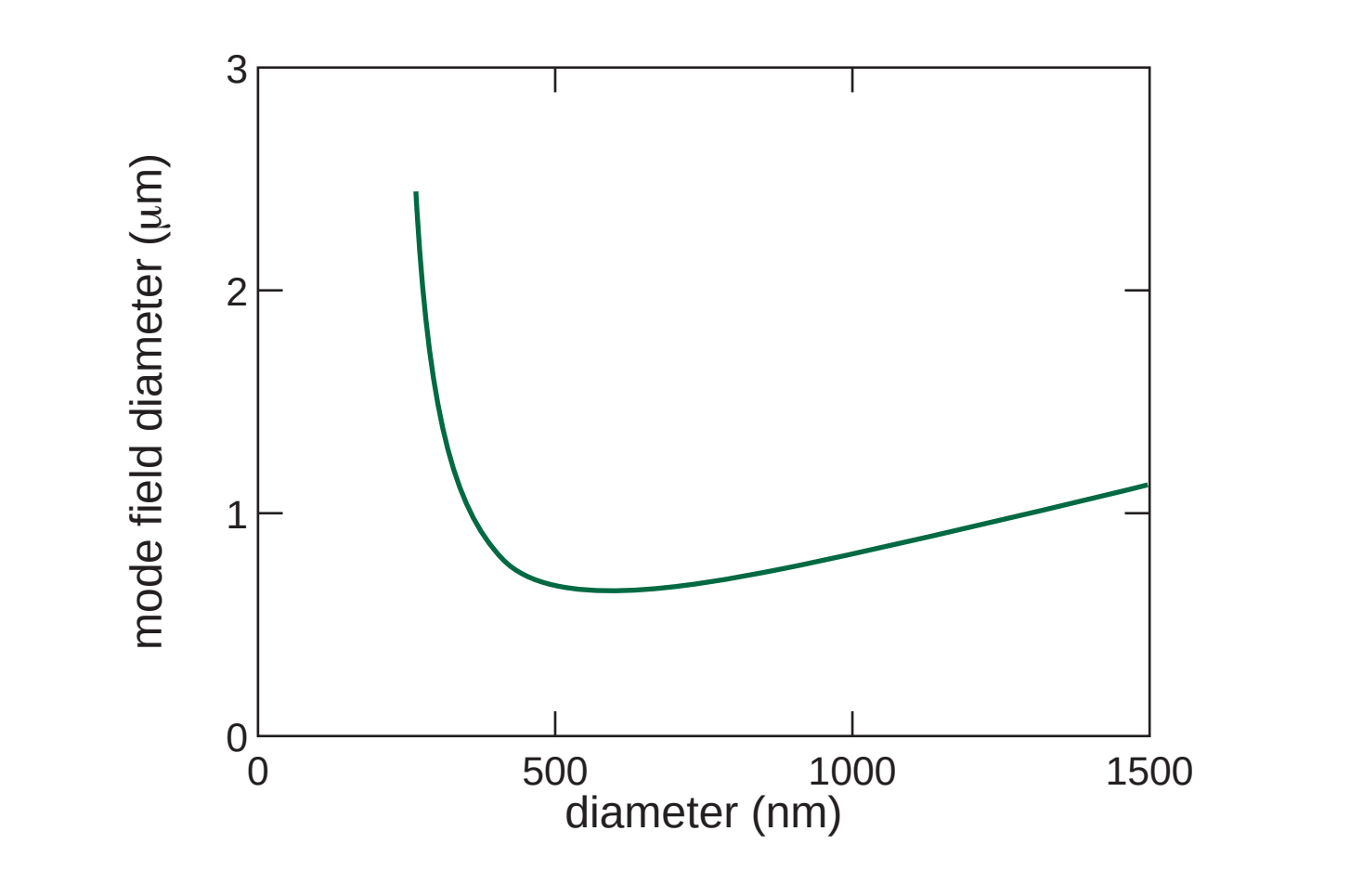
Nanoscale nonlinear optics

Nanoscale nonlinear optics

strong confinement $\longrightarrow$ high intensity

Nanoscale nonlinear optics

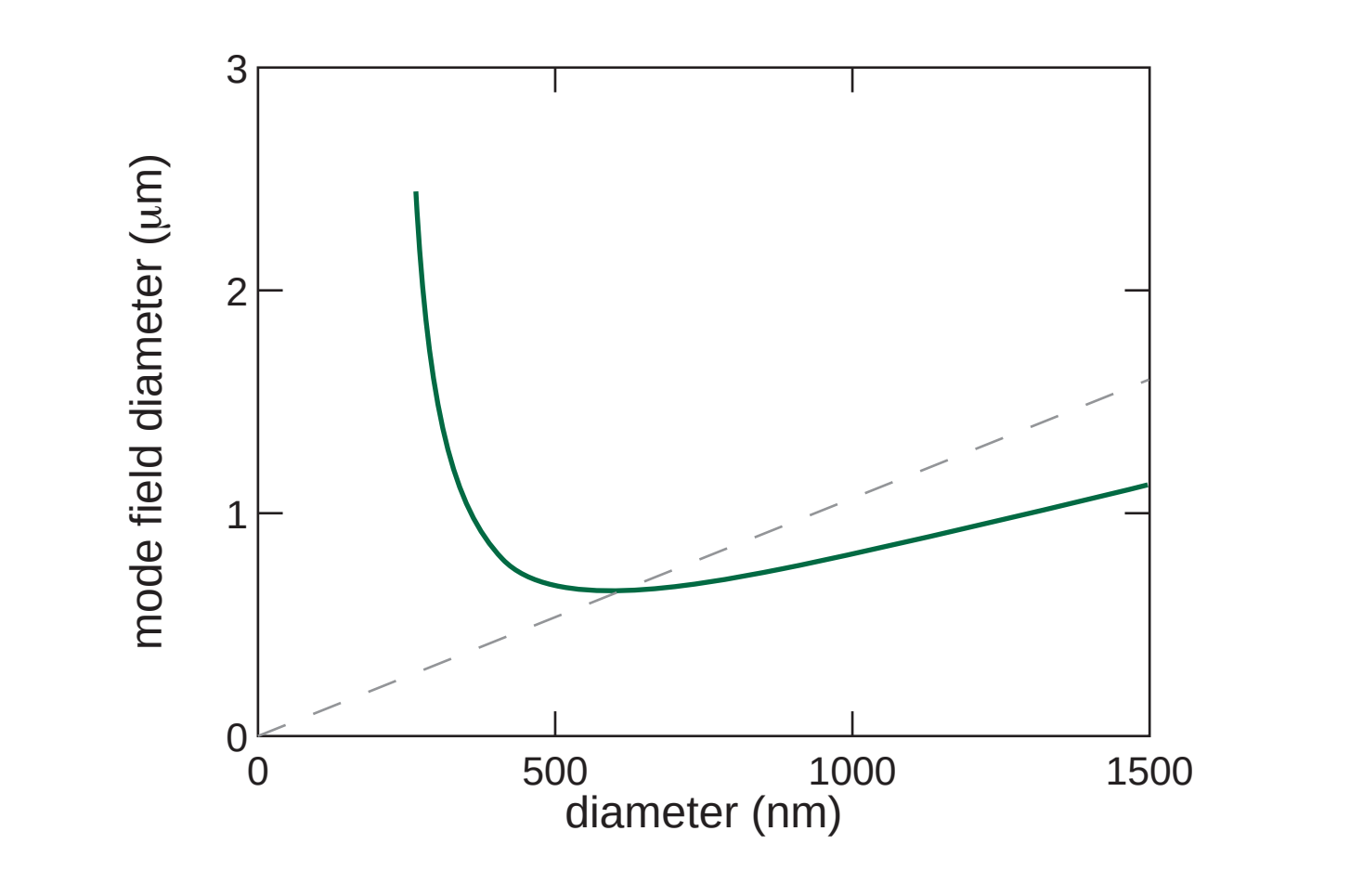
mode field diameter (λ = 800 nm)



