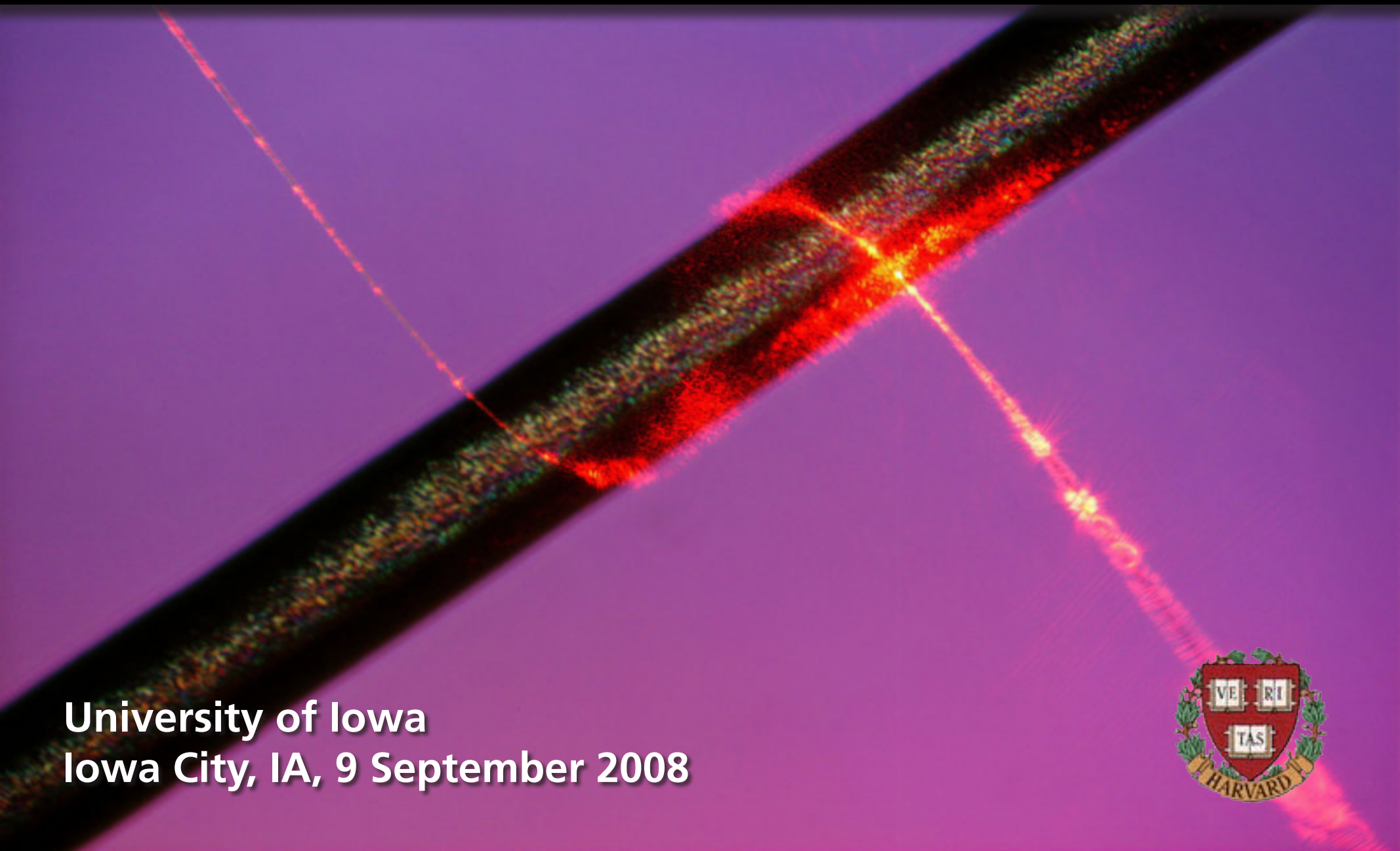


# Wrapping light around a hair



University of Iowa  
Iowa City, IA, 9 September 2008

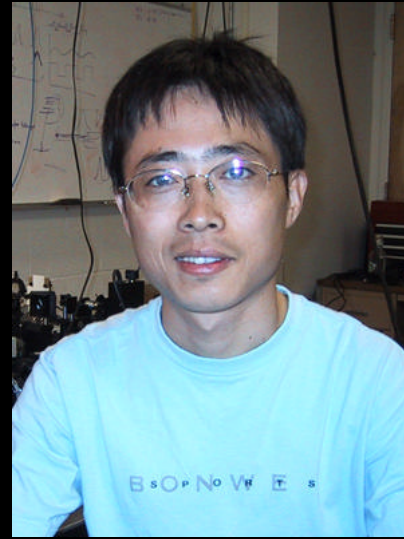




**Rafael Gattass**



**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**

**Xuwen Chen (Zhejiang)**

**Zhanghua Han (Zhejiang)**

**Dr. Sailing He (Zhejiang)**

**Liu Liu (Zhejiang)**

**Dr. Jingyi Lou (Zhejiang)**

**Dr. Ray Mariella (LLNL)**

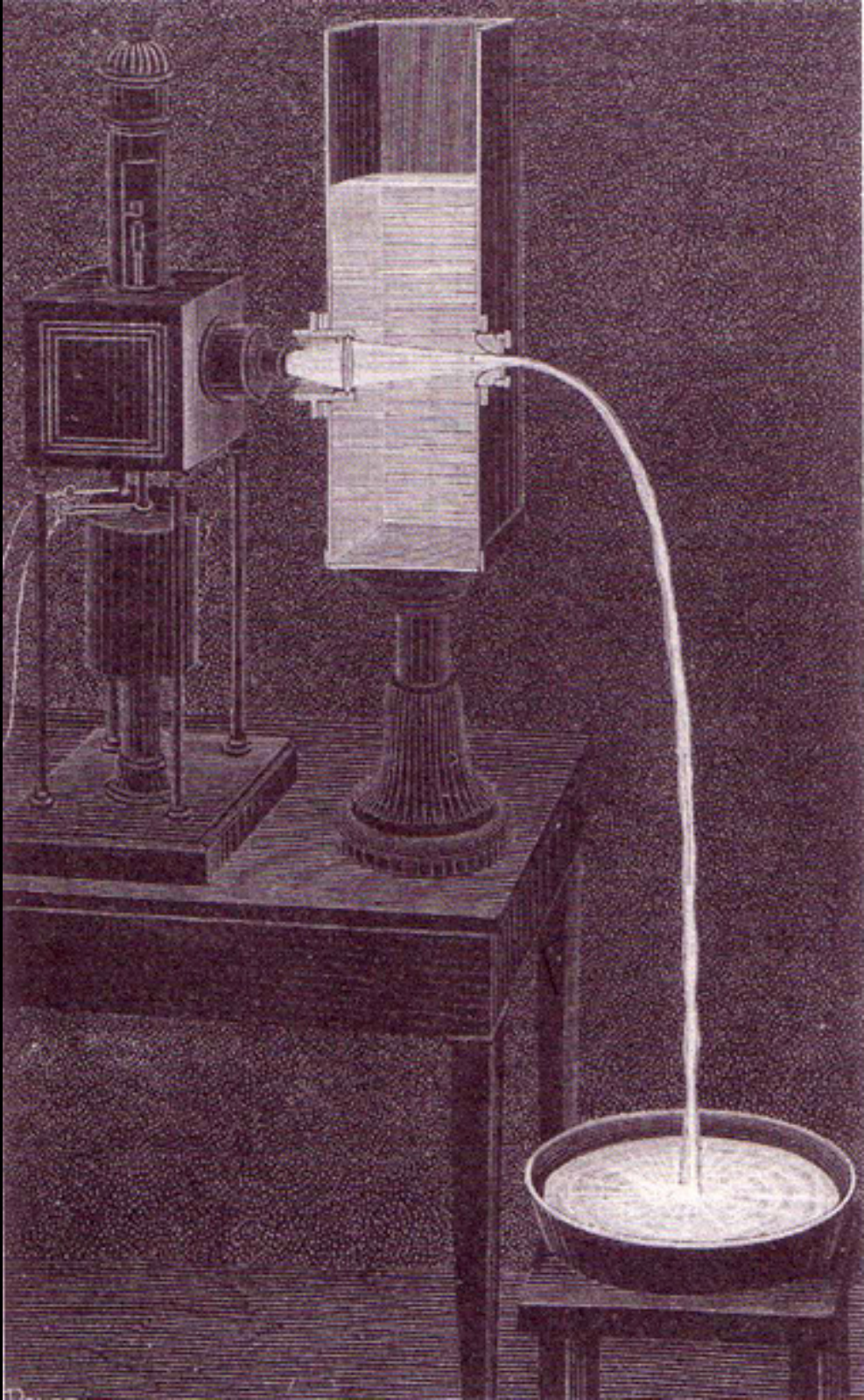
**Prof. Frank Marlow (MPI Mülheim)**

**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.

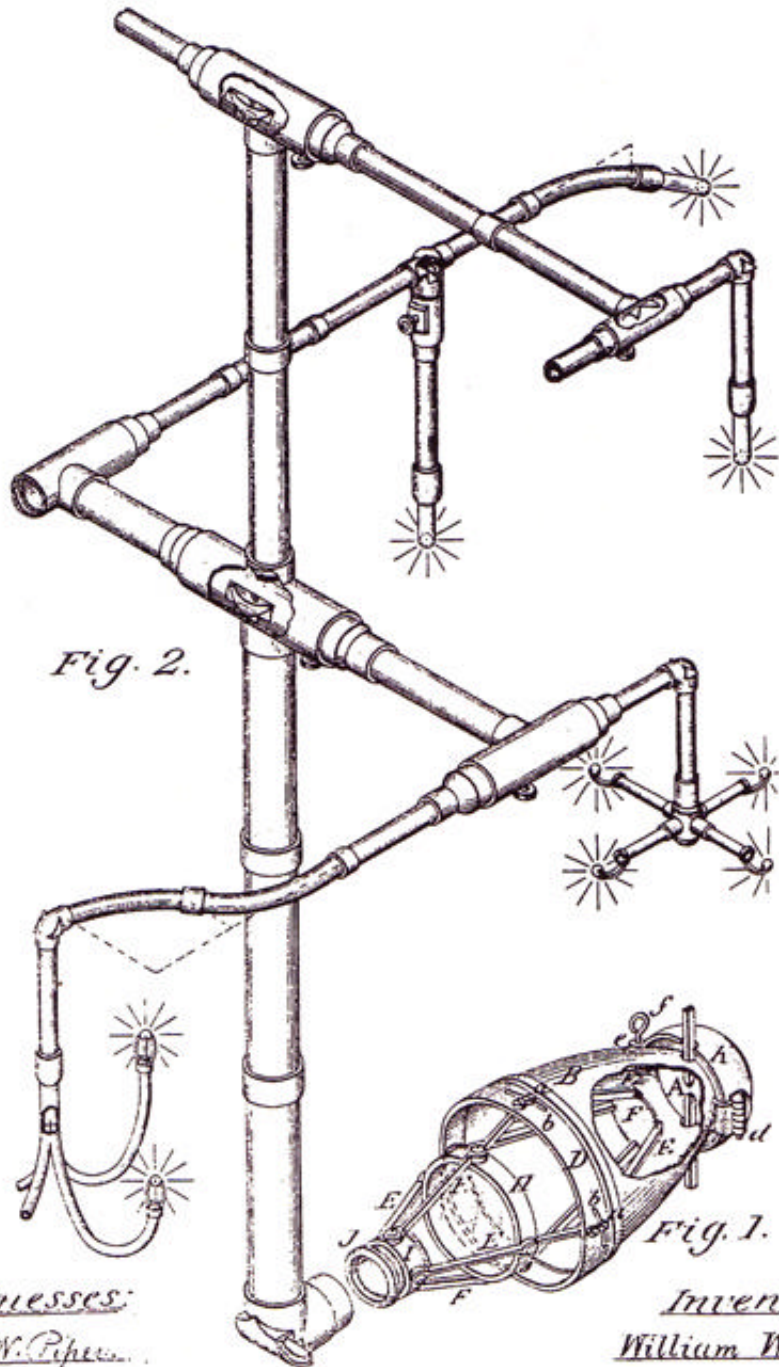


Fig. 2.

Fig. 1.

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

Inventor:  
*William Wheeler*  
 by attorney  
*[Signature]*

US Patent 247, 229 (1881)

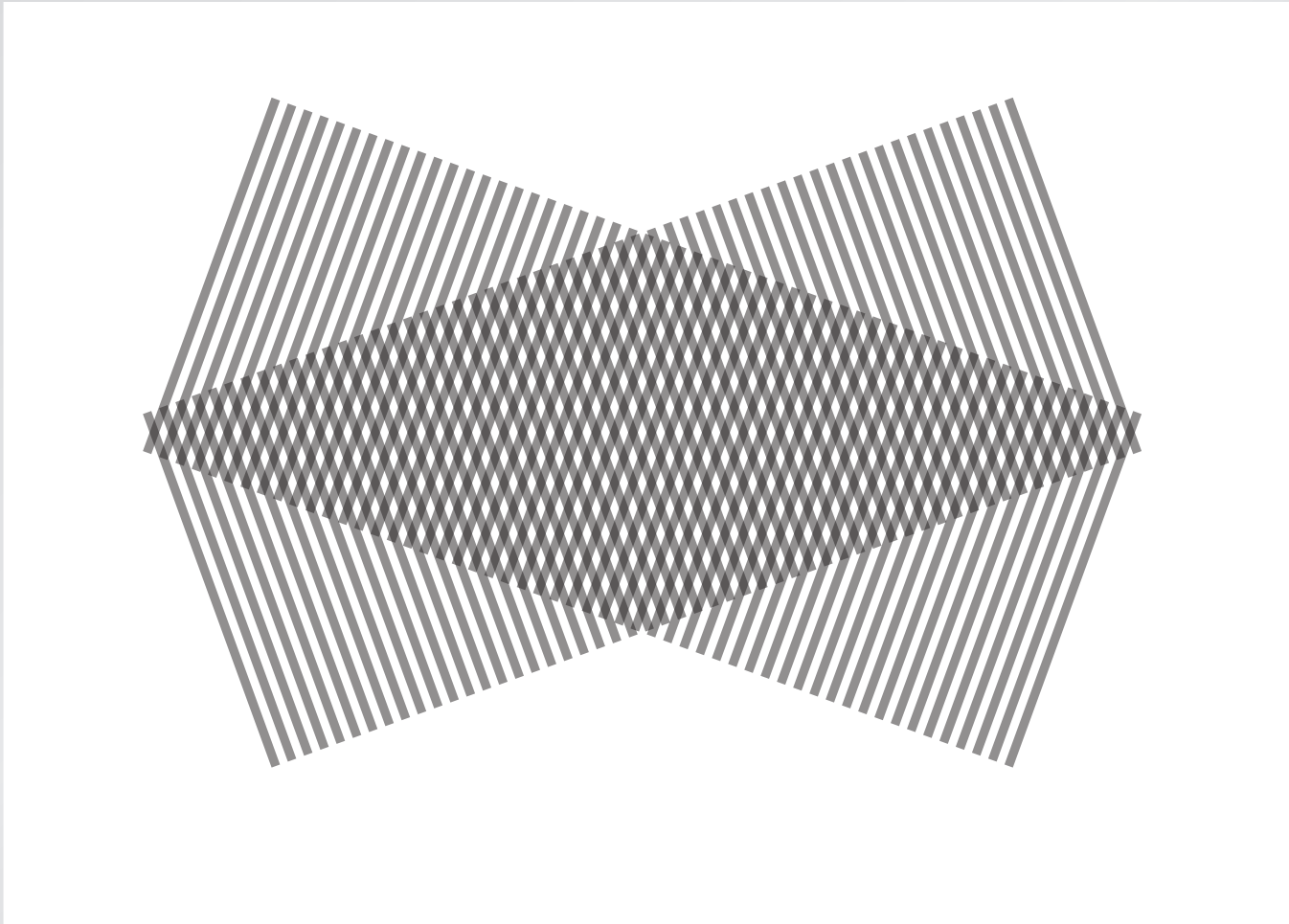
# Outline

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



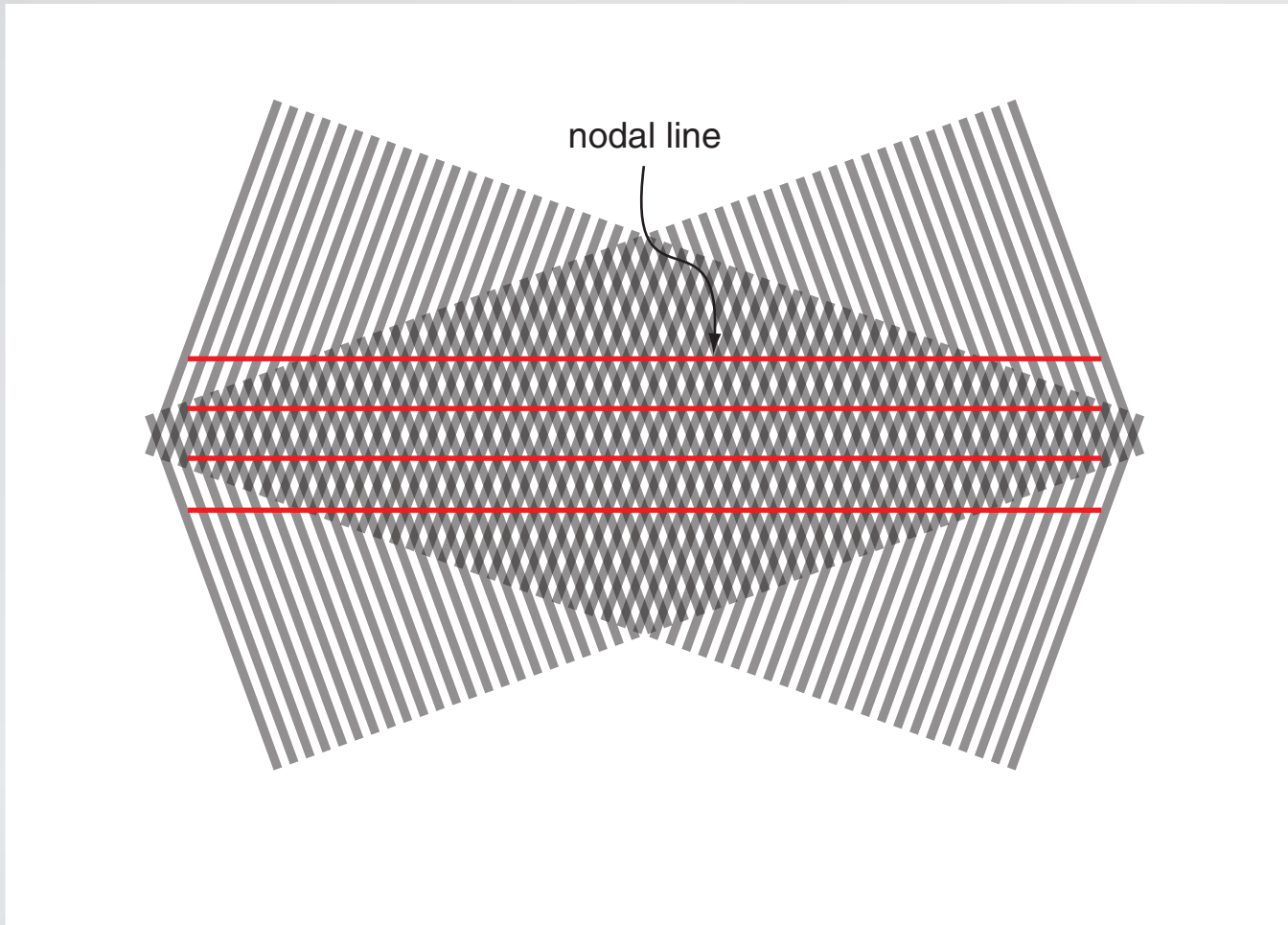
# Waveguiding

two crossed planar waves...



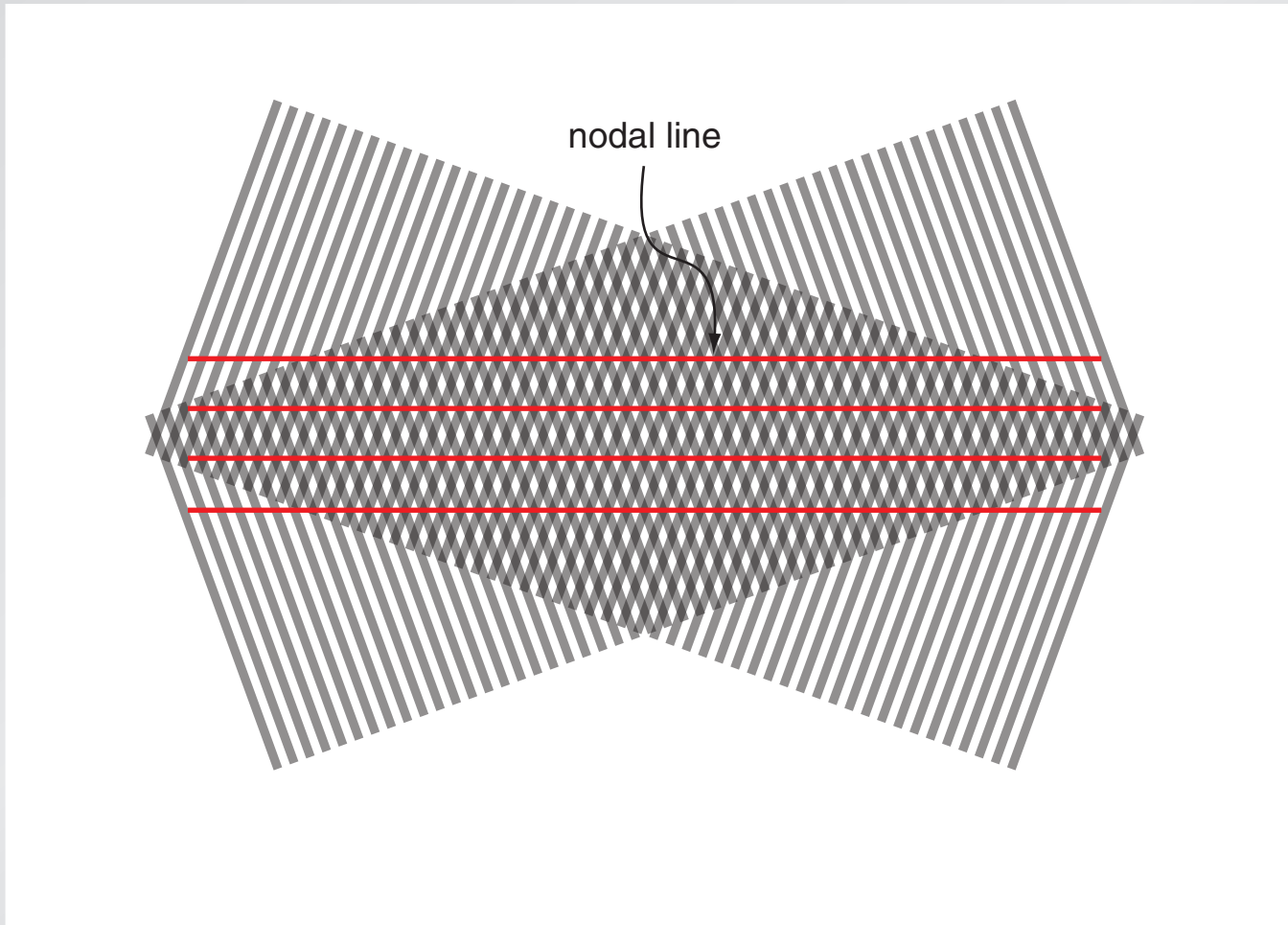
# Waveguiding

...cause an interference pattern



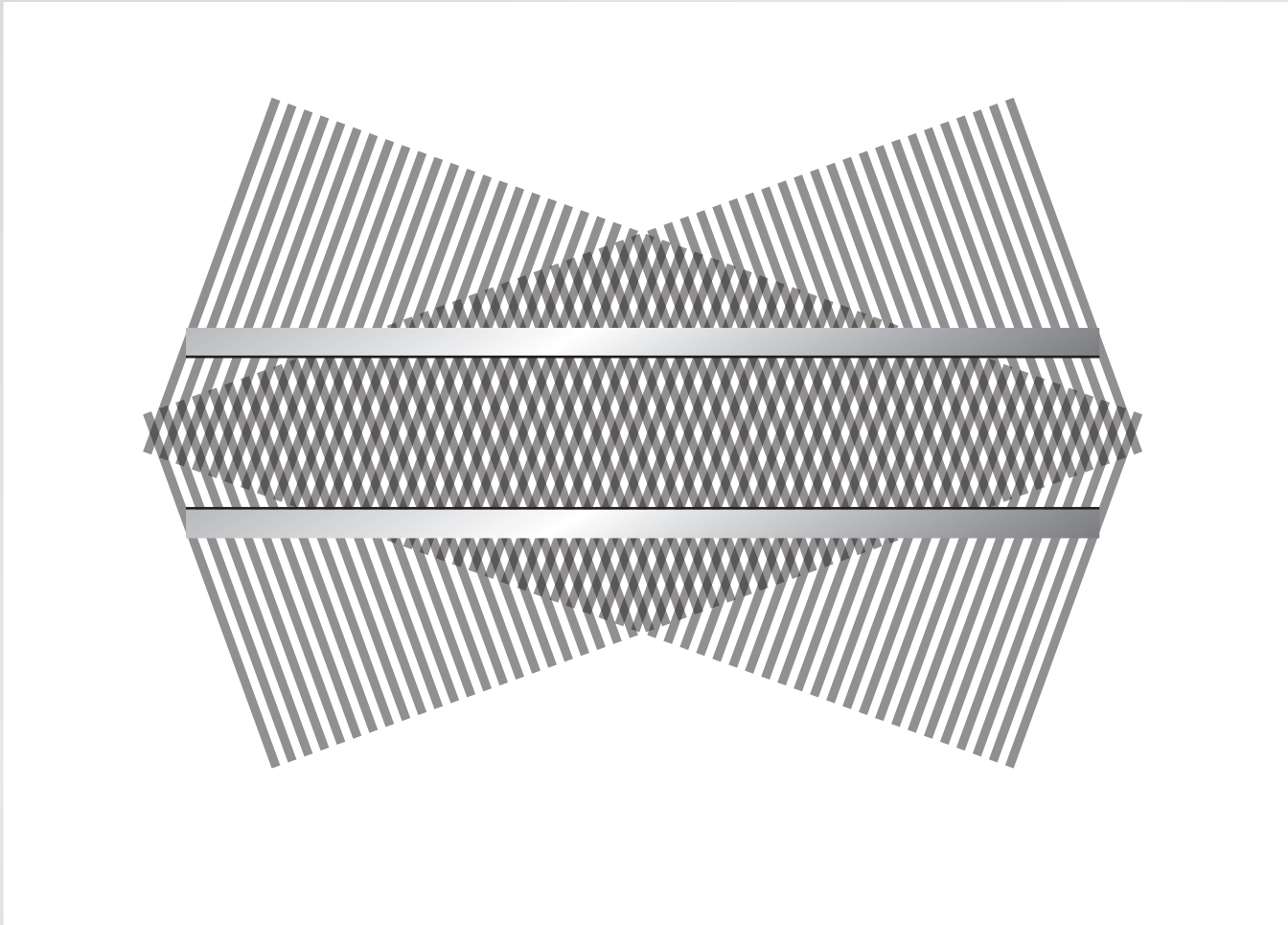
# Waveguiding

$E = 0$  on the nodal lines



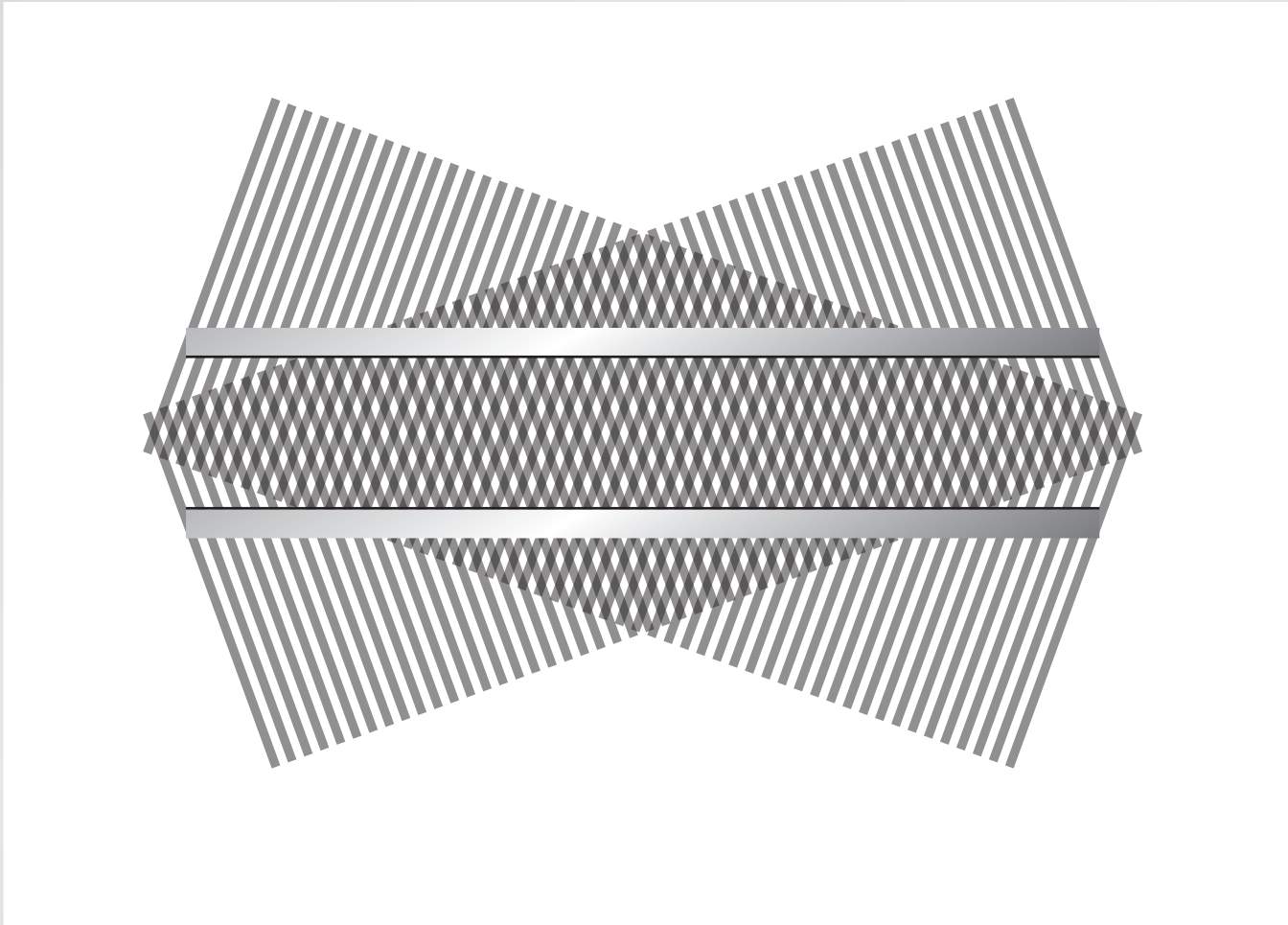
# Waveguiding

...satisfying boundary conditions for planar-mirror waveguide



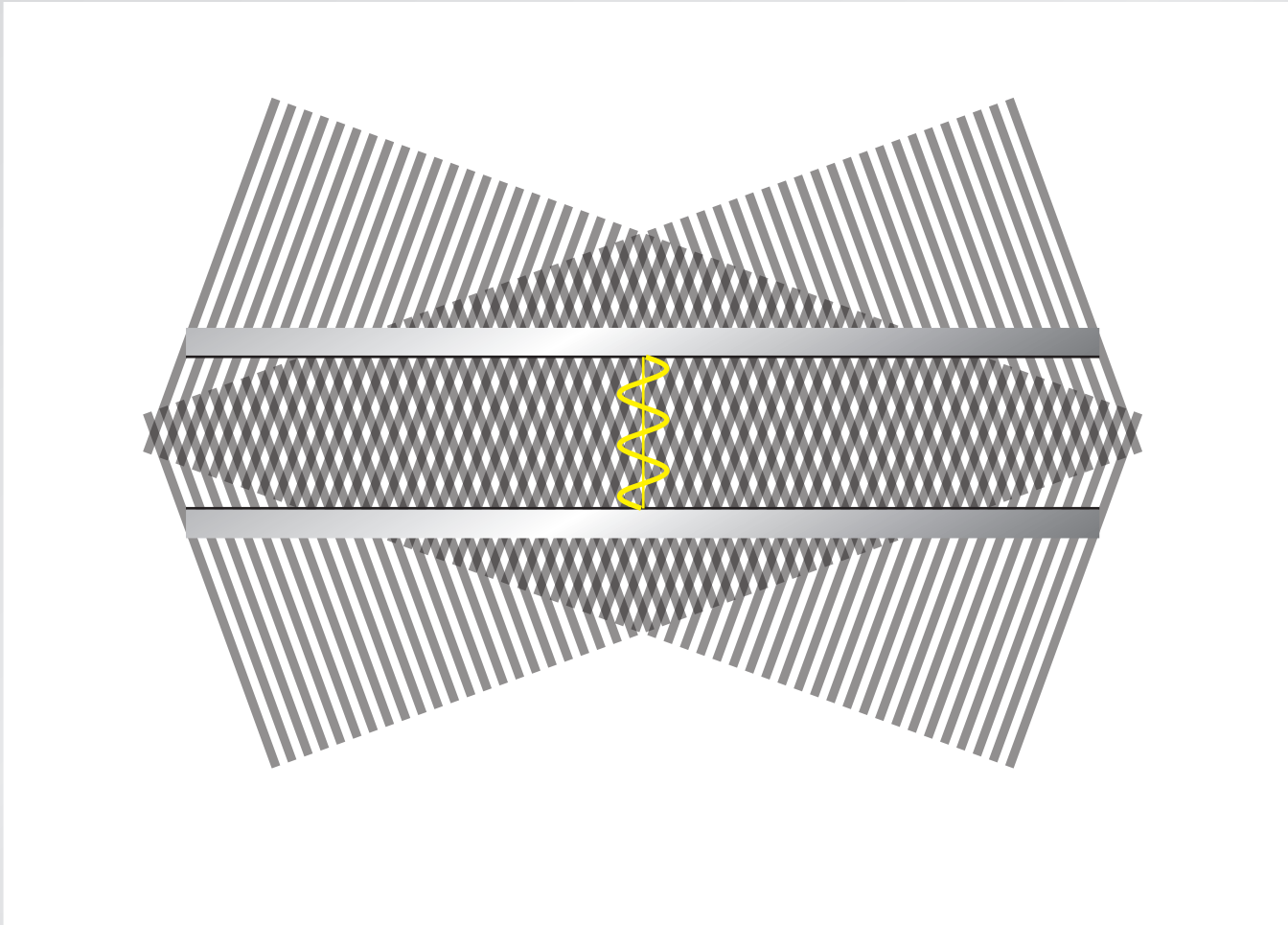
# Waveguiding

transverse standing wave, traveling along axis



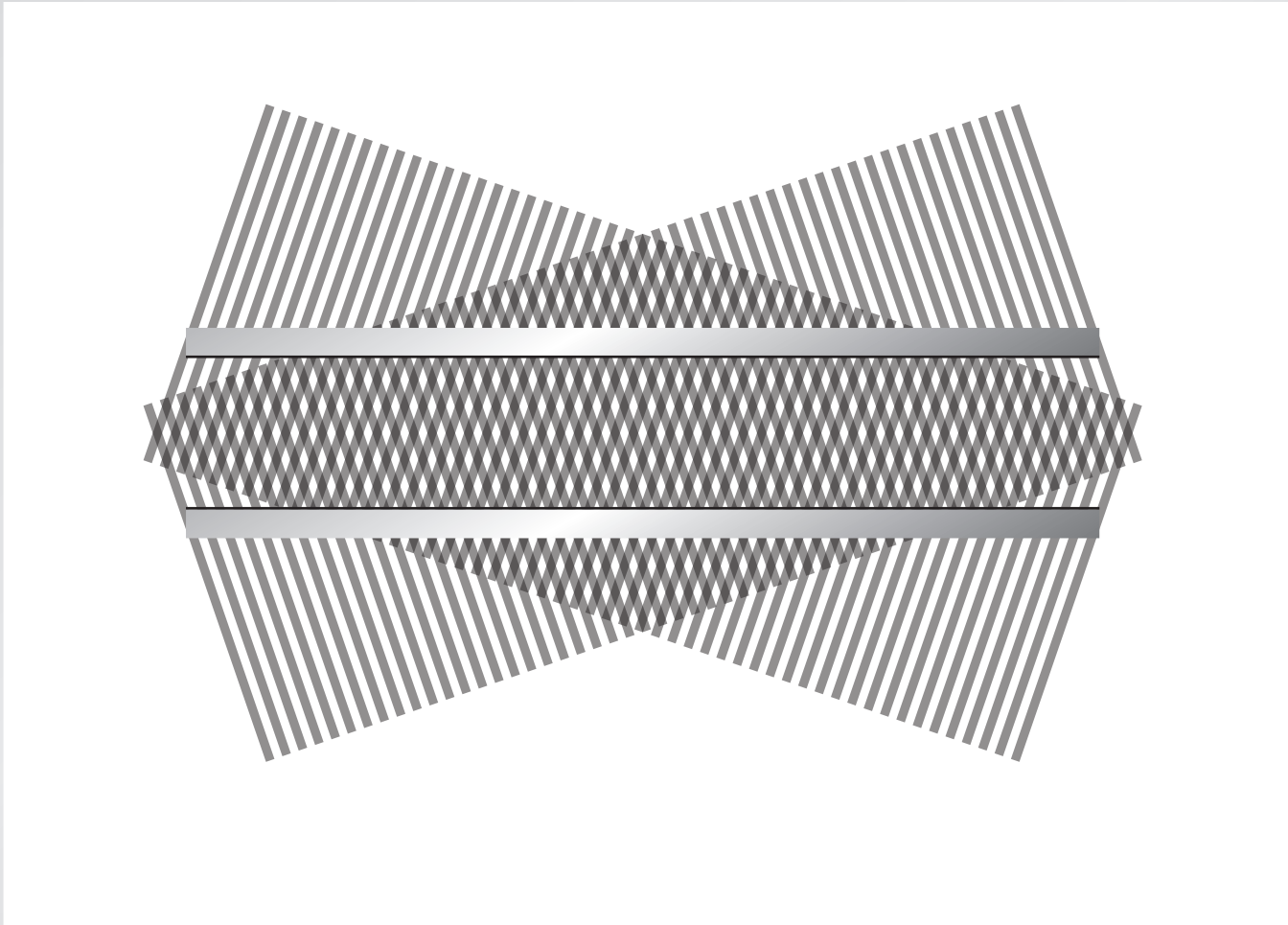
# Waveguiding

transverse standing wave, traveling along axis



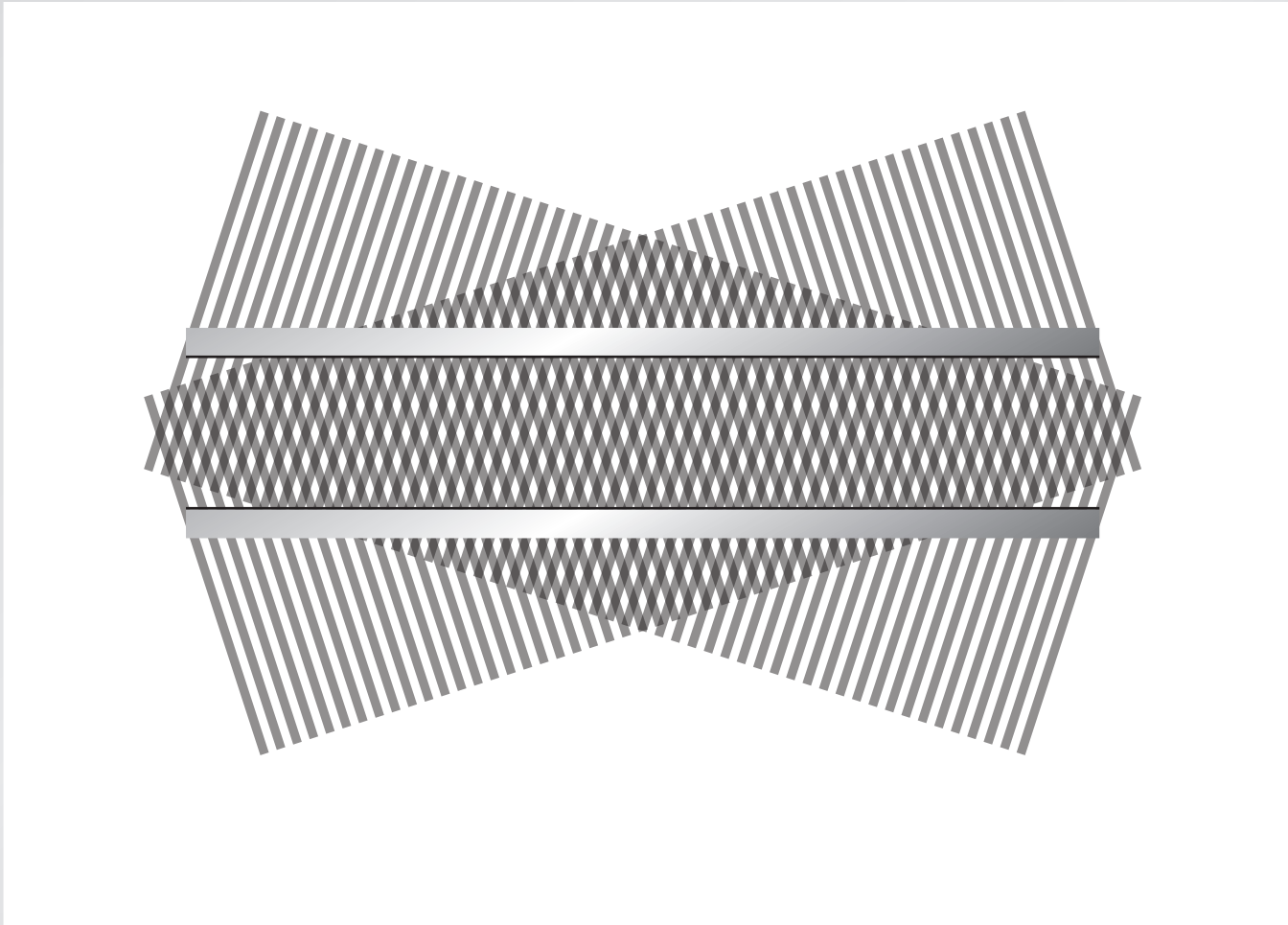
# Waveguiding

change angle of incident waves...



# Waveguiding

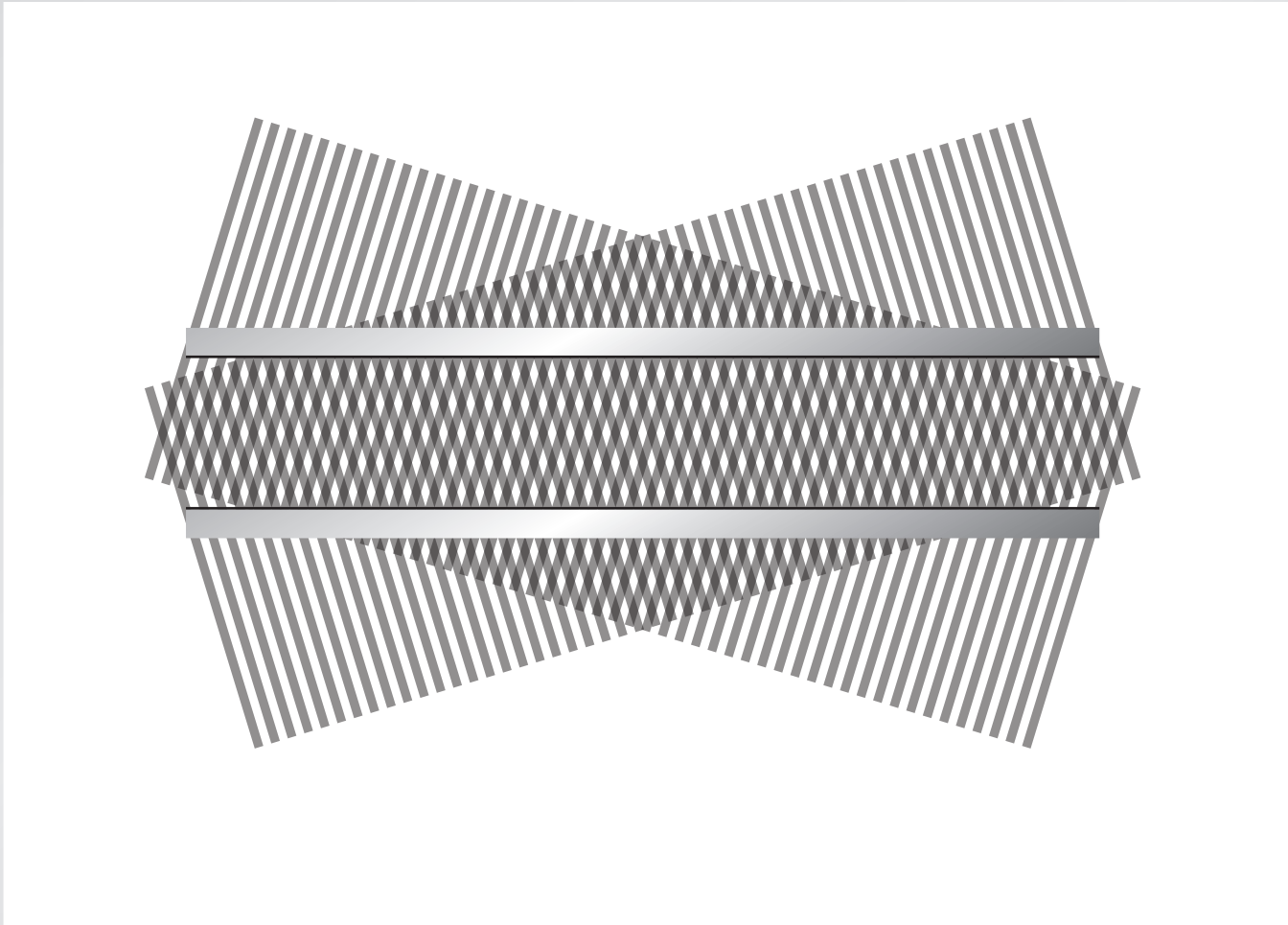
change angle of incident waves...





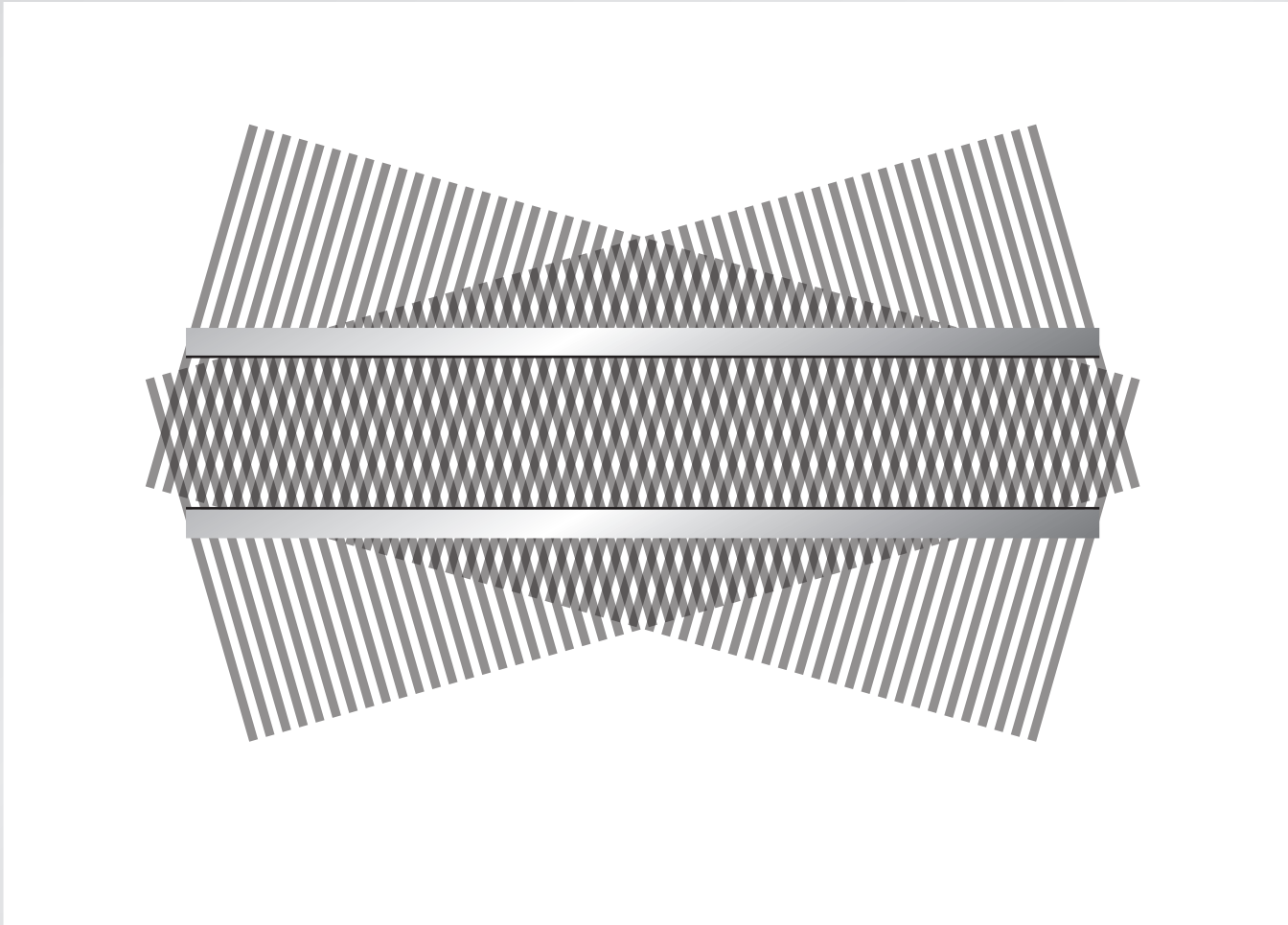
# Waveguiding

change angle of incident waves...



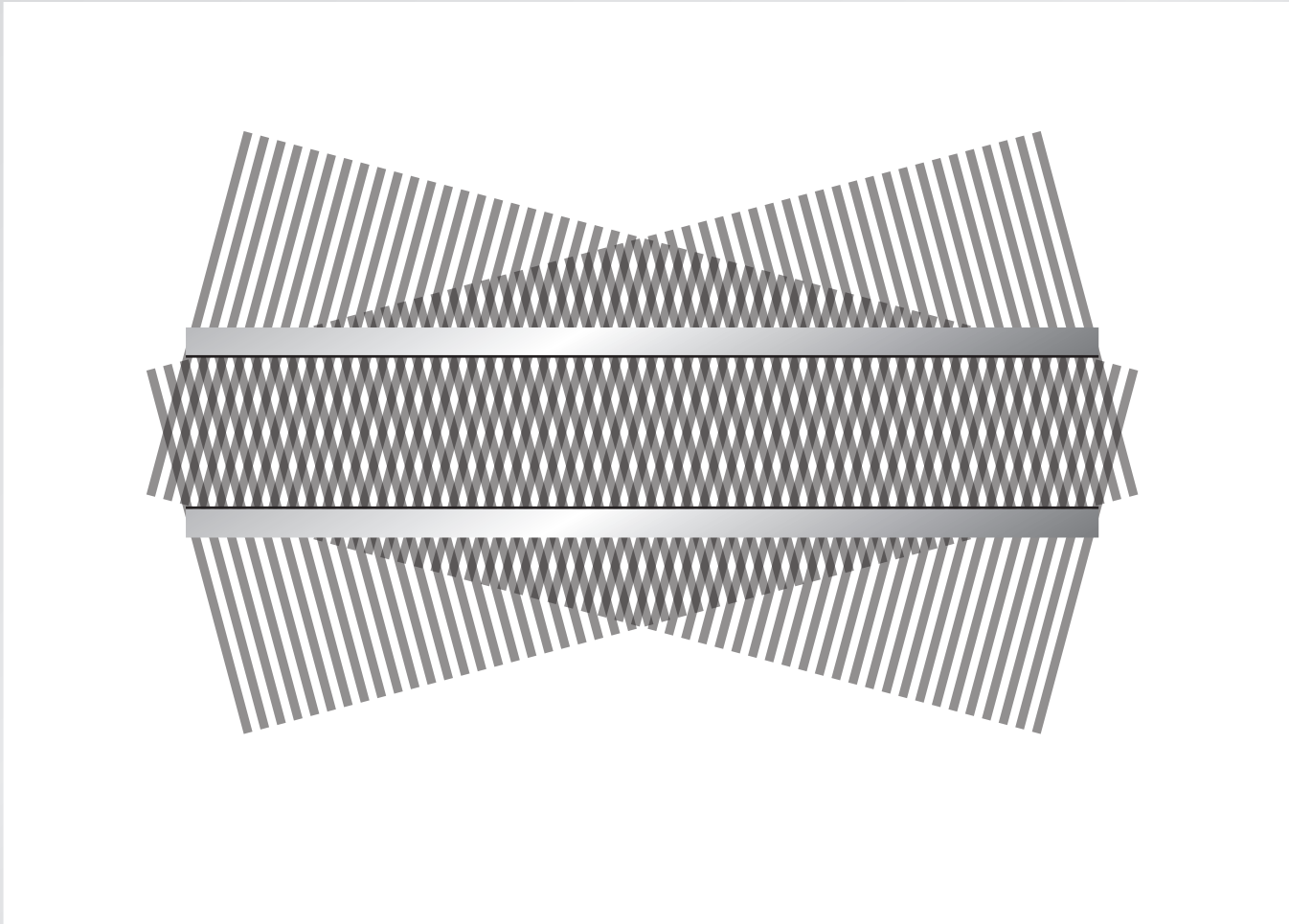
# Waveguiding

change angle of incident waves...



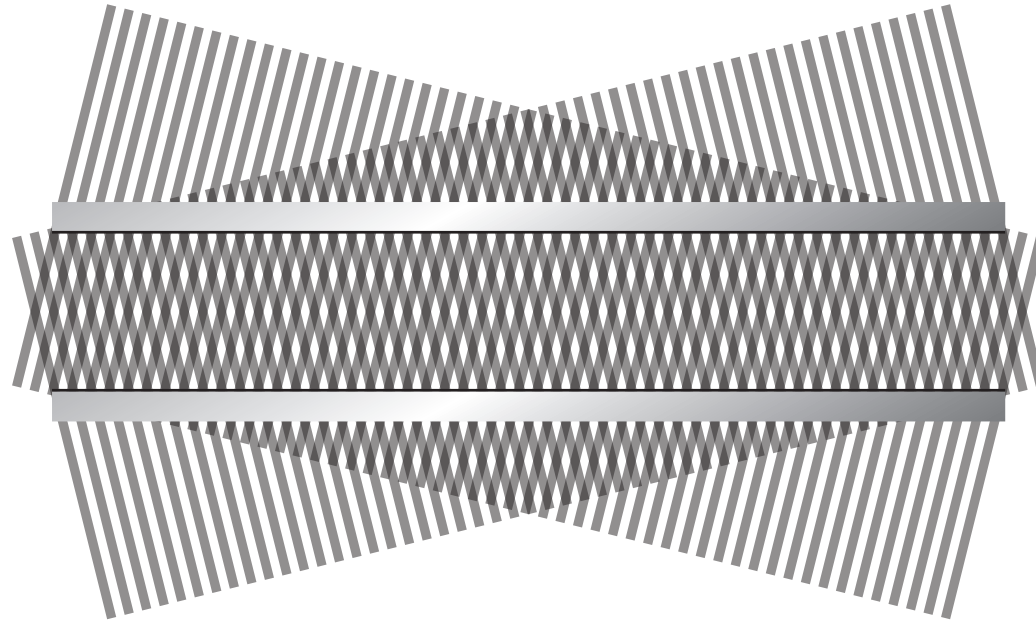
# Waveguiding

change angle of incident waves...



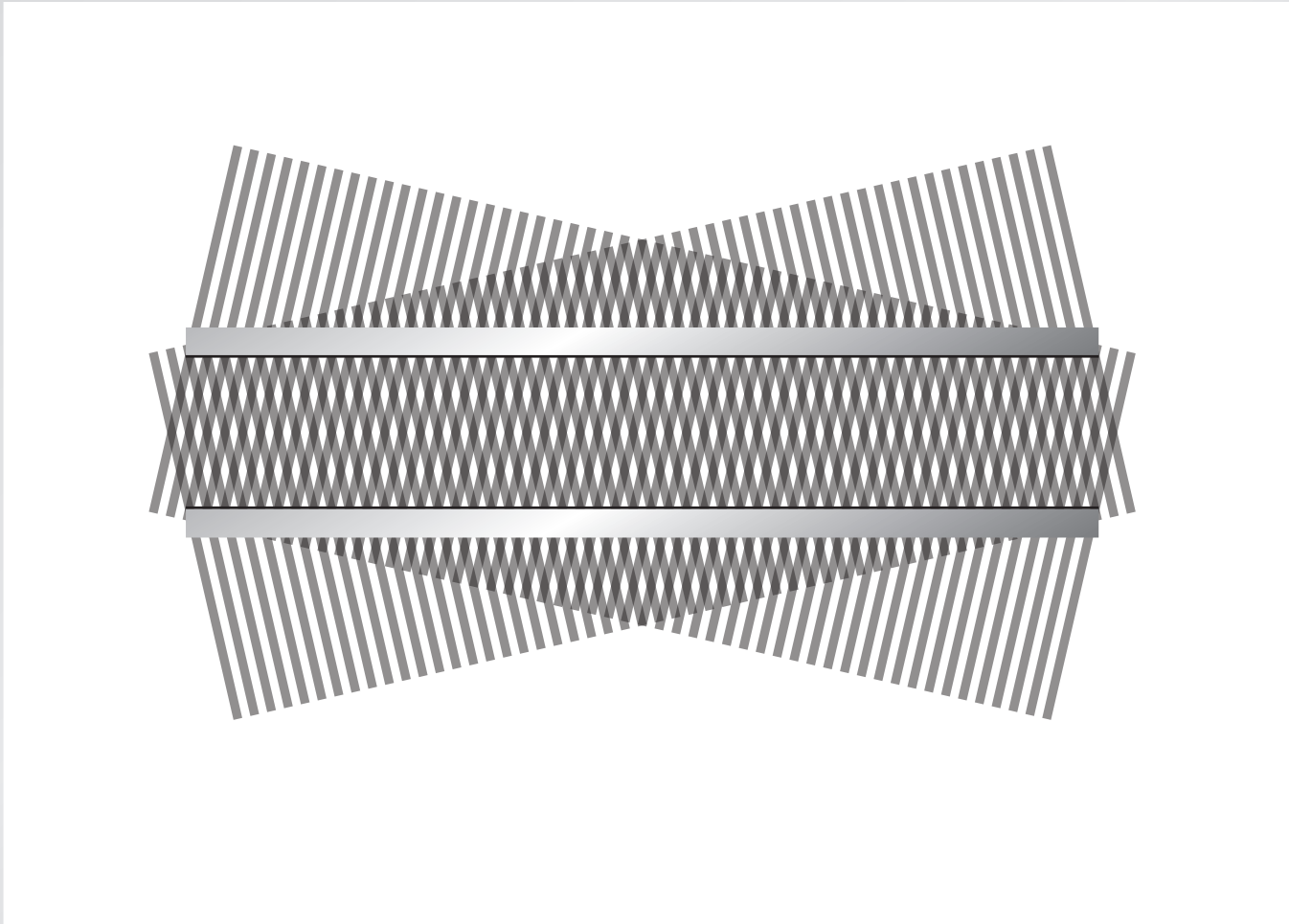
# Waveguiding

change angle of incident waves...



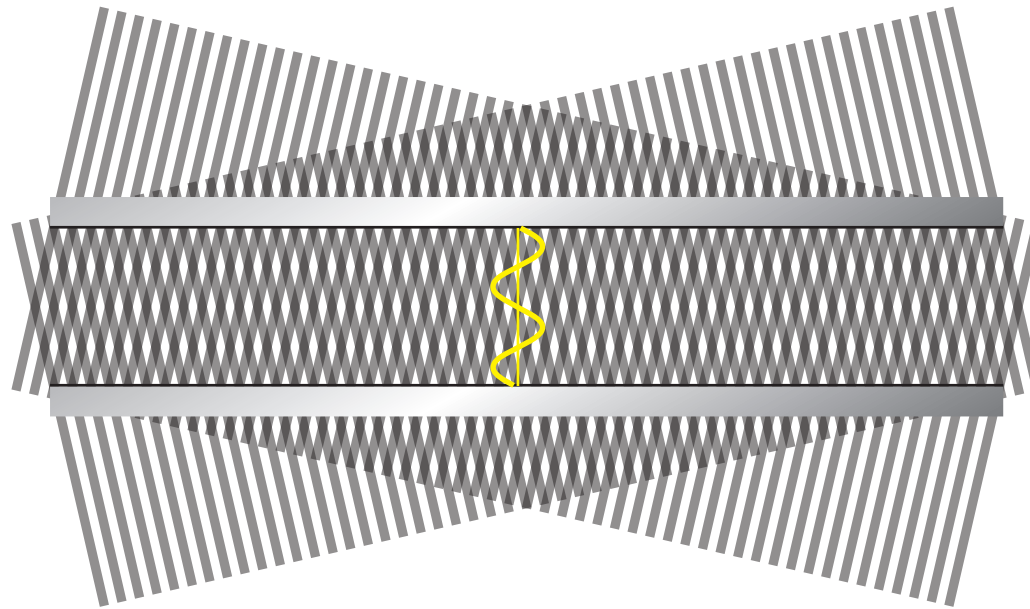
# Waveguiding

change angle of incident waves...



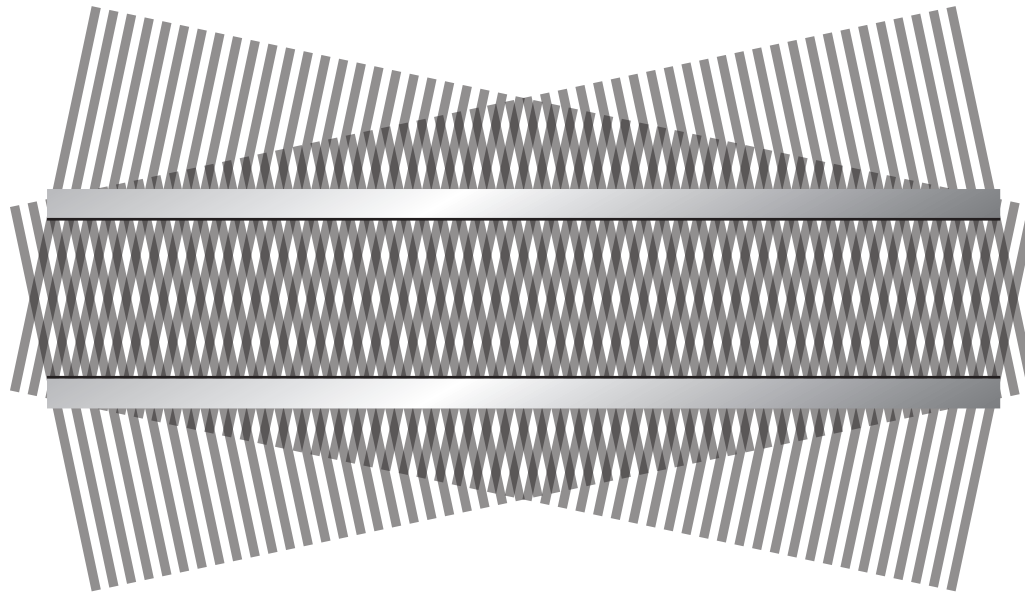
# Waveguiding

change angle of incident waves...



