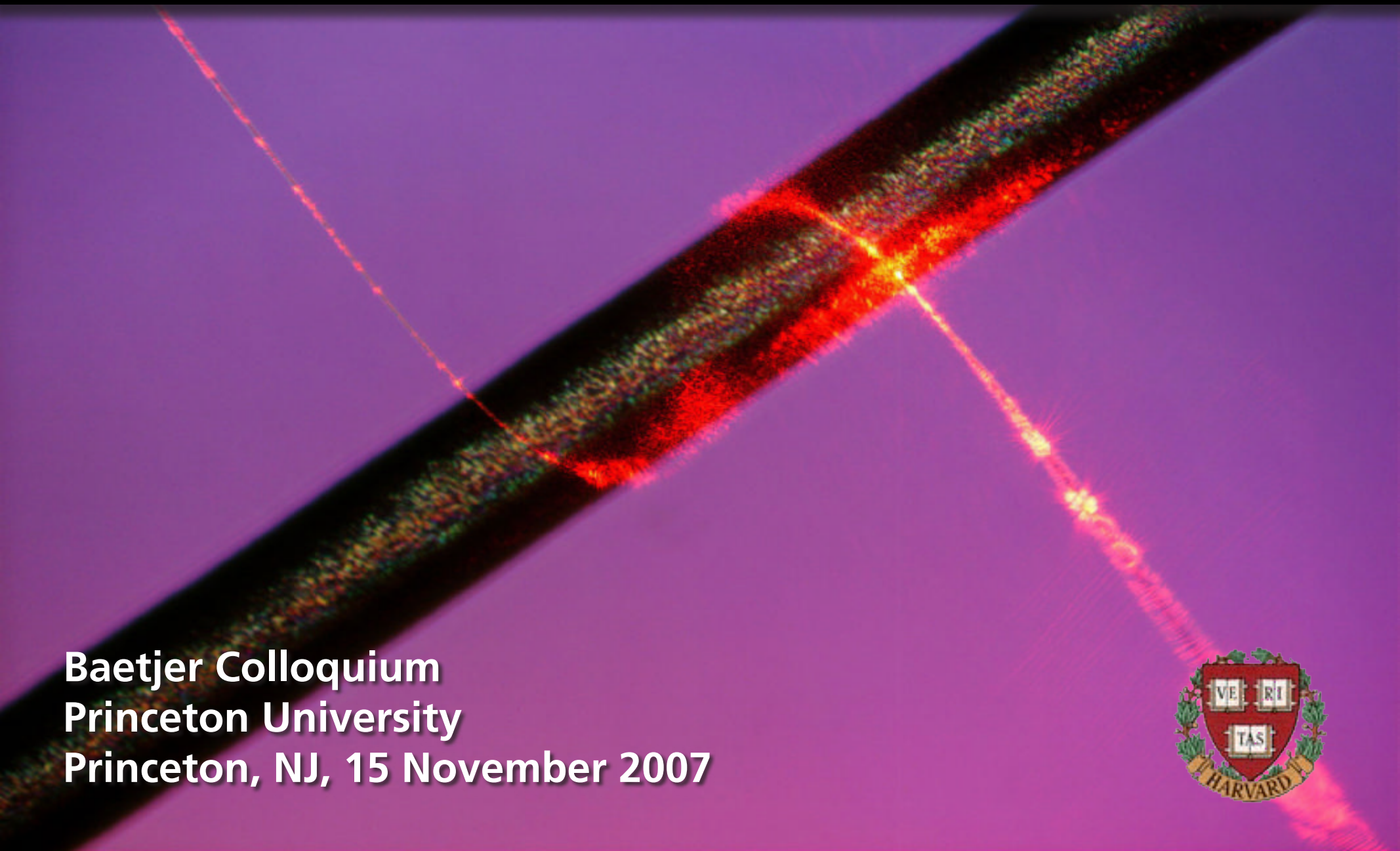


Wrapping light around a hair



Baetjer Colloquium
Princeton University
Princeton, NJ, 15 November 2007

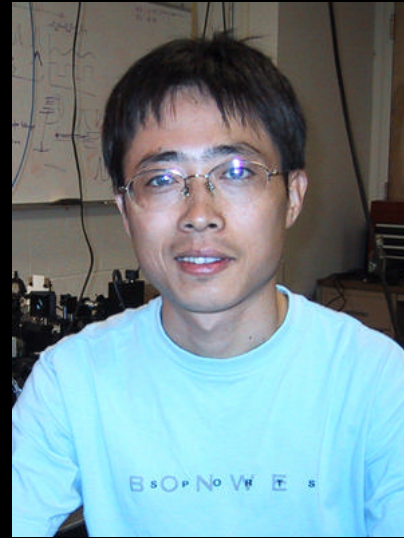




Rafael Gattass



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

Xuwen Chen (Zhejiang)

Zhanghua Han (Zhejiang)

Dr. Sailing He (Zhejiang)

Liu Liu (Zhejiang)

Dr. Jingyi Lou (Zhejiang)

Dr. Ray Mariella (LLNL)

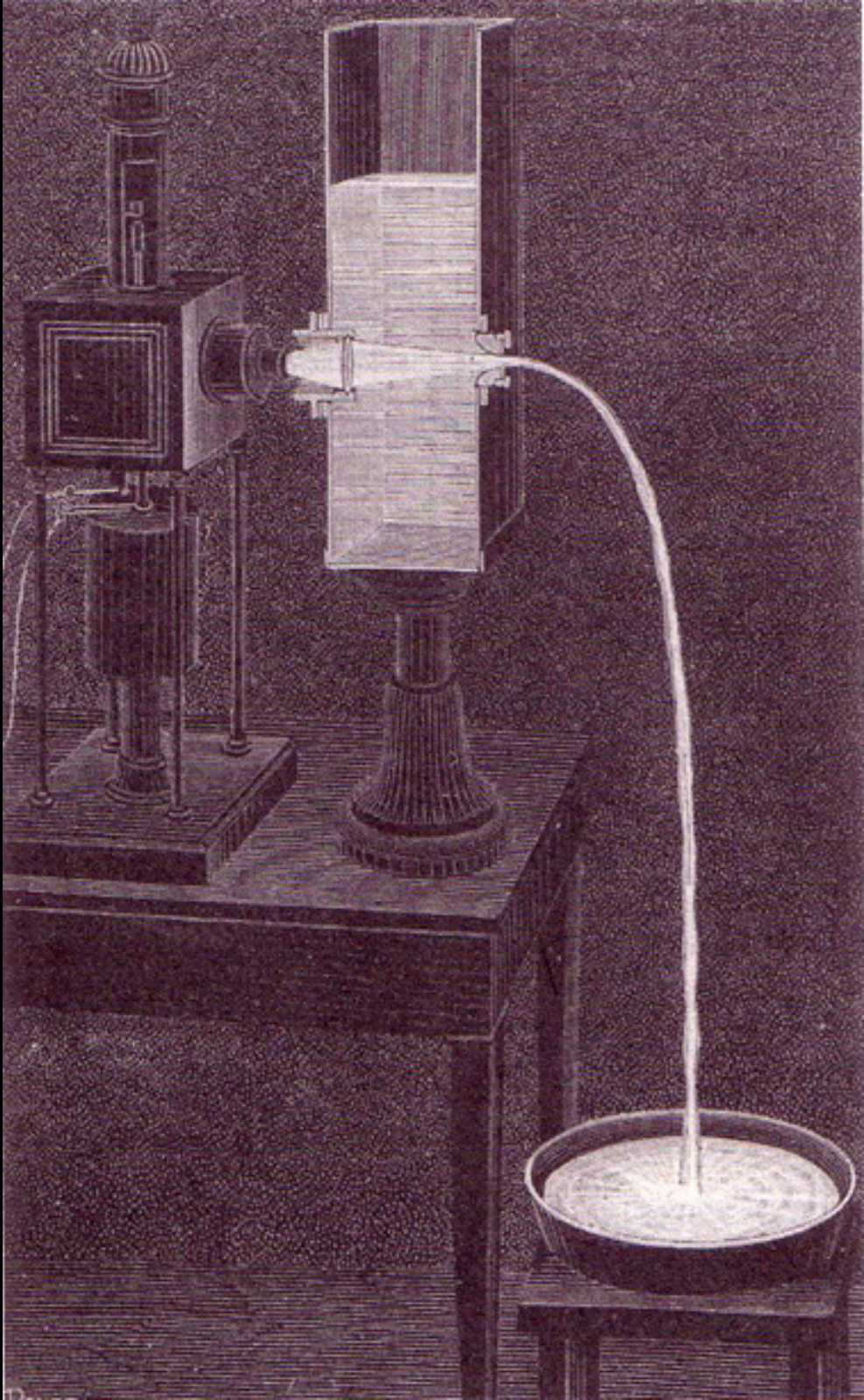
Prof. Frank Marlow (MPI Mülheim)

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)



W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.

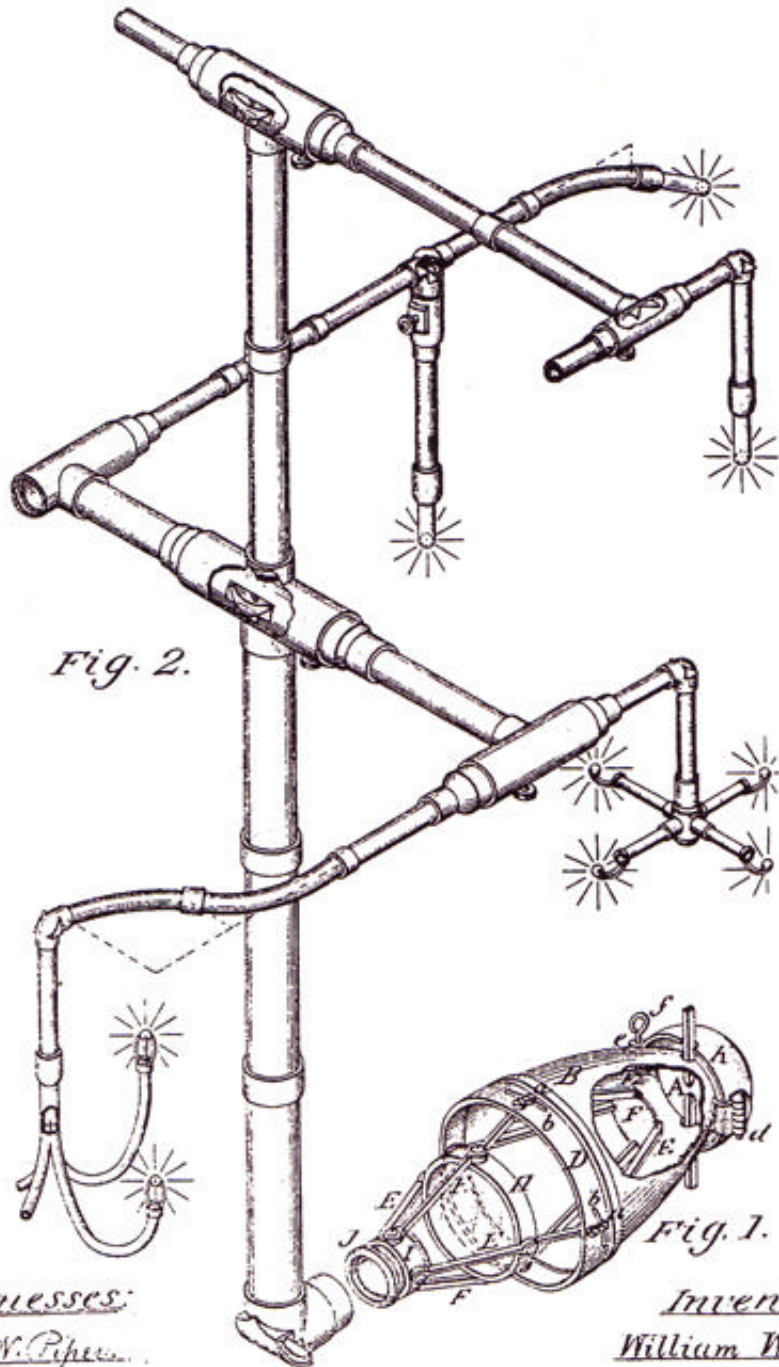


Fig. 2.

Fig. 1.

Witnesses:
J. N. Piper
Ed. [unclear]

Inventor:
William Wheeler
 by attorney
[Signature]

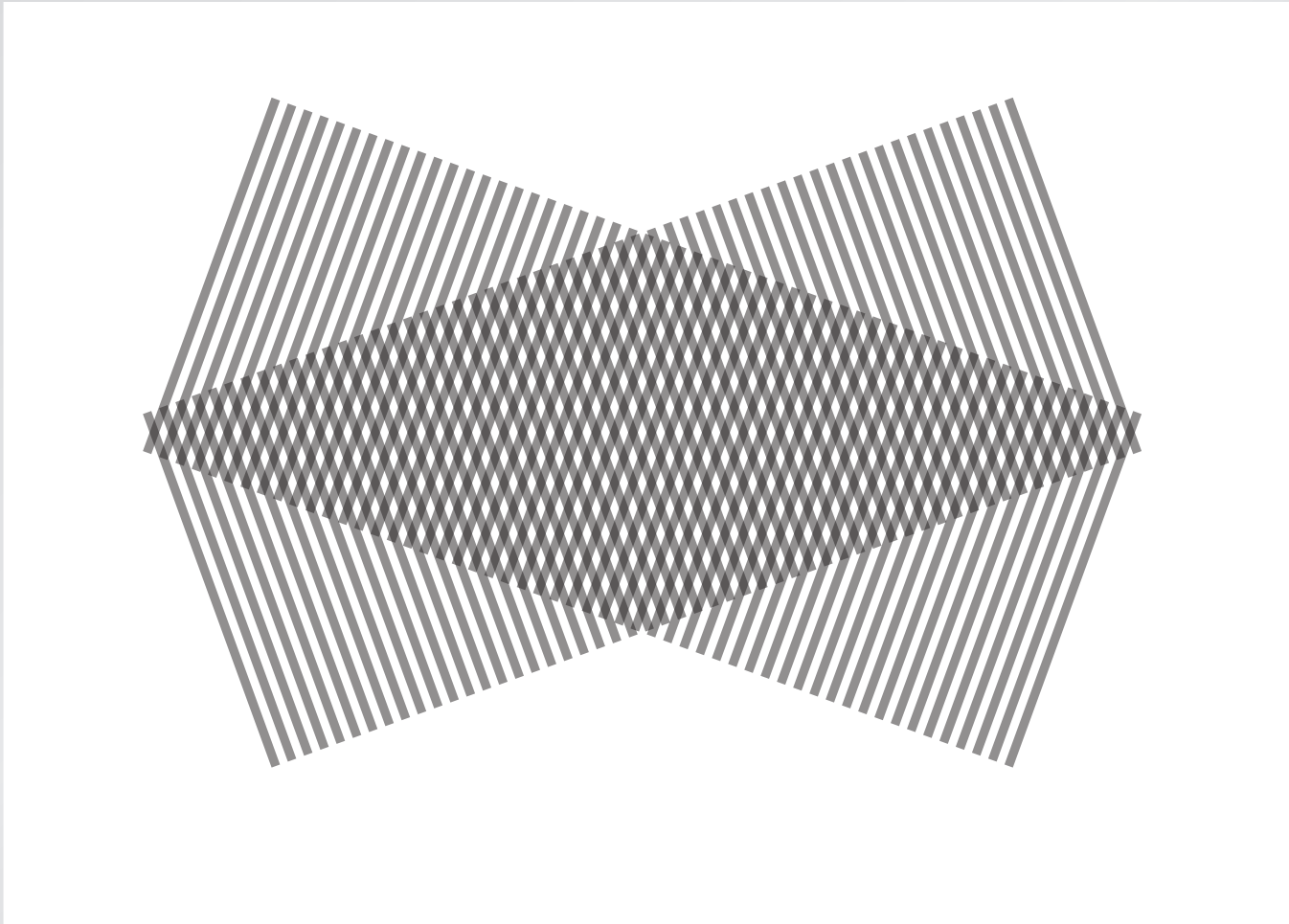
US Patent 247, 229 (1881)

Outline

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

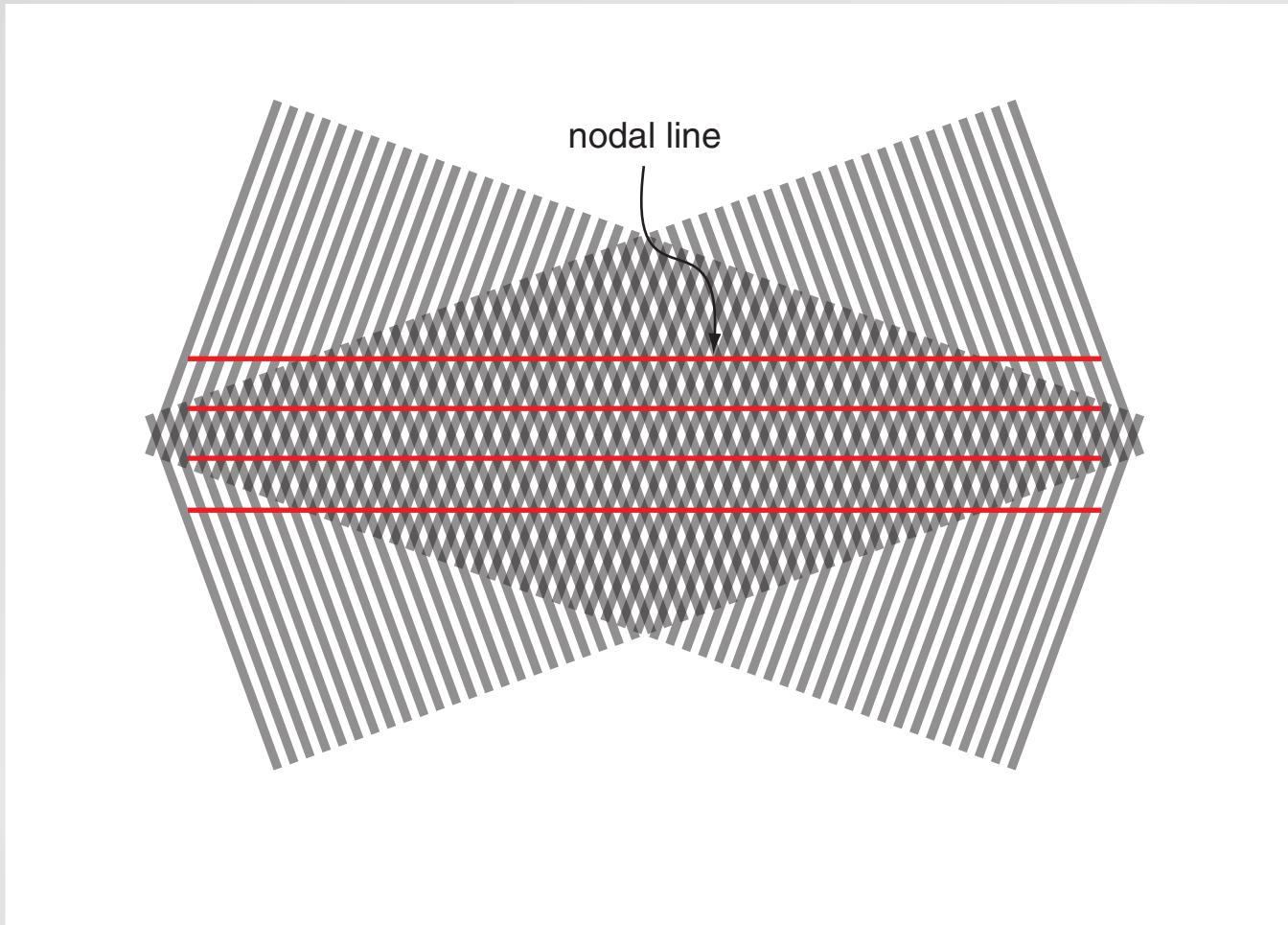
Waveguiding

two crossed planar waves...



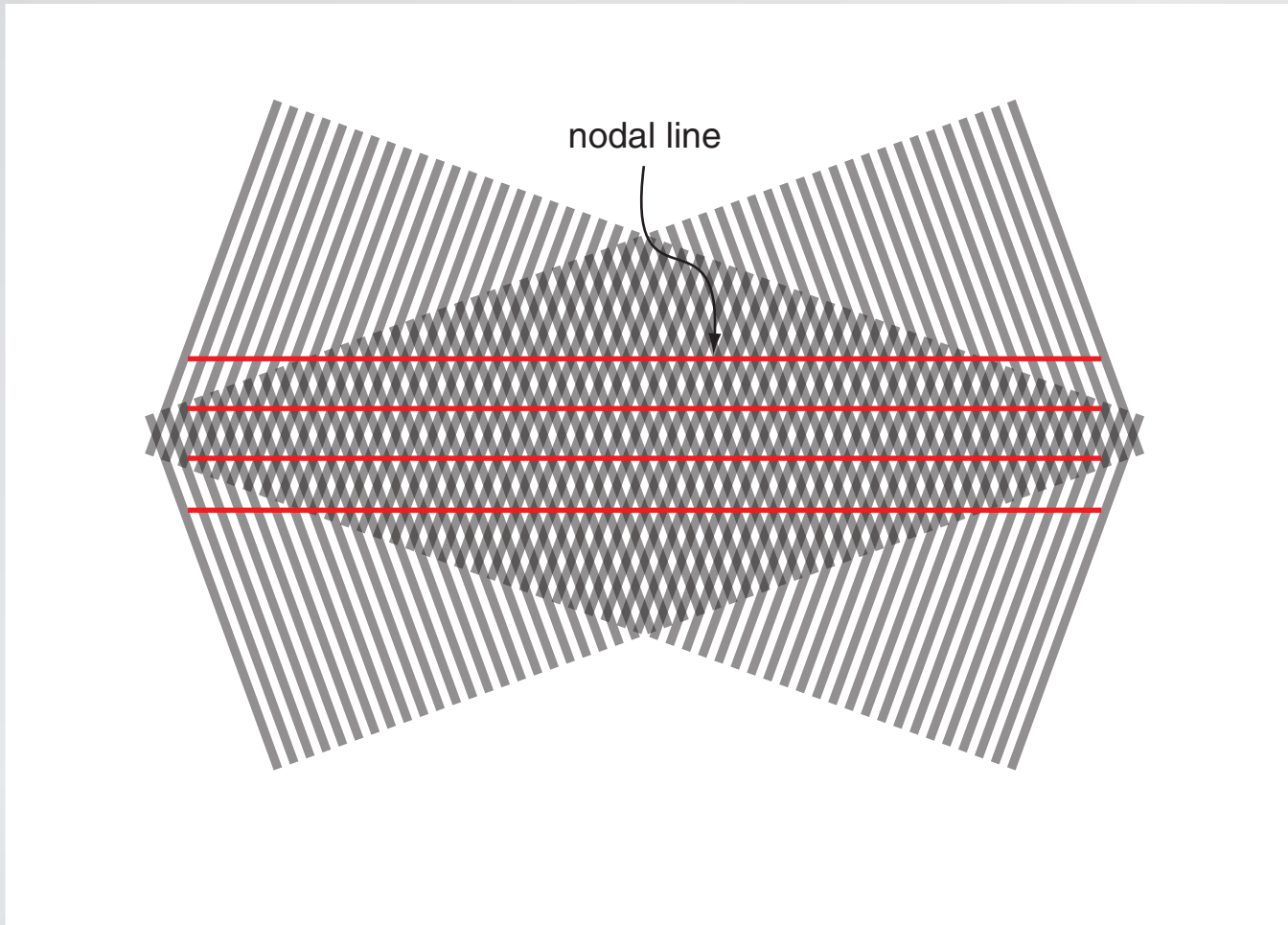
Waveguiding

...cause an interference pattern



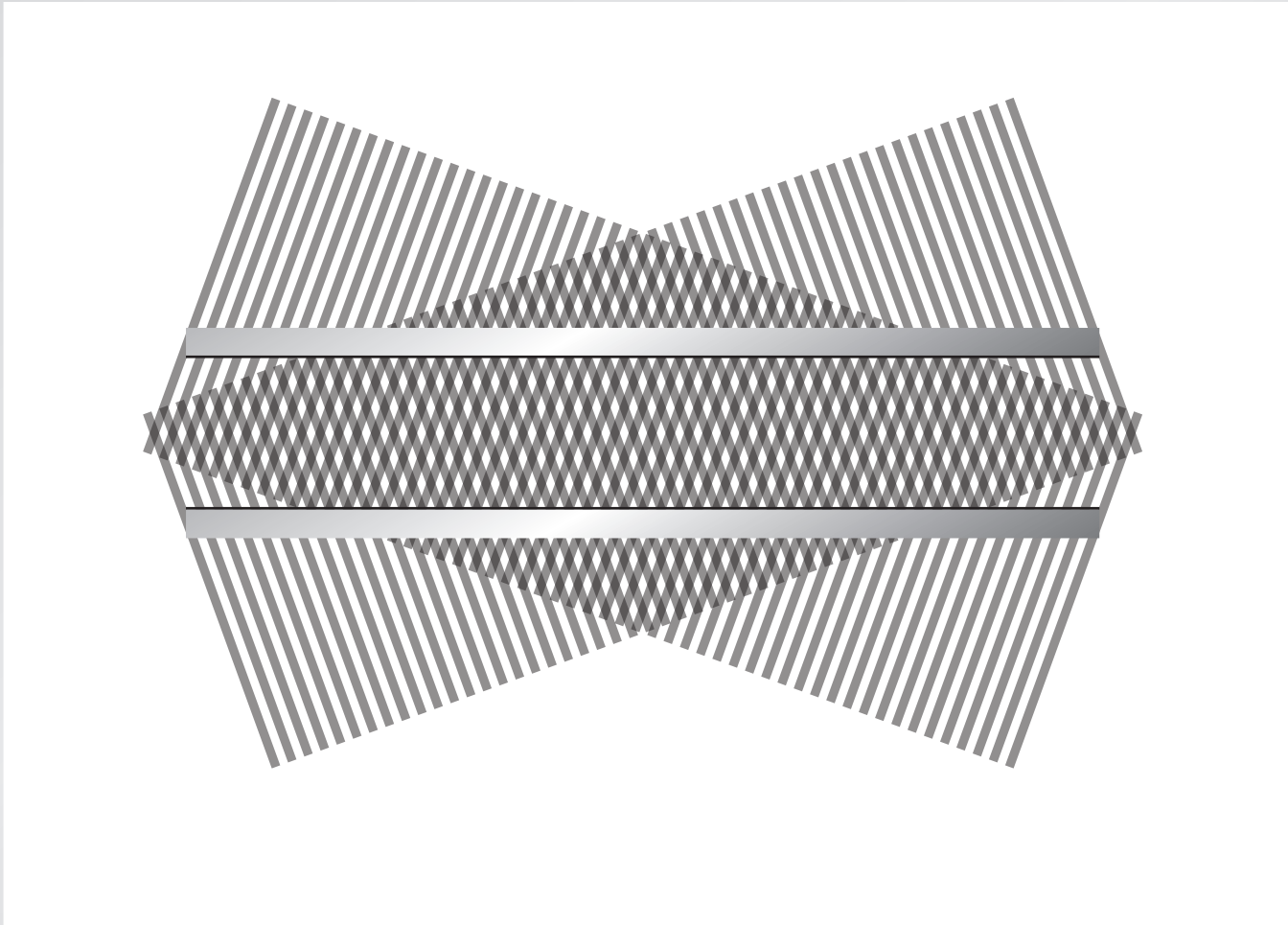
Waveguiding

$E = 0$ on the nodal lines



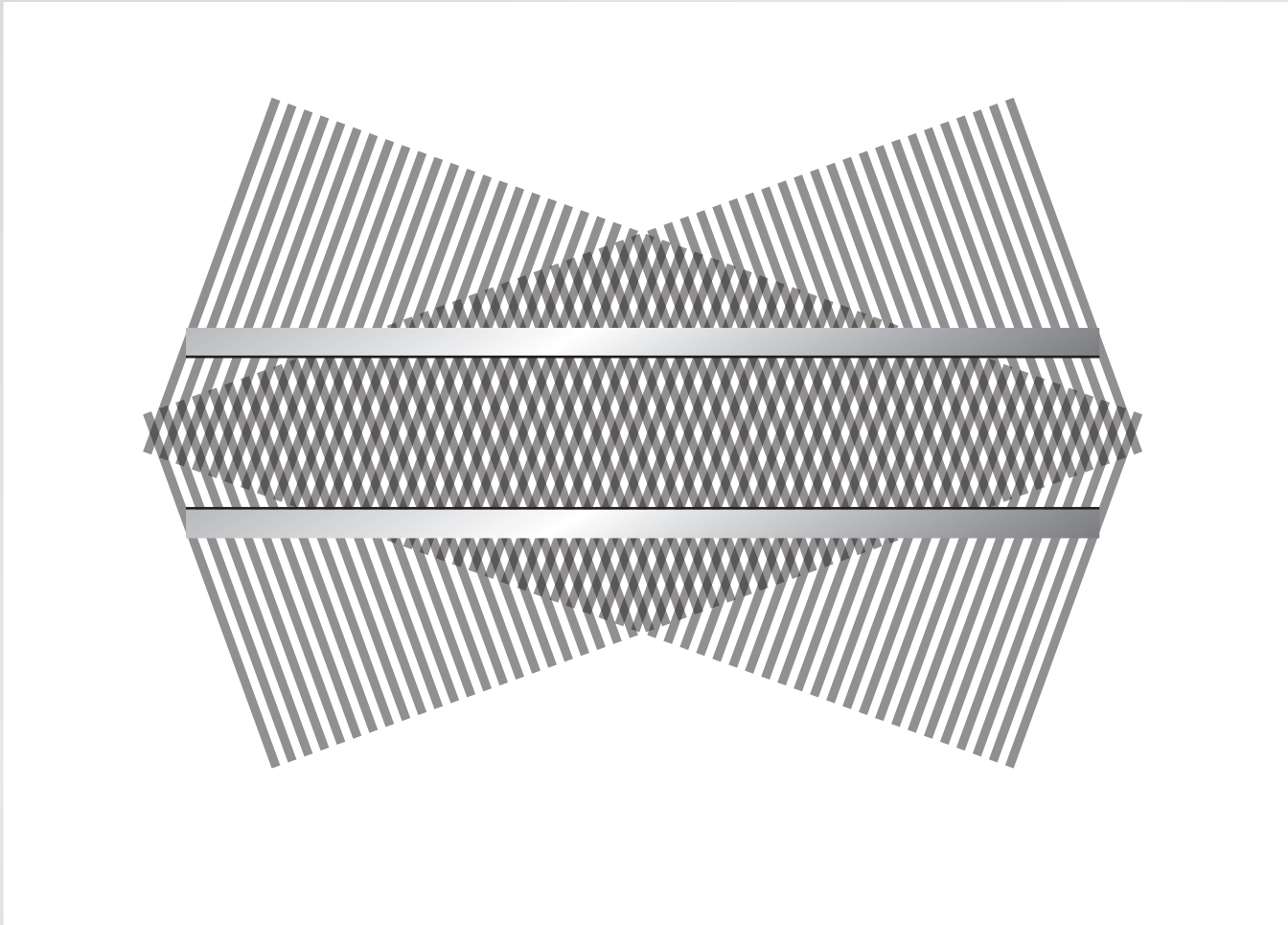
Waveguiding

...satisfying boundary conditions for planar-mirror waveguide



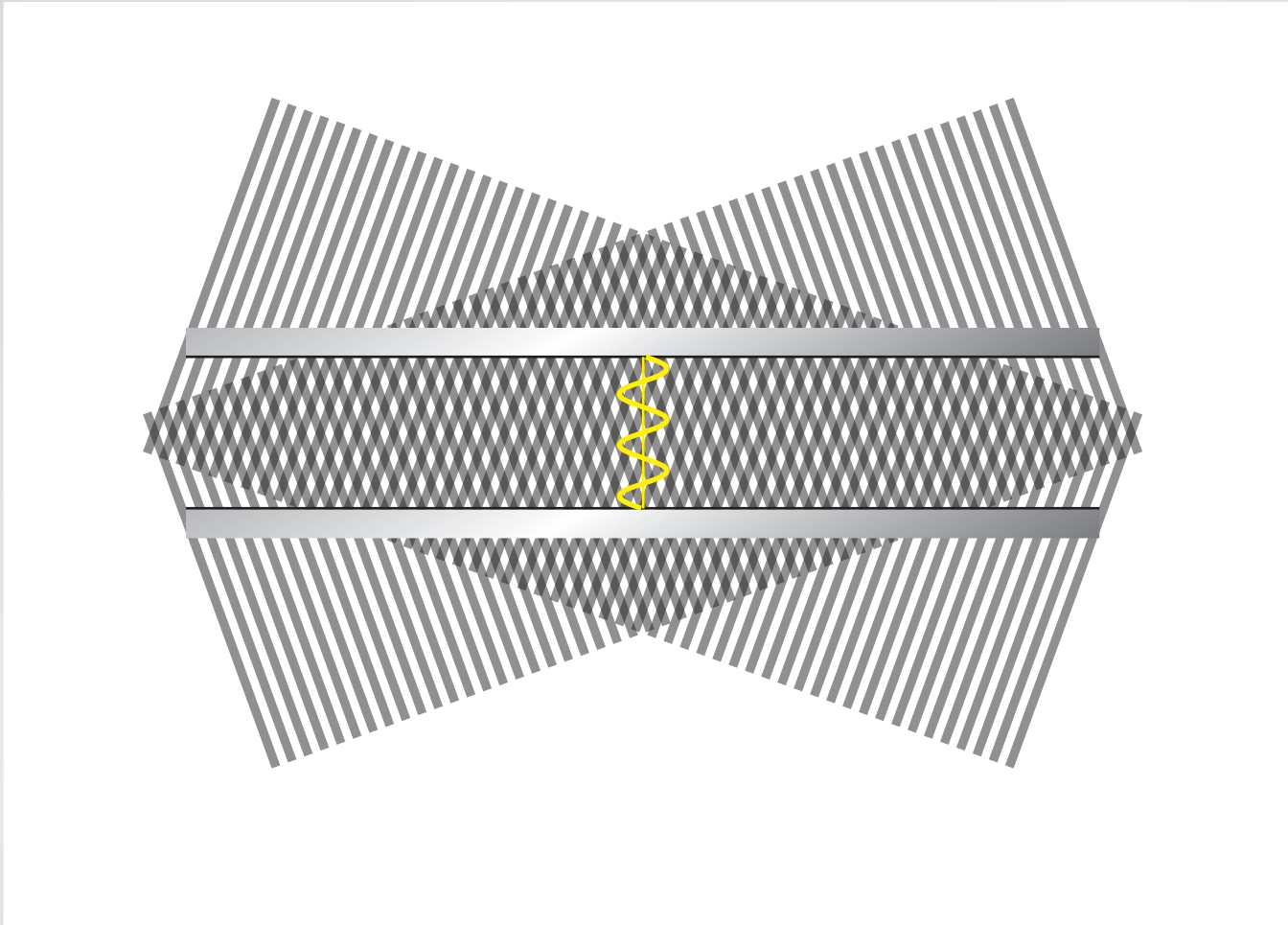
Waveguiding

transverse standing wave, traveling along axis



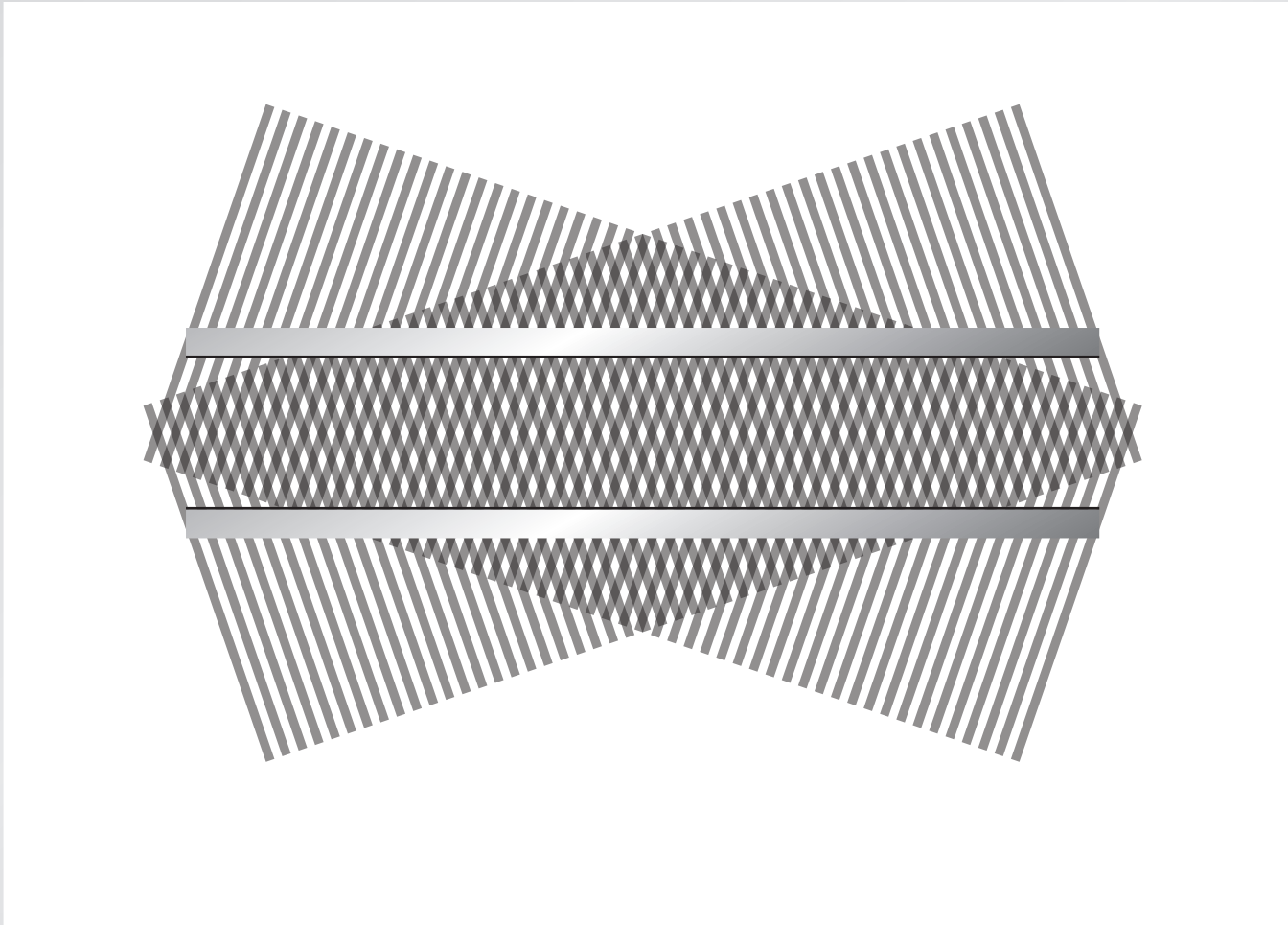
Waveguiding

transverse standing wave, traveling along axis



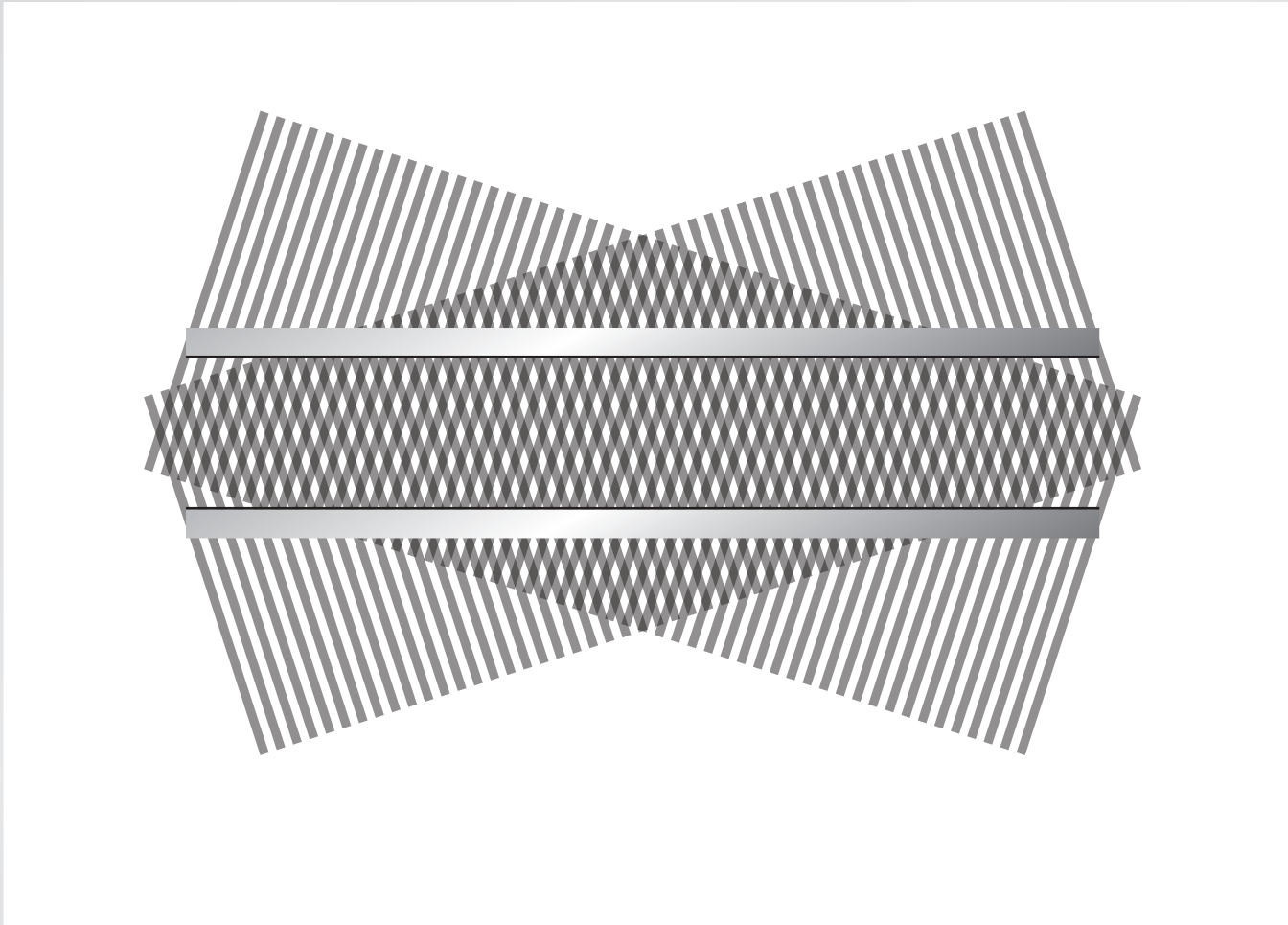
Waveguiding

change angle of incident waves...



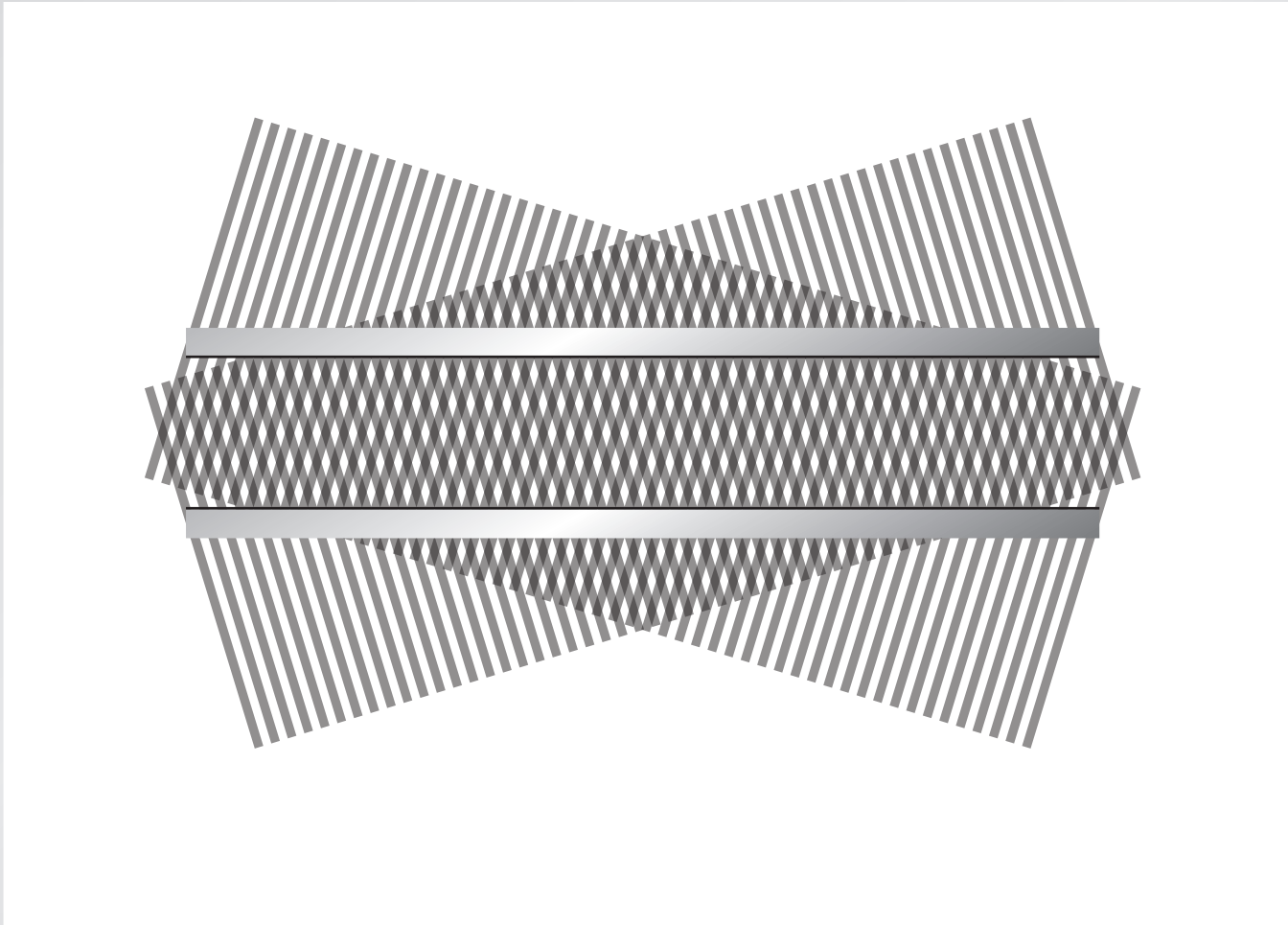
Waveguiding

change angle of incident waves...



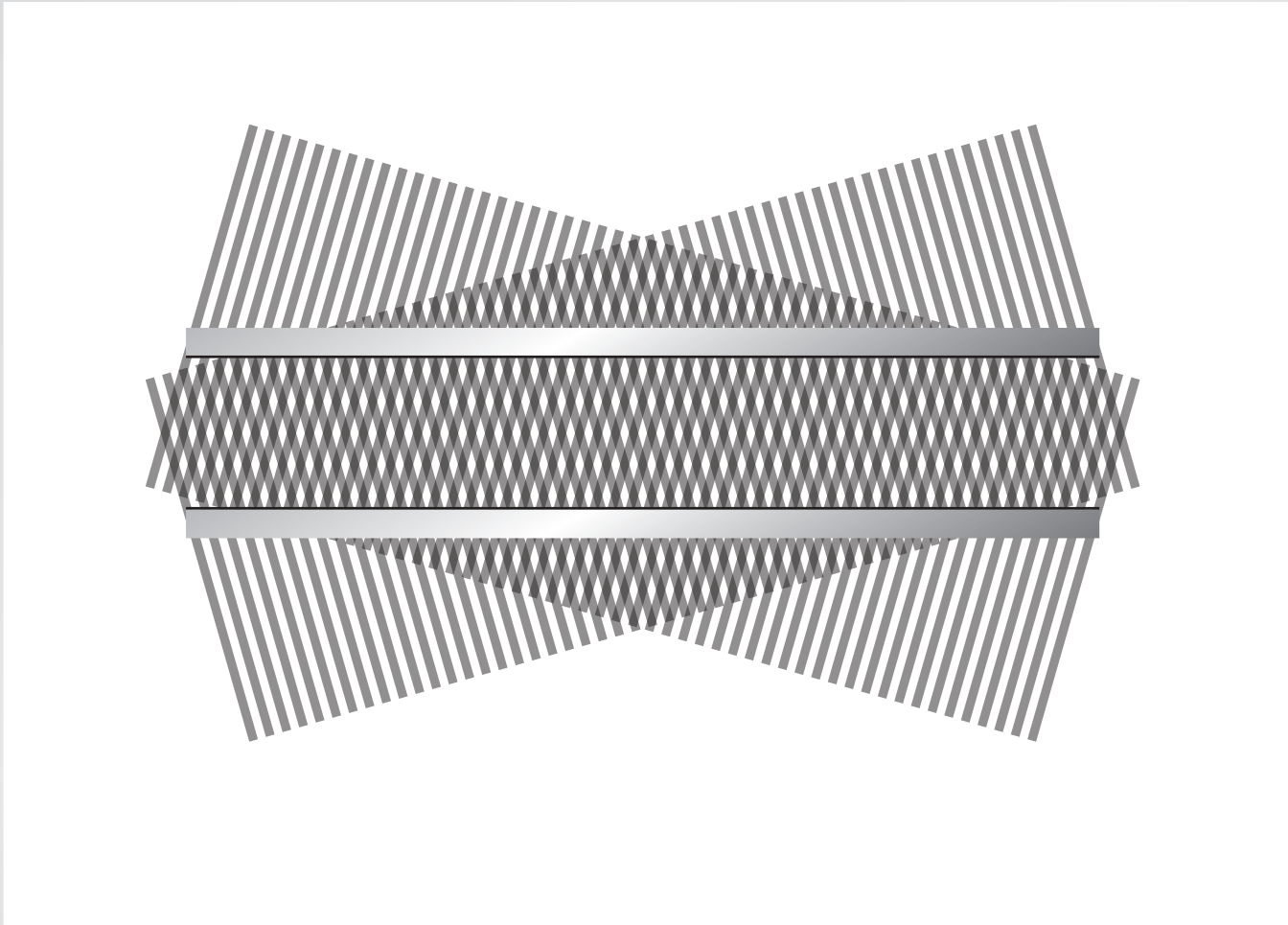
Waveguiding

change angle of incident waves...



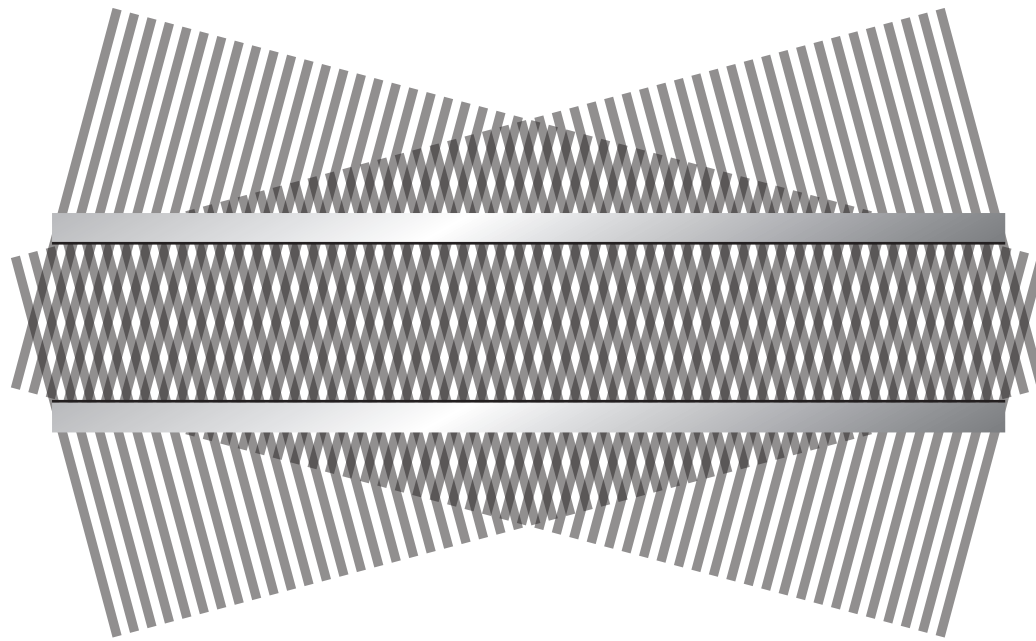
Waveguiding

change angle of incident waves...



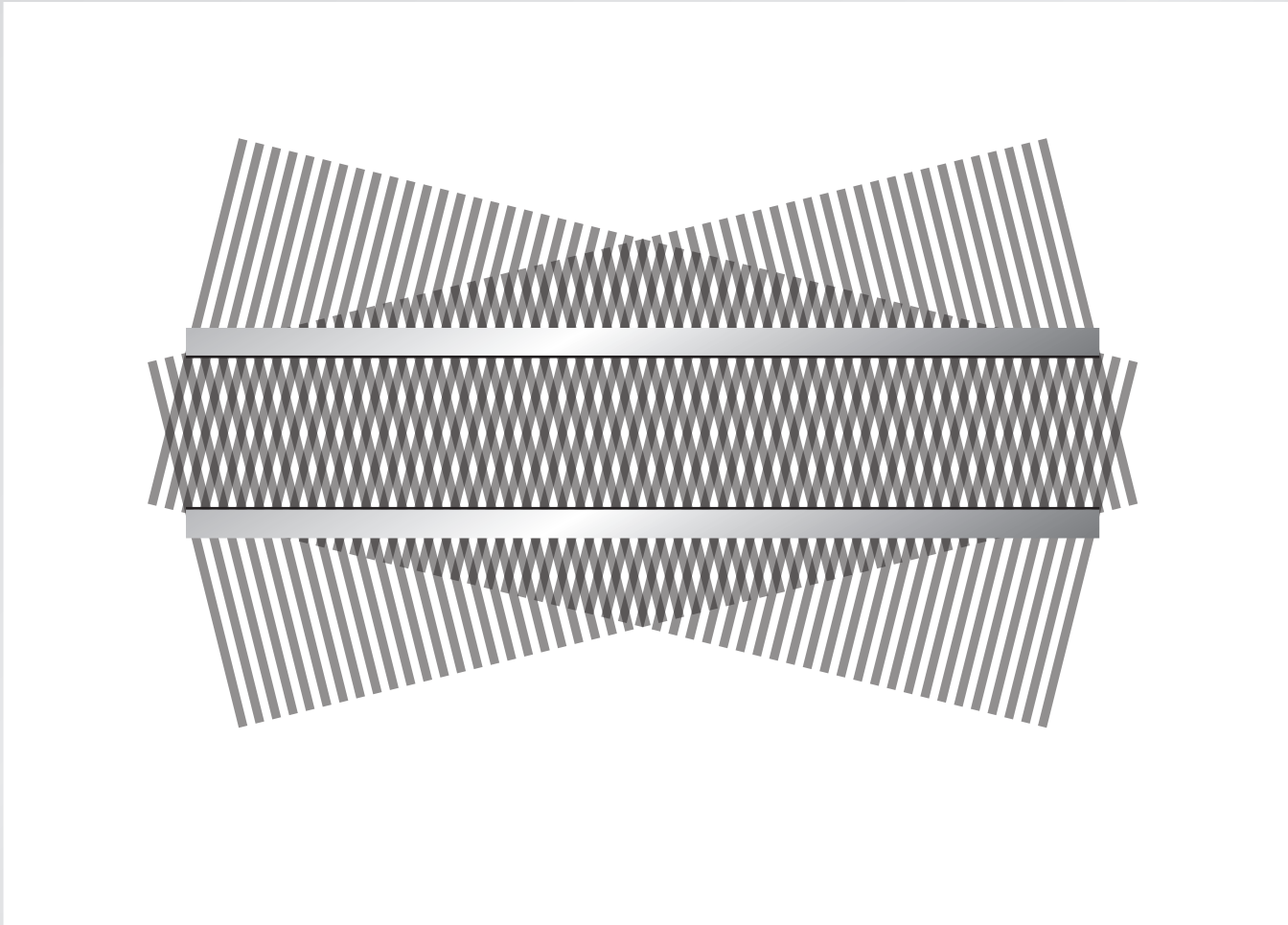
Waveguiding

change angle of incident waves...



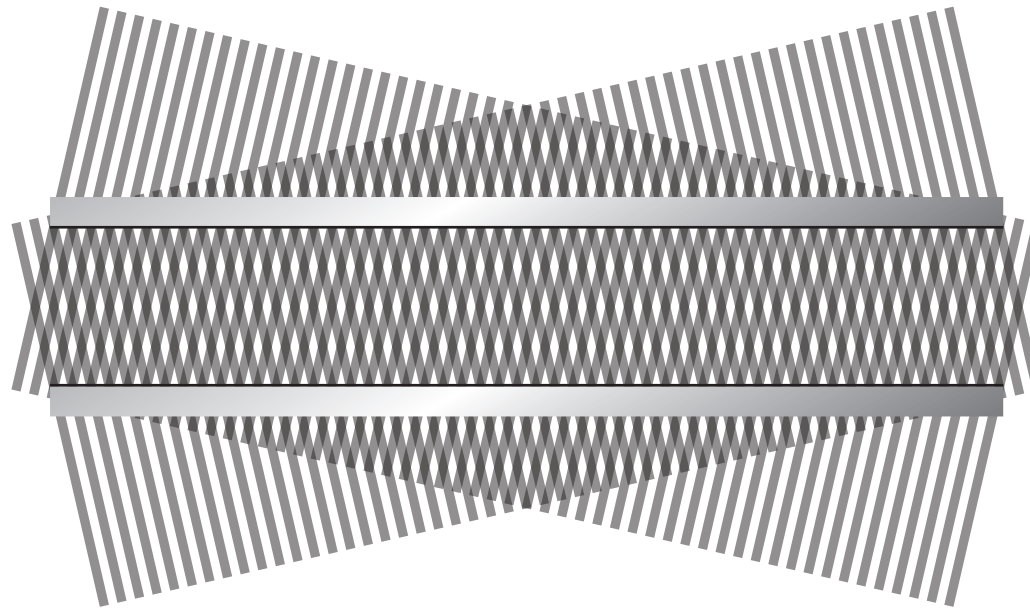
Waveguiding

change angle of incident waves...



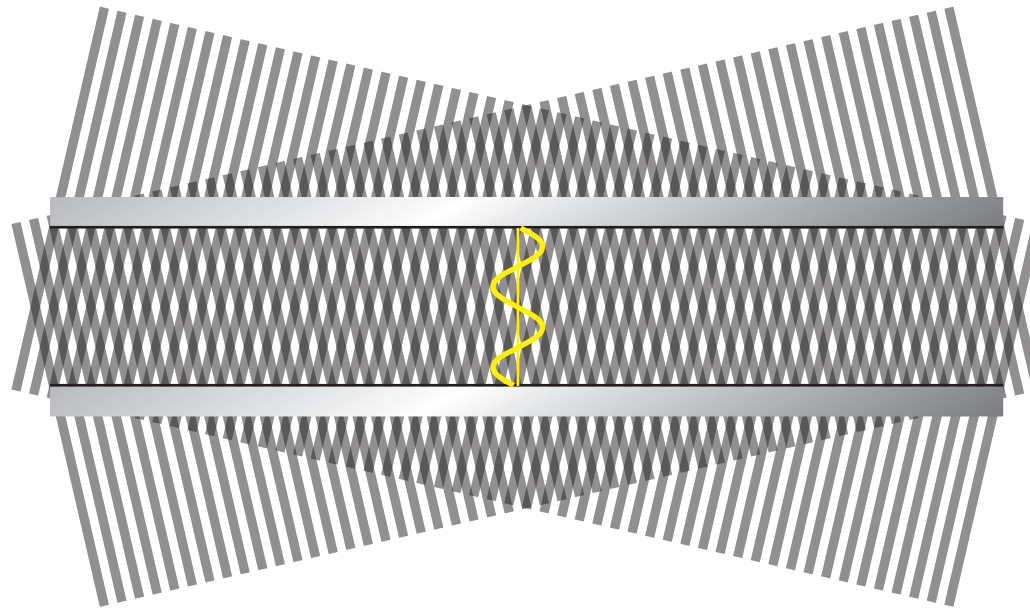
Waveguiding

change angle of incident waves...



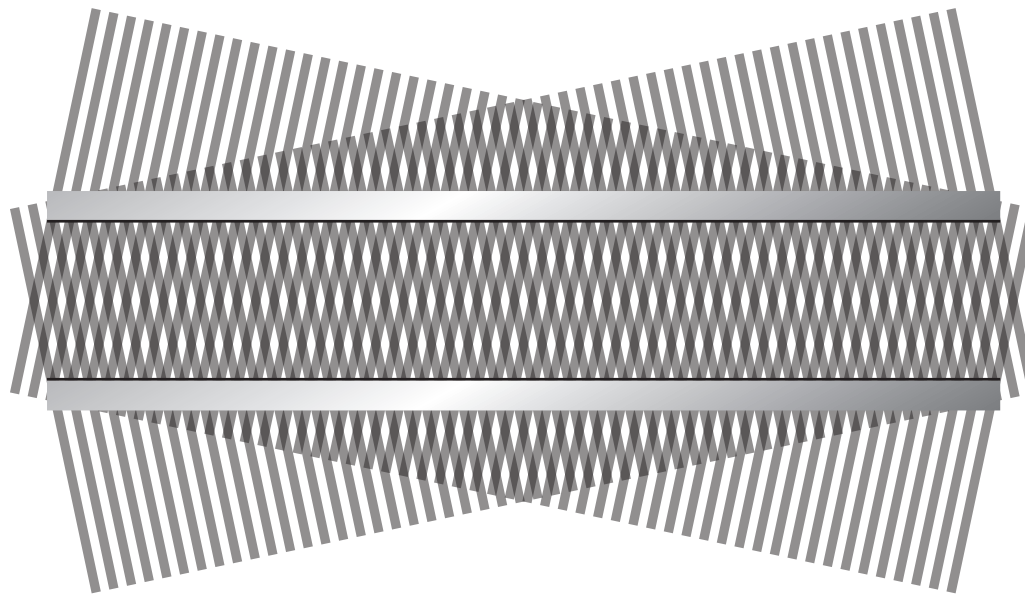
Waveguiding

change angle of incident waves...



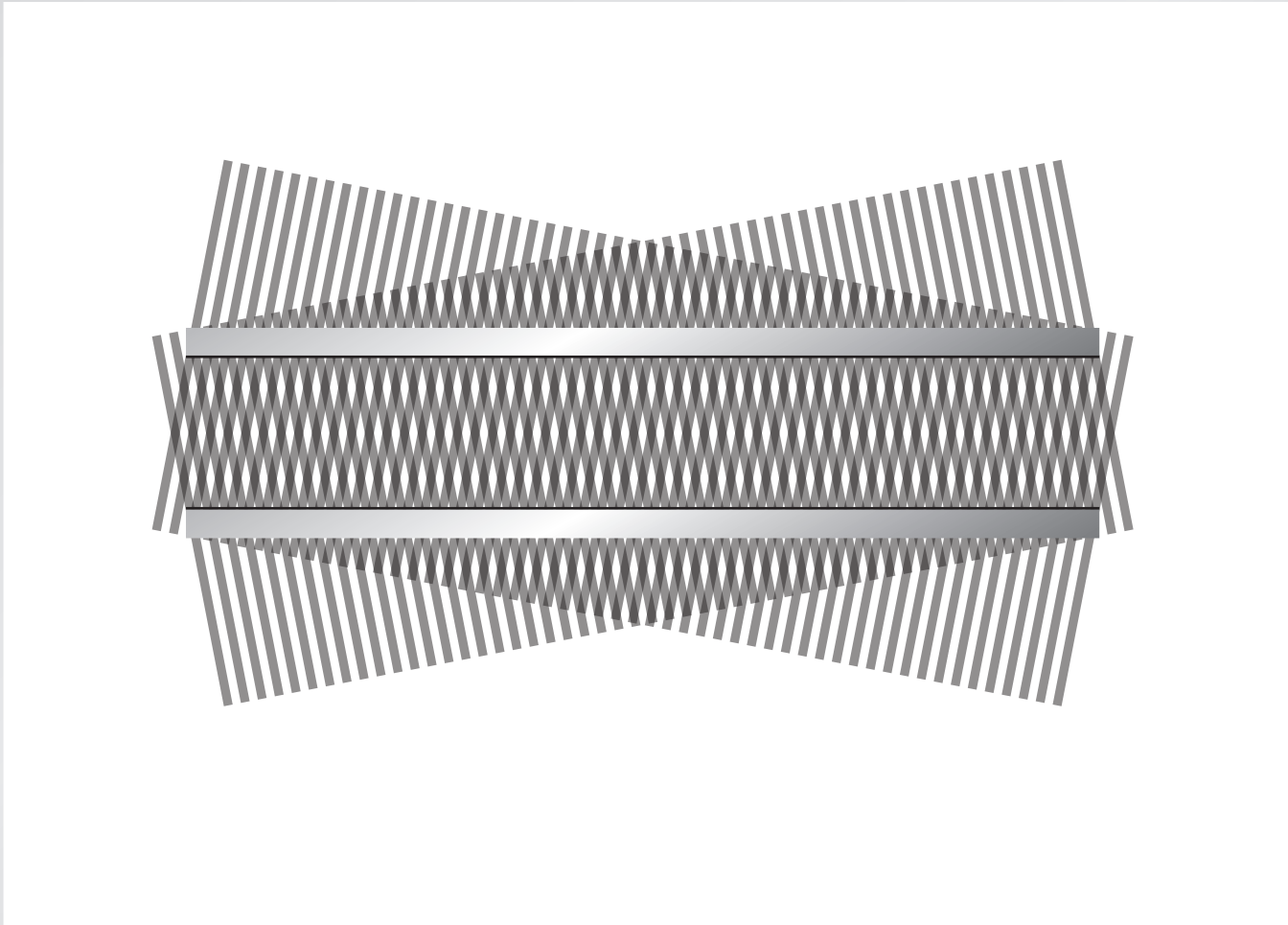
Waveguiding

change angle of incident waves...



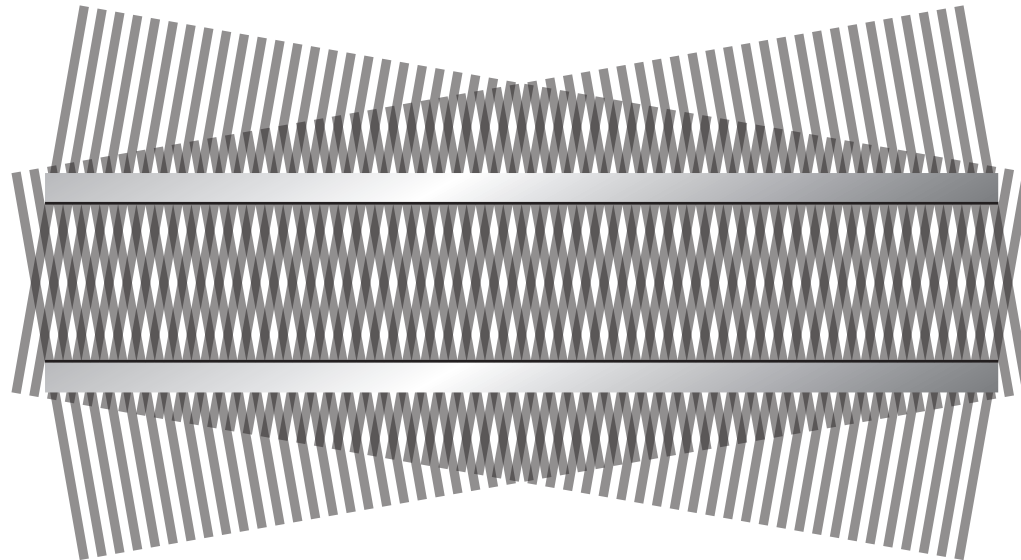
Waveguiding

change angle of incident waves...



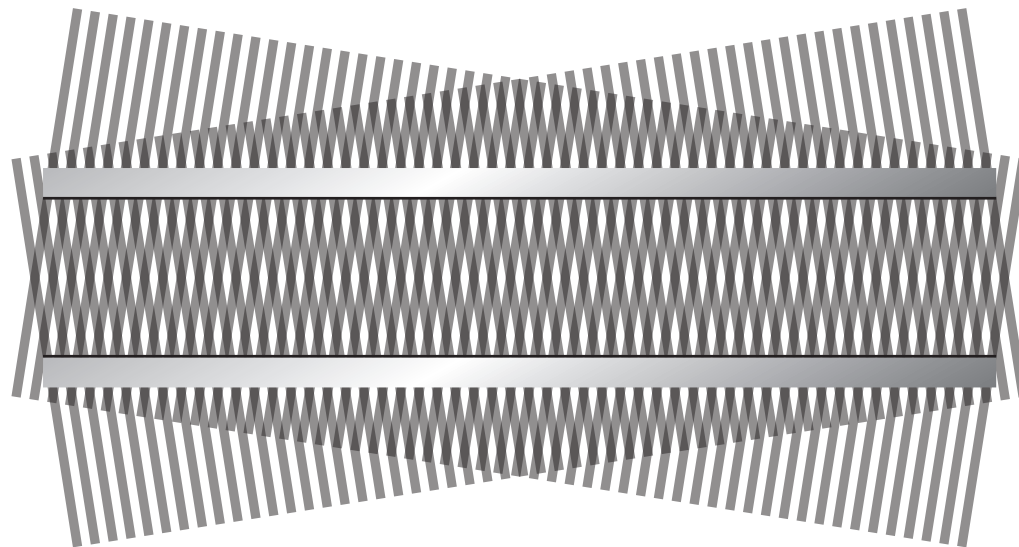
Waveguiding

change angle of incident waves...



