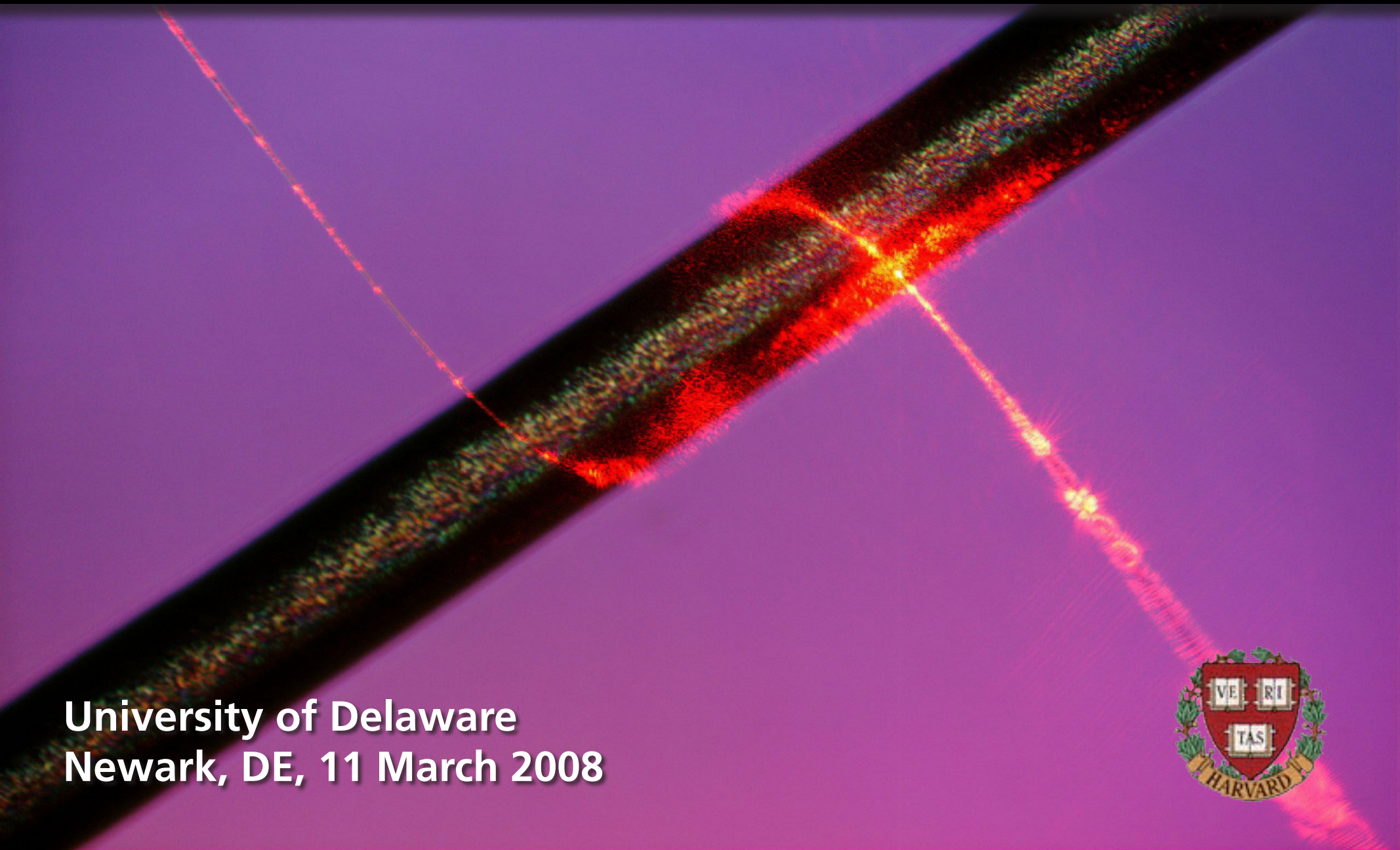
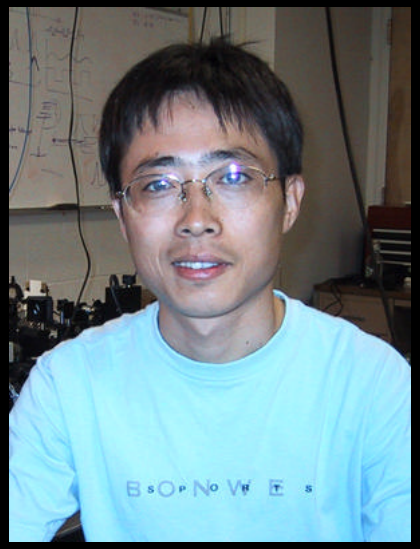
Wrapping light around a hair



University of Delaware
Newark, DE, 11 March 2008

Rafael Gattass

Geoff Svacha



Limin Tong

Tobias Voss

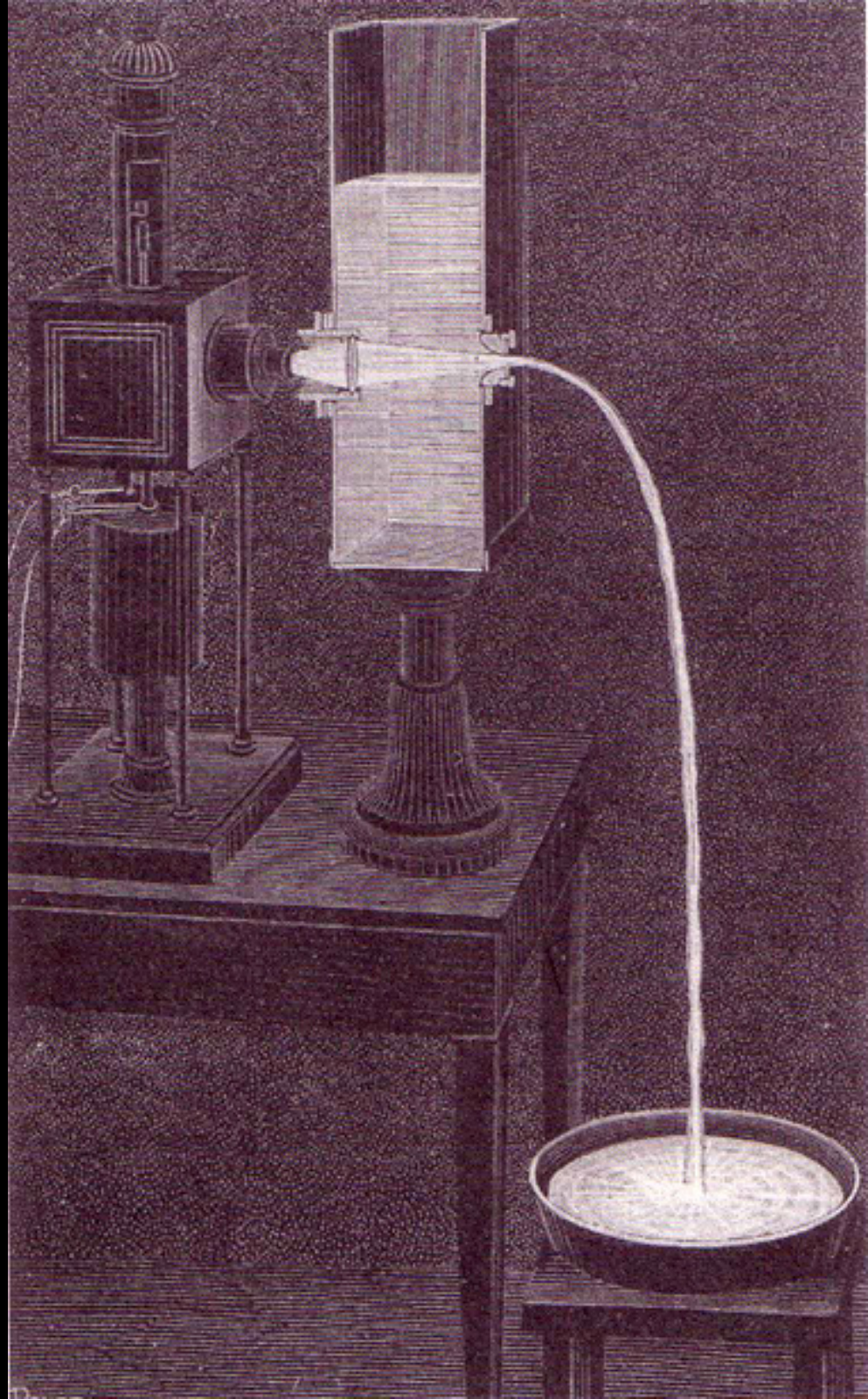
and also....

Jonathan Aschom
Mengyan Shen
Iva Maxwell
James Carey
Brian Tull
Dr. Yuan Lu
Dr. Richard Schalek
Prof. Federico Capasso
Prof. Cynthia Friend

Xuewen Chen (Zhejiang)
Zhanghua Han (Zhejiang)
Dr. Sailing He (Zhejiang)
Liu Liu (Zhejiang)
Dr. Jingyi Lou (Zhejiang)
Dr. Ray Mariella (LLNL)
Prof. Frank Marlow (MPI Mühlheim)
Prof. Sven Müller (Göttingen)
Prof. Carsten Ronning (Göttingen)

"I managed to illuminate the interior of a stream in a dark space. I have discovered that this strange arrangement offers one of the most beautiful, and most curious experiments that one can perform in a course on Optics."

Daniel Colladon, *Comptes Rendus*, 15, 800–802 (1842)



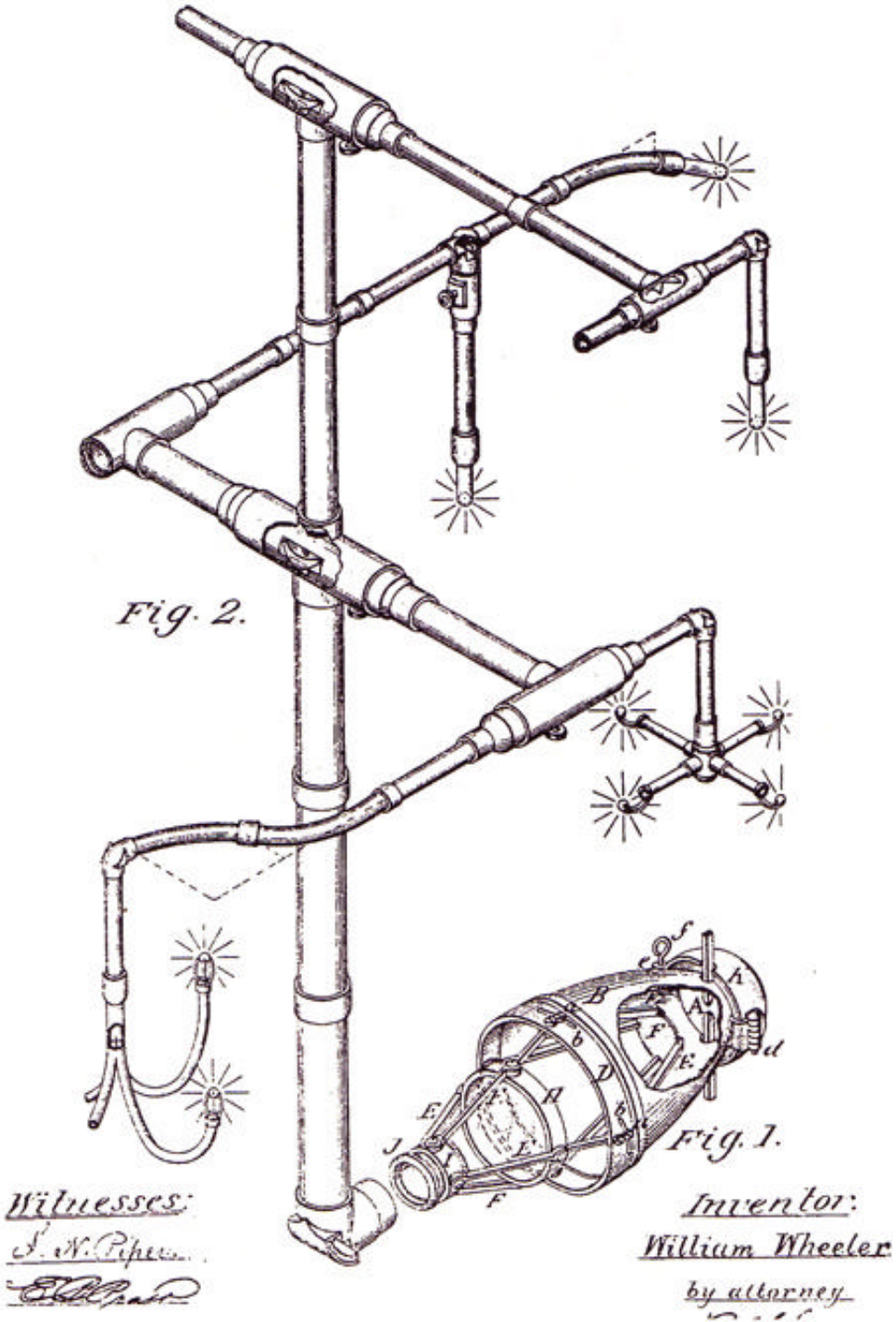
D. Colladon, *La Nature*, 325 (1884)

(No model.) 4 Sheets—Sheet

W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229. Patented Sept. 20, 1881.



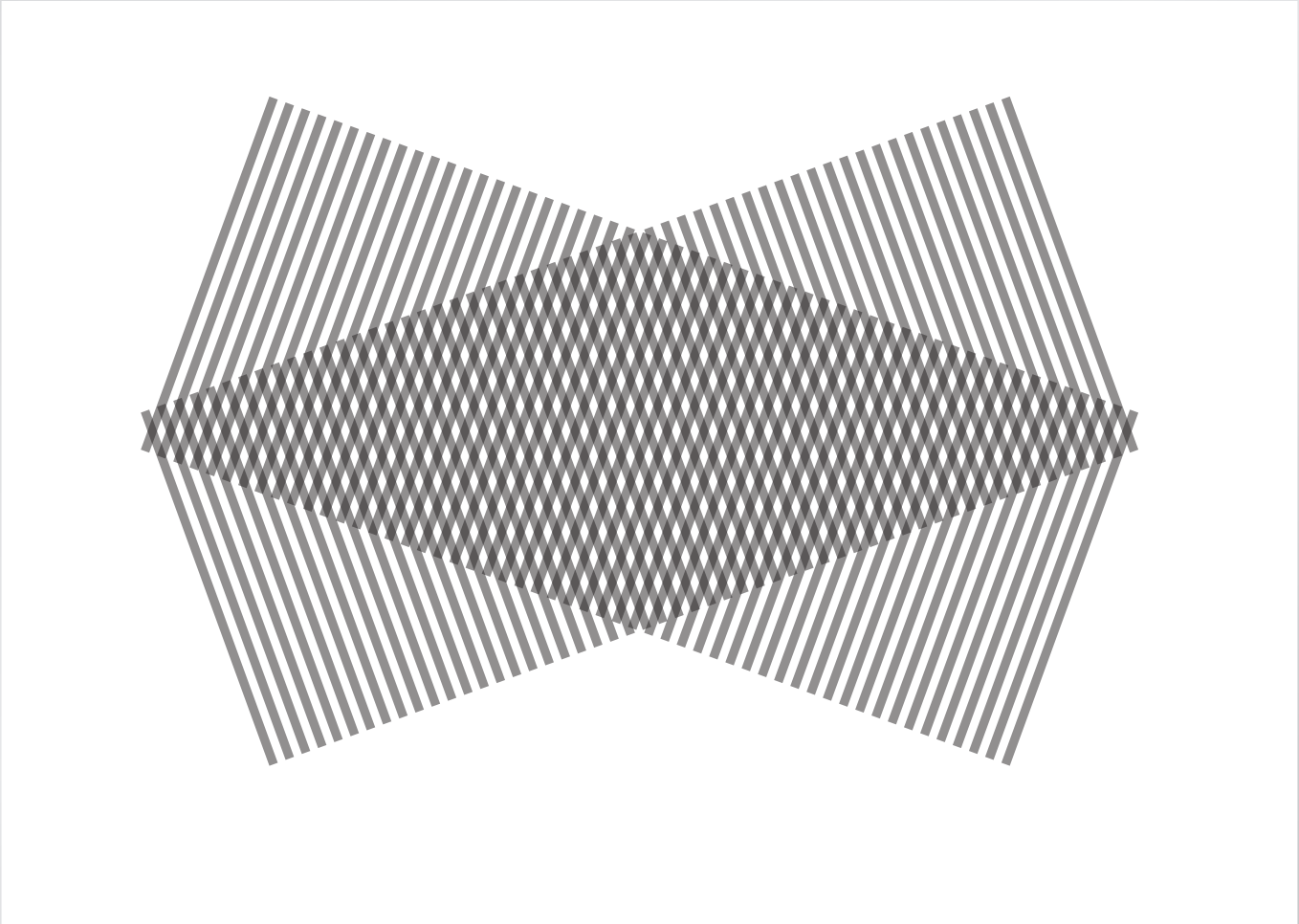
US Patent 247, 229 (1881)

Outline

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

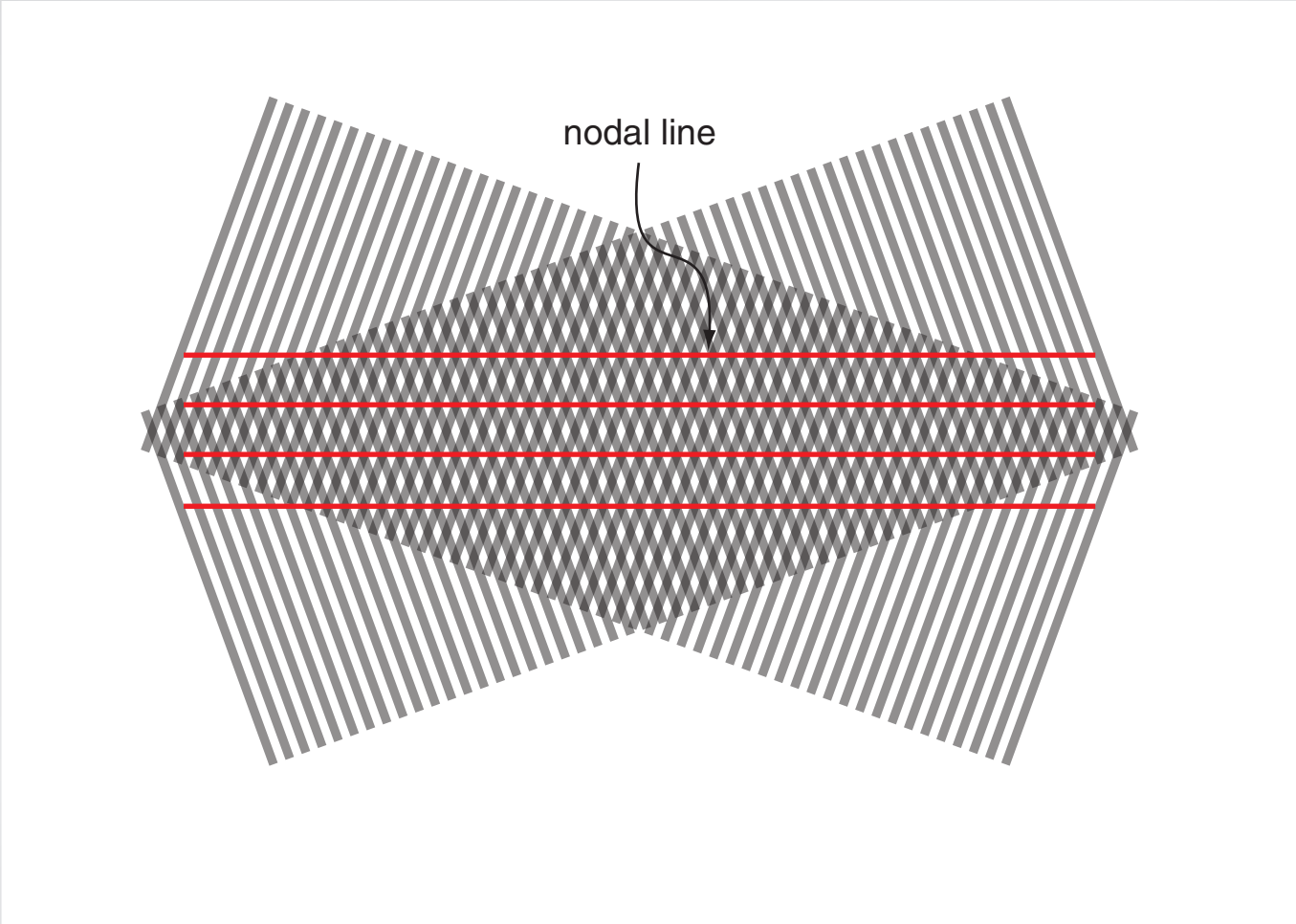
Waveguiding

two crossed planar waves…



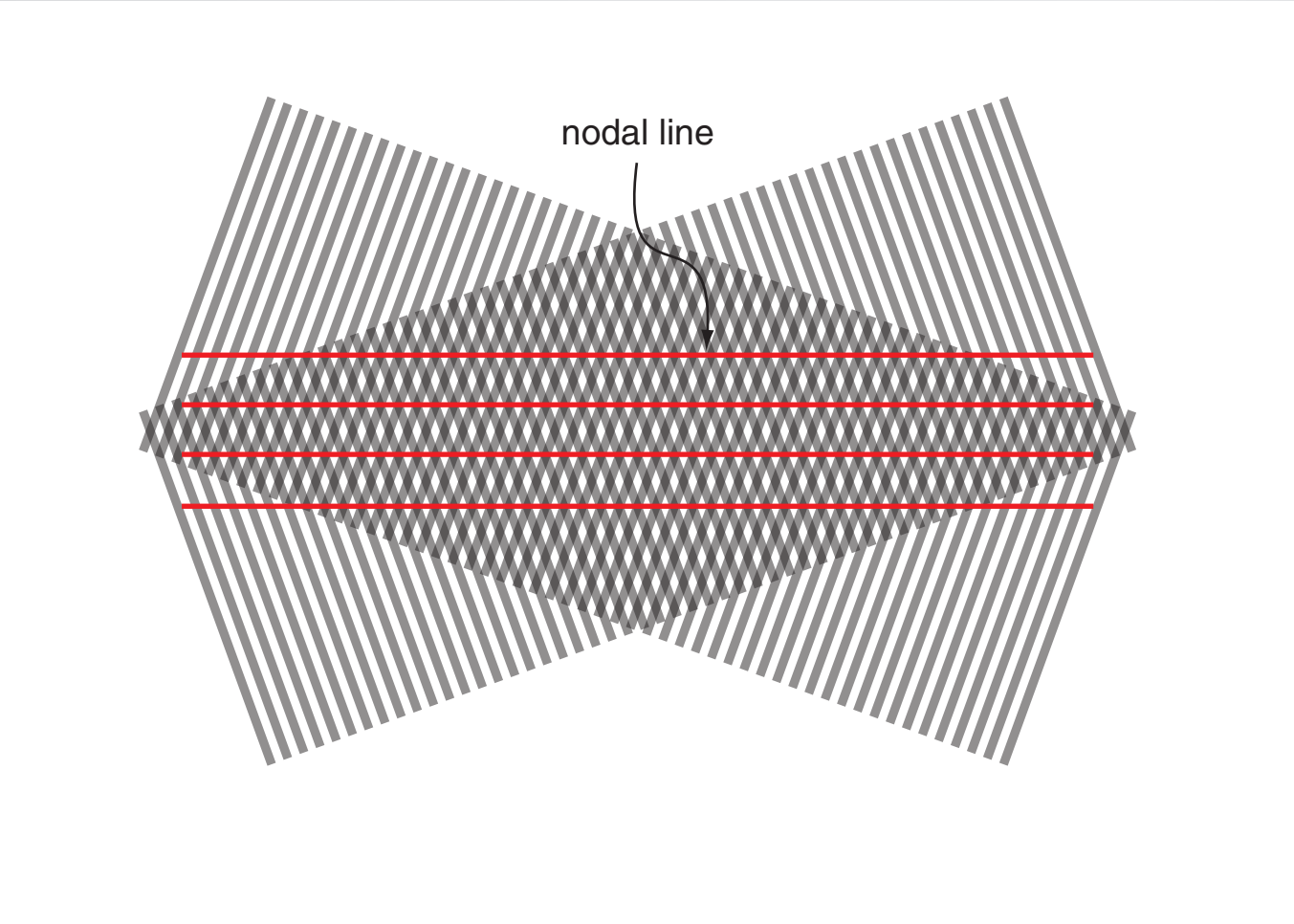
Waveguiding

…cause an interference pattern



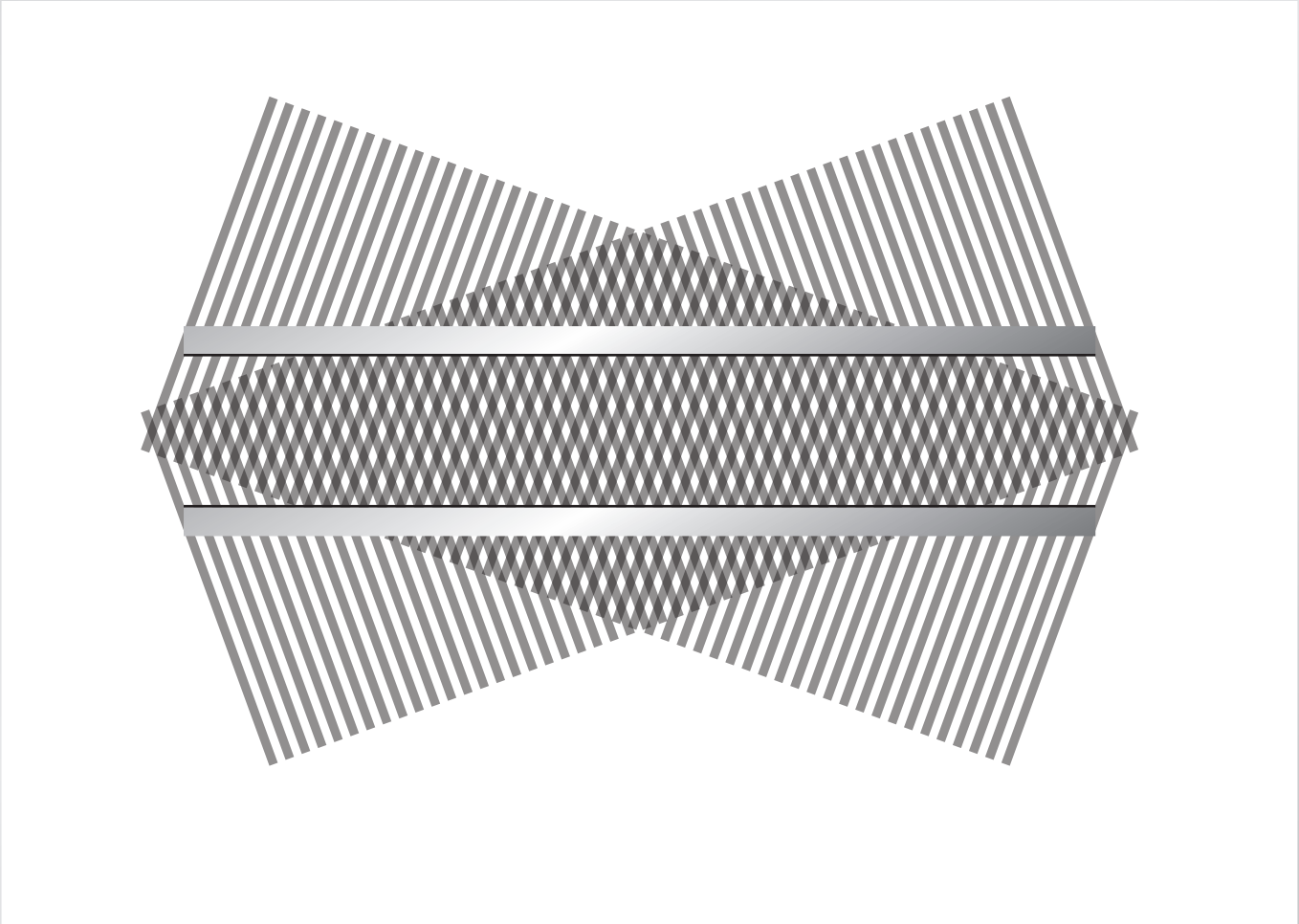
Waveguiding

$E = 0$ **on the nodal lines**



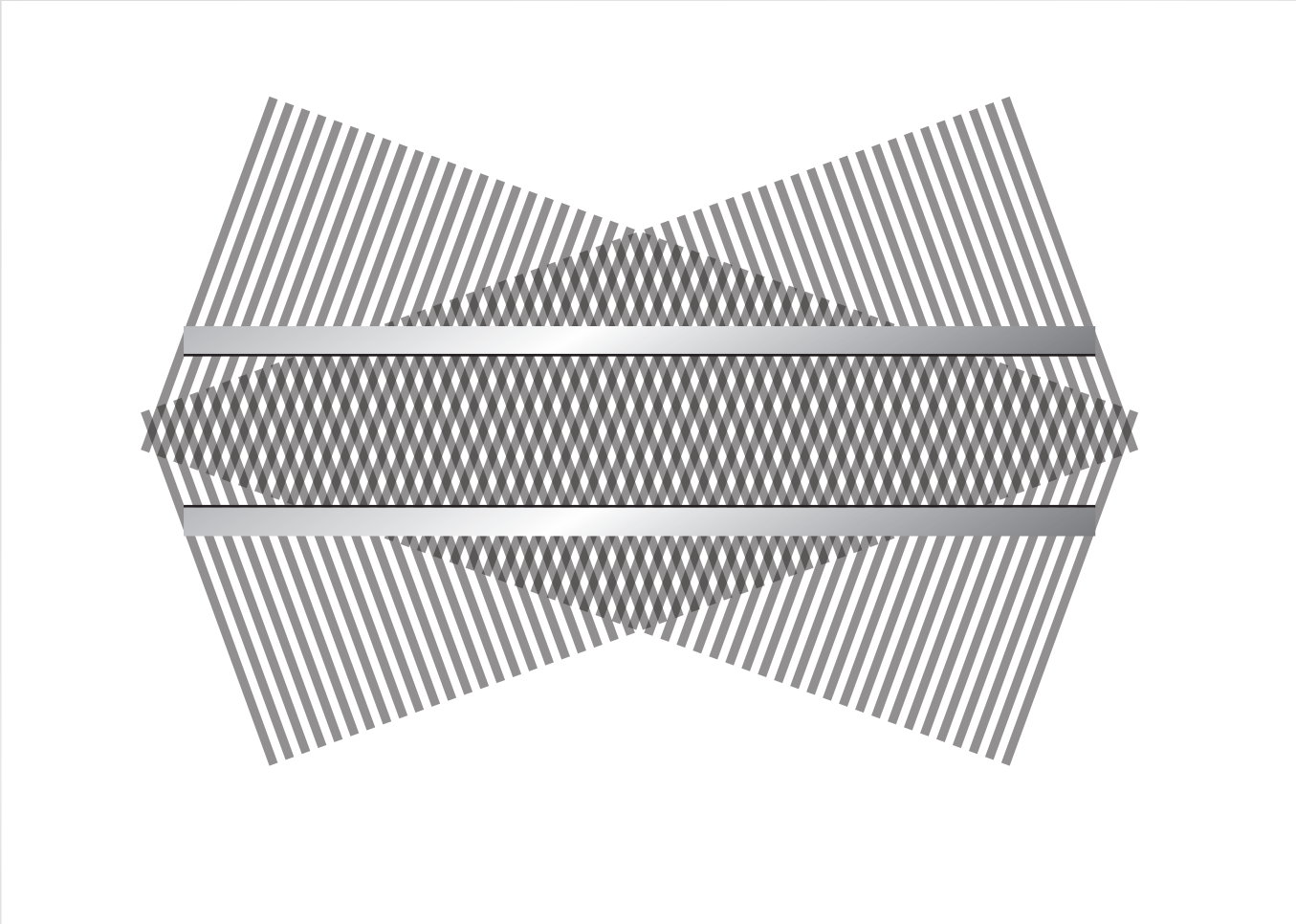
Waveguiding

…satisfying boundary conditions for planar-mirror waveguide



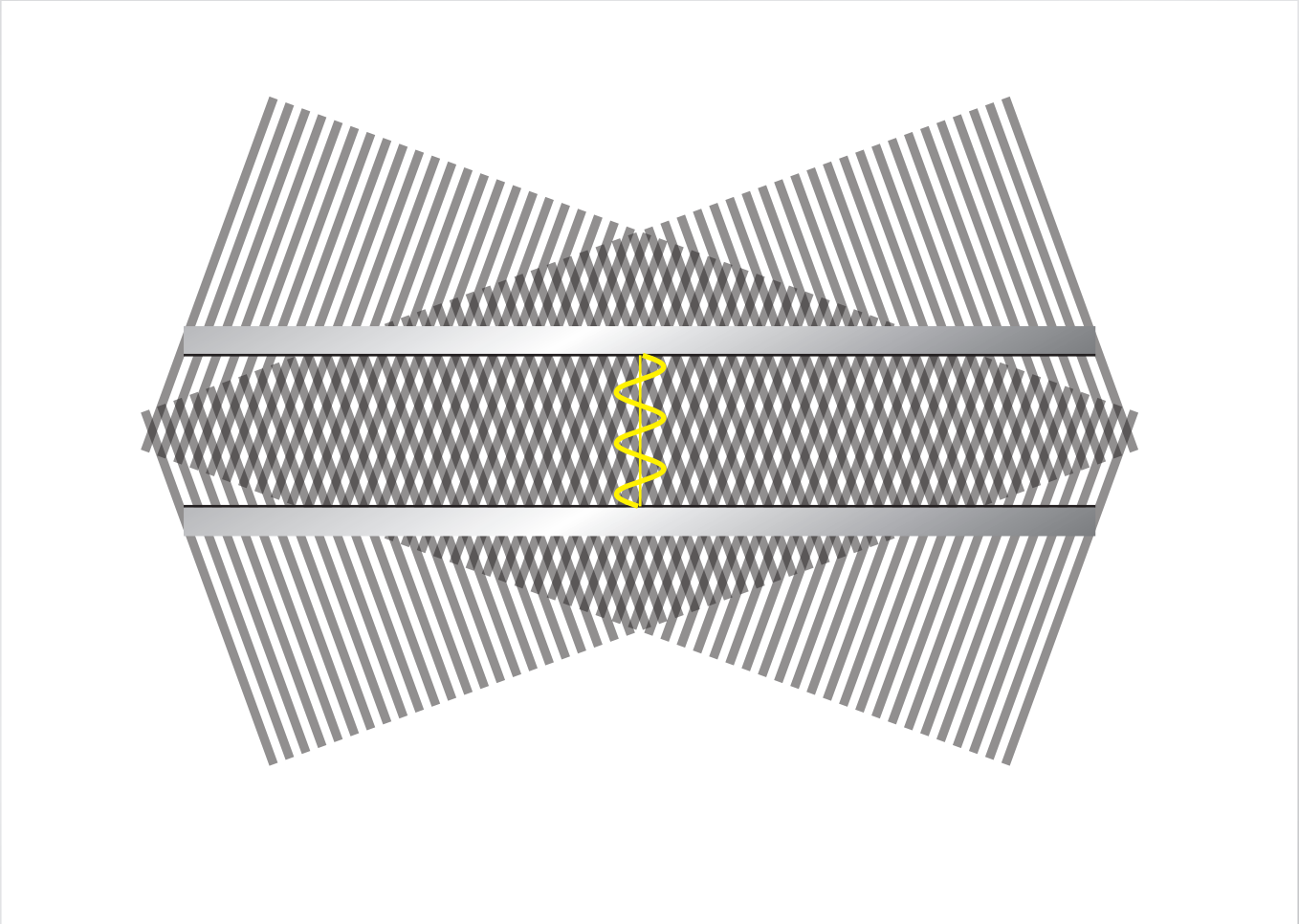
Waveguiding

transverse standing wave, traveling along axis



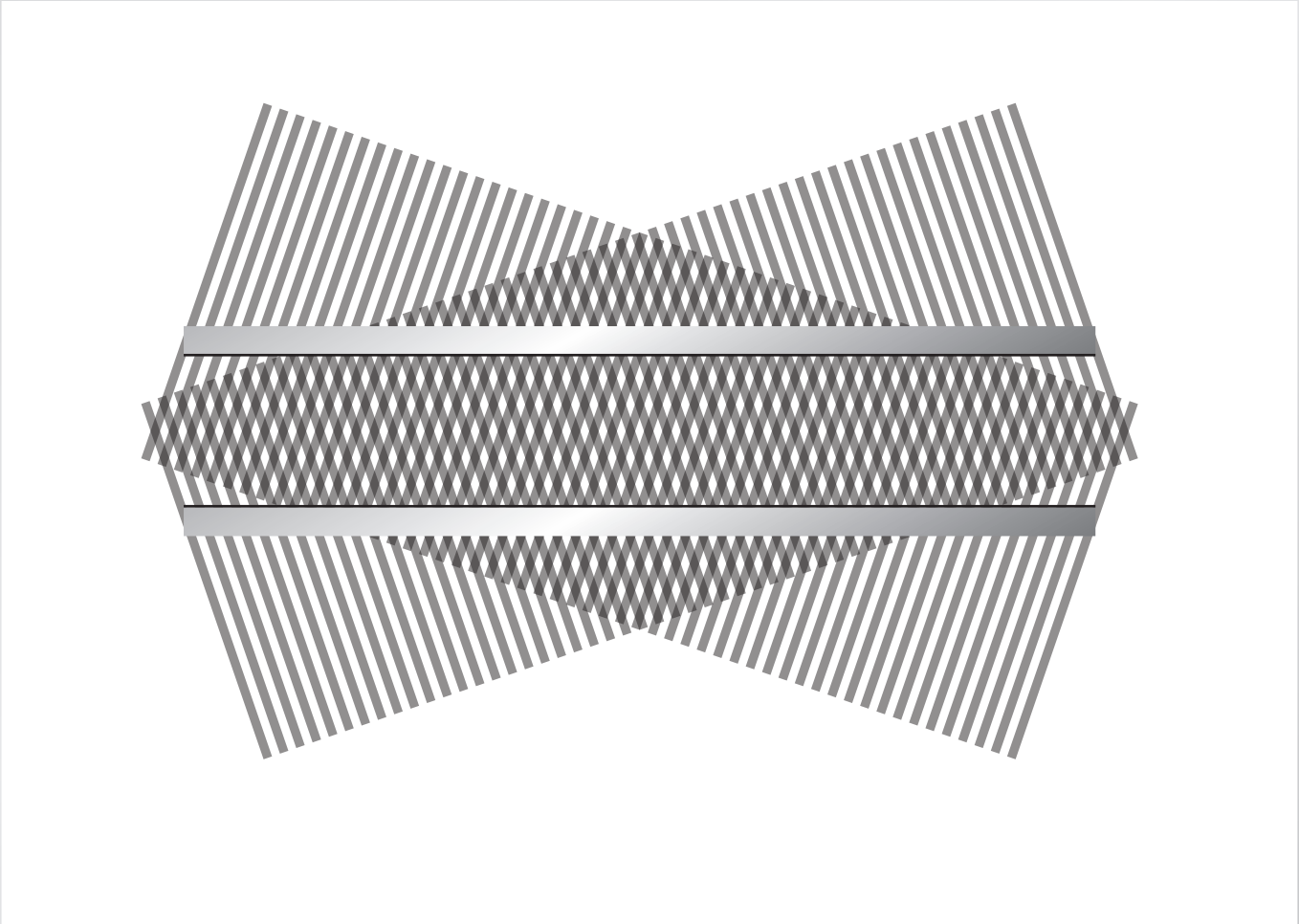
Waveguiding

transverse standing wave, traveling along axis



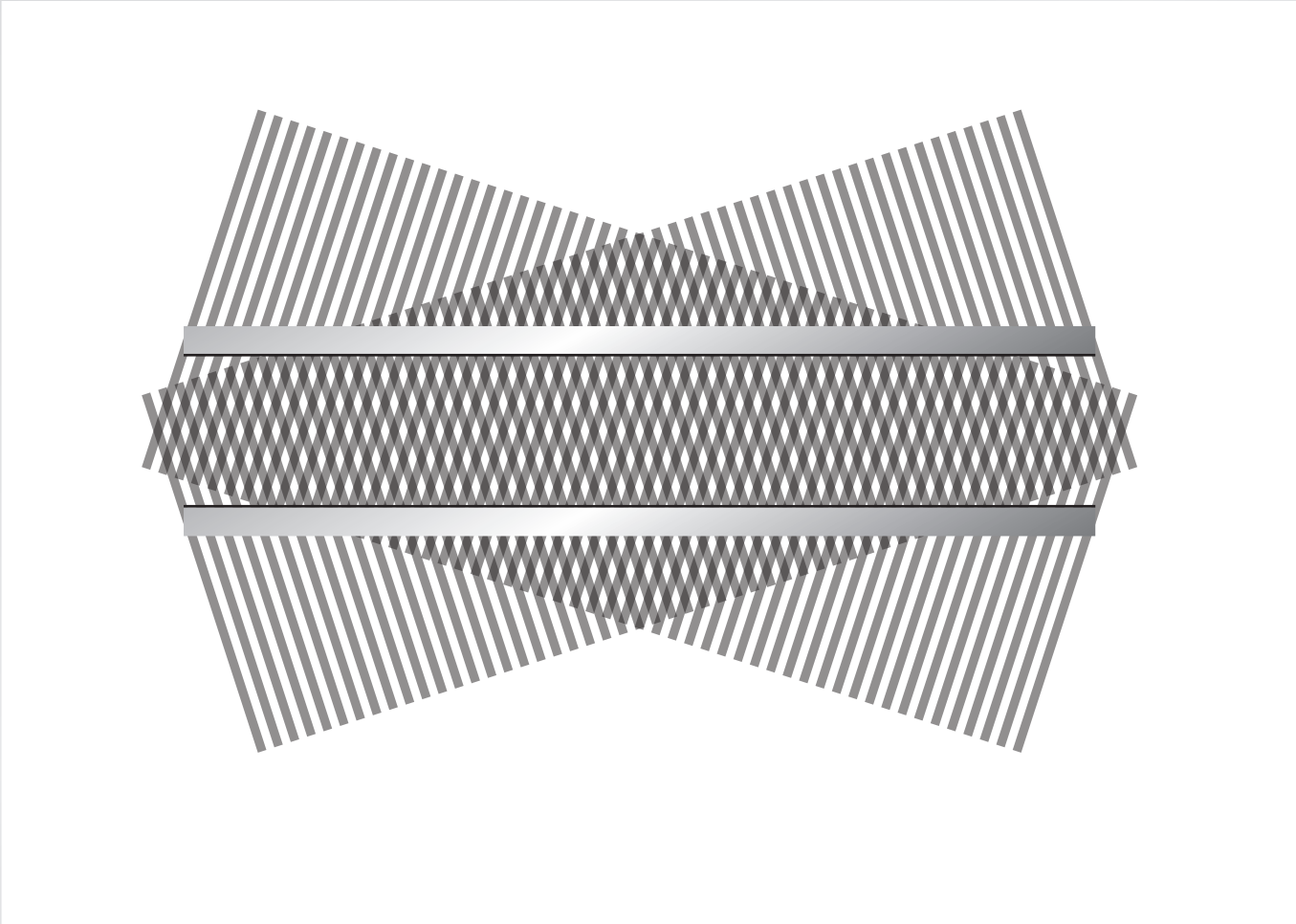
Waveguiding

change angle of incident waves…



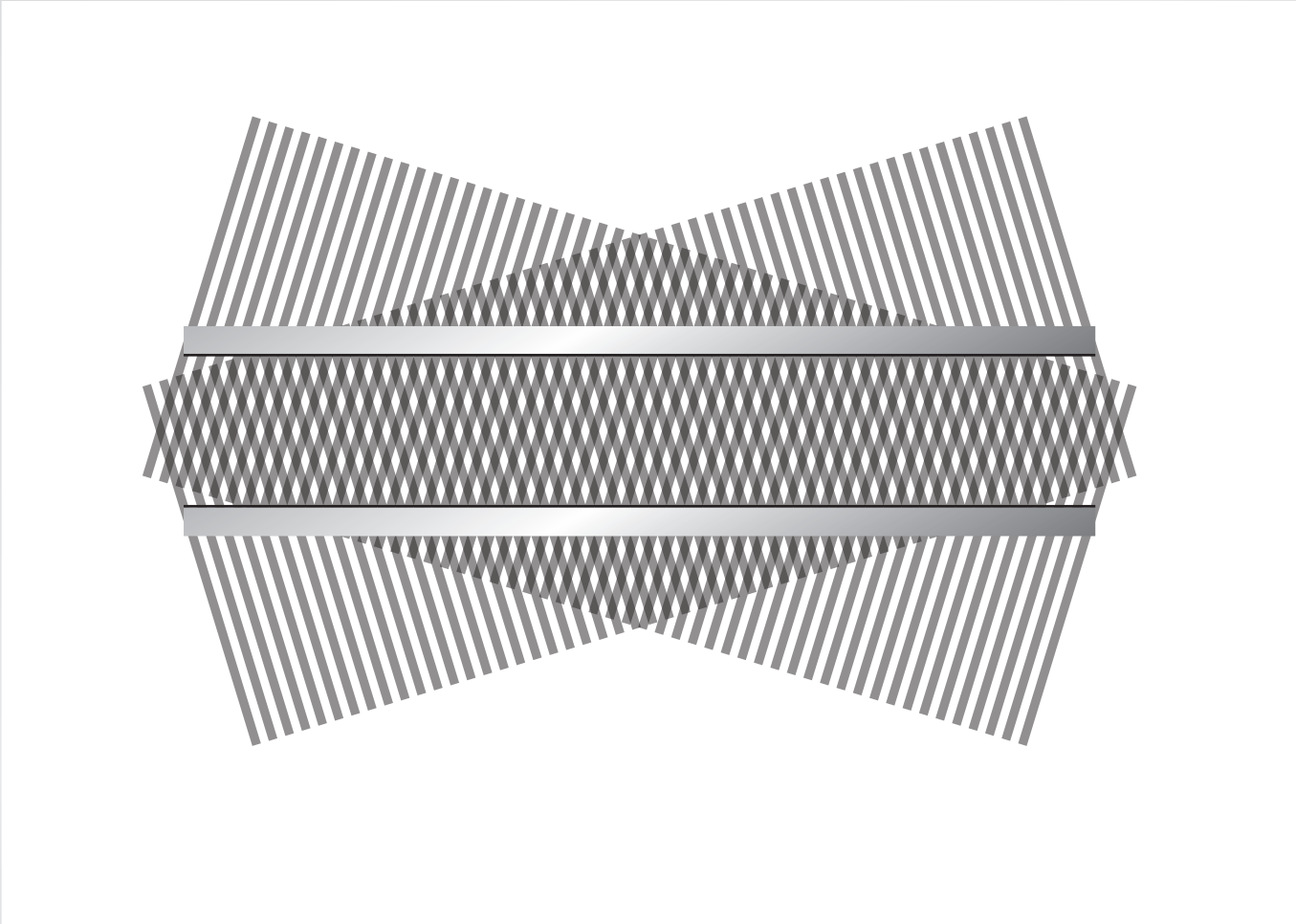
Waveguiding

change angle of incident waves…



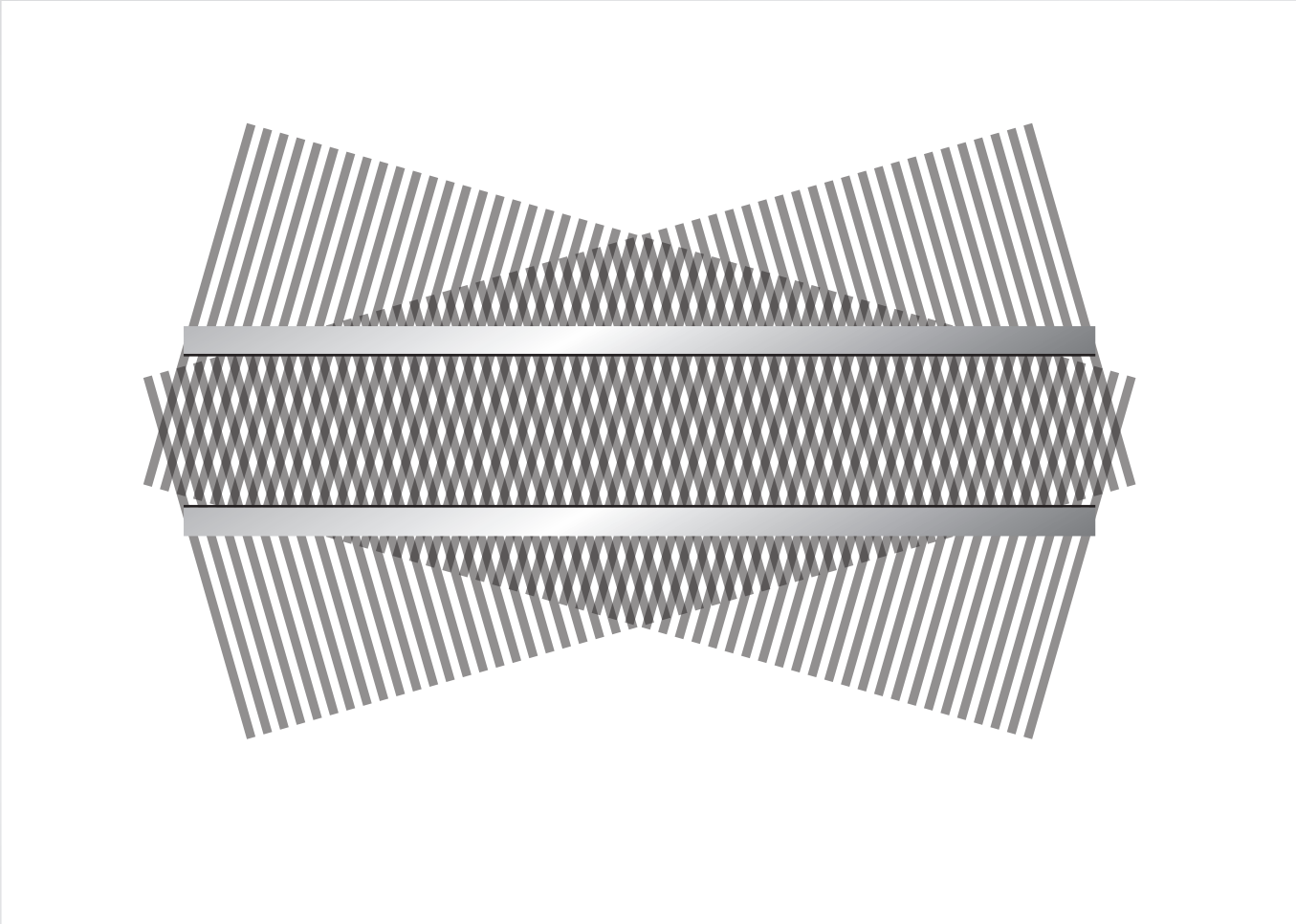
Waveguiding

change angle of incident waves…



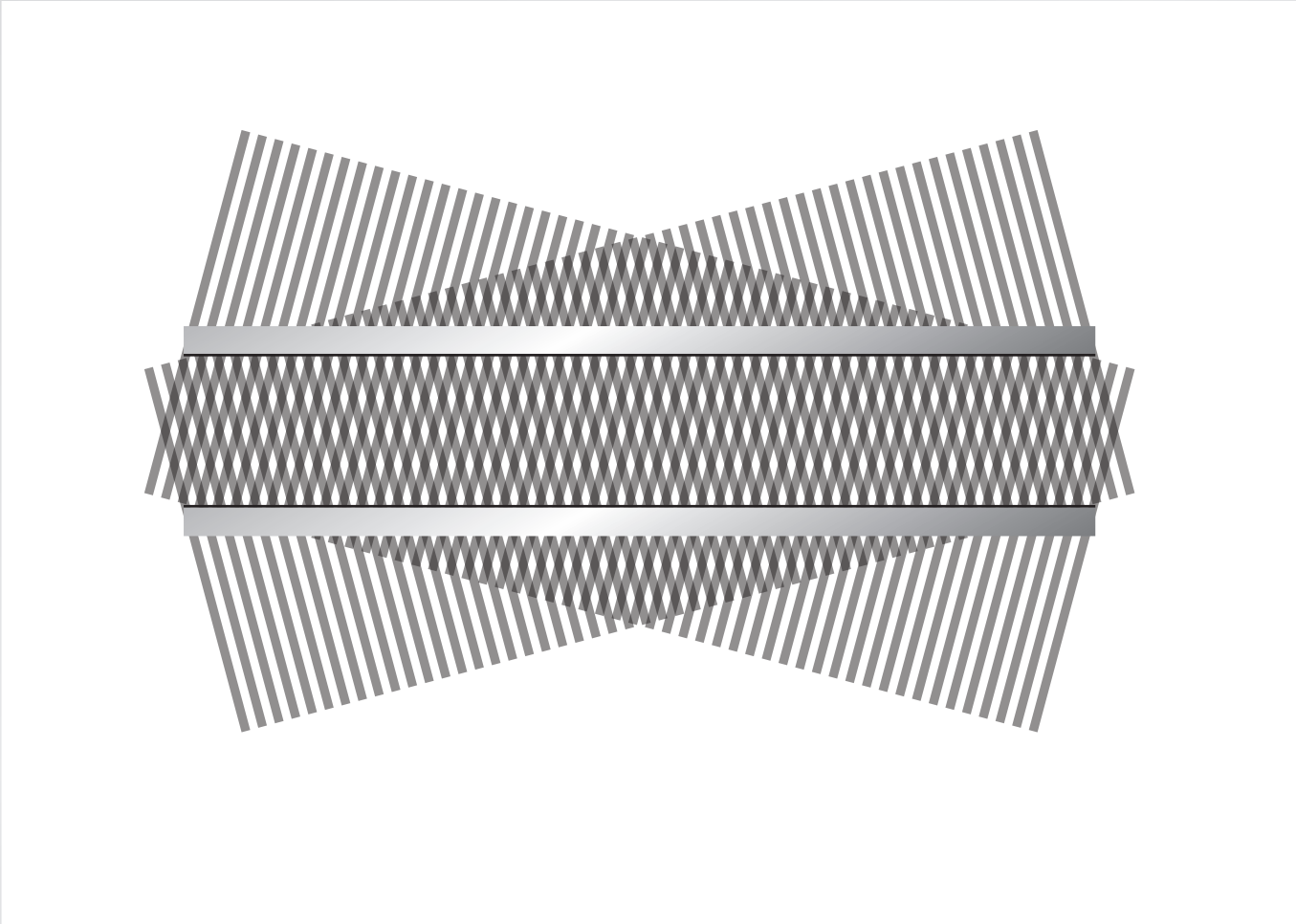
Waveguiding

change angle of incident waves…



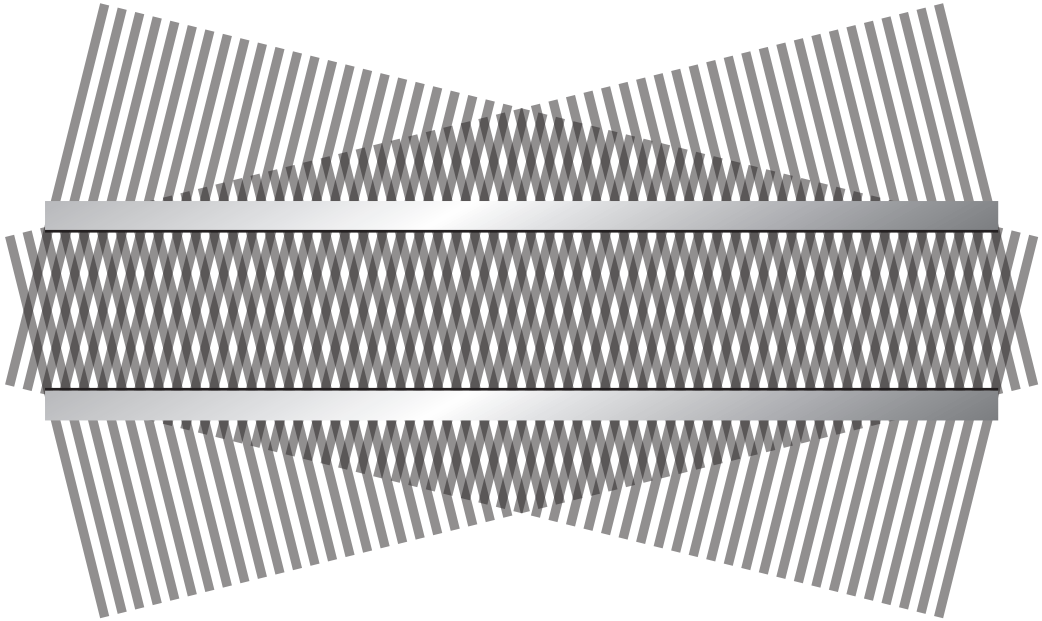
Waveguiding

change angle of incident waves…



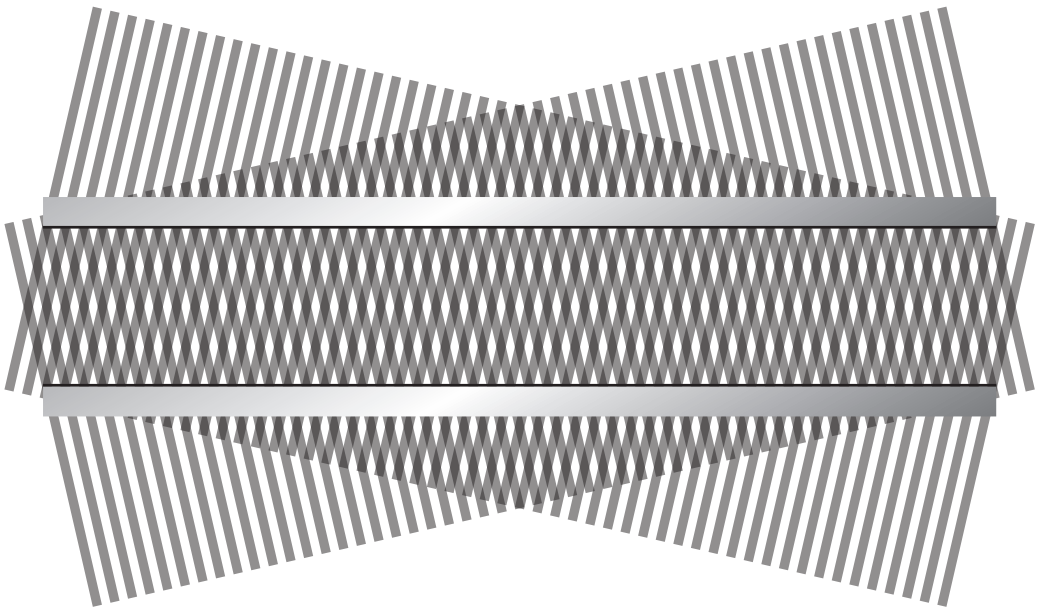
Waveguiding

change angle of incident waves…



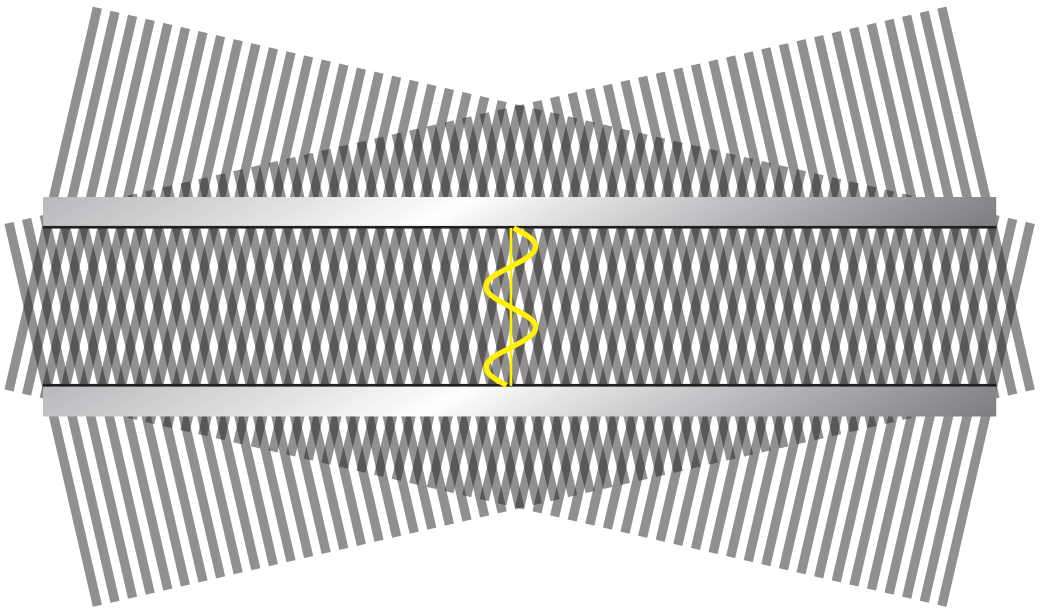
Waveguiding

change angle of incident waves…



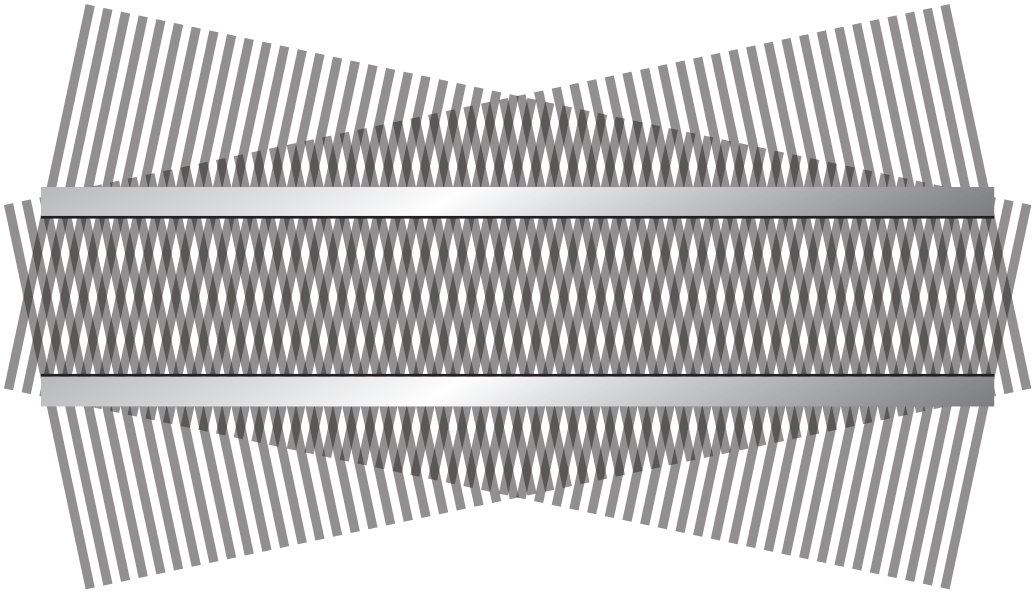
Waveguiding

change angle of incident waves…



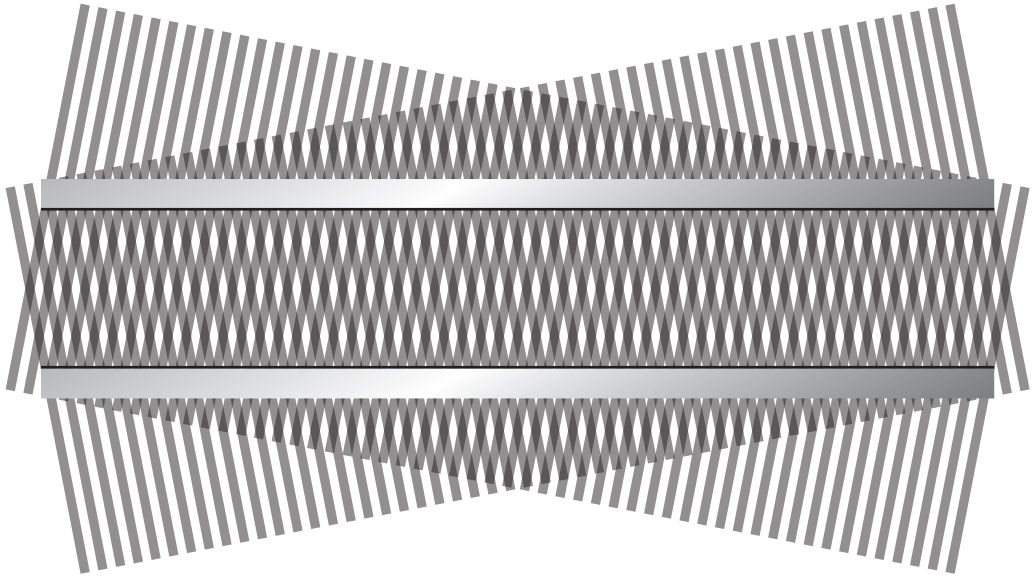
Waveguiding

change angle of incident waves…



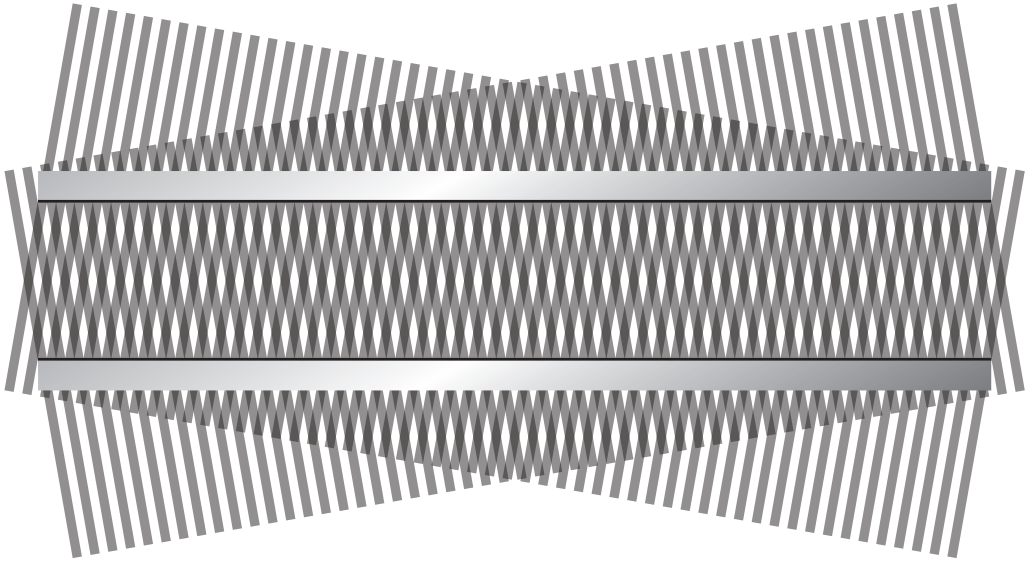
Waveguiding

change angle of incident waves…



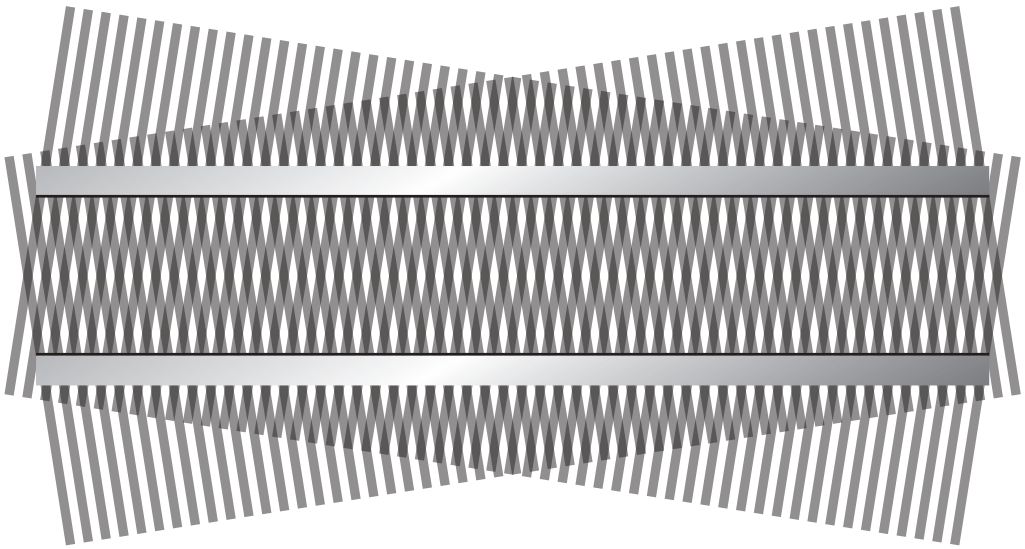
Waveguiding

change angle of incident waves…



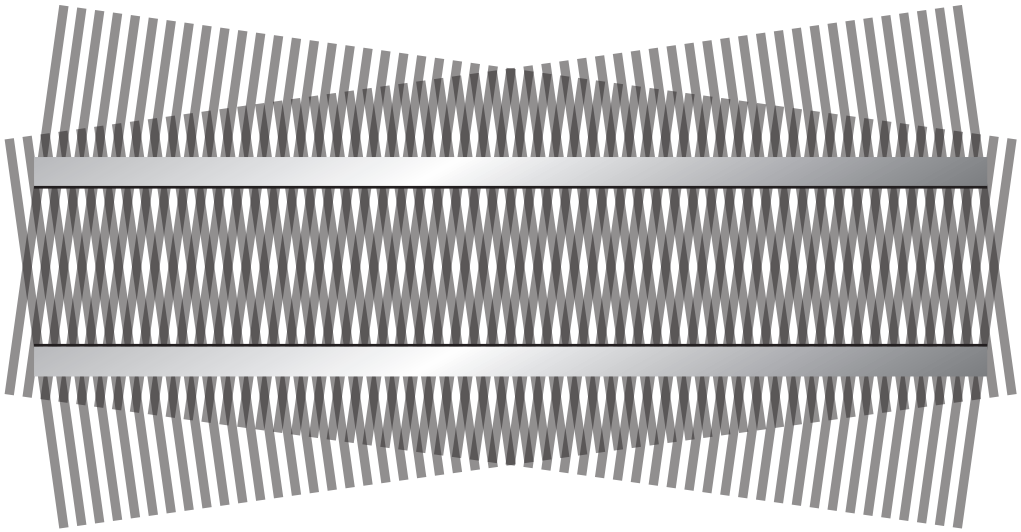
Waveguiding

change angle of incident waves…



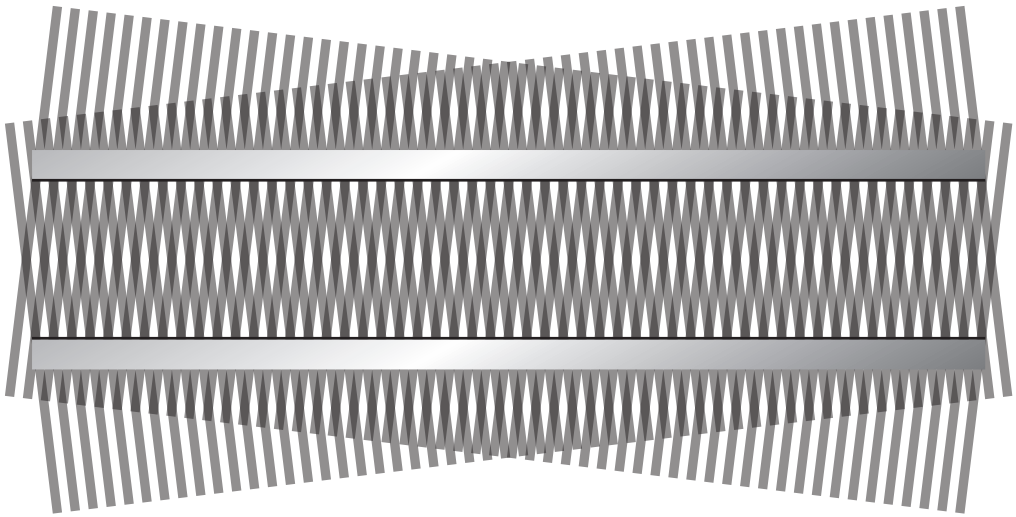
Waveguiding

change angle of incident waves…



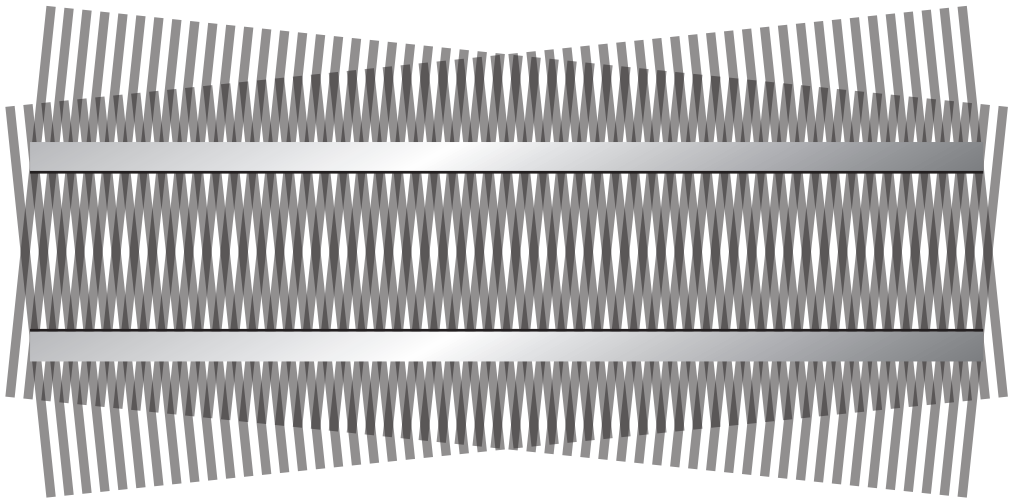
Waveguiding

change angle of incident waves…



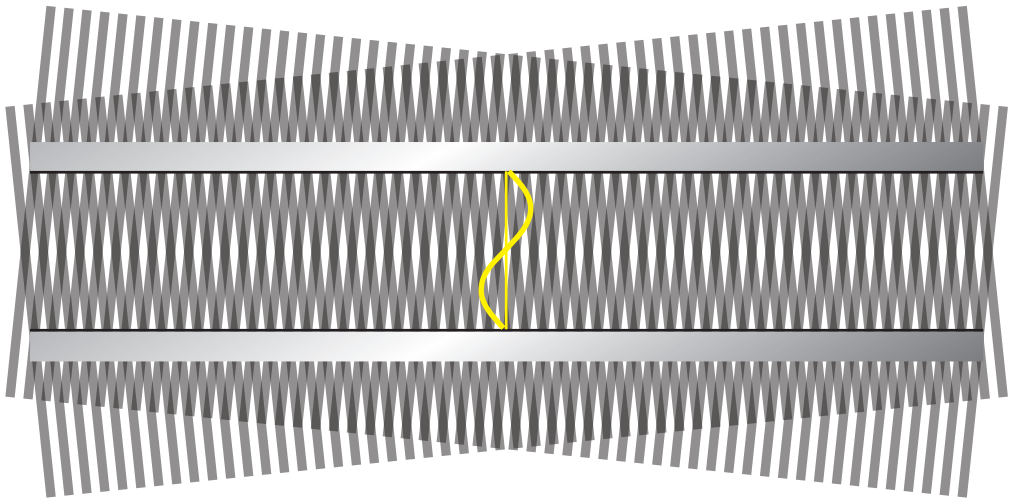
Waveguiding

change angle of incident waves…



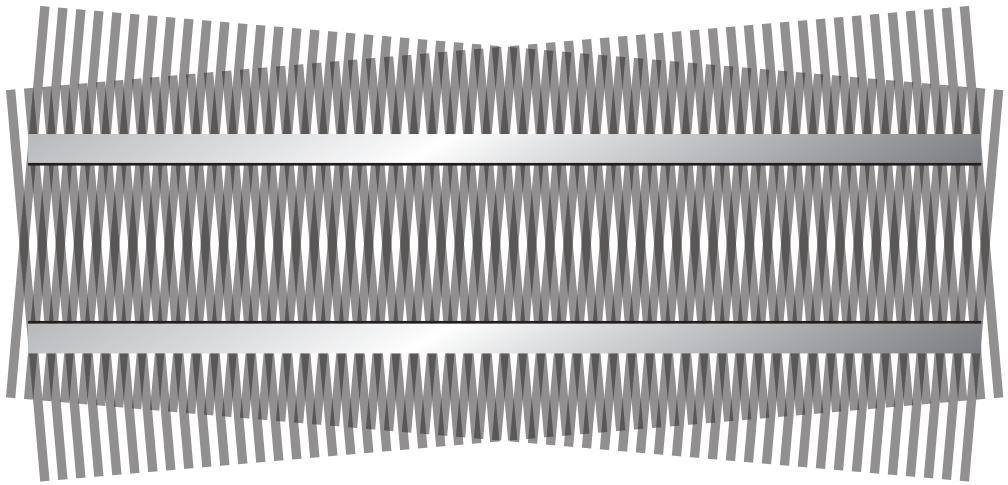
Waveguiding

change angle of incident waves…



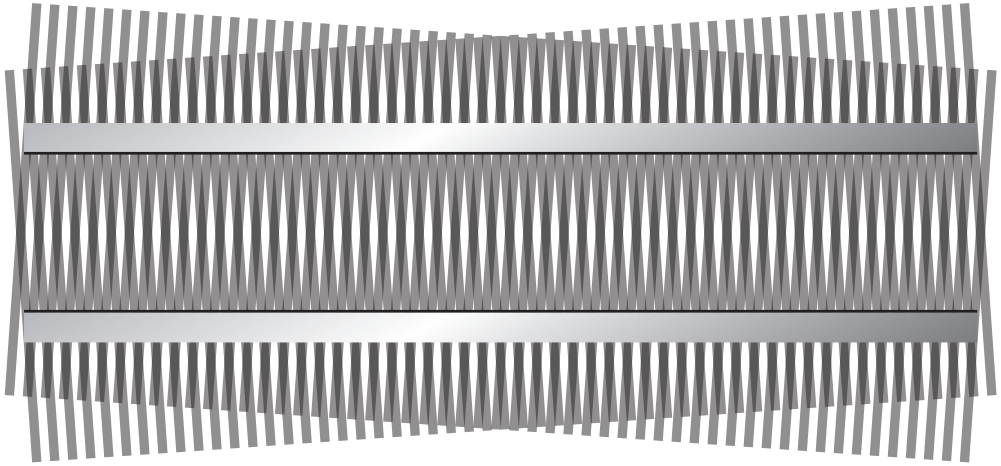
Waveguiding

change angle of incident waves…



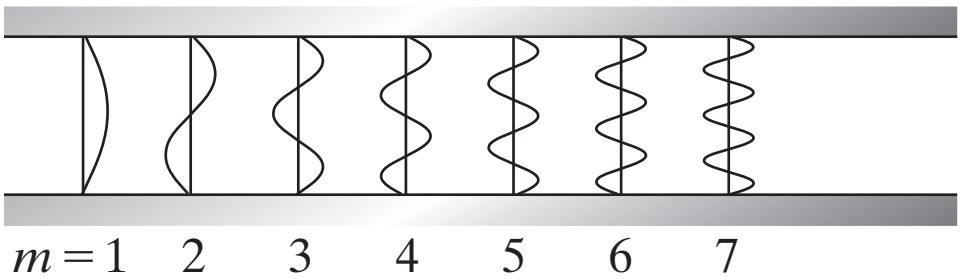
Waveguiding

change angle of incident waves…



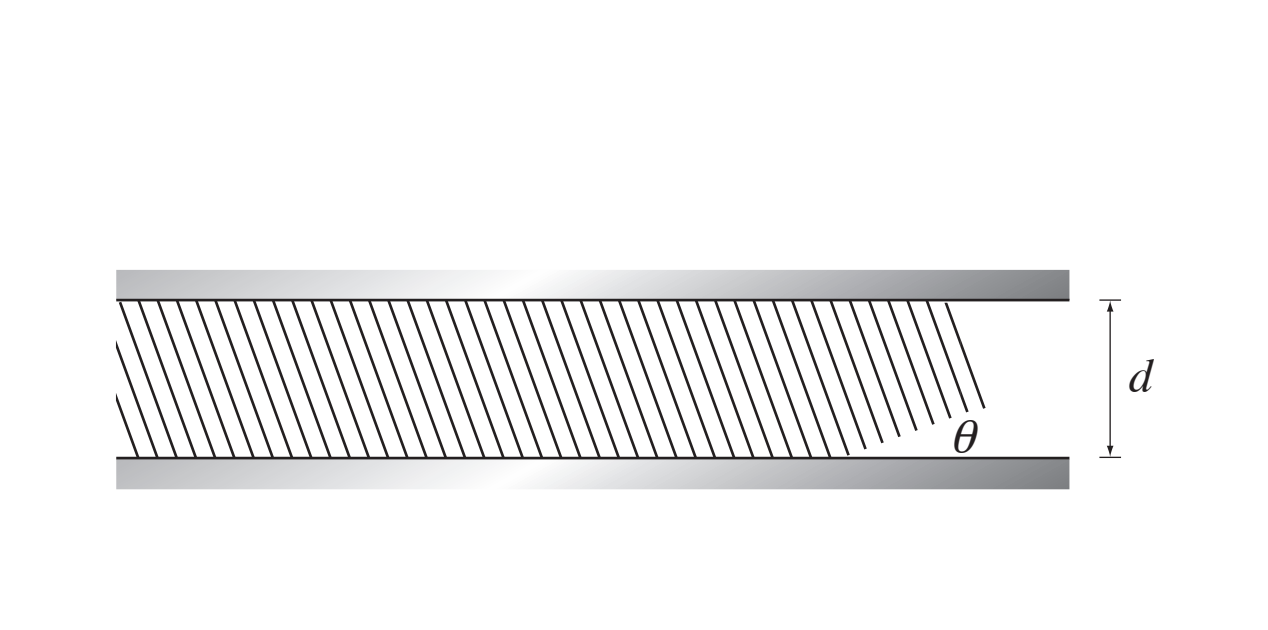
Waveguiding

boundary conditions only satisfied for certain θ



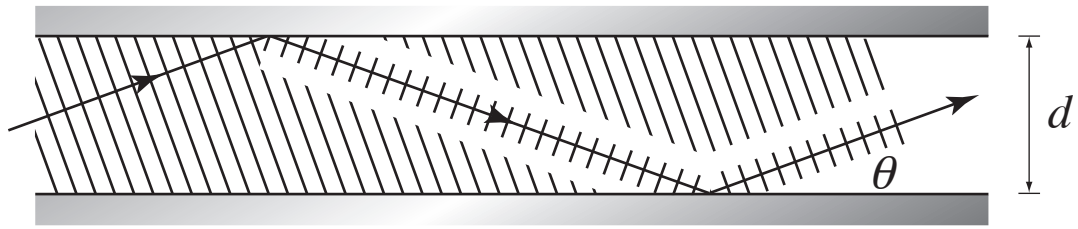
standing wave in *y*-direction, traveling in *z*-direction