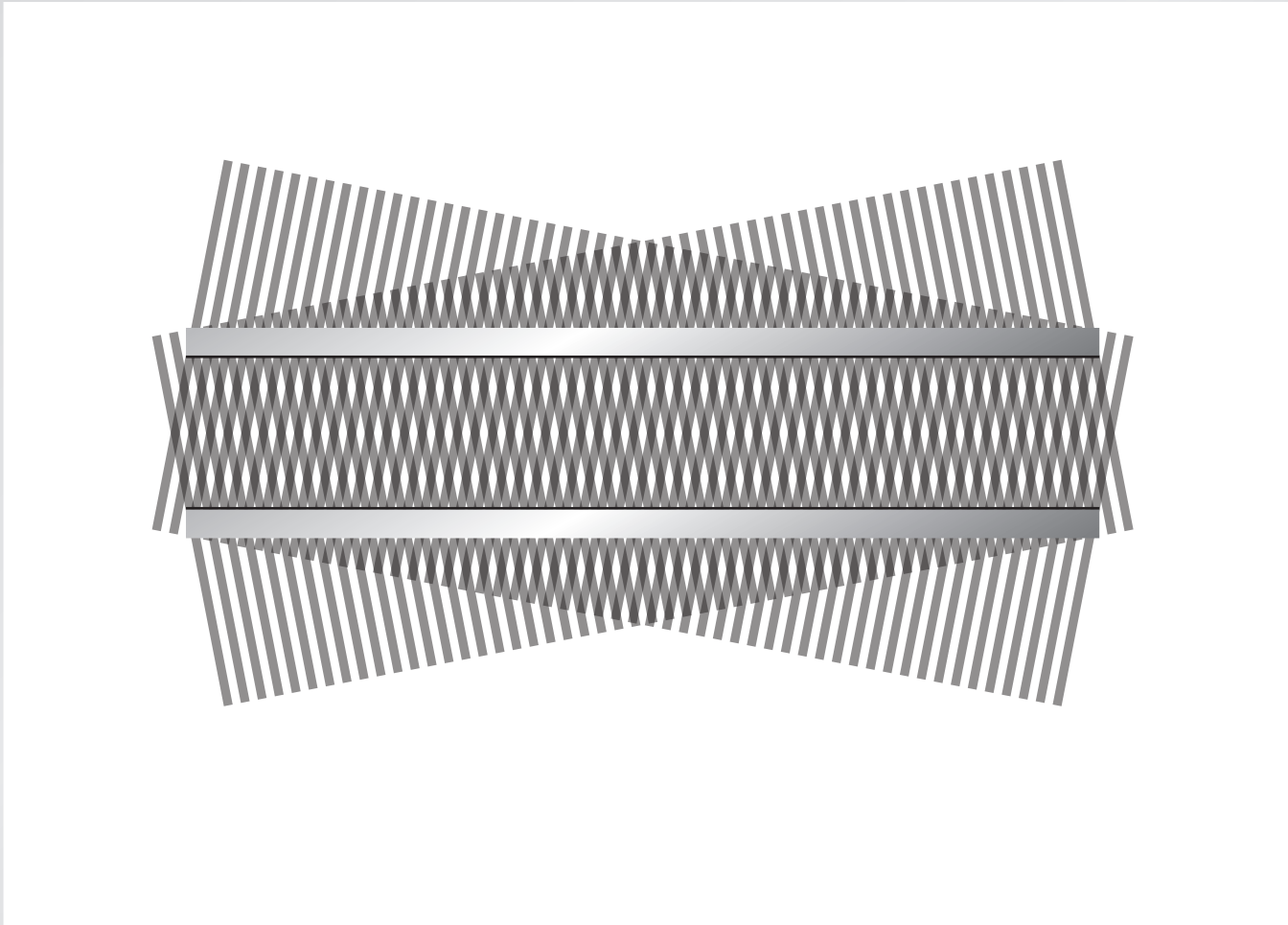
# Waveguiding

change angle of incident waves...



# Waveguiding

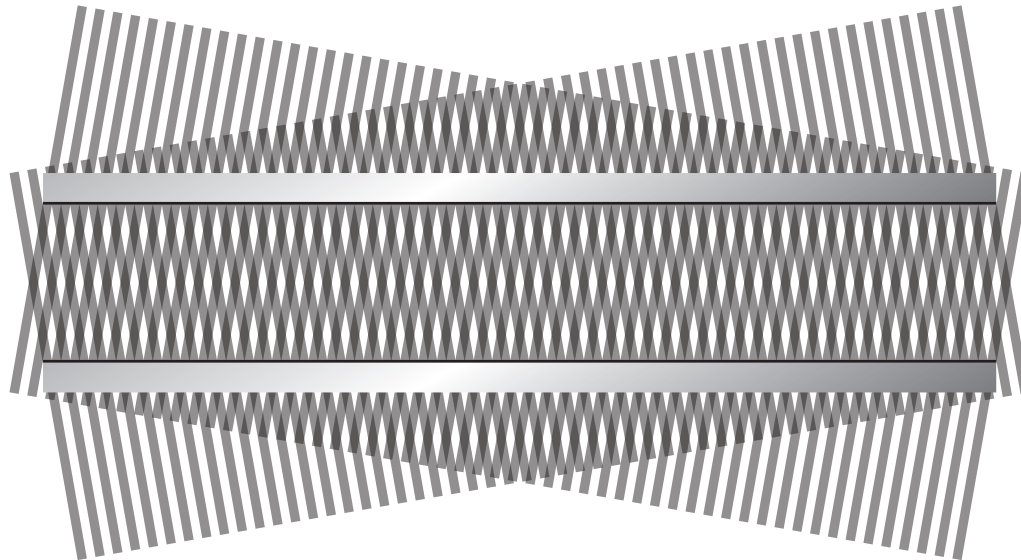
change angle of incident waves...





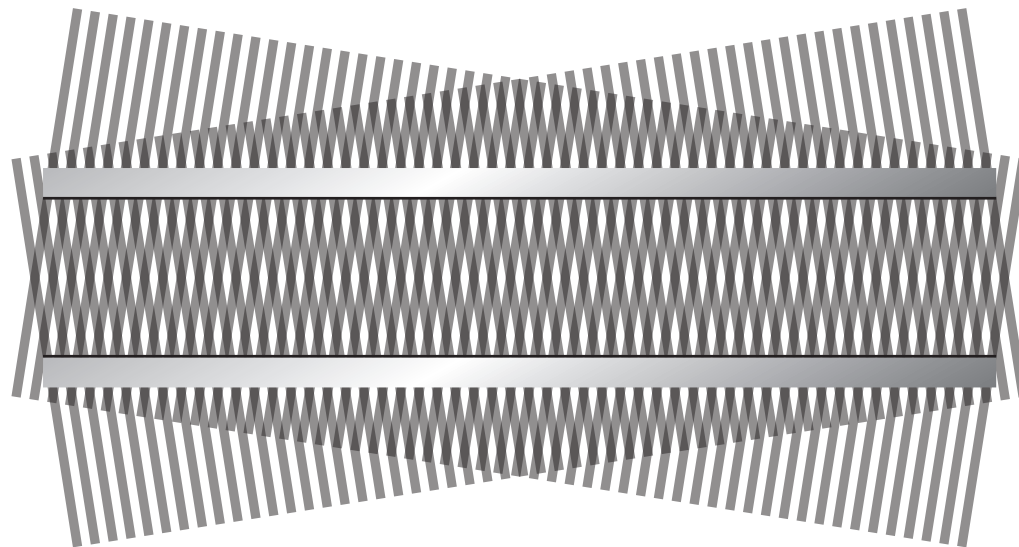
# Waveguiding

change angle of incident waves...



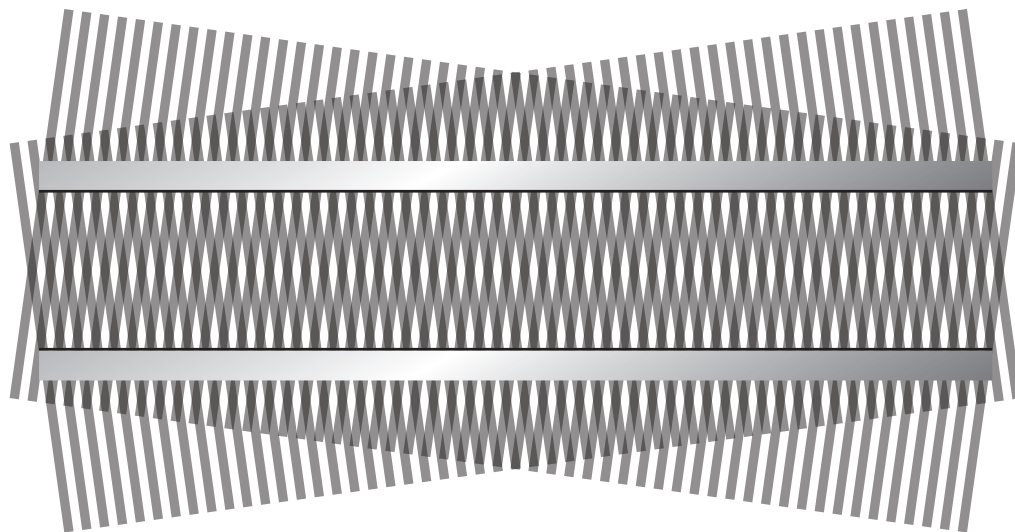
# Waveguiding

change angle of incident waves...



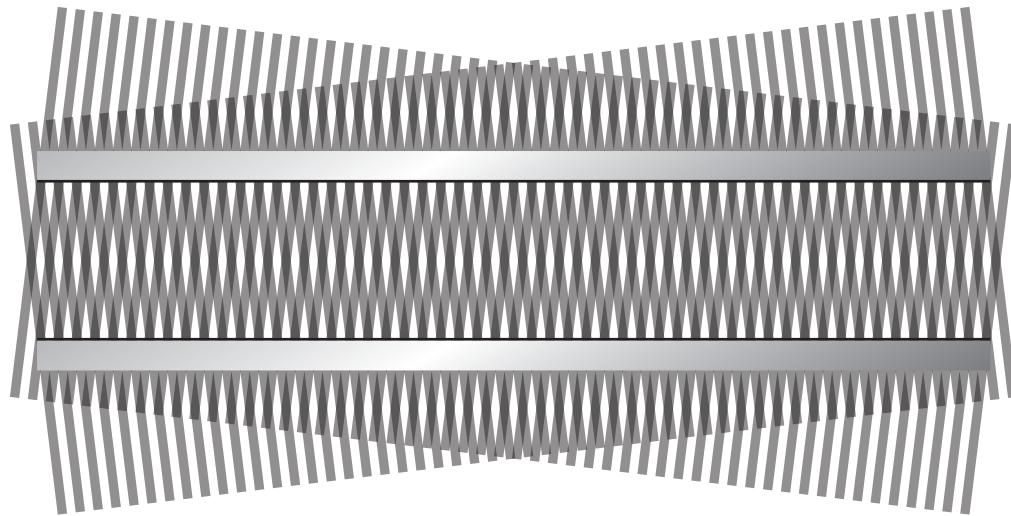
# Waveguiding

change angle of incident waves...



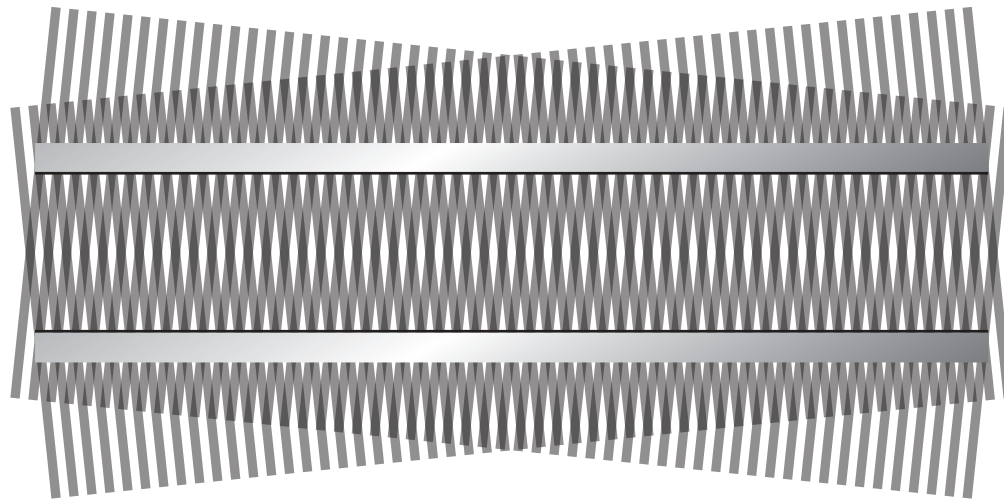
# Waveguiding

change angle of incident waves...



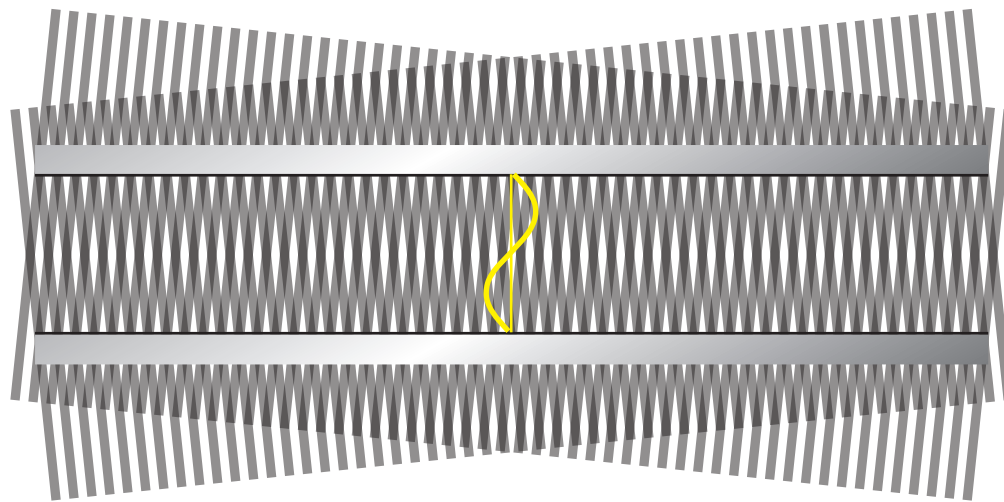
# Waveguiding

change angle of incident waves...



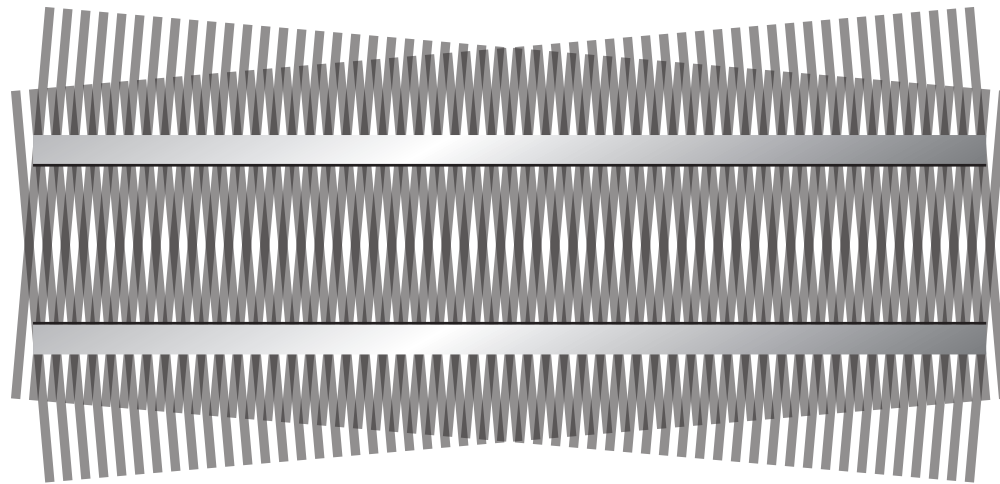
# Waveguiding

change angle of incident waves...



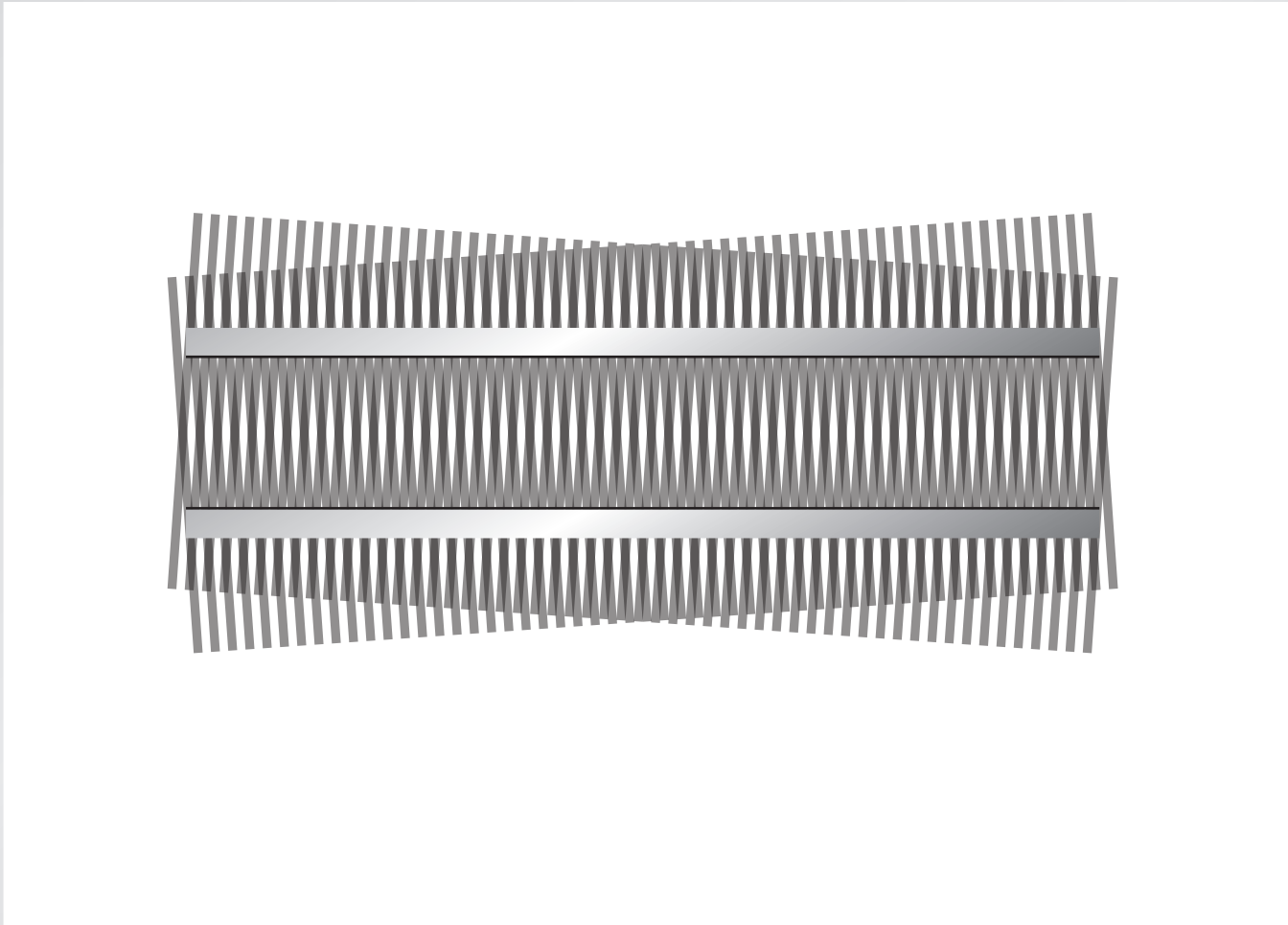
# Waveguiding

change angle of incident waves...



# Waveguiding

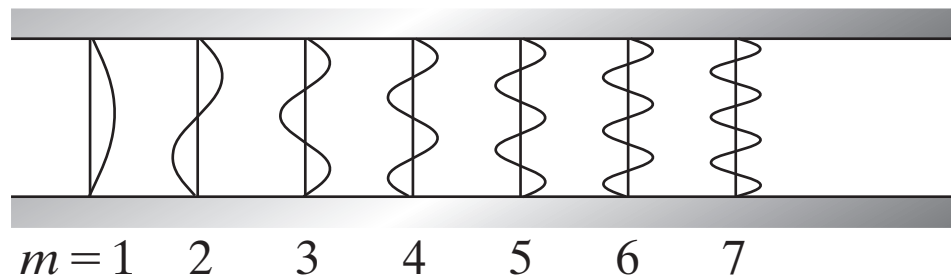
change angle of incident waves...





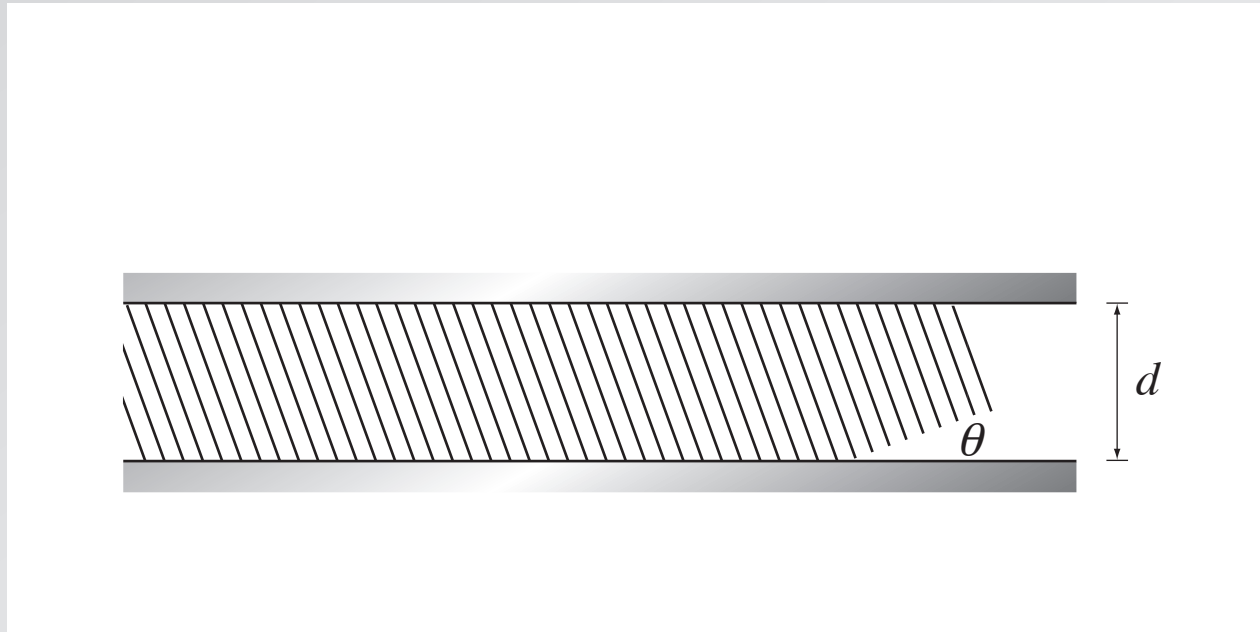
# Waveguiding

boundary conditions only satisfied for certain  $\theta$



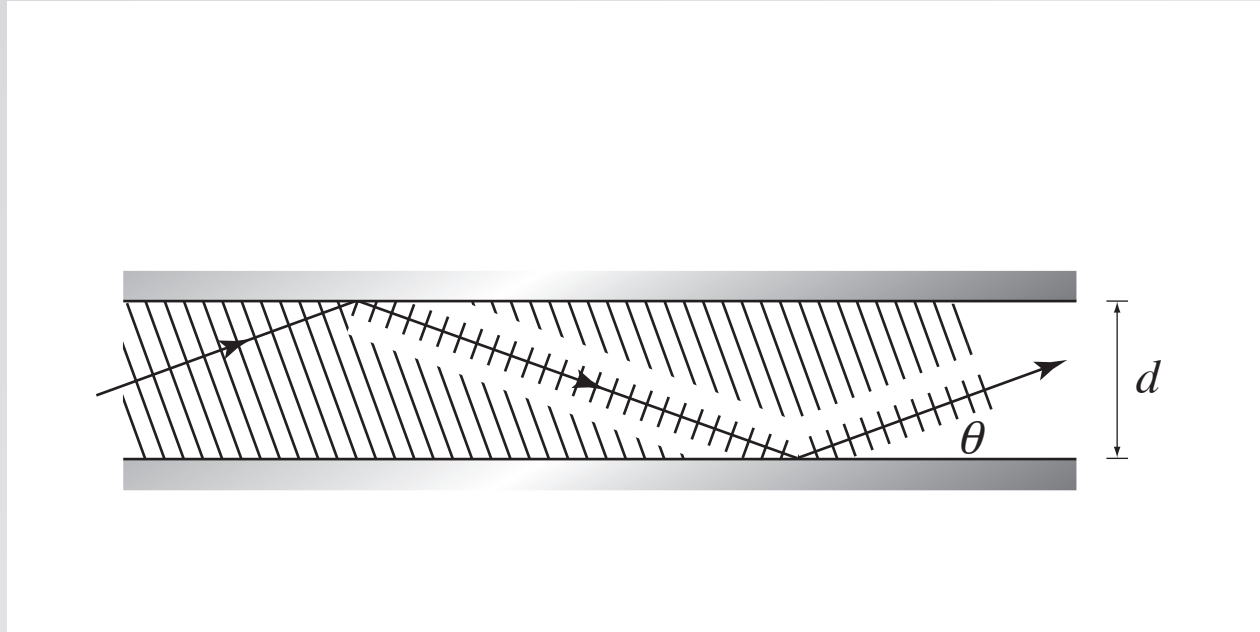
standing wave in  $y$ -direction, traveling in  $z$ -direction

# Waveguiding



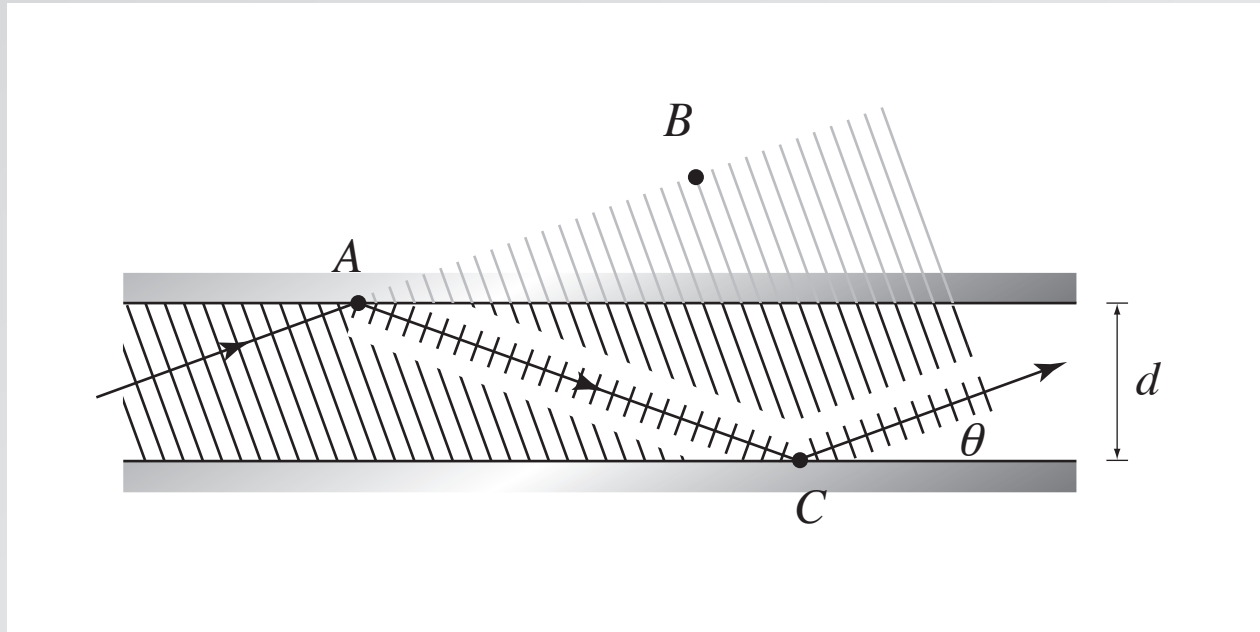
consider wave incident at angle  $\theta$

# Waveguiding



**twice-reflected wave**

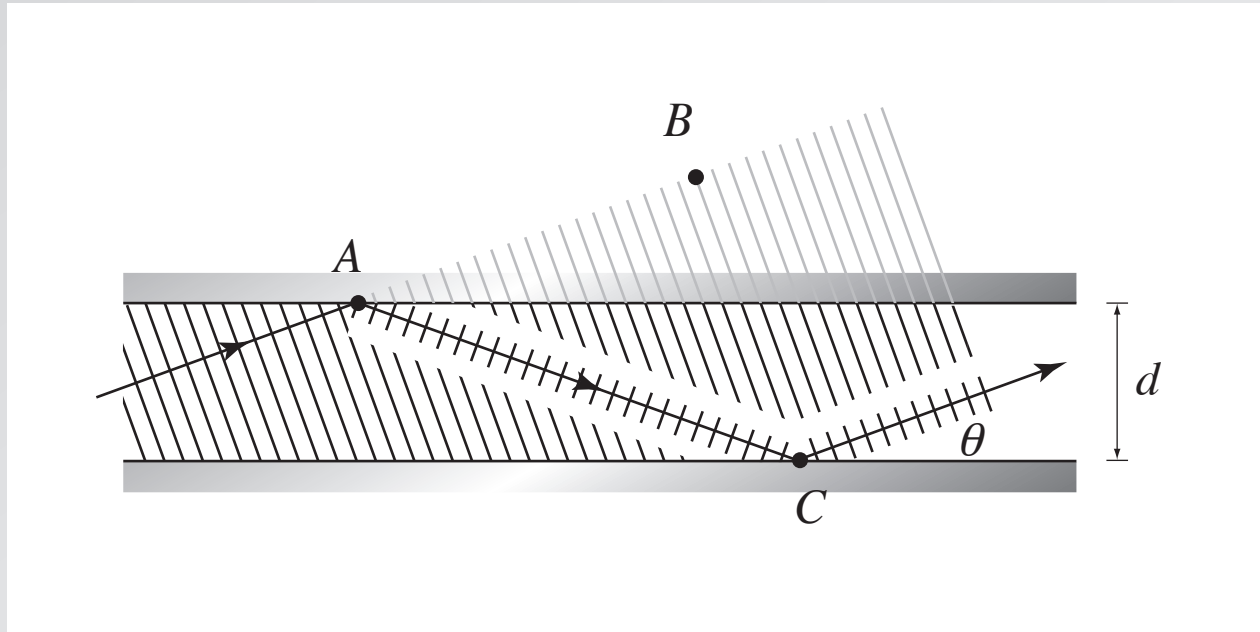
# Waveguiding



self consistency:

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

# Waveguiding



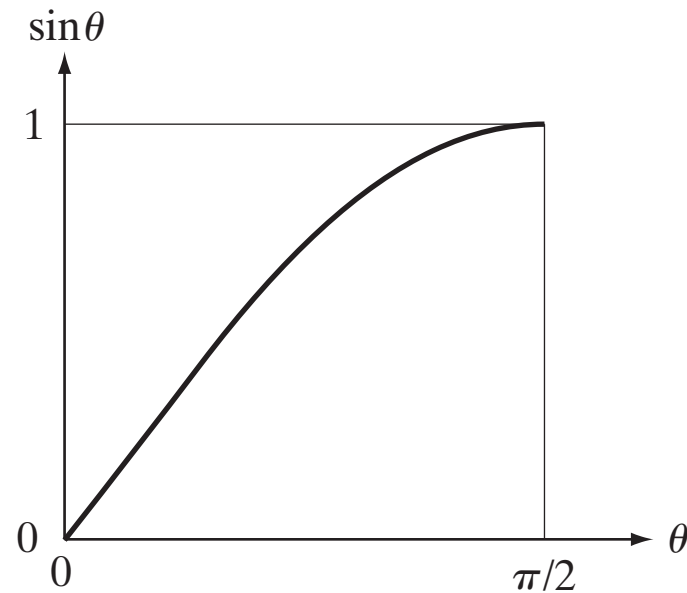
self consistency:

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

so:

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

# Waveguiding



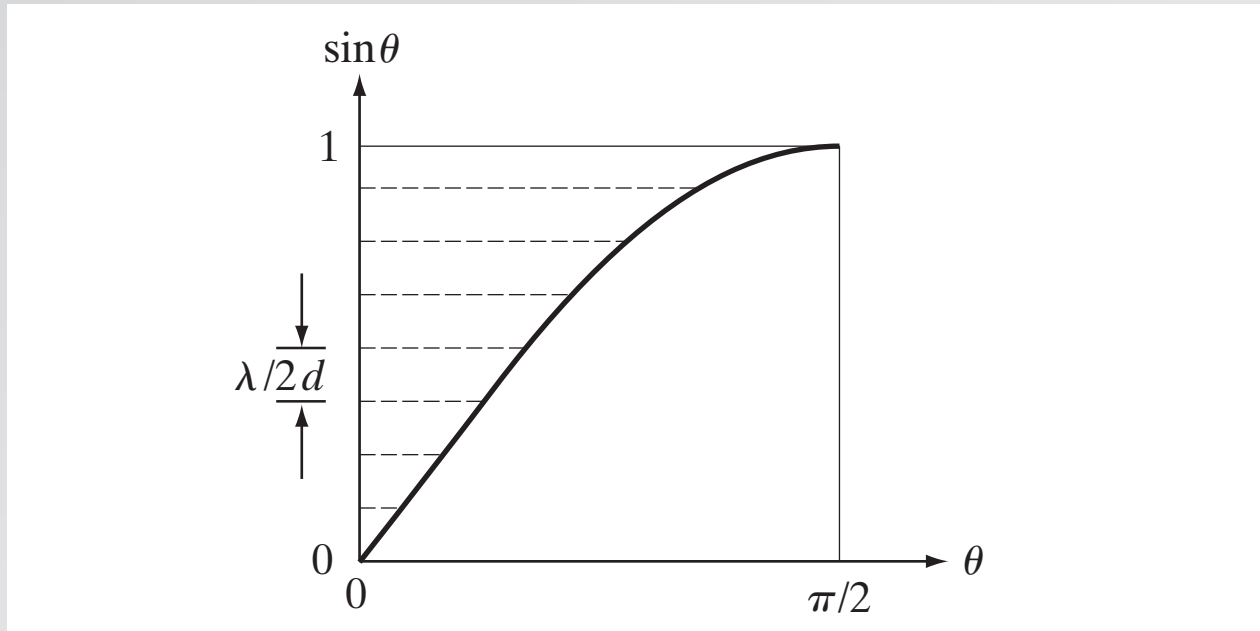
**self consistency:**

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

**so:**

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

# Waveguiding



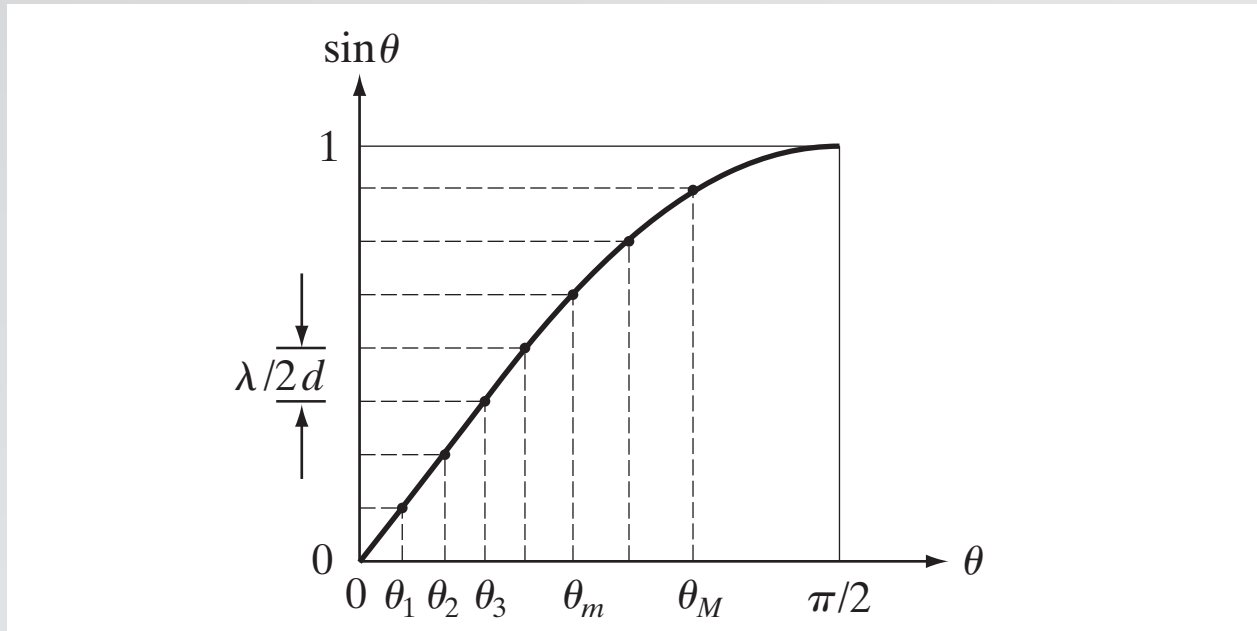
**self consistency:**

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

**so:**

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

# Waveguiding



**self consistency:**

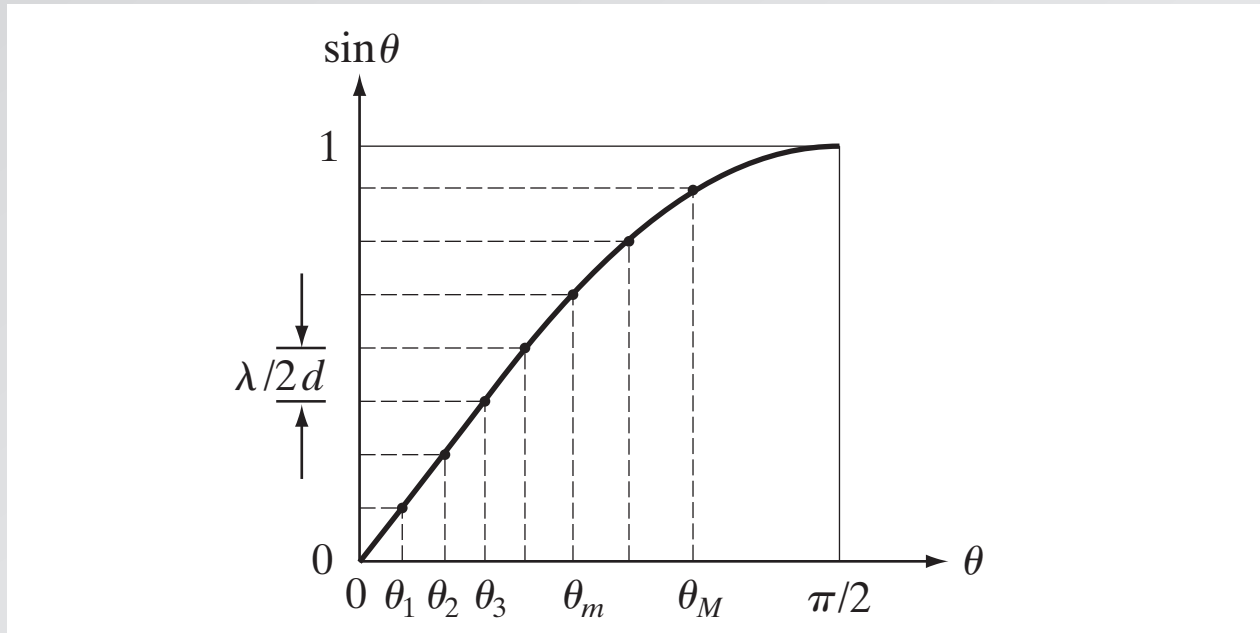
$$AC - AB = 2d \sin \theta = m\lambda \quad (m = 1, 2, \dots)$$

**so:**

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



# Waveguiding



number of modes:

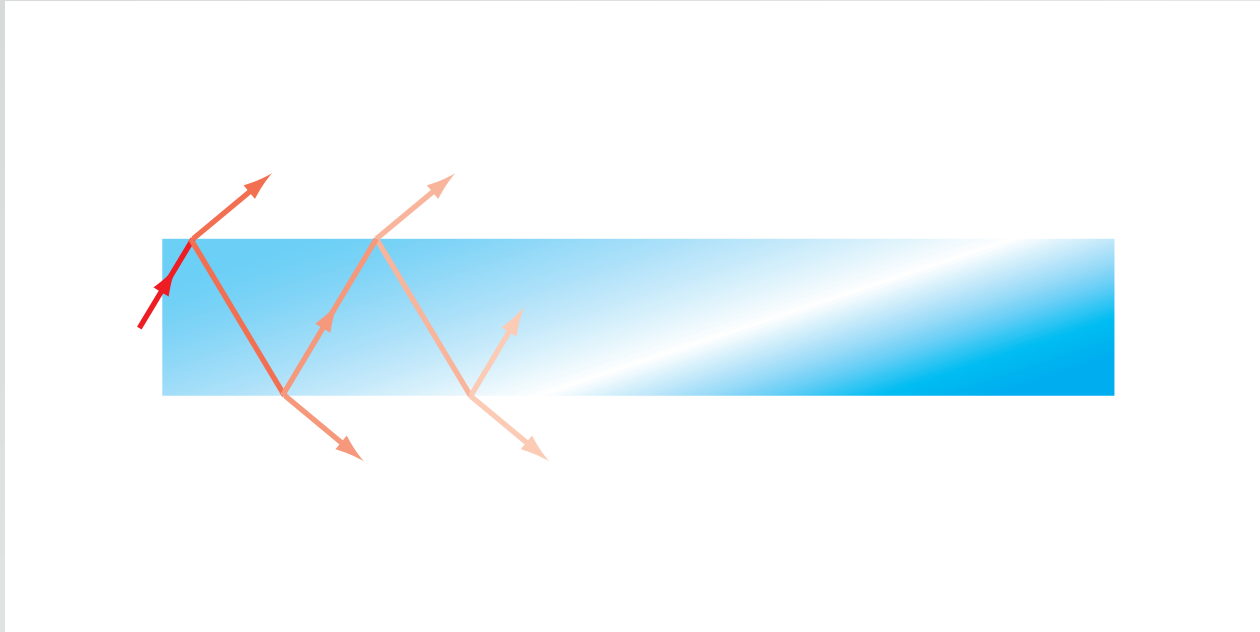
$$M = \frac{2d}{\lambda}$$

# Waveguiding



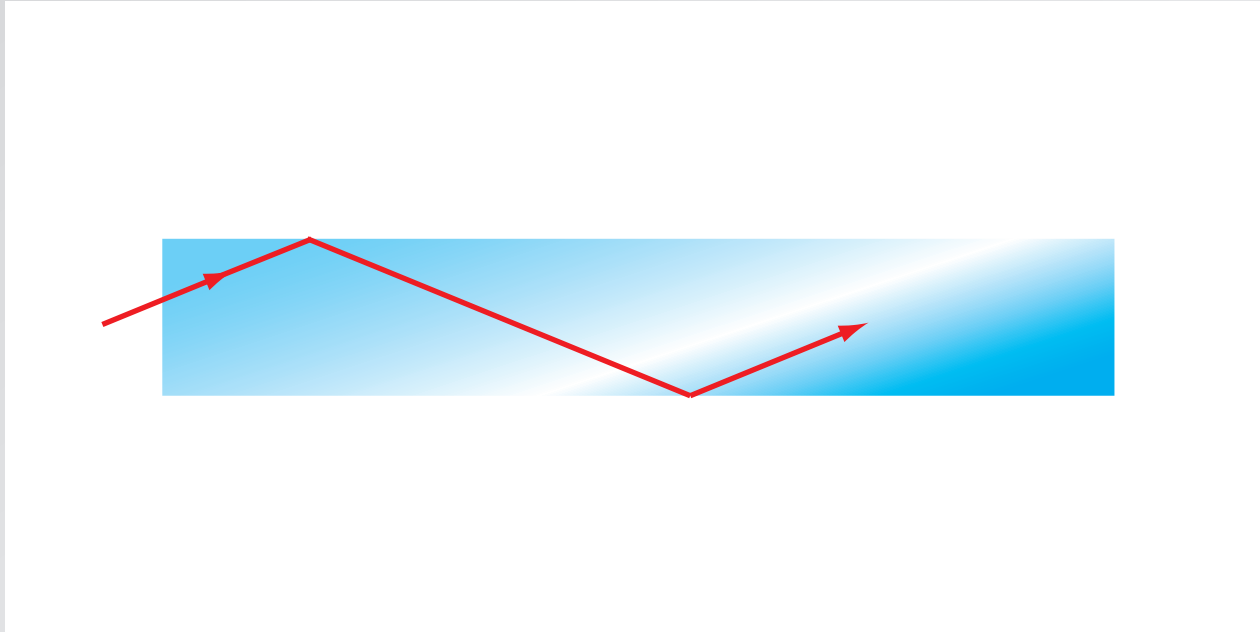
now consider a planar dielectric waveguide

# Waveguiding



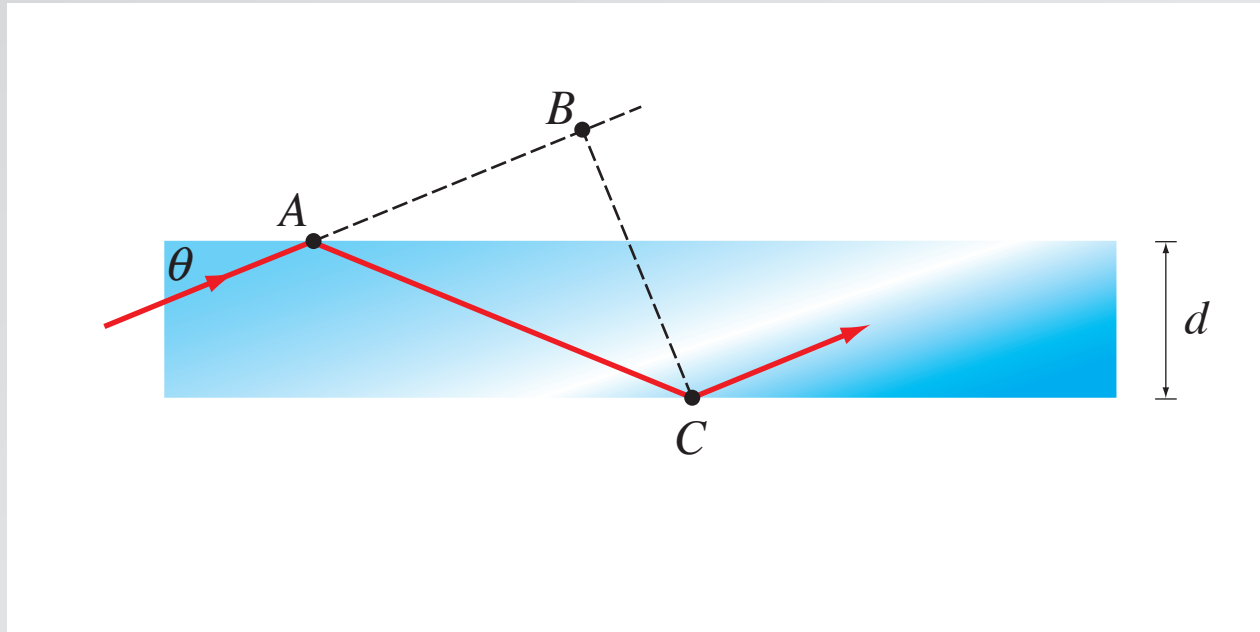
rays incident at angle  $\theta > \pi/2 - \theta_c$  are unguided

# Waveguiding



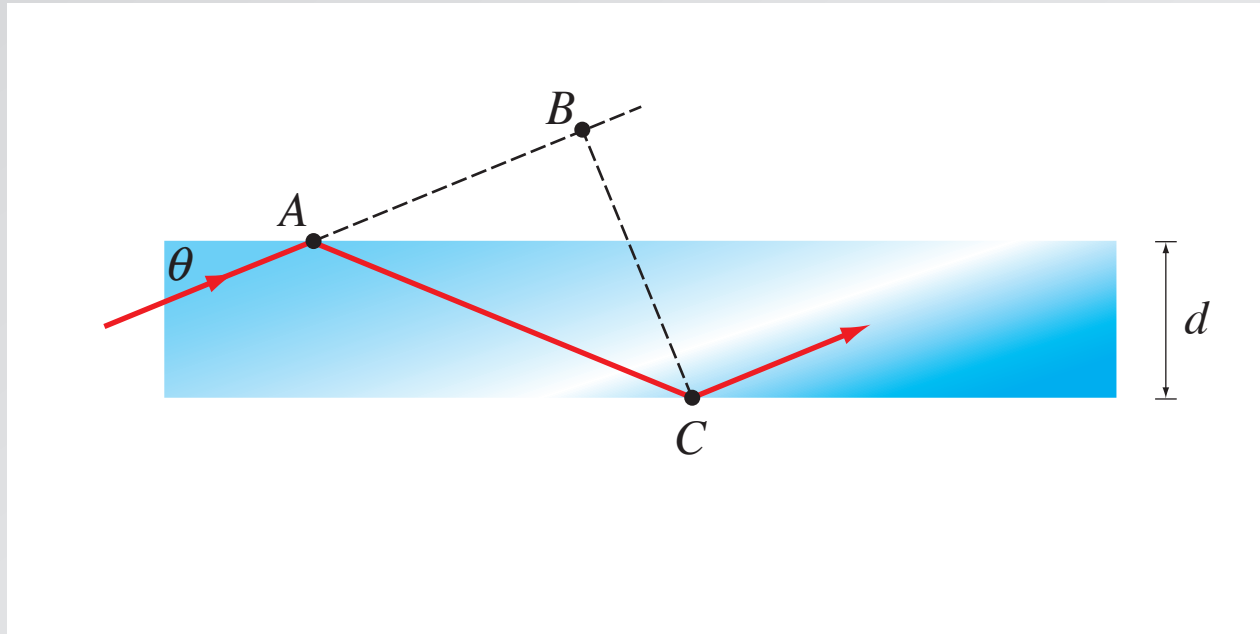
rays incident at angle  $\theta < \pi/2 - \theta_c$  are guided

# Waveguiding



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

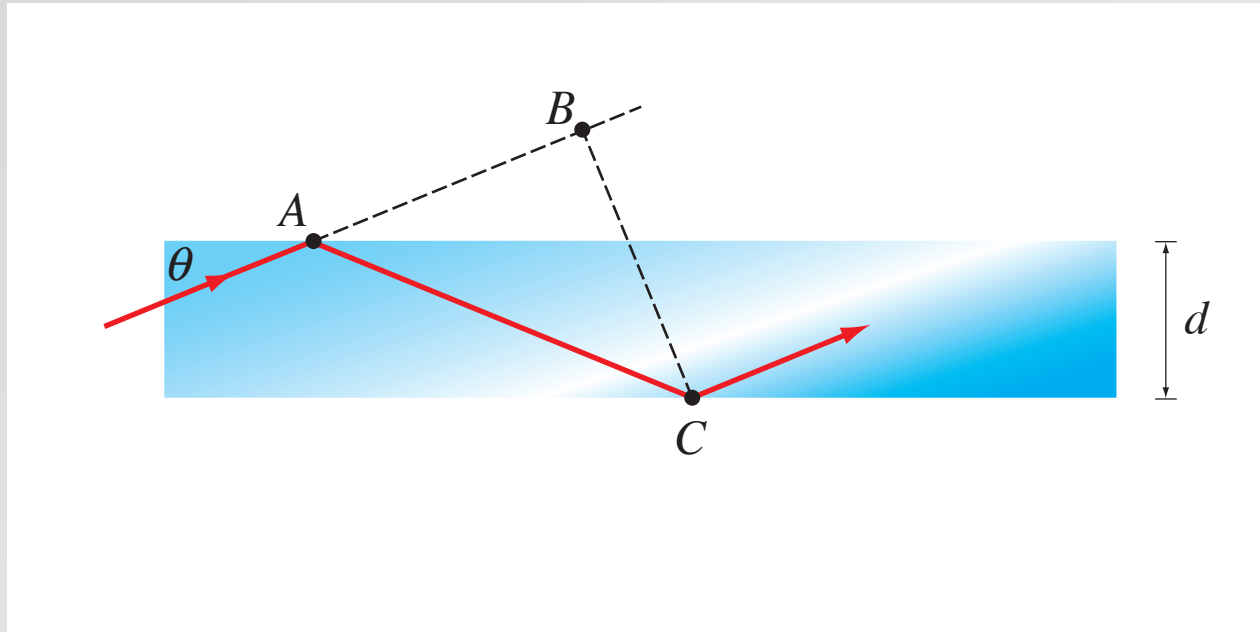
# Waveguiding



self consistency:

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

# Waveguiding



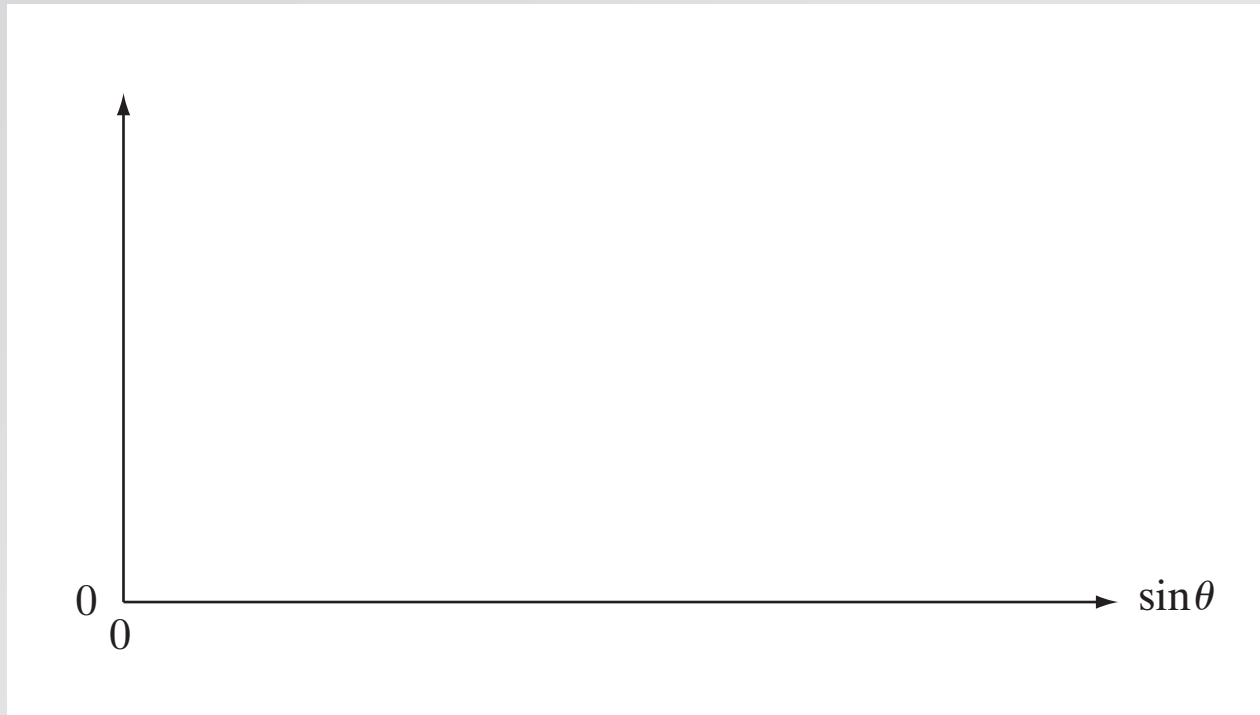
self consistency:

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

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



**self consistency:**

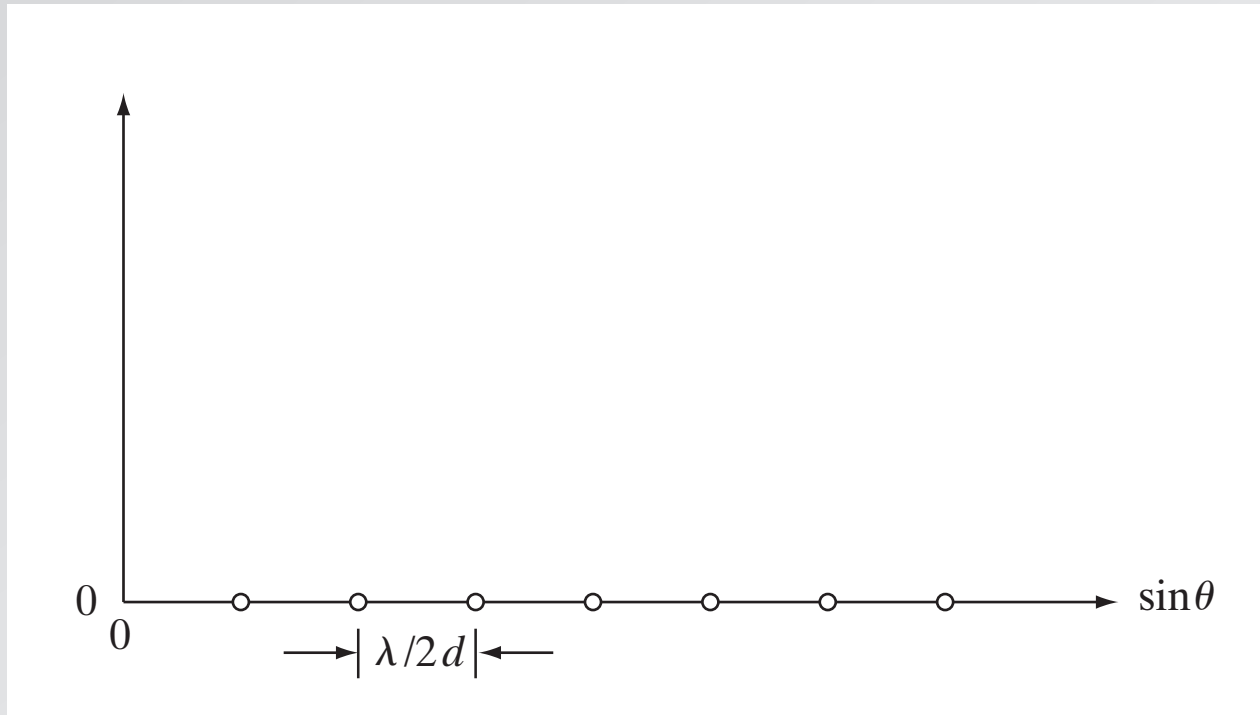
$$AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m \lambda \quad (m = 0, 1, 2 \dots)$$

**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



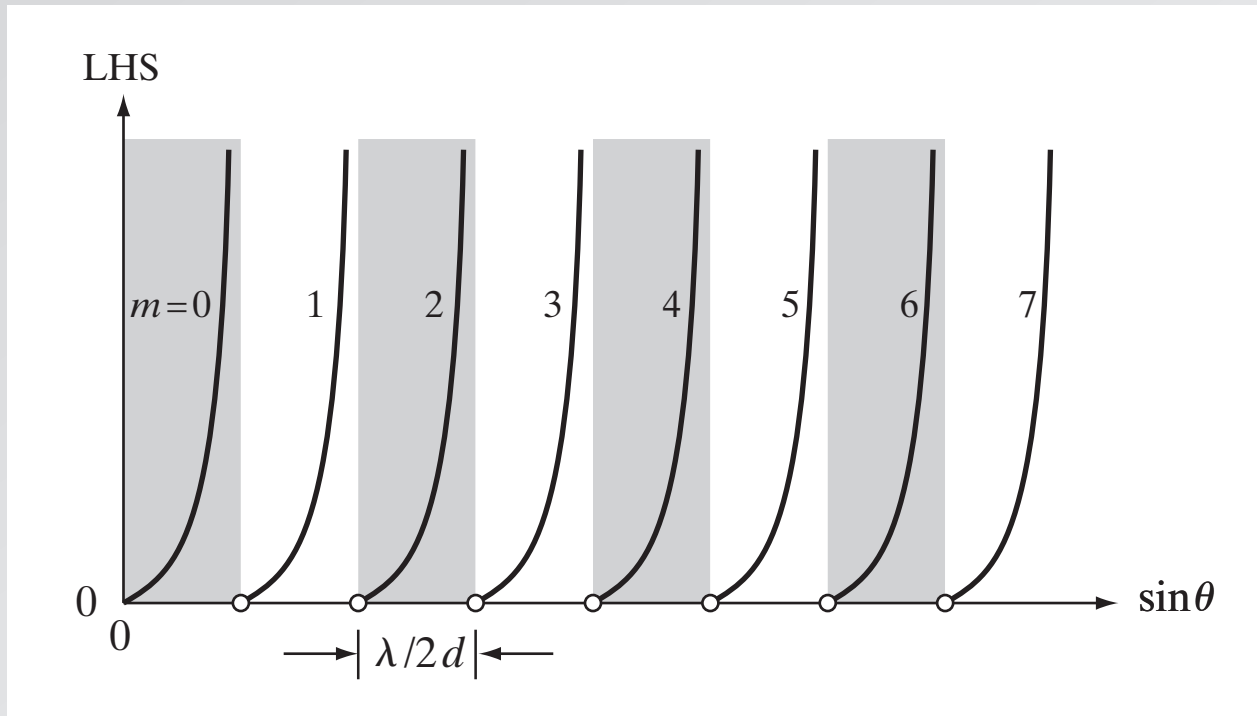
**self consistency:**

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

**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



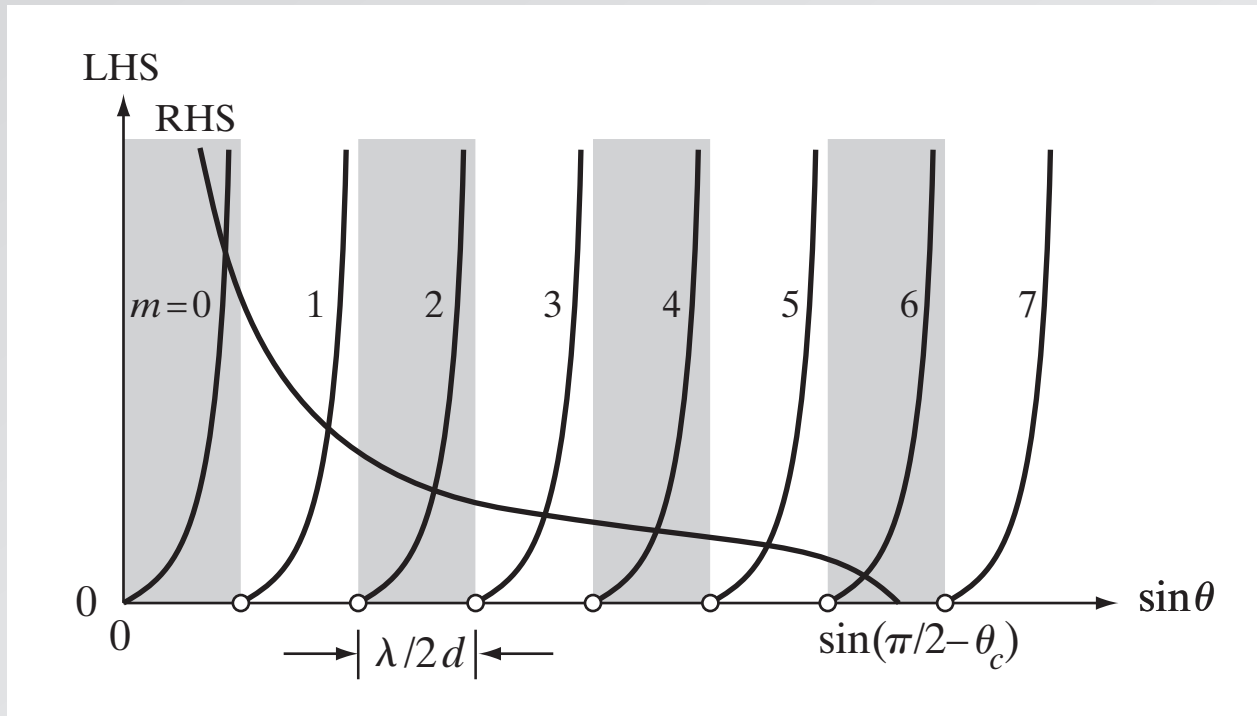
**self consistency:**

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

**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



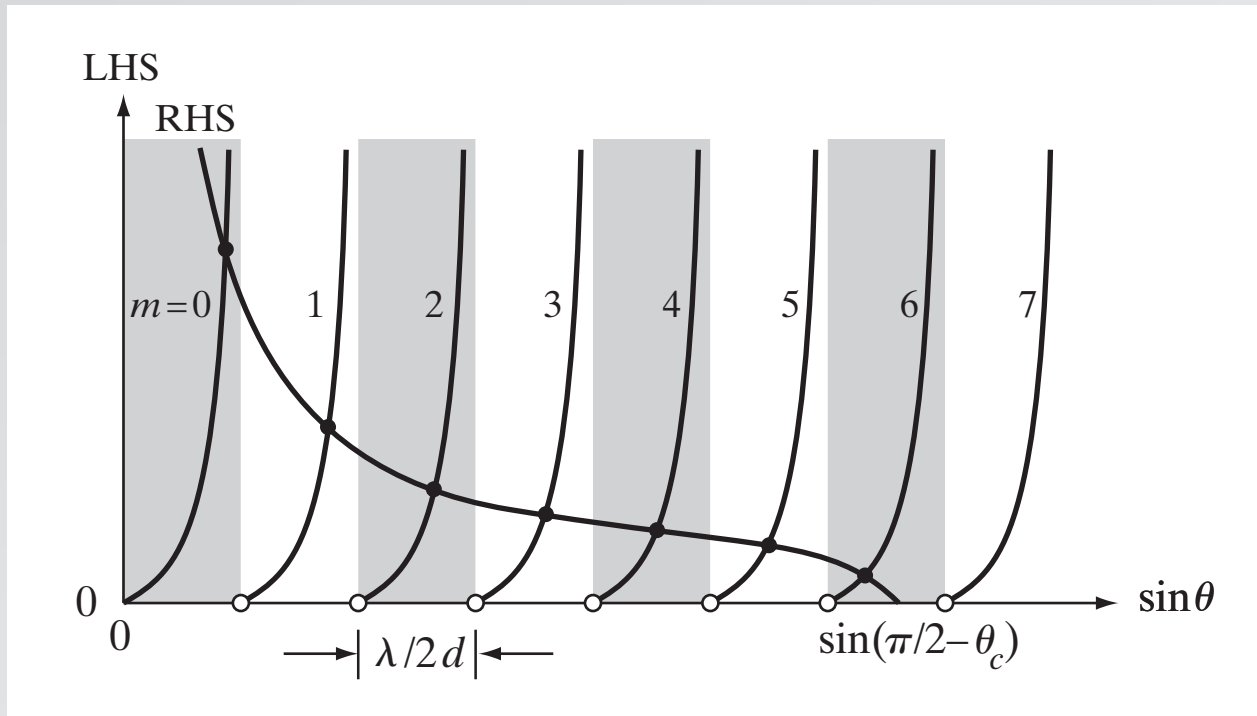
**self consistency:**

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

**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



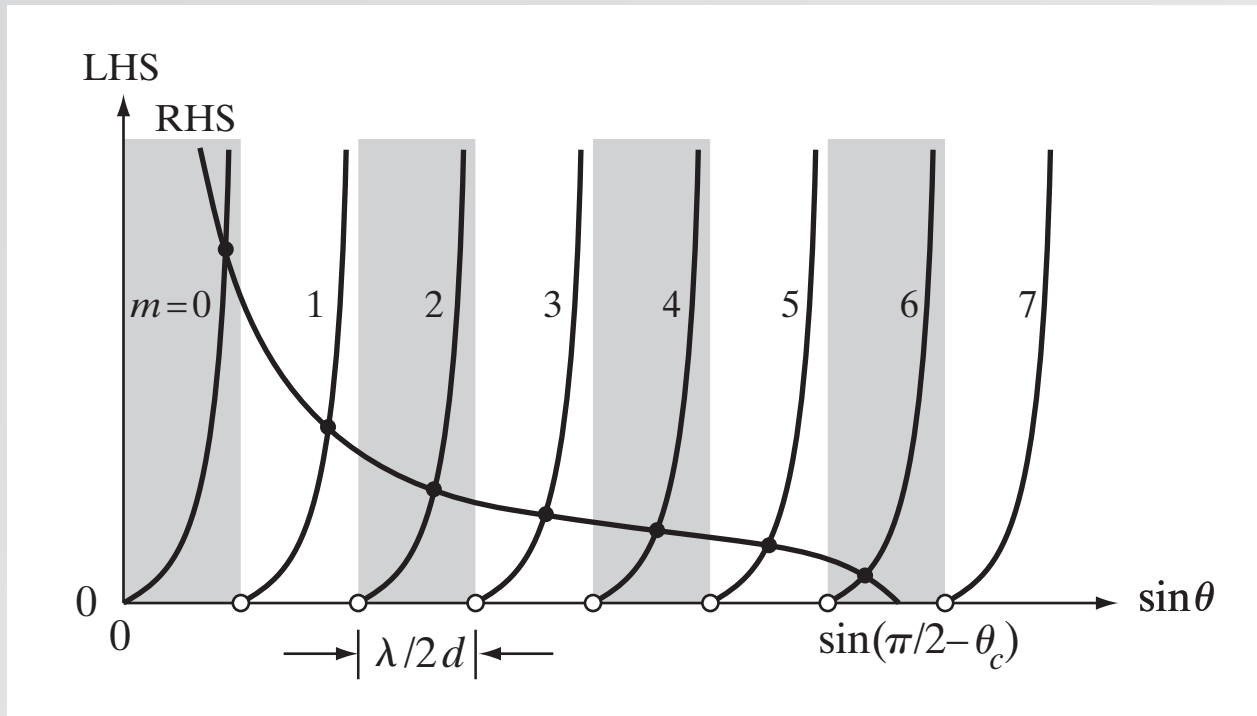
self consistency:

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

SO:

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

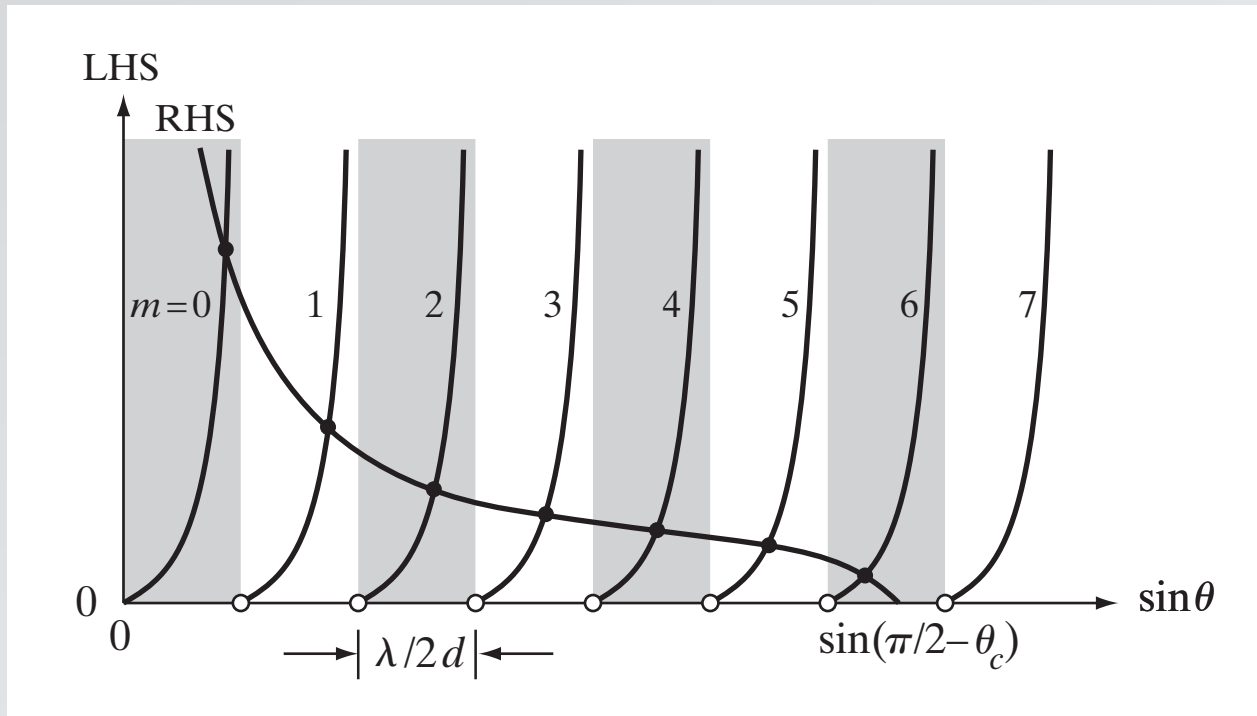
# Waveguiding



number of modes:

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

# Waveguiding



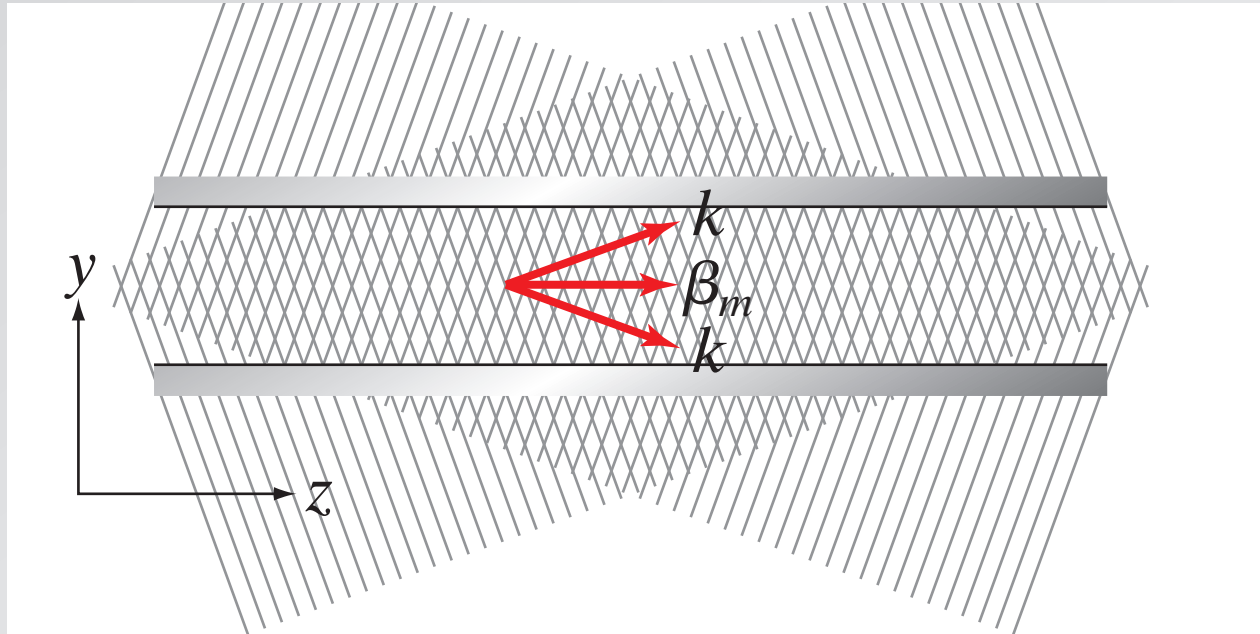
number of modes:

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

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

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

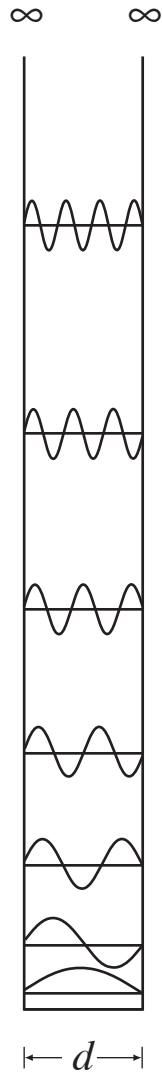
yields:

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

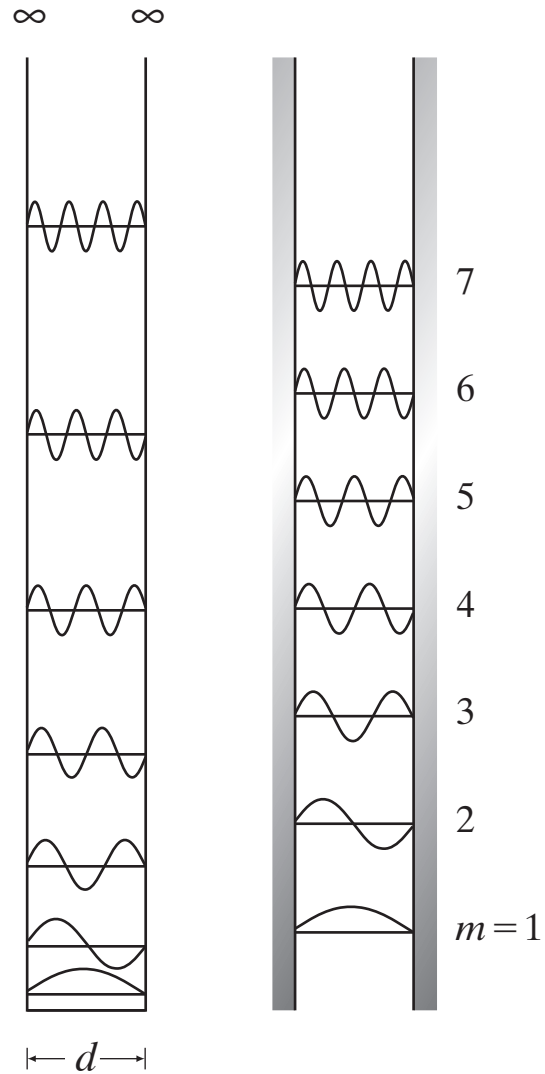
Compare to time-independent Schrödinger equation:

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

# Waveguiding

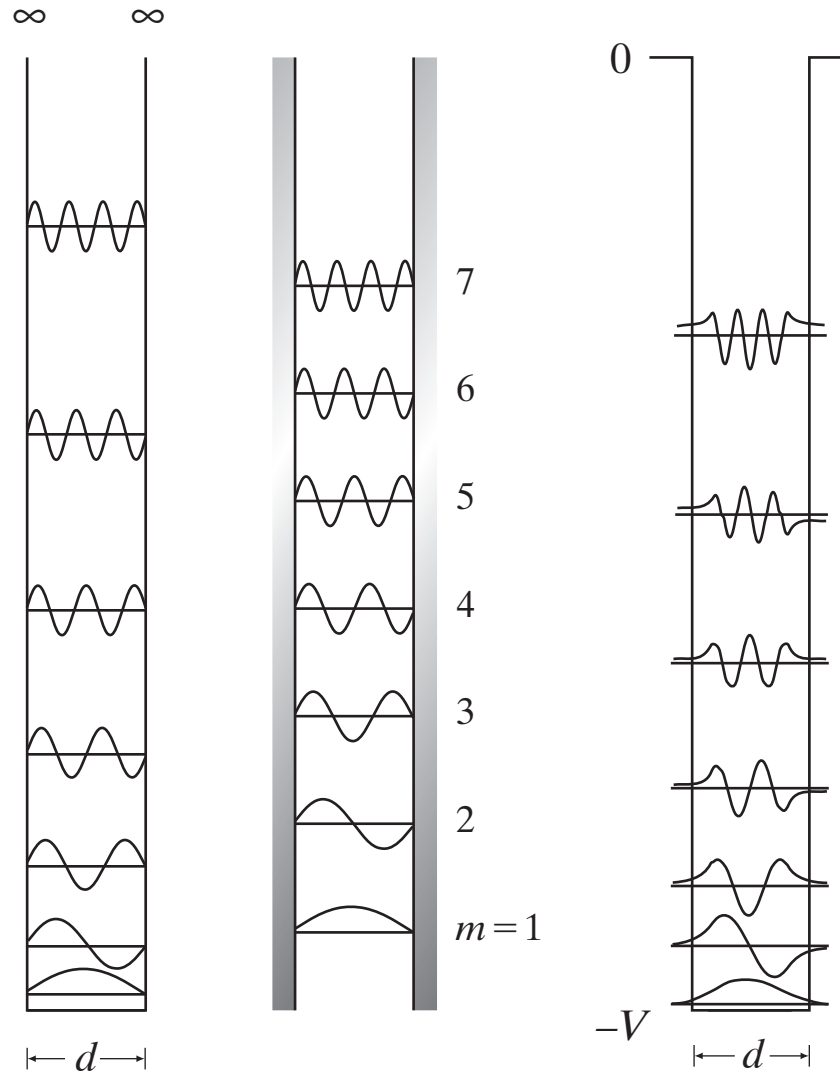


# Waveguiding

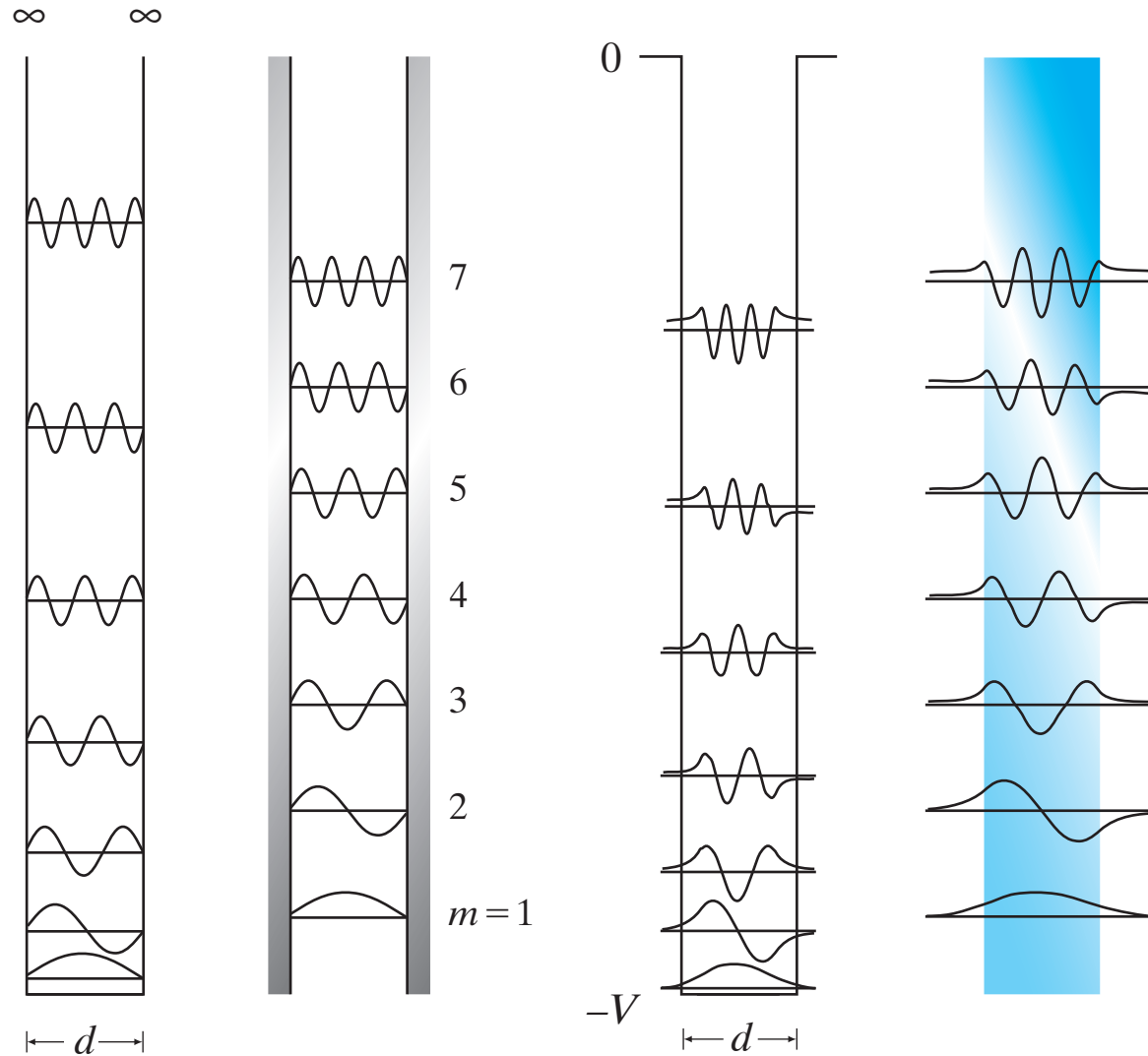




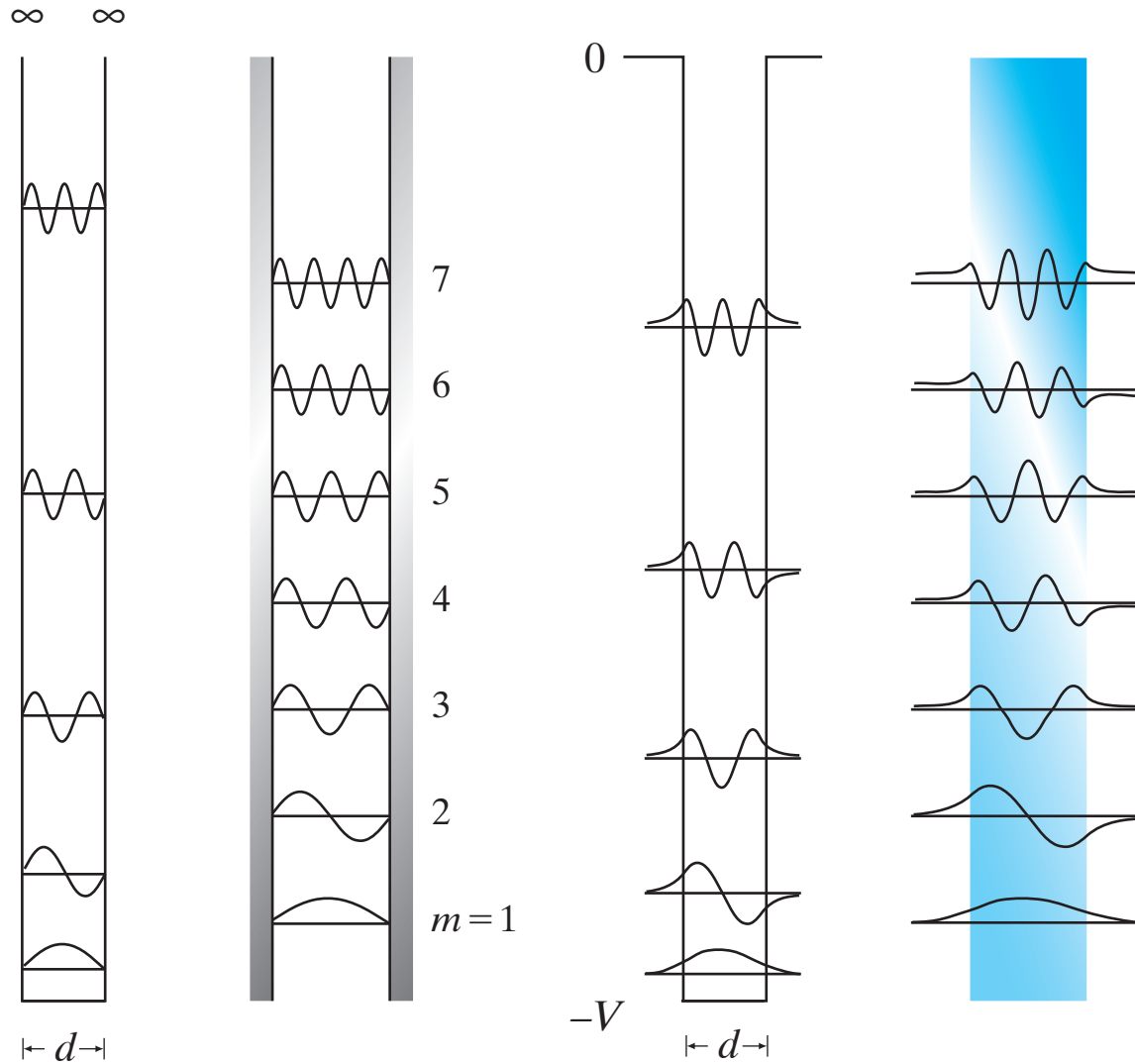
# Waveguiding



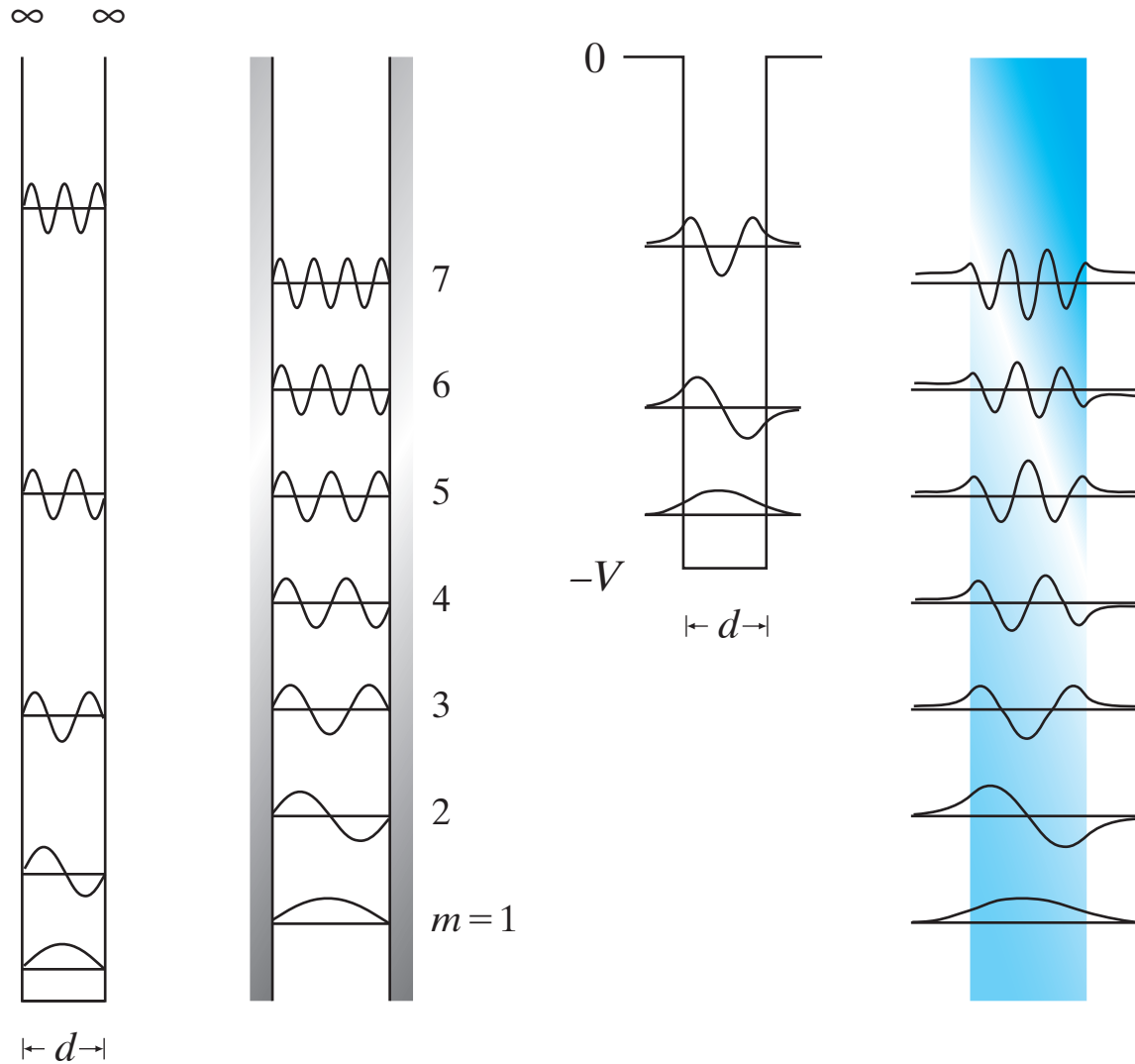
# Waveguiding



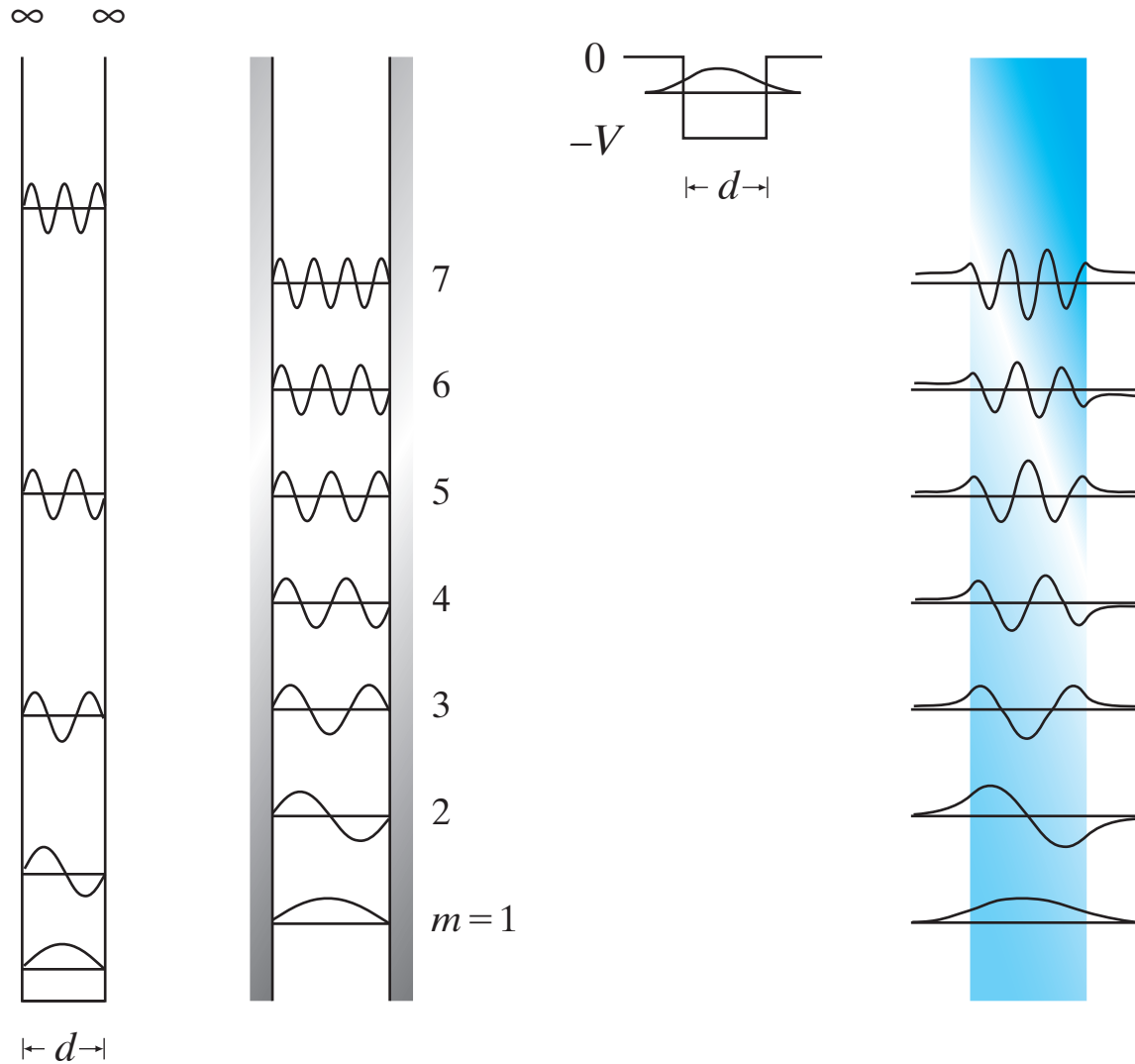
# Waveguiding



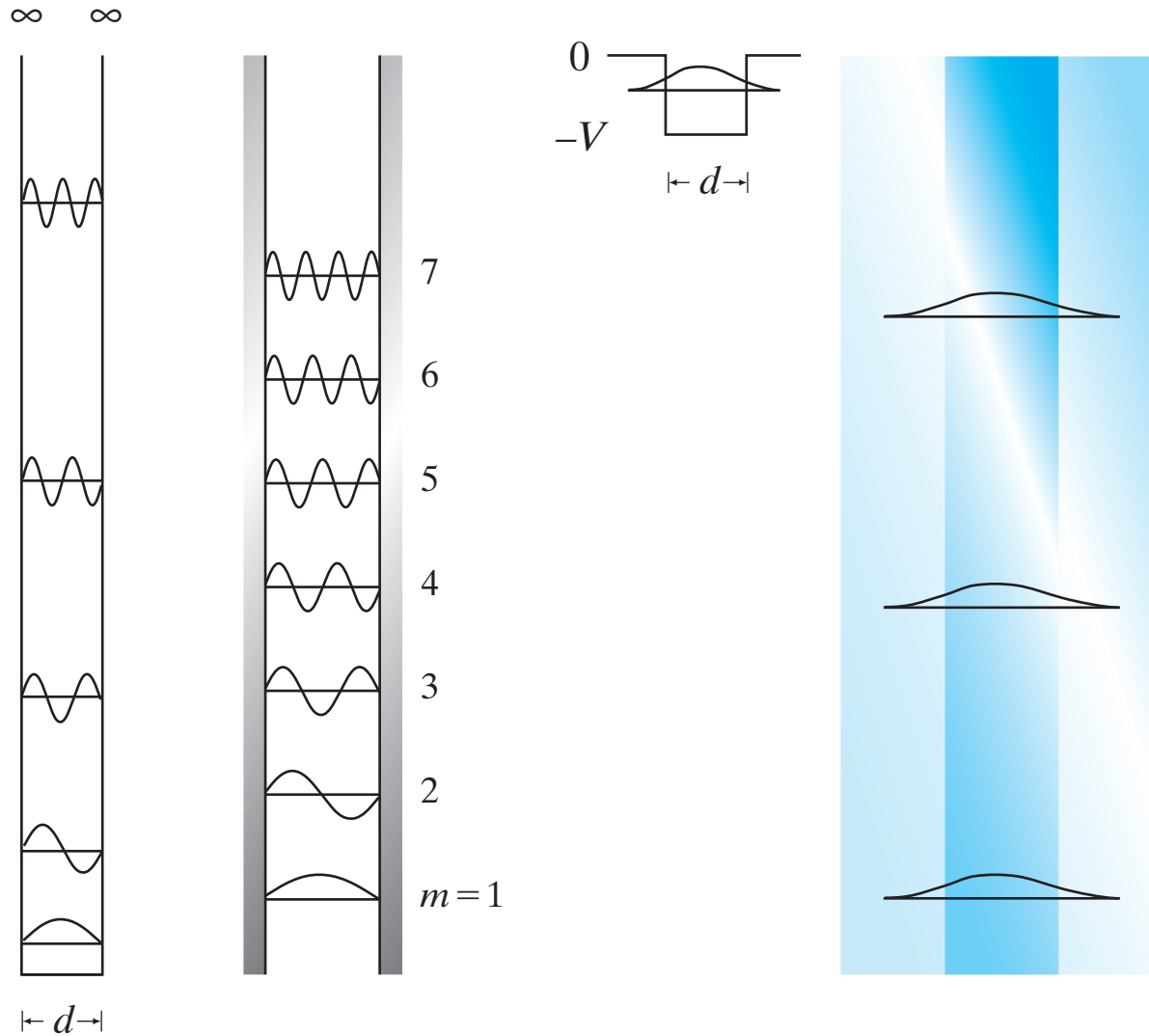
# Waveguiding



# 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<sup>®</sup>)



	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

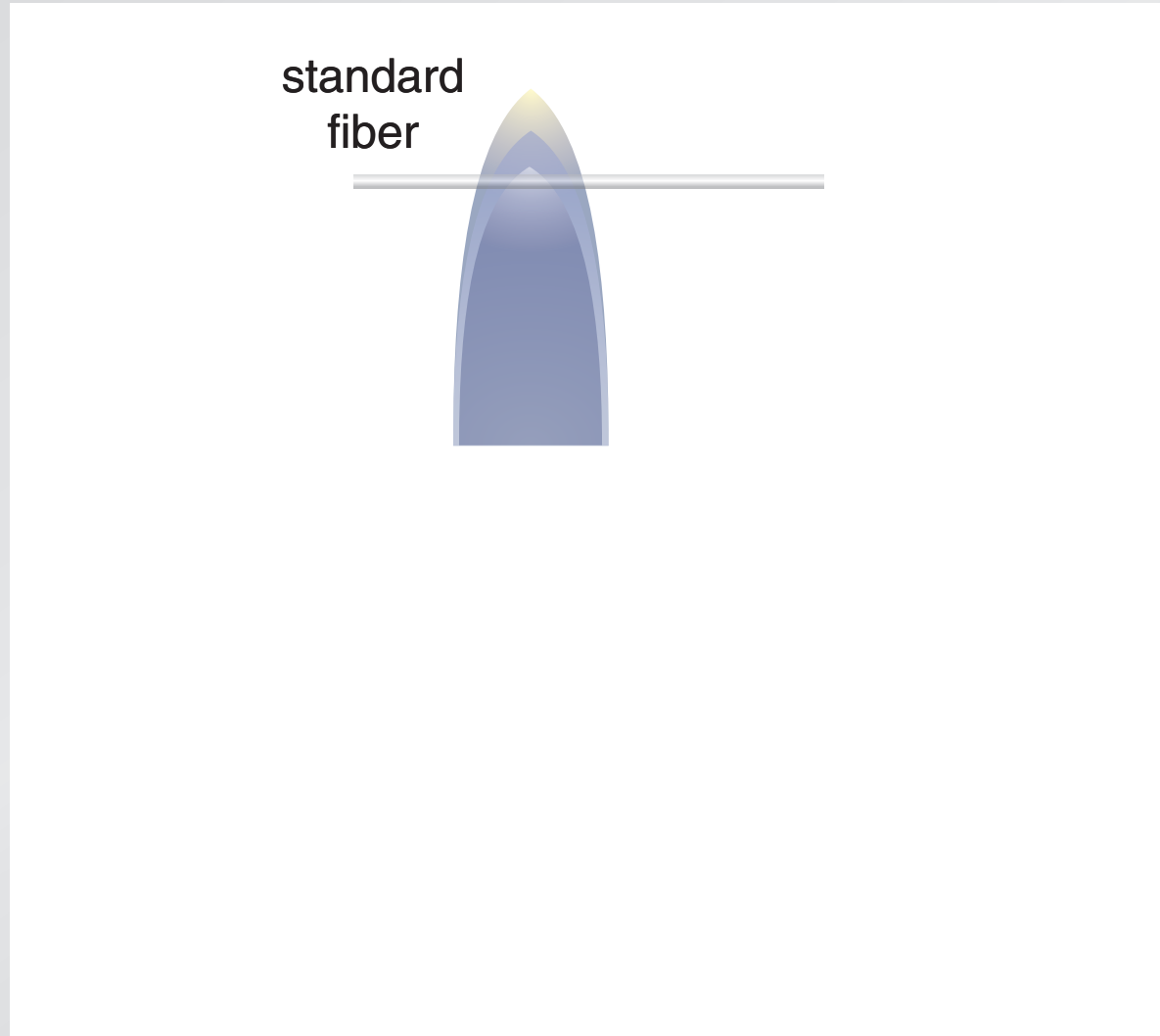
## two-step drawing process

standard  
fiber



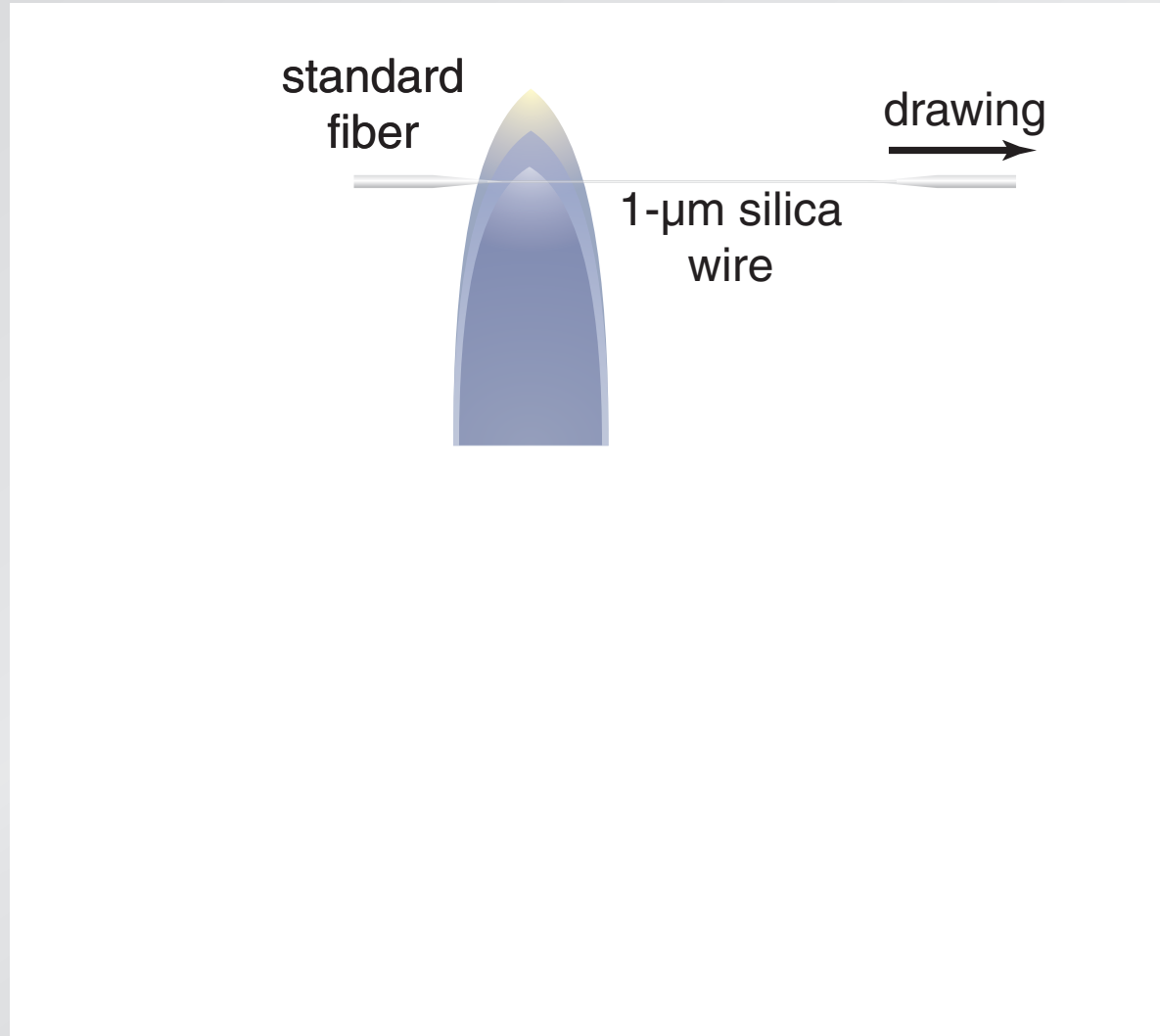
# Silica nanowires

two-step drawing process



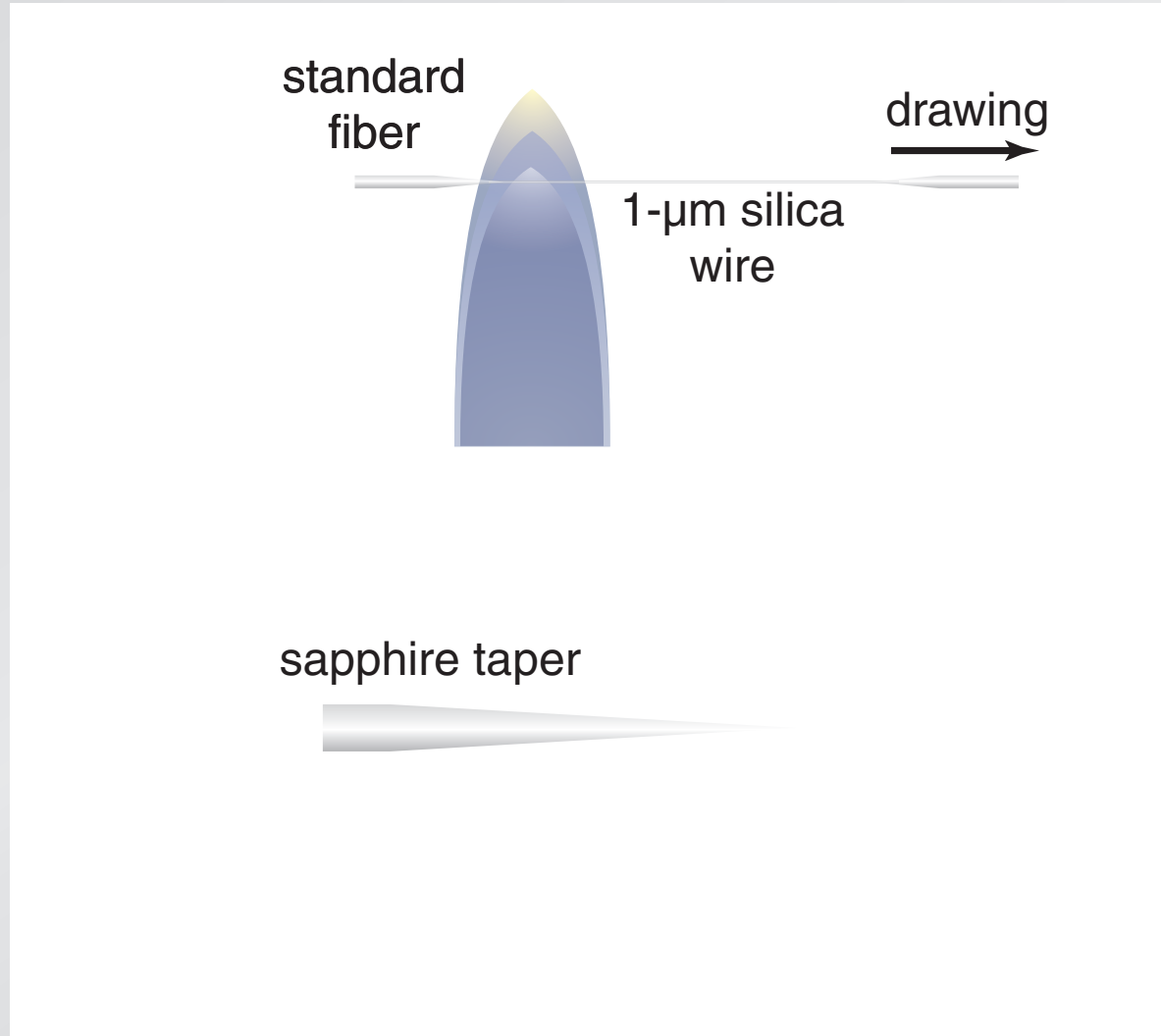
# Silica nanowires

two-step drawing process



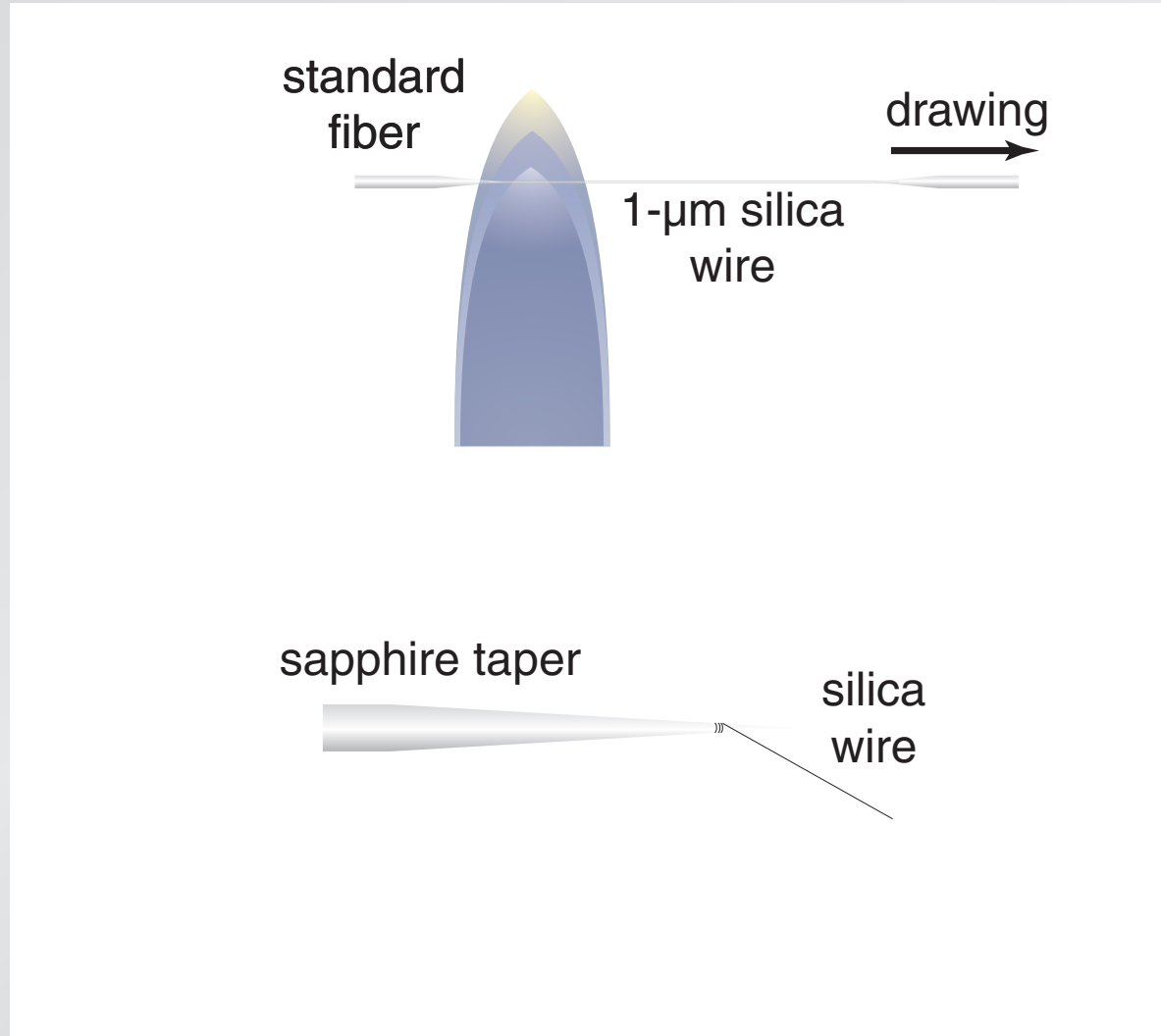
# Silica nanowires

## two-step drawing process



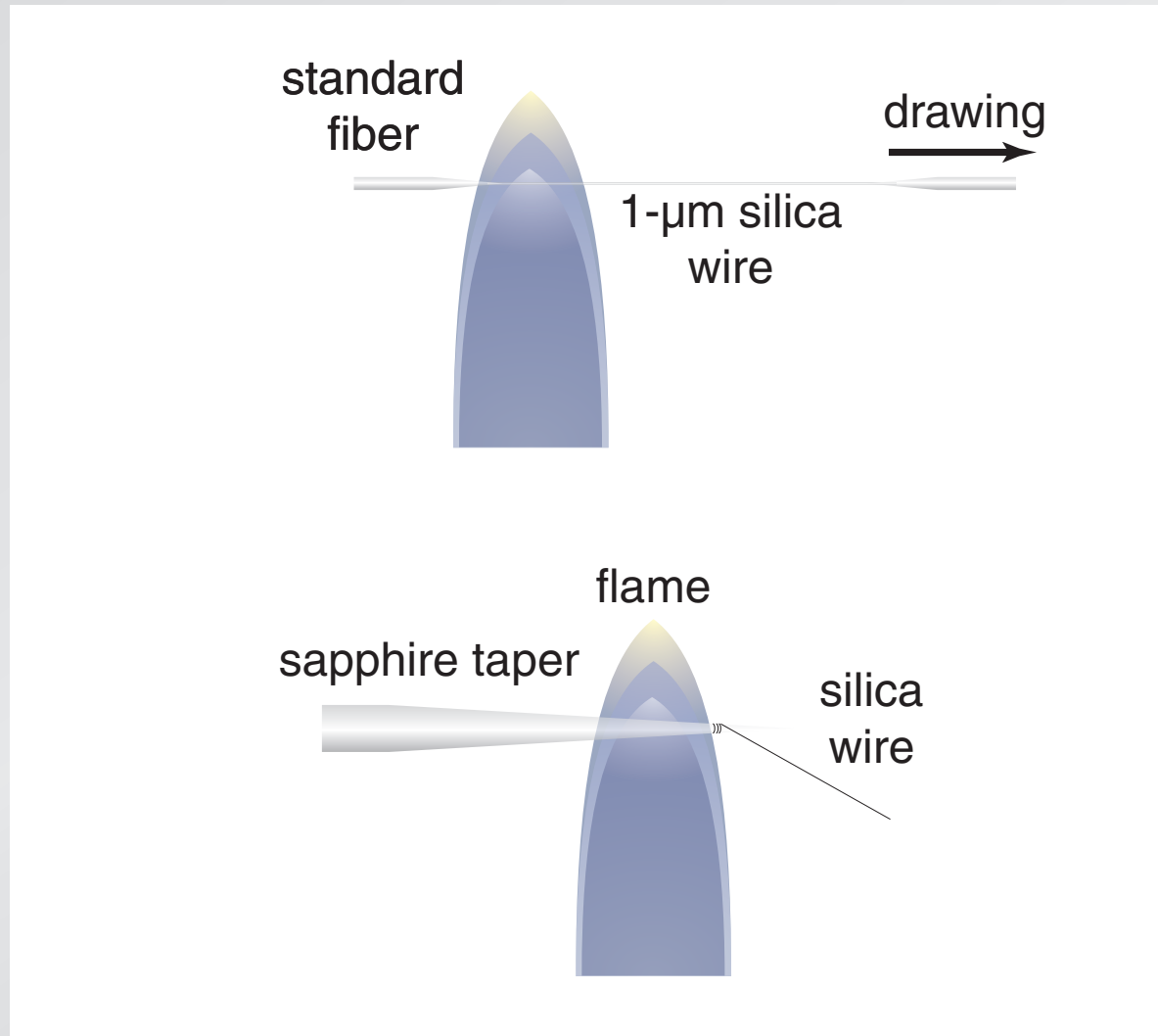
# Silica nanowires

## two-step drawing process



# Silica nanowires

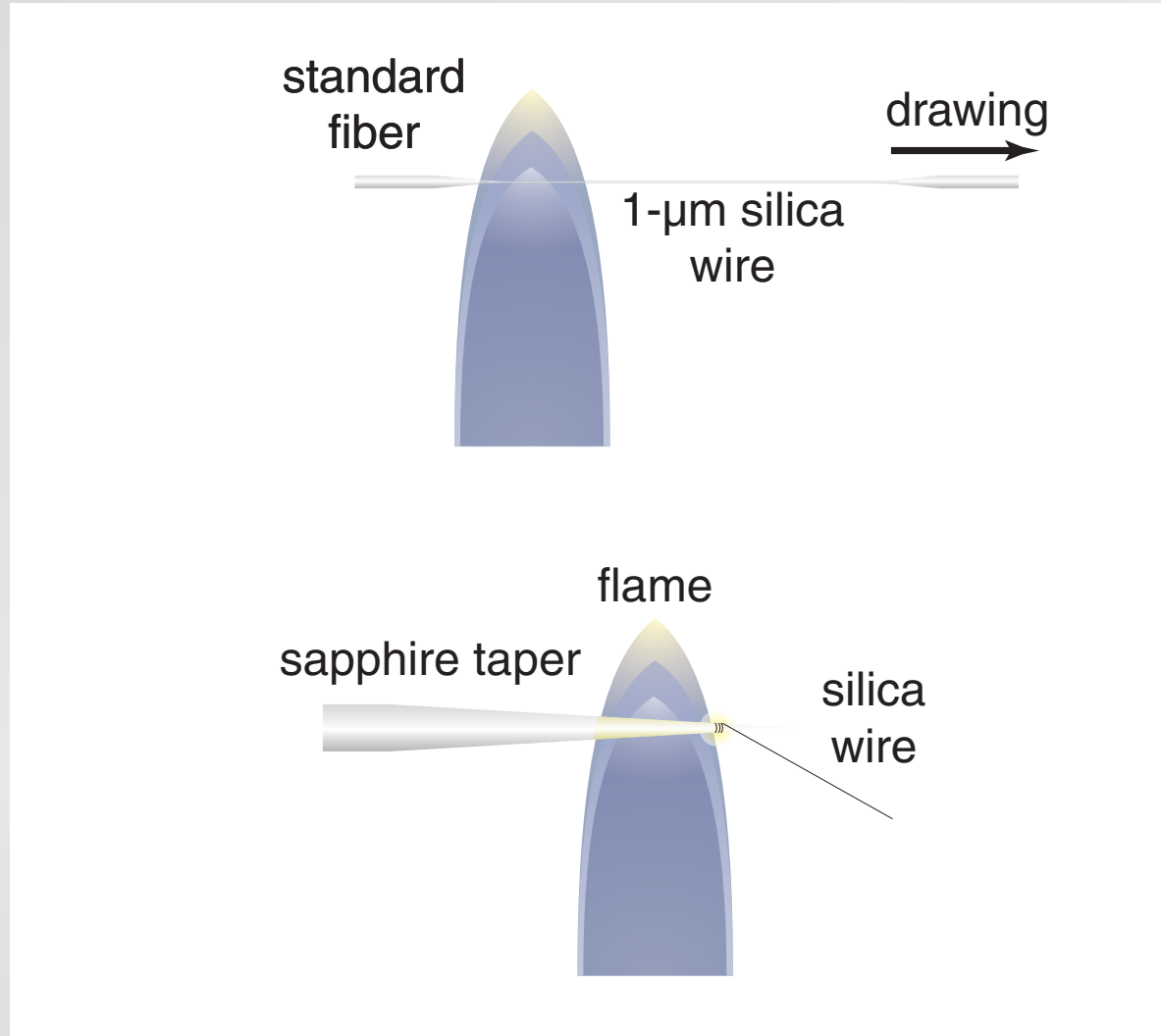
## two-step drawing process





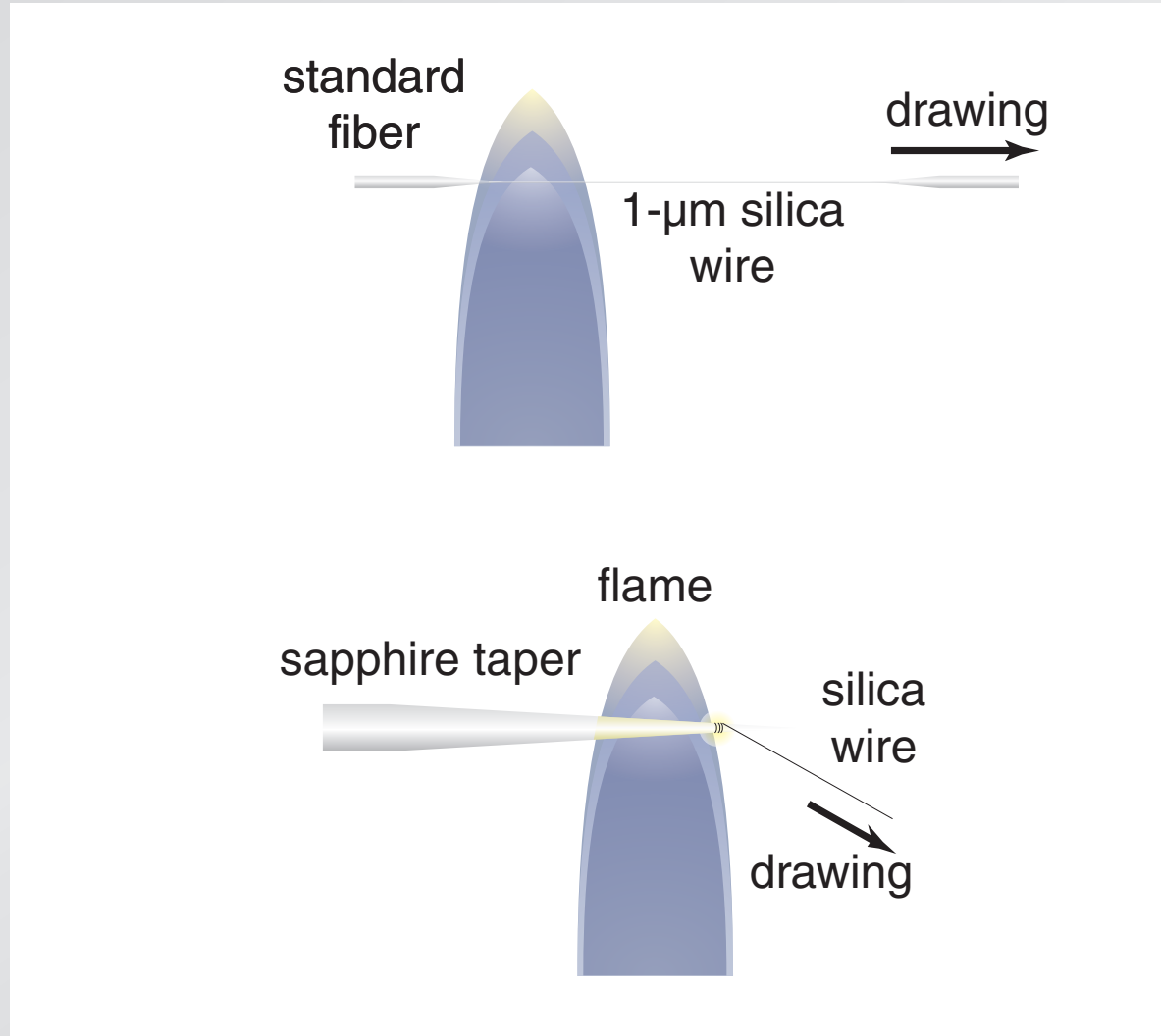
# Silica nanowires

## two-step drawing process

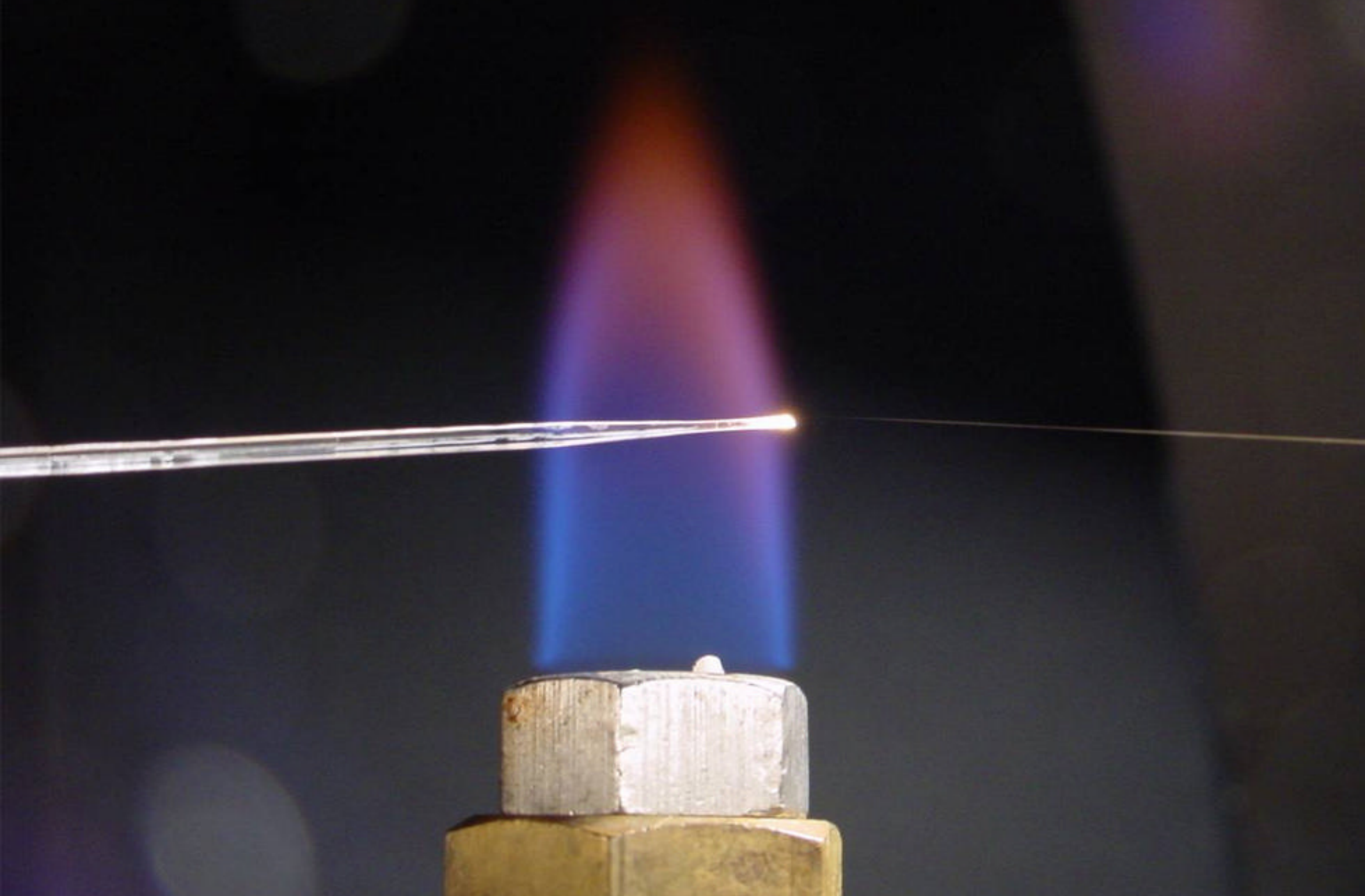


# Silica nanowires

## two-step drawing process



# Silica nanowires



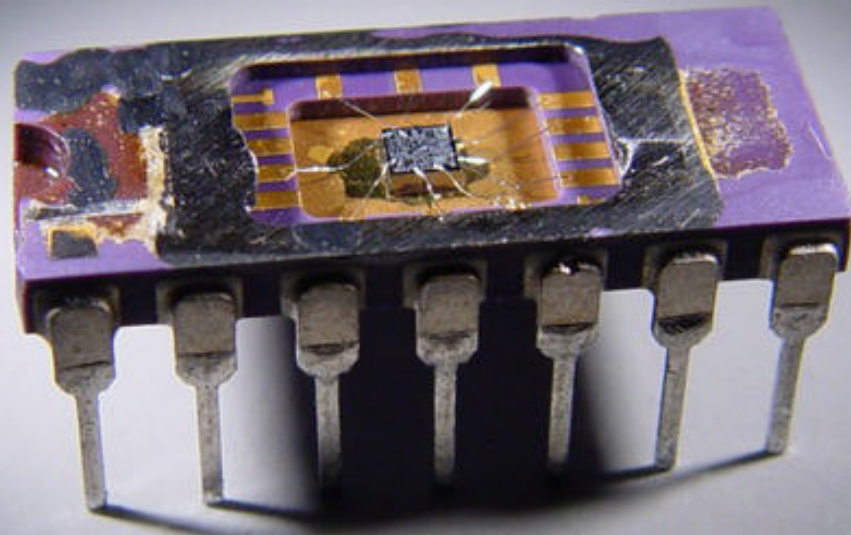
# Silica nanowires

1  $\mu\text{m}$

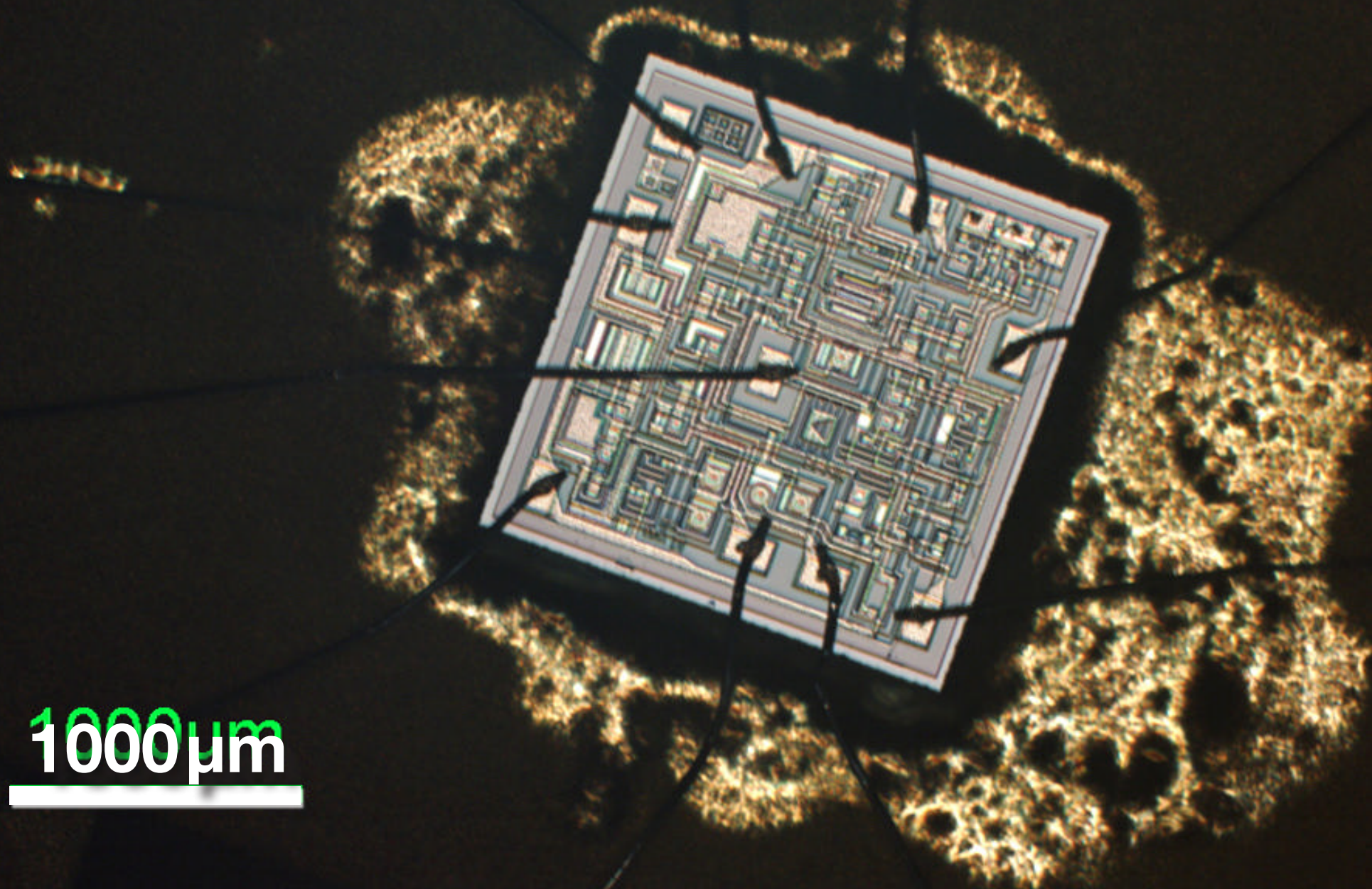


*Nature*, 426, 816 (2003)