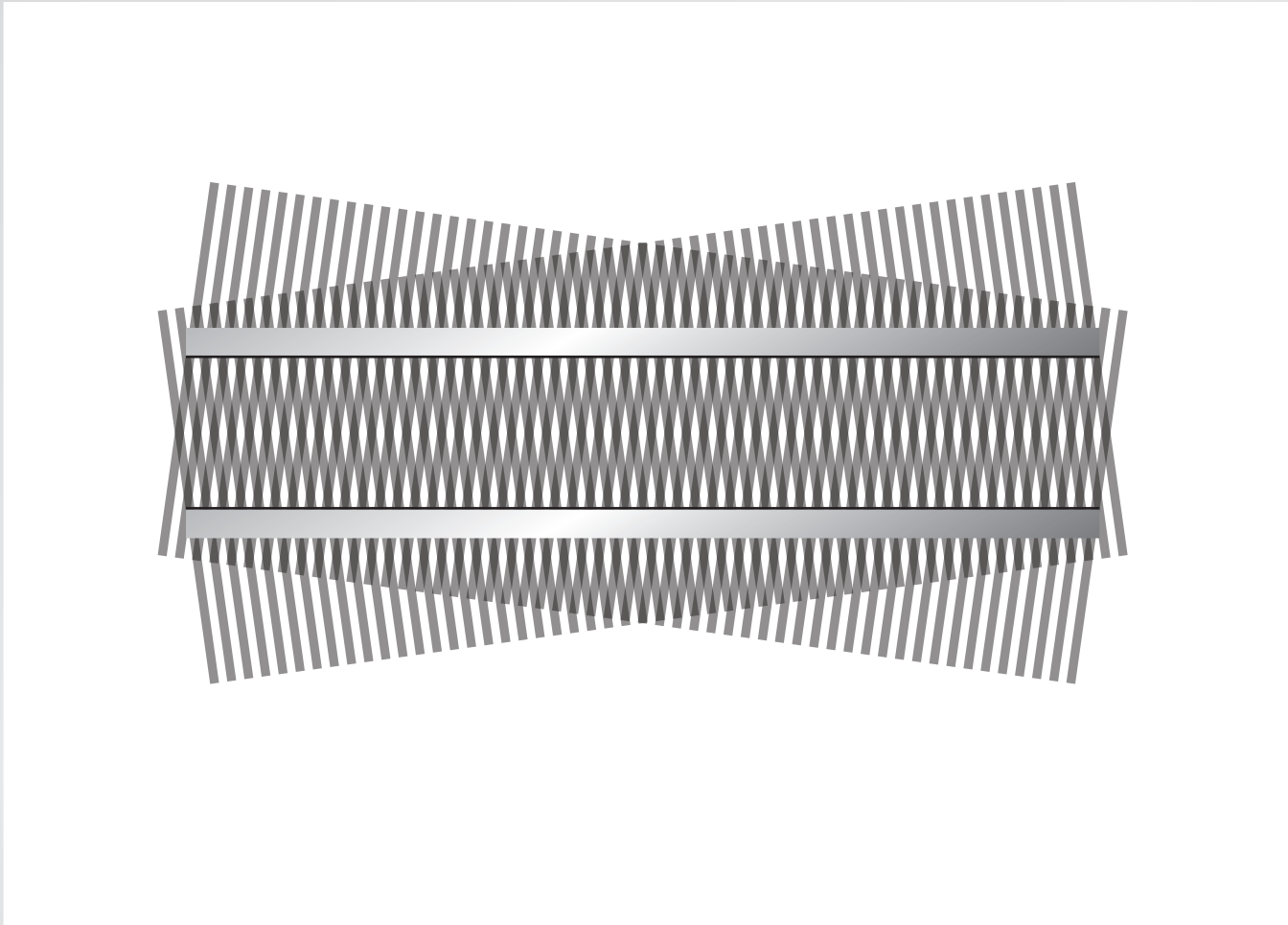
Waveguiding

change angle of incident waves...



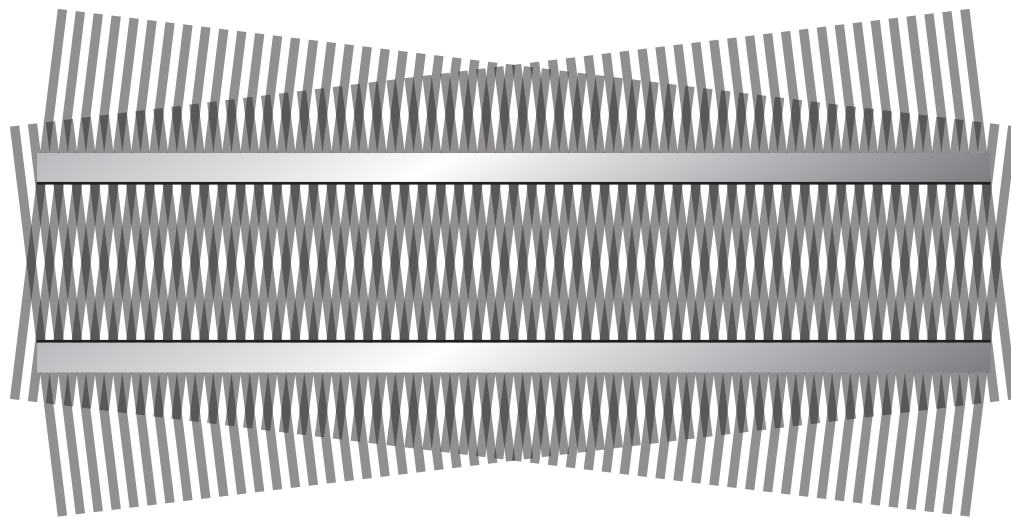
Waveguiding

change angle of incident waves...



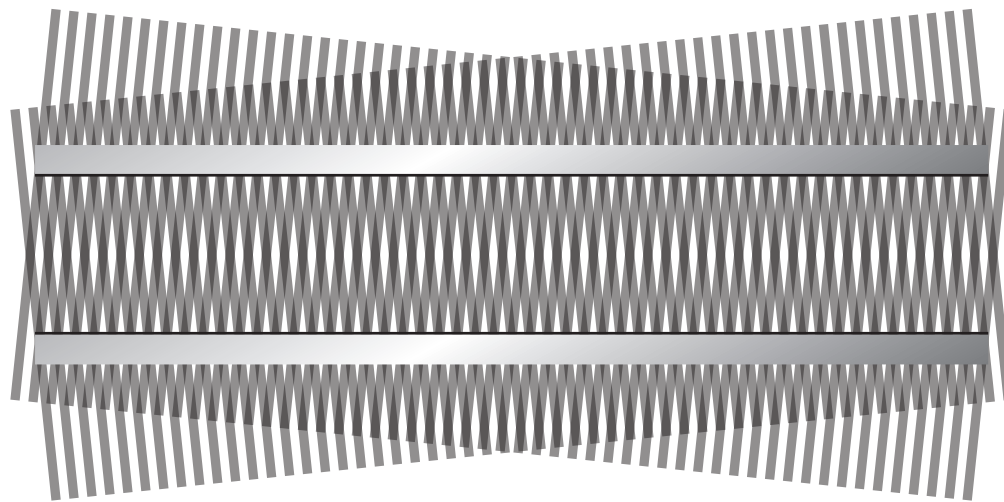
Waveguiding

change angle of incident waves...



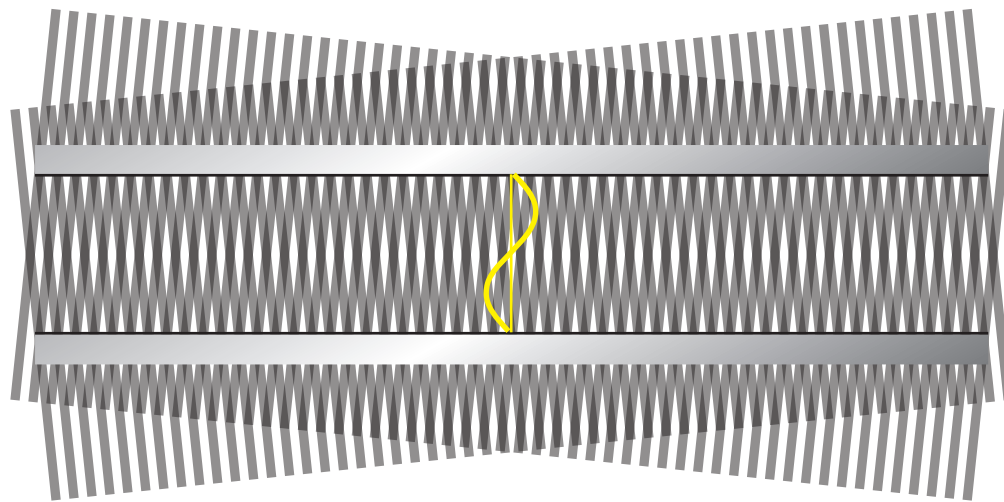
Waveguiding

change angle of incident waves...



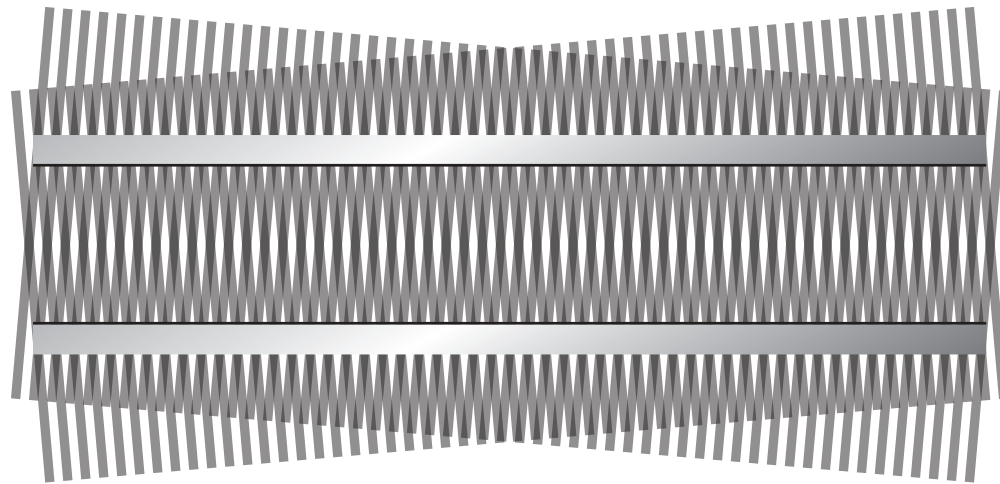
Waveguiding

change angle of incident waves...



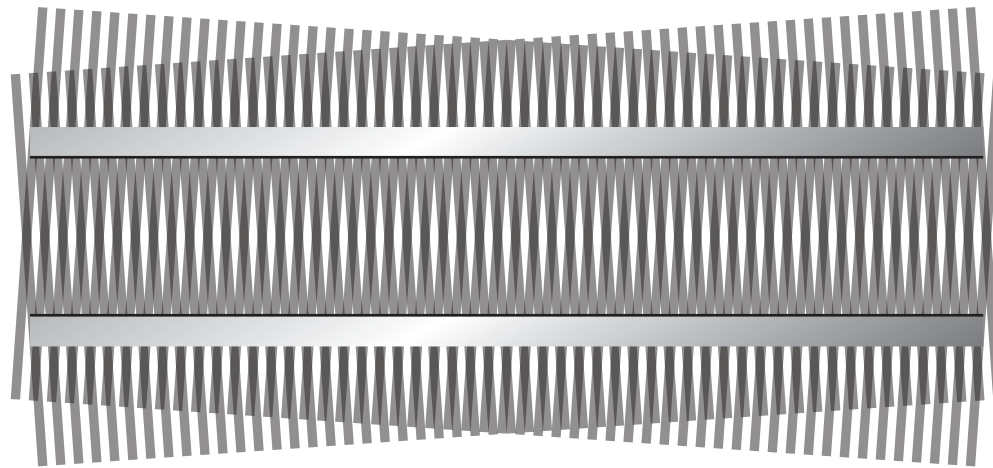
Waveguiding

change angle of incident waves...



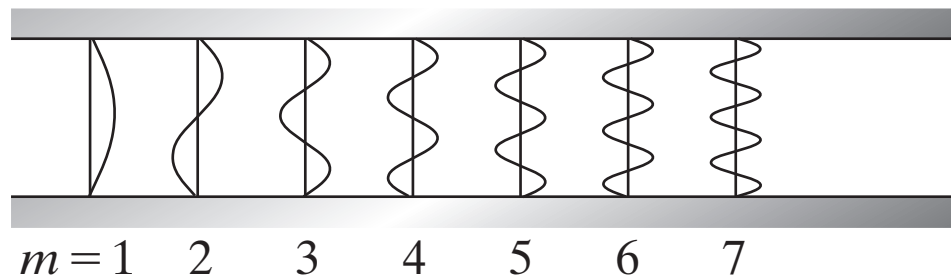
Waveguiding

change angle of incident waves...



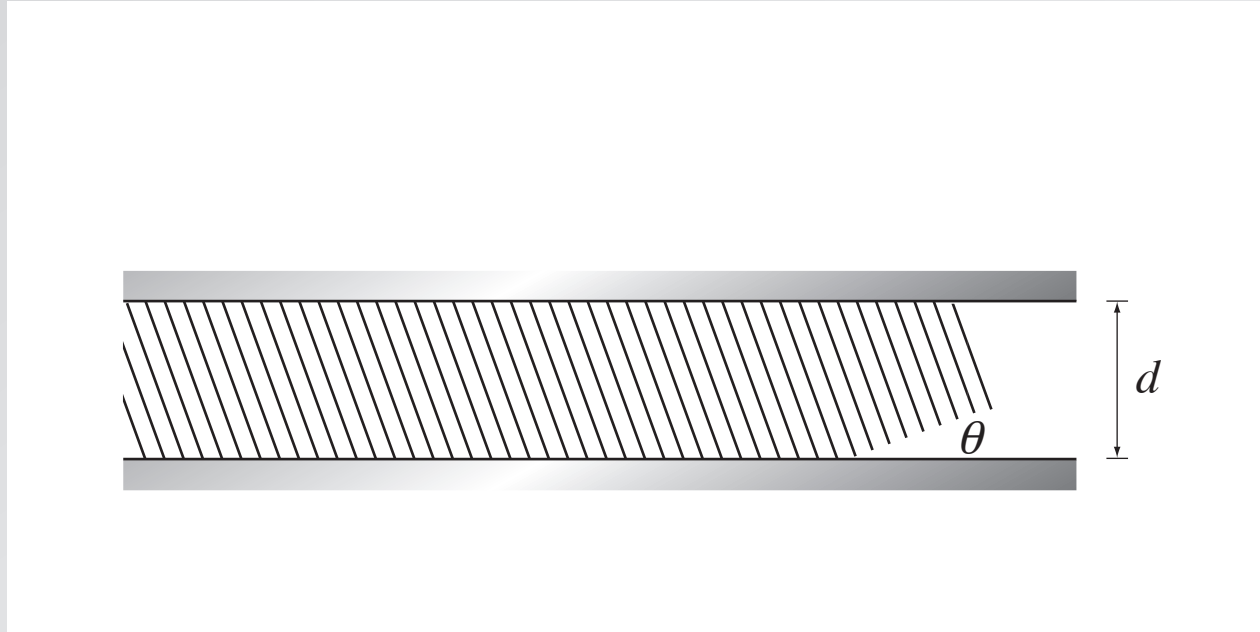
Waveguiding

boundary conditions only satisfied for certain θ



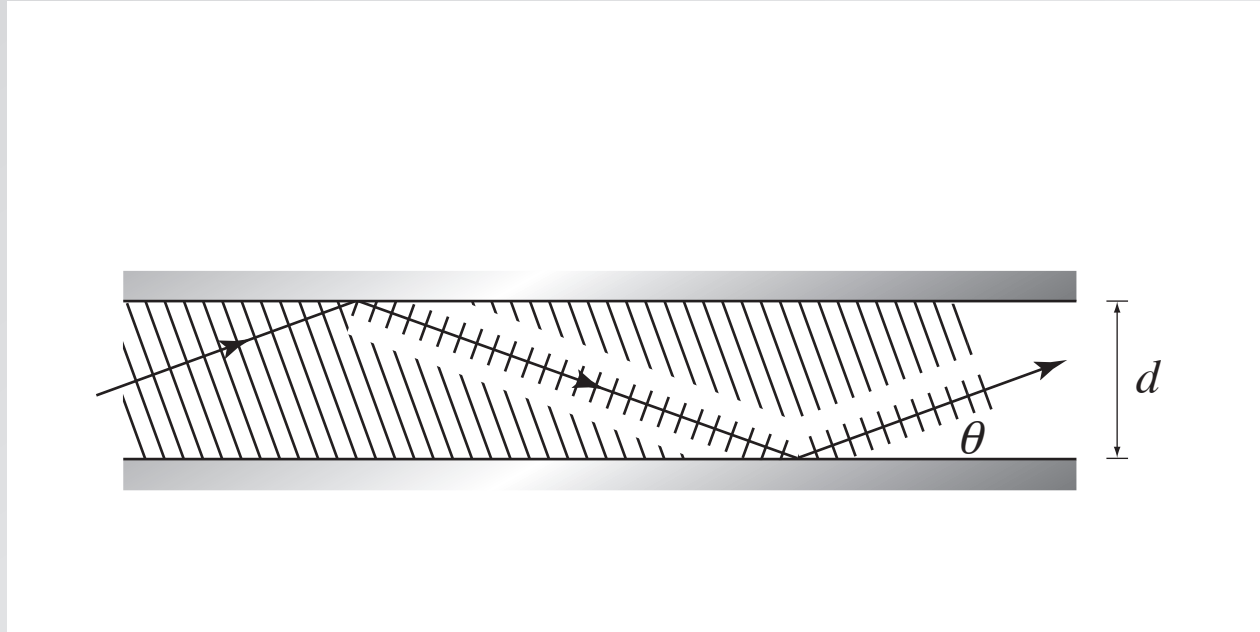
standing wave in y -direction, traveling in z -direction

Waveguiding



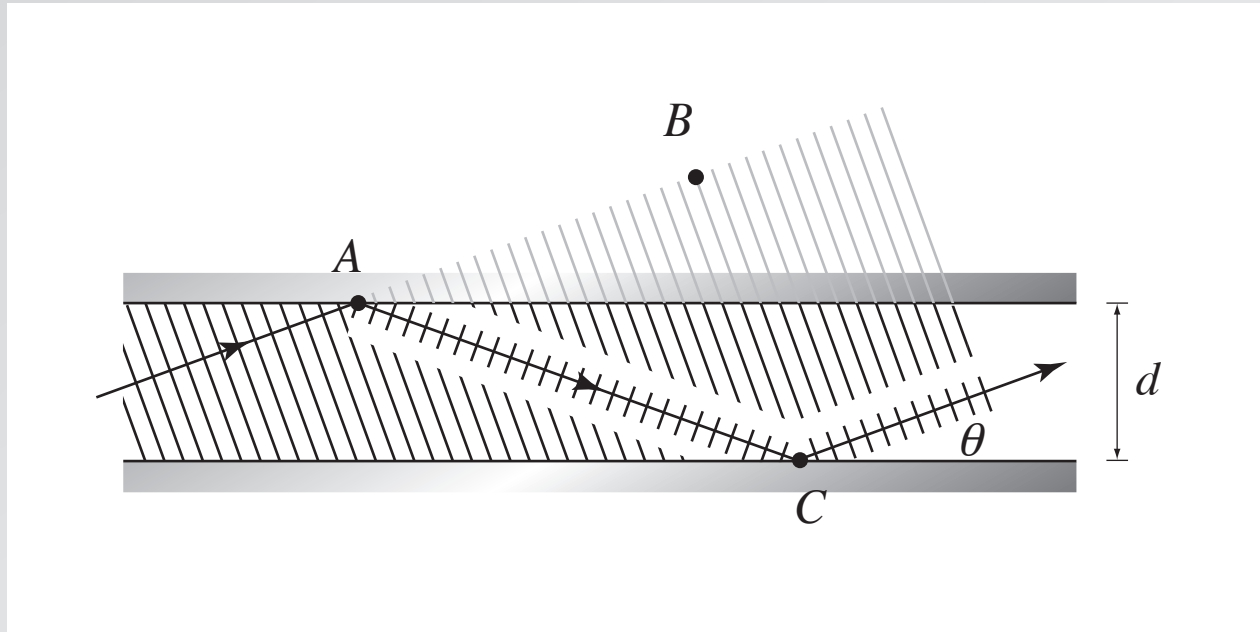
consider wave incident at angle θ

Waveguiding



twice-reflected wave

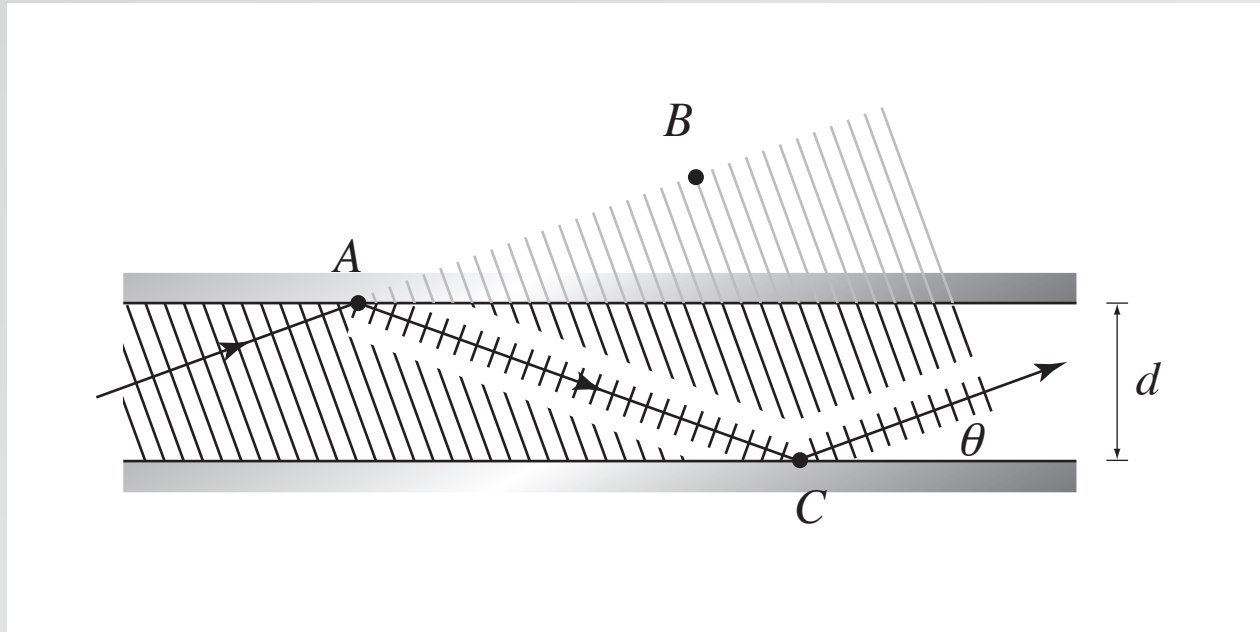
Waveguiding



self consistency:

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

Waveguiding



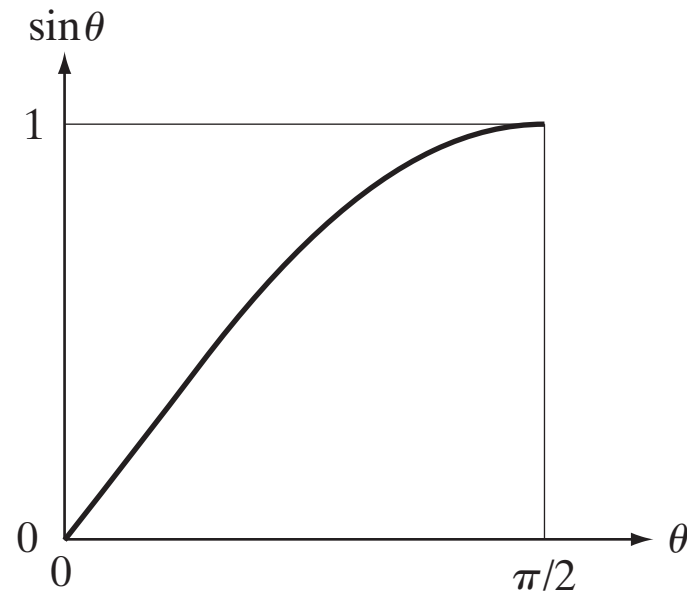
self consistency:

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

so:

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

Waveguiding



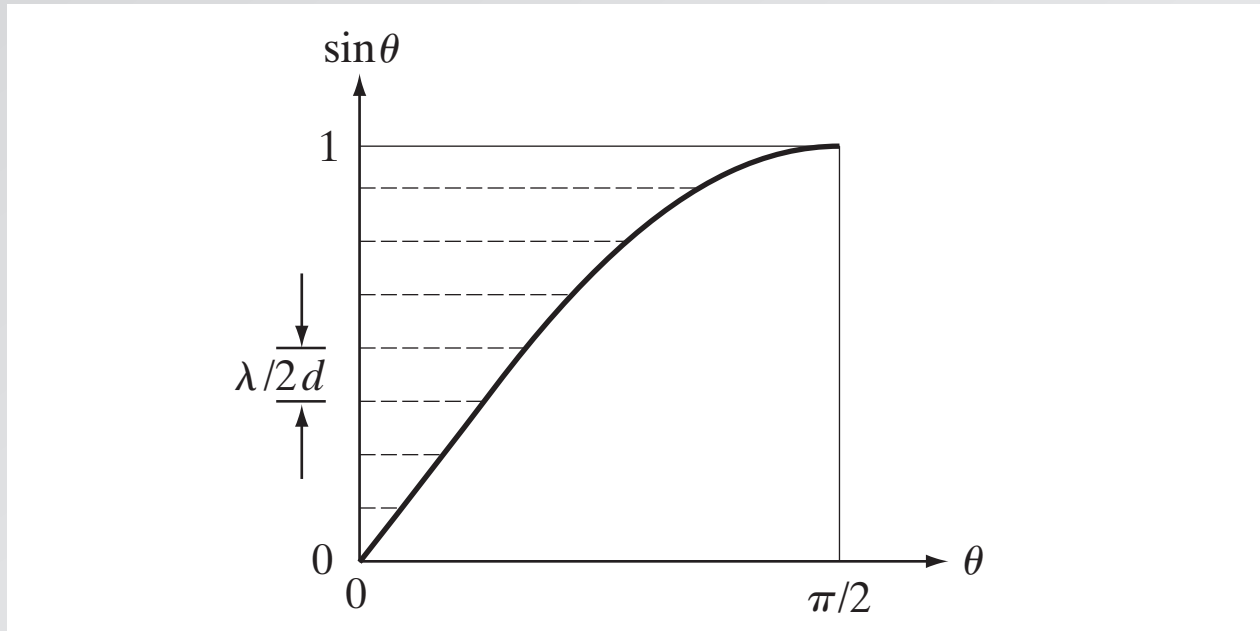
self consistency:

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

so:

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

Waveguiding



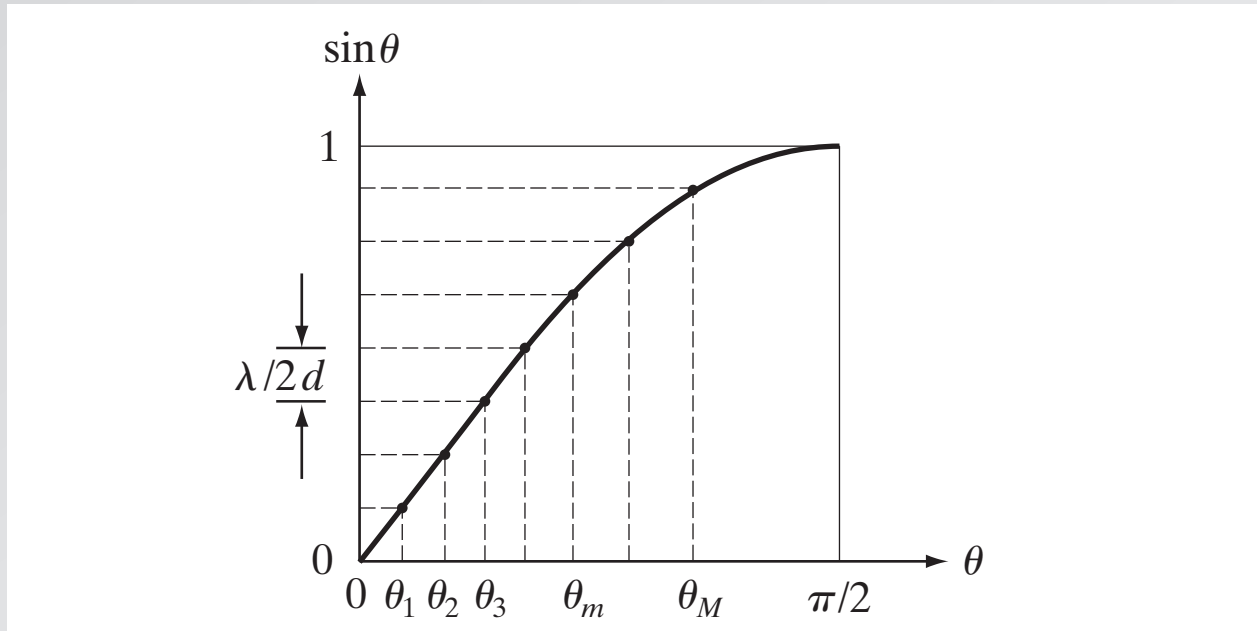
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Waveguiding



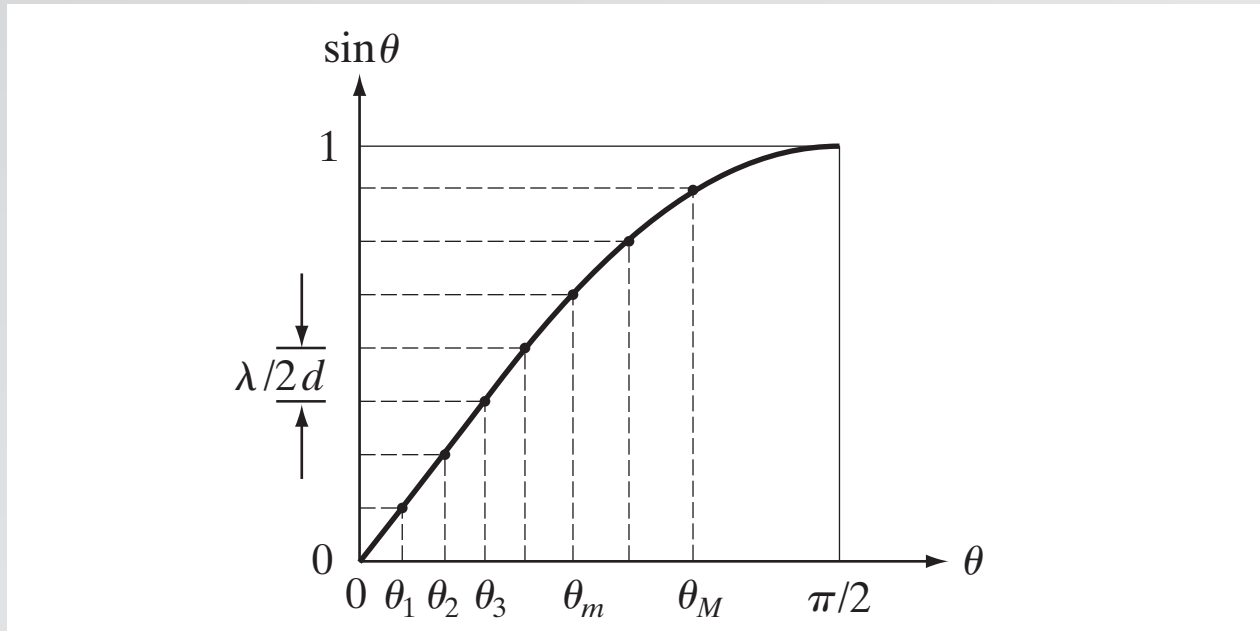
self consistency:

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

so:

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

Waveguiding



number of modes:

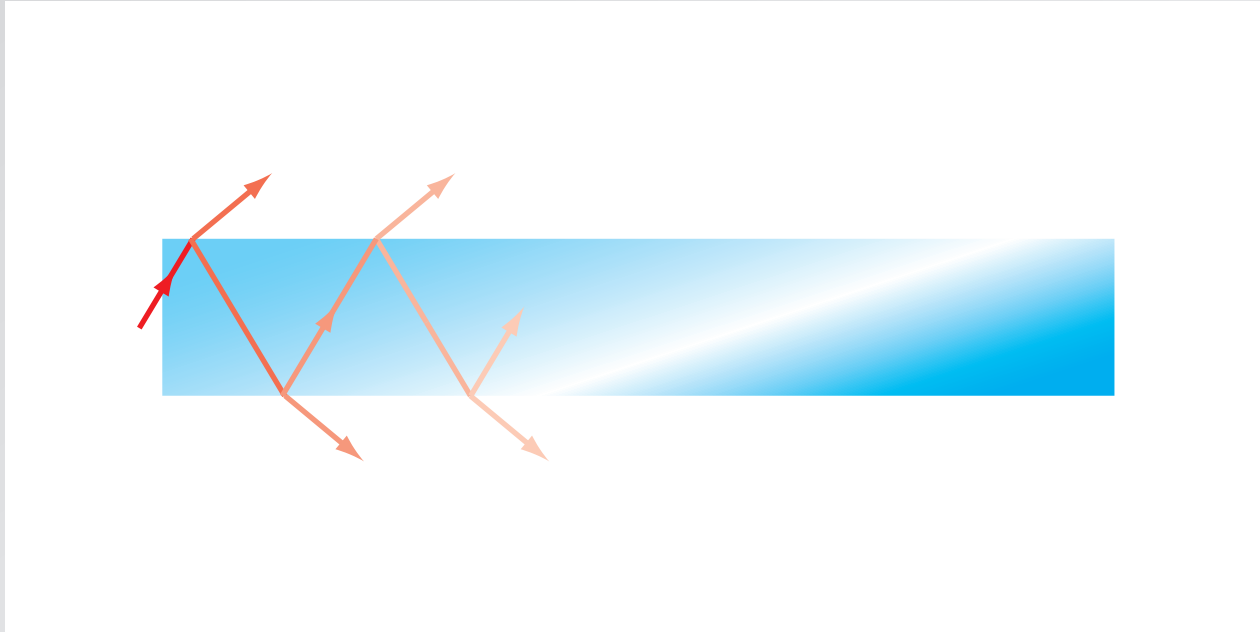
$$M = \frac{2d}{\lambda}$$

Waveguiding



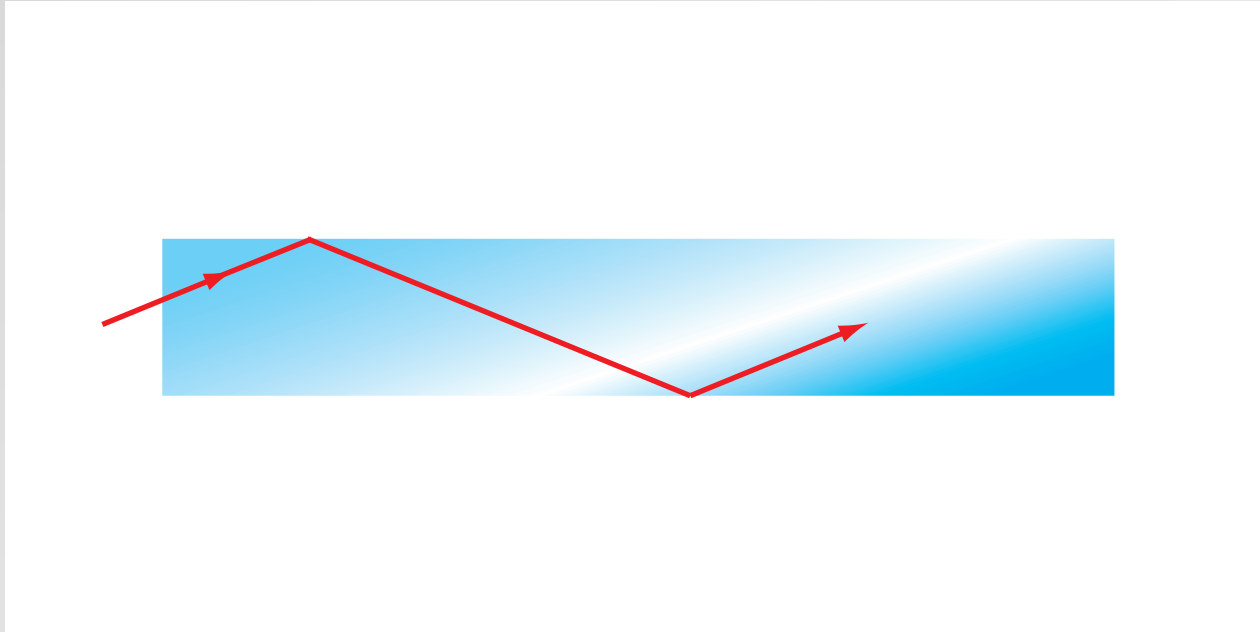
now consider a planar dielectric waveguide

Waveguiding



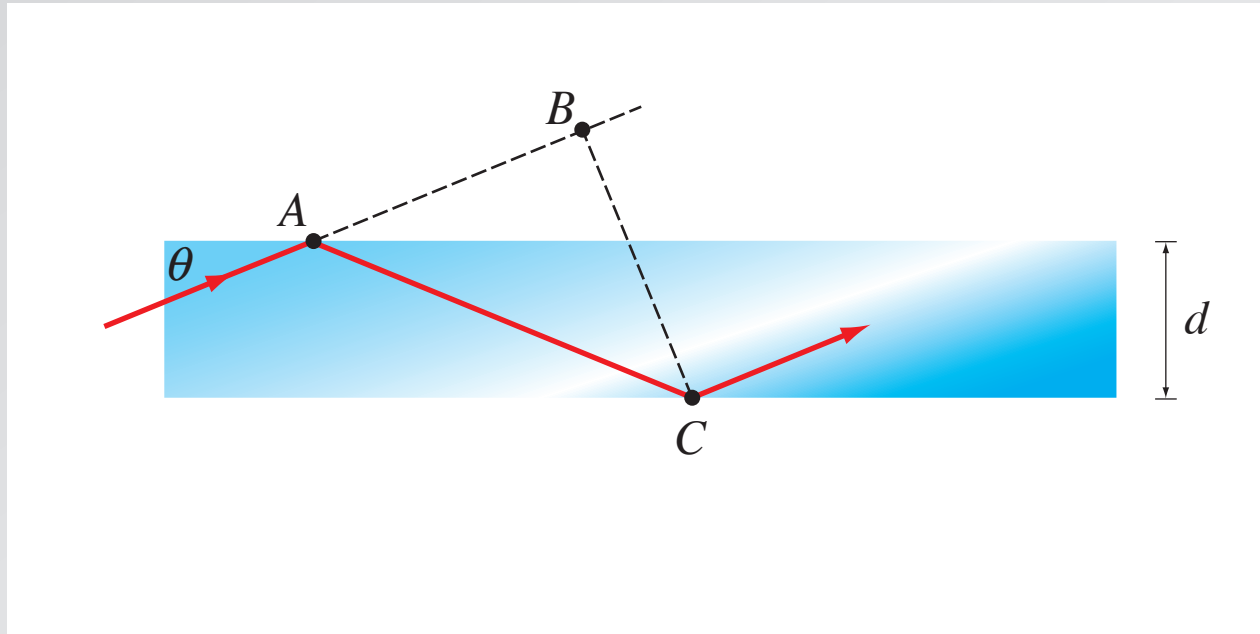
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



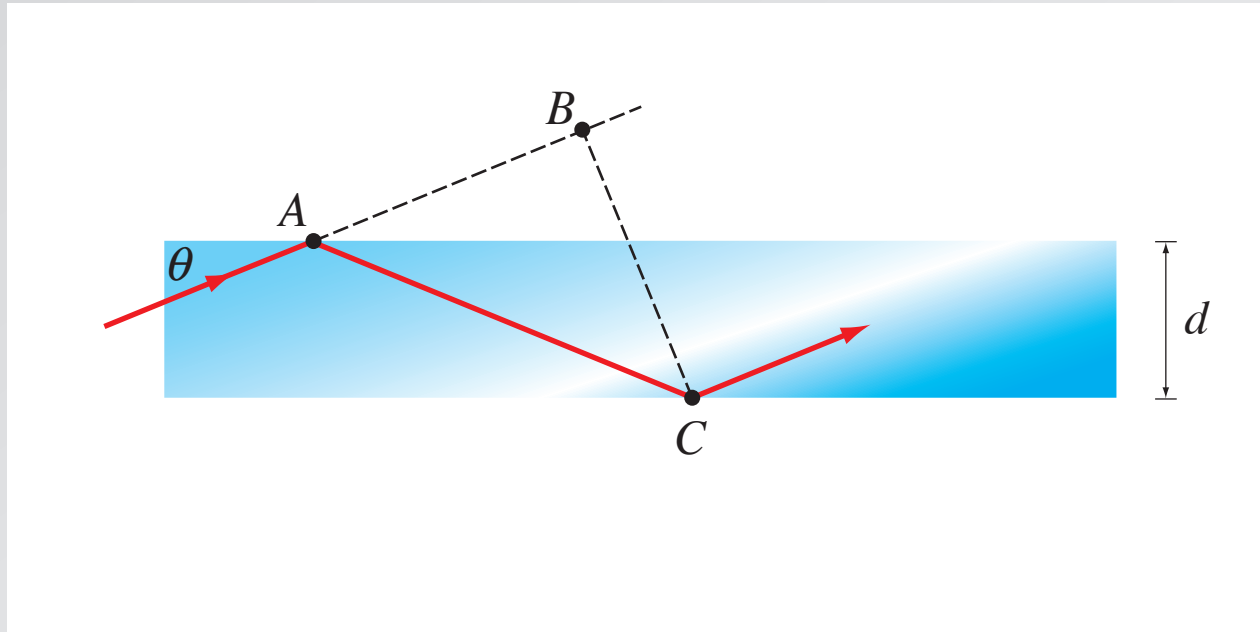
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

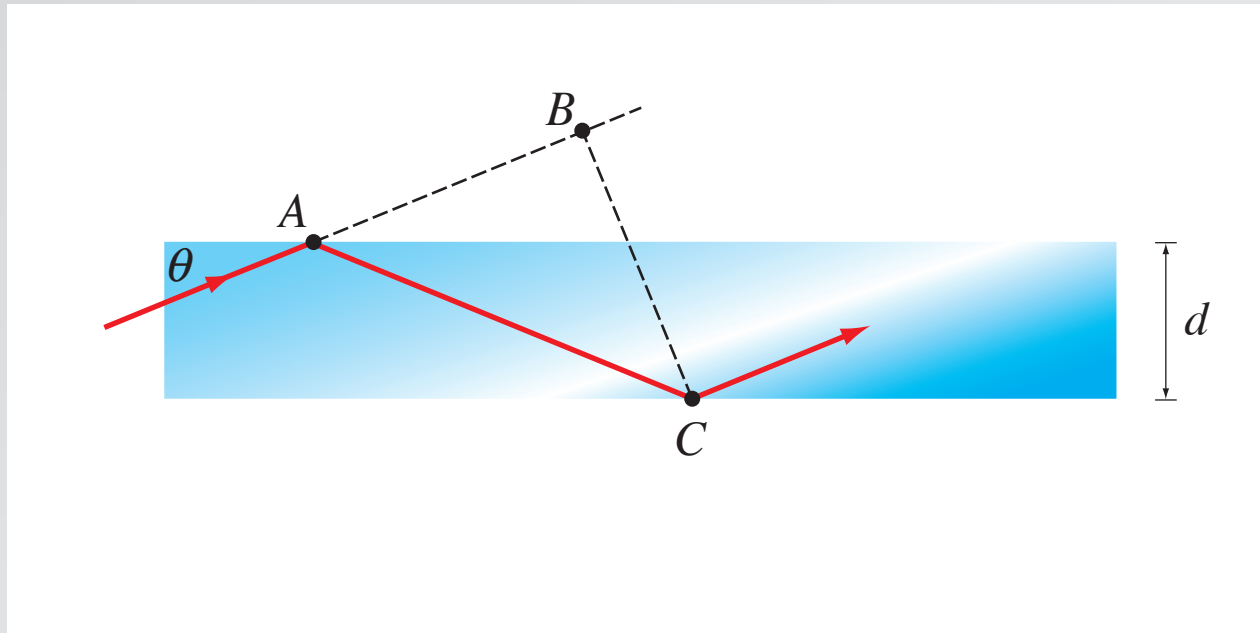
Waveguiding



self consistency:

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

Waveguiding



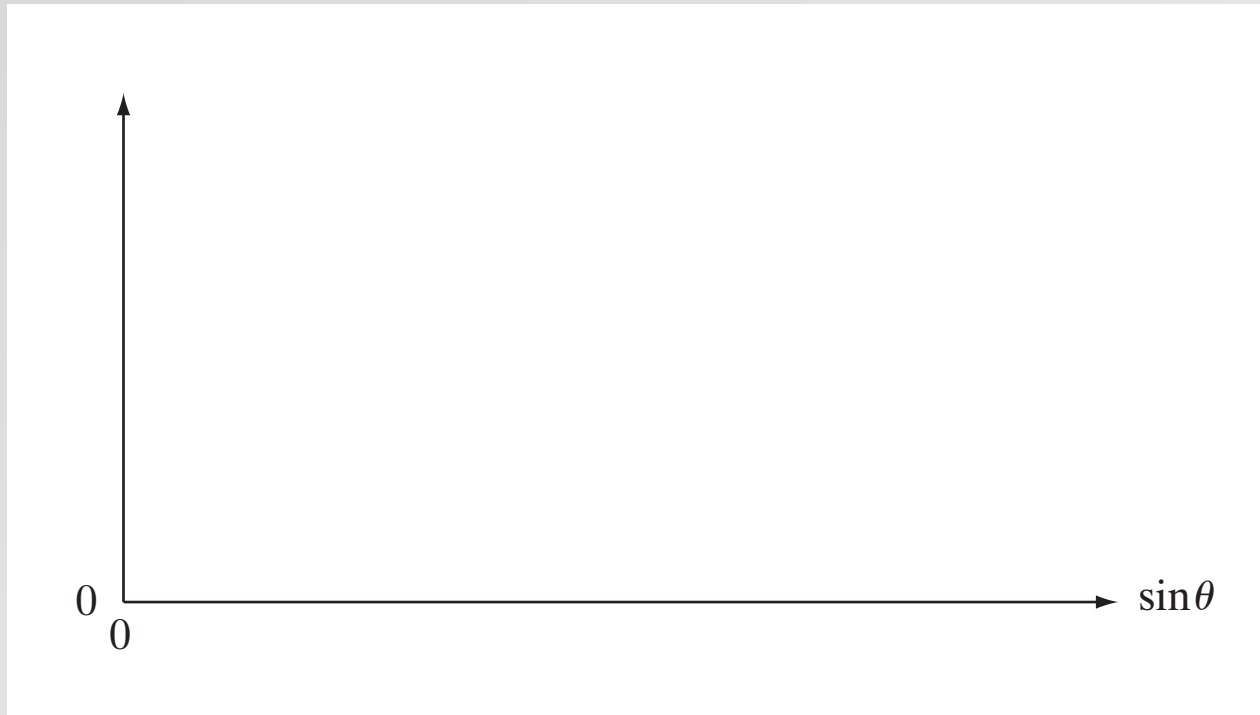
self consistency:

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

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



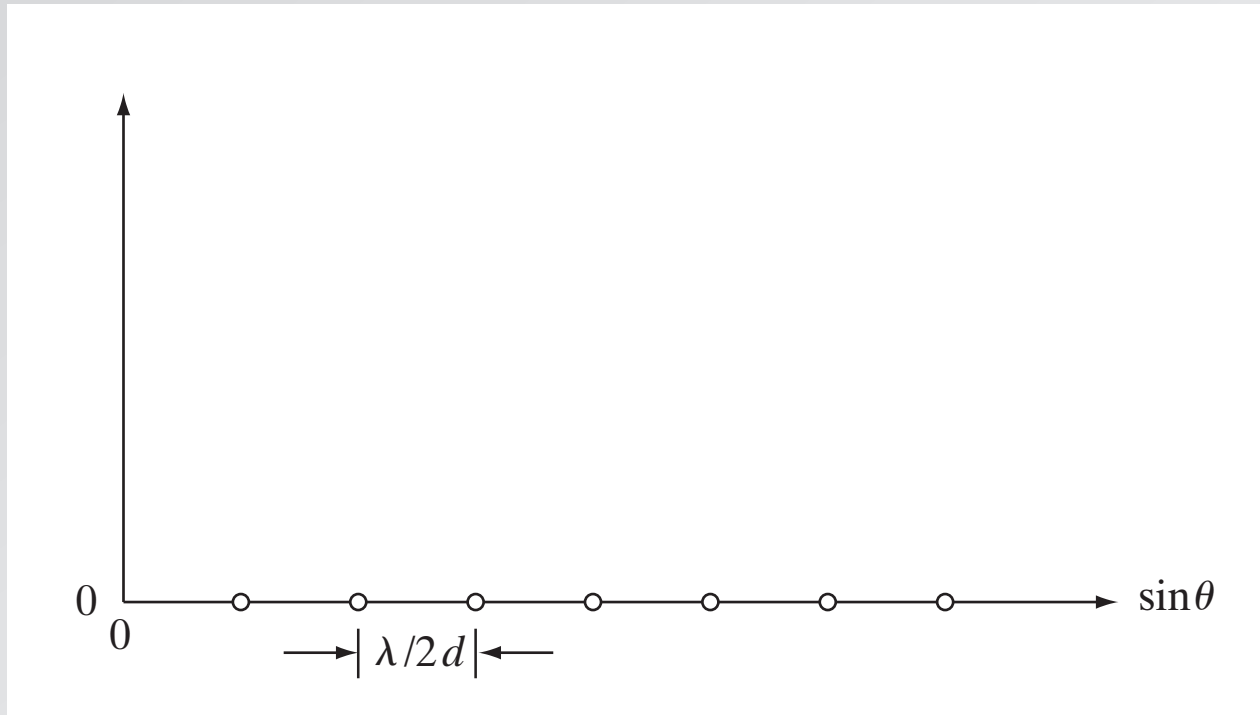
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Waveguiding



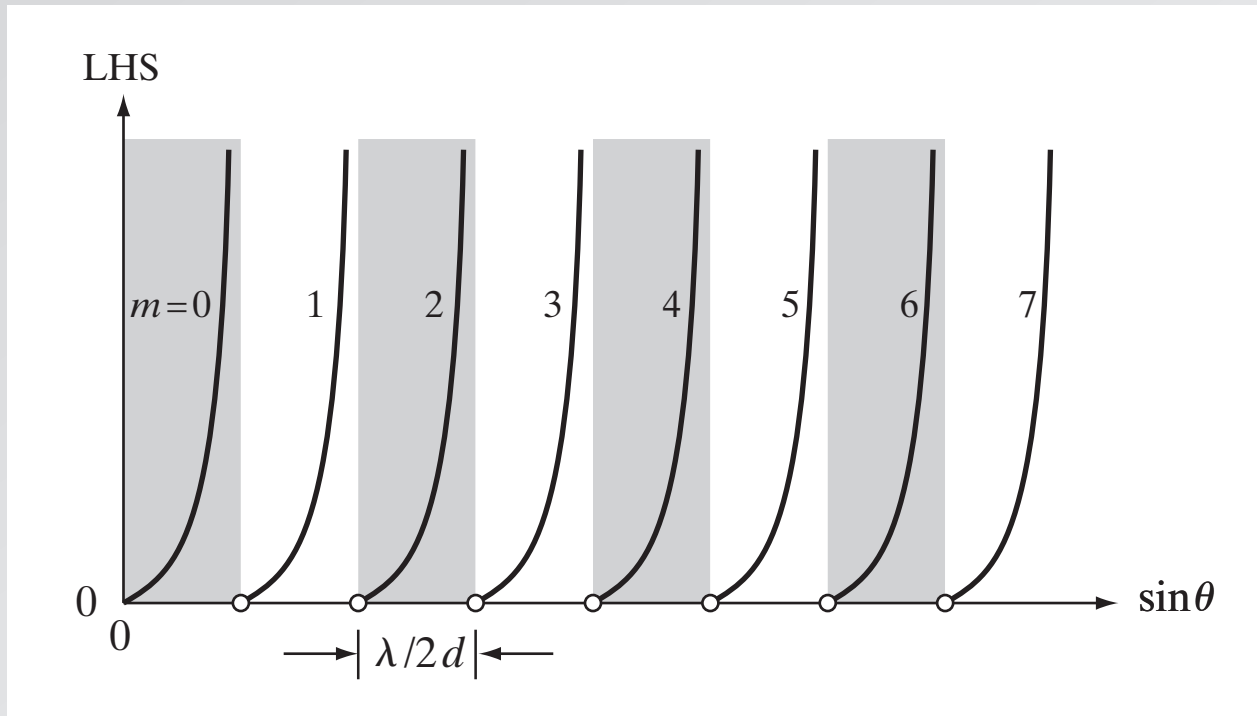
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Waveguiding



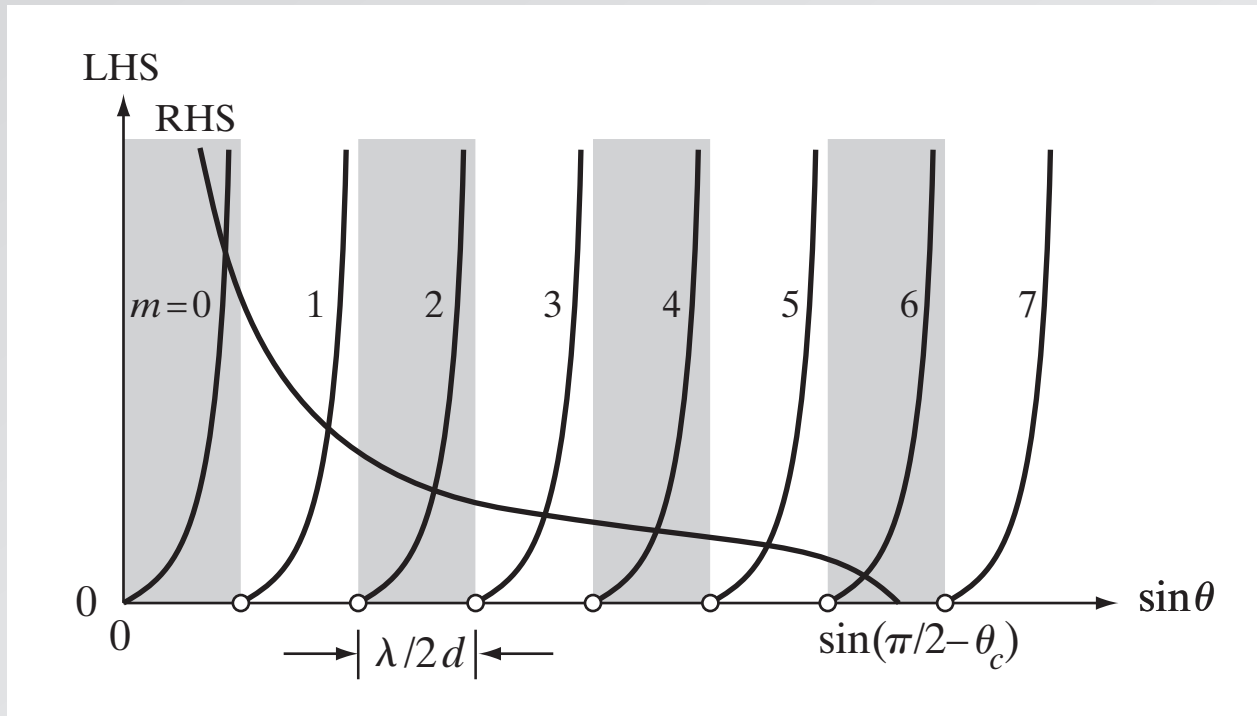
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Waveguiding



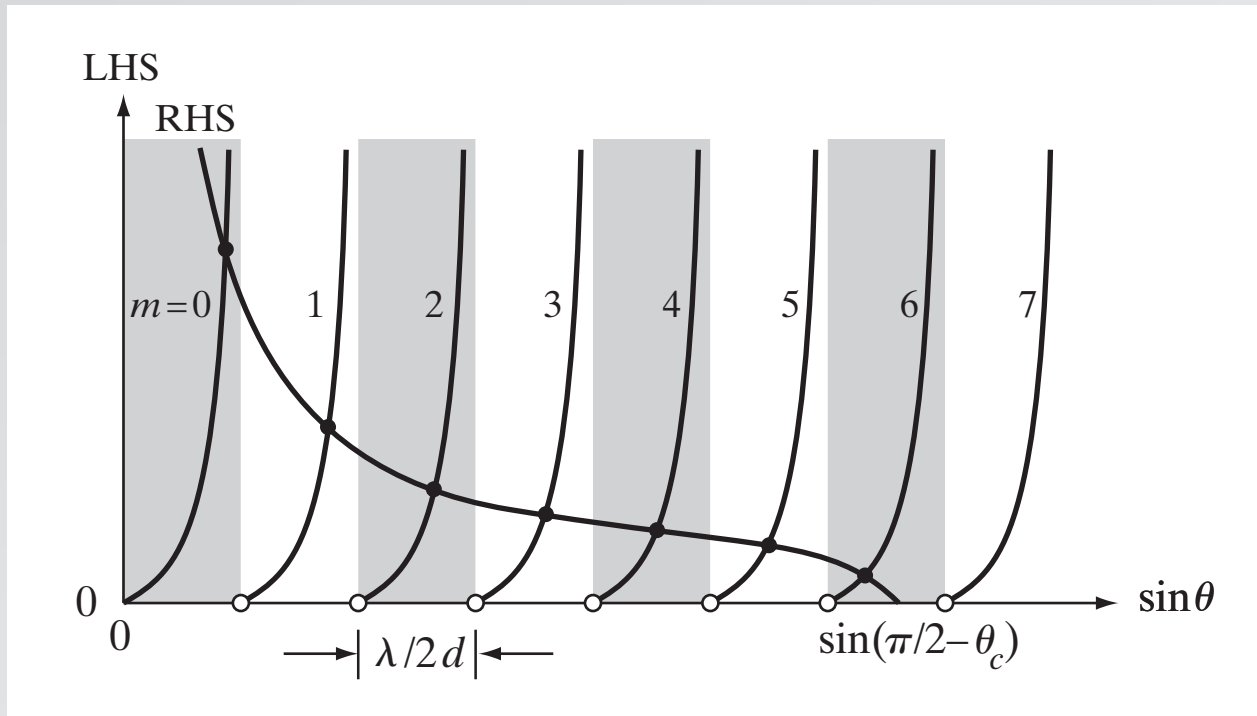
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Waveguiding



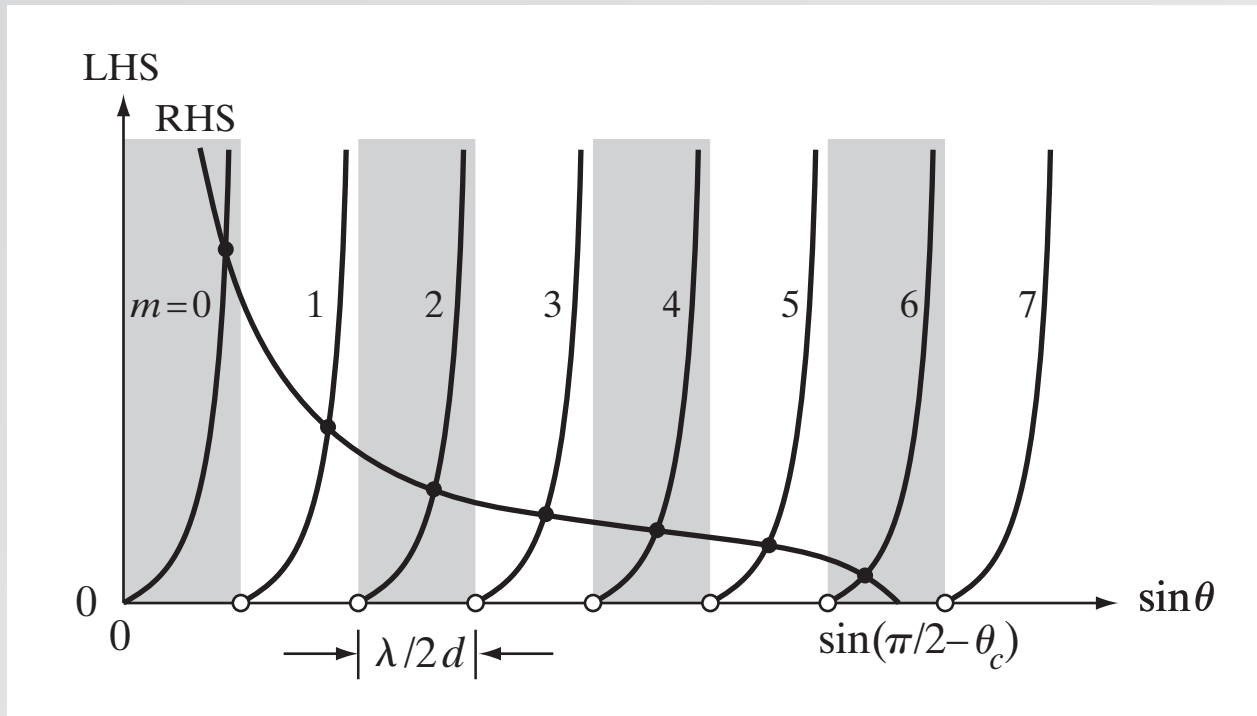
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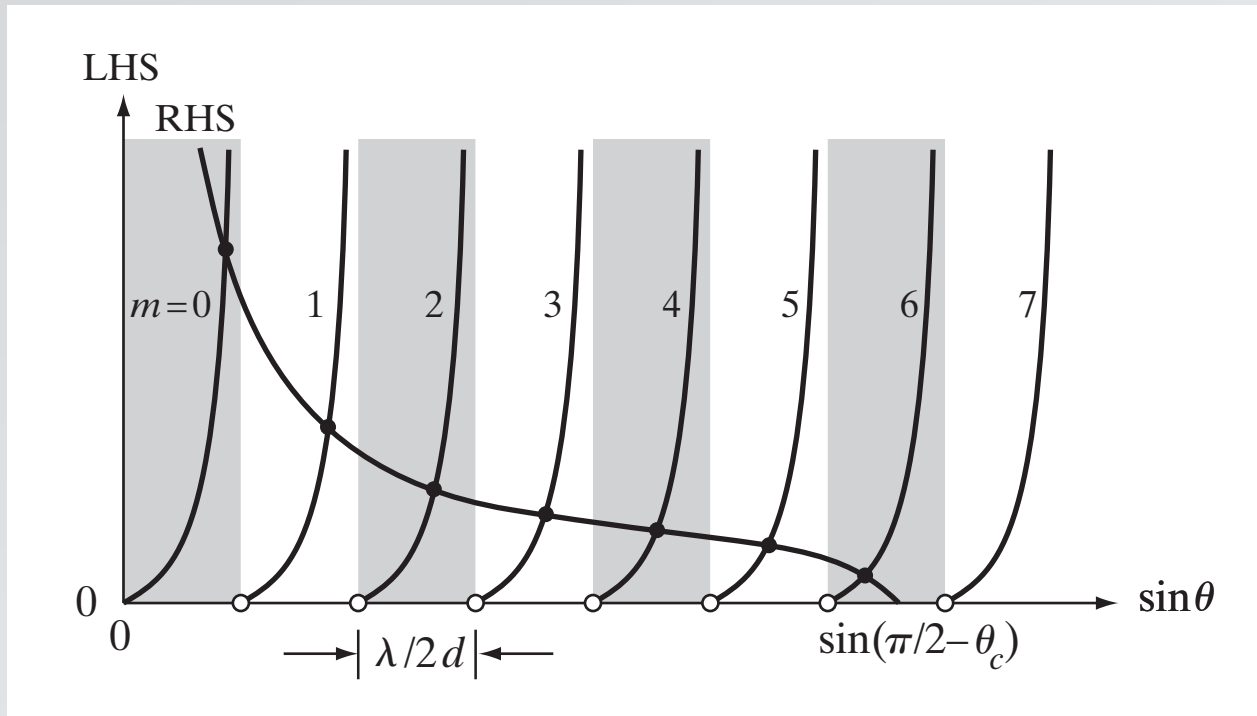
Waveguiding



number of modes:

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

Waveguiding



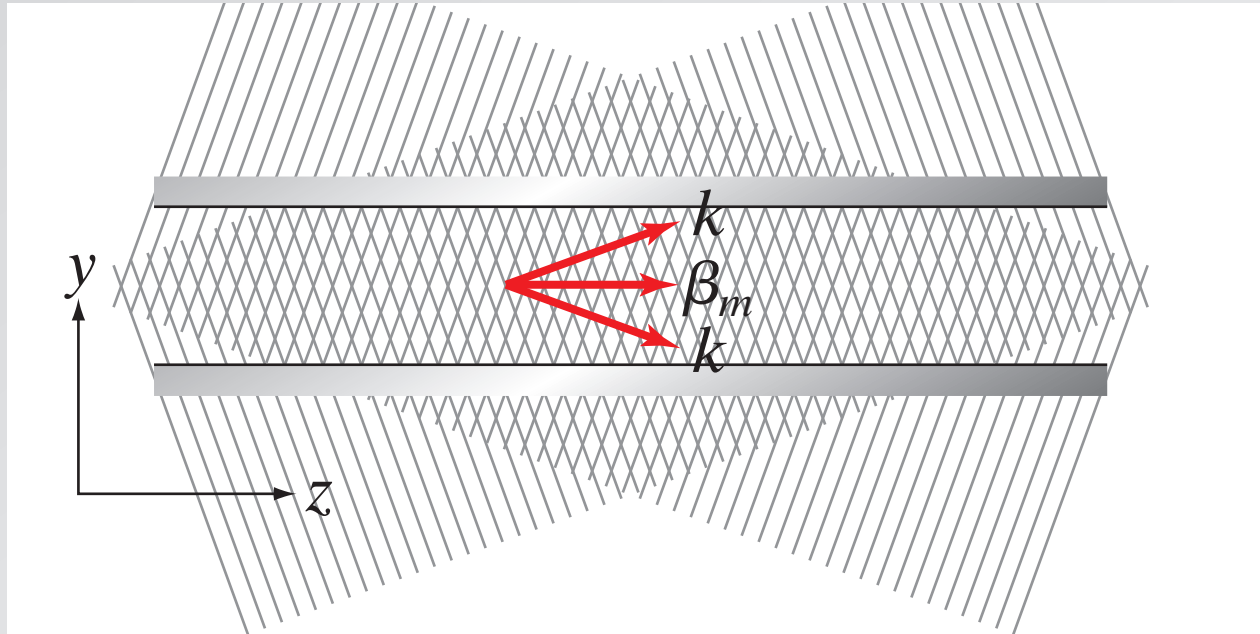
number of modes:

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

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

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

$$300 < d < 600 \text{ nm}$$

dielectric

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

$$d < 268 \text{ nm}$$

Waveguiding

single mode condition for 600-nm light:

planar mirror

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

$$300 < d < 600 \text{ nm}$$

dielectric

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

$$d < 268 \text{ nm}$$

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

Vector potential obeys:

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

Substituting

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

yields:

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

Waveguiding

Vector potential obeys:

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

Substituting

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

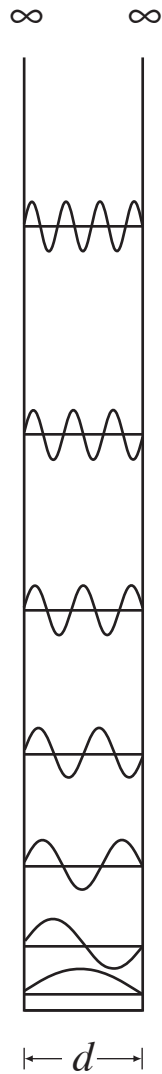
yields:

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

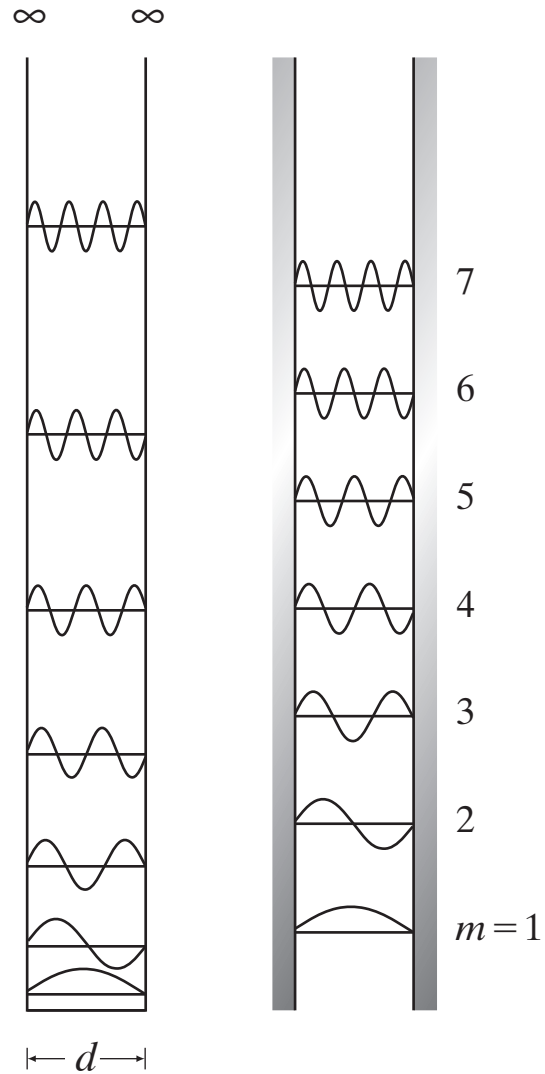
Compare to time-independent Schrödinger equation:

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

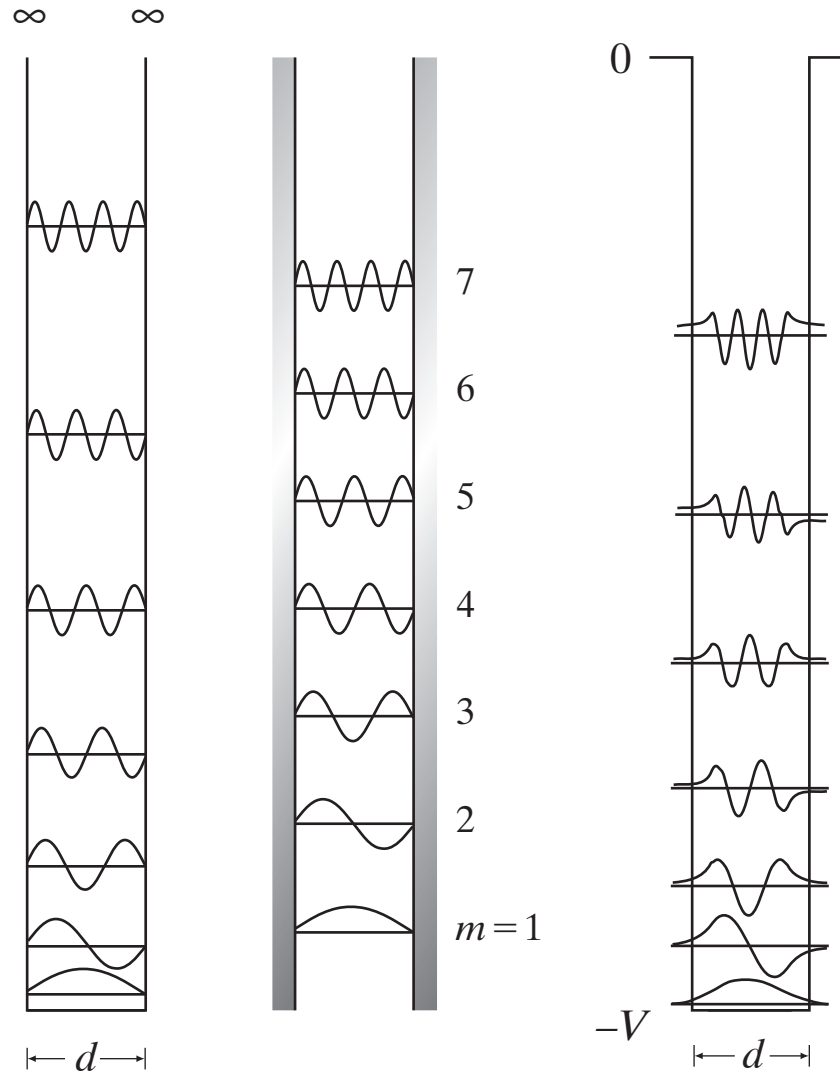
Waveguiding



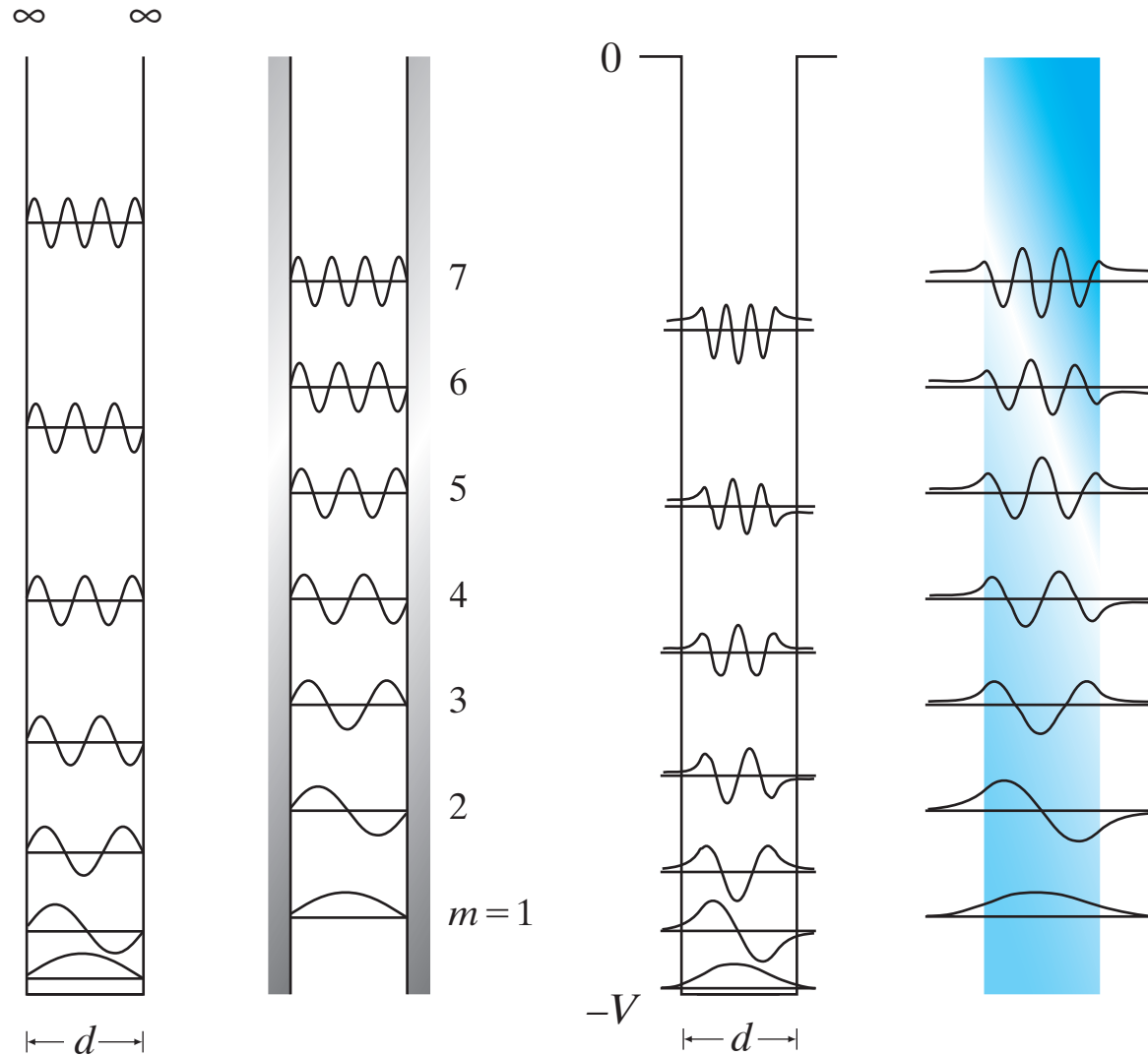
Waveguiding



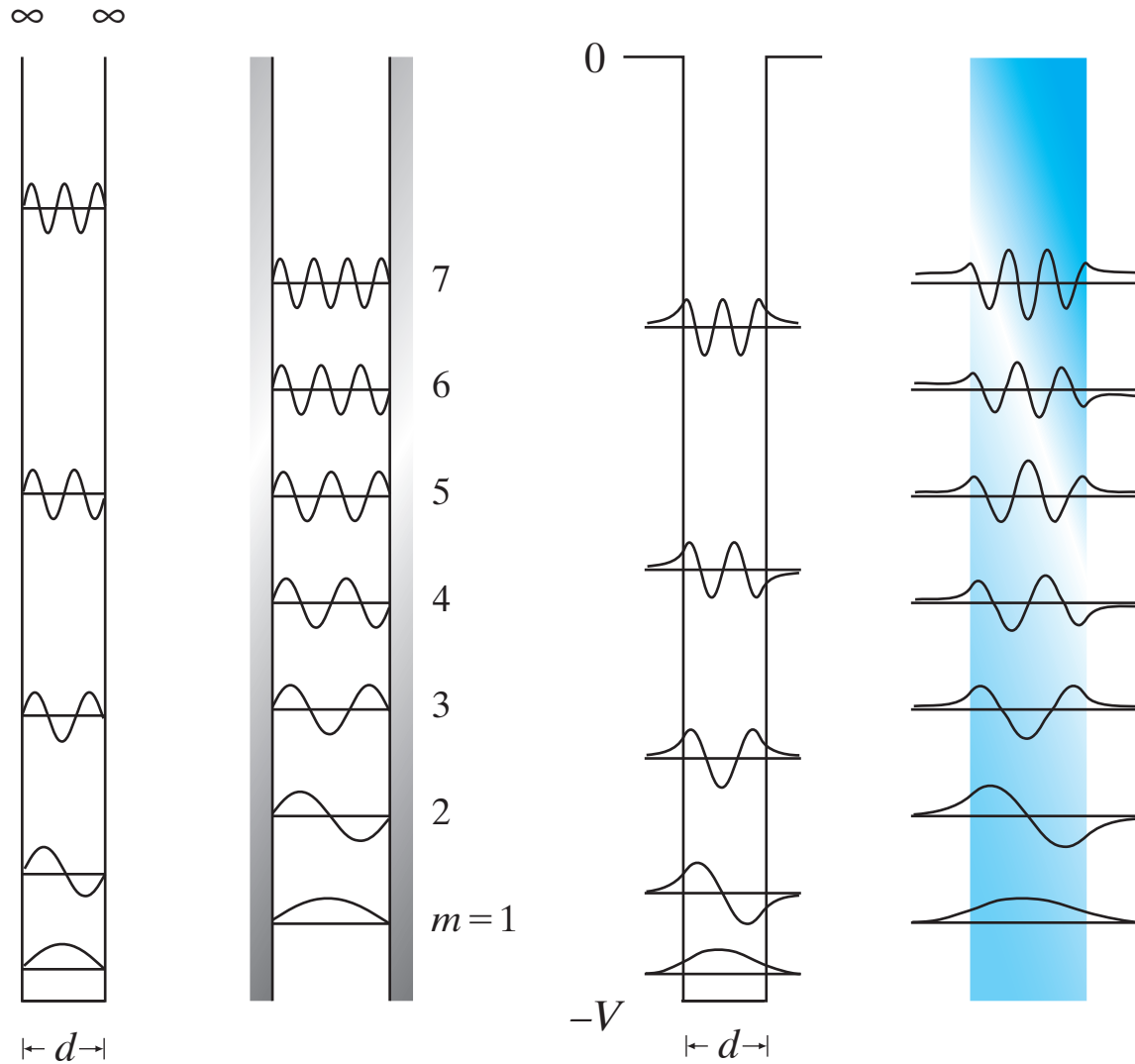
Waveguiding



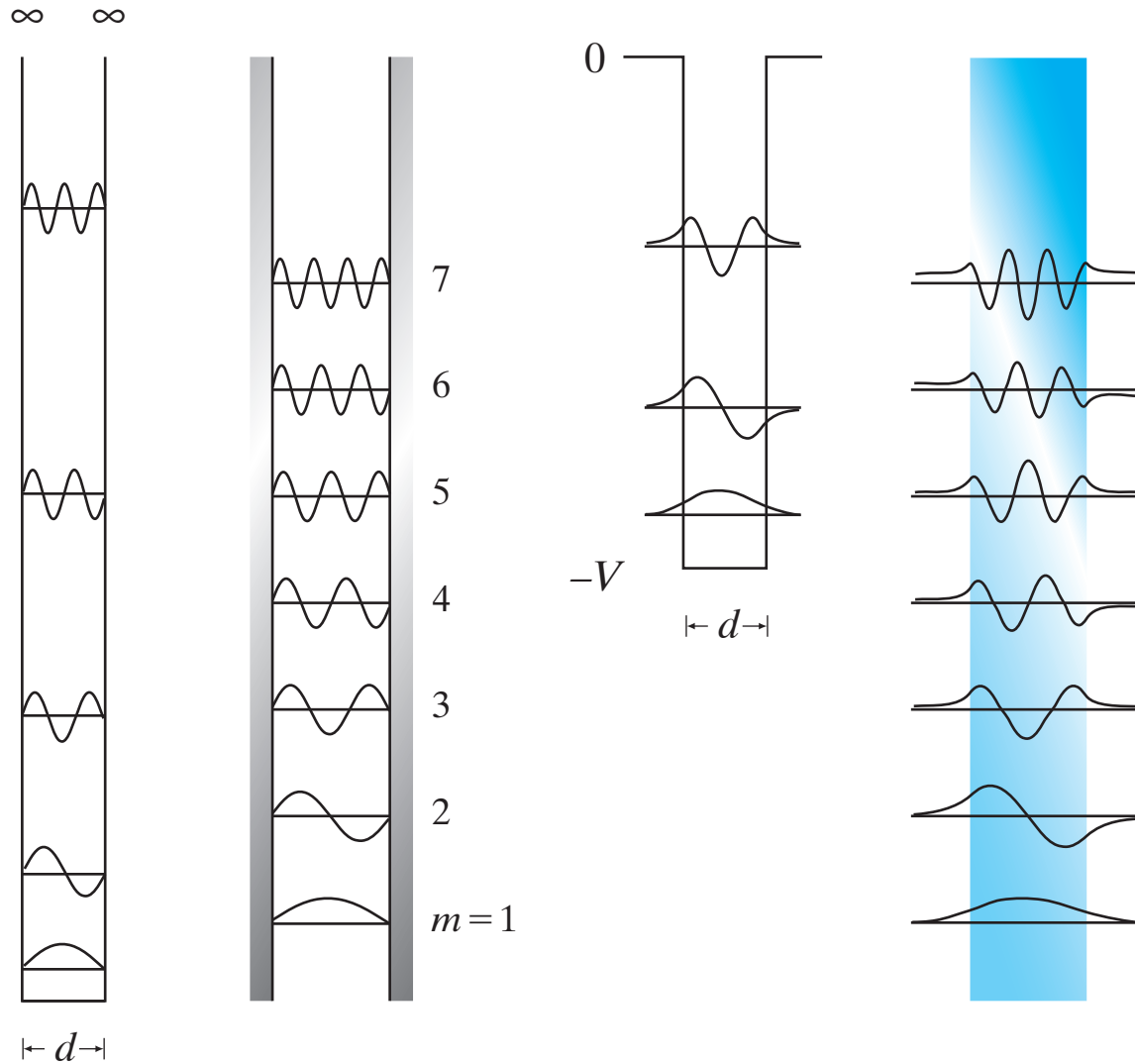
Waveguiding



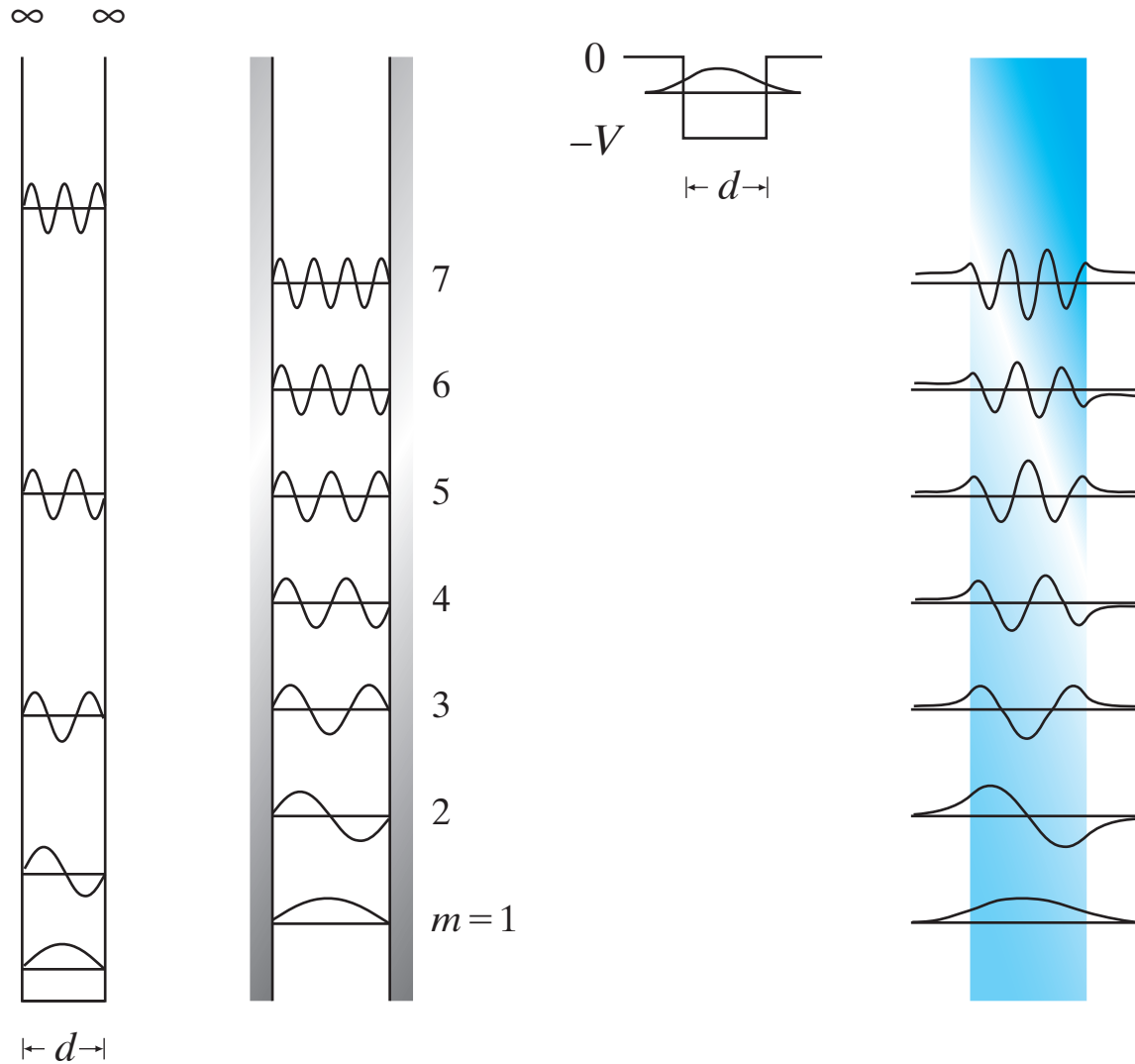
Waveguiding



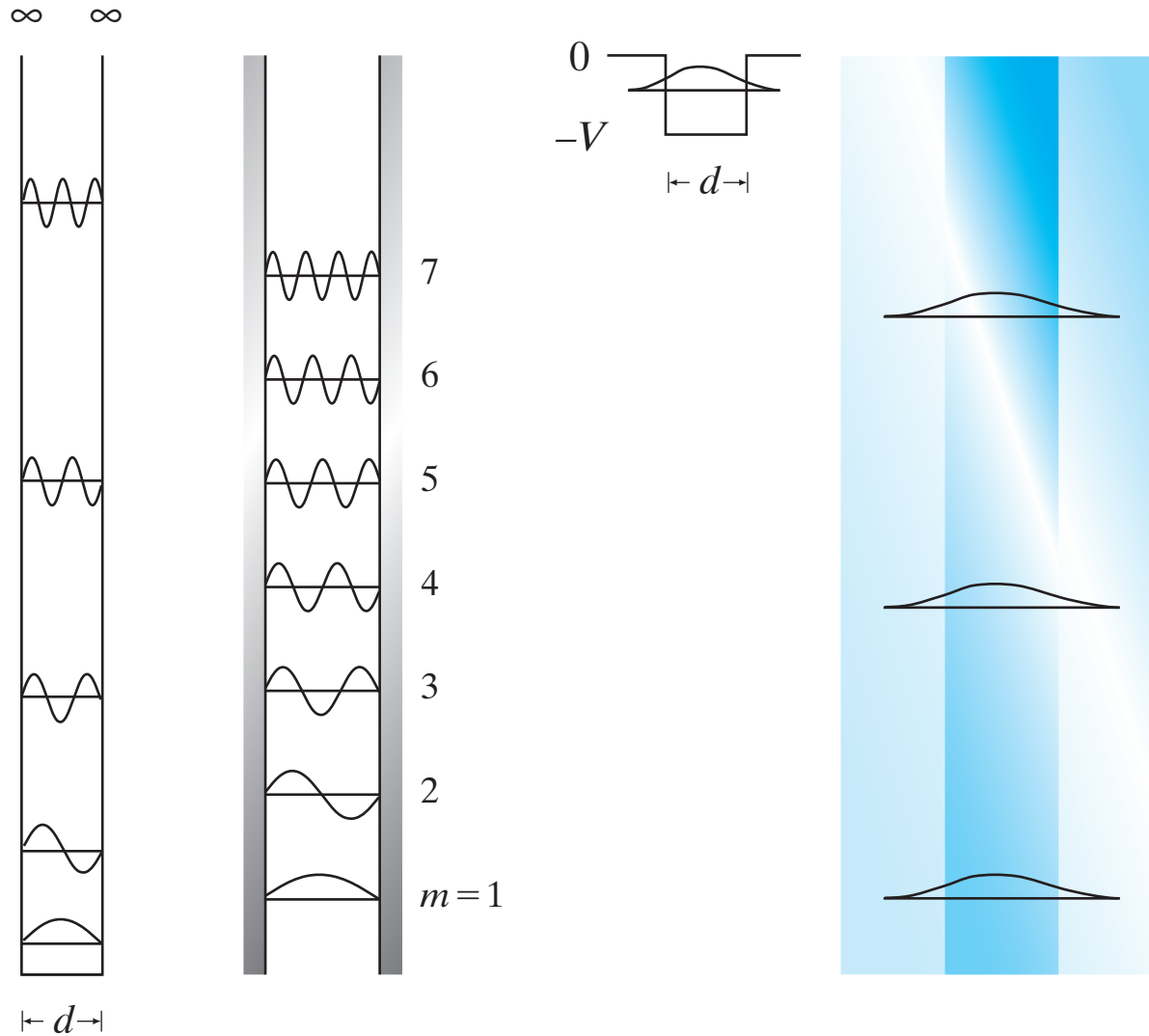
Waveguiding



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:

$$d < 268 \text{ nm}$$

Add cladding with 0.4% index difference:

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

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

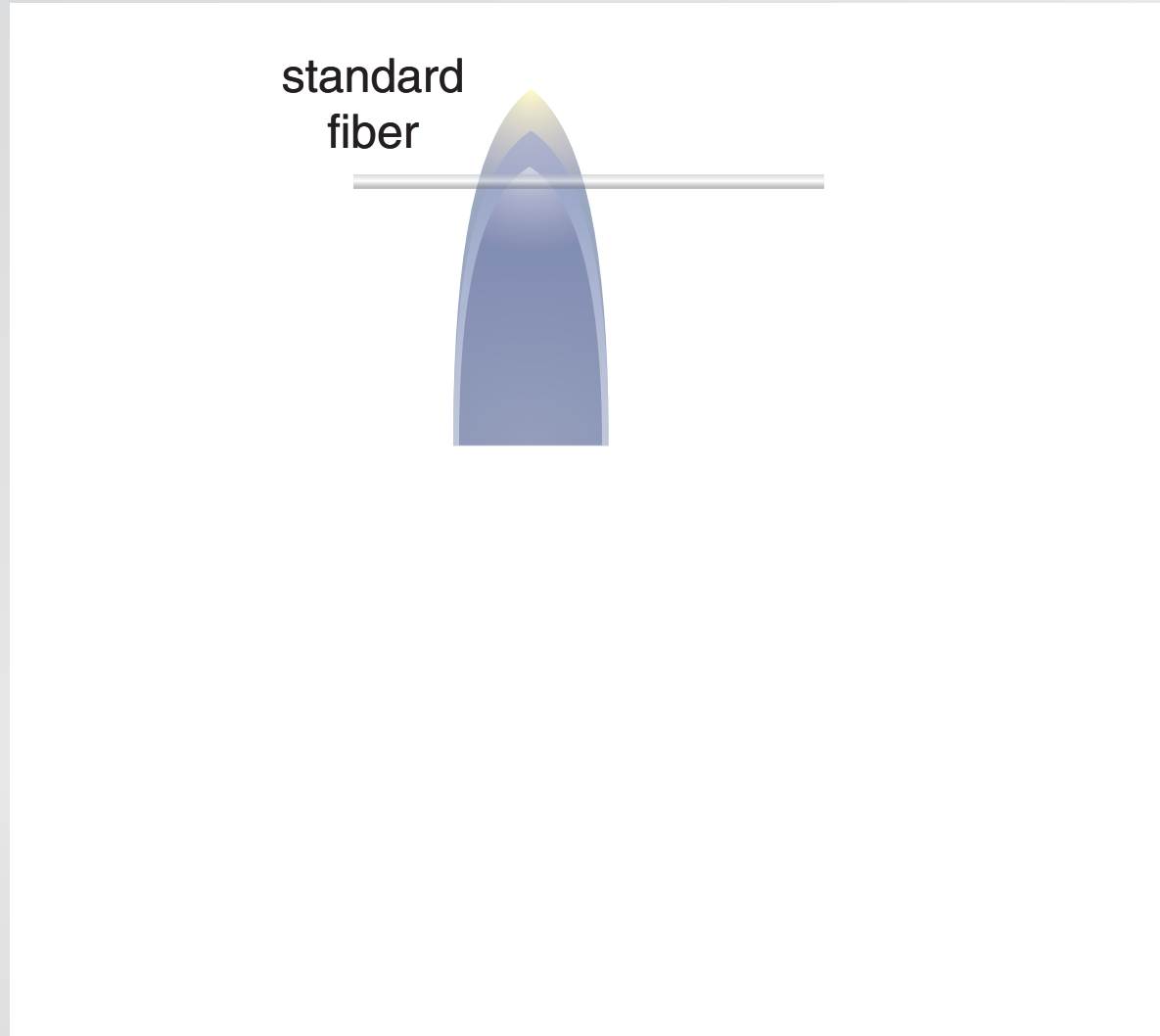
two-step drawing process

standard
fiber



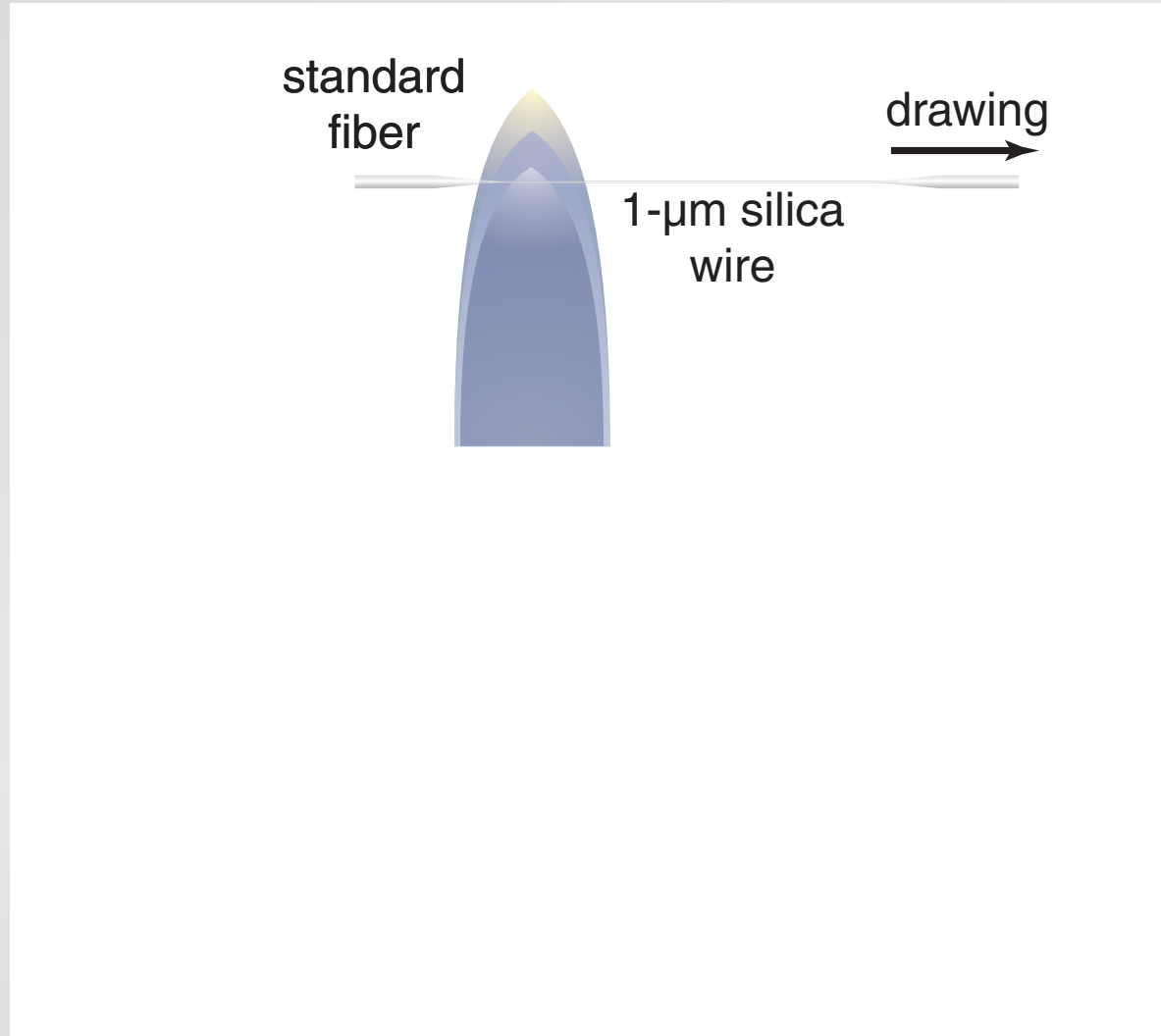
Silica nanowires

two-step drawing process



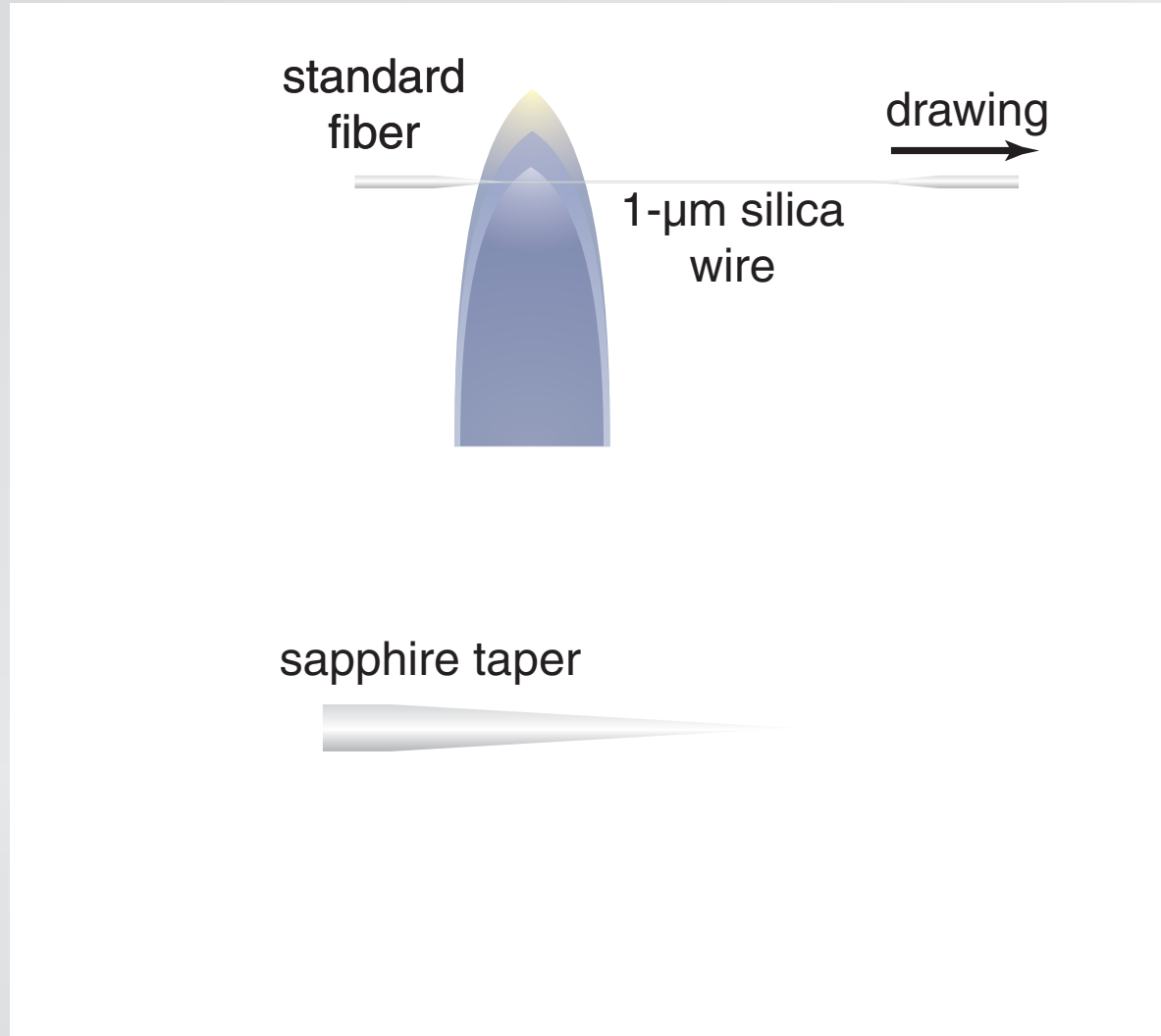
Silica nanowires

two-step drawing process



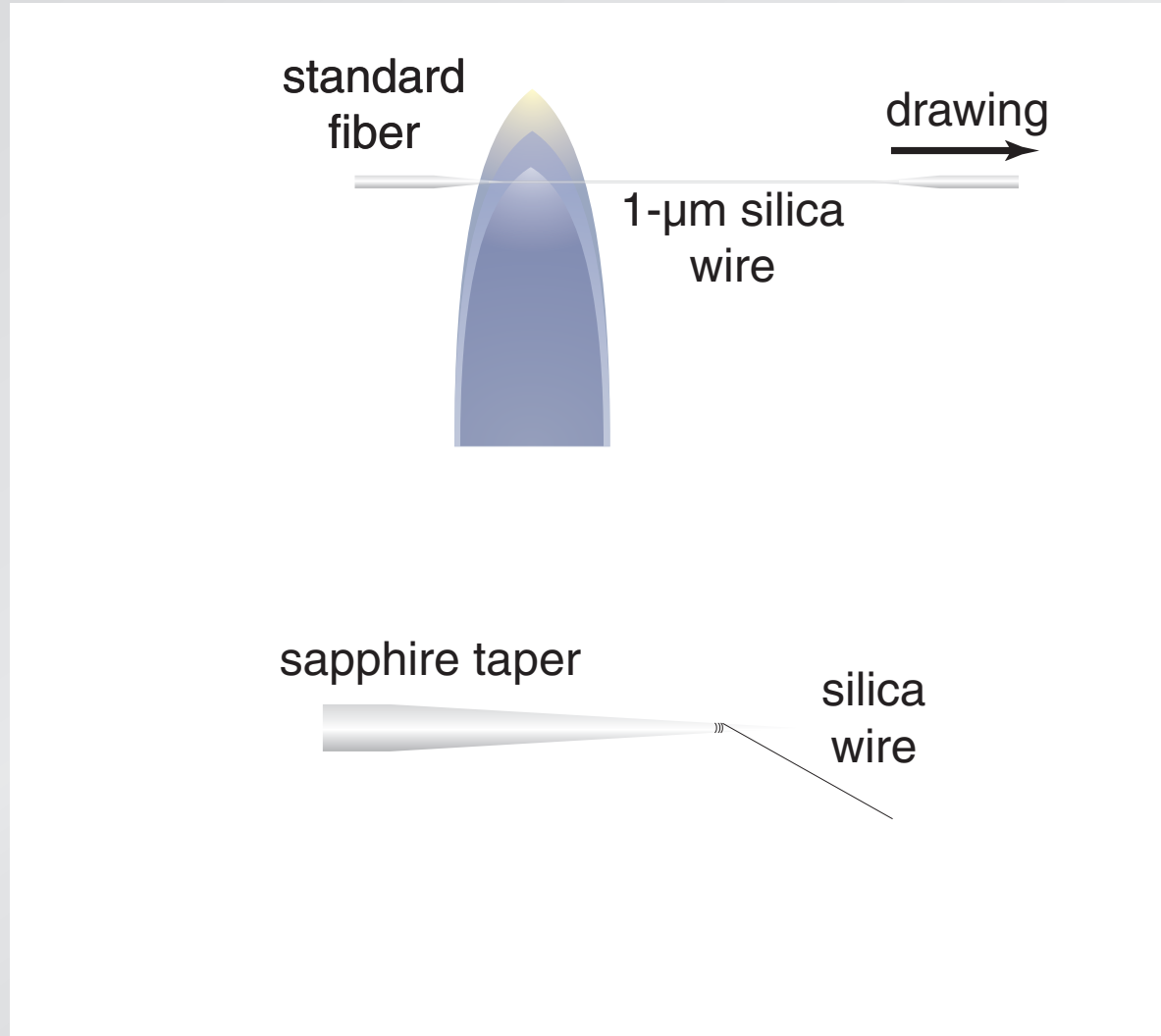
Silica nanowires

two-step drawing process



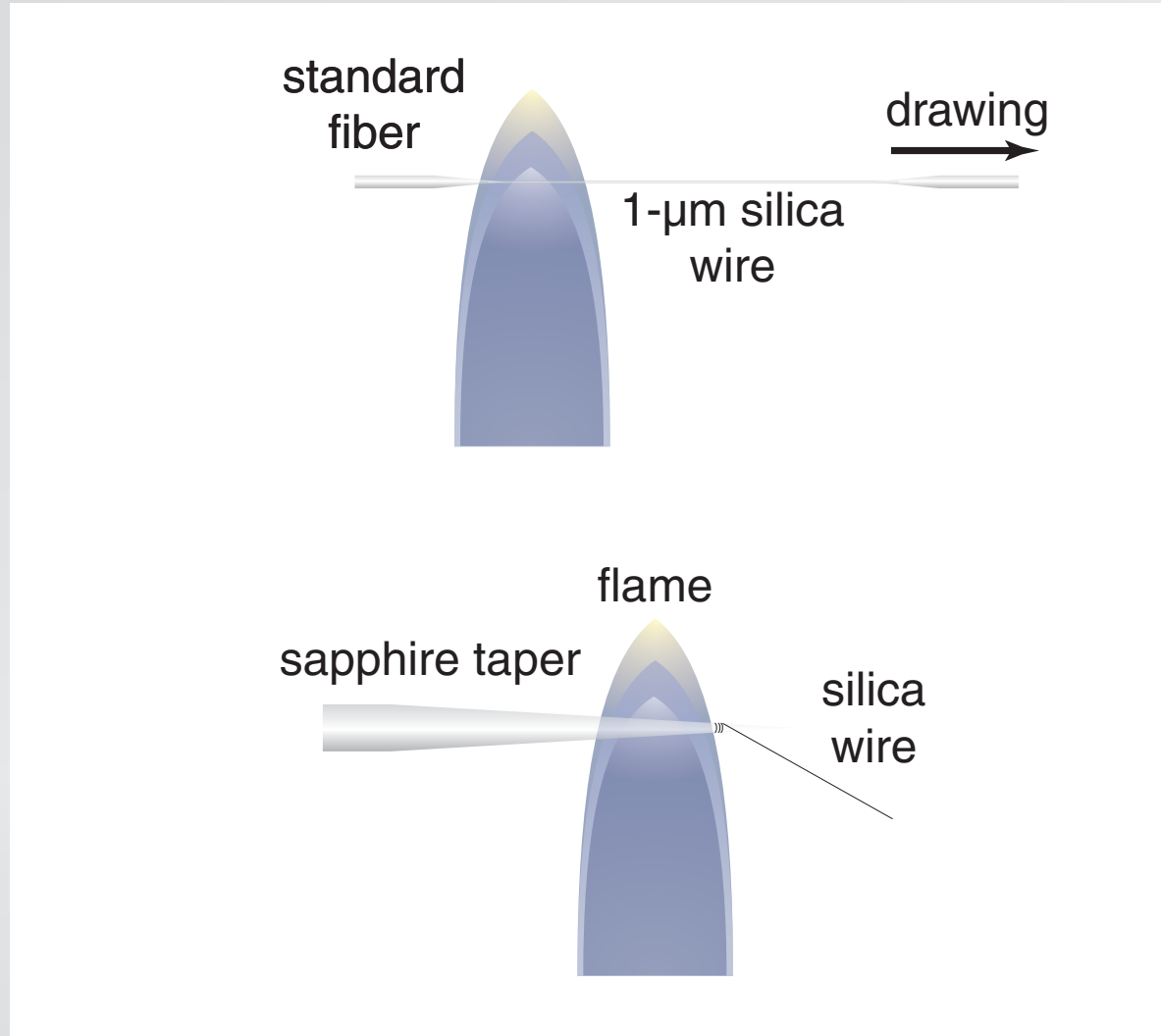
Silica nanowires

two-step drawing process



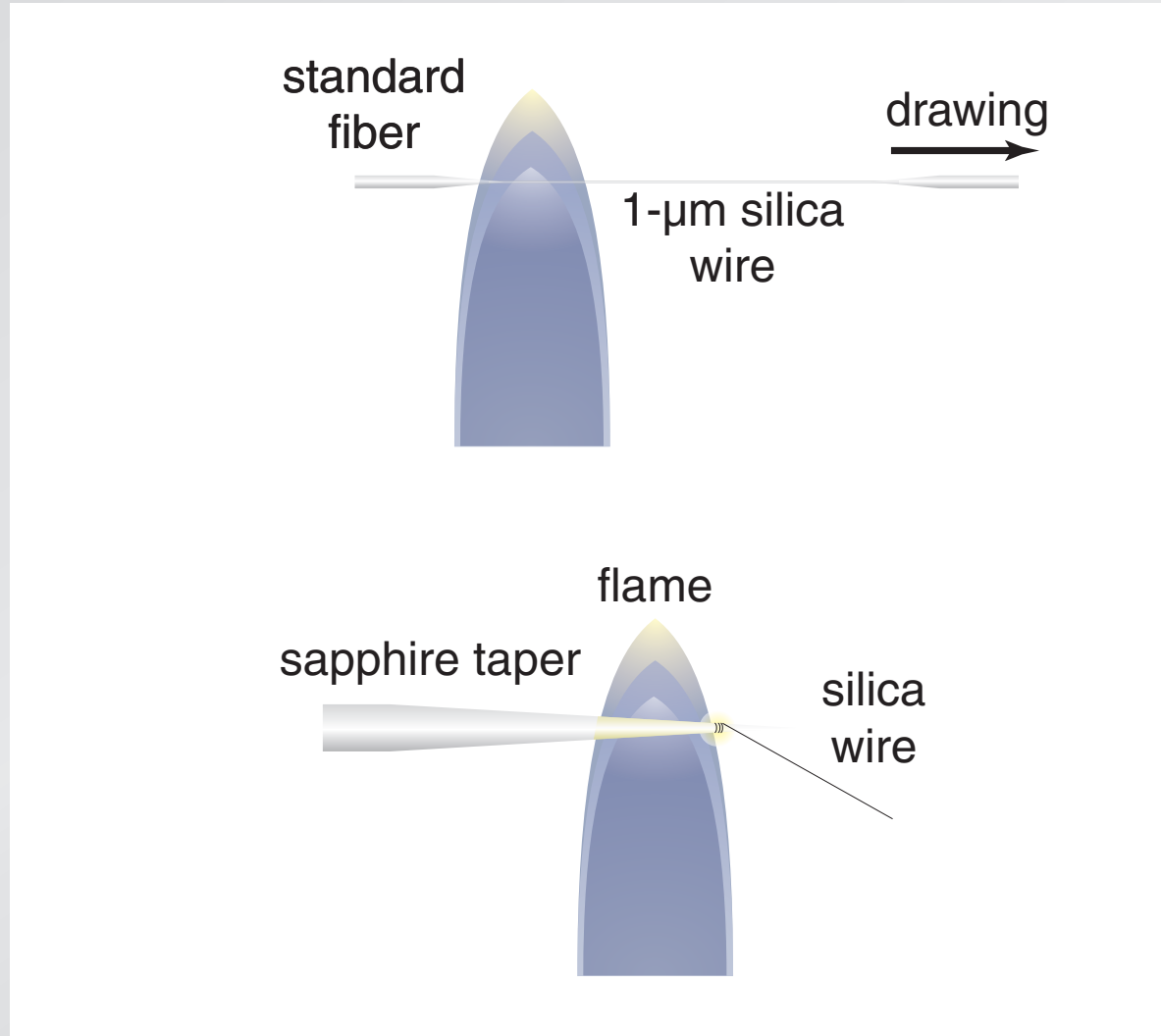
Silica nanowires

two-step drawing process



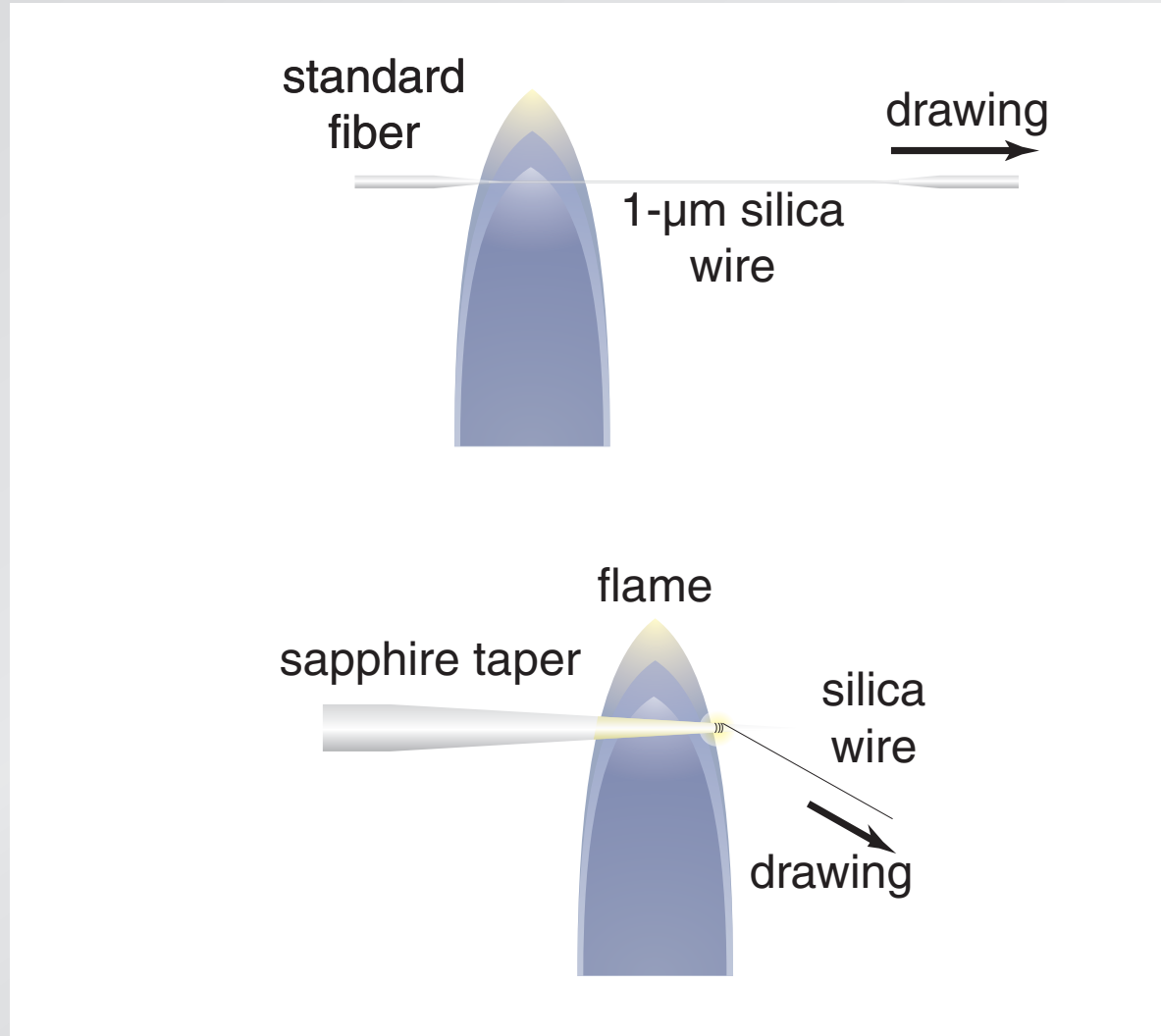
Silica nanowires

two-step drawing process

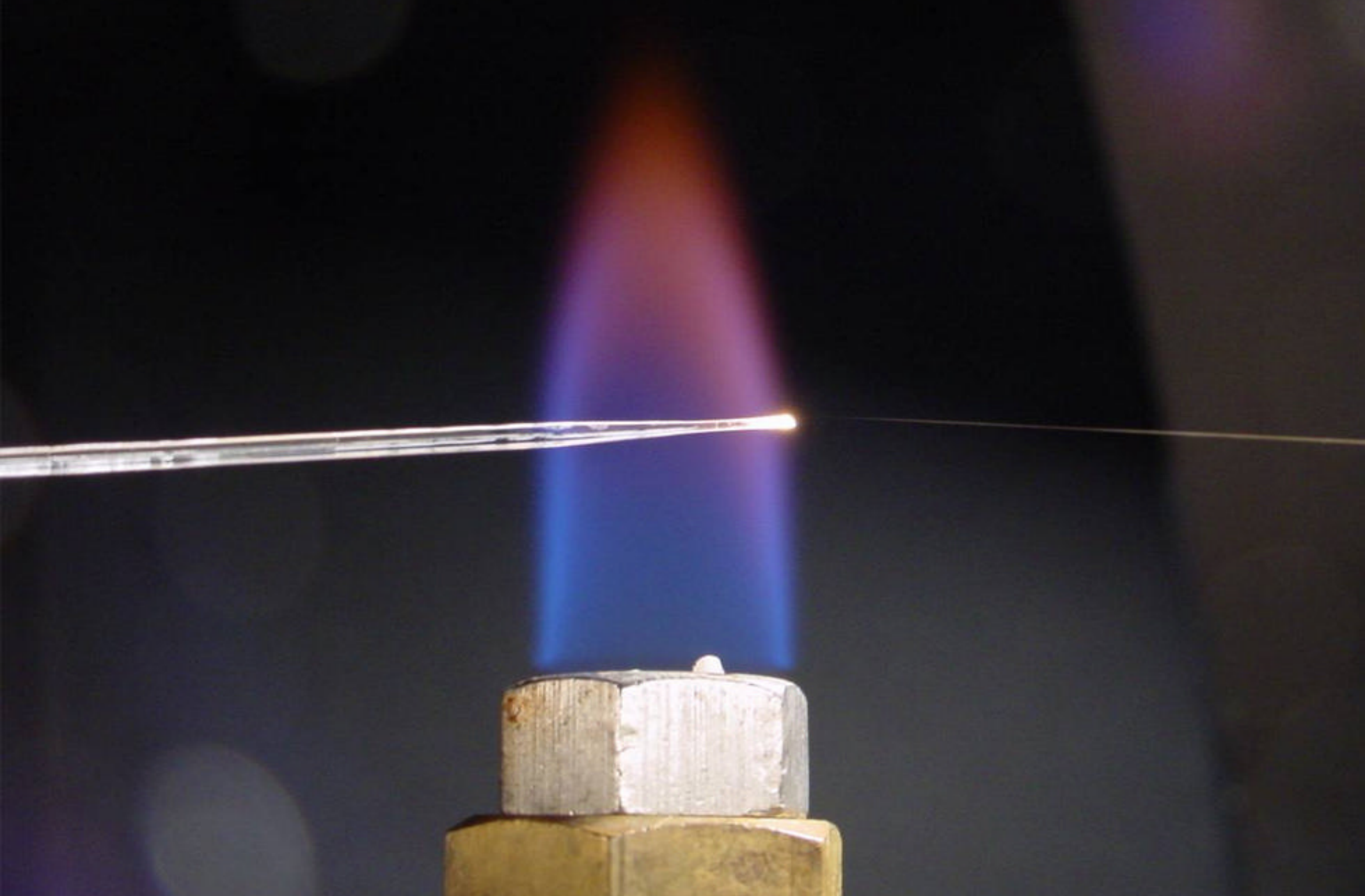


Silica nanowires

two-step drawing process

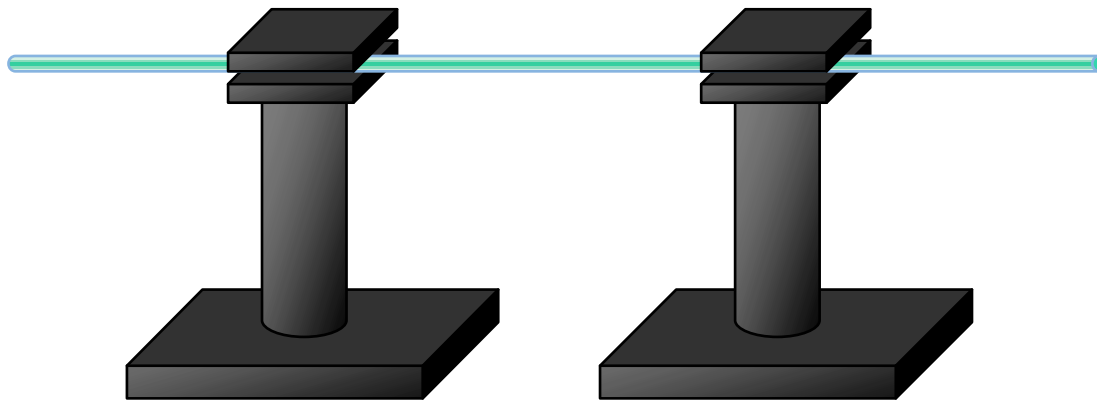


Silica nanowires



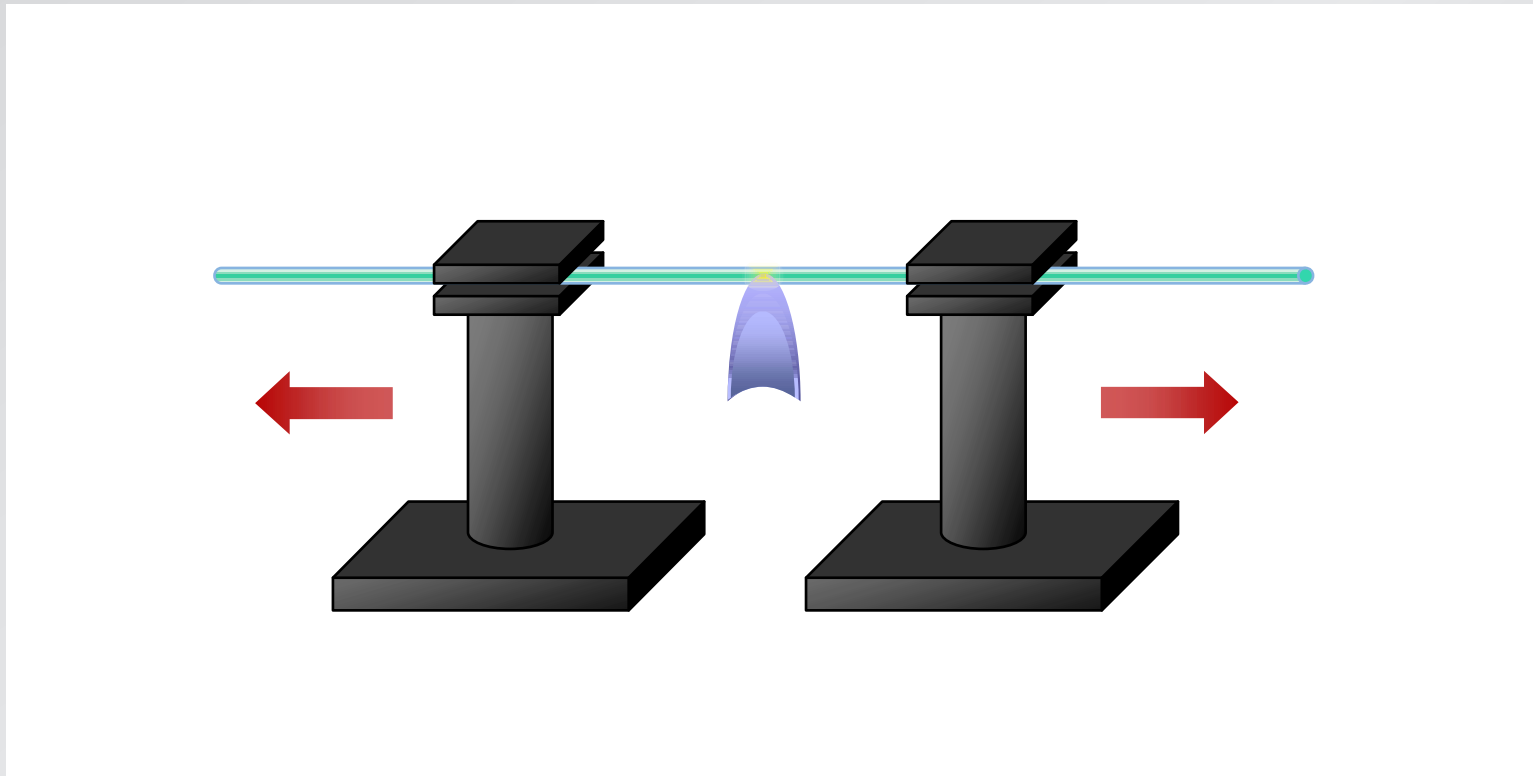
Silica nanowires

automated drawing process



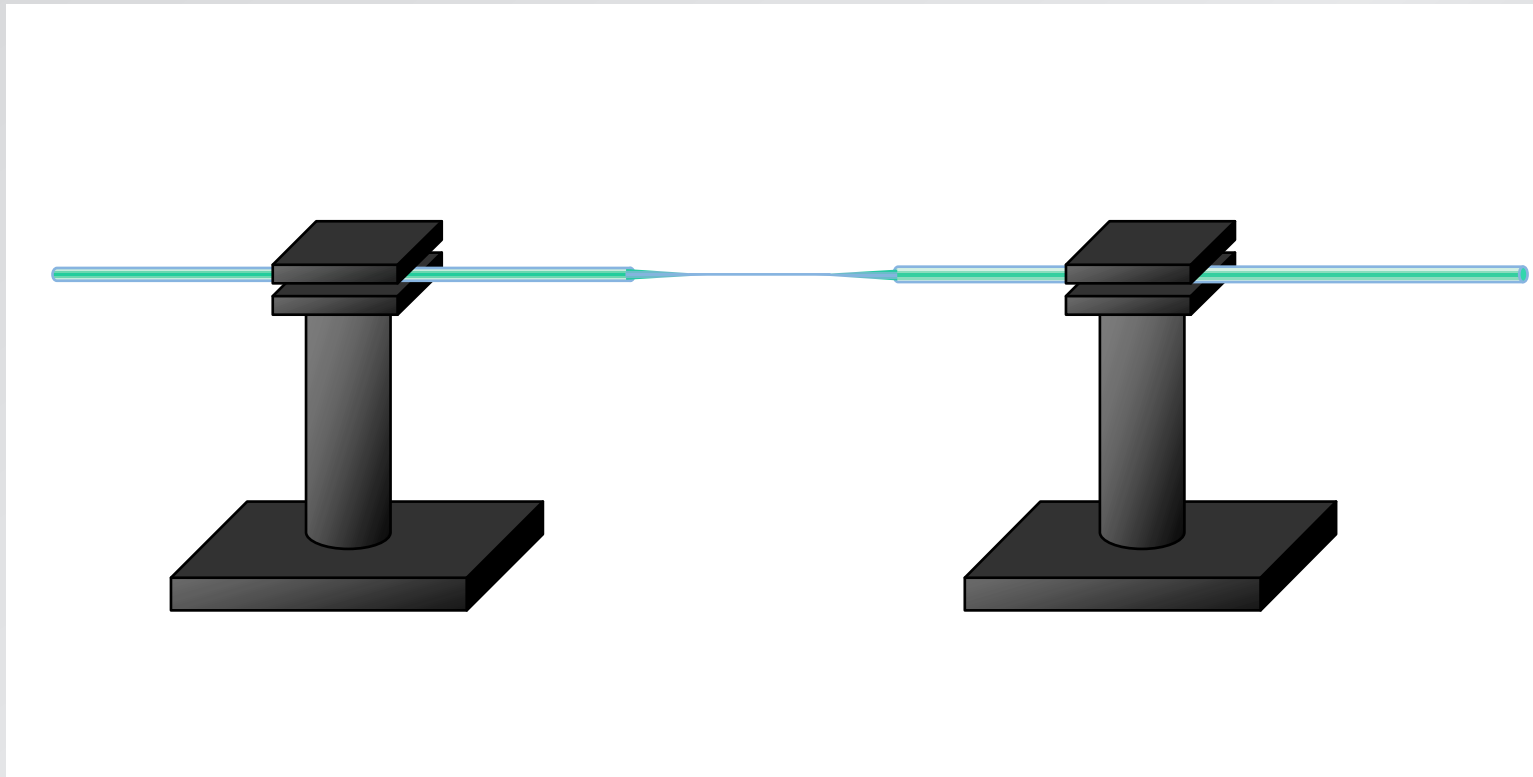
Silica nanowires

automated drawing process



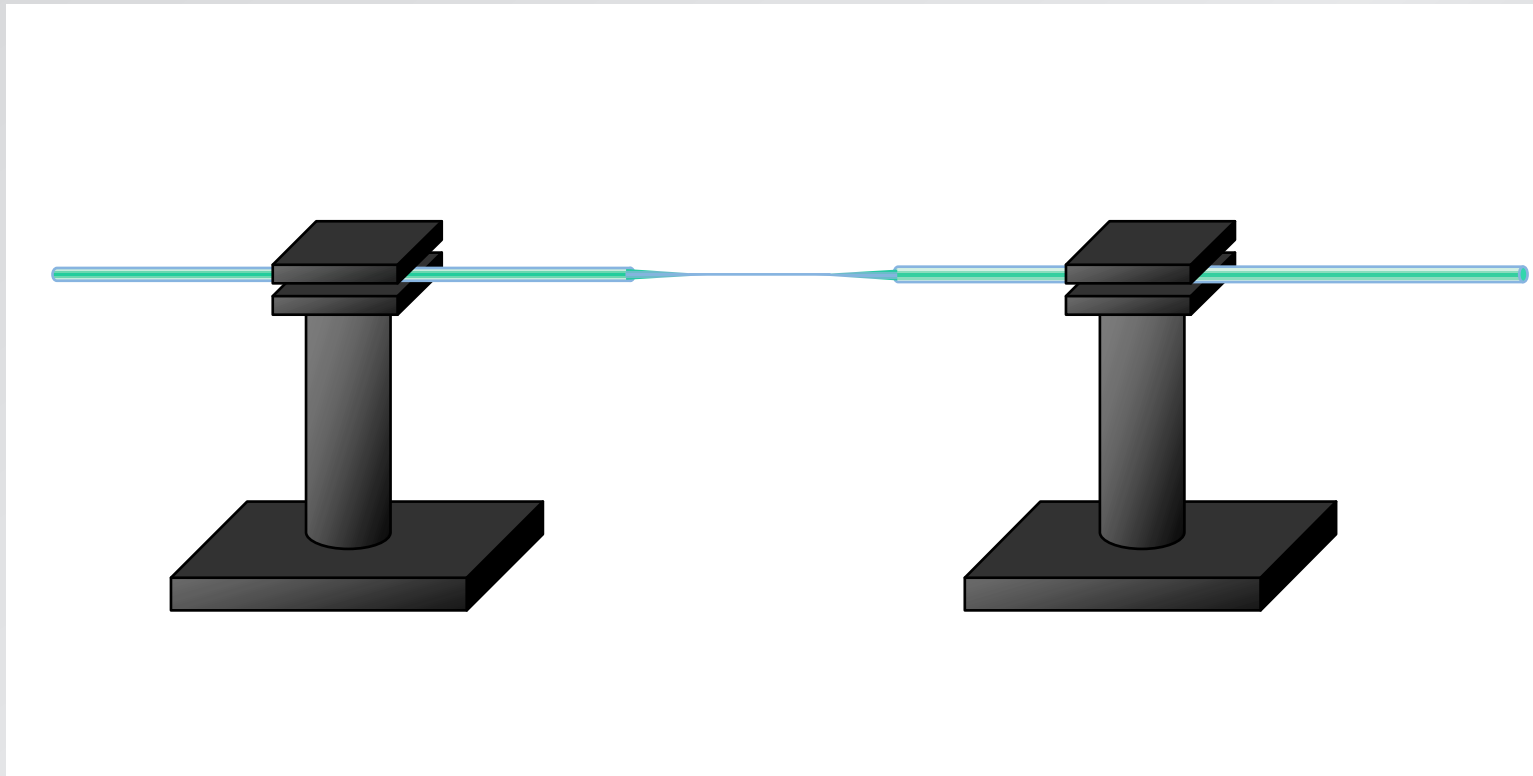
Silica nanowires

automated drawing process



Silica nanowires

automated drawing process



advantage: tapers on both sides

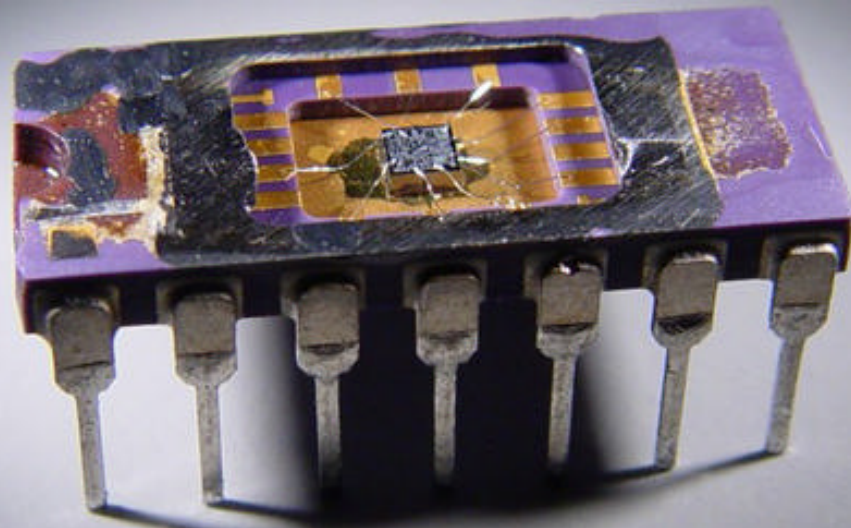
Silica nanowires

1 μm

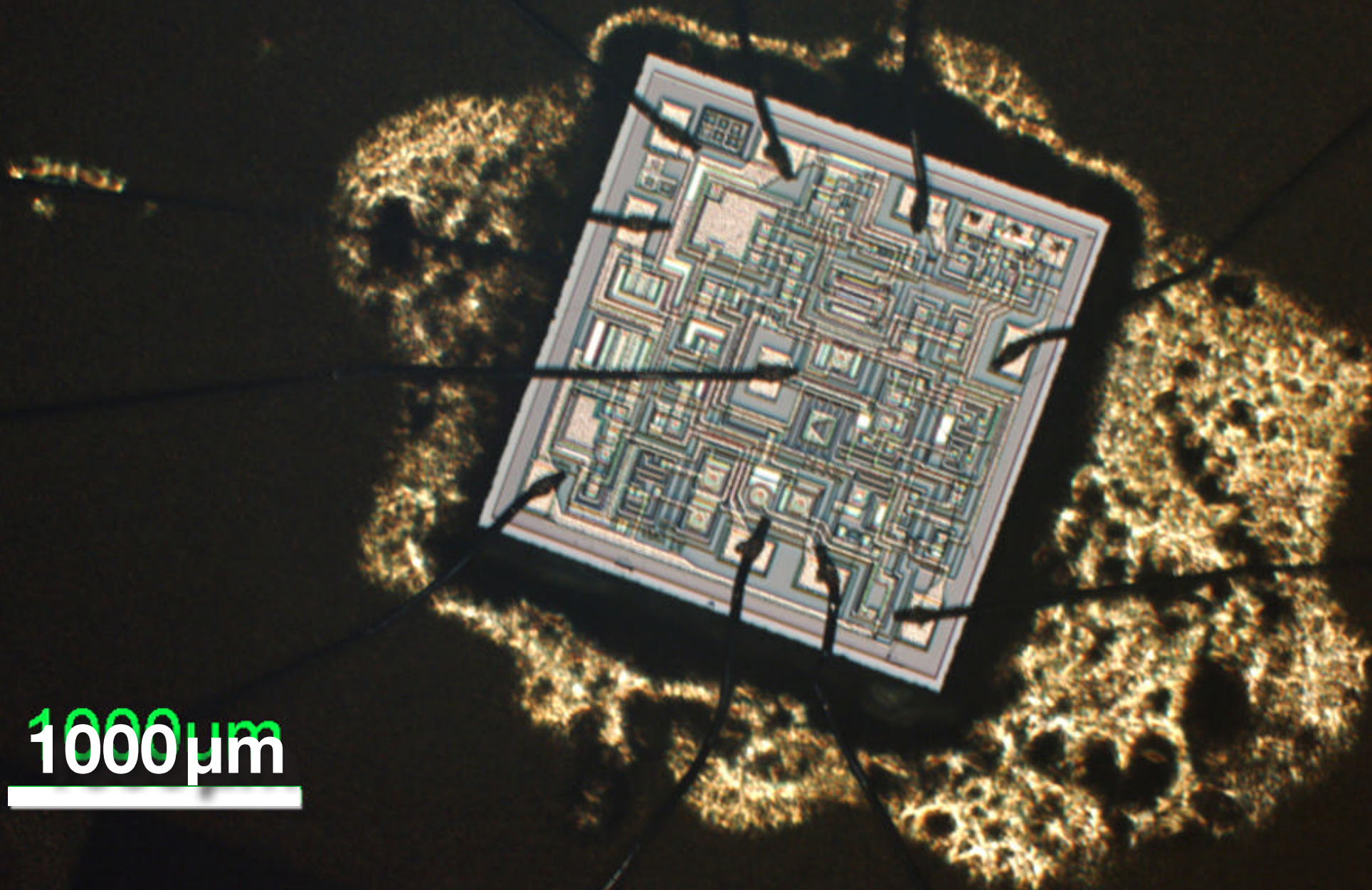


Nature, 426, 816 (2003)