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Nanoscale nonlinear optics

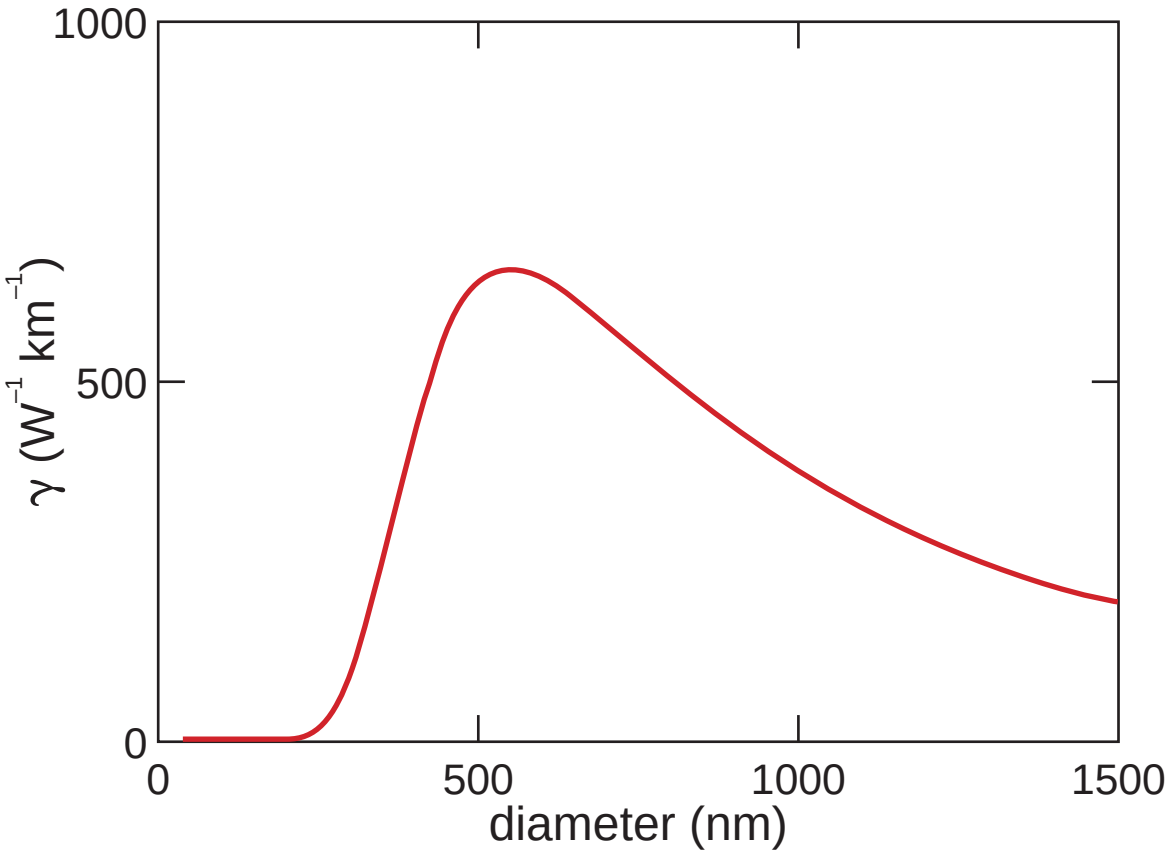
mode field diameter (λ = 800 nm)



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Nanoscale nonlinear optics

nonlinear parameter



M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

Nanoscale nonlinear optics

dispersion important!

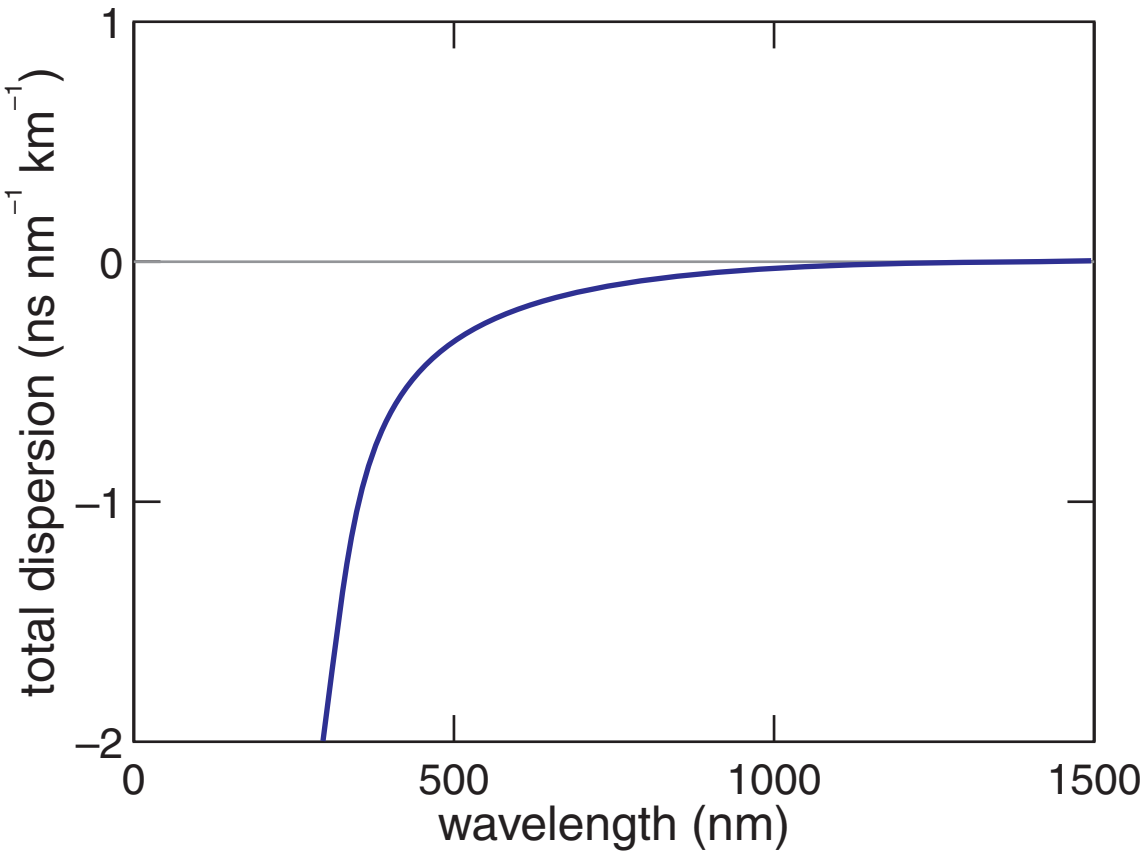
Nanoscale nonlinear optics

dispersion:

- modal dispersion
- material dispersion
- waveguide dispersion
- nonlinear dispersion

Nanoscale nonlinear optics

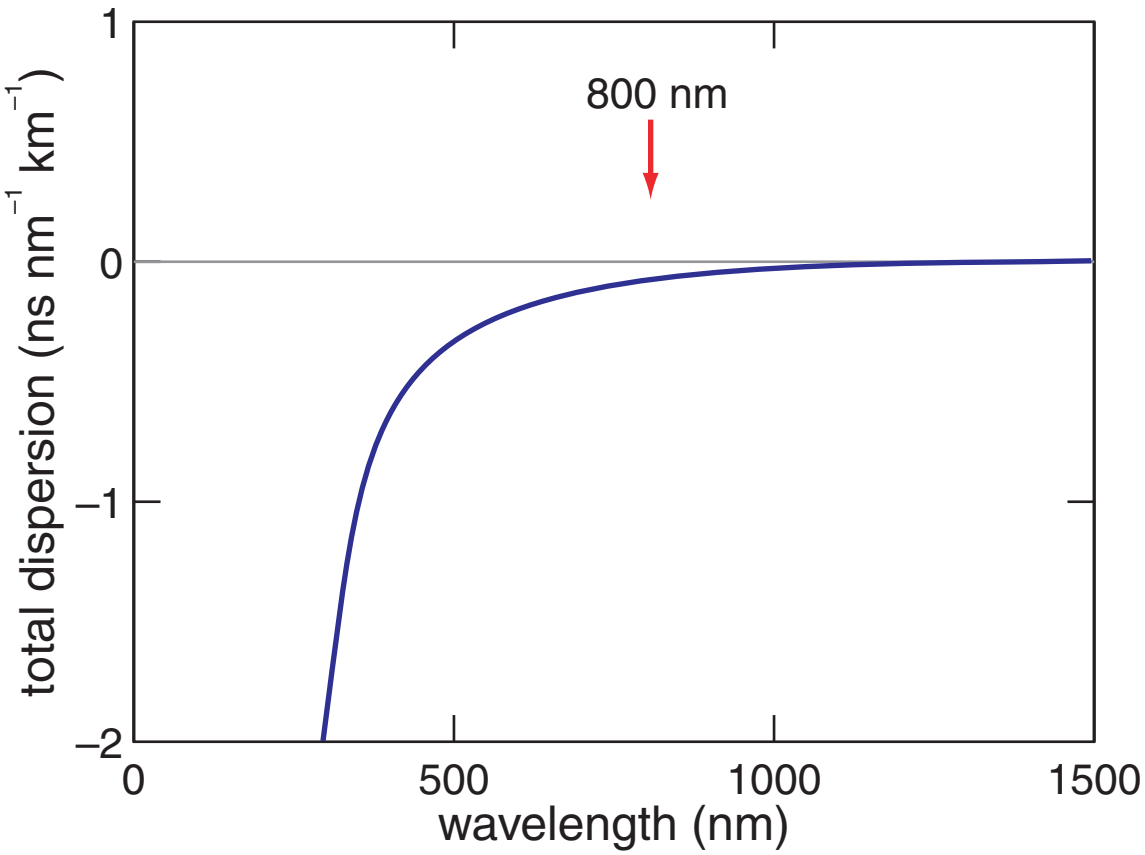
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