# Silica nanowires

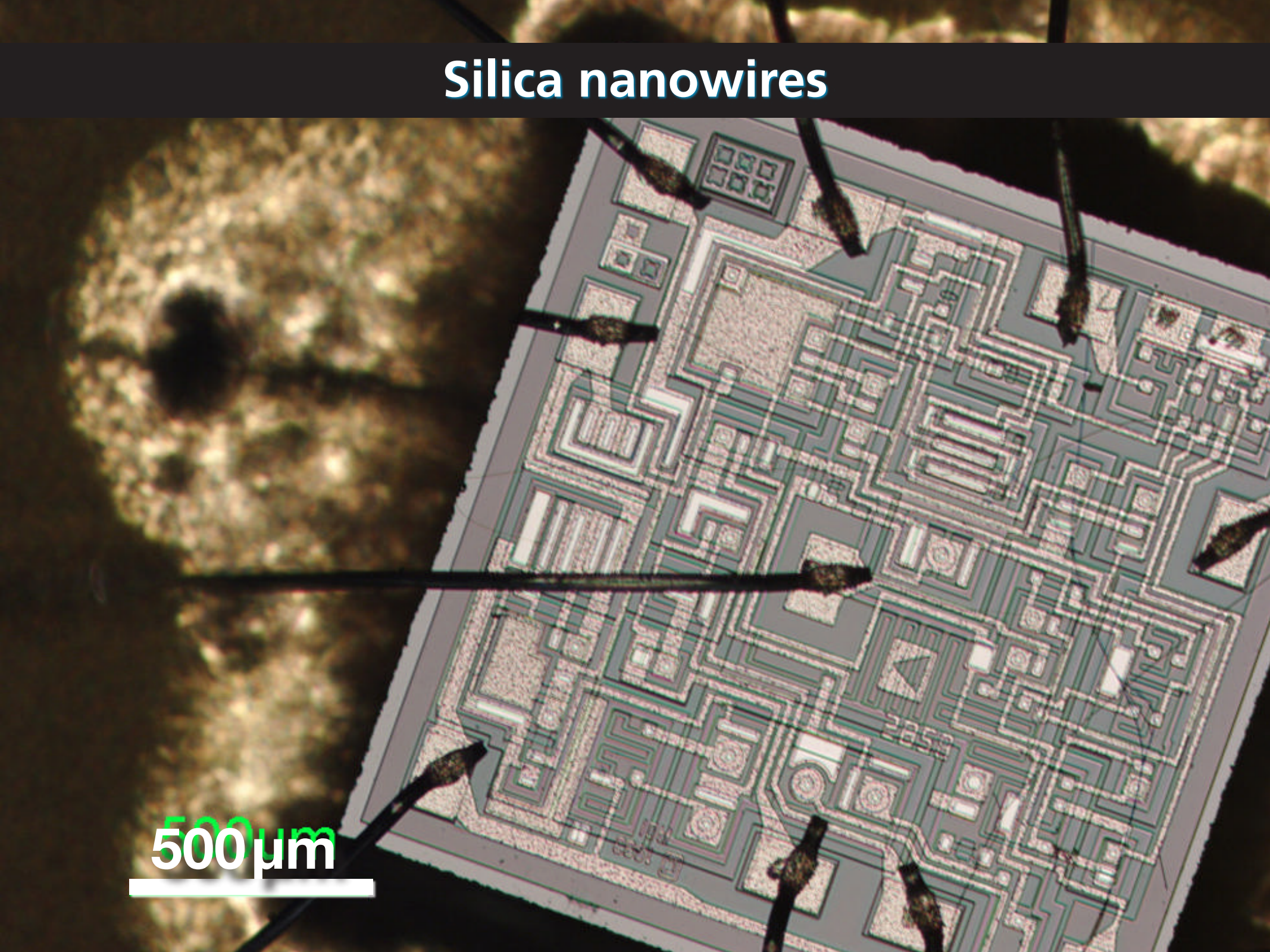
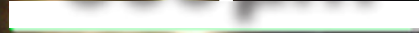


# Silica nanowires



# Silica nanowires

500  $\mu\text{m}$



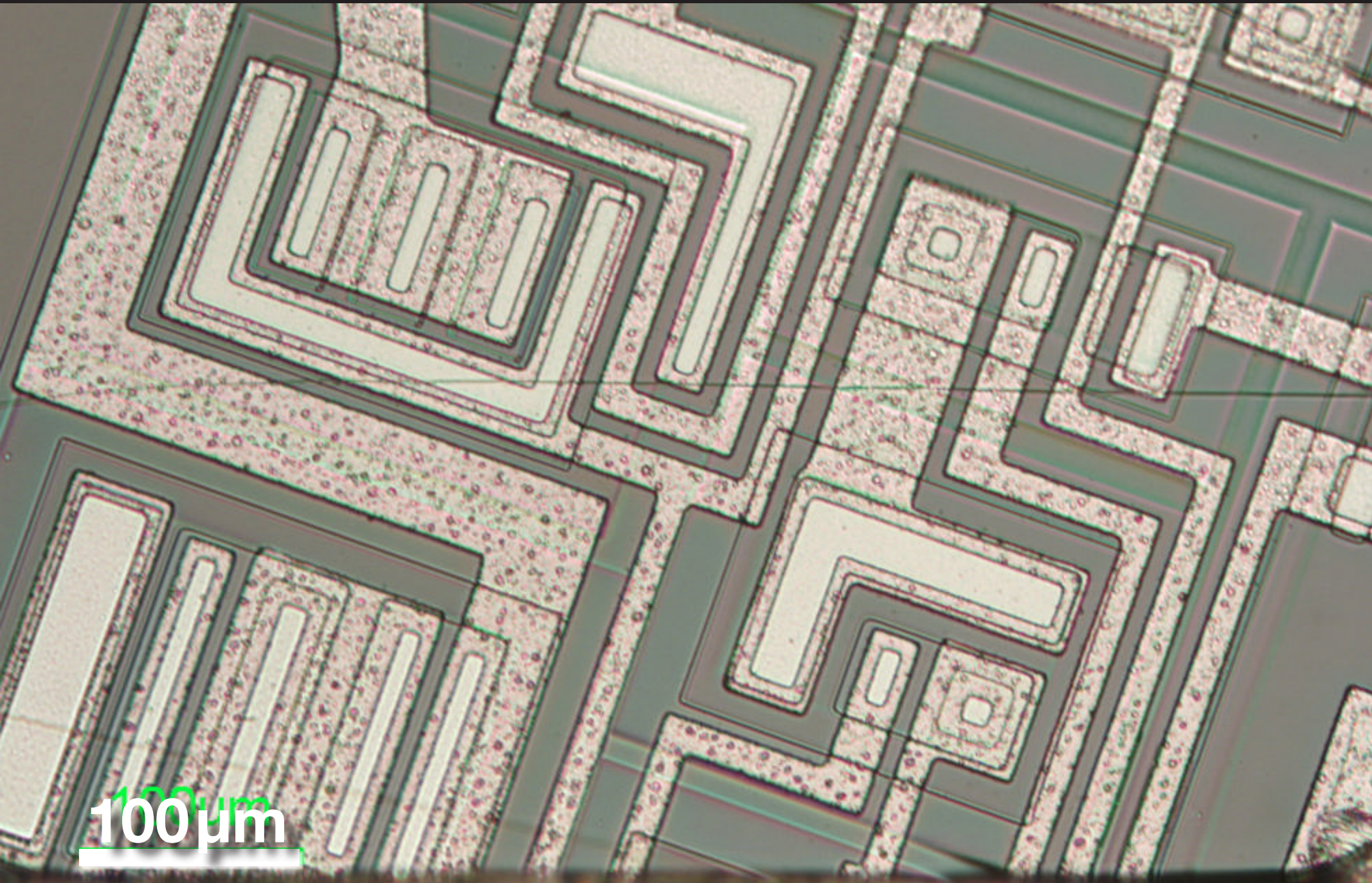
# Silica nanowires

200  $\mu\text{m}$

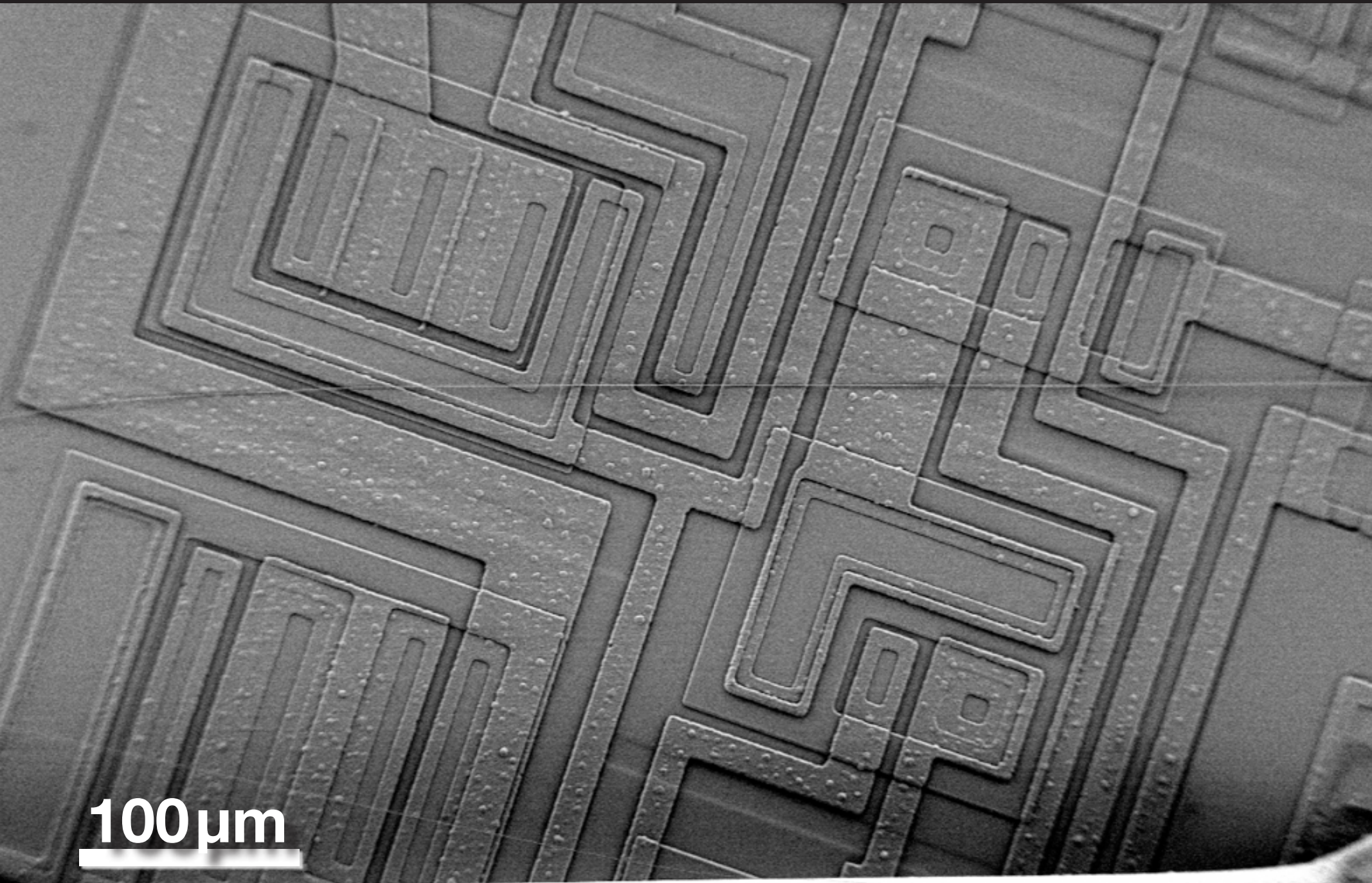
A scanning electron micrograph (SEM) showing a silicon chip with a complex circuit pattern. Two long, thin silica nanowires are positioned across the chip. One nanowire is oriented vertically, and the other is oriented horizontally. The chip surface is covered with various rectangular and circular patterns, likely representing different layers or components of the device. A scale bar in the bottom left corner indicates a length of 200 micrometers.



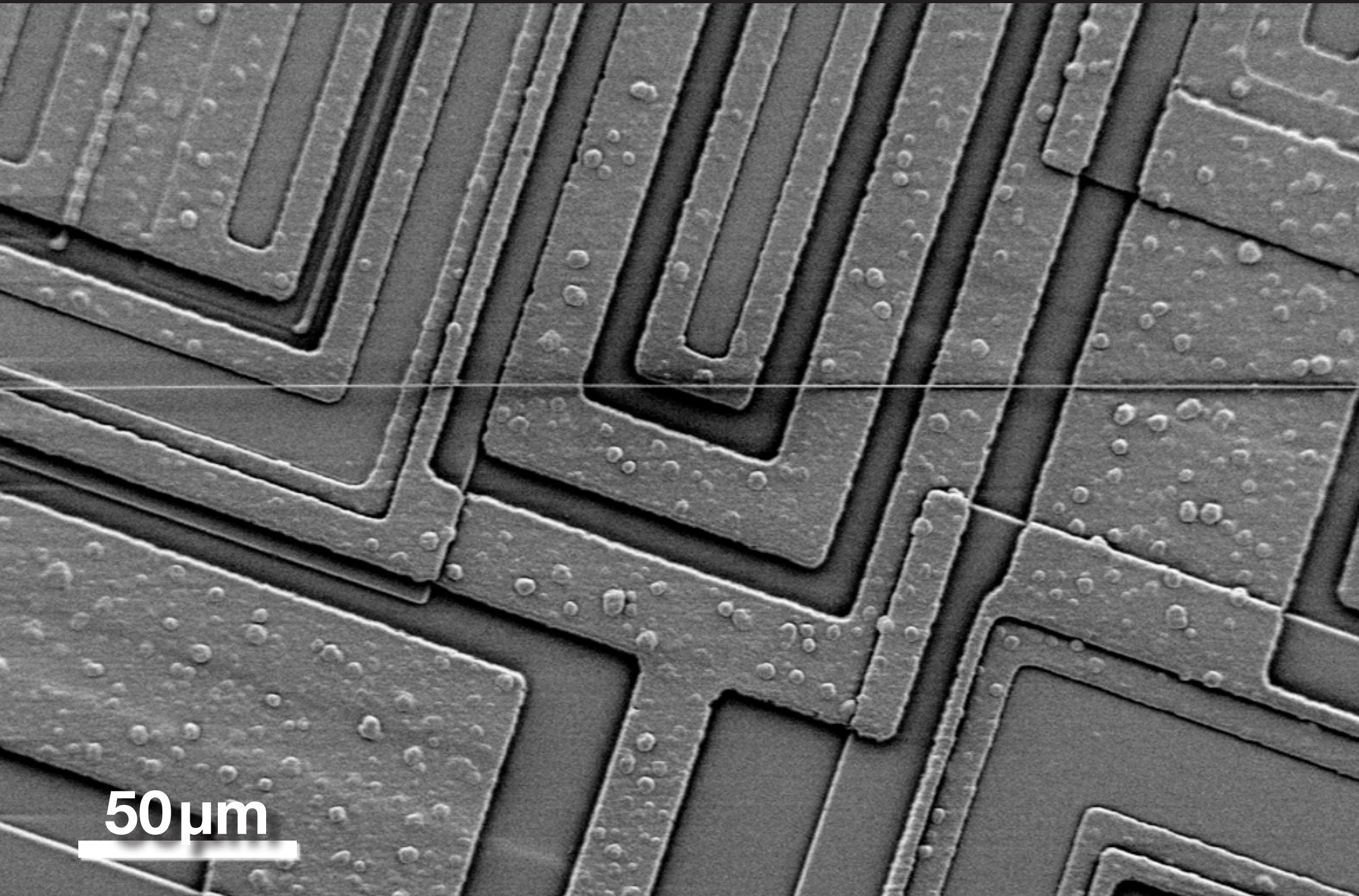
# Silica nanowires



# Silica nanowires

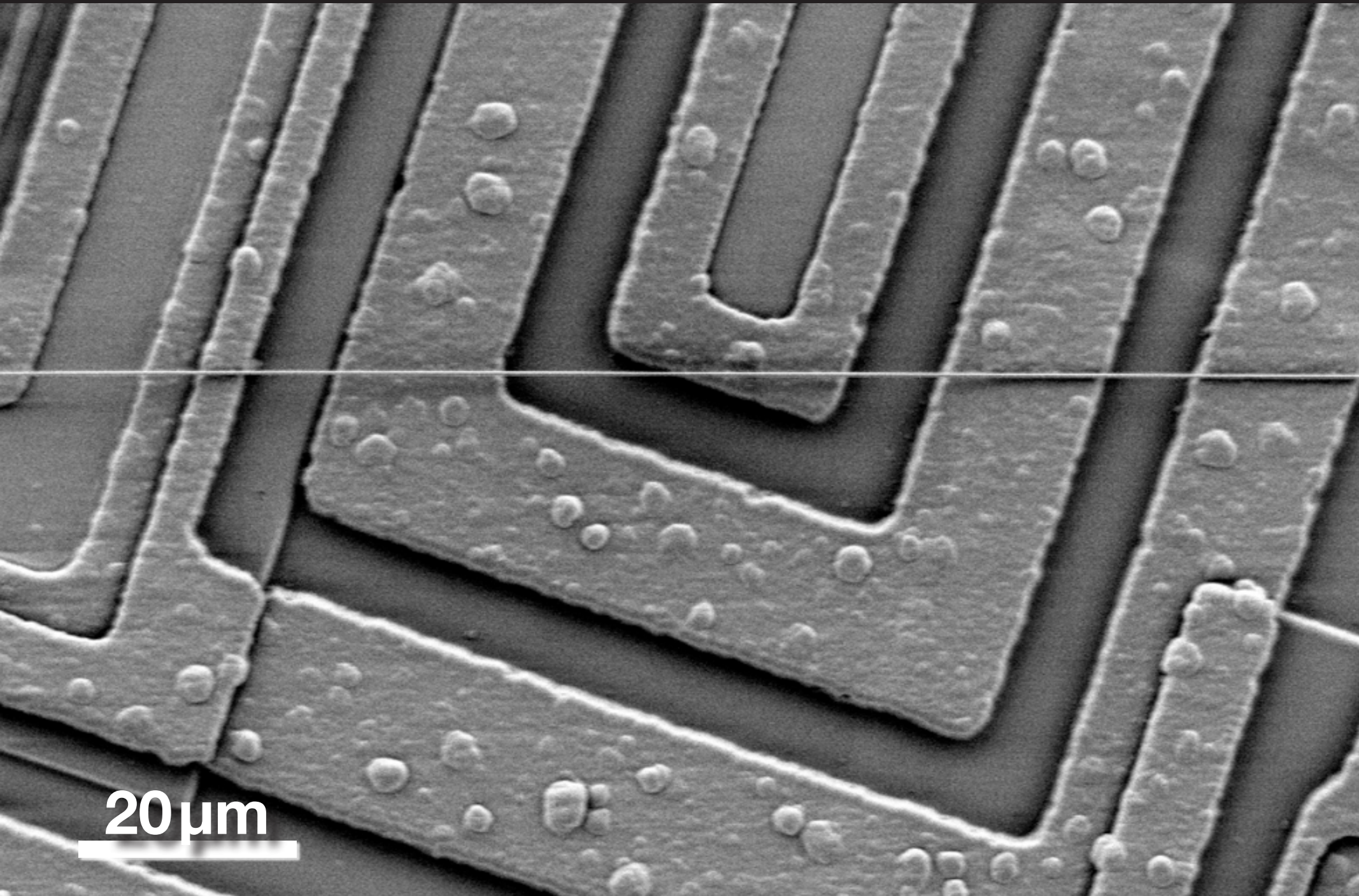


# Silica nanowires



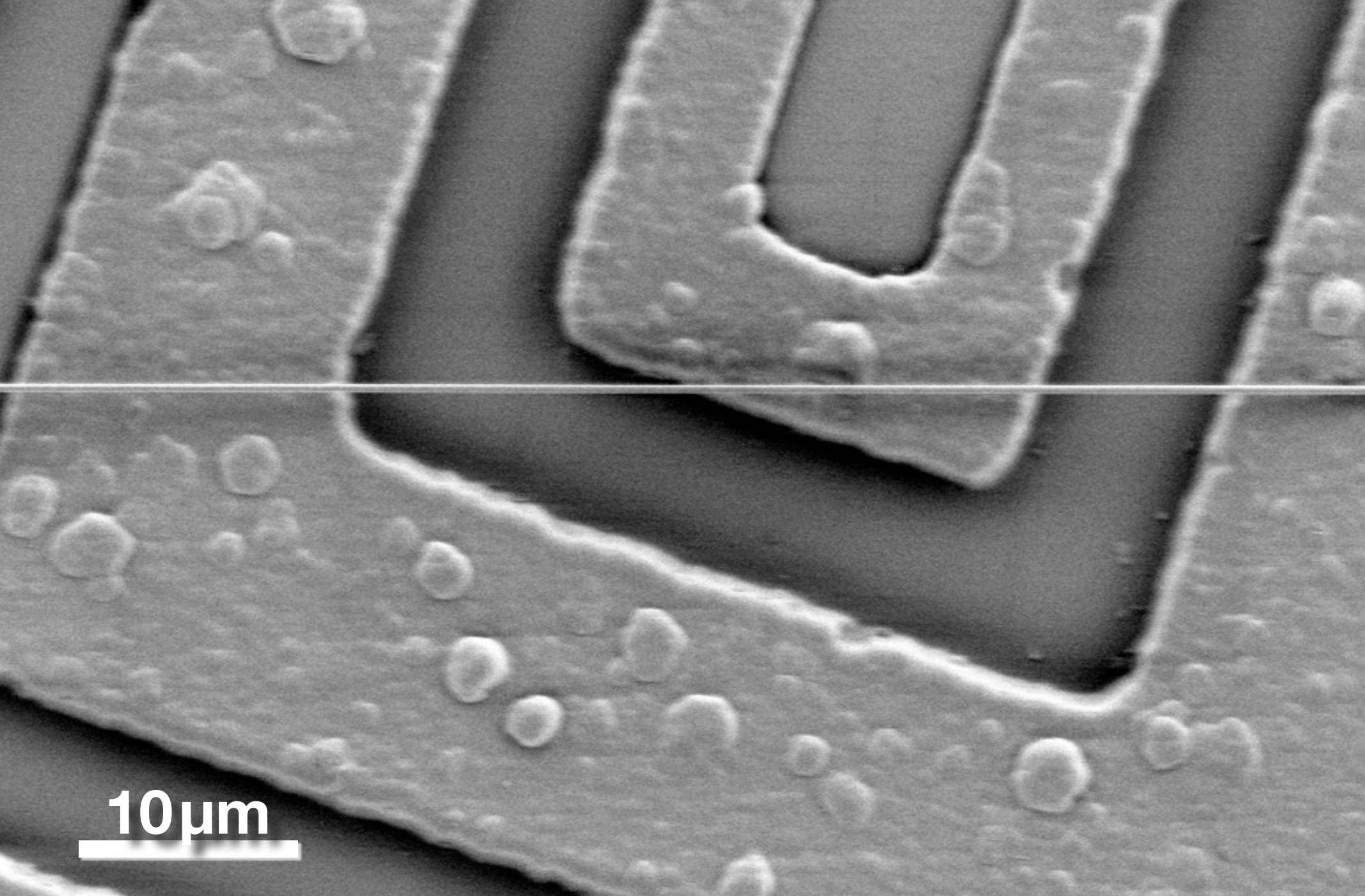
50  $\mu\text{m}$

# Silica nanowires



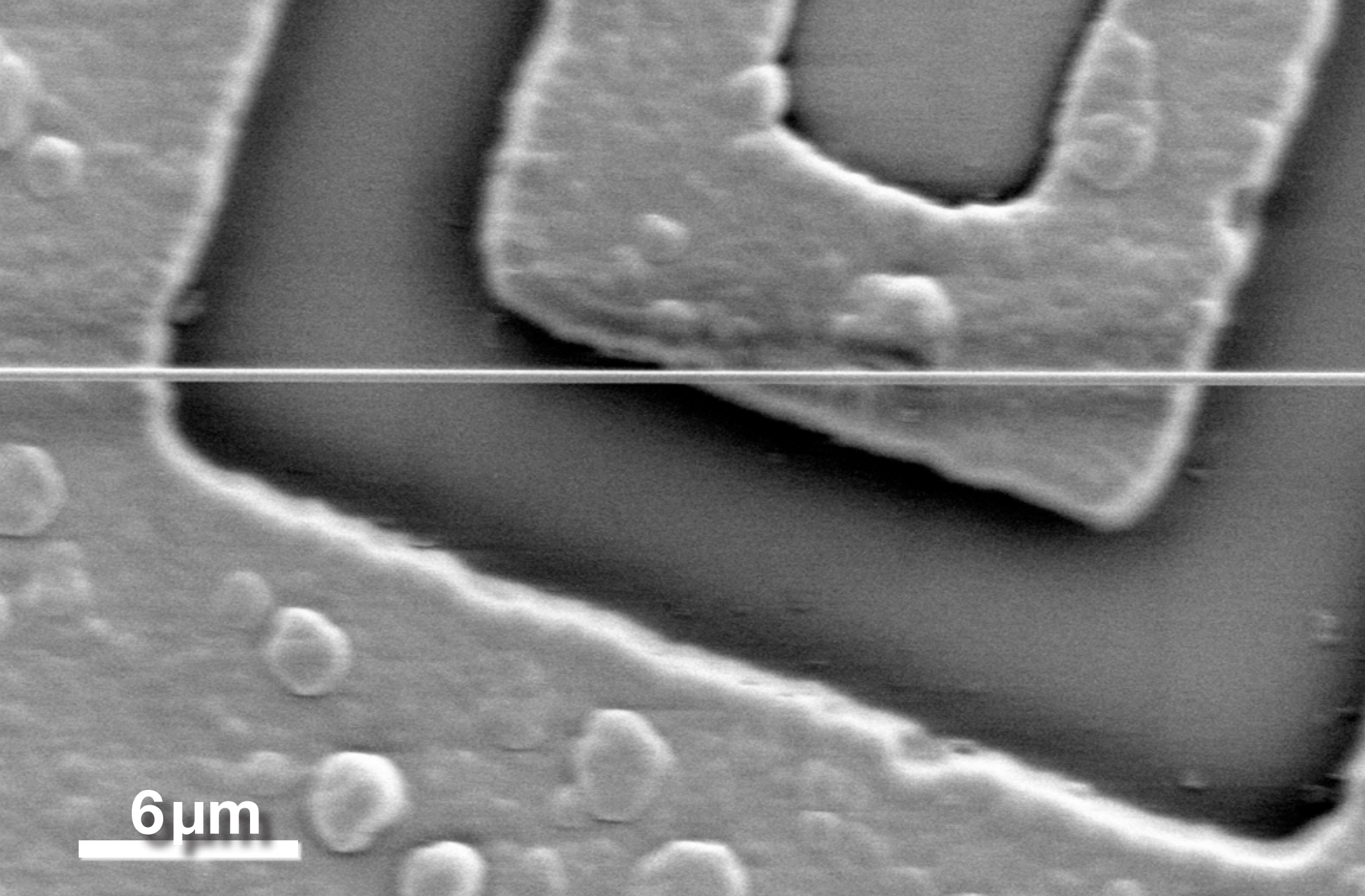
20  $\mu\text{m}$

# Silica nanowires



10  $\mu\text{m}$

# Silica nanowires

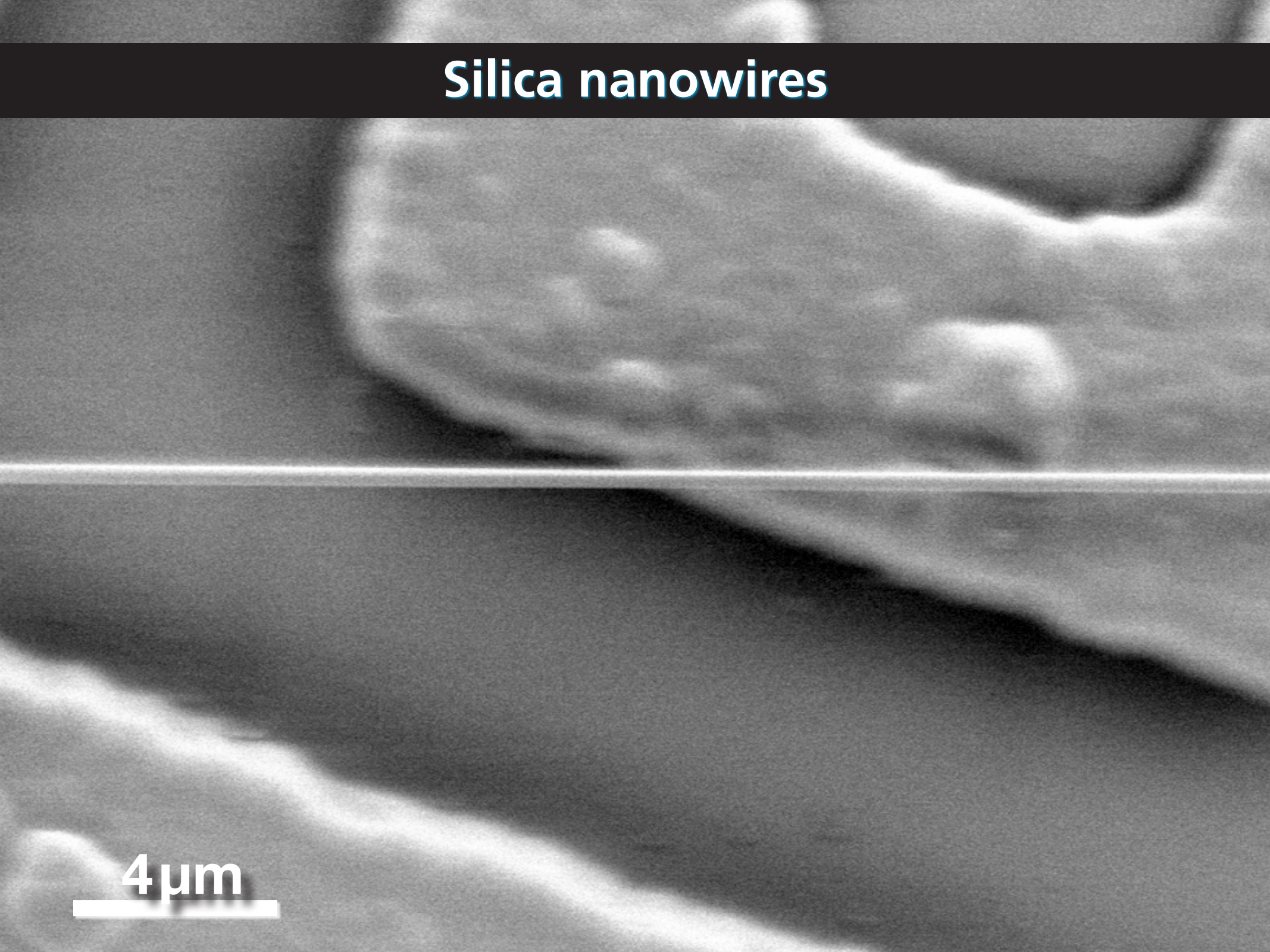


6  $\mu\text{m}$



# Silica nanowires

4  $\mu\text{m}$



# Silica nanowires

2  $\mu\text{m}$

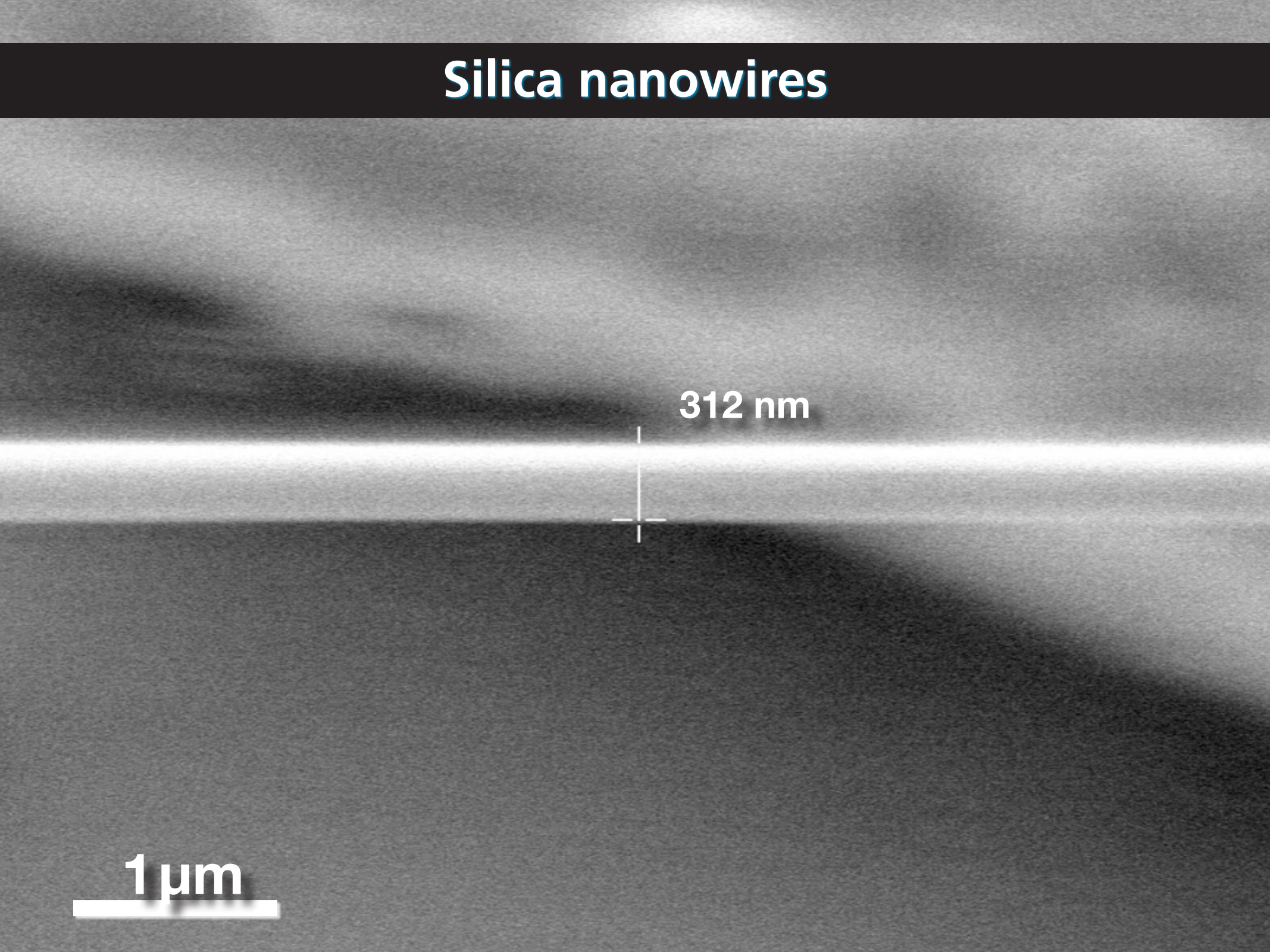
A grayscale micrograph showing a single, long, thin silica nanowire oriented horizontally across the center of the frame. The nanowire is very uniform in thickness and extends across most of the width of the image. In the bottom-left corner, there is a white horizontal scale bar with the text "2 μm" positioned above it.



# Silica nanowires

312 nm

1  $\mu\text{m}$



# Silica nanowires

## Specifications

diameter  $D$ : down to 20 nm

length  $L$ : up to 90 mm

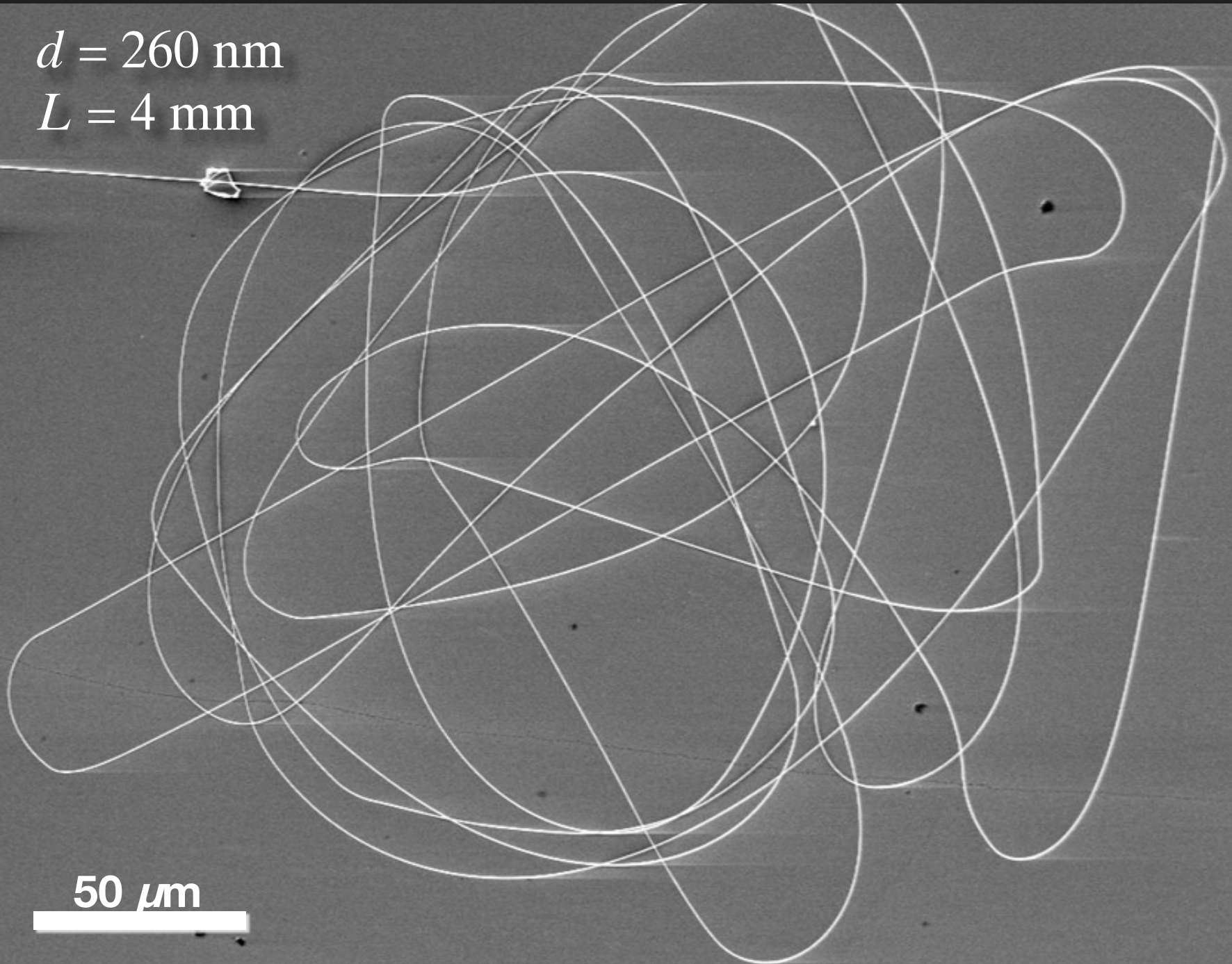
aspect ratio  $D/L$ : up to  $10^6$

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

# Silica nanowires

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50  $\mu\text{m}$

# 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. The text '240-nm wire' is positioned to the left of the wire, and the title 'Silica nanowires' is at the top.

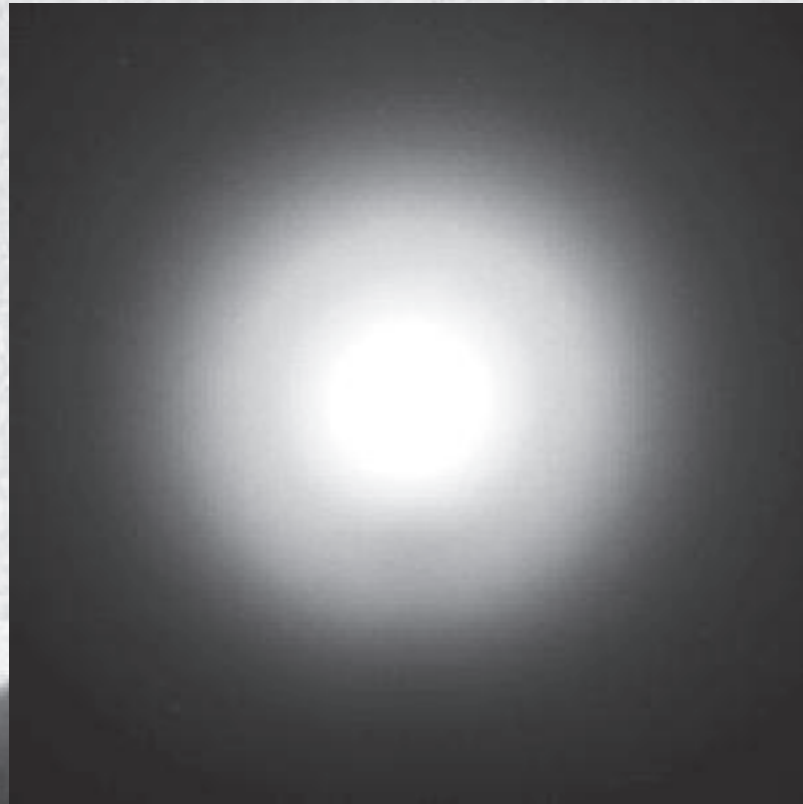
# Silica nanowires

RMS roughness < 0.5 nm

20 nm



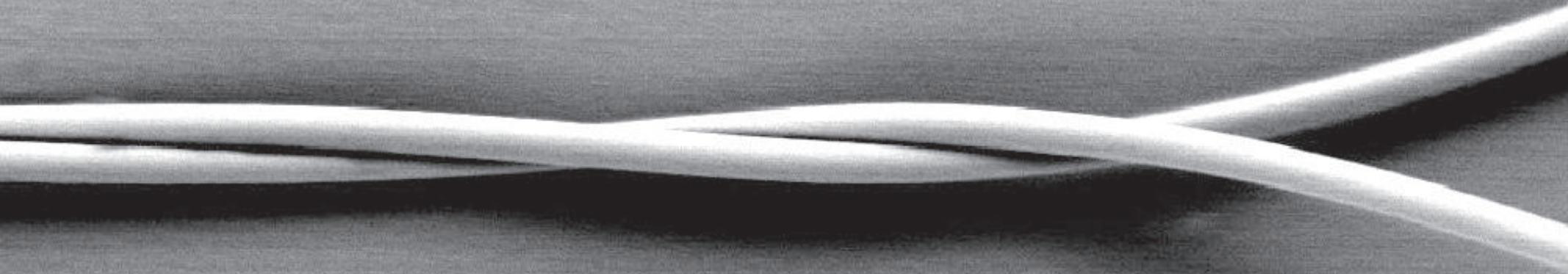
# Silica nanowires



20 nm

A white horizontal scale bar located at the bottom left of the image, used for size reference.

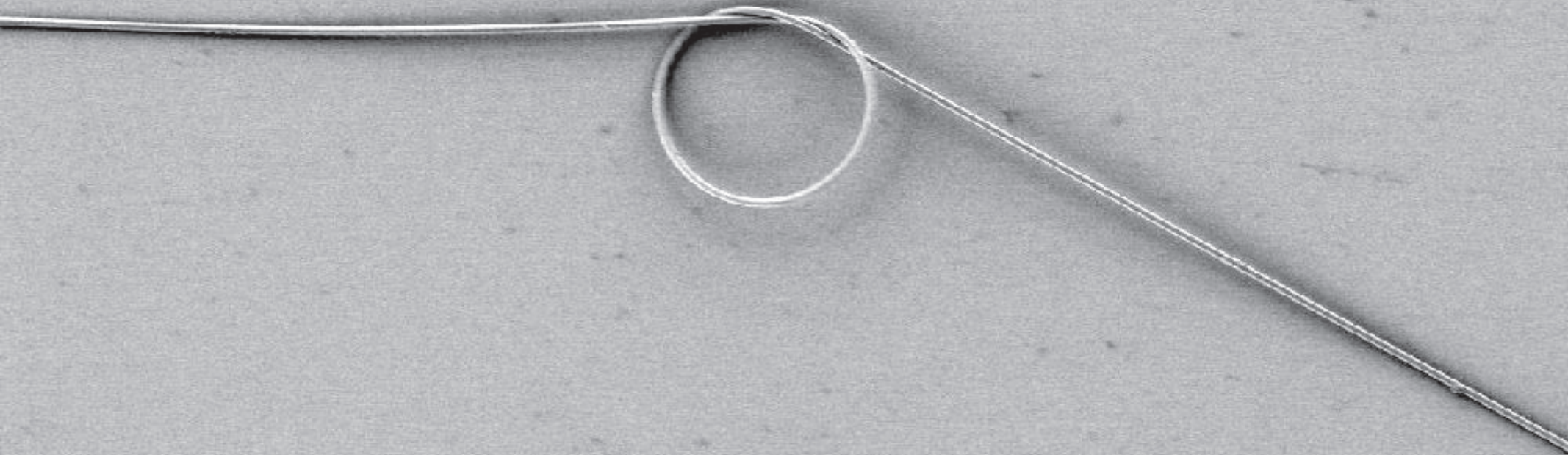
# Silica nanowires



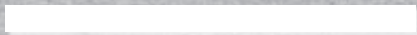
2  $\mu\text{m}$



# Silica nanowires

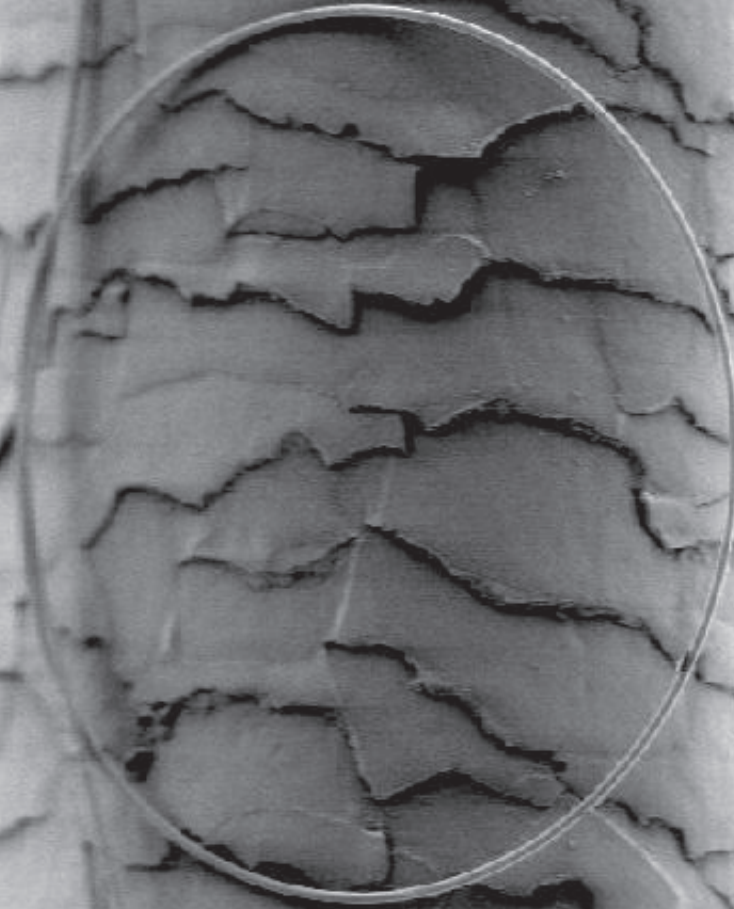


20  $\mu\text{m}$





# Silica nanowires



20  $\mu\text{m}$



# Silica nanowires

**Points to keep in mind:**

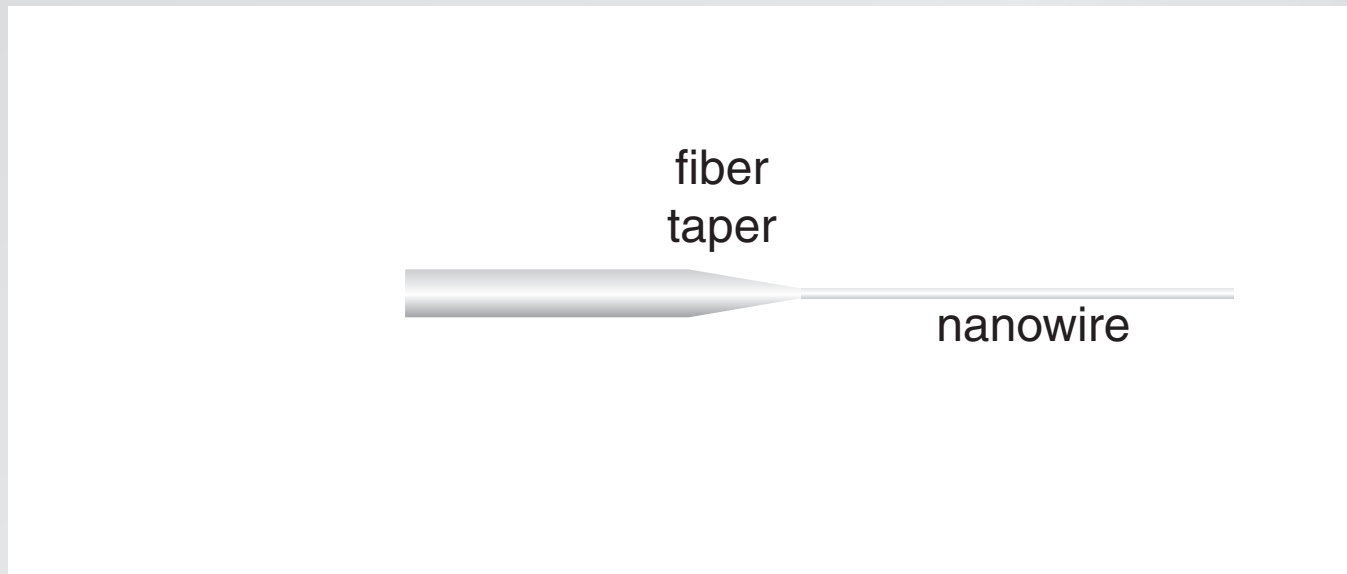
- **easy fabrication**
- **atomic level smoothness**
- **malleable**

# Outline

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

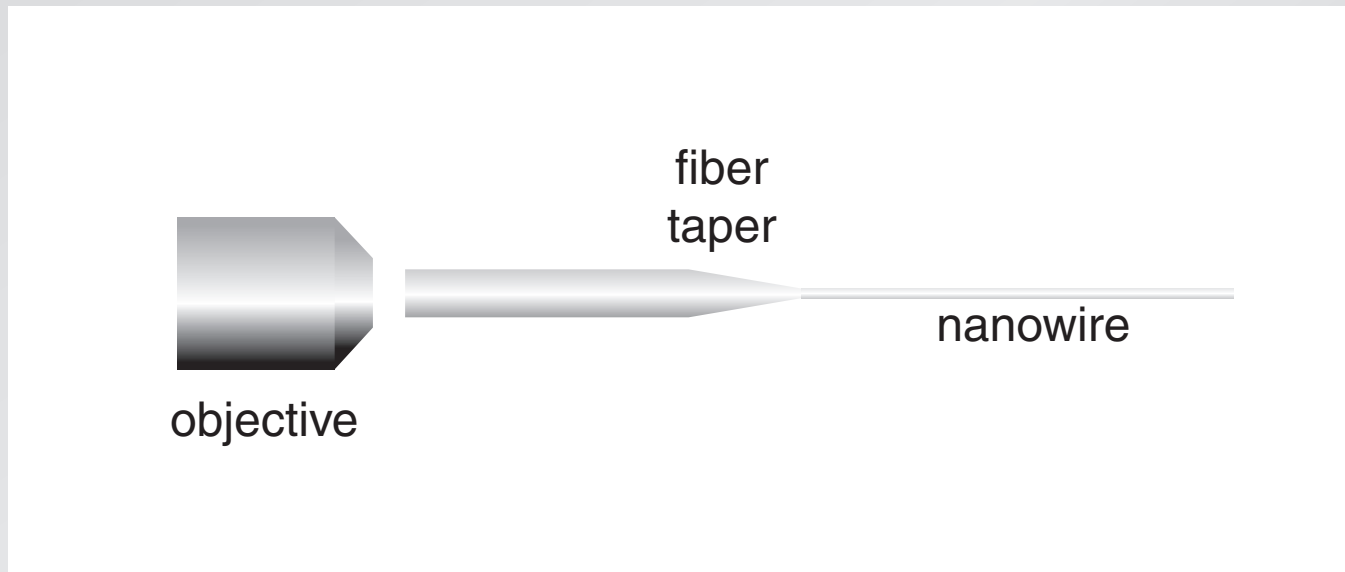
# Manipulating light at the nanoscale

coupling light into nanowires



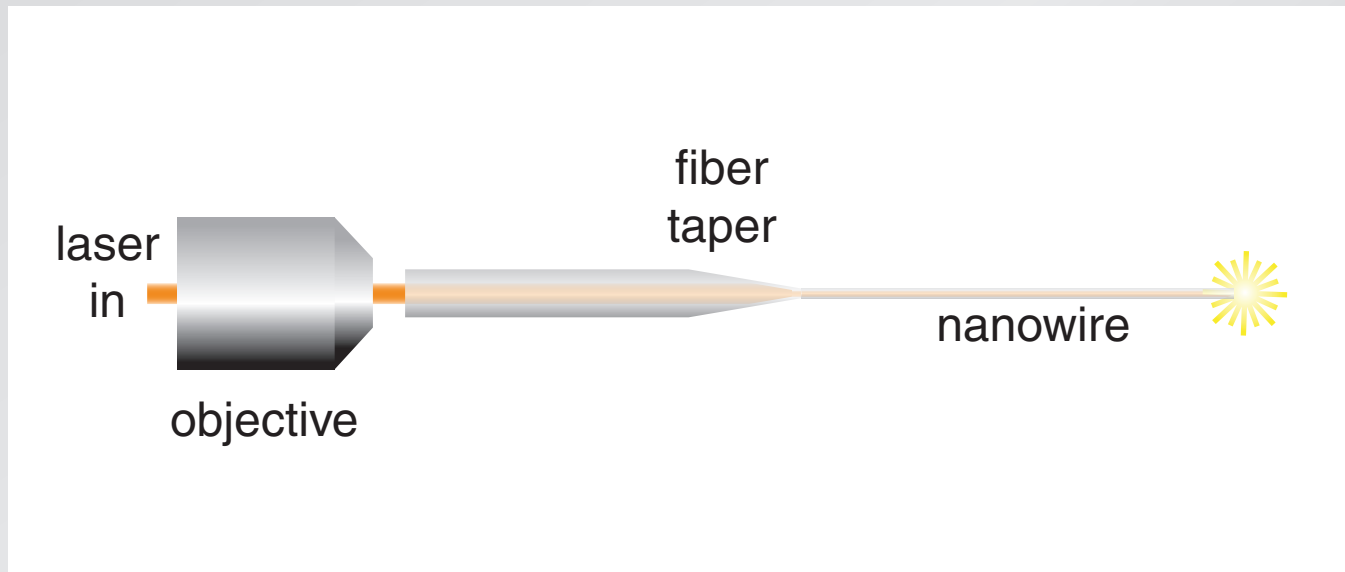
# Manipulating light at the nanoscale

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 the narrowest of the three structures shown.

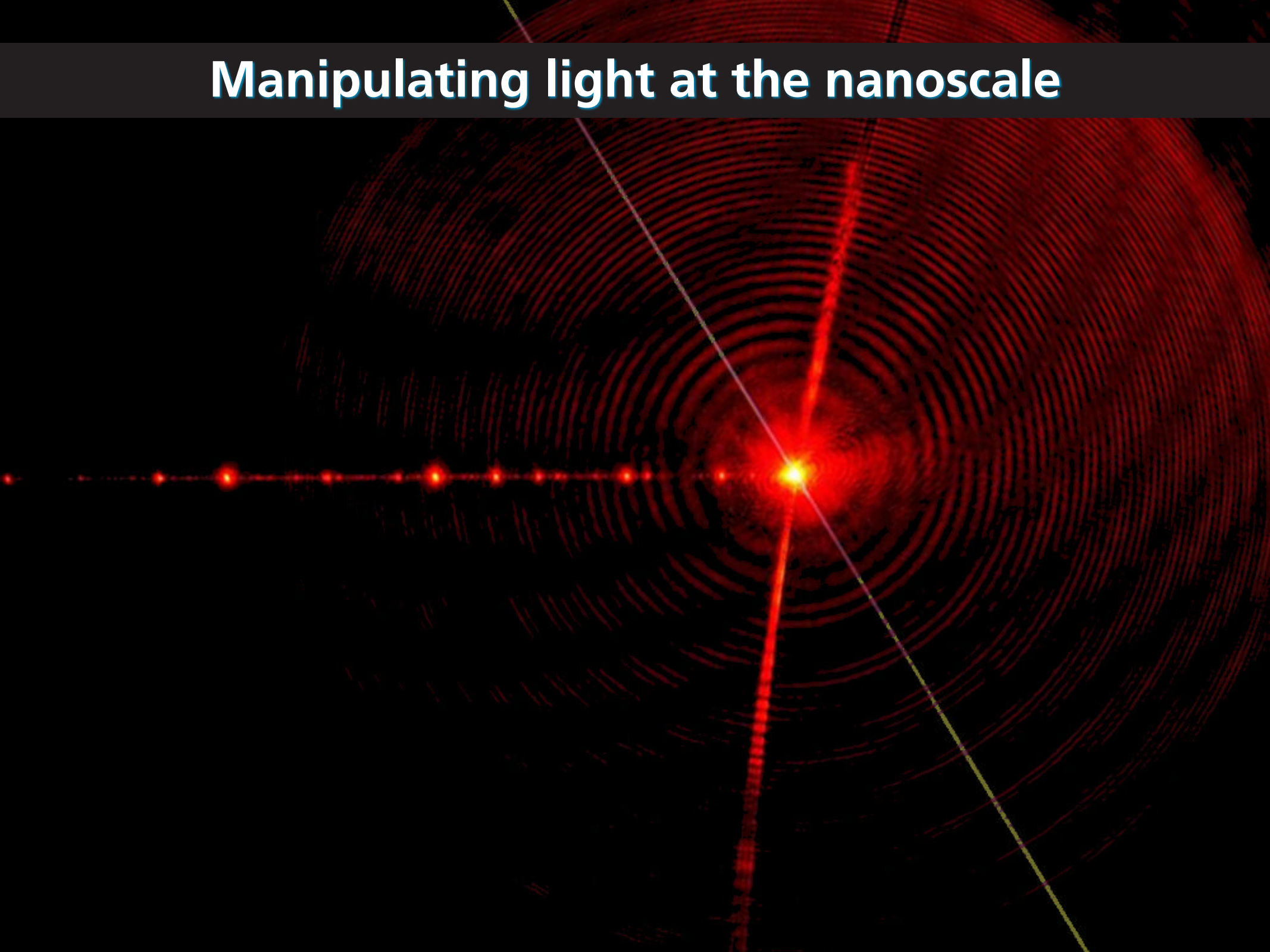
360 nm

A scanning electron microscope (SEM) image of a single nanowire. This nanowire is thicker than the 280-nm nanowire, appearing as a slightly wider, dark line. It is oriented horizontally and is the middle structure in the set.

450 nm

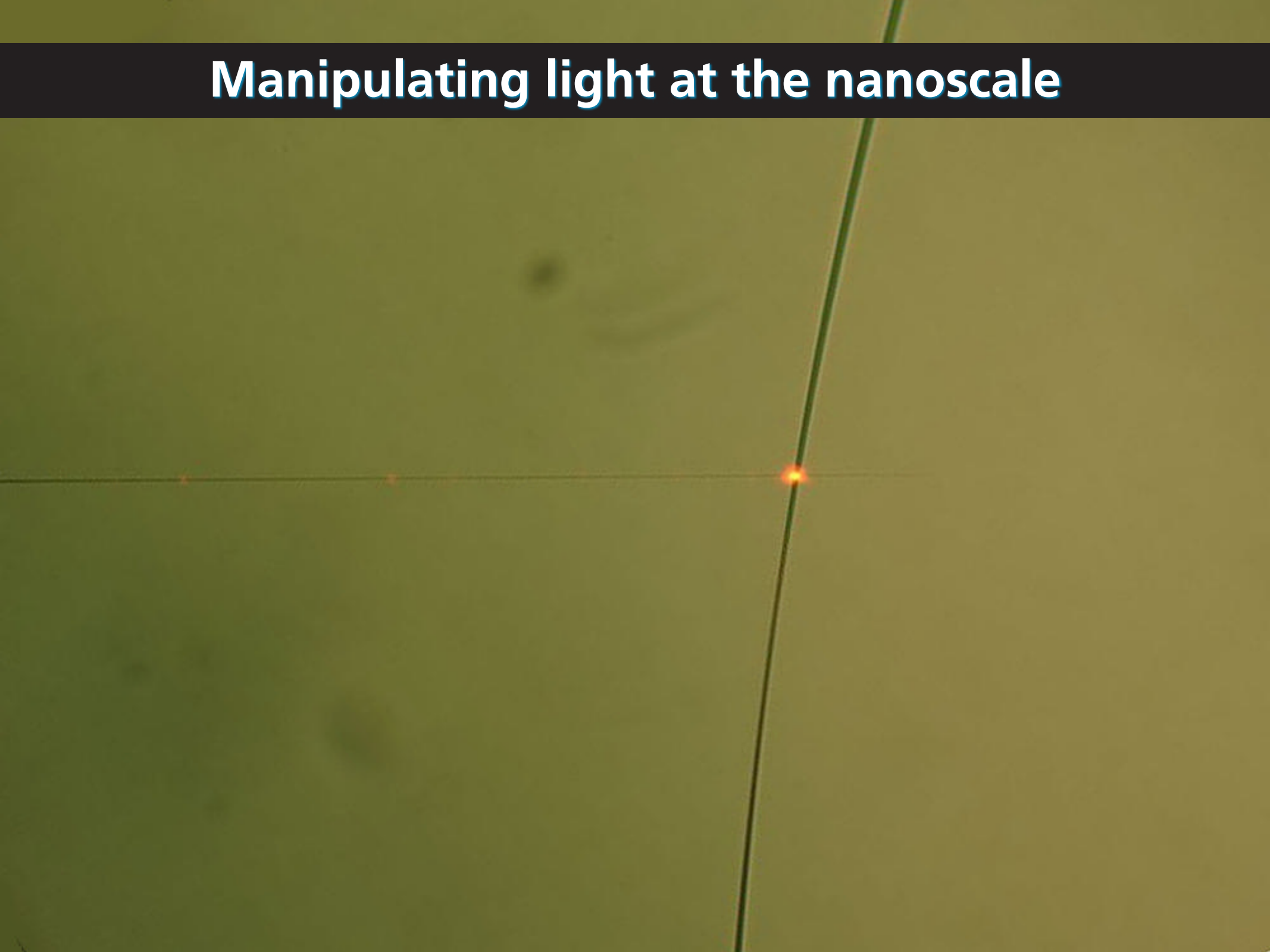
A scanning electron microscope (SEM) image of a single nanowire. This nanowire is the thickest of the three, appearing as a wide, dark line. It is oriented horizontally and is the bottom structure in the set.