Silica nanowires

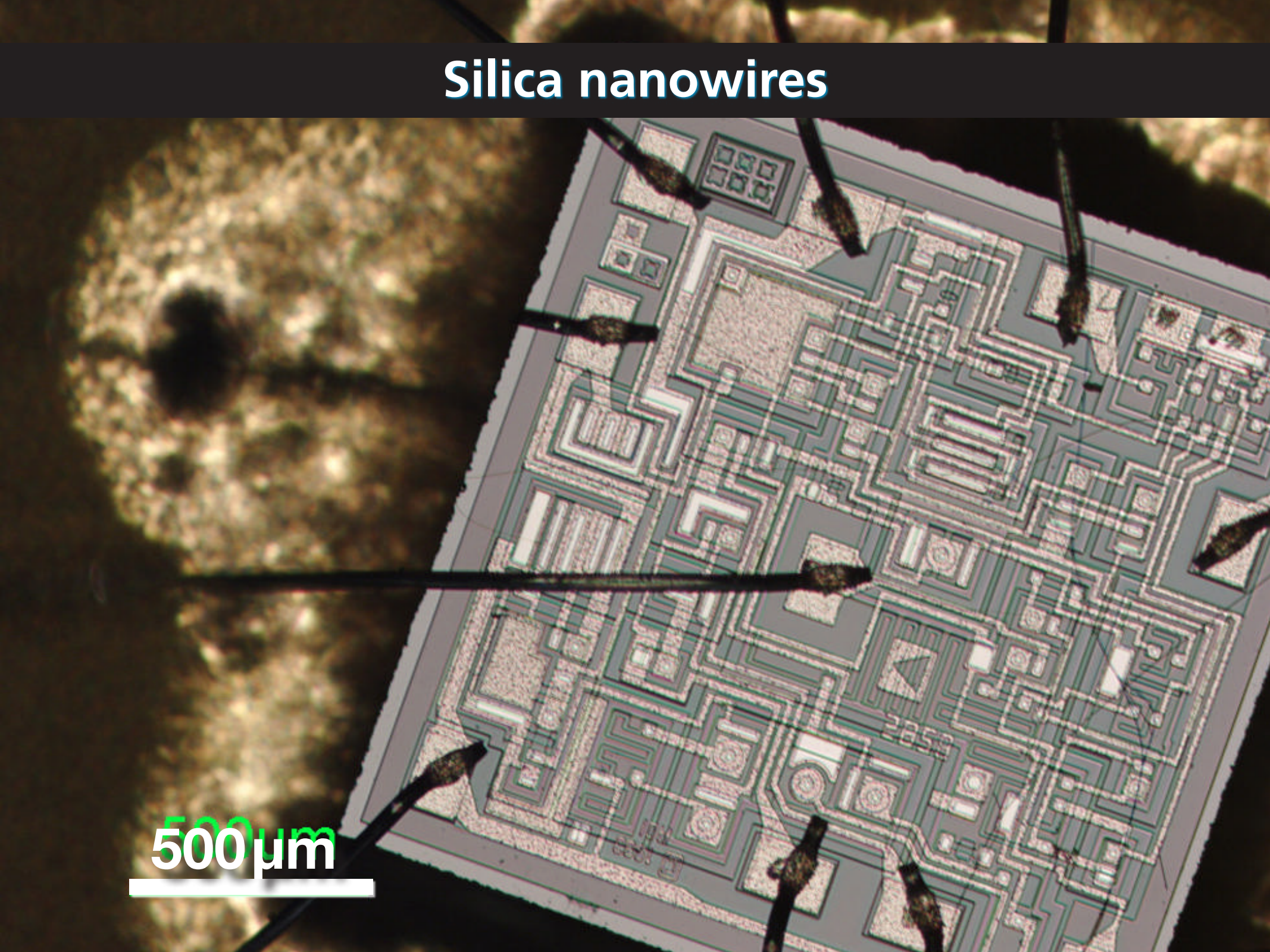
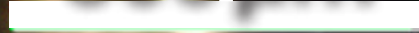


Silica nanowires



Silica nanowires

500 μm

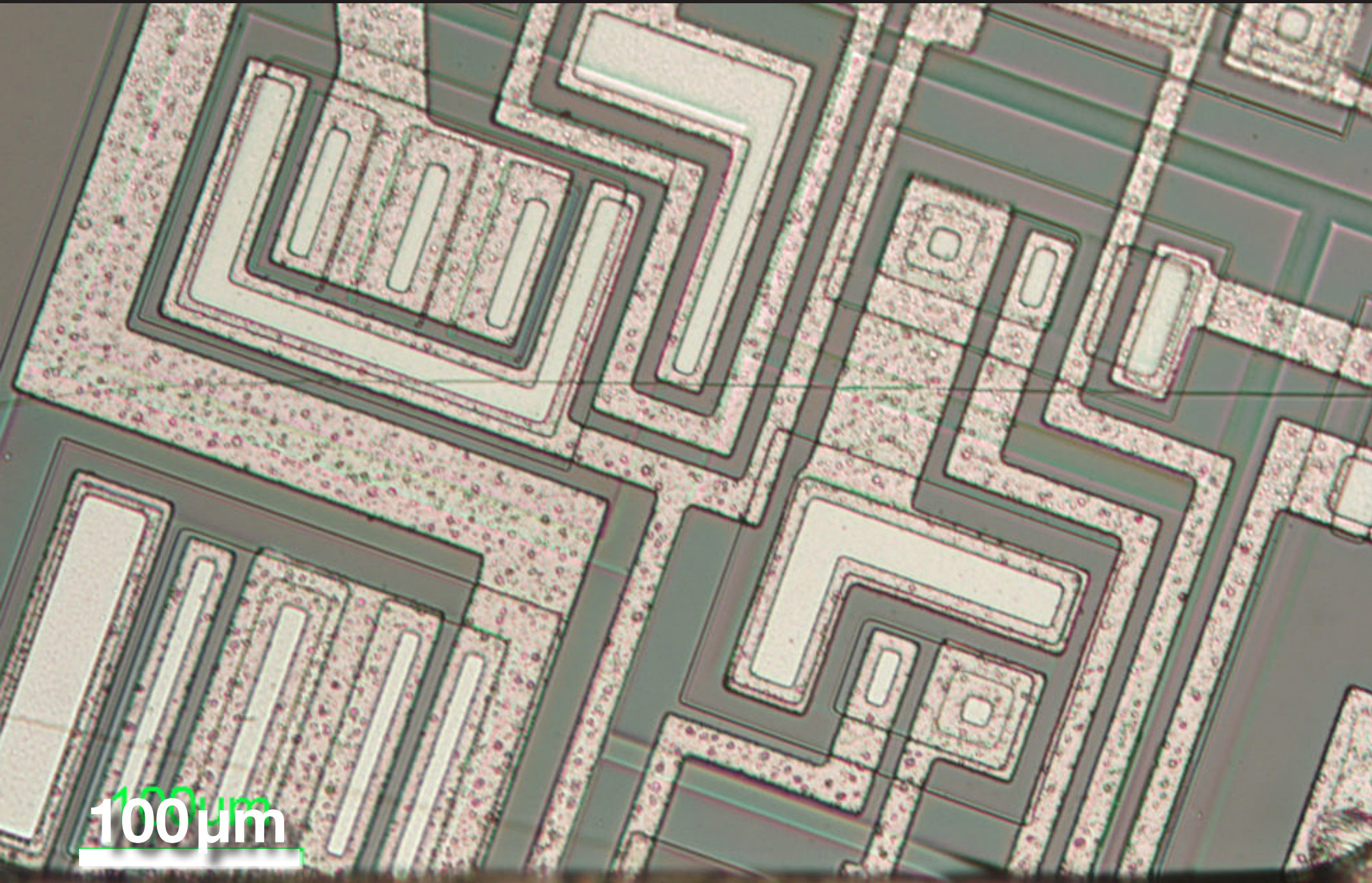


Silica nanowires

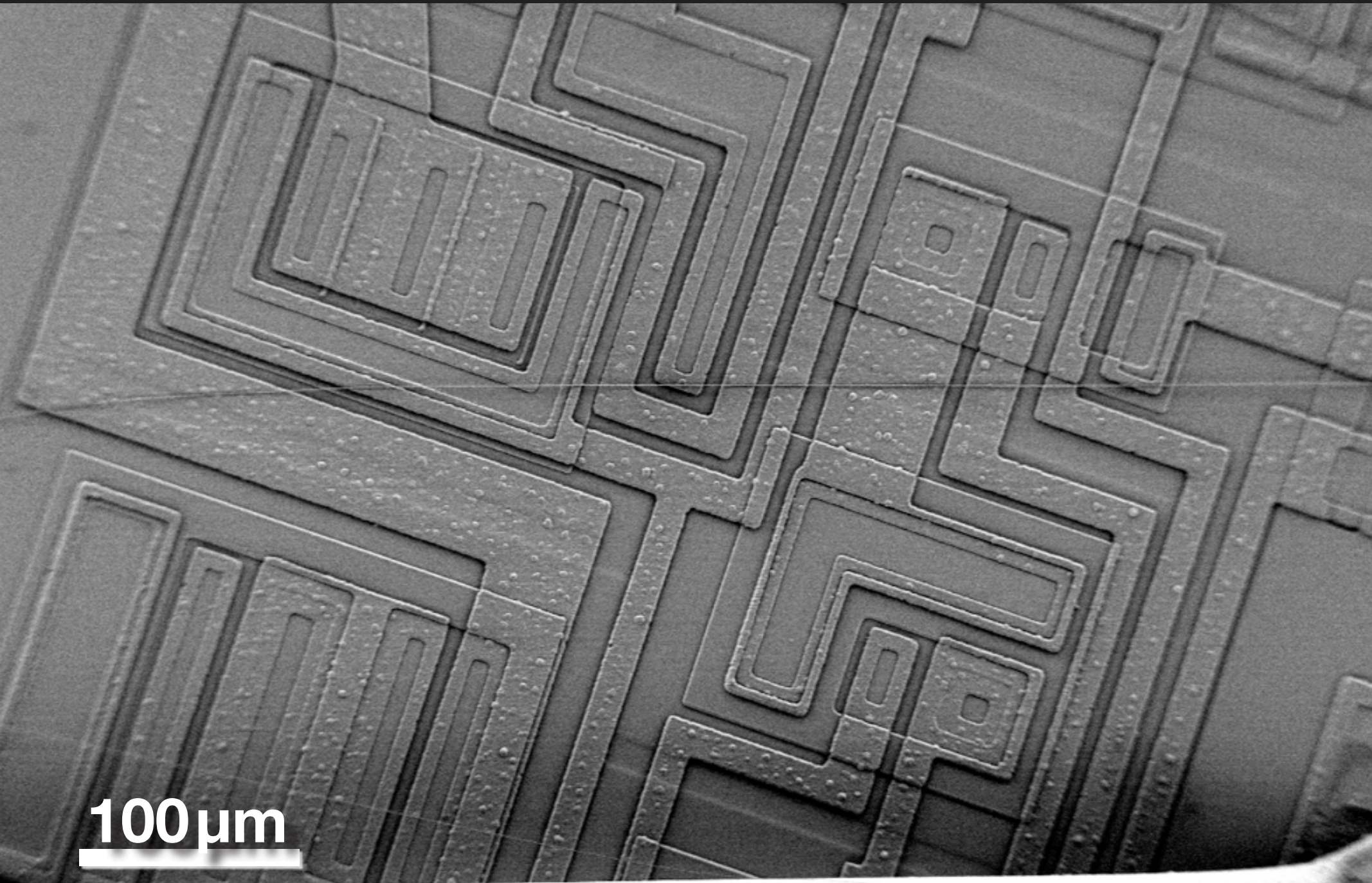
200 μm

A scanning electron micrograph (SEM) of a silicon chip. The chip surface is covered with a complex, repeating pattern of rectangular and square structures, likely a microarray or a sensor array. Two long, thin, cylindrical silica nanowires are positioned across the chip. One nanowire is oriented vertically, and the other is oriented horizontally. The nanowires appear to be resting on the surface of the chip. A scale bar in the bottom left corner indicates a length of 200 micrometers.

Silica nanowires

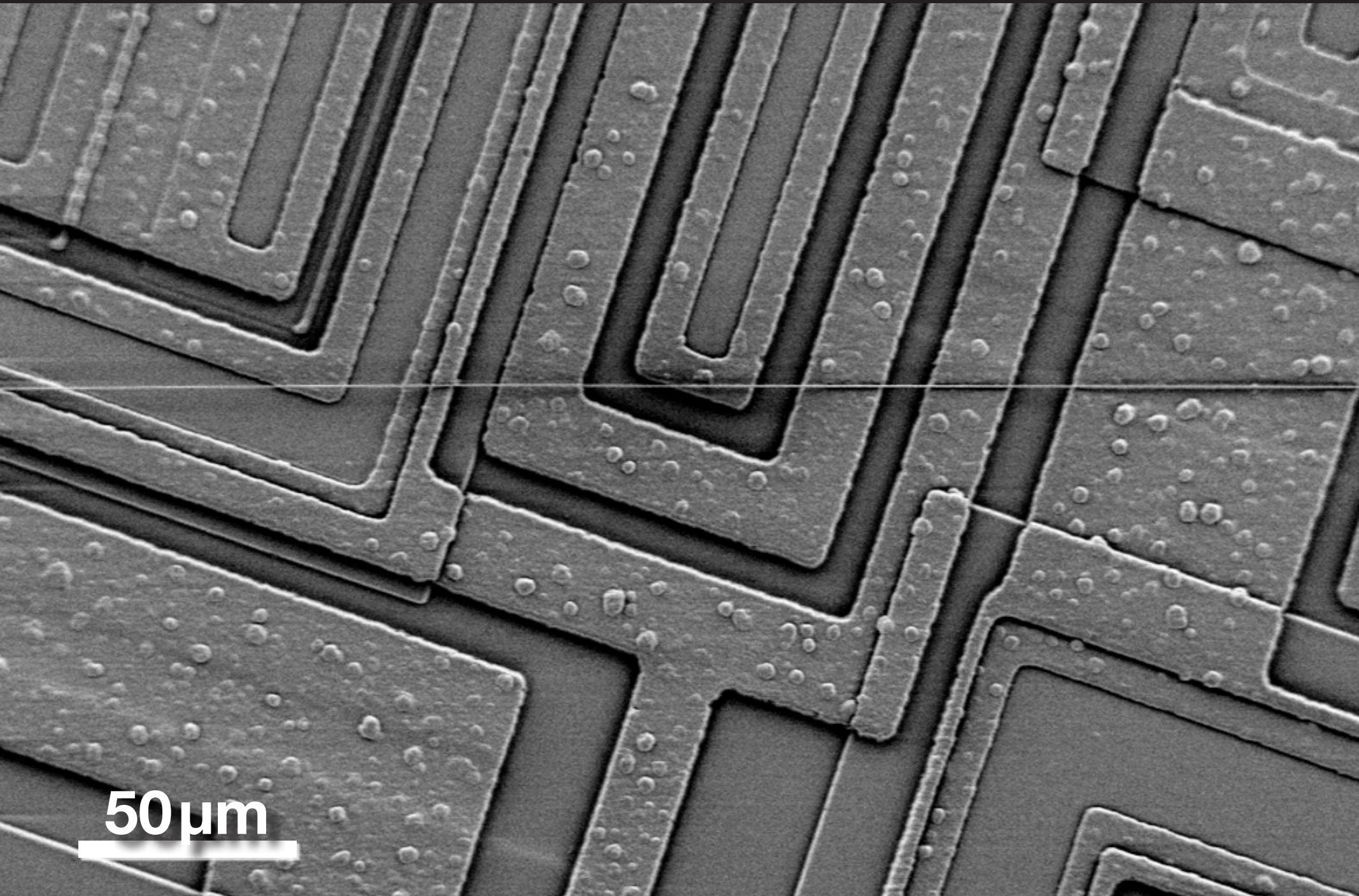


Silica nanowires



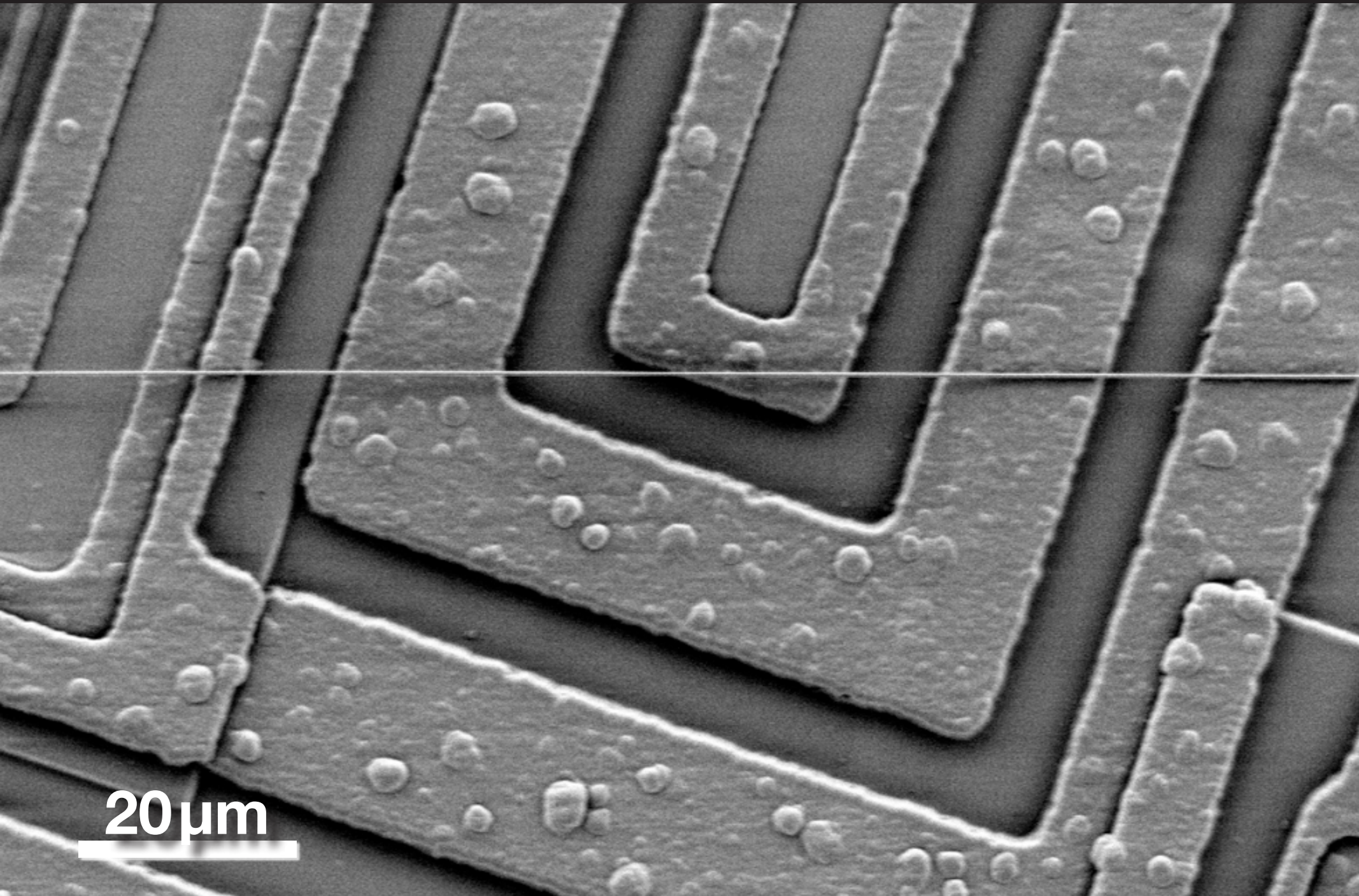
100 μm

Silica nanowires



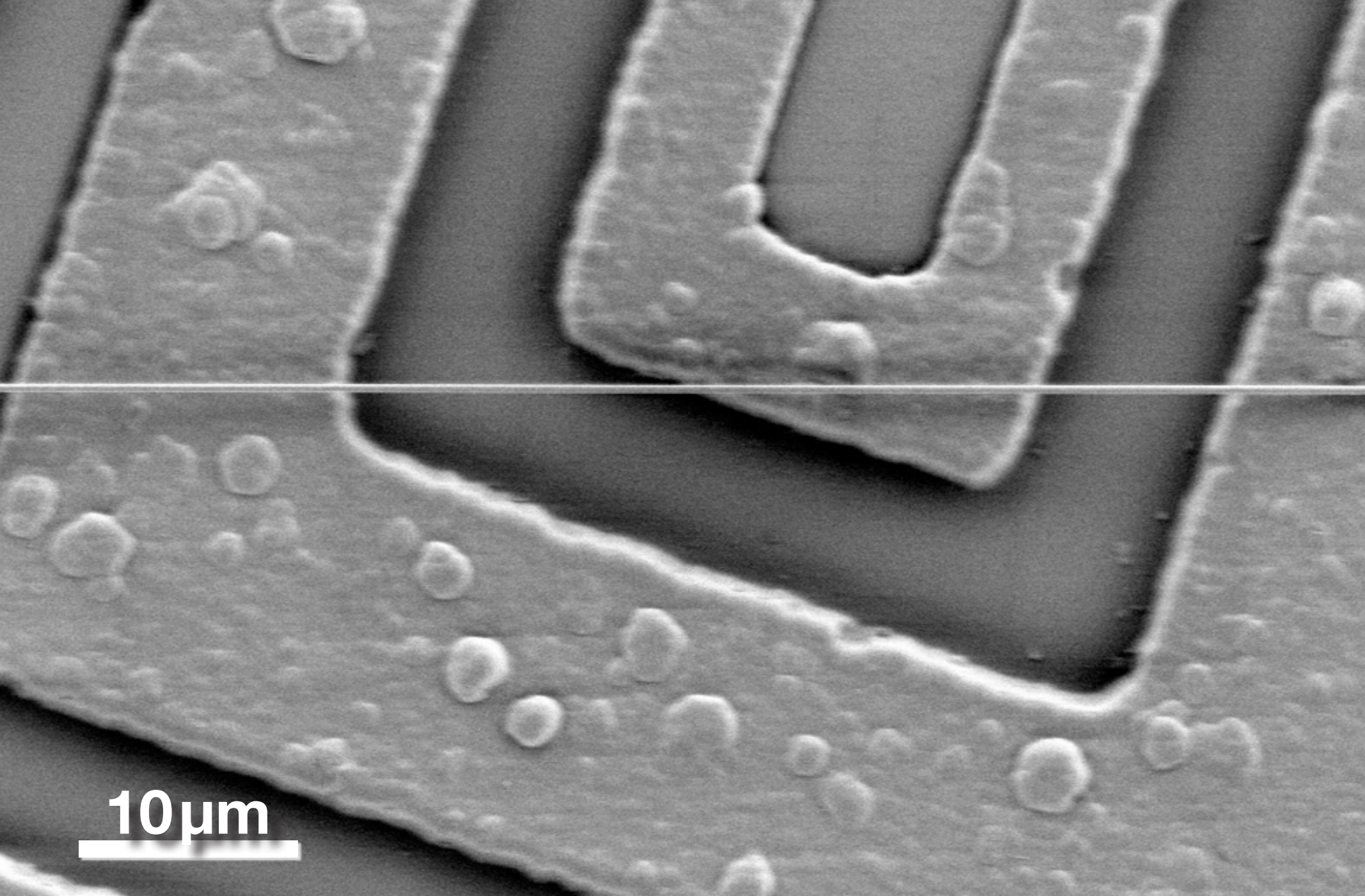
50 μm

Silica nanowires



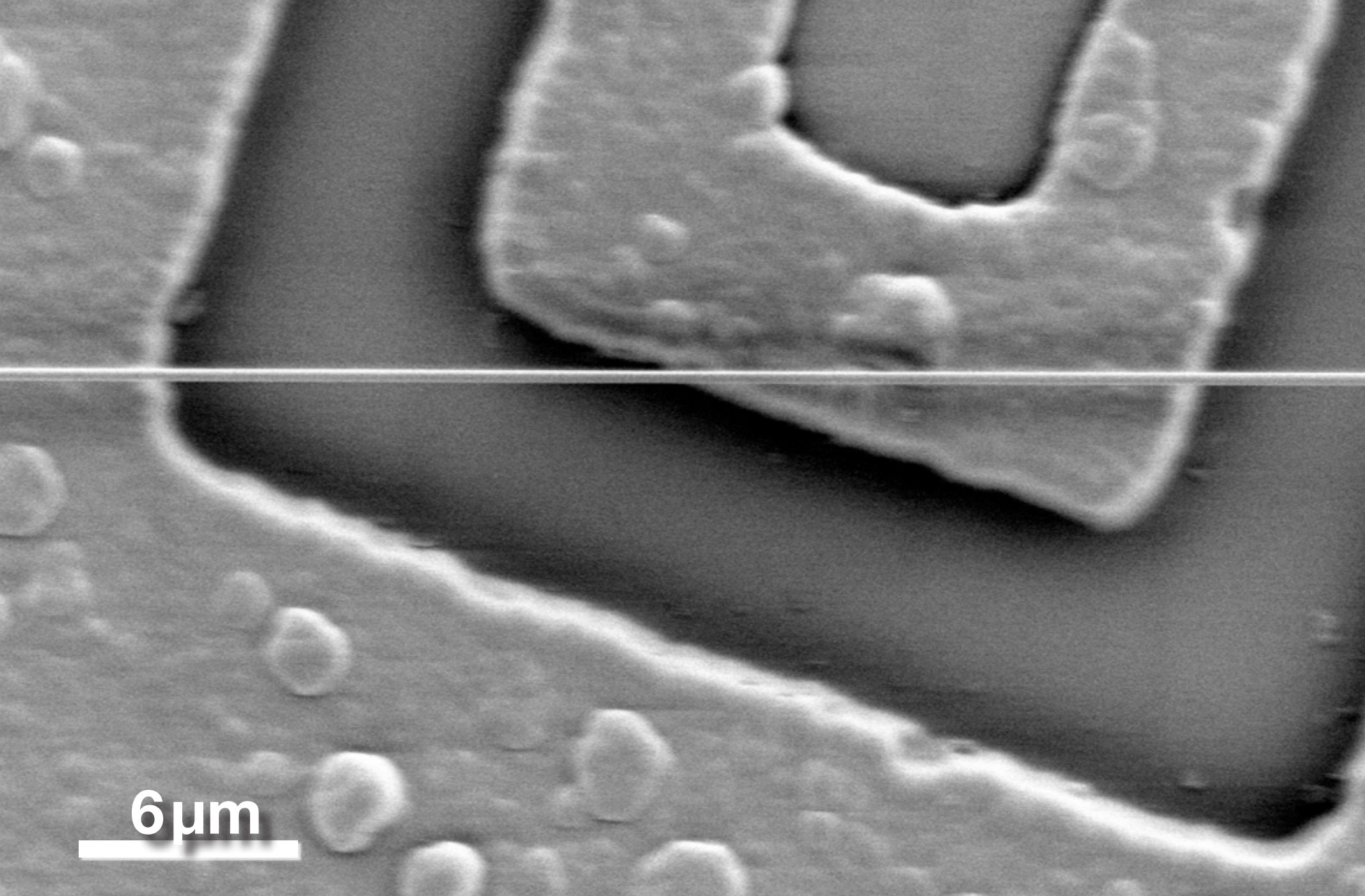
20 μm

Silica nanowires



10 μm

Silica nanowires



6 μm

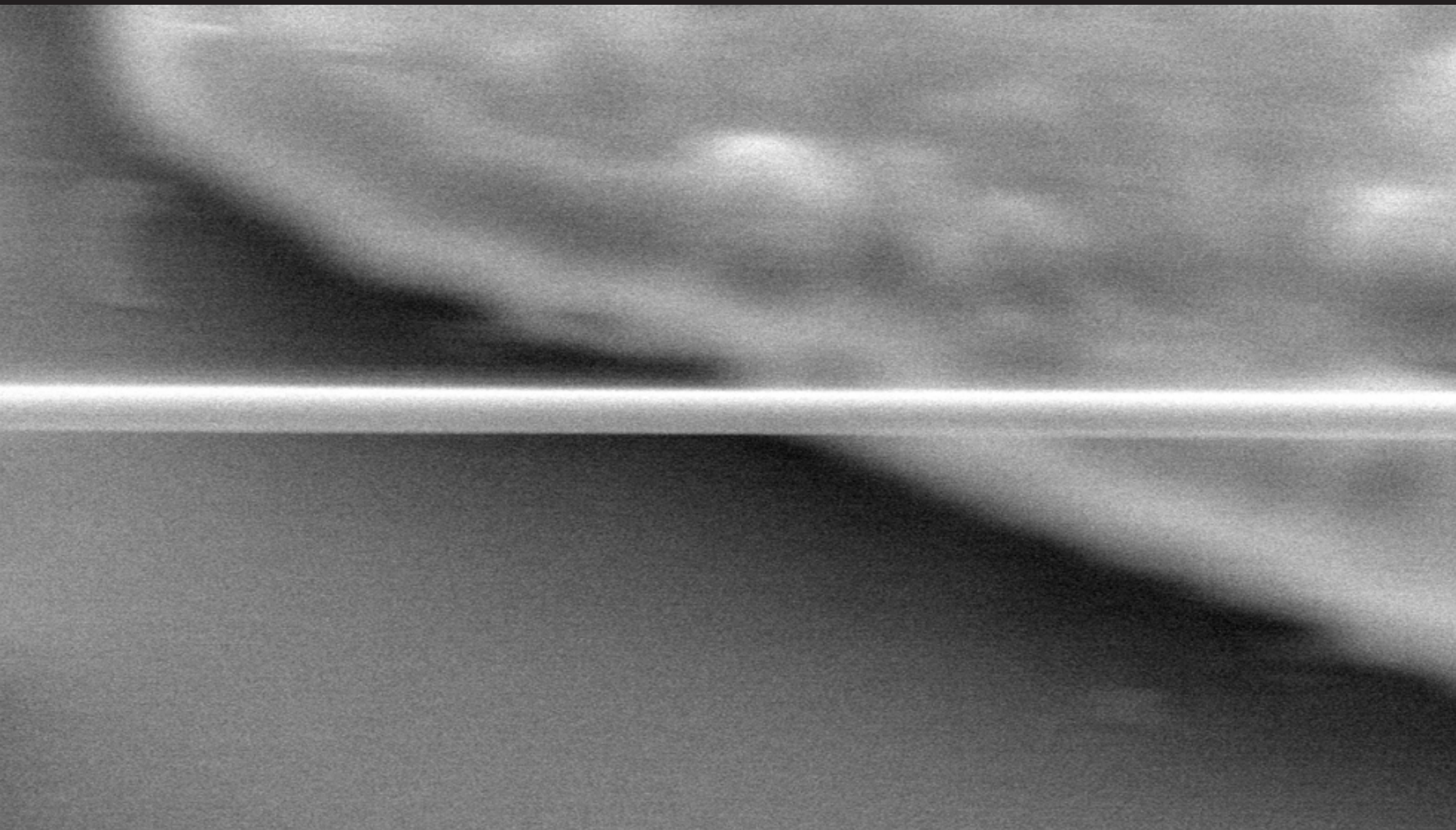


Silica nanowires

4 μm

This scanning electron microscope (SEM) image displays silica nanowires. A single, thin nanowire is clearly visible, extending horizontally across the middle of the frame. The background shows a textured surface, likely the substrate or other nanowires, with some larger, irregular features. A scale bar in the bottom left corner indicates a length of 4 micrometers.

Silica nanowires



2 μm

Silica nanowires

312 nm

A transmission electron micrograph (TEM) showing a single, long, cylindrical silica nanowire. The nanowire is oriented horizontally and appears as a bright, uniform line against a dark background. A vertical white line with a crossbar at the bottom is drawn across the nanowire to indicate its diameter. The text "312 nm" is placed above this vertical line. In the bottom left corner, there is a horizontal white scale bar with the text "1 μm" above it.

1 μm

Silica nanowires

Specifications

diameter D : down to 20 nm

length L : up to 90 mm

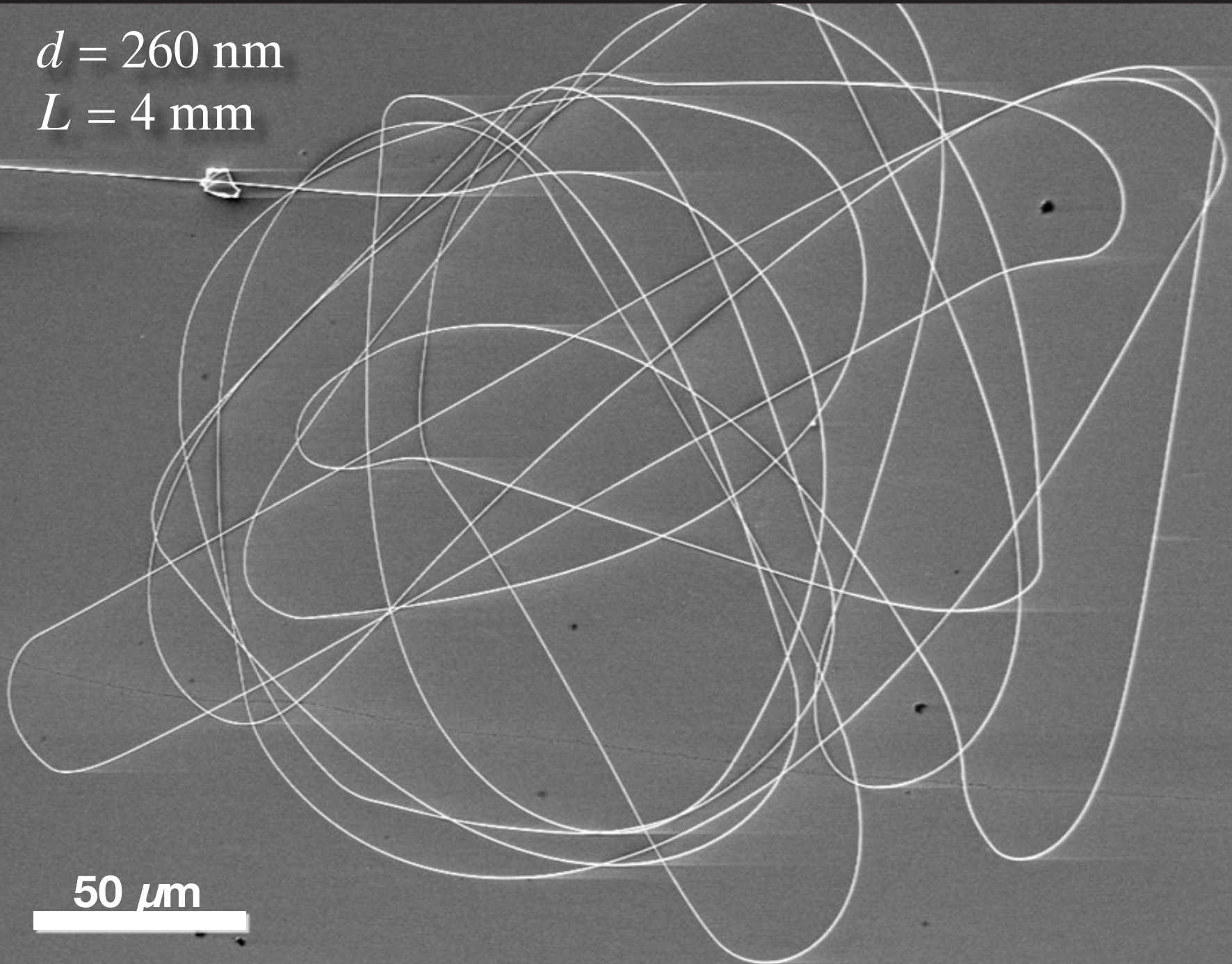
aspect ratio D/L : up to 10^6

diameter uniformity $\Delta D/L$: 2×10^{-6}

Silica nanowires

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50 μm

Silica nanowires

240-nm wire

200 nm

A transmission electron micrograph showing a single, dark, cylindrical silica nanowire oriented diagonally from the bottom-left to the top-right. The wire has a uniform diameter and a smooth surface. The background is a light gray, textured surface. A scale bar in the bottom right corner indicates a length of 200 nm.

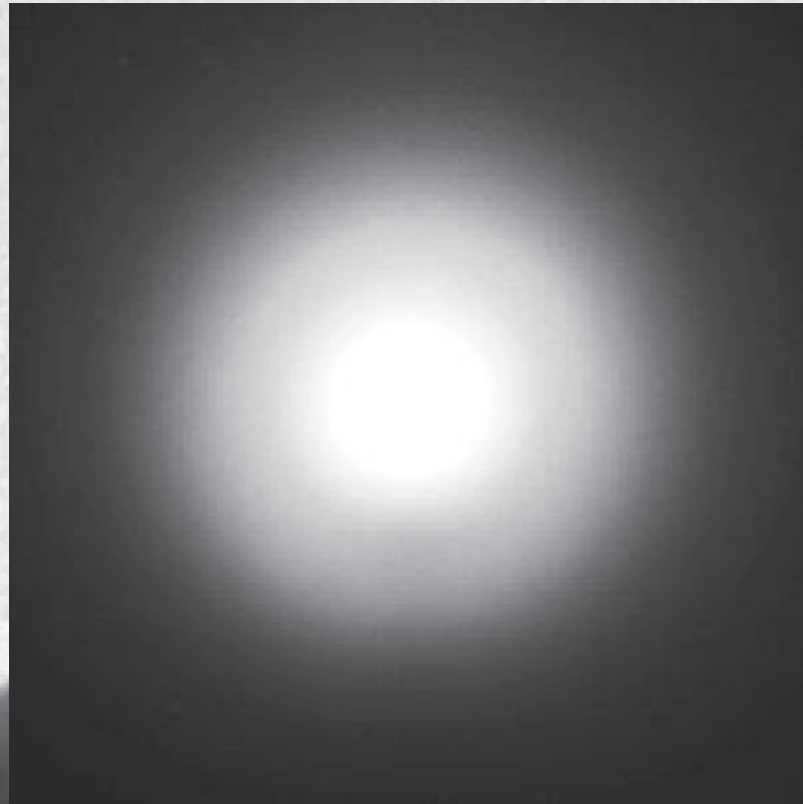
Silica nanowires

RMS roughness < 0.5 nm

20 nm



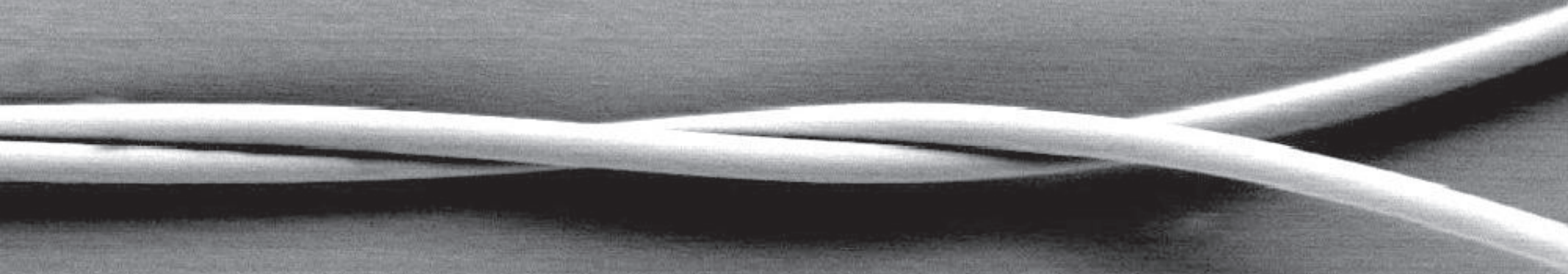
Silica nanowires



20 nm



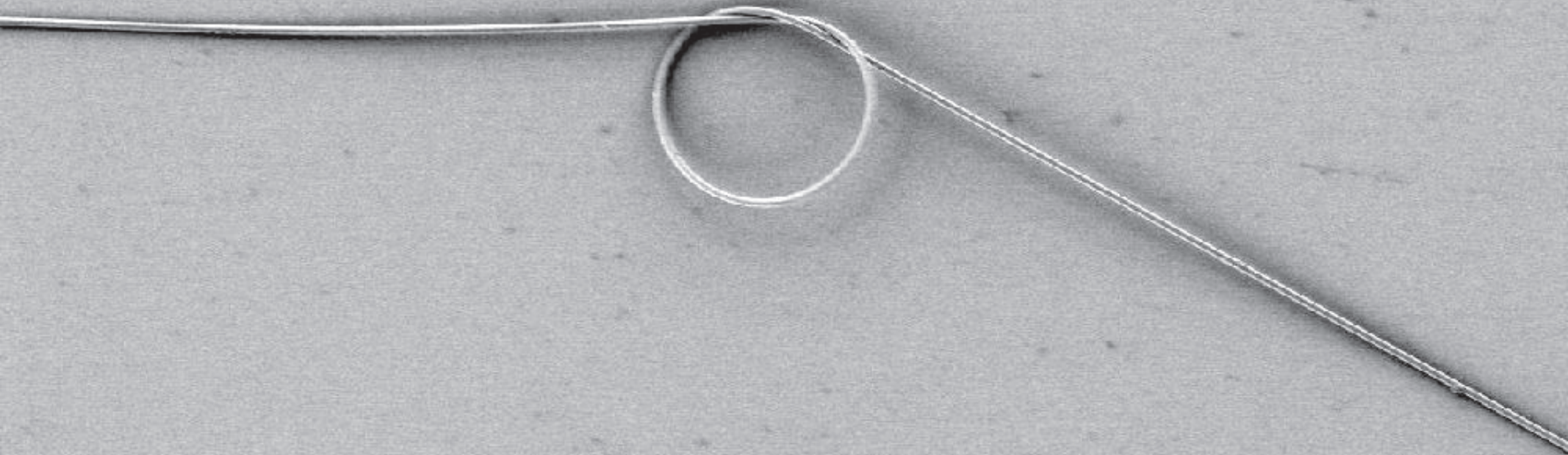
Silica nanowires



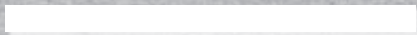
2 μm



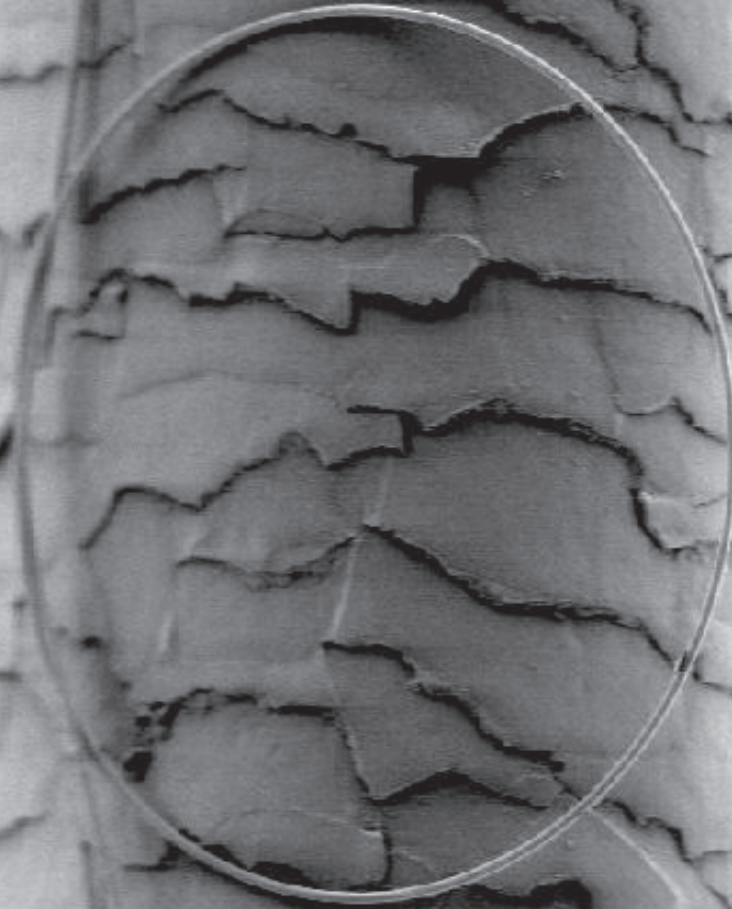
Silica nanowires



20 μm



Silica nanowires



20 μm



Silica nanowires

Points to keep in mind:

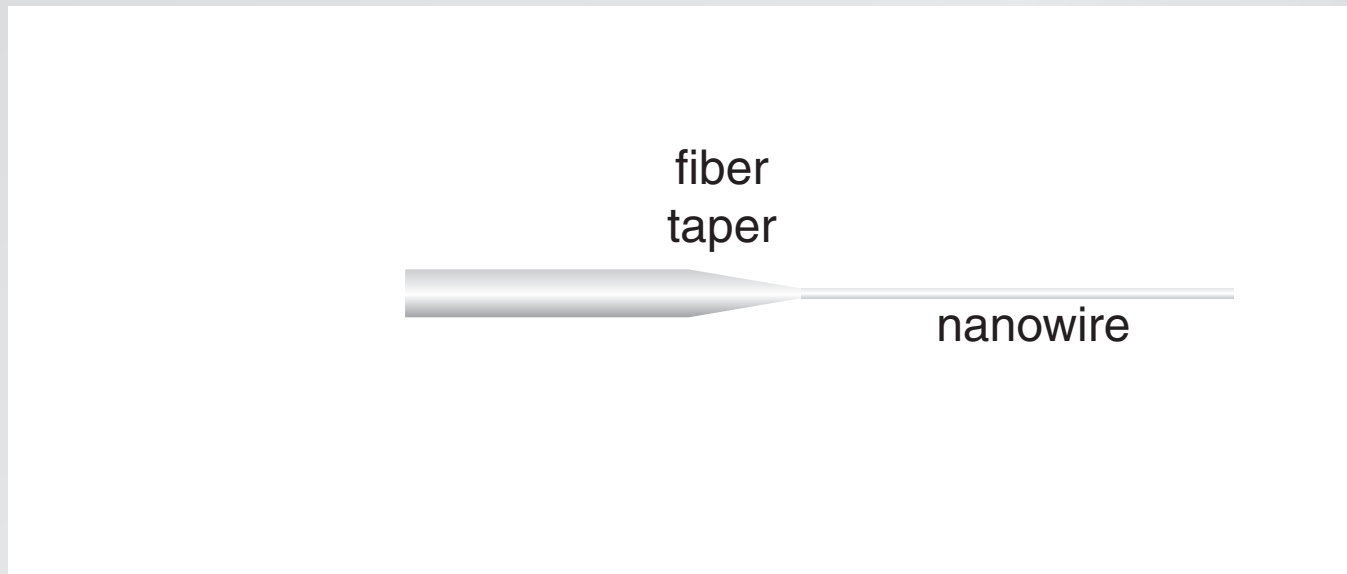
- **easy fabrication**
- **atomic level smoothness**
- **malleable**

Outline

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

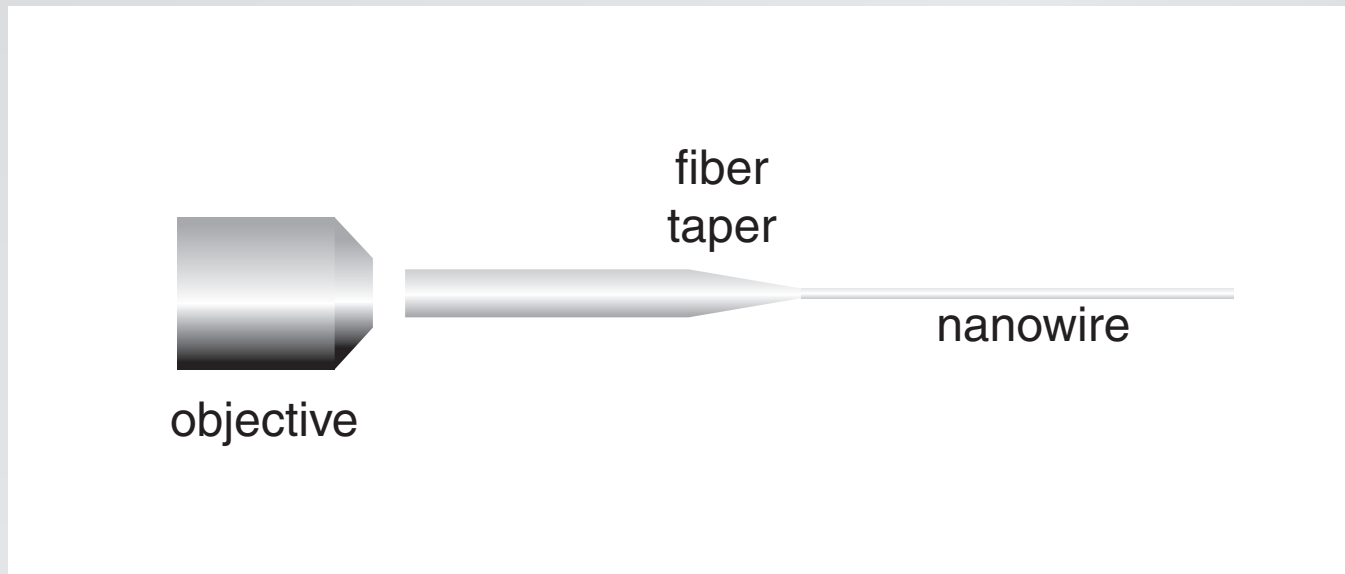
Manipulating light at the nanoscale

coupling light into nanowires



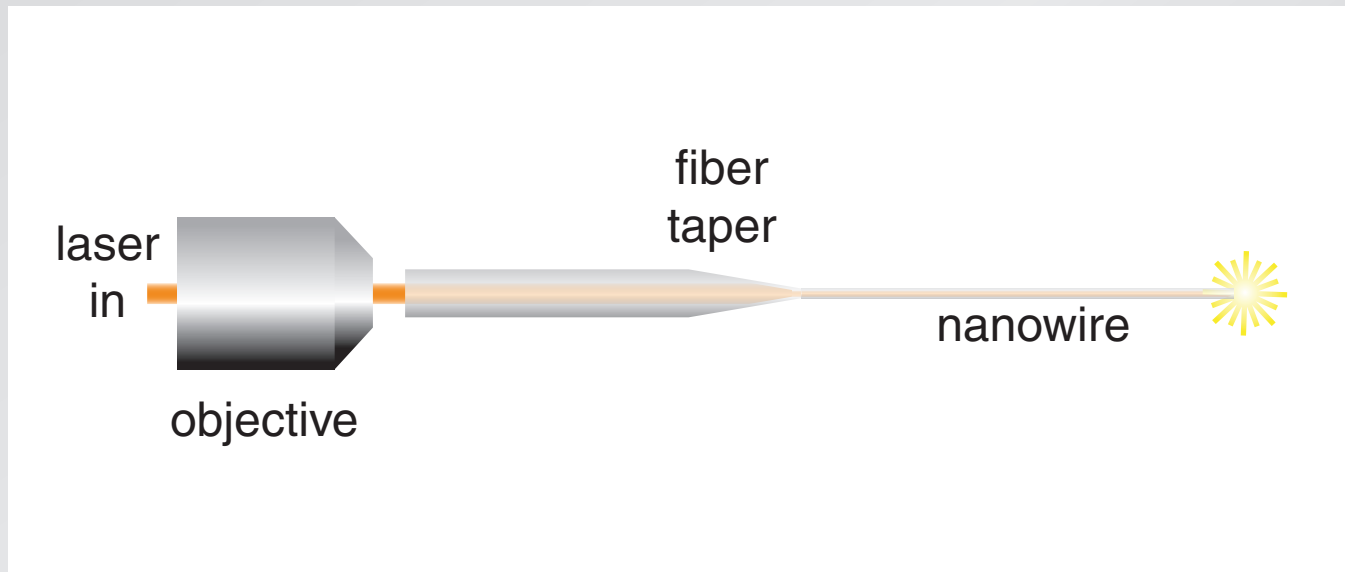
Manipulating light at the nanoscale

coupling light into nanowires



Manipulating light at the nanoscale

coupling light into nanowires



Manipulating light at the nanoscale

280-nm nanowire

A scanning electron microscope (SEM) image of a single, thin nanowire. The nanowire is a single, continuous line of material, appearing as a thin, dark line against a lighter background. It is oriented horizontally and is relatively straight.

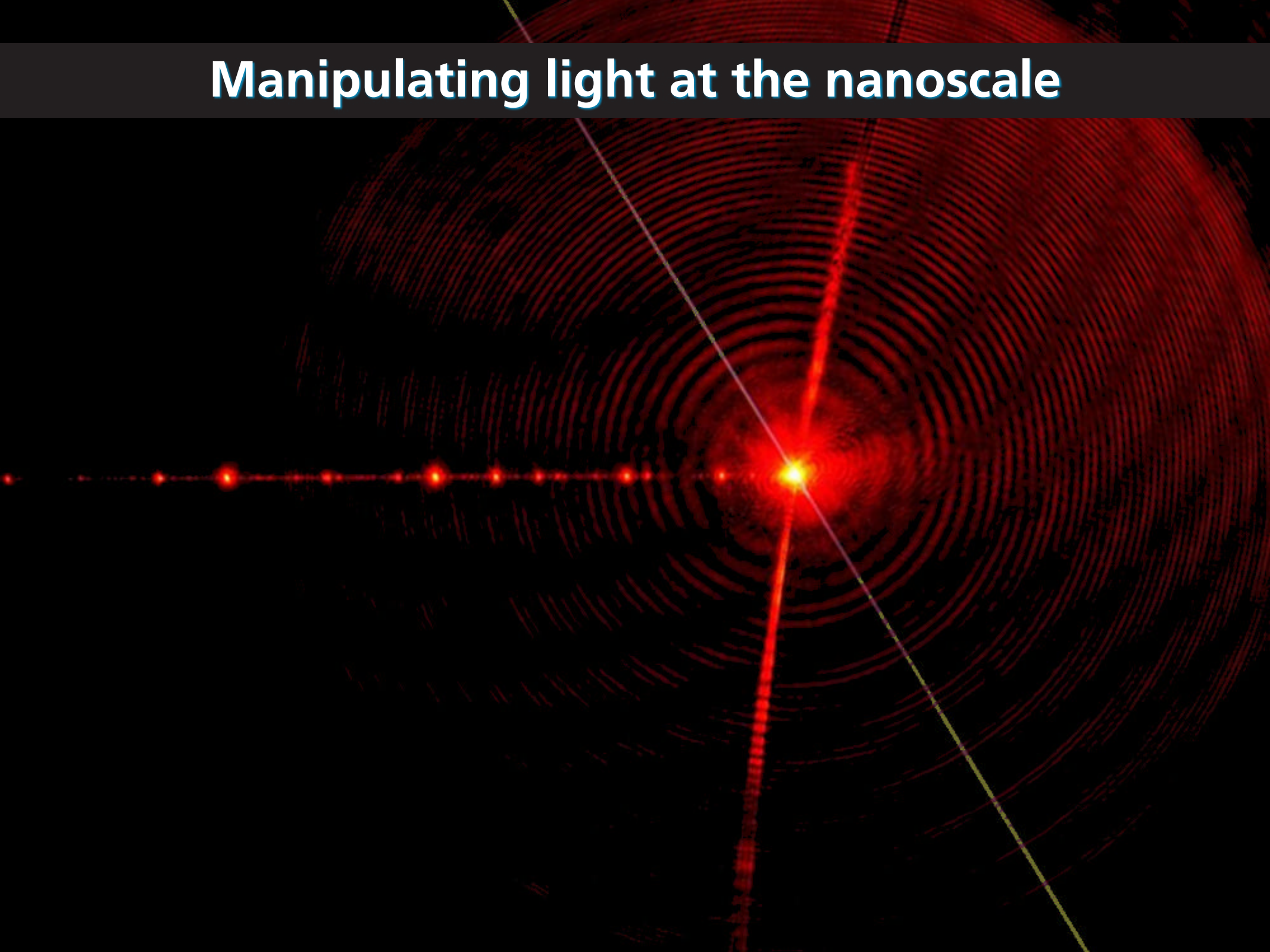
360 nm

A scanning electron microscope (SEM) image of a single nanowire. This nanowire is thicker than the one above, appearing as a more prominent dark line. It is oriented horizontally and shows some slight undulations.

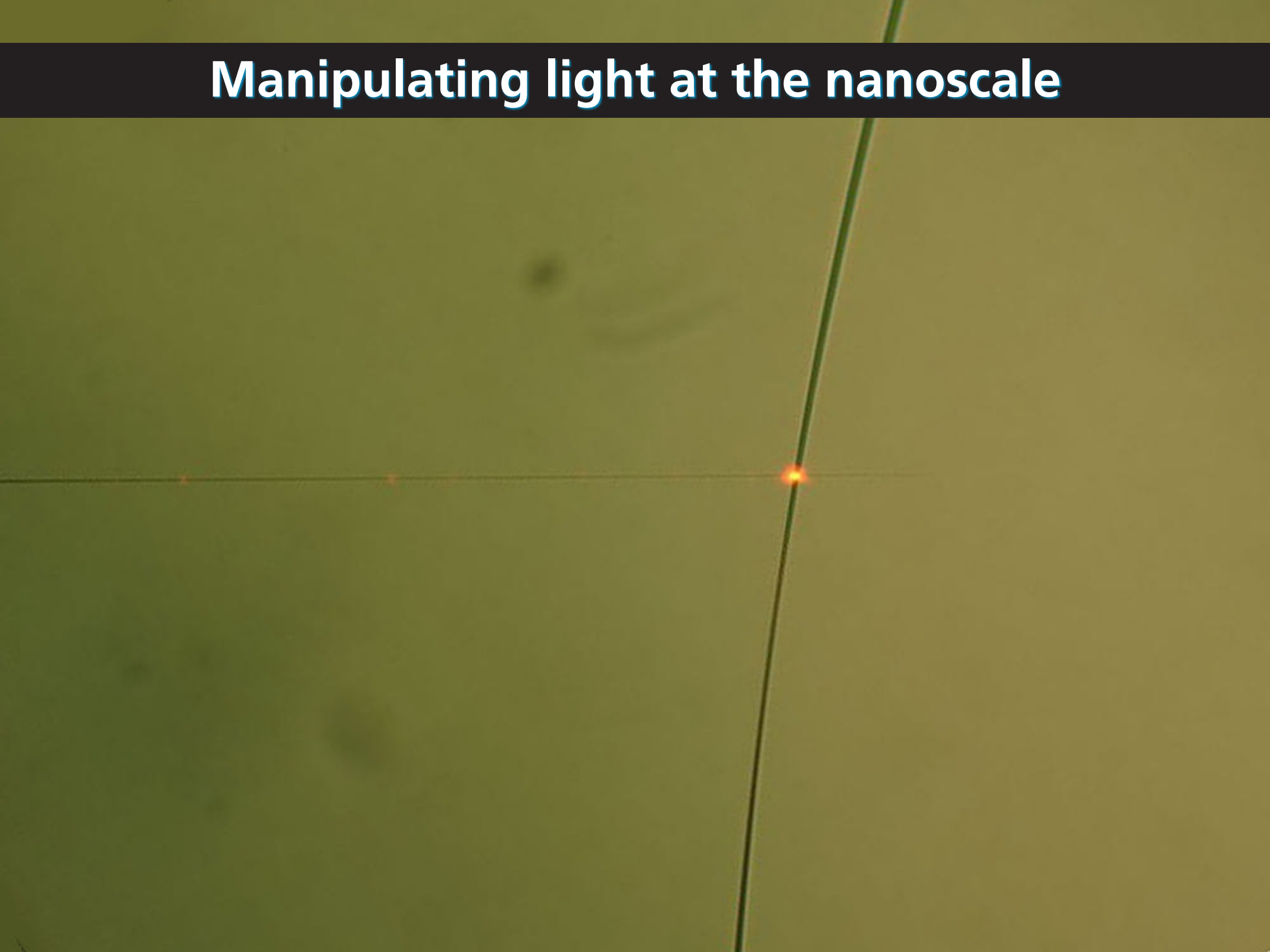
450 nm

A scanning electron microscope (SEM) image of a single nanowire. This nanowire is the thickest of the three, appearing as a very dark, wide line. It is oriented horizontally and shows some irregularities in its shape, including some small gaps or protrusions.