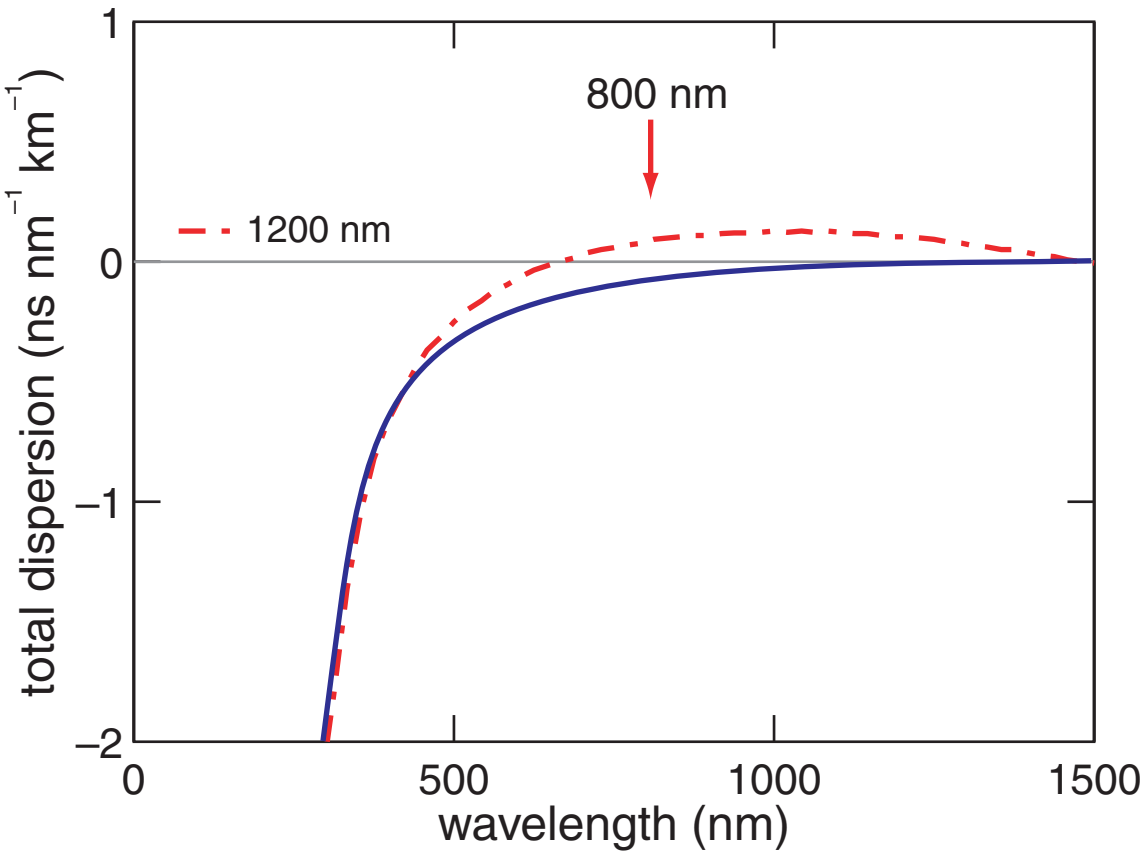
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

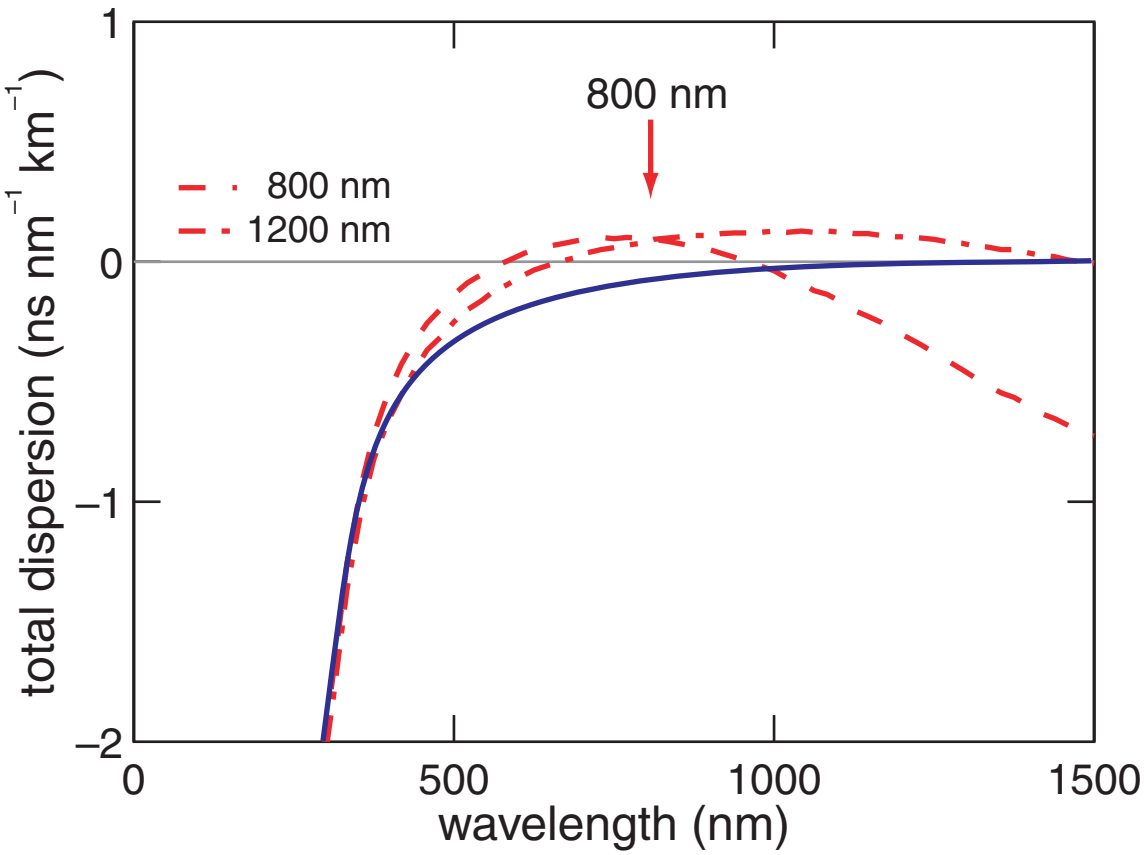
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

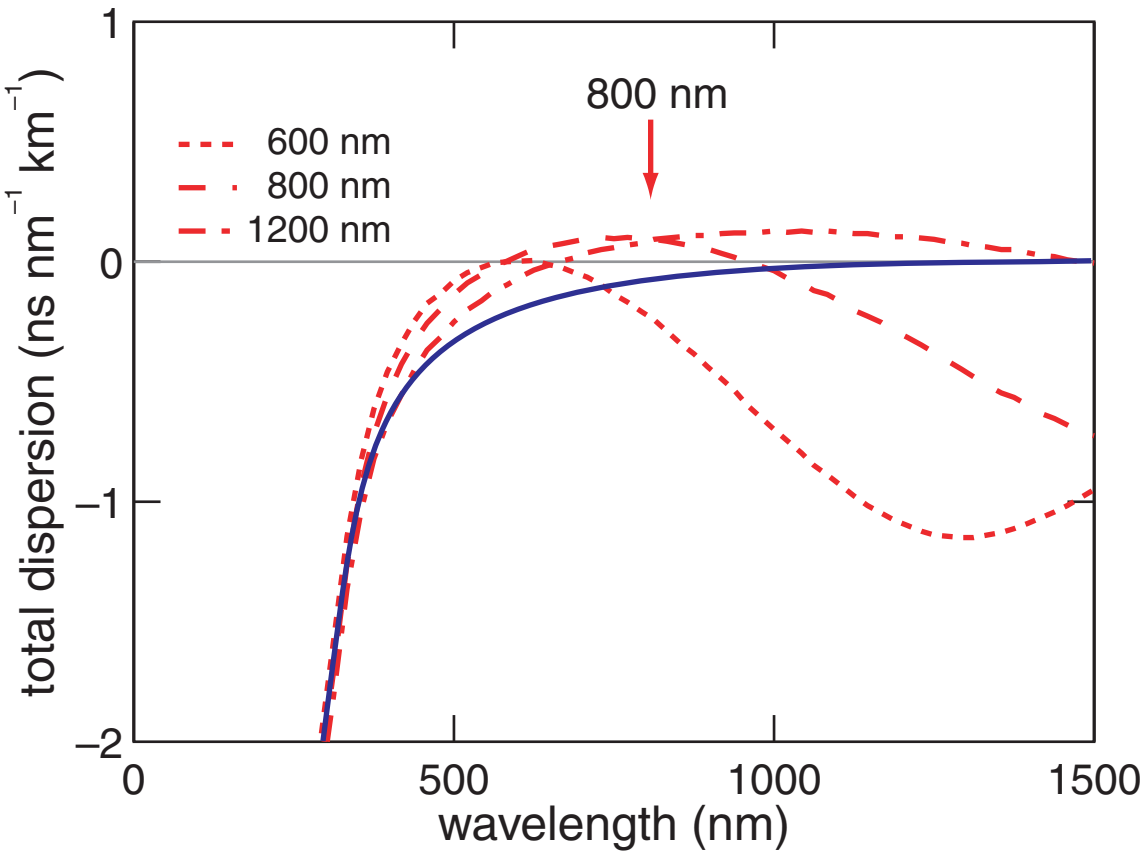
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