Waveguiding



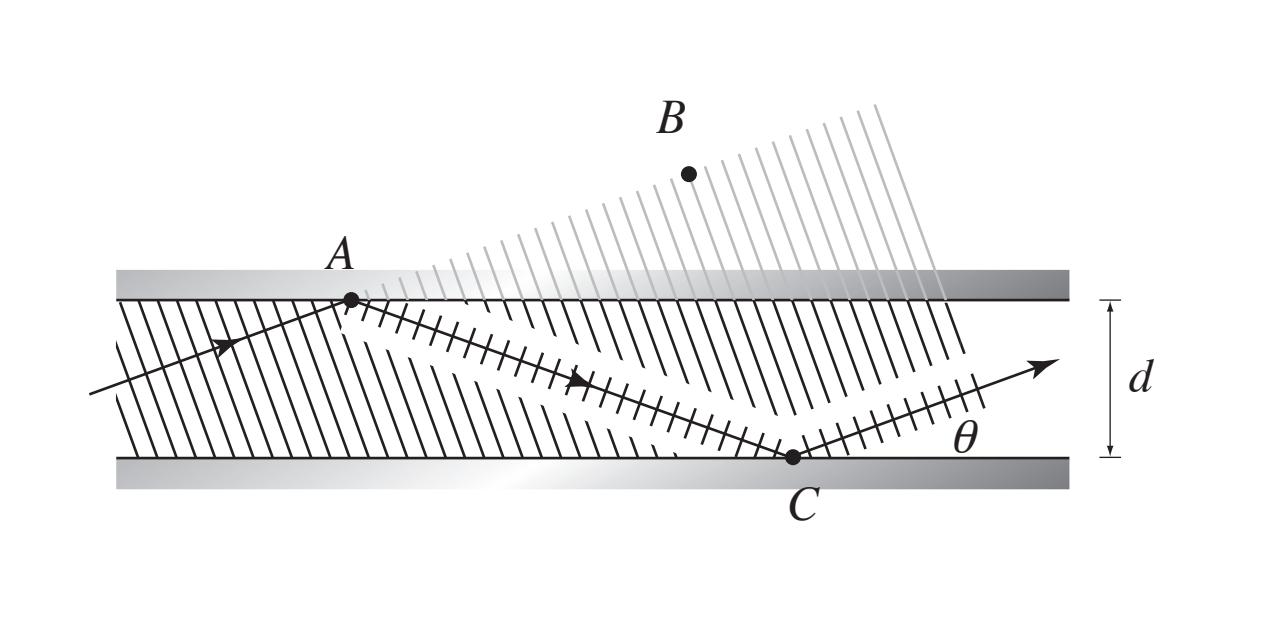
consider wave incident at angle θ

Waveguiding



twice-reflected wave

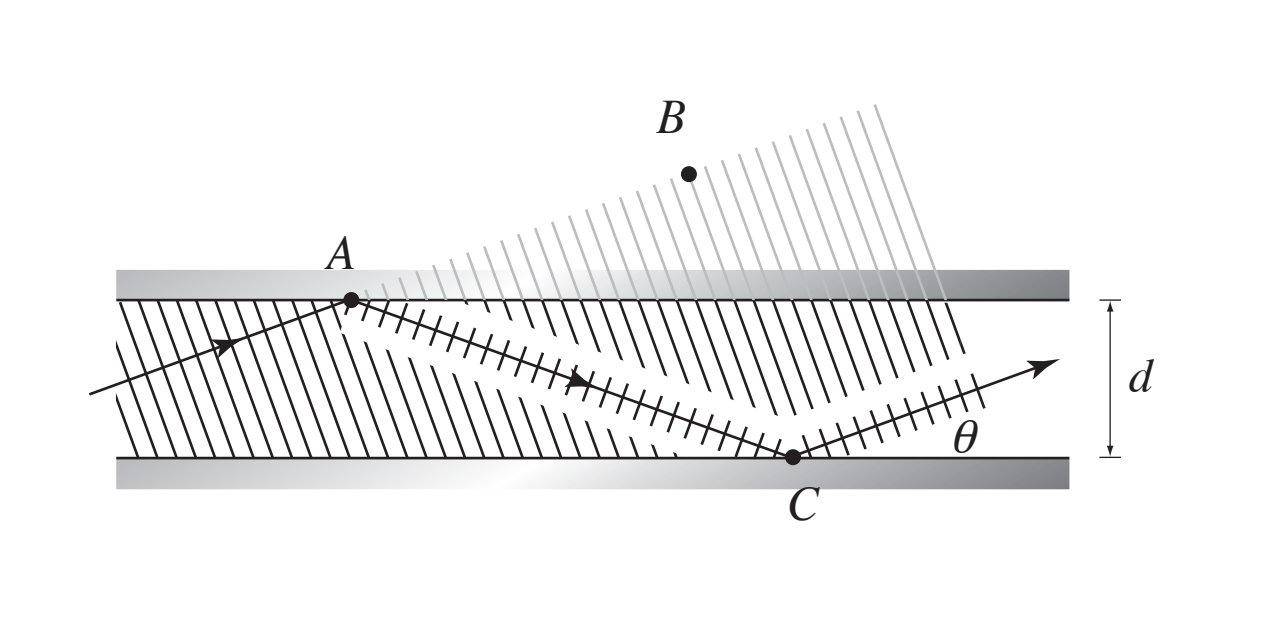
Waveguiding



self consistency:

$$AC - AB = 2d\sin\theta = m\lambda \quad (m = 1, 2, ...)$$

Waveguiding



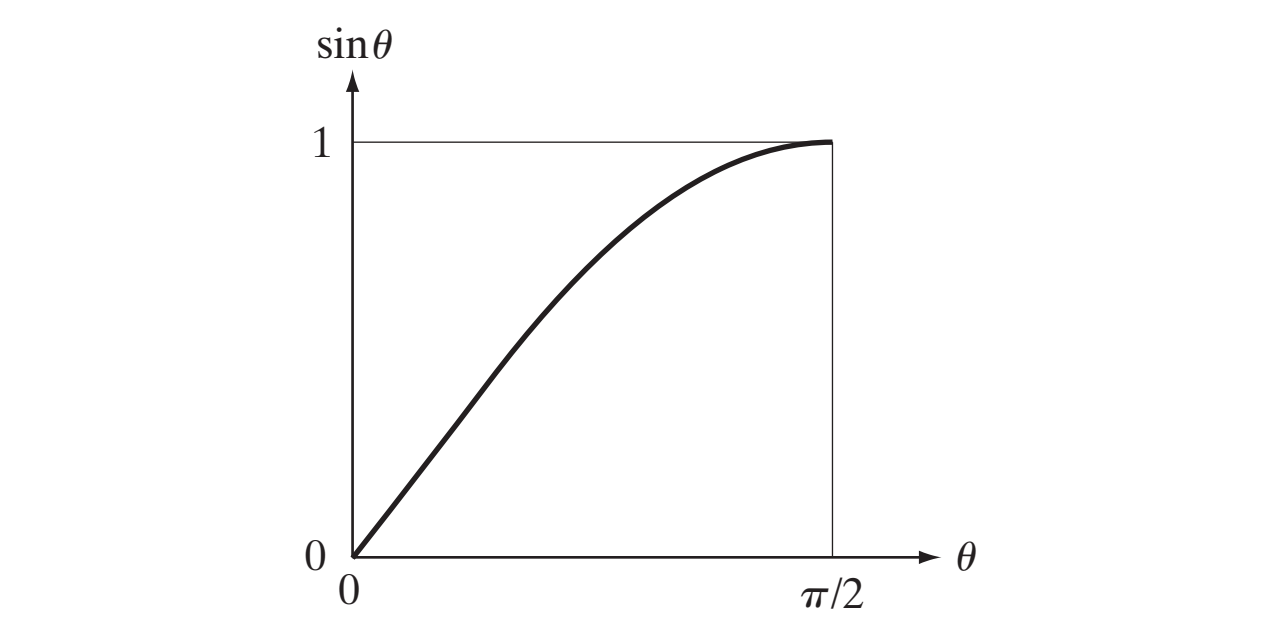
self consistency:

$$AC - AB = 2d\sin\theta = m\lambda \quad (m = 1, 2, ...)$$

so:

$$\sin\theta_m = m\frac{\lambda}{2d}$$

Waveguiding



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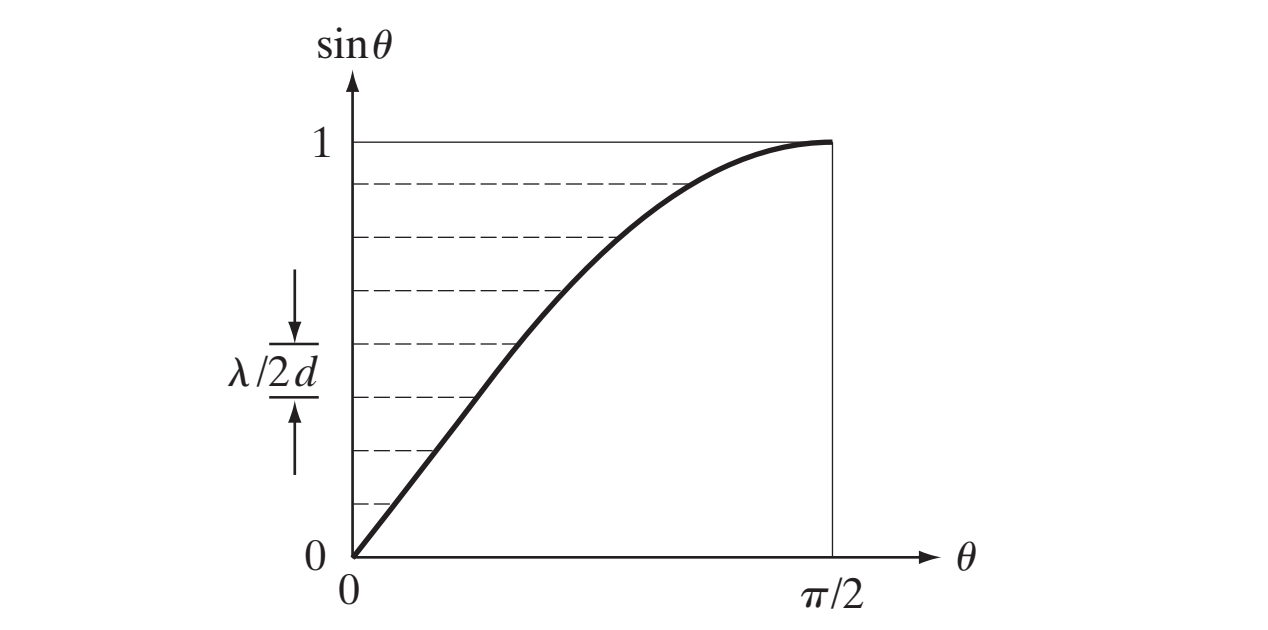
Waveguiding



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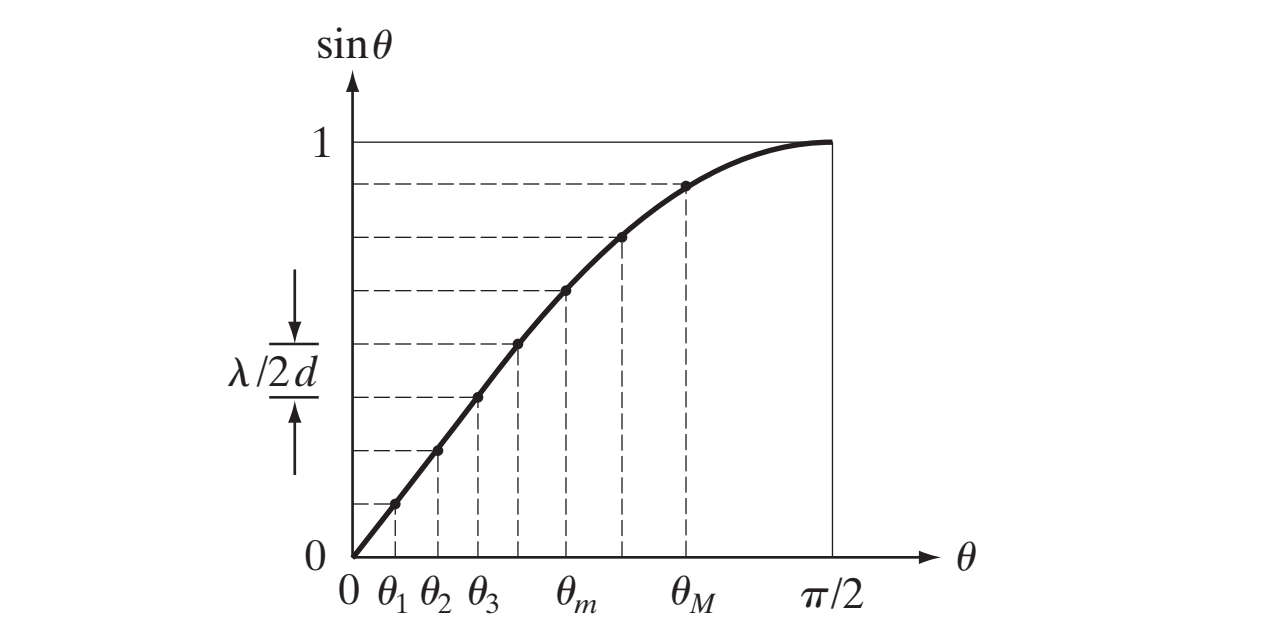
Waveguiding



self consistency:

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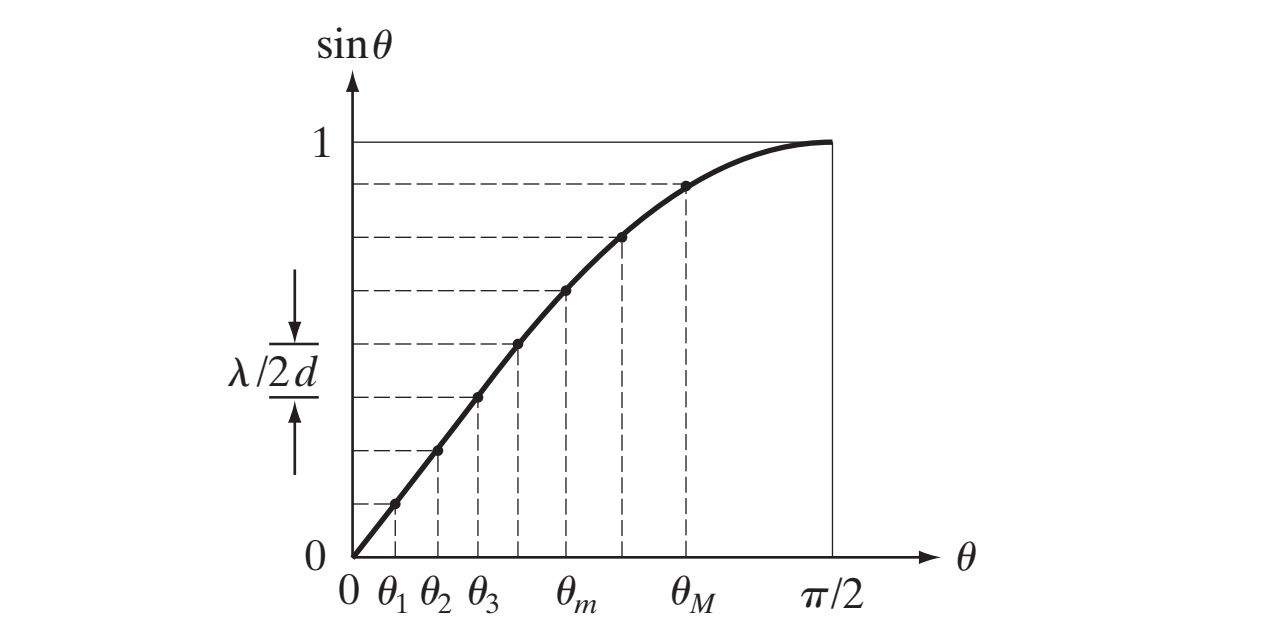
Waveguiding



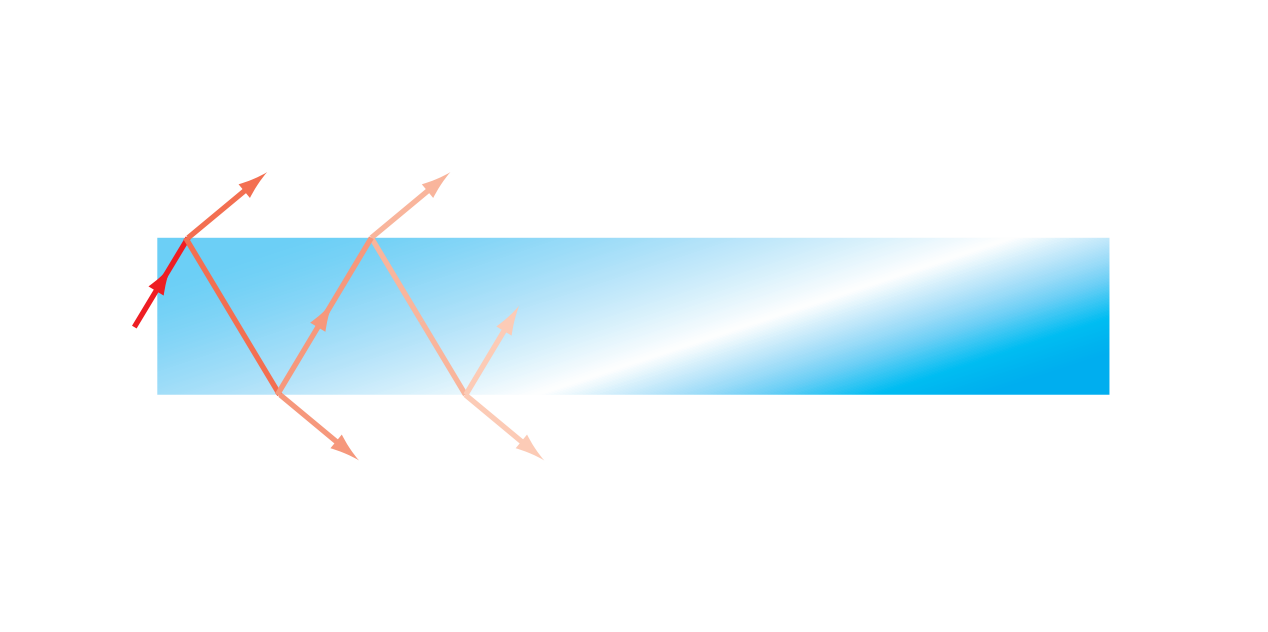
number of modes:

$$M \doteq \frac{2d}{\lambda}$$

Waveguiding

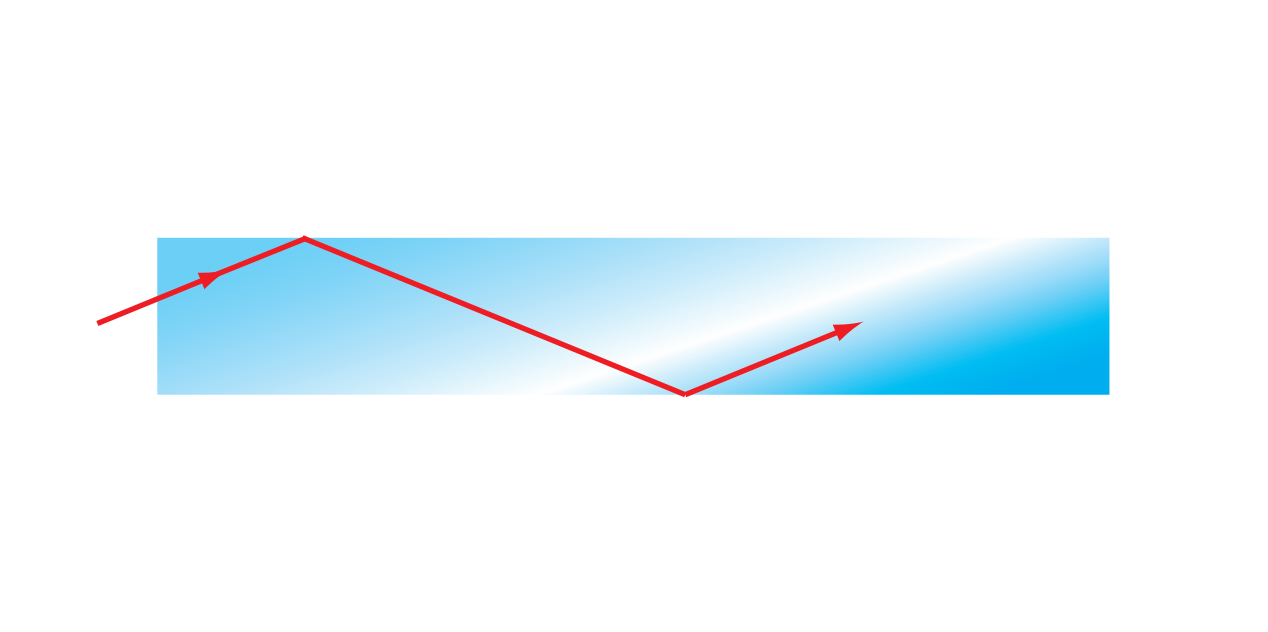
now consider a planar dielectric waveguide

Waveguiding



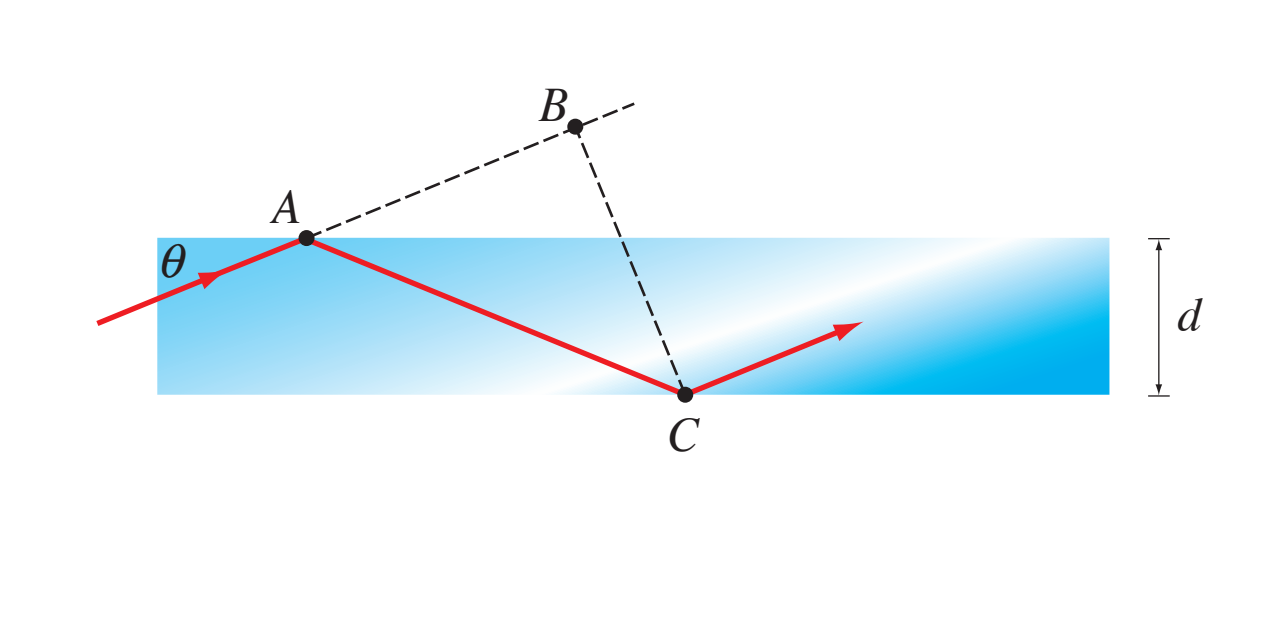
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



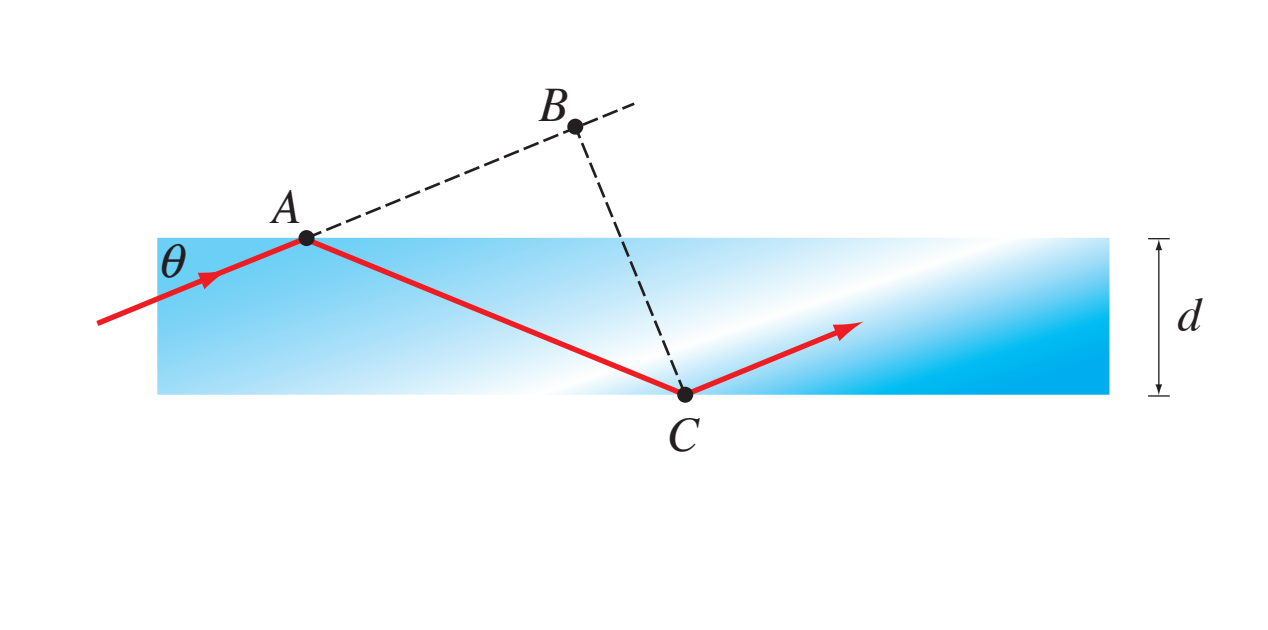
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

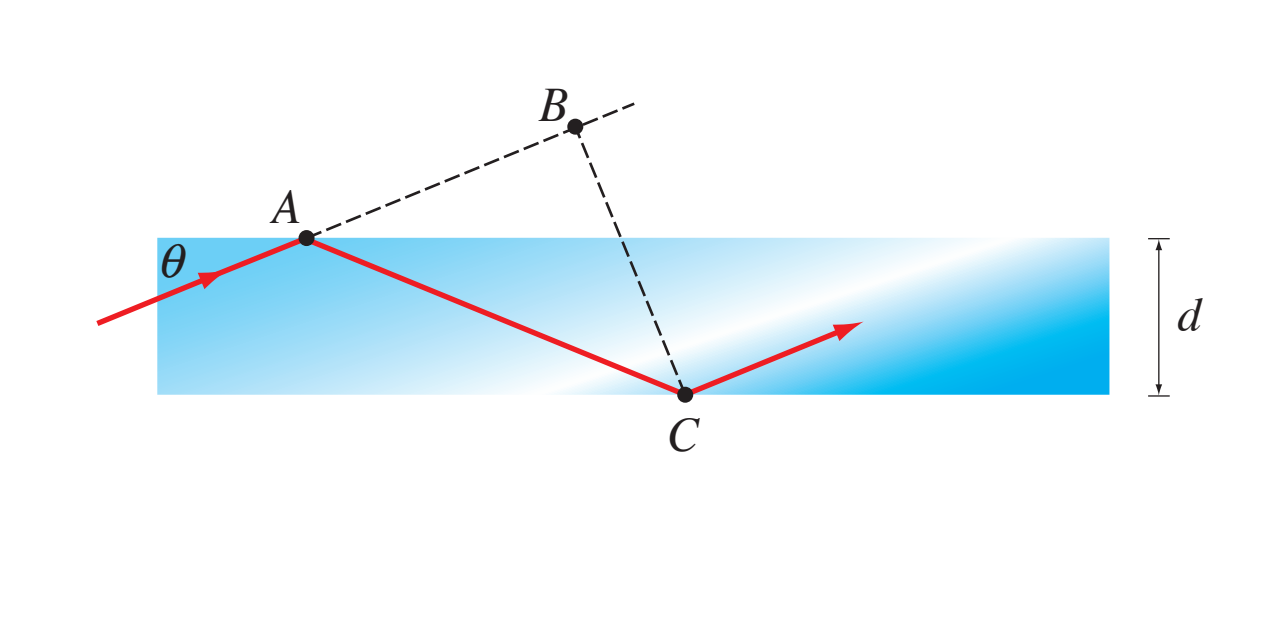
Waveguiding



self consistency:

$$AC - AB = 2d\sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\ldots)$$

Waveguiding



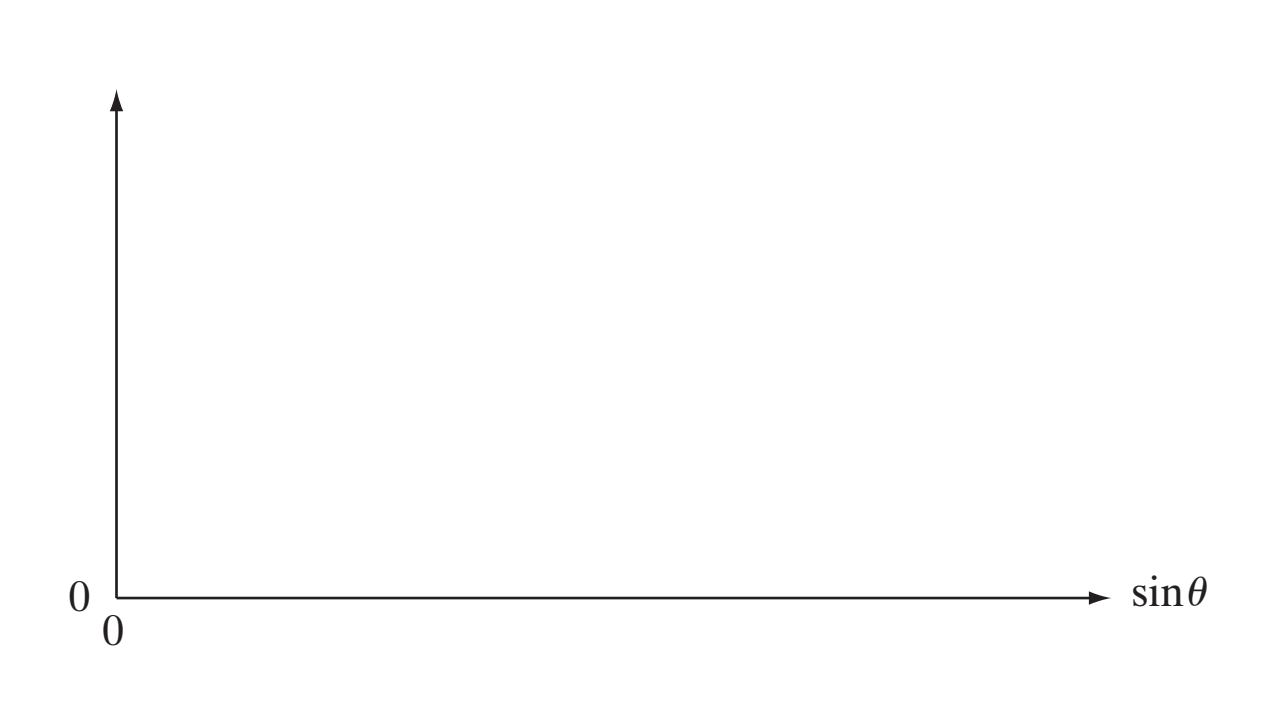
self consistency:

$$AC - AB = 2d\sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\ldots)$$

so:

$$\tan\left(\frac{\pi d}{\lambda}\sin\theta - m\frac{\pi}{2}\right) = \left(\frac{\sin^2(\pi/2 - \theta_c)}{\sin^2\theta} - 1\right)^{1/2}$$

Waveguiding



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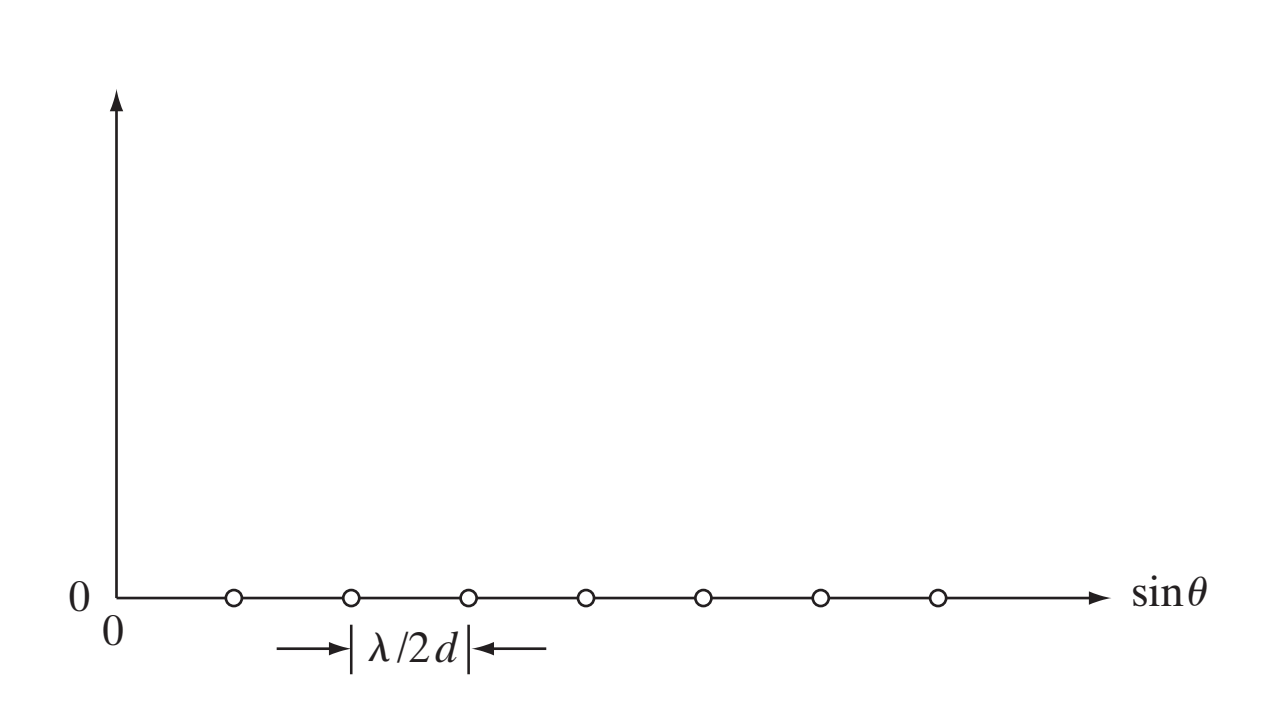

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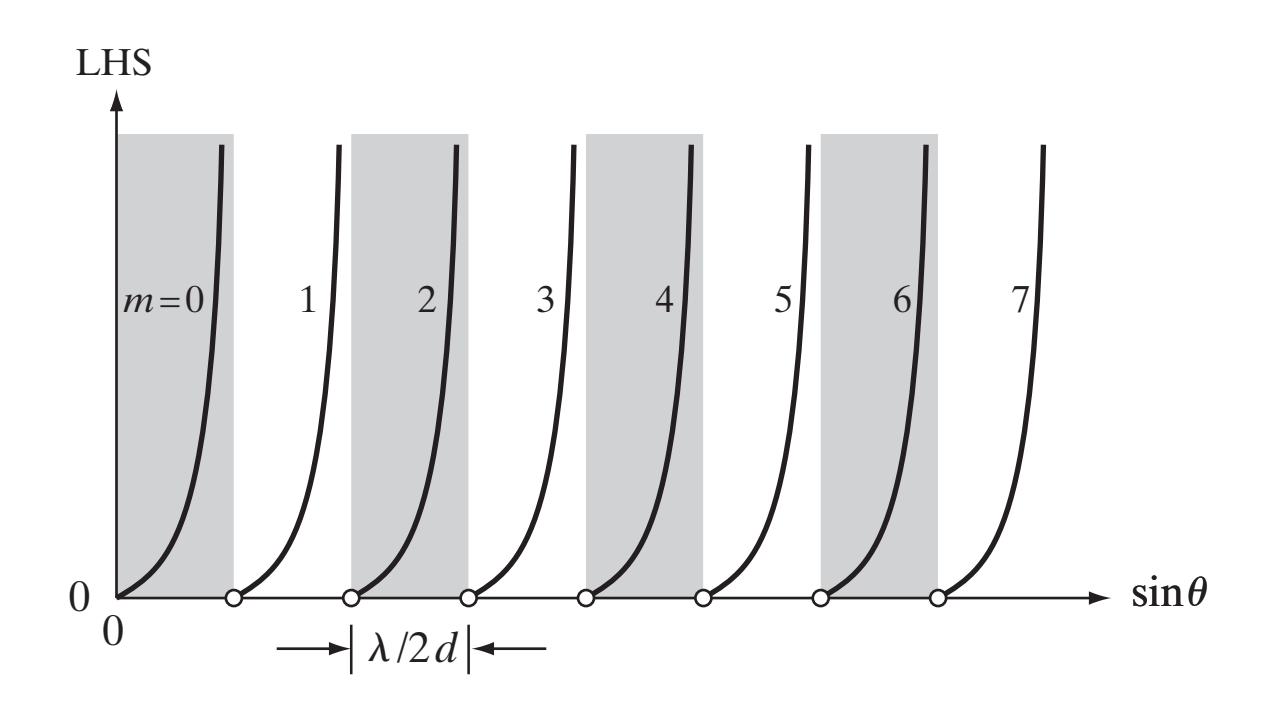
Waveguiding



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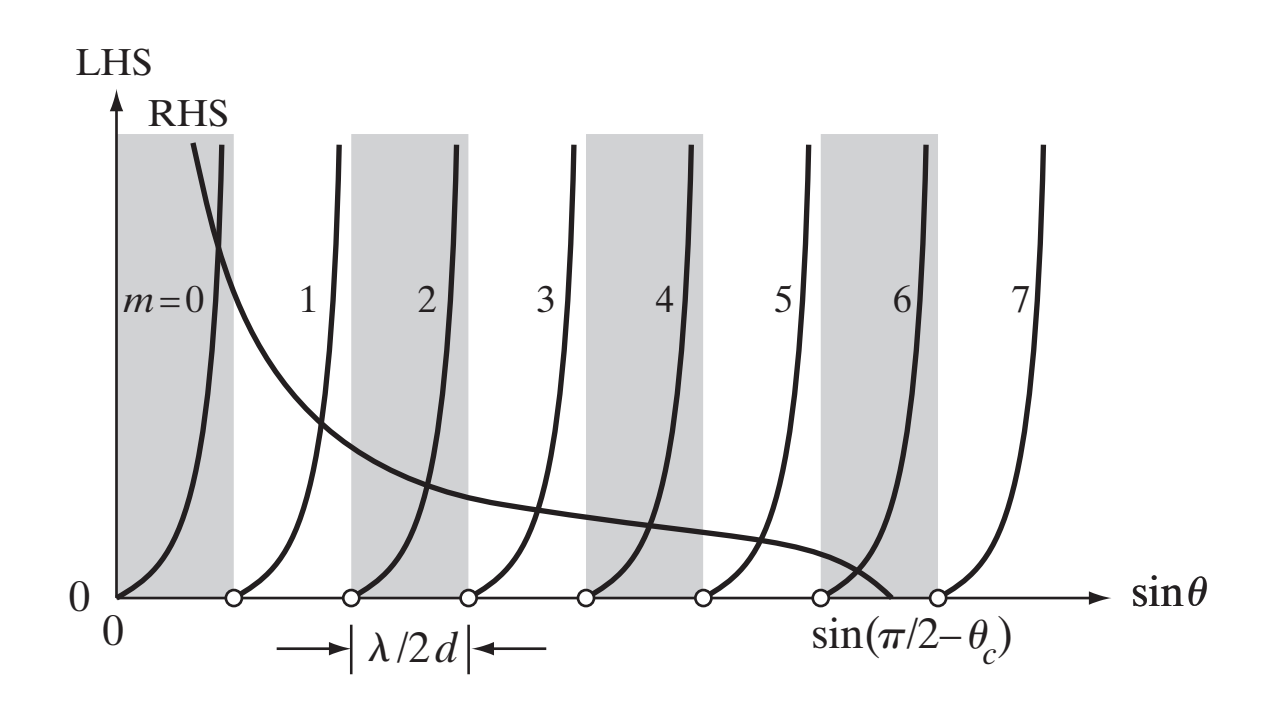
Waveguiding



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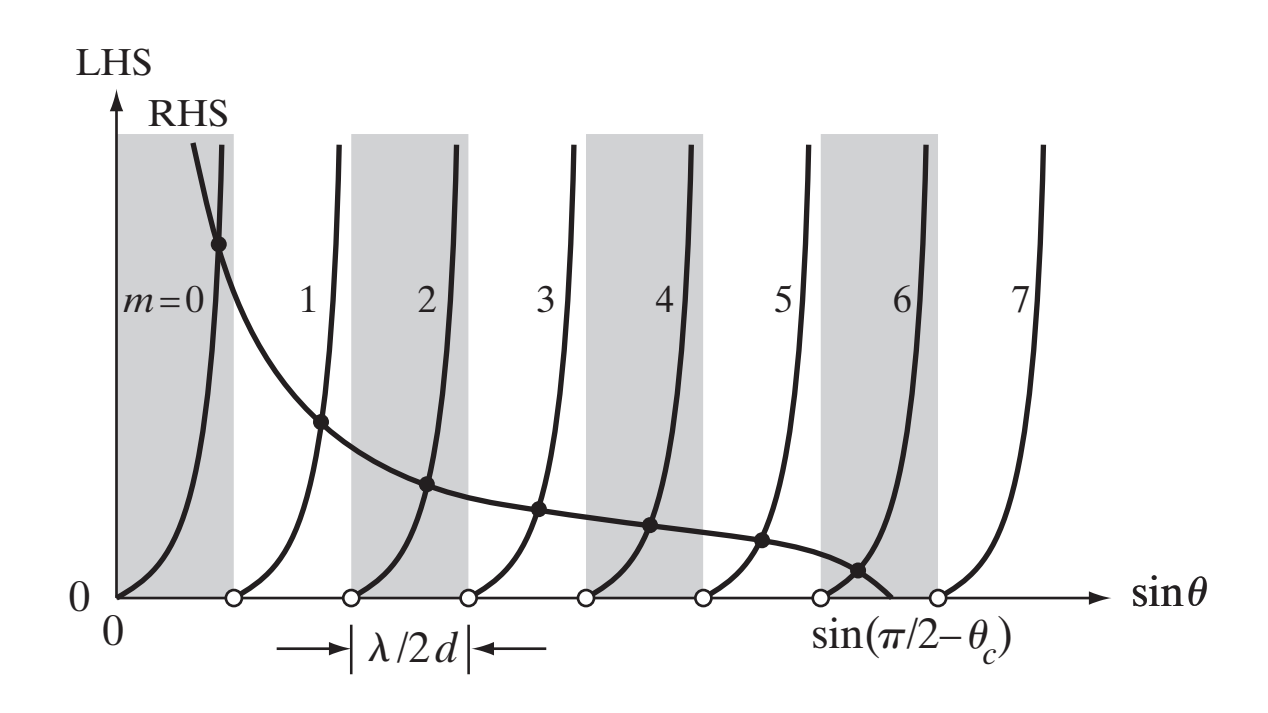
Waveguiding



self consistency:

$$AC - AB = 2d\sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\ldots)$$

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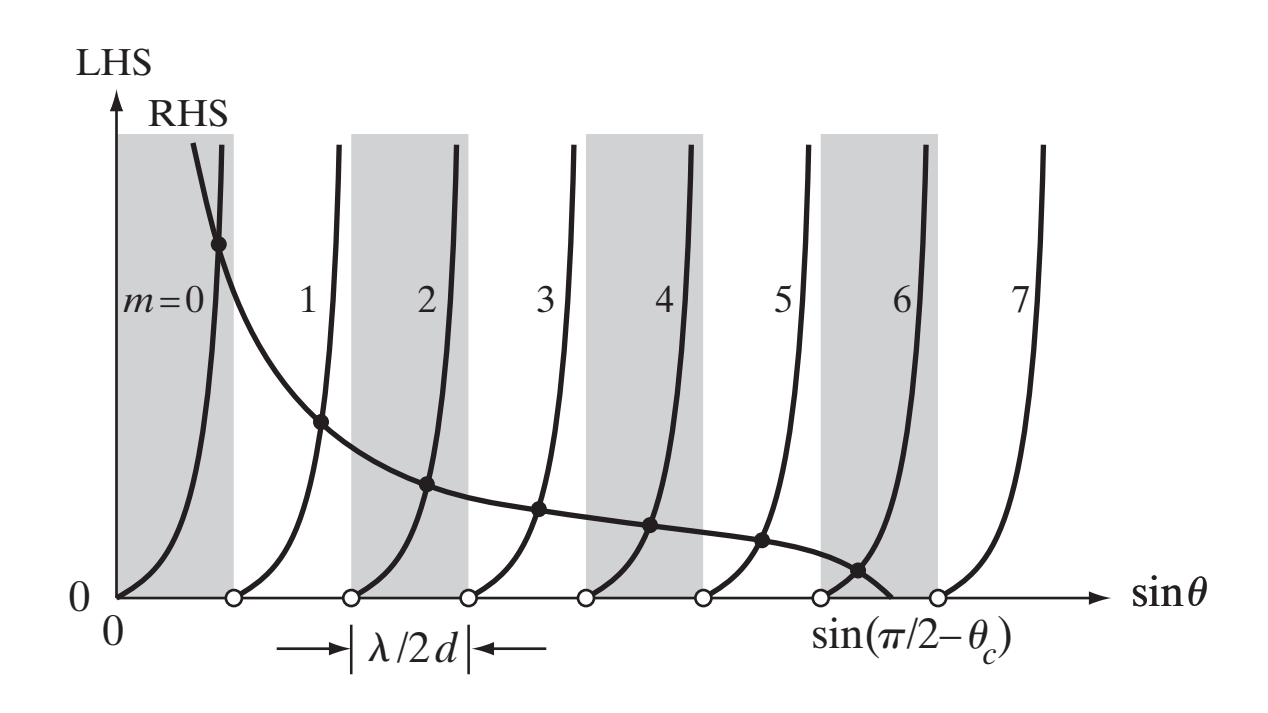
$$\tan\left(\frac{\pi d}{\lambda}\sin\theta - m\frac{\pi}{2}\right) = \left(\frac{\sin^2(\pi/2-\theta_c)}{\sin^2\theta} - 1\right)^{1/2}$$

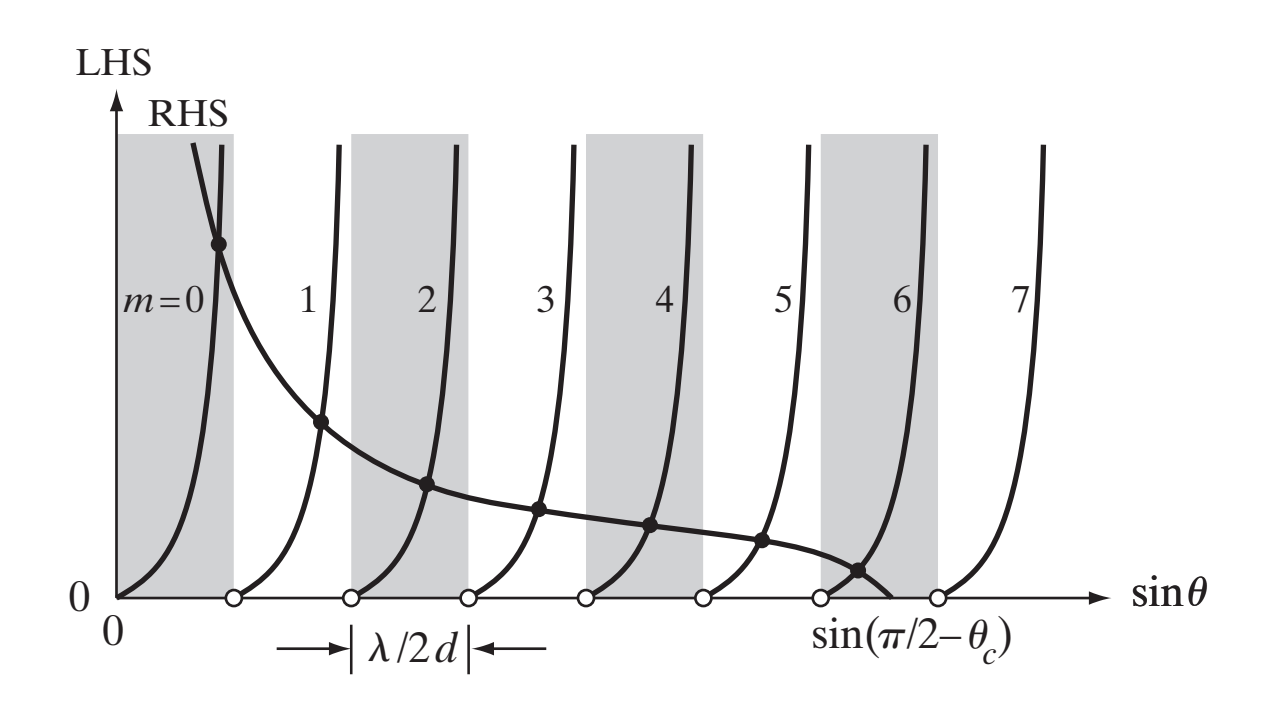
Waveguiding



number of modes:

$$M \doteq \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d}$$

Waveguiding



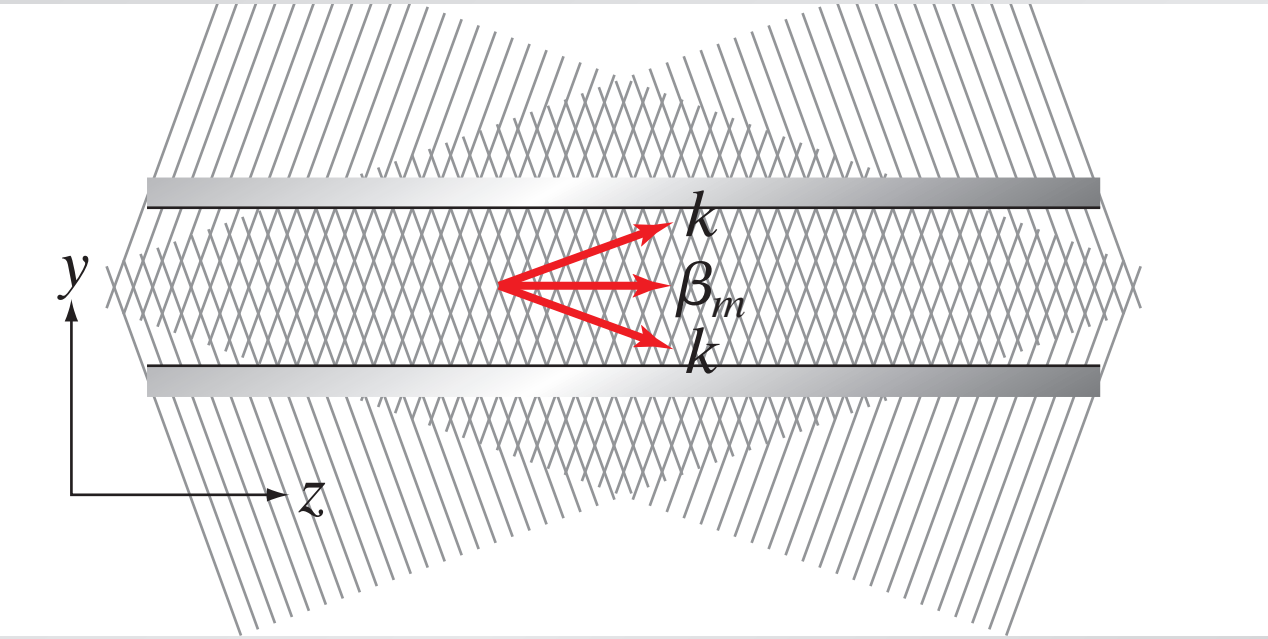
number of modes:

$$M \doteq \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d}$$

or:

$$M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

Waveguiding



propagation constant of guided wave:

$$\beta_m^2 = k^2 - k_y^2 = k^2 - \frac{m^2\pi^2}{d^2}$$

group velocity:

$$v_m = c\cos\theta_m$$

Waveguiding

single mode condition for 600-nm light:

planar mirror $$M \doteqdot \frac{2d}{\lambda}$$ $$300 < d < 600 \text{ nm}$$

dielectric $$M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$$ $$d < 268 \text{ nm}$$

Waveguiding

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can make d **larger by making** $n_1 - n_2$ **smaller!**

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = -i\omega\mu_o \nabla \epsilon \Phi$$

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = 0$$

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = 0$$

Substituting $$\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$$

Waveguiding

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Substituting $$\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$$

yields:

$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0$$

Waveguiding

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Substituting $$\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$$

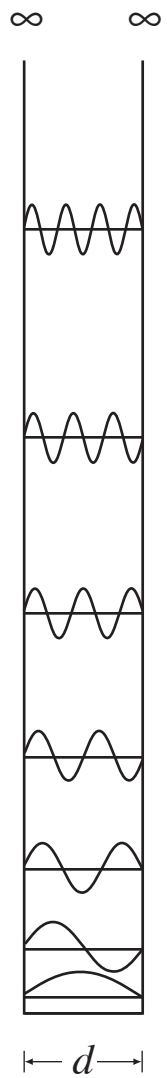
yields:

$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0$$

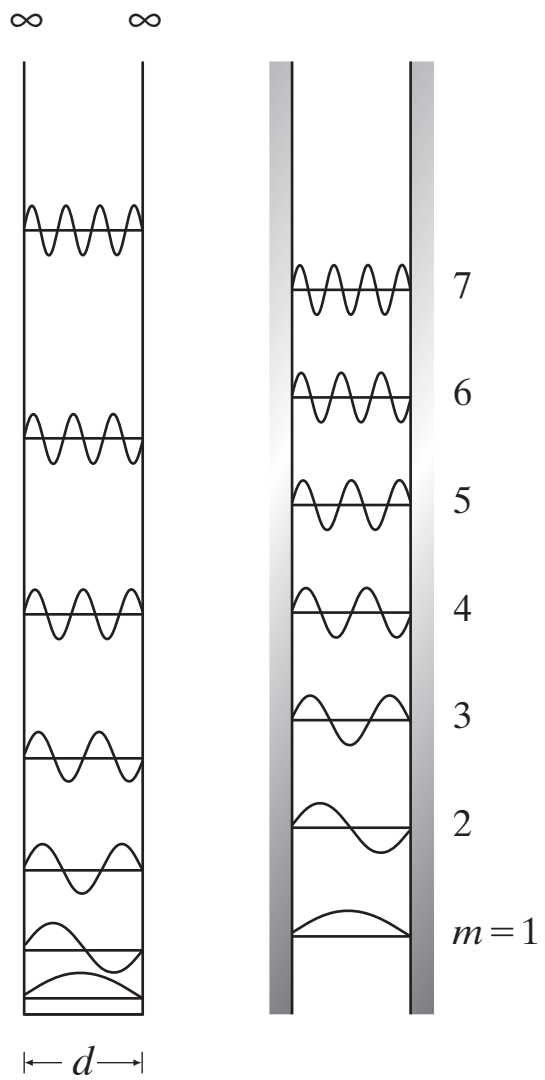
Compare to time-independent Schrödinger equation:

$$\nabla^2 \psi + \frac{2m}{\hbar^2}[E - V(r)]\psi = 0$$

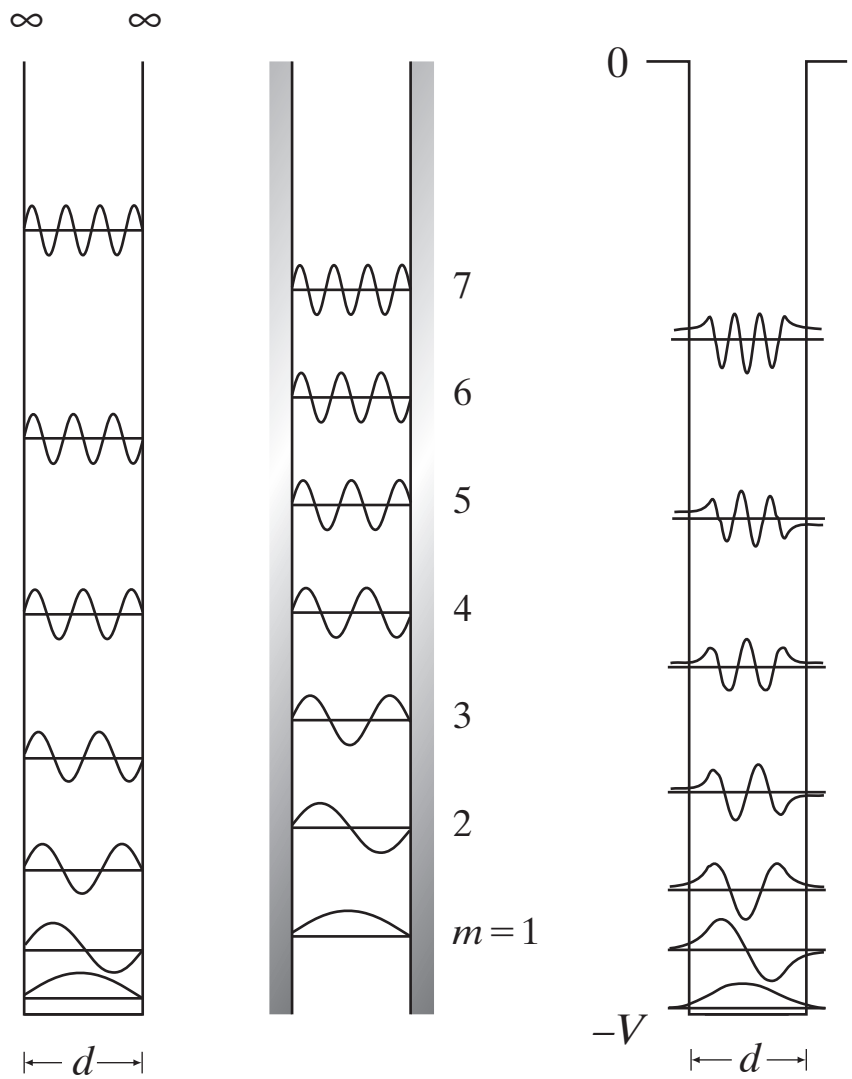
Waveguiding



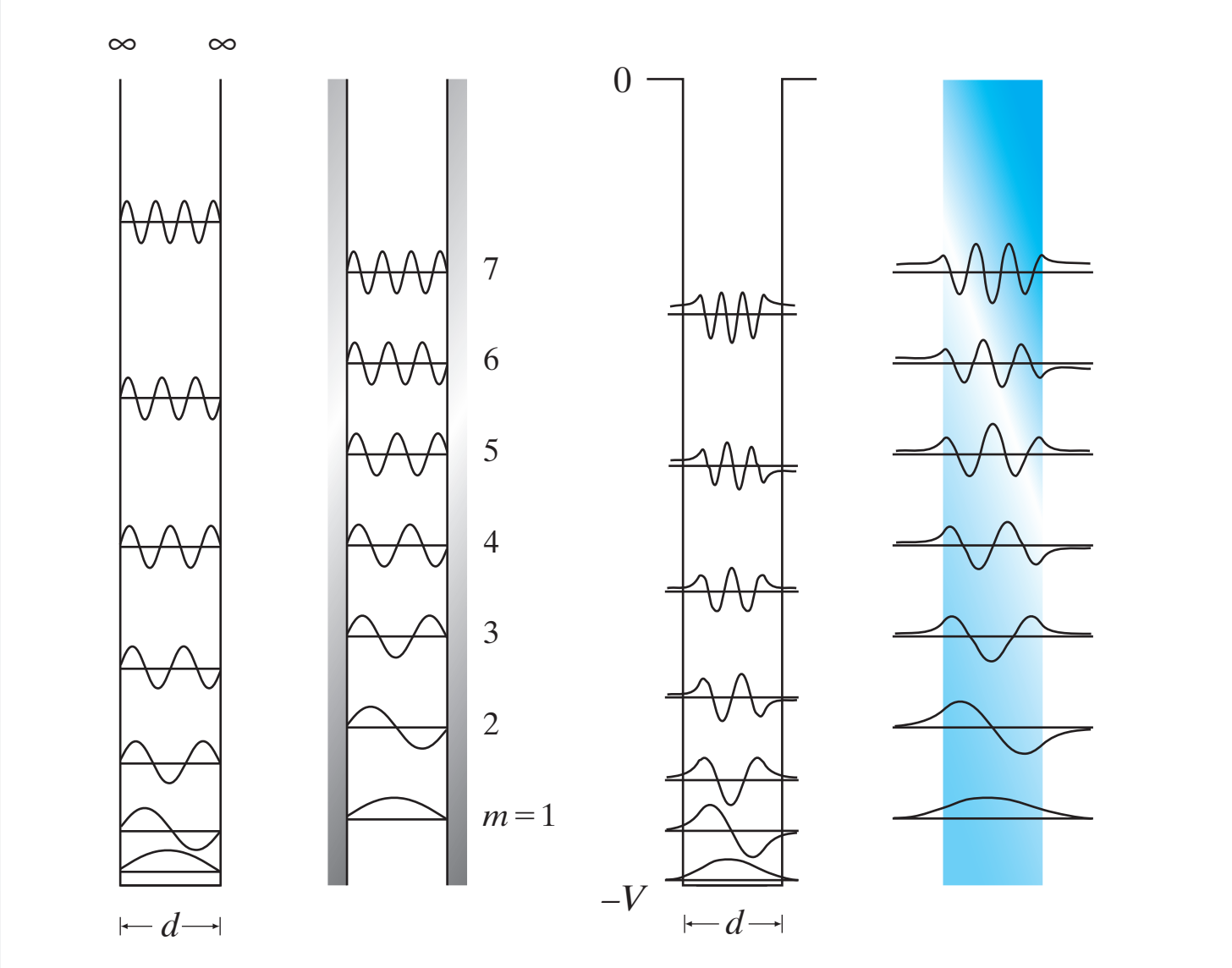
Waveguiding



Waveguiding



Waveguiding



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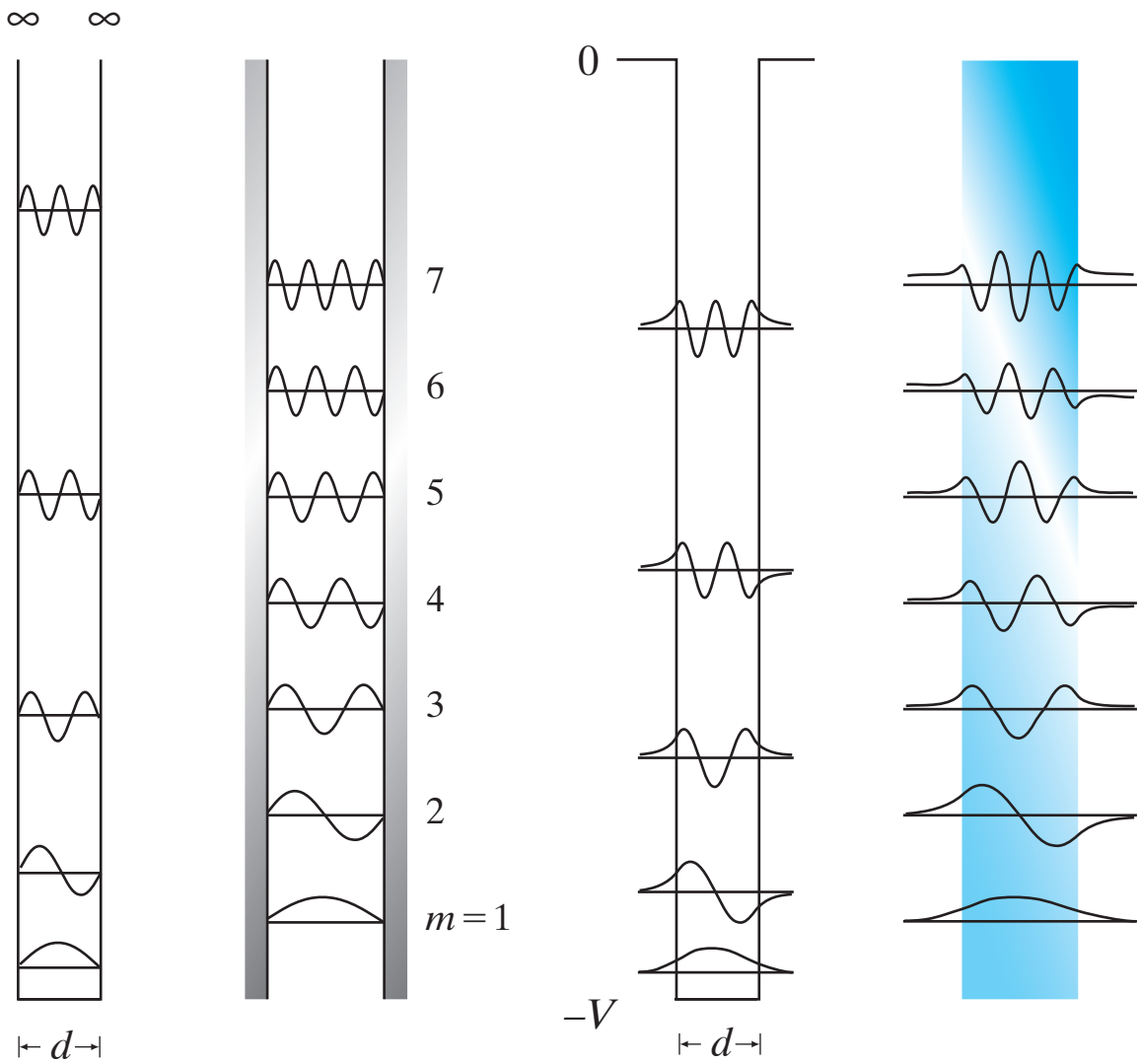
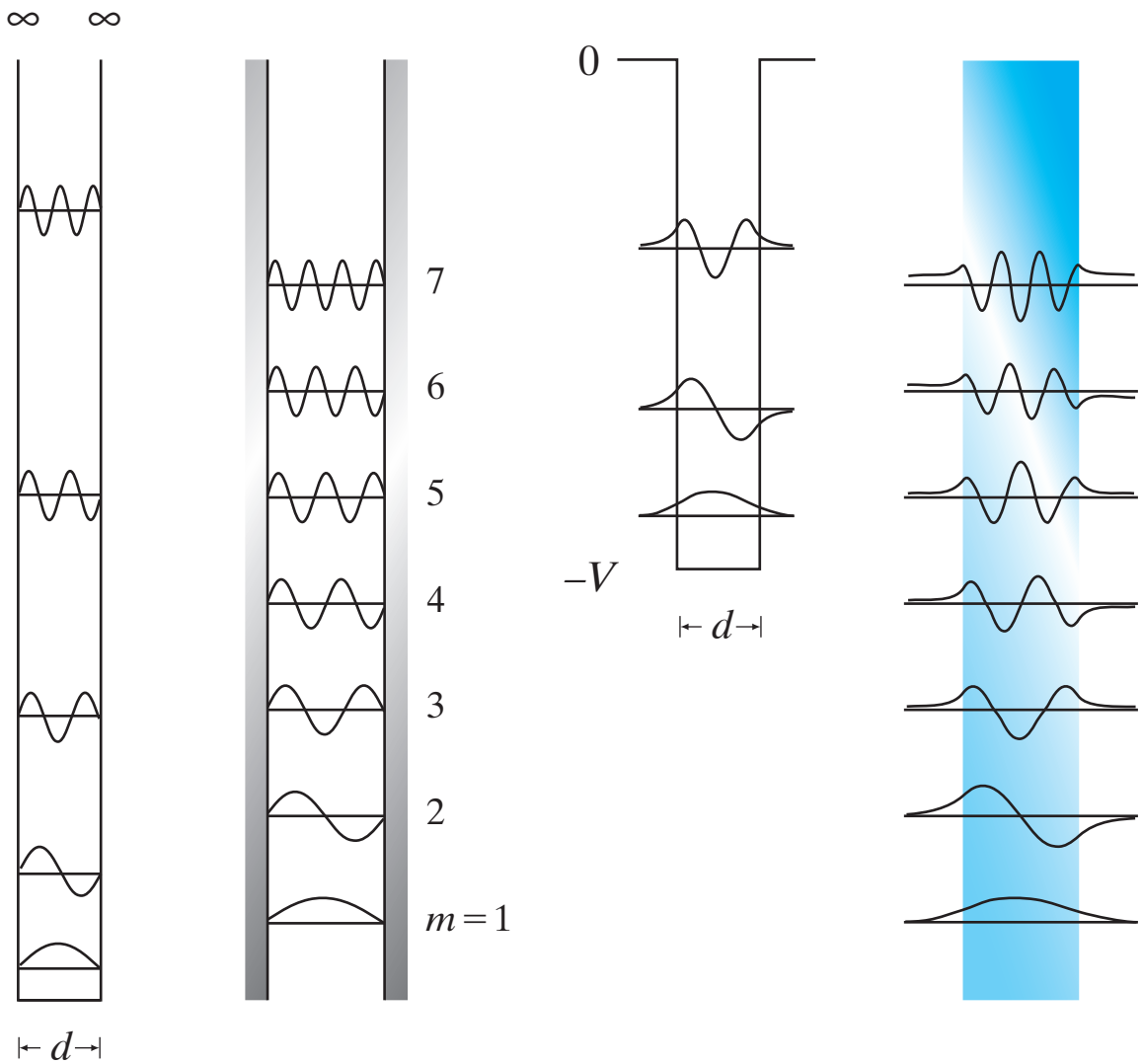
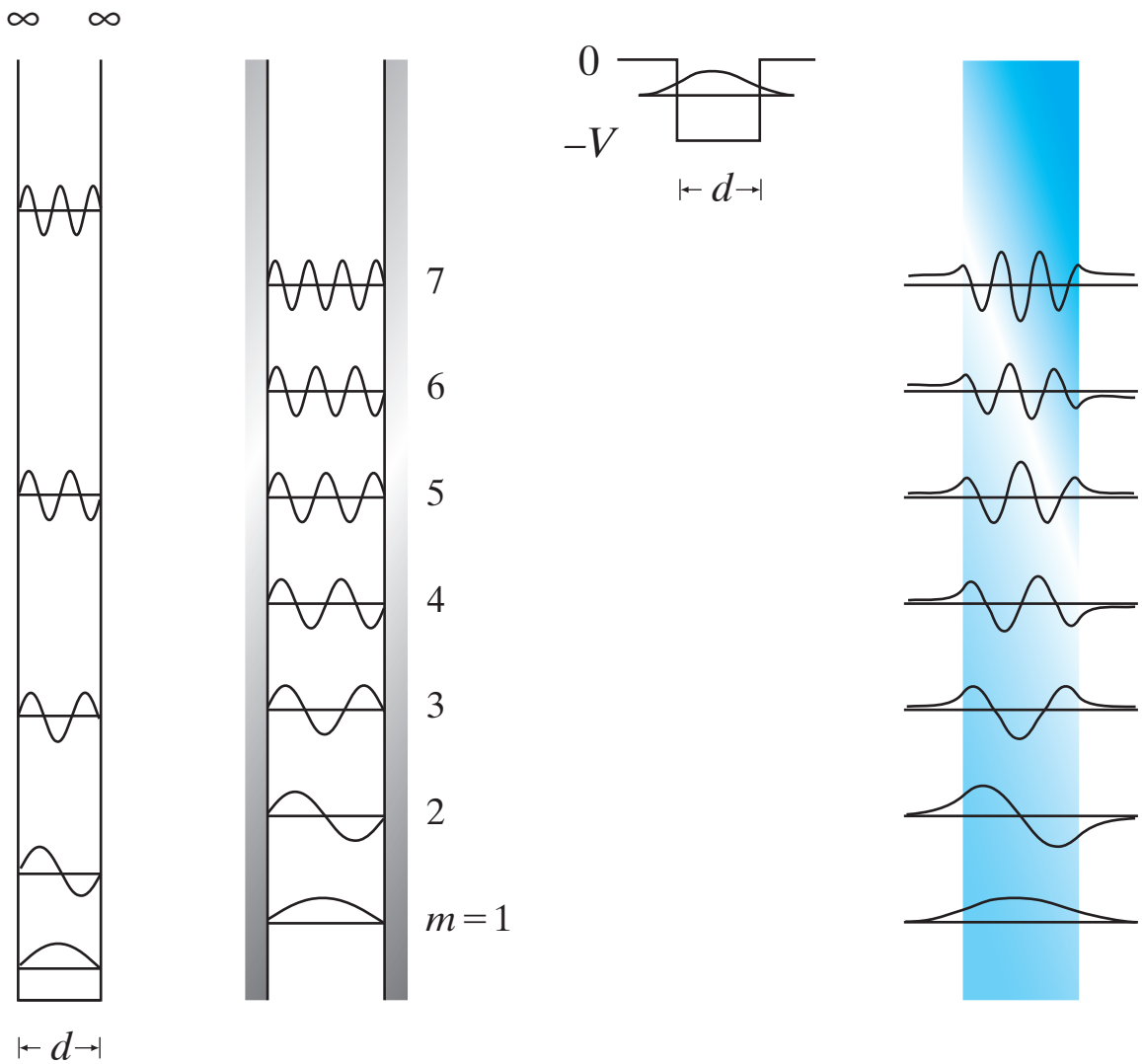


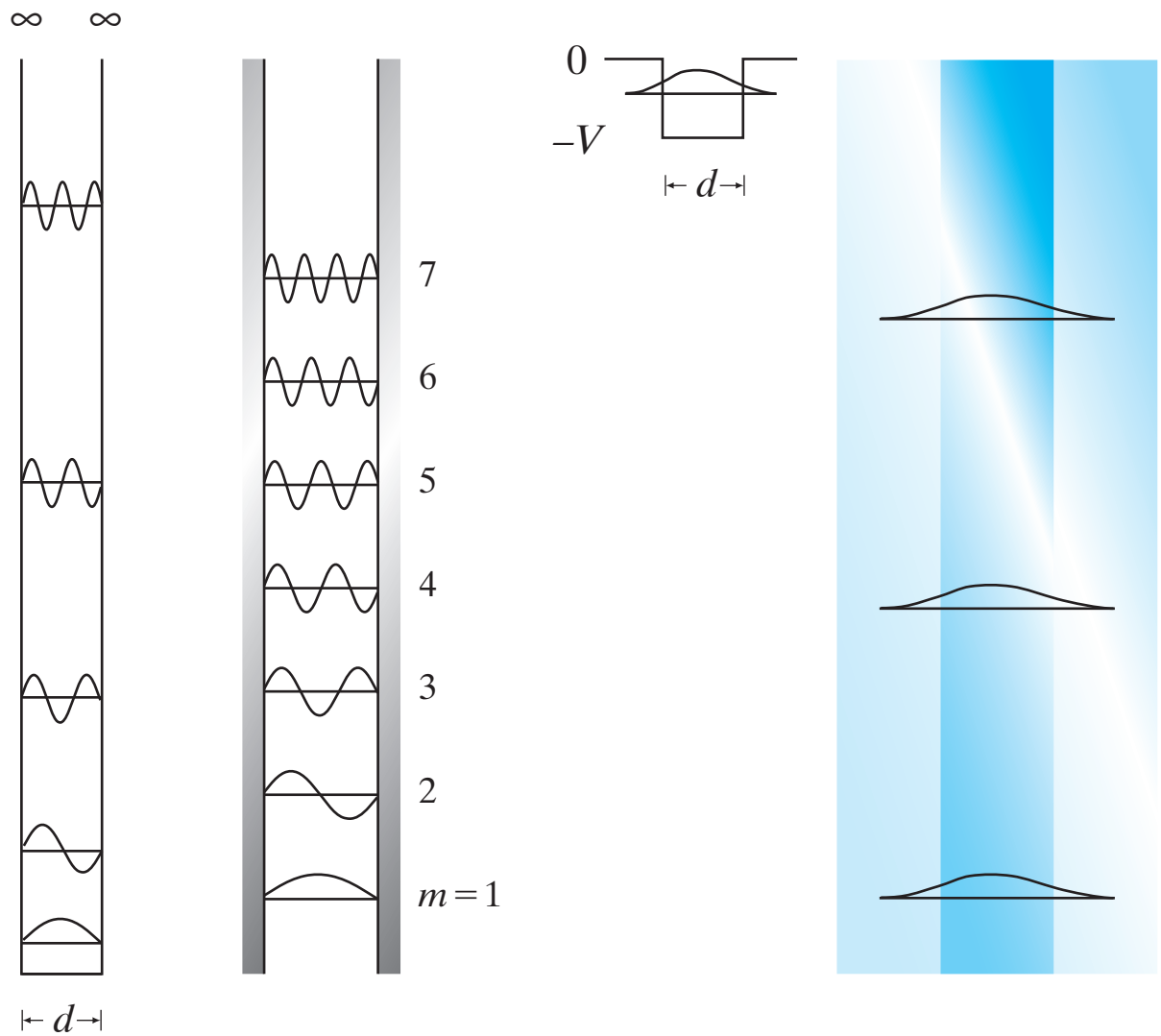
Waveguiding



Waveguiding



Waveguiding



Waveguiding

single mode condition for 600-nm light:

$$M \doteq 2\,\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$$

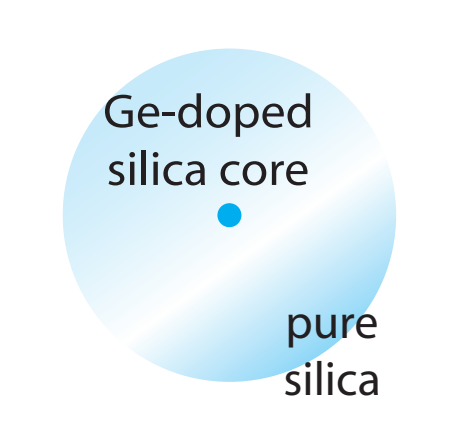
without cladding: $d < 268\ \mathrm{nm}$

Add cladding with 0.4% index difference:

$$d < 5\ \mu\mathrm{m}$$

Waveguiding

commercial single-mode fiber (Corning Titan®)



	core	cladding
index	$n_1 = 1.468$	$n_2 = 1.462$
diameter:	$8.3\ \mu\text{m}$	$125.0 \pm 1.0\ \mu\text{m}$

operating wavelength: $\lambda = 1310\ \text{nm}/1550\ \text{nm}$

Waveguiding

drawbacks of clad fibers:

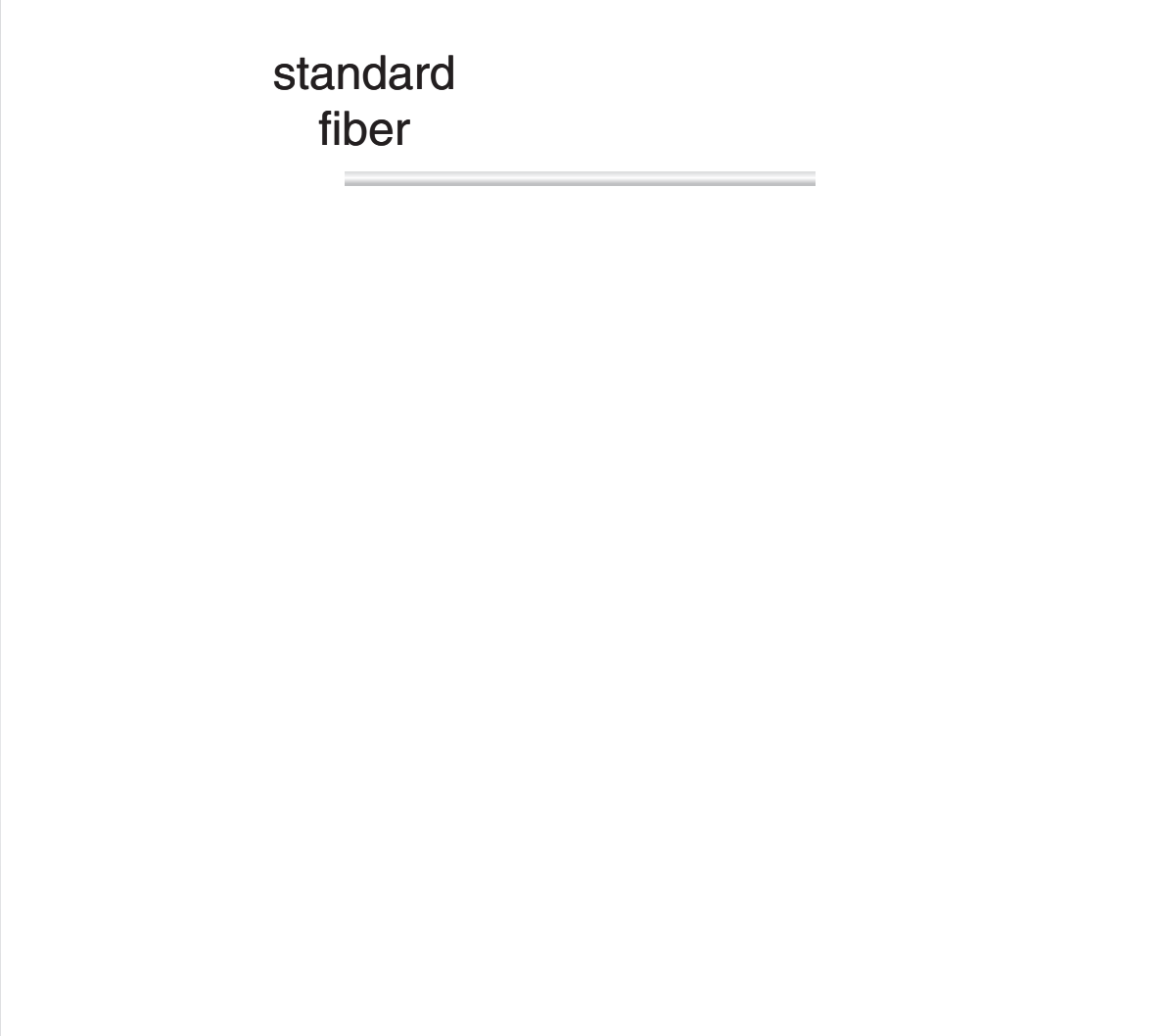
- weak confinement
- no tight bending
- coupling requires splicing

Outline

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

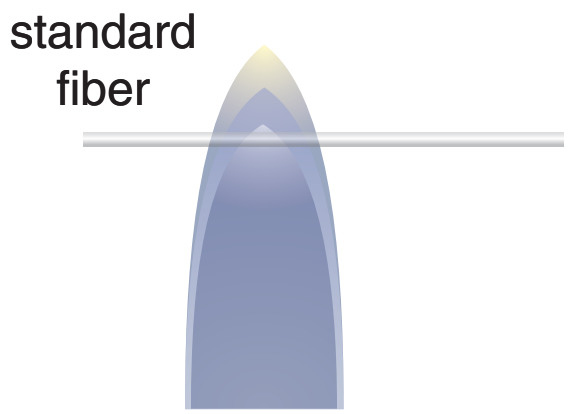
Silica nanowires

two-step drawing process



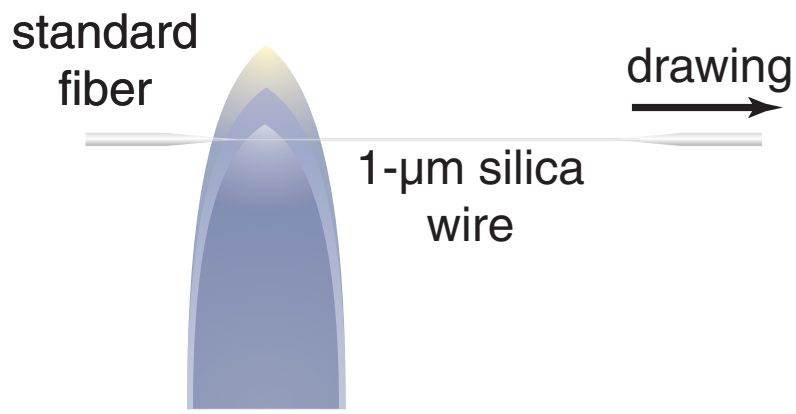
Silica nanowires

two-step drawing process



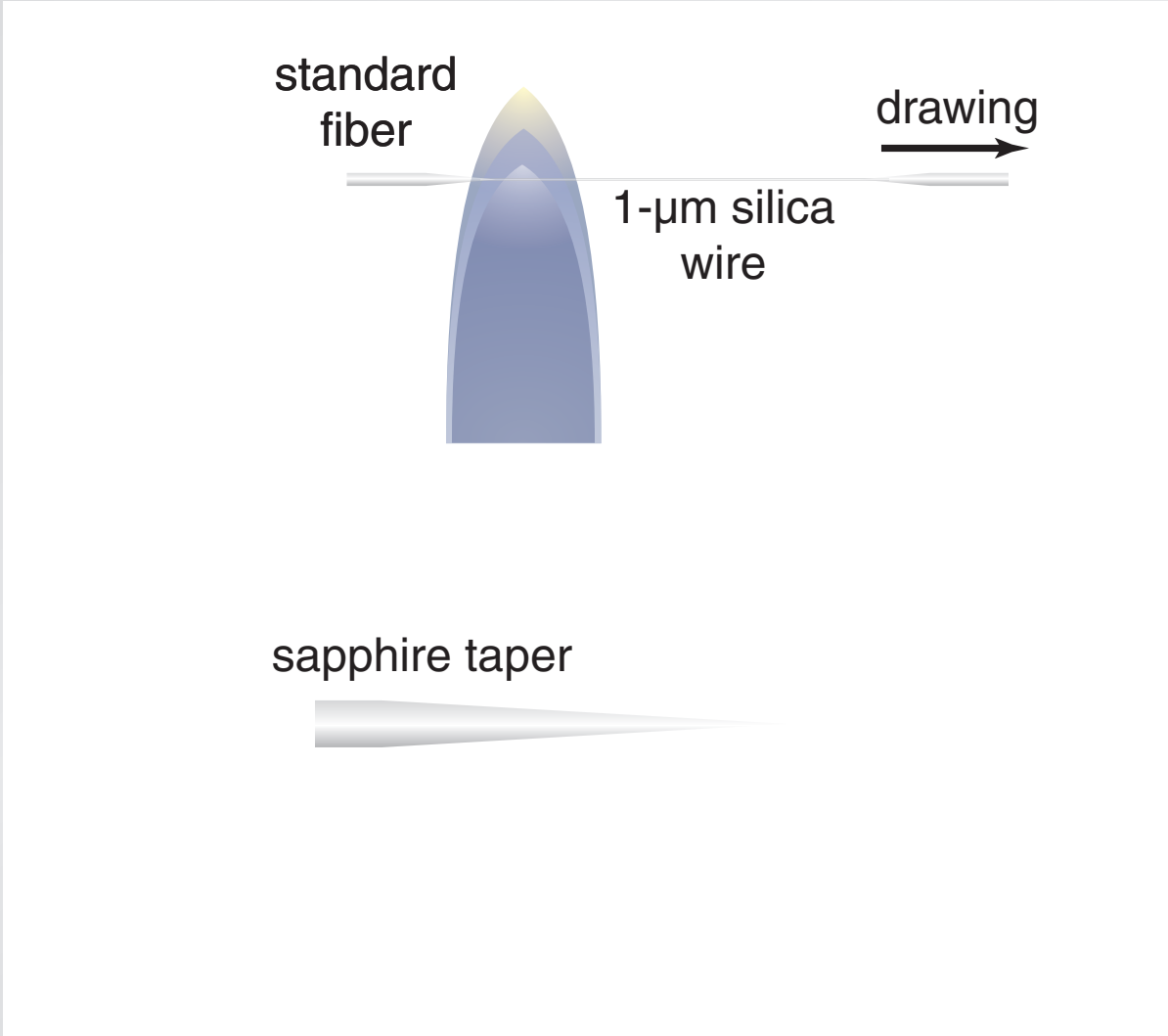
Silica nanowires

two-step drawing process



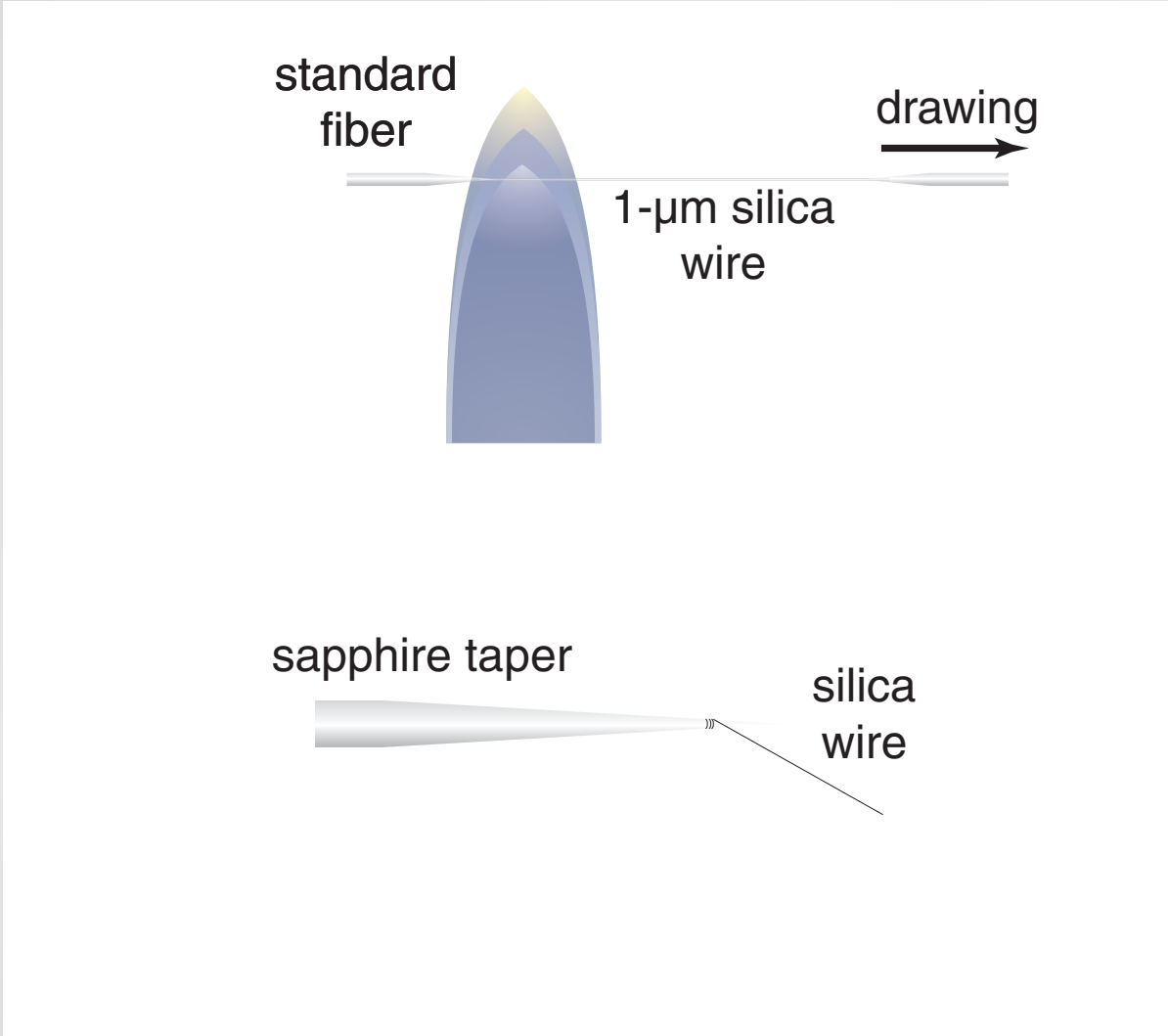
Silica nanowires

two-step drawing process



Silica nanowires

two-step drawing process



Silica nanowires

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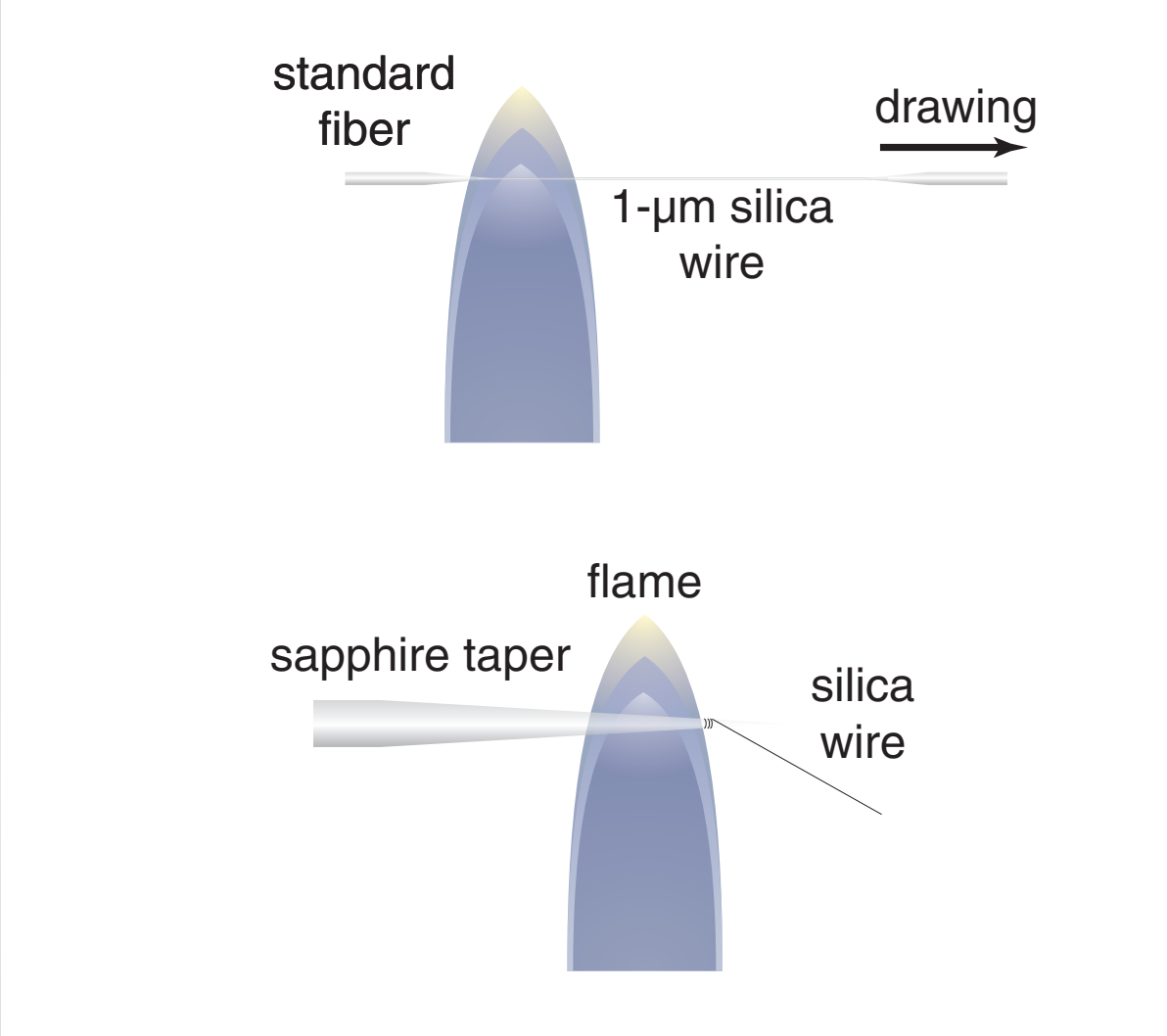
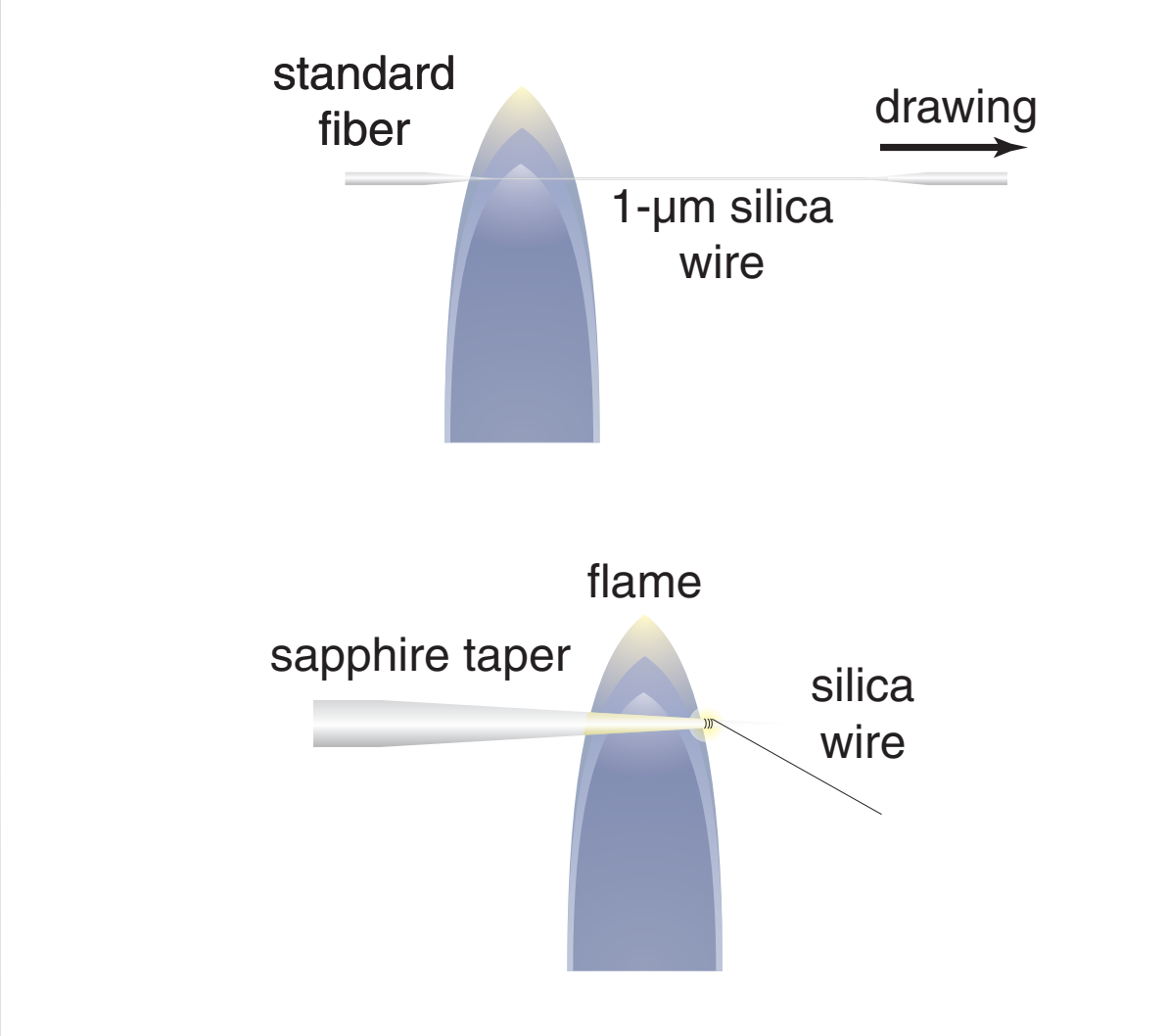


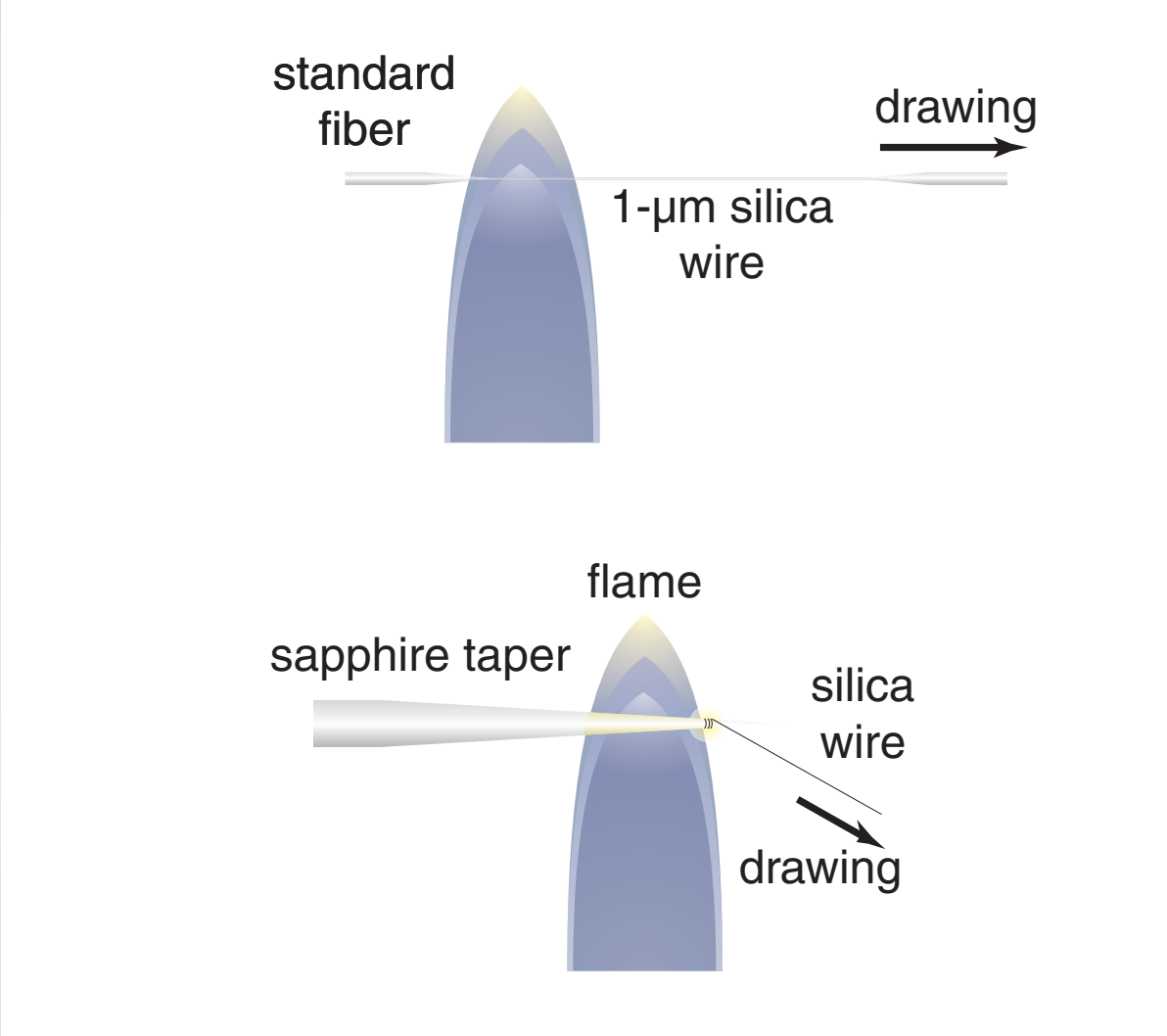
Silica nanowires

two-step drawing process

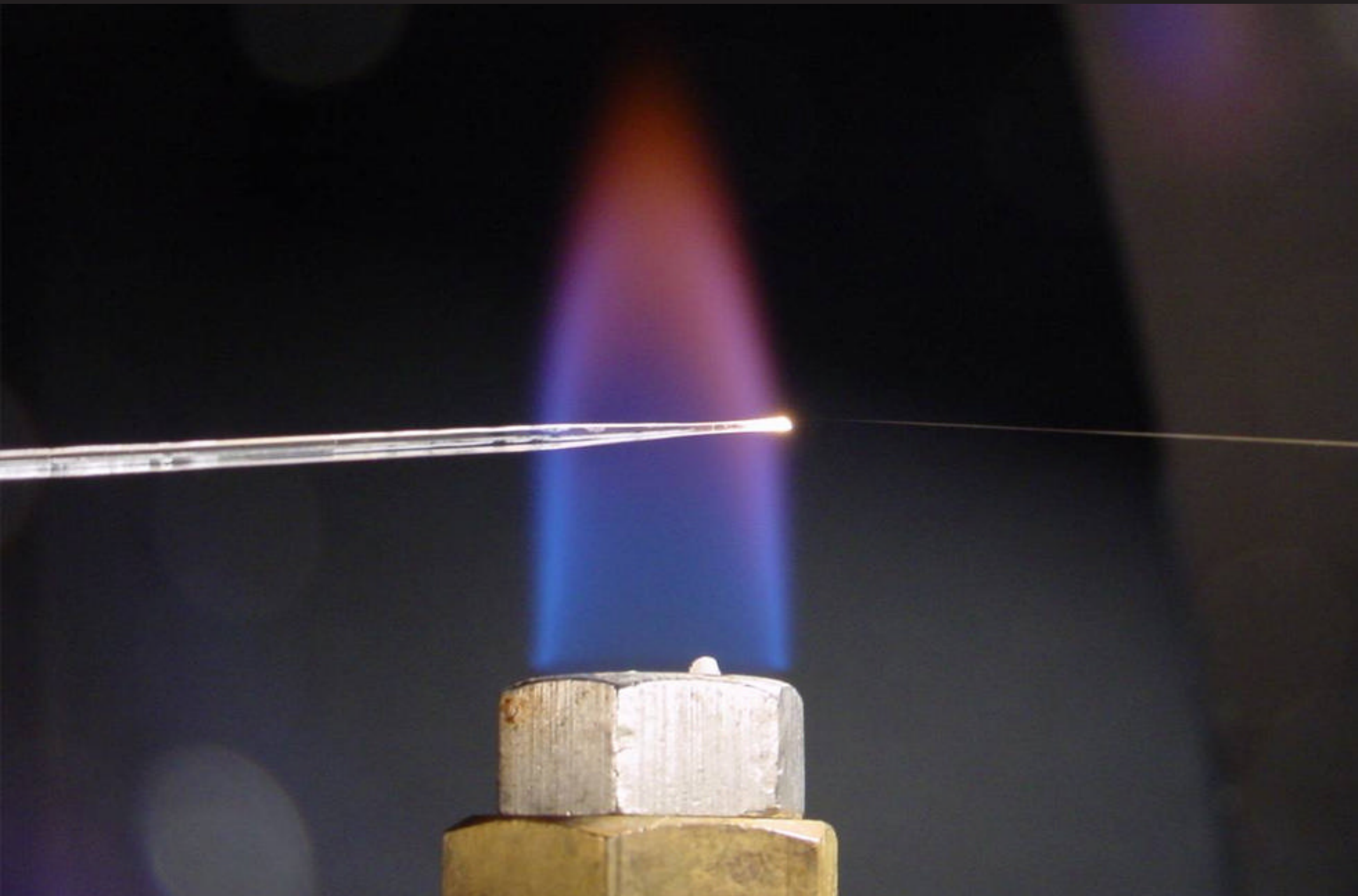


Silica nanowires

two-step drawing process



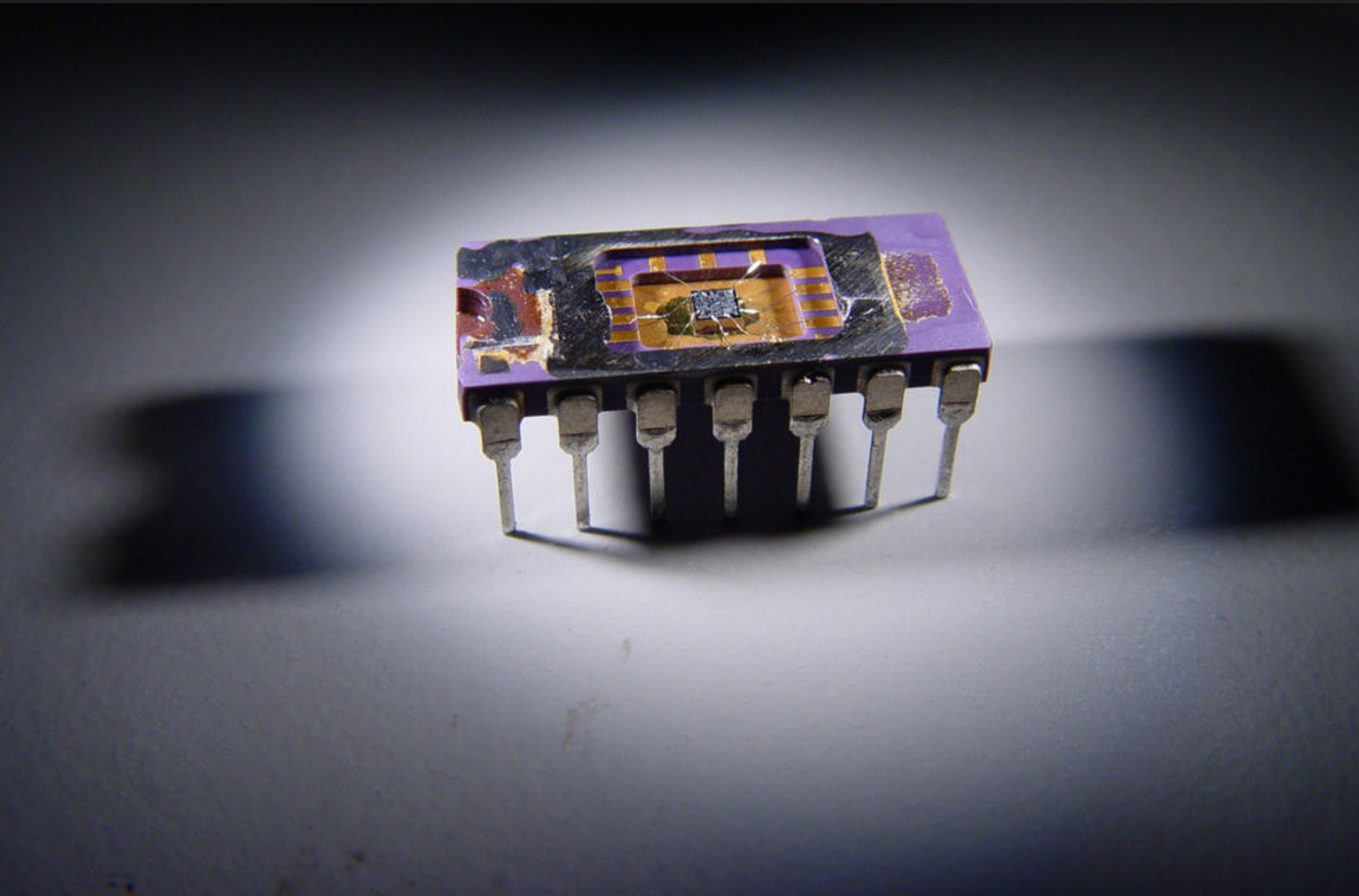
Silica nanowires



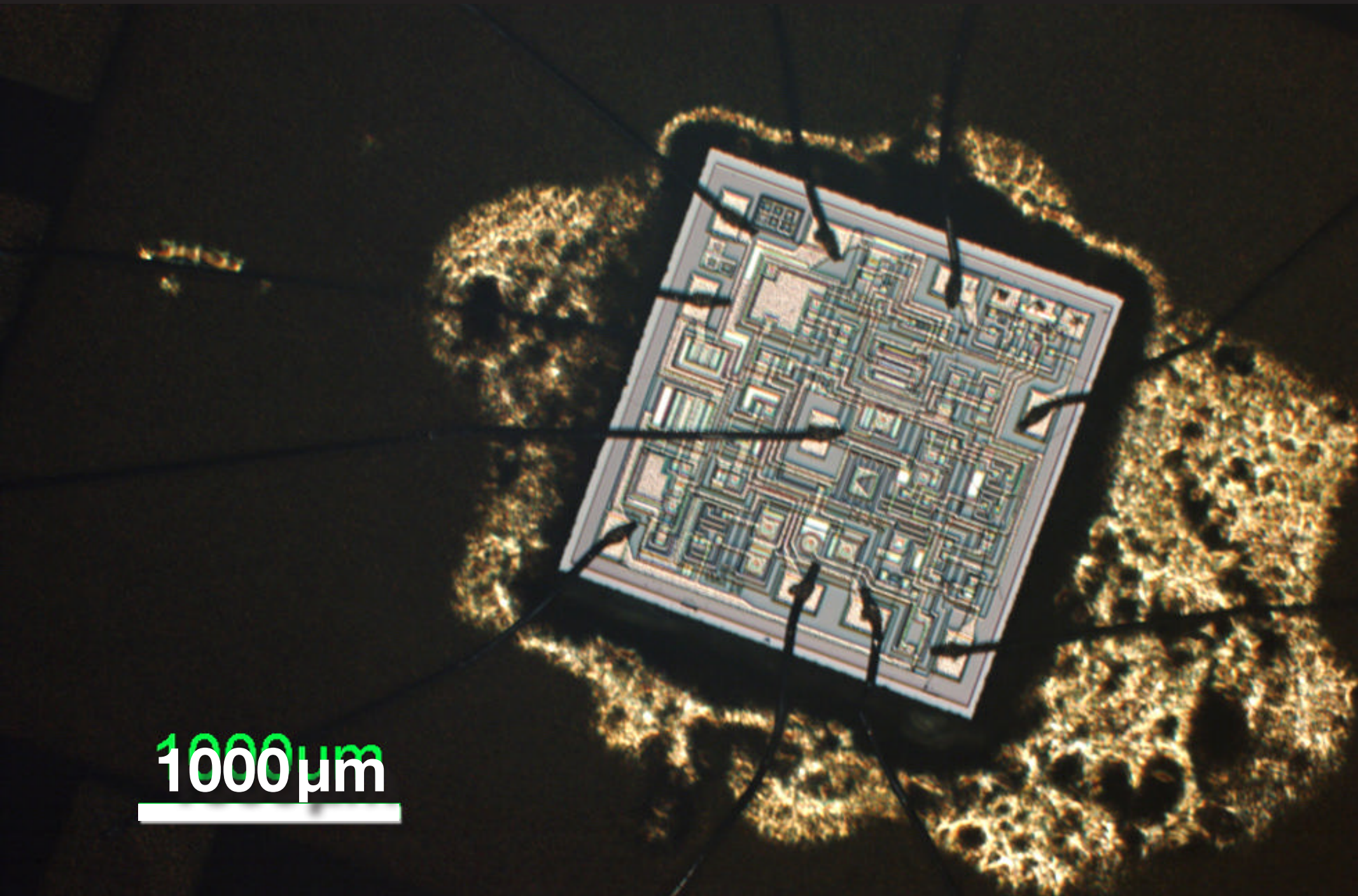
Silica nanowires

Nature, 426, 816 (2003)