Manipulating light at the nanoscale

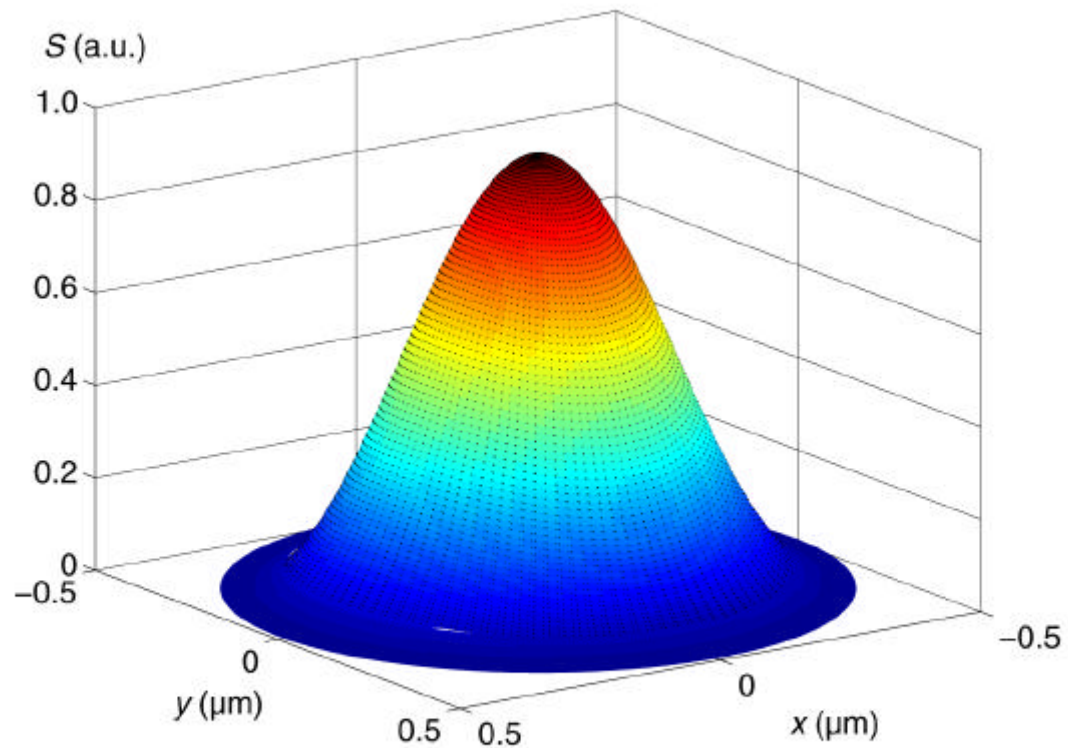


Manipulating light at the nanoscale



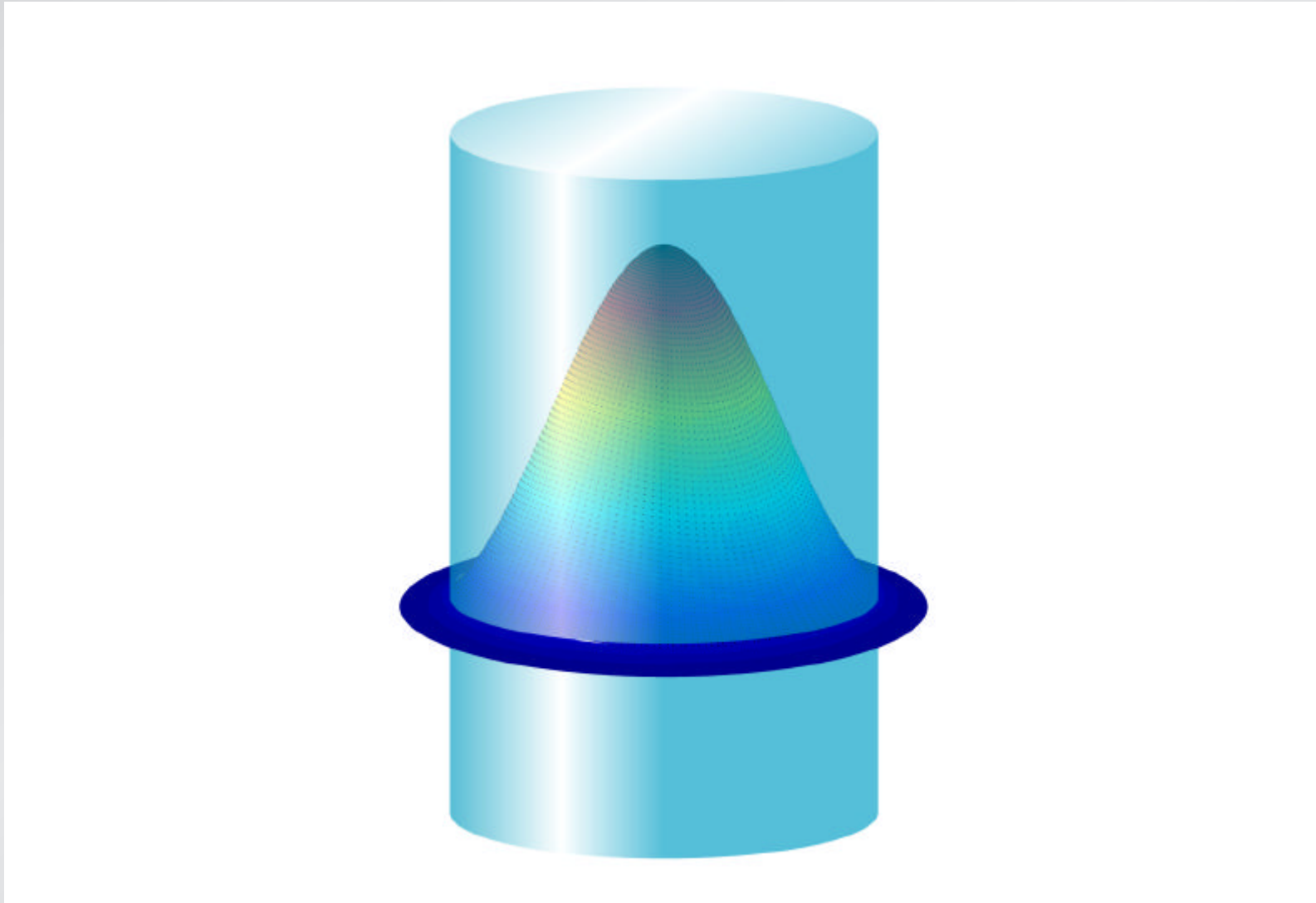
Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



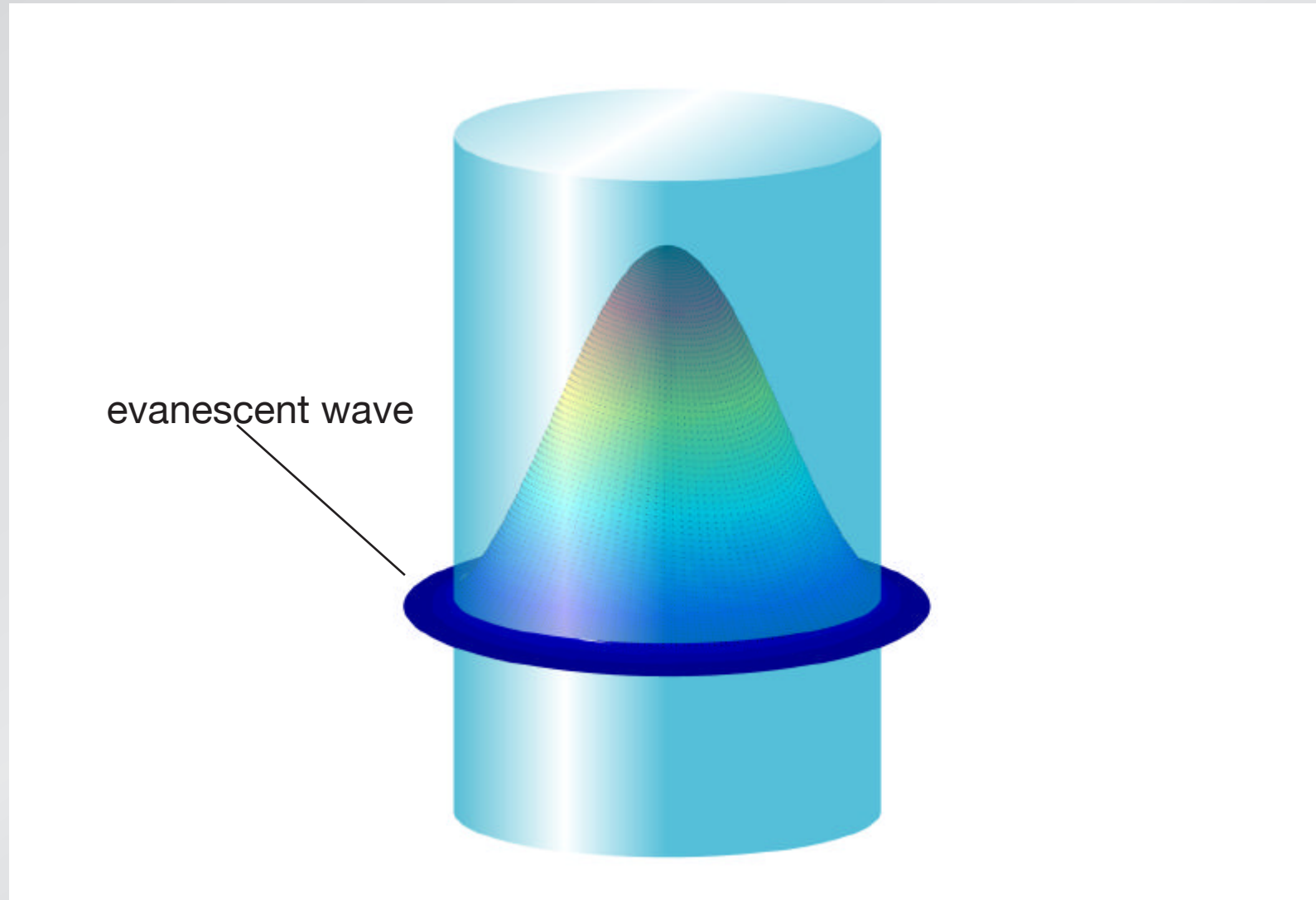
Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



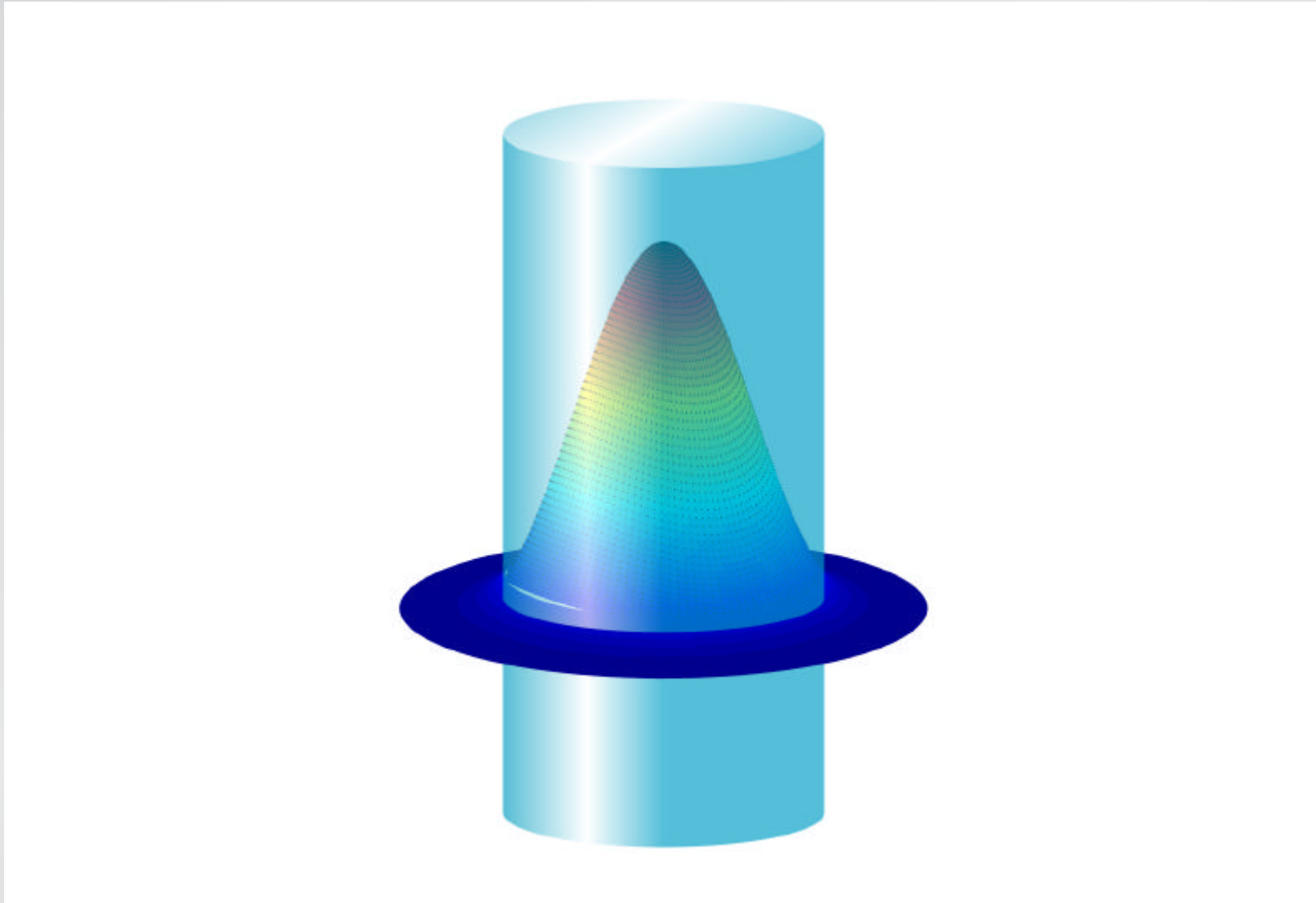
Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



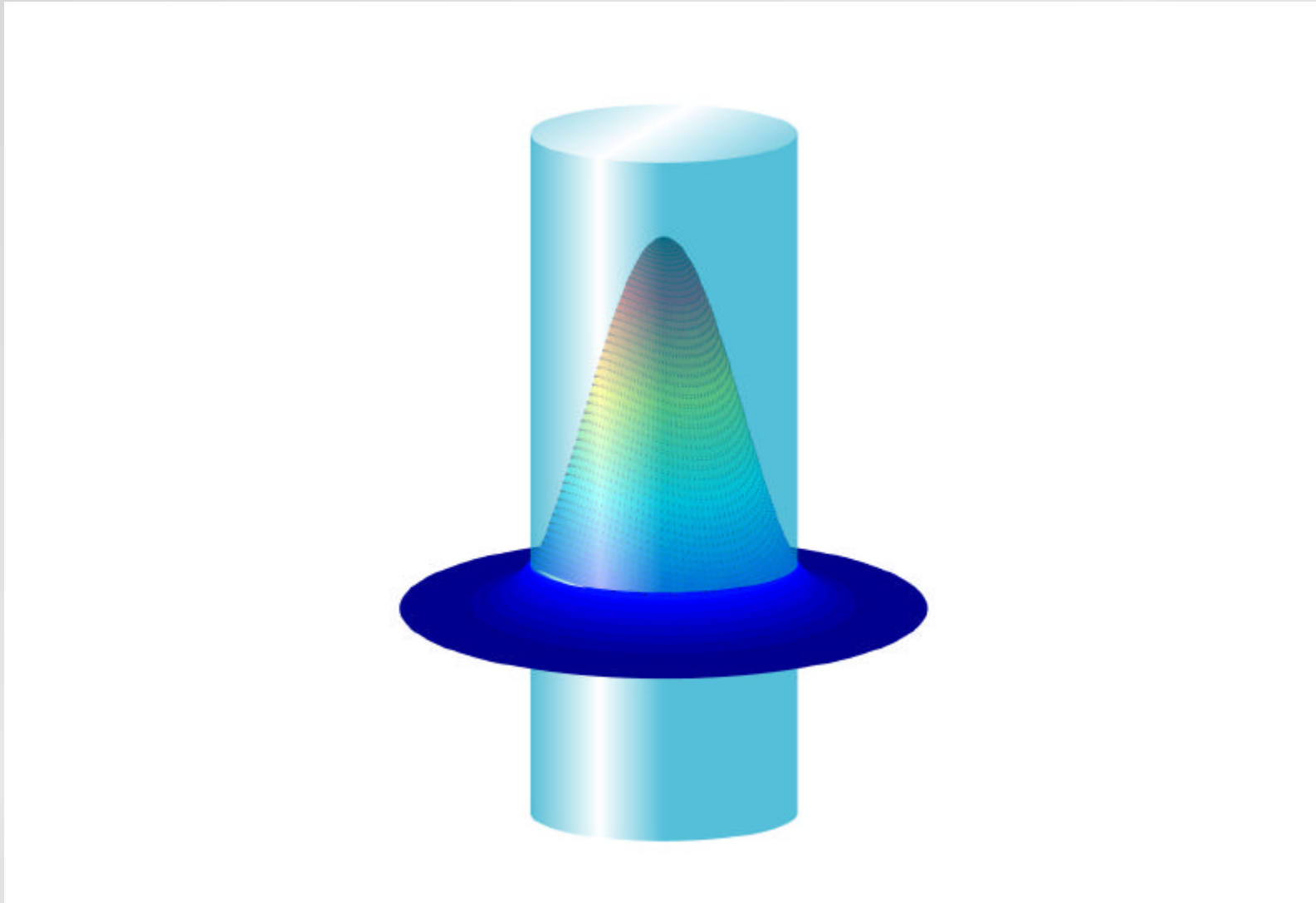
Manipulating light at the nanoscale

Poynting vector profile for 600-nm nanowire



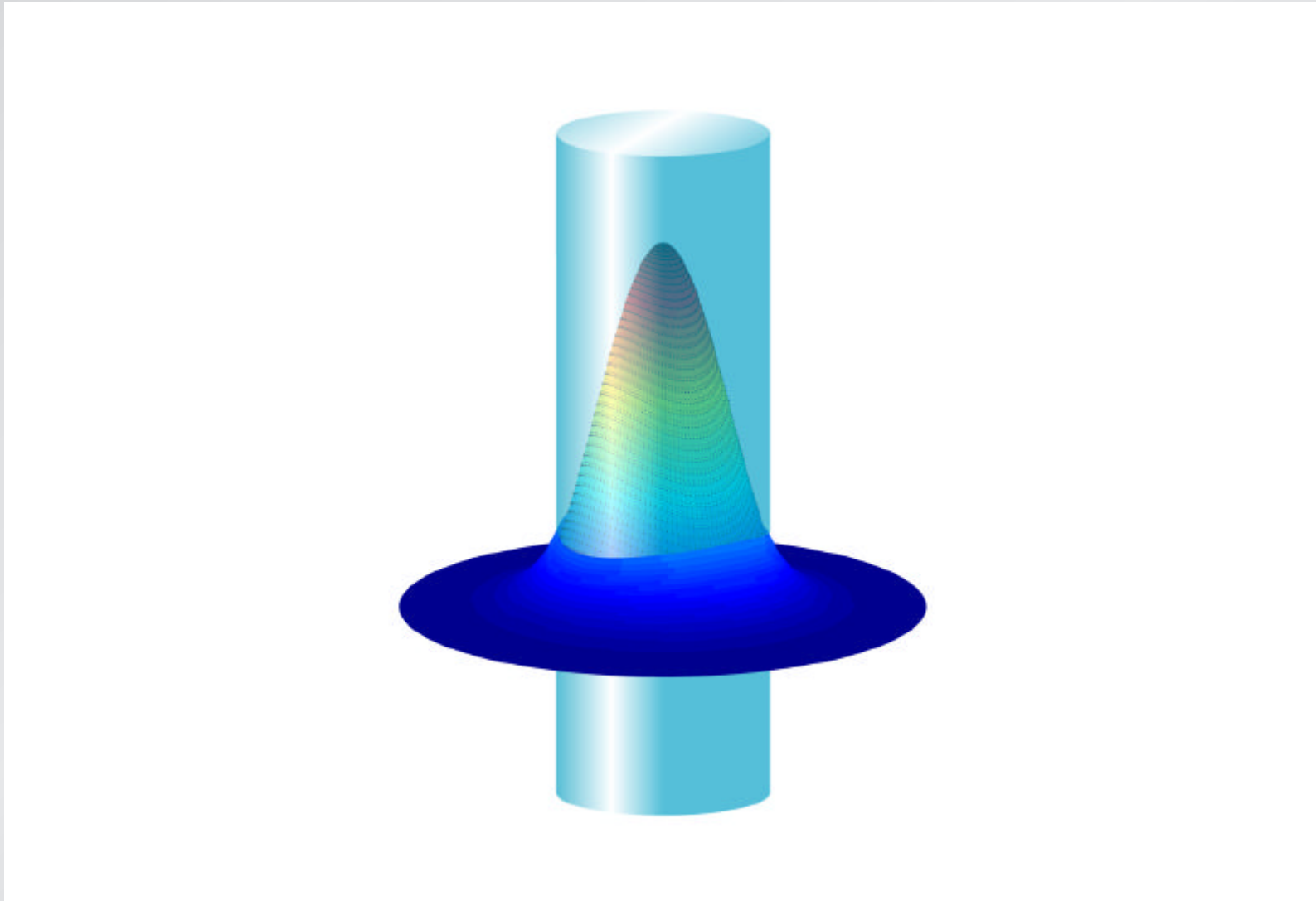
Manipulating light at the nanoscale

Poynting vector profile for 500-nm nanowire



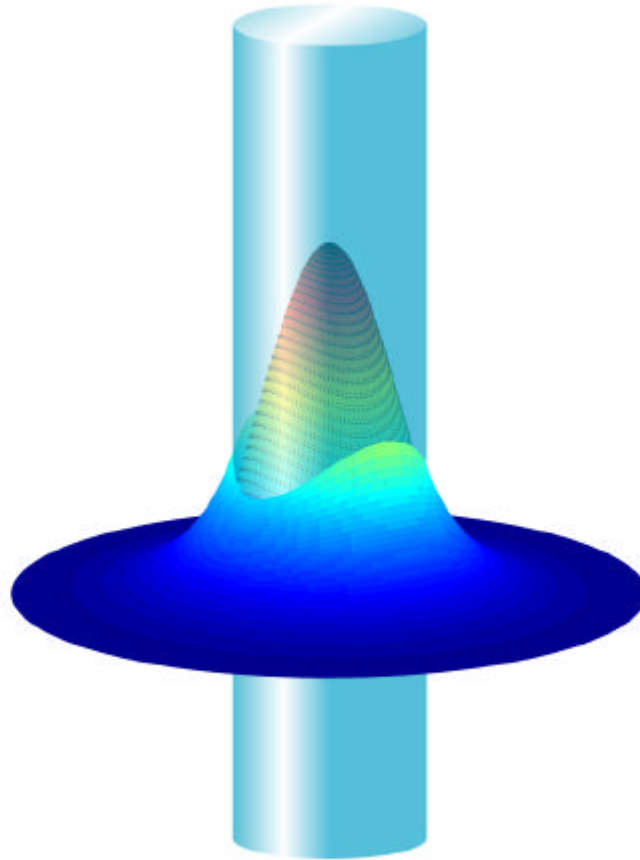
Manipulating light at the nanoscale

Poynting vector profile for 400-nm nanowire



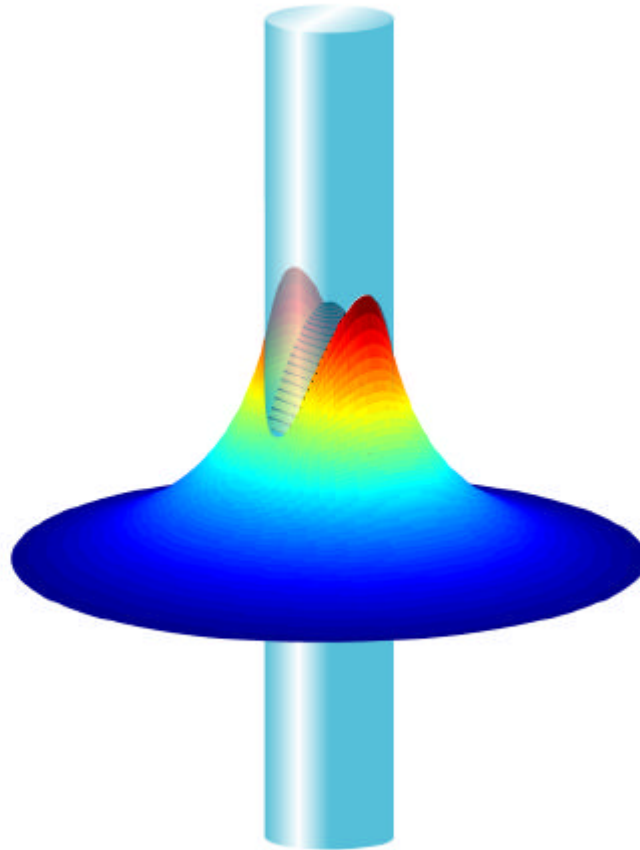
Manipulating light at the nanoscale

Poynting vector profile for 300-nm nanowire



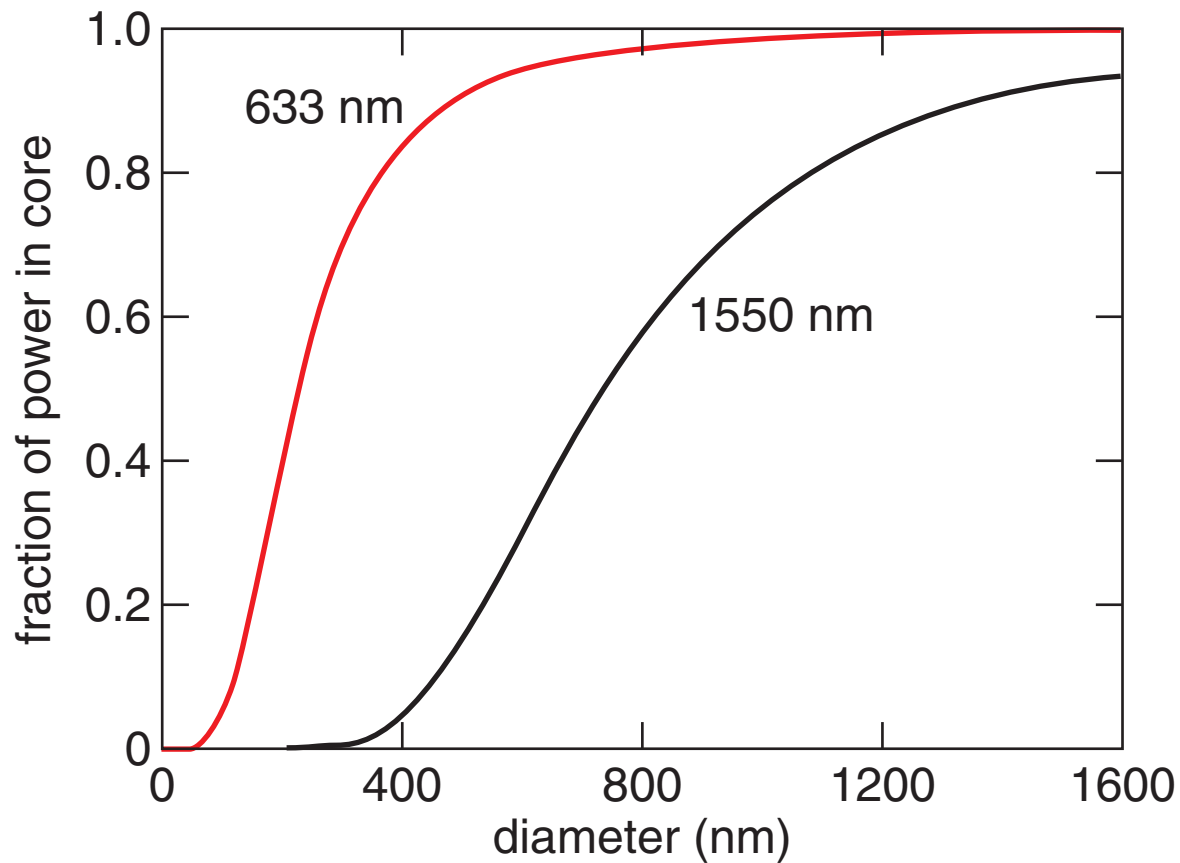
Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



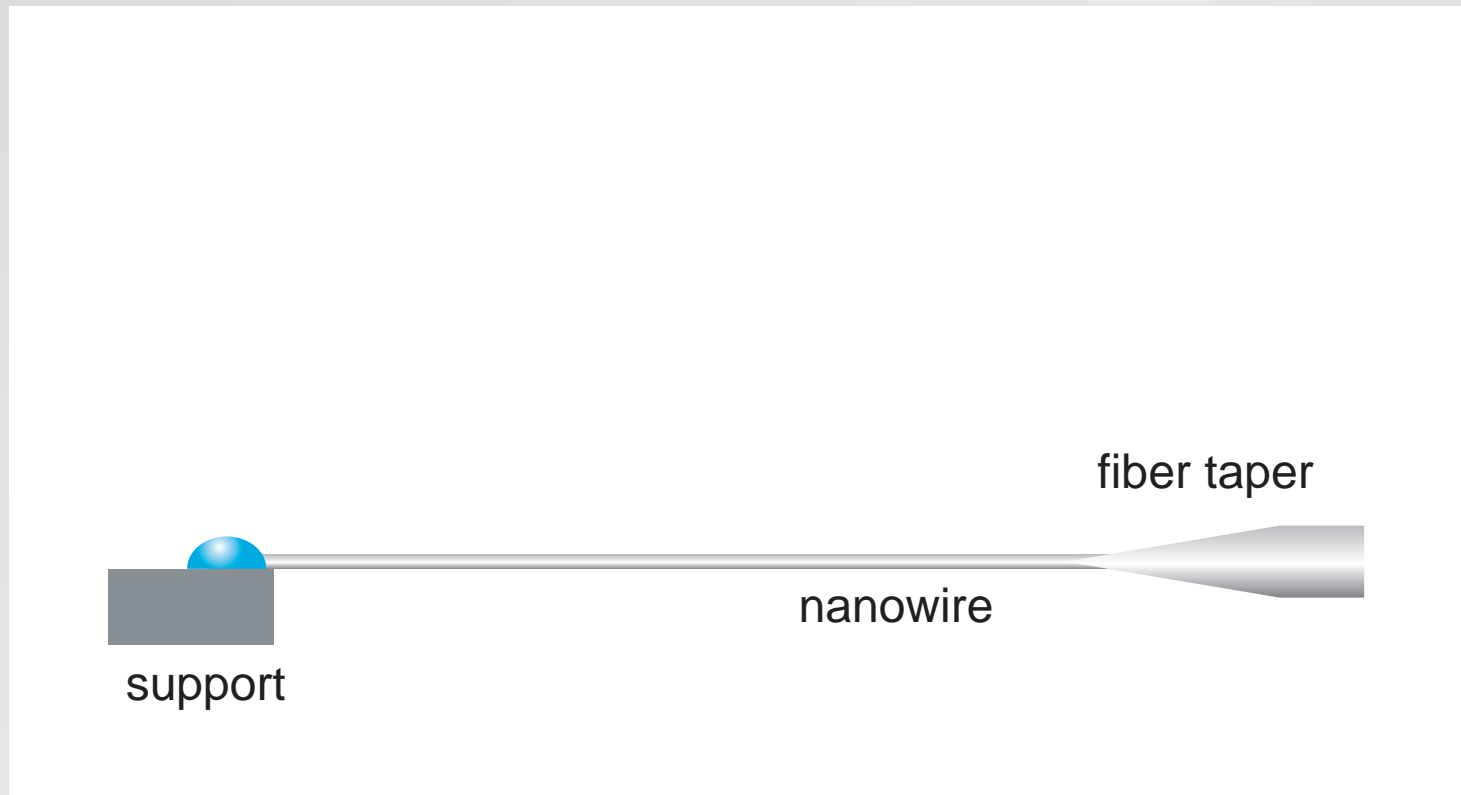
Manipulating light at the nanoscale

fraction of power carried in core



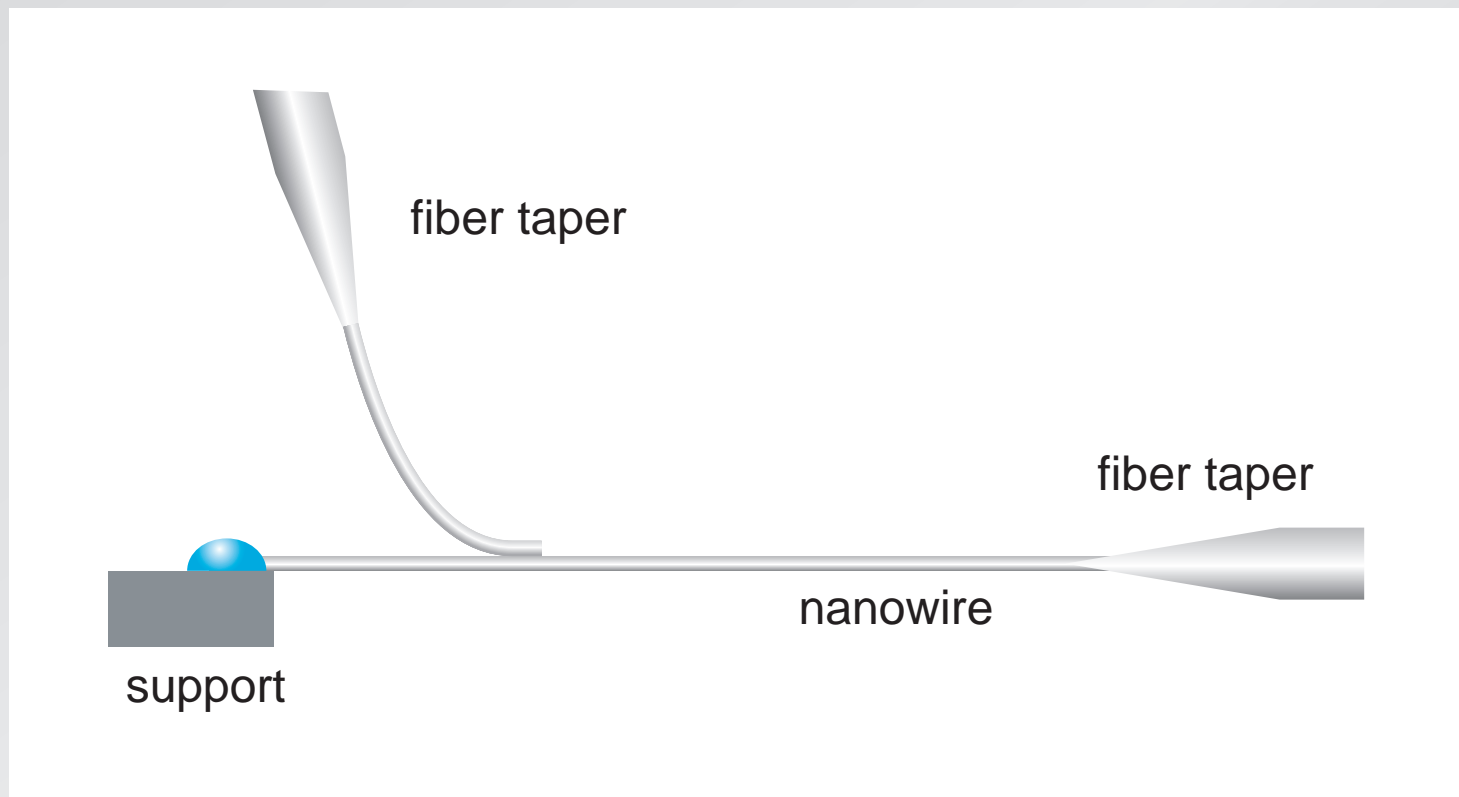
Manipulating light at the nanoscale

coupling light between nanowires



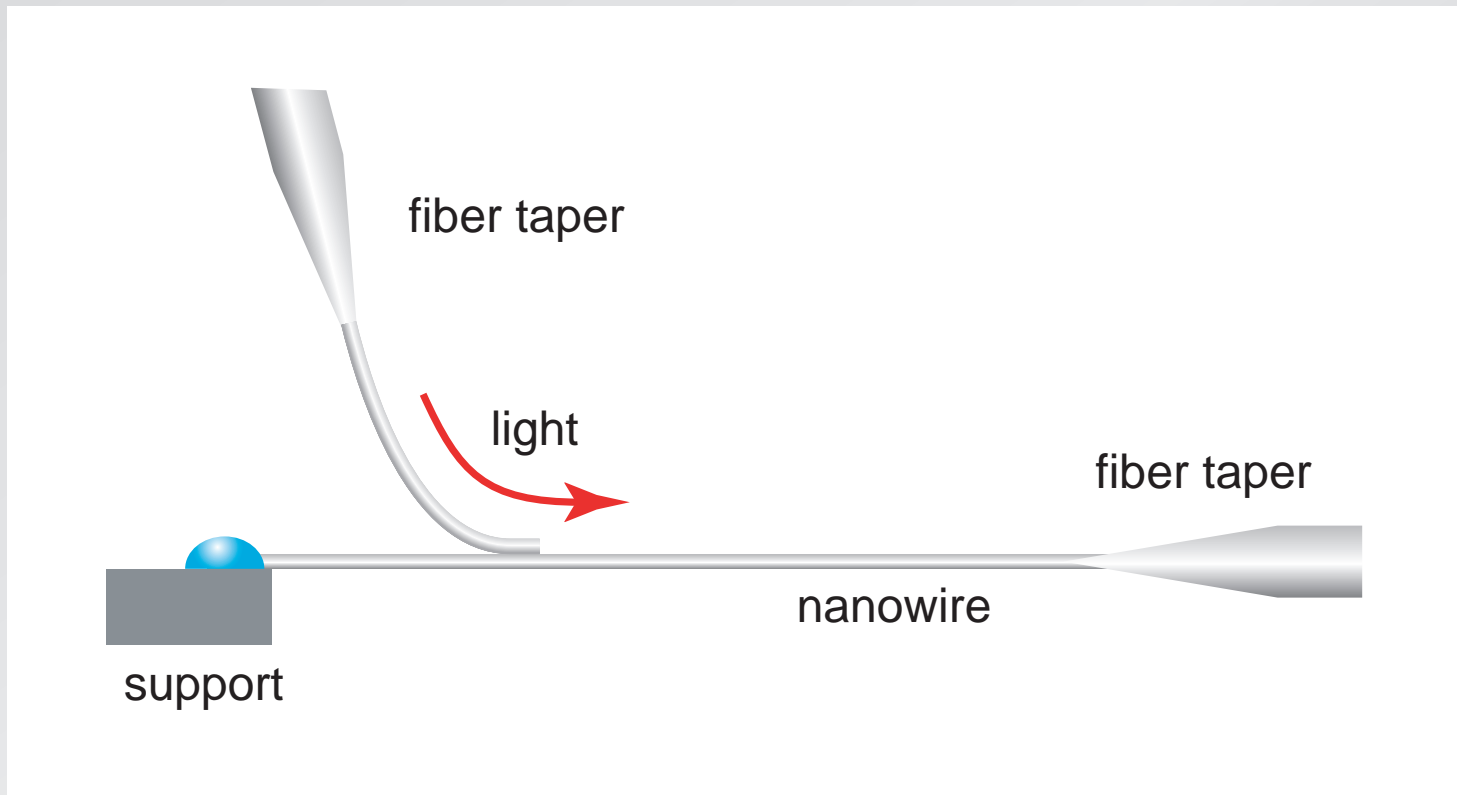
Manipulating light at the nanoscale

coupling light between nanowires

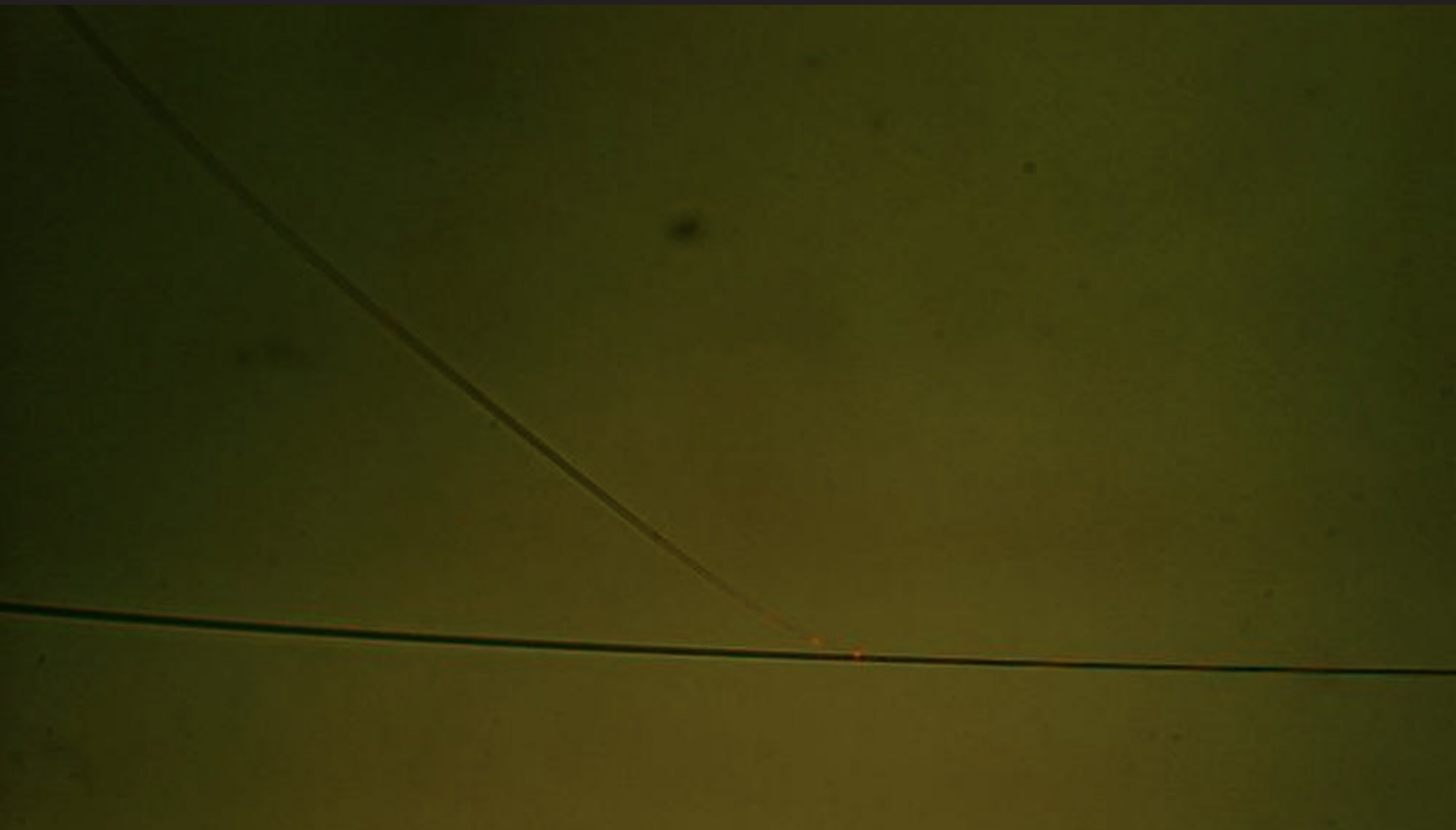


Manipulating light at the nanoscale

coupling light between nanowires



Manipulating light at the nanoscale



50 μm

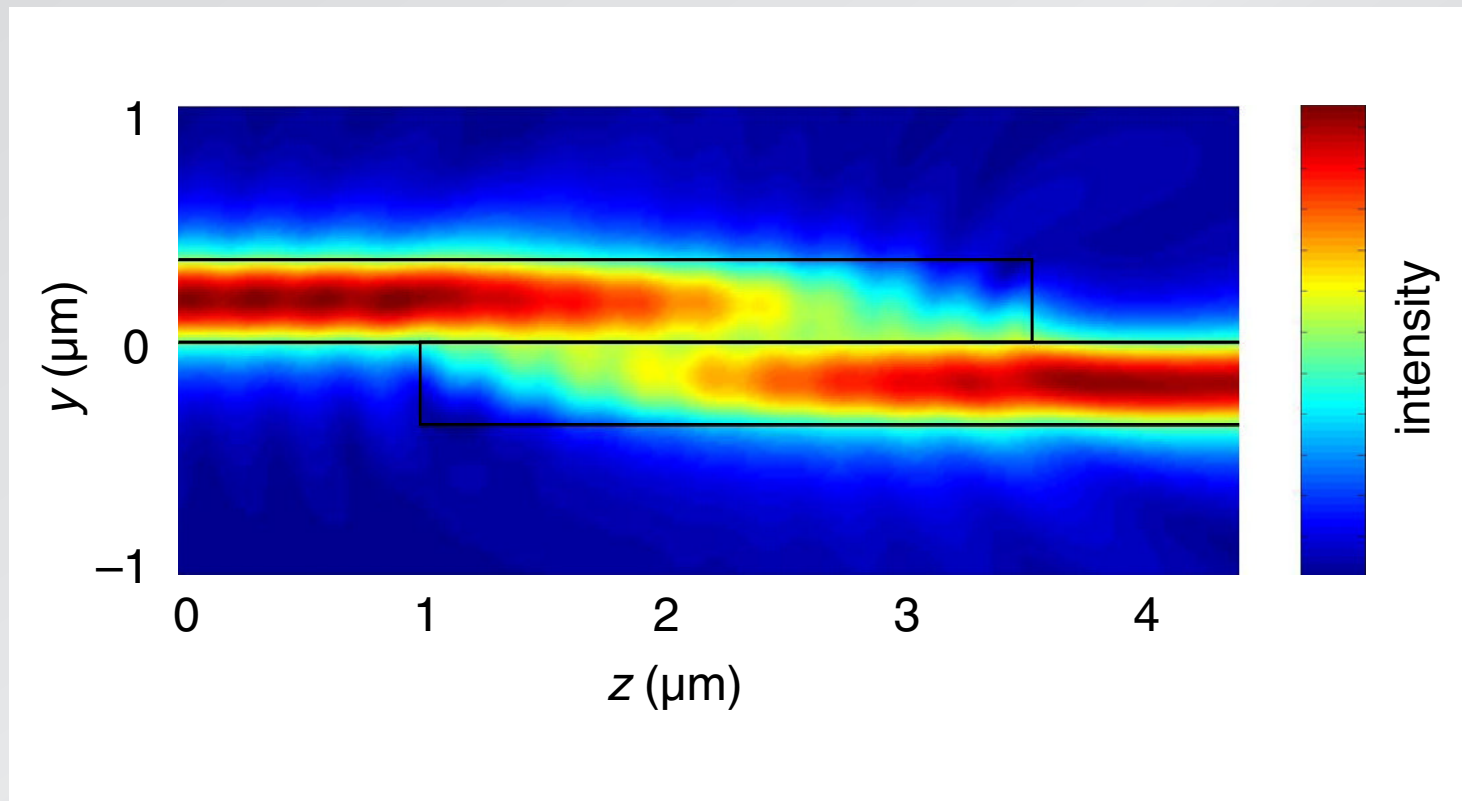
Manipulating light at the nanoscale



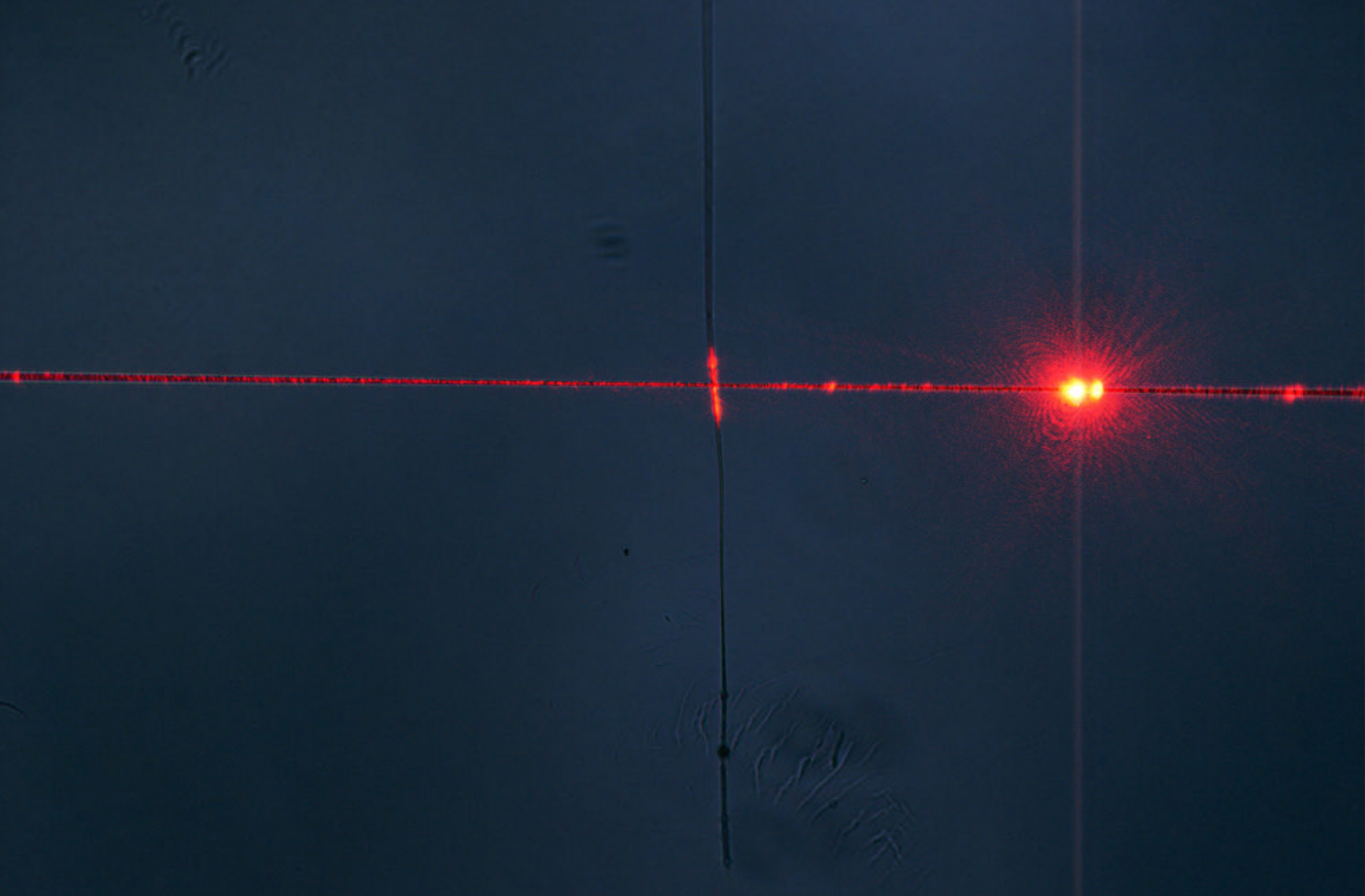
50 μm

Manipulating light at the nanoscale

intensity distribution

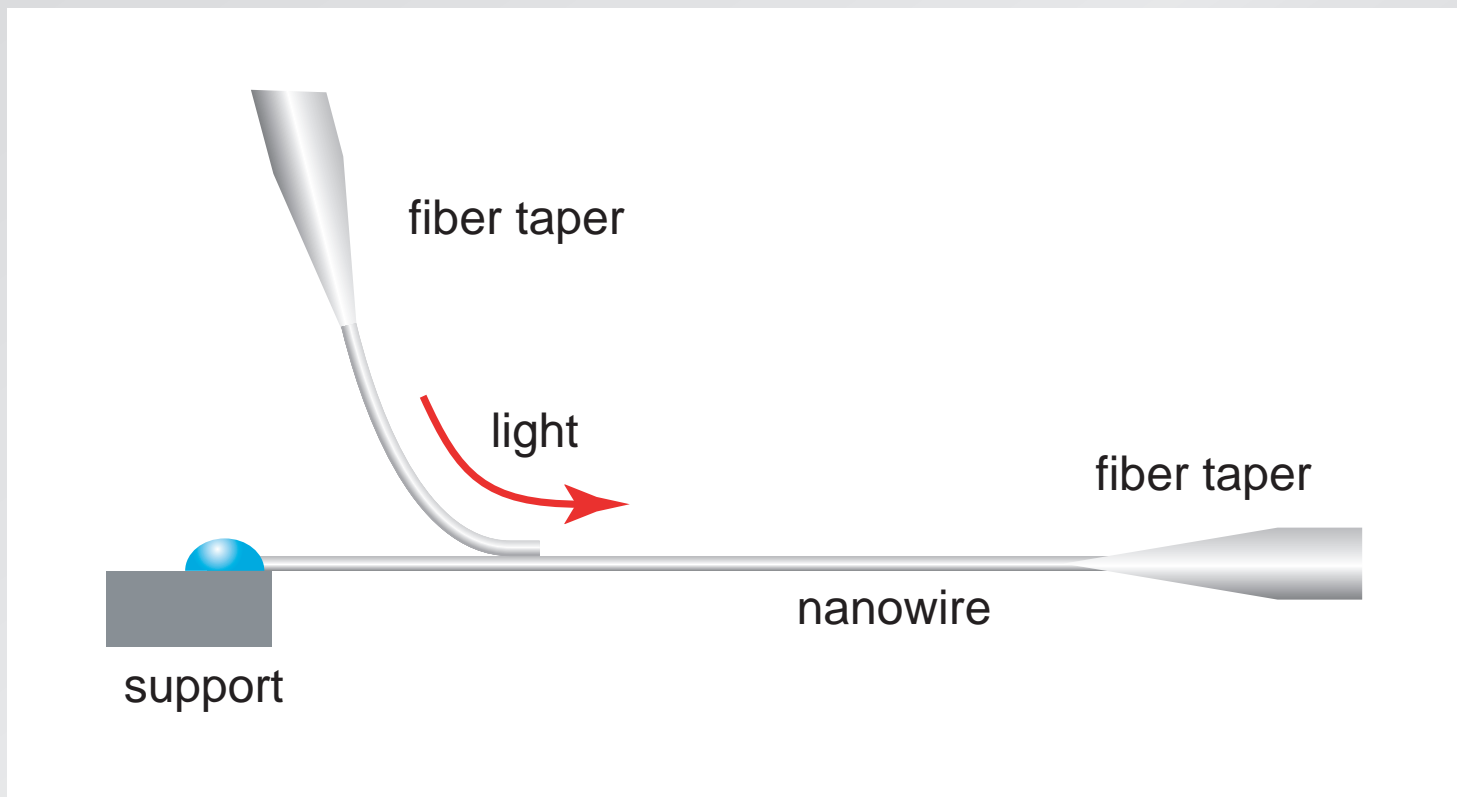


Manipulating light at the nanoscale



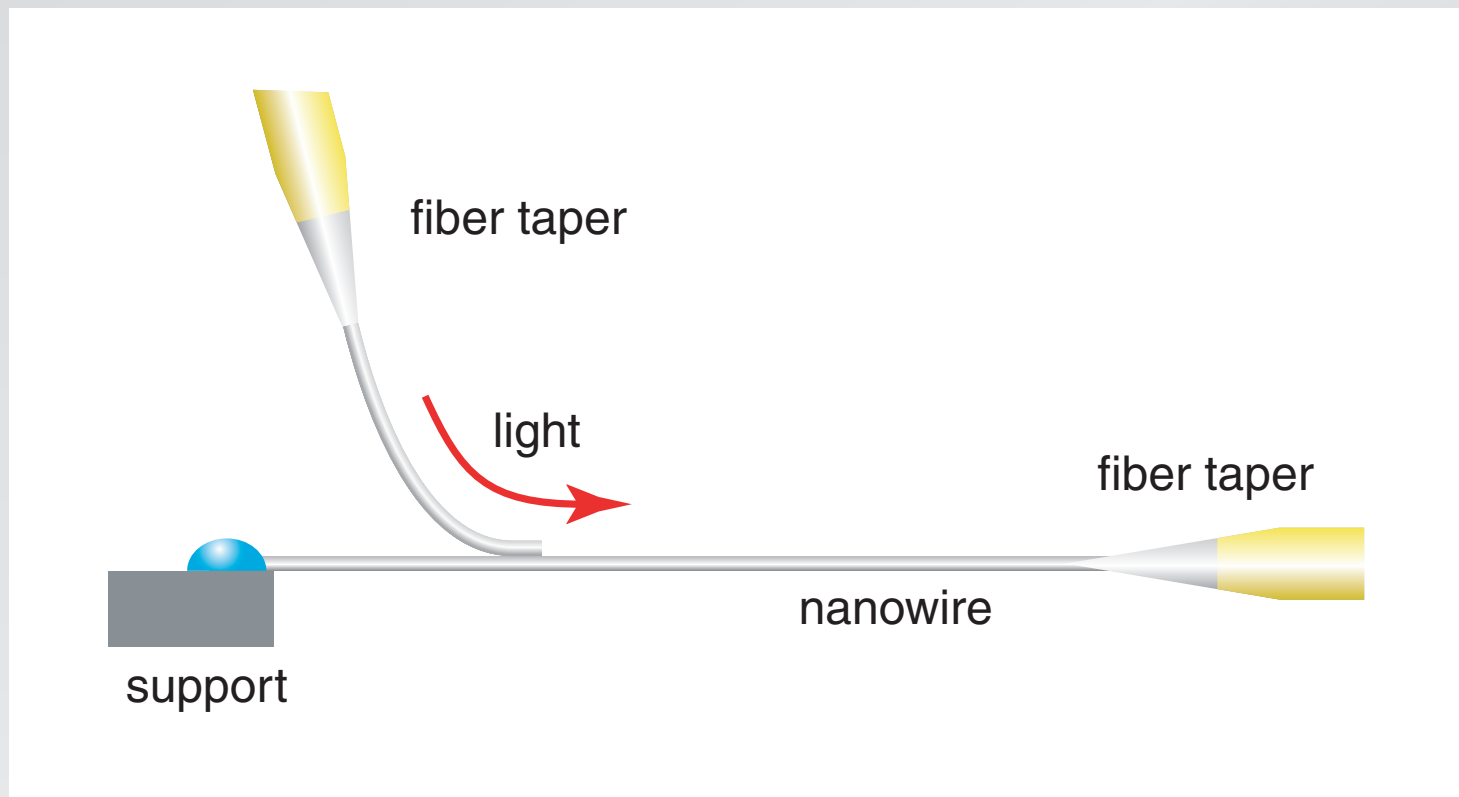
Manipulating light at the nanoscale

loss measurement



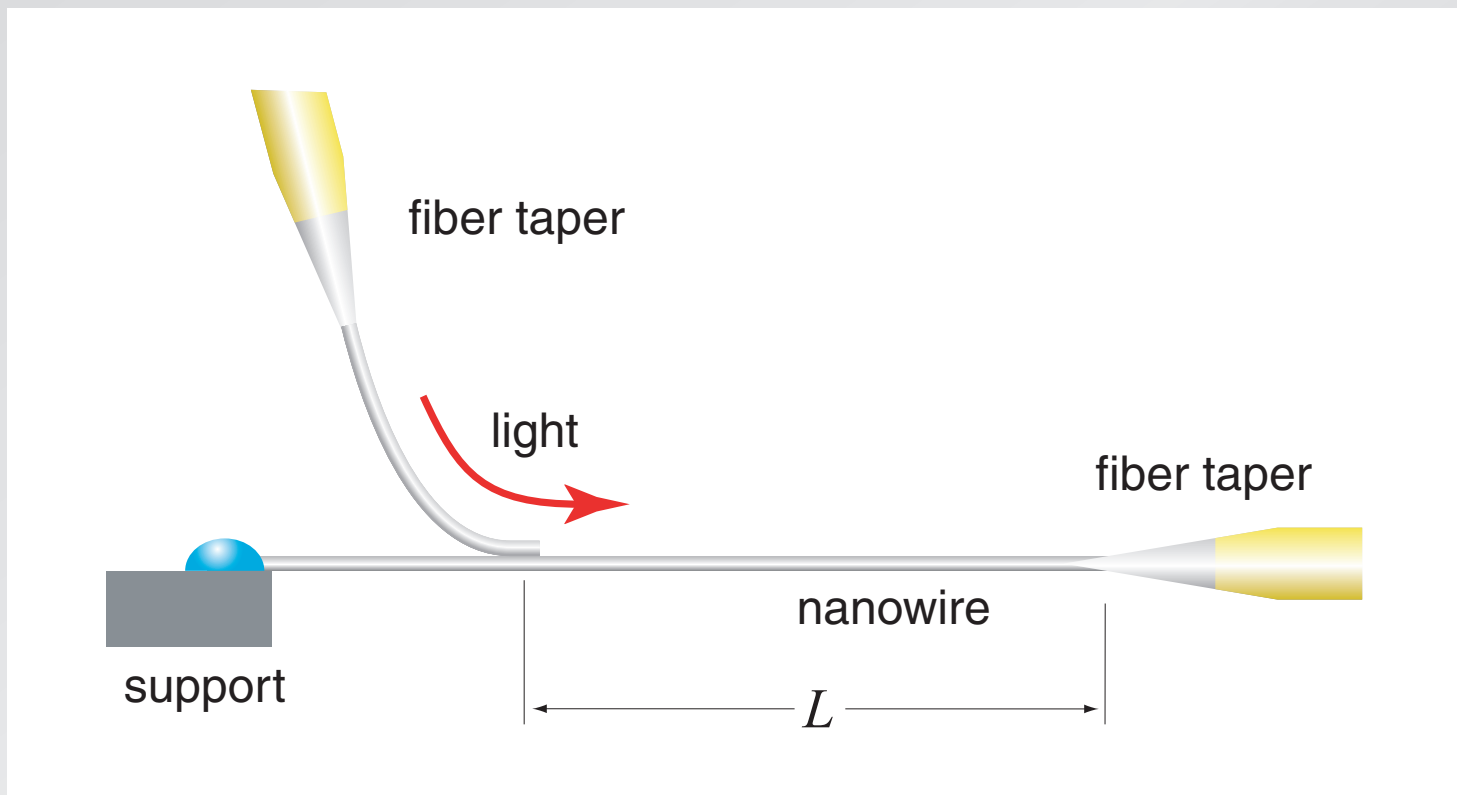
Manipulating light at the nanoscale

loss measurement



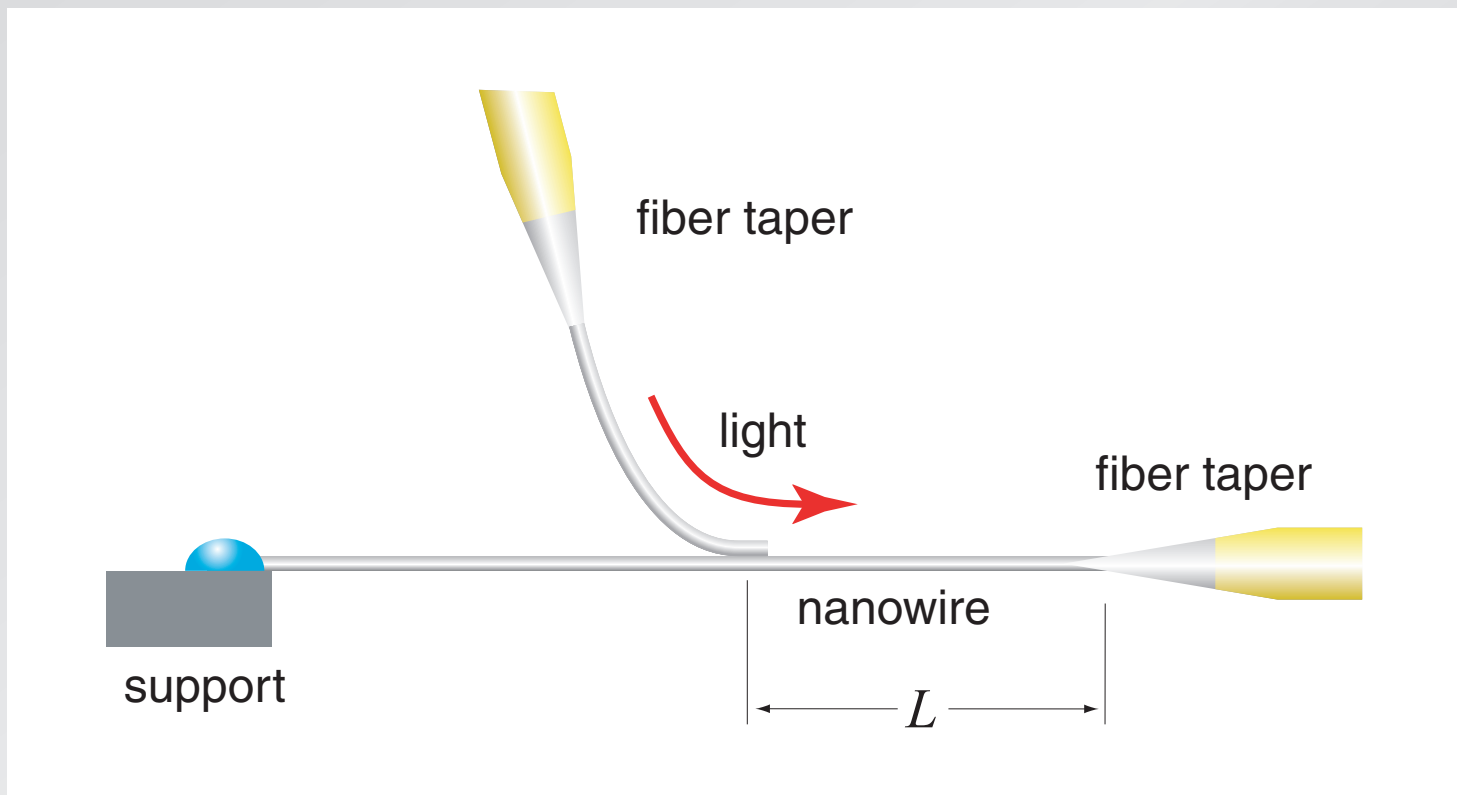
Manipulating light at the nanoscale

loss measurement



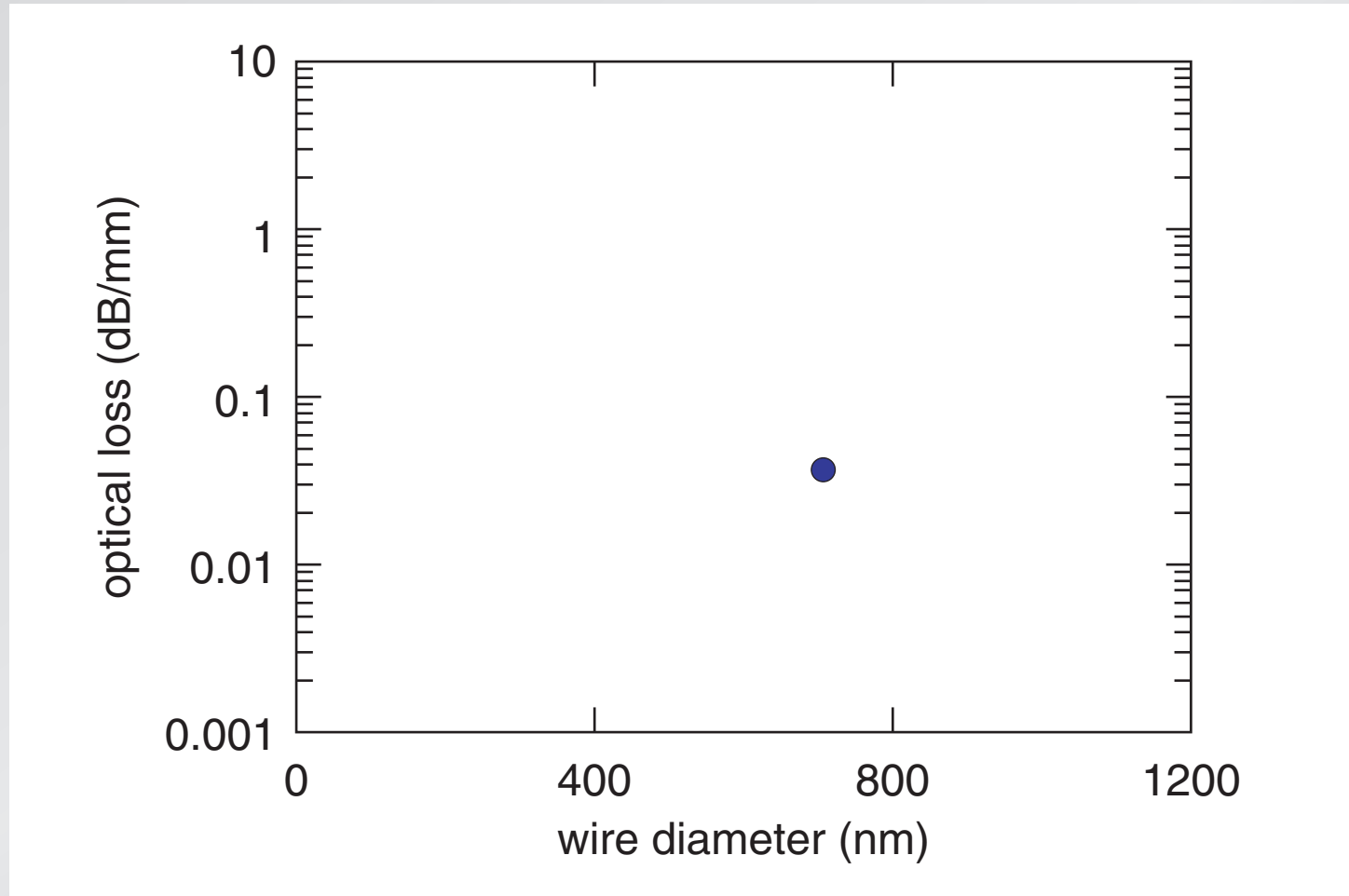
Manipulating light at the nanoscale

loss measurement



Manipulating light at the nanoscale

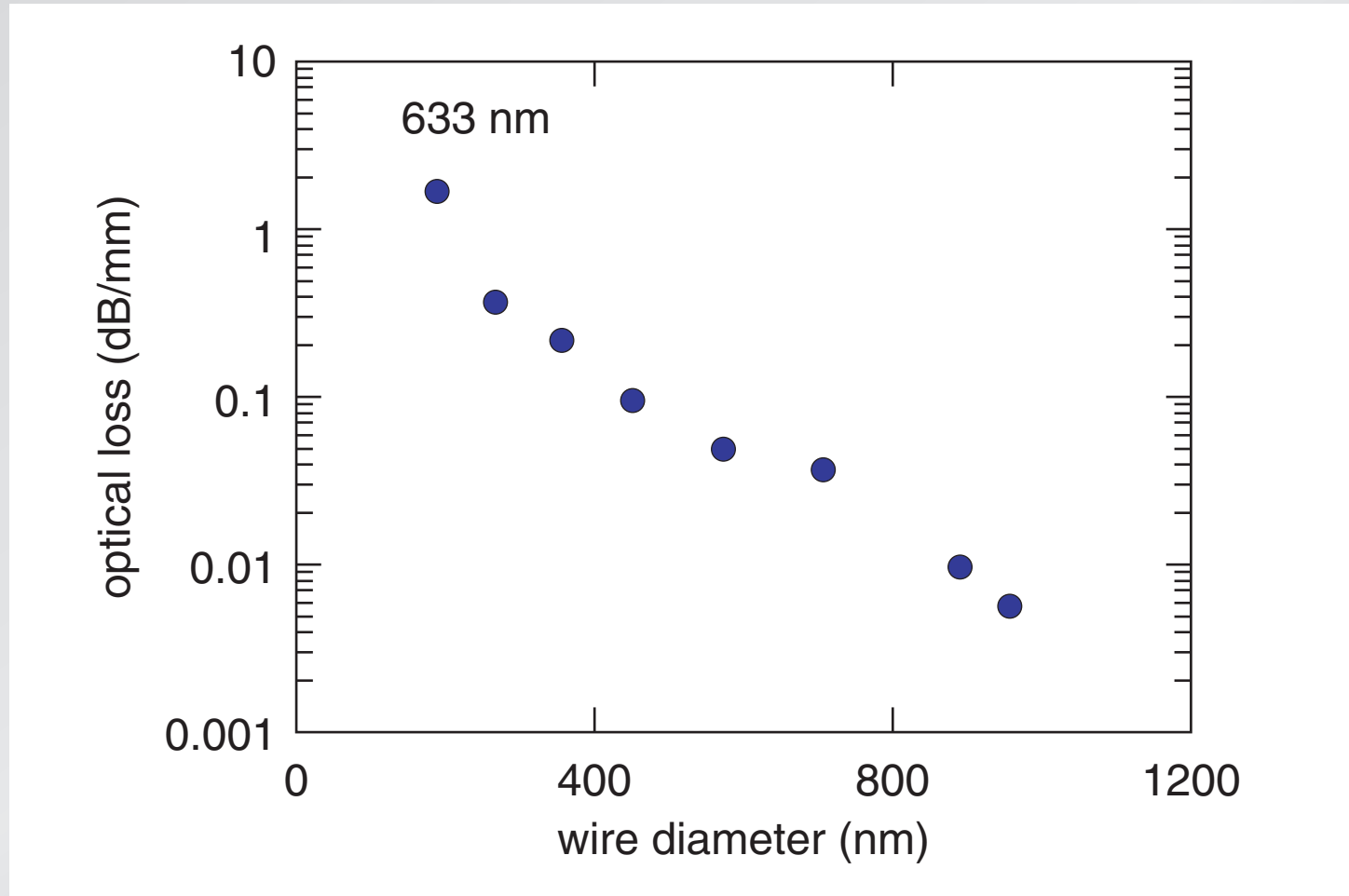
loss measurement



Nature, 426, 816 (2003)