# Manipulating light at the nanoscale



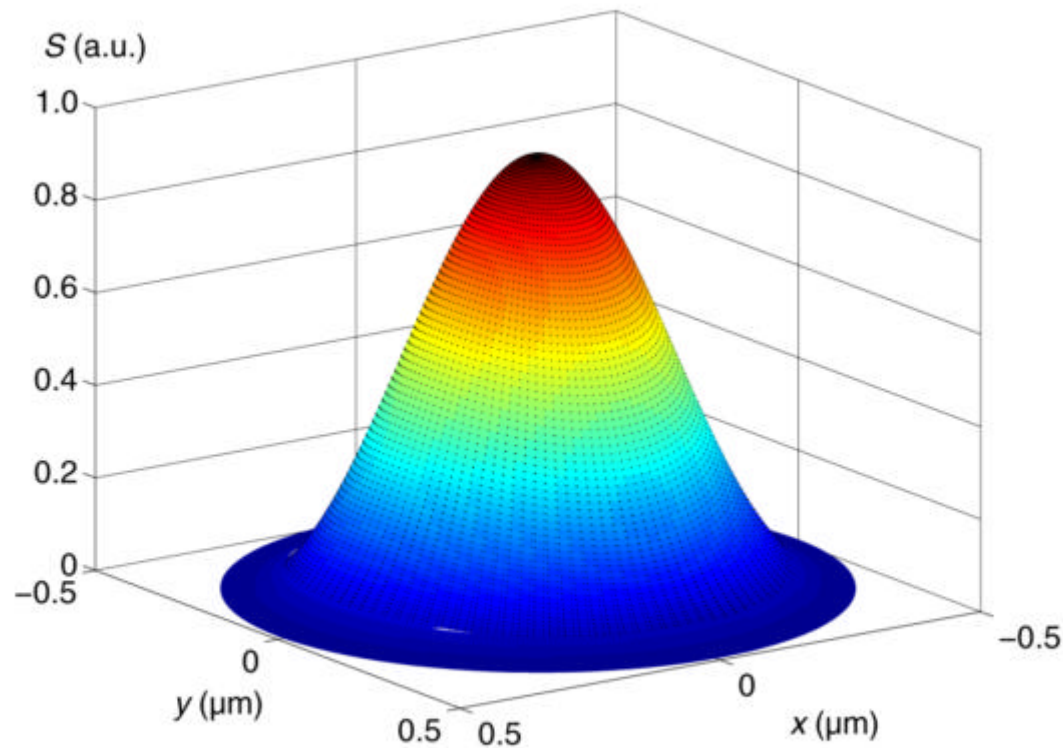


# Manipulating light at the nanoscale



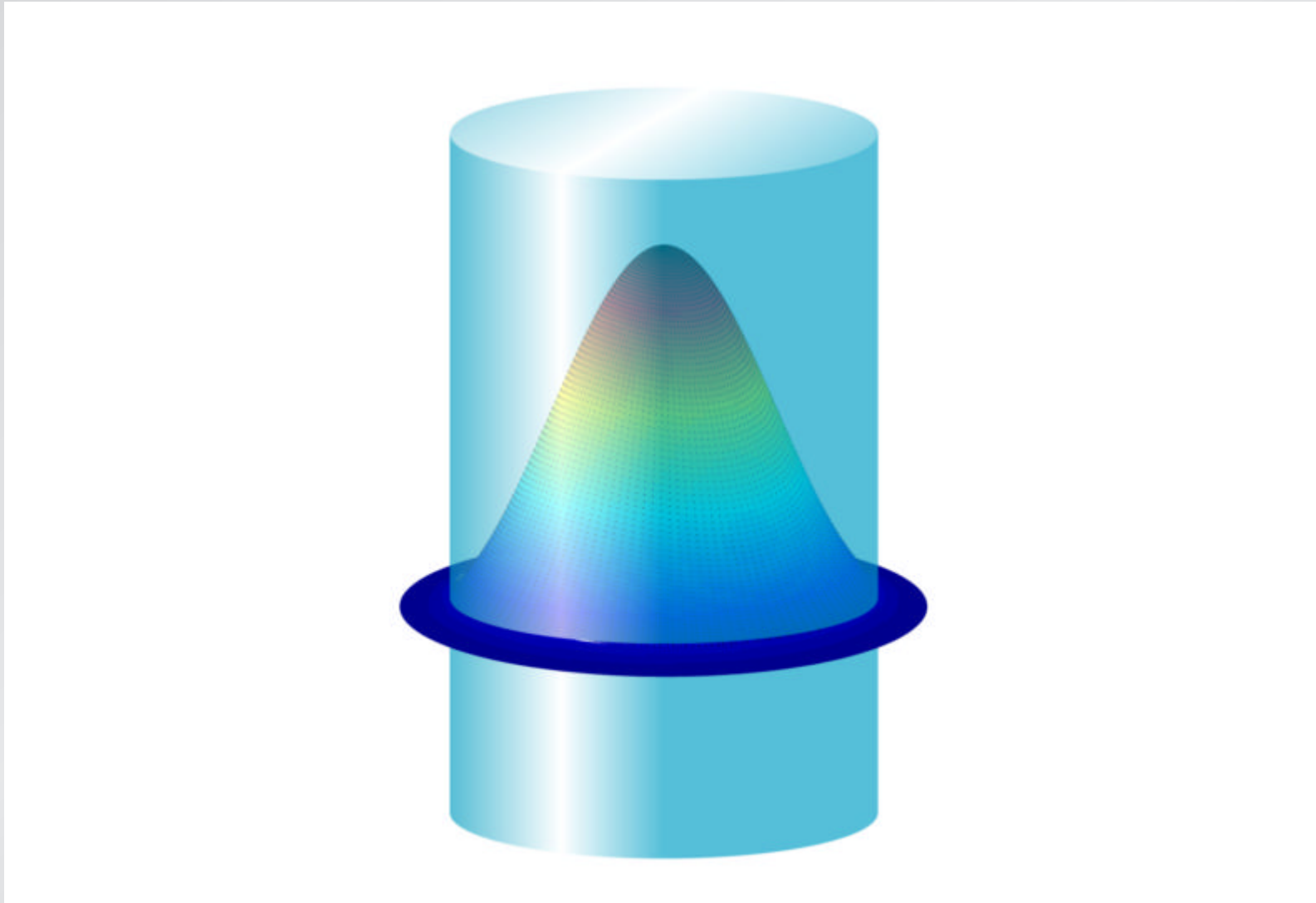
# Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



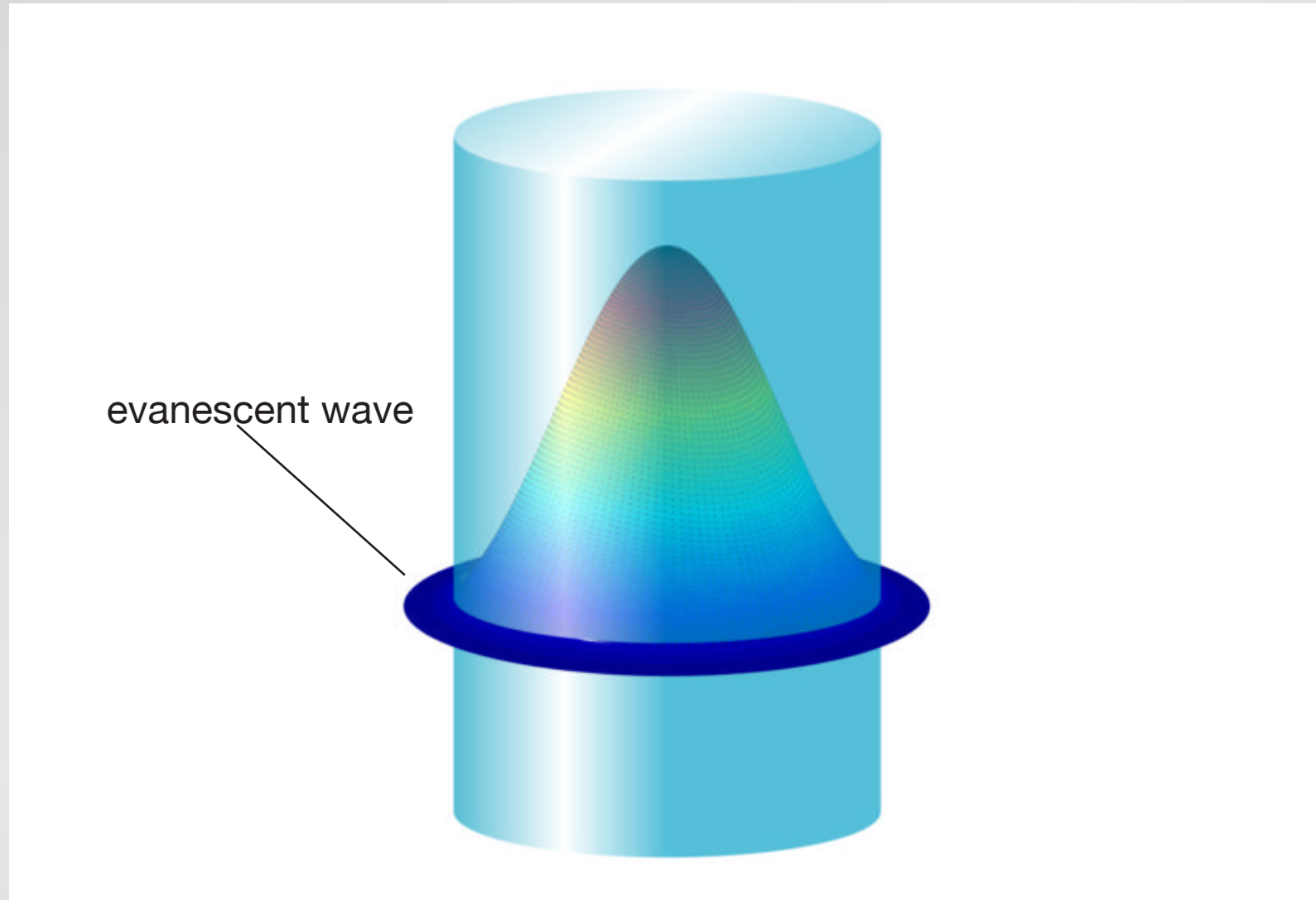
# Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



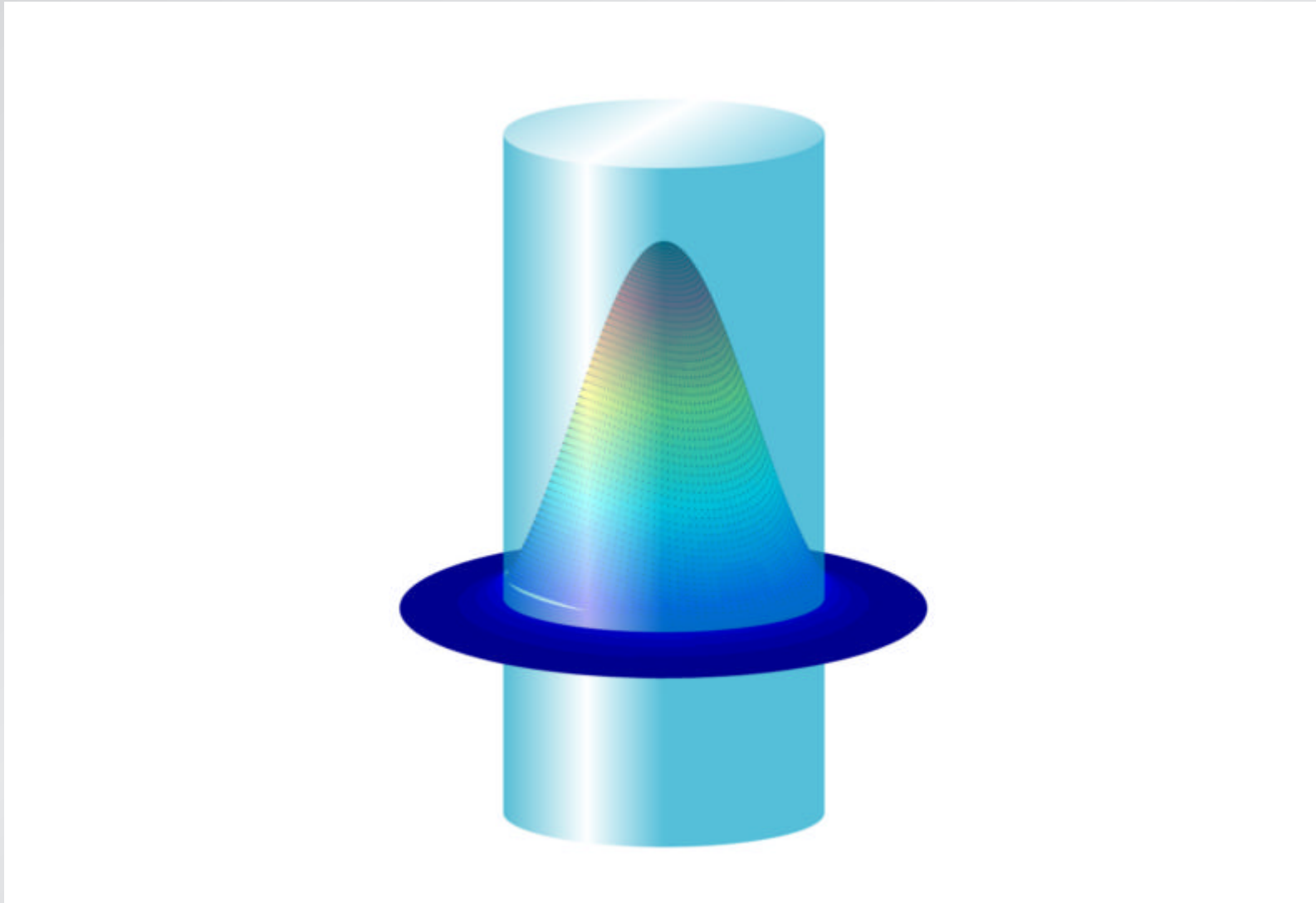
# Manipulating light at the nanoscale

Poynting vector profile for 800-nm nanowire



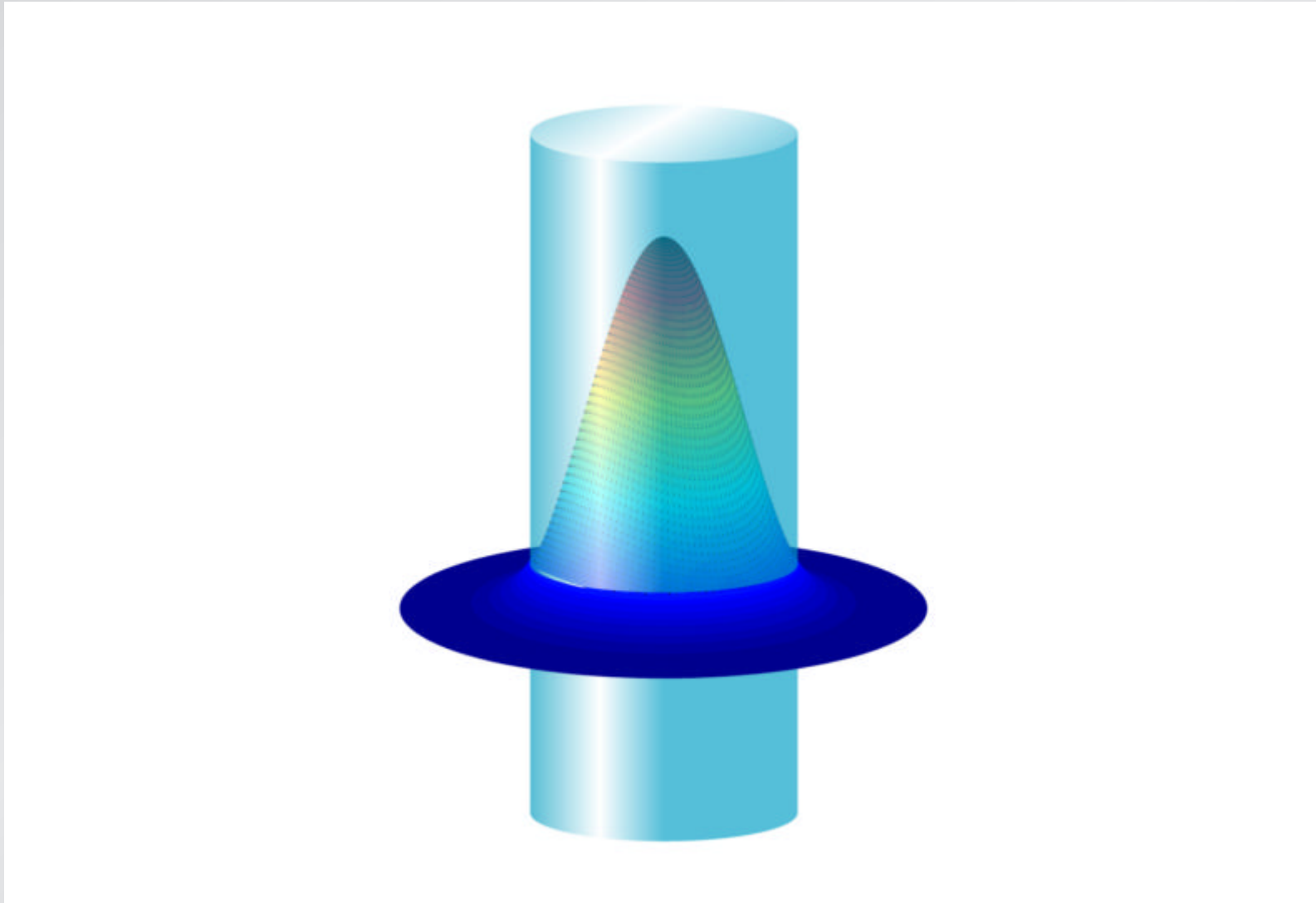
# Manipulating light at the nanoscale

Poynting vector profile for 600-nm nanowire



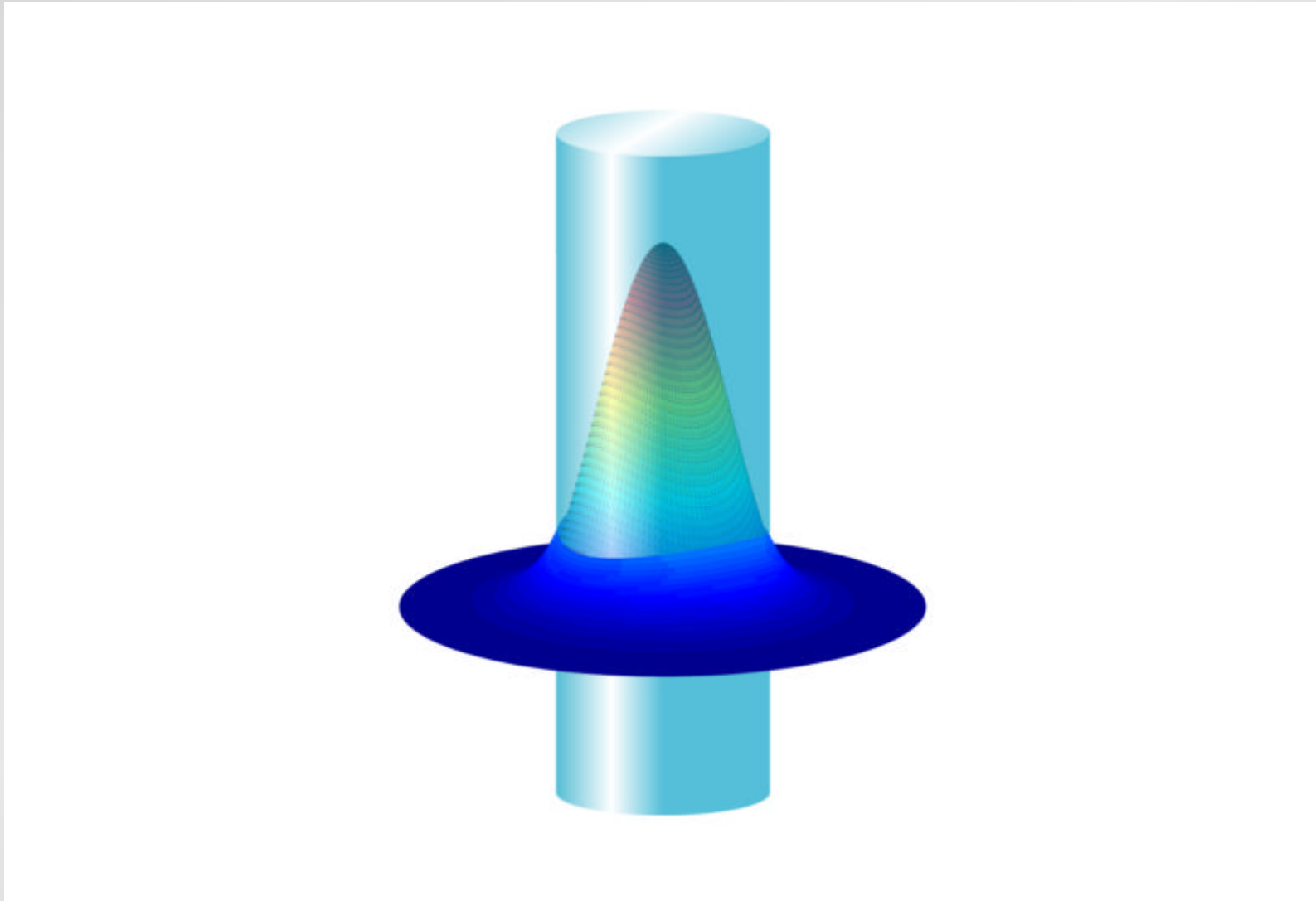
# Manipulating light at the nanoscale

Poynting vector profile for 500-nm nanowire



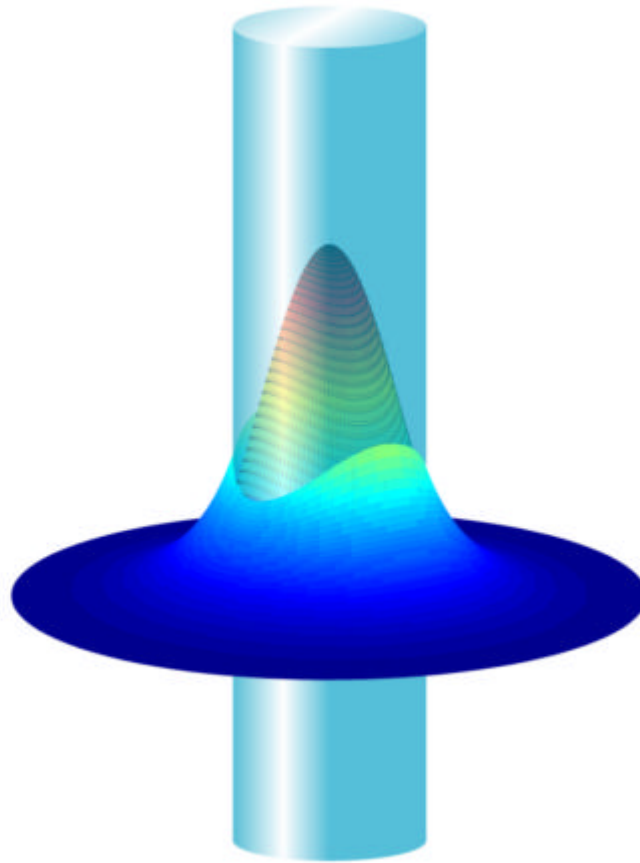
# Manipulating light at the nanoscale

Poynting vector profile for 400-nm nanowire



# Manipulating light at the nanoscale

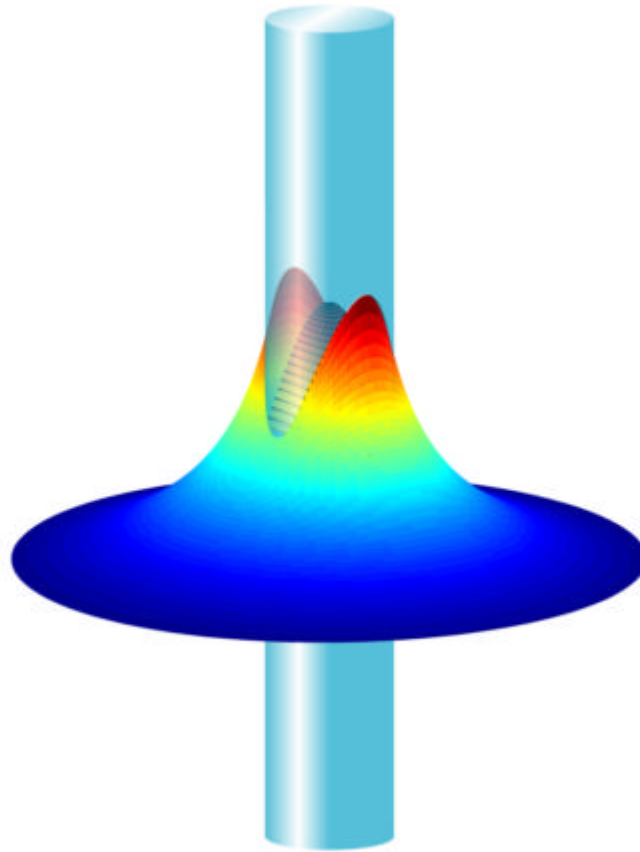
Poynting vector profile for 300-nm nanowire





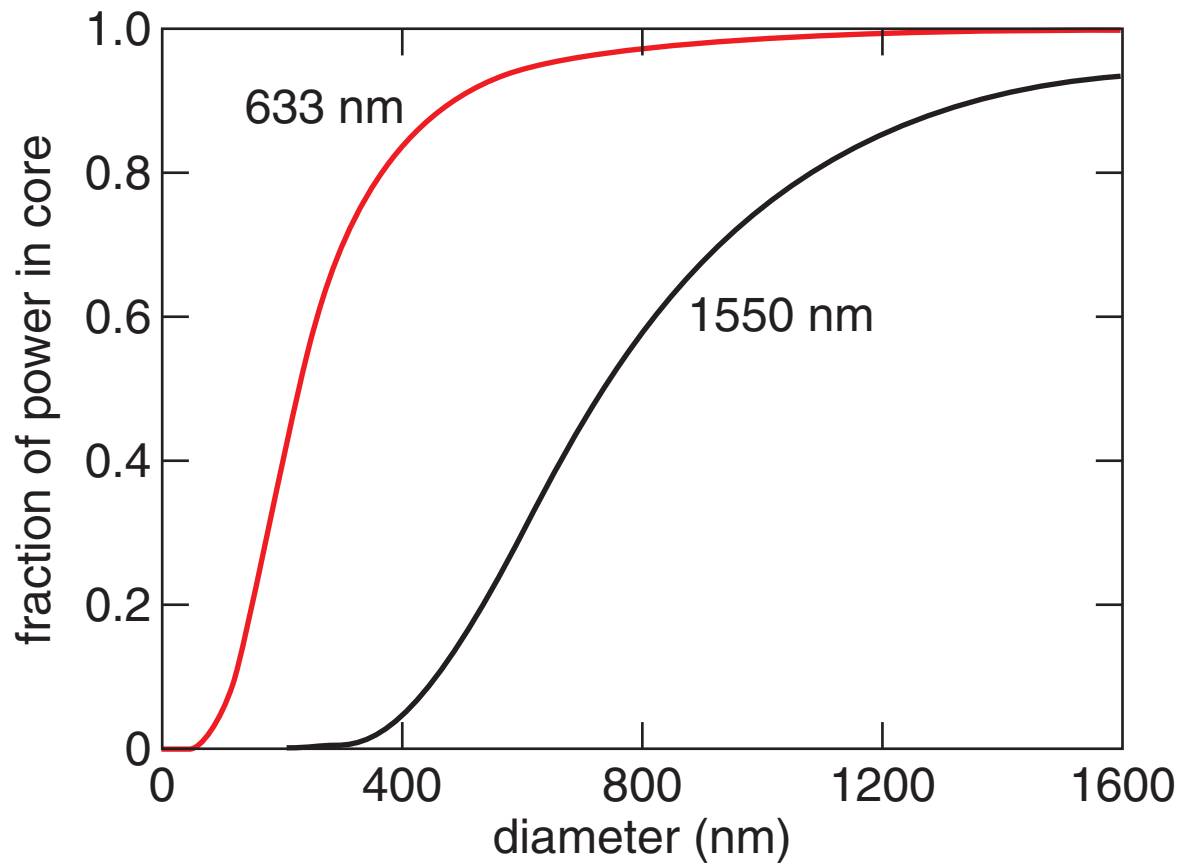
# Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



# Manipulating light at the nanoscale

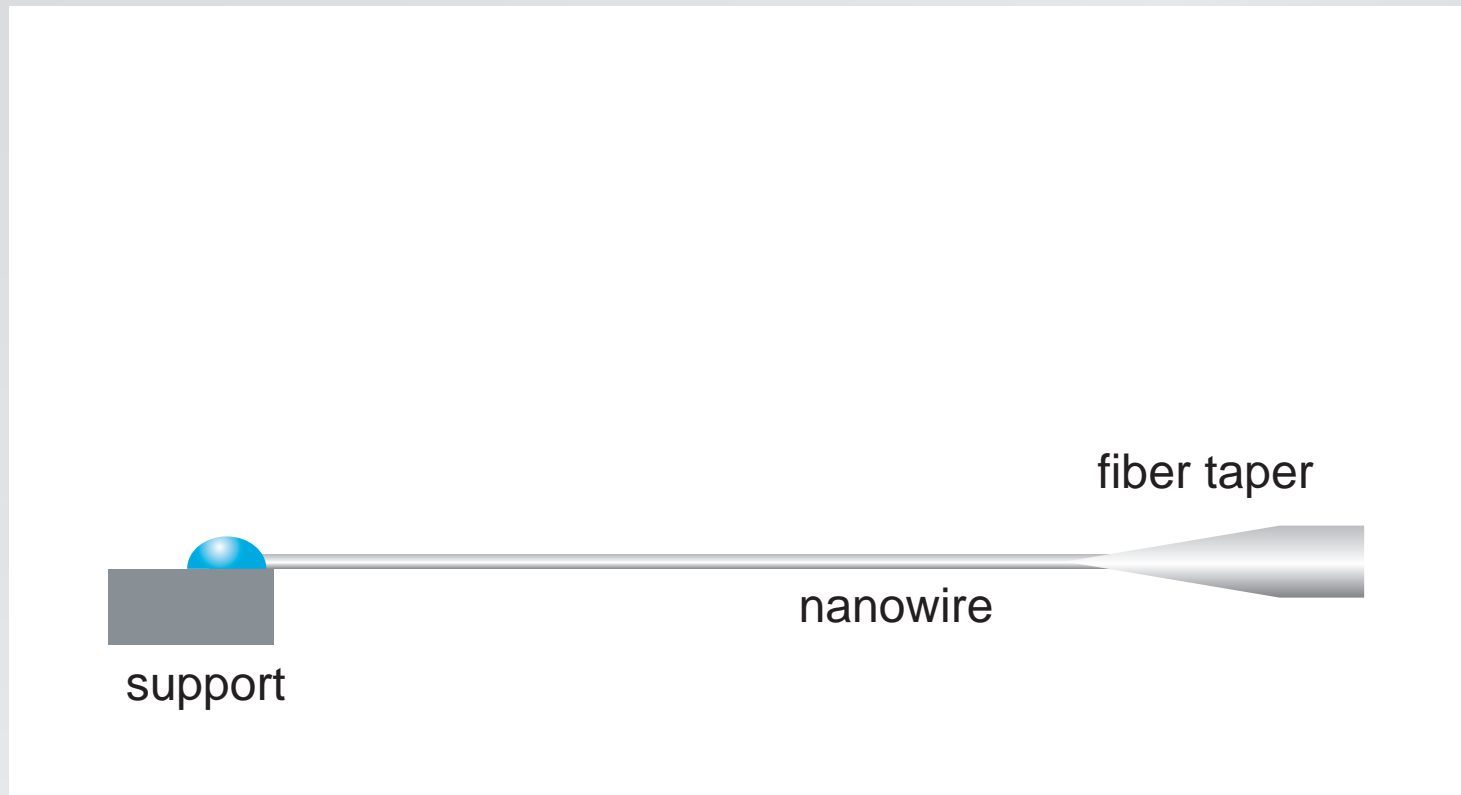
fraction of power carried in core





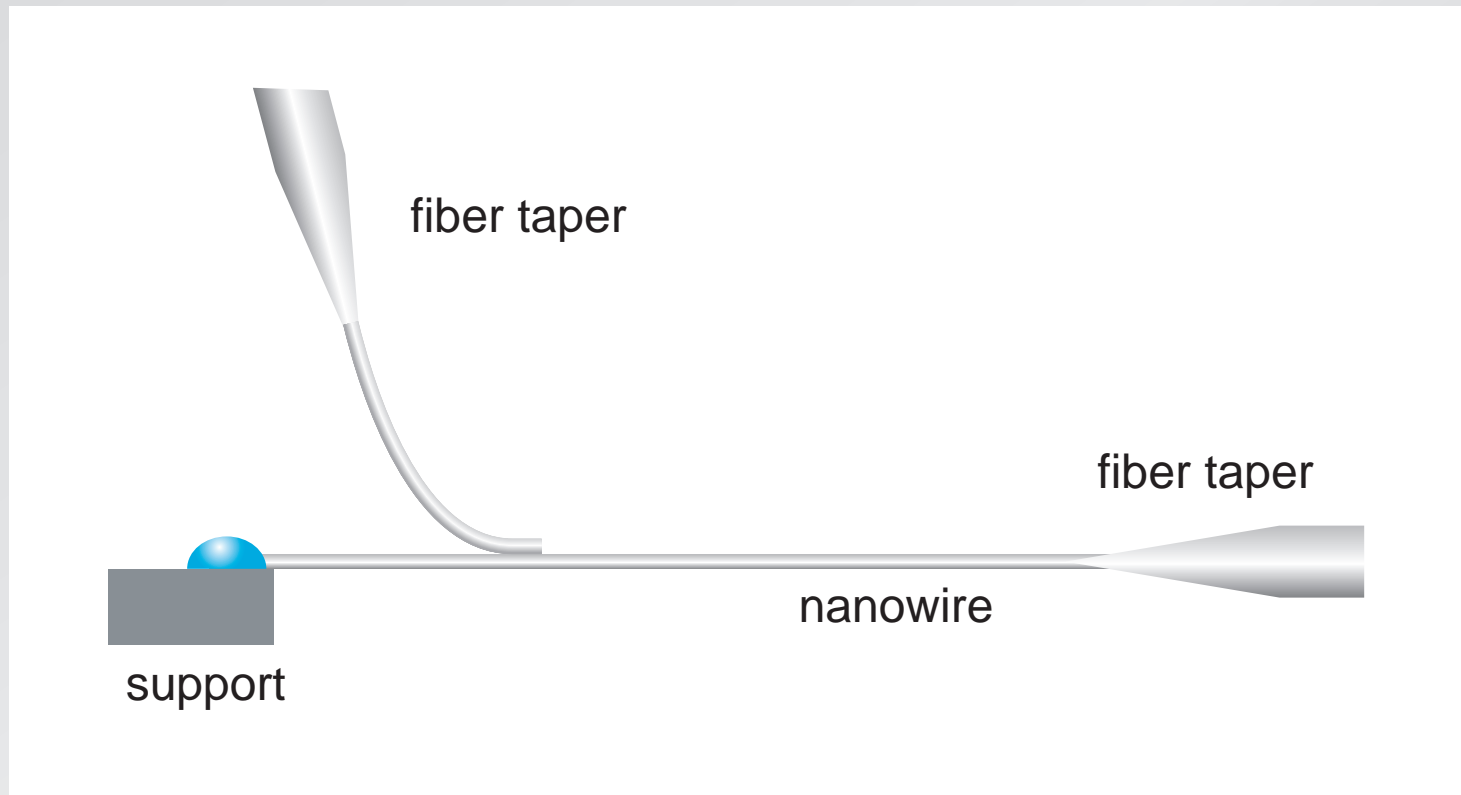
# Manipulating light at the nanoscale

coupling light between nanowires



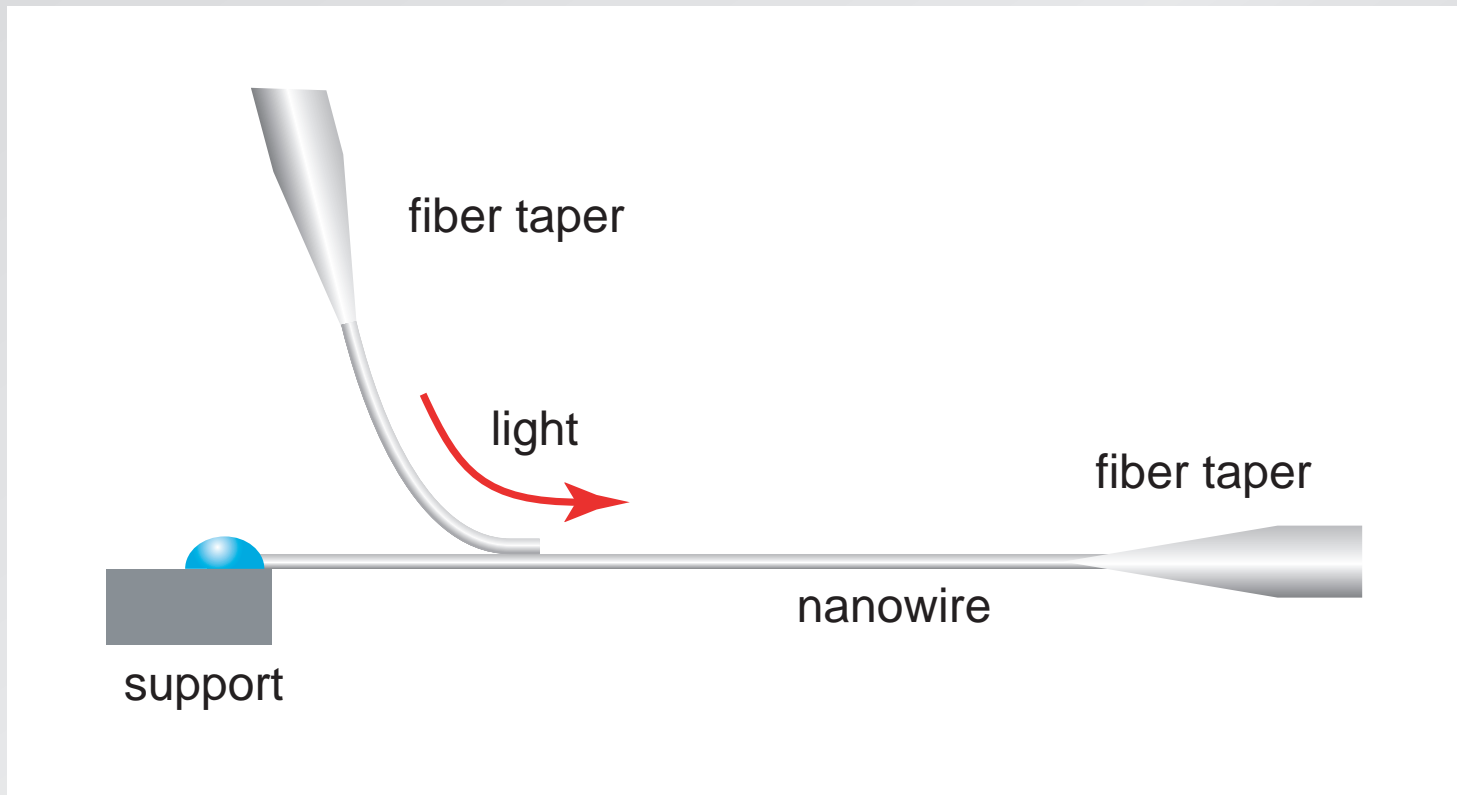
# Manipulating light at the nanoscale

coupling light between nanowires

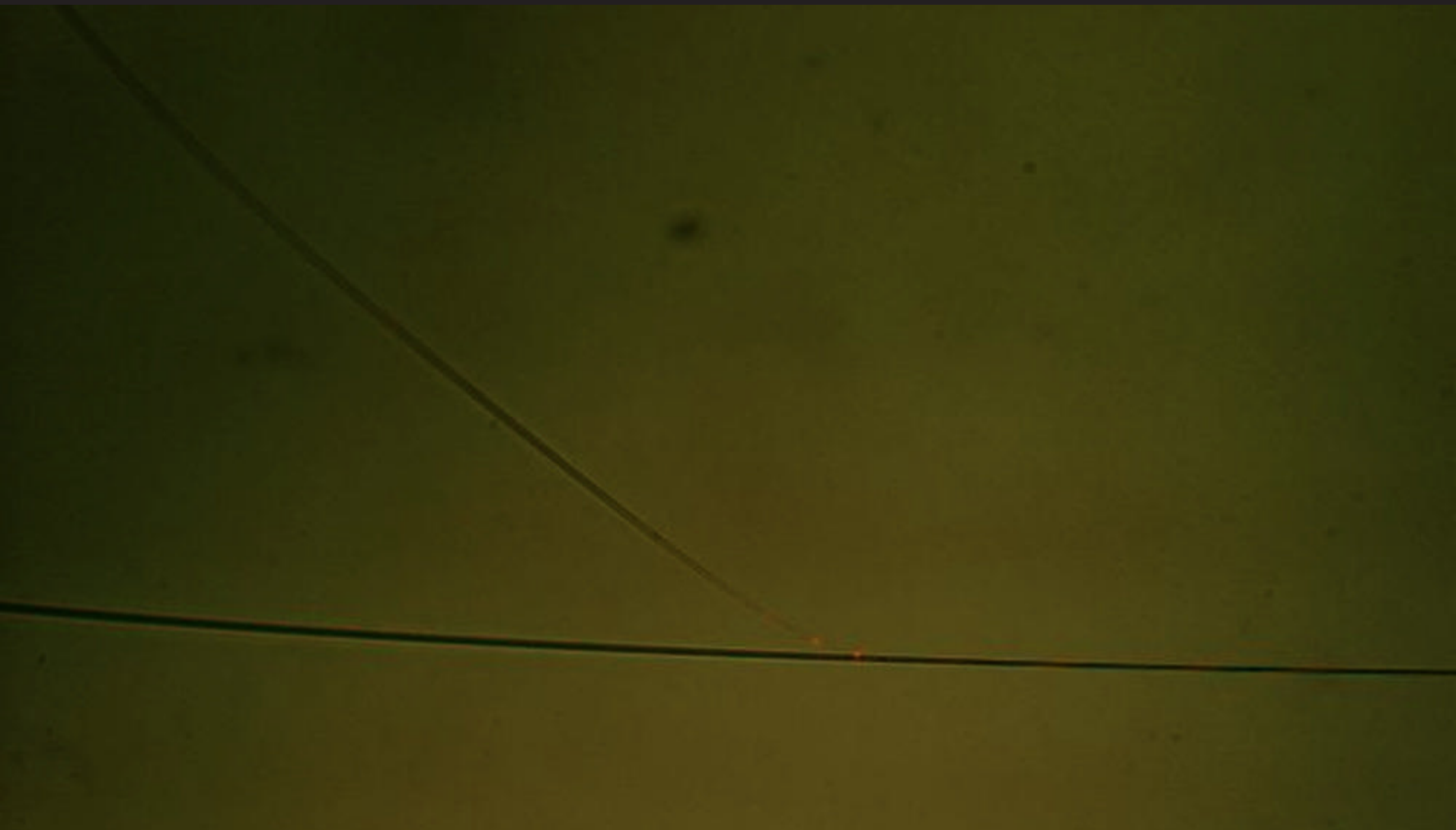


# Manipulating light at the nanoscale

coupling light between nanowires



# Manipulating light at the nanoscale



**50  $\mu\text{m}$**

# Manipulating light at the nanoscale

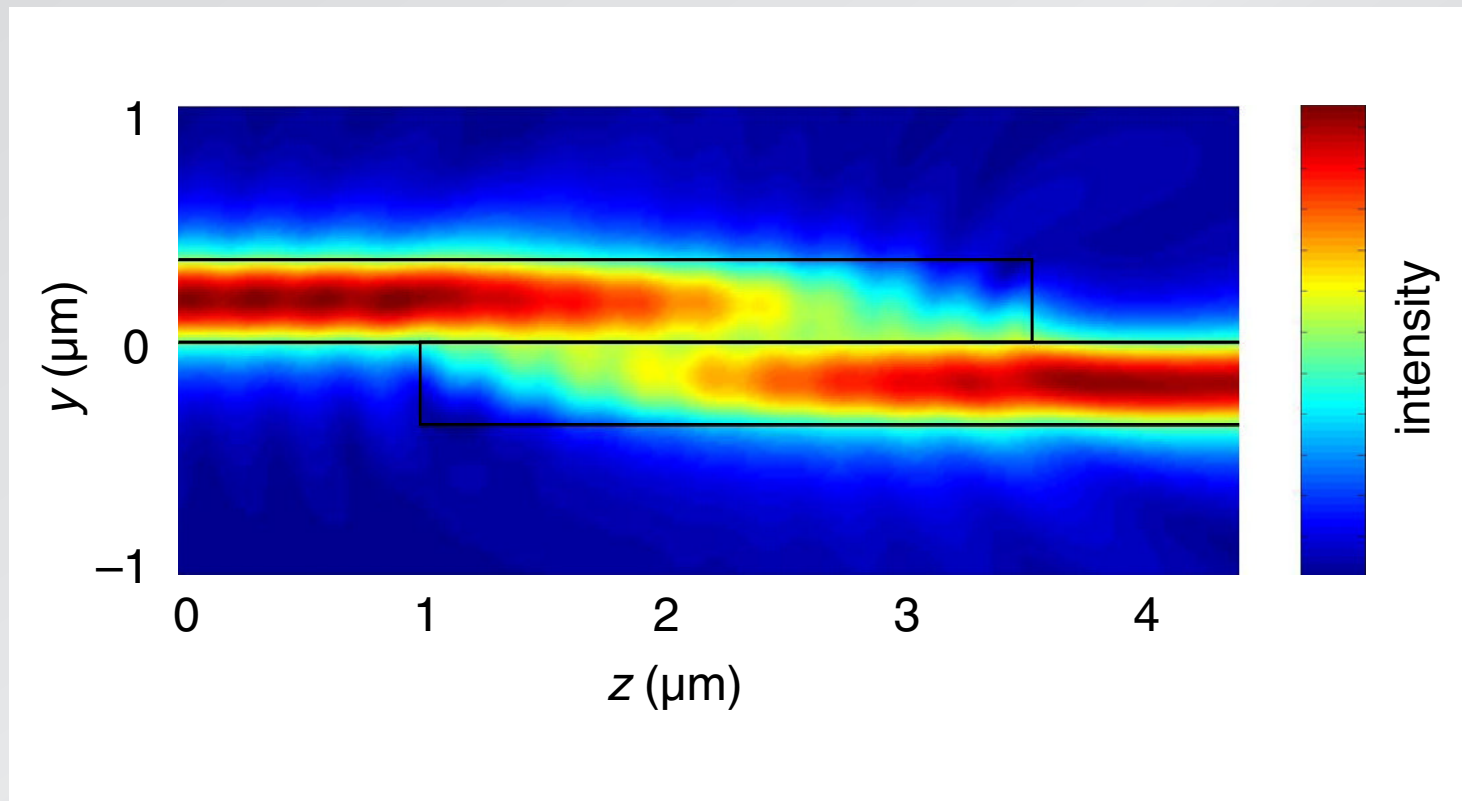


**50  $\mu\text{m}$**

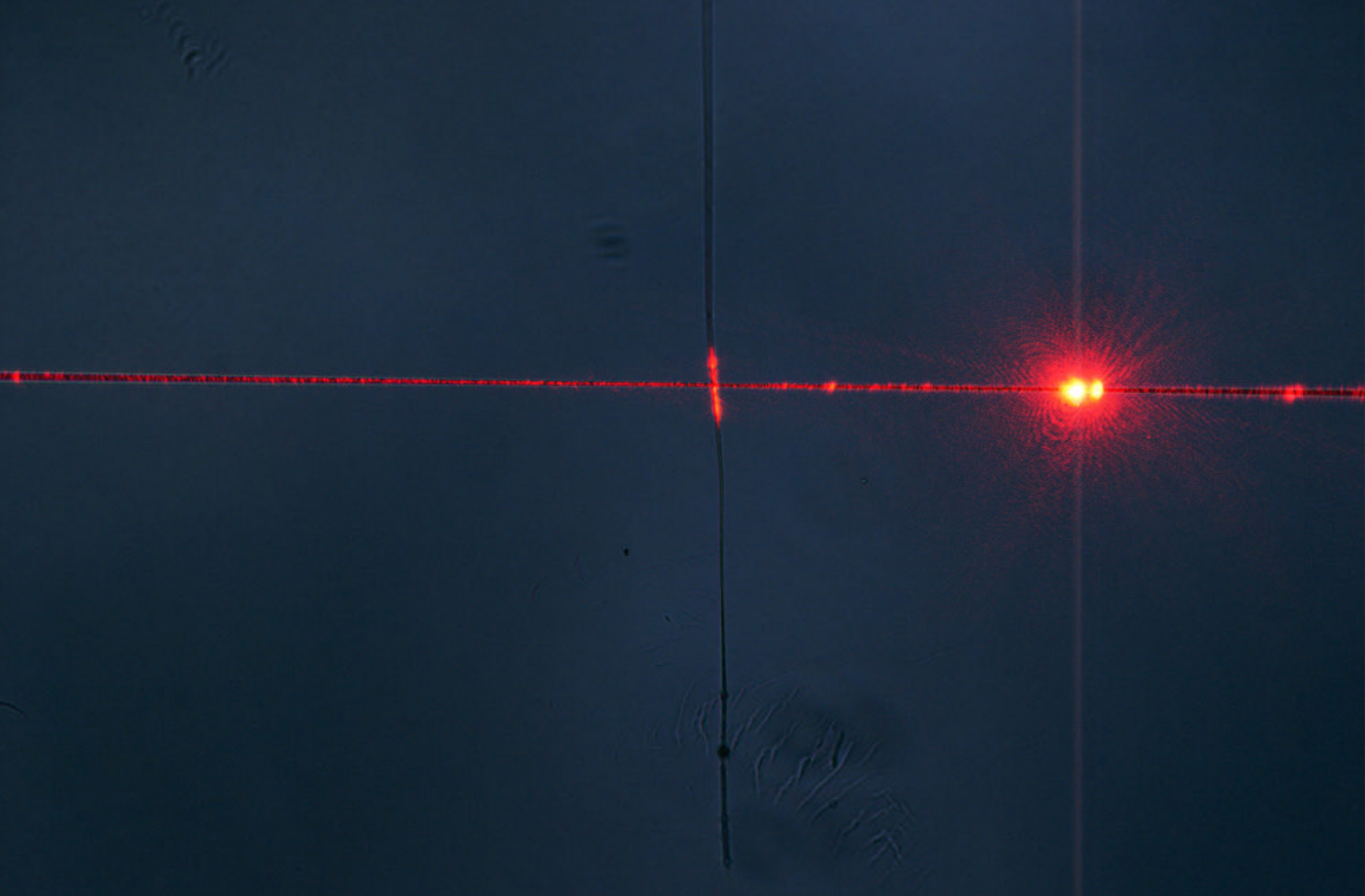


# Manipulating light at the nanoscale

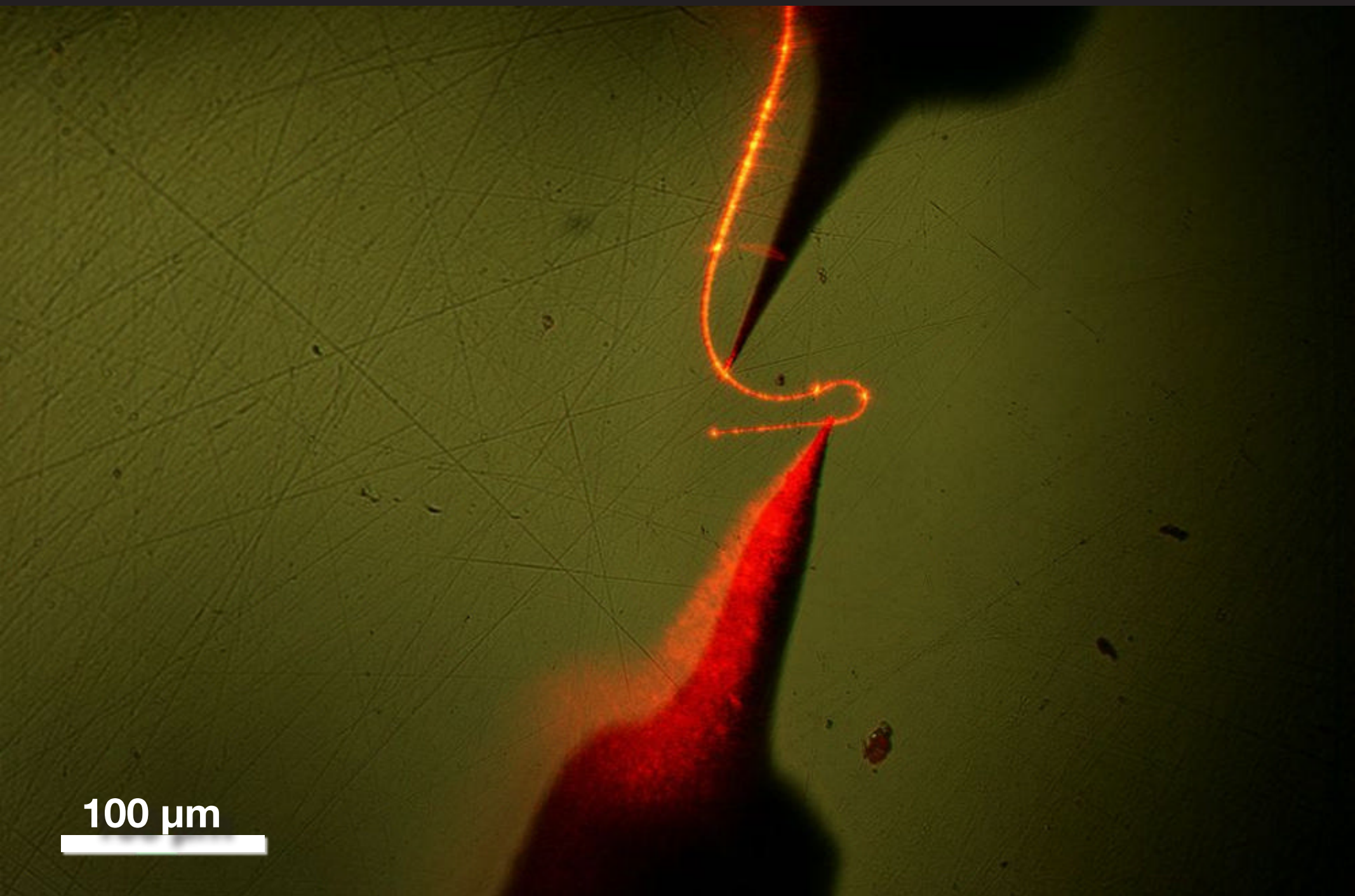
intensity distribution



# Manipulating light at the nanoscale

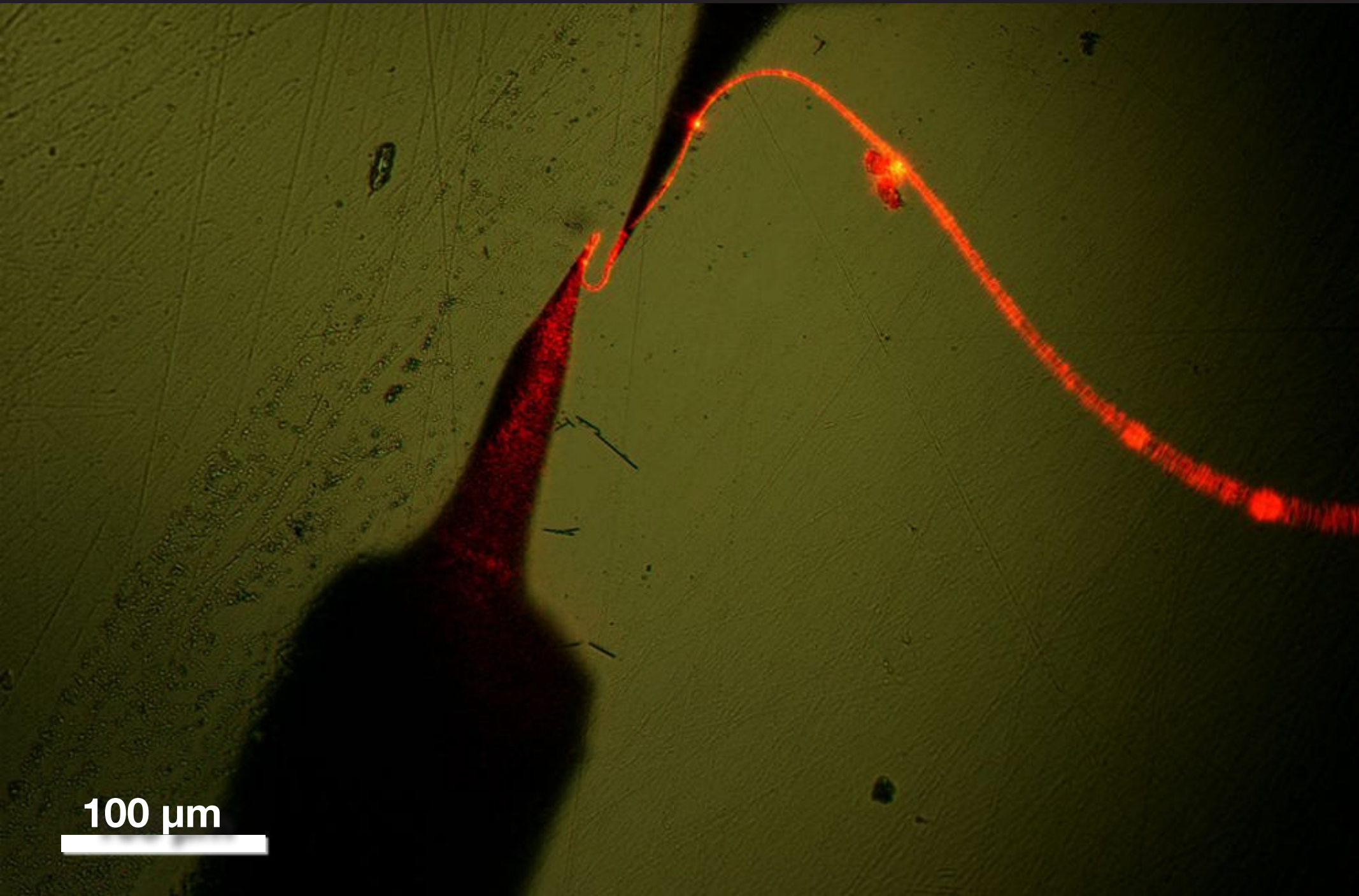


# Manipulating light at the nanoscale



100  $\mu\text{m}$

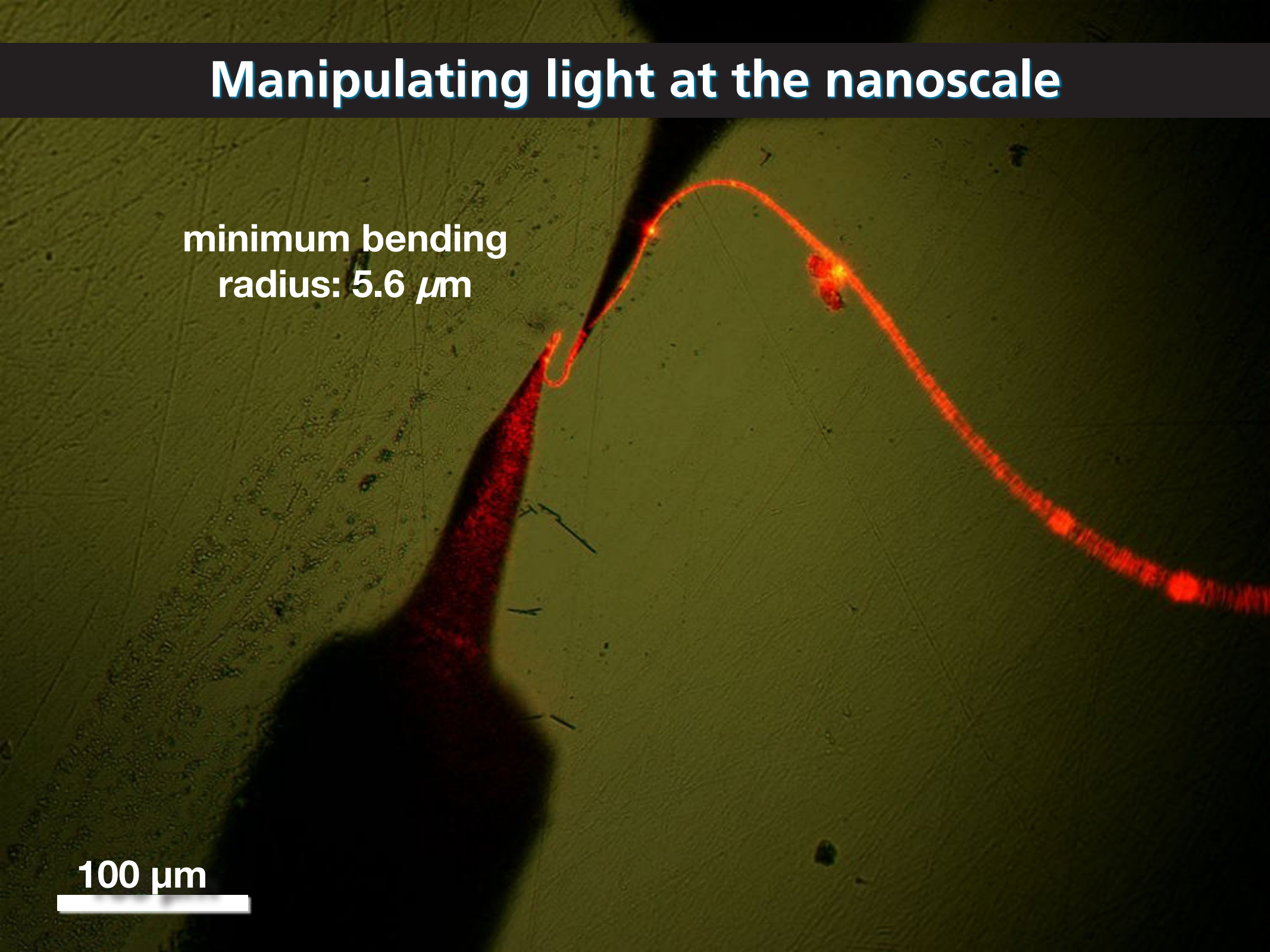
# Manipulating light at the nanoscale



# Manipulating light at the nanoscale

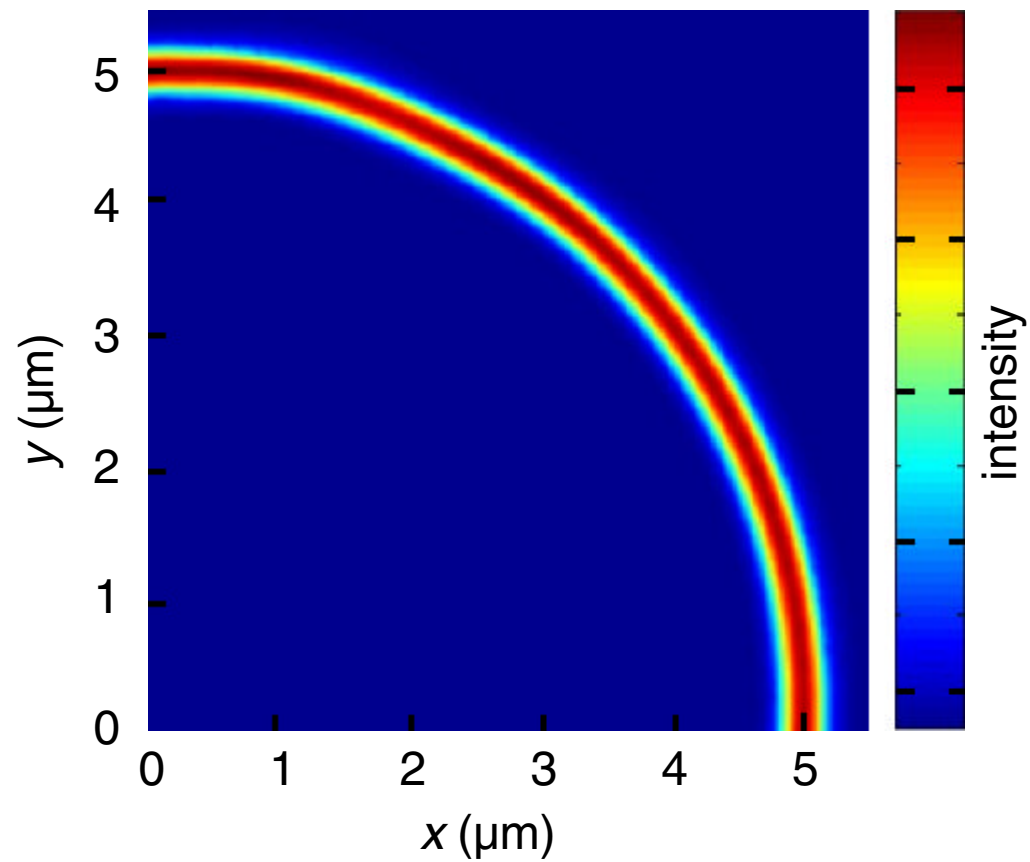
minimum bending  
radius:  $5.6 \mu\text{m}$

100  $\mu\text{m}$

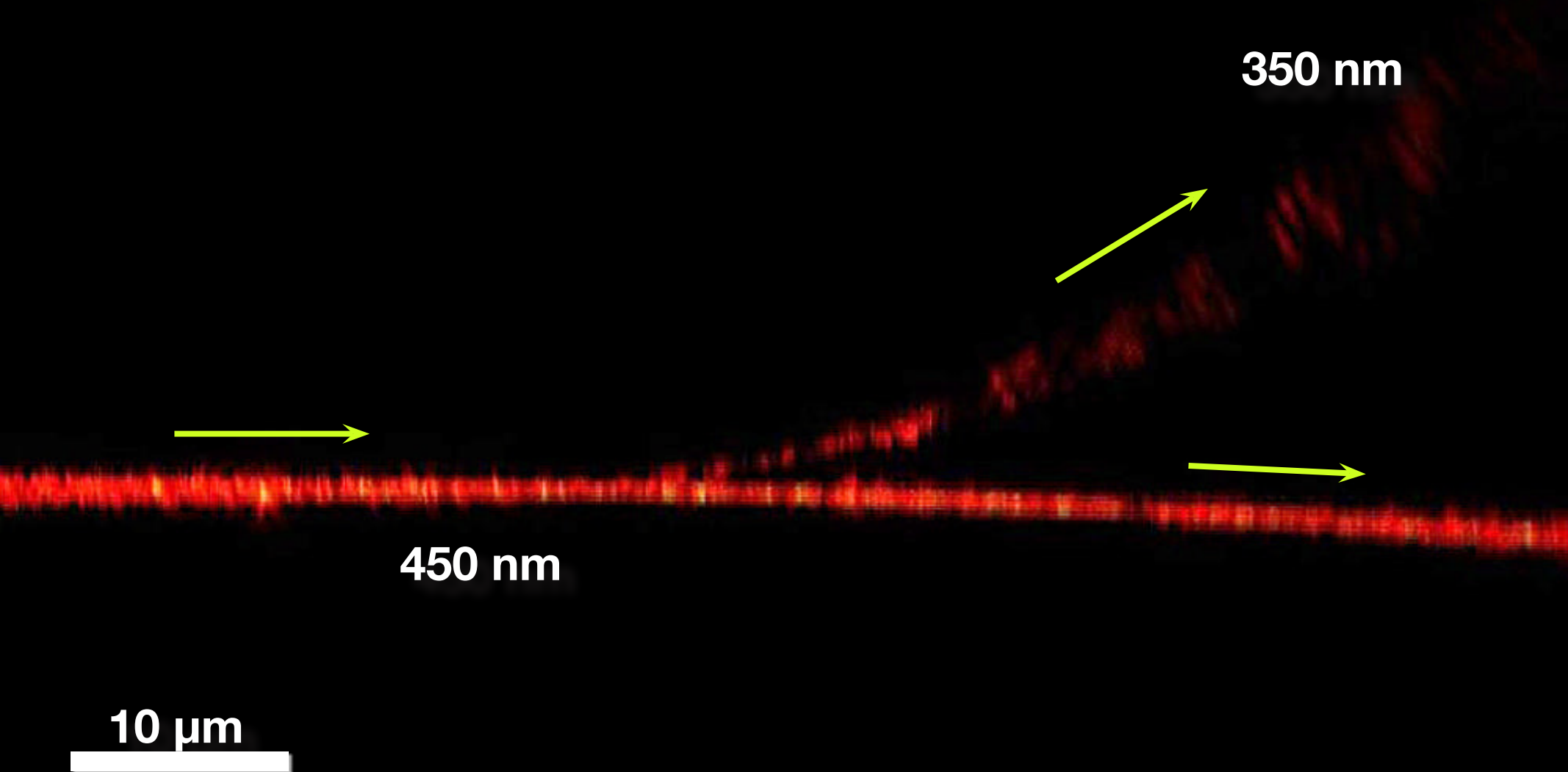
A micrograph showing a fiber optic cable with a sharp bend. The fiber is illuminated from the left, creating a bright red glow. The bend is very tight, and the light is visible as a continuous line along the length of the fiber. The background is a dark, textured surface. A scale bar is located in the bottom left corner, and text is overlaid on the image.