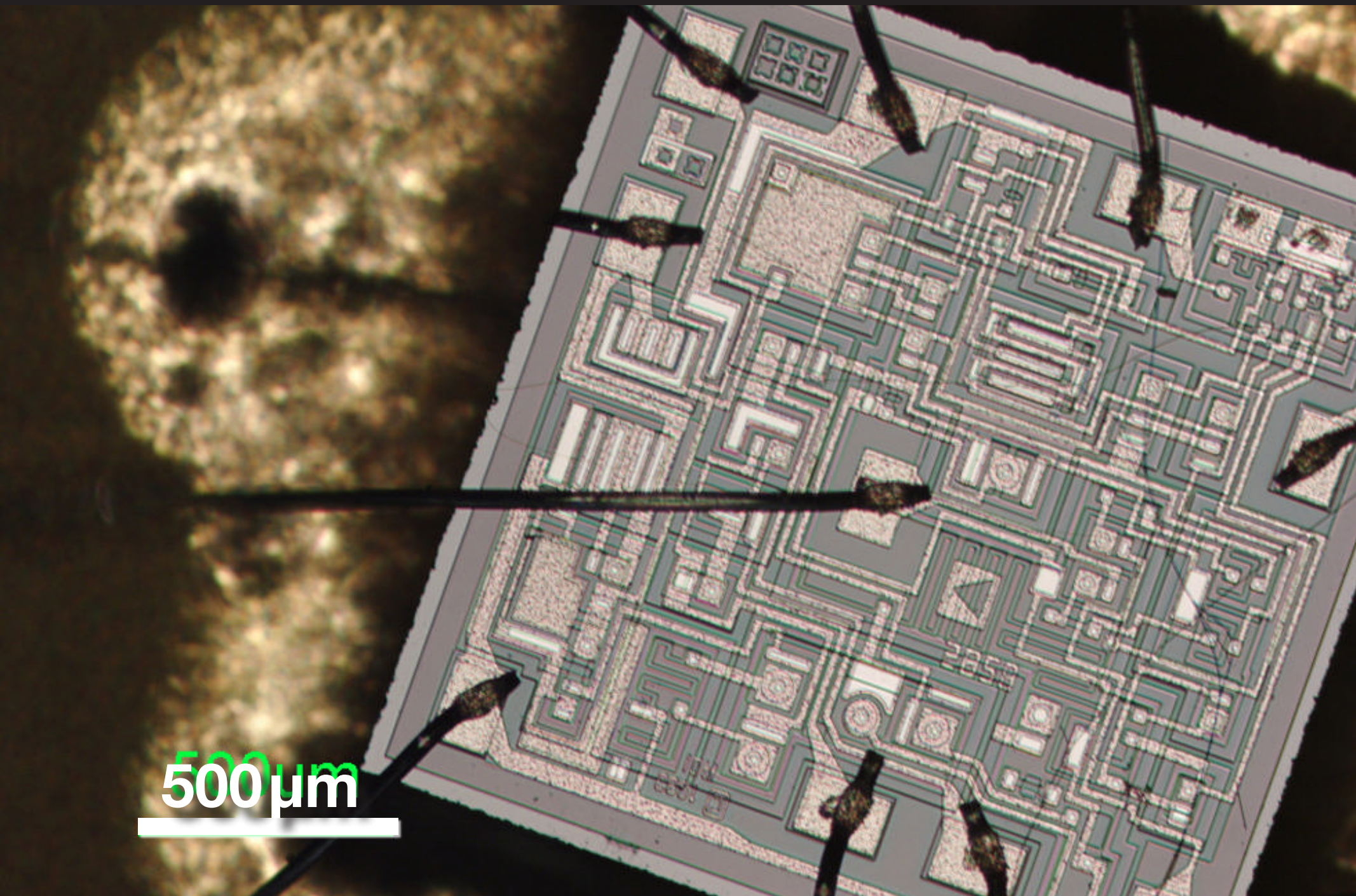
Silica nanowires



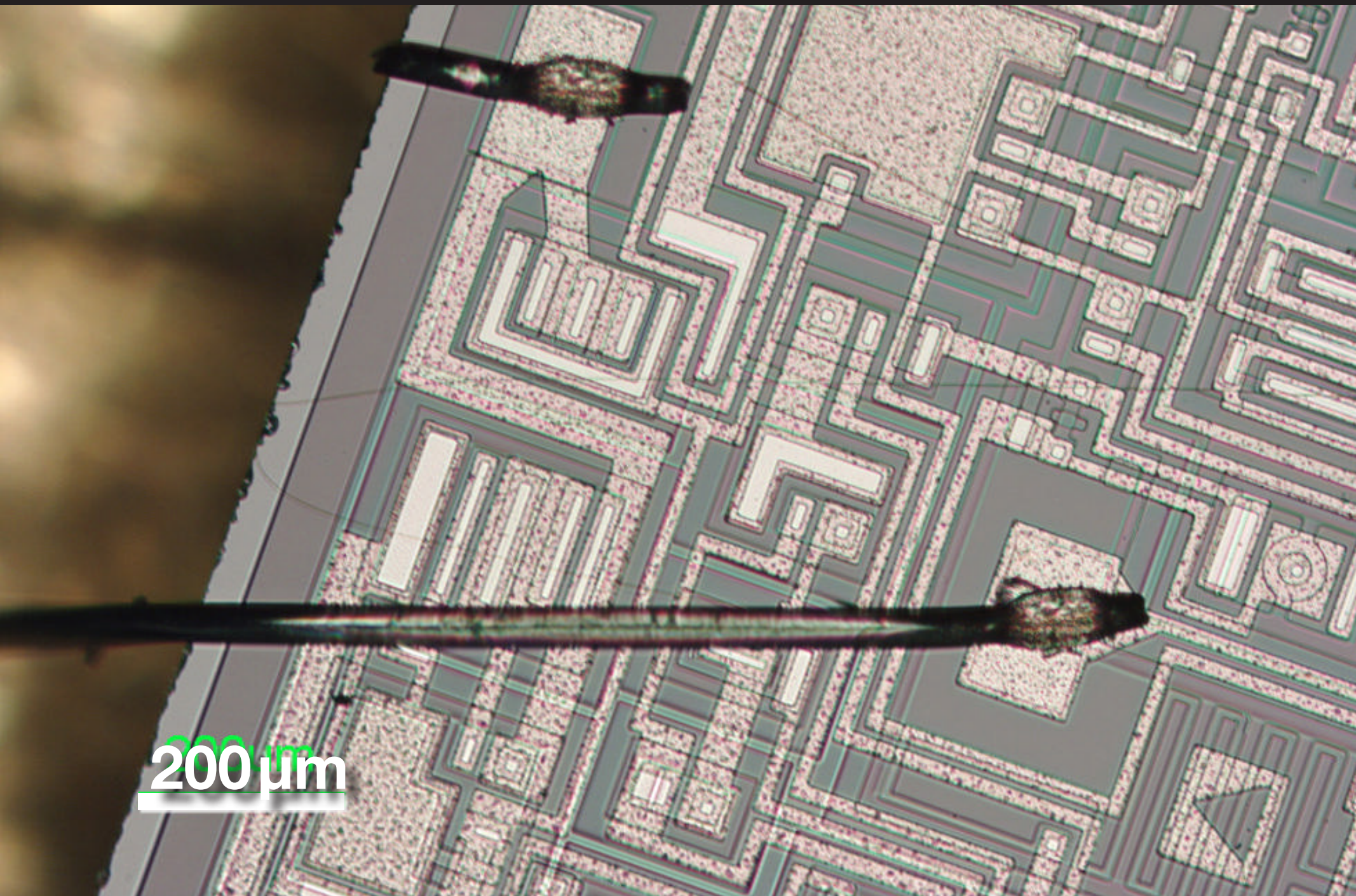
Silica nanowires



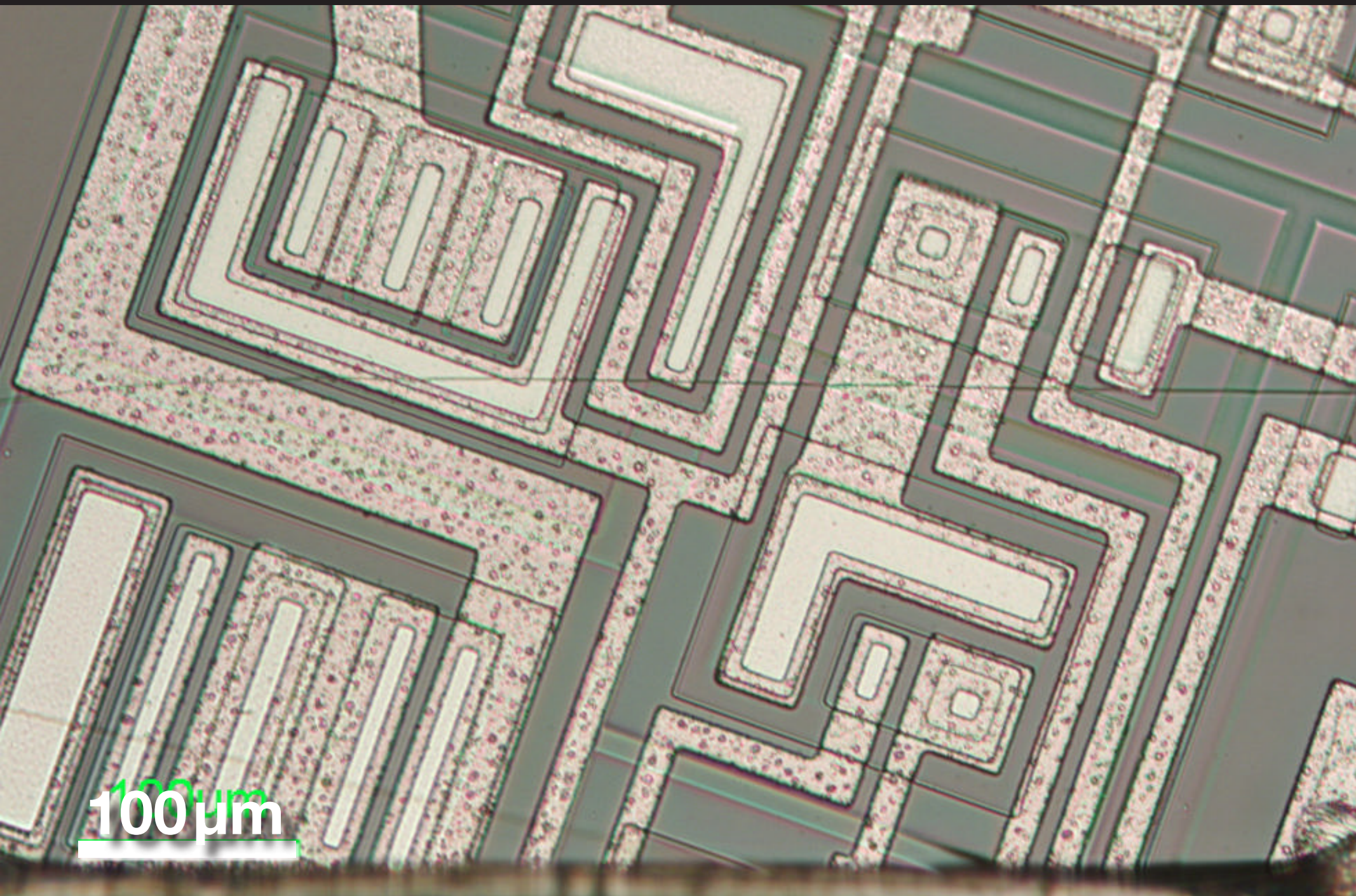
Silica nanowires



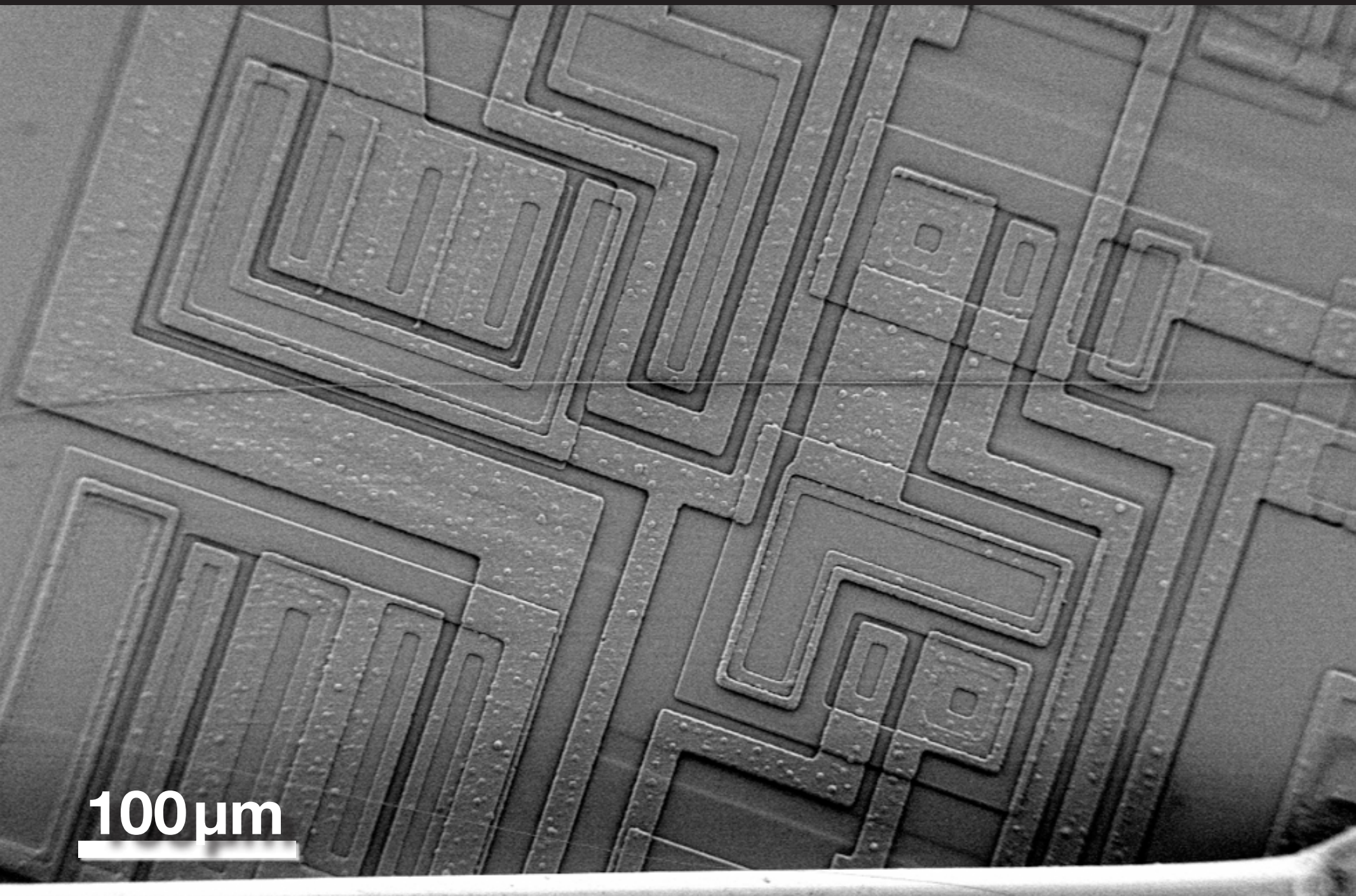
Silica nanowires



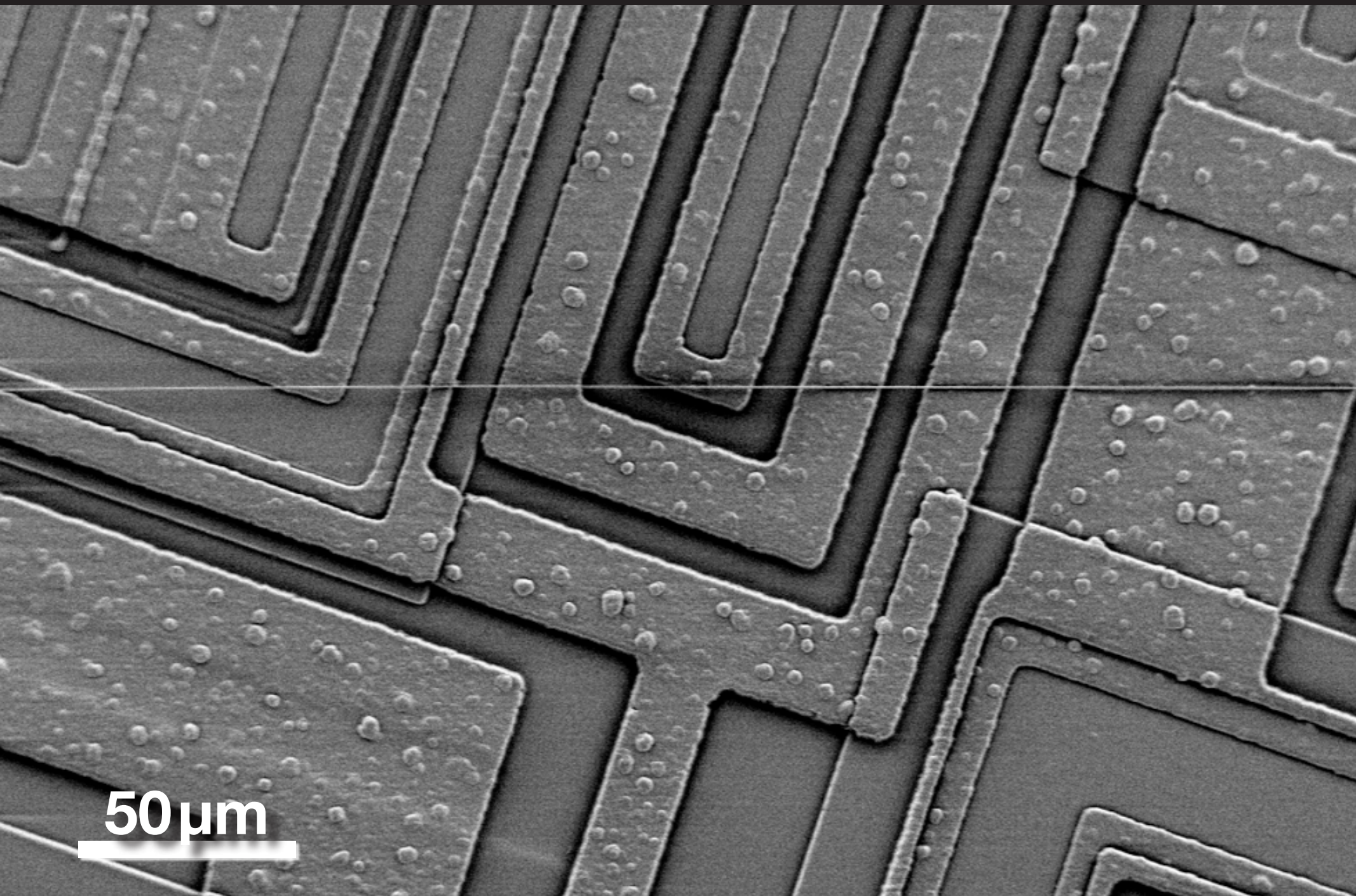
Silica nanowires



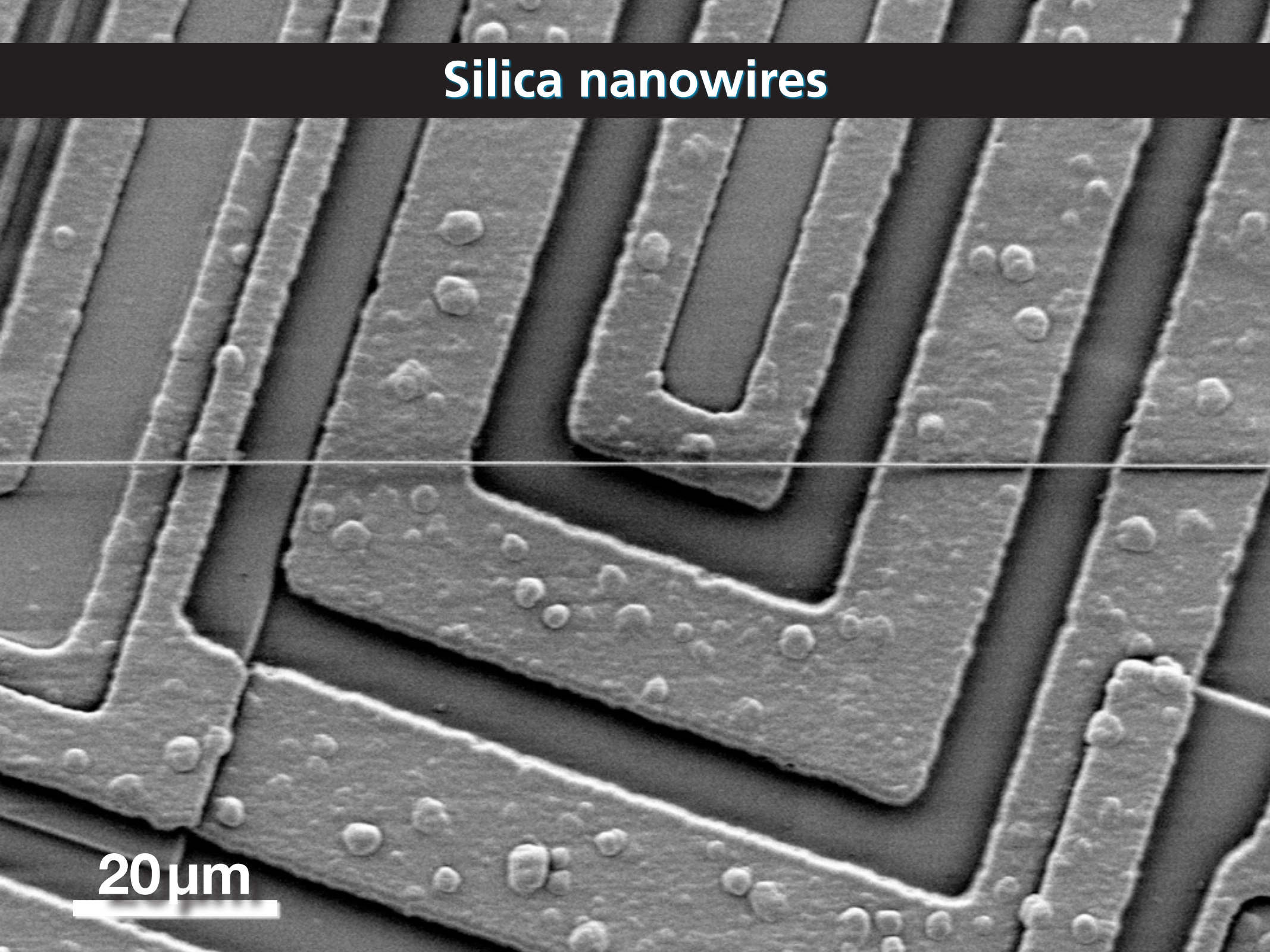
Silica nanowires



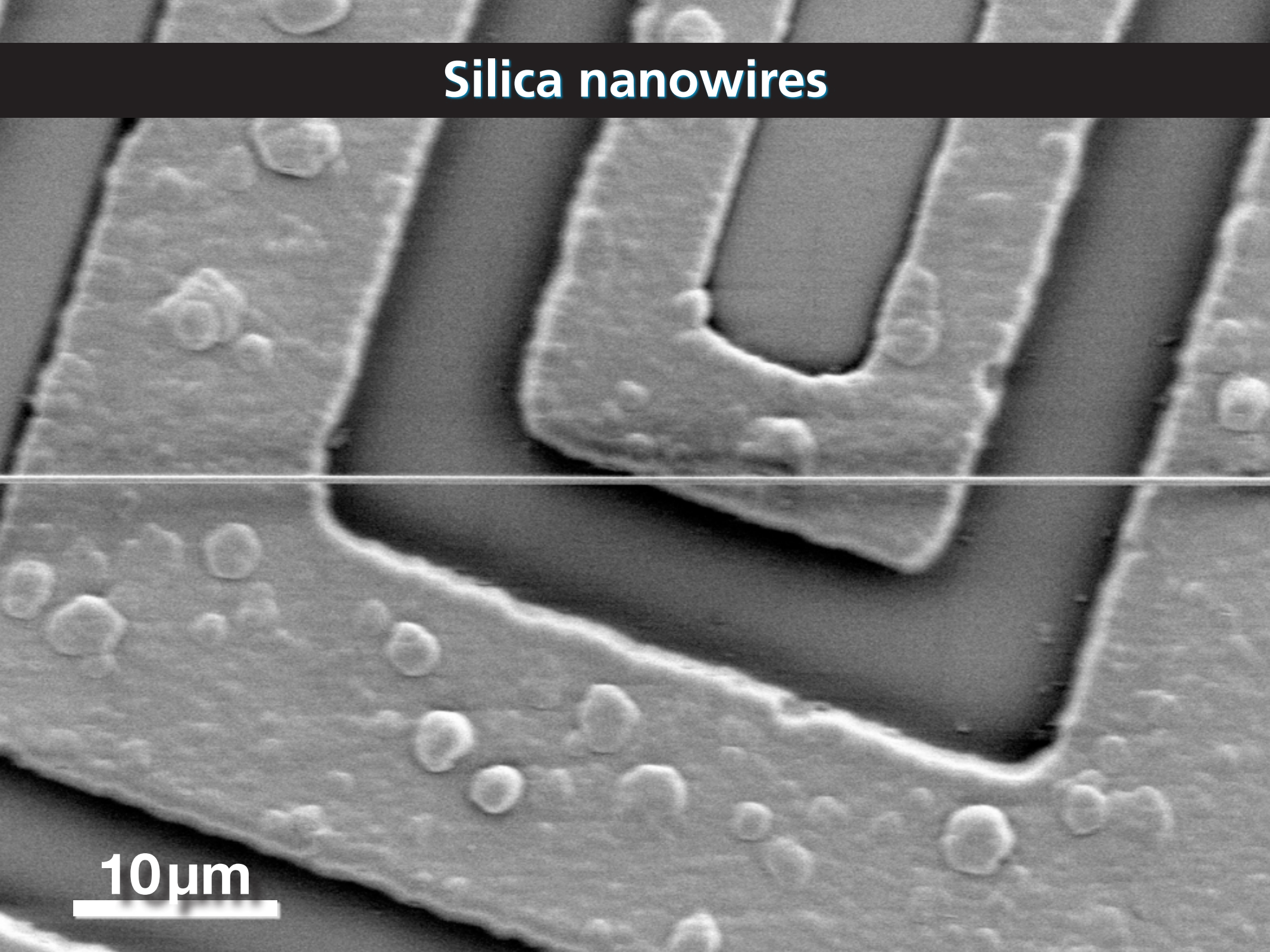
Silica nanowires



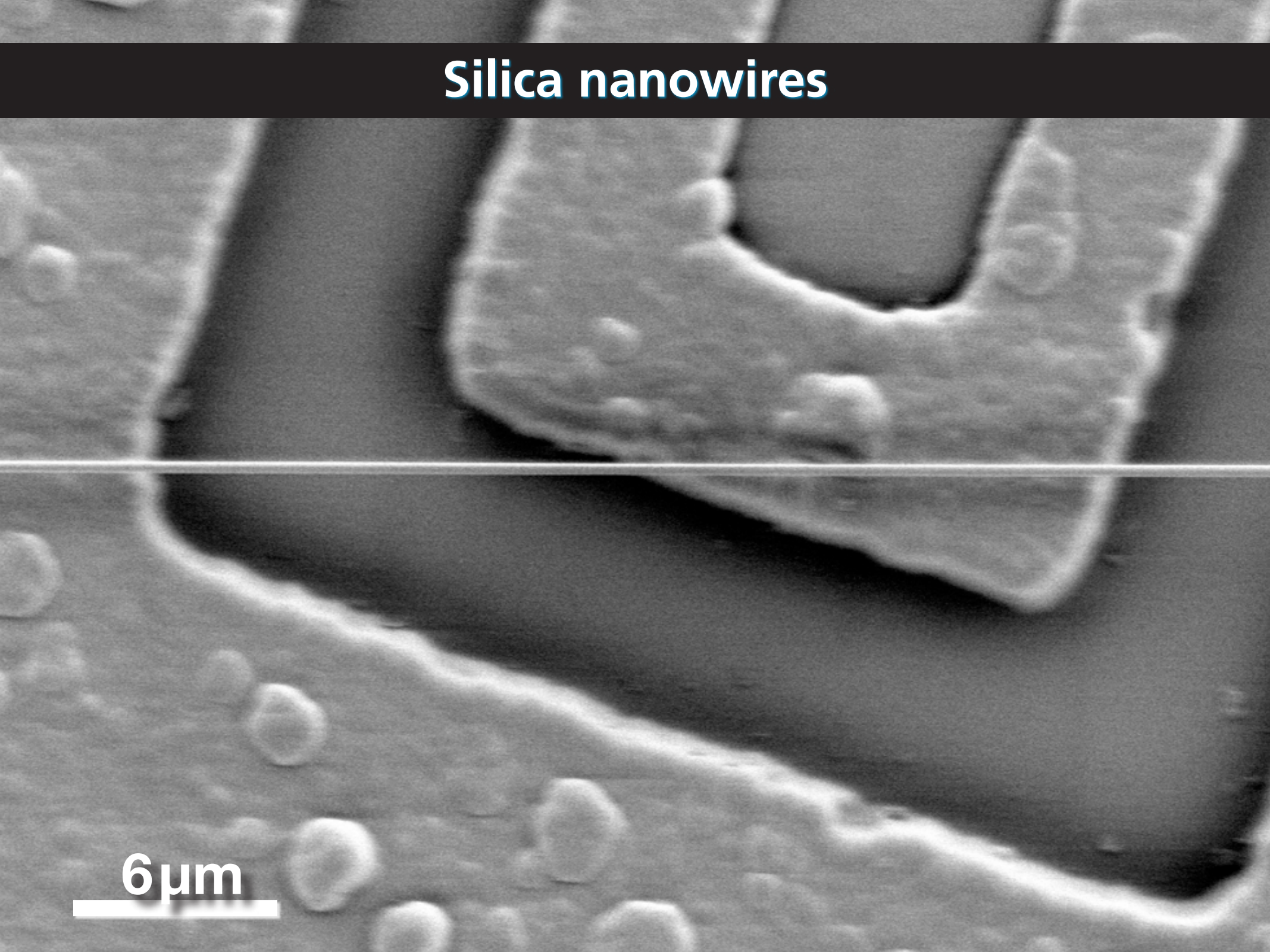
Silica nanowires



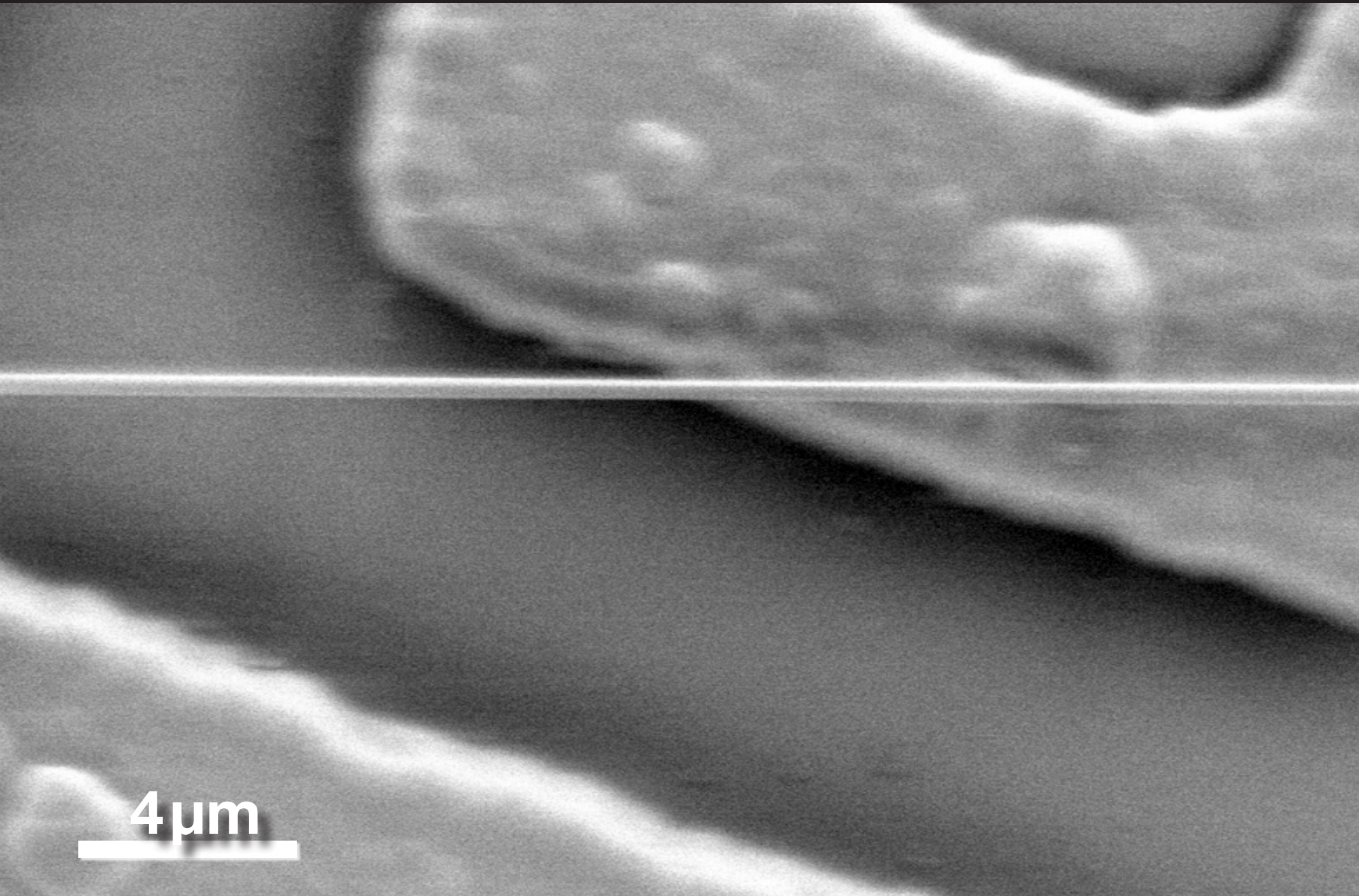
Silica nanowires



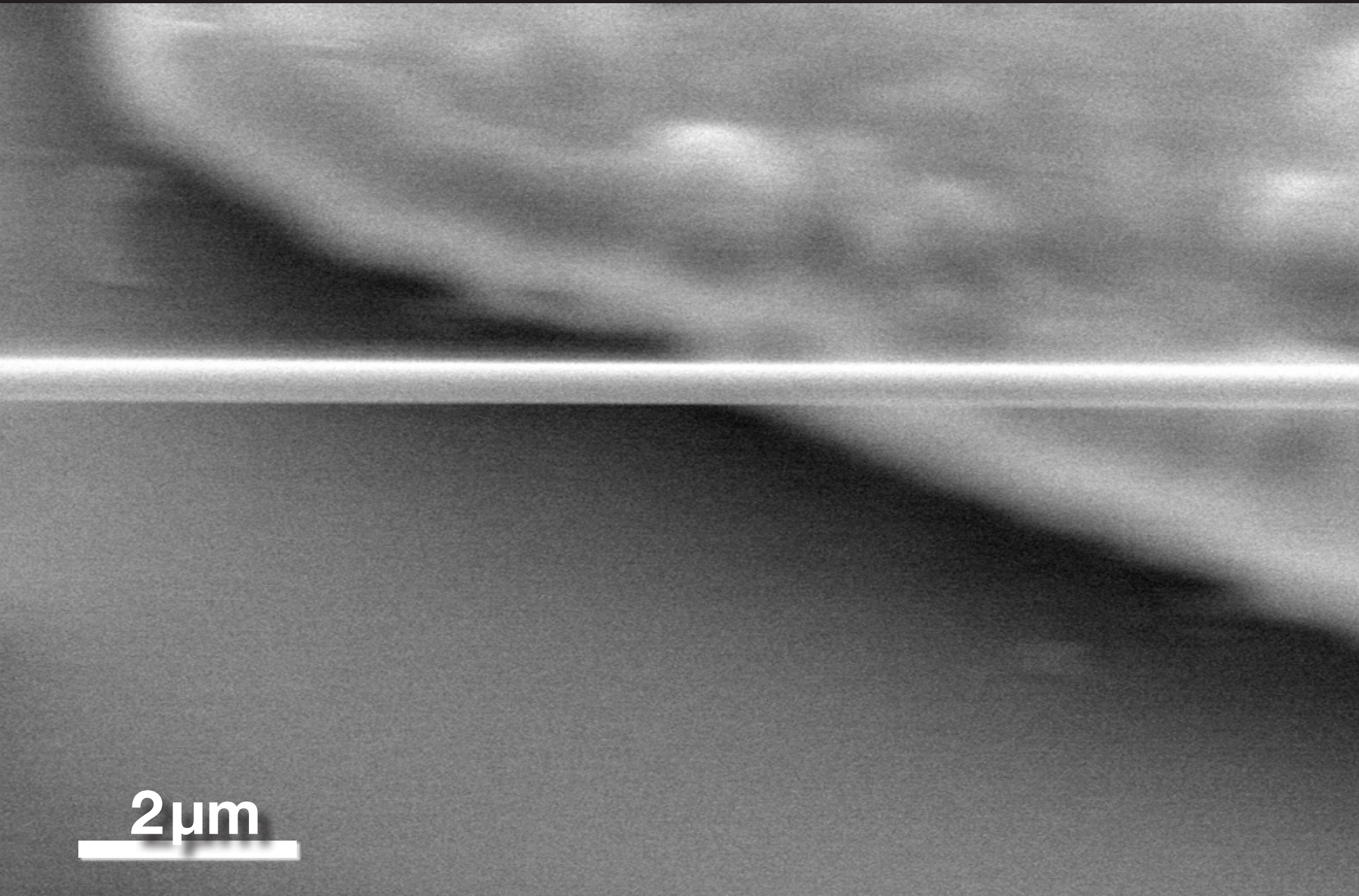
Silica nanowires



Silica nanowires



Silica nanowires



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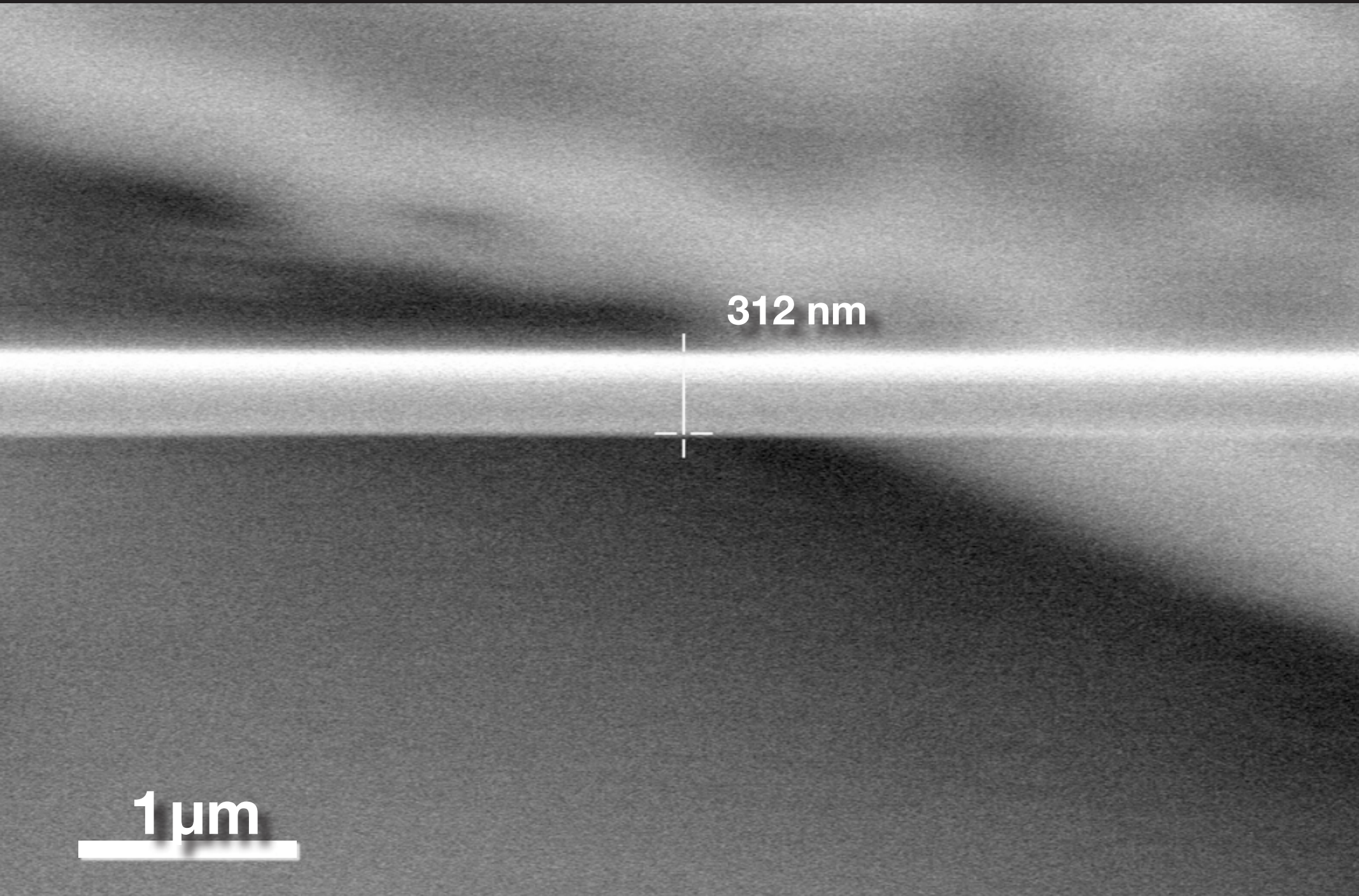


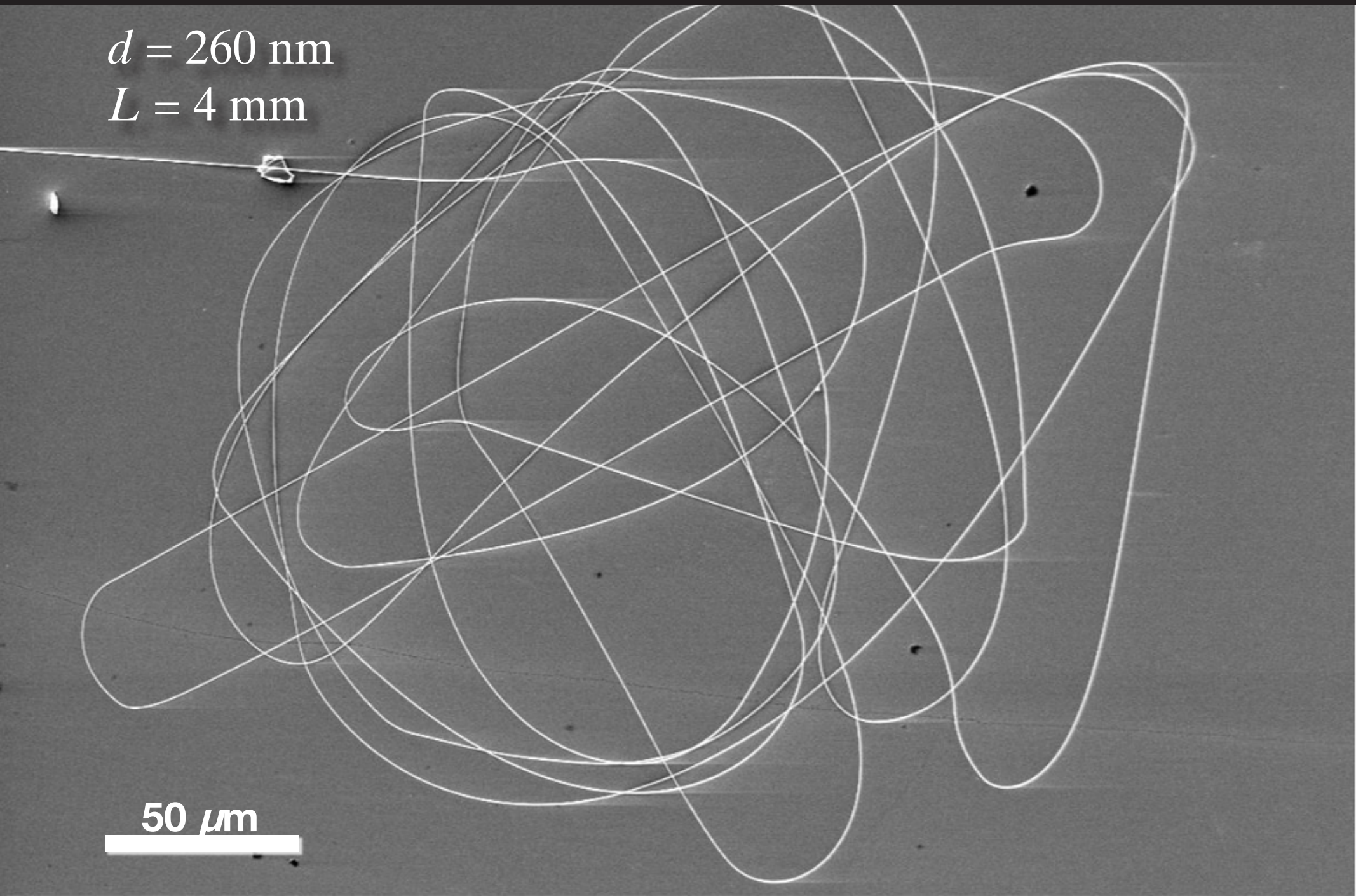
Silica nanowires

Specifications

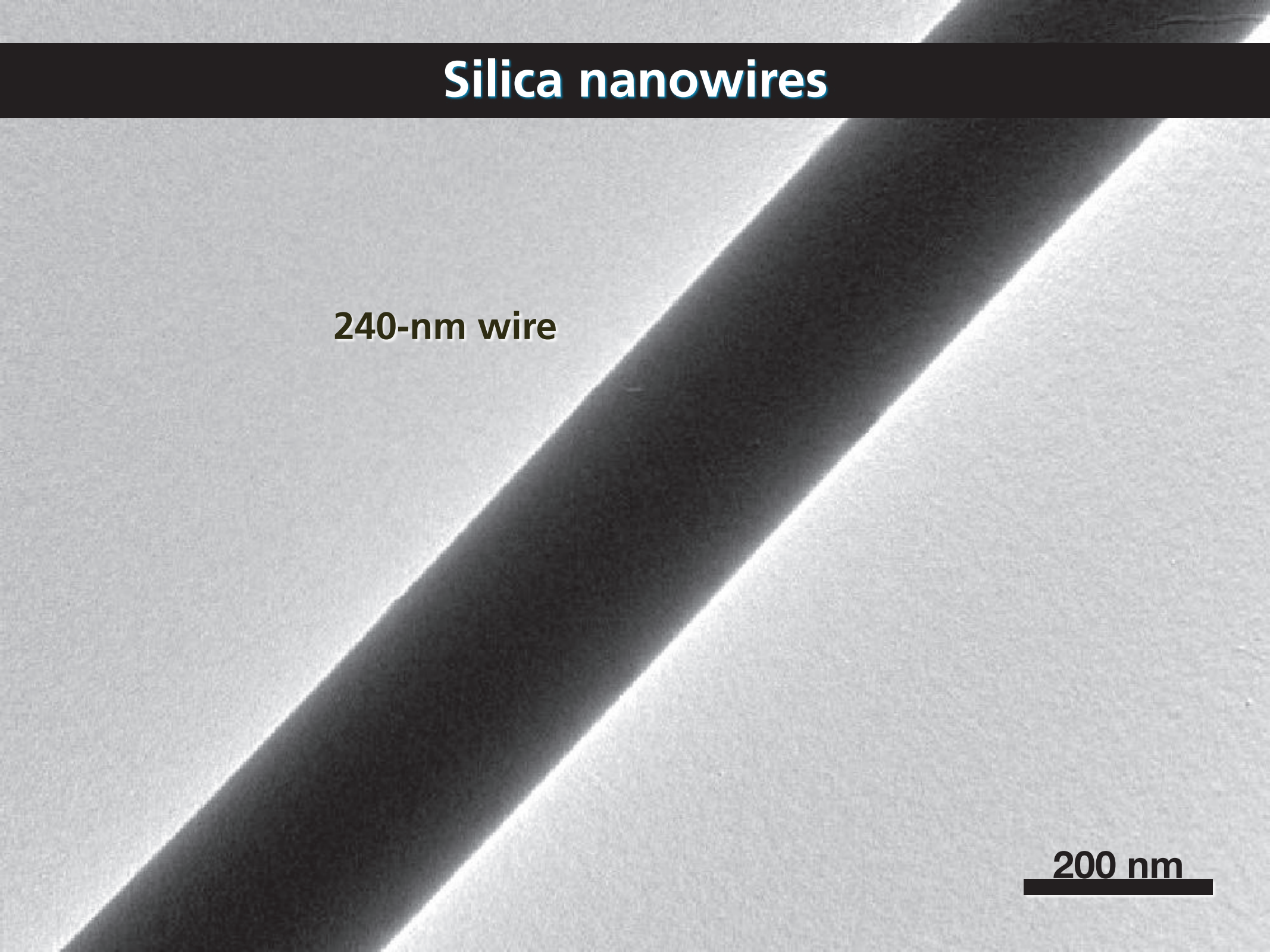
diameter D:	down to 20 nm
length L:	up to 90 mm
aspect ratio D/L:	up to 10^6
diameter uniformity $\Delta D/L$:	2×10^{-6}

Nature, 426, 816 (2003)

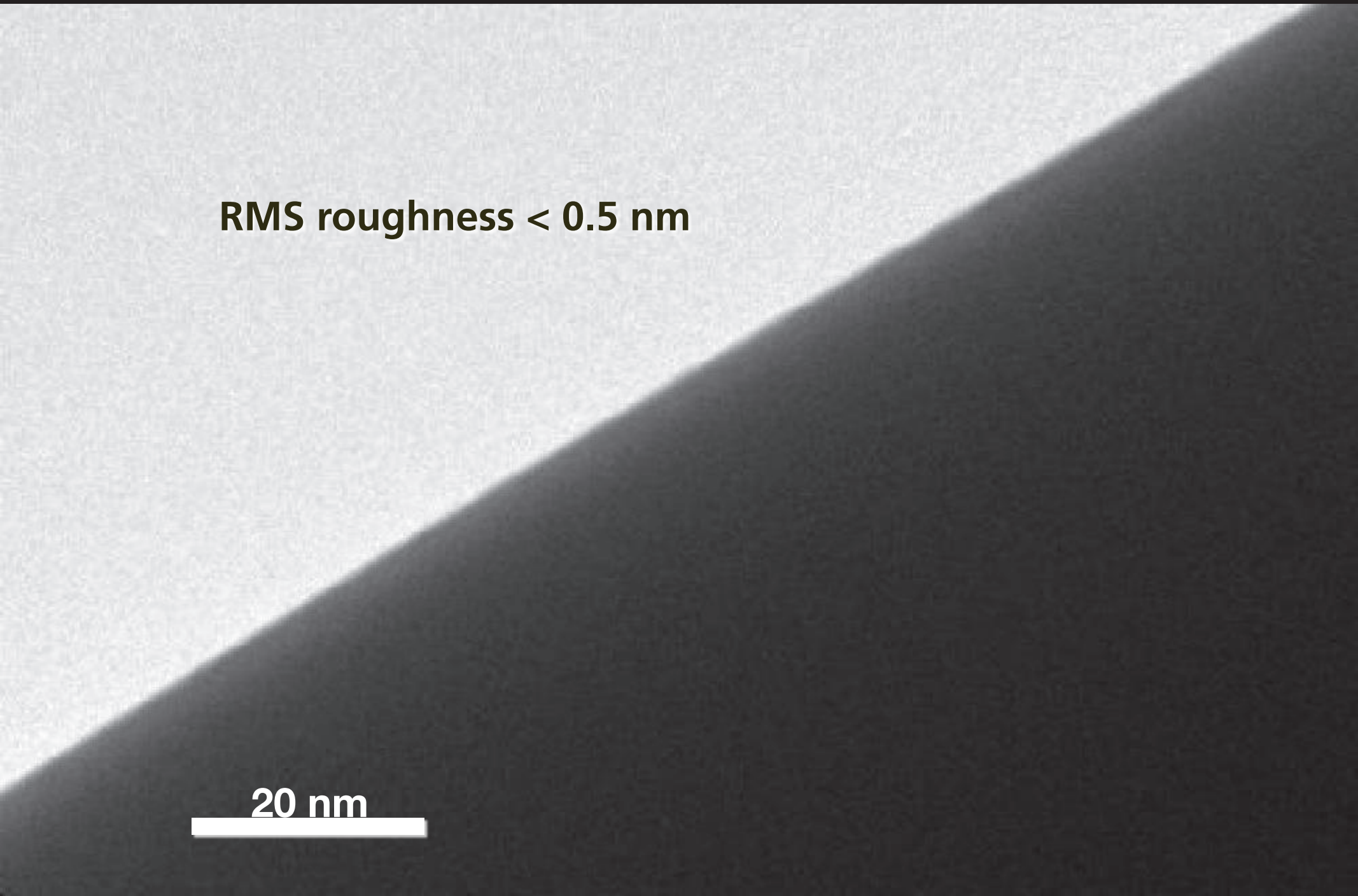
Silica nanowires



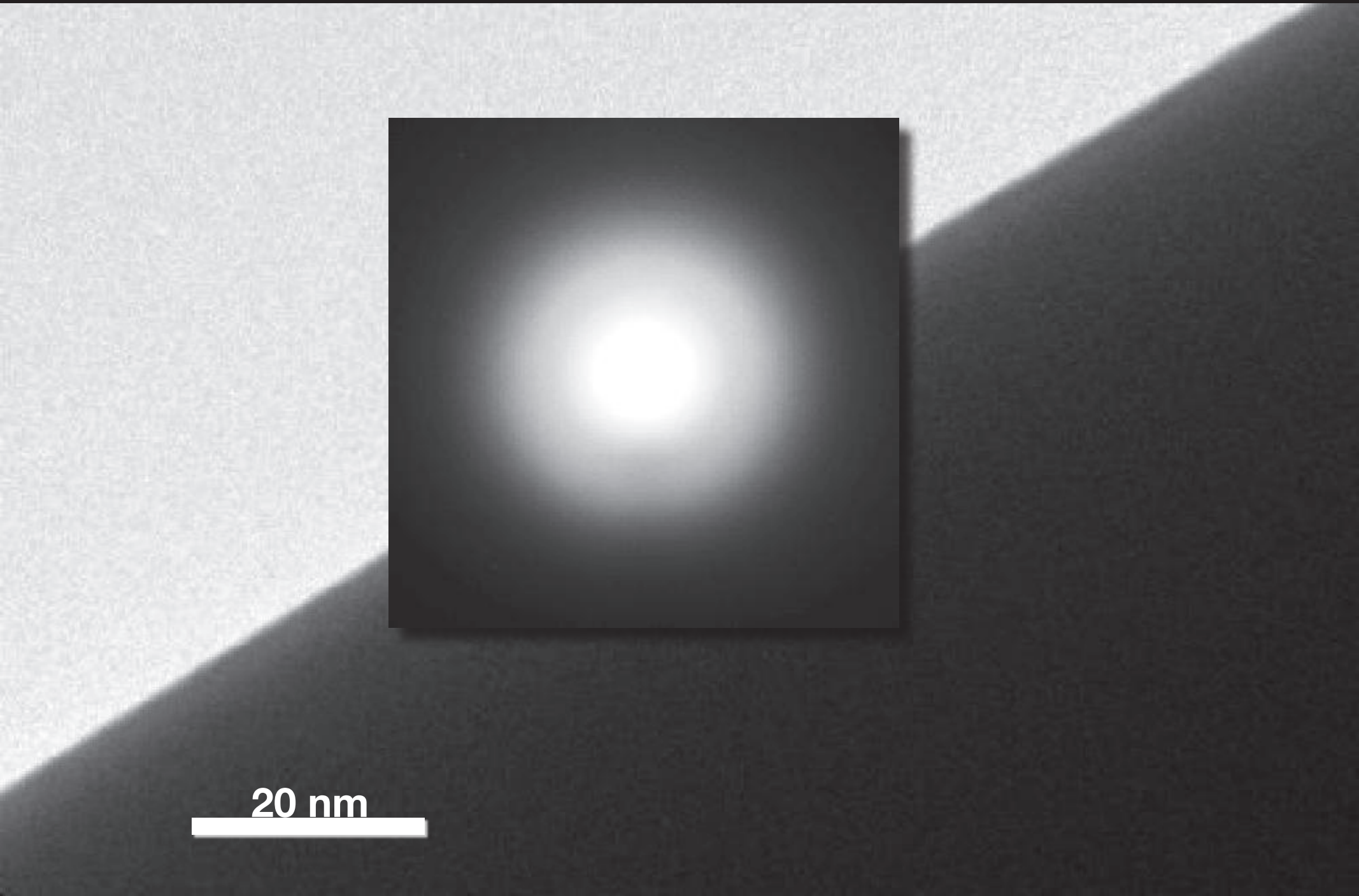
Silica nanowires



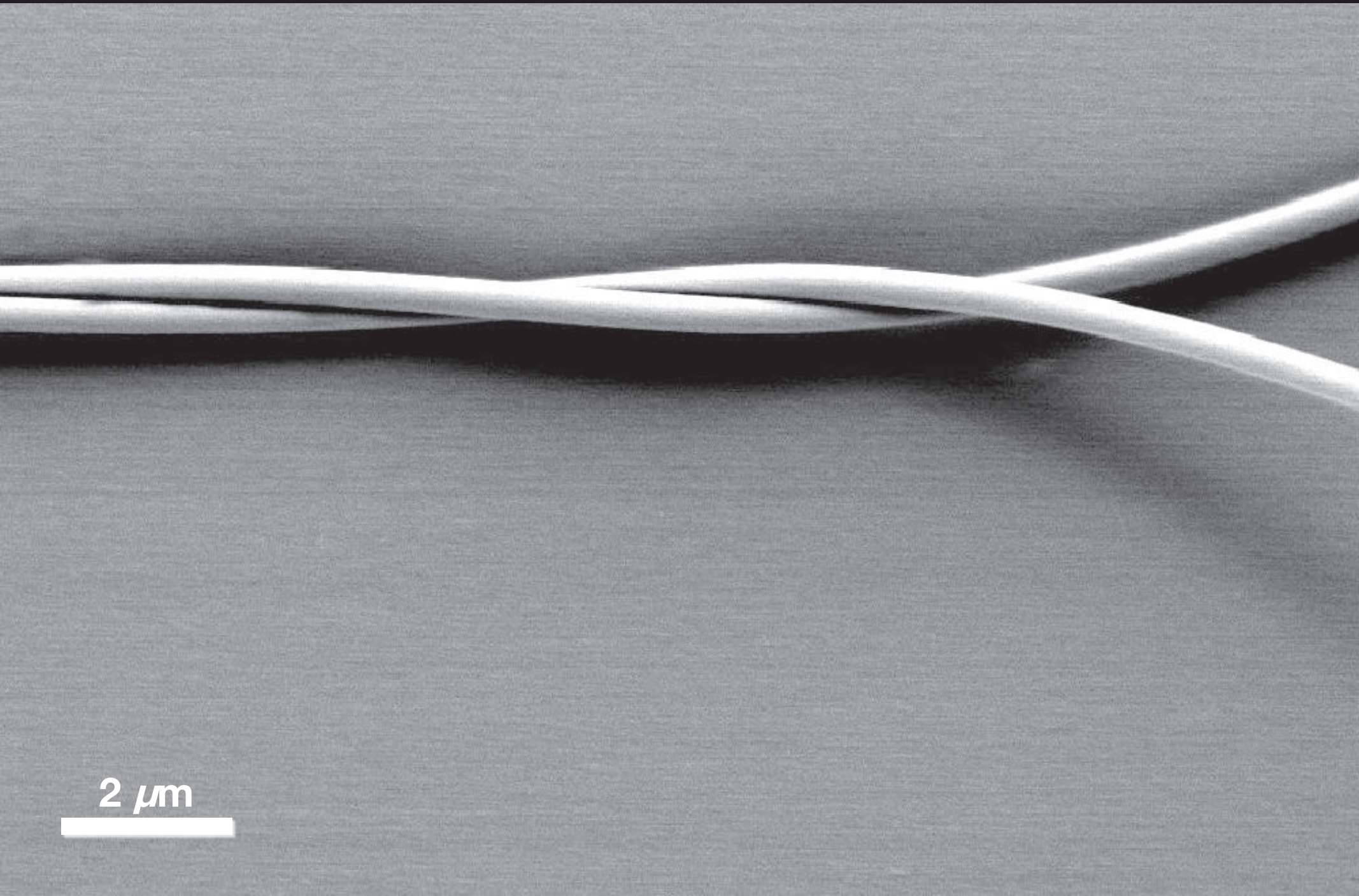
Silica nanowires



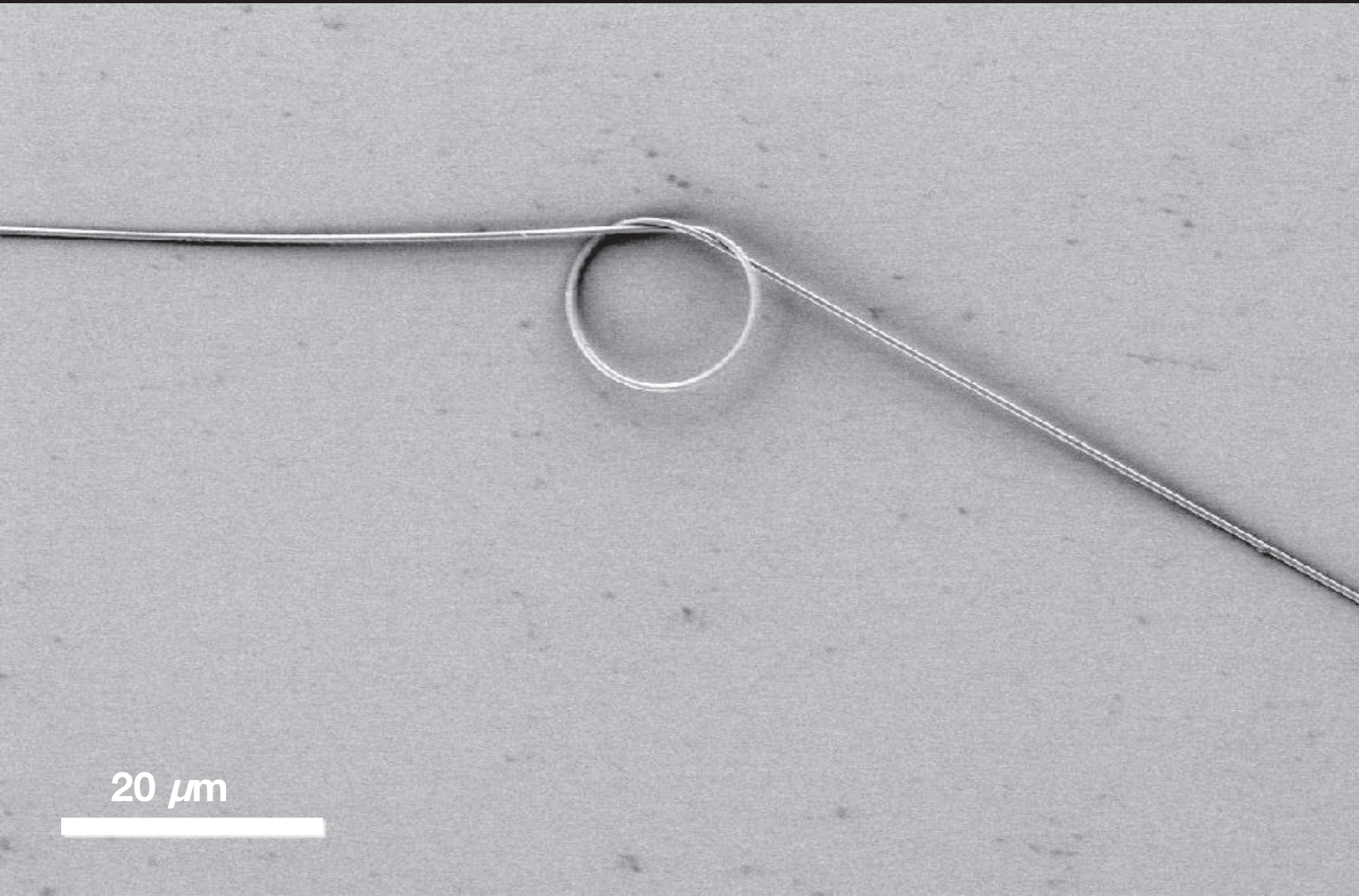
Silica nanowires



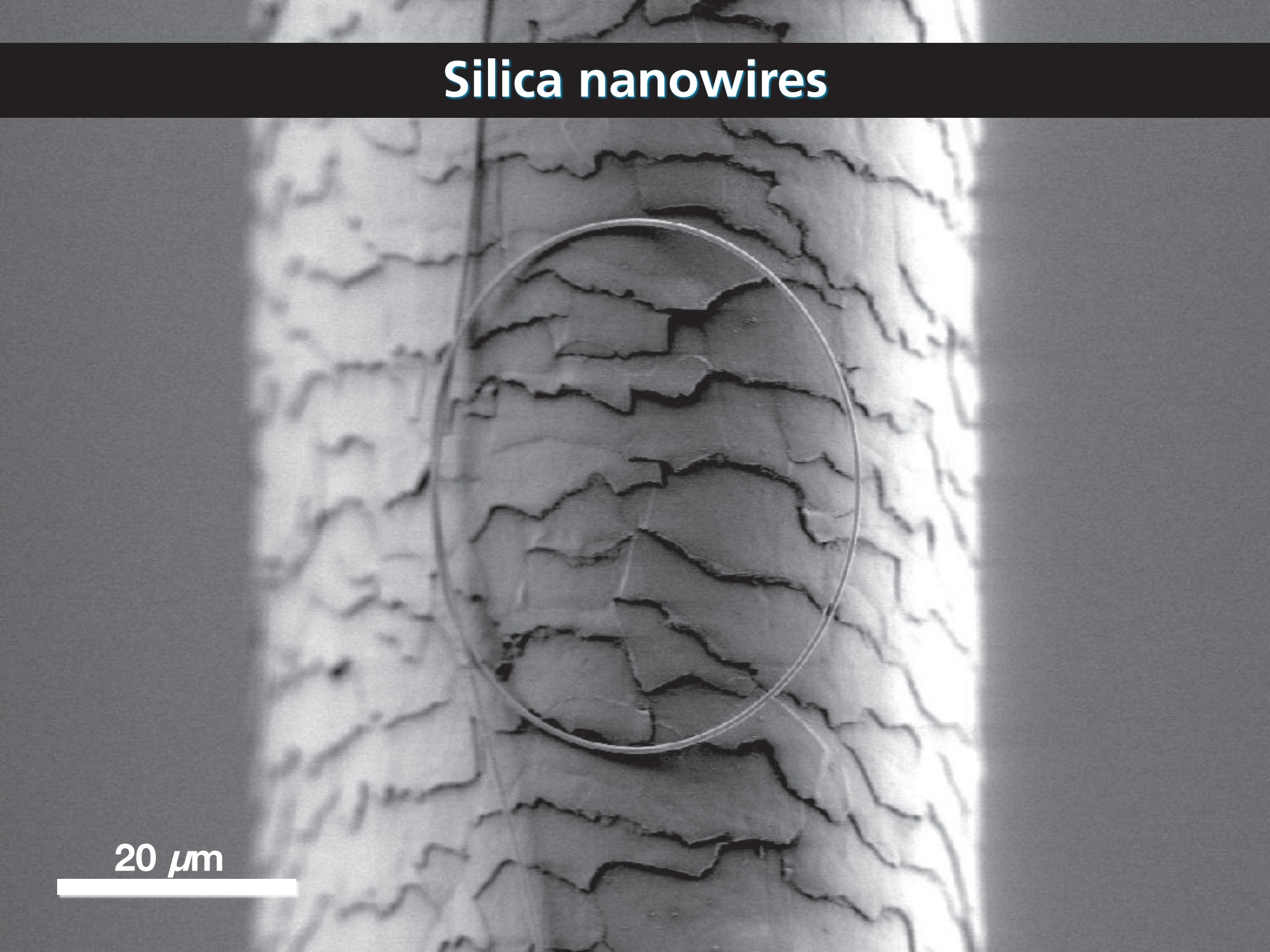
Silica nanowires



Silica nanowires



Silica nanowires



Silica nanowires

Points to keep in mind:

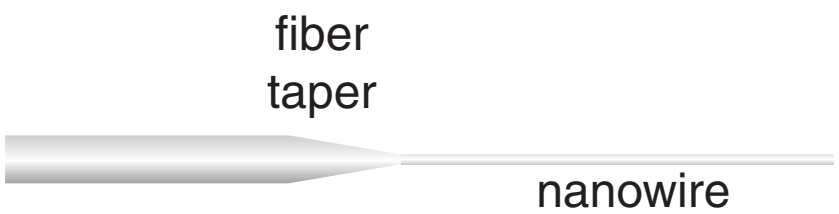
- easy fabrication
- atomic level smoothness
- malleable

Outline

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

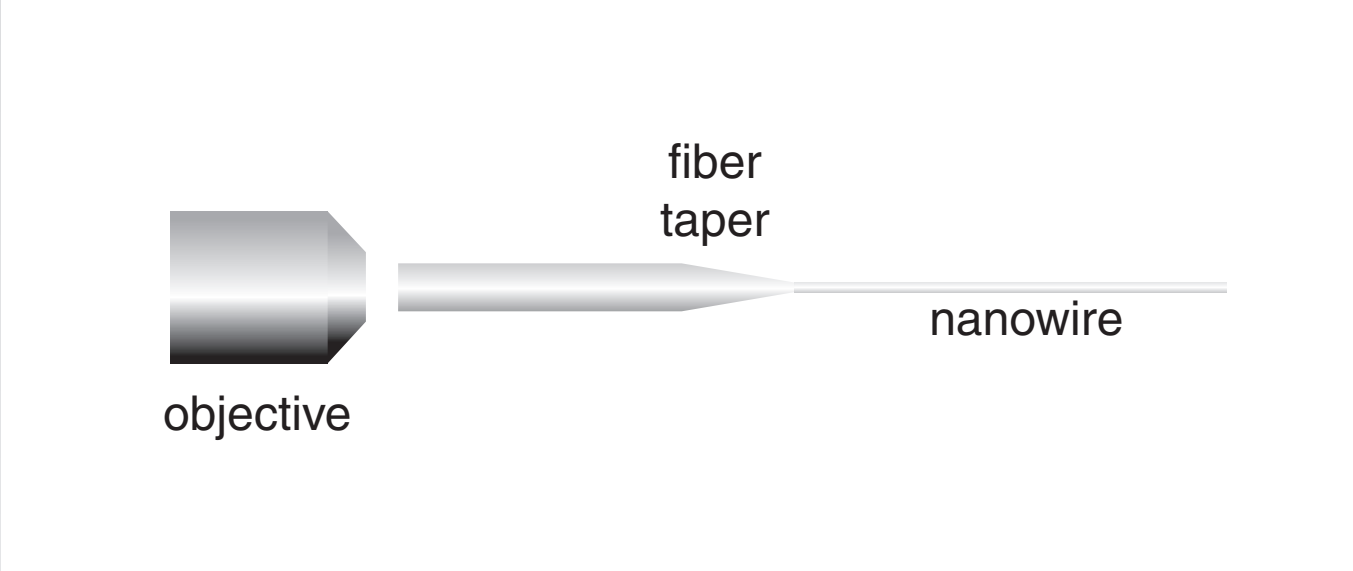
Manipulating light at the nanoscale

coupling light into nanowires



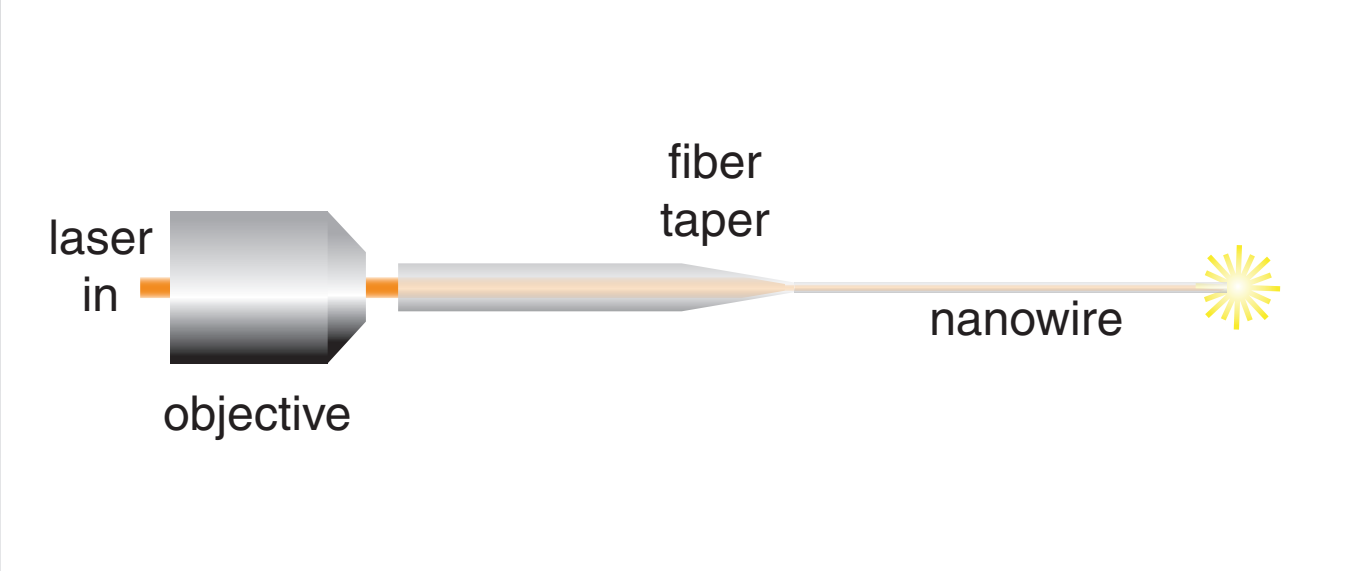
Manipulating light at the nanoscale

coupling light into nanowires

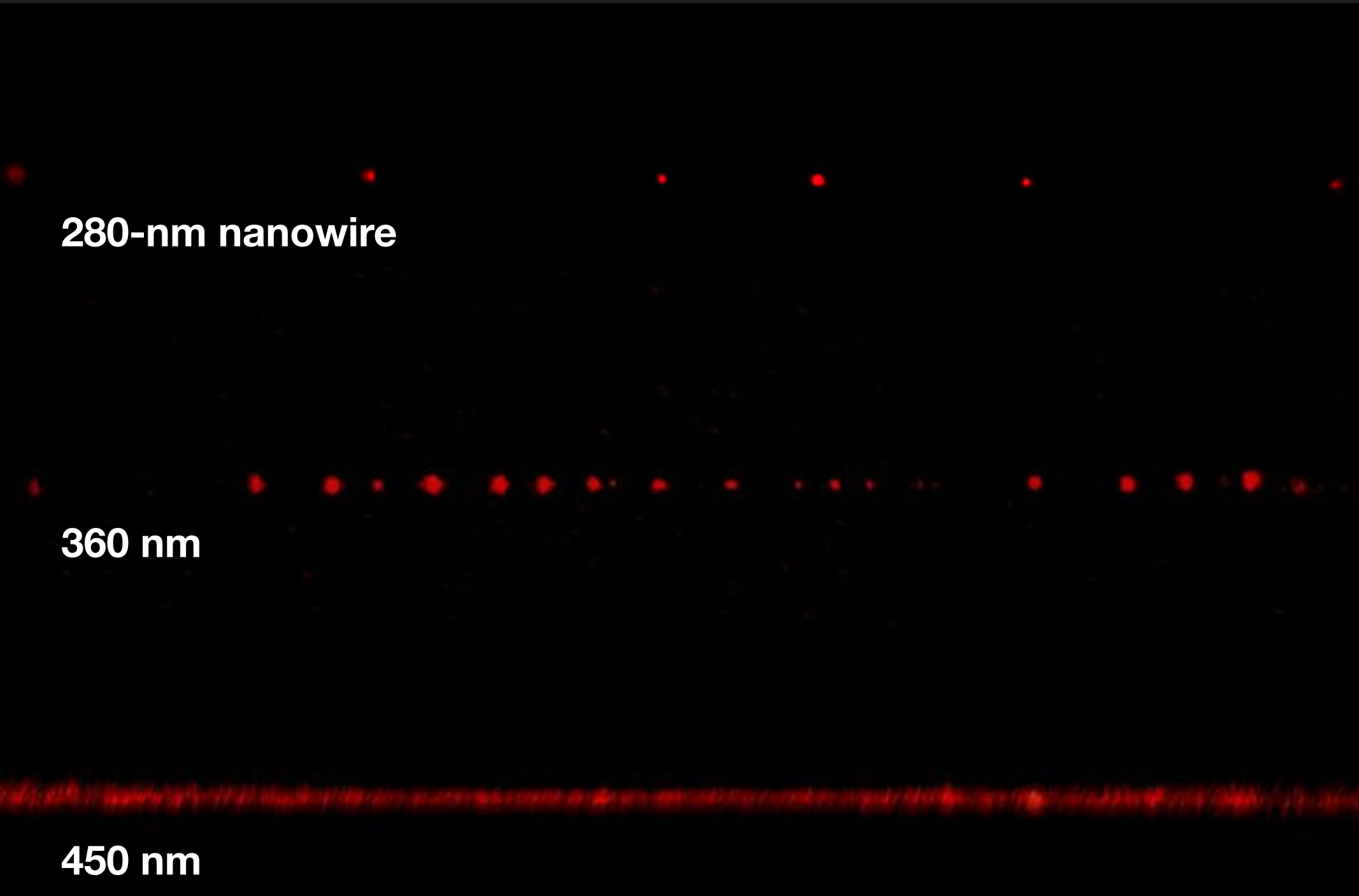


Manipulating light at the nanoscale

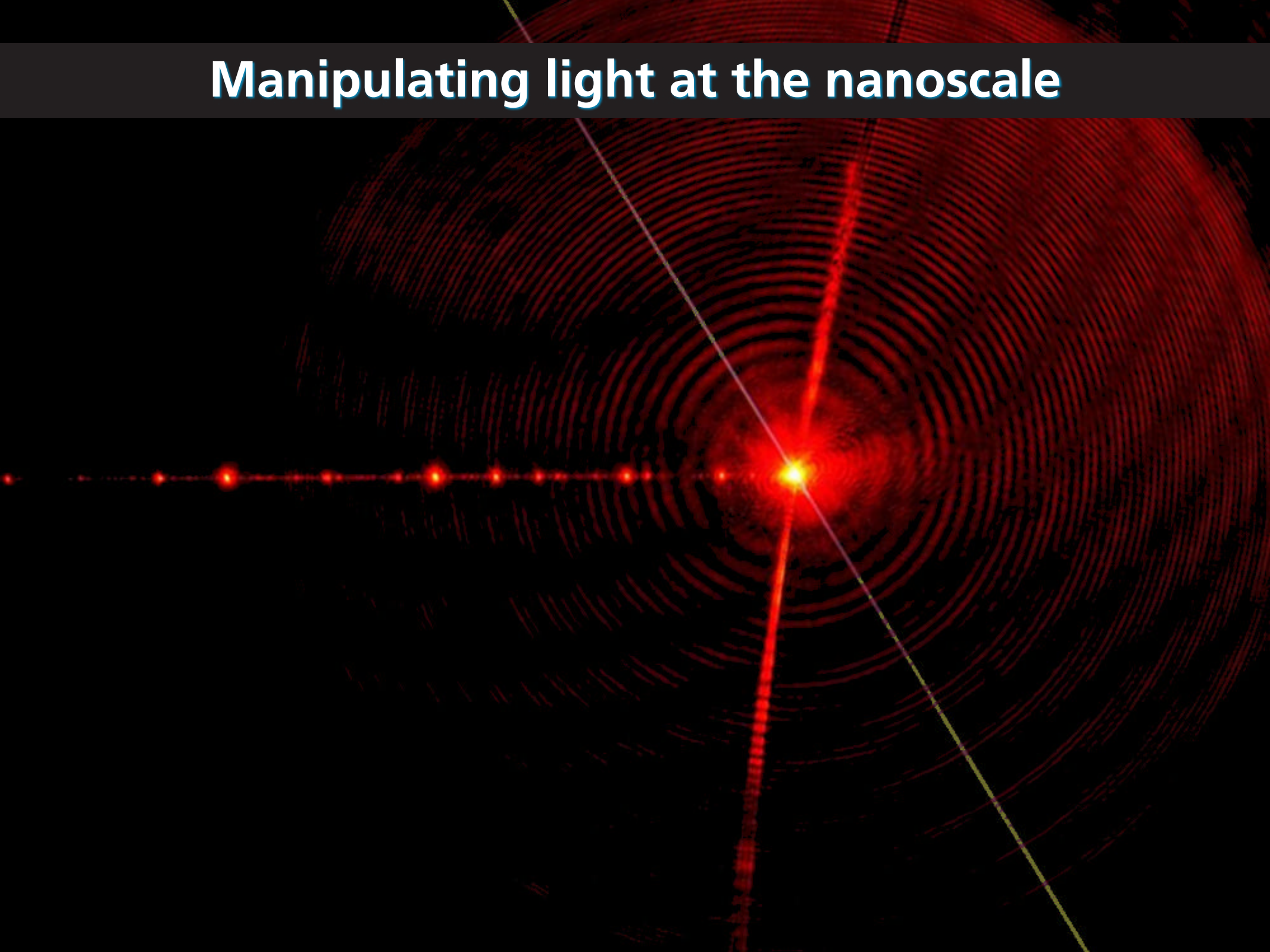
coupling light into nanowires



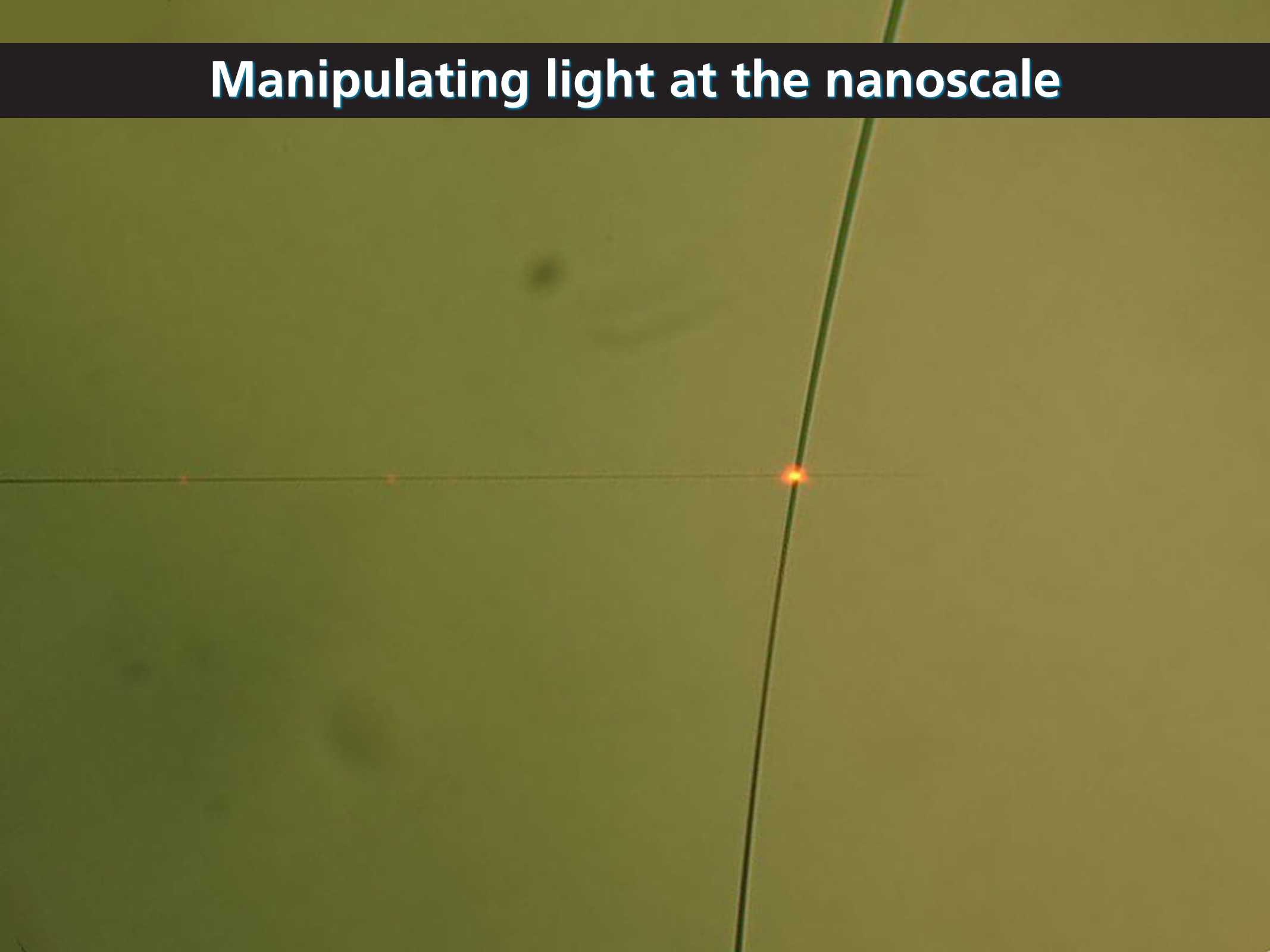
Manipulating light at the nanoscale



Manipulating light at the nanoscale

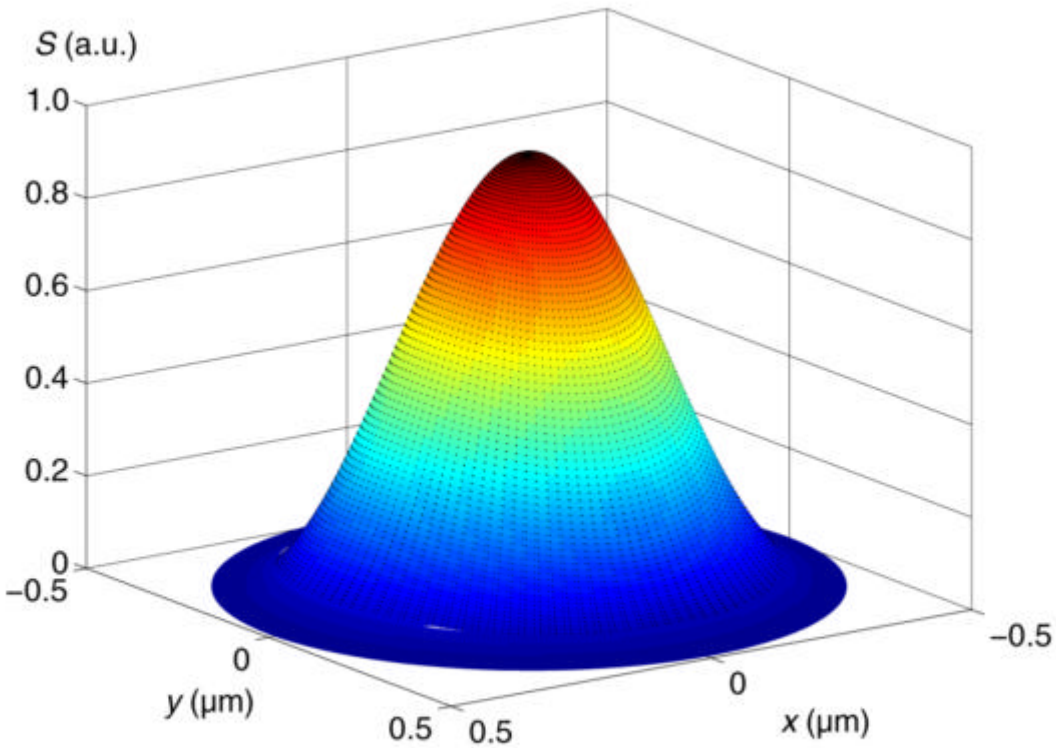


Manipulating light at the nanoscale



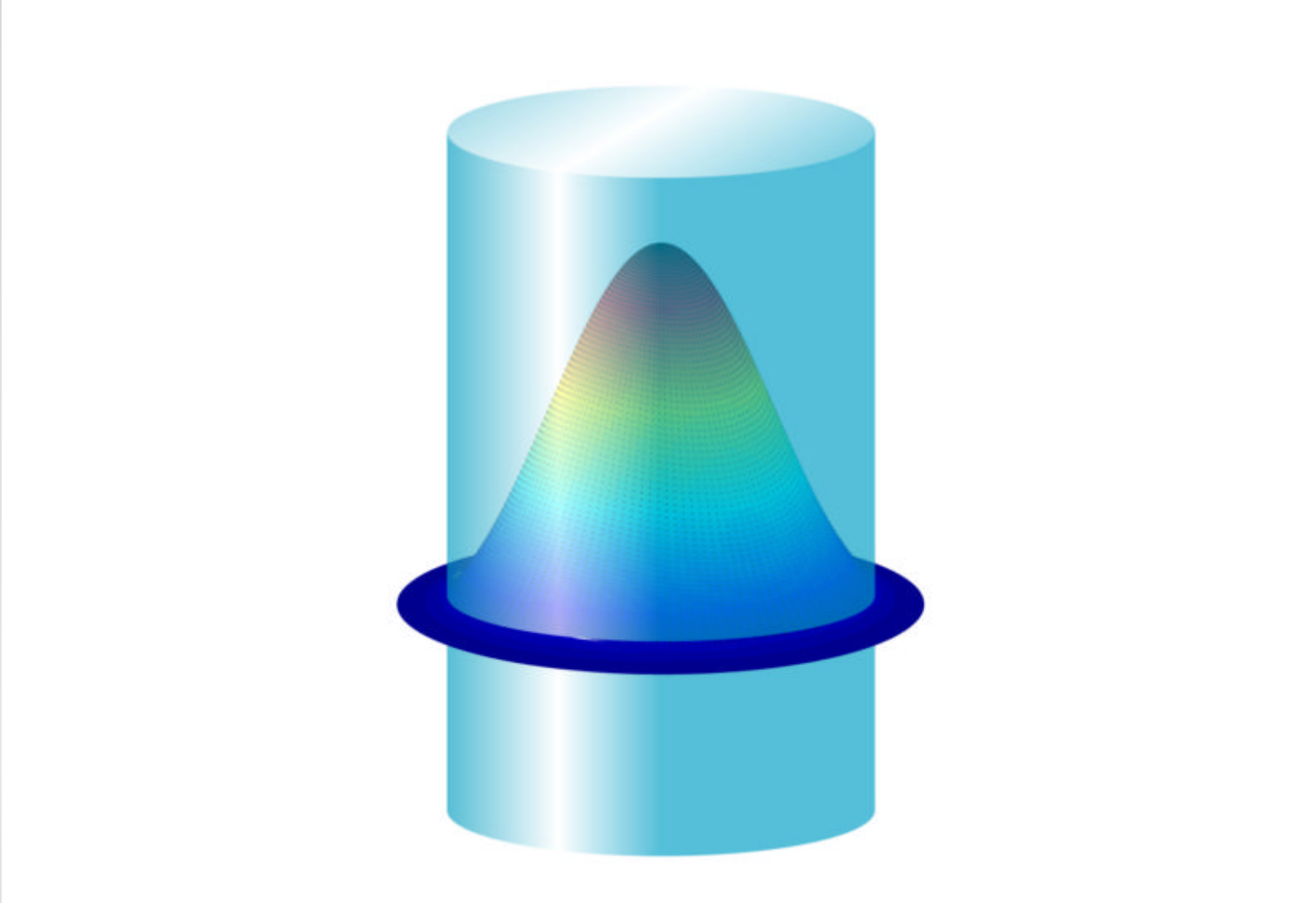
Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



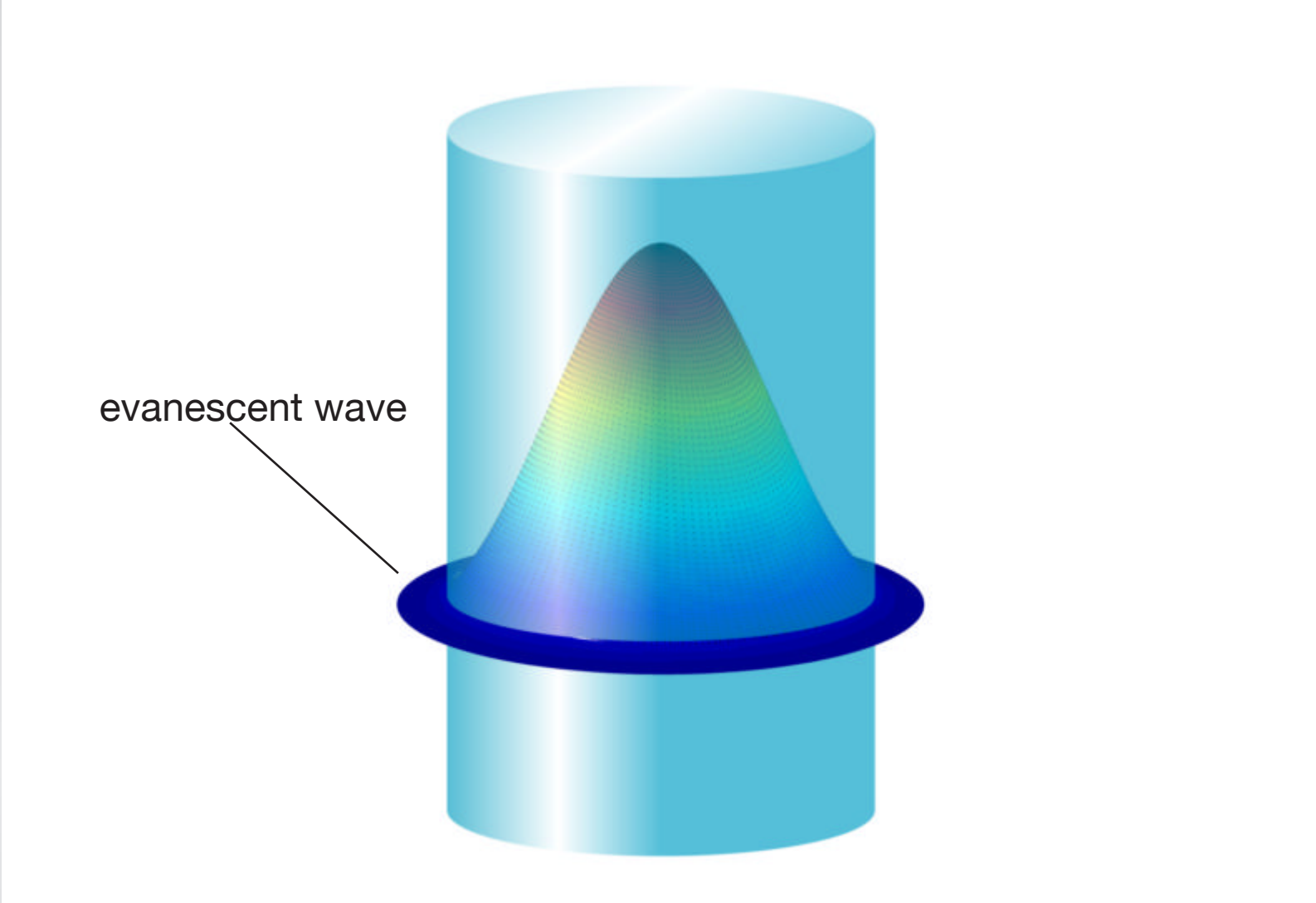
Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