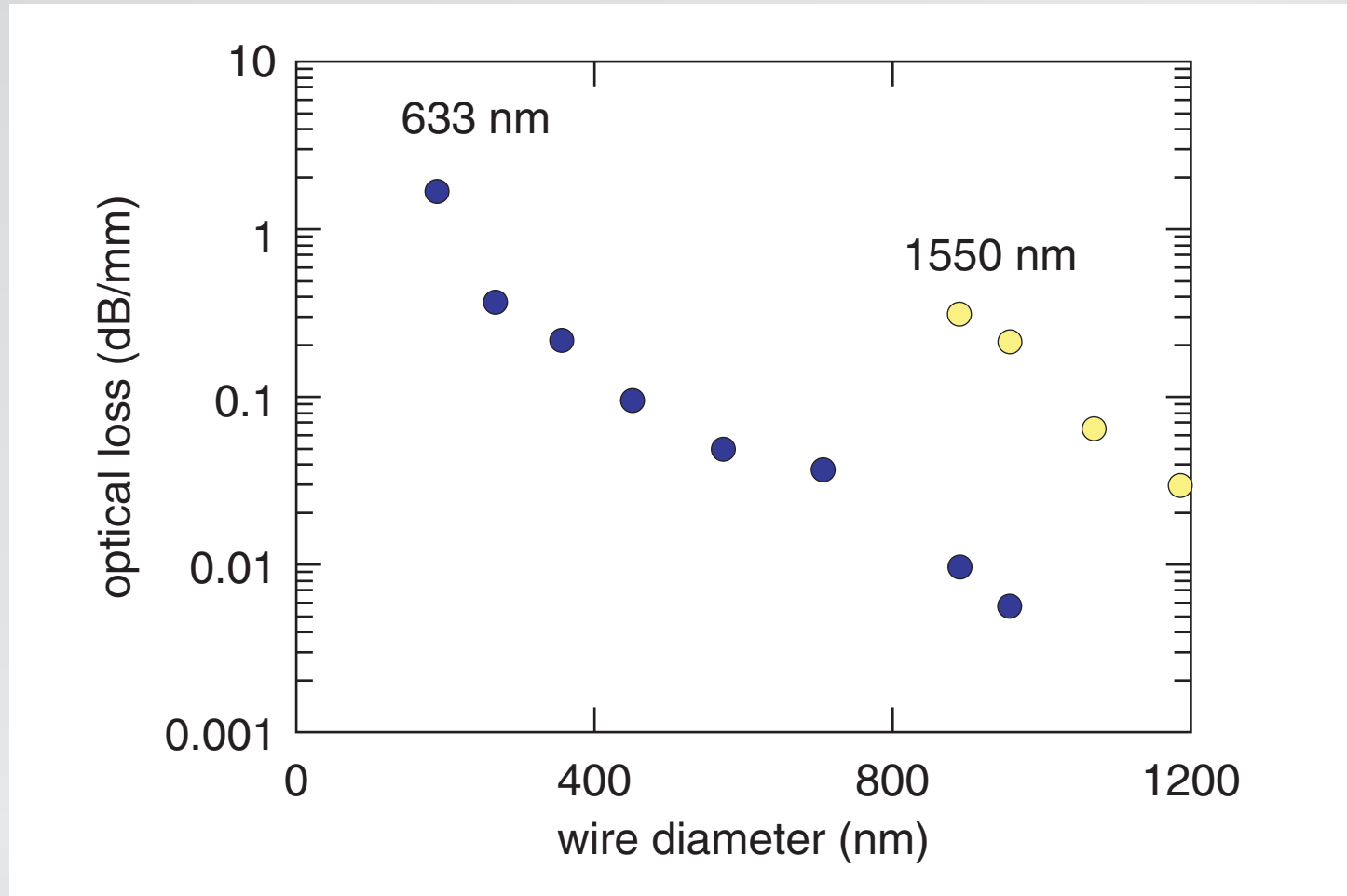
Manipulating light at the nanoscale

loss measurement



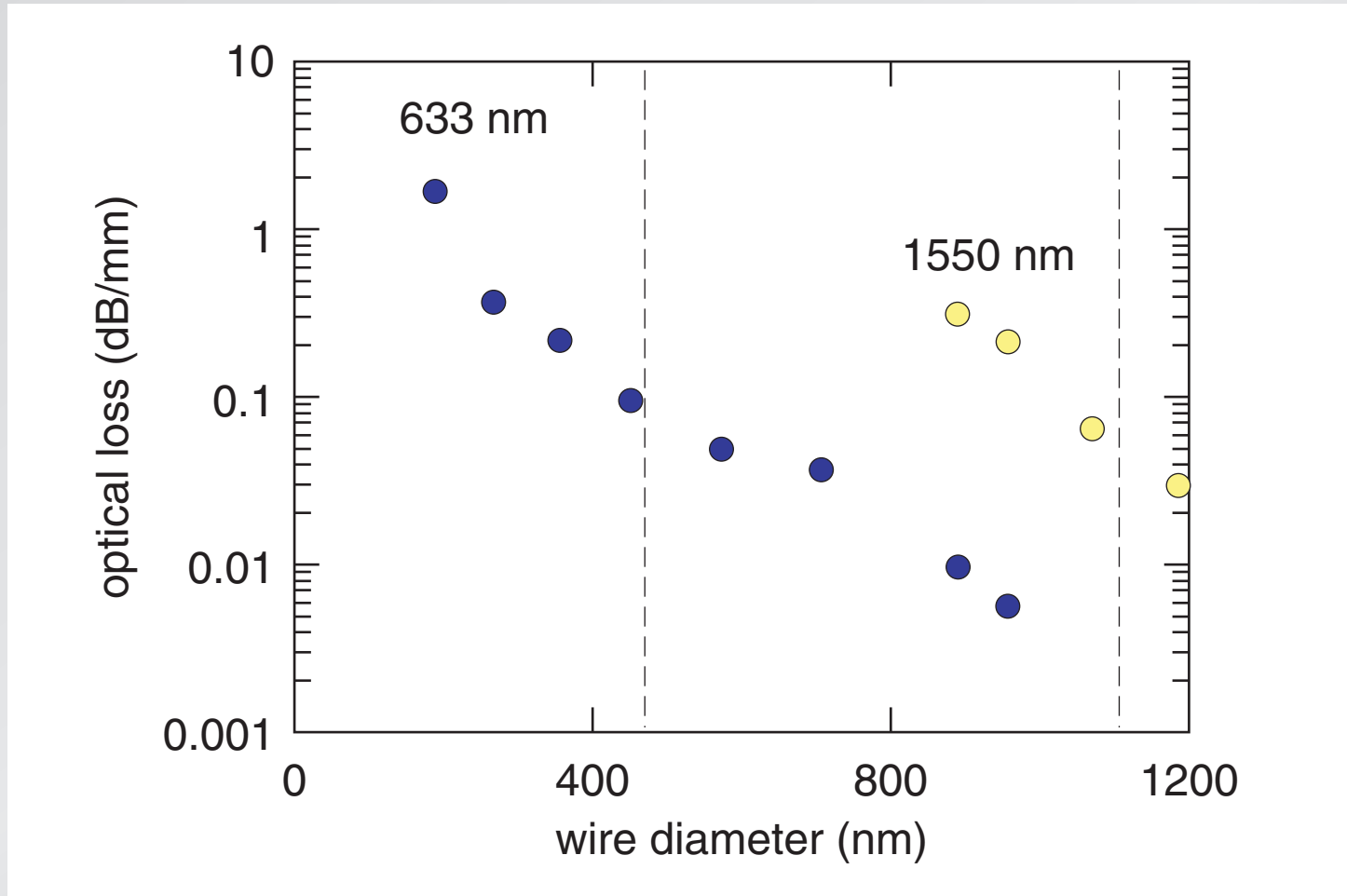
Manipulating light at the nanoscale

loss measurement

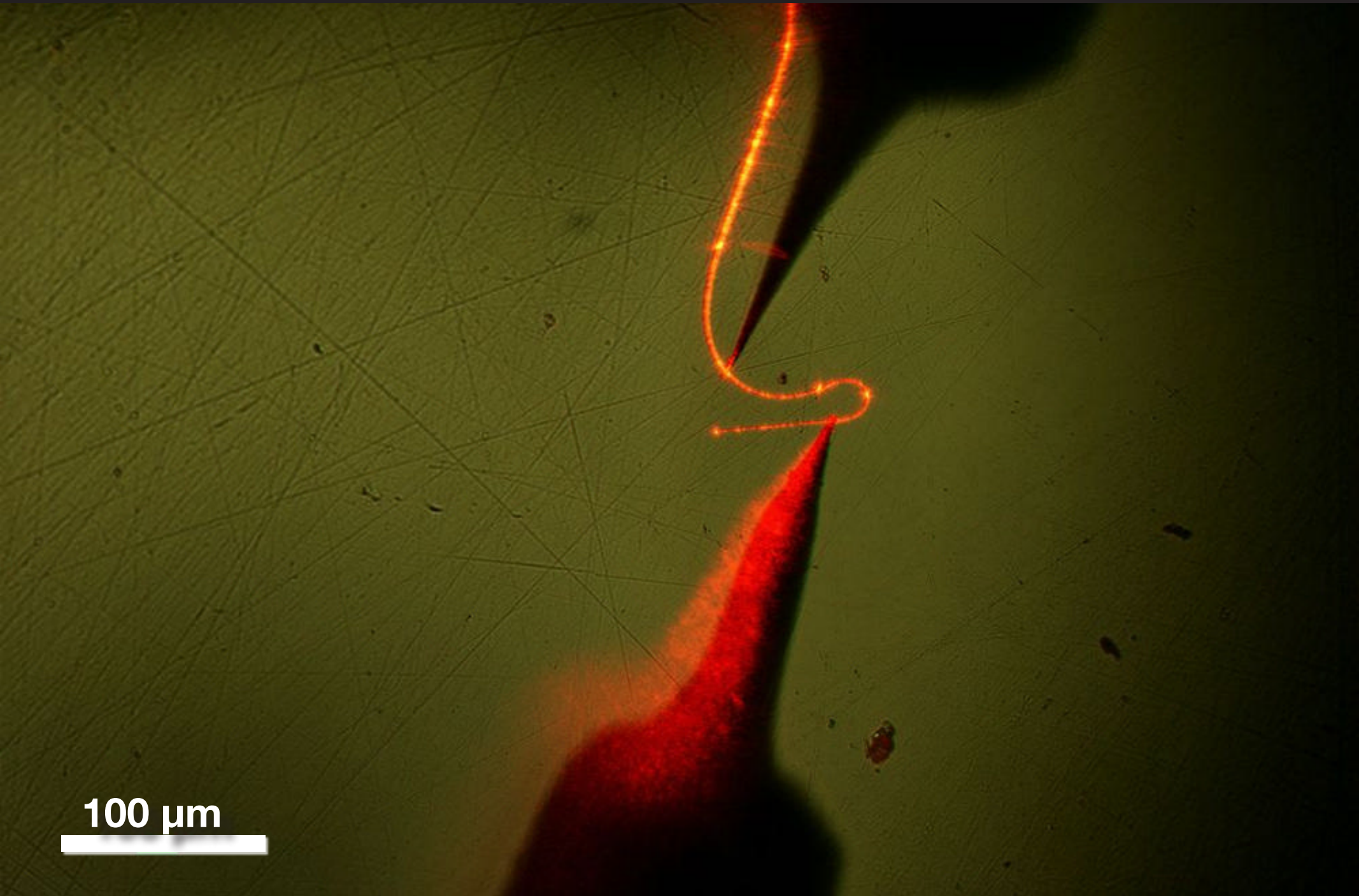


Manipulating light at the nanoscale

loss at single-mode diameter < 0.1 dB/mm

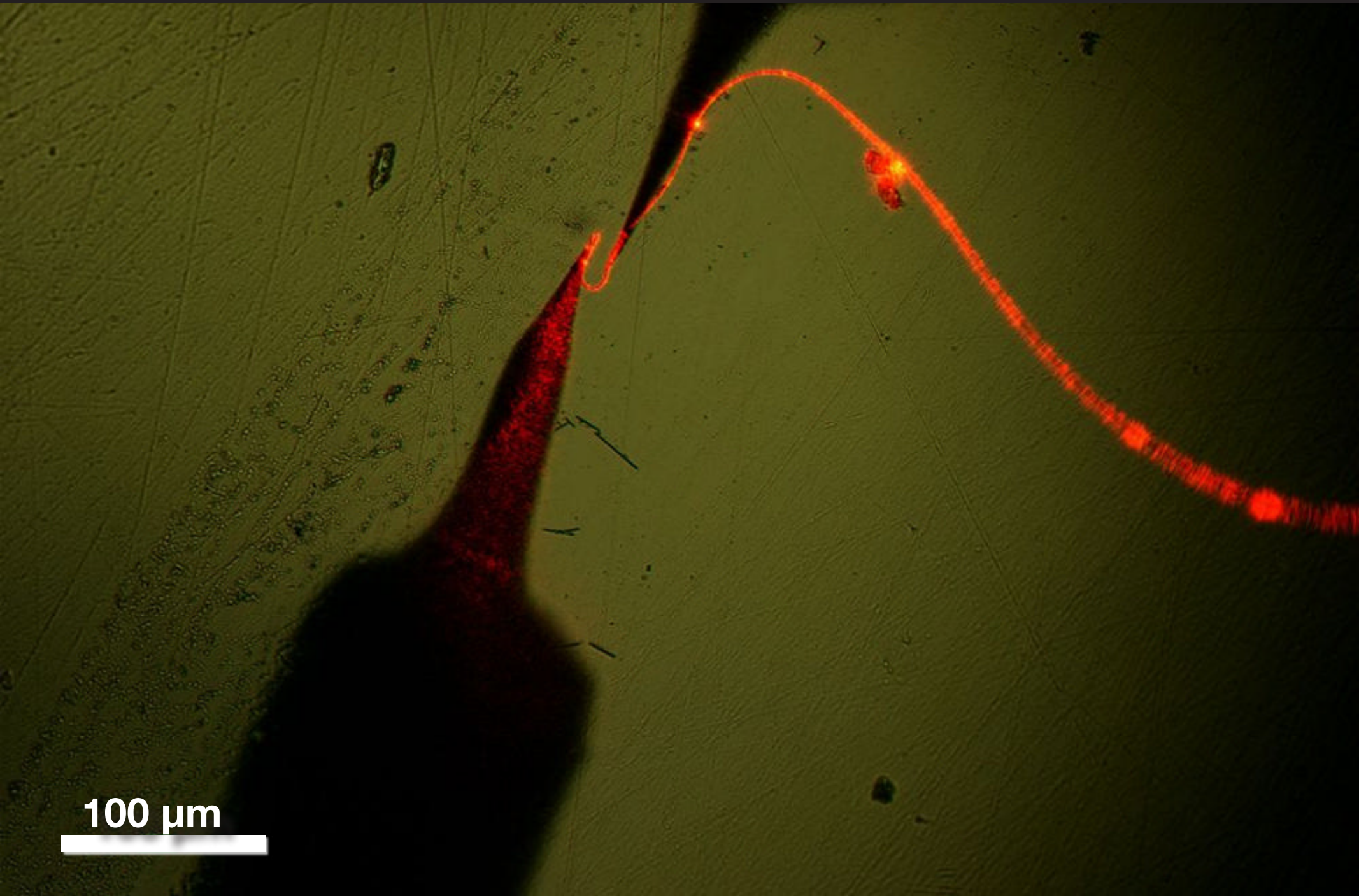


Manipulating light at the nanoscale



100 μm

Manipulating light at the nanoscale

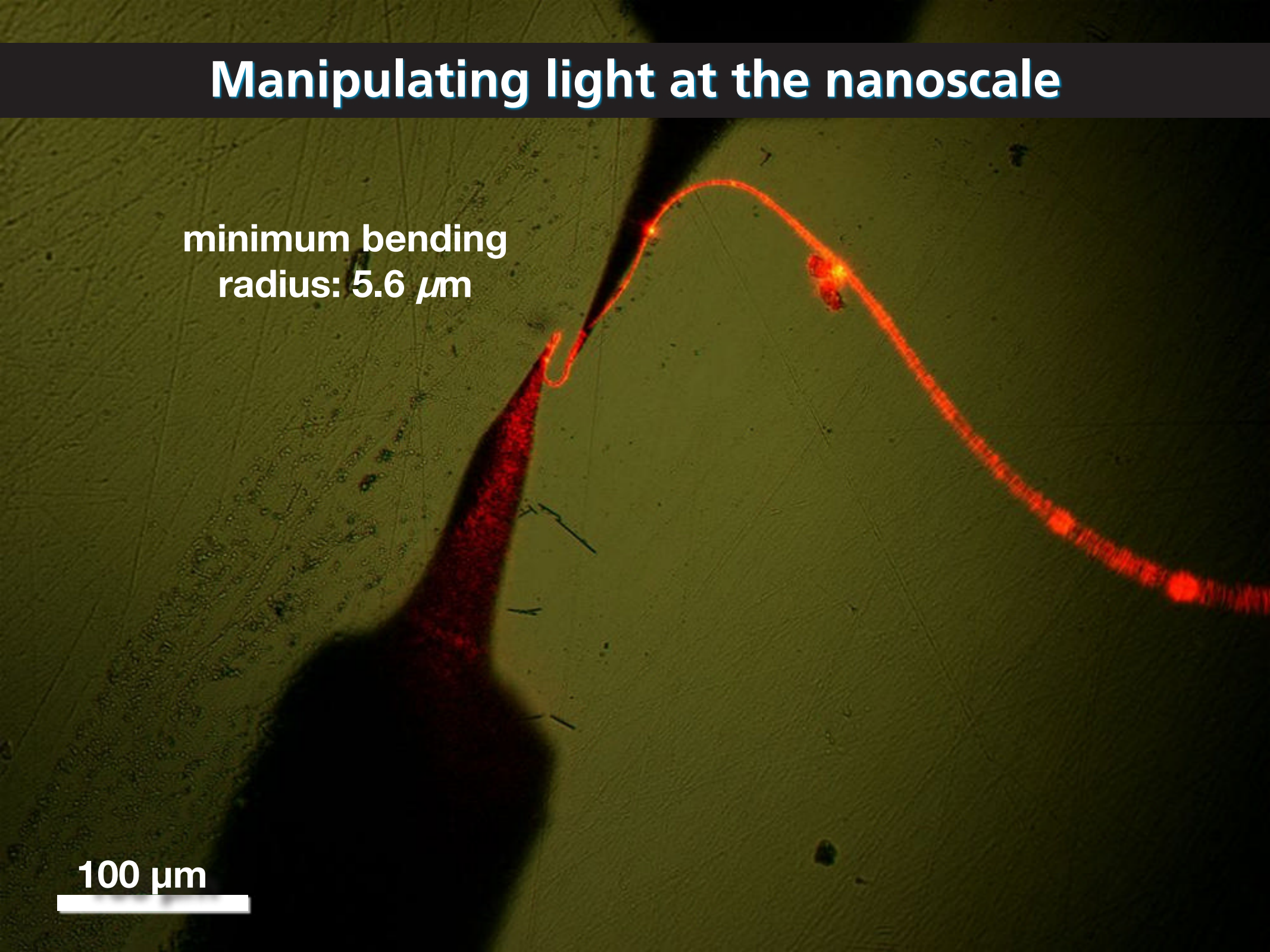


100 μm

Manipulating light at the nanoscale

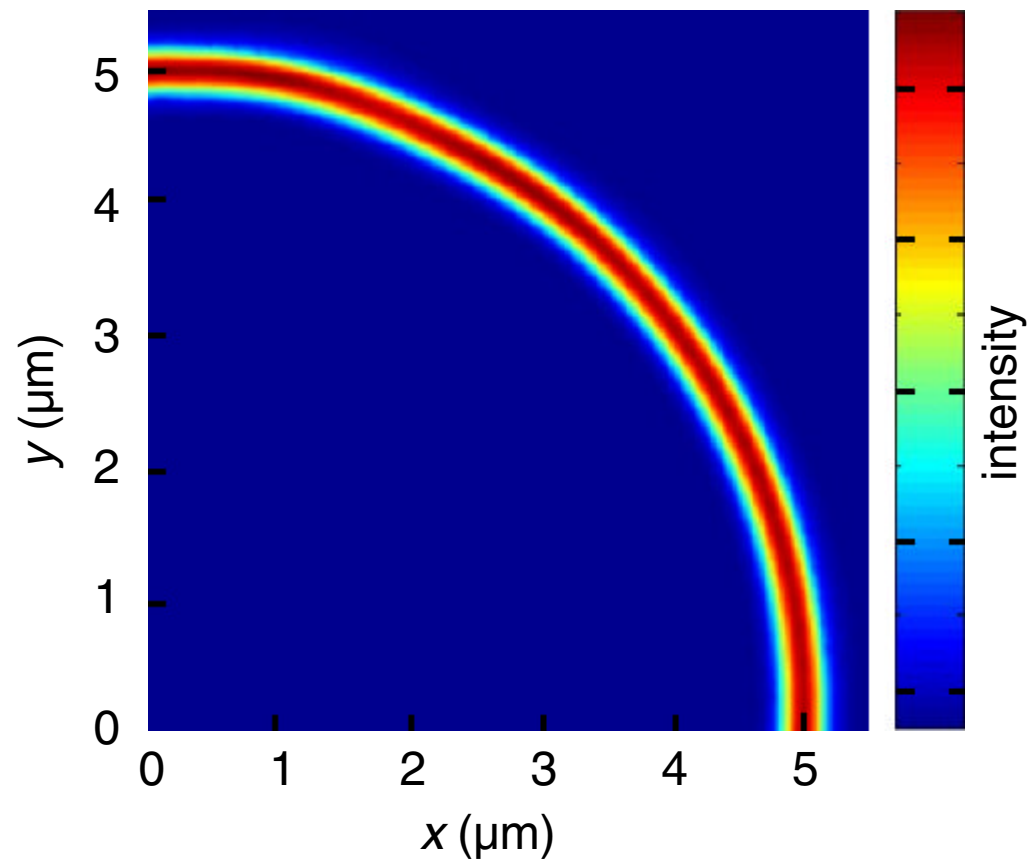
minimum bending
radius: $5.6 \mu\text{m}$

100 μm

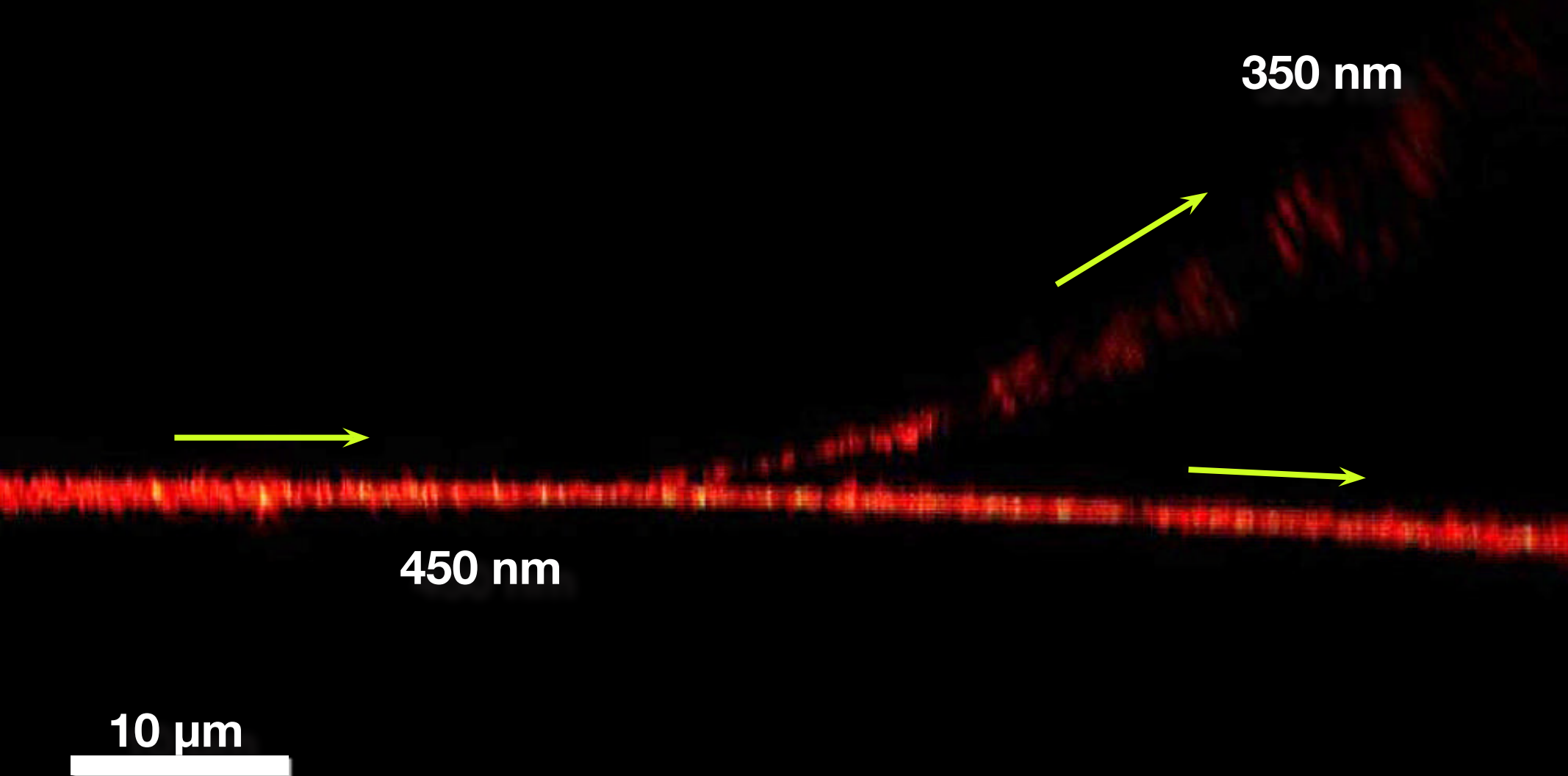
A micrograph showing a fiber optic cable with a sharp bend. The fiber is illuminated from the left, creating a bright red glow. The bend is very tight, and the light is visible as a thin, curved line. The background is dark green with some faint scratches and dust. A scale bar is located in the bottom left corner, and text is overlaid on the image.

Manipulating light at the nanoscale

virtually no loss through 5 μm corner!



Manipulating light at the nanoscale

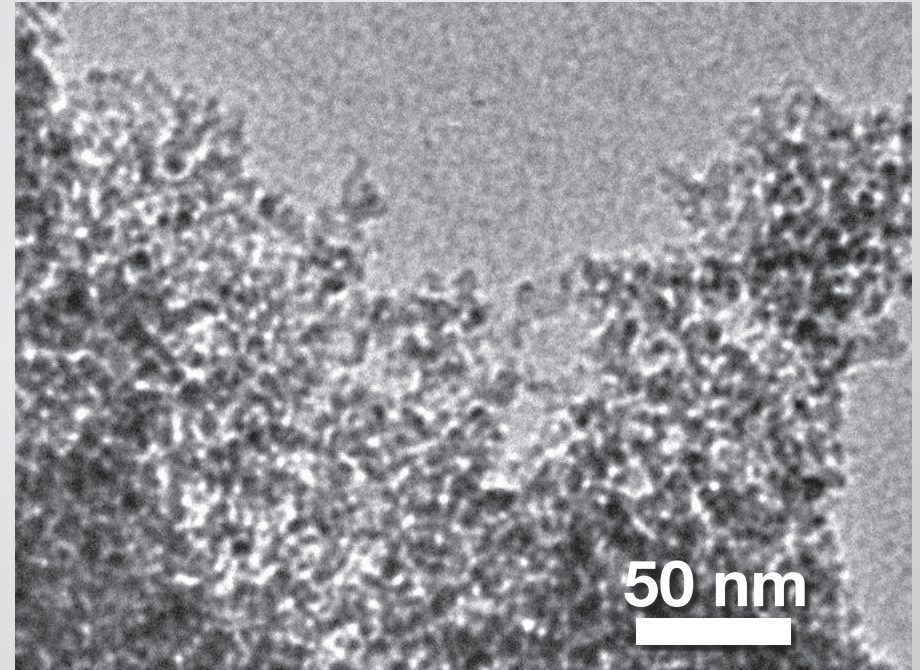
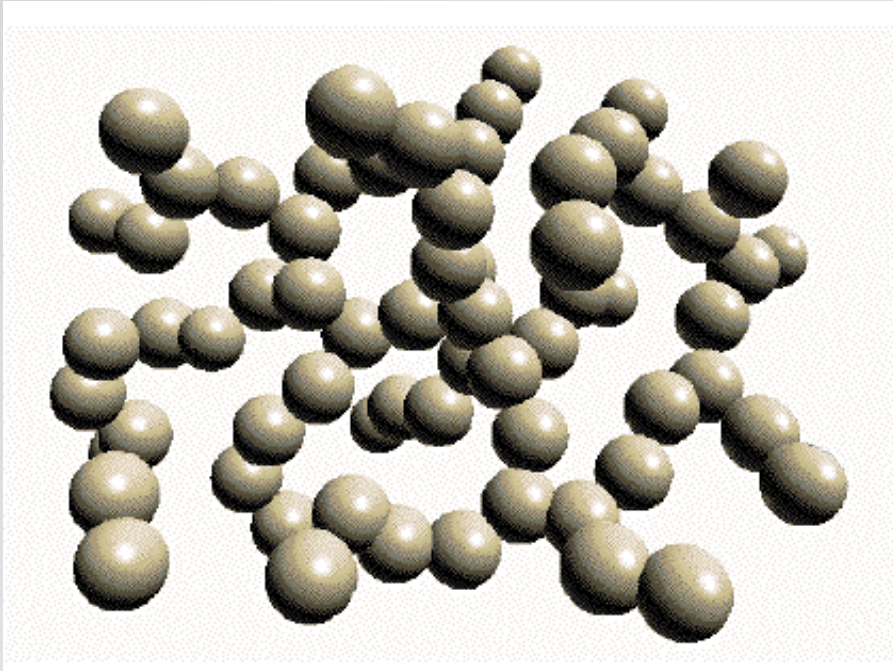


Manipulating light at the nanoscale



Manipulating light at the nanoscale

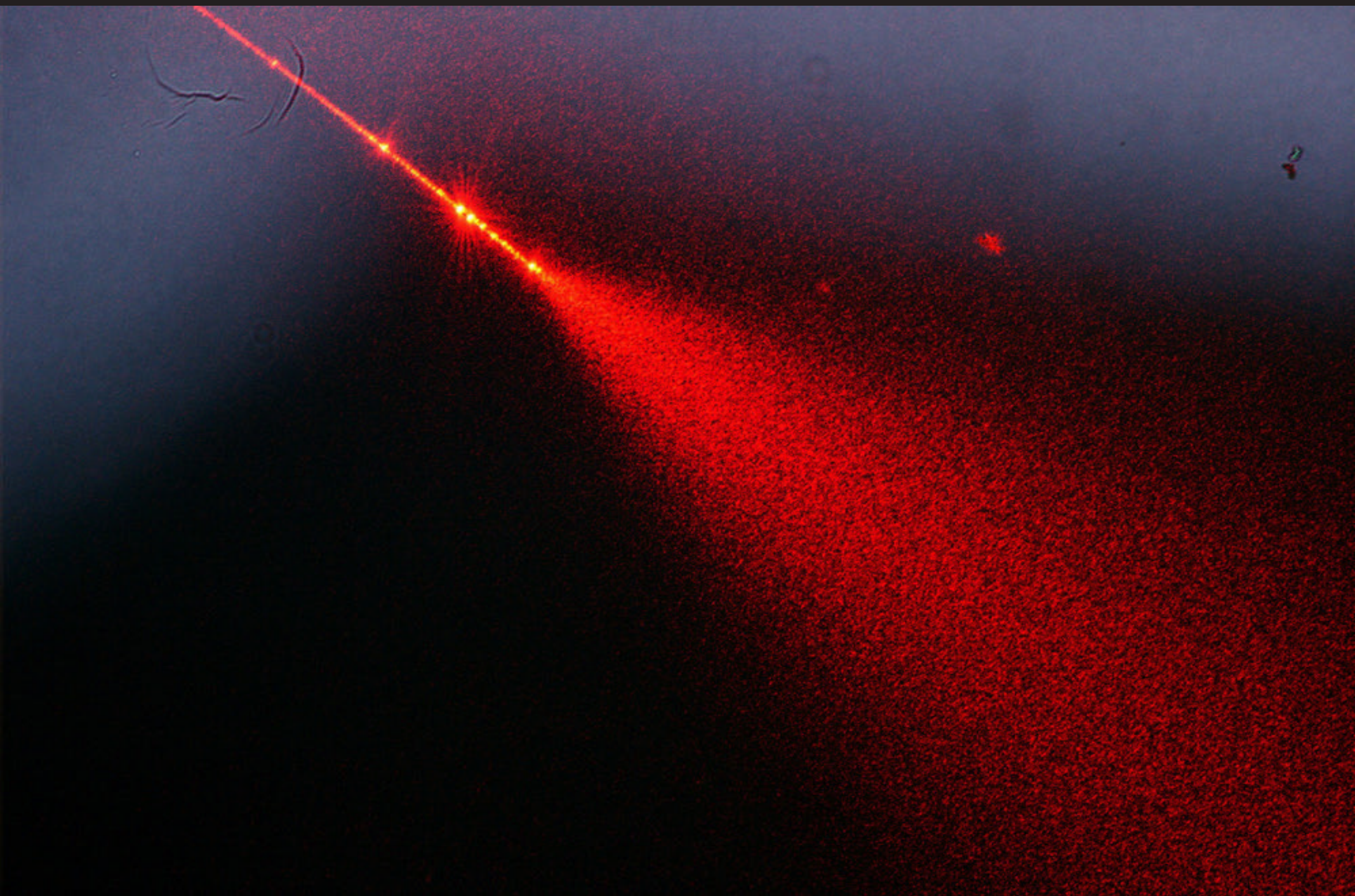
Aerogel



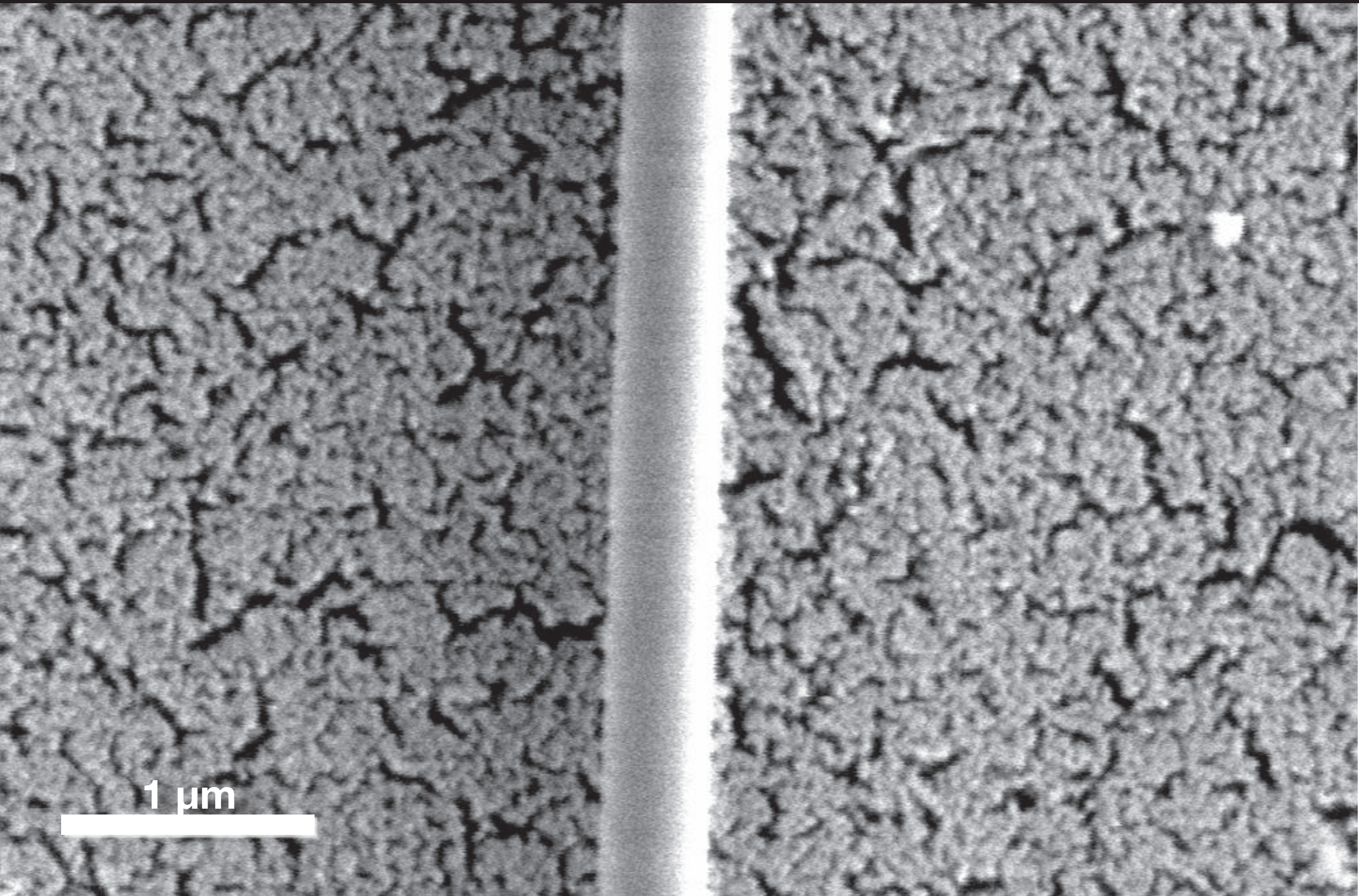
density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Manipulating light at the nanoscale



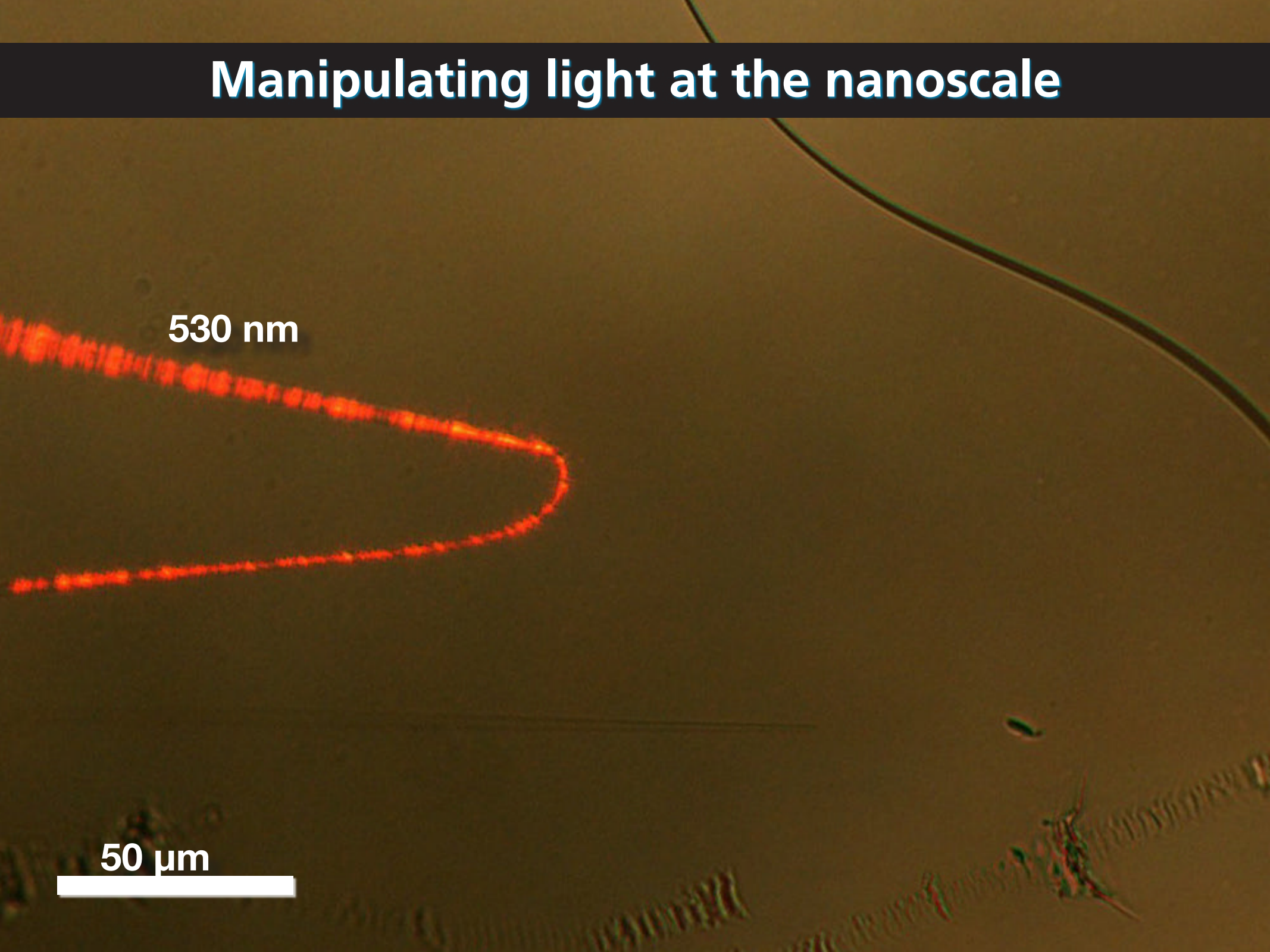
Manipulating light at the nanoscale



1 μm

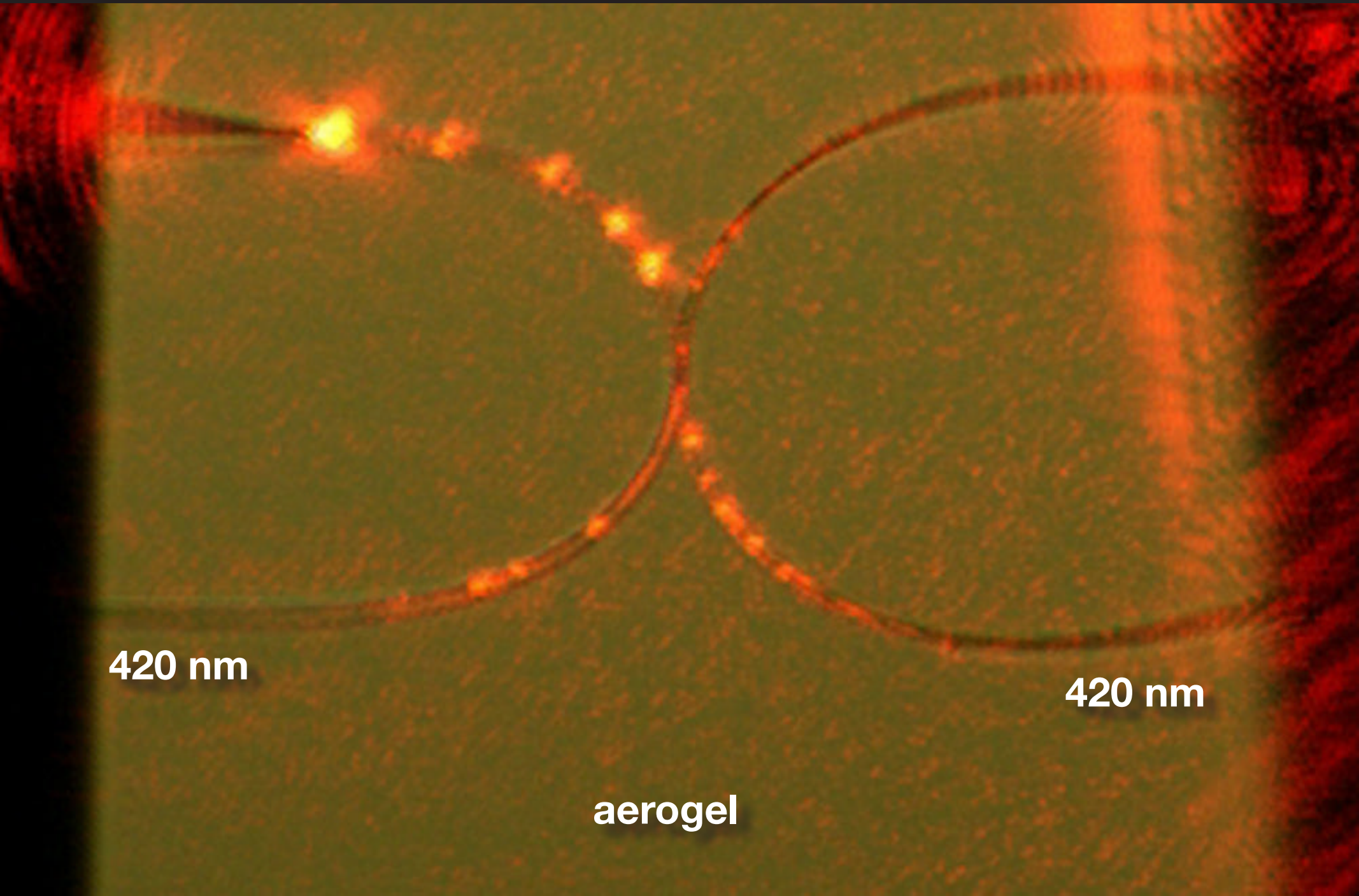
Manipulating light at the nanoscale

530 nm



50 μm

Manipulating light at the nanoscale

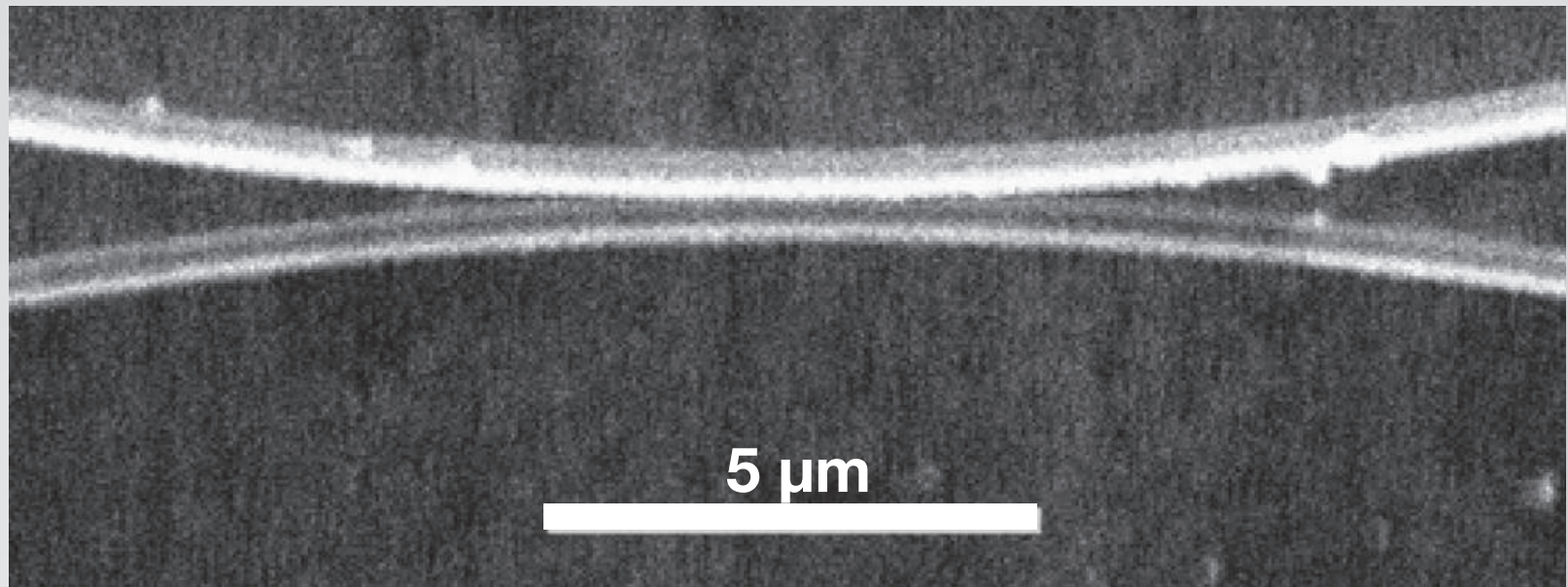


420 nm

420 nm

aerogel

Manipulating light at the nanoscale



Manipulating light at the nanoscale

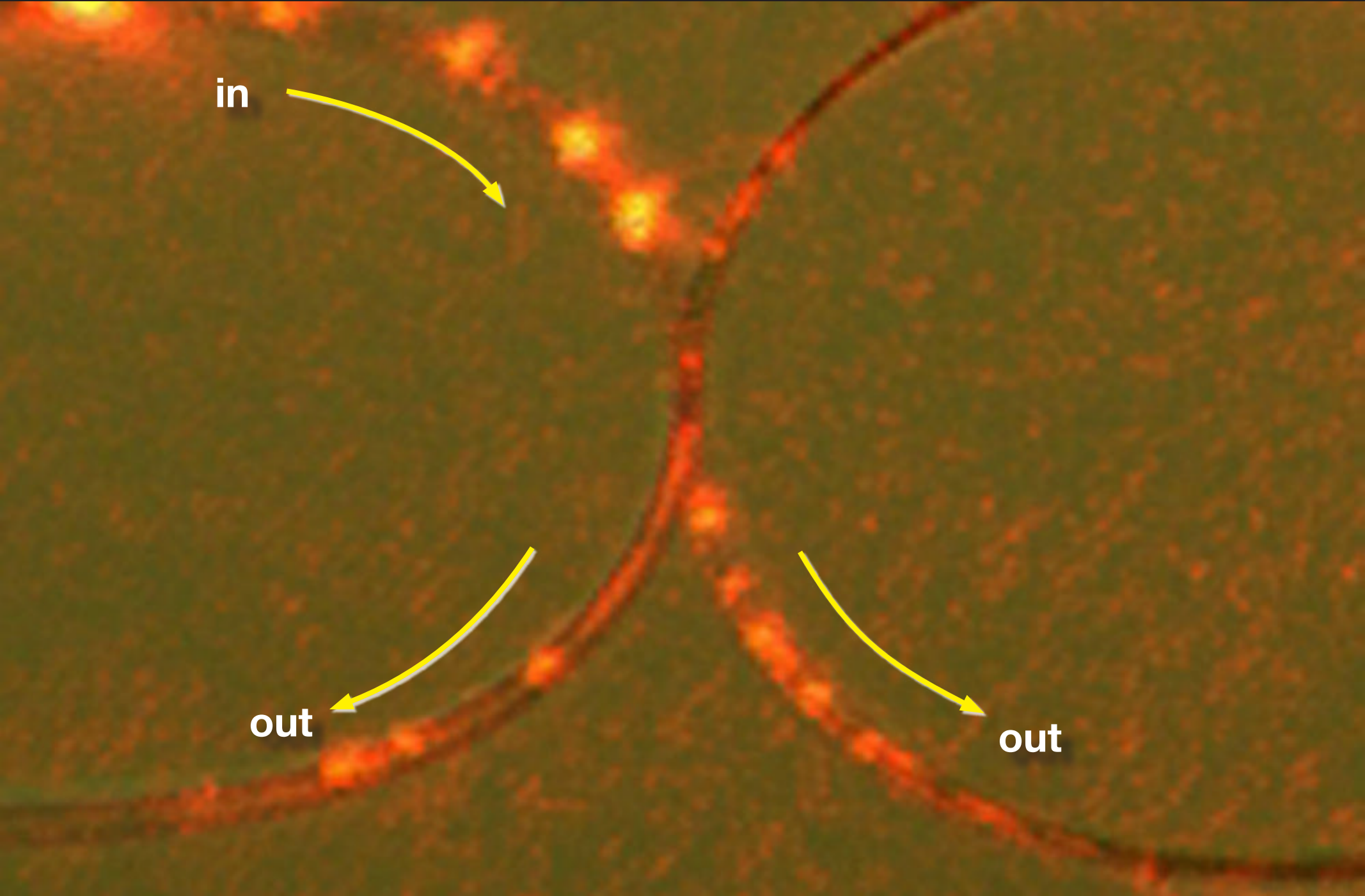
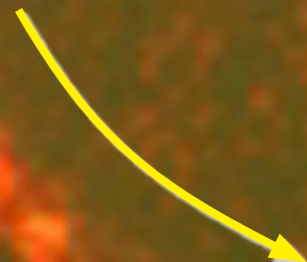
in



out



out



Manipulating light at the nanoscale

use tapered fibers to couple light to nanoscale objects

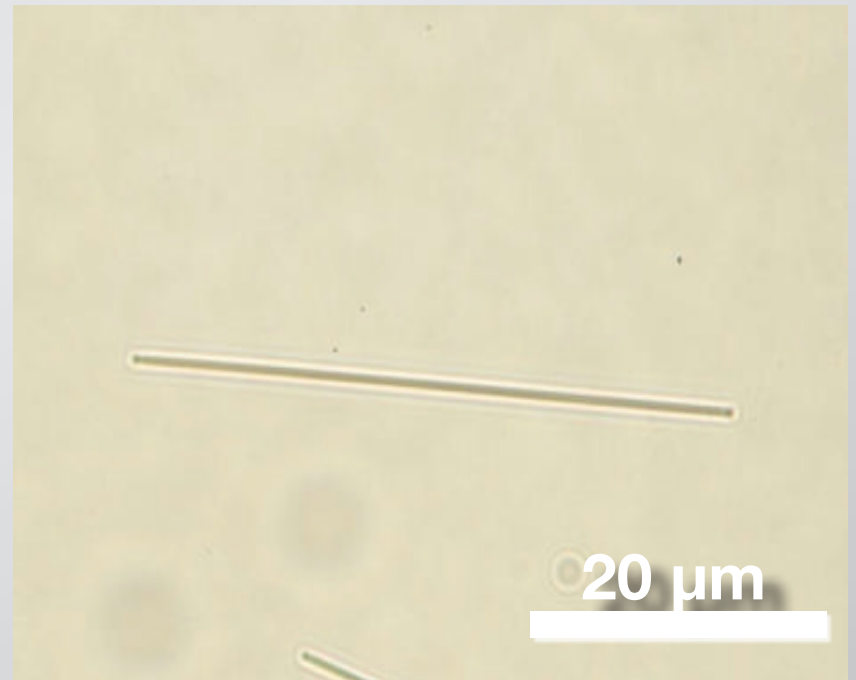
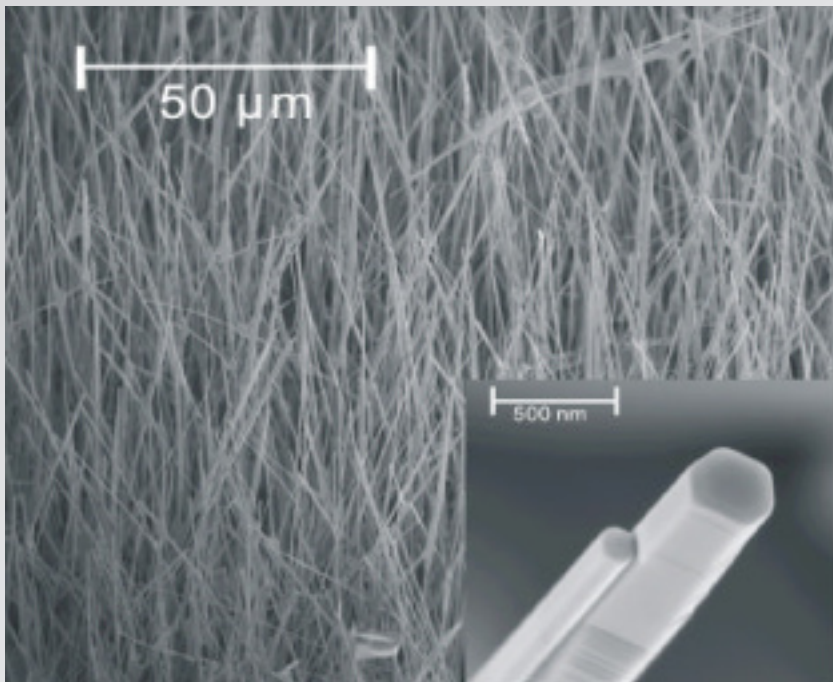
Manipulating light at the nanoscale

ZnO: non-toxic, wide bandgap semiconductor

A photograph of a petri dish containing a white, granular powder. The powder is piled in the center of the dish. To the right of the powder, a dark, cylindrical object, possibly a pipette tip or a small tool, is resting on the surface of the dish. The background is dark, and the lighting highlights the texture of the powder.

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

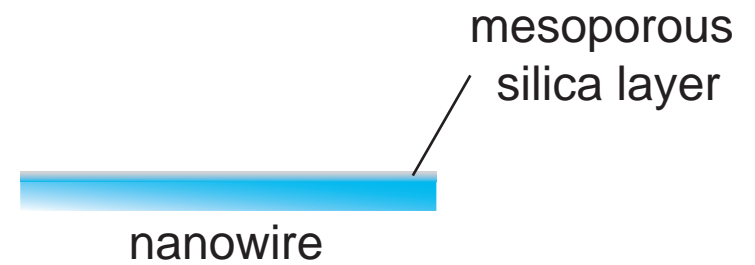
passive waveguides

electrical operation

link to macroworld

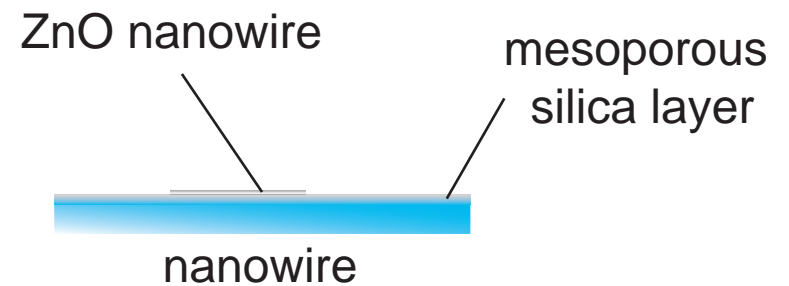
Manipulating light at the nanoscale

coupling to ZnO nanowires



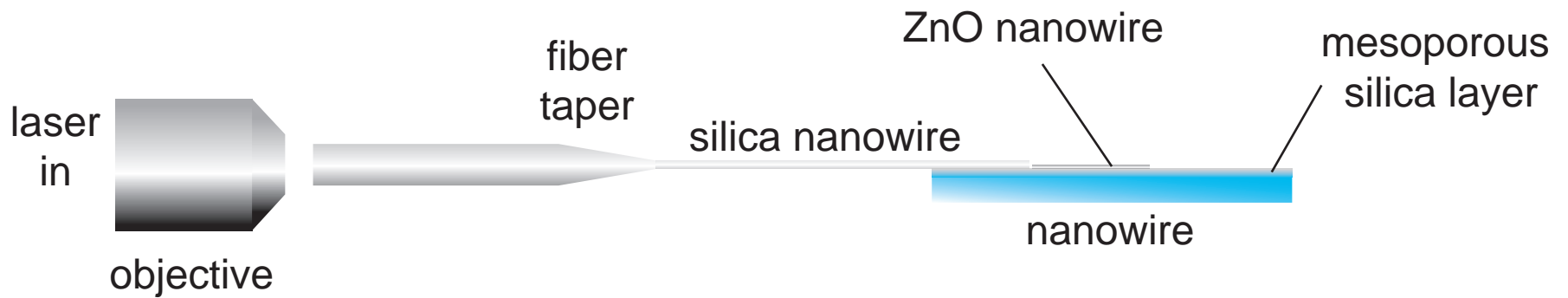
Manipulating light at the nanoscale

coupling to ZnO nanowires



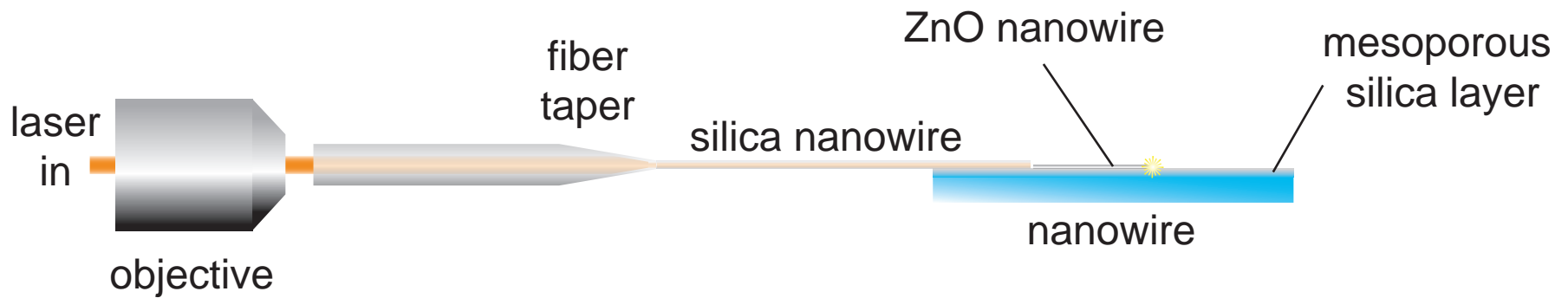
Manipulating light at the nanoscale

coupling to ZnO nanowires

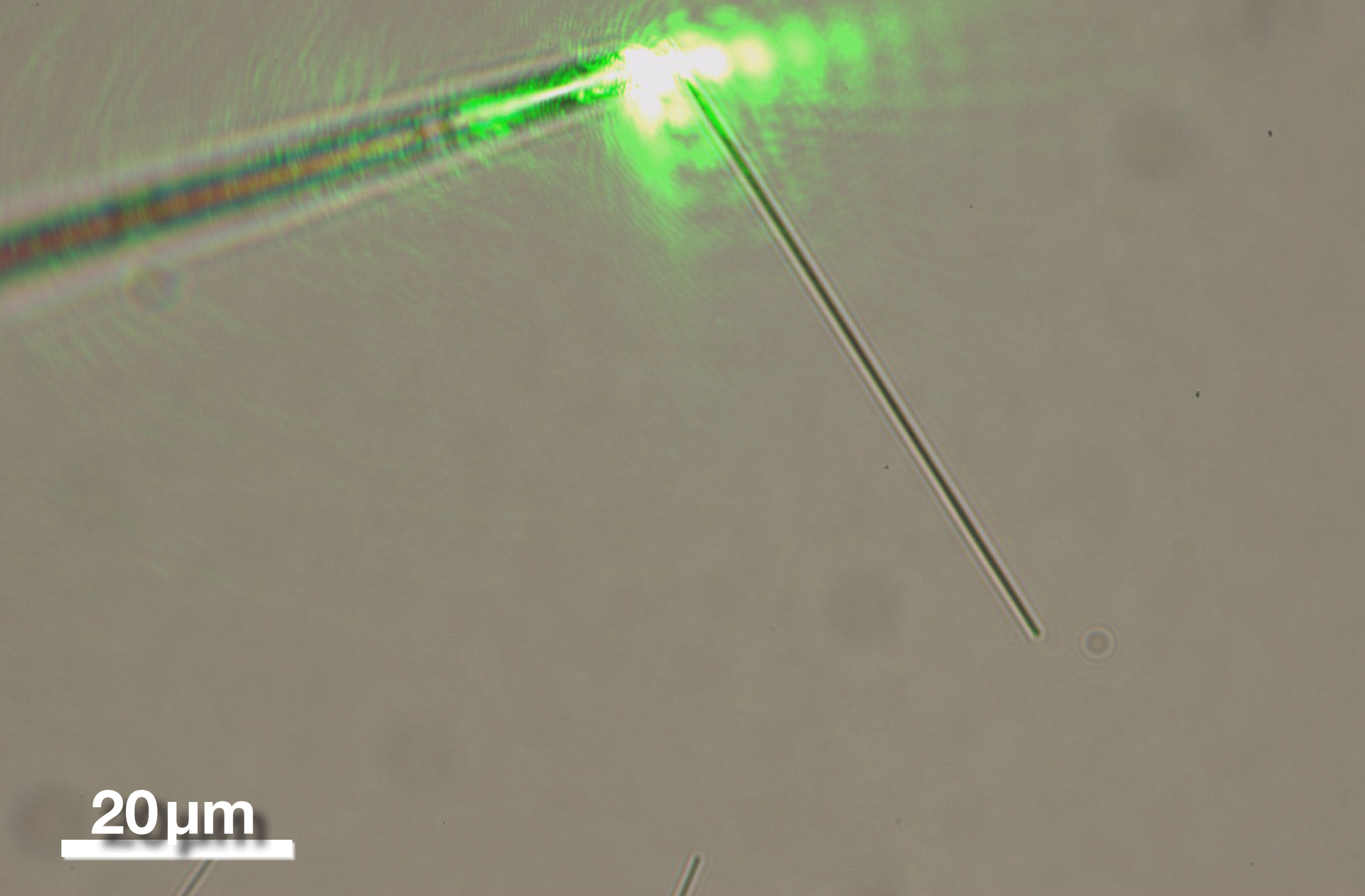


Manipulating light at the nanoscale

coupling to ZnO nanowires

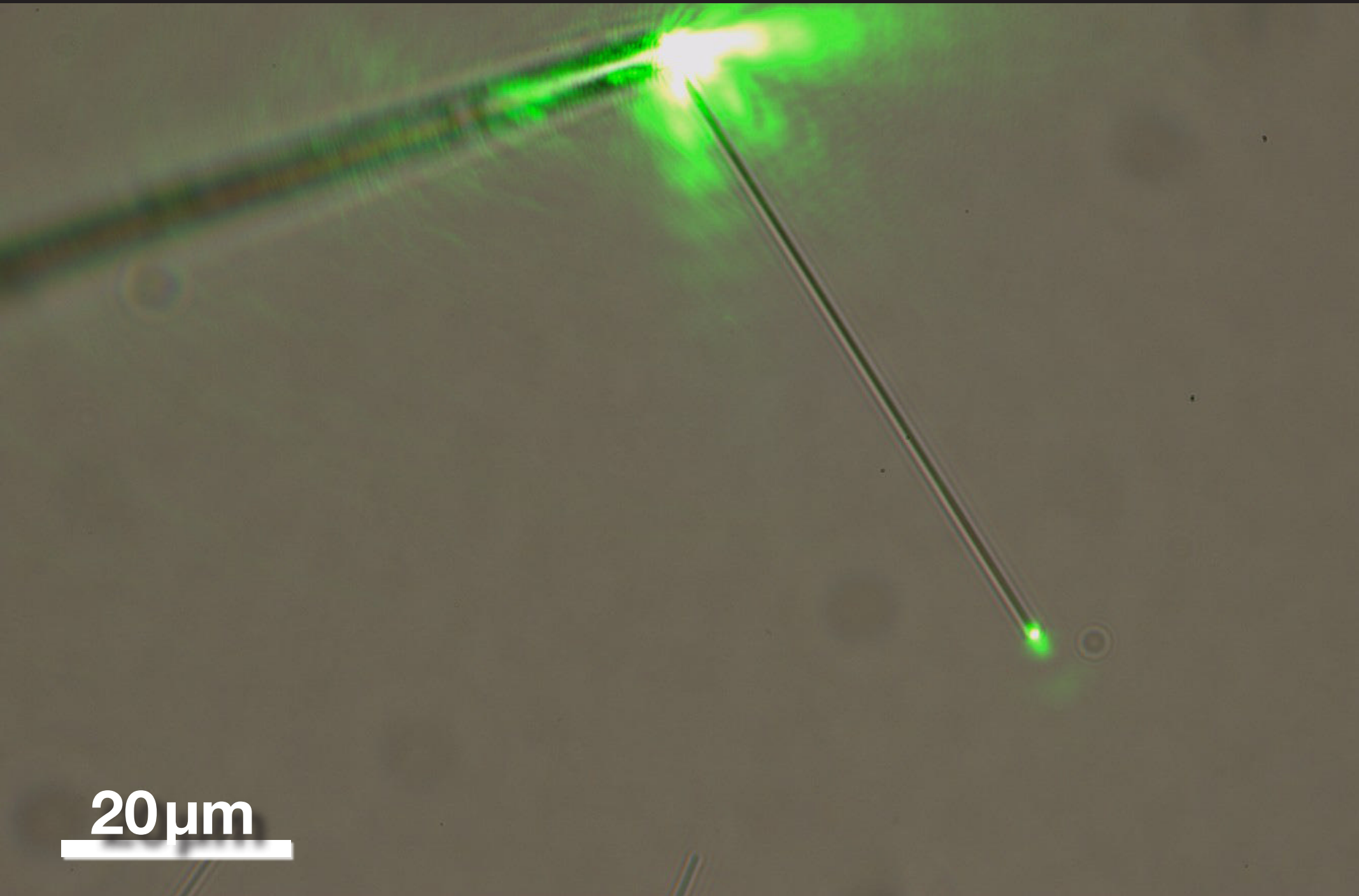


Manipulating light at the nanoscale



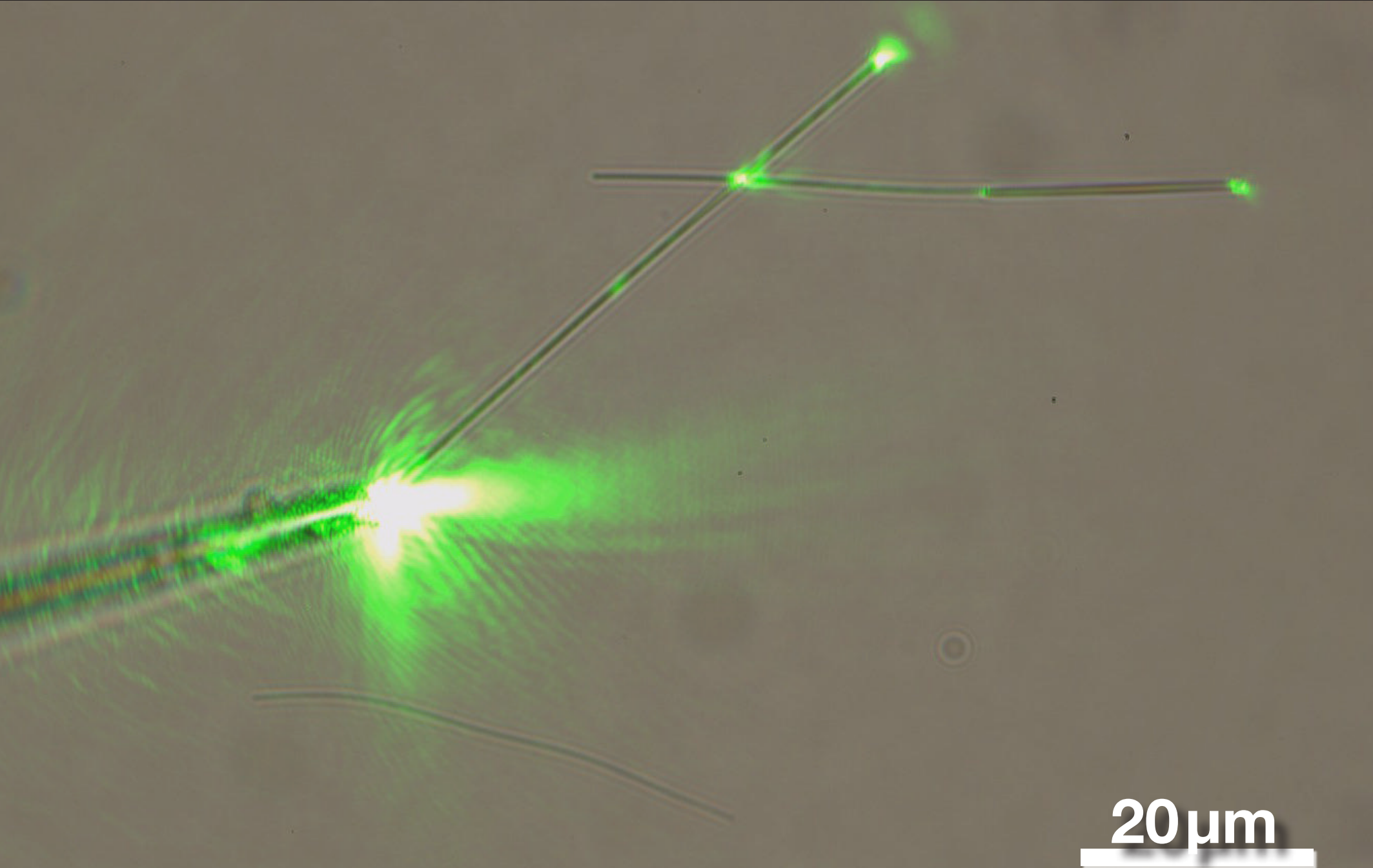
20 μm

Manipulating light at the nanoscale

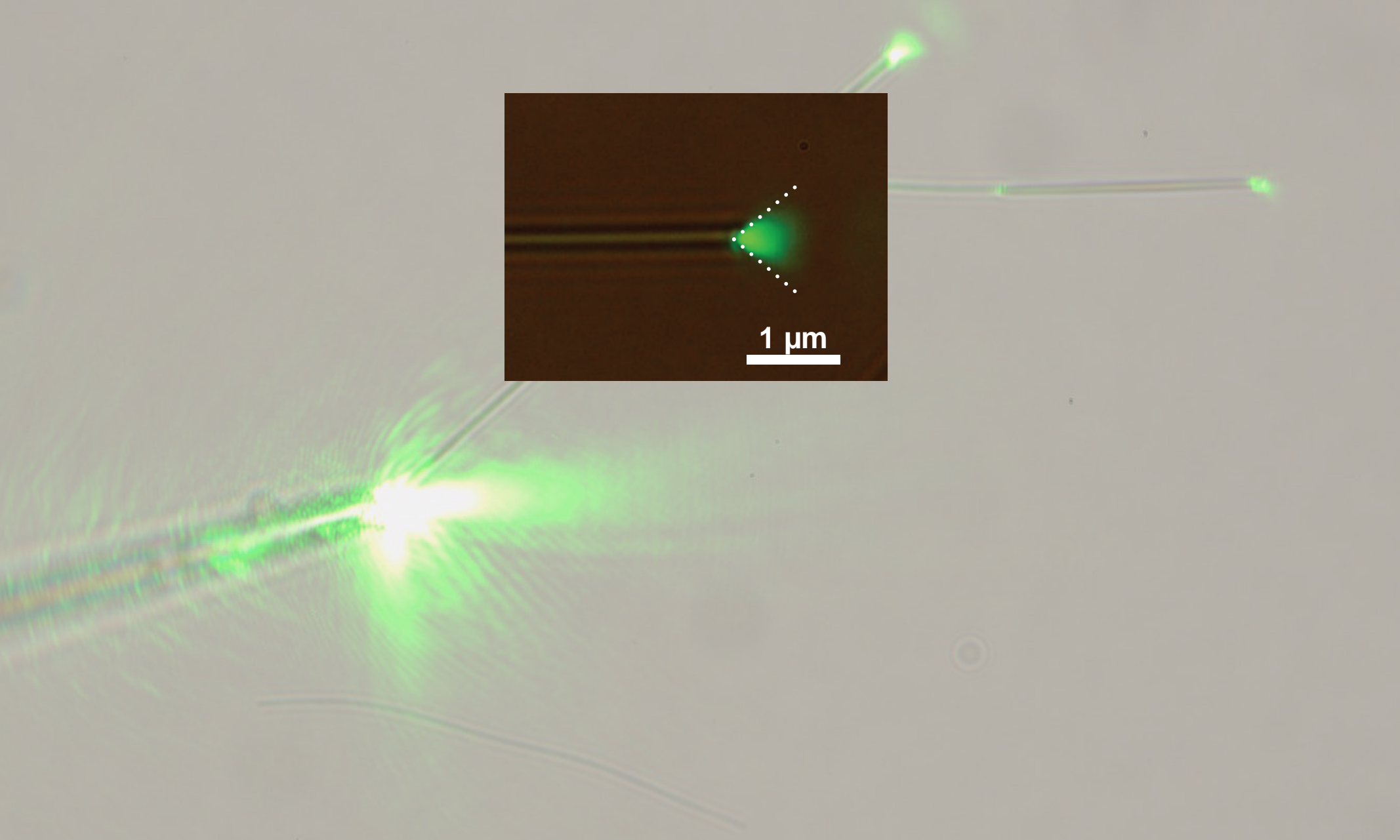
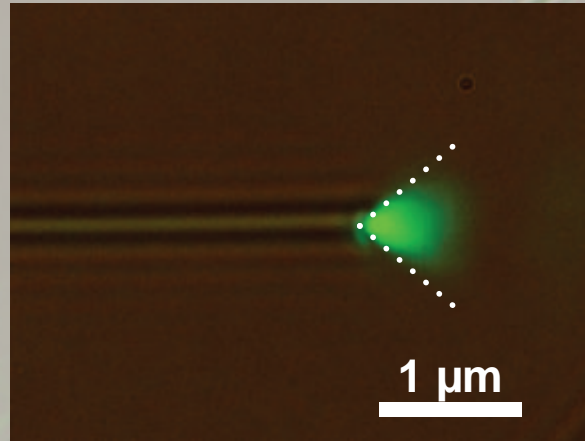