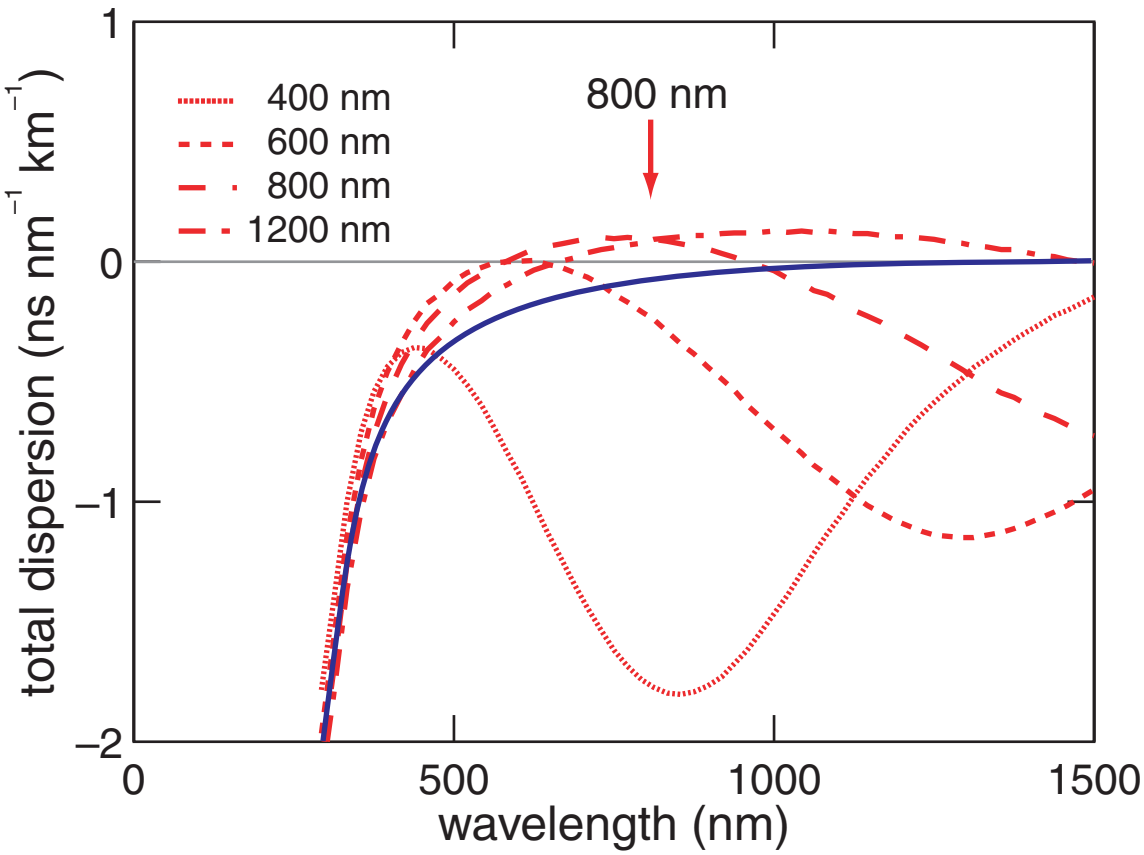
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

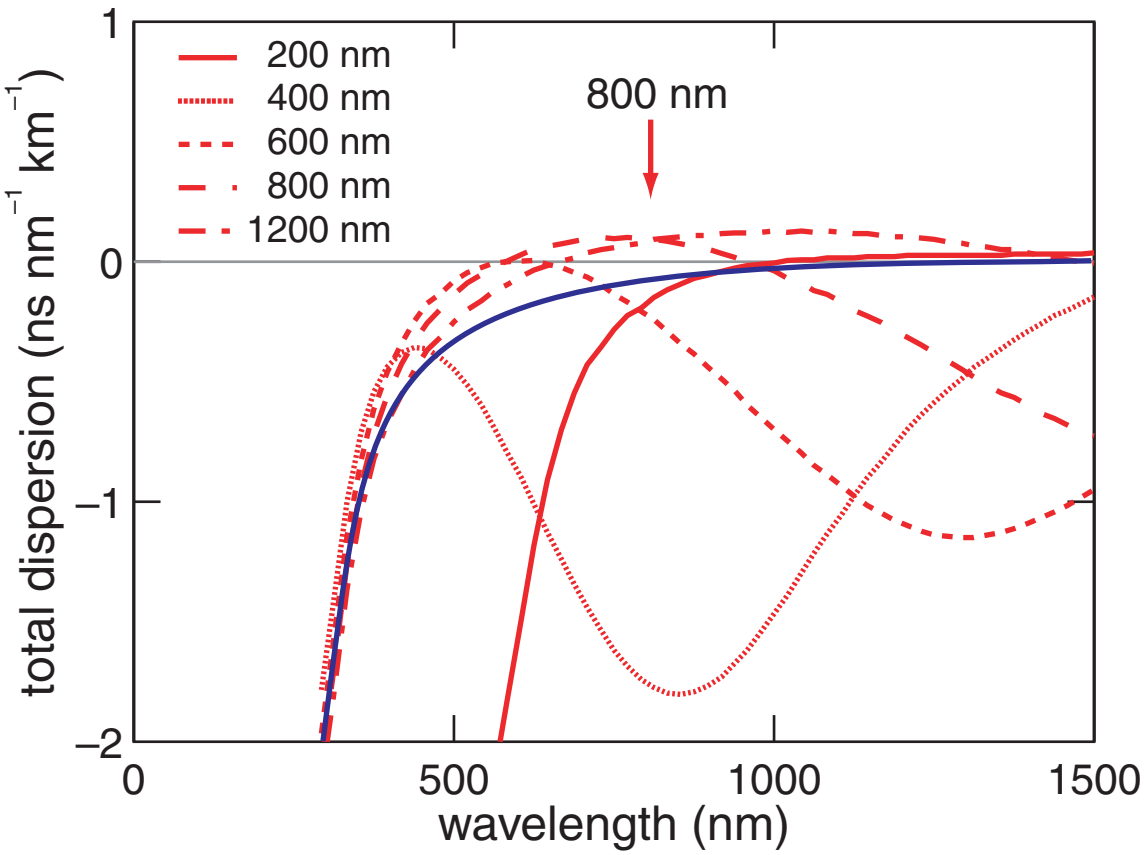
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

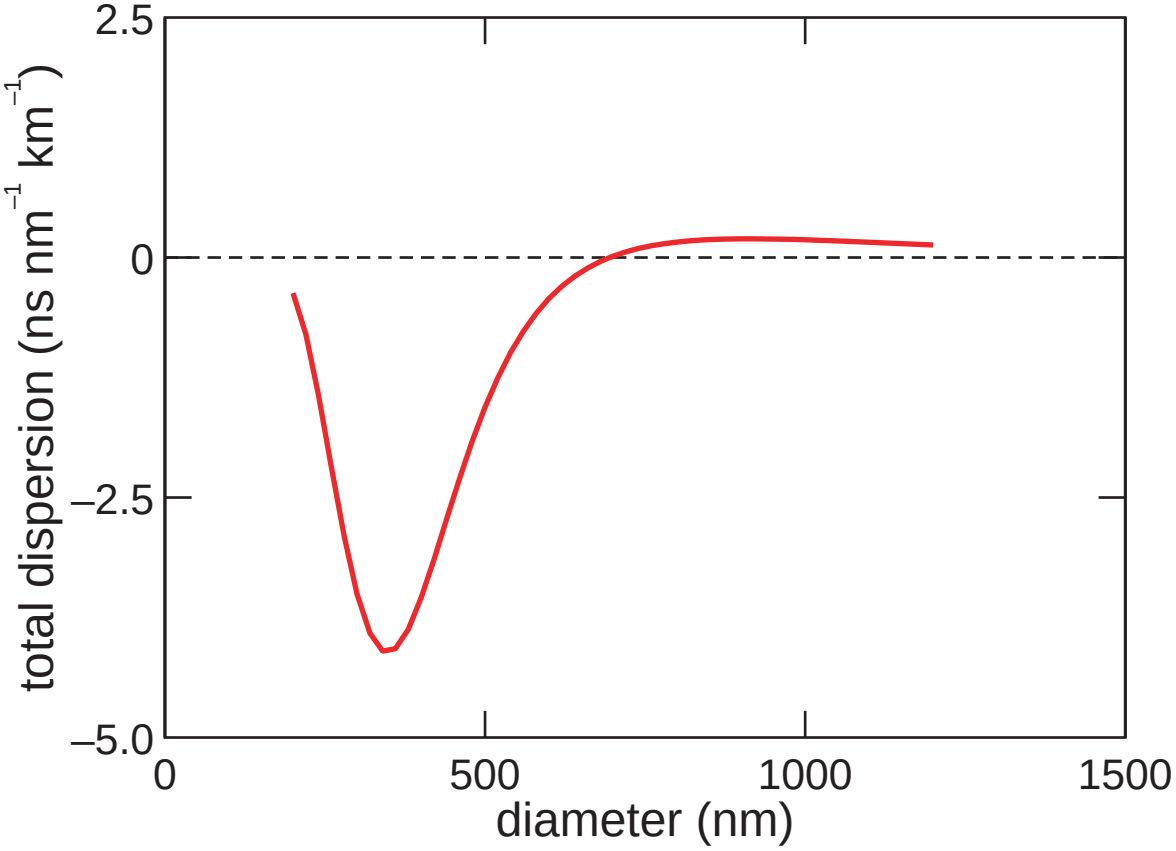
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