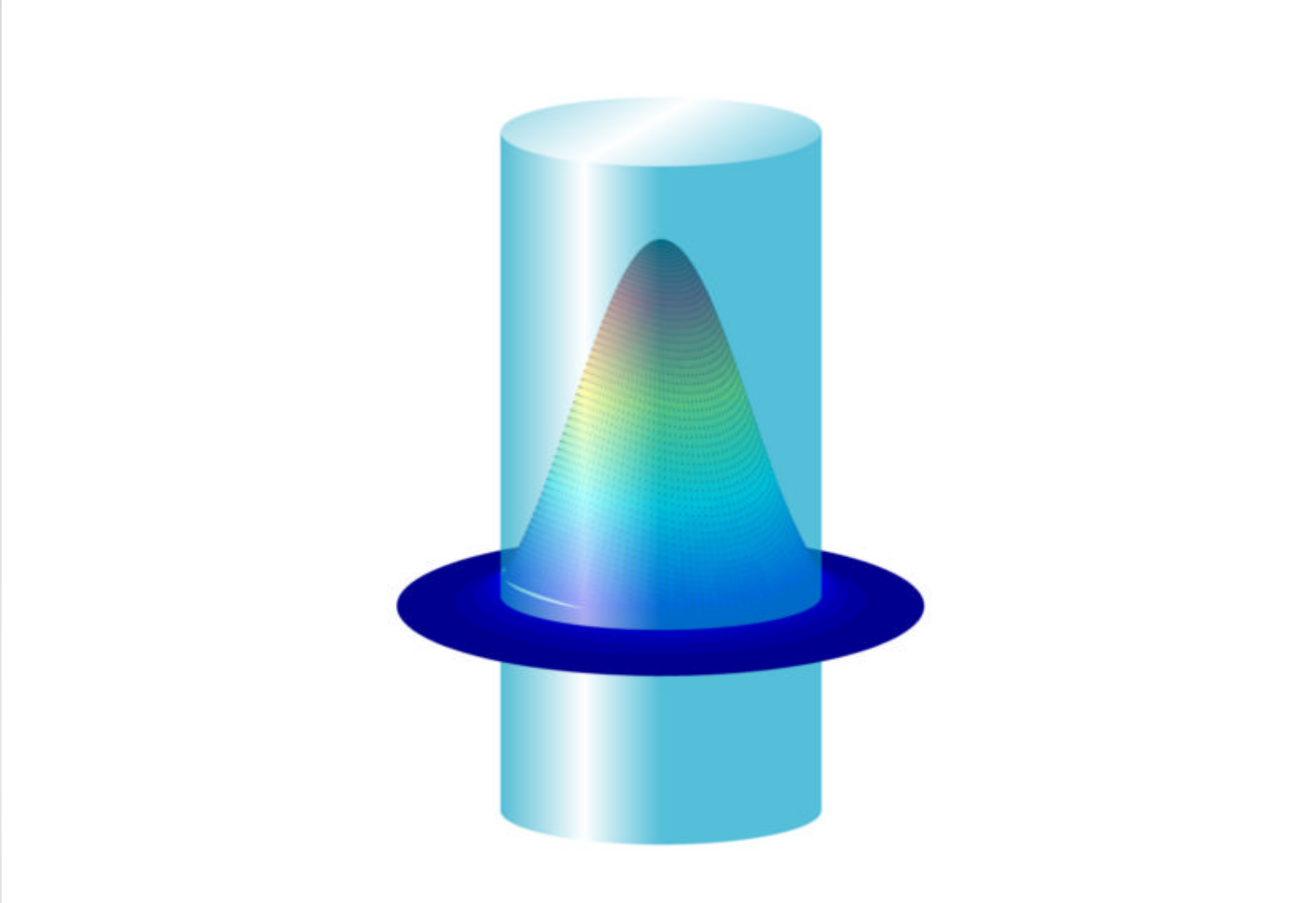
Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



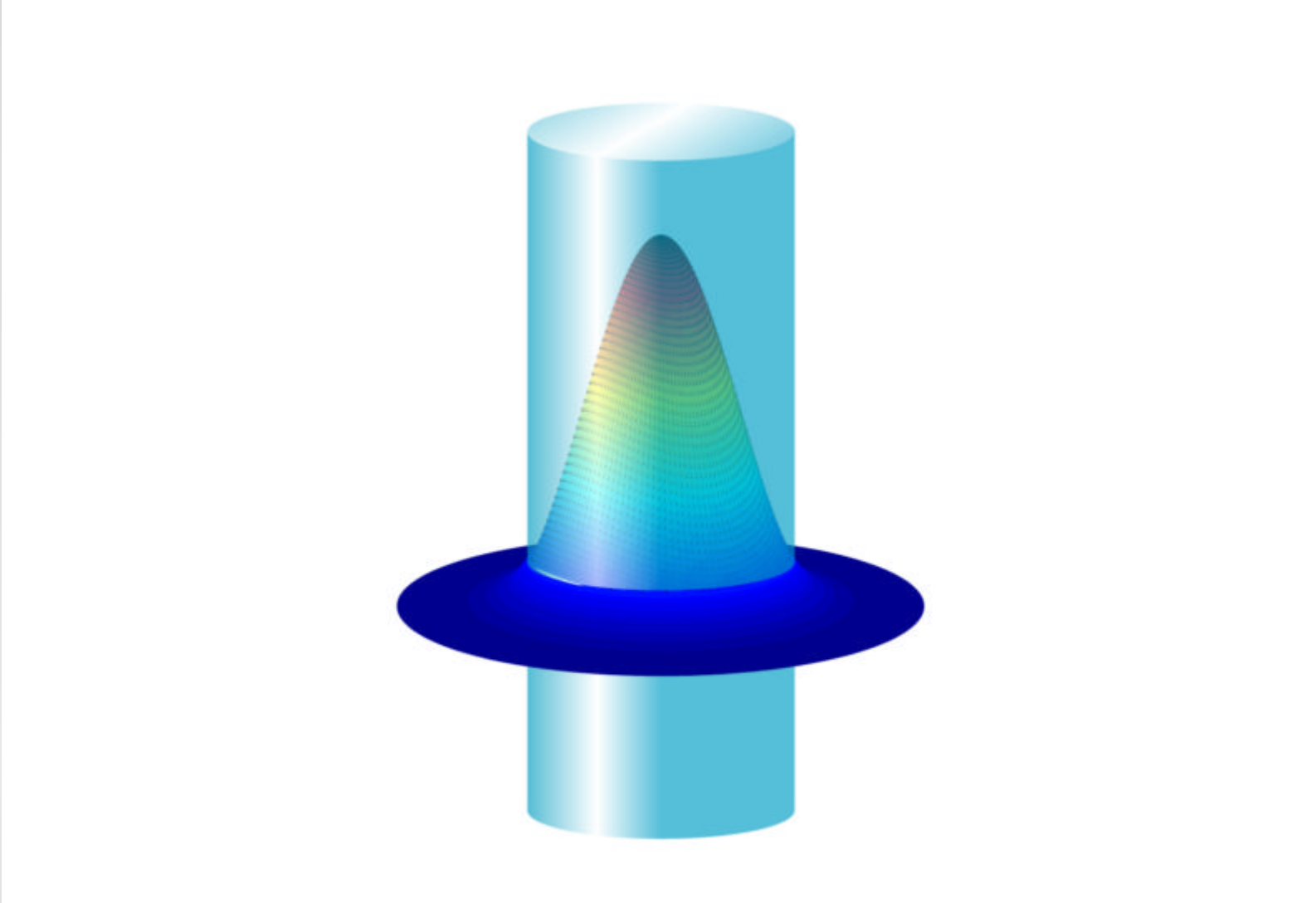
Manipulating light at the nanoscale

Poynting vector profile for 600-nm nanowire



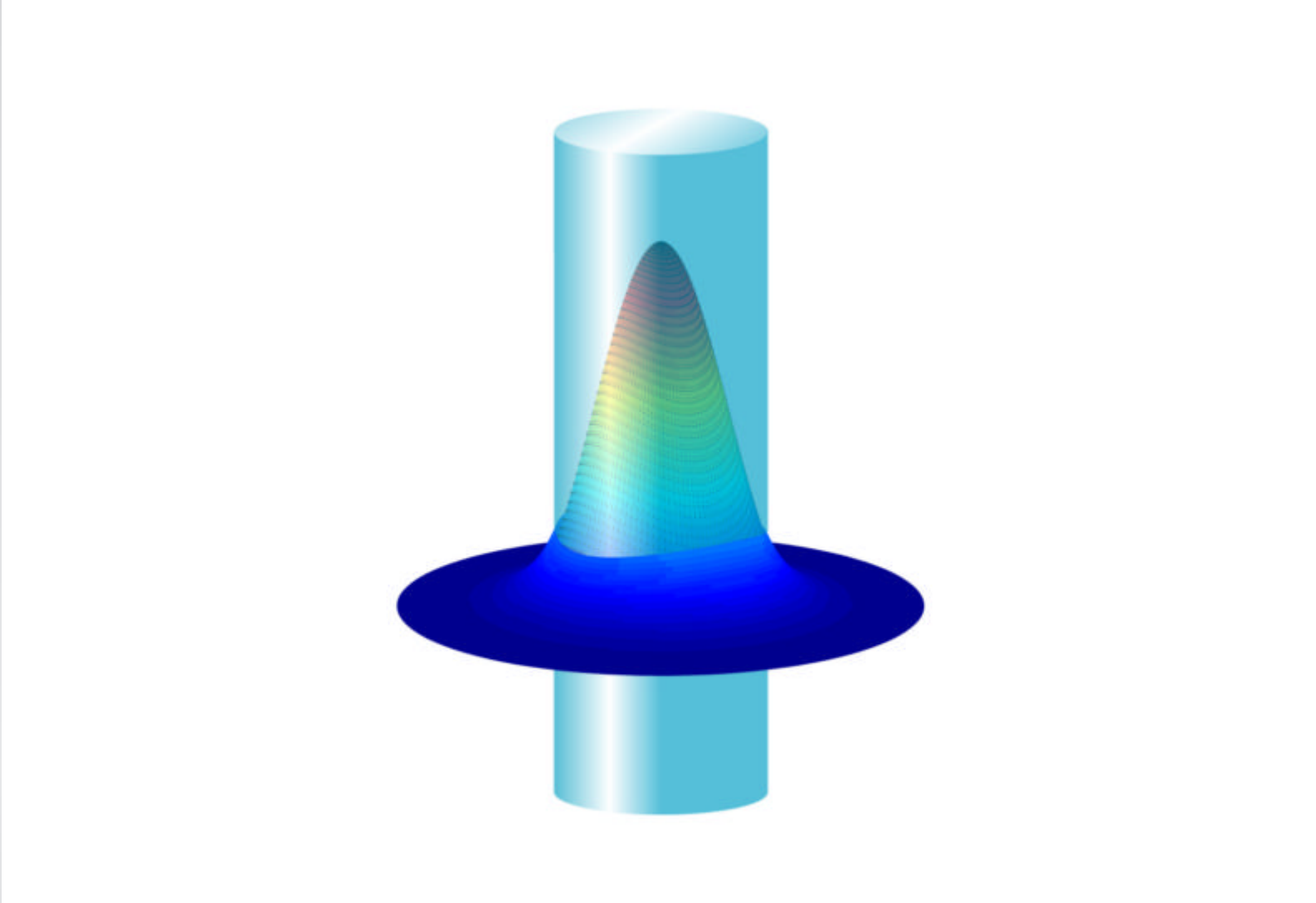
Manipulating light at the nanoscale

Poynting vector profile for 500-nm nanowire



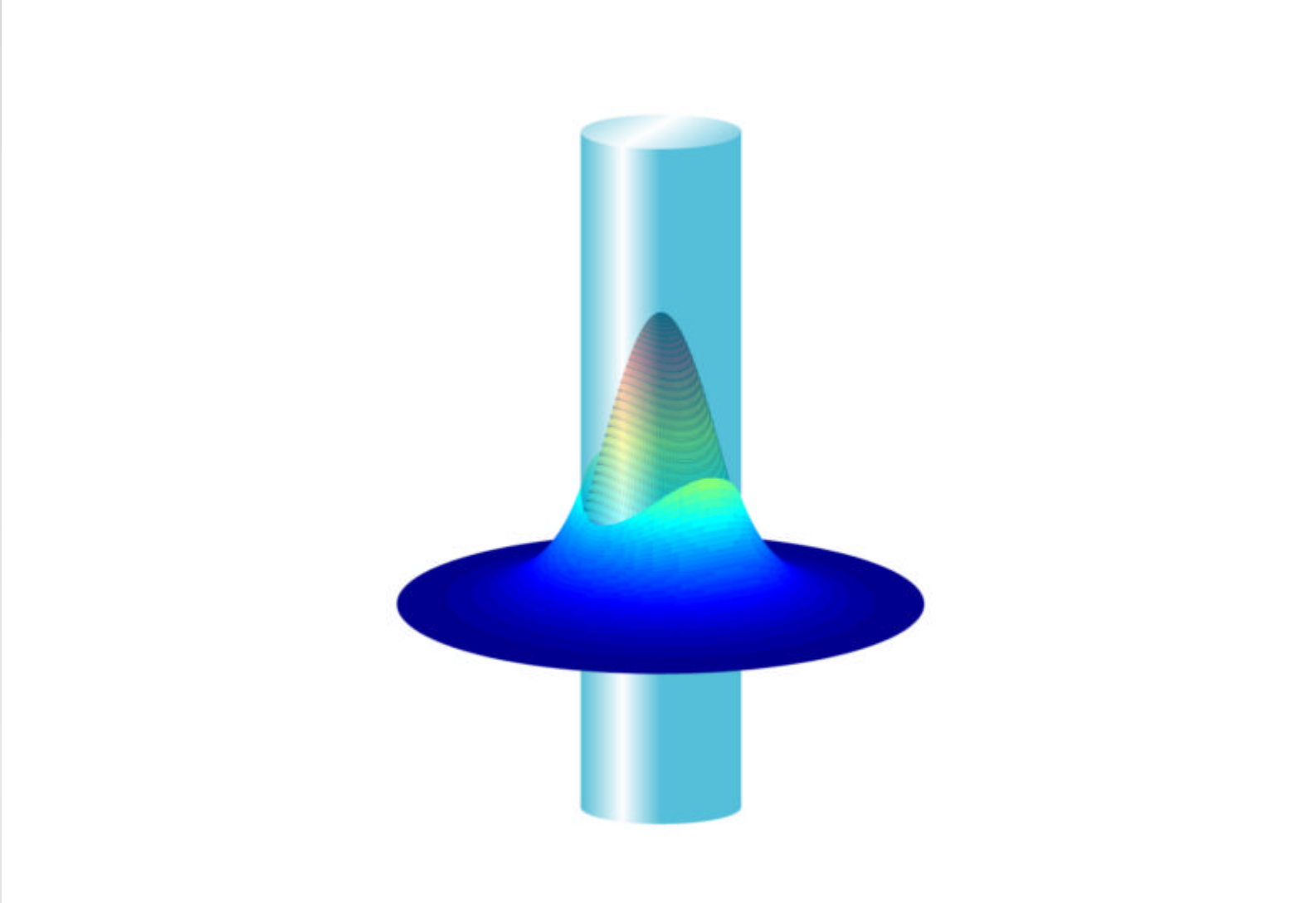
Manipulating light at the nanoscale

Poynting vector profile for 400-nm nanowire



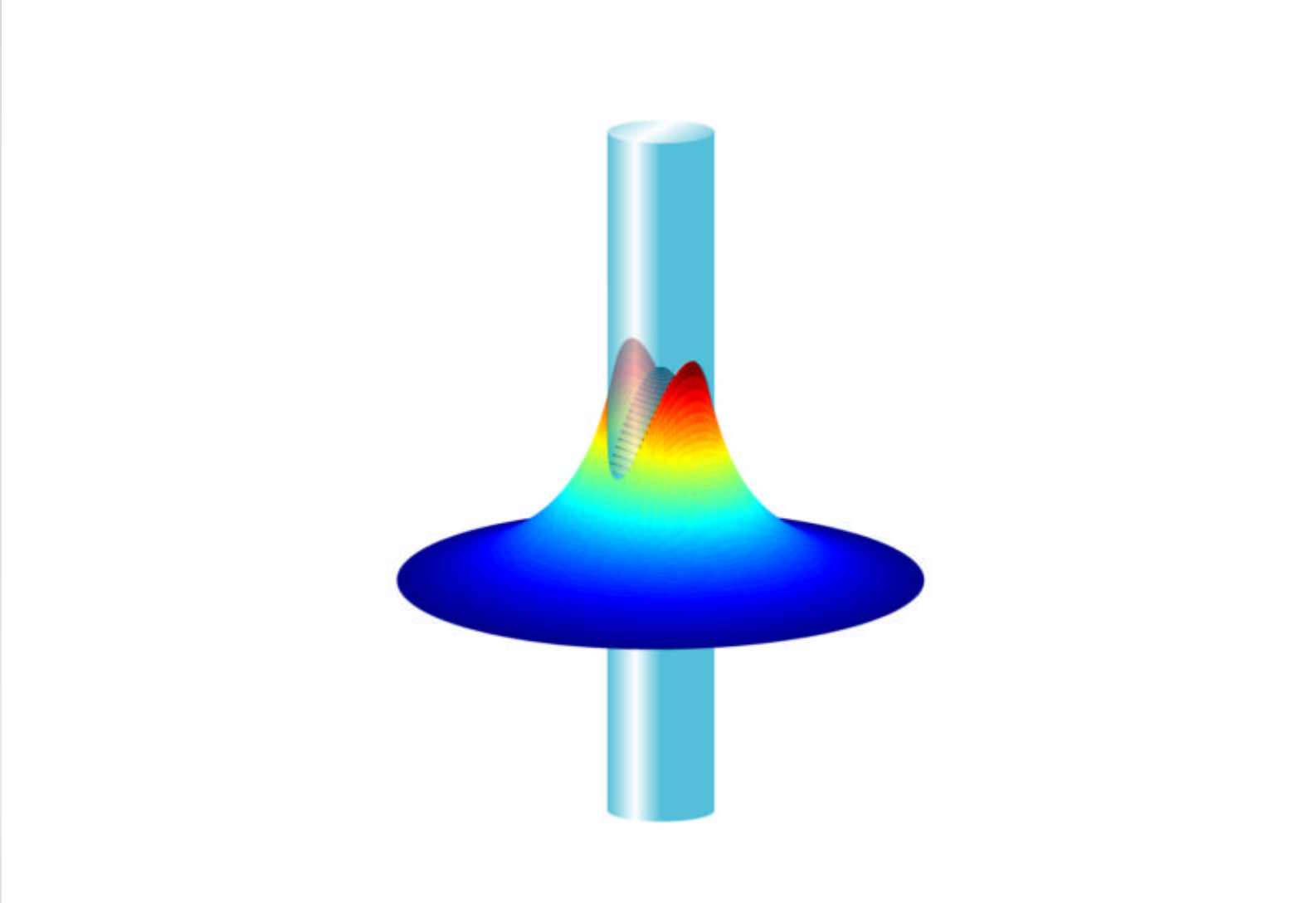
Manipulating light at the nanoscale

Poynting vector profile for 300-nm nanowire



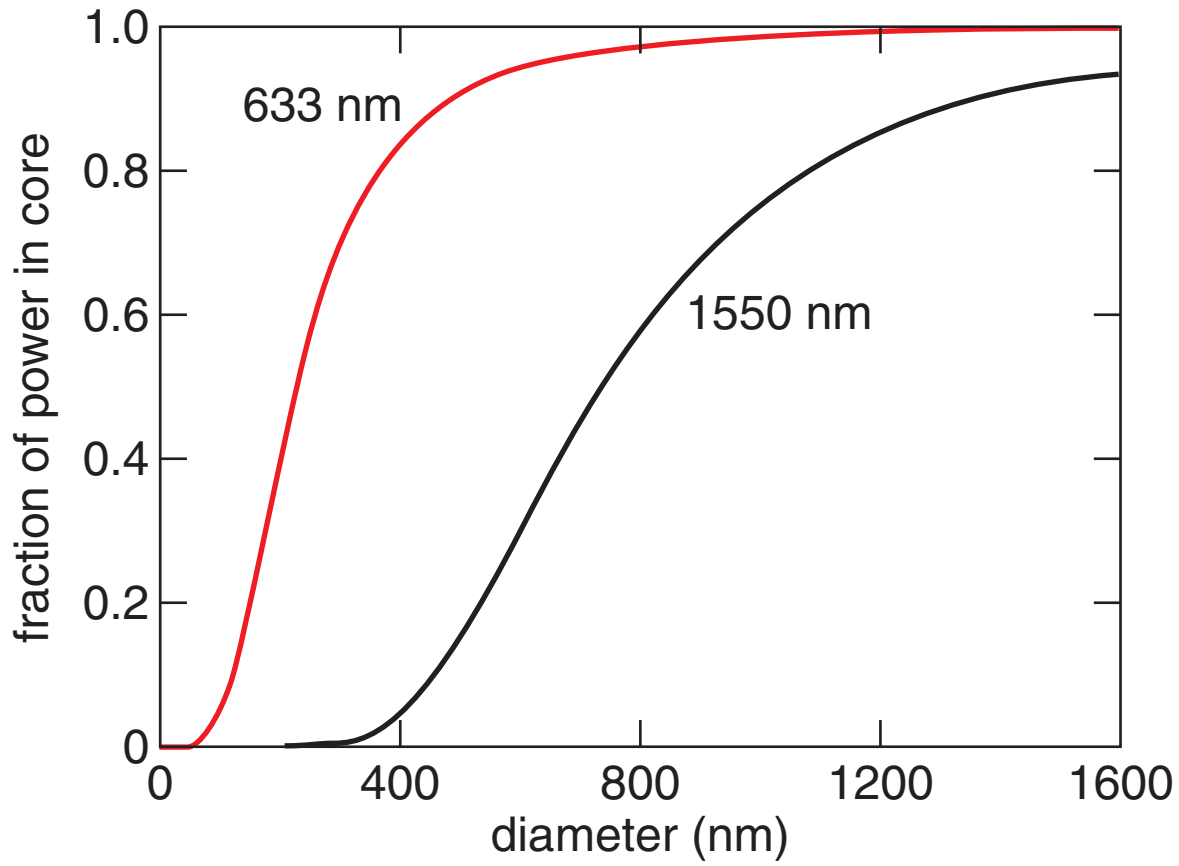
Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



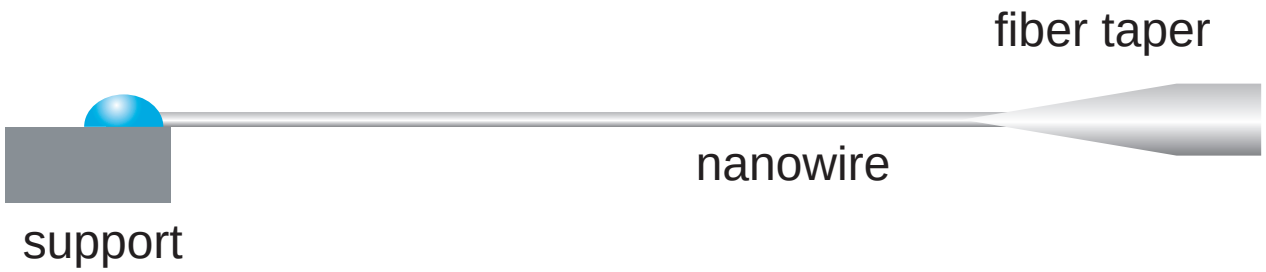
Manipulating light at the nanoscale

fraction of power carried in core



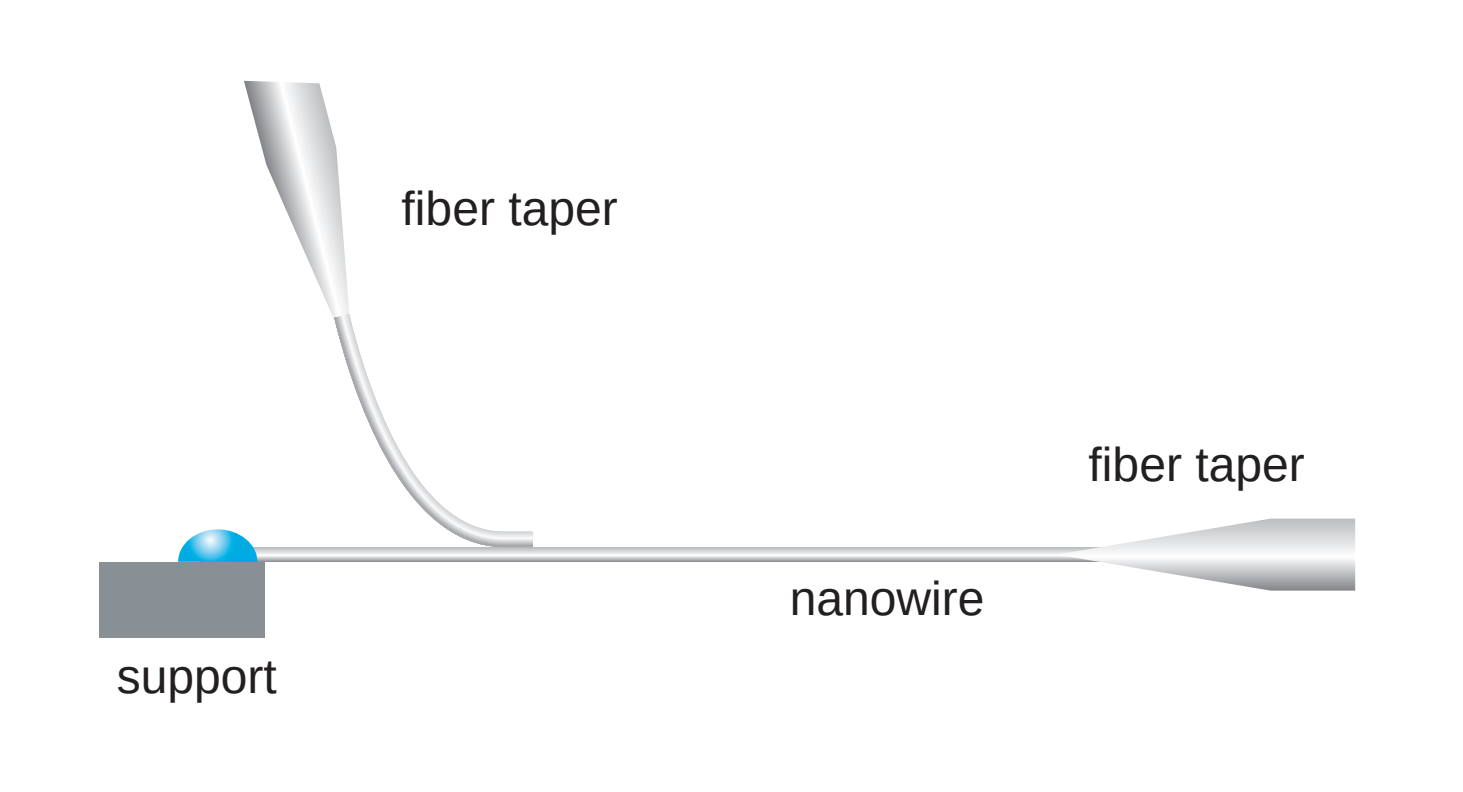
Manipulating light at the nanoscale

coupling light between nanowires



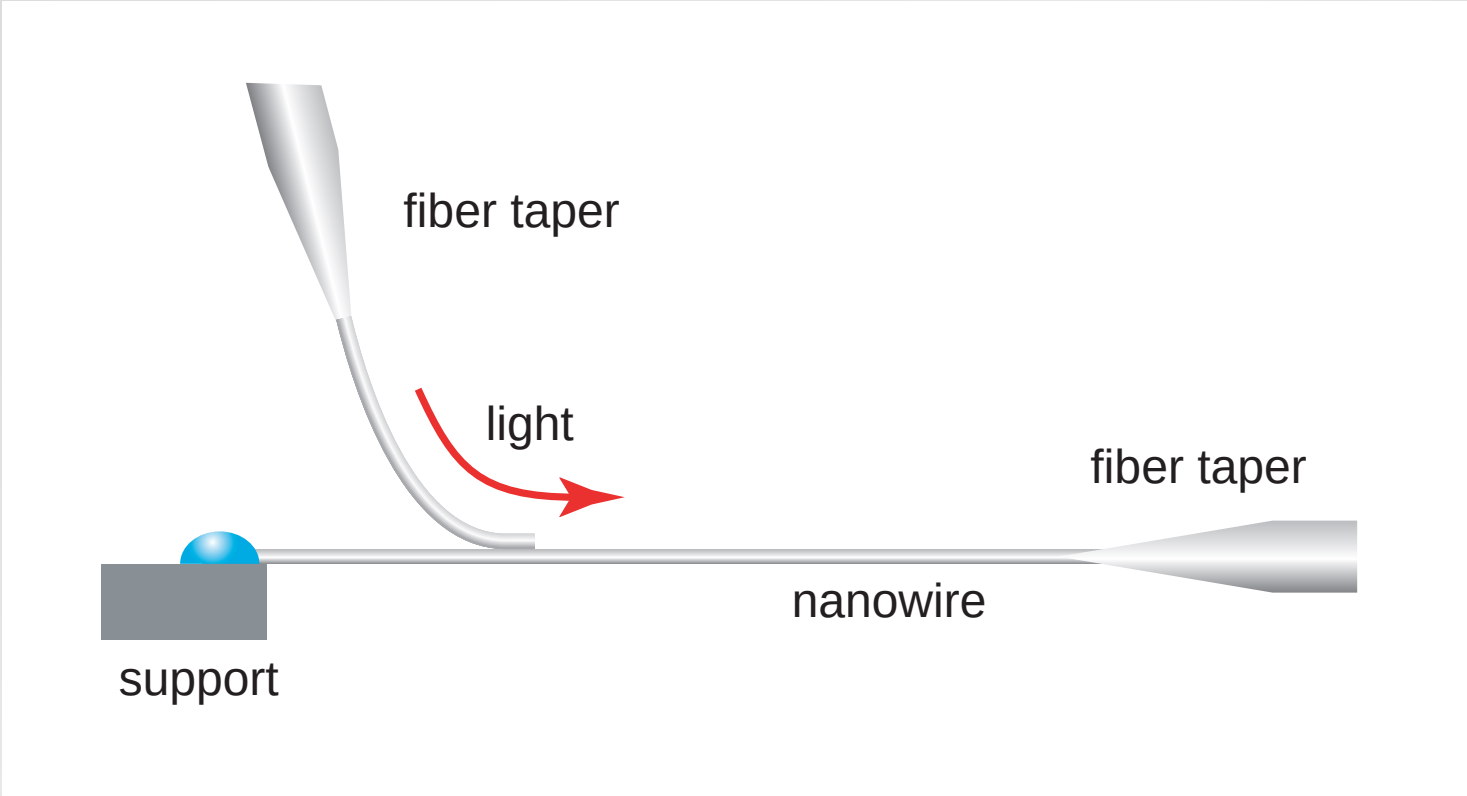
Manipulating light at the nanoscale

coupling light between nanowires

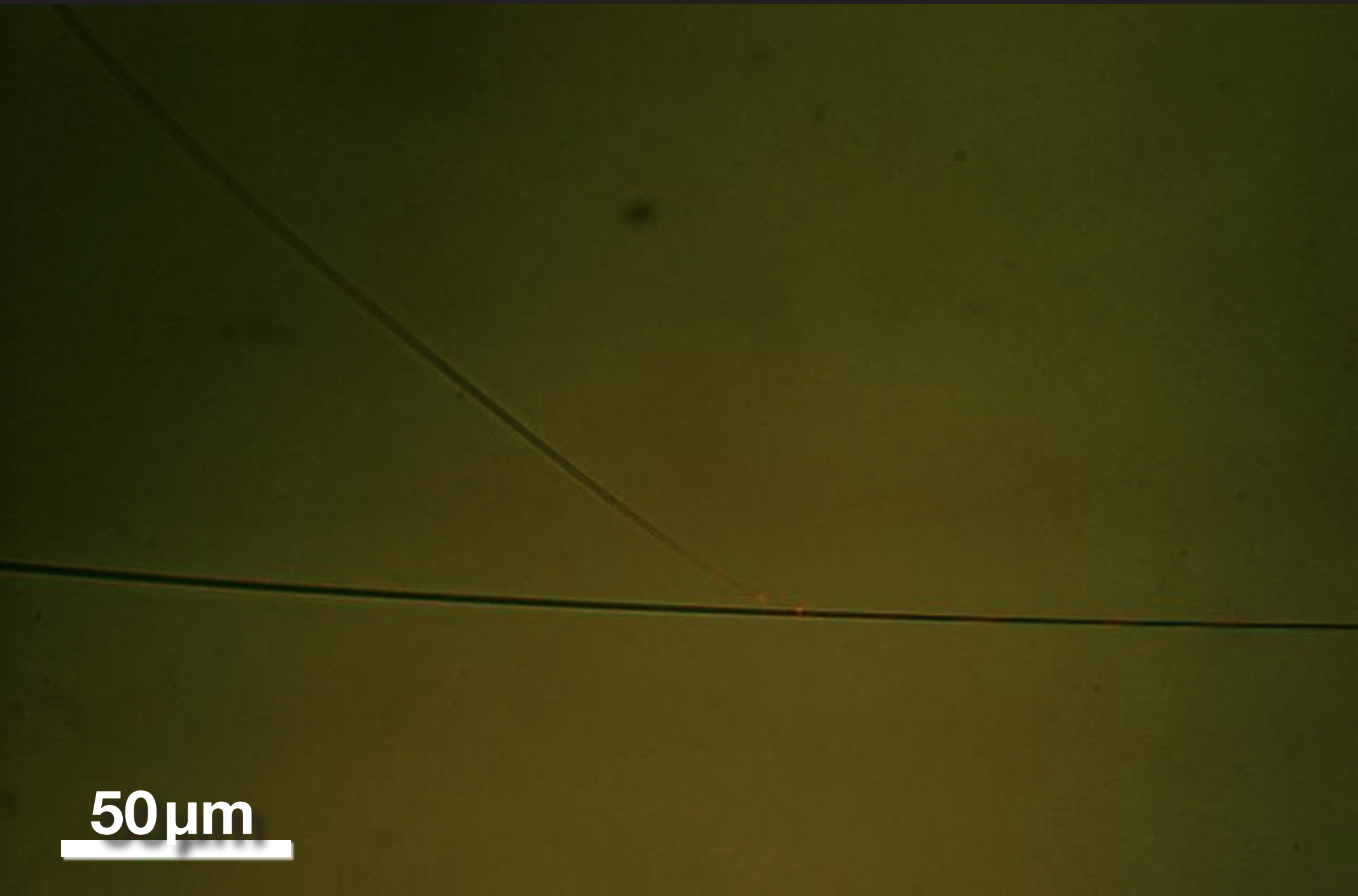


Manipulating light at the nanoscale

coupling light between nanowires



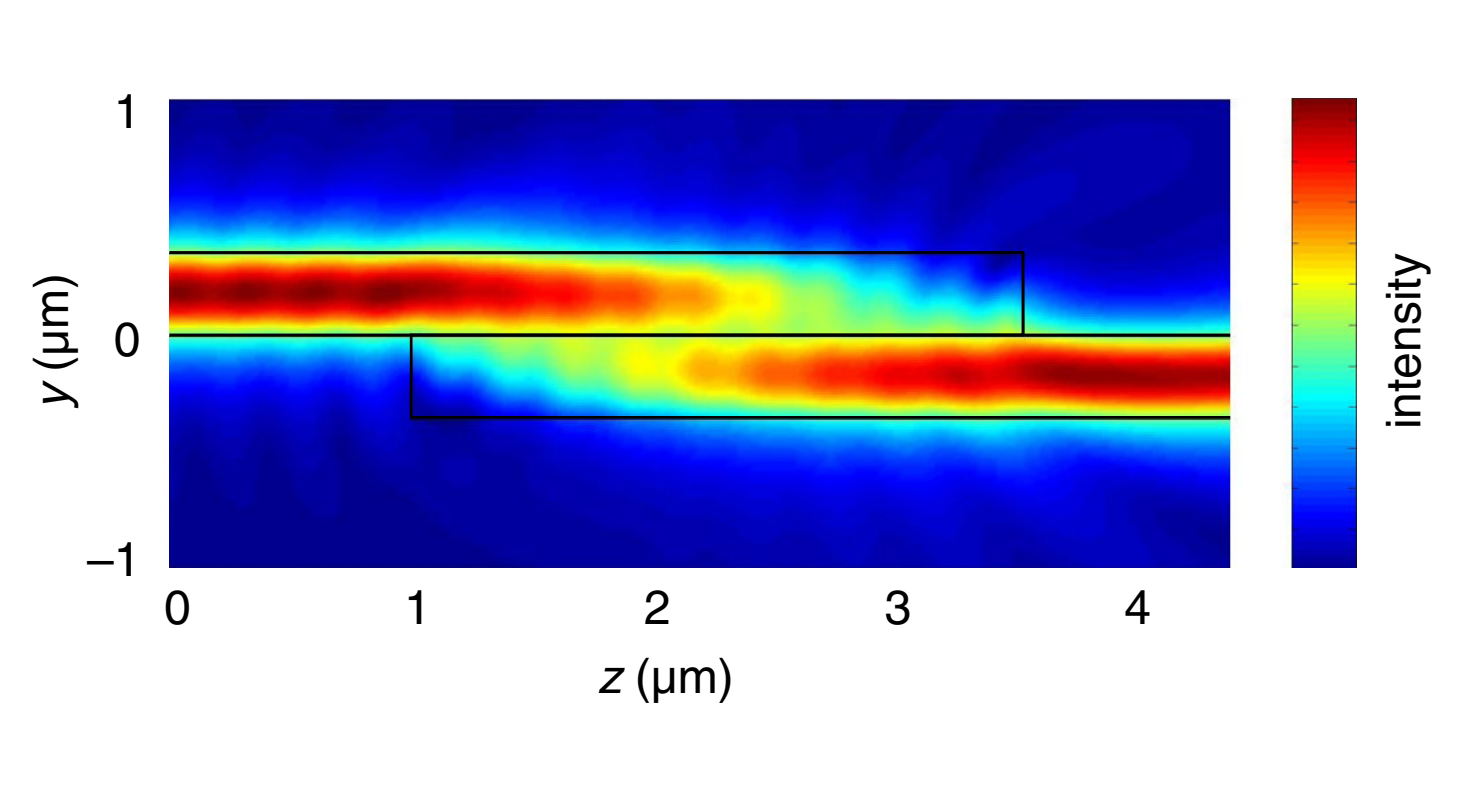
Manipulating light at the nanoscale



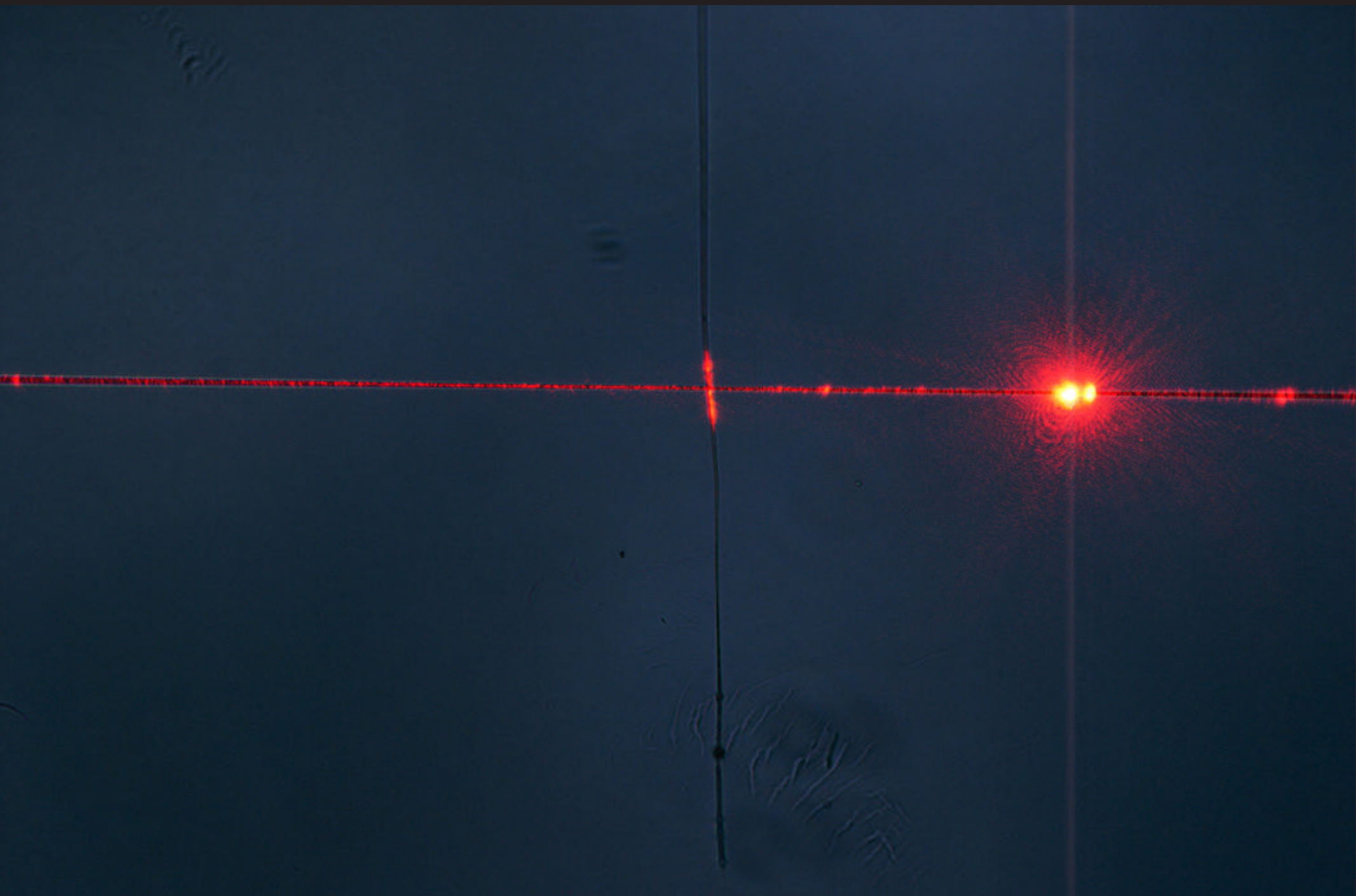
Manipulating light at the nanoscale

Manipulating light at the nanoscale

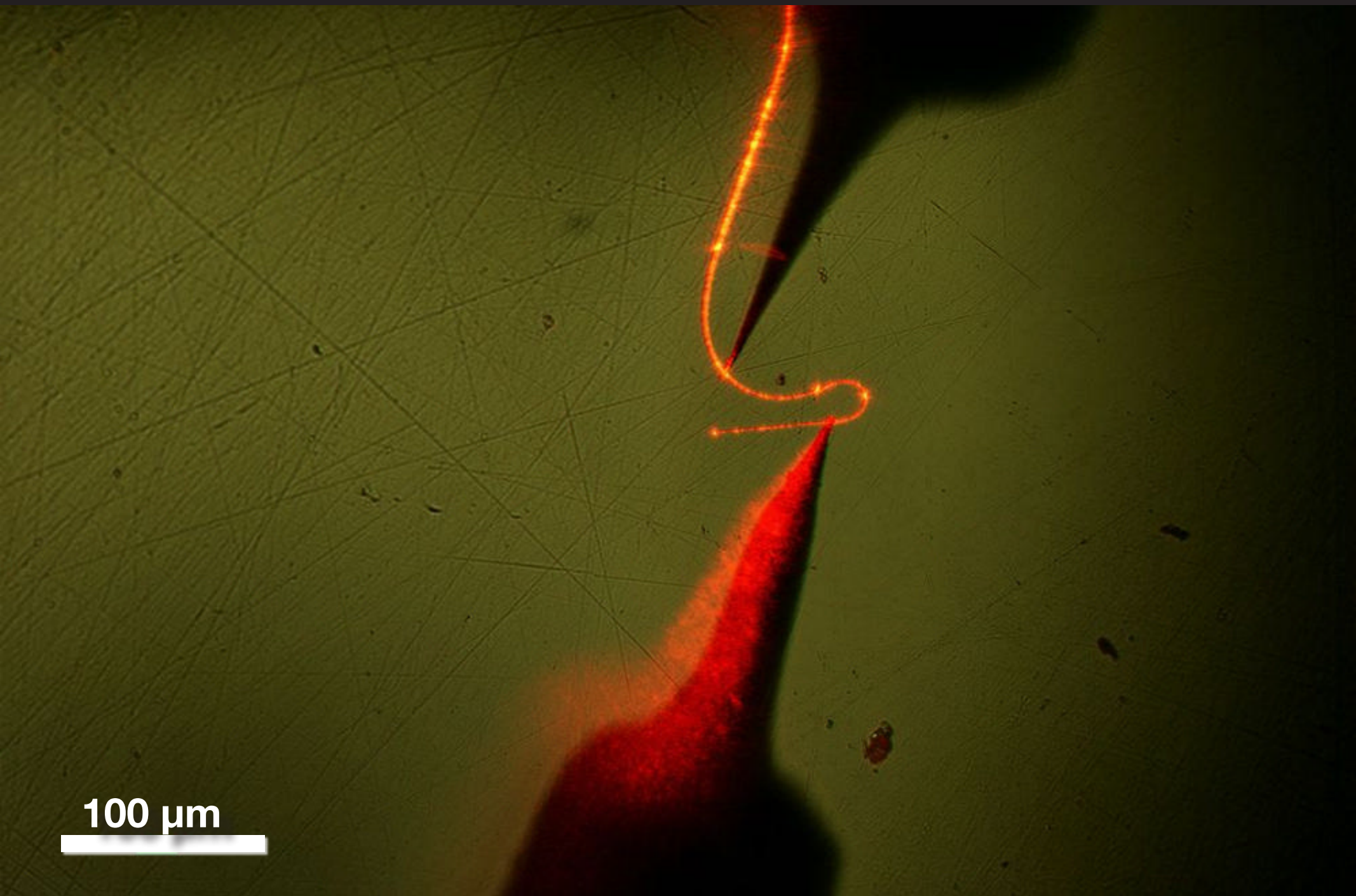
intensity distribution



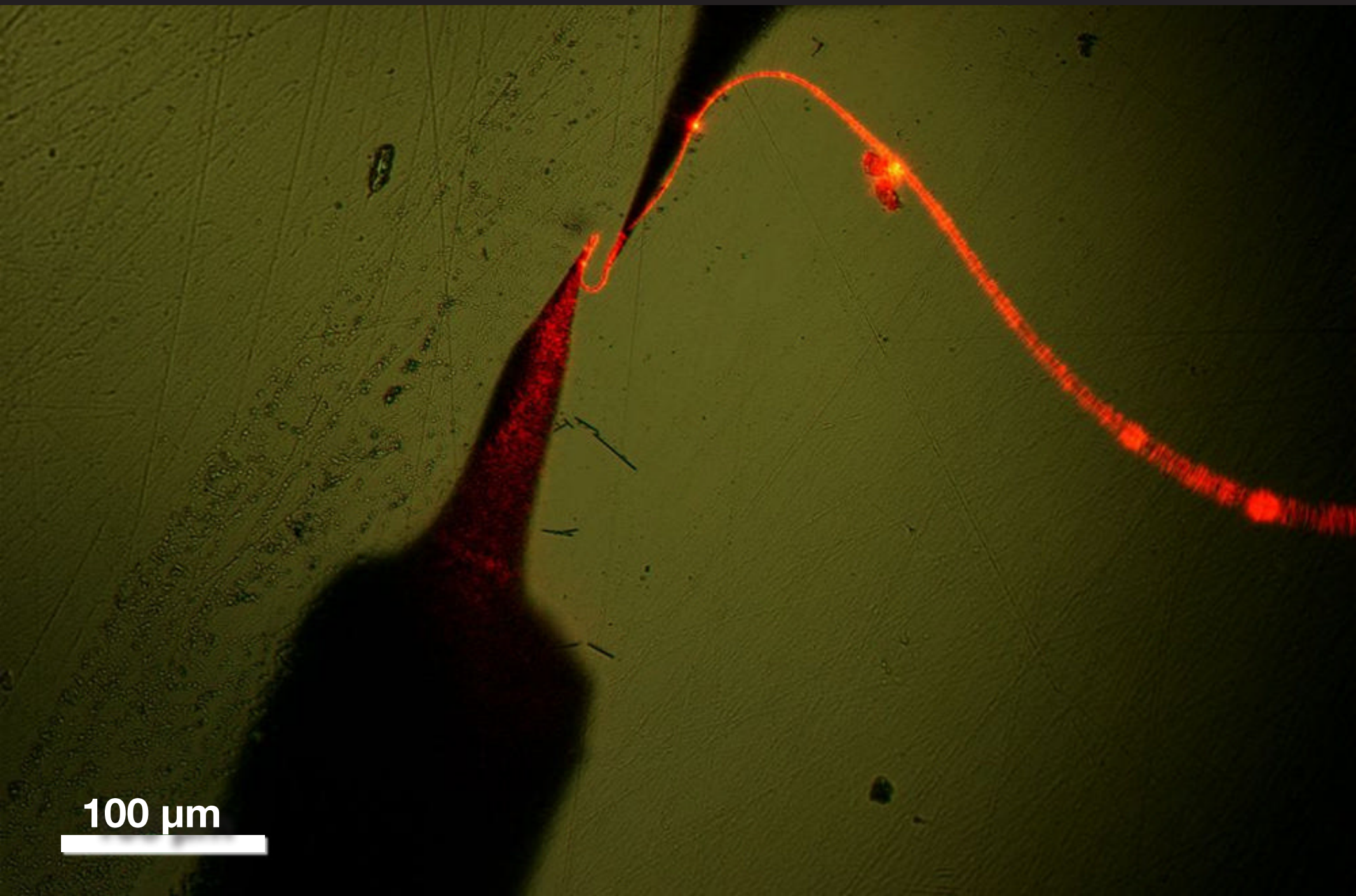
Manipulating light at the nanoscale



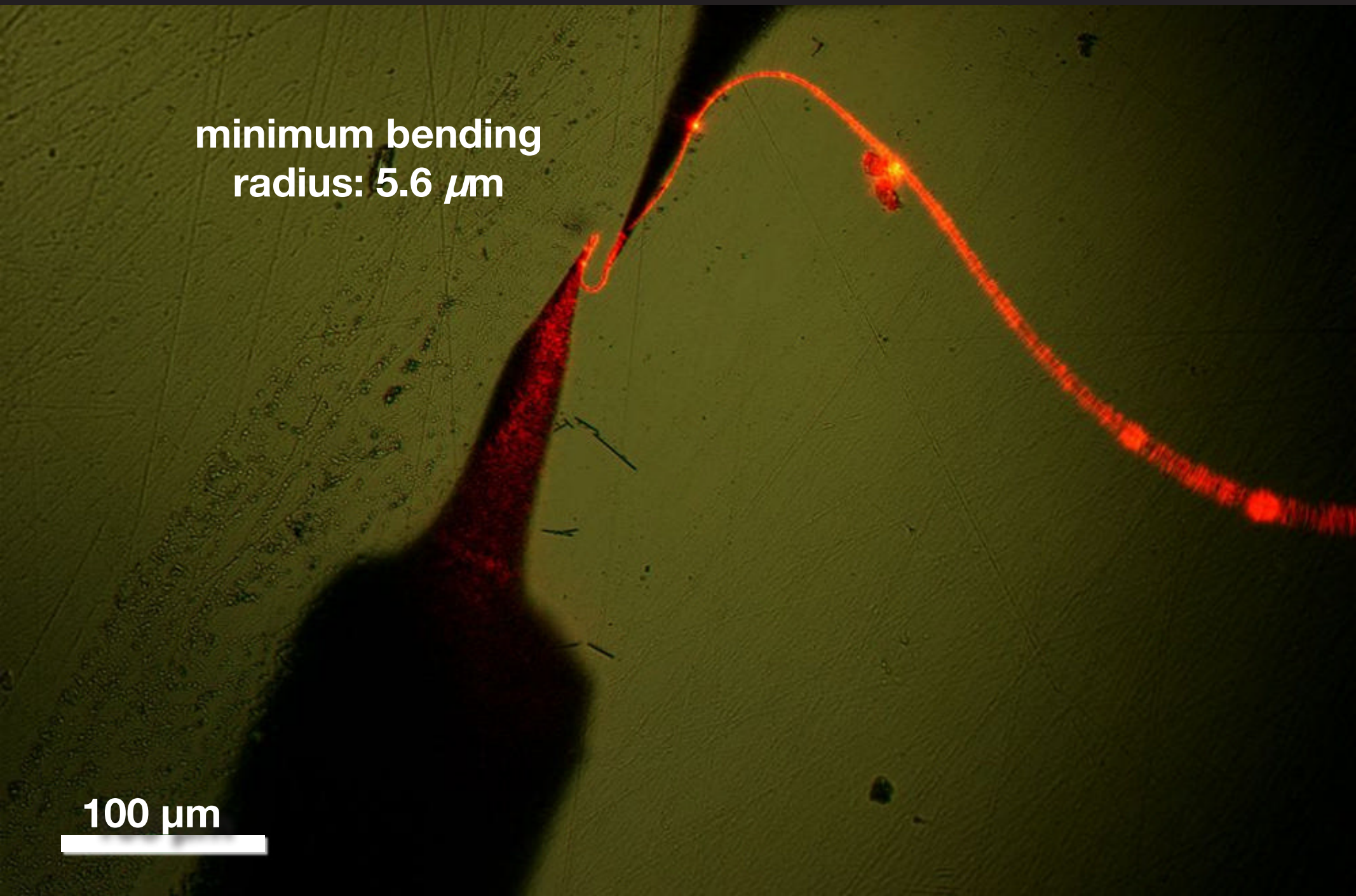
Manipulating light at the nanoscale



Manipulating light at the nanoscale

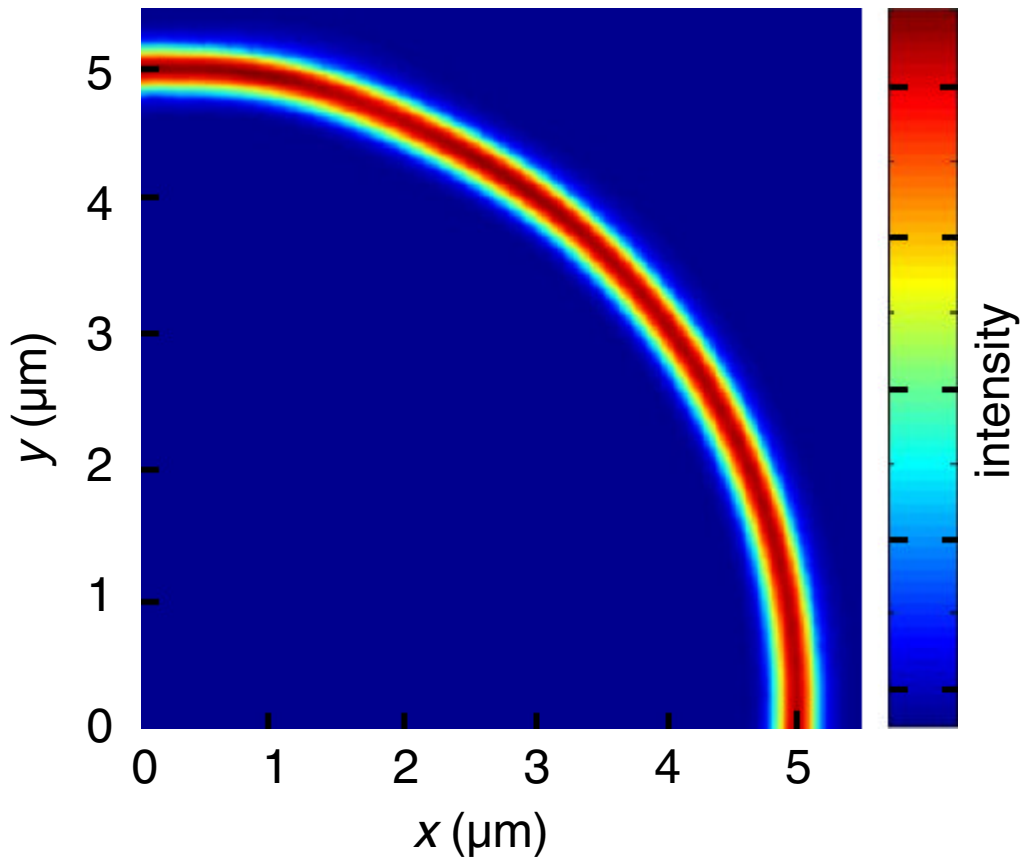


Manipulating light at the nanoscale

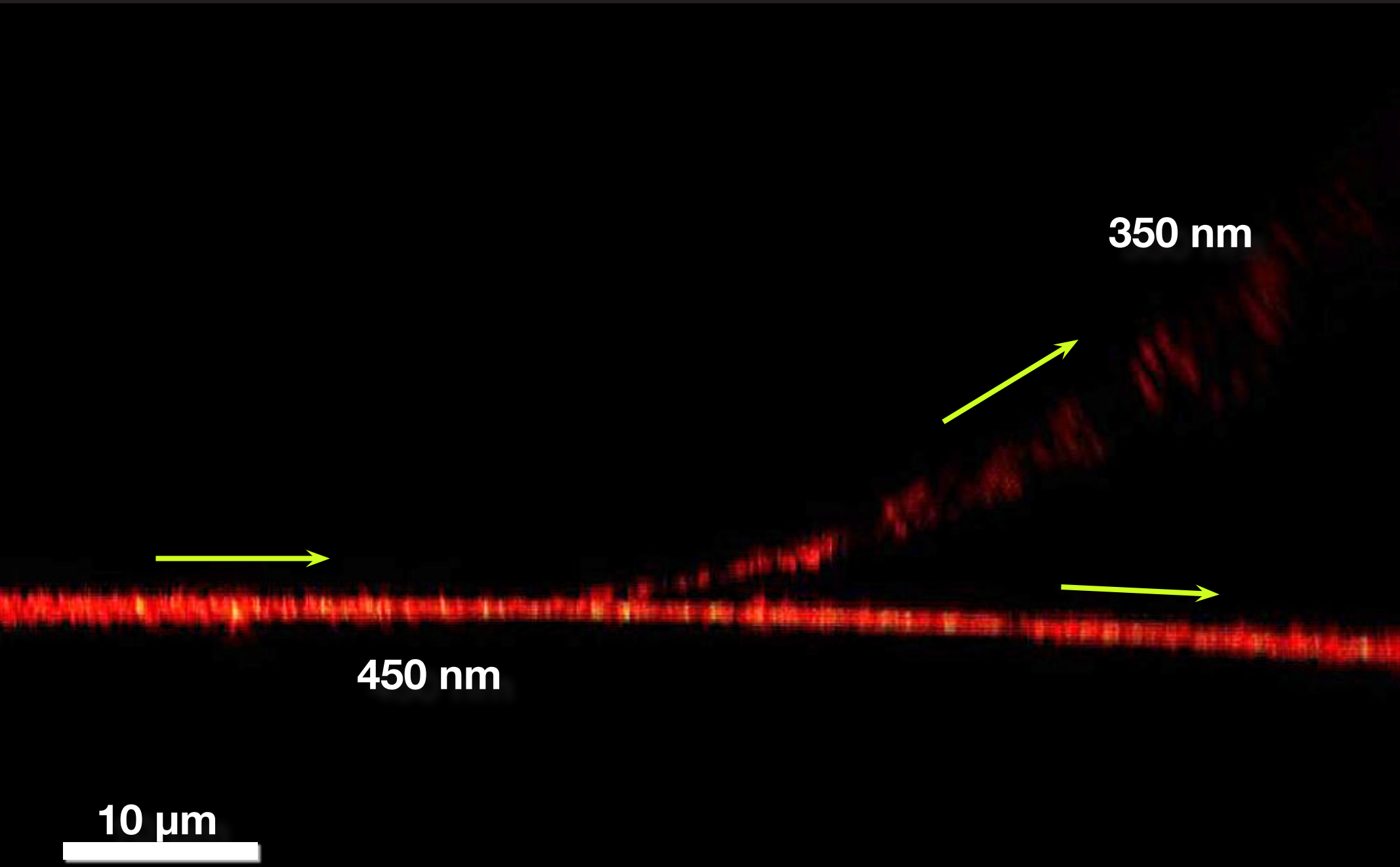


Manipulating light at the nanoscale

virtually no loss through 5 μm corner!