# Manipulating light at the nanoscale

virtually no loss through 5  $\mu\text{m}$  corner!



# Manipulating light at the nanoscale



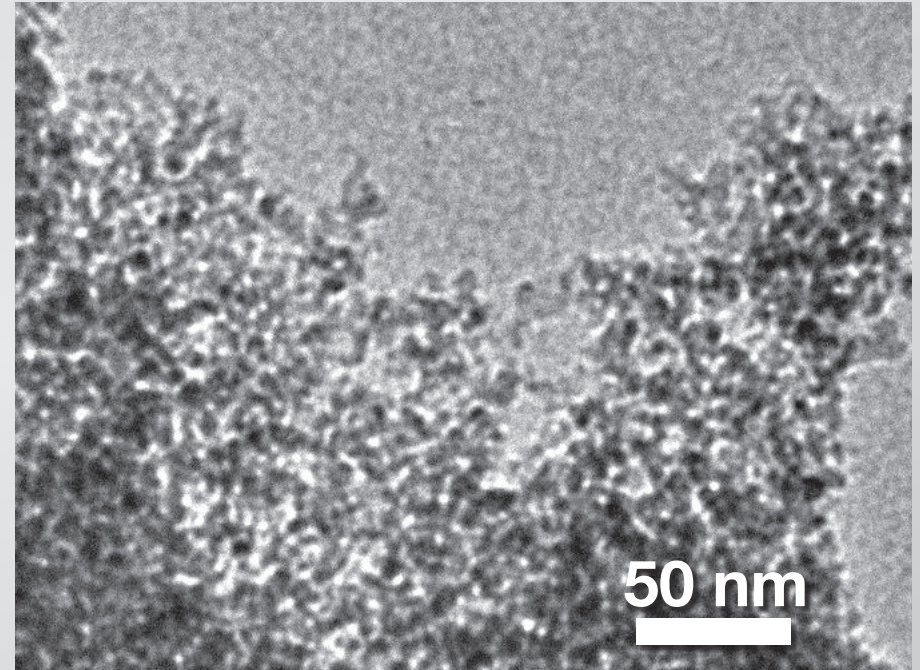
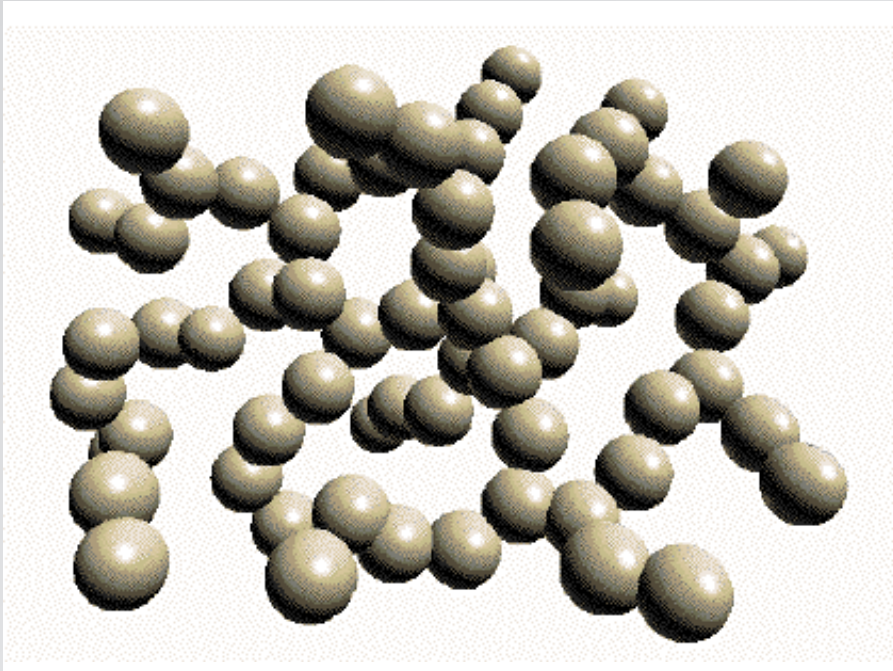
# Manipulating light at the nanoscale





# Manipulating light at the nanoscale

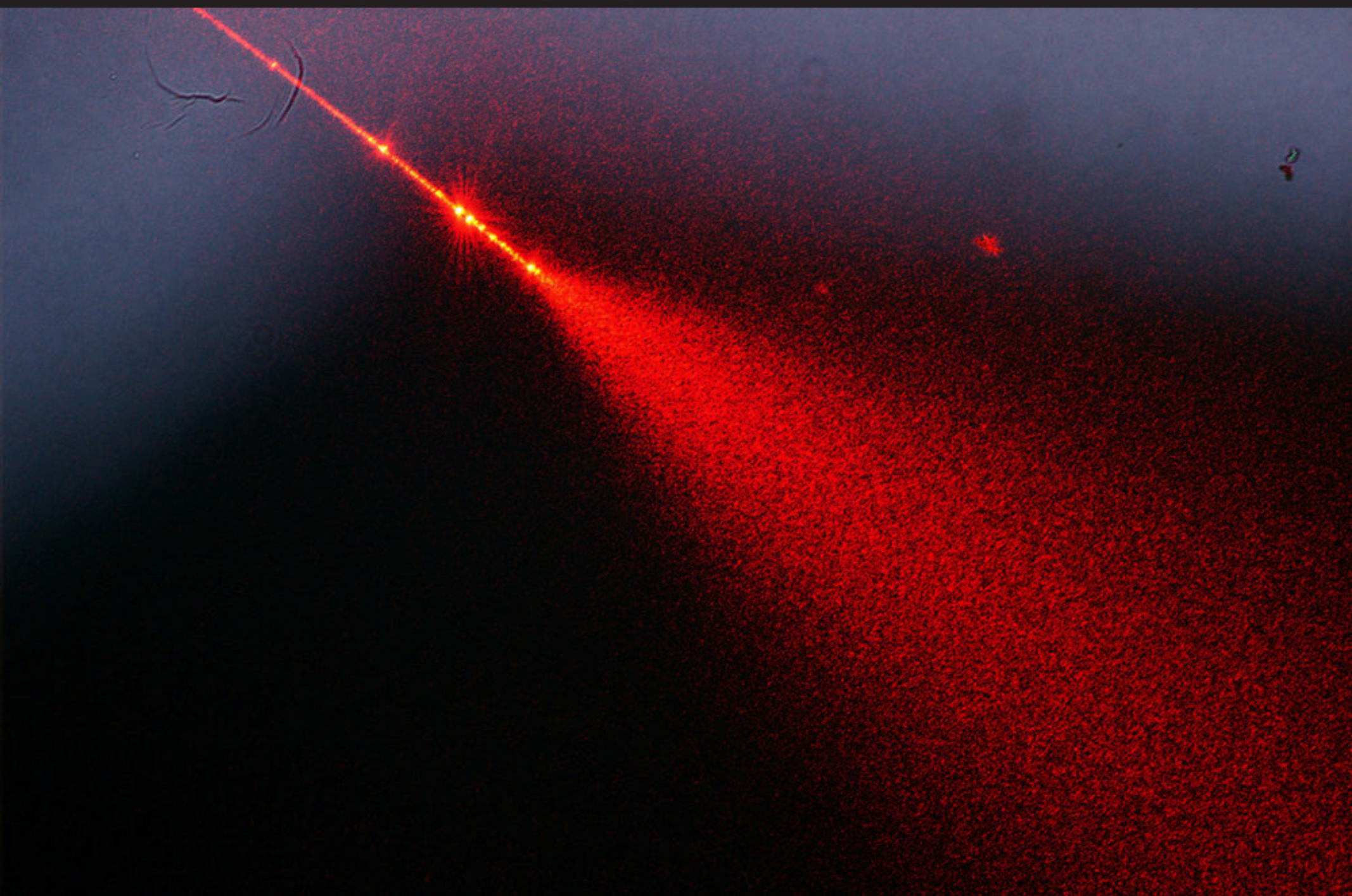
## Aerogel



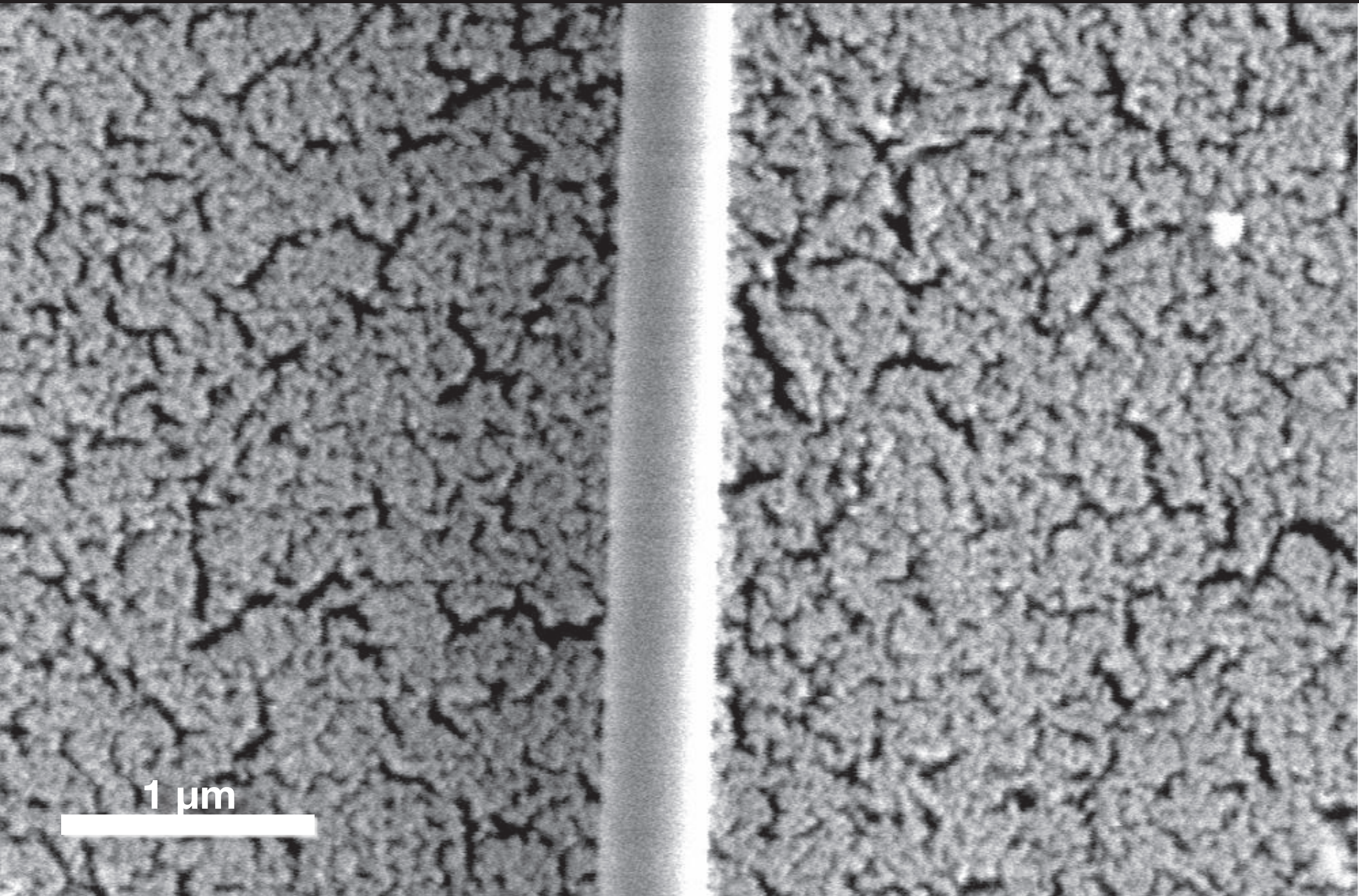
density:  $1.9 \text{ kg/m}^3$

index of refraction: 1.03–1.08

# Manipulating light at the nanoscale



# Manipulating light at the nanoscale



1  $\mu\text{m}$



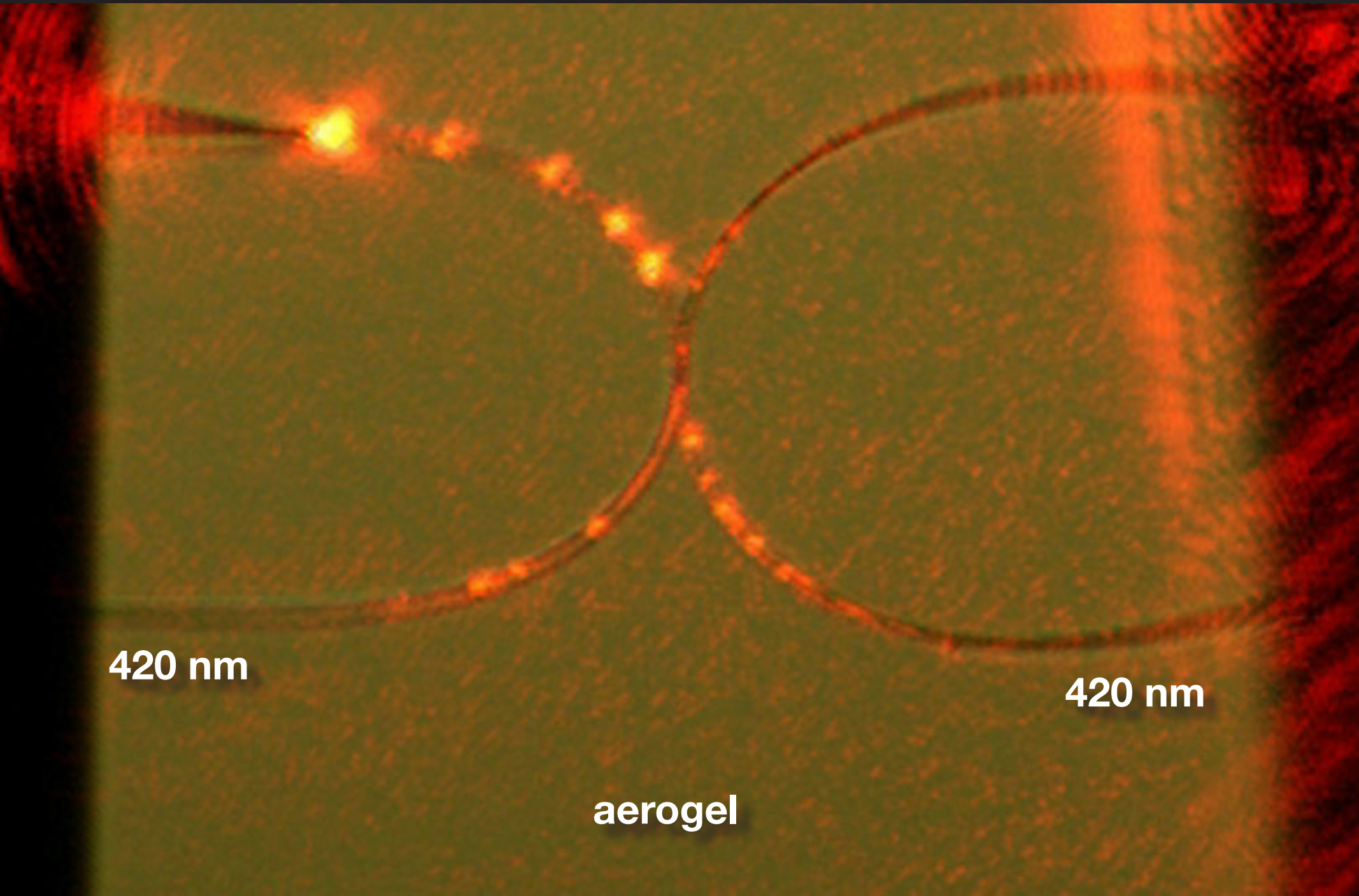
# Manipulating light at the nanoscale

530 nm



50  $\mu\text{m}$

# Manipulating light at the nanoscale

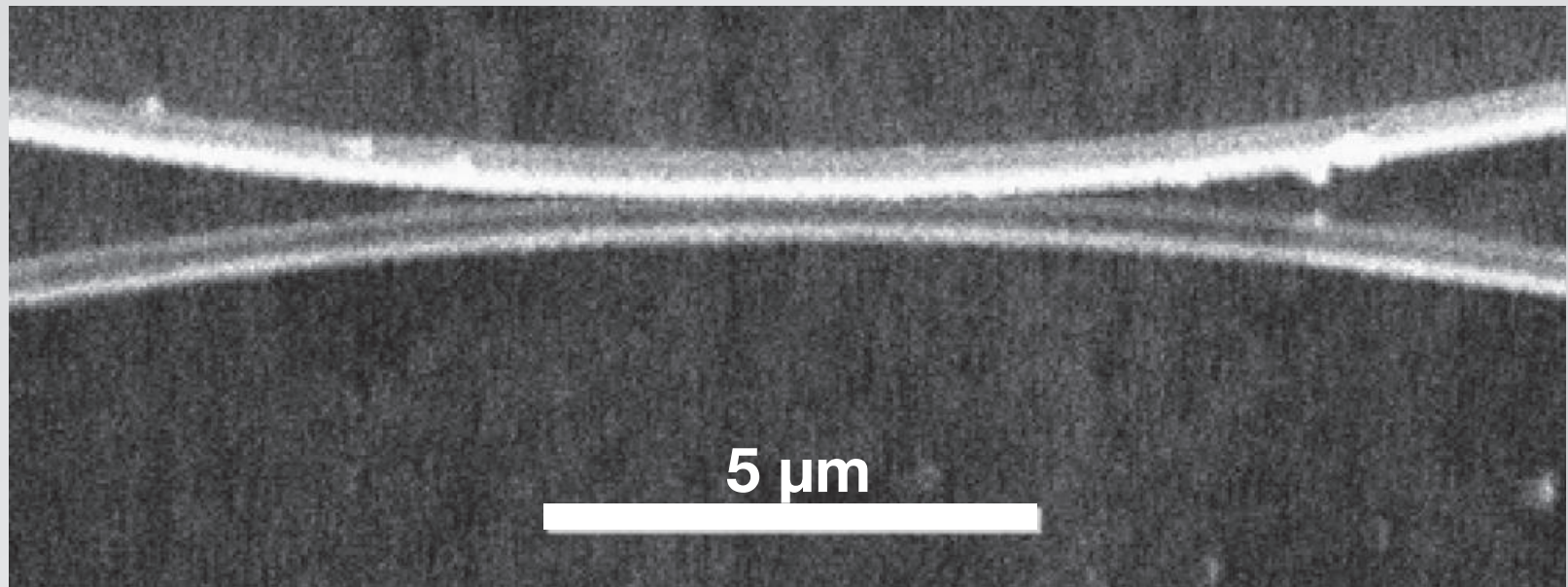


420 nm

420 nm

aerogel

# Manipulating light at the nanoscale



# Manipulating light at the nanoscale

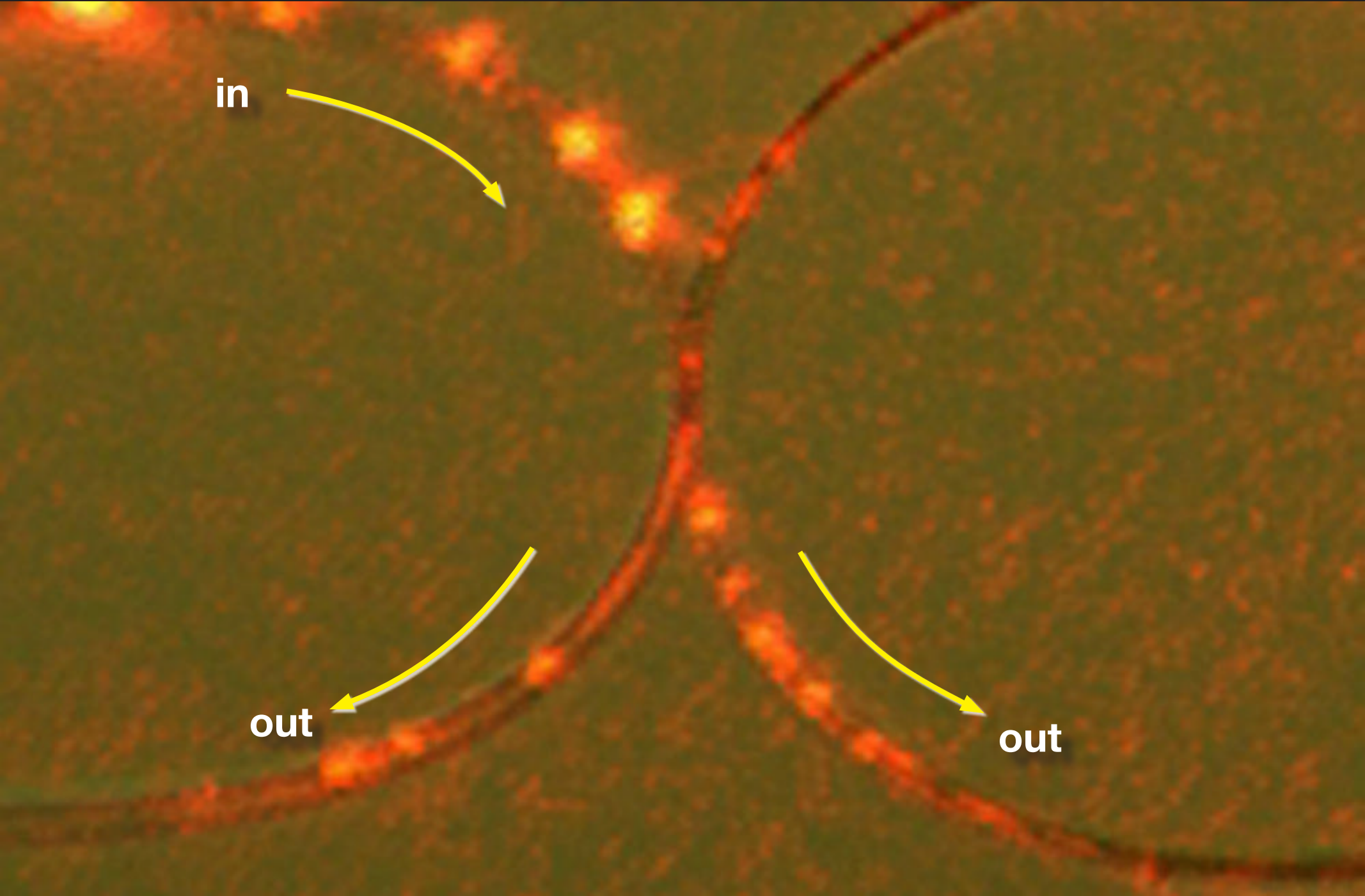
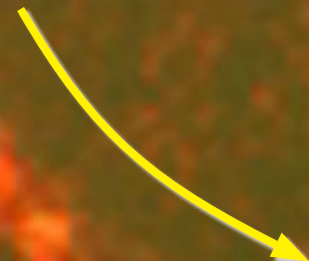
in



out



out



# Manipulating light at the nanoscale

**use tapered fibers to couple light to nanoscale objects**



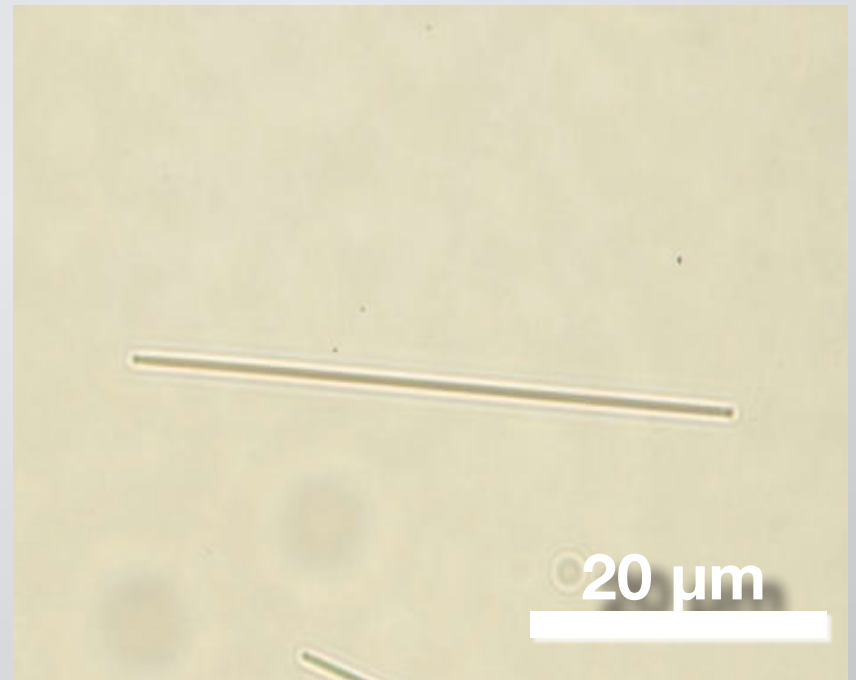
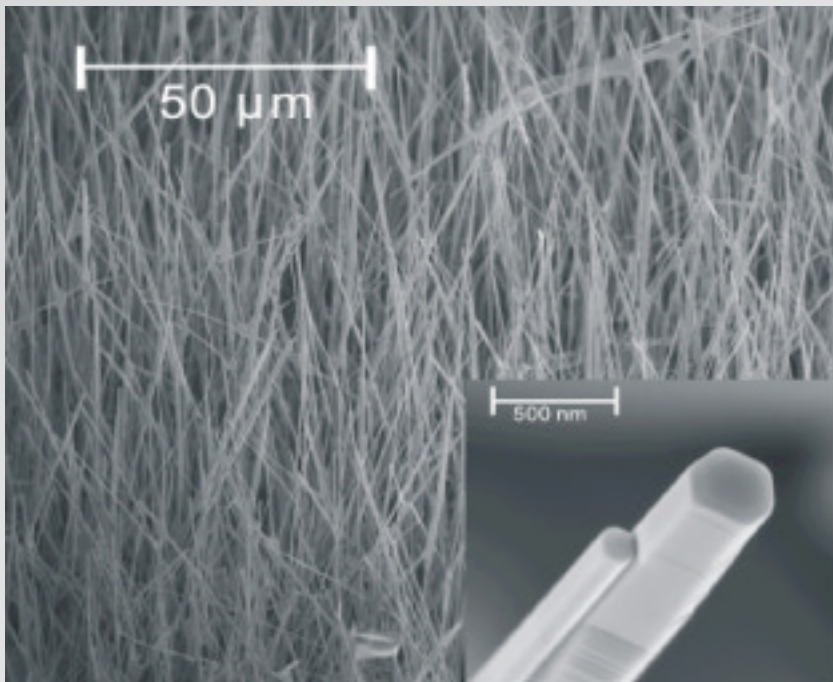
# Manipulating light at the nanoscale

**ZnO: non-toxic, wide bandgap semiconductor**

A petri dish containing a white, powdery substance, likely ZnO nanoparticles, with a dark, cylindrical object resting on the right side.

# 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

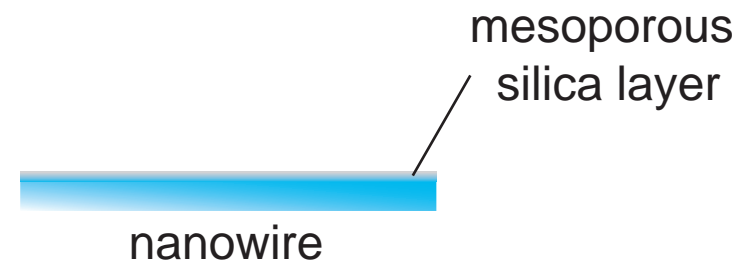
passive waveguides

electrical operation

link to macroworld

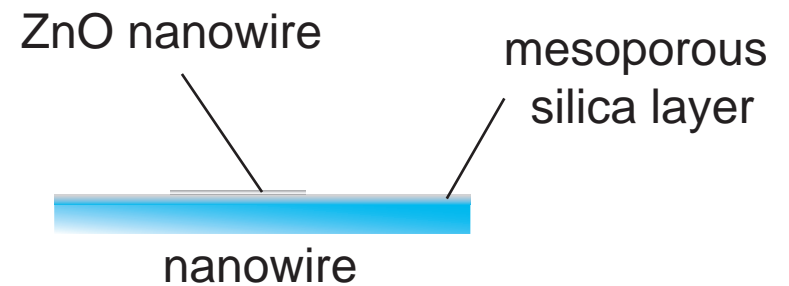
# Manipulating light at the nanoscale

coupling to ZnO nanowires



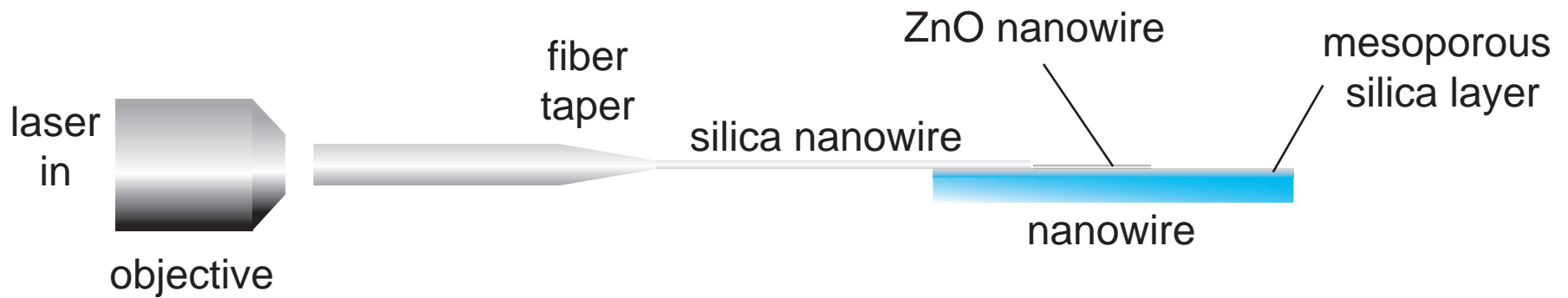
# Manipulating light at the nanoscale

coupling to ZnO nanowires



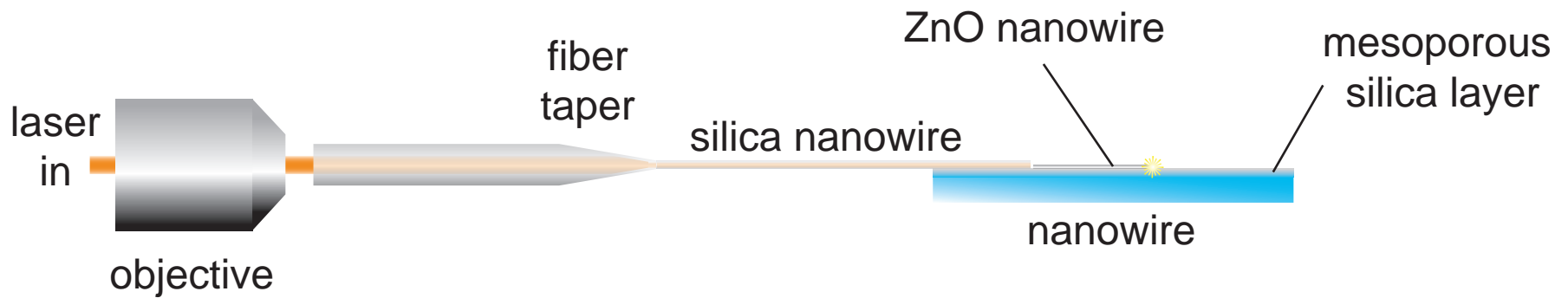
# Manipulating light at the nanoscale

## coupling to ZnO nanowires

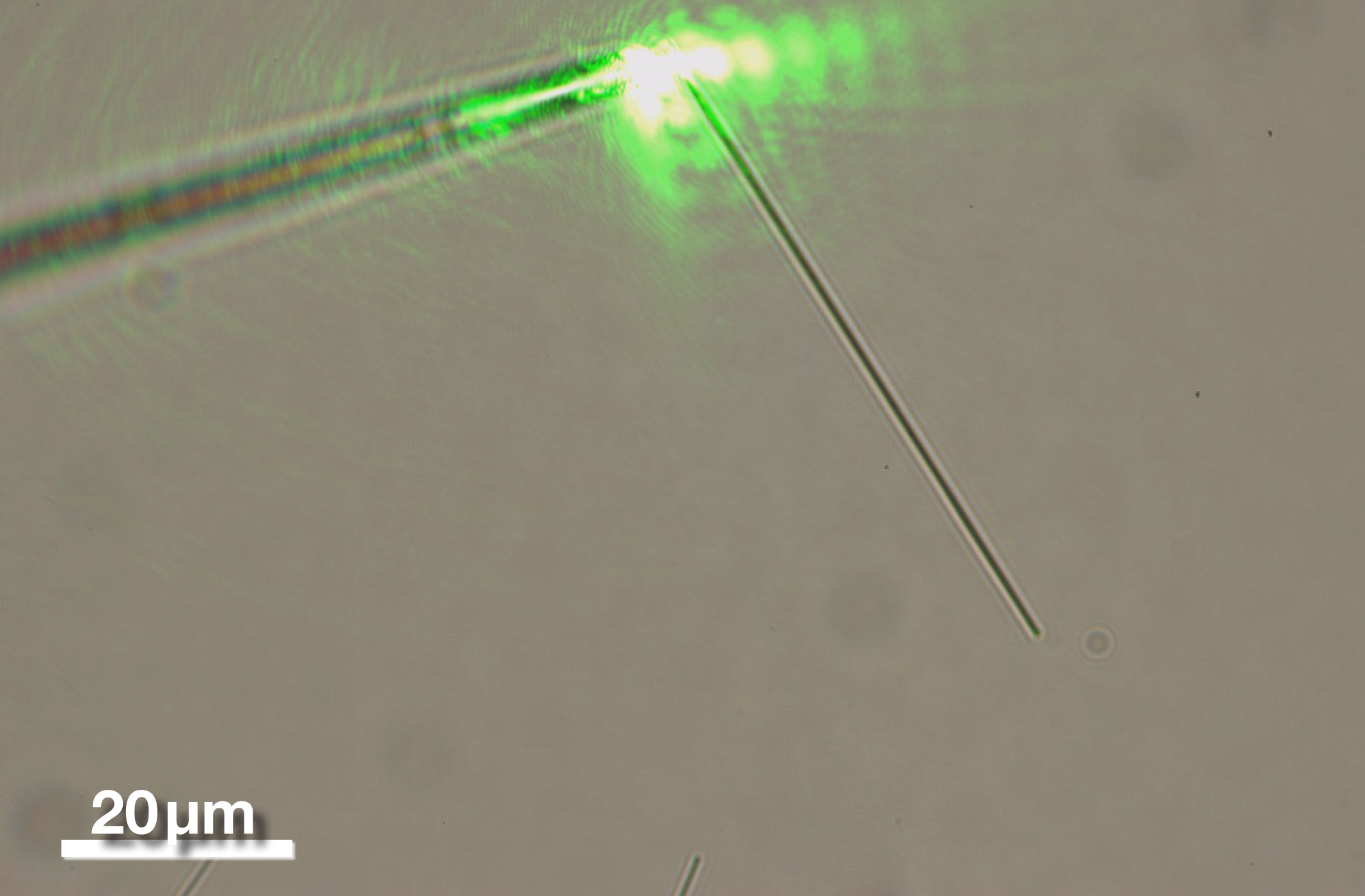


# Manipulating light at the nanoscale

## coupling to ZnO nanowires



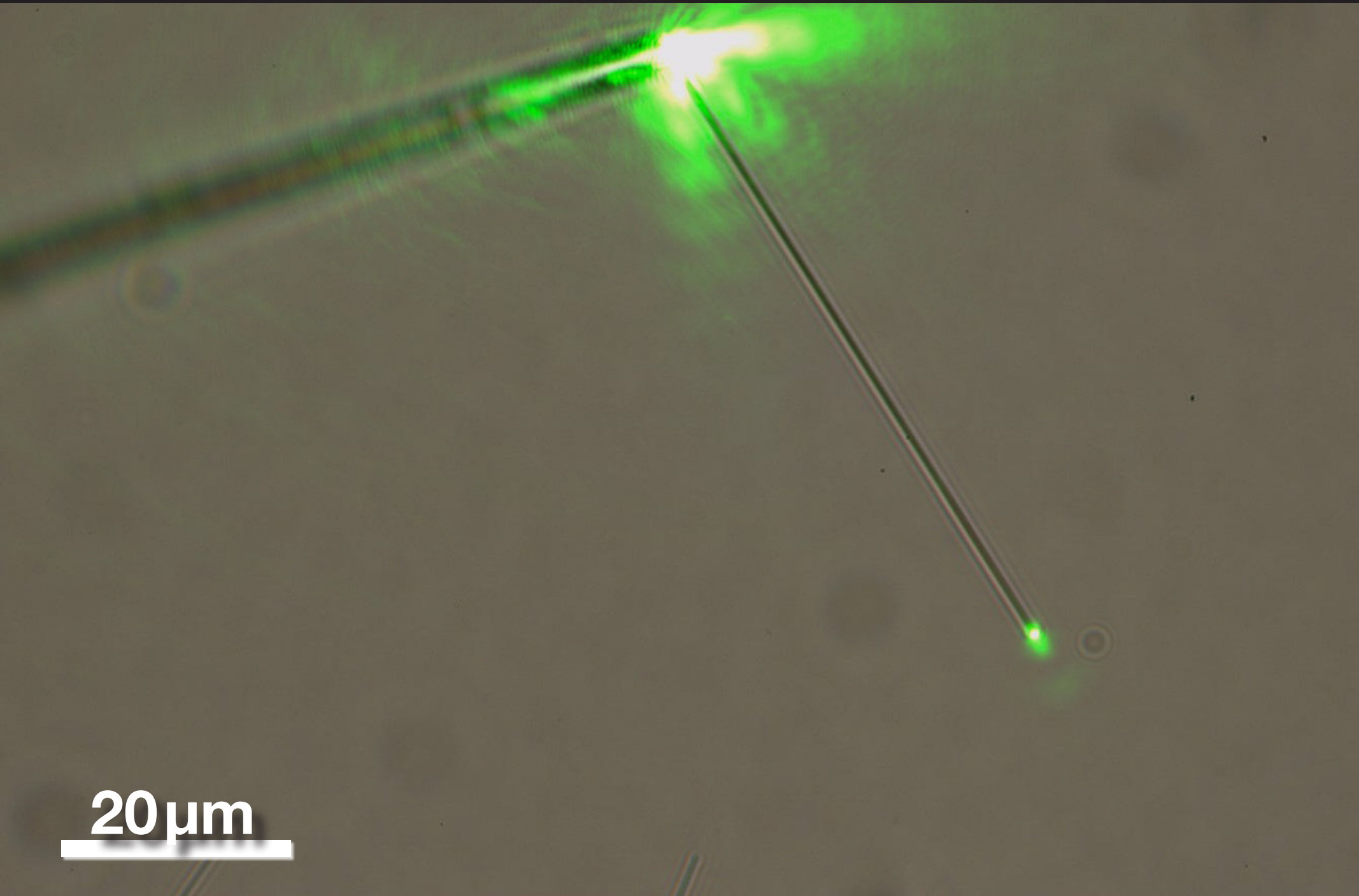
# Manipulating light at the nanoscale



20  $\mu\text{m}$

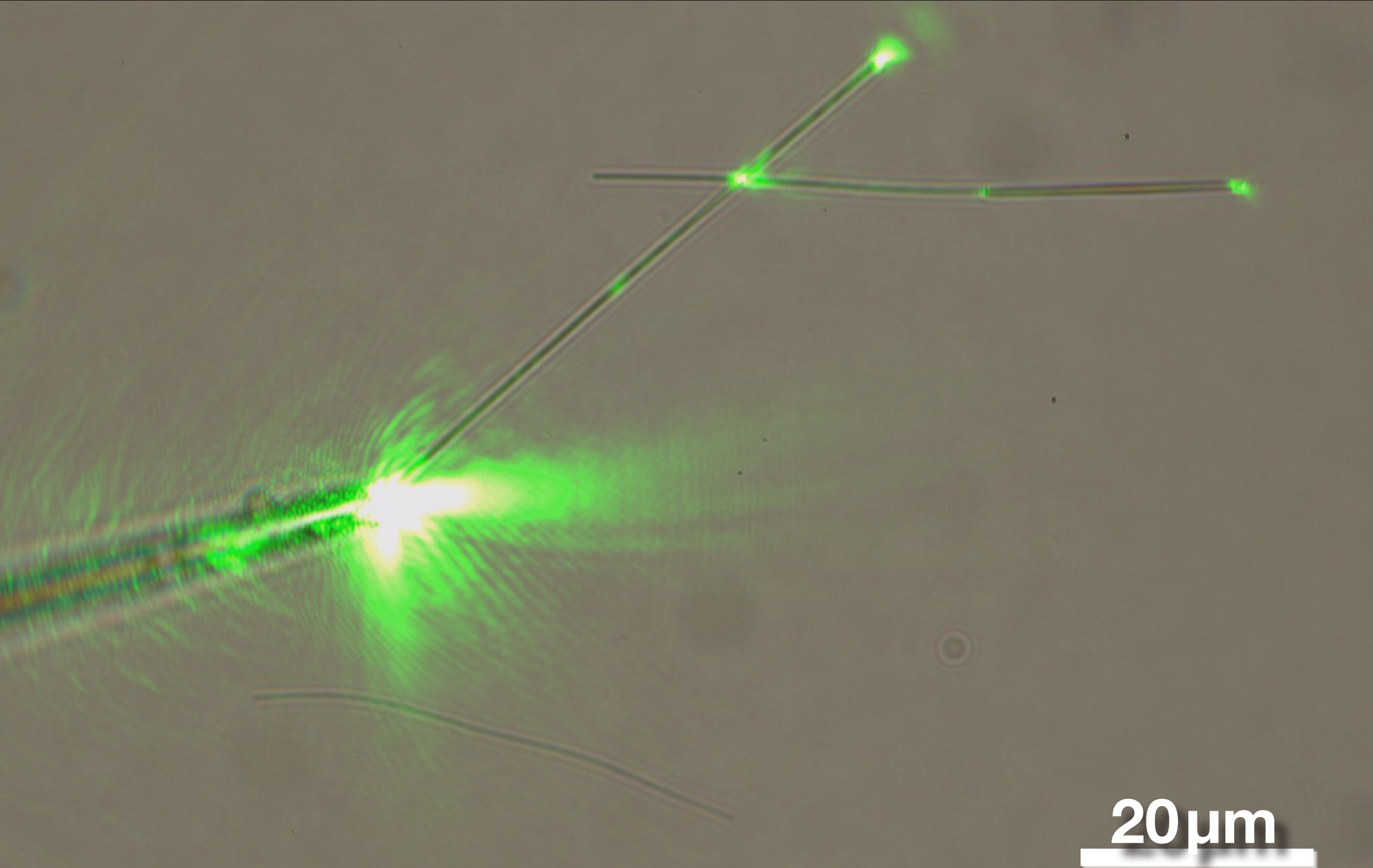


# Manipulating light at the nanoscale

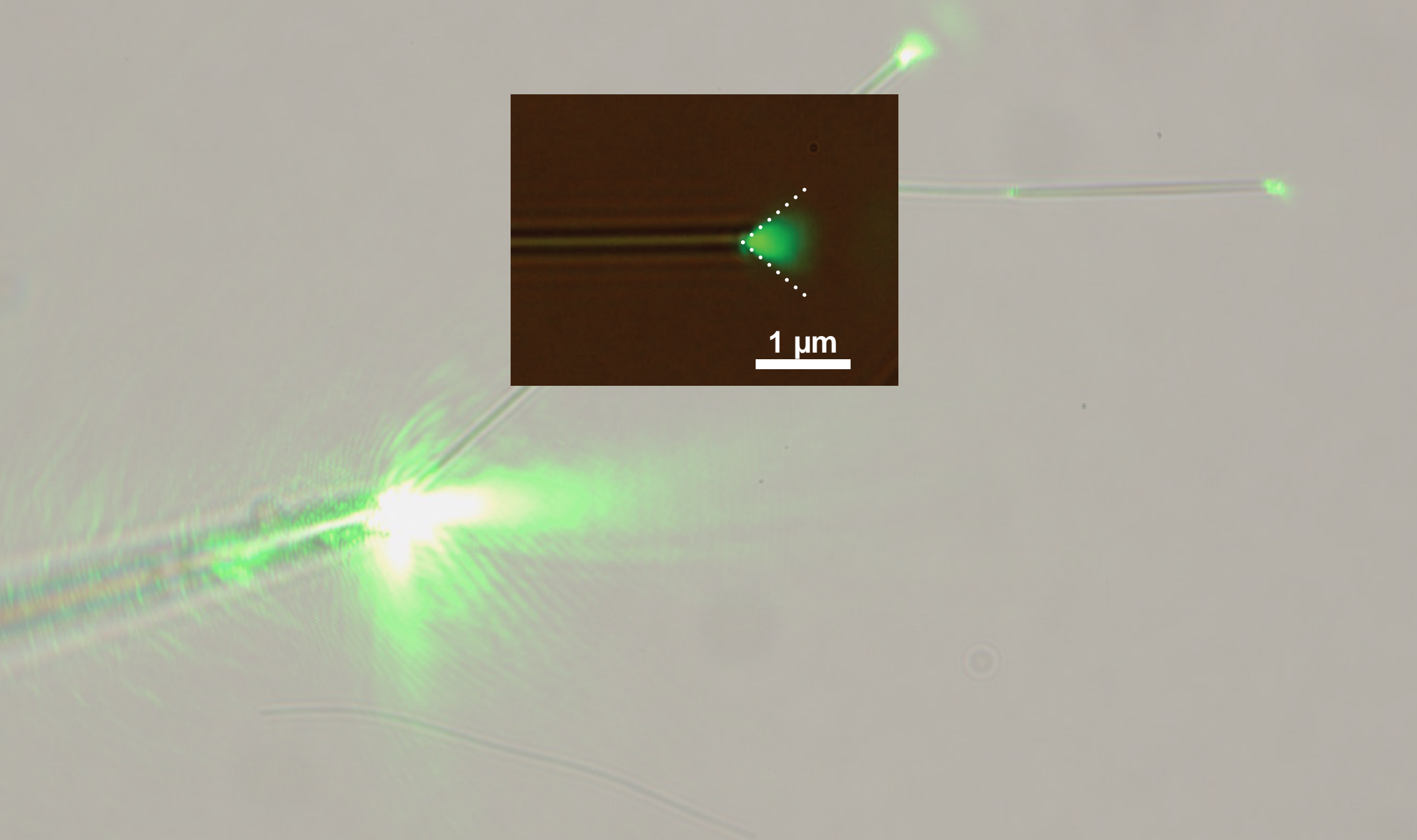
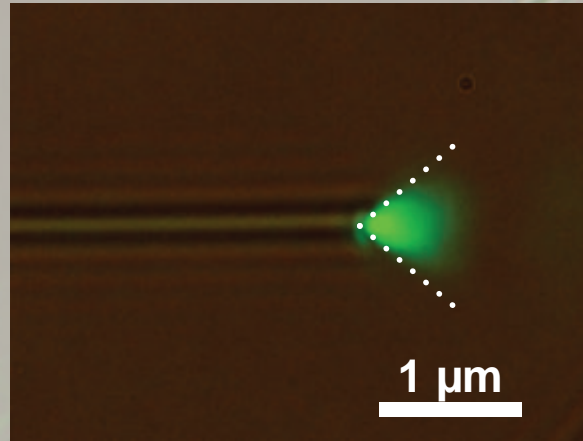