20 μm

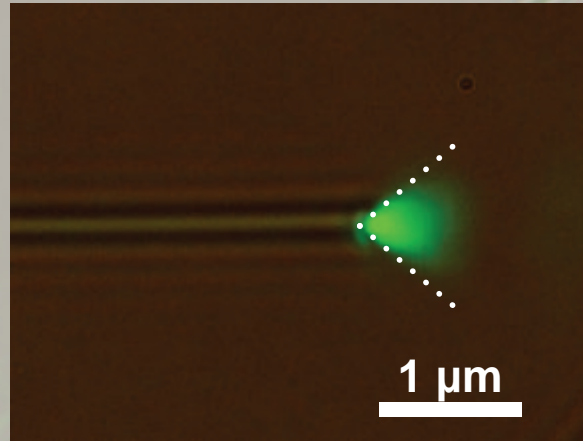
Manipulating light at the nanoscale



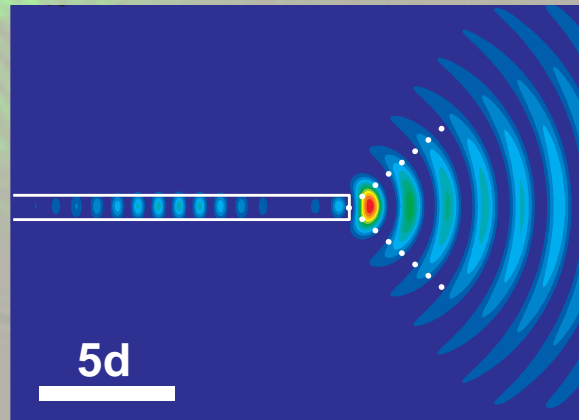
Manipulating light at the nanoscale



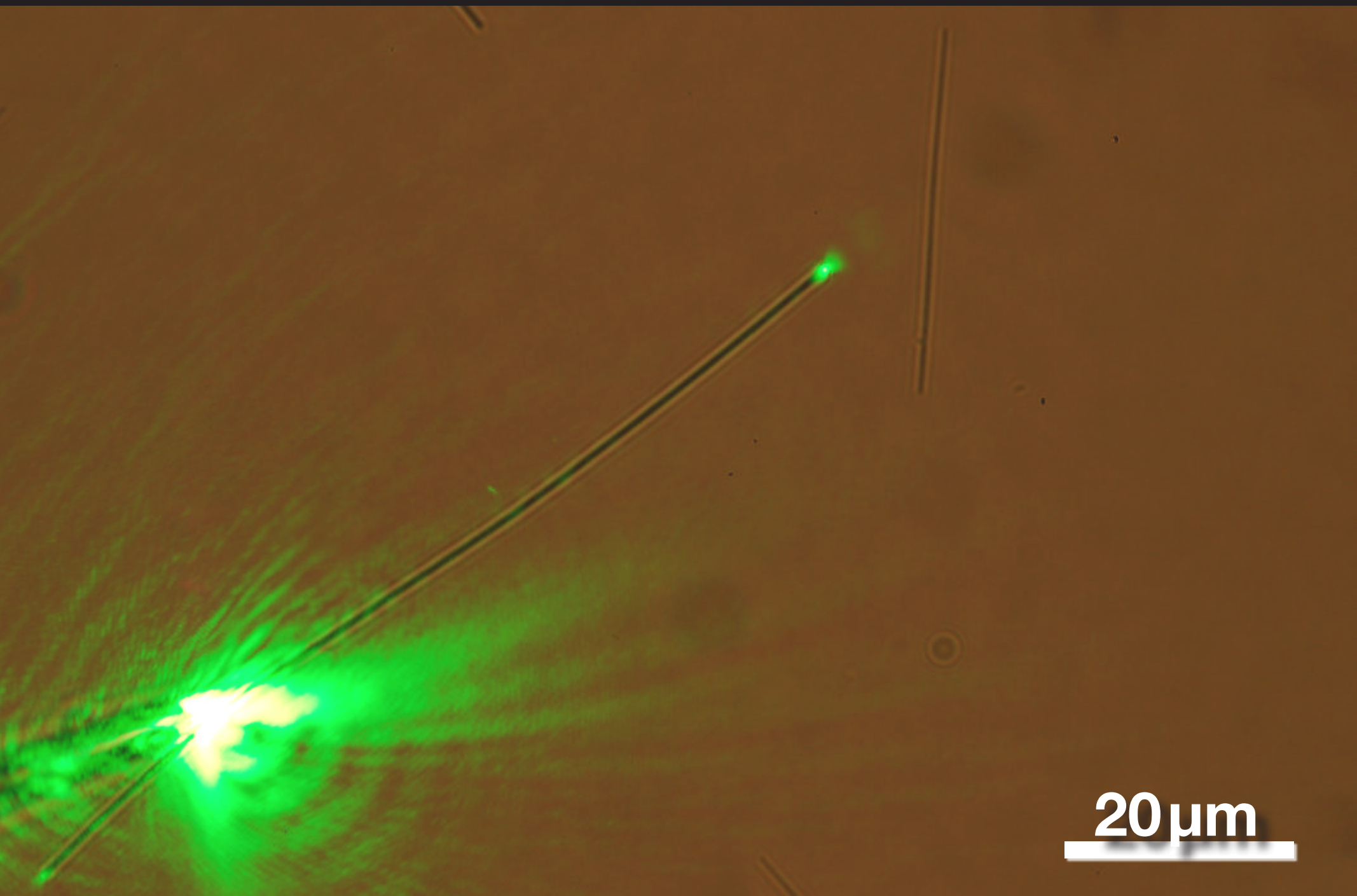
Manipulating light at the nanoscale



FDTD simulation

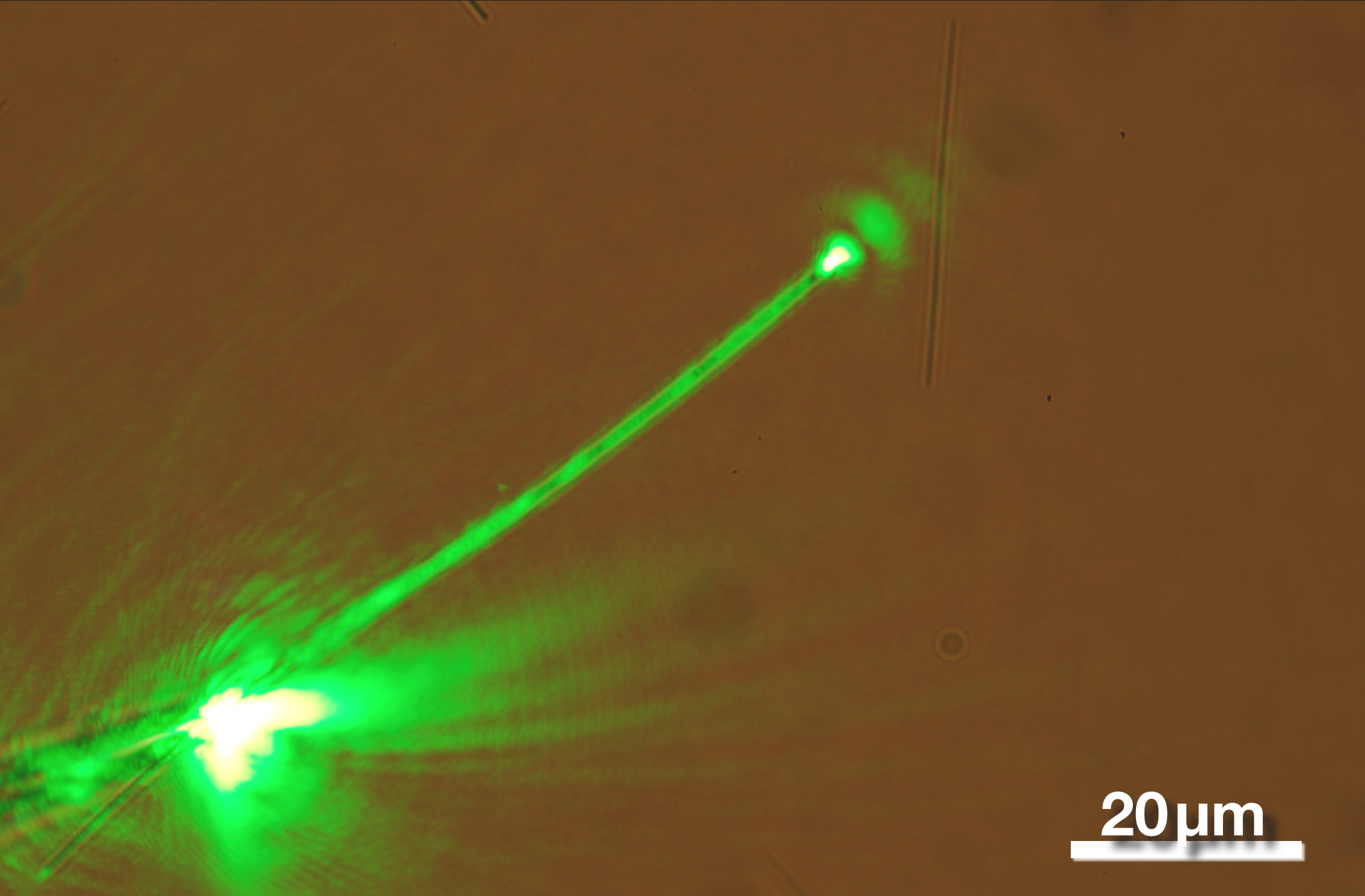


Manipulating light at the nanoscale



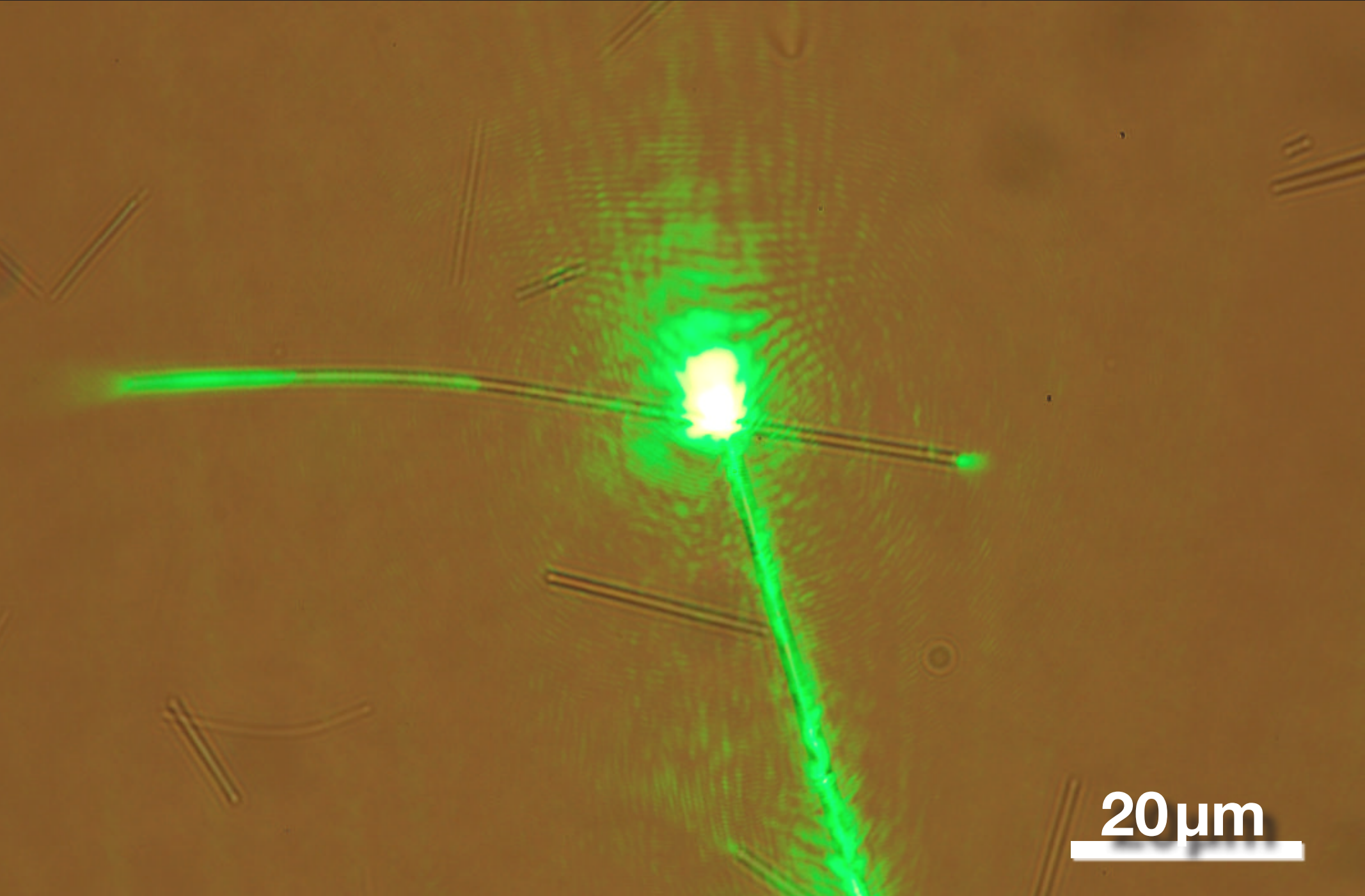
20 μm

Manipulating light at the nanoscale



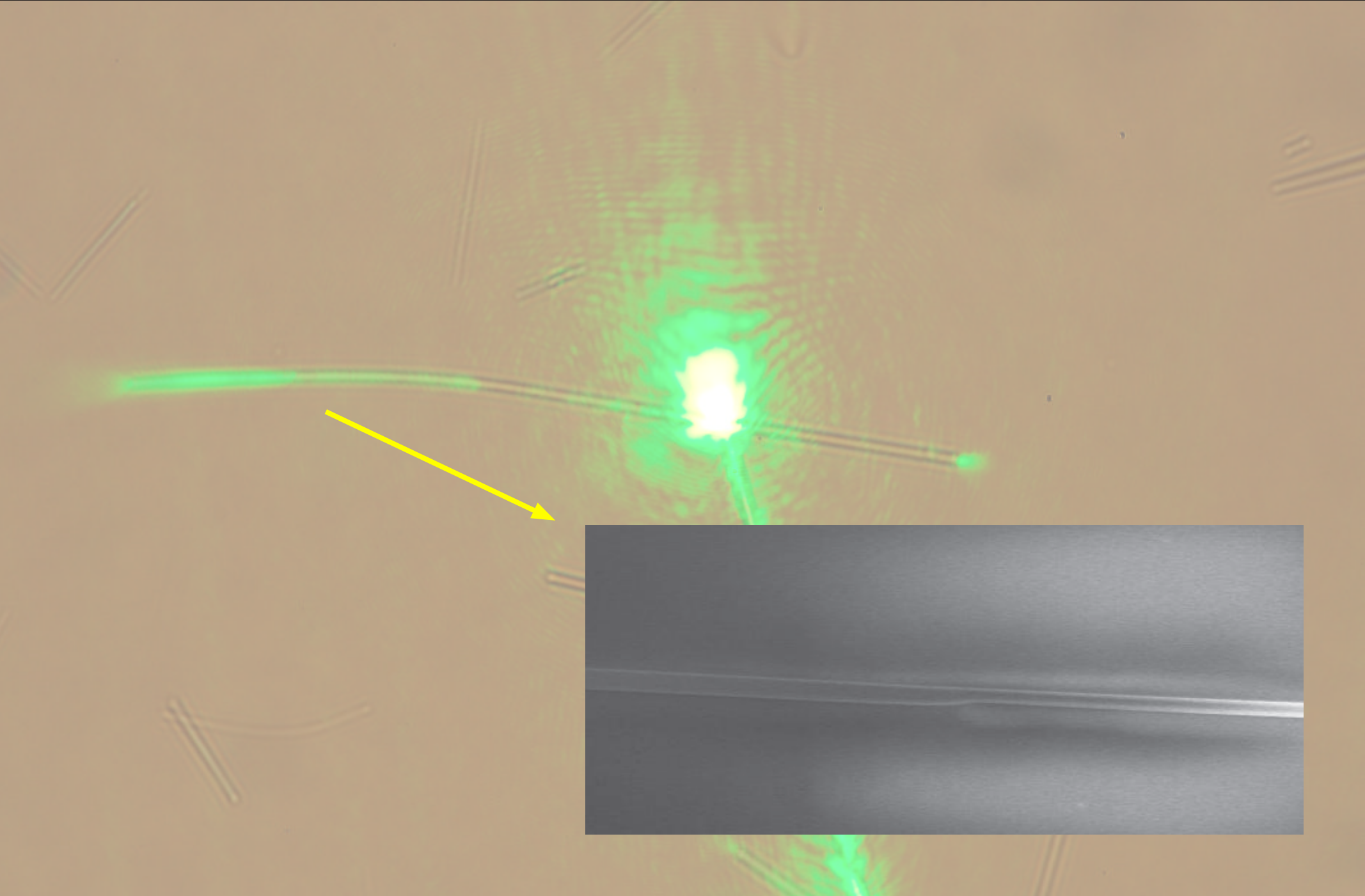
20 μm

Manipulating light at the nanoscale



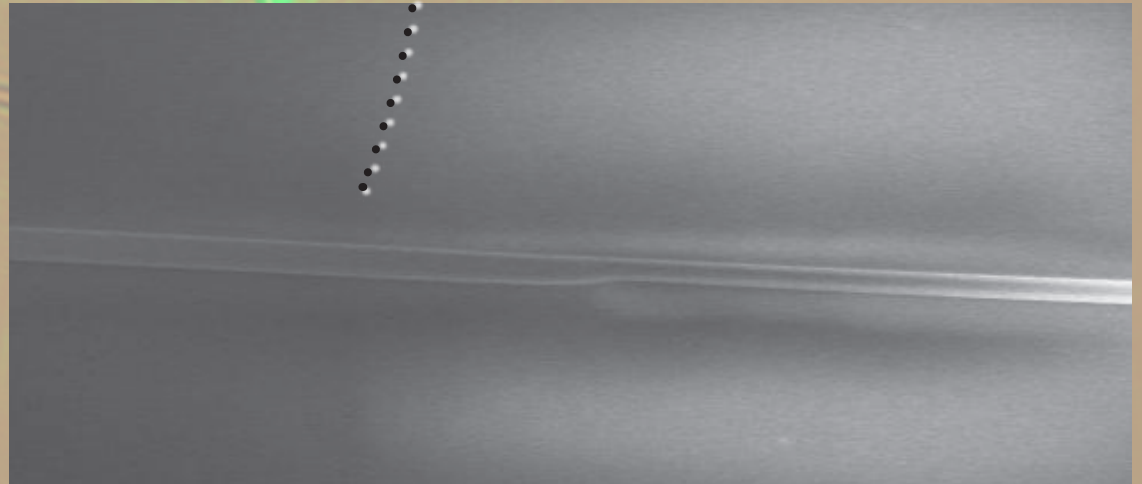
20 μm

Manipulating light at the nanoscale



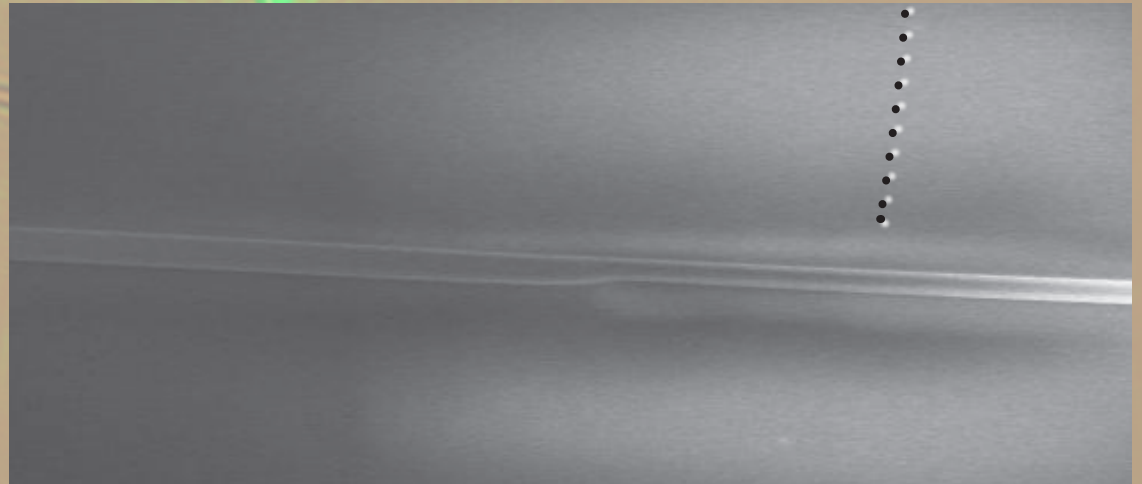
Manipulating light at the nanoscale

large diameter:
multimode



Manipulating light at the nanoscale

small diameter:
single mode



Manipulating light at the nanoscale

Points to keep in mind:

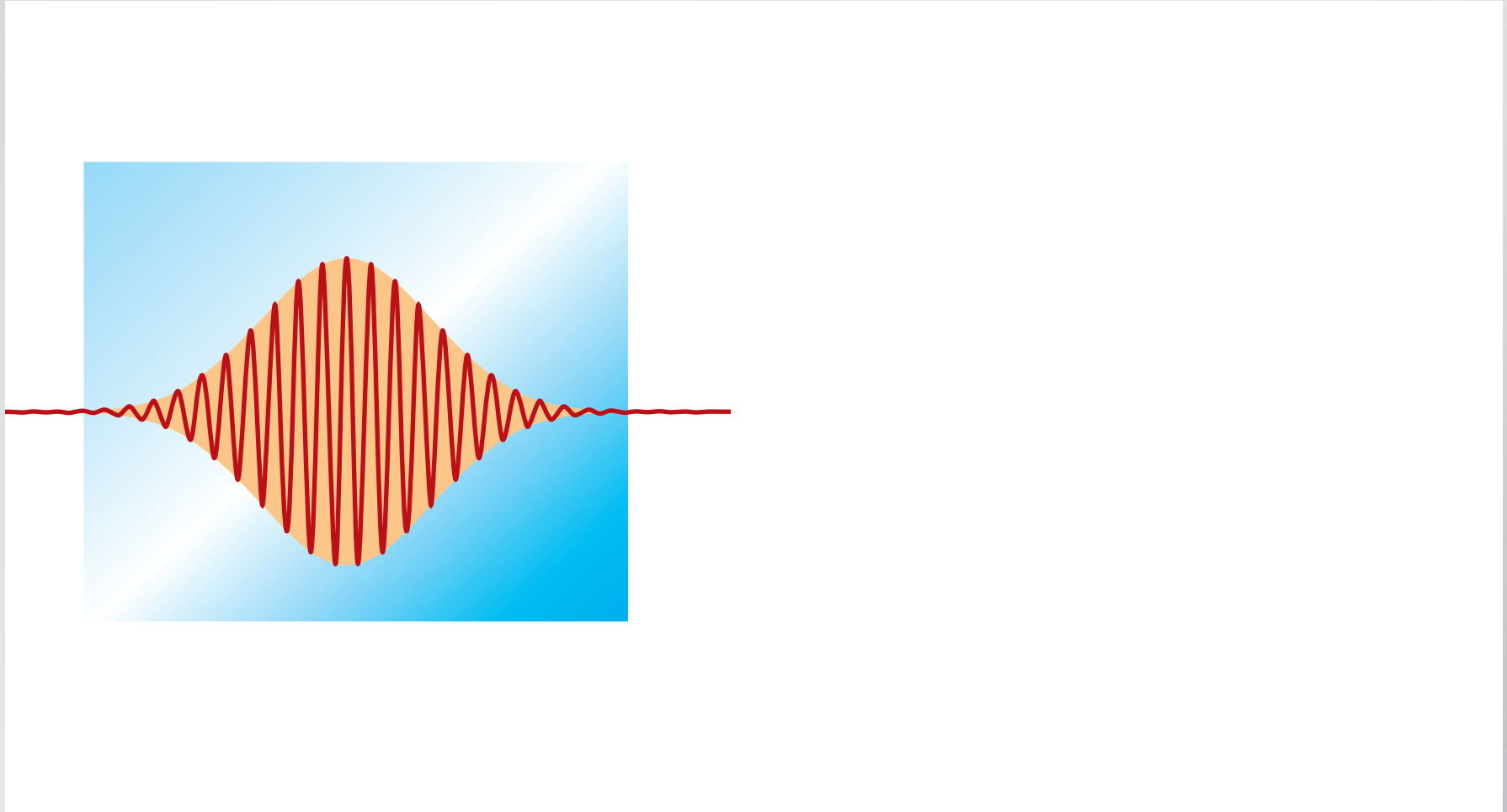
- **low loss**
- **large evanescent field**
- **convenient coupling to nanoscale**

Outline

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

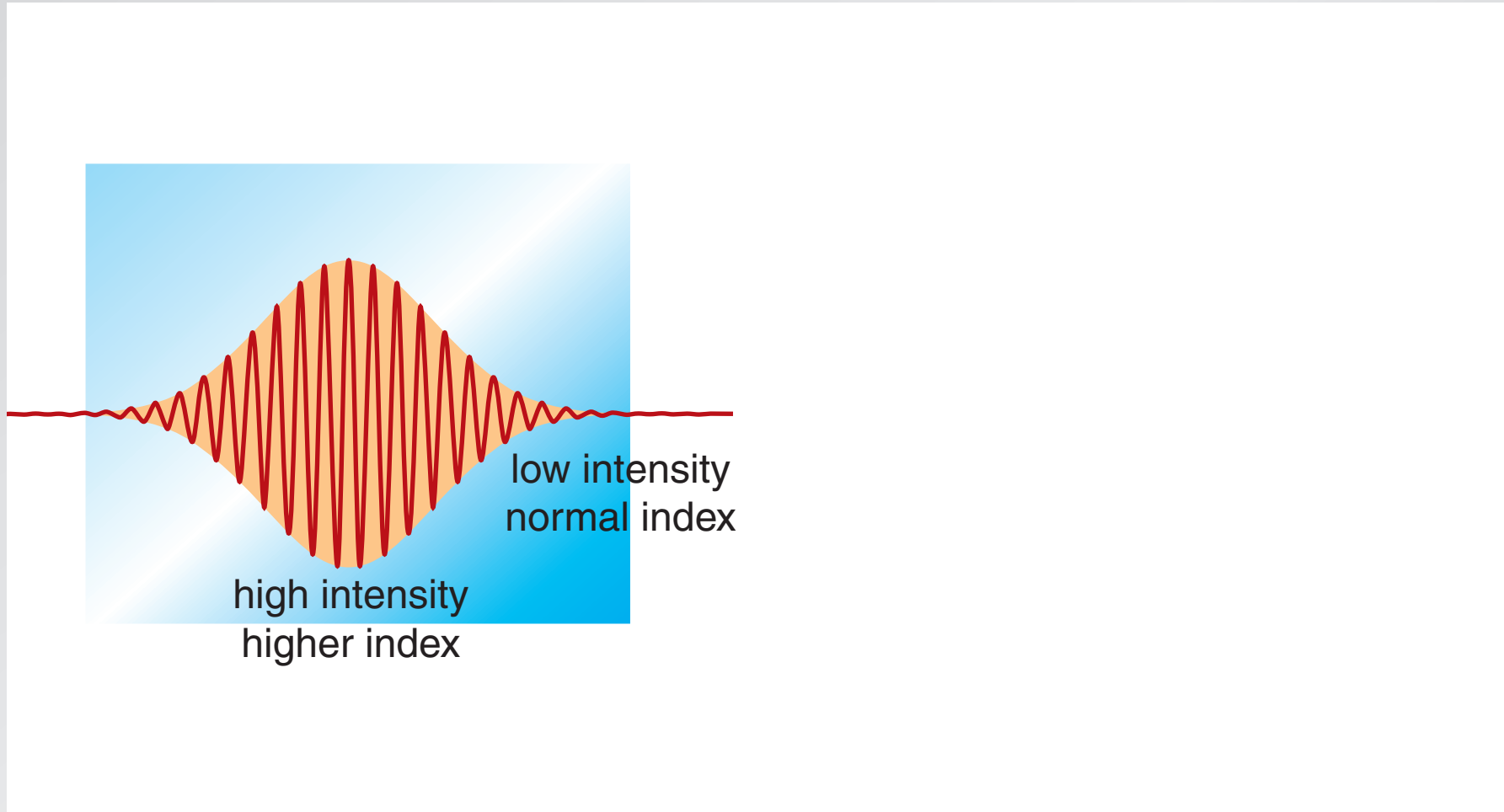
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



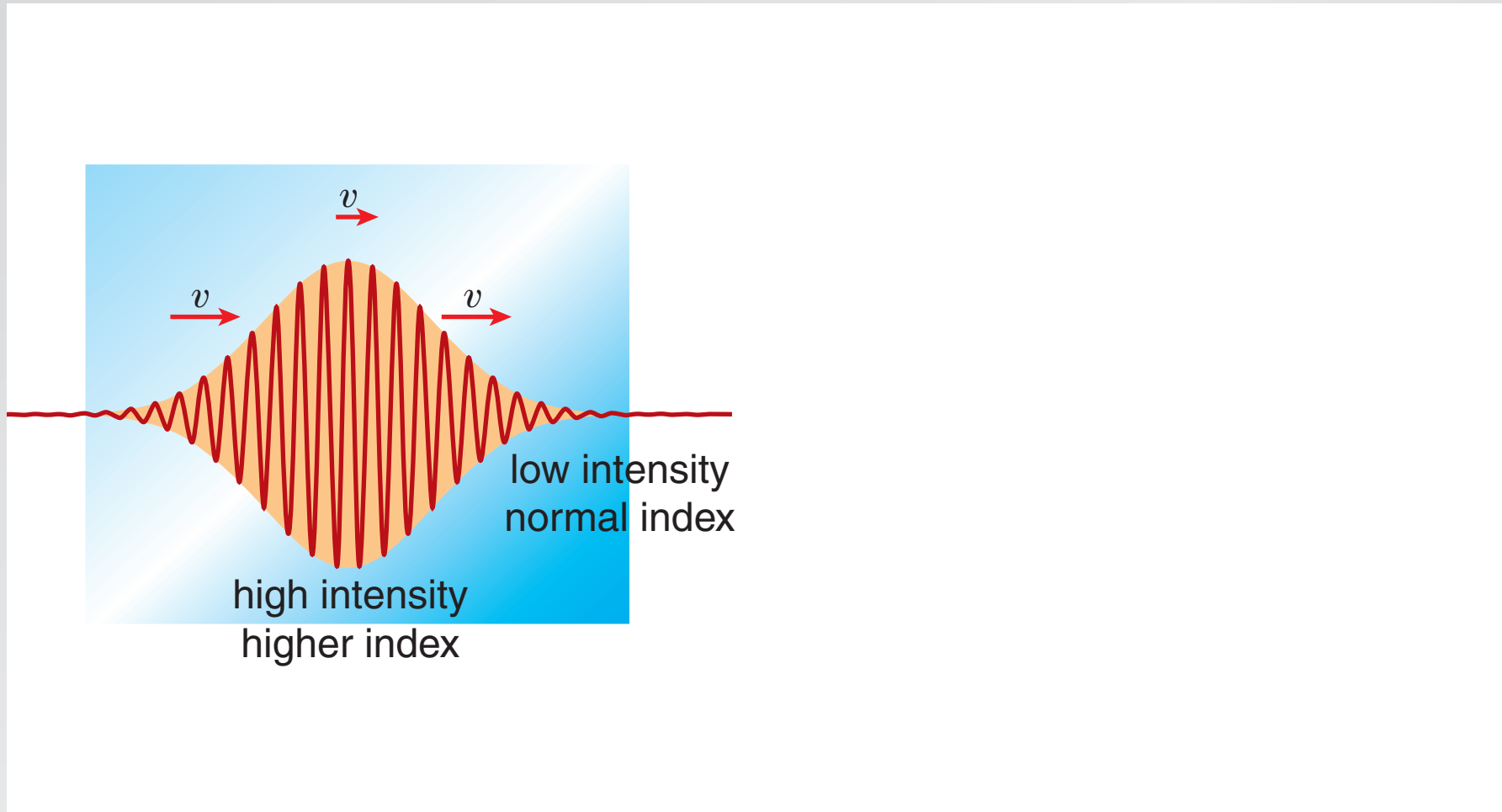
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



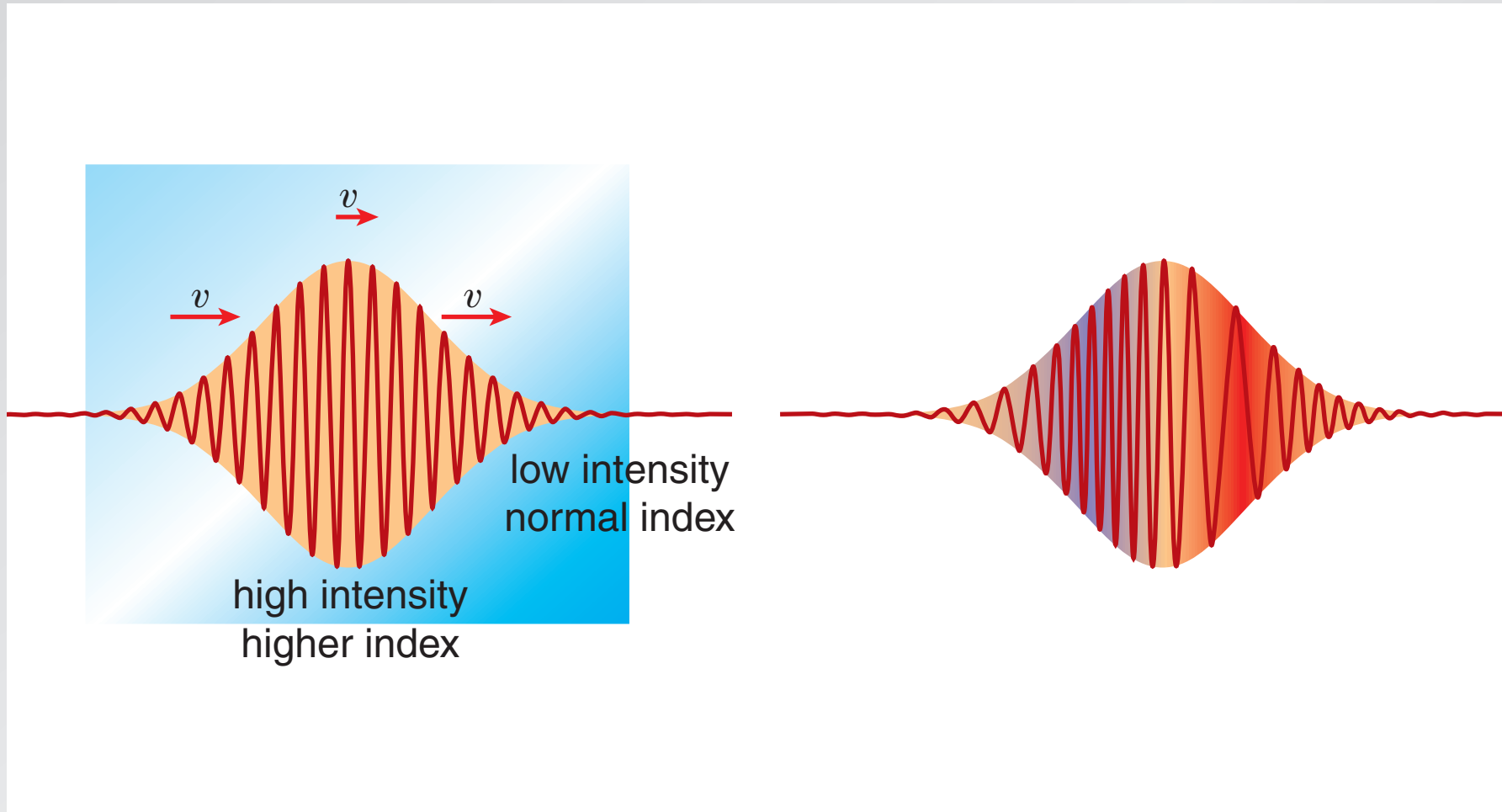
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



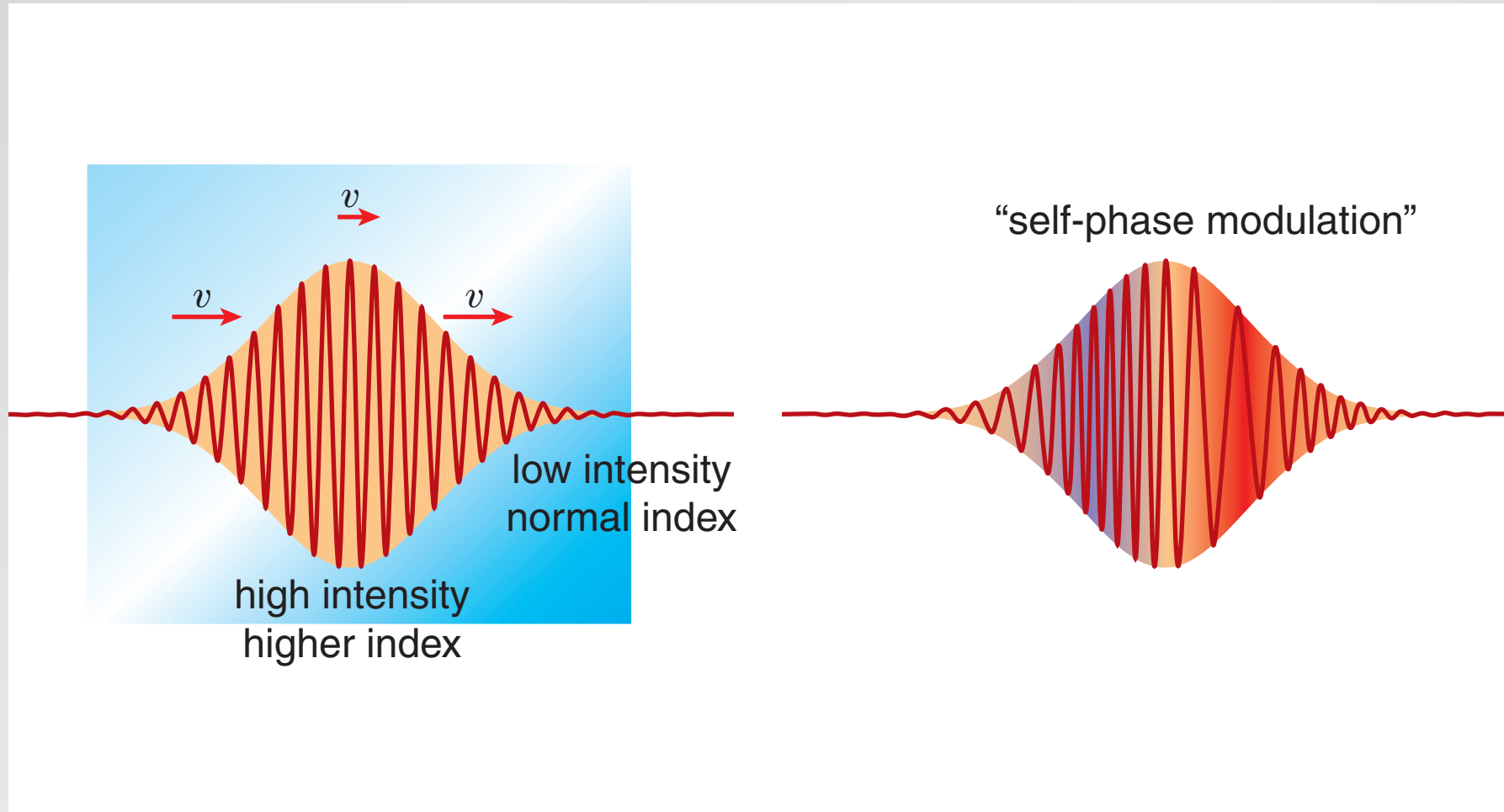
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$

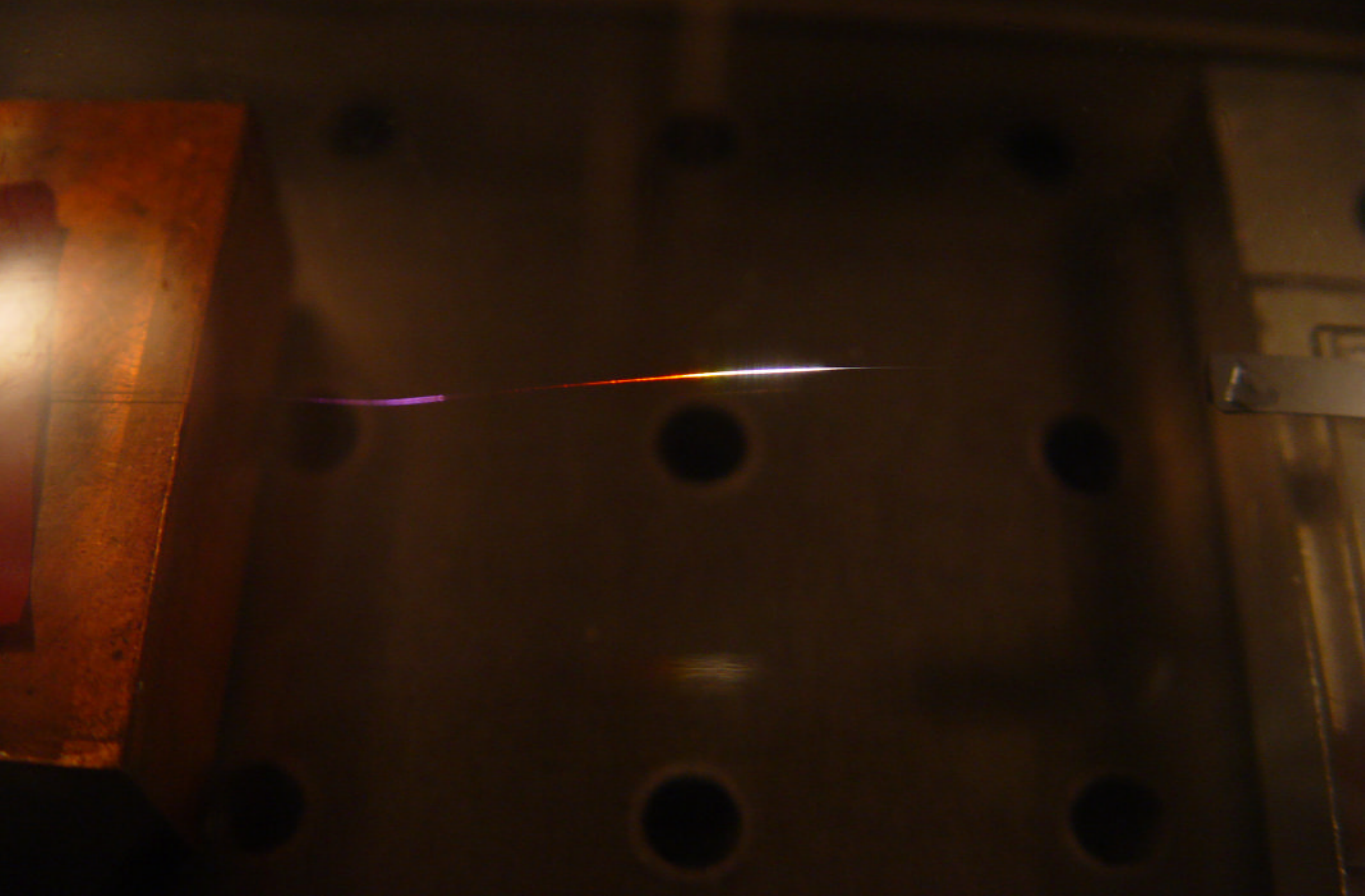


Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



Nanoscale nonlinear optics



Nanoscale nonlinear optics

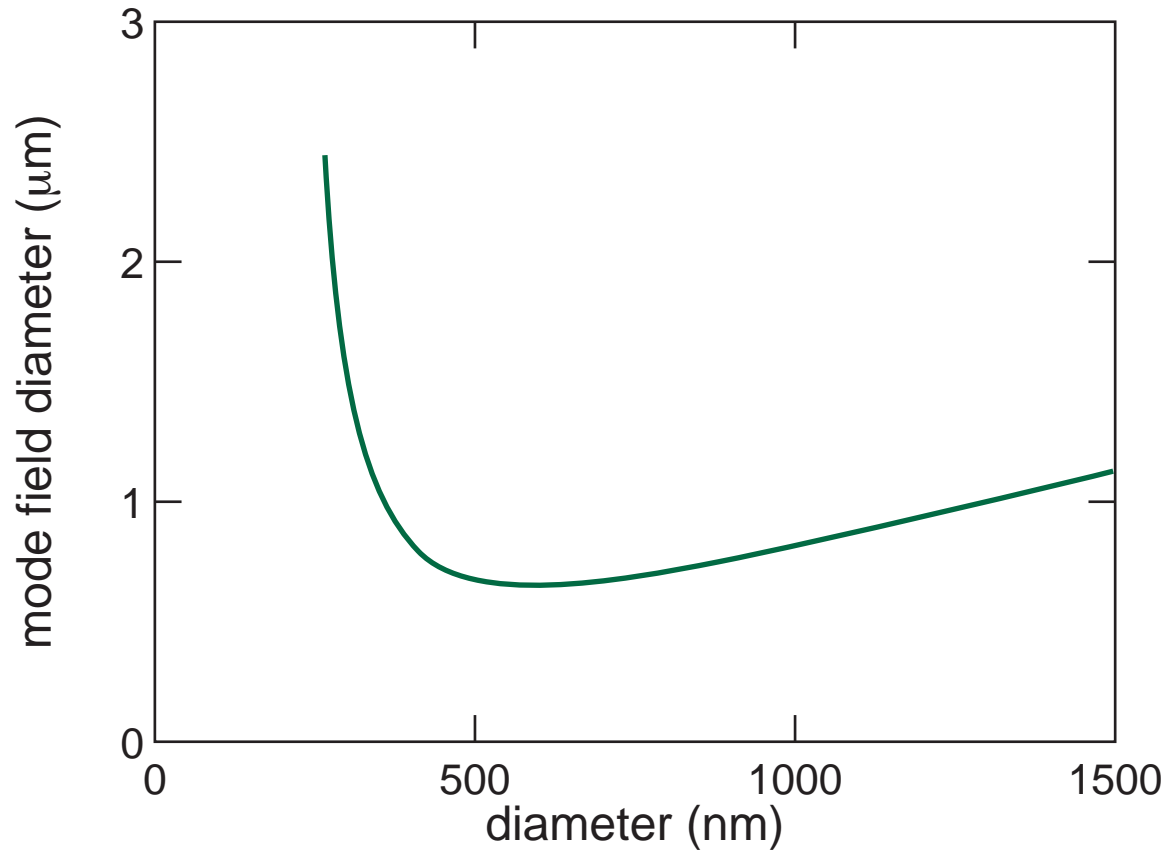


Nanoscale nonlinear optics

strong confinement \longrightarrow **high intensity**

Nanoscale nonlinear optics

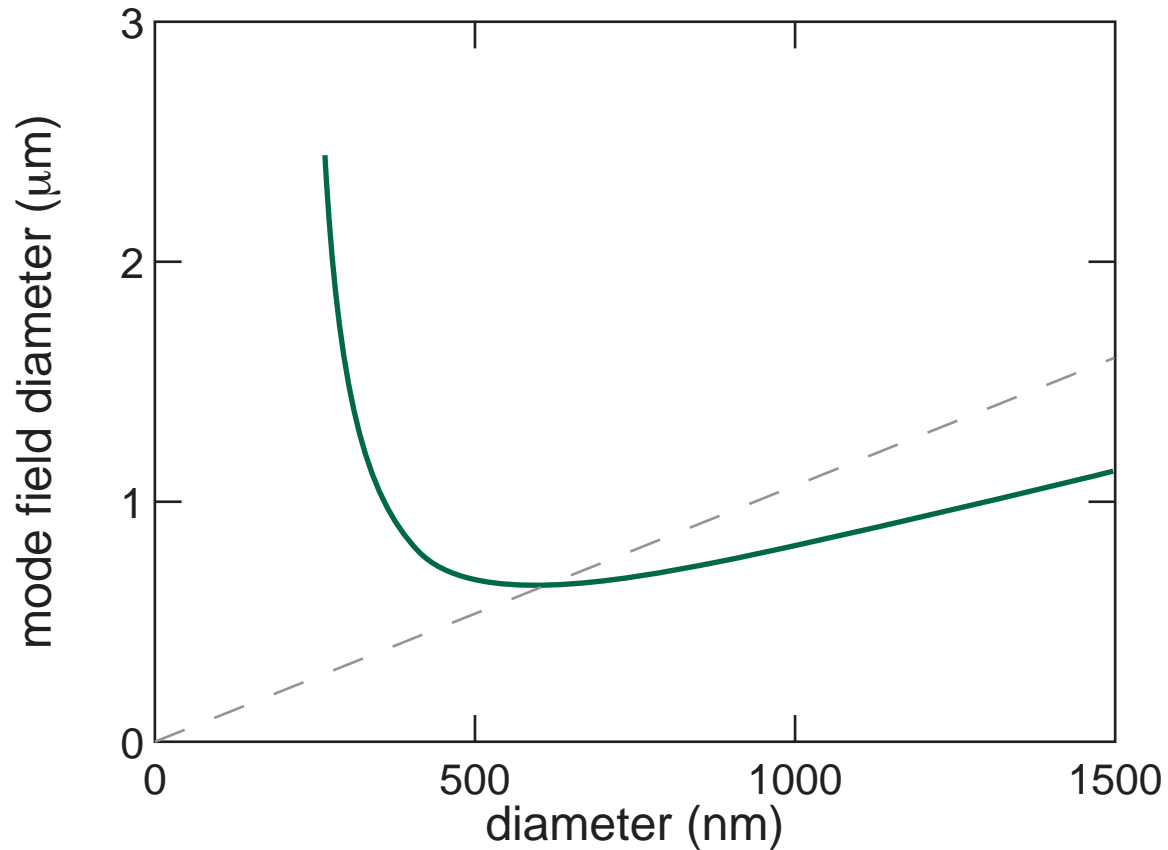
mode field diameter ($\lambda = 800$ nm)



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

Nanoscale nonlinear optics

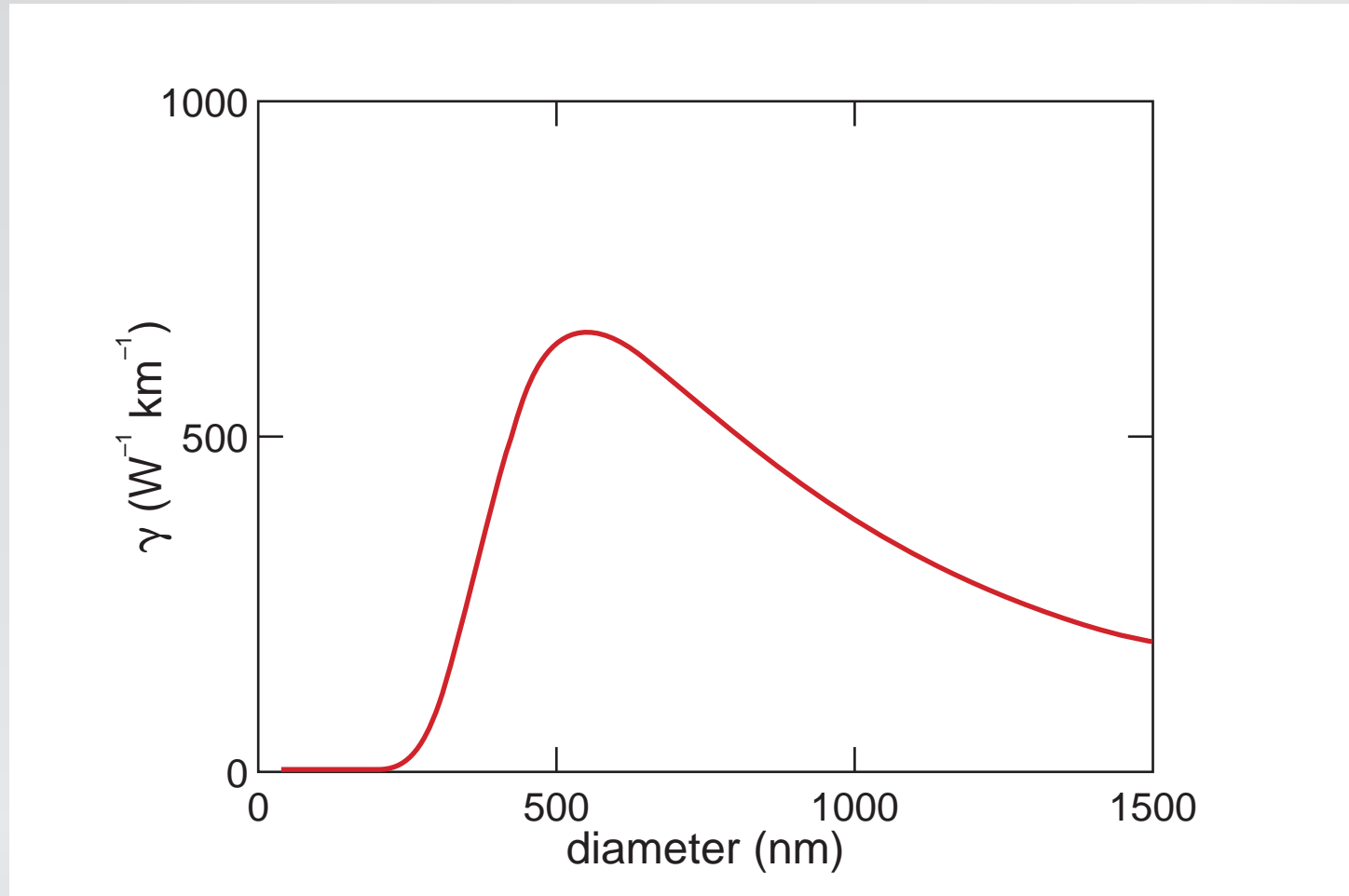
mode field diameter ($\lambda = 800$ nm)



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!