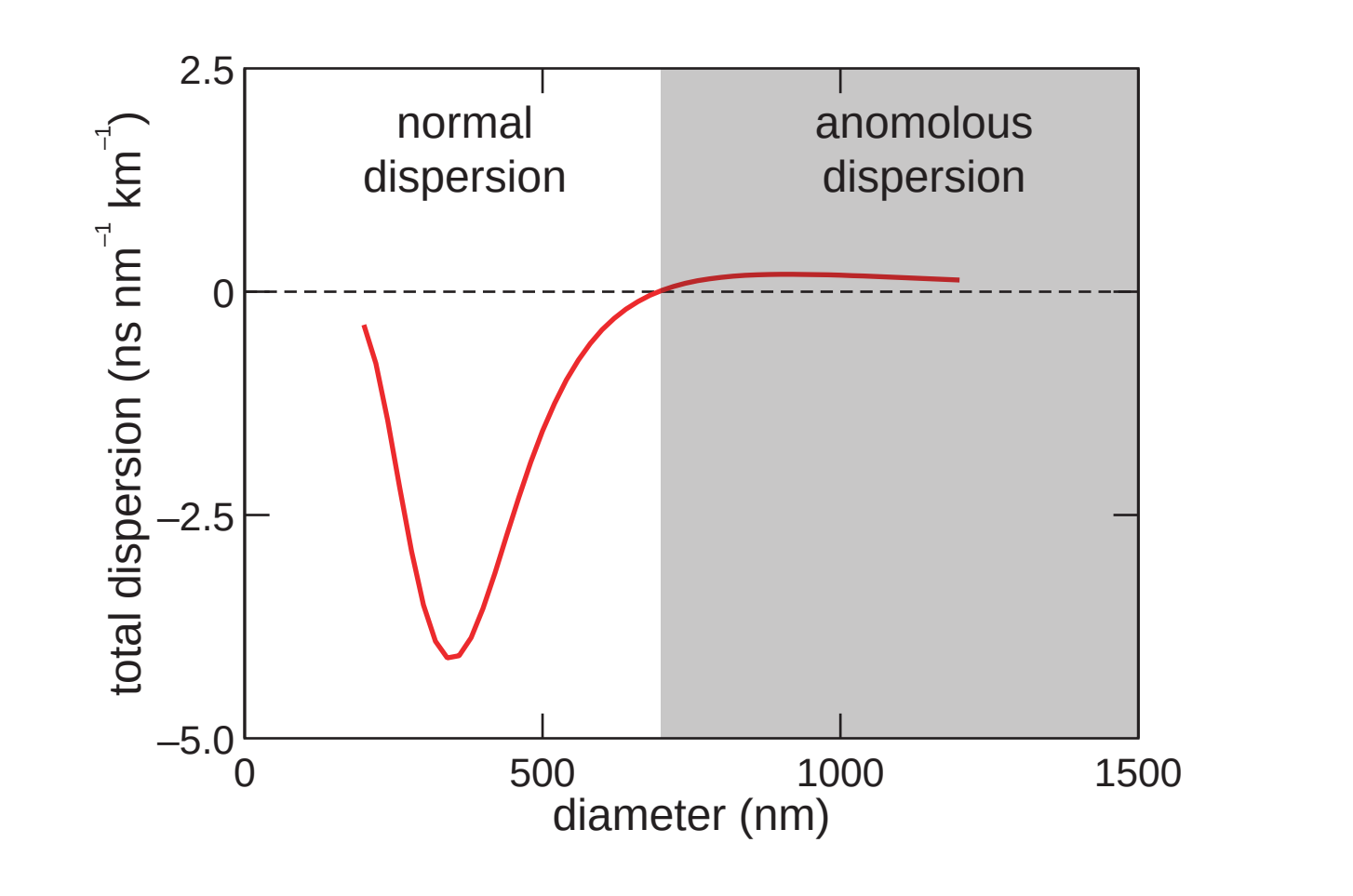
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

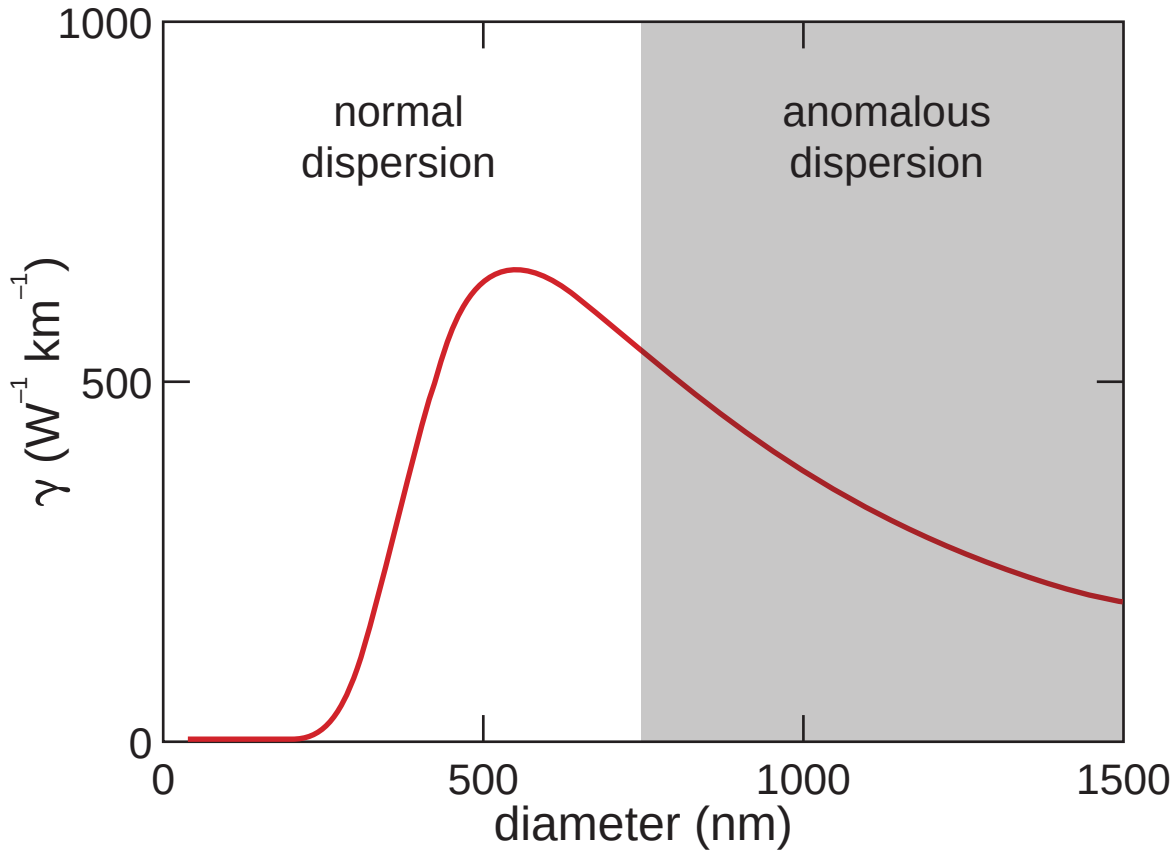
waveguide dispersion



Optics Express, 12, 1025 (2004)