20  $\mu\text{m}$

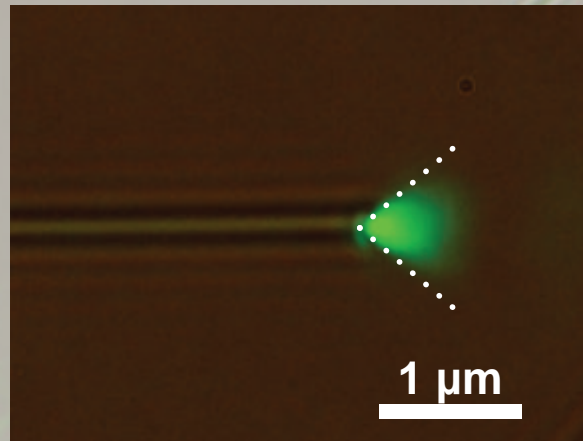
# Manipulating light at the nanoscale



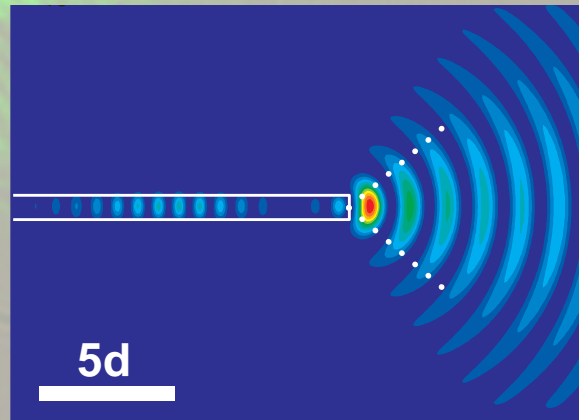
# Manipulating light at the nanoscale



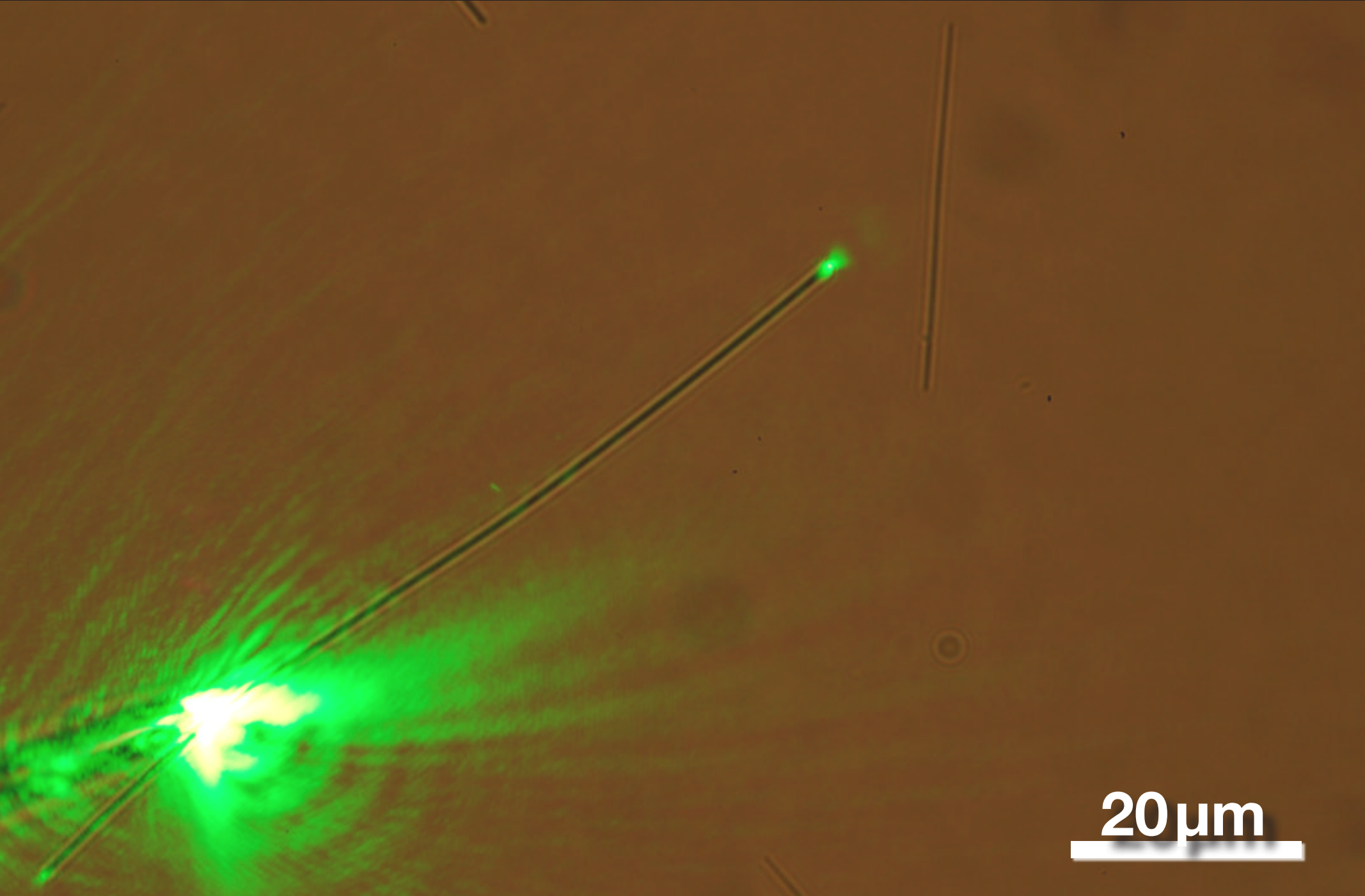
# Manipulating light at the nanoscale



FDTD simulation

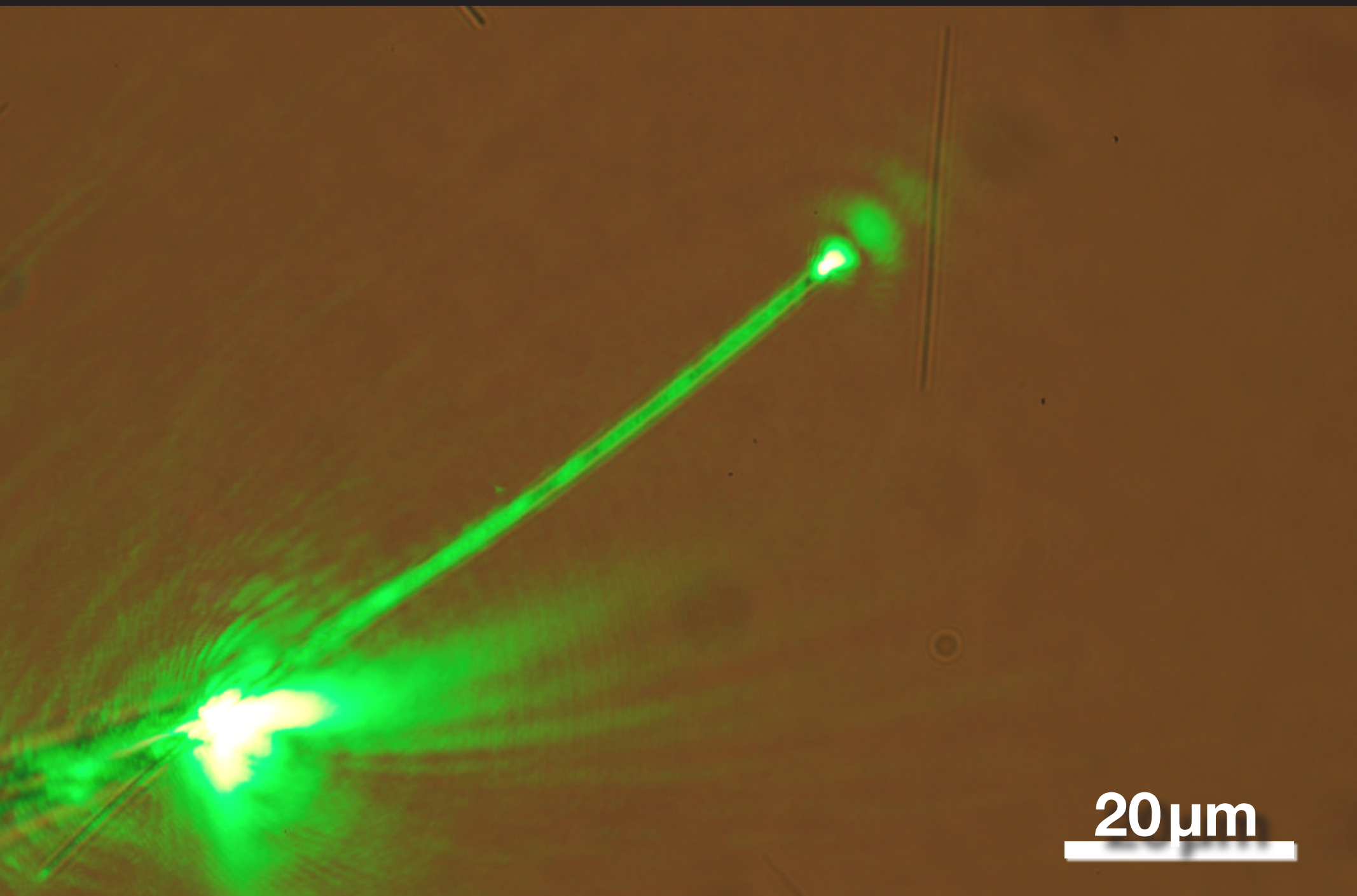


# Manipulating light at the nanoscale



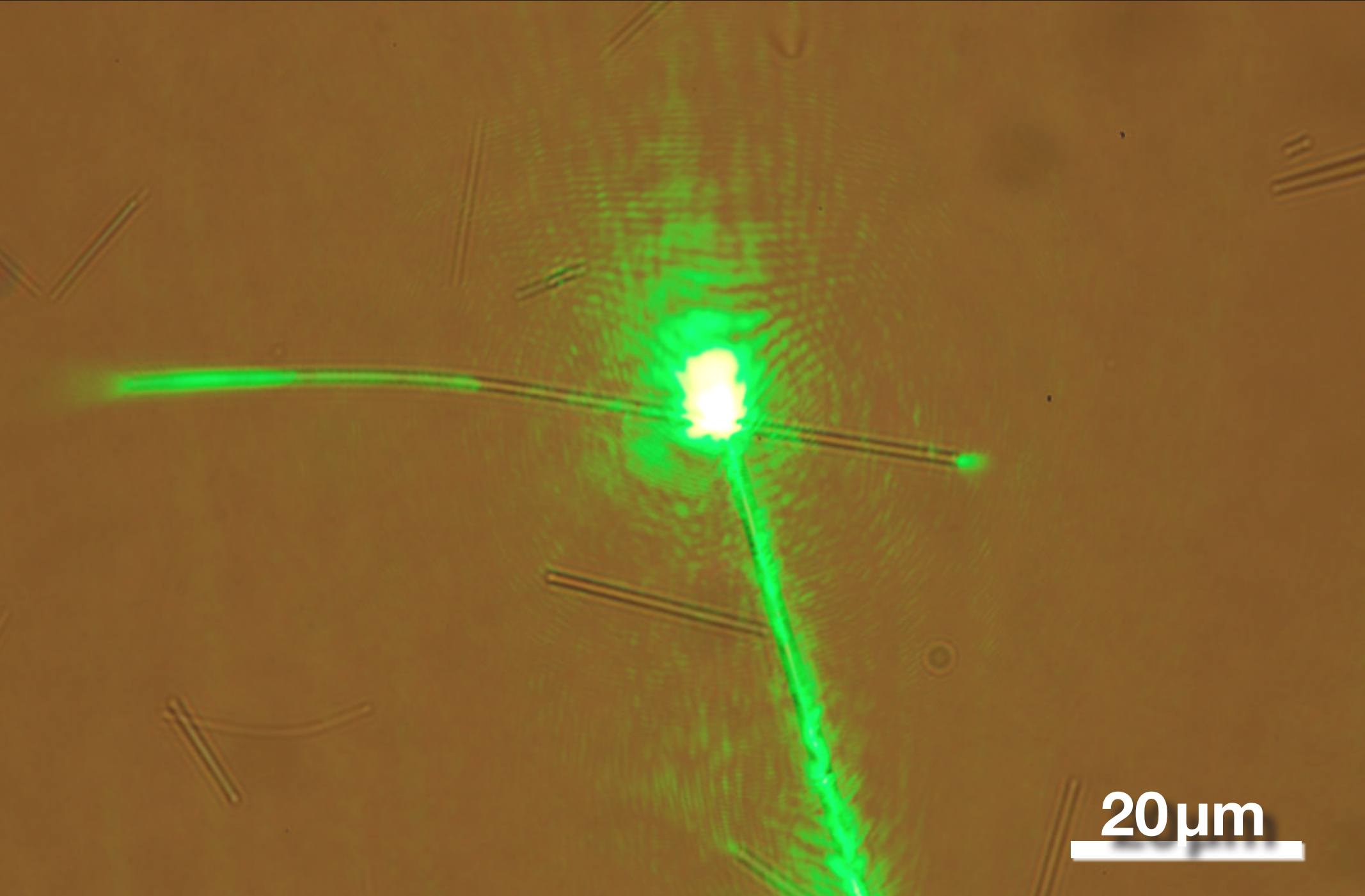
20 μm

# Manipulating light at the nanoscale



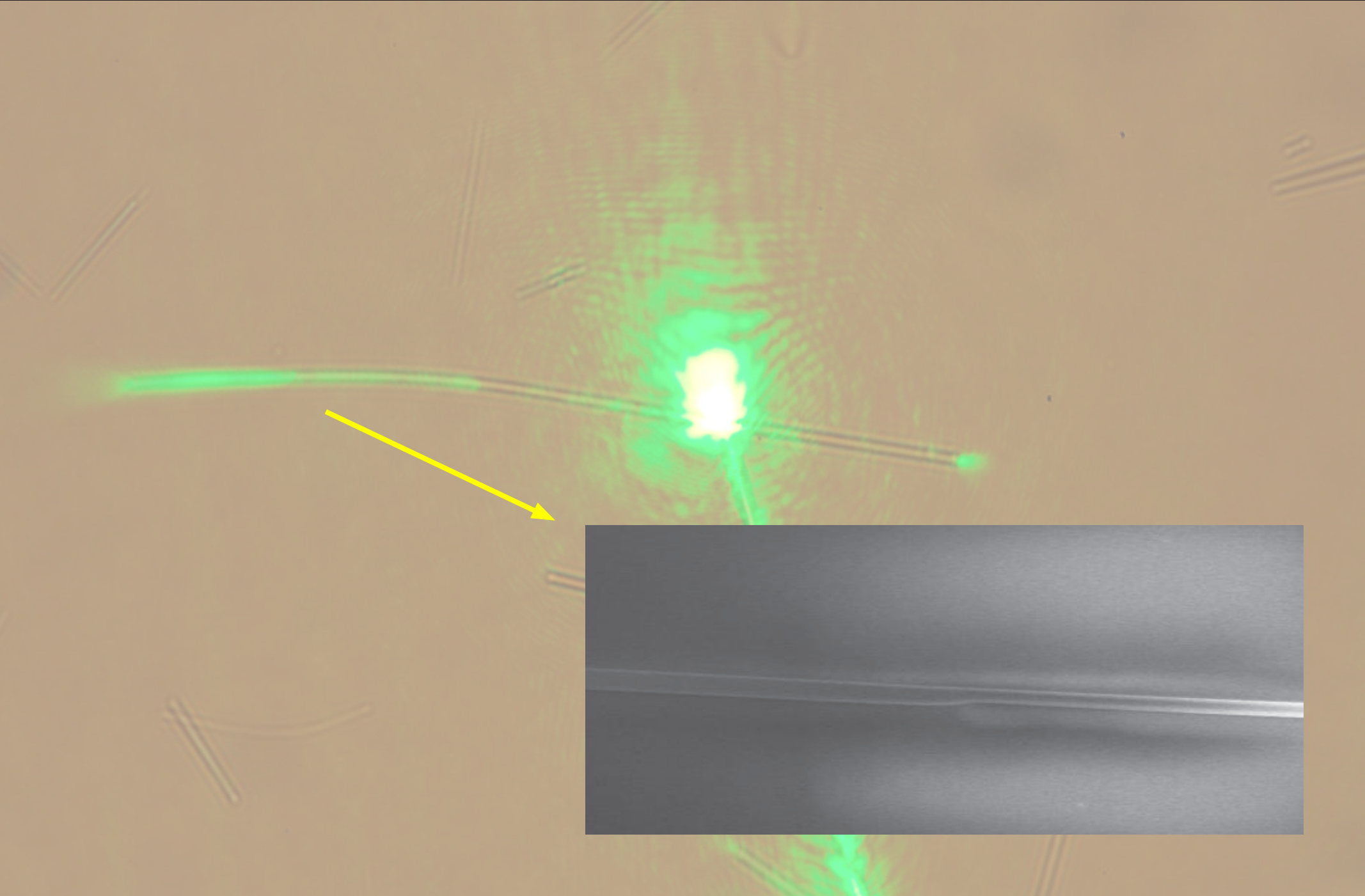
20  $\mu\text{m}$

# Manipulating light at the nanoscale



20  $\mu\text{m}$

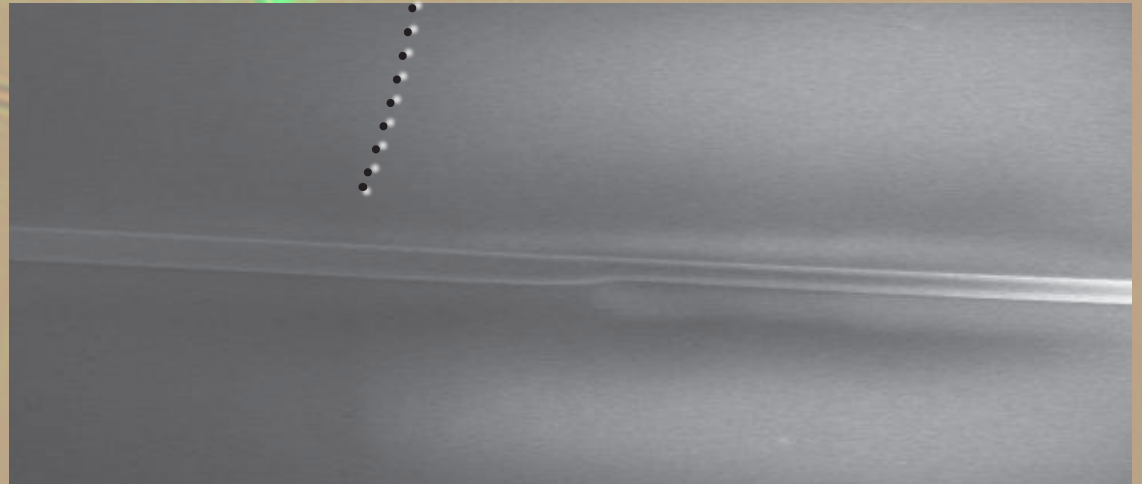
# Manipulating light at the nanoscale





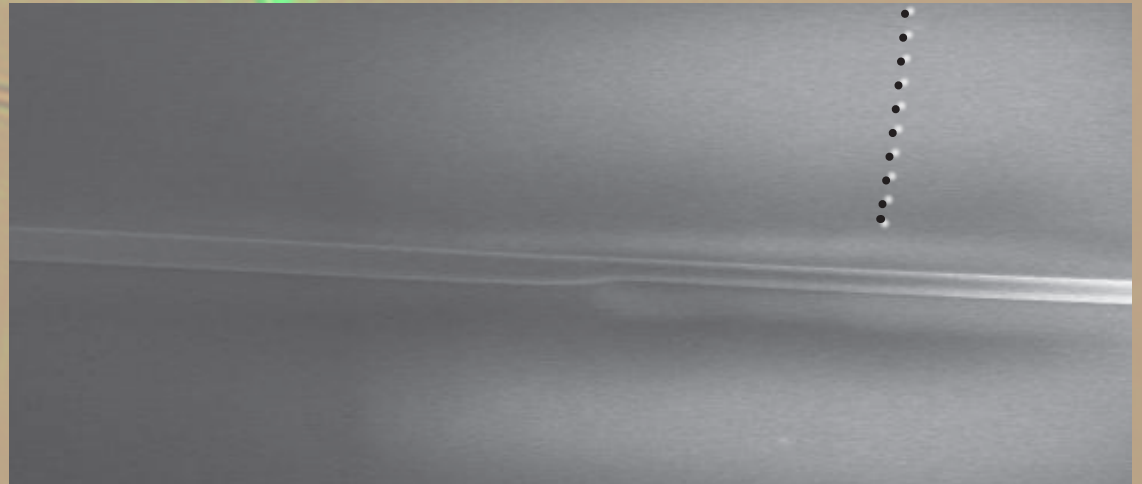
# Manipulating light at the nanoscale

large diameter:  
multimode



# Manipulating light at the nanoscale

small diameter:  
single mode



# Manipulating light at the nanoscale

**Points to keep in mind:**

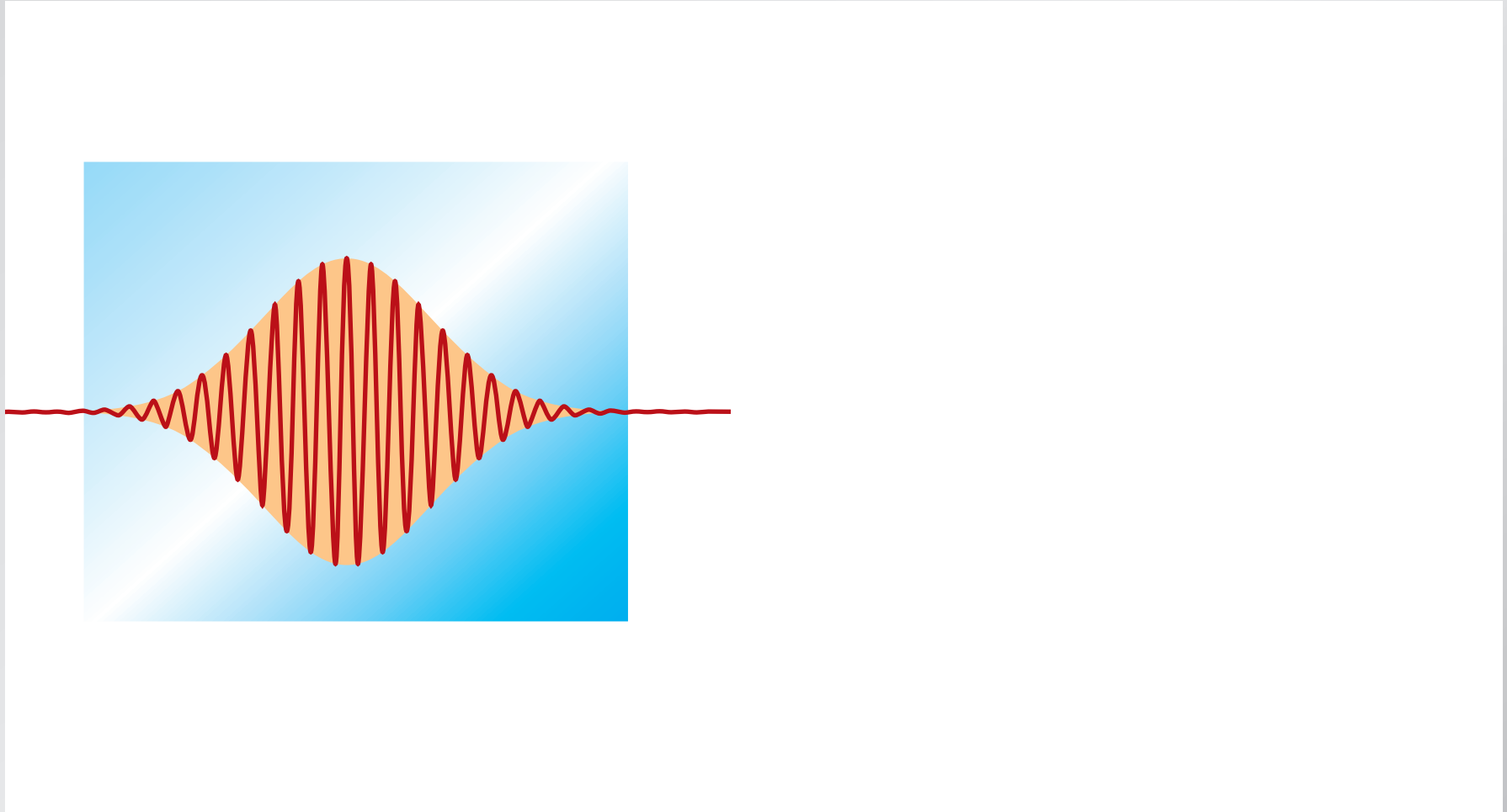
- **low loss**
- **large evanescent field**
- **convenient coupling to nanoscale**

# Outline

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

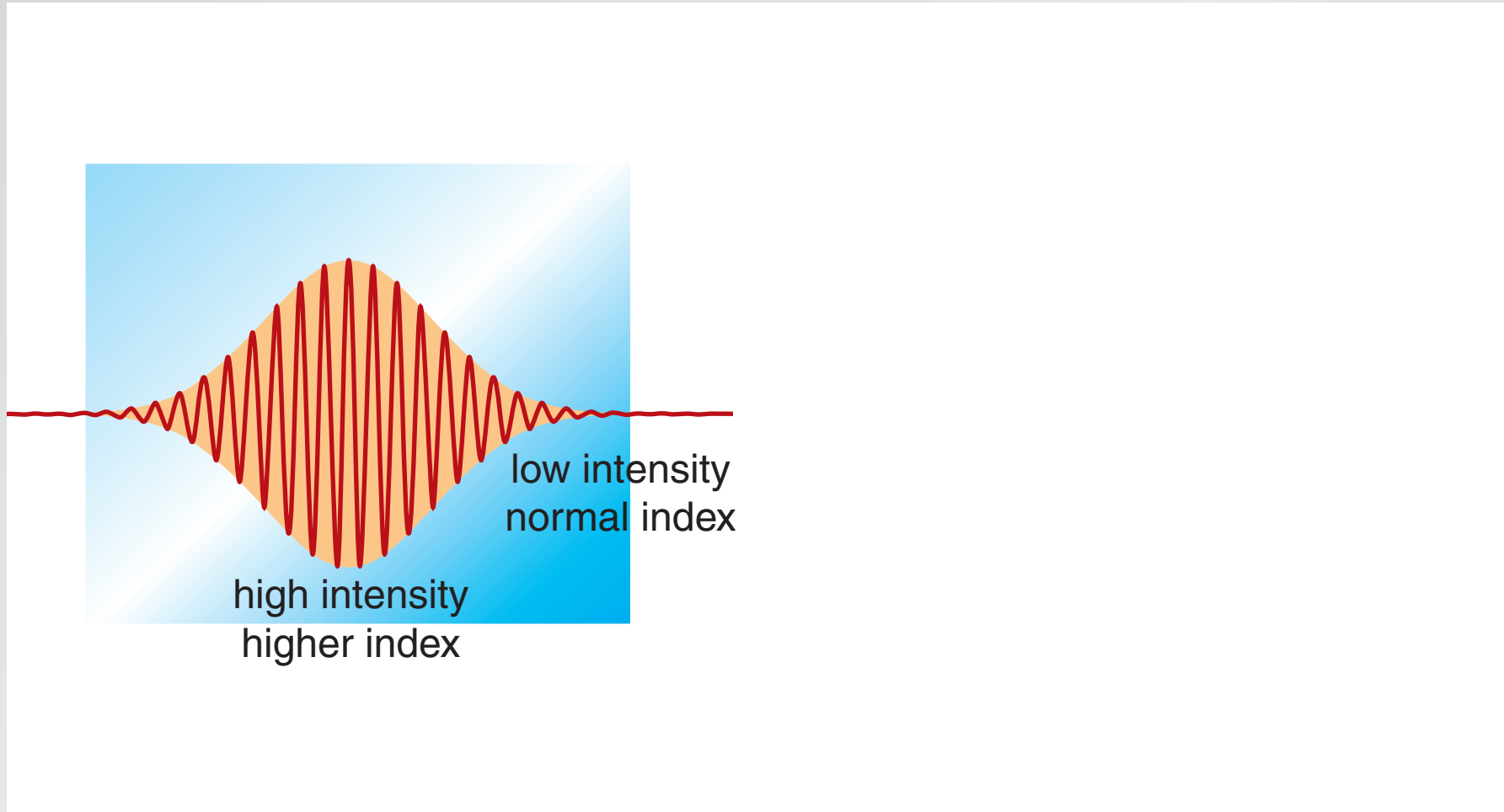
# Nanoscale nonlinear optics

nonlinear dispersion:  $n = n_0 + n_2 I$



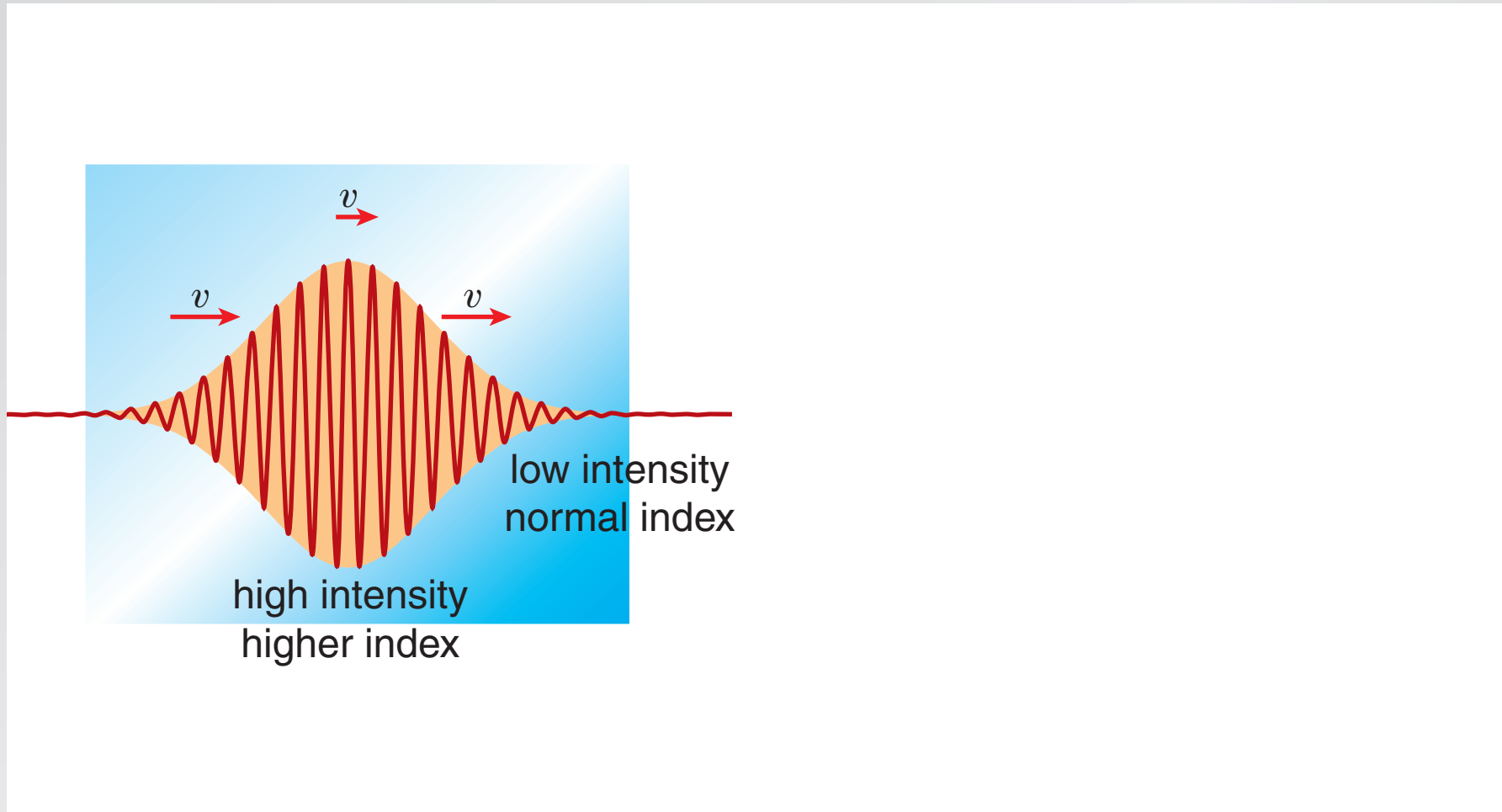
# Nanoscale nonlinear optics

nonlinear dispersion:  $n = n_0 + n_2 I$



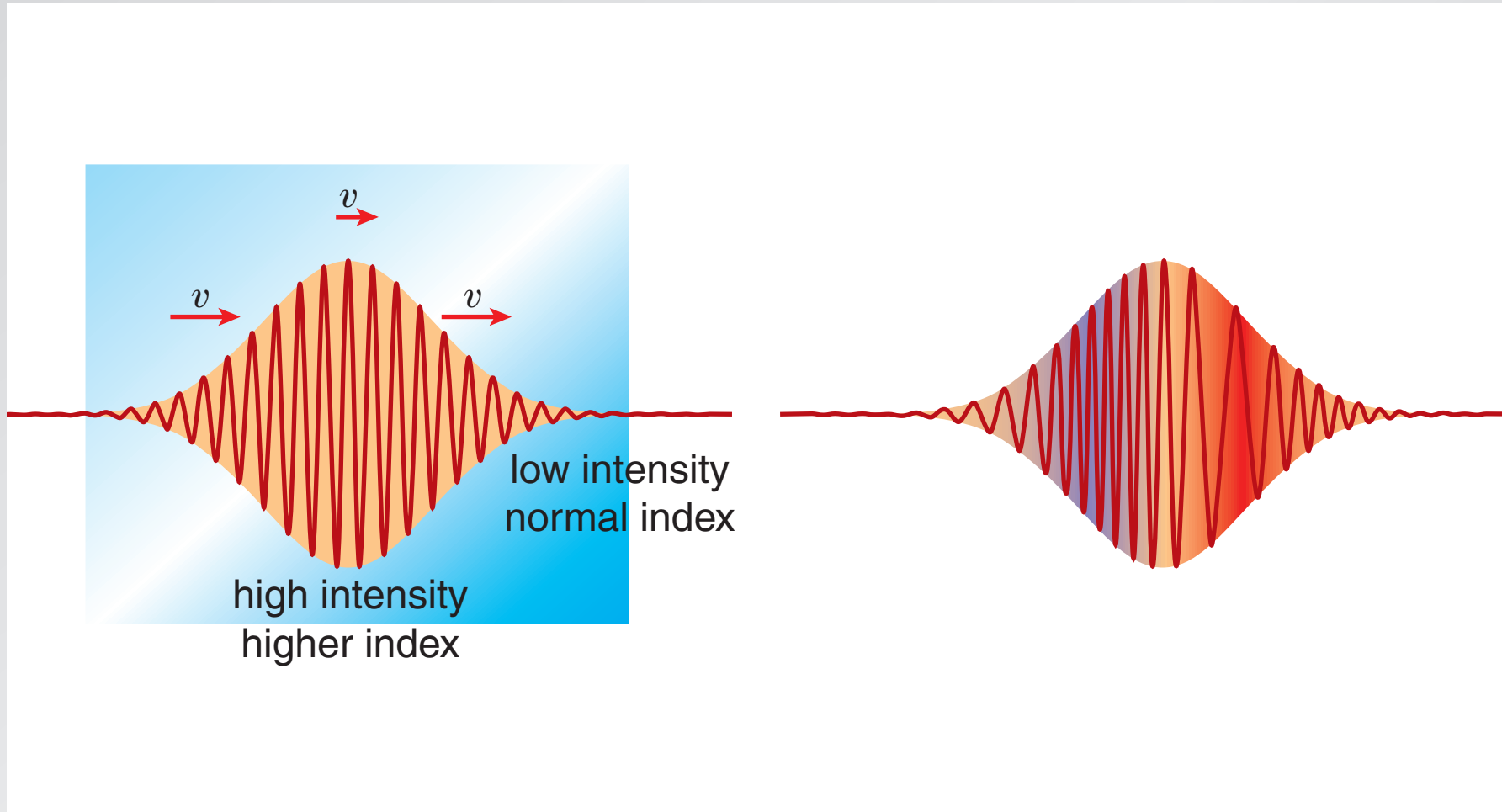
# Nanoscale nonlinear optics

nonlinear dispersion:  $n = n_0 + n_2 I$



# Nanoscale nonlinear optics

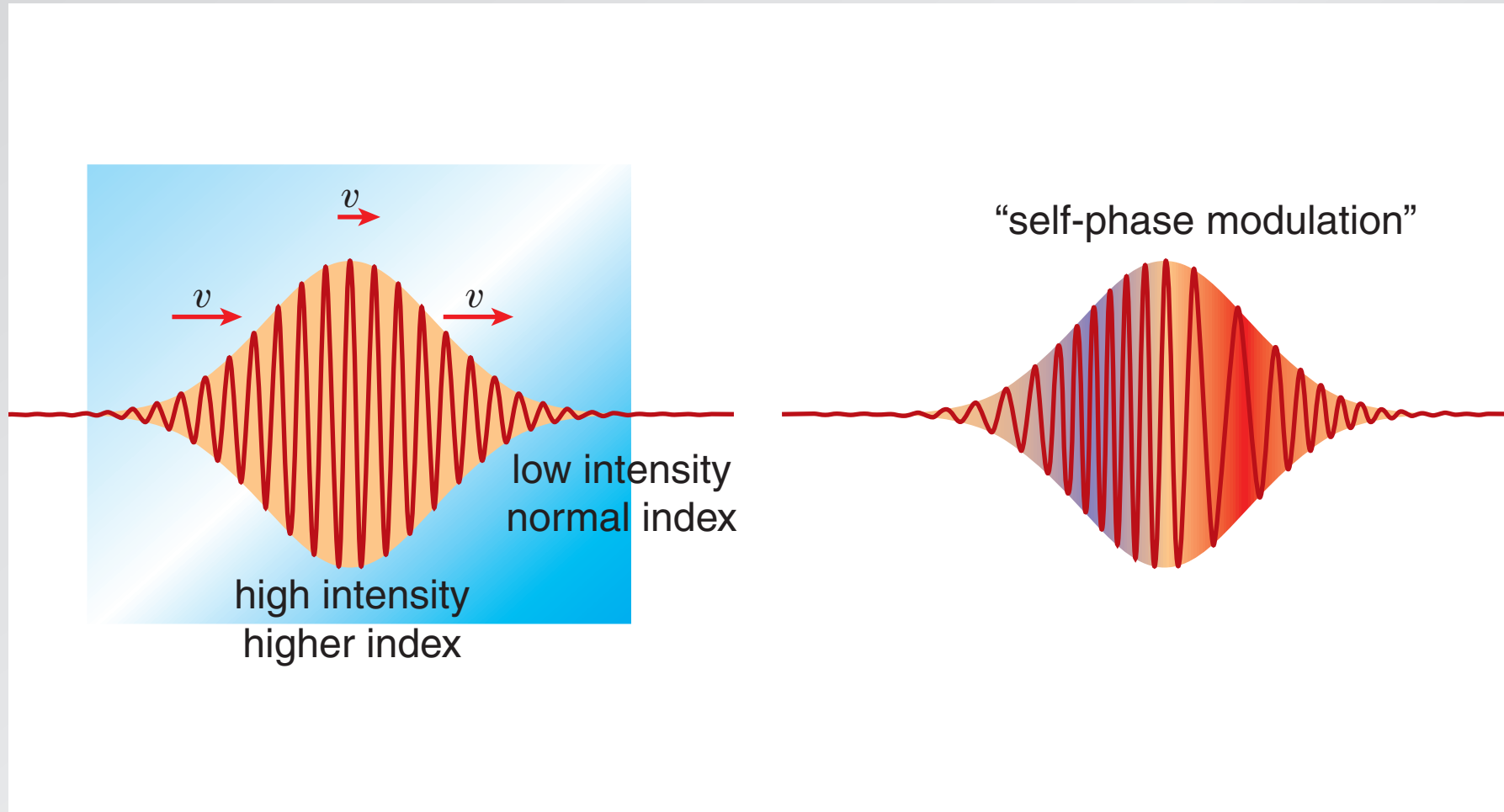
nonlinear dispersion:  $n = n_0 + n_2 I$



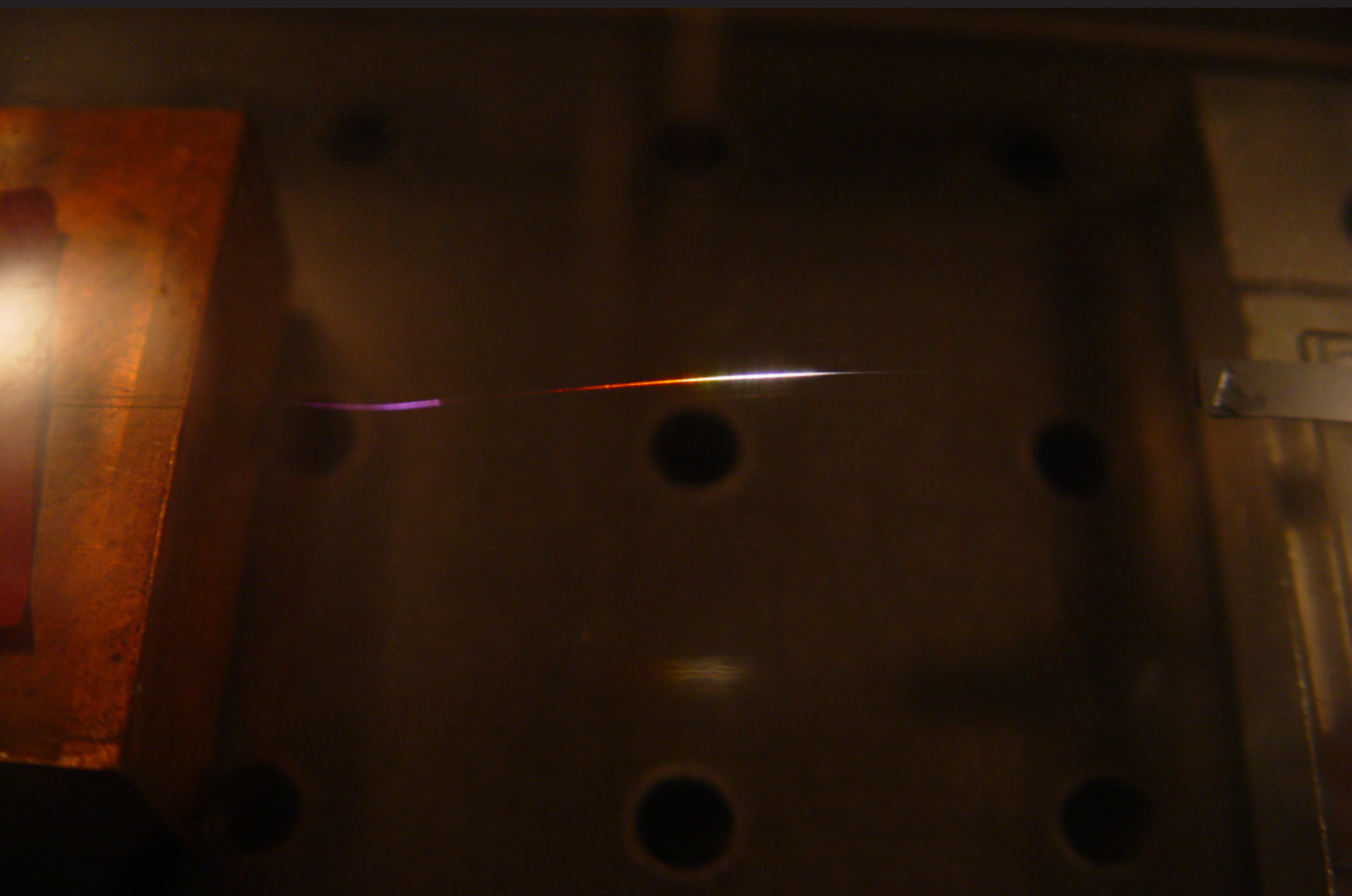


# Nanoscale nonlinear optics

nonlinear dispersion:  $n = n_0 + n_2 I$



# Nanoscale nonlinear optics



# Nanoscale nonlinear optics

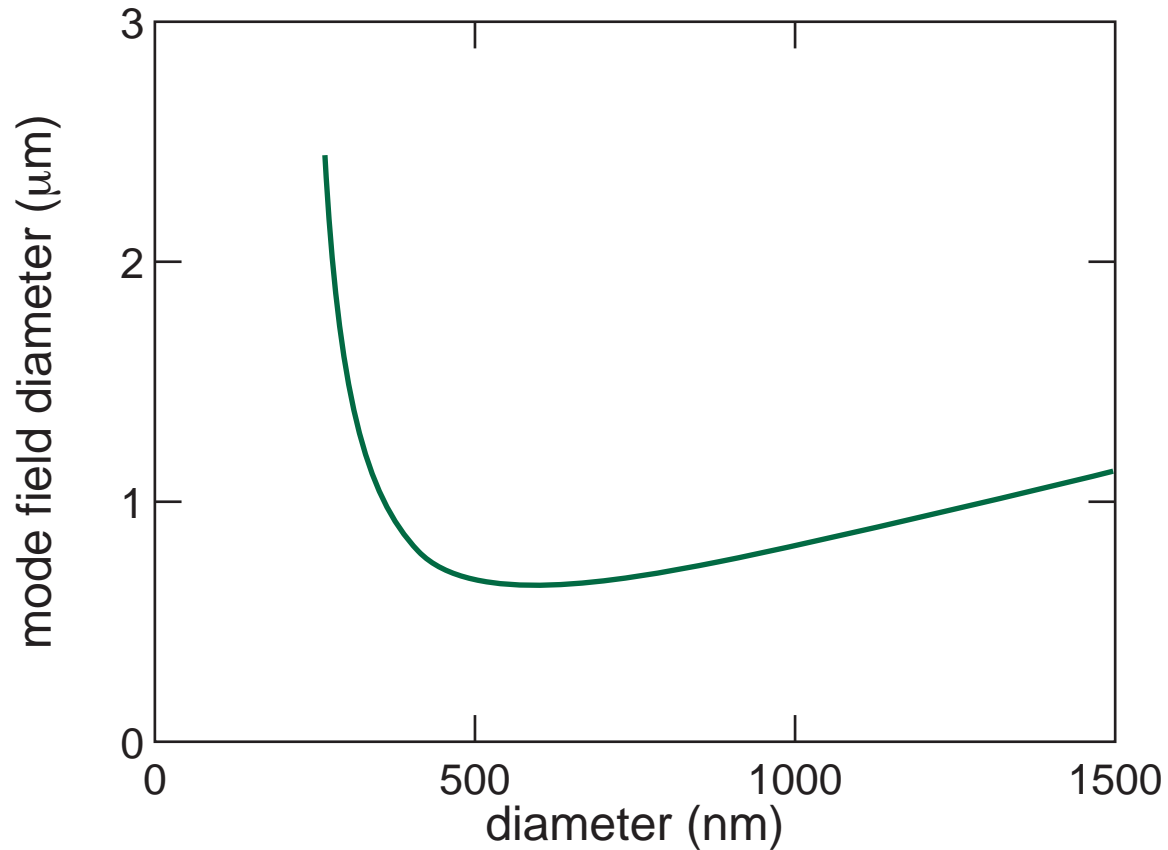


# Nanoscale nonlinear optics

**strong confinement**  $\longrightarrow$  **high intensity**

# Nanoscale nonlinear optics

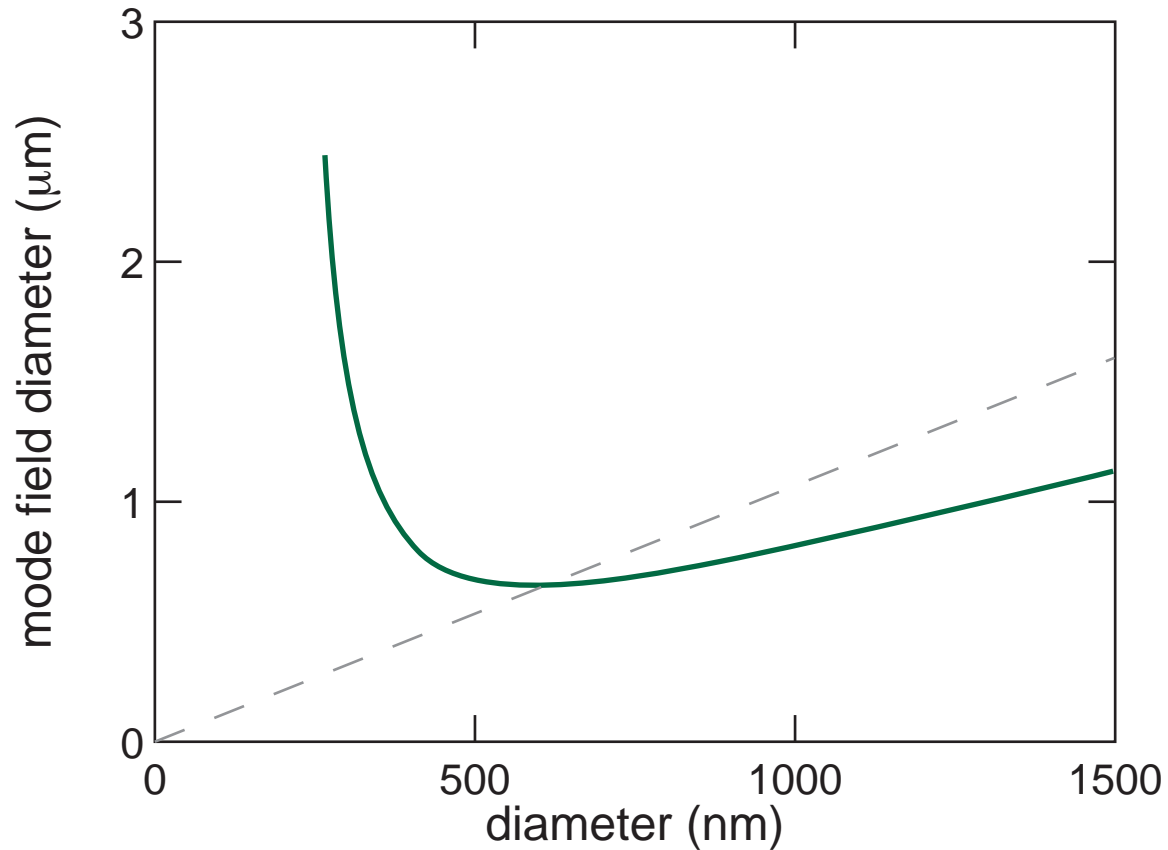
mode field diameter ( $\lambda = 800$  nm)



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

# Nanoscale nonlinear optics

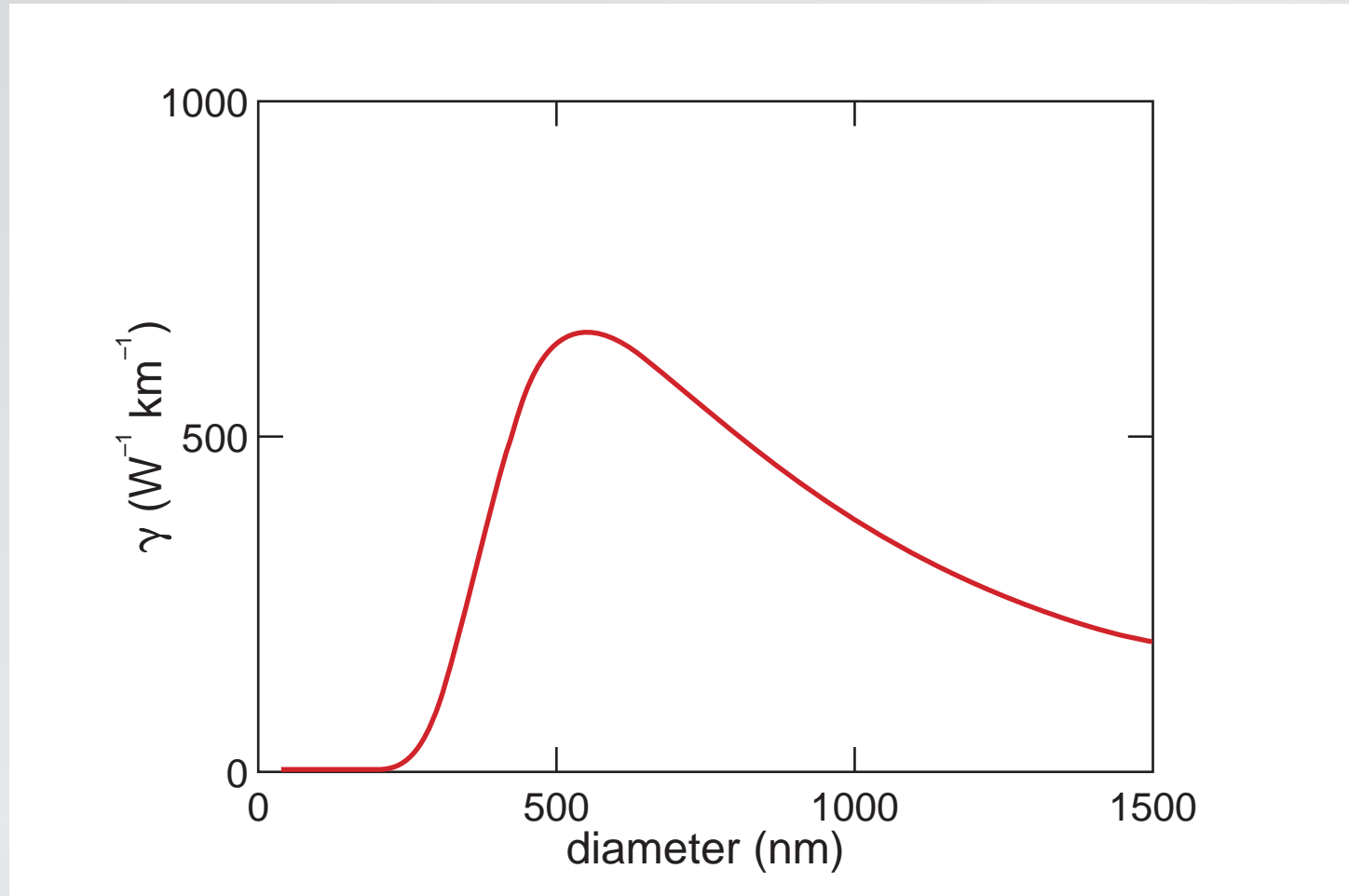
mode field diameter ( $\lambda = 800$  nm)