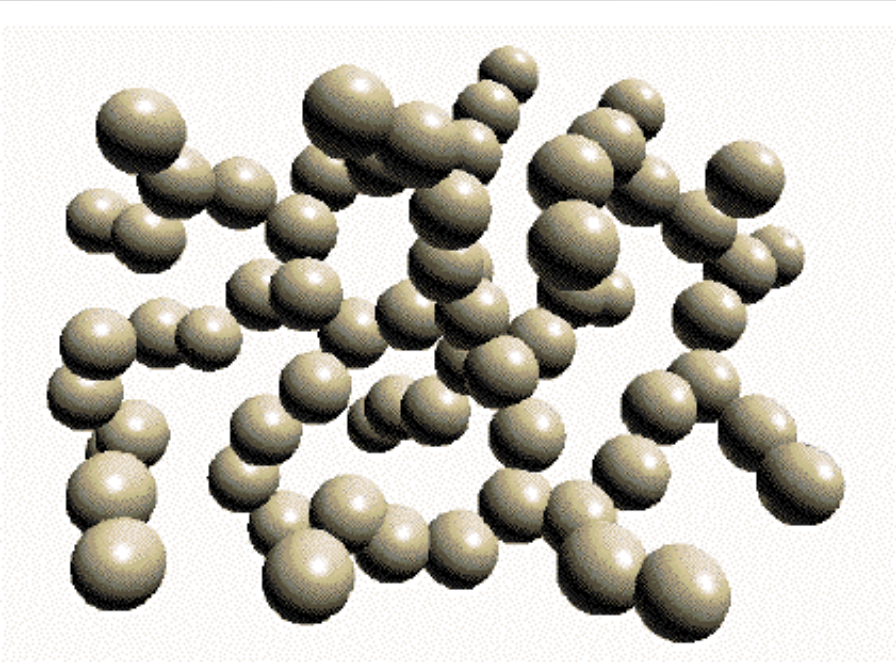
Manipulating light at the nanoscale

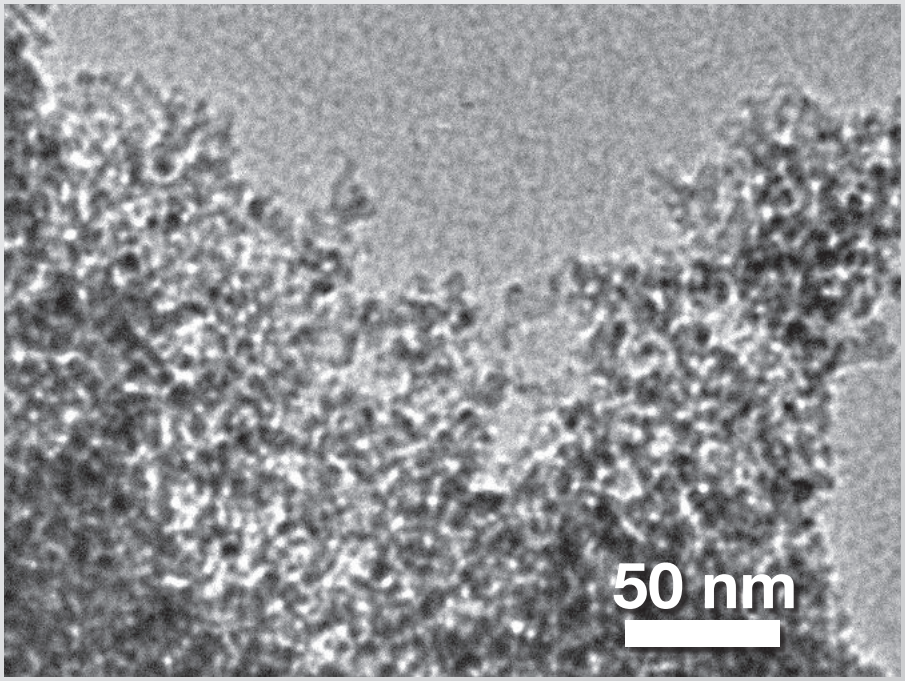


Manipulating light at the nanoscale

Manipulating light at the nanoscale

Aerogel

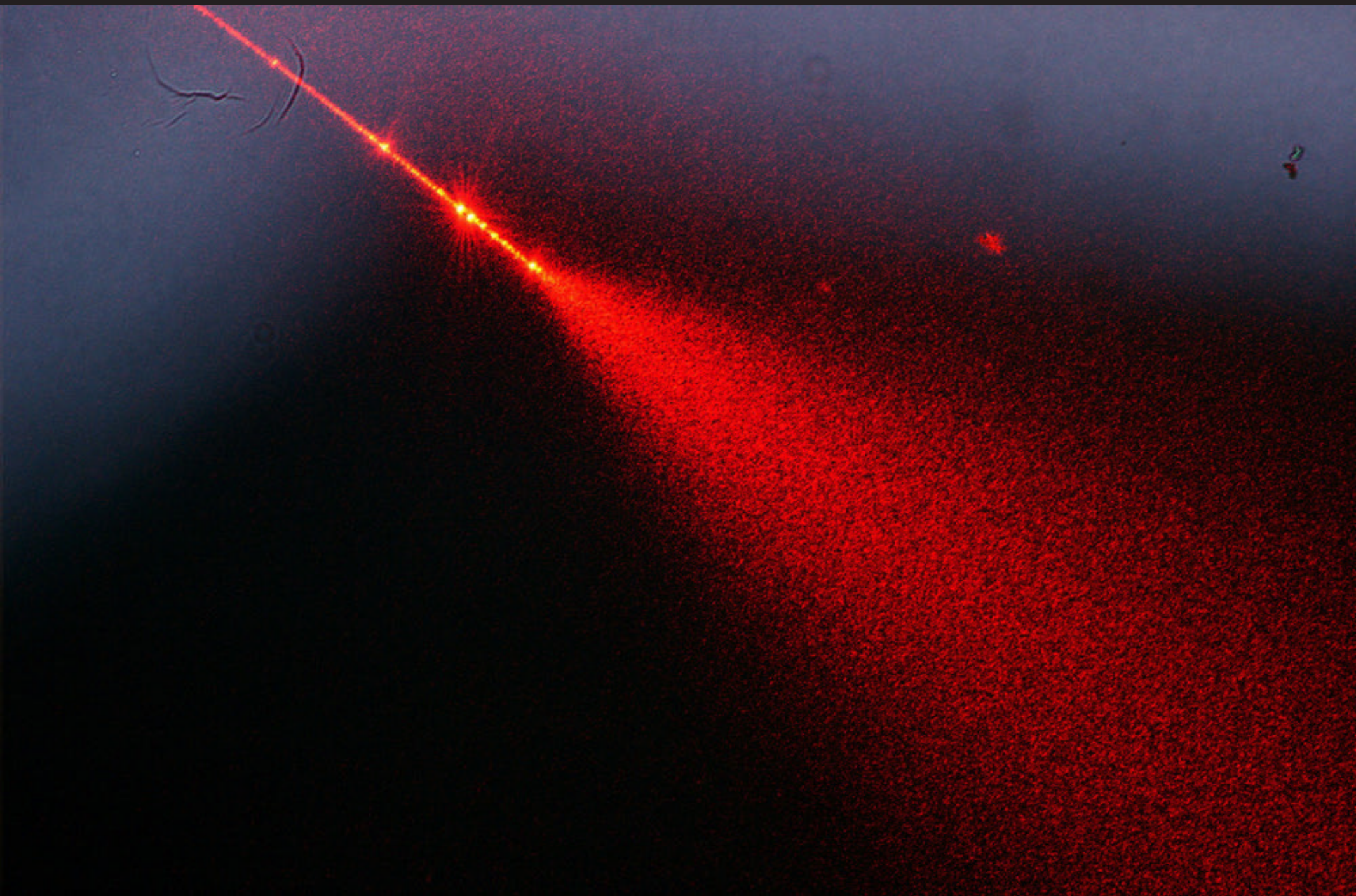




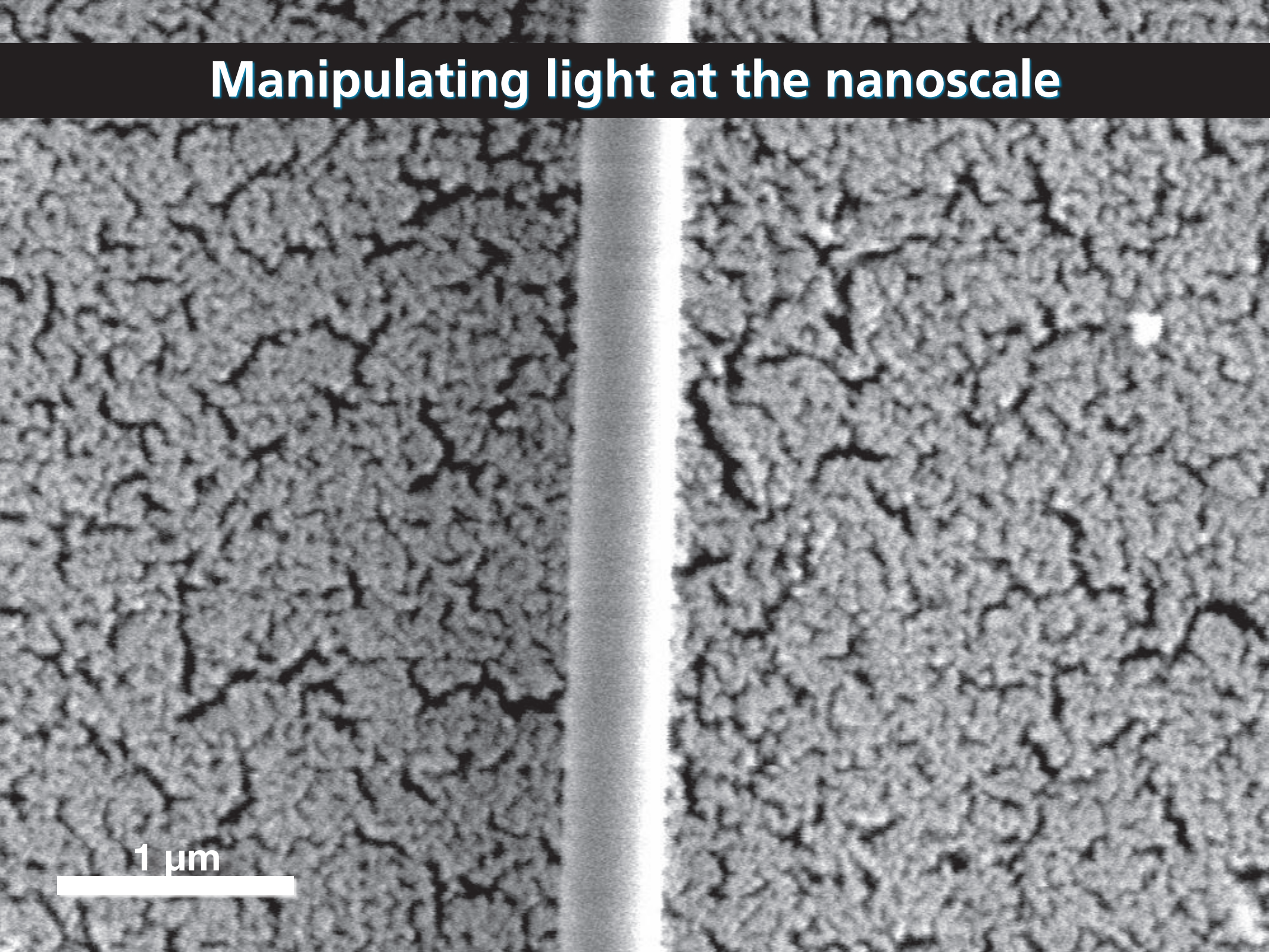
density: 1.9 kg/m^3

index of refraction: 1.03–1.08

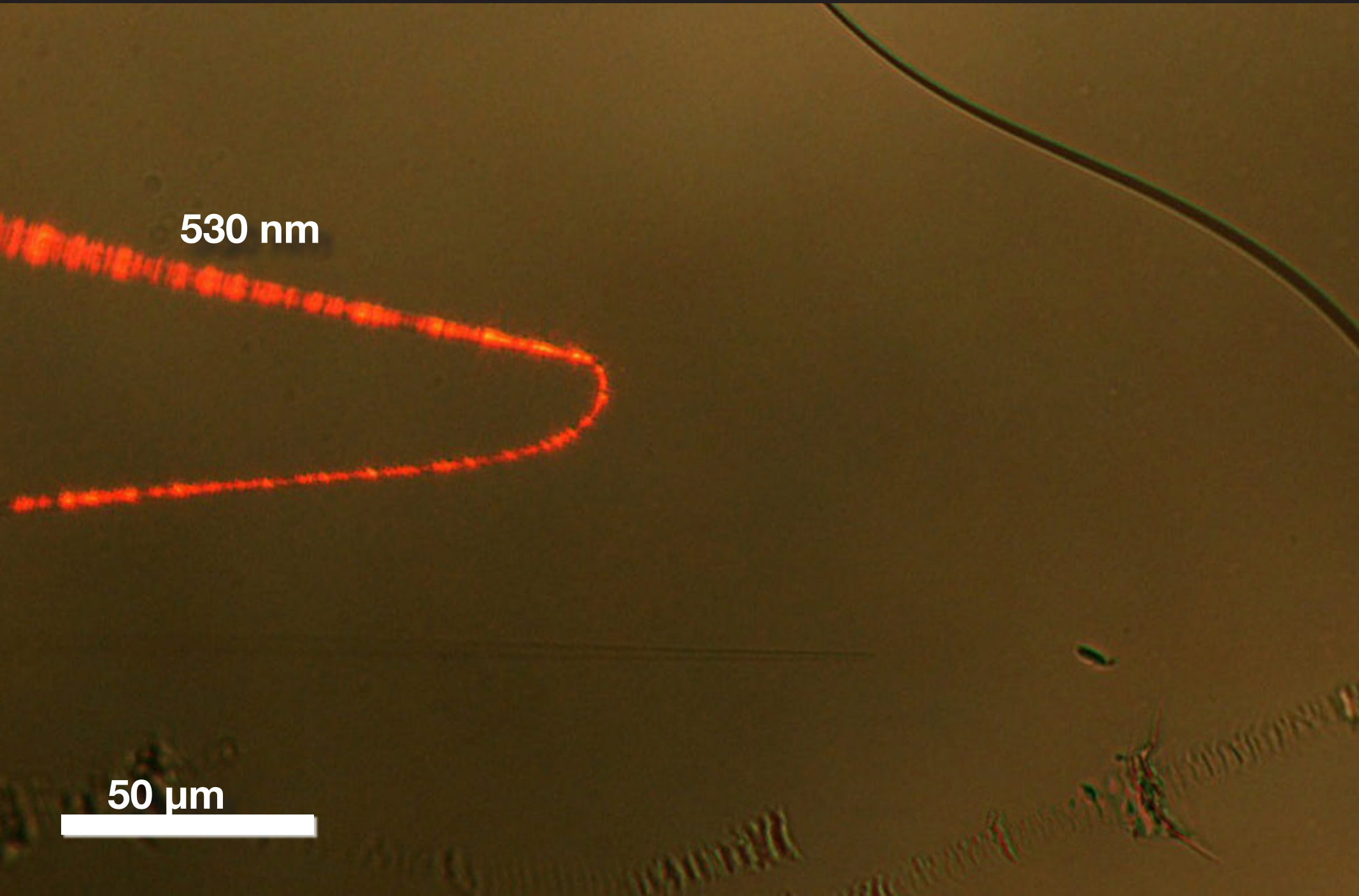
Manipulating light at the nanoscale



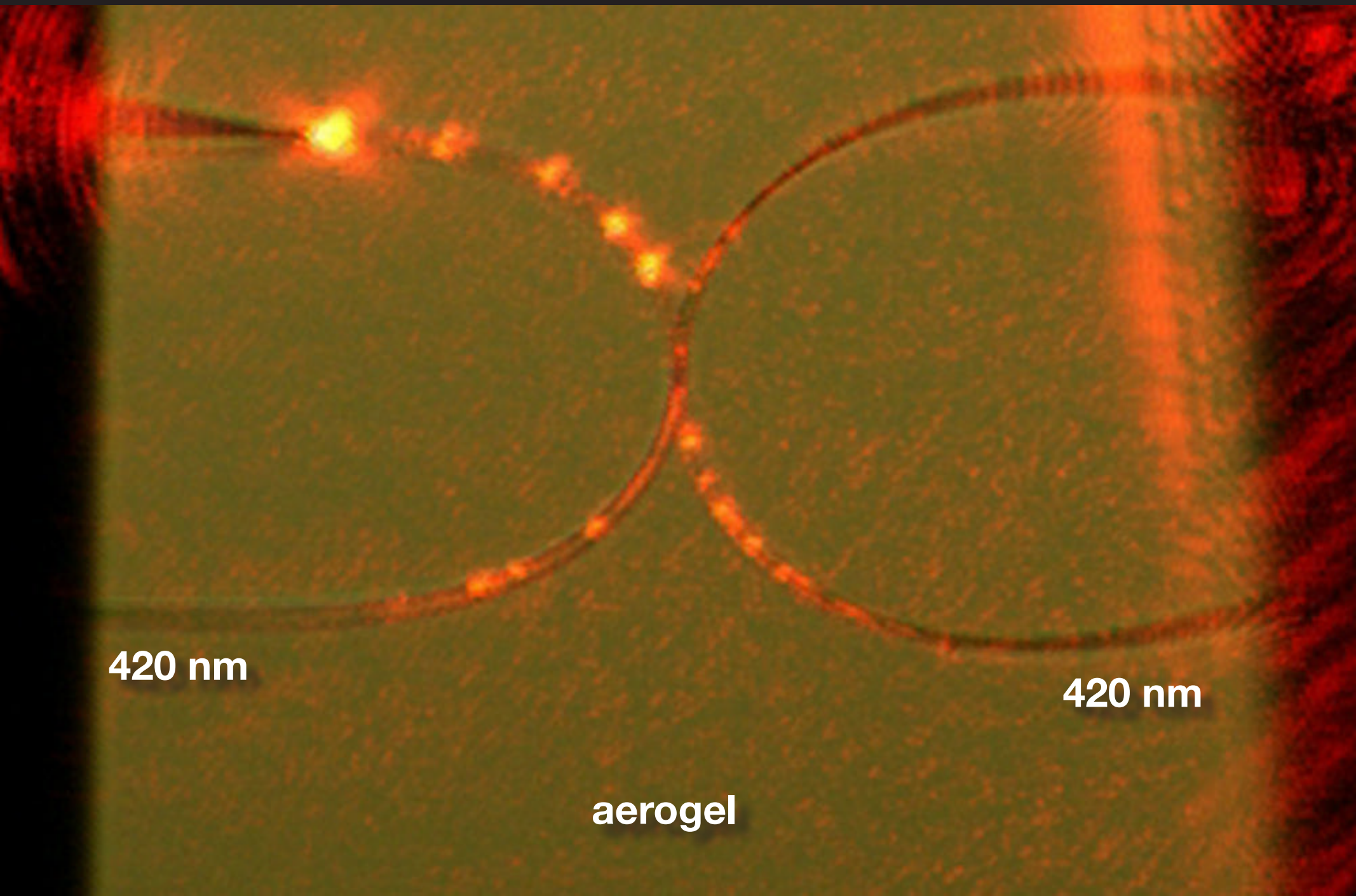
Manipulating light at the nanoscale



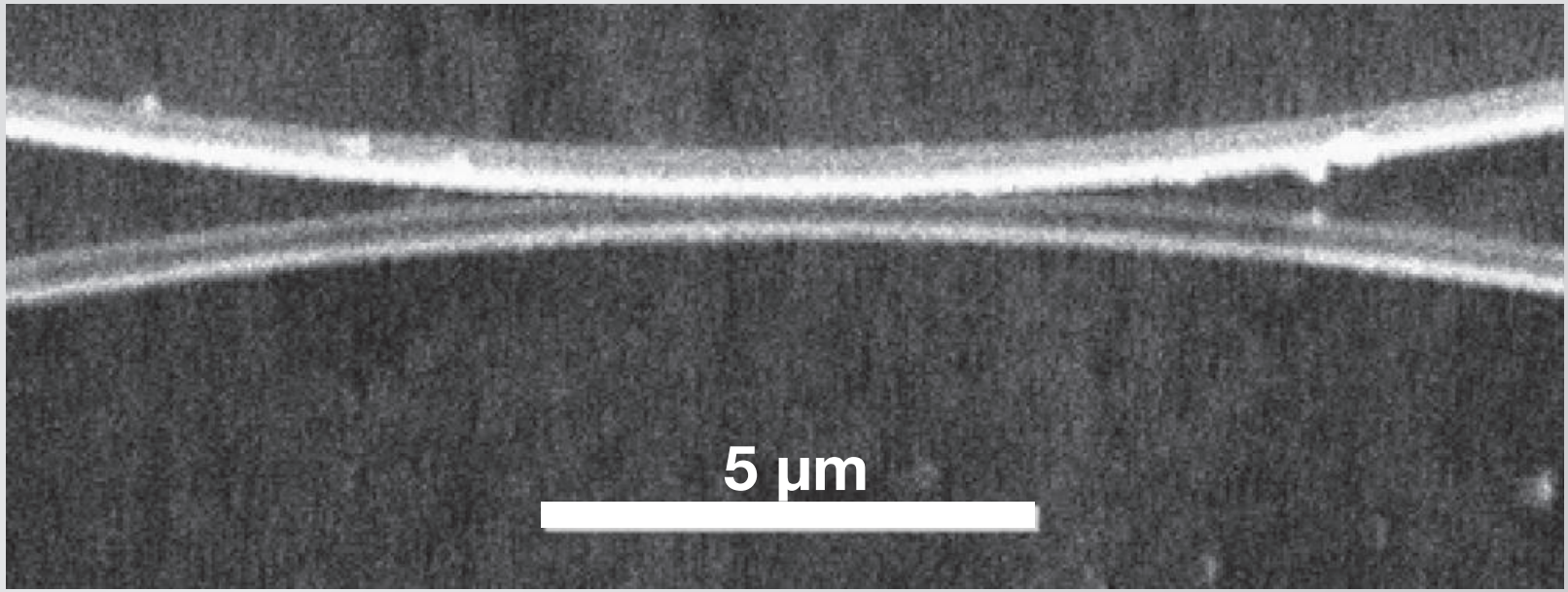
Manipulating light at the nanoscale



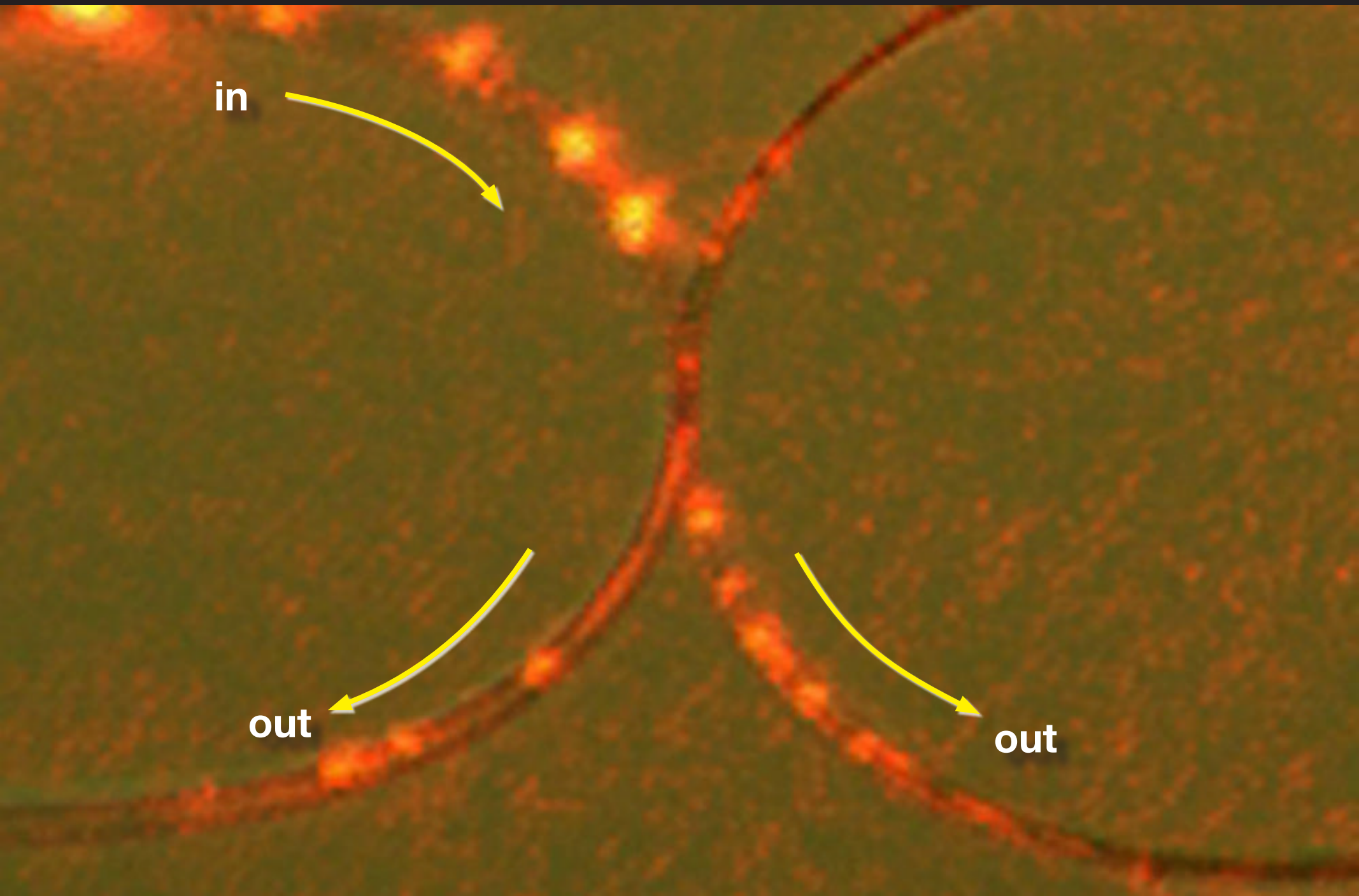
Manipulating light at the nanoscale



Manipulating light at the nanoscale



Manipulating light at the nanoscale



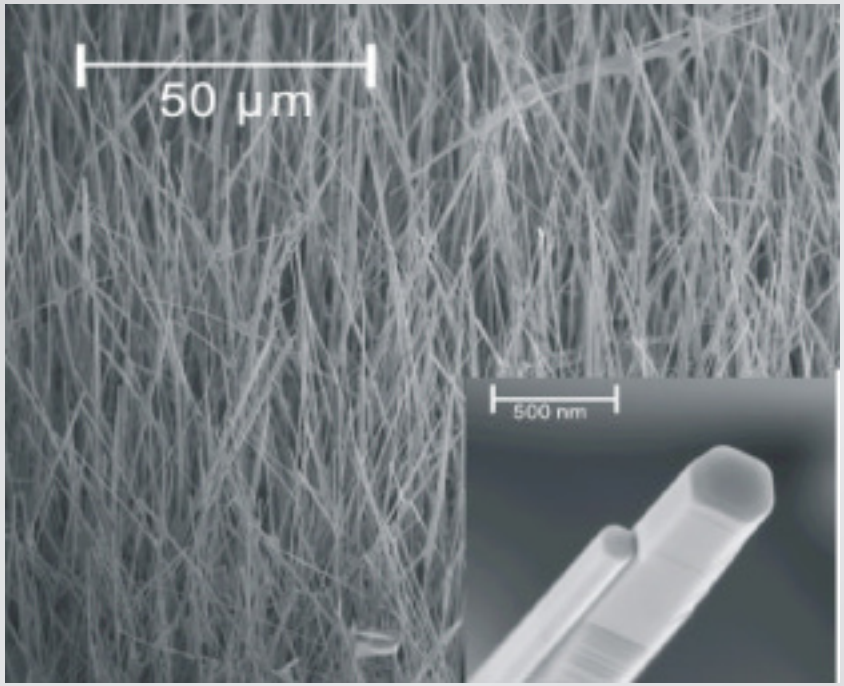
Manipulating light at the nanoscale

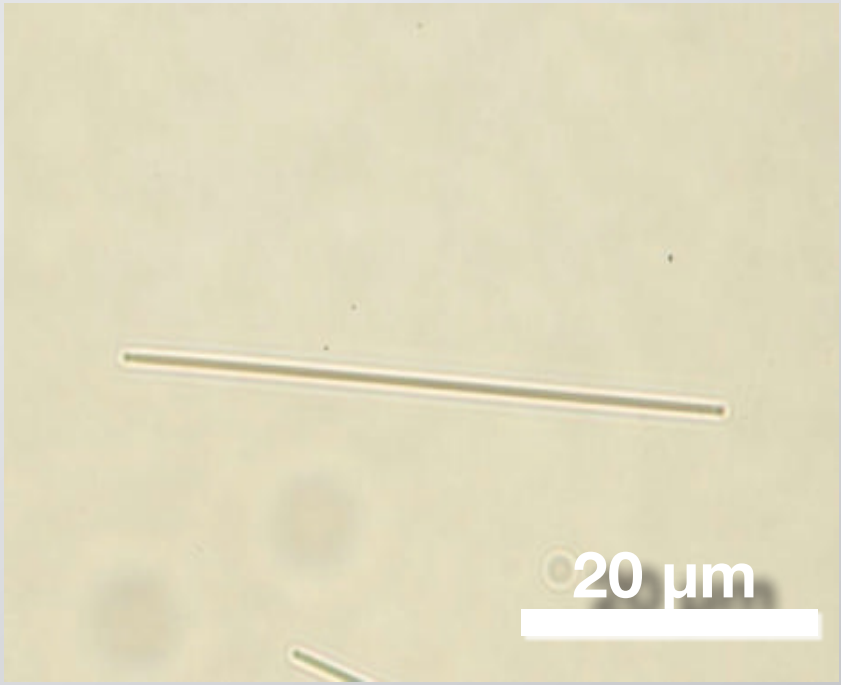
use tapered fibers to couple light to nanoscale objects

Manipulating light at the nanoscale

Manipulating light at the nanoscale

vapor transport grown ZnO nanowires





80–400 nm diameter, up to 80 µm long

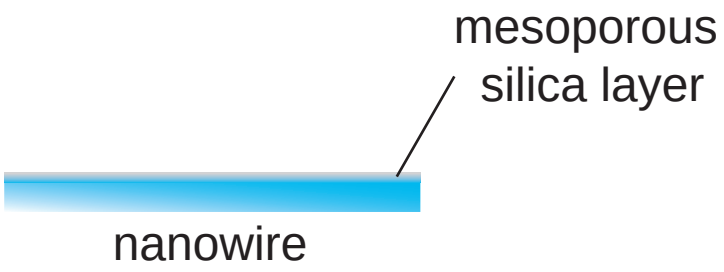
Manipulating light at the nanoscale

best of both worlds

ZnO	silica
bottom-up	top-down
semiconductor	glass
active photonic devices	passive waveguides
electrical operation	link to macroworld

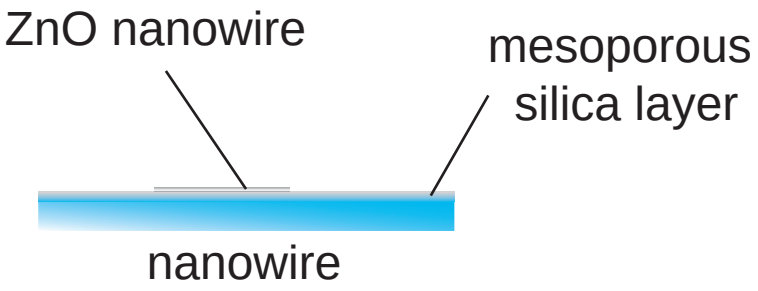
Manipulating light at the nanoscale

coupling to ZnO nanowires



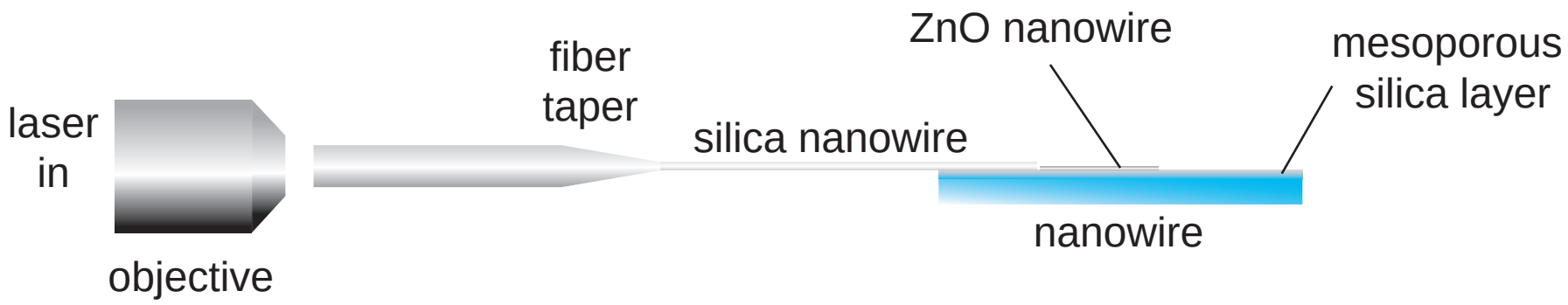
Manipulating light at the nanoscale

coupling to ZnO nanowires



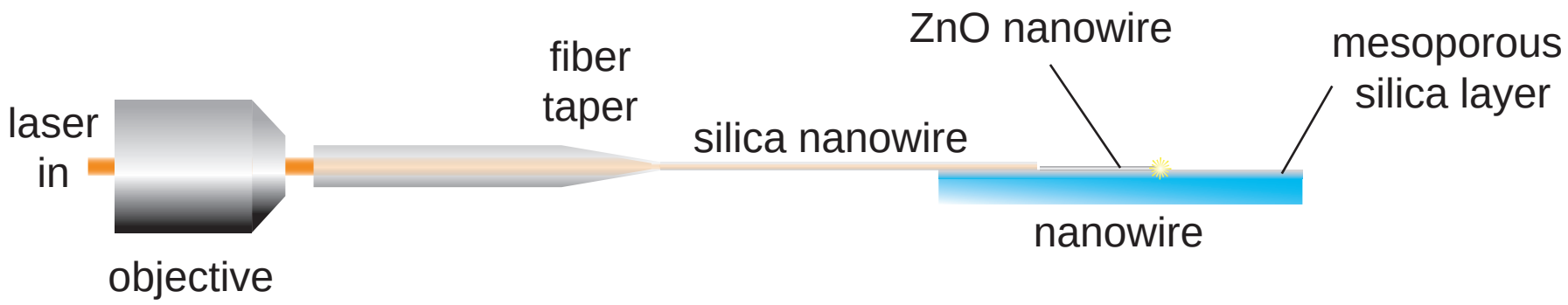
Manipulating light at the nanoscale

coupling to ZnO nanowires

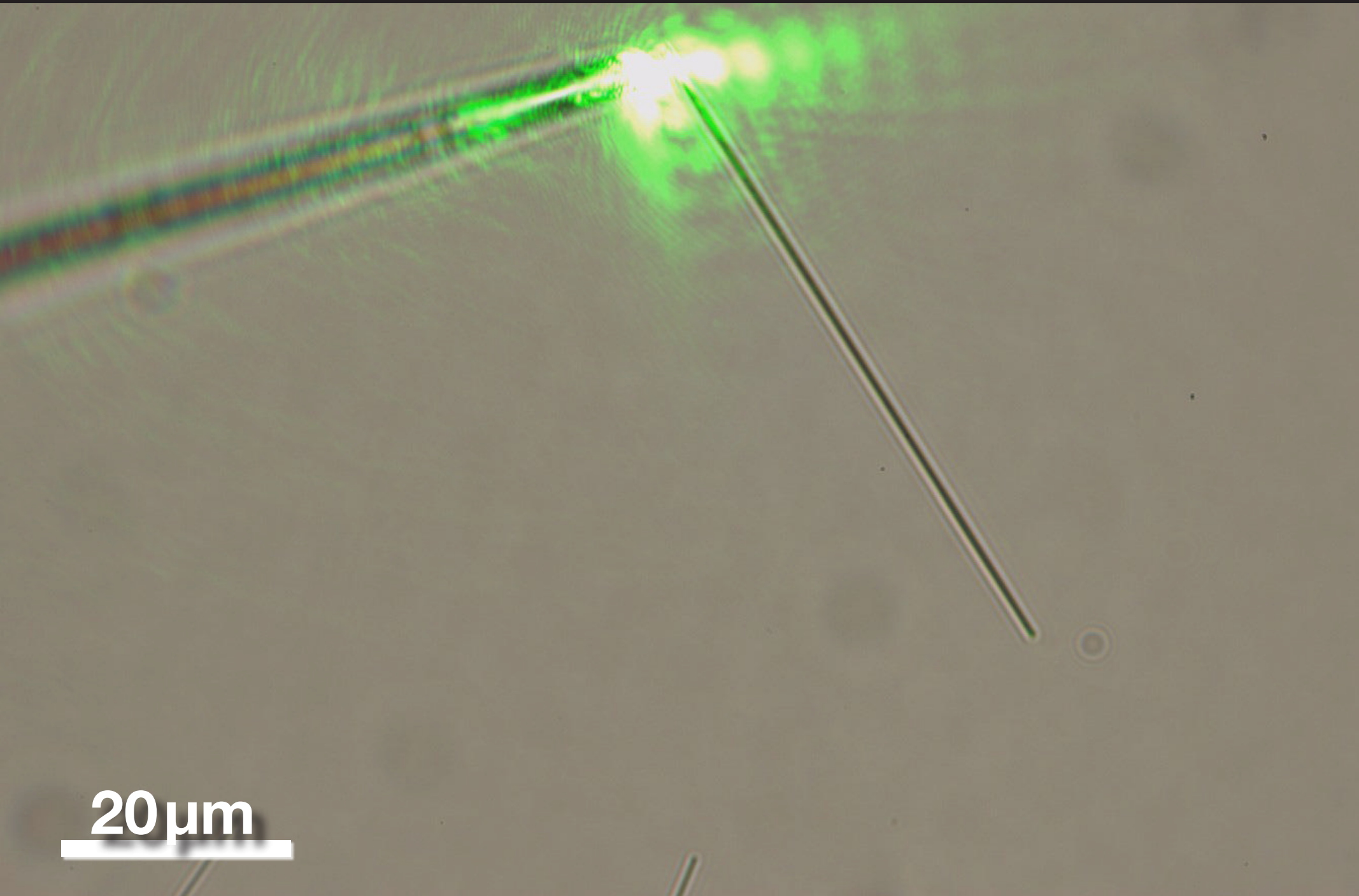


Manipulating light at the nanoscale

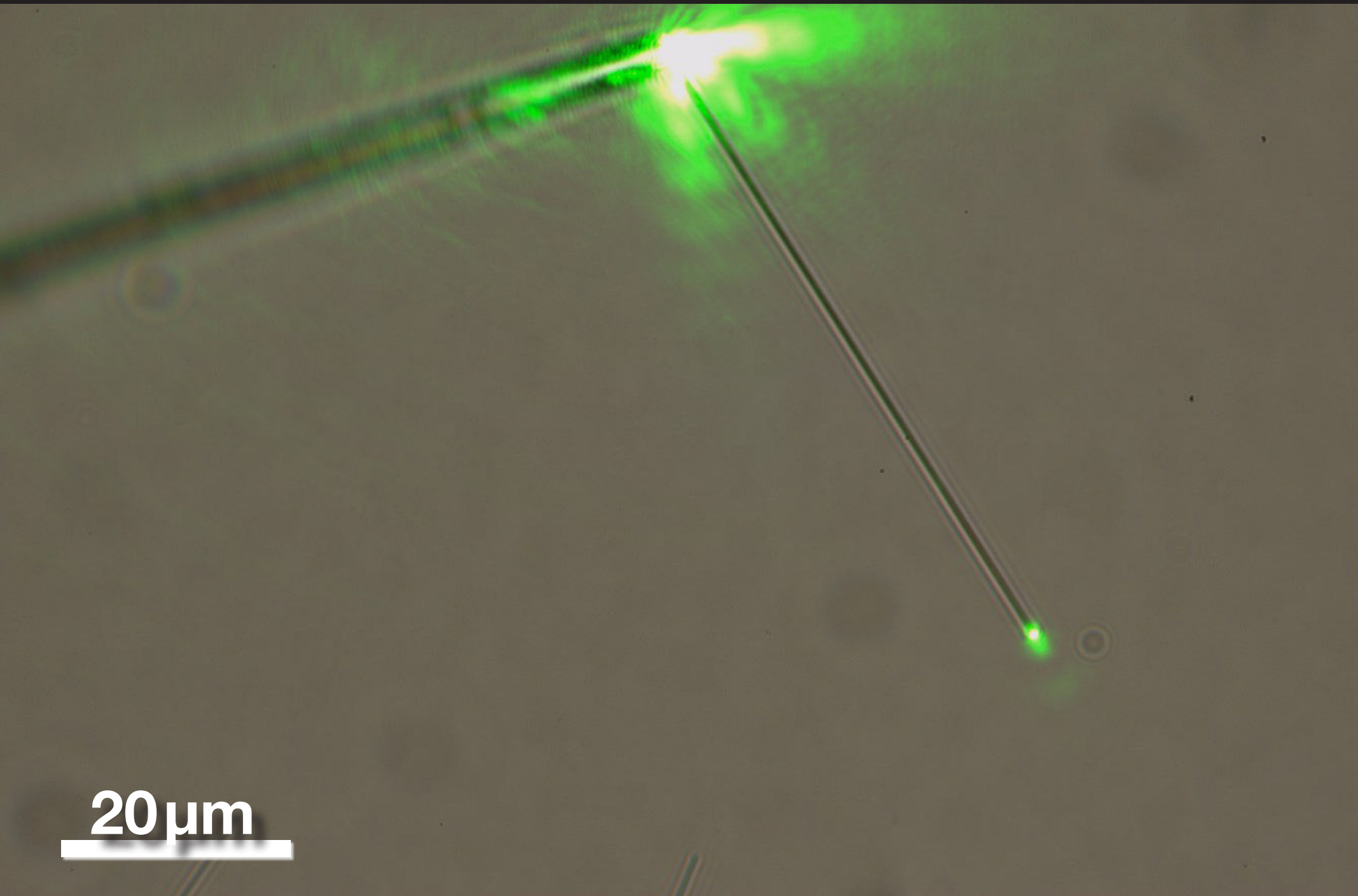
coupling to ZnO nanowires



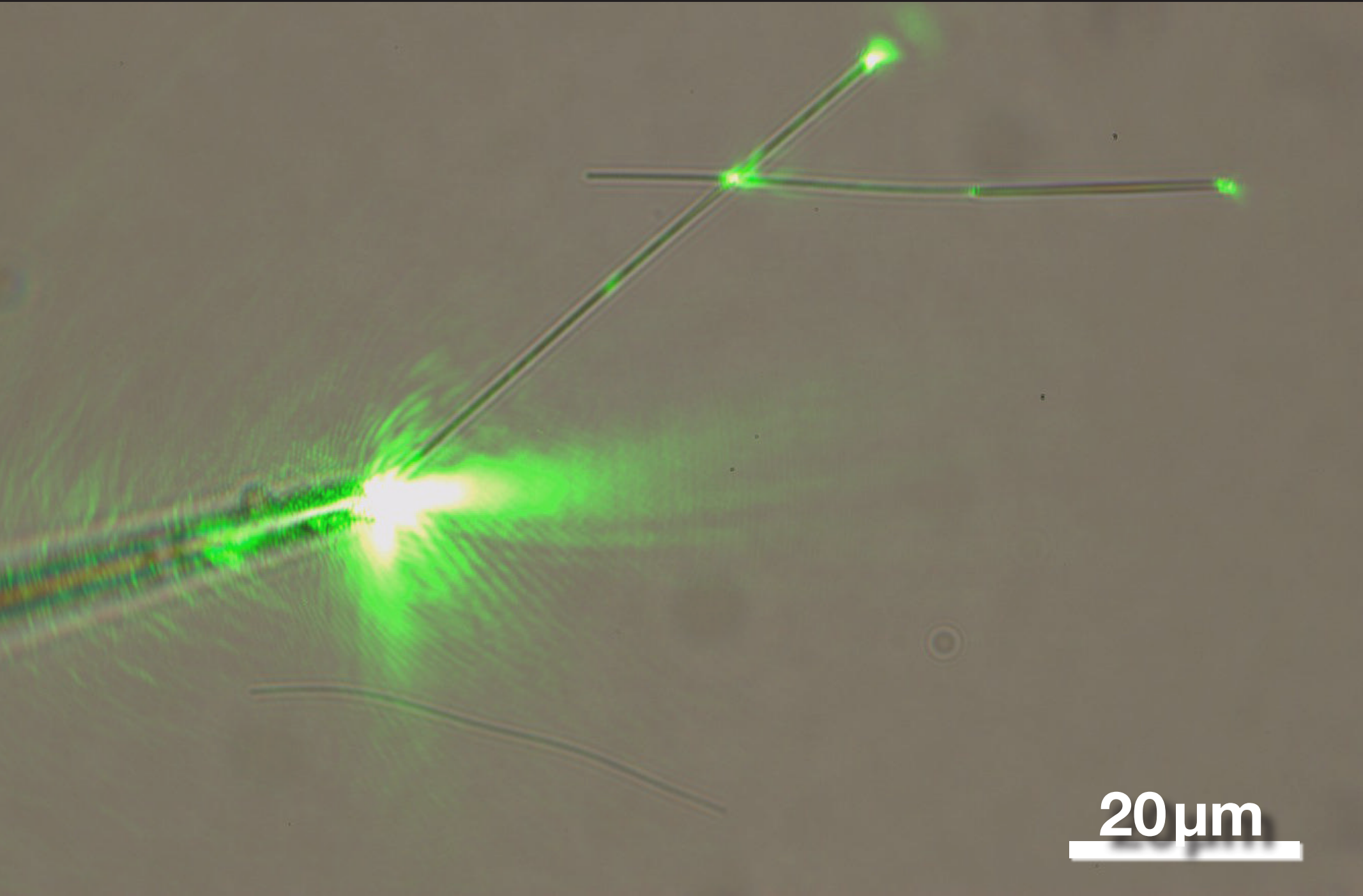
Manipulating light at the nanoscale



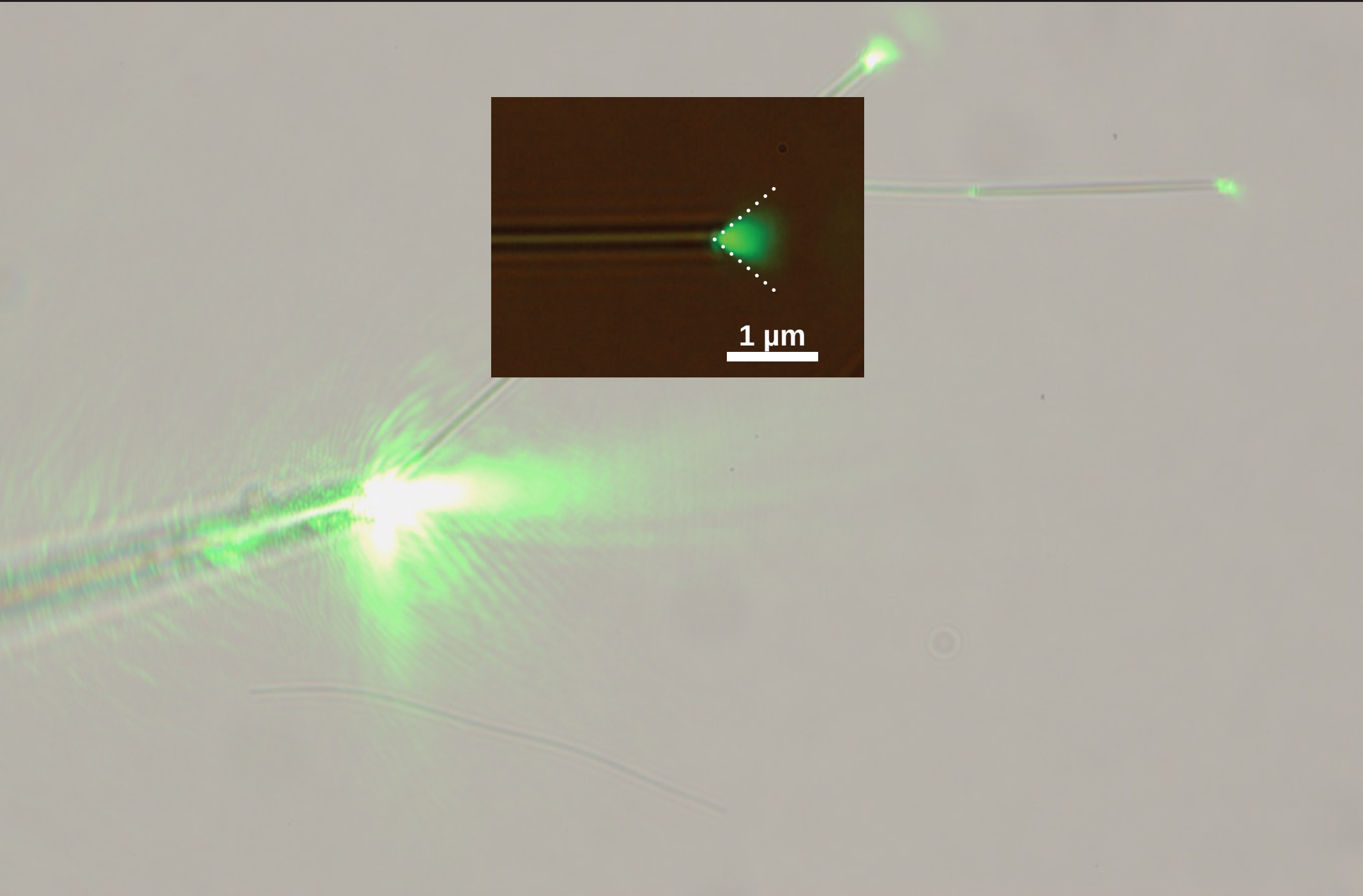
Manipulating light at the nanoscale



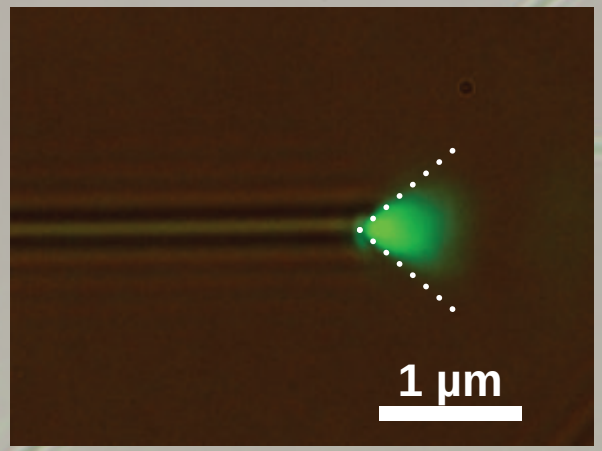
Manipulating light at the nanoscale



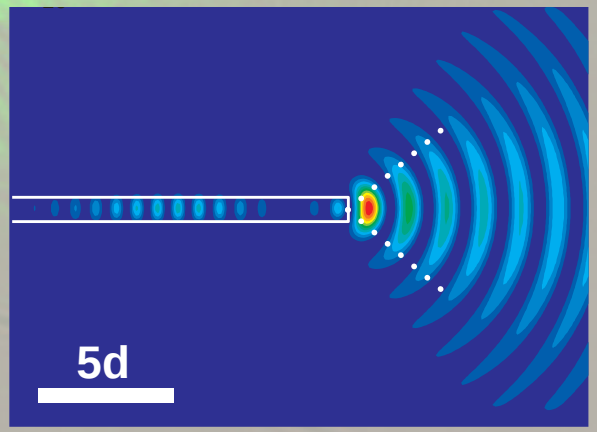
Manipulating light at the nanoscale



Manipulating light at the nanoscale

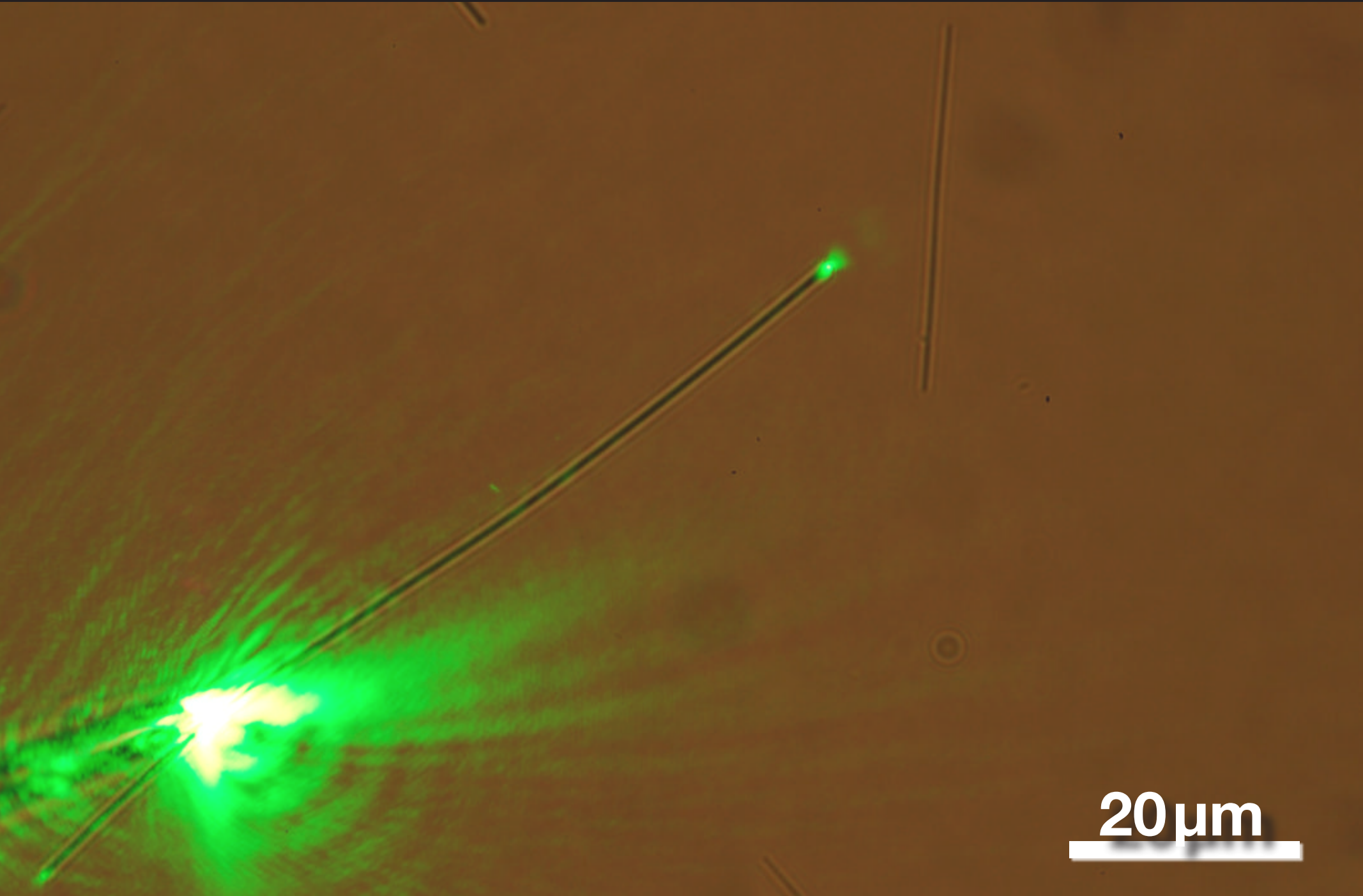


FDTD simulation

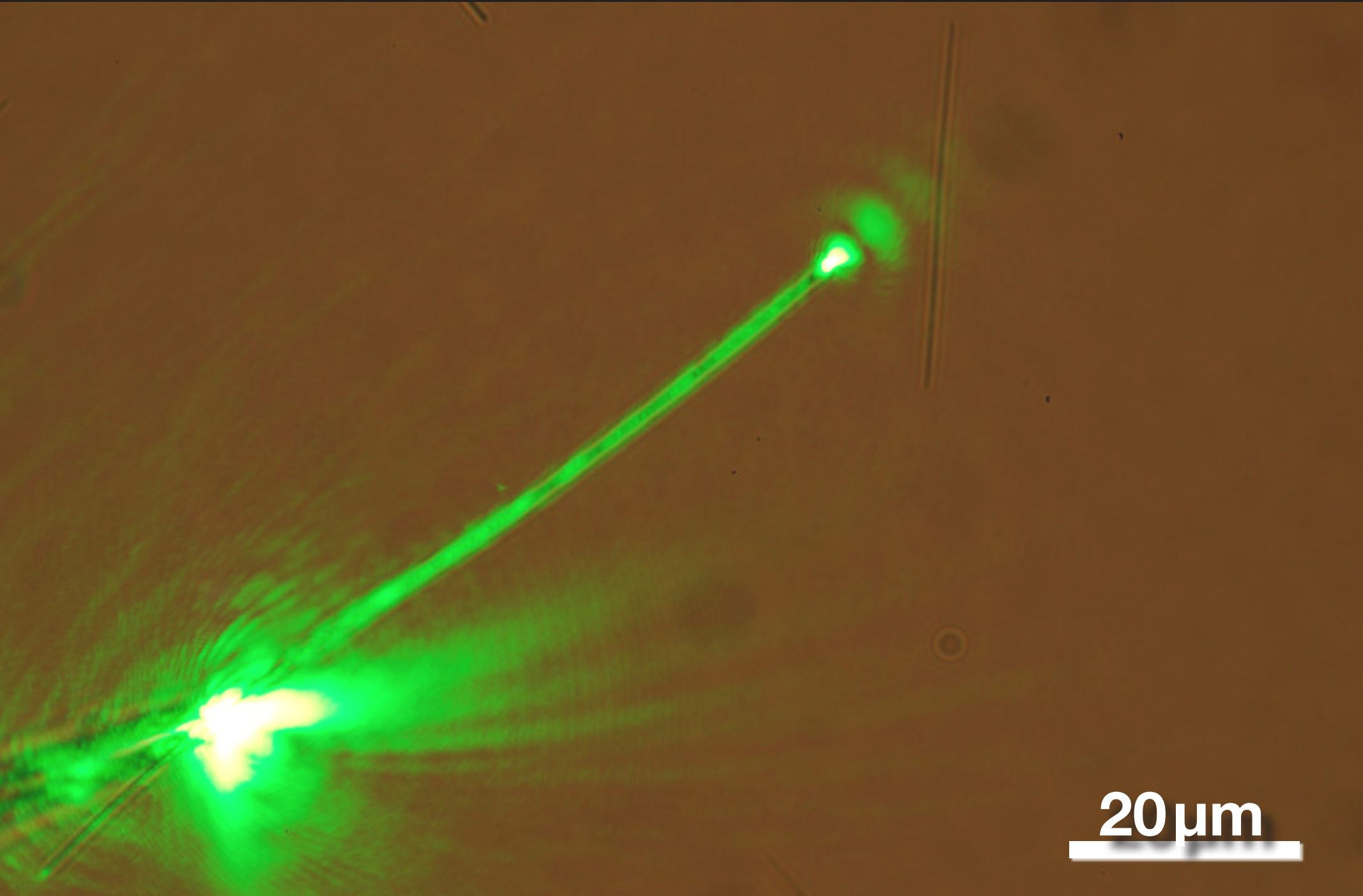


ab-initio.mit.edu/wiki/index/Meep

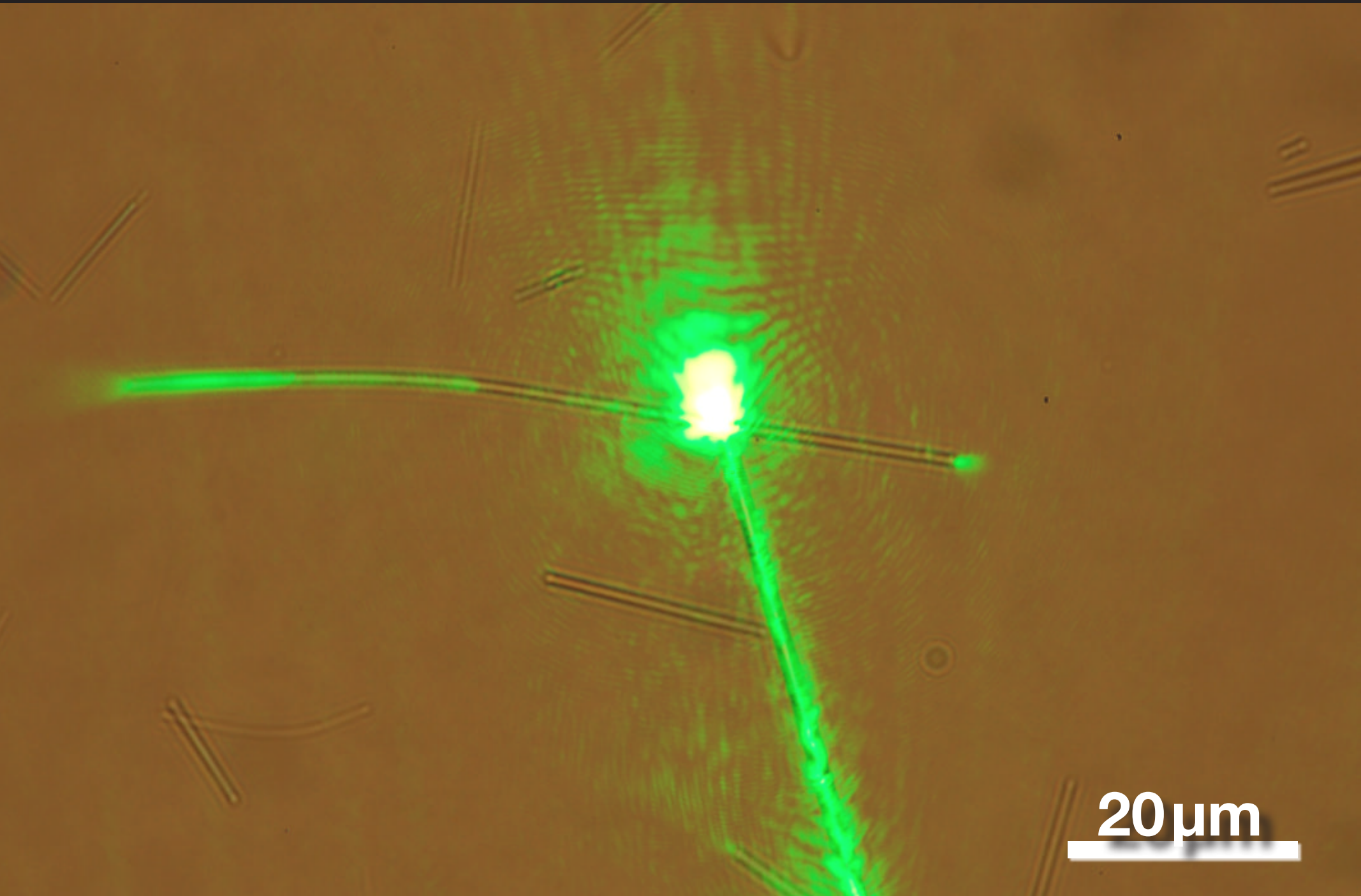
Manipulating light at the nanoscale



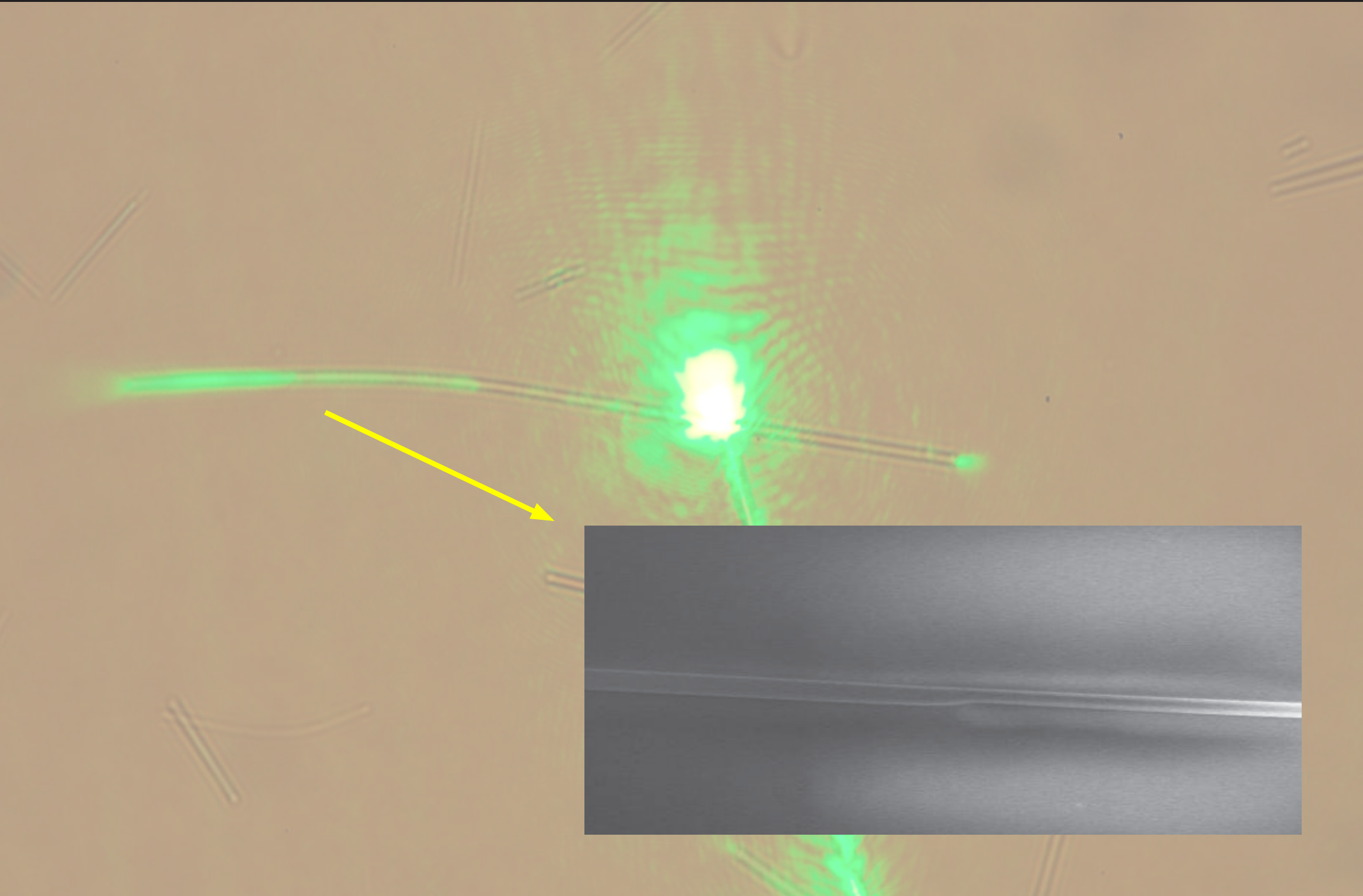
Manipulating light at the nanoscale



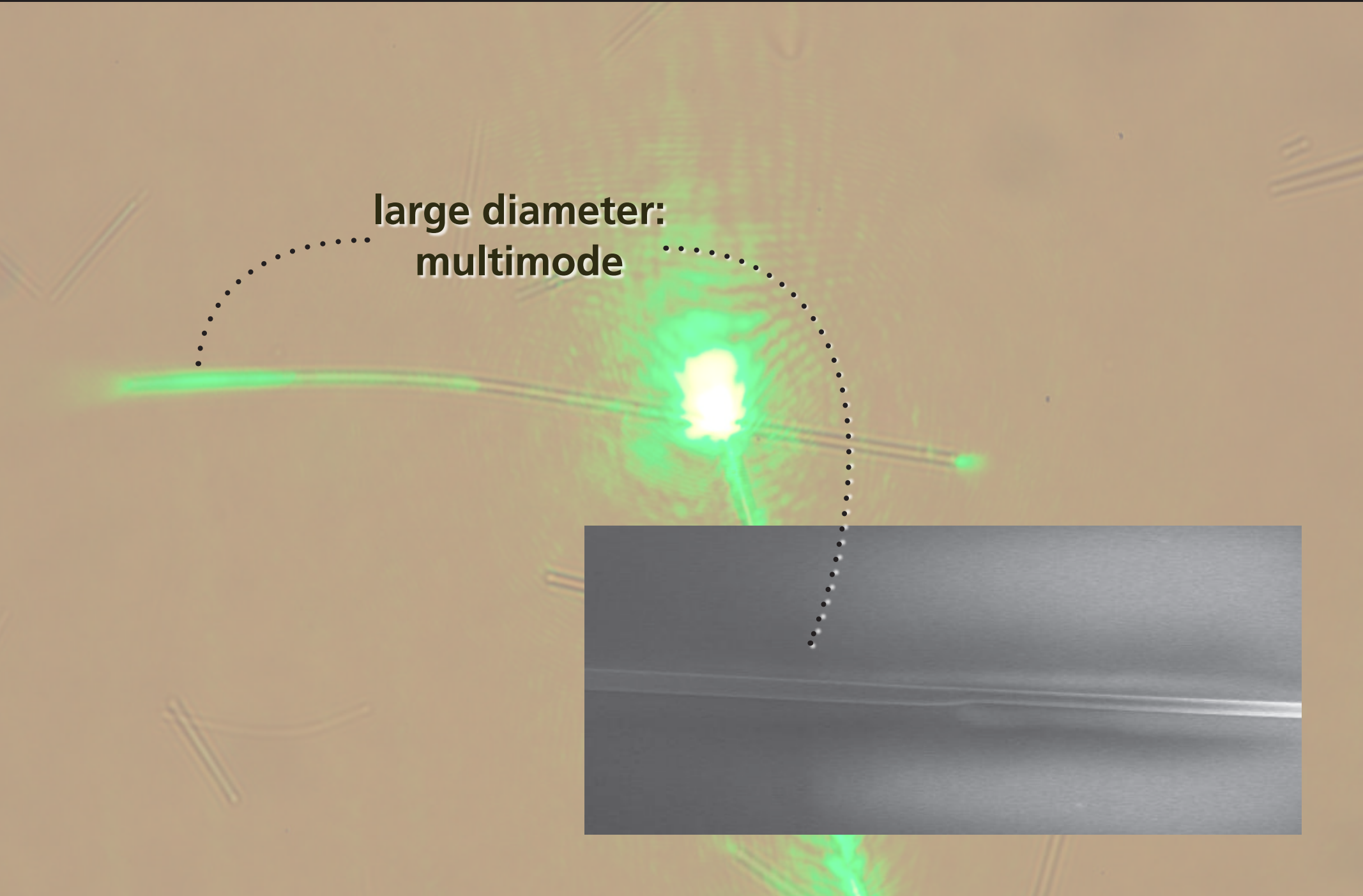
Manipulating light at the nanoscale



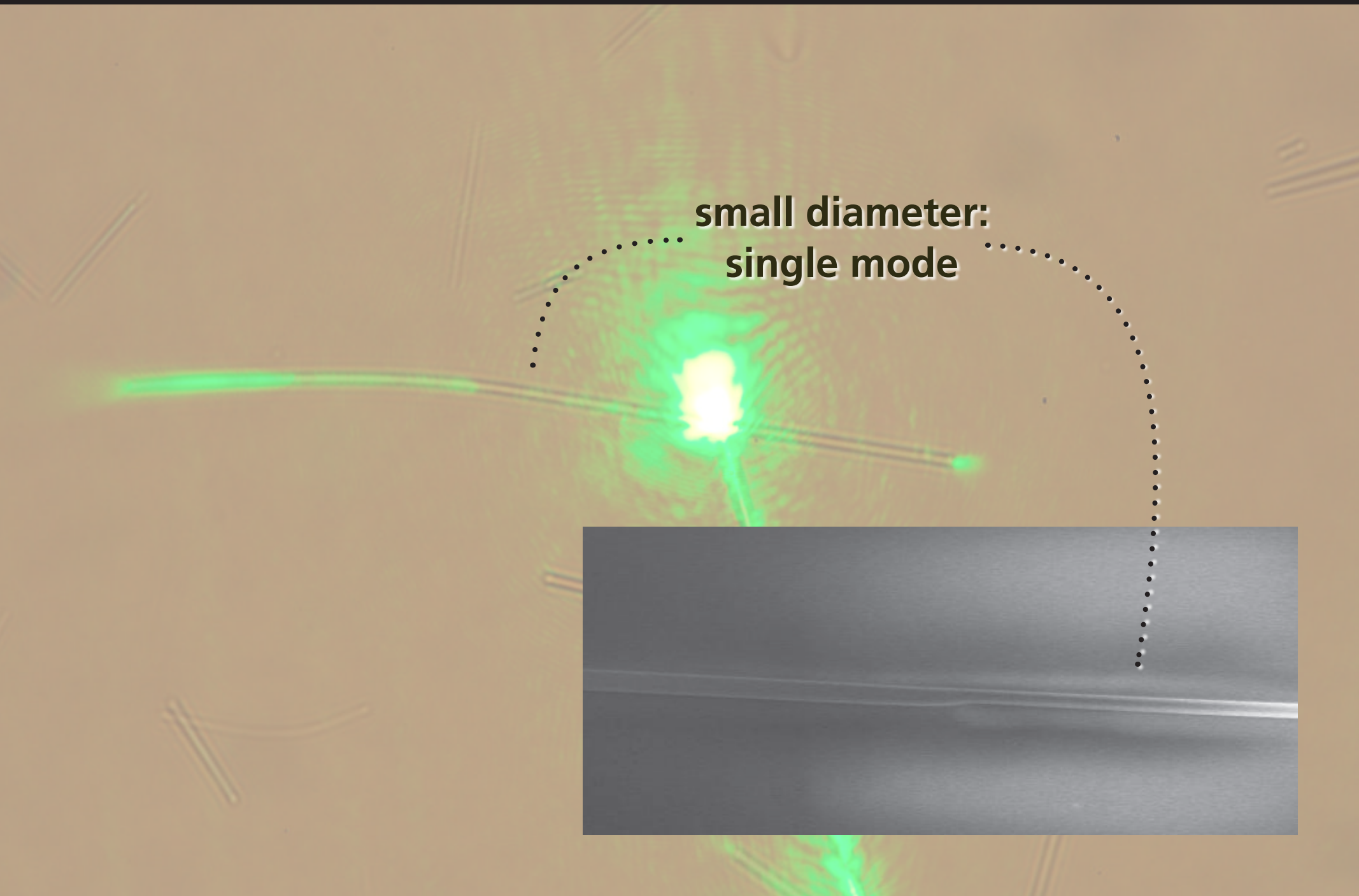
Manipulating light at the nanoscale



Manipulating light at the nanoscale



Manipulating light at the nanoscale



Manipulating light at the nanoscale

Points to keep in mind:

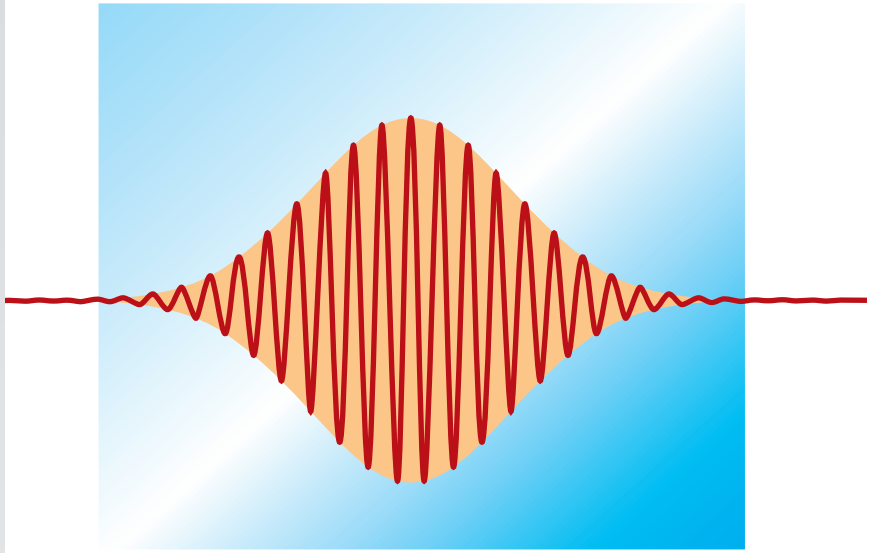
- low loss
- large evanescent field
- convenient coupling to nanoscale

Outline

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

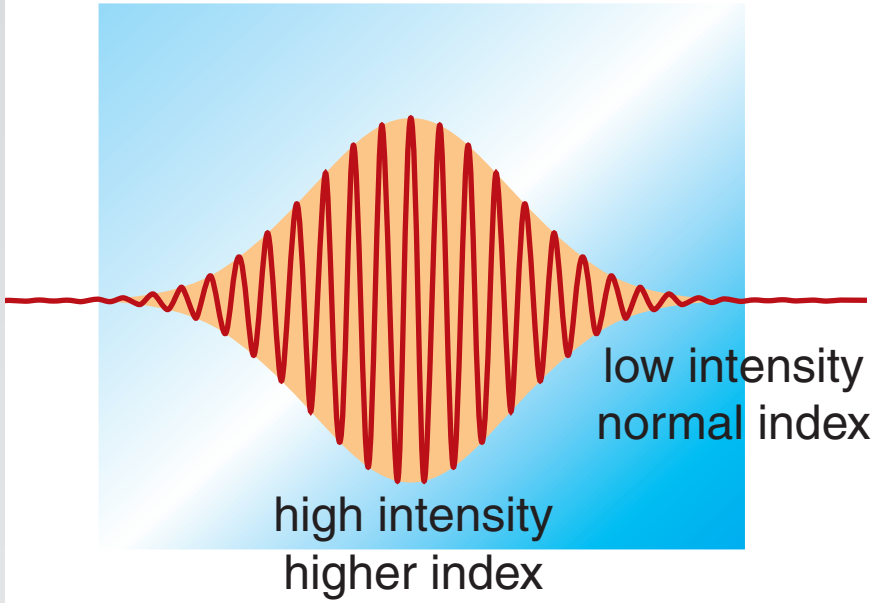
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



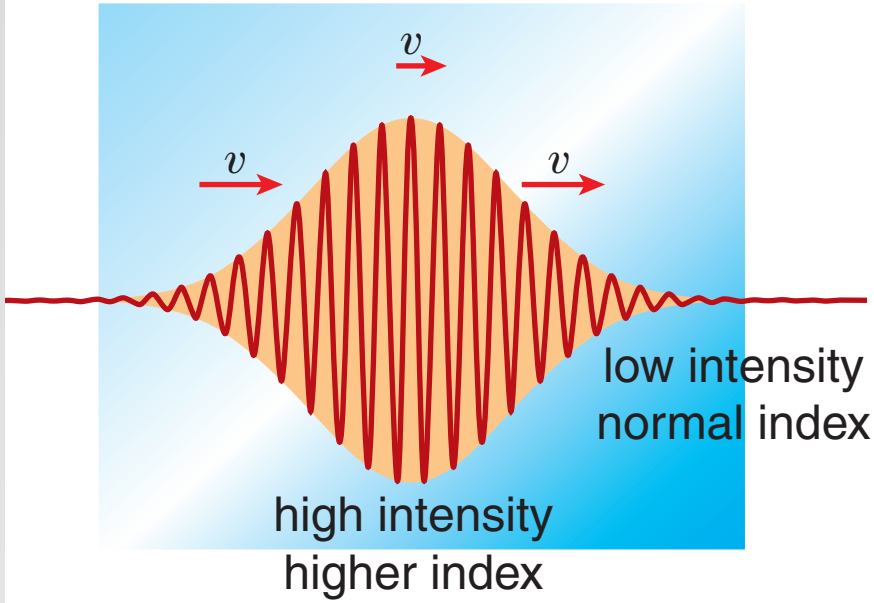
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



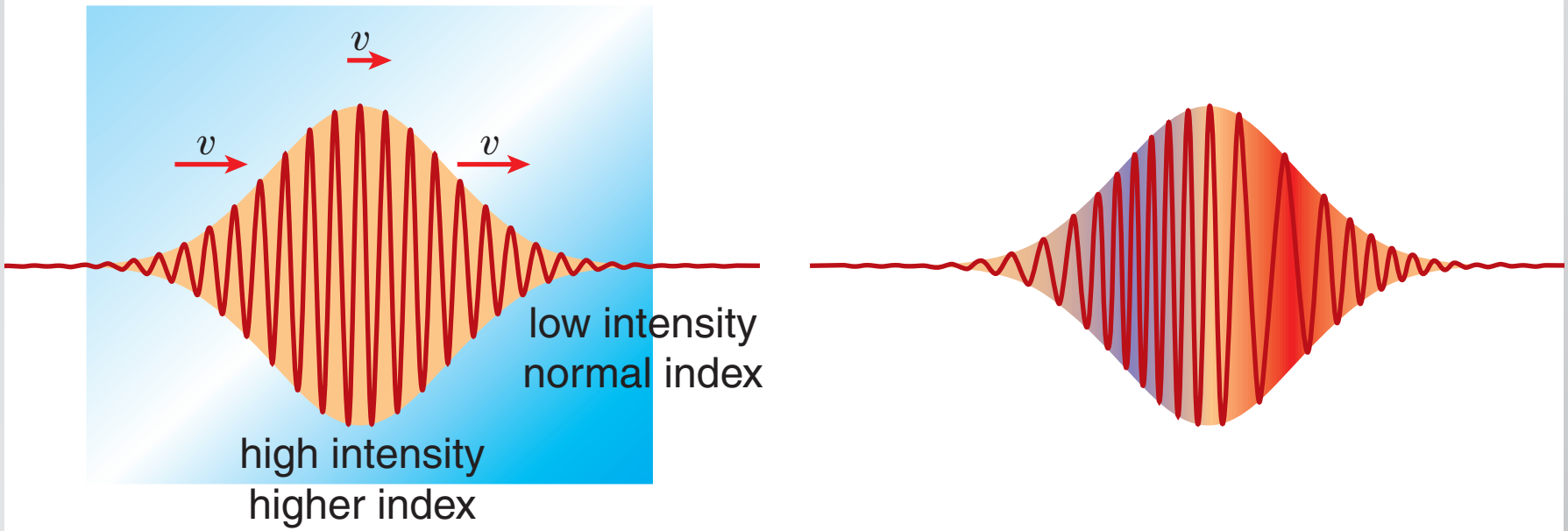
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