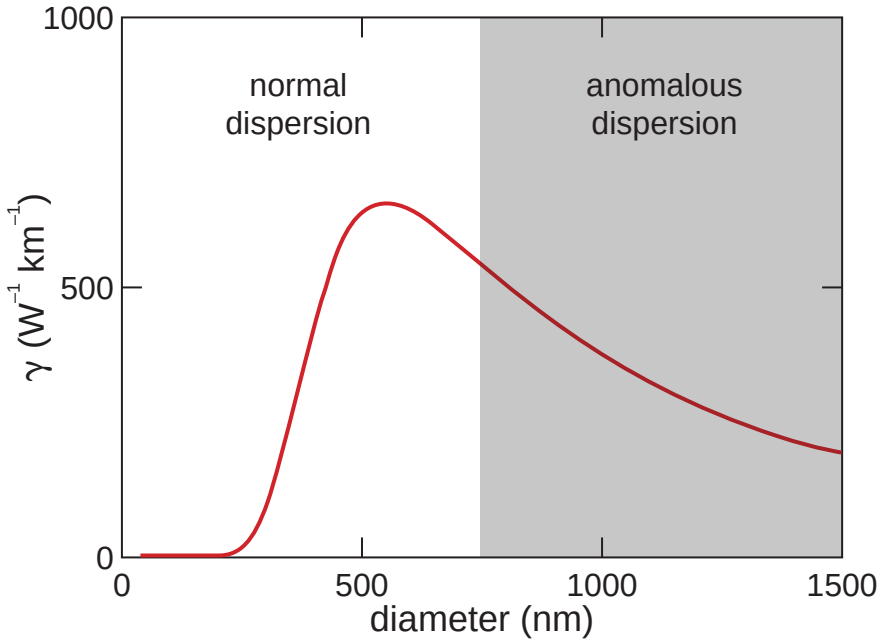
Nanoscale nonlinear optics

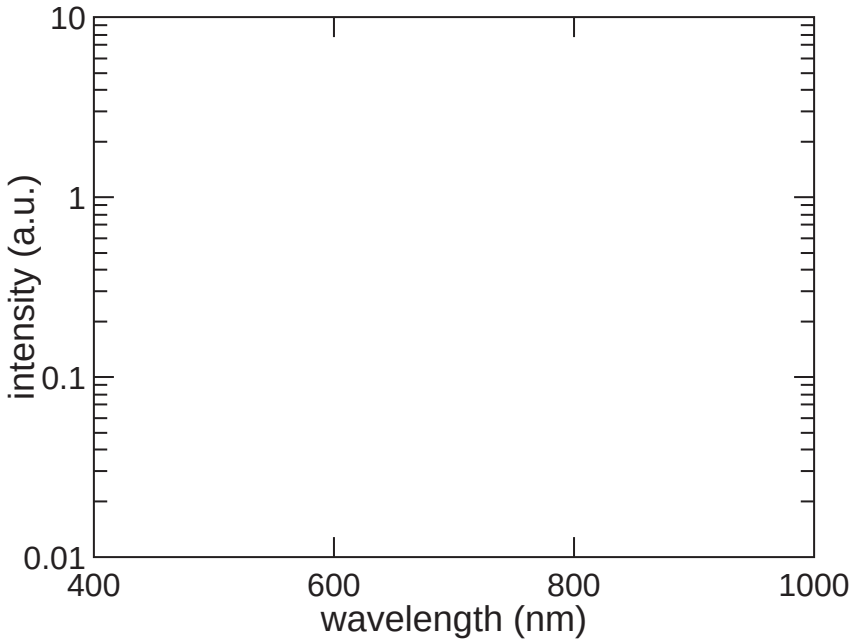
nonlinear parameter



Nanoscale nonlinear optics

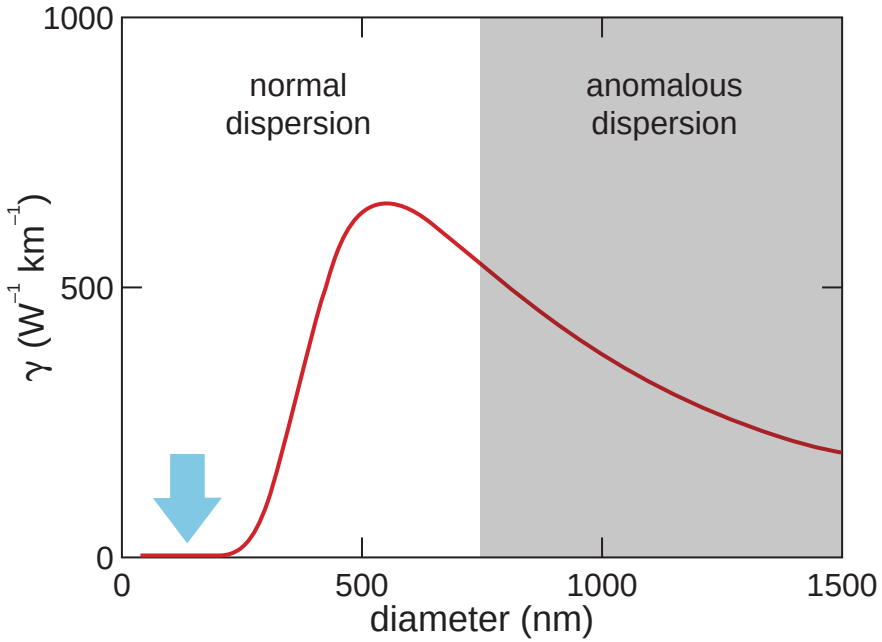
nanowire continuum generation

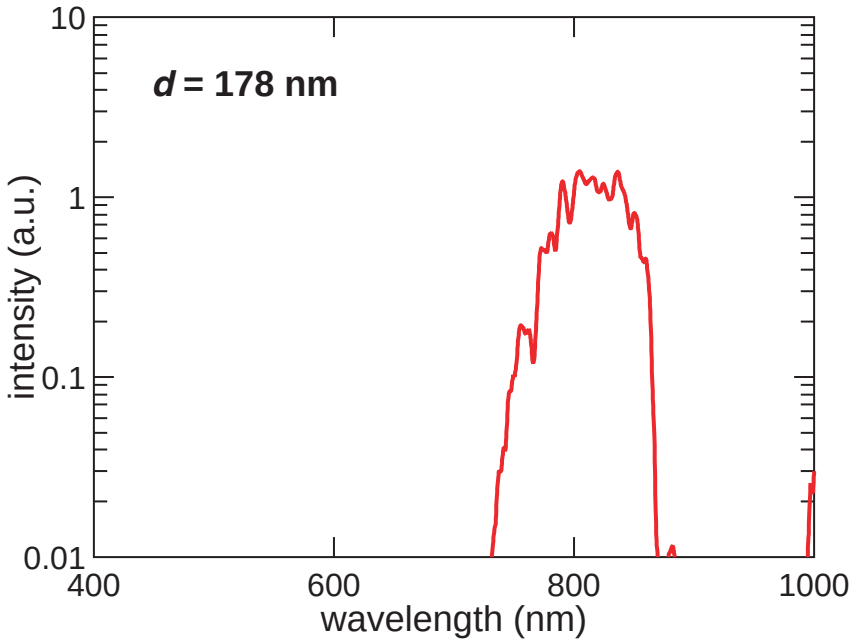




Nanoscale nonlinear optics

nanowire continuum generation

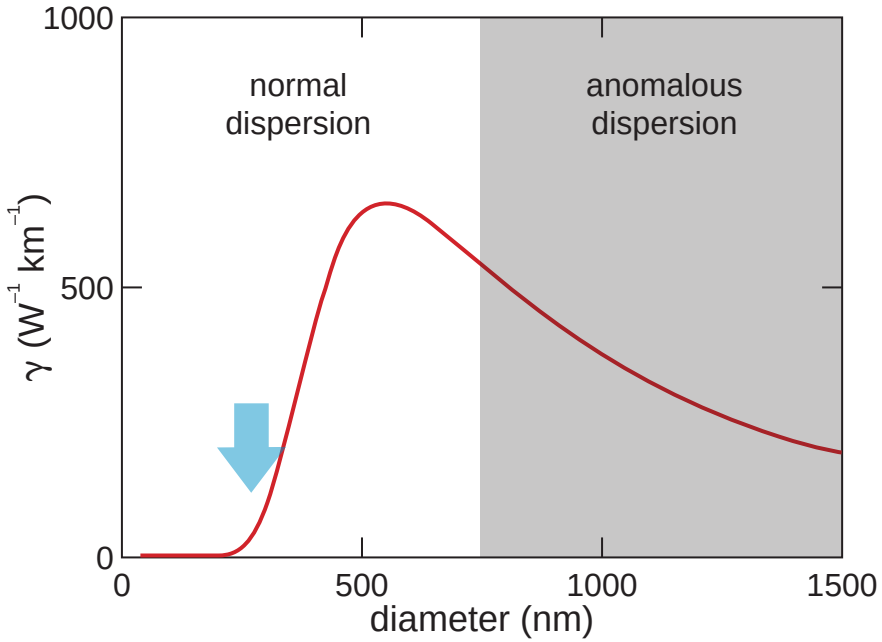


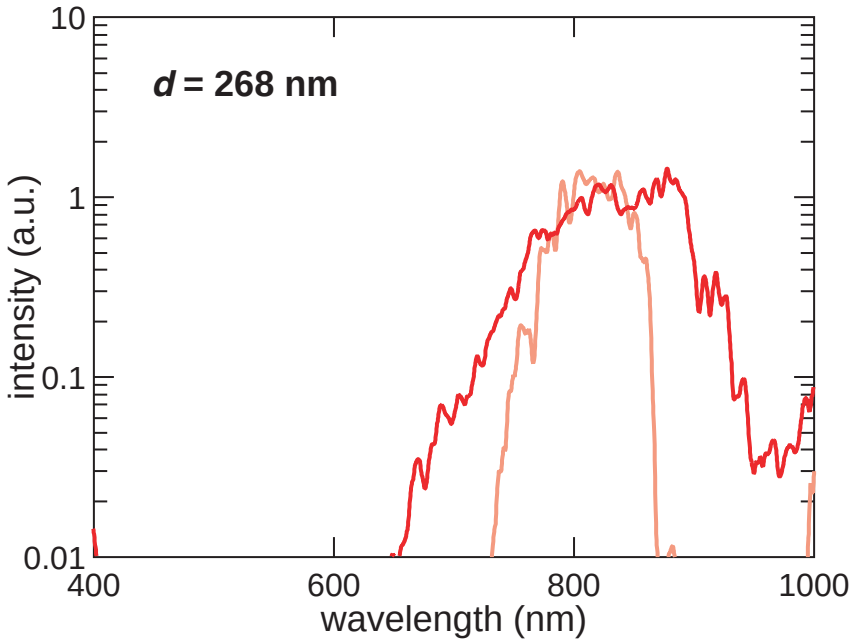


Optics Express, 14, 9408 (2006)