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!**



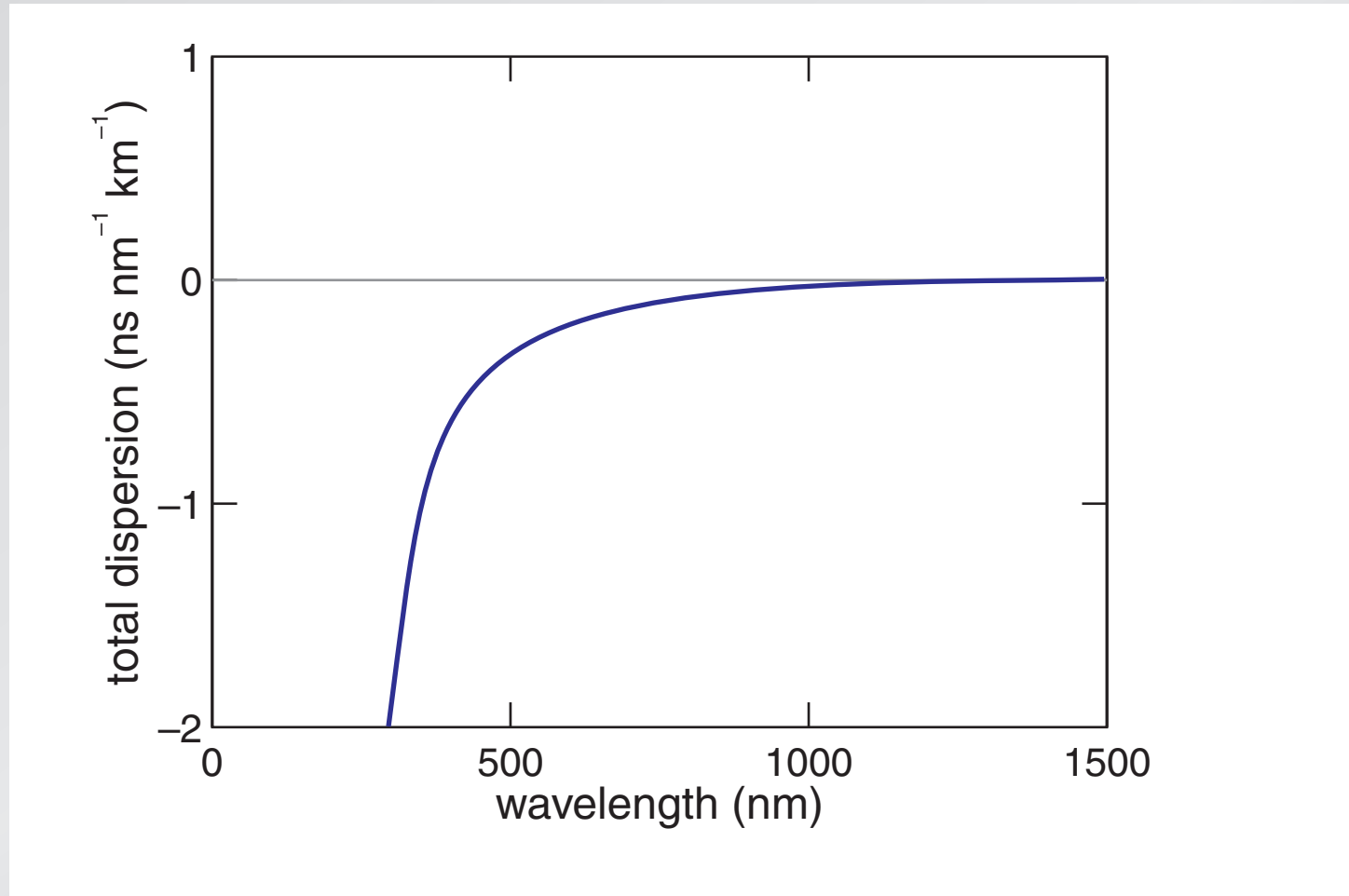
# Nanoscale nonlinear optics

**dispersion:**

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

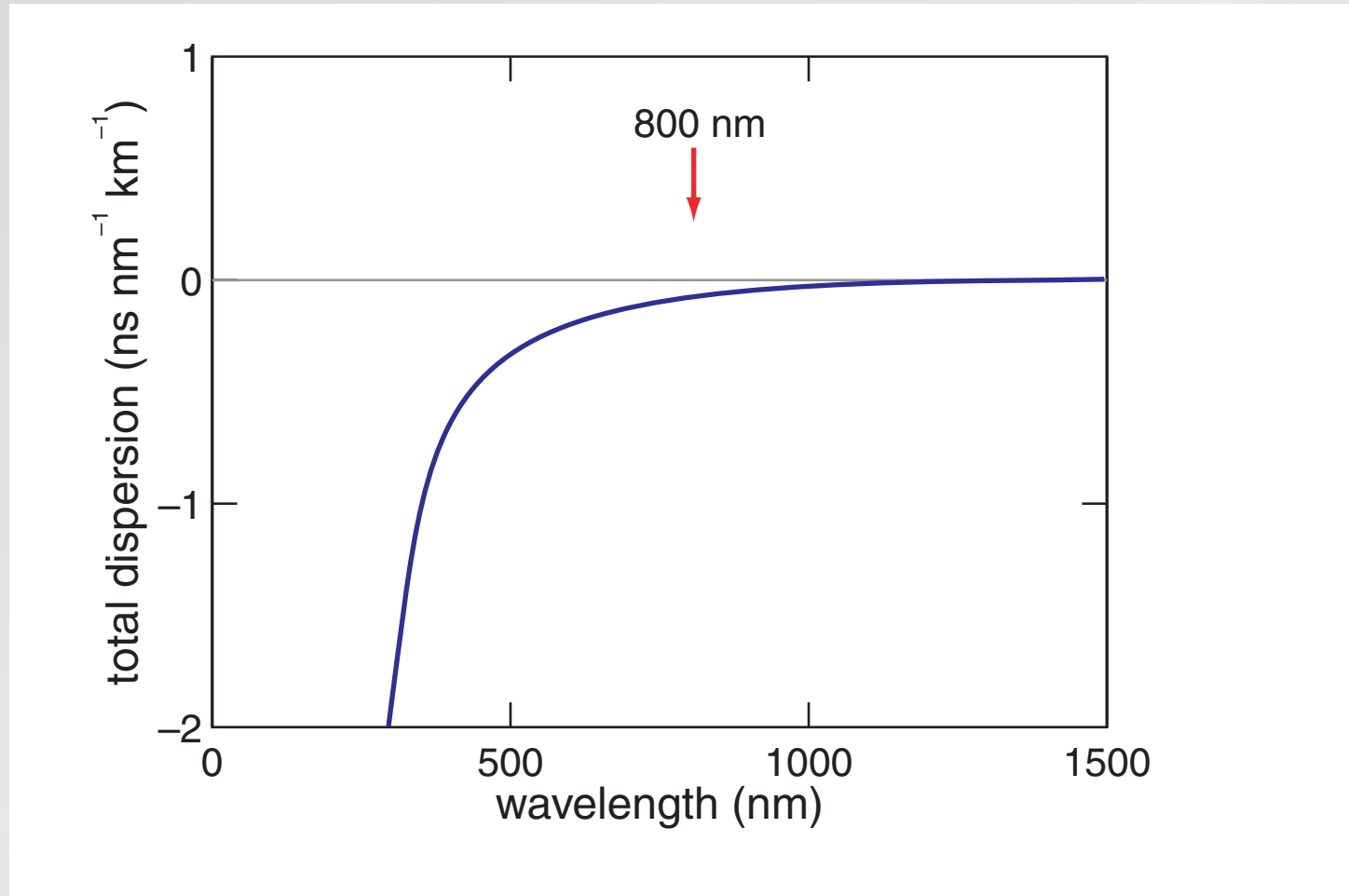
# Nanoscale nonlinear optics

## waveguide dispersion



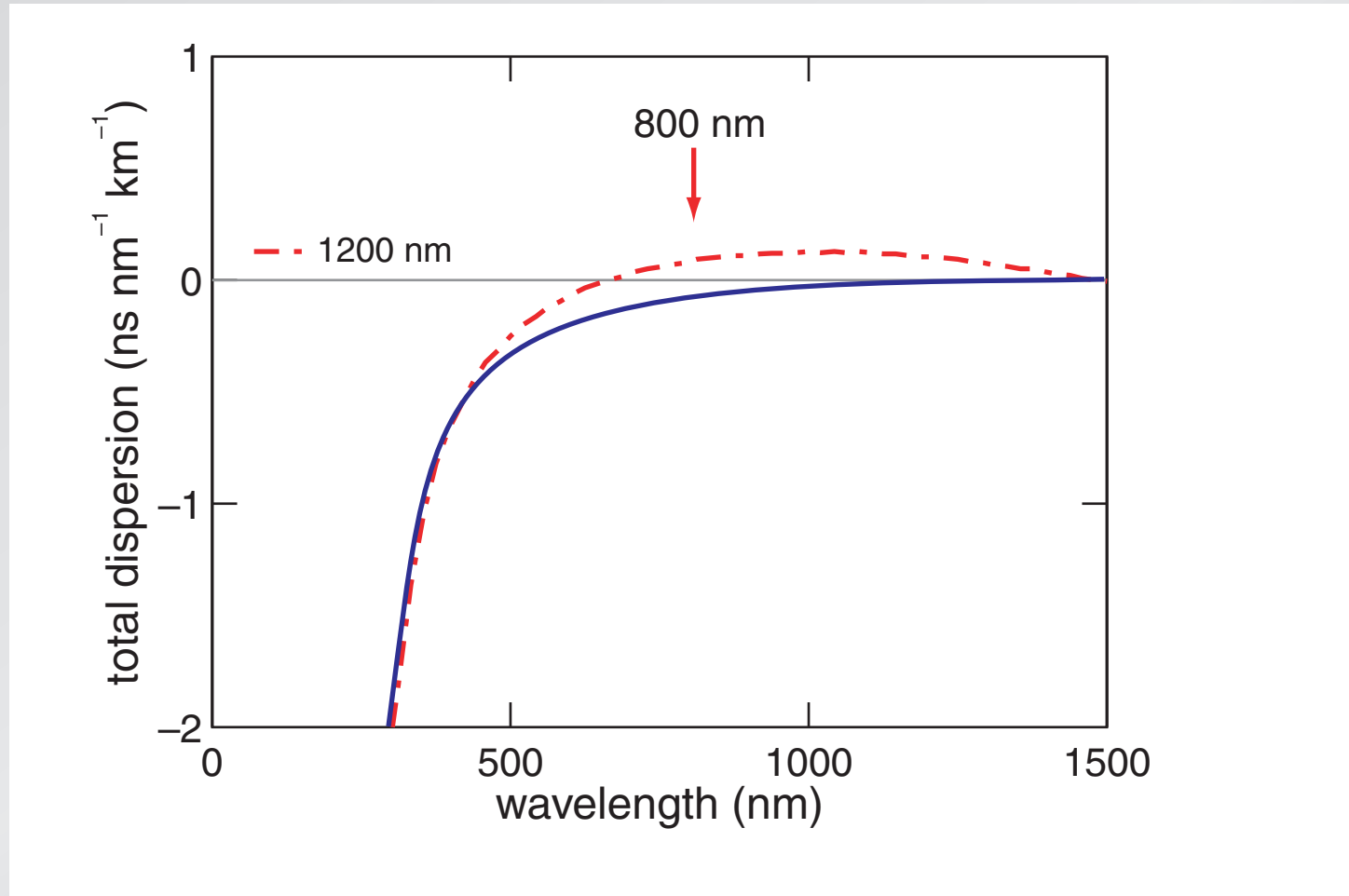
# Nanoscale nonlinear optics

## waveguide dispersion



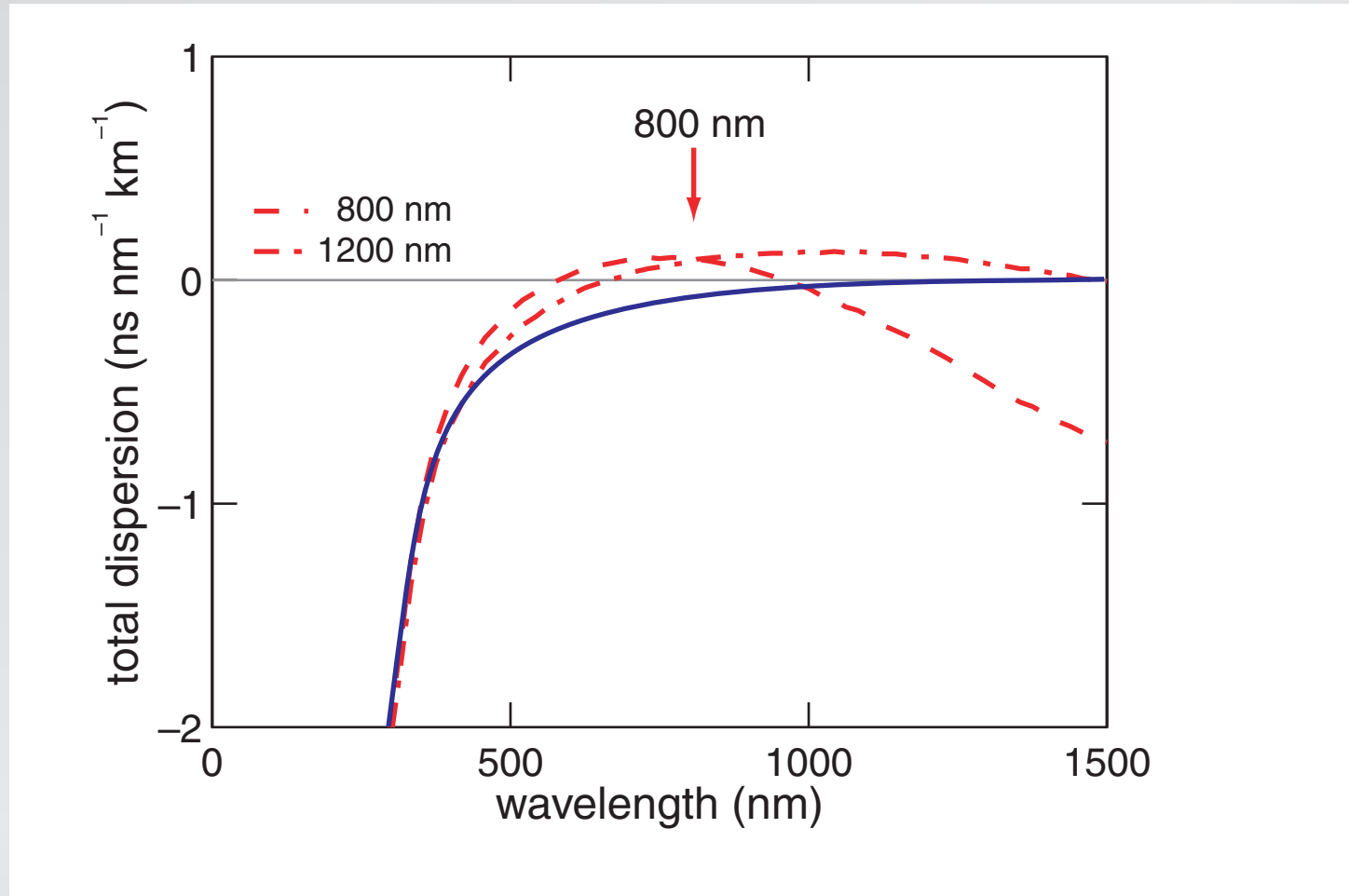
# Nanoscale nonlinear optics

## waveguide dispersion



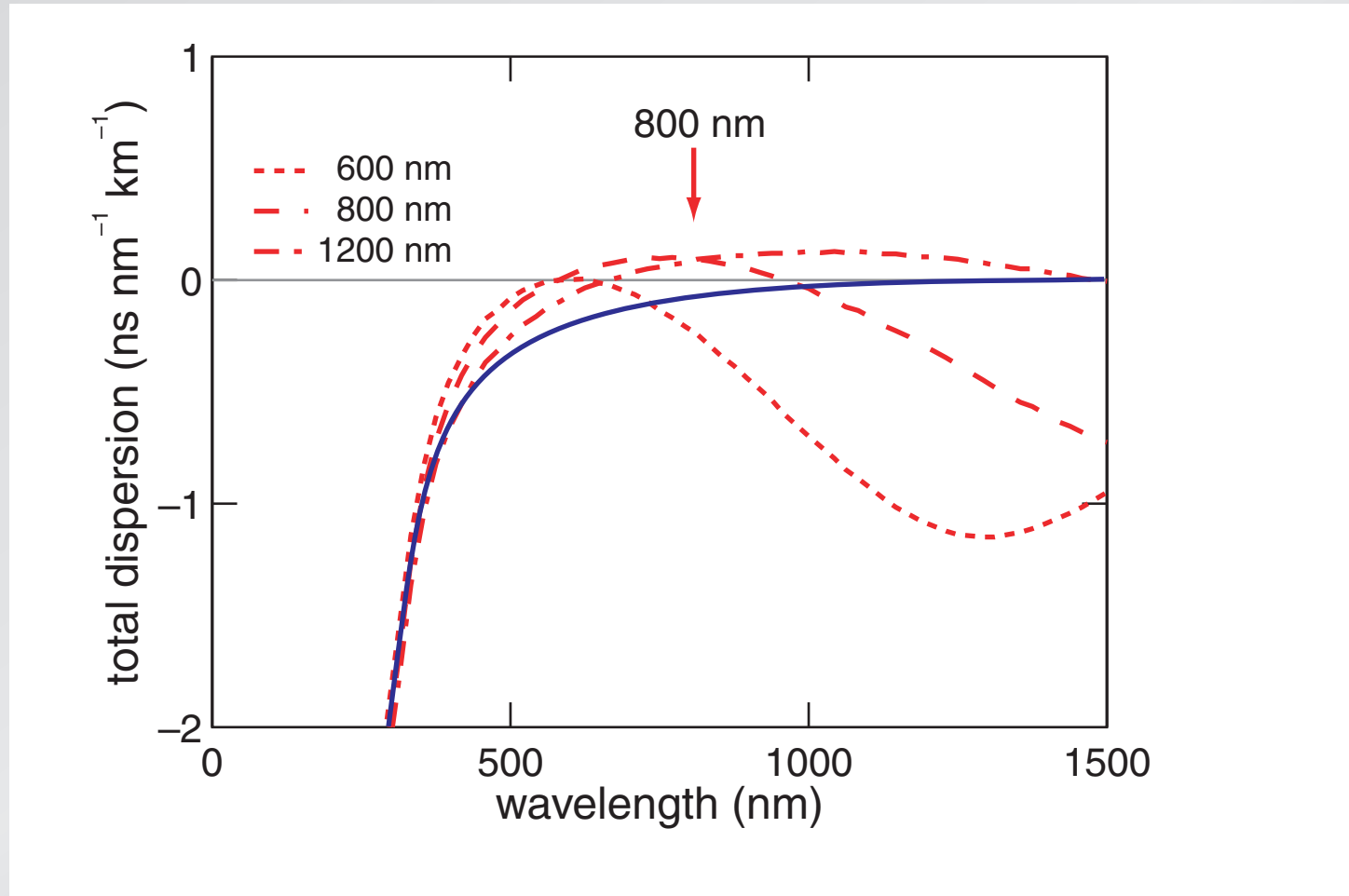
# Nanoscale nonlinear optics

## waveguide dispersion



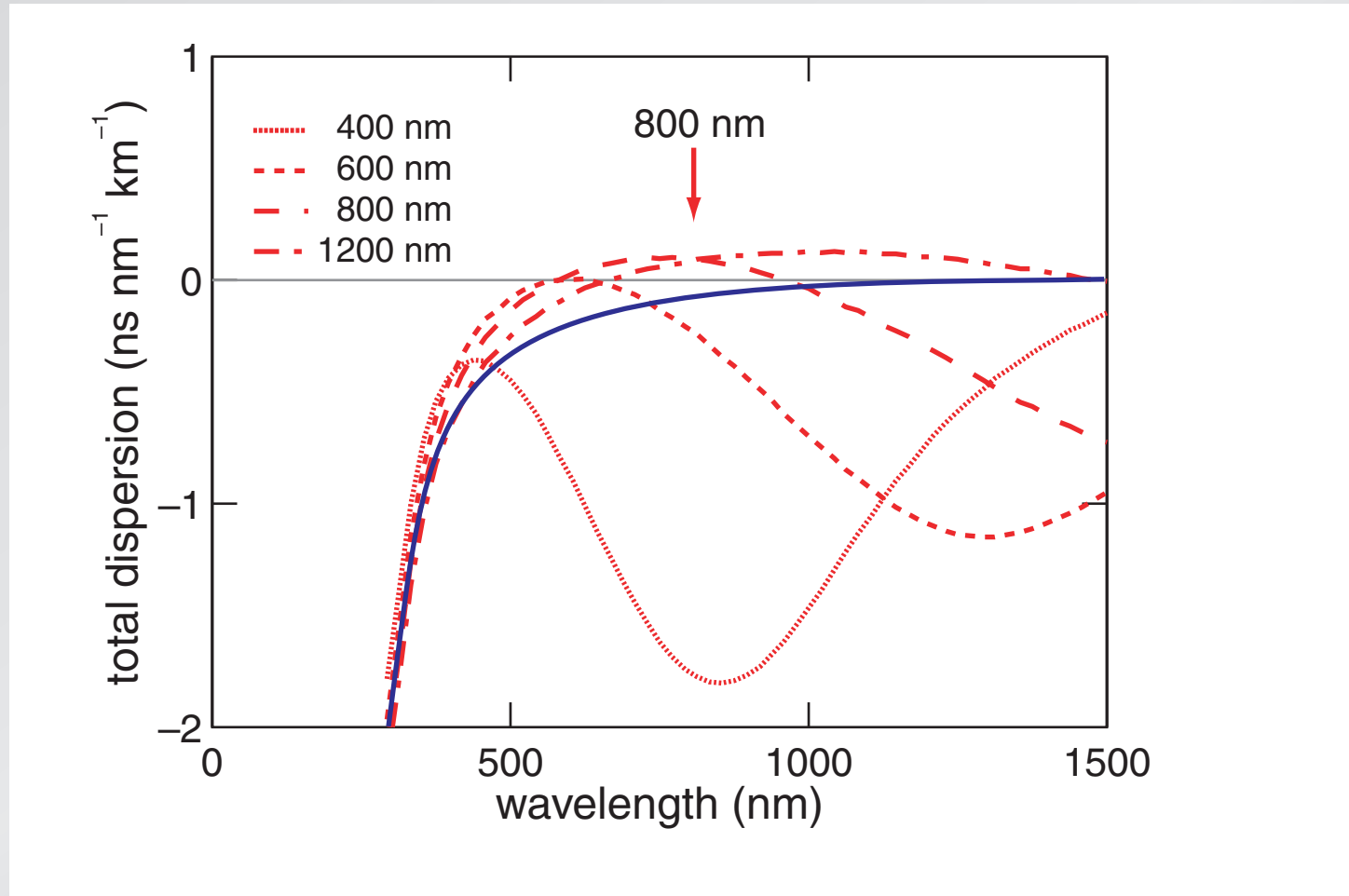
# Nanoscale nonlinear optics

## waveguide dispersion



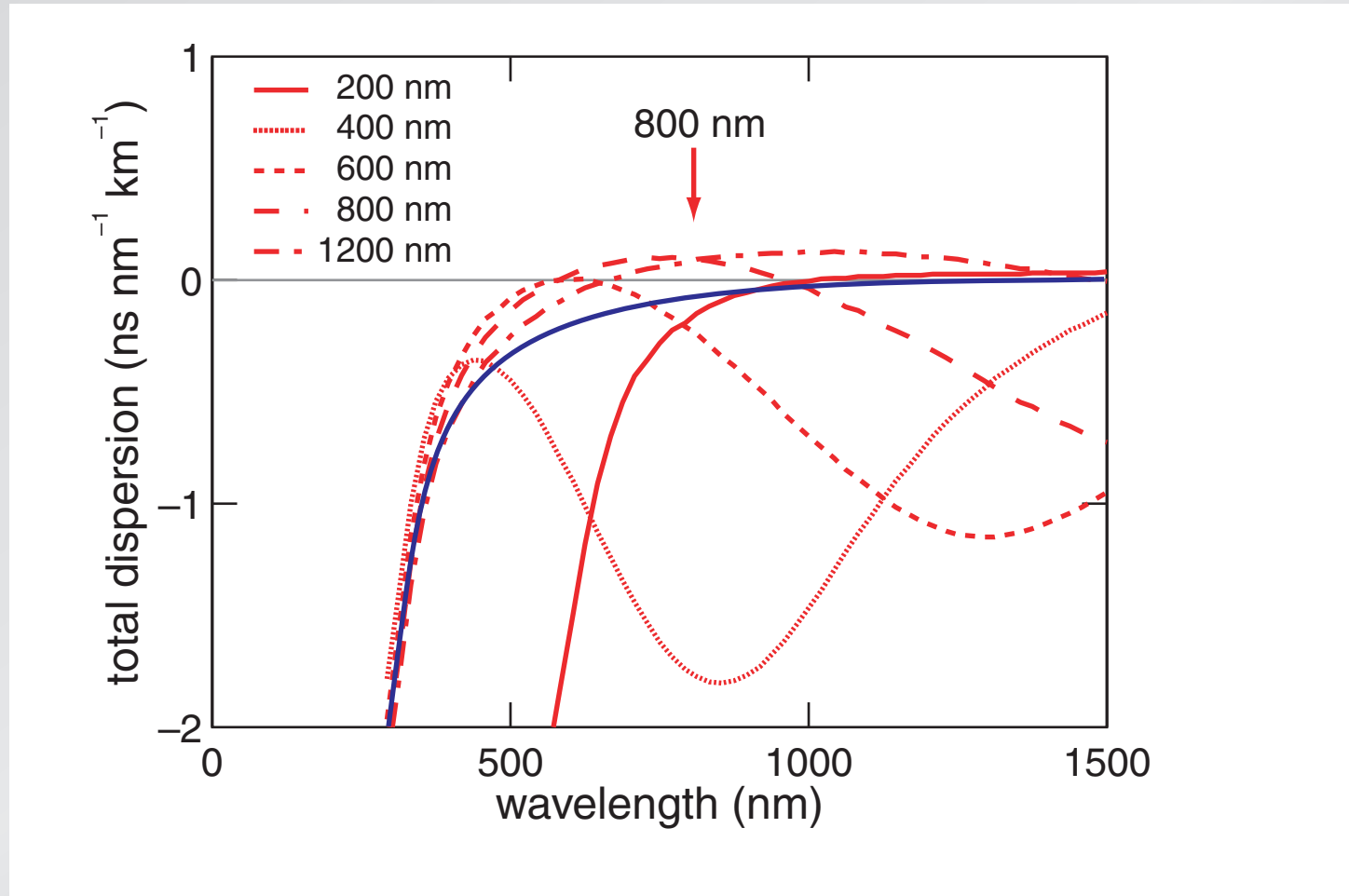
# Nanoscale nonlinear optics

## waveguide dispersion



# Nanoscale nonlinear optics

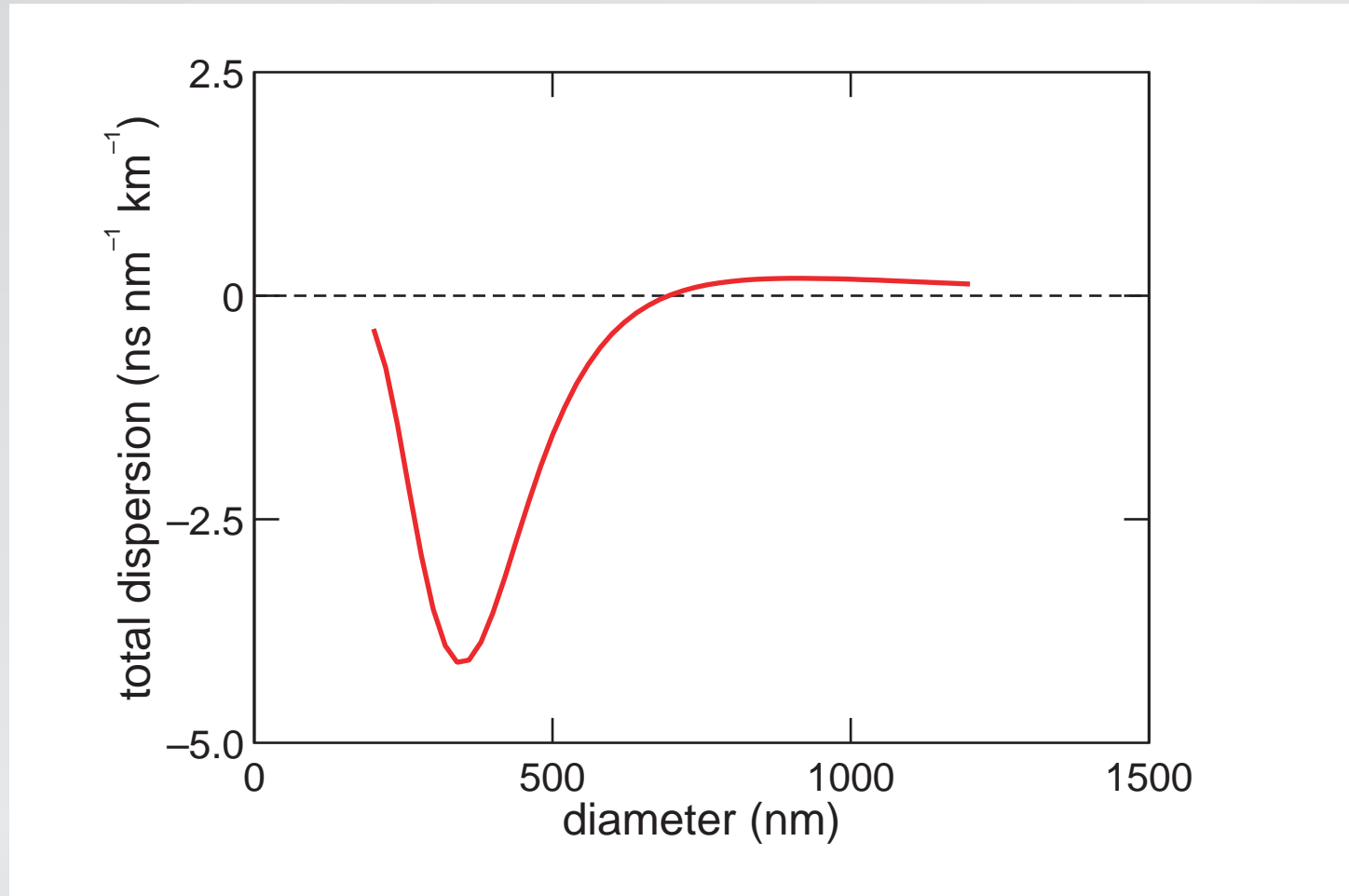
## waveguide dispersion





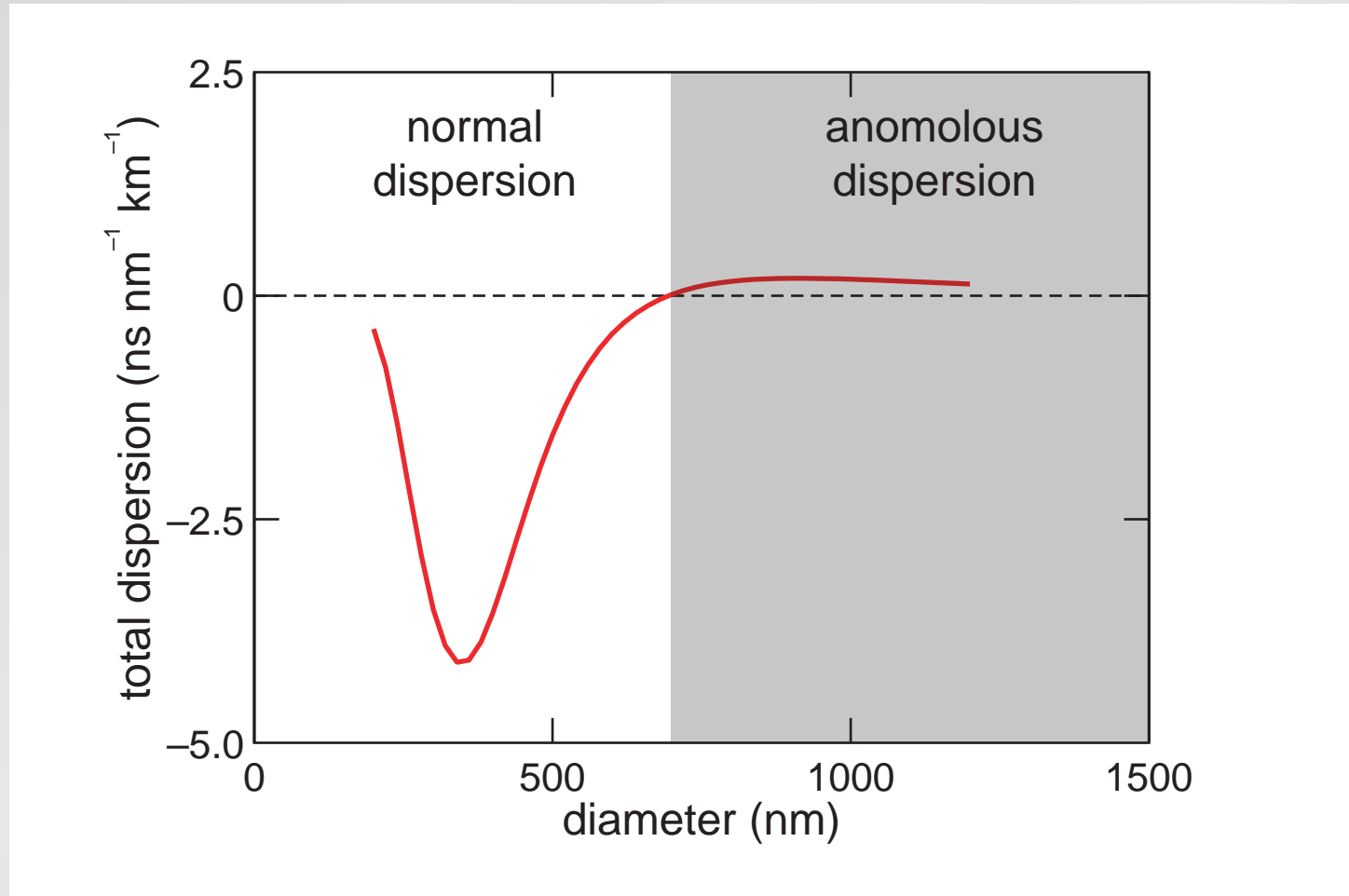
# Nanoscale nonlinear optics

## waveguide dispersion



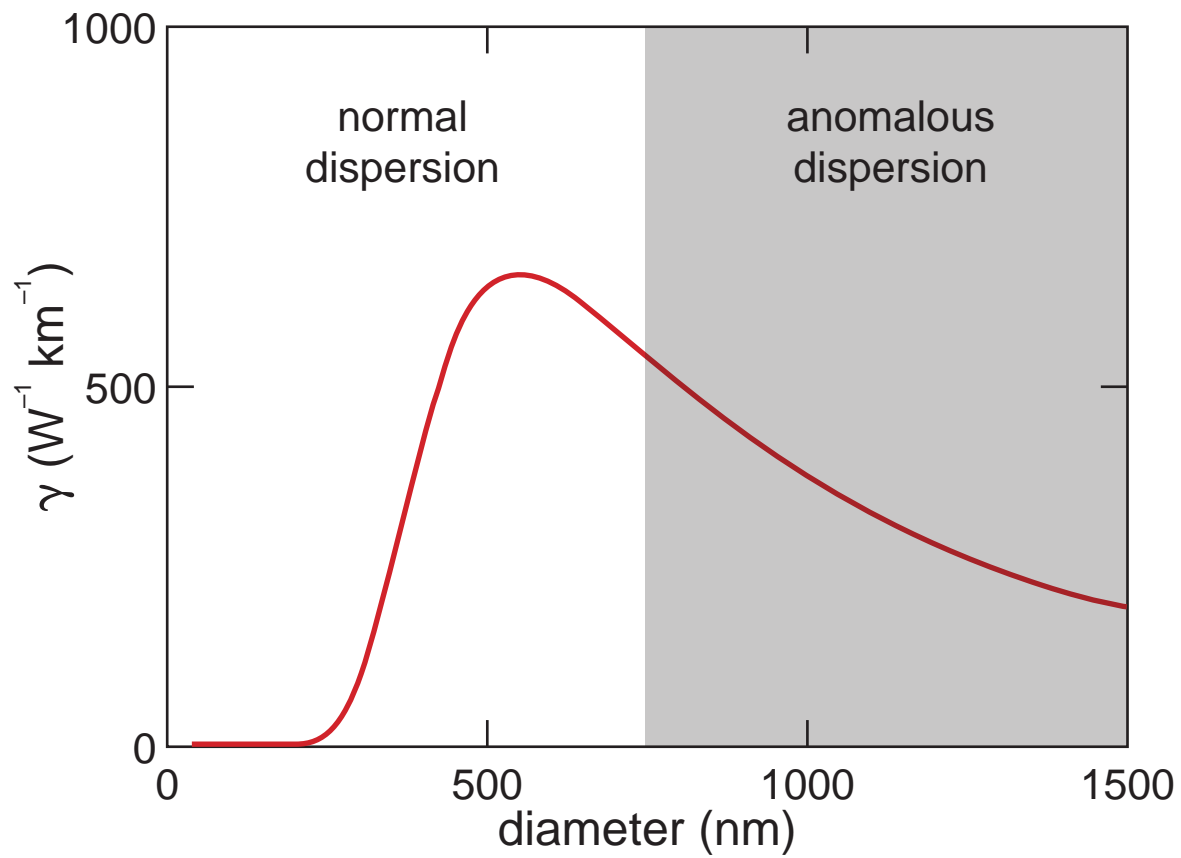
# Nanoscale nonlinear optics

## waveguide dispersion



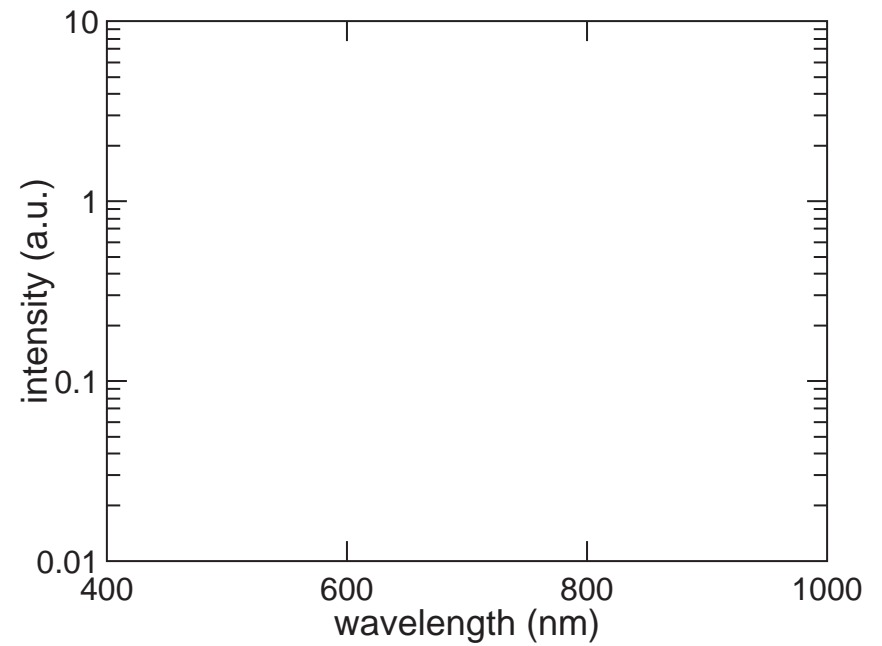
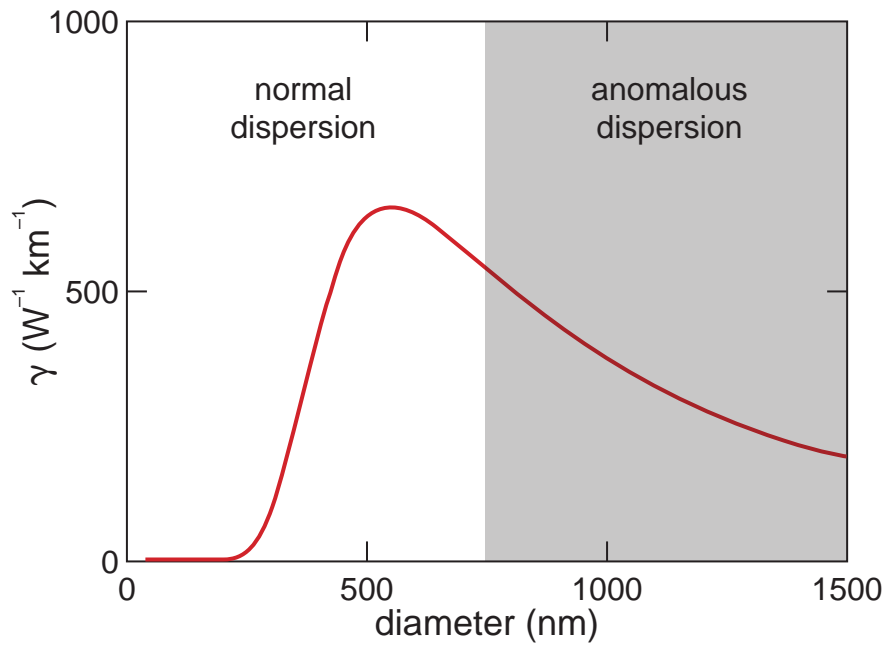
# Nanoscale nonlinear optics

nonlinear parameter



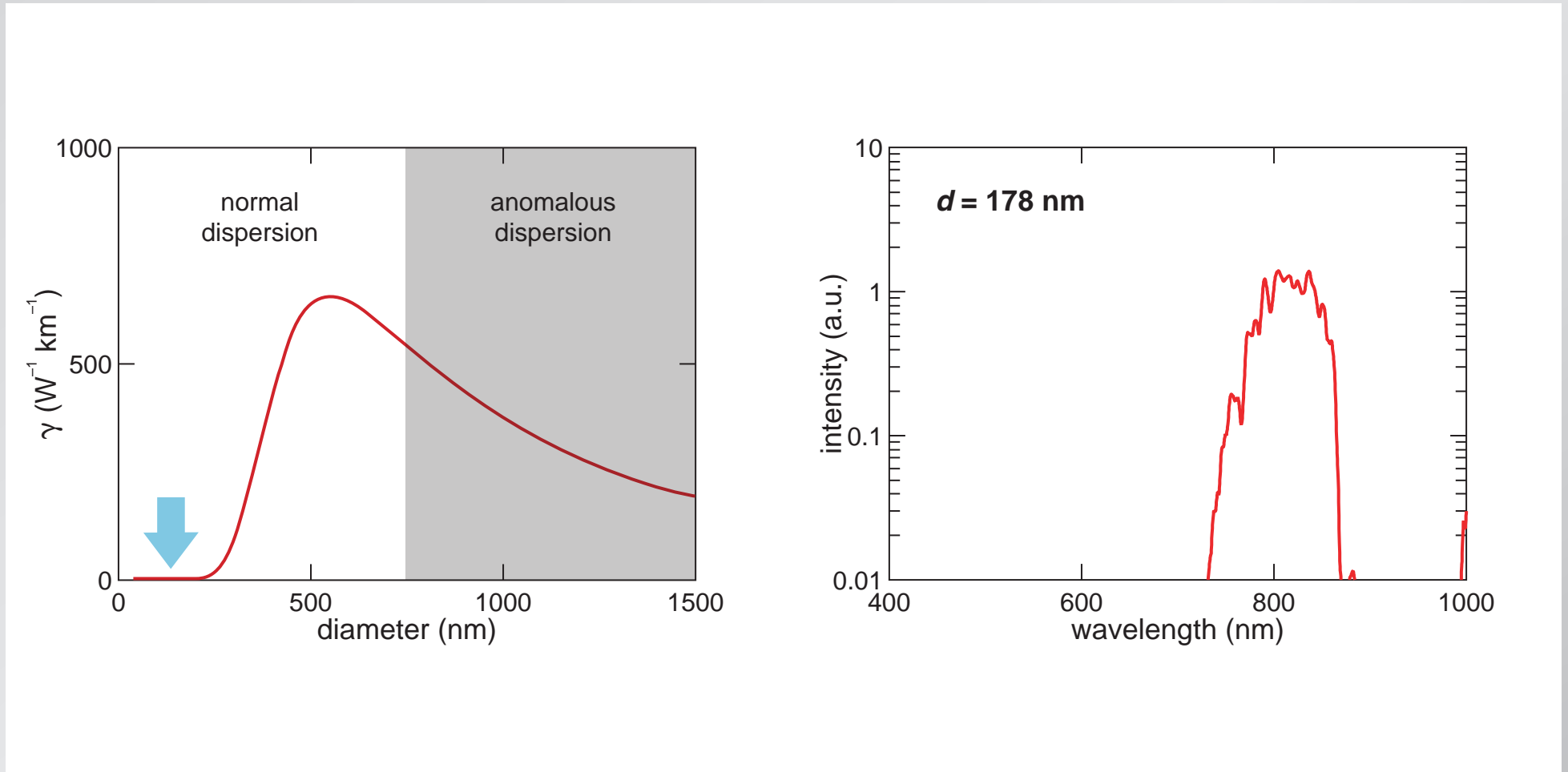
# Nanoscale nonlinear optics

## nanowire continuum generation



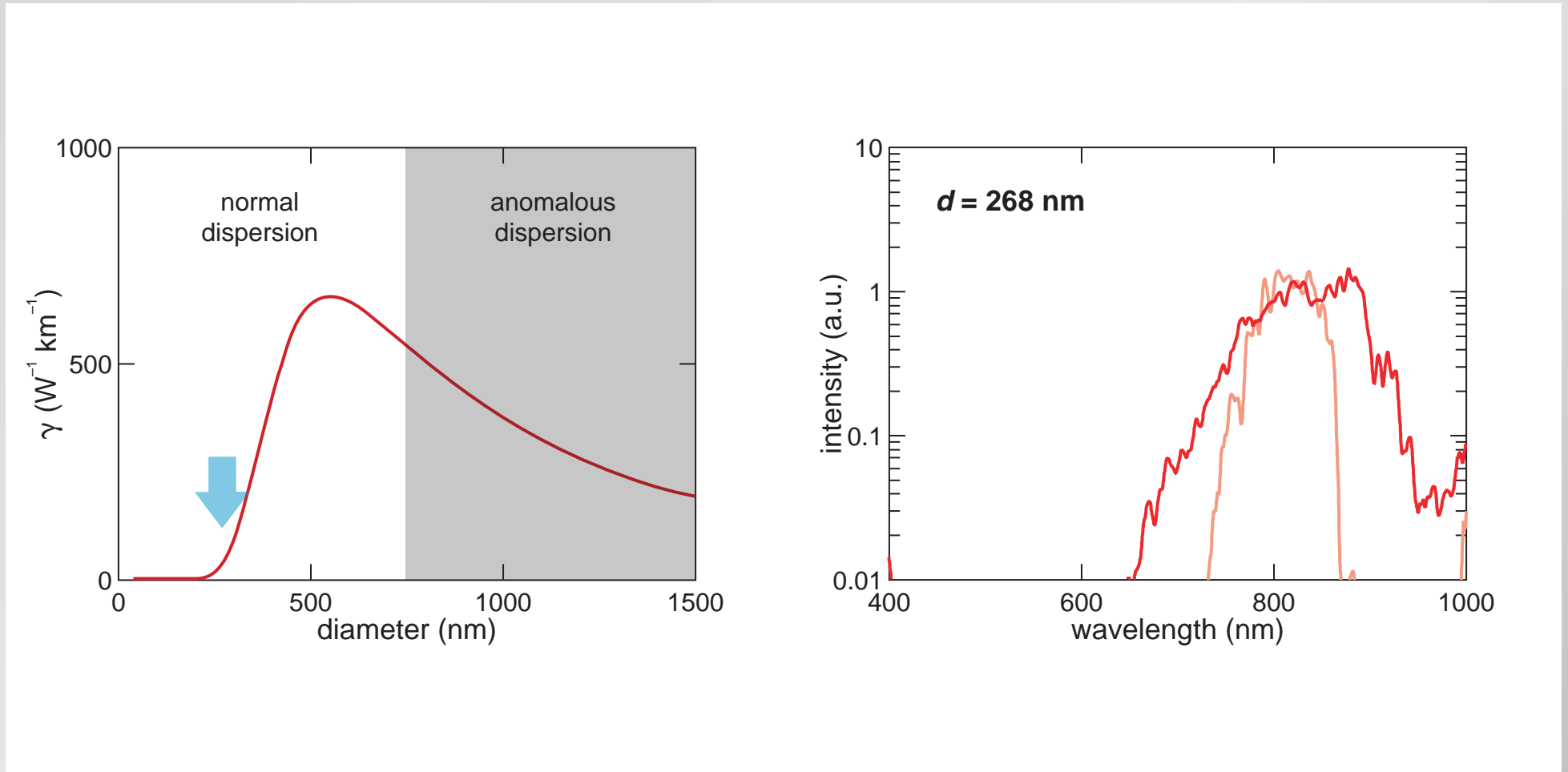
# Nanoscale nonlinear optics

## nanowire continuum generation



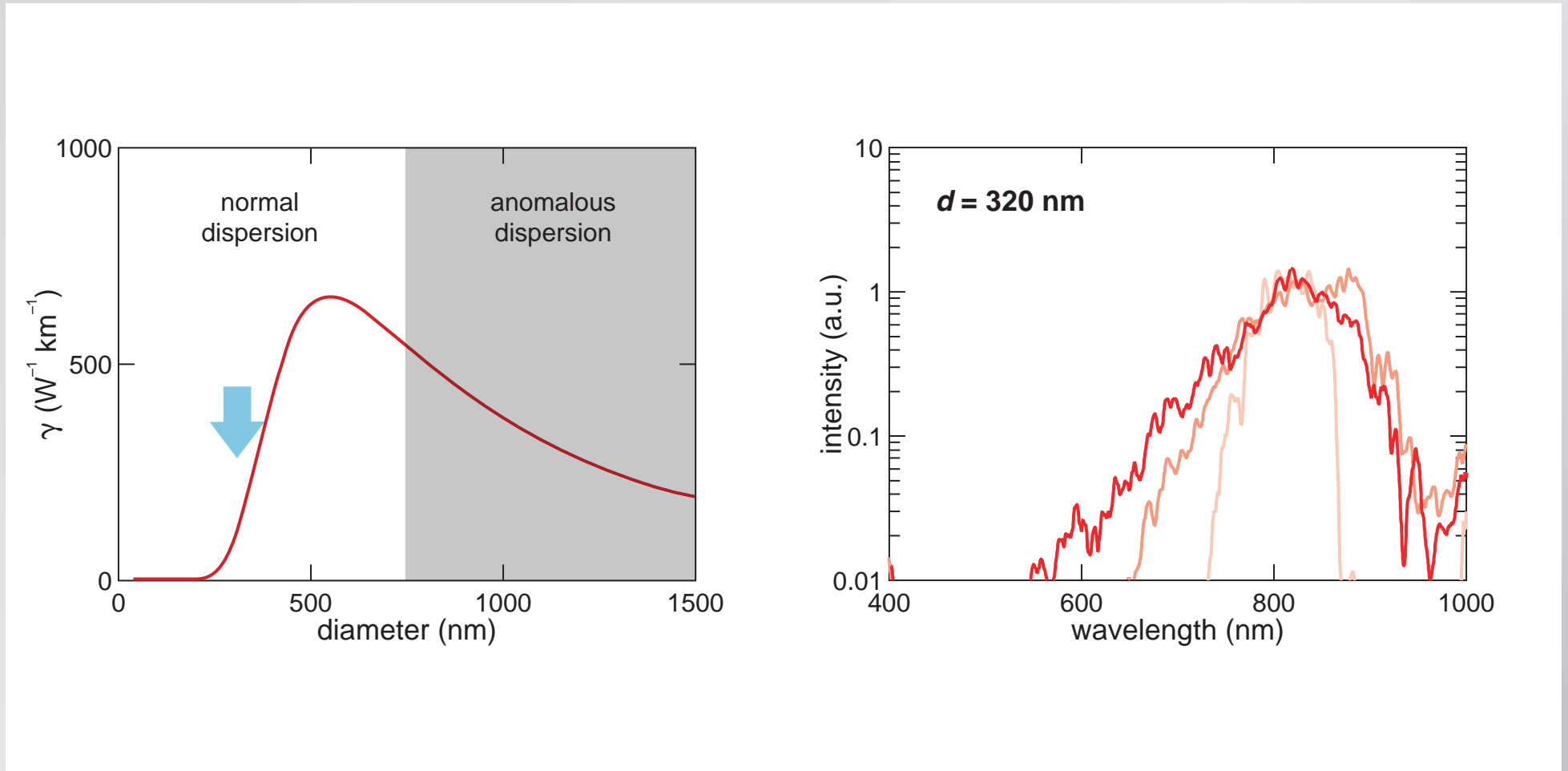
# Nanoscale nonlinear optics

## nanowire continuum generation



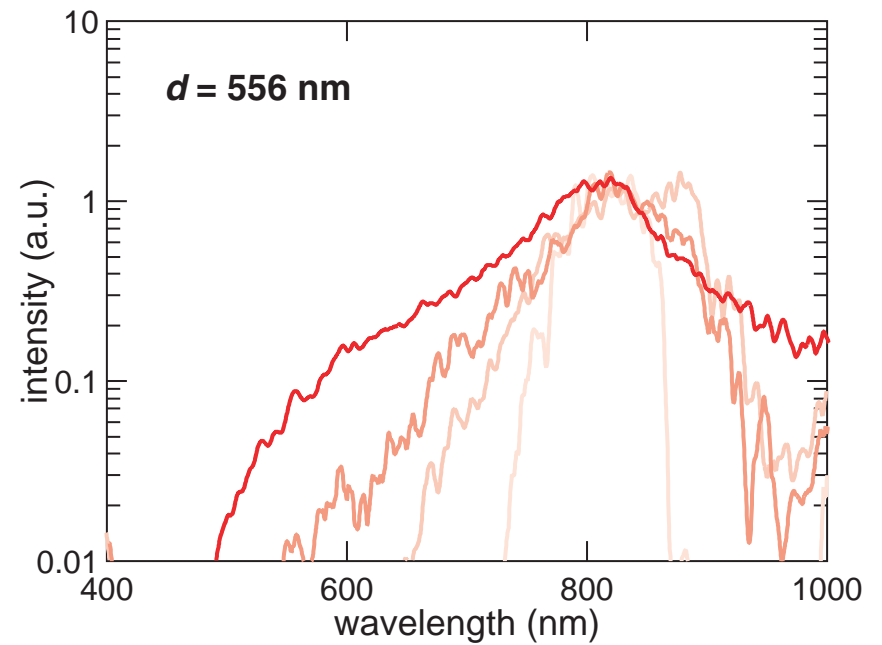
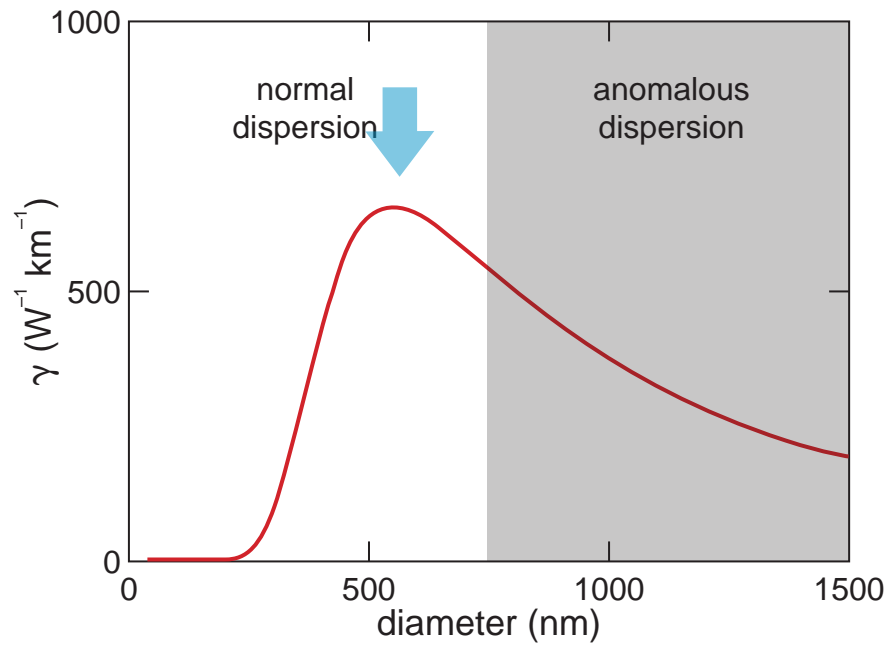
# Nanoscale nonlinear optics

## nanowire continuum generation



# Nanoscale nonlinear optics

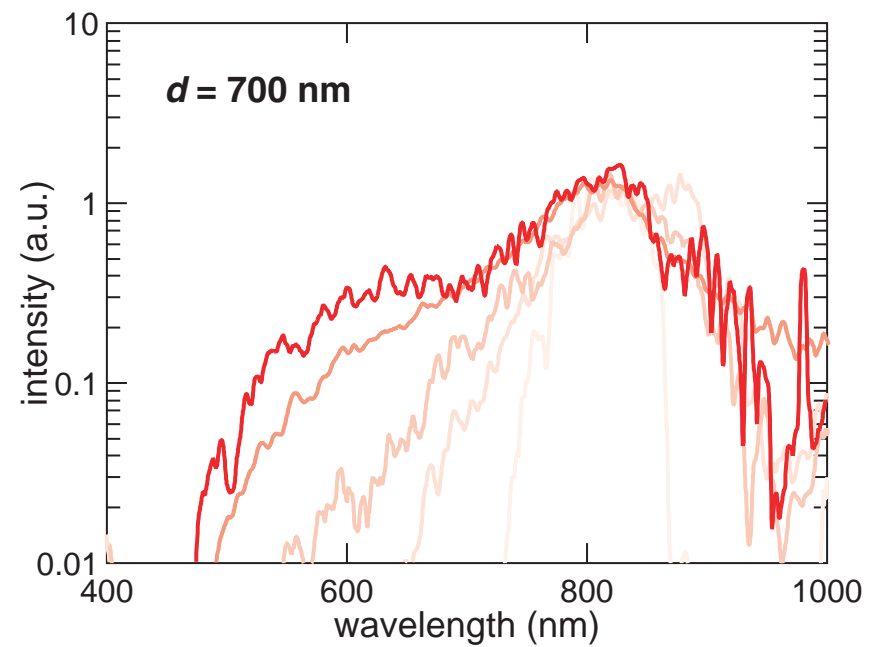
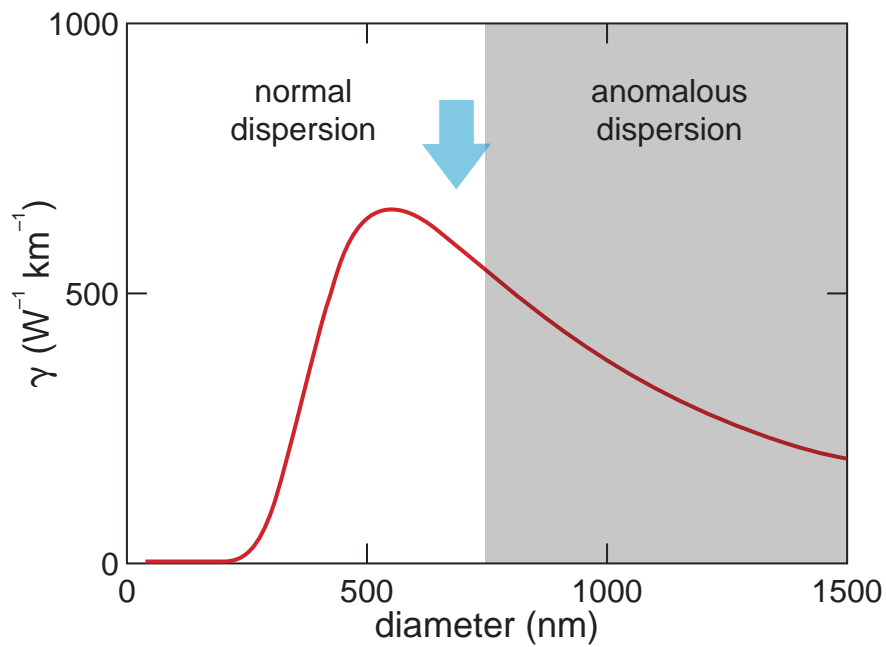
## nanowire continuum generation





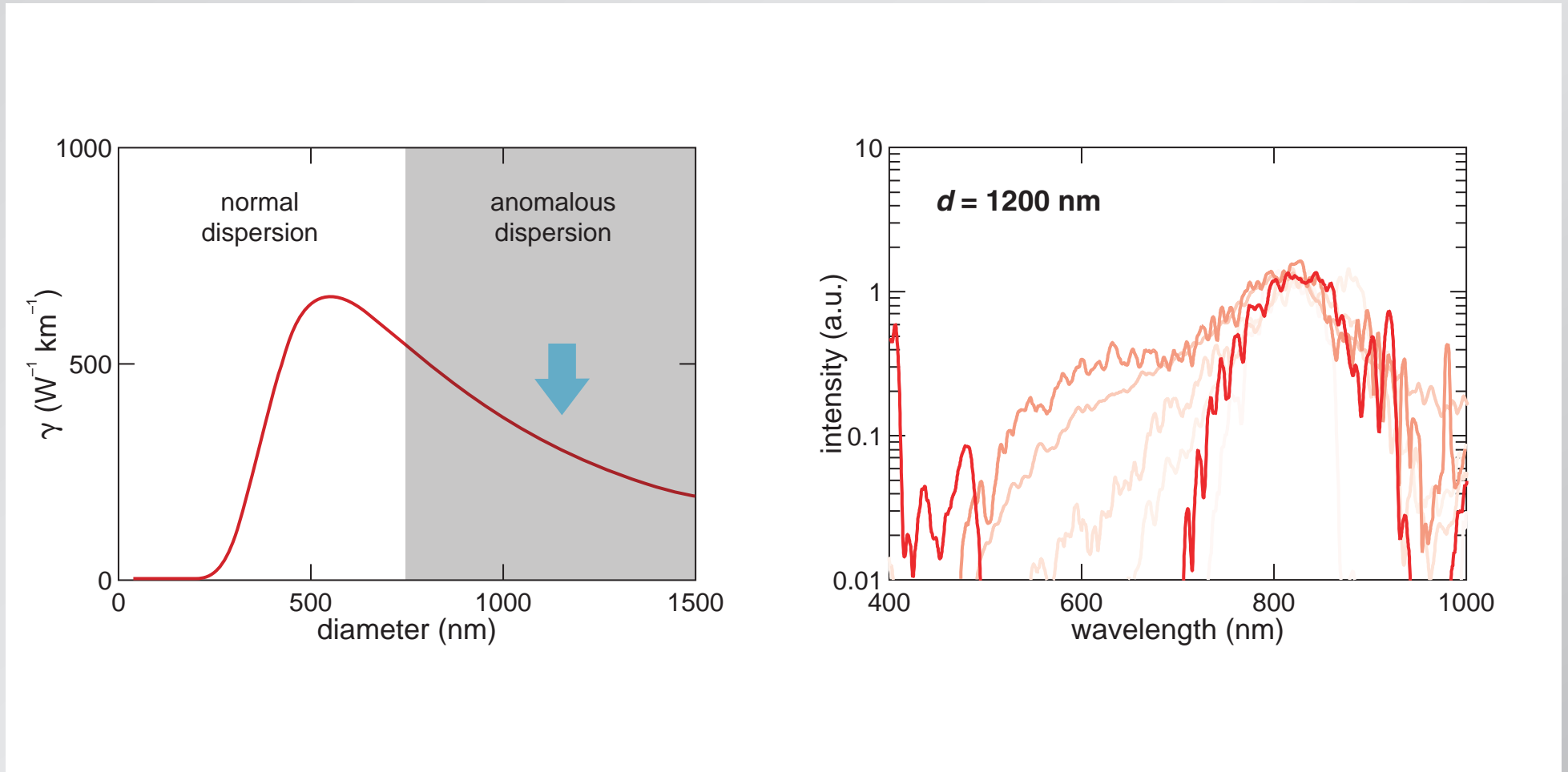
# Nanoscale nonlinear optics

## nanowire continuum generation



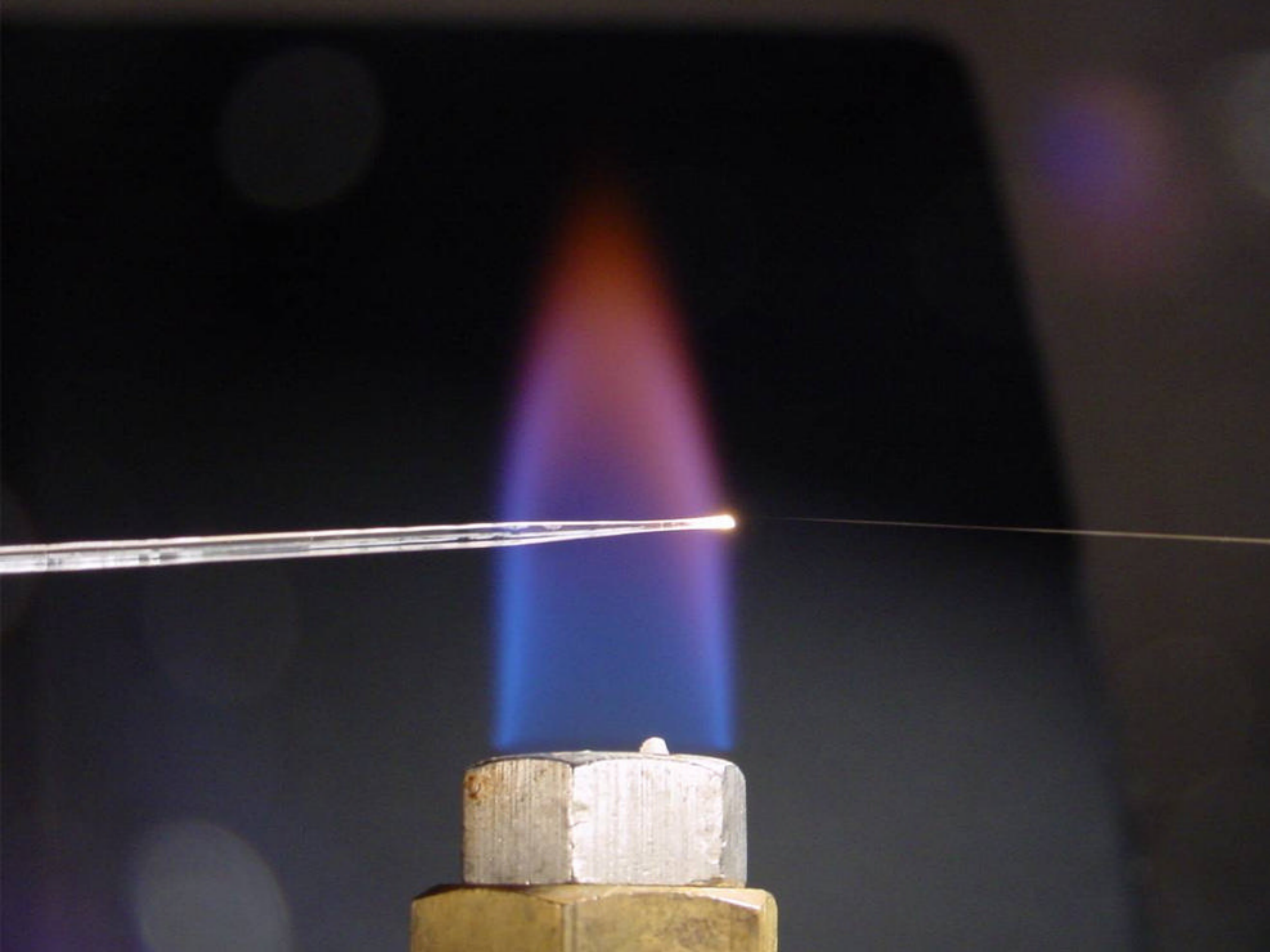
# Nanoscale nonlinear optics

## nanowire continuum generation

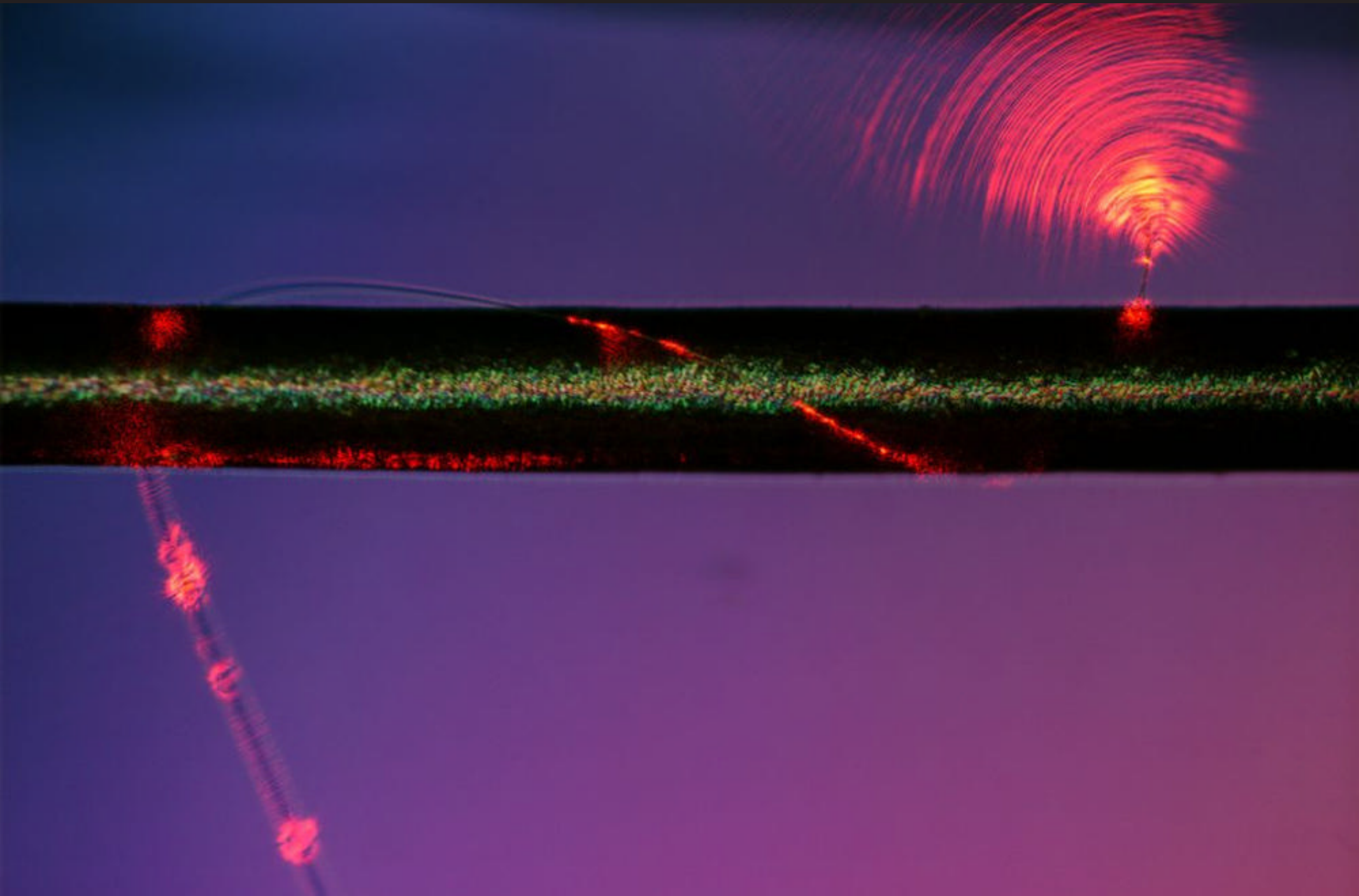


# Nanoscale nonlinear optics

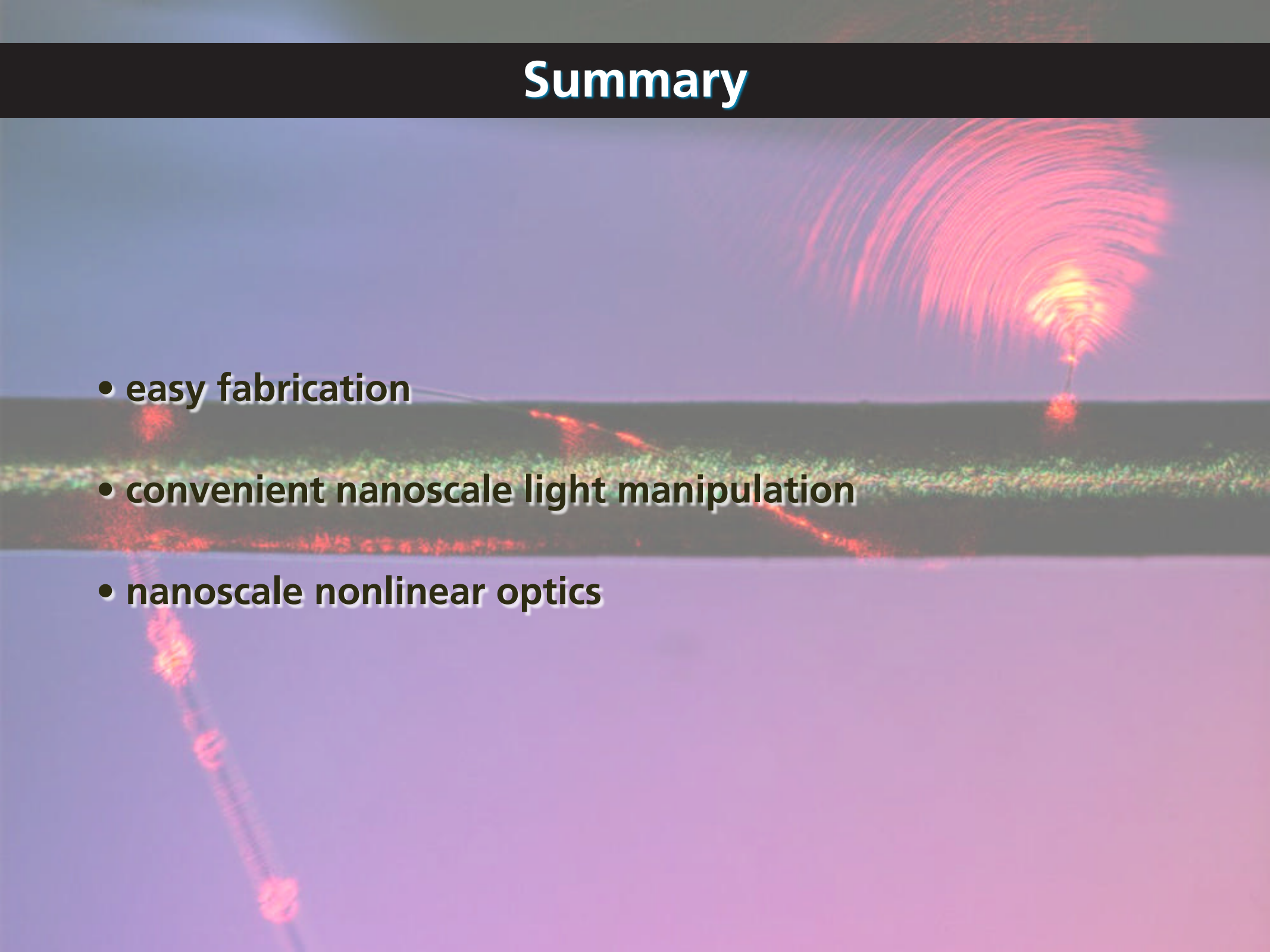
energy in nanowire  $< 100$  pJ!



# 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**

**for a copy of this presentation:**

**<http://mazur-www.harvard.edu>**



Google™

Google Search

I'm Feeling Lucky

Google™

mazur

Google Search

I'm Feeling Lucky

Google™

mazur

Google Search

I'm Feeling Lucky

# Google™

Google Search

I'm Feeling Lucky



**Funding:**

**Harvard Center for Imaging and Mesoscopic Structures**

**National Science Foundation**

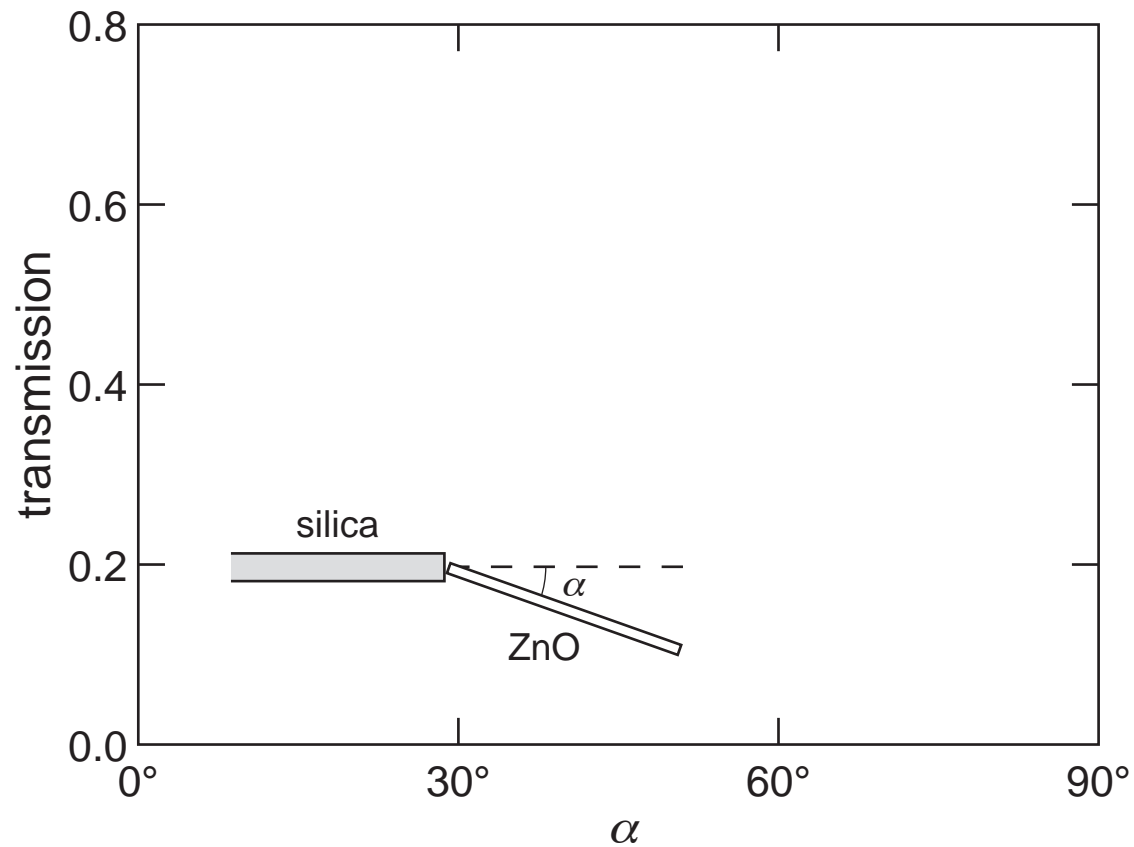
**National Natural Science Foundation of China**

**for a copy of this presentation:**

**<http://mazur-www.harvard.edu>**

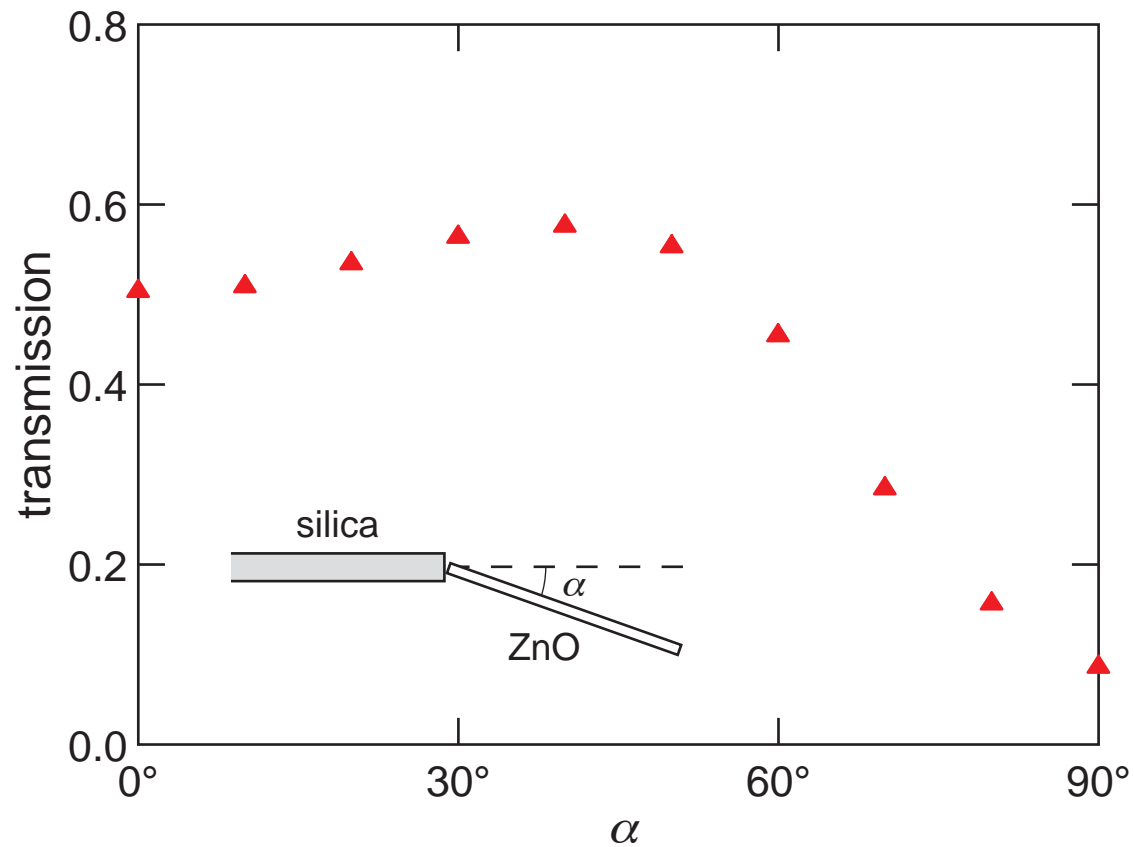
# Manipulating light at the nanoscale

## coupling efficiency



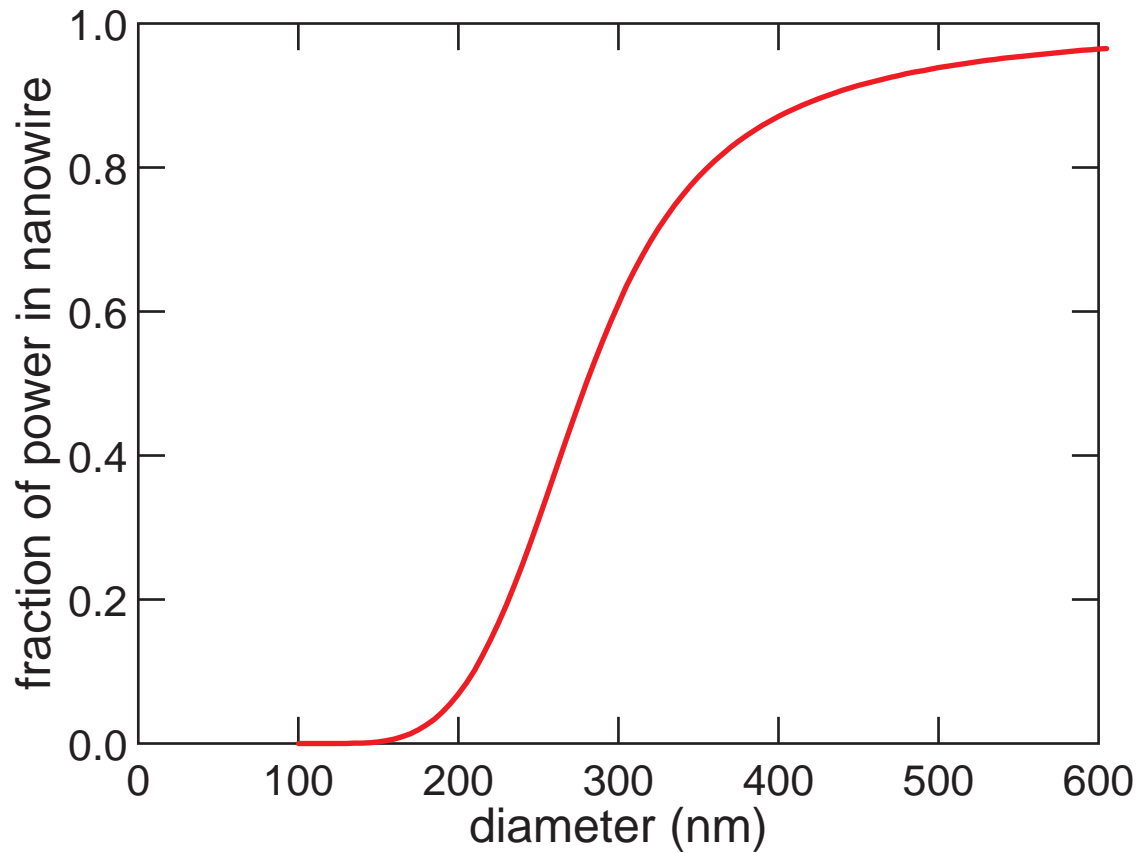
# Manipulating light at the nanoscale

## coupling efficiency



# Manipulating light at the nanoscale

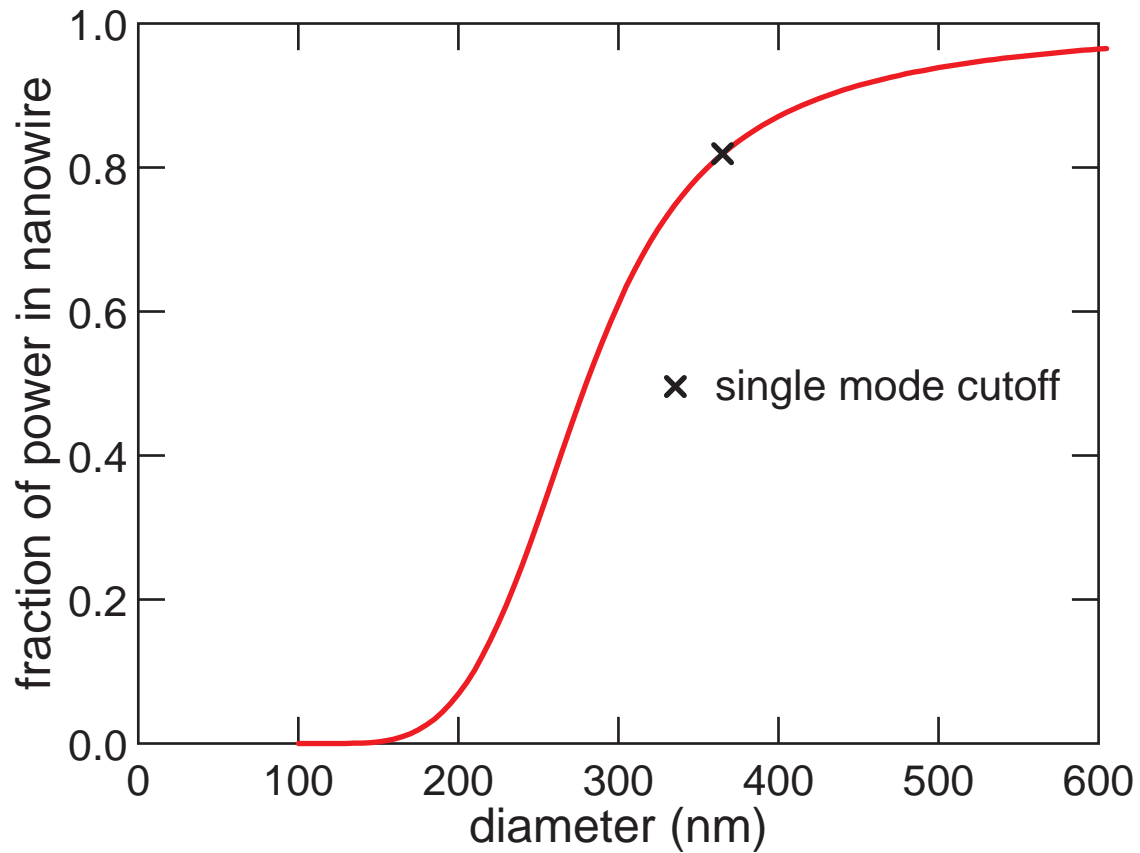
## single-mode cutoff