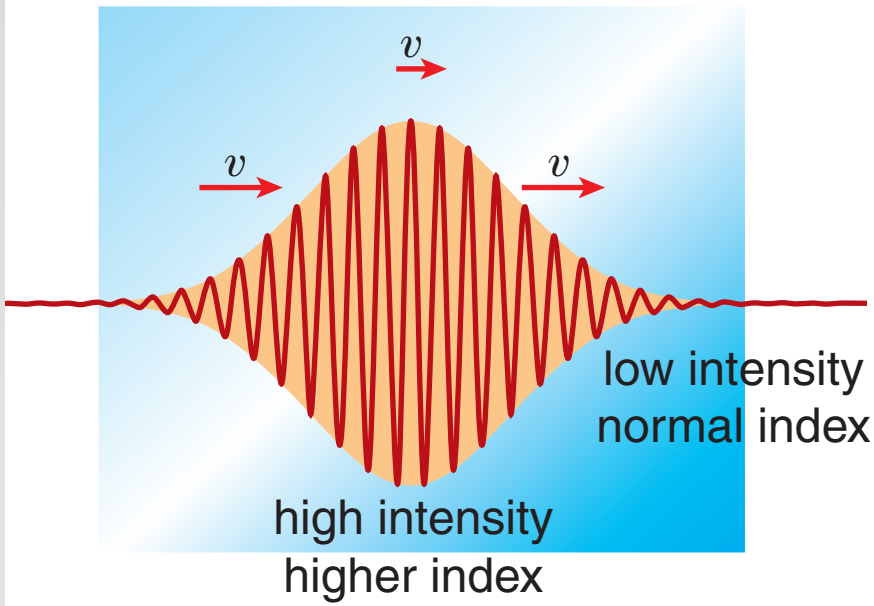
Nanoscale nonlinear optics

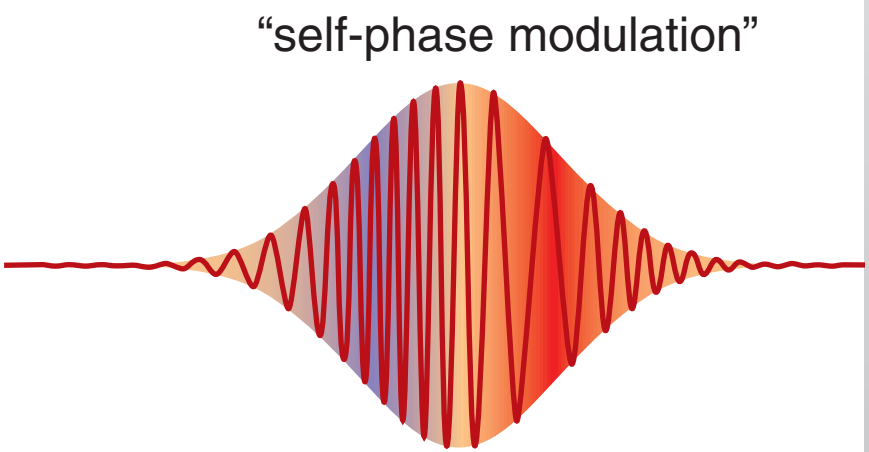
nonlinear dispersion: $n = n_o + n_2 I$



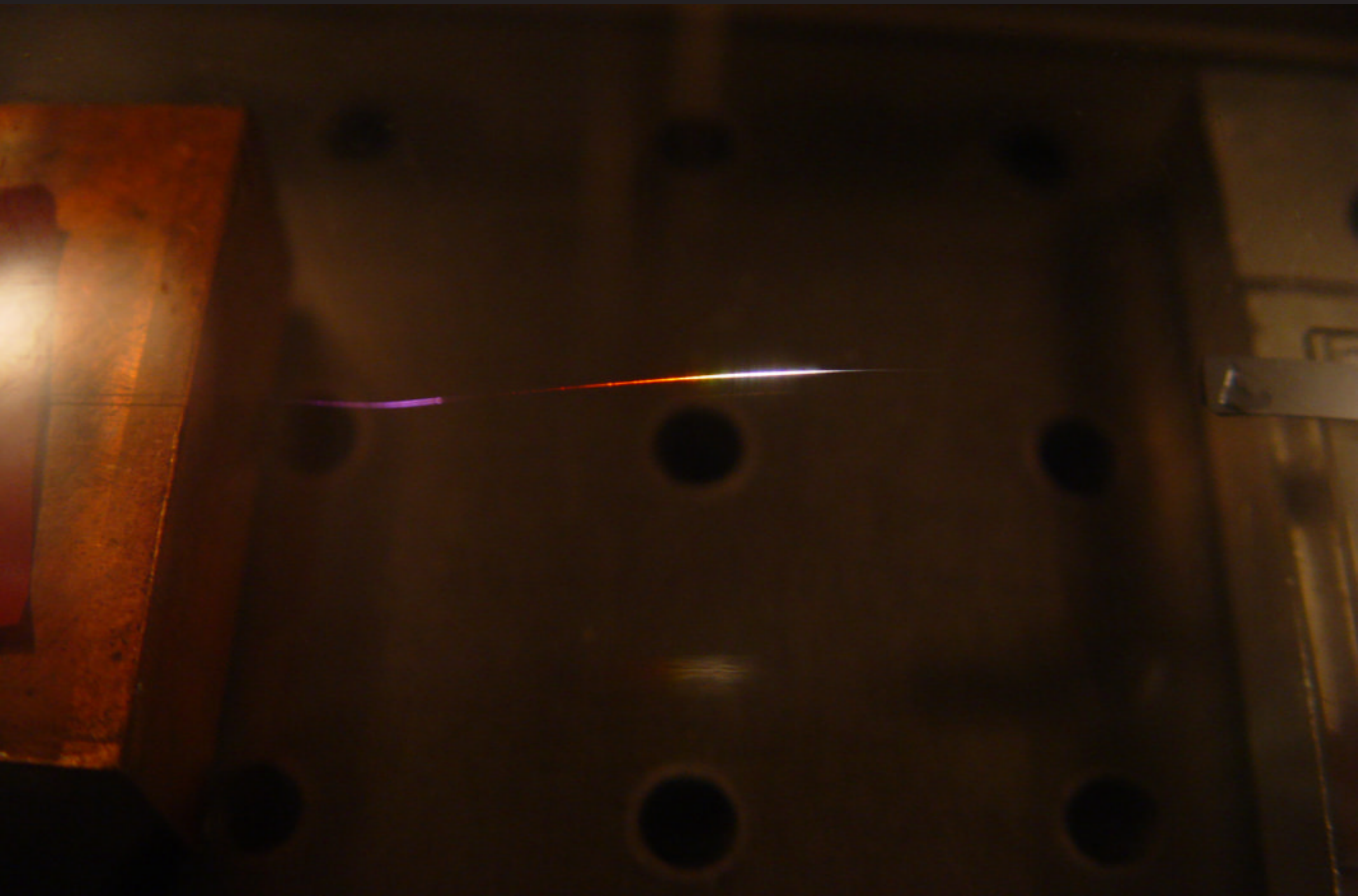
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$

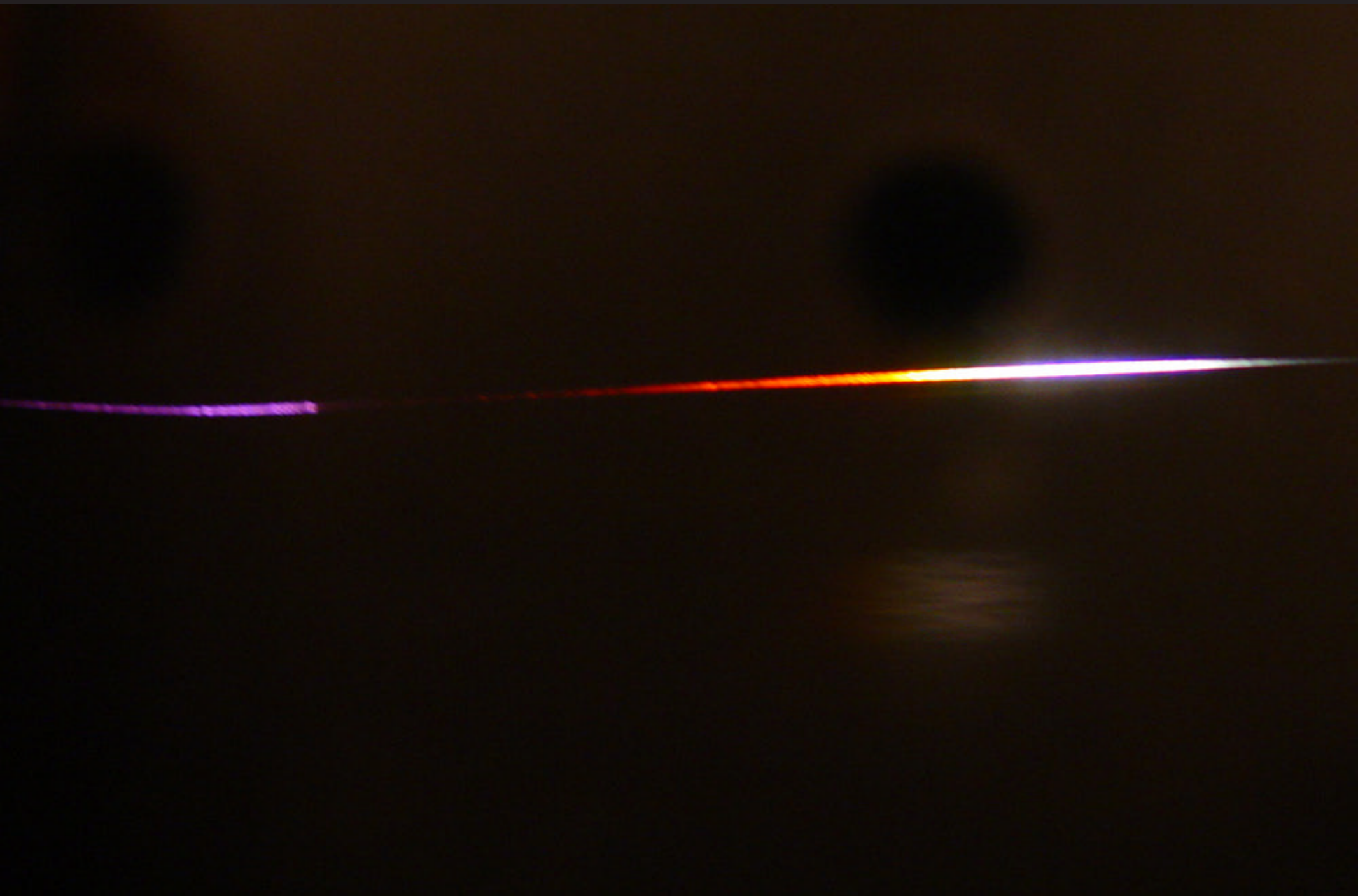




Nanoscale nonlinear optics



Nanoscale nonlinear optics

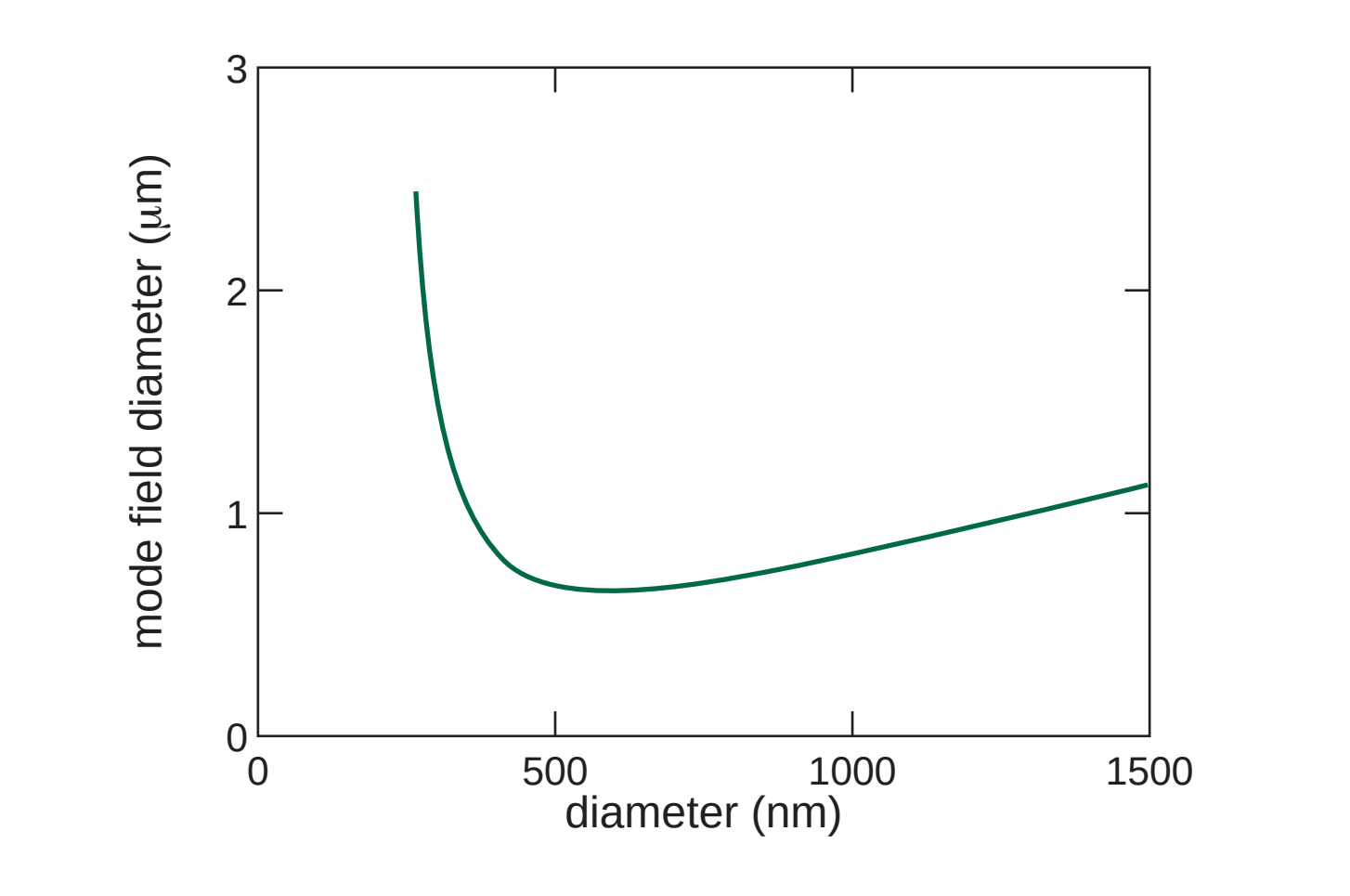


Nanoscale nonlinear optics

strong confinement $\longrightarrow$ high intensity

Nanoscale nonlinear optics

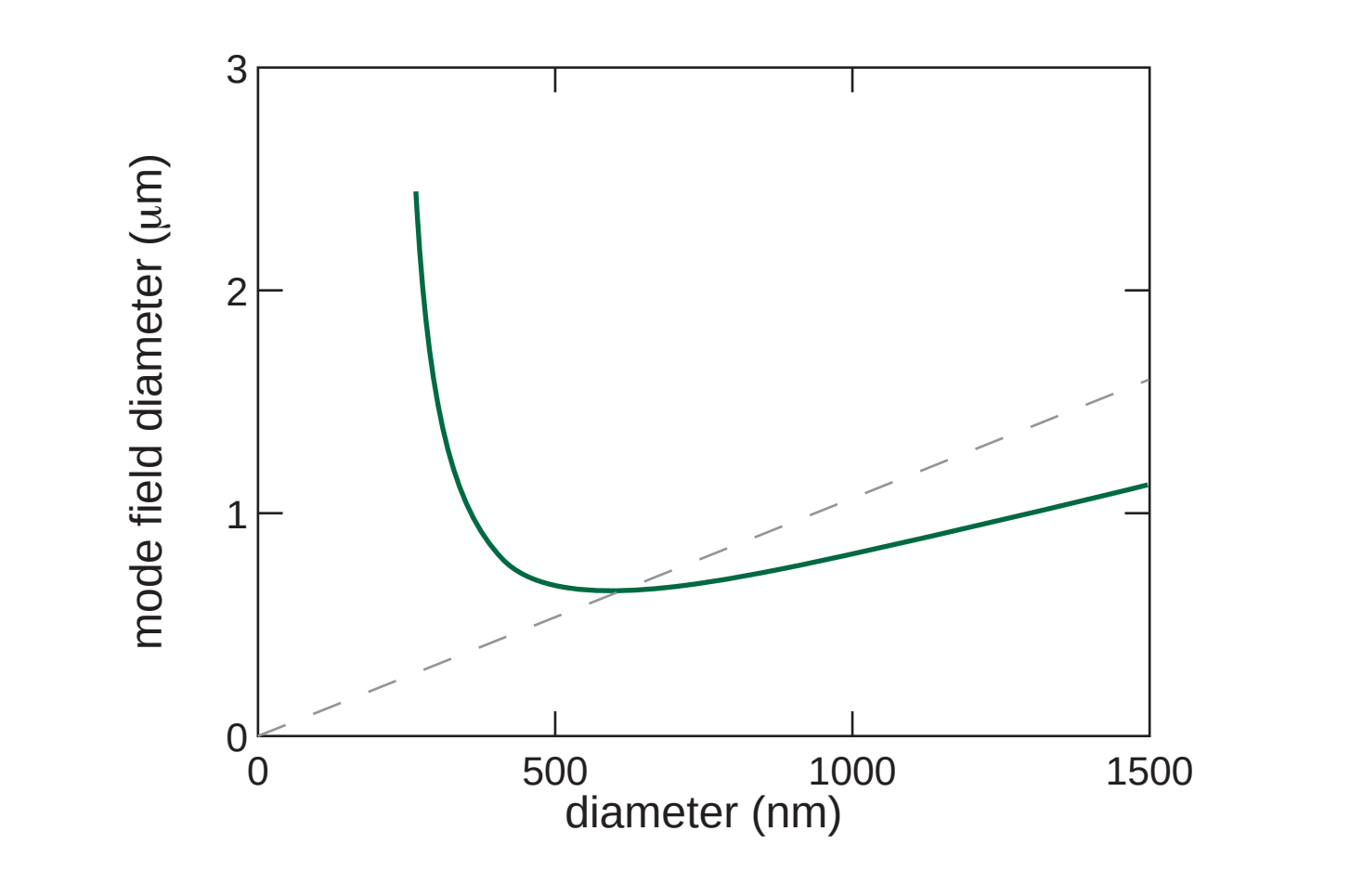
mode field diameter (λ = 800 nm)



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

Nanoscale nonlinear optics

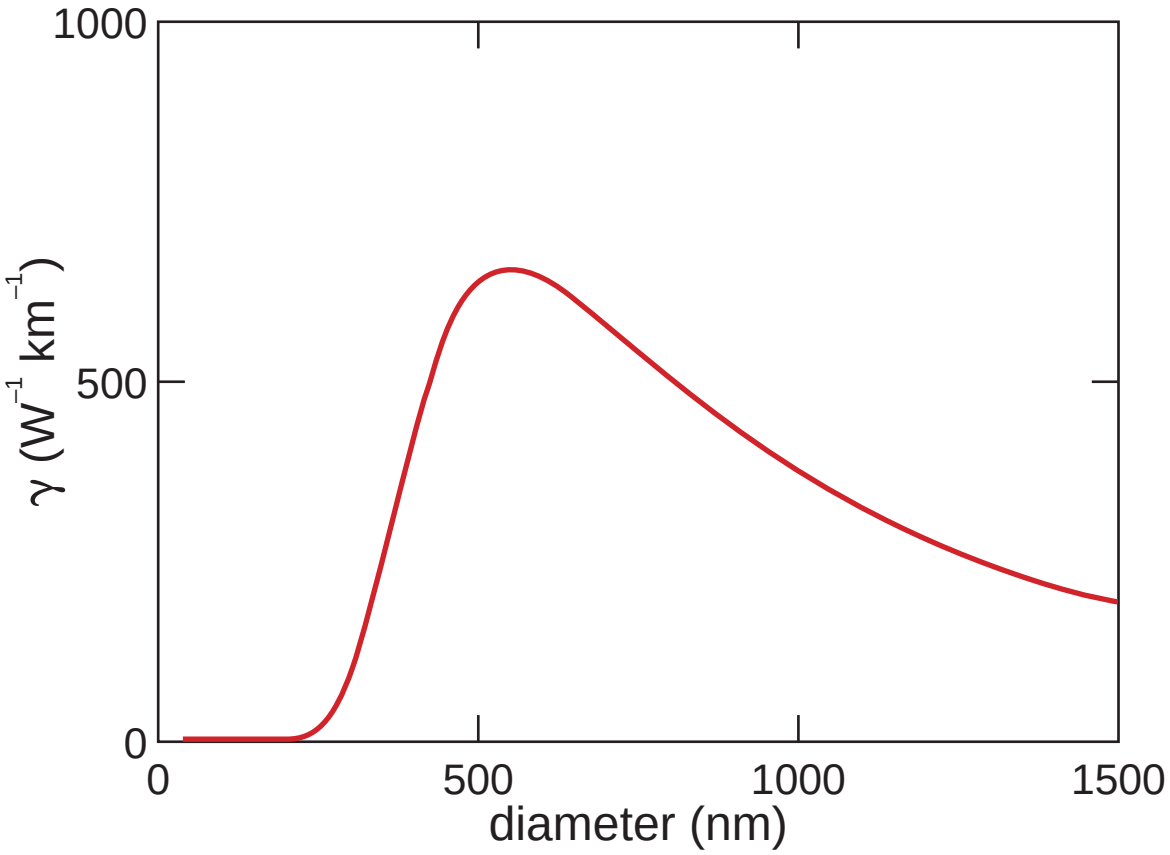
mode field diameter (λ = 800 nm)



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!

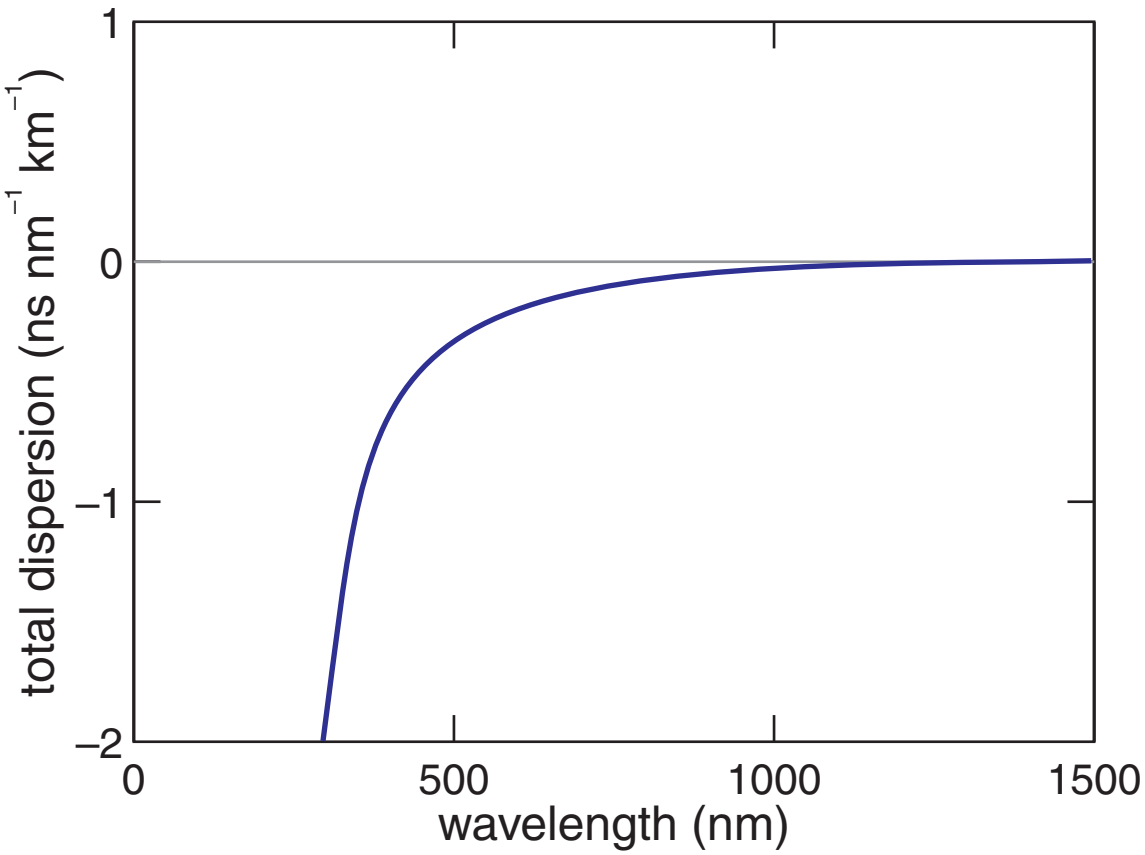
Nanoscale nonlinear optics

dispersion:

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

Nanoscale nonlinear optics

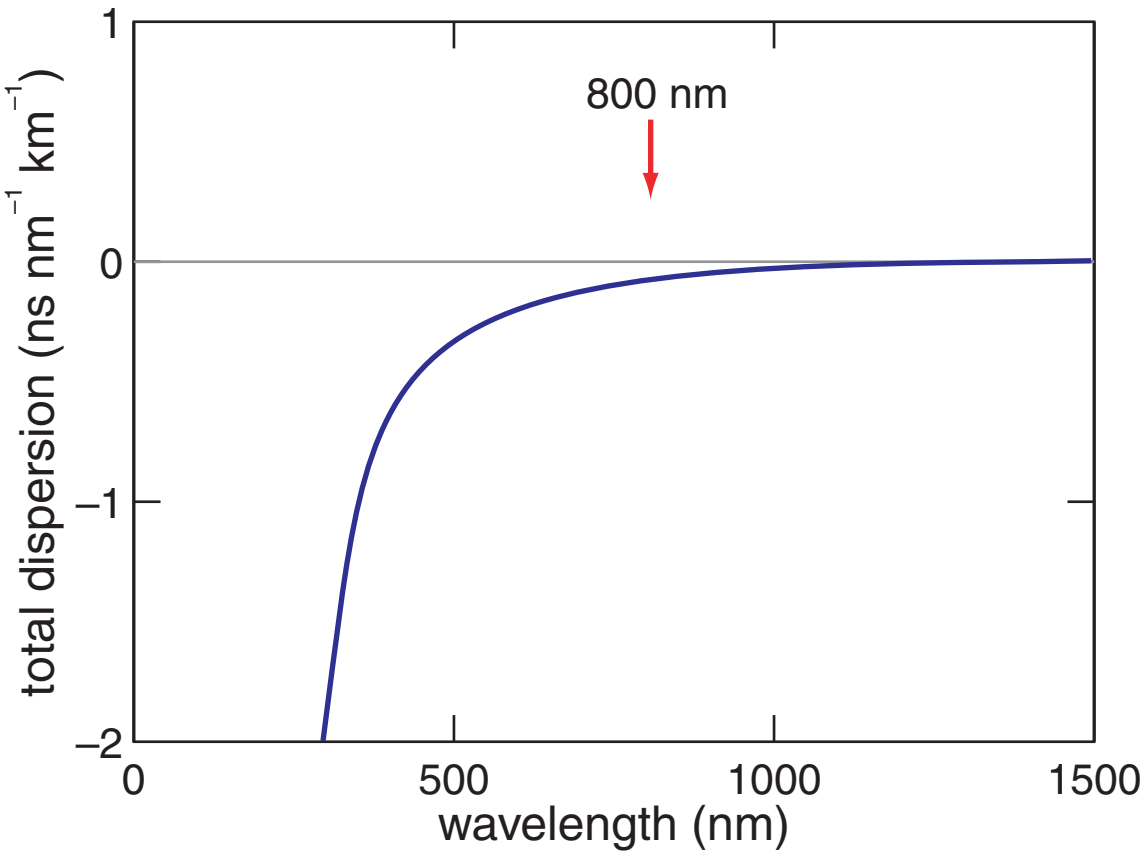
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

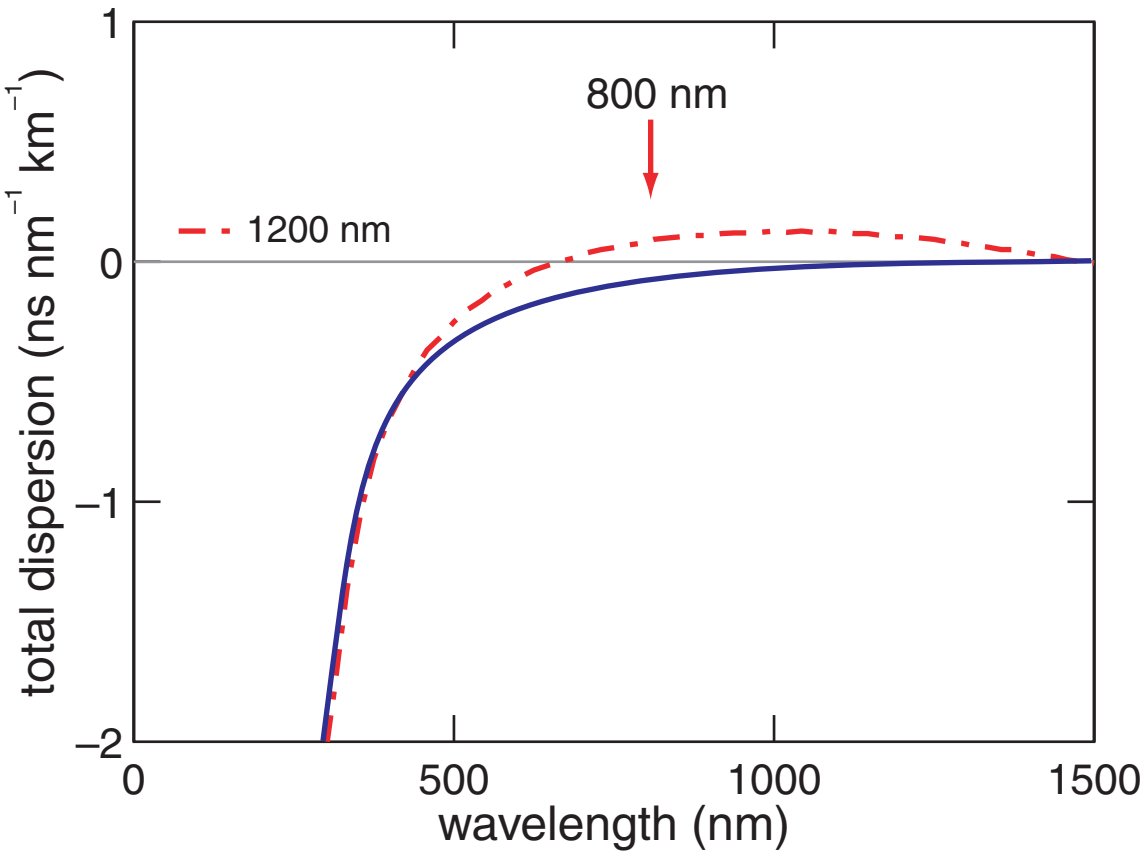
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

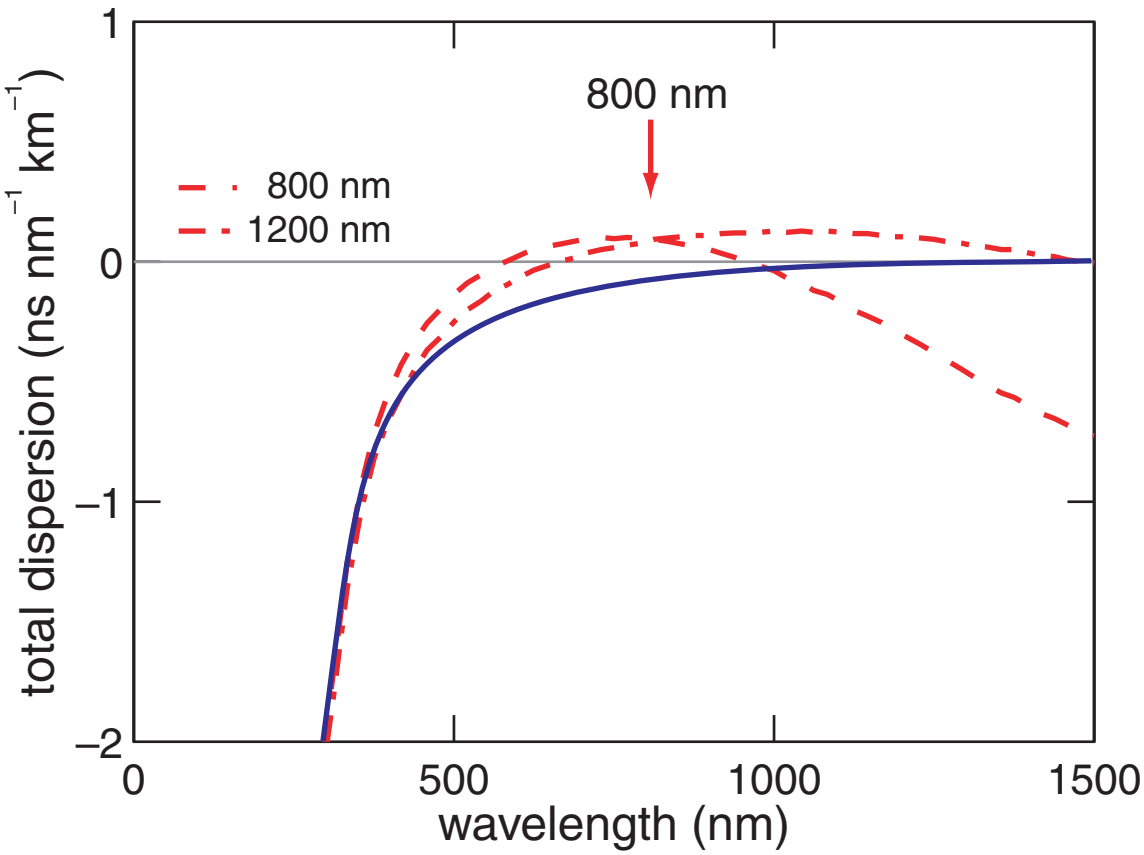
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

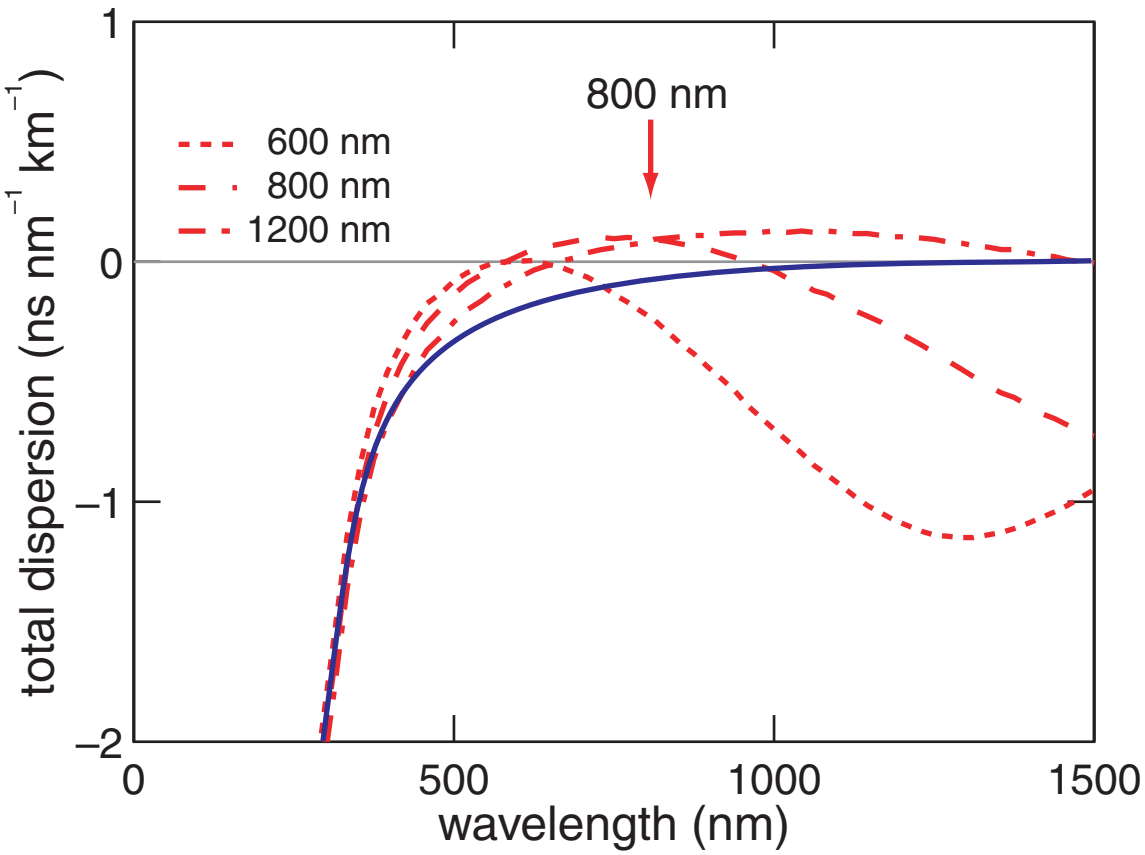
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

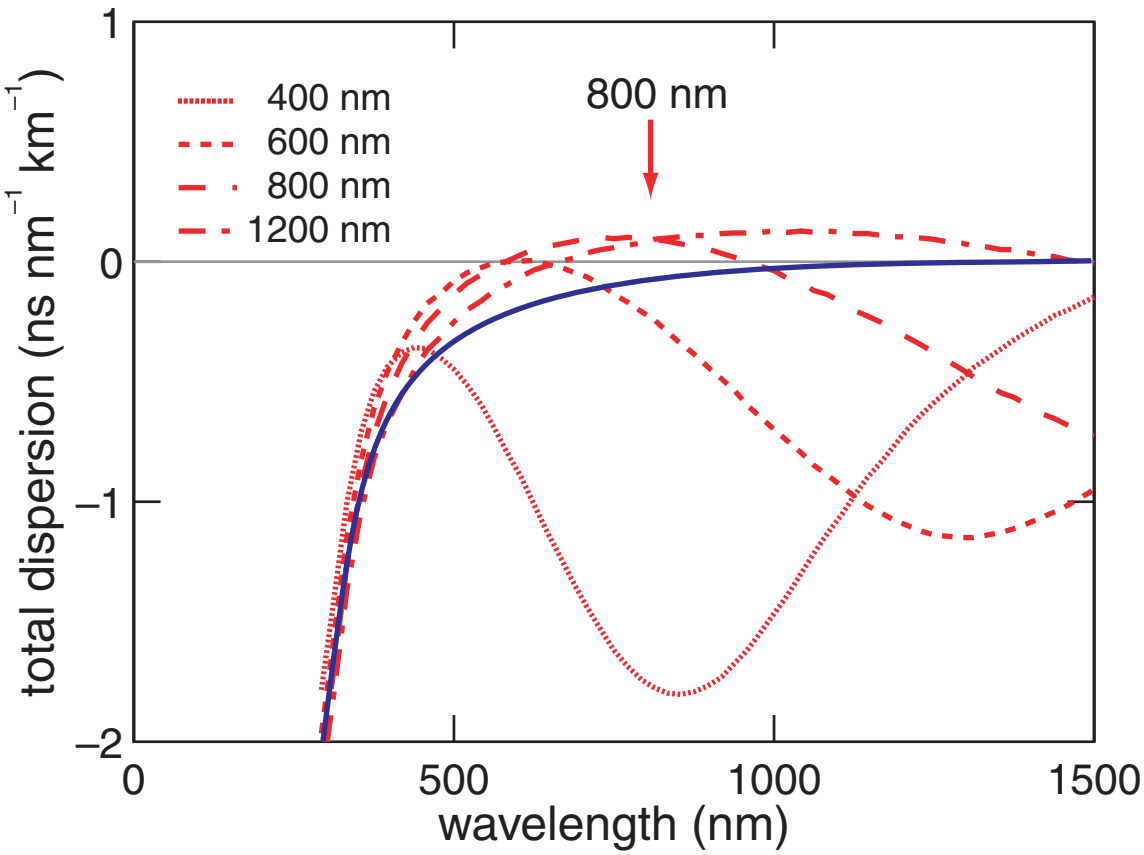
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

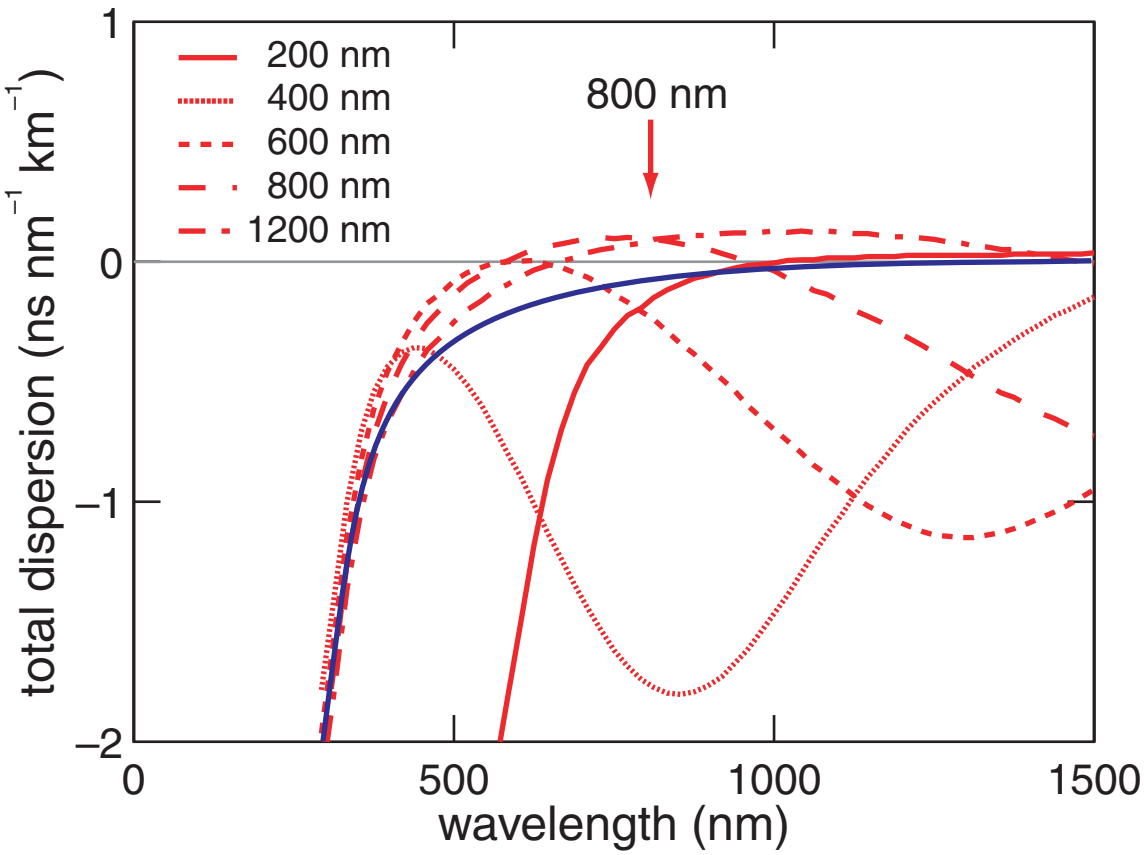
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nanoscale nonlinear optics

waveguide dispersion



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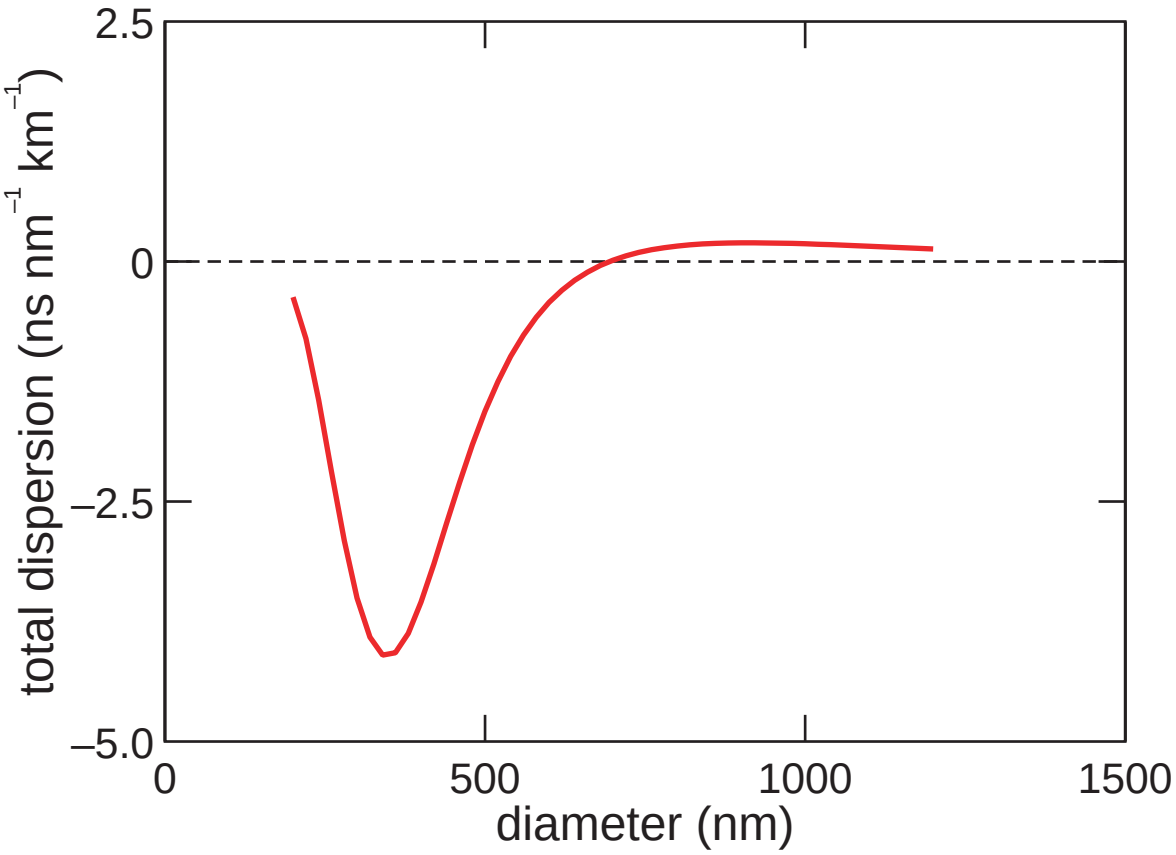
Nanoscale nonlinear optics

waveguide dispersion



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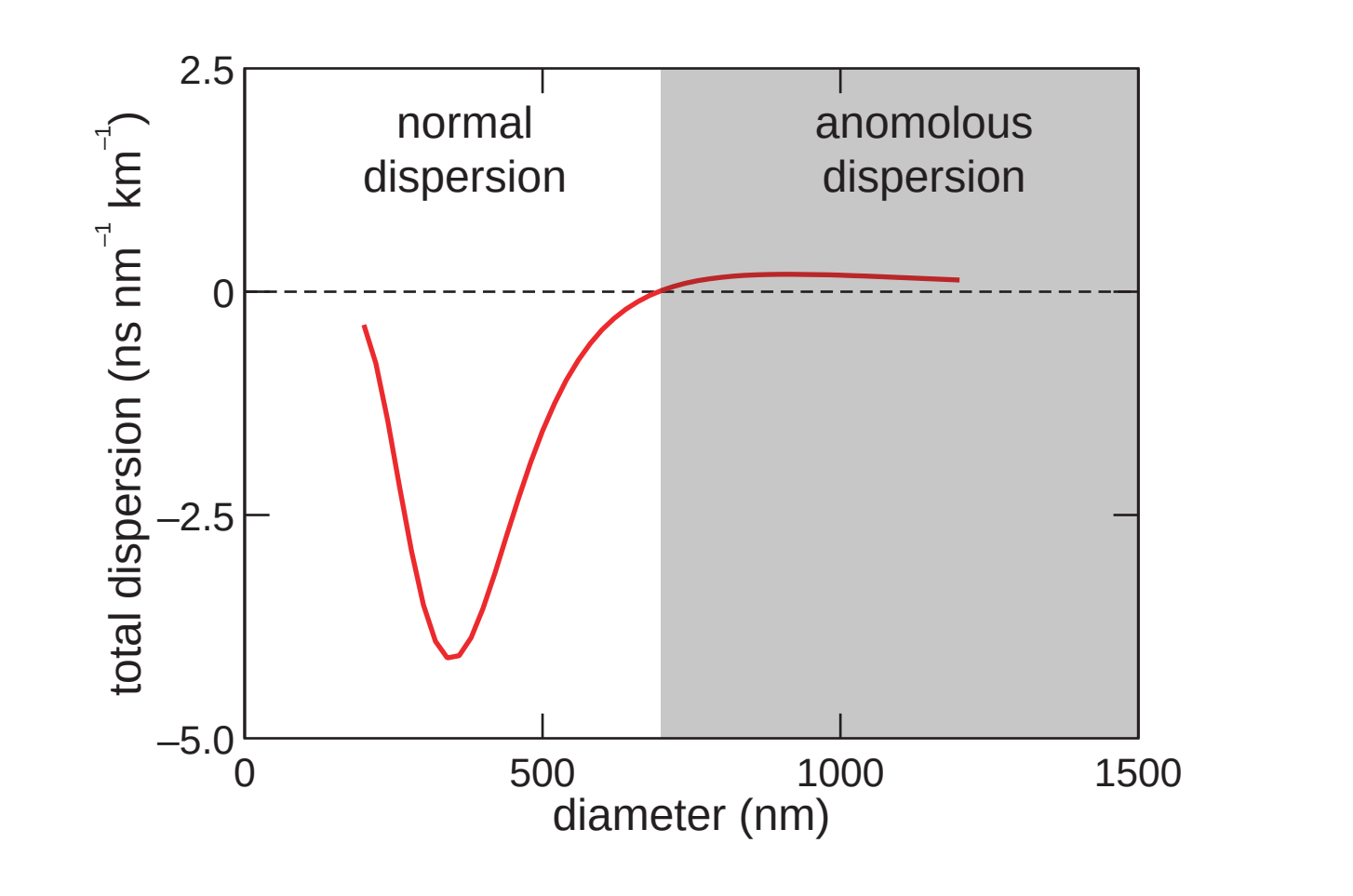
Nanoscale nonlinear optics

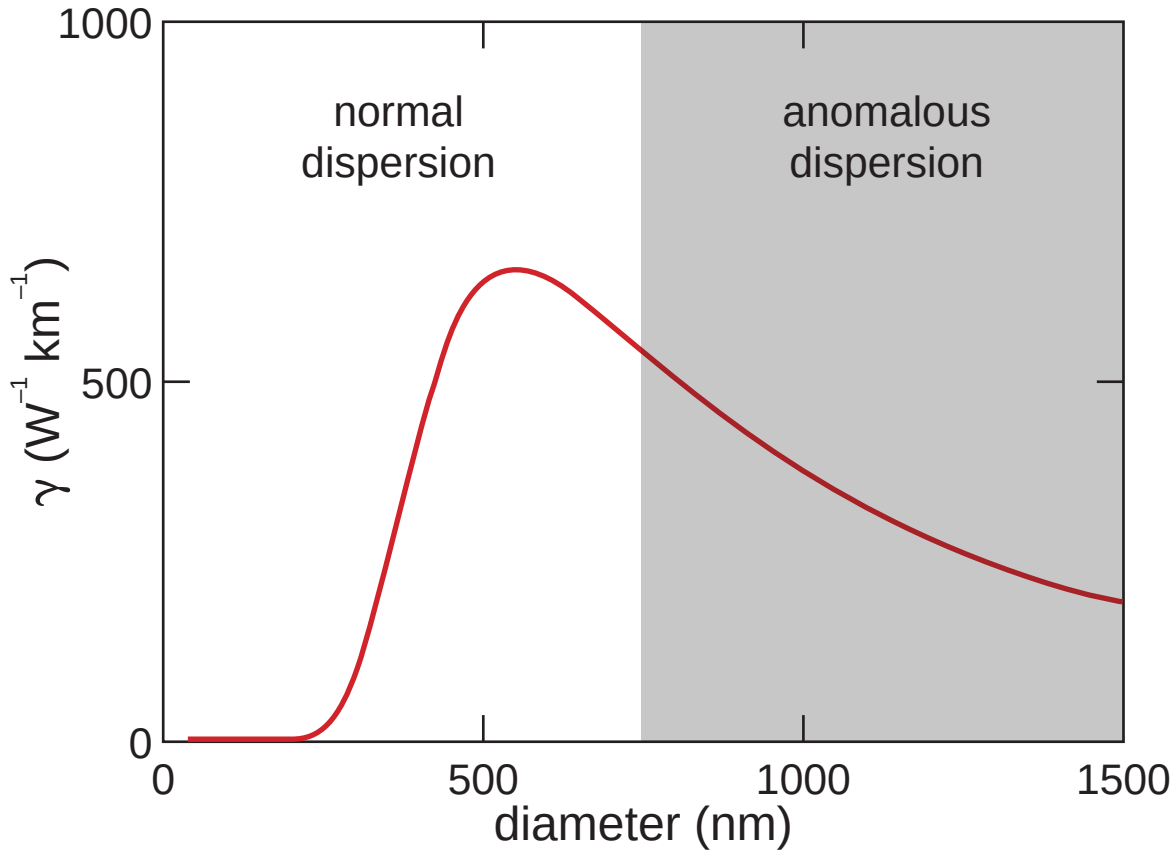
waveguide dispersion



Optics Express, 12, 1025 (2004)

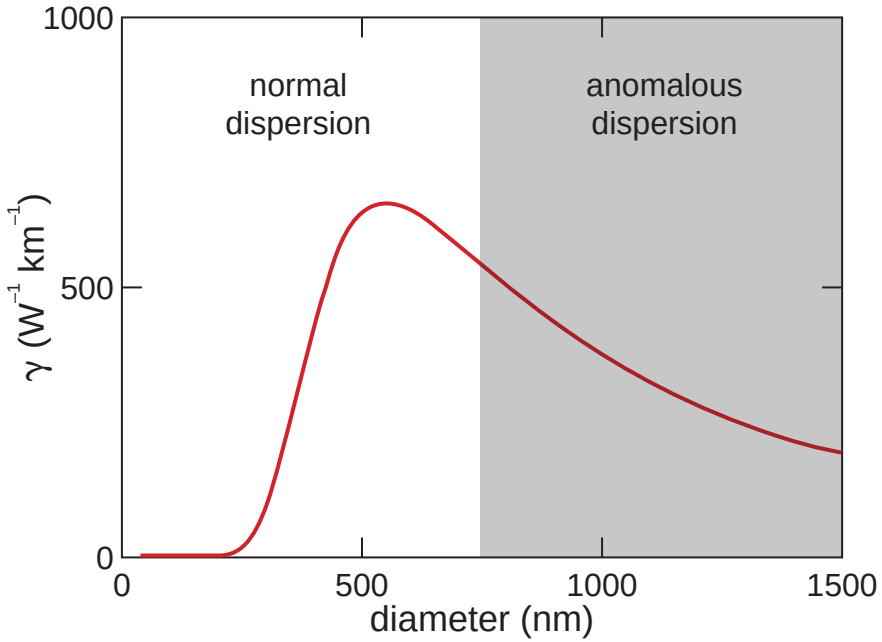
Nanoscale nonlinear optics

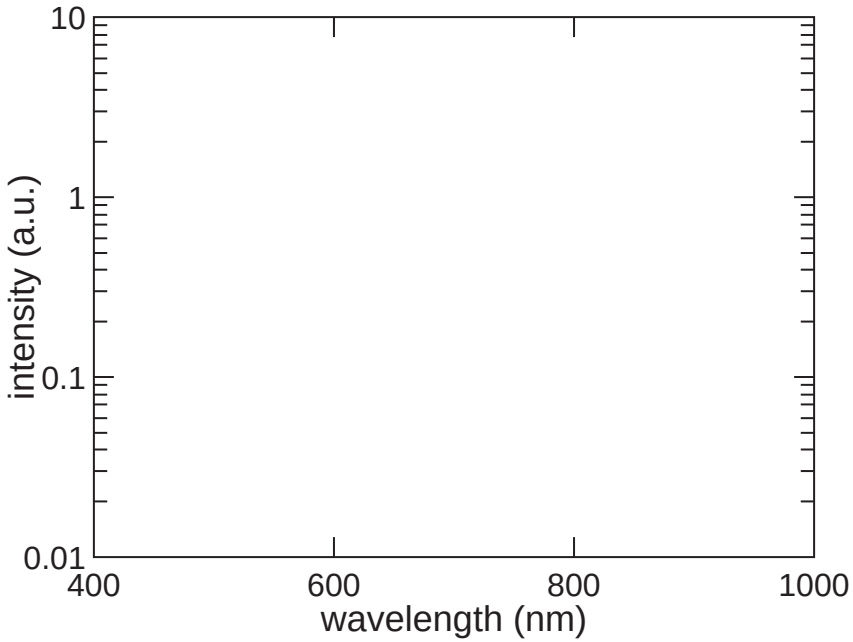
nonlinear parameter



Nanoscale nonlinear optics

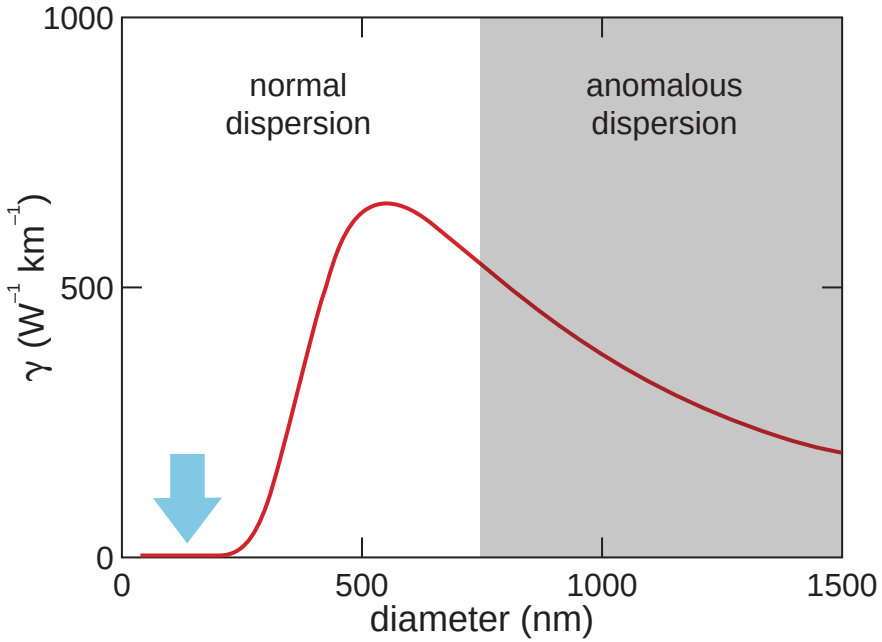
nanowire continuum generation

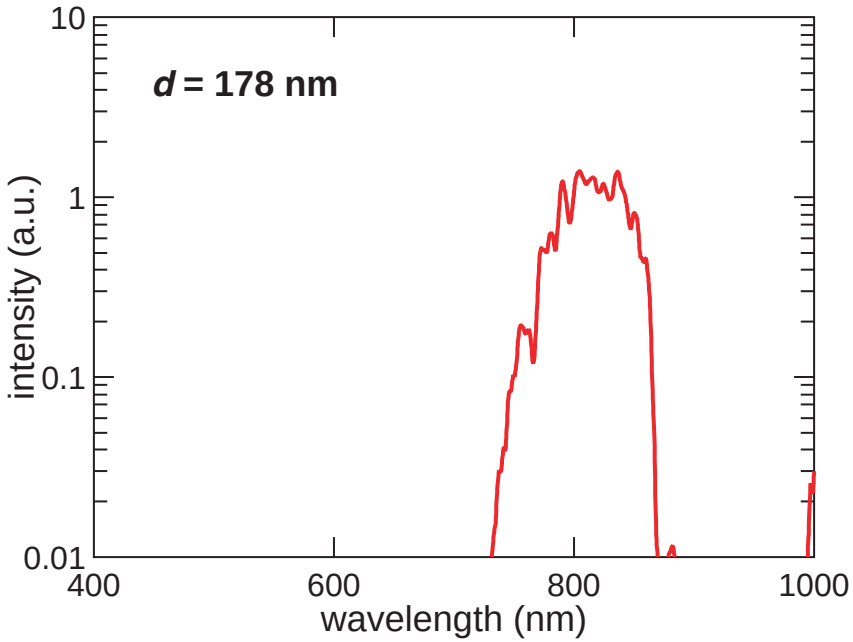




Nanoscale nonlinear optics

nanowire continuum generation

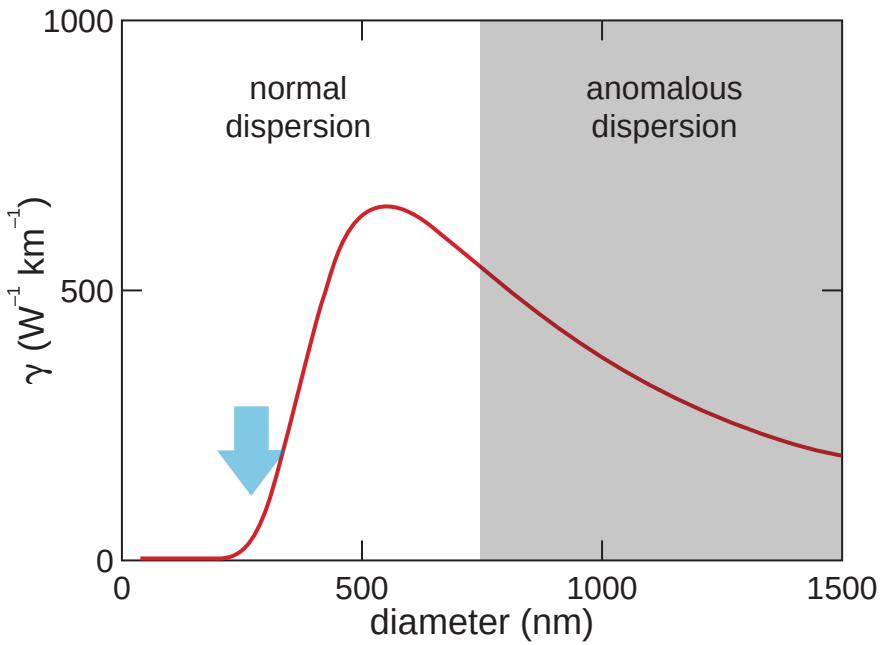


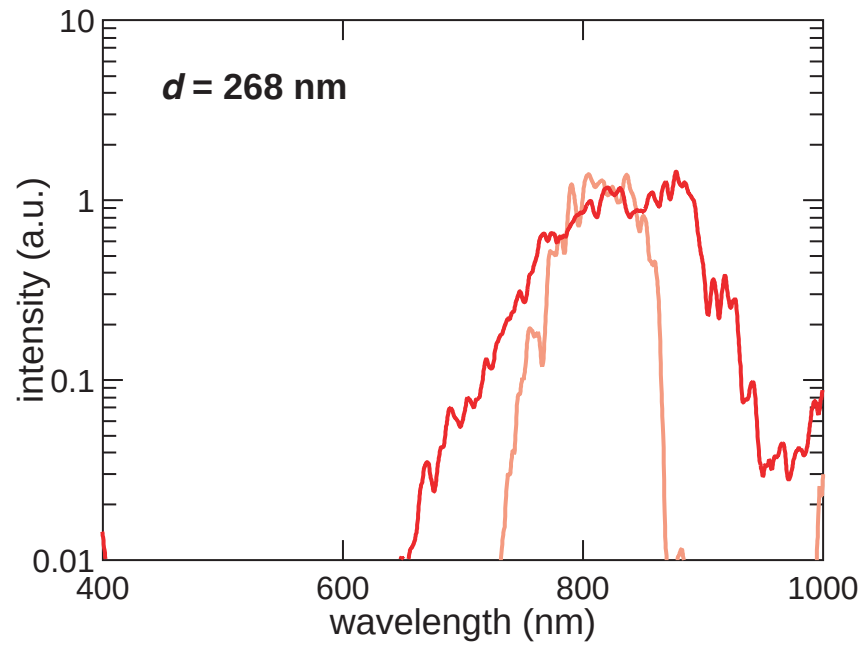


Optics Express, 14, 9408 (2006)

Nanoscale nonlinear optics

nanowire continuum generation

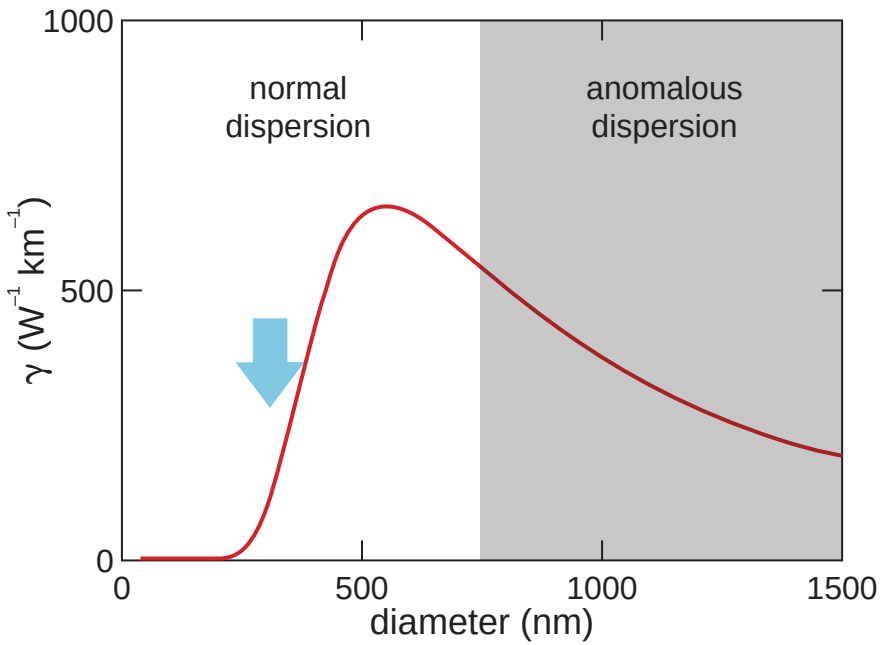


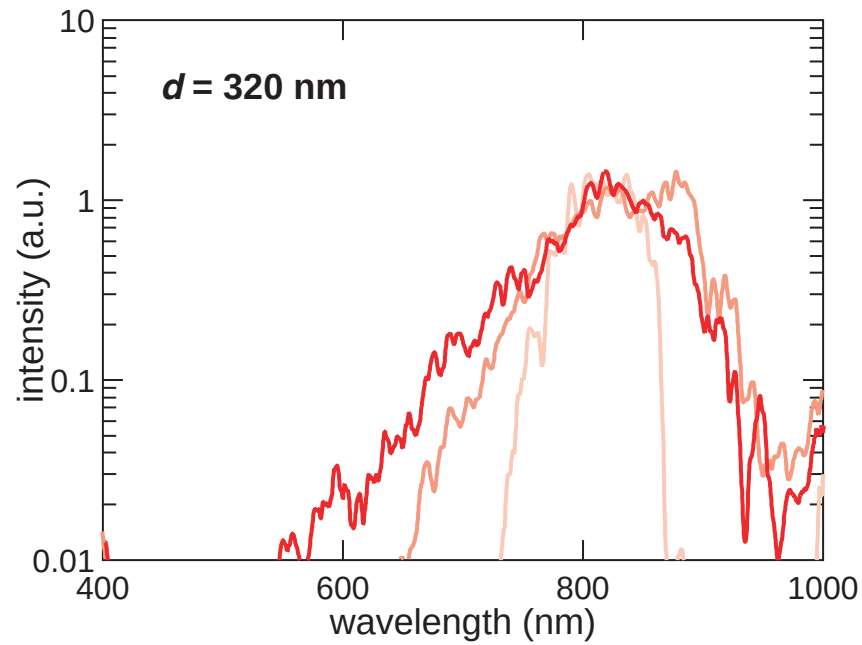


Optics Express, 14, 9408 (2006)

Nanoscale nonlinear optics

nanowire continuum generation

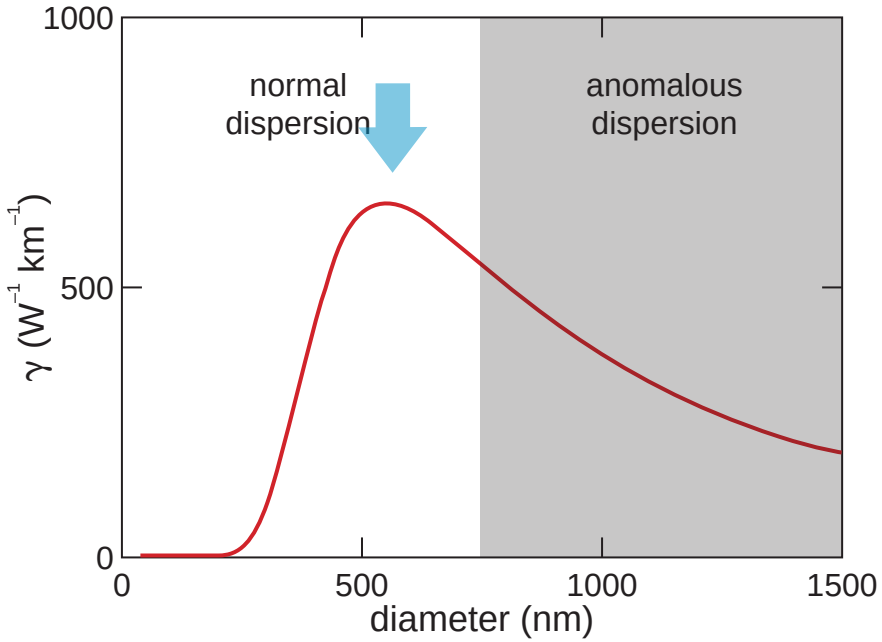


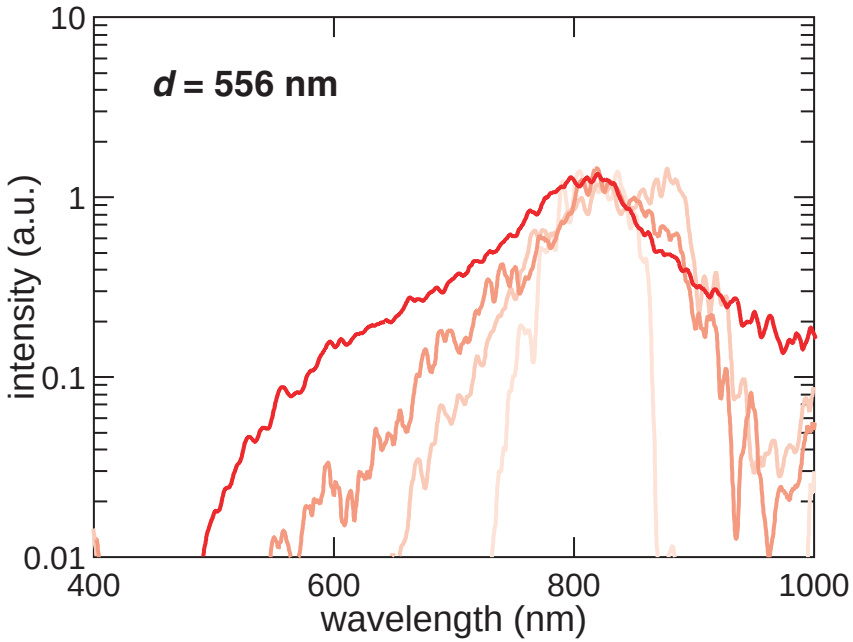


Optics Express, 14, 9408 (2006)