Nanoscale nonlinear optics

nanowire continuum generation

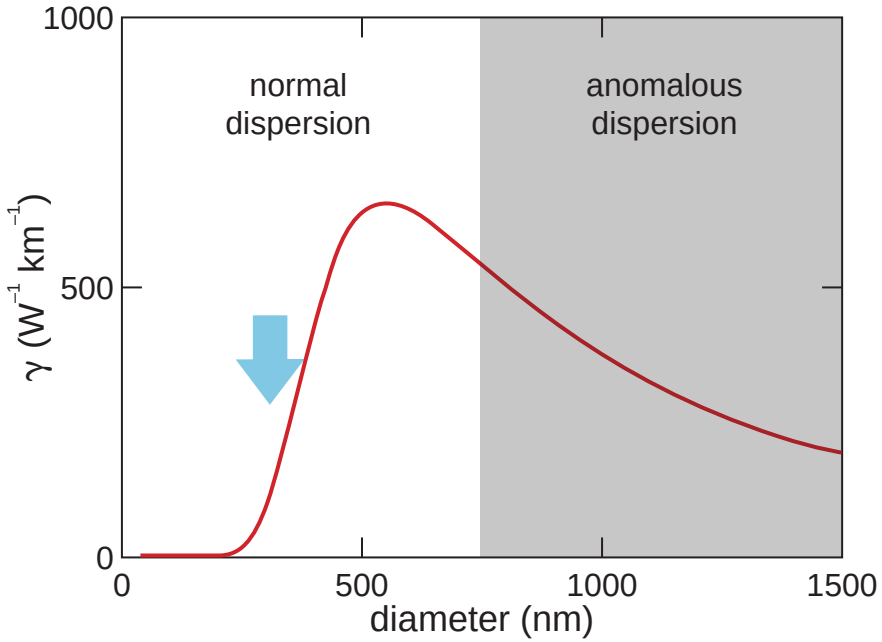


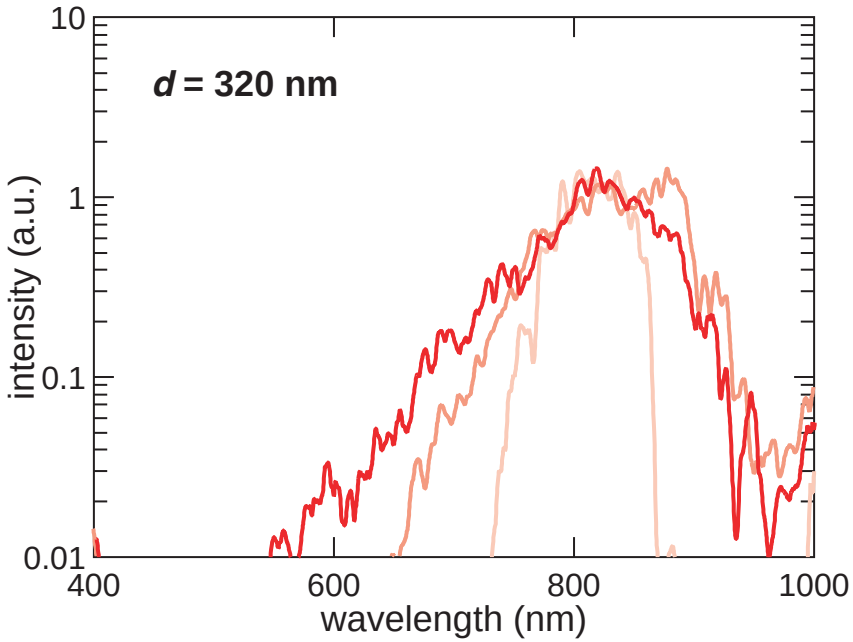


Optics Express, 14, 9408 (2006)

Nanoscale nonlinear optics

nanowire continuum generation





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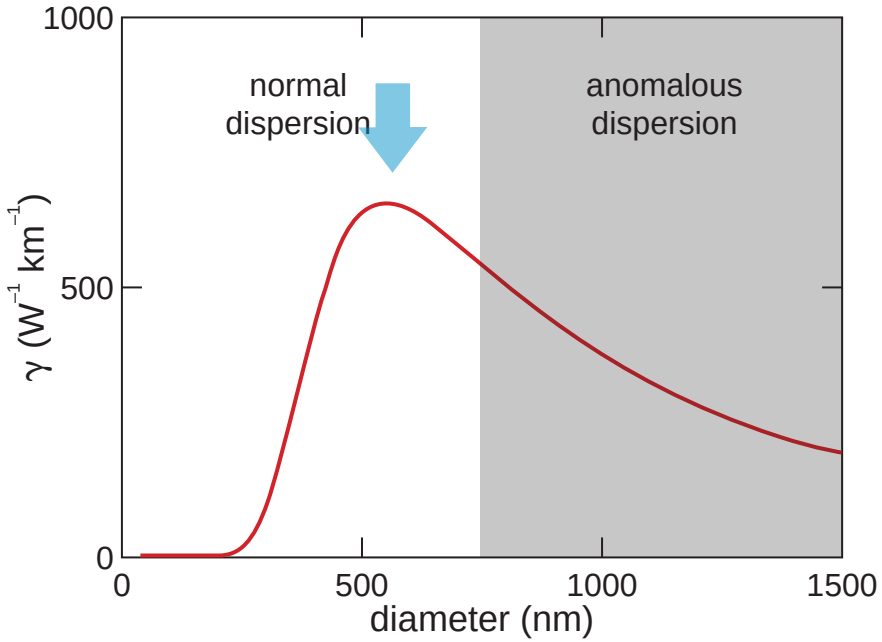
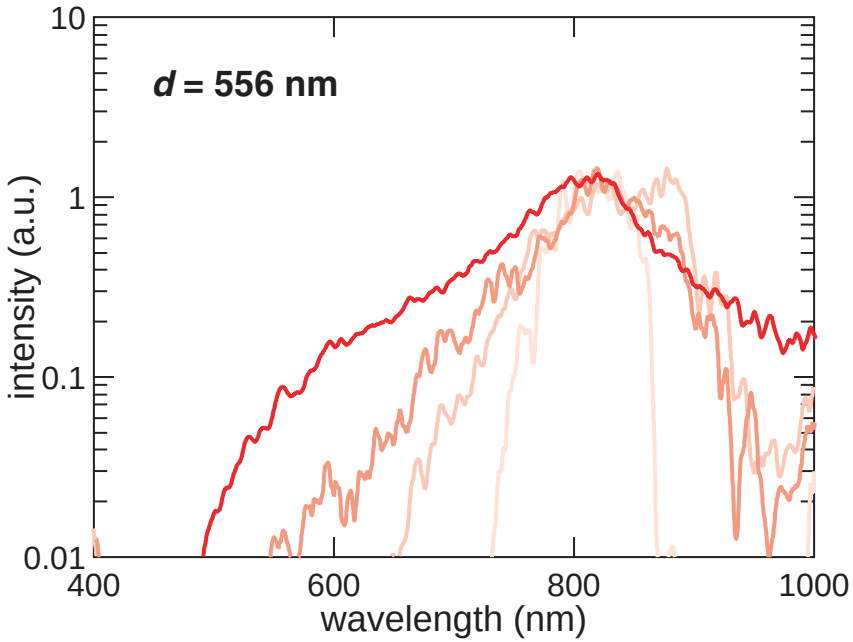
Nanoscale nonlinear optics

nanowire continuum generation





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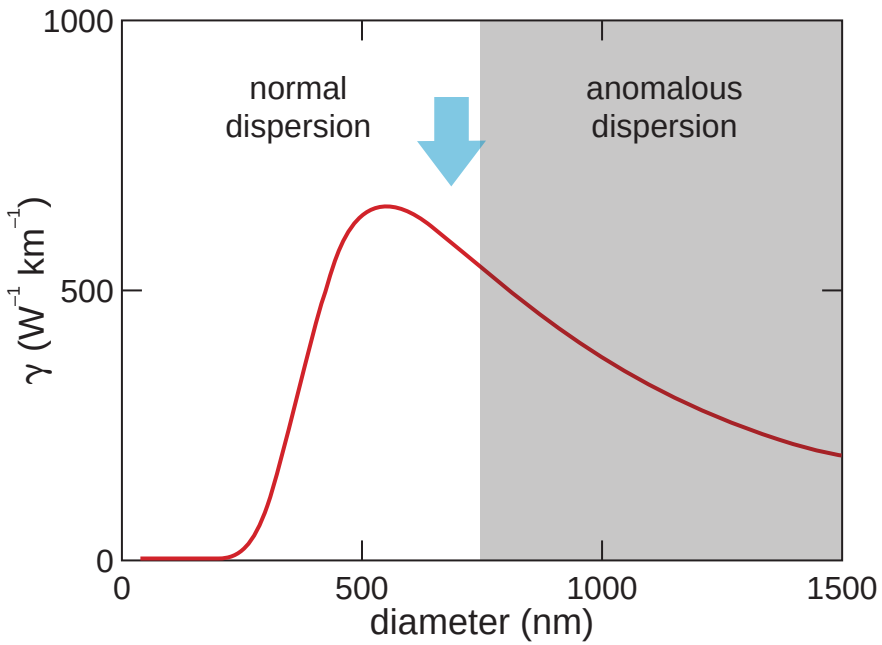
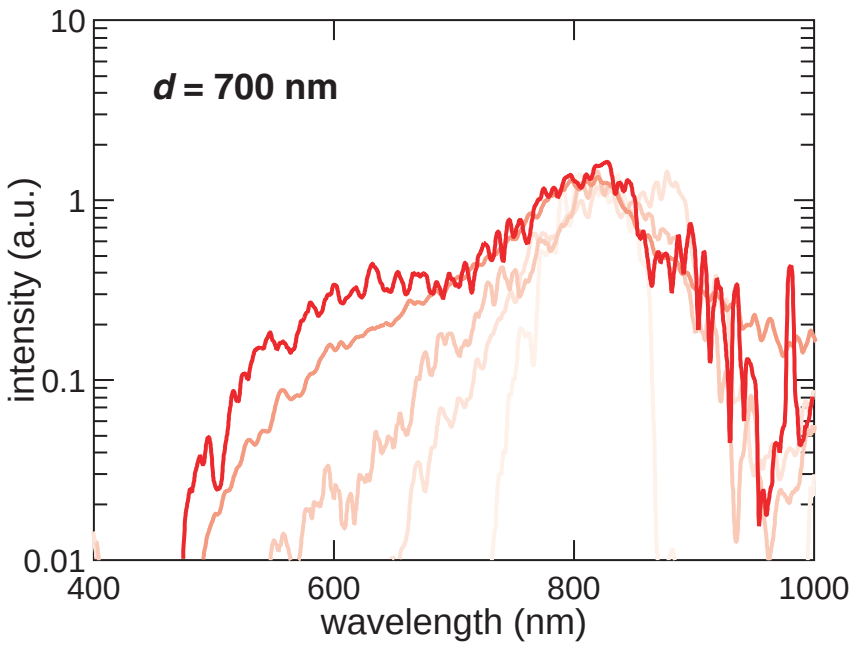
Nanoscale nonlinear optics