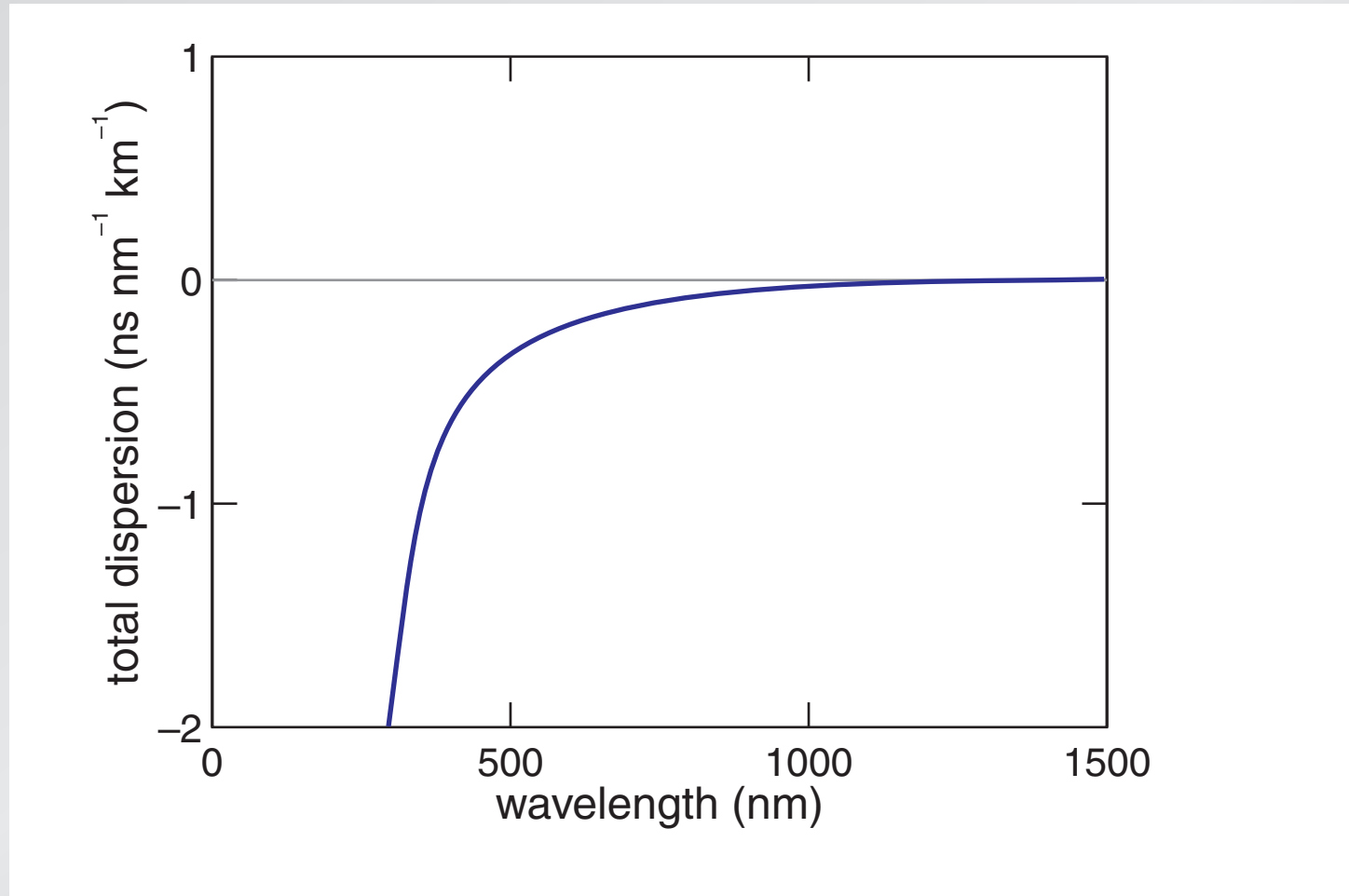
Nanoscale nonlinear optics

dispersion:

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

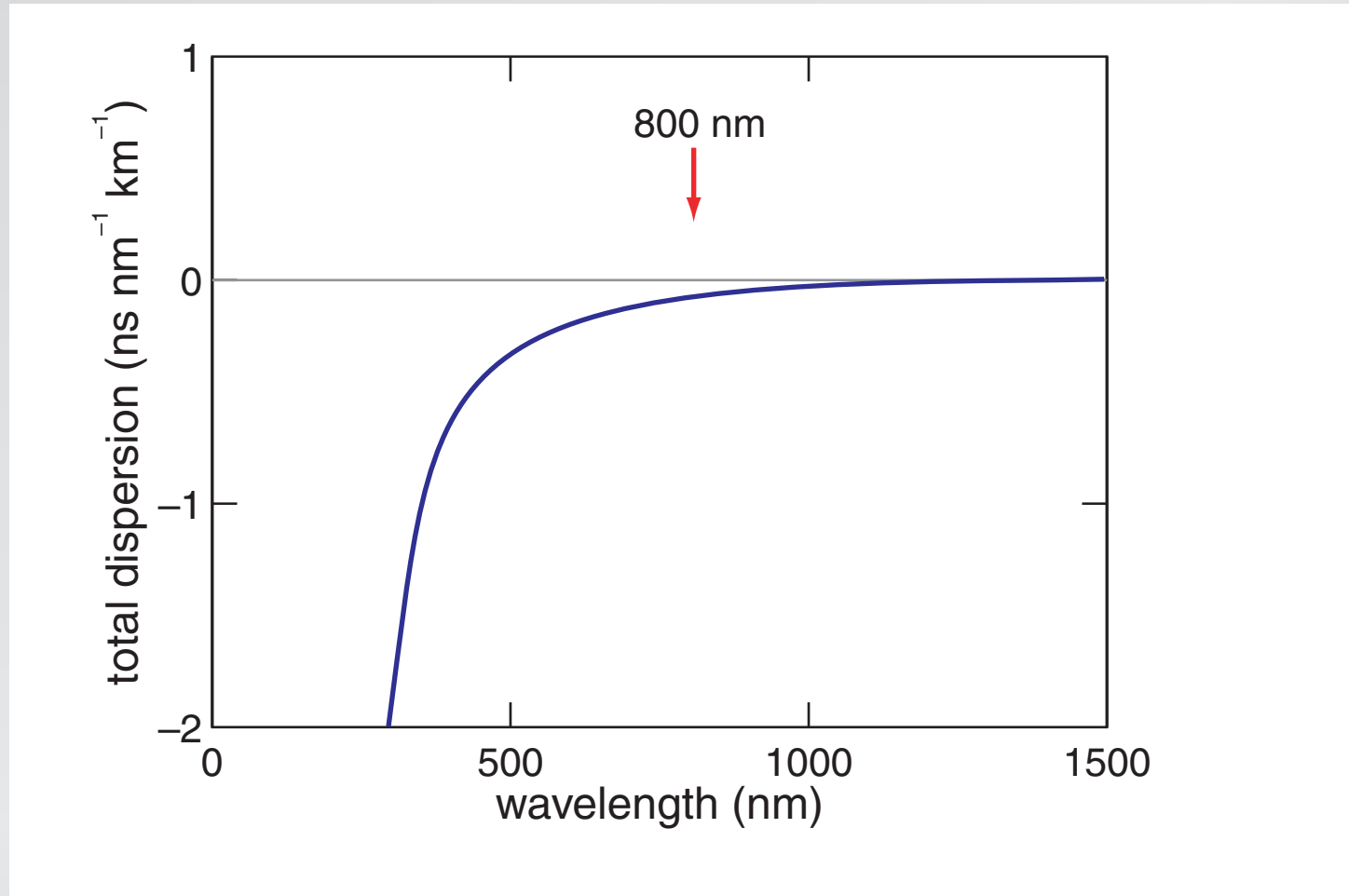
Nanoscale nonlinear optics

waveguide dispersion



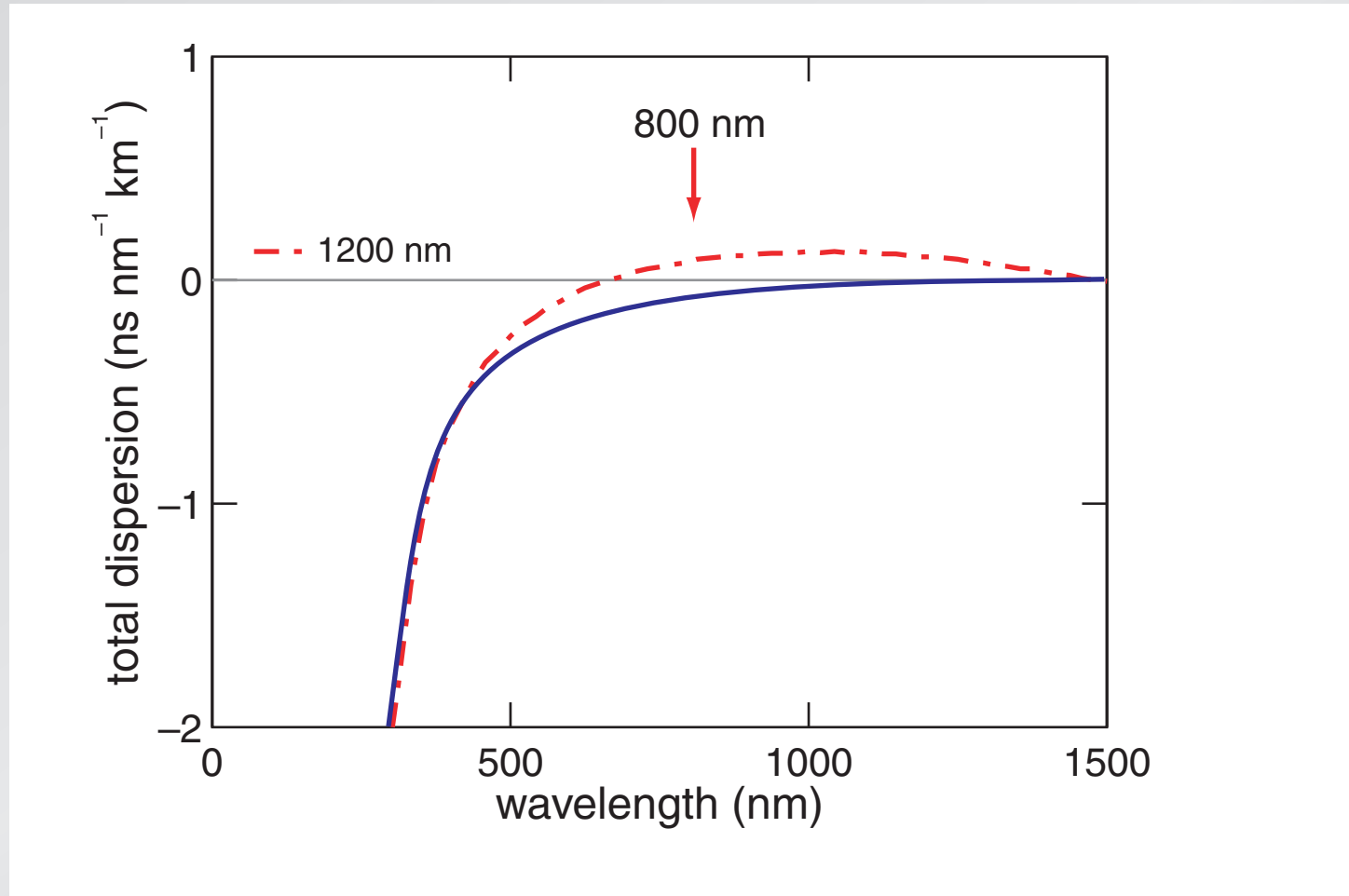
Nanoscale nonlinear optics

waveguide dispersion



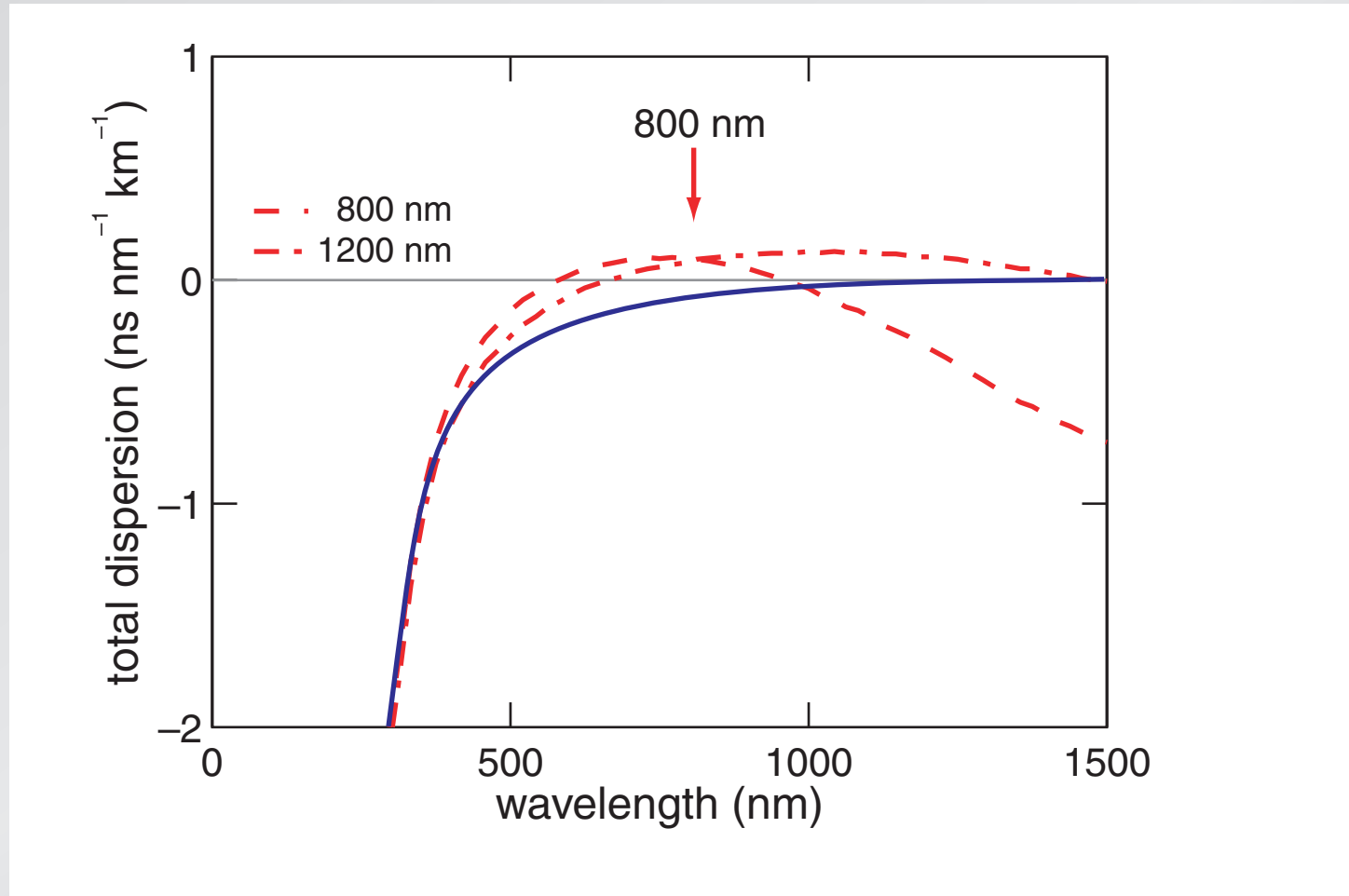
Nanoscale nonlinear optics

waveguide dispersion



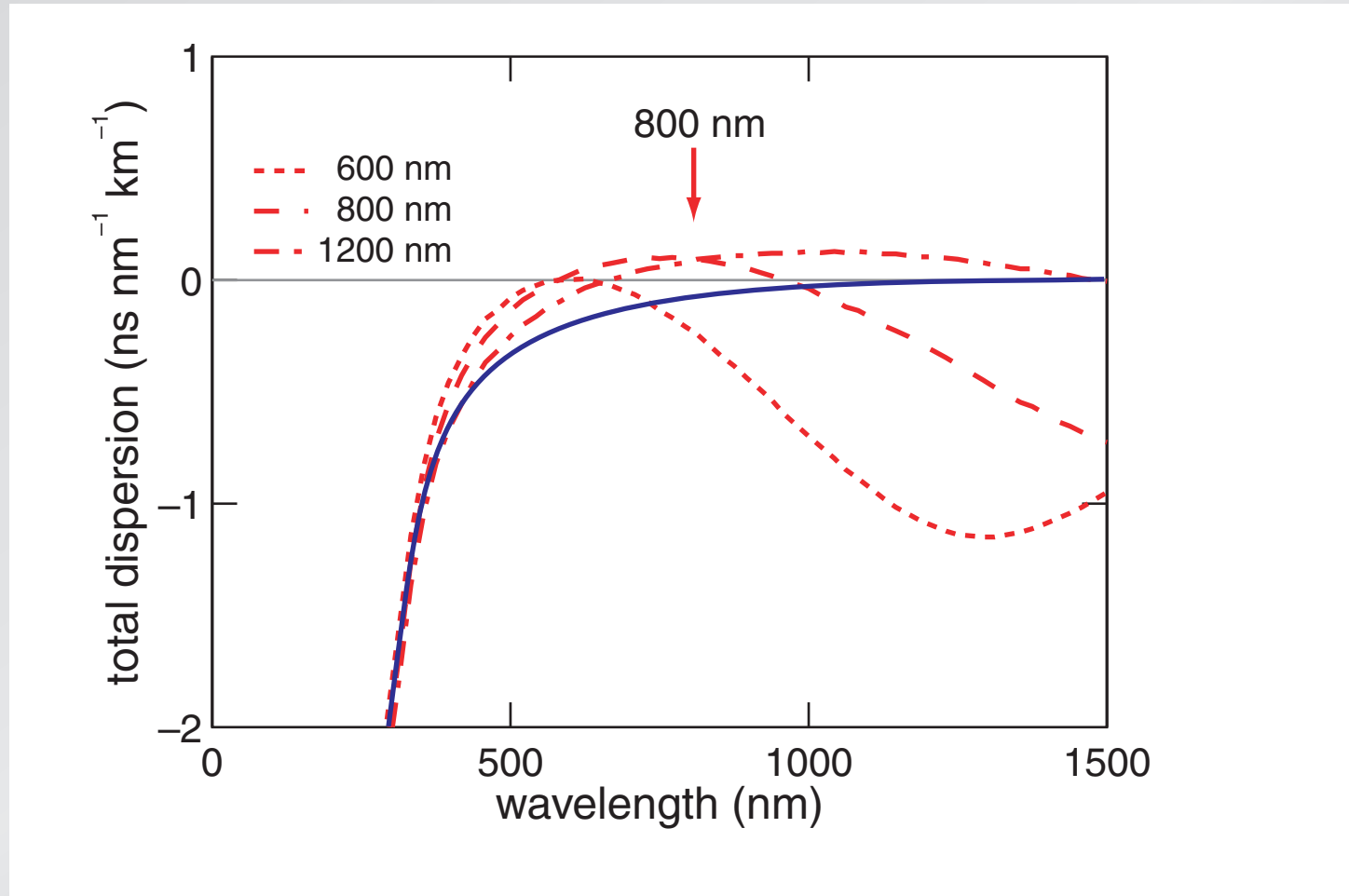
Nanoscale nonlinear optics

waveguide dispersion



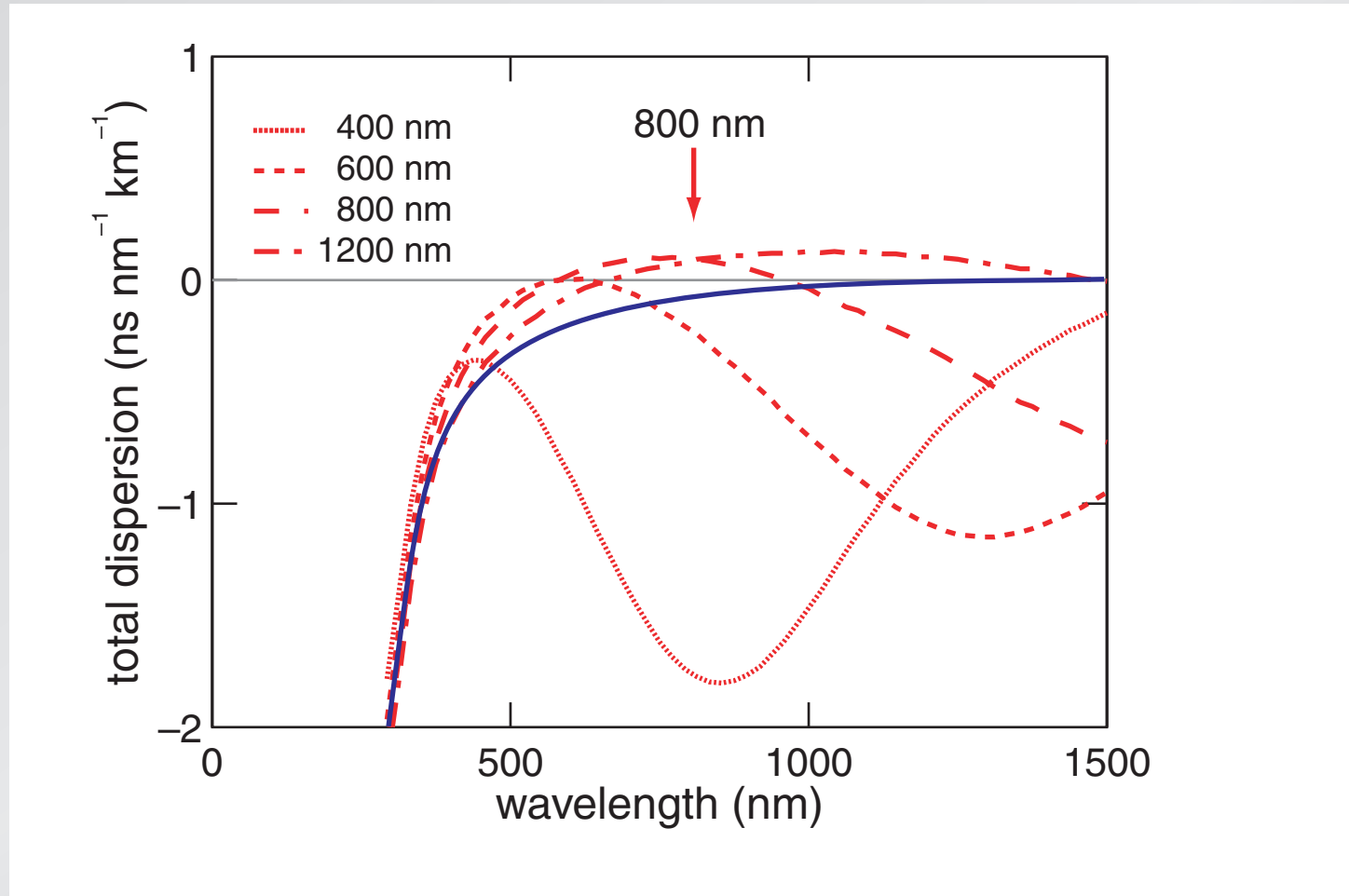
Nanoscale nonlinear optics

waveguide dispersion



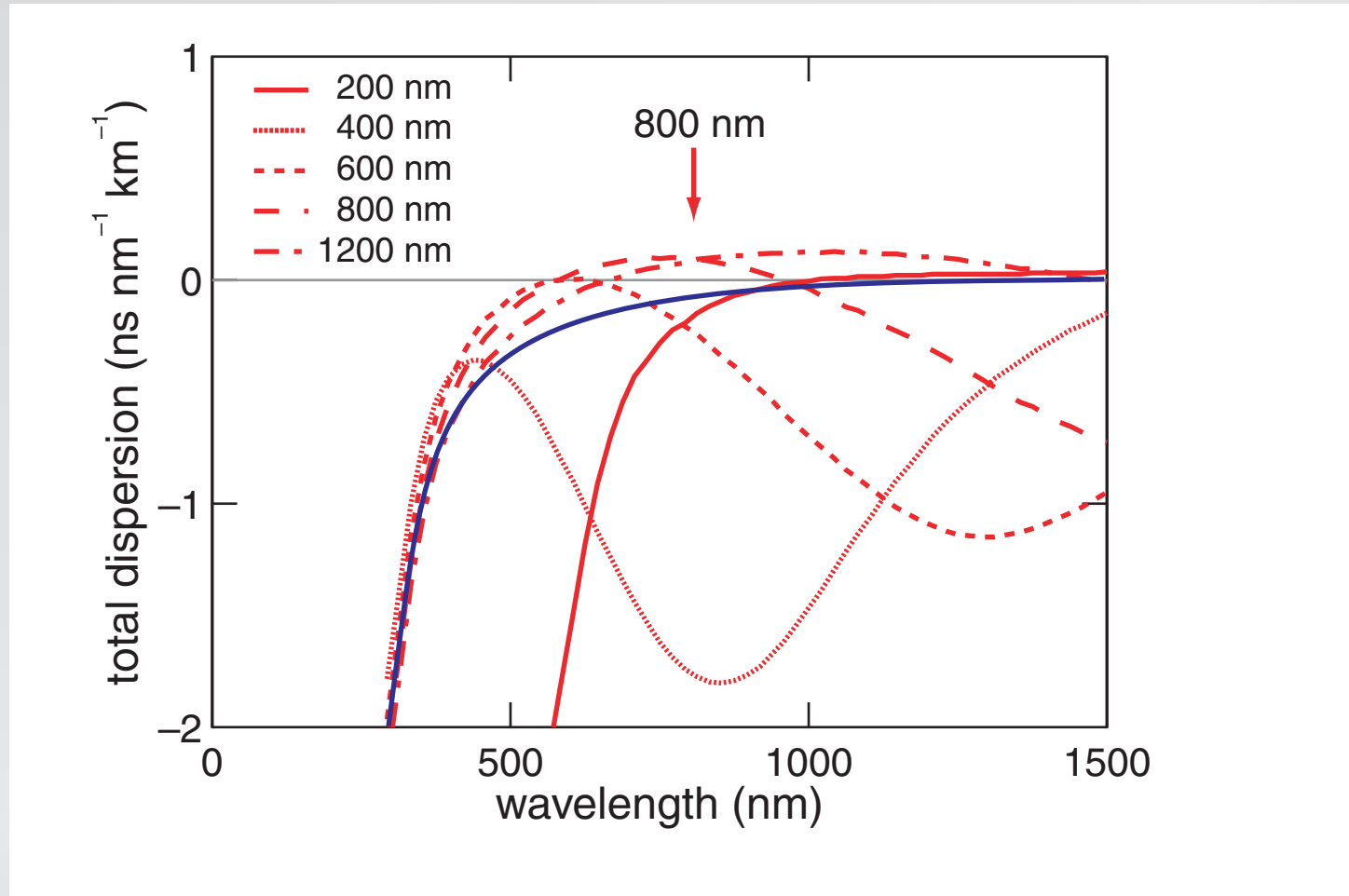
Nanoscale nonlinear optics

waveguide dispersion



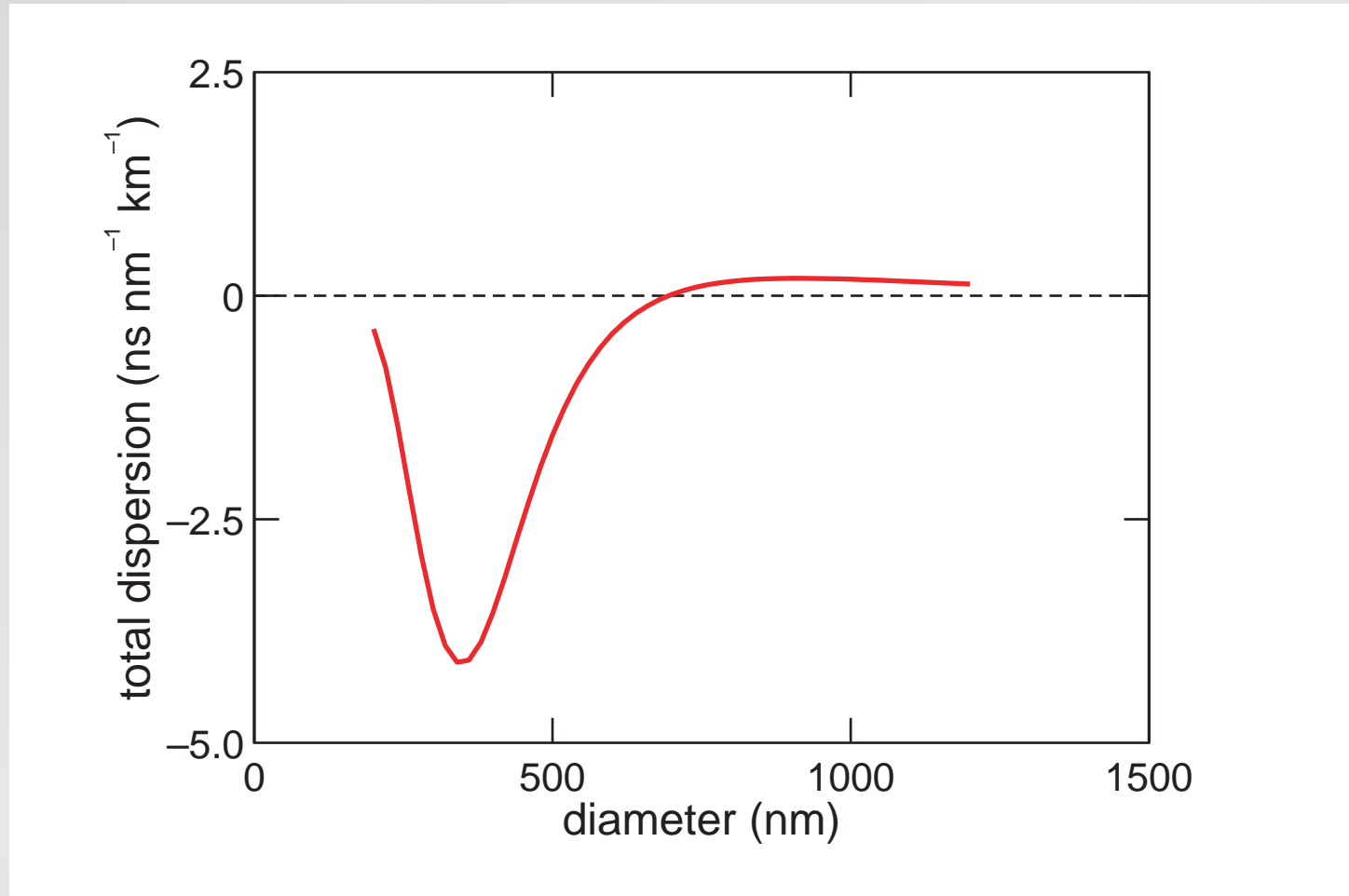
Nanoscale nonlinear optics

waveguide dispersion



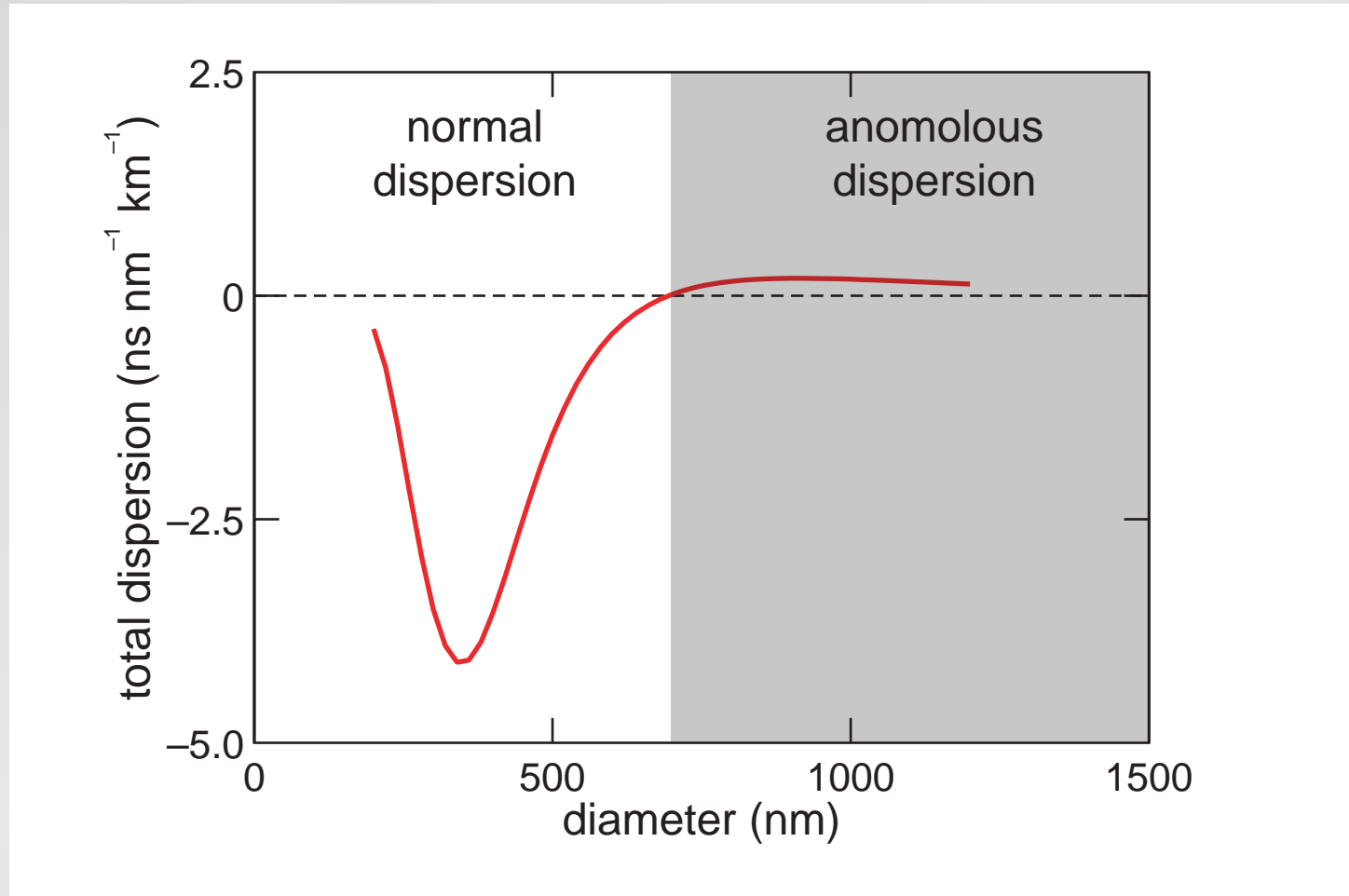
Nanoscale nonlinear optics

waveguide dispersion



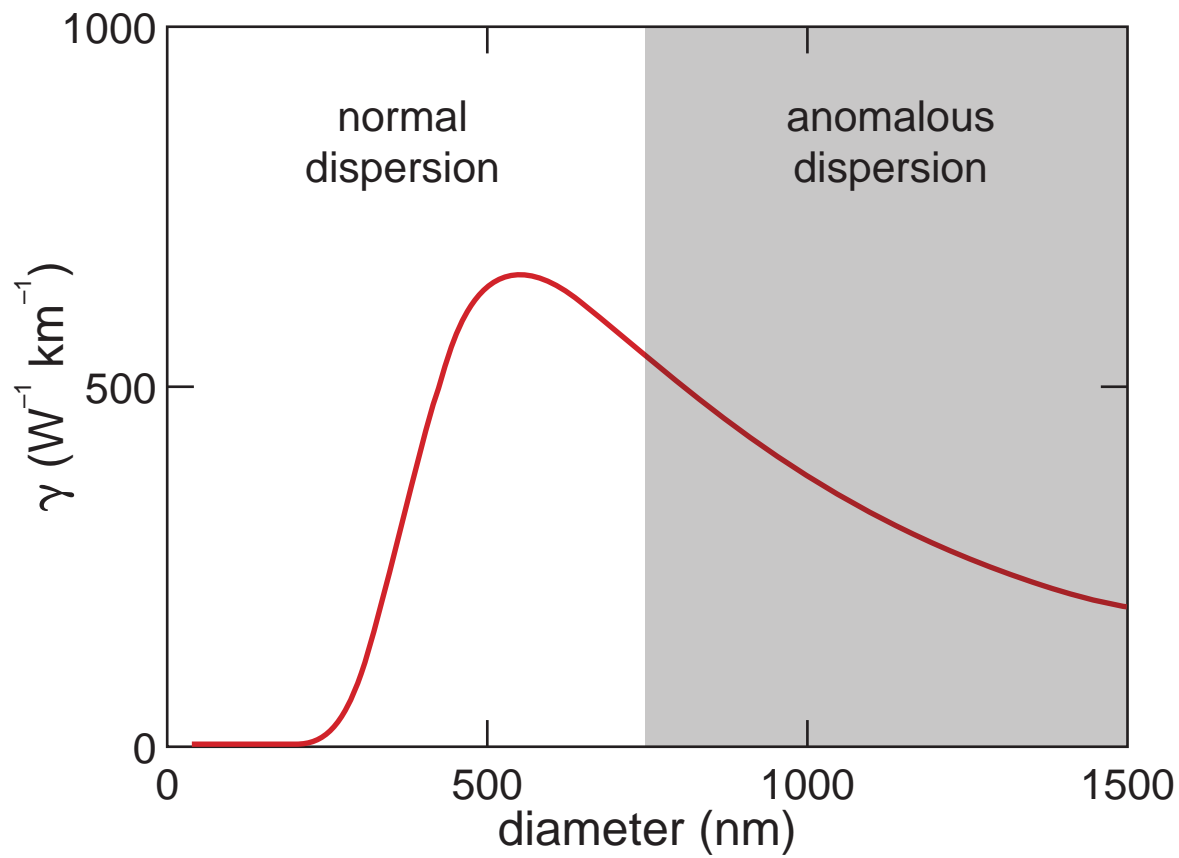
Nanoscale nonlinear optics

waveguide dispersion



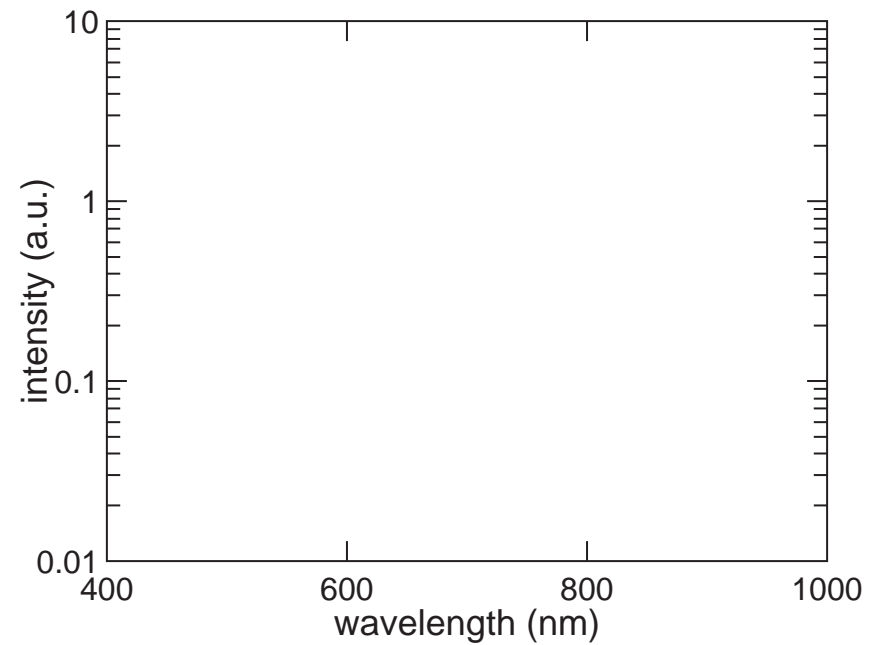
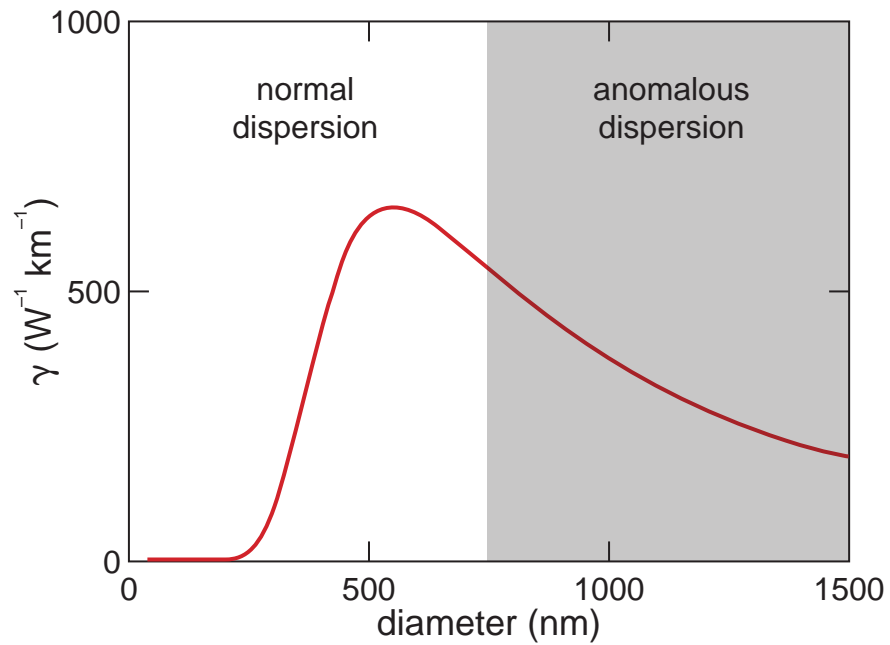
Nanoscale nonlinear optics

nonlinear parameter



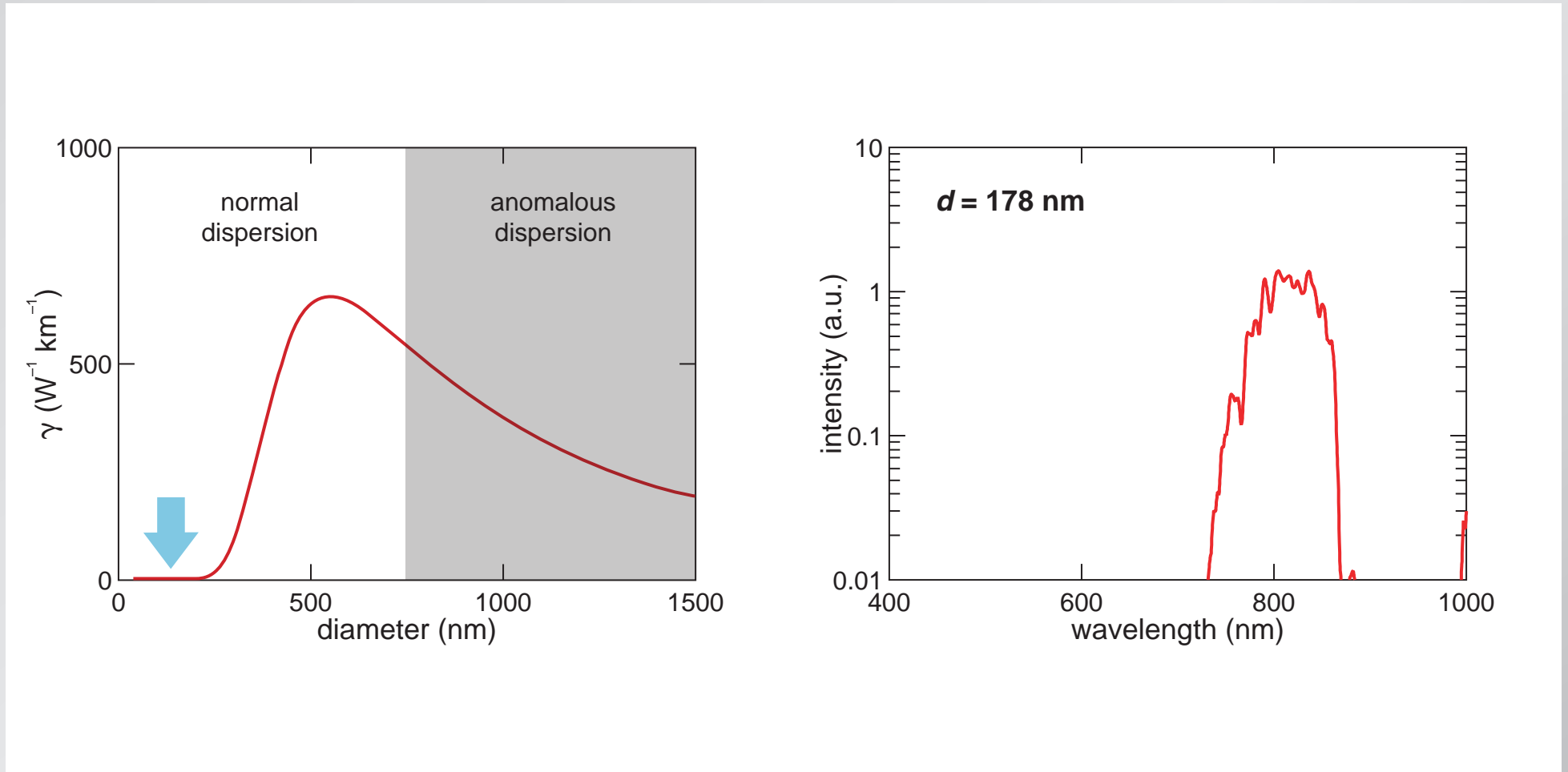
Nanoscale nonlinear optics

nanowire continuum generation



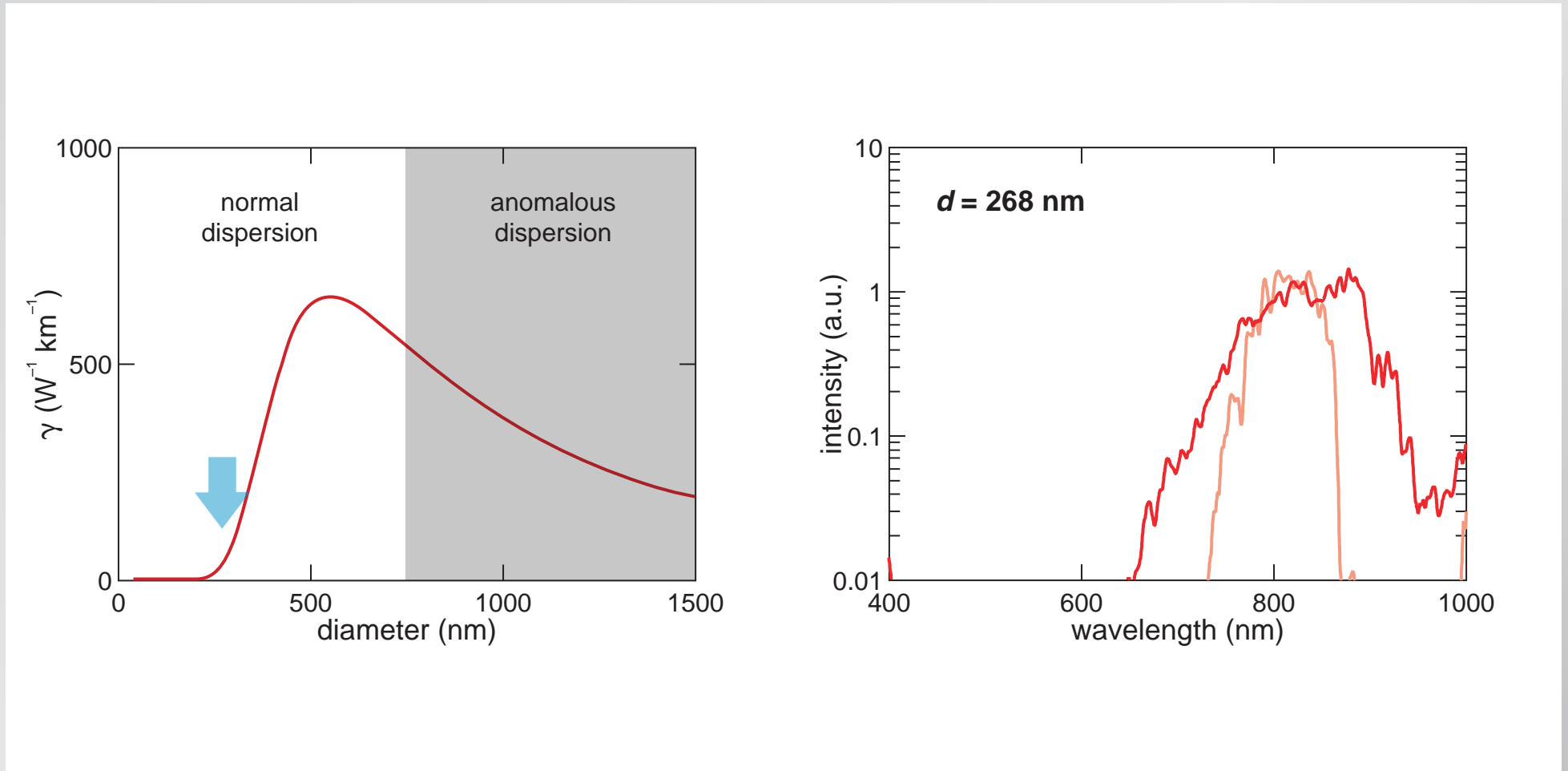
Nanoscale nonlinear optics

nanowire continuum generation



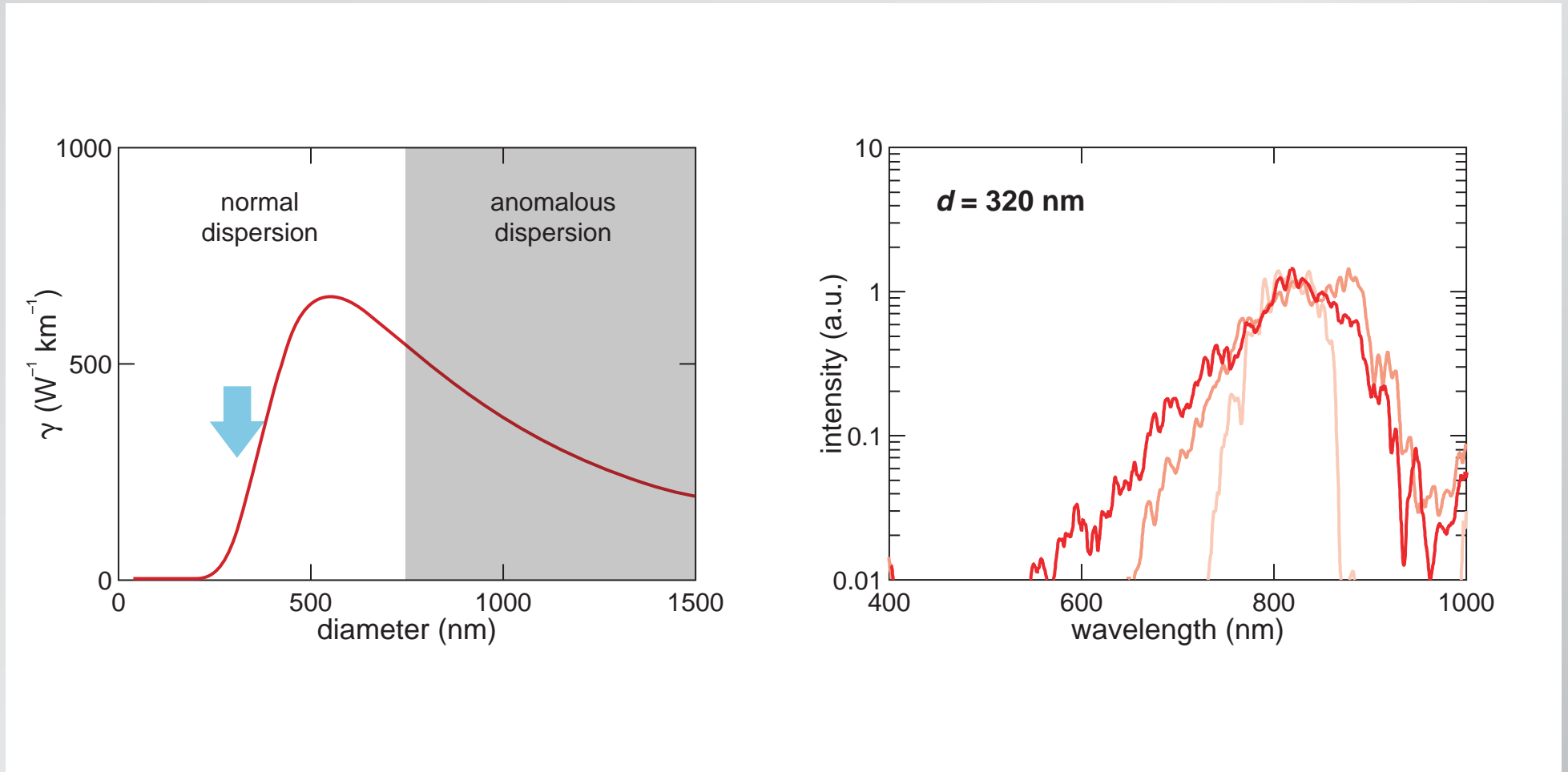
Nanoscale nonlinear optics

nanowire continuum generation



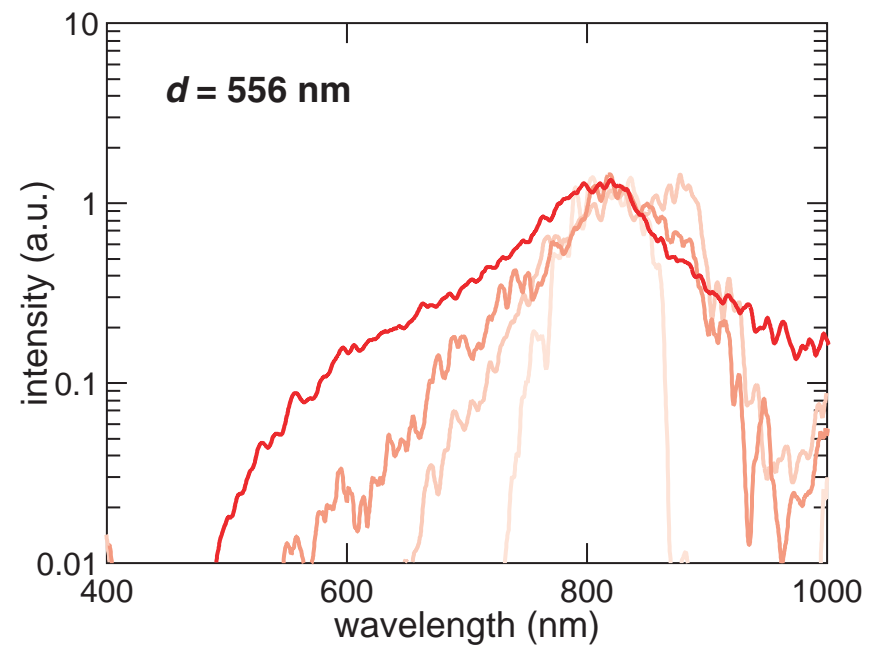
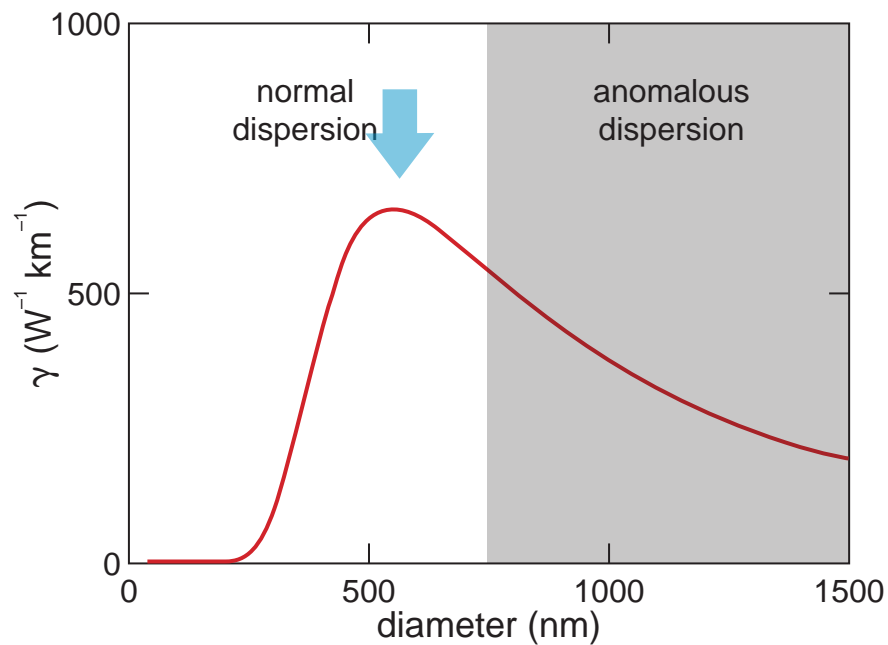
Nanoscale nonlinear optics

nanowire continuum generation



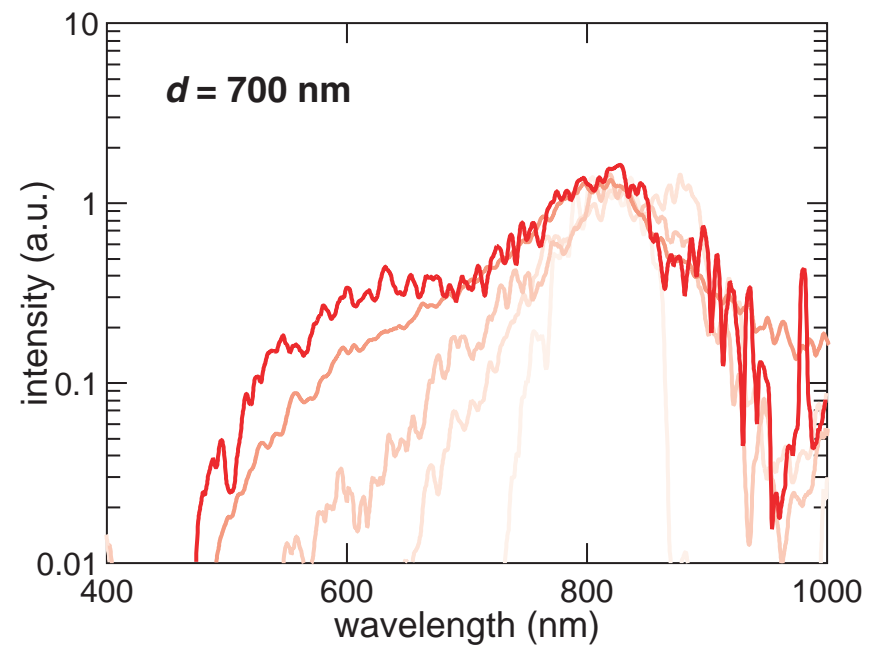
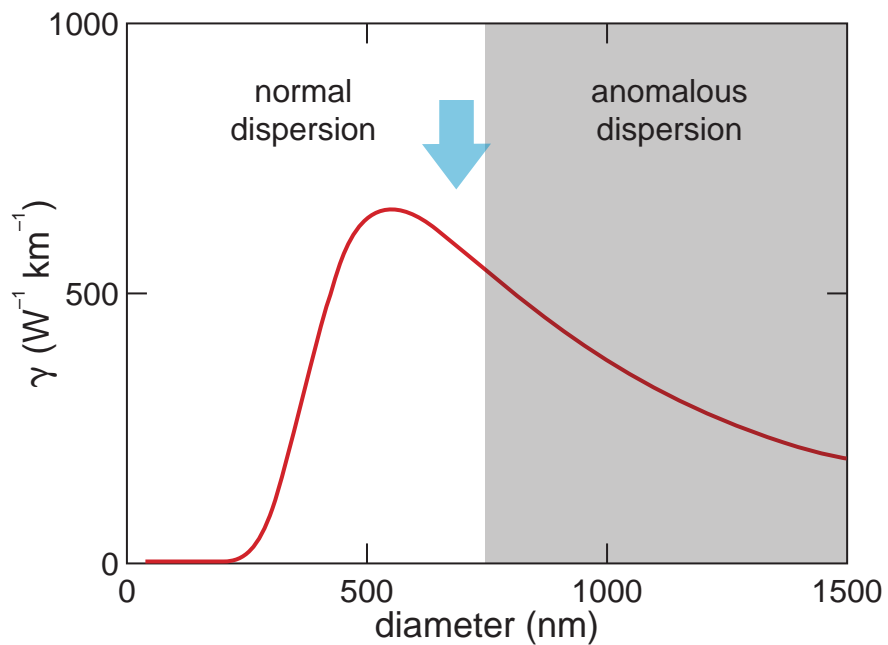
Nanoscale nonlinear optics

nanowire continuum generation



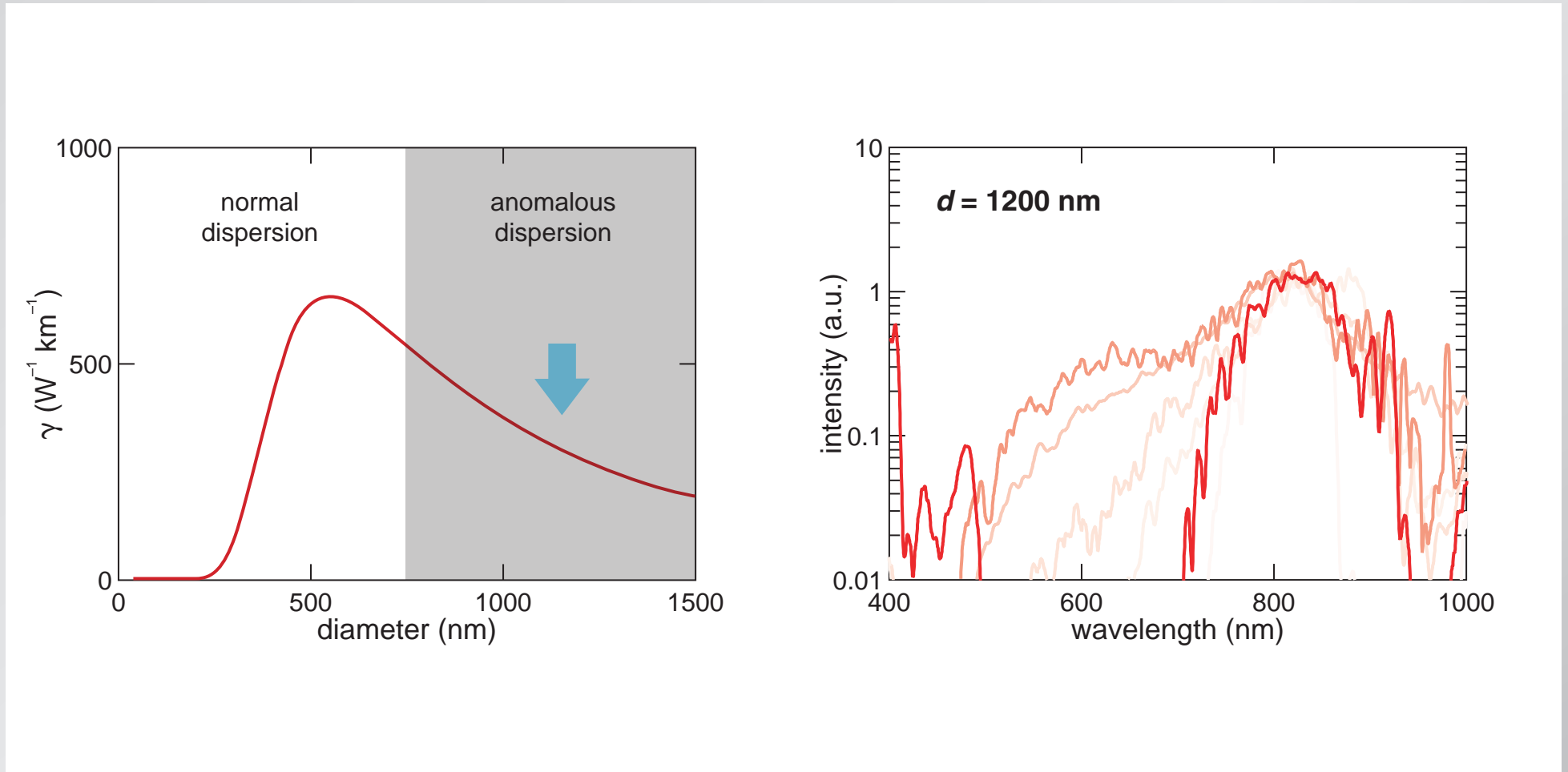
Nanoscale nonlinear optics

nanowire continuum generation



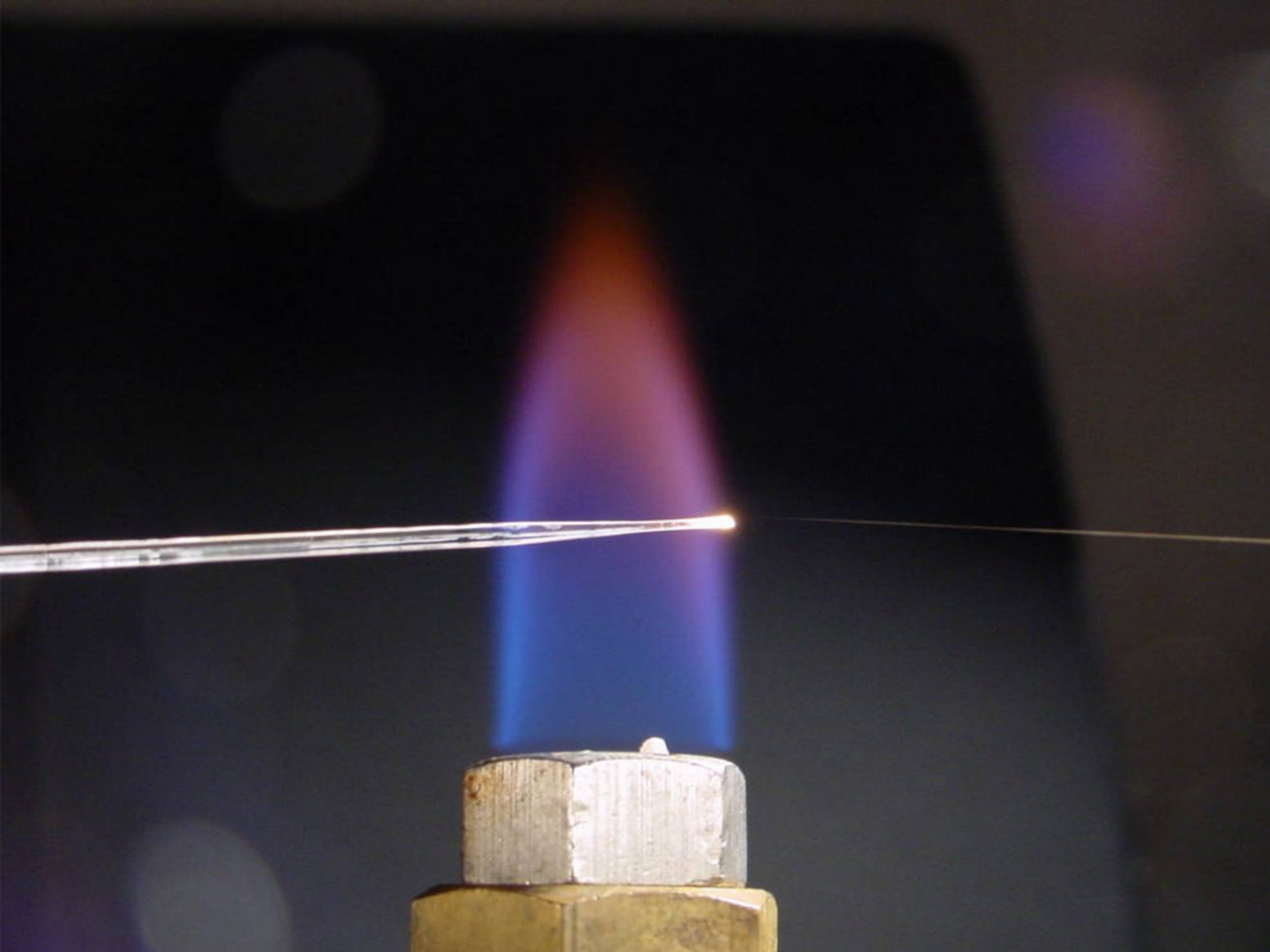
Nanoscale nonlinear optics

nanowire continuum generation

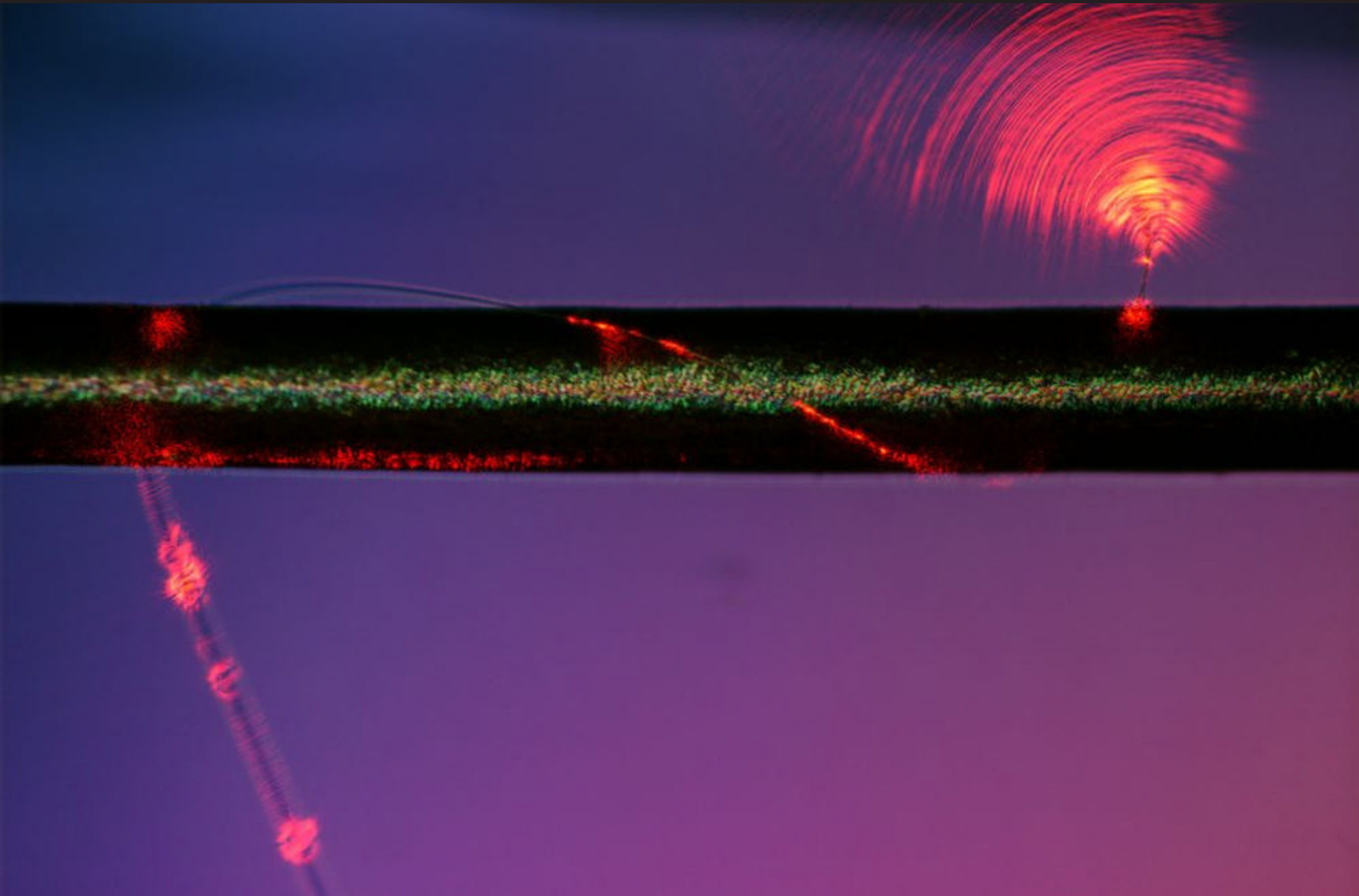


Nanoscale nonlinear optics

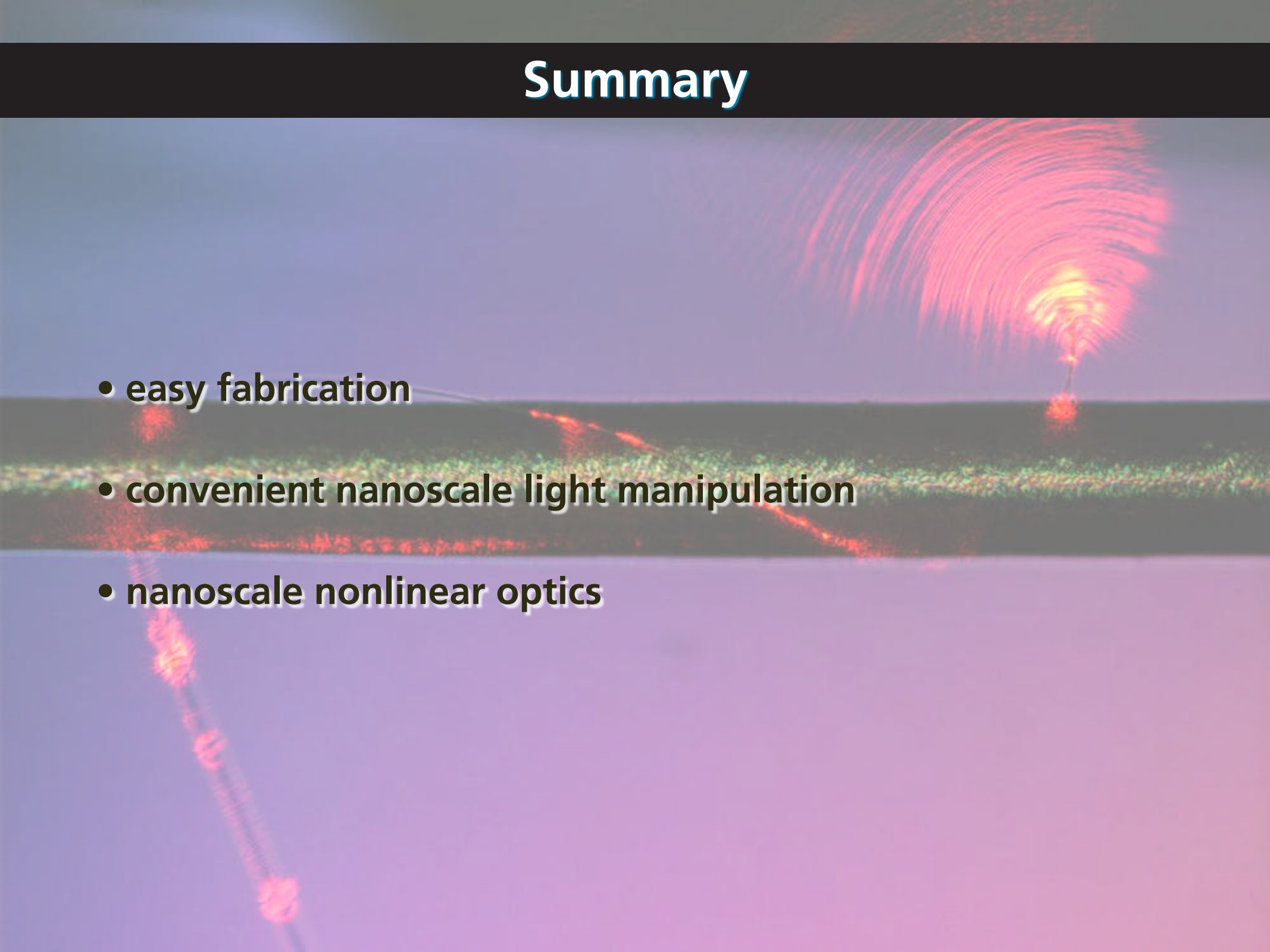
energy in nanowire < 100 pJ!



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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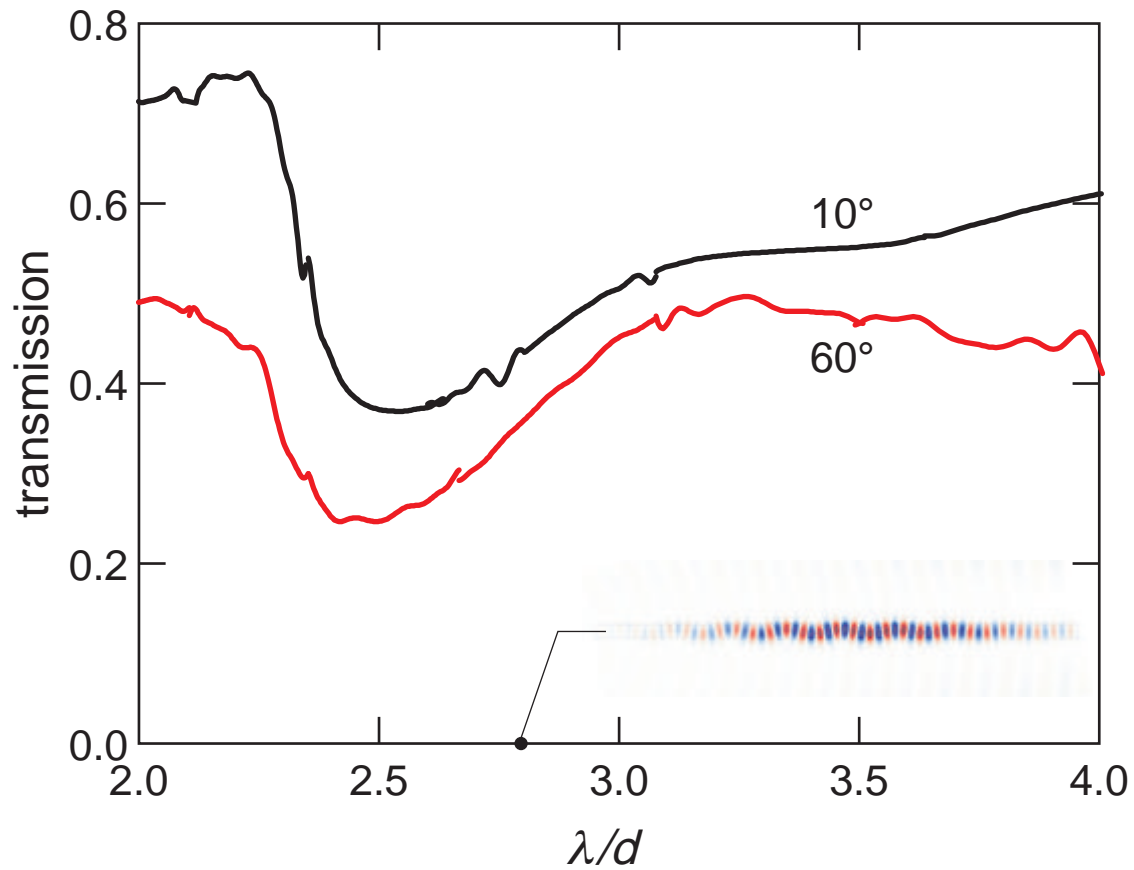
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Manipulating light at the nanoscale

transmission spectrum



Manipulating light at the nanoscale

transmission spectrum