Nanoscale nonlinear optics

nanowire continuum generation





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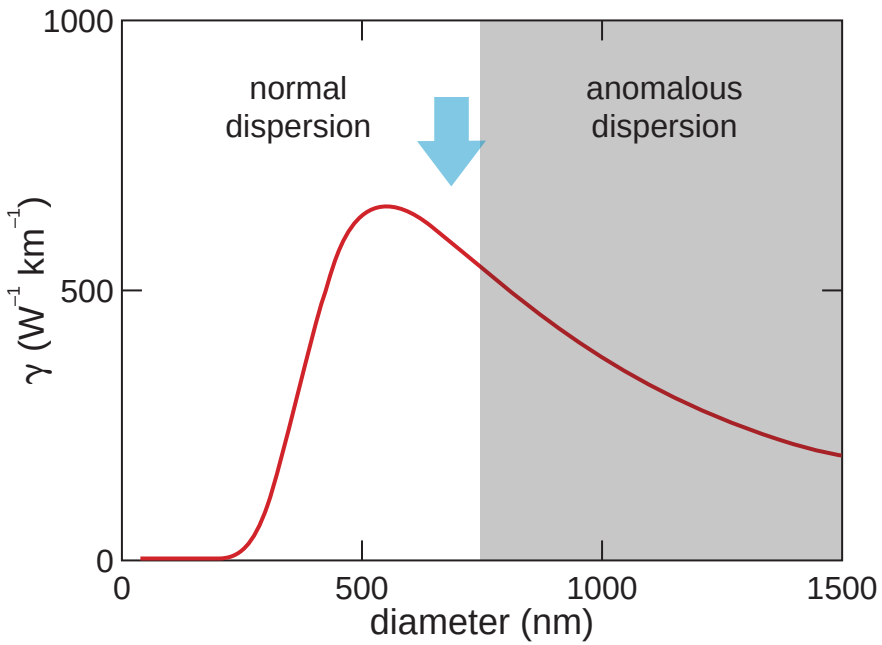
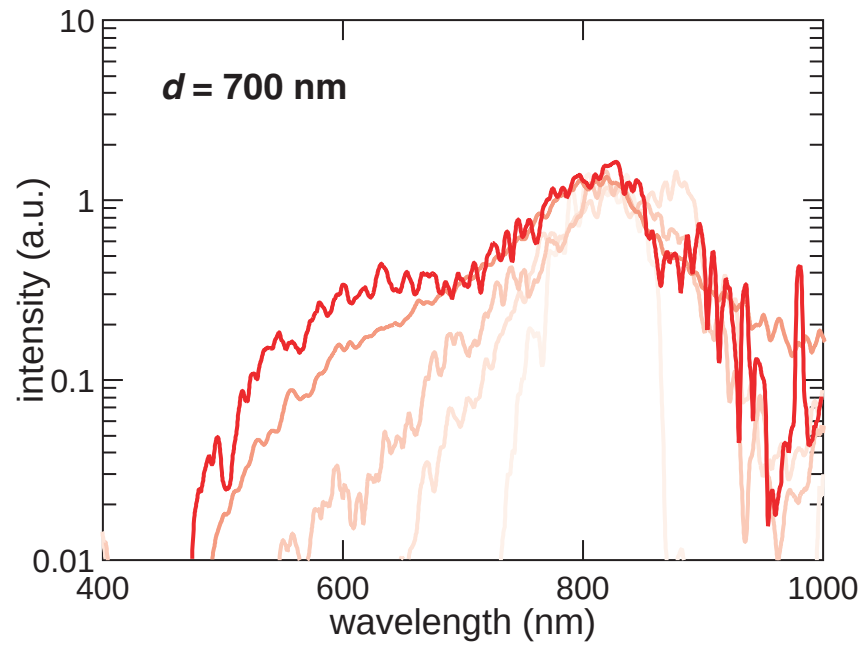
Nanoscale nonlinear optics

nanowire continuum generation





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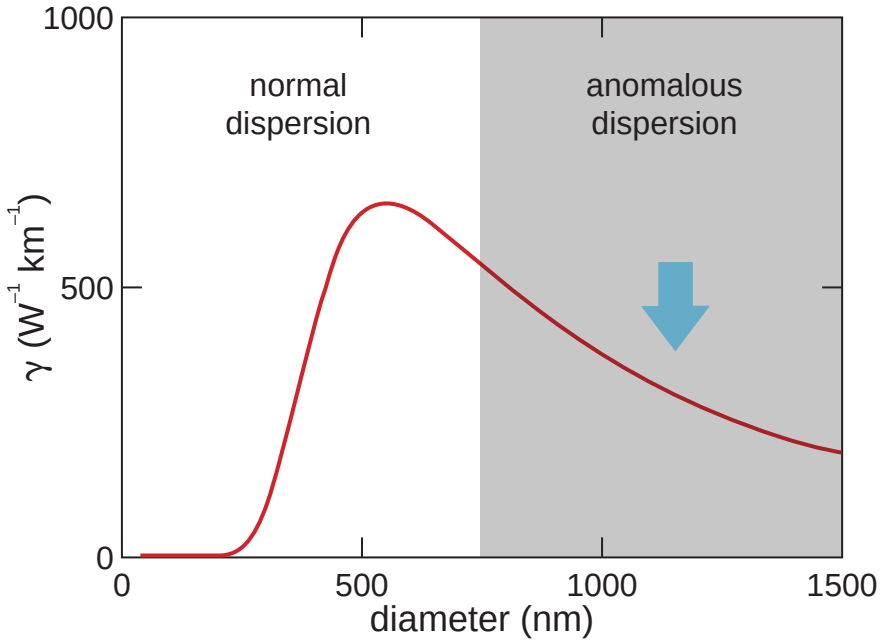
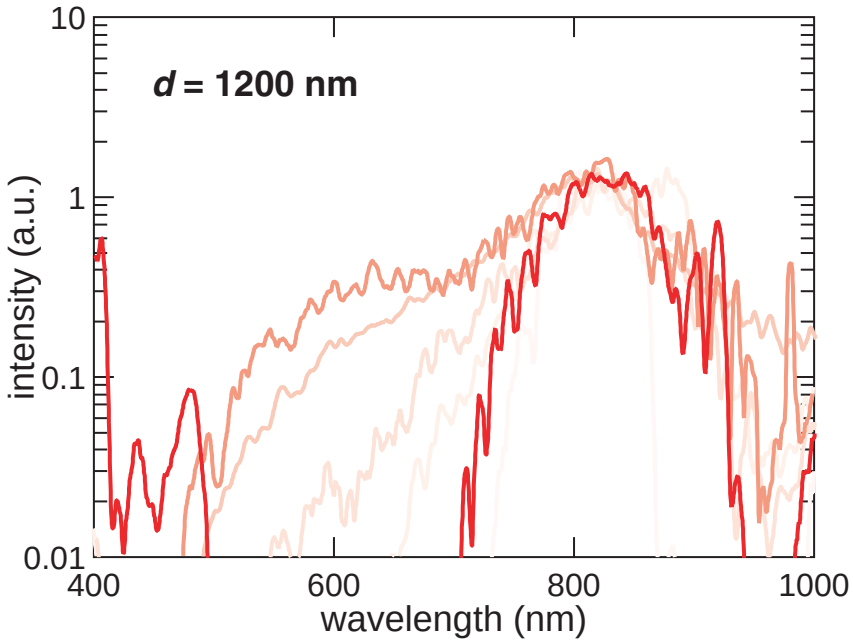
Nanoscale nonlinear optics

nanowire continuum generation





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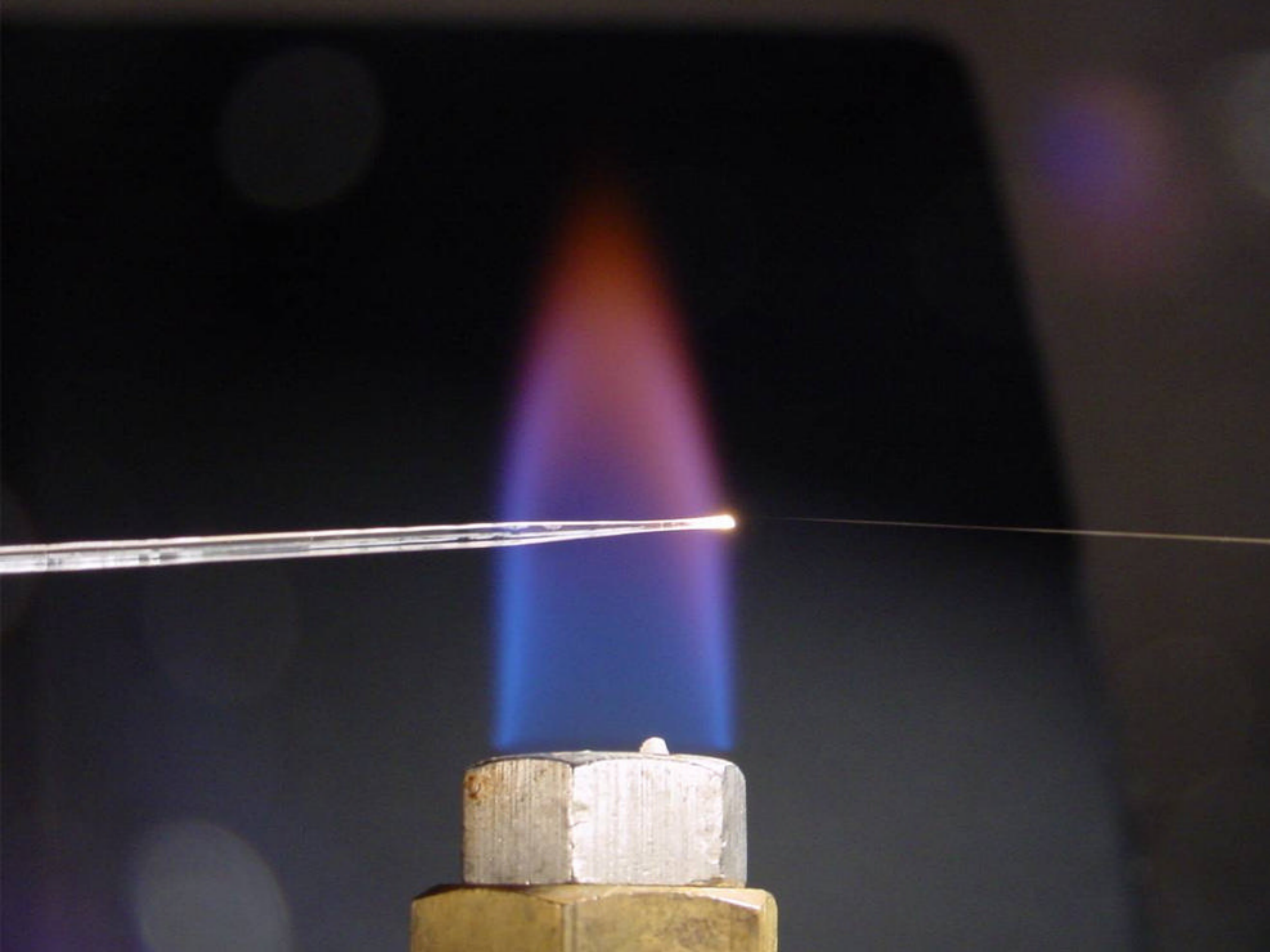
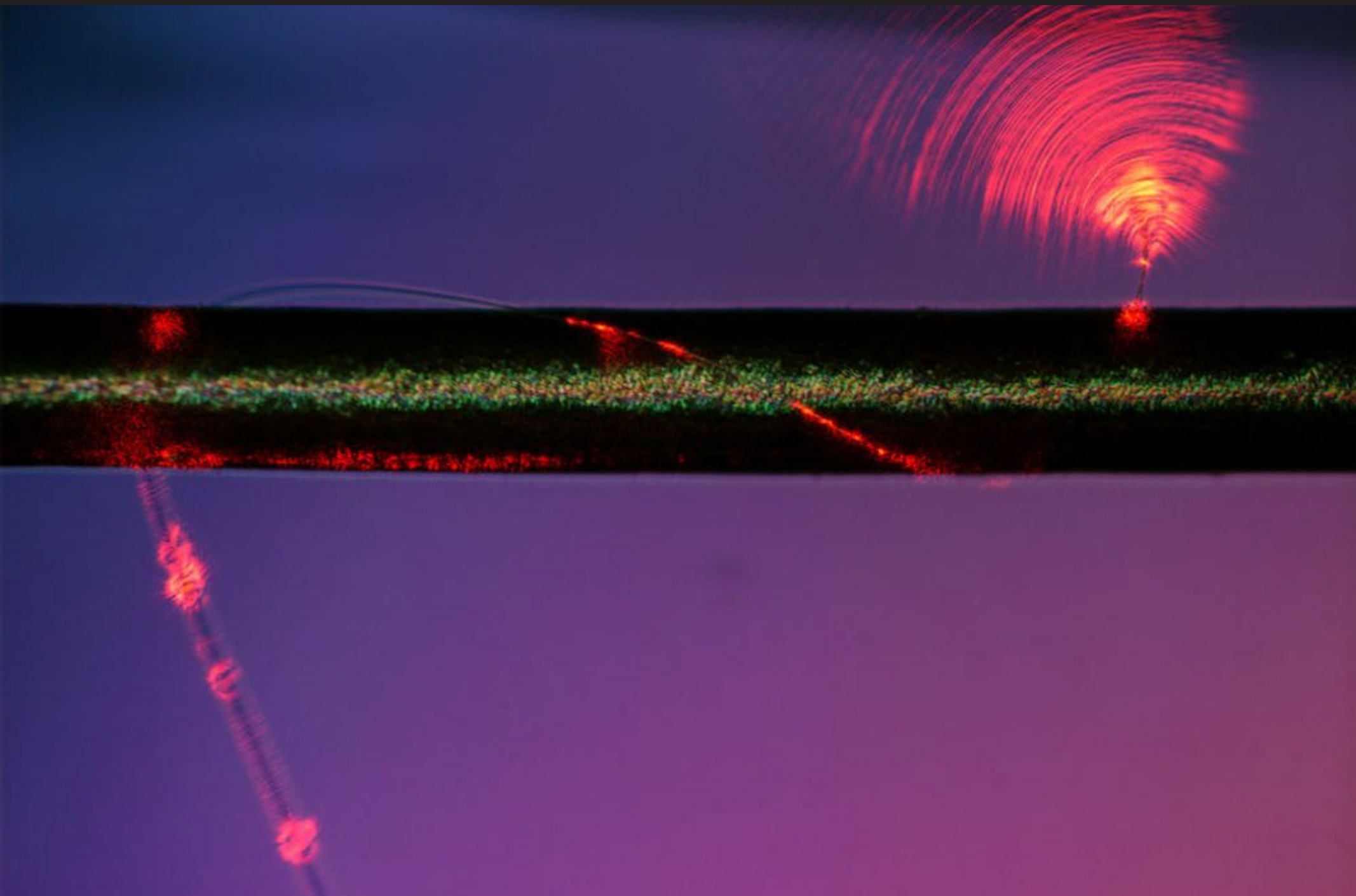
Nanoscale nonlinear optics

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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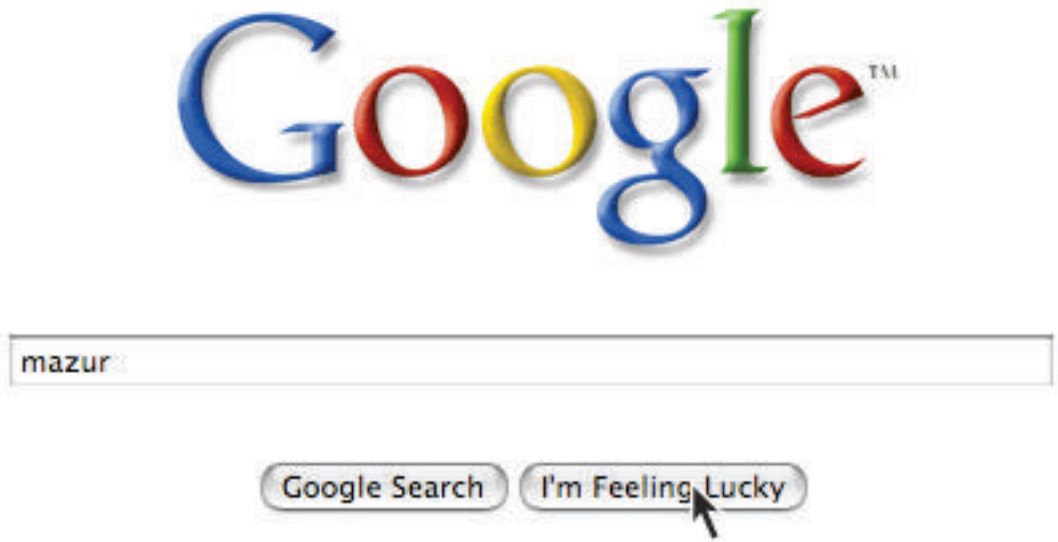
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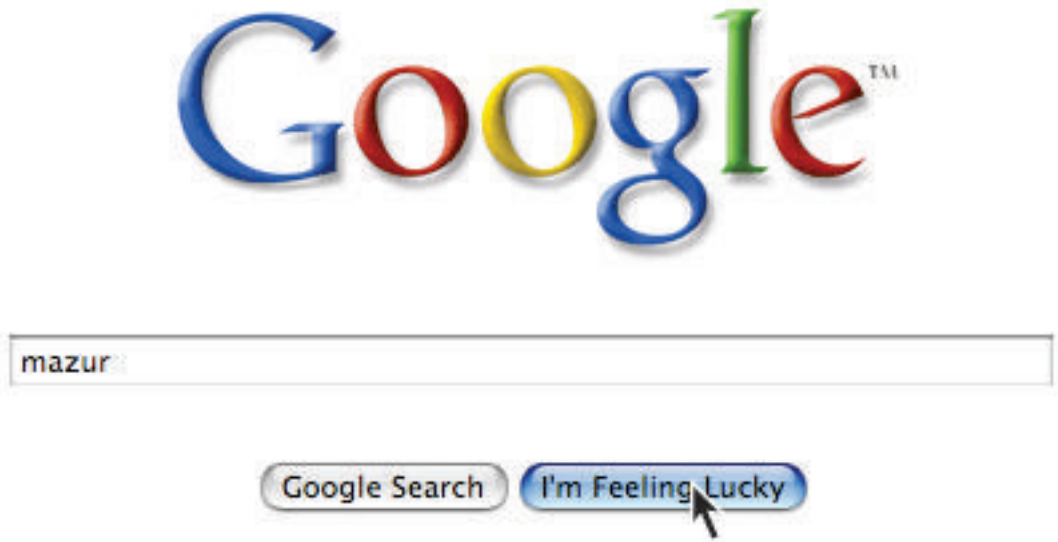
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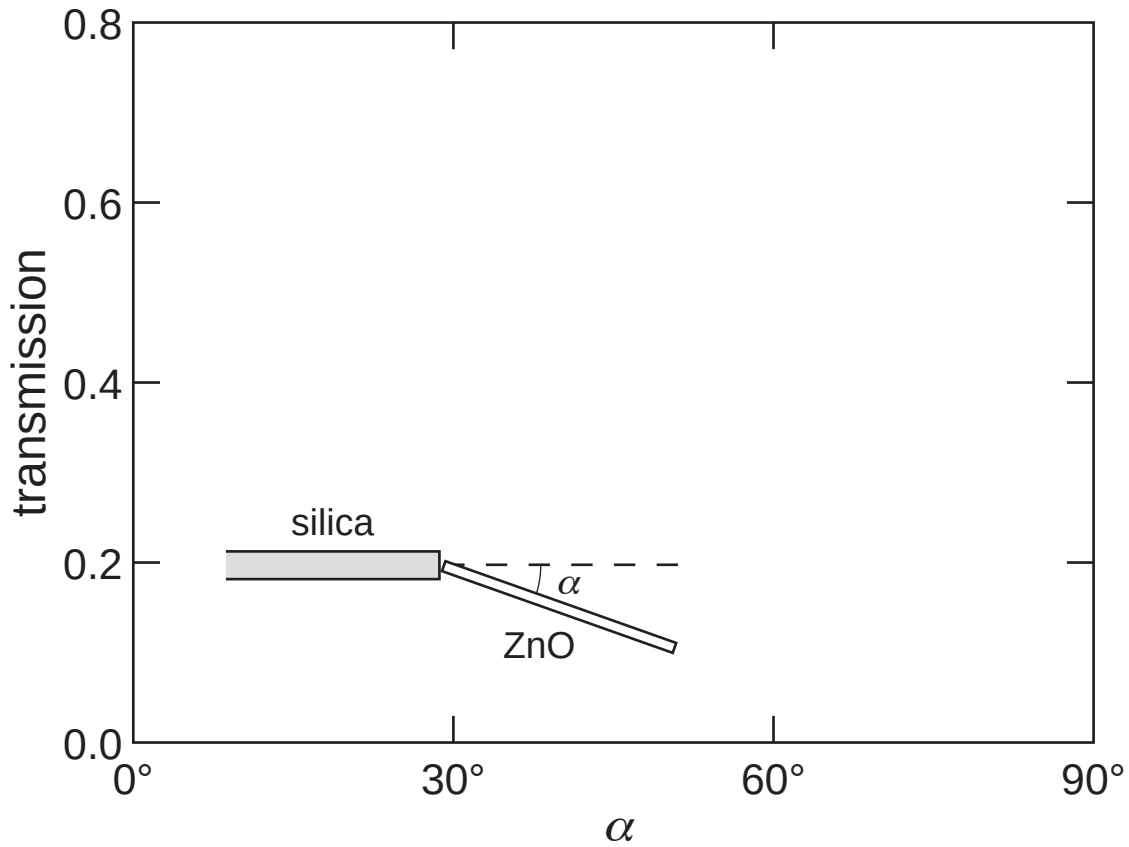
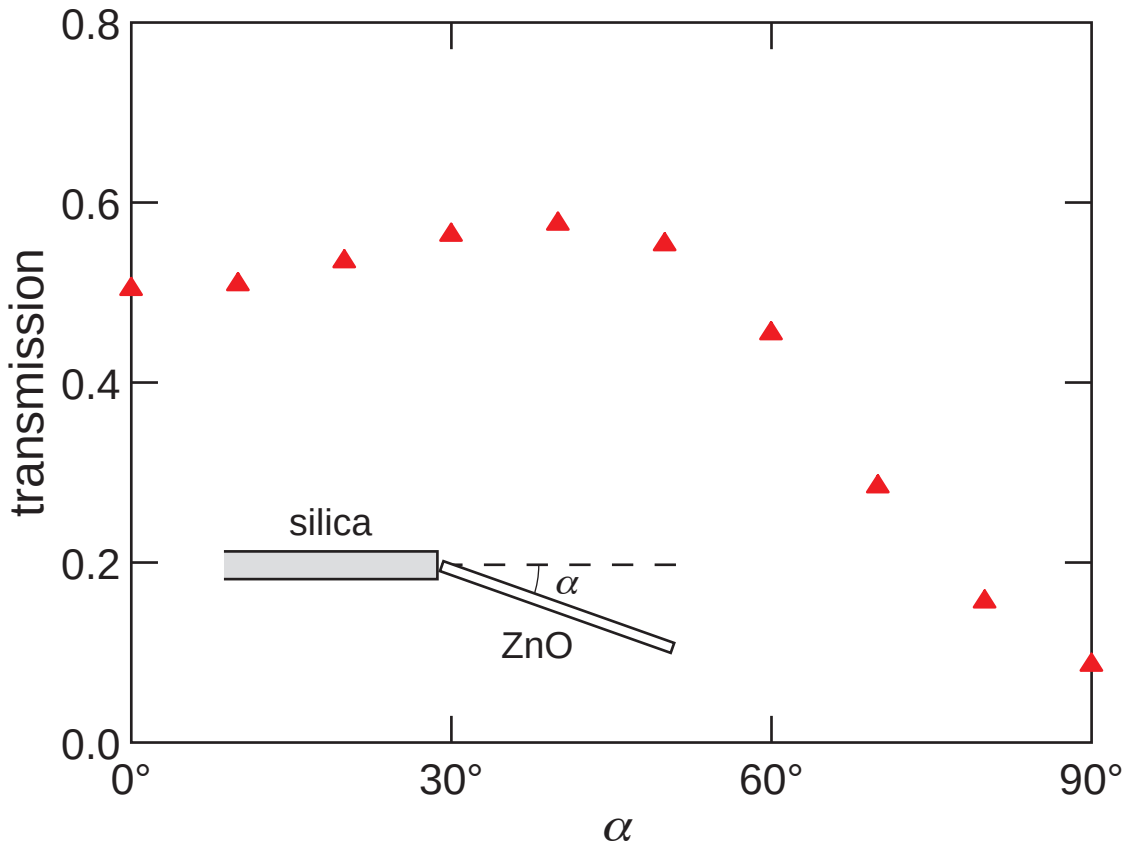
Manipulating light at the nanoscale

coupling efficiency



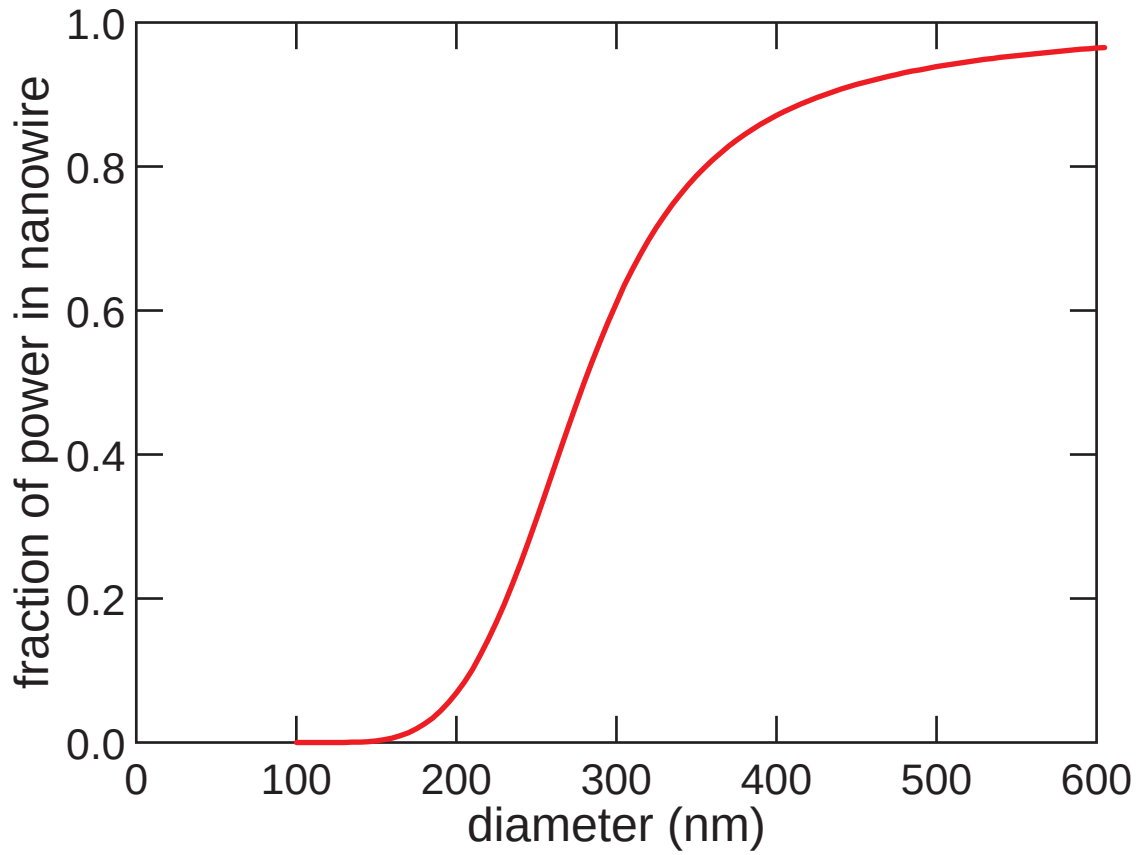
Manipulating light at the nanoscale

coupling efficiency



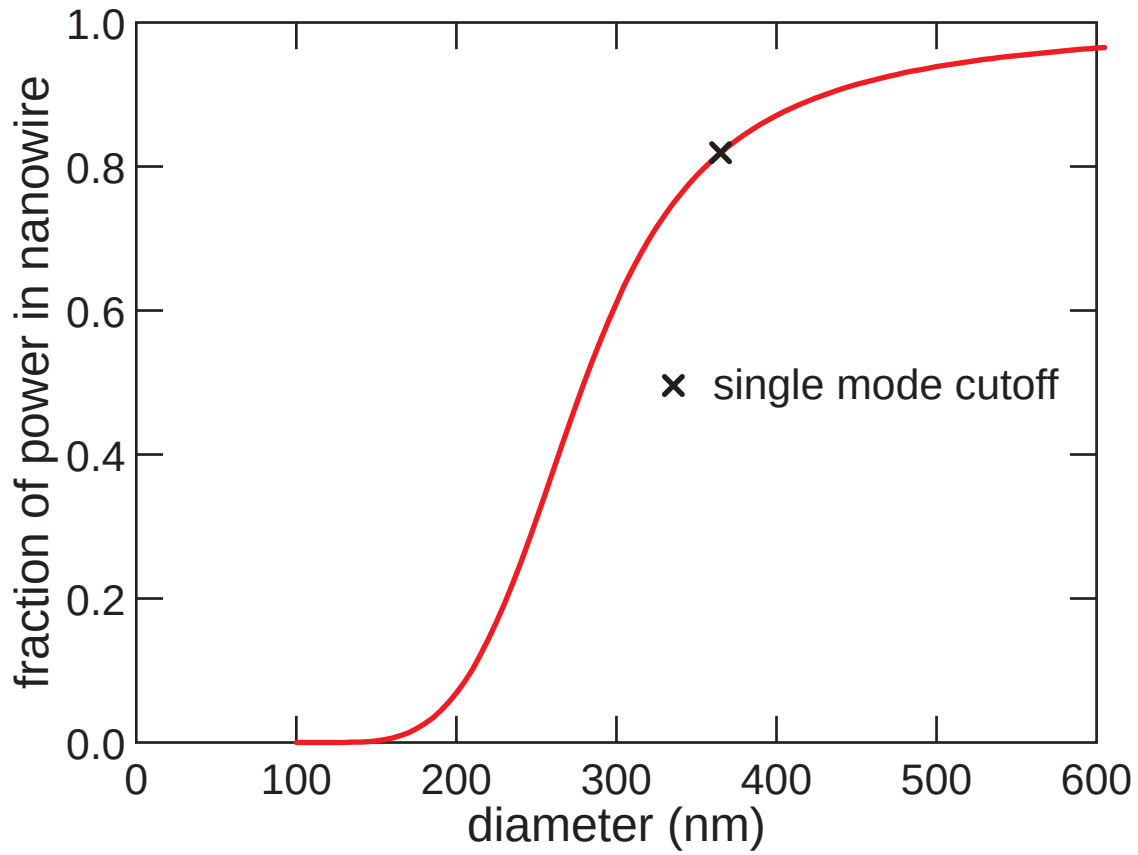
Manipulating light at the nanoscale

single-mode cutoff



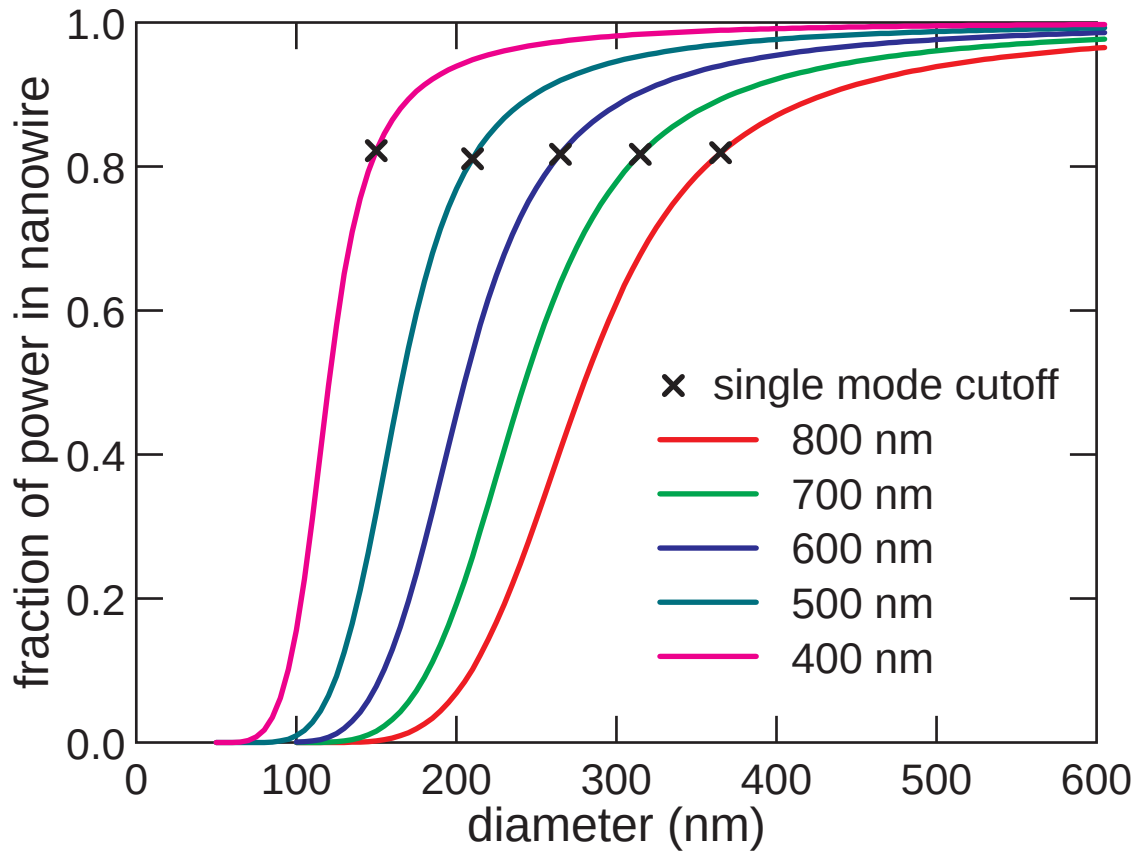
Manipulating light at the nanoscale

single-mode cutoff



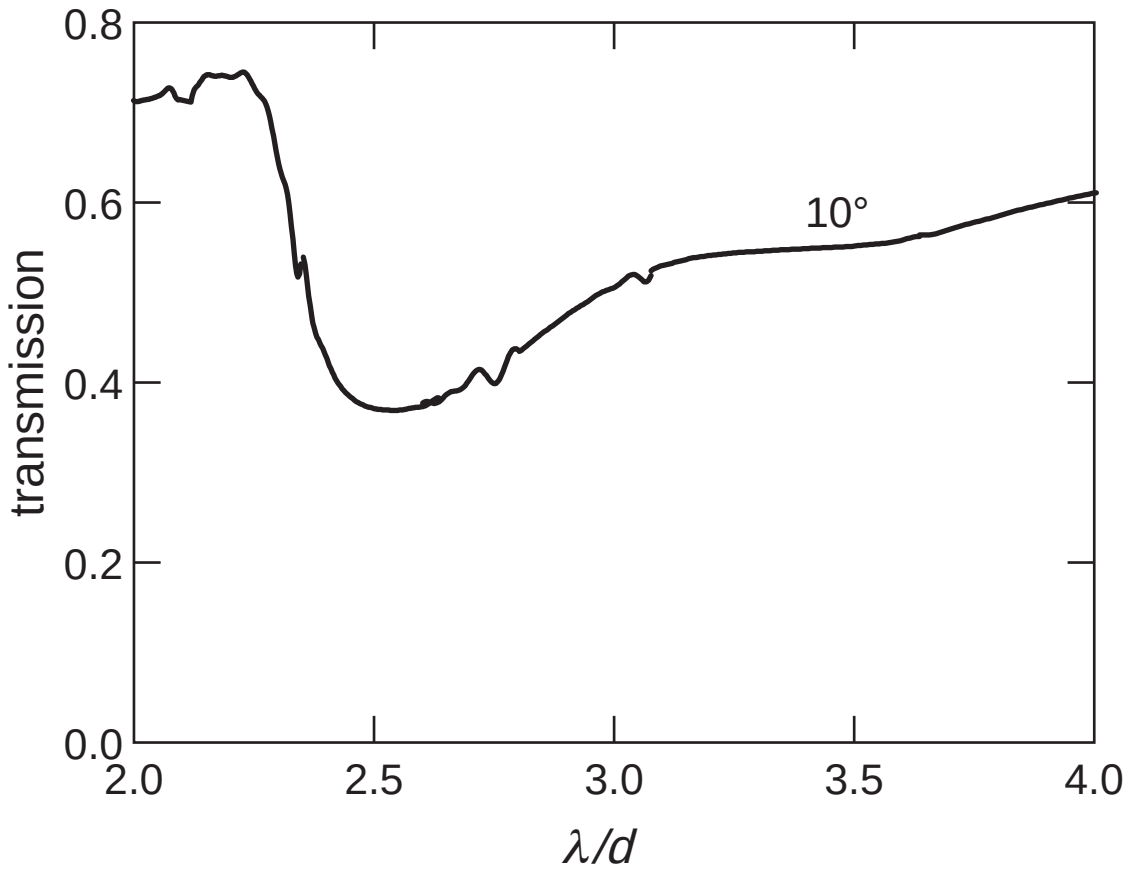
Manipulating light at the nanoscale

single-mode cutoff



Manipulating light at the nanoscale

transmission spectrum



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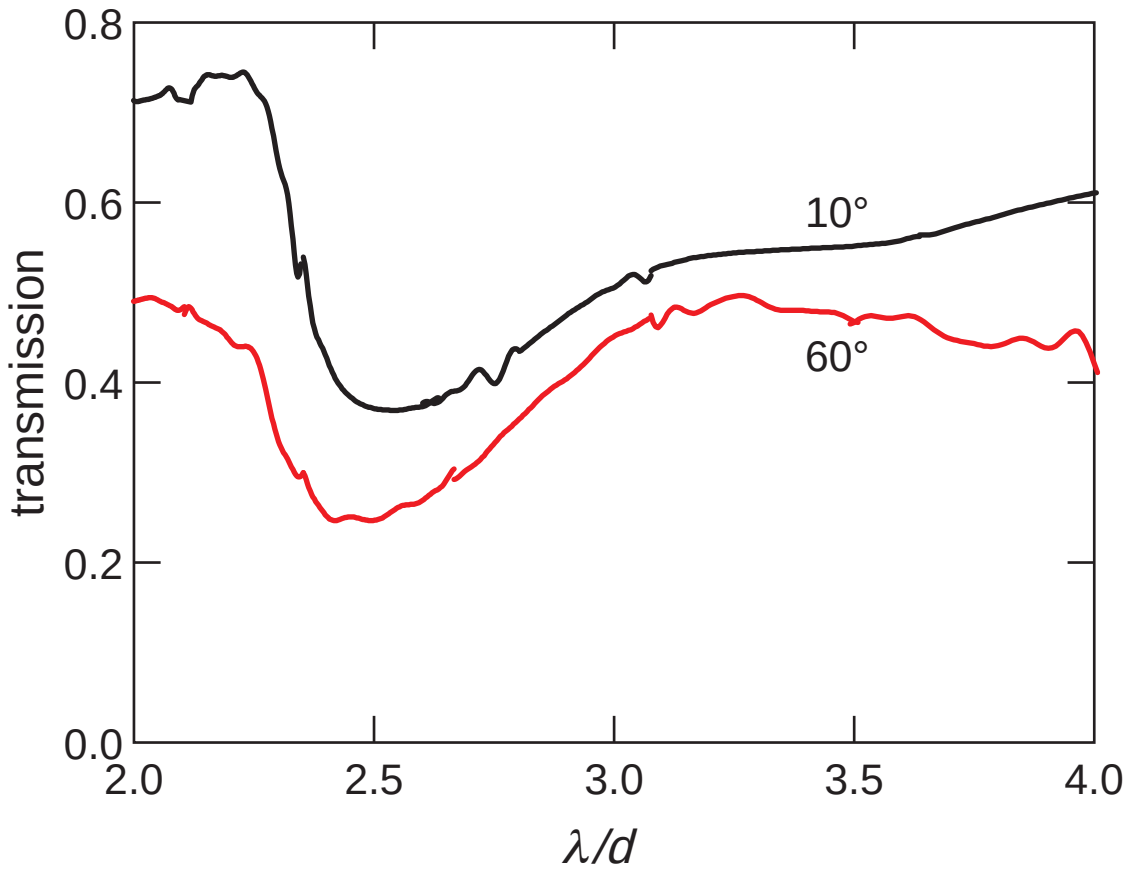

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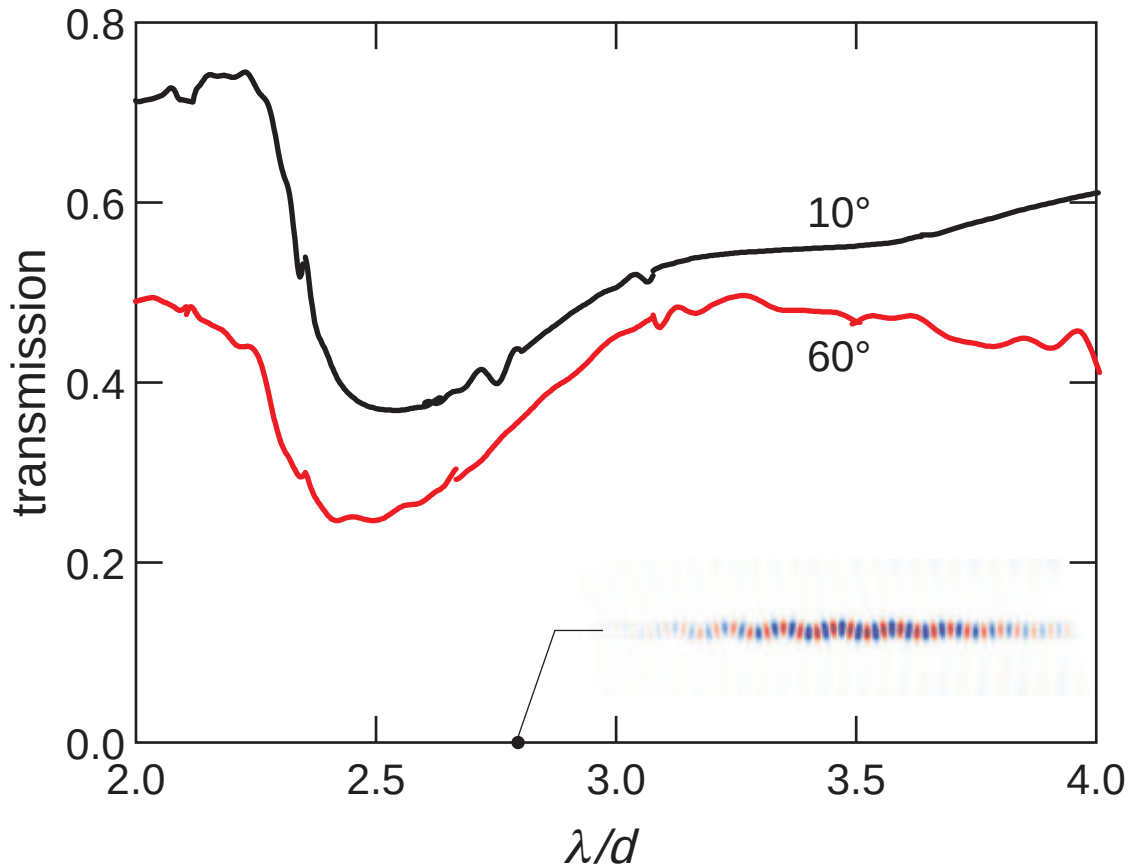

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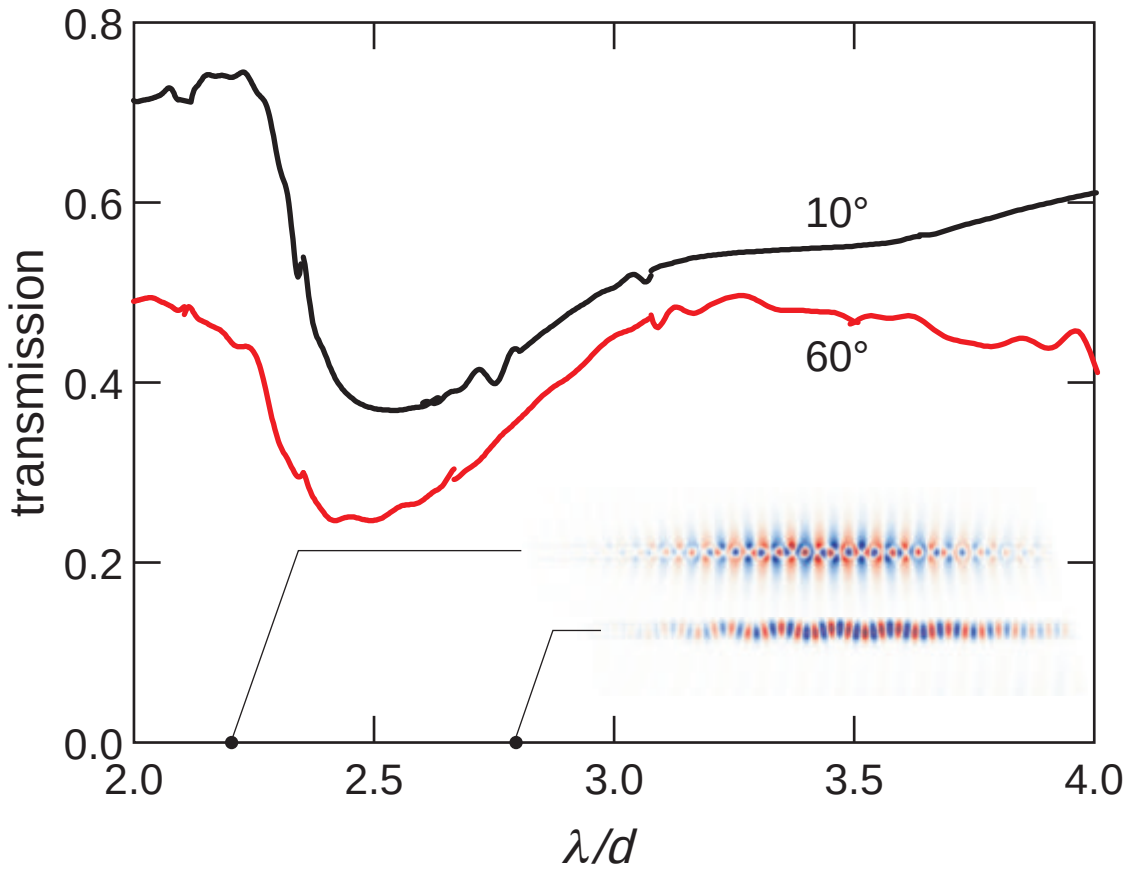
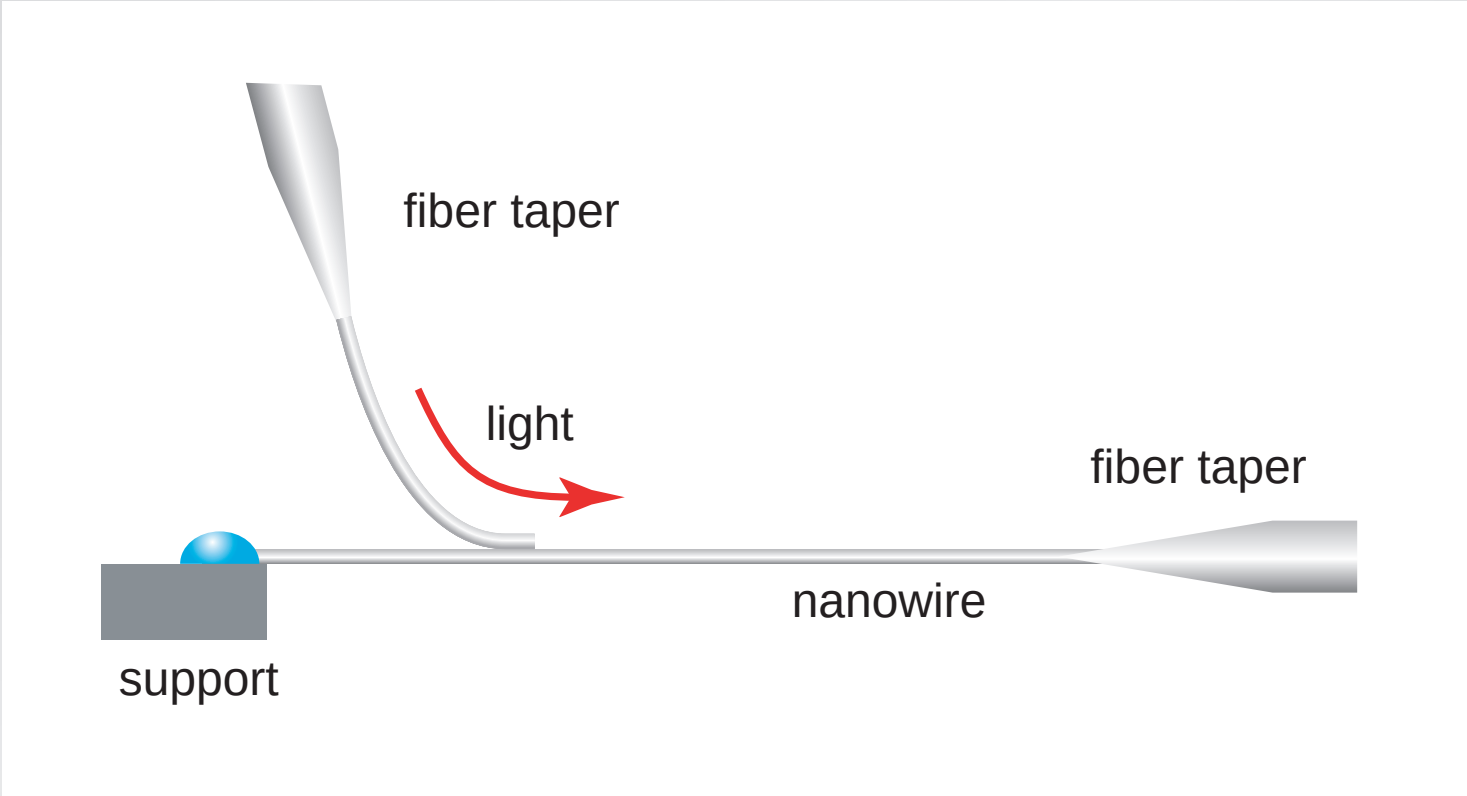


Manipulating light at the nanoscale

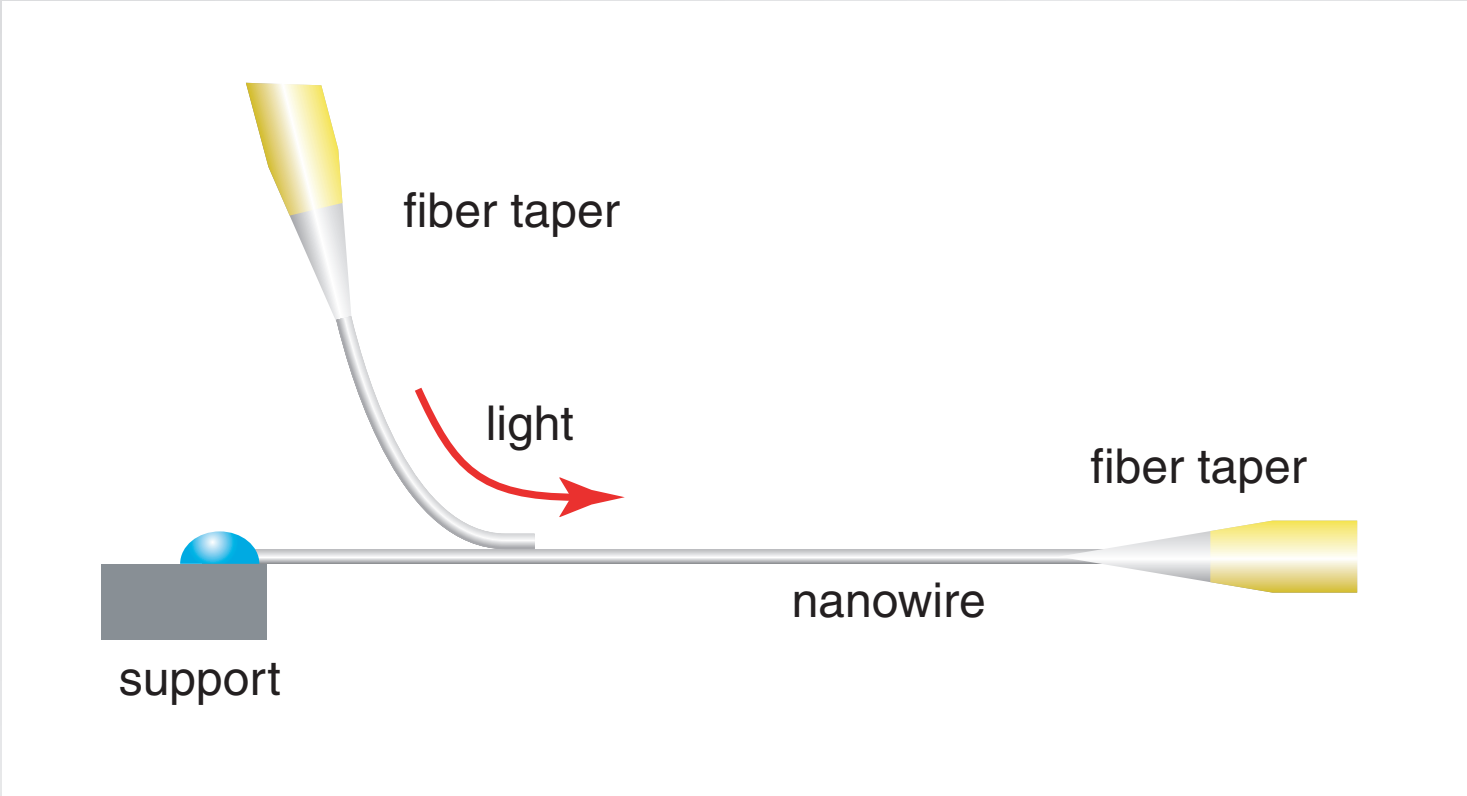
loss measurement



Nature, 426, 816 (2003)

Manipulating light at the nanoscale

loss measurement



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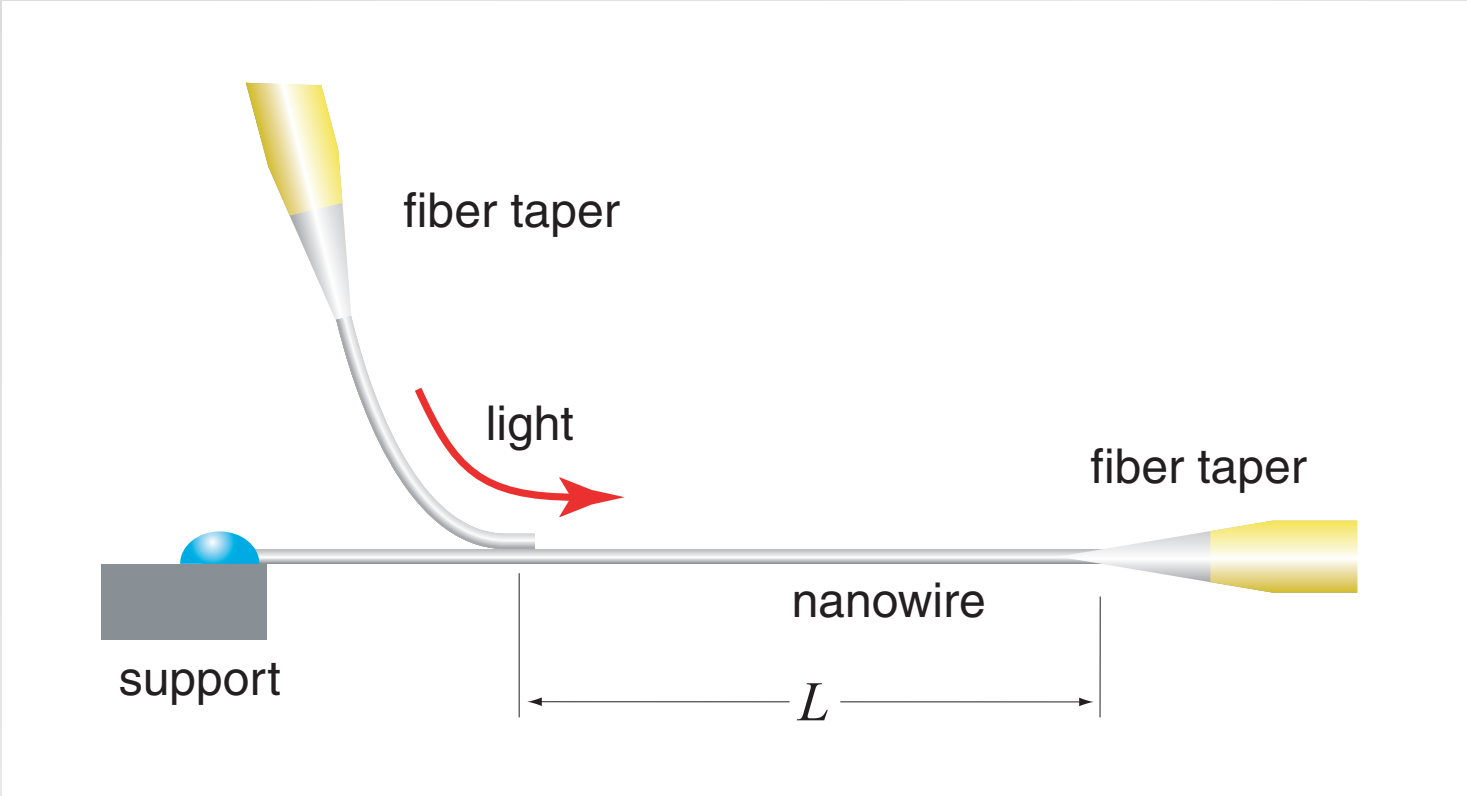

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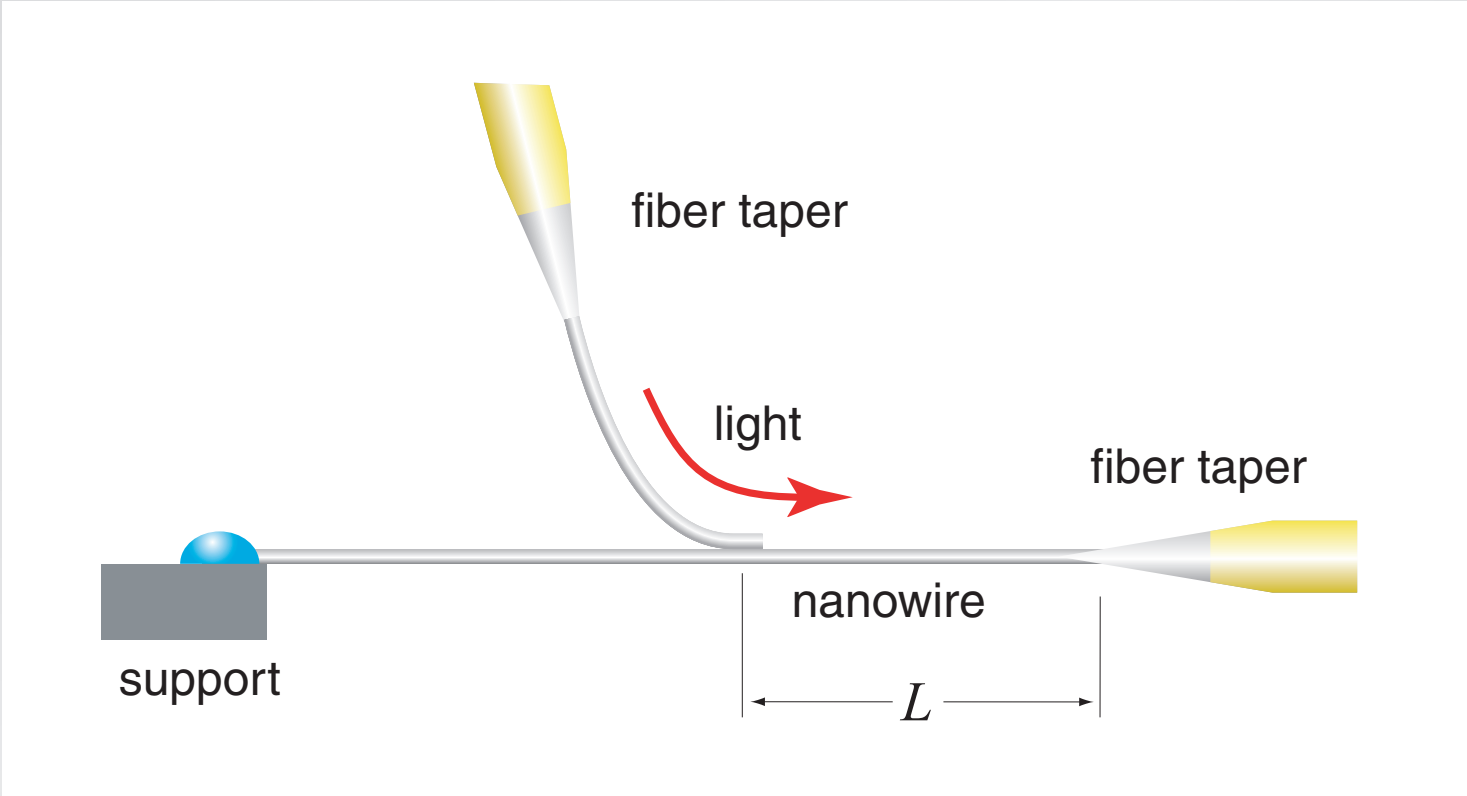

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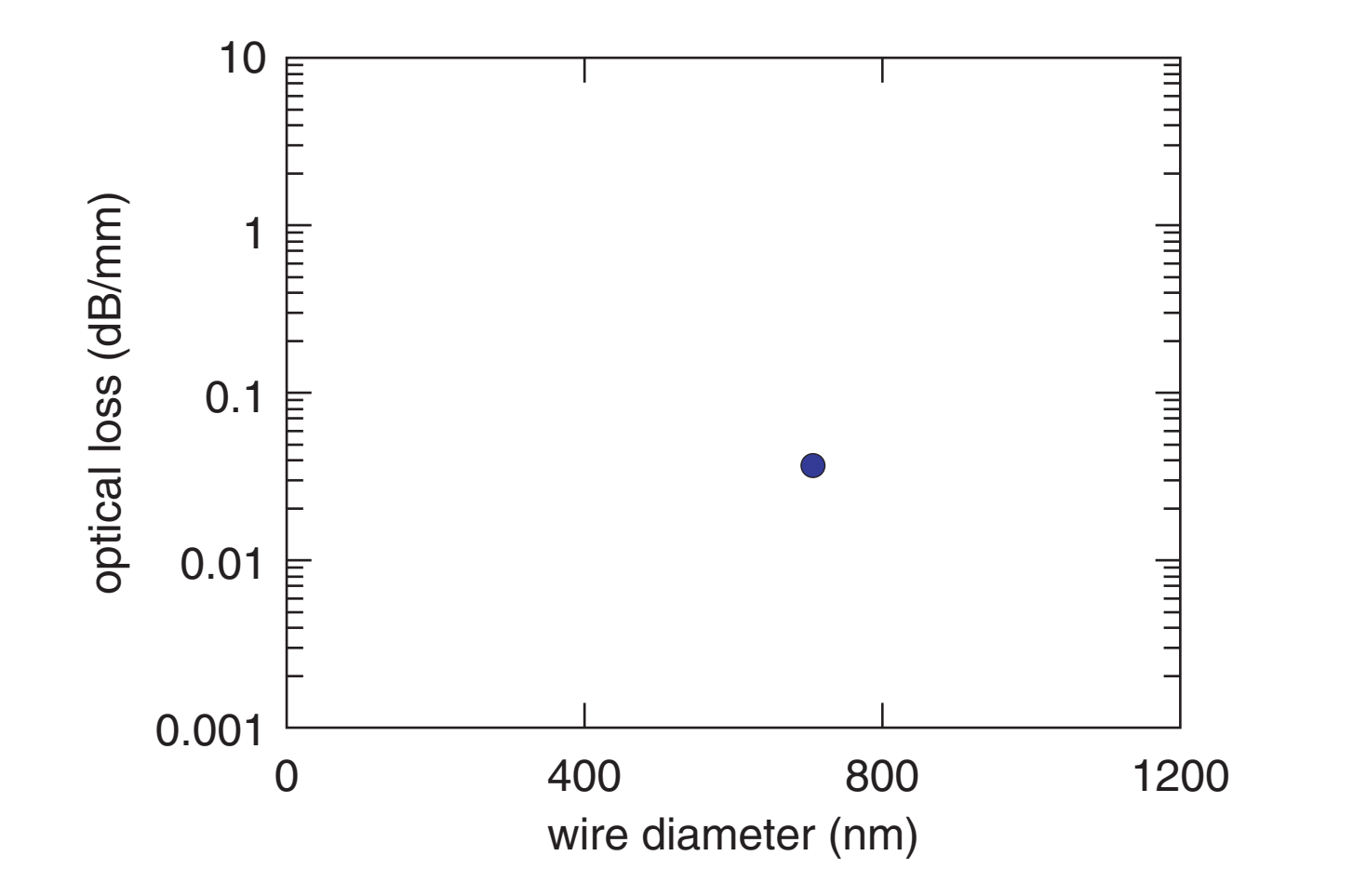

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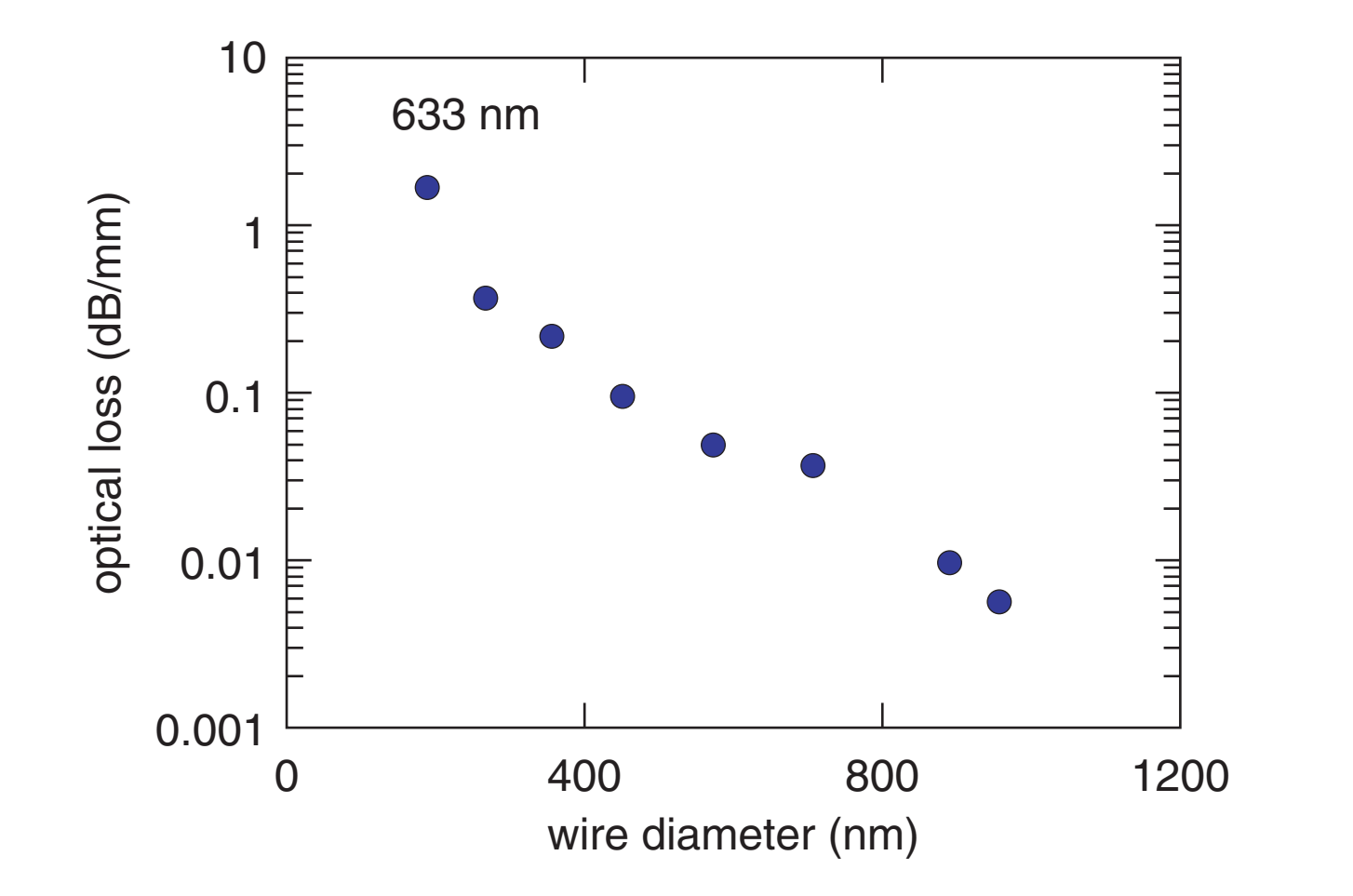

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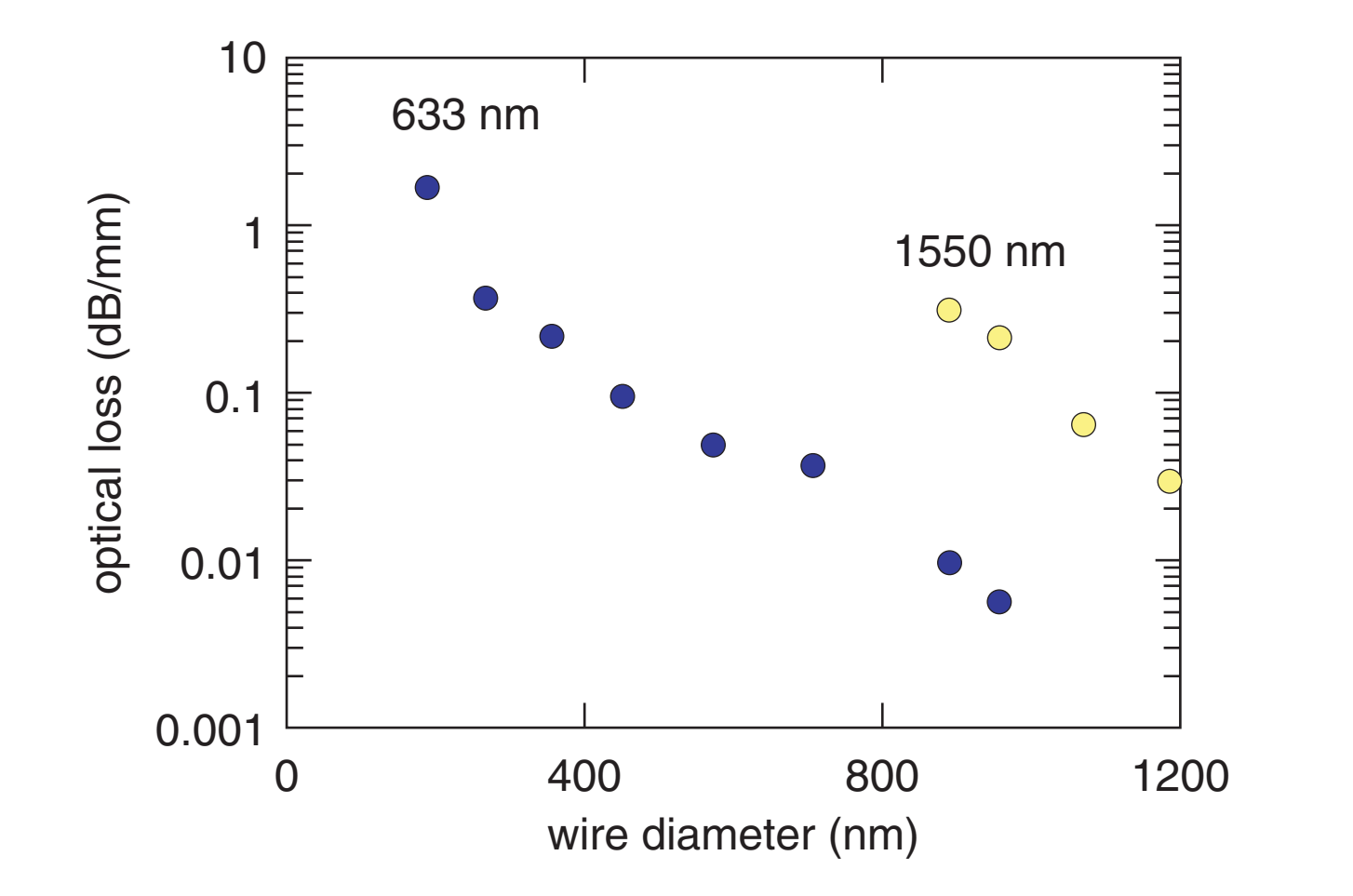
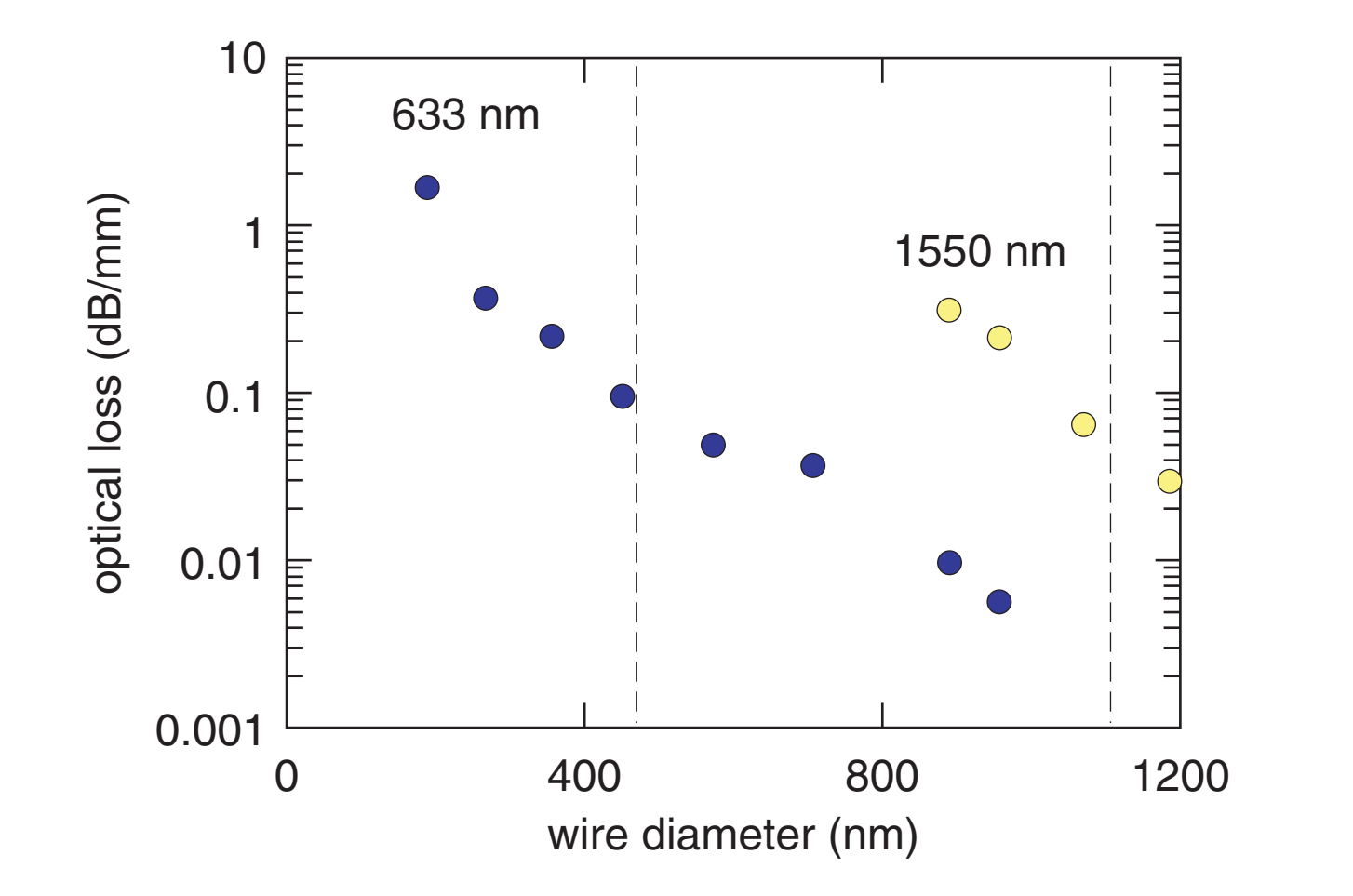


Nature, 426, 816 (2003)

Manipulating light at the nanoscale

loss at single-mode diameter < 0.1 dB/mm



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