nanowire continuum generation





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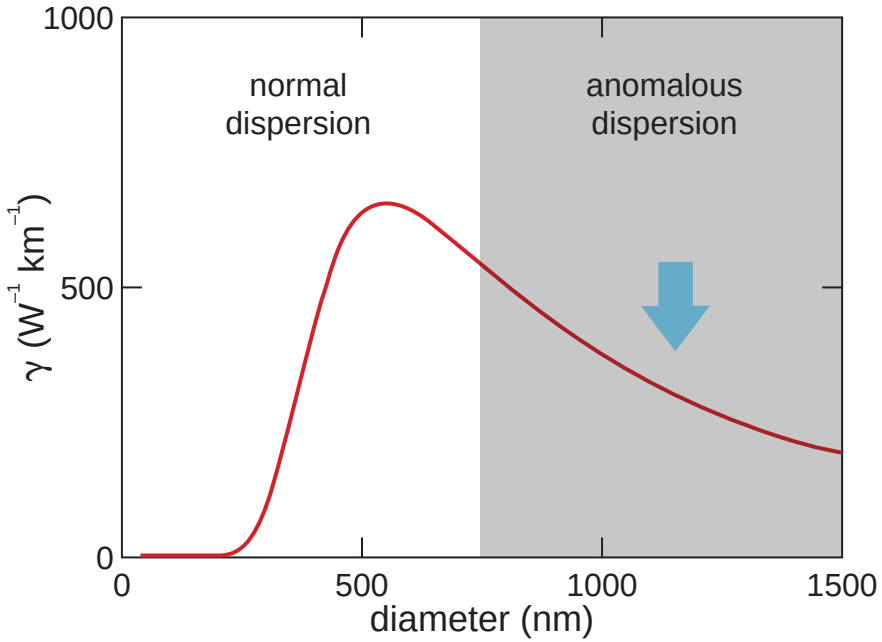
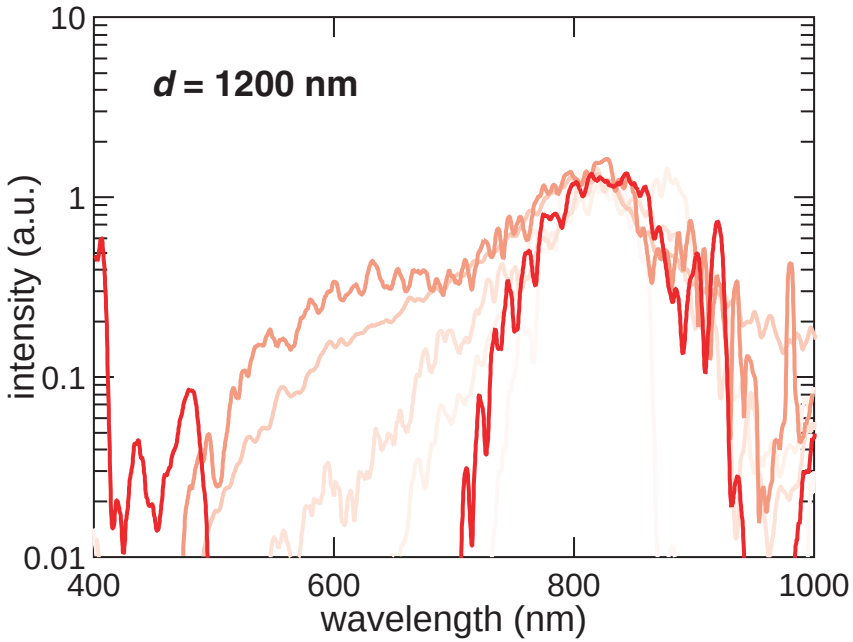
Nanoscale nonlinear optics

nanowire continuum generation





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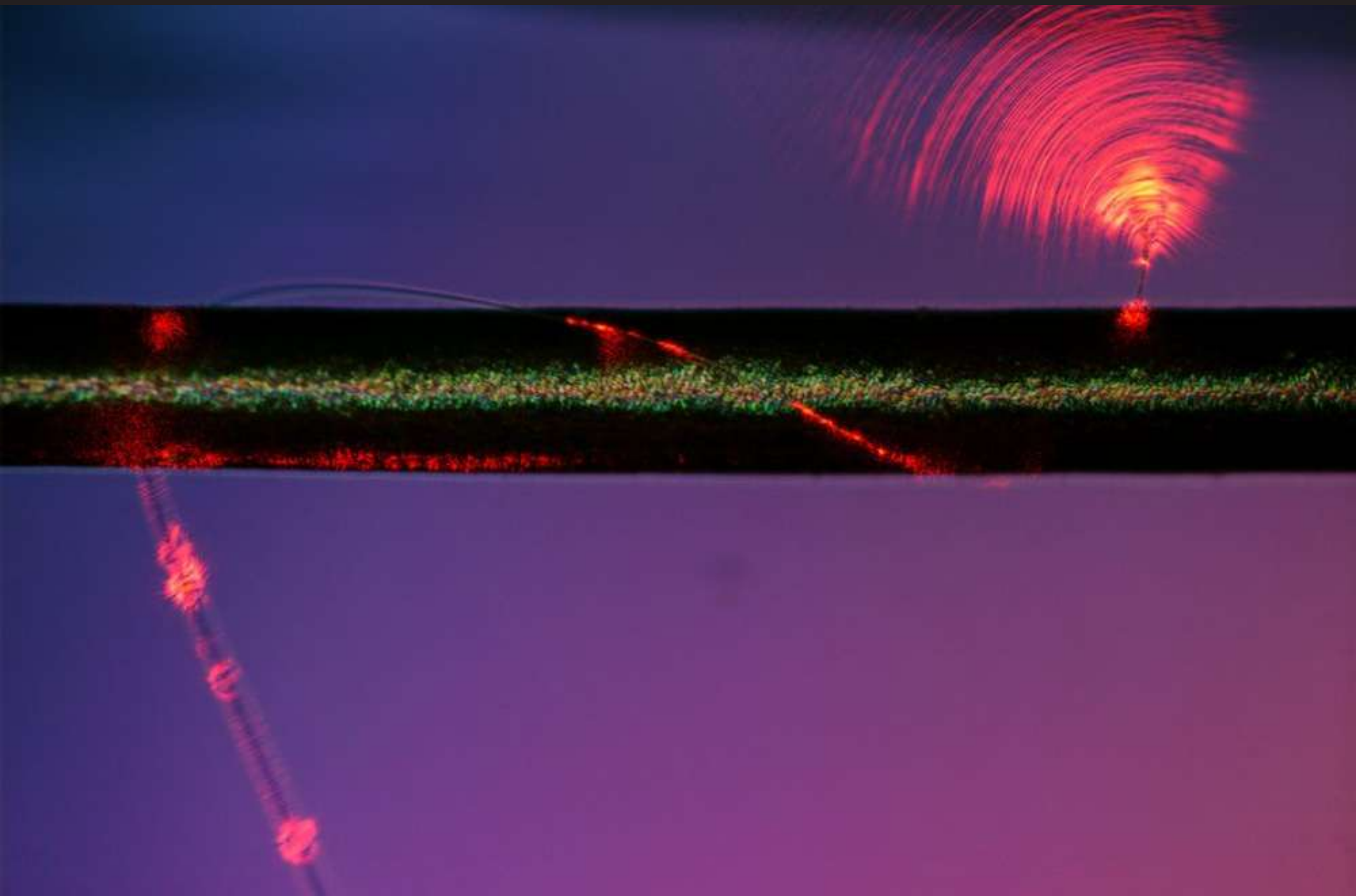
Nanoscale nonlinear optics

energy in nanowire < 100 pJ!

Summary



Summary

- easy fabrication
- convenient nanoscale light manipulation
- nanoscale nonlinear optics

Funding:

Harvard Center for Imaging and Mesoscopic Structures
National Science Foundation
National Natural Science Foundation of China

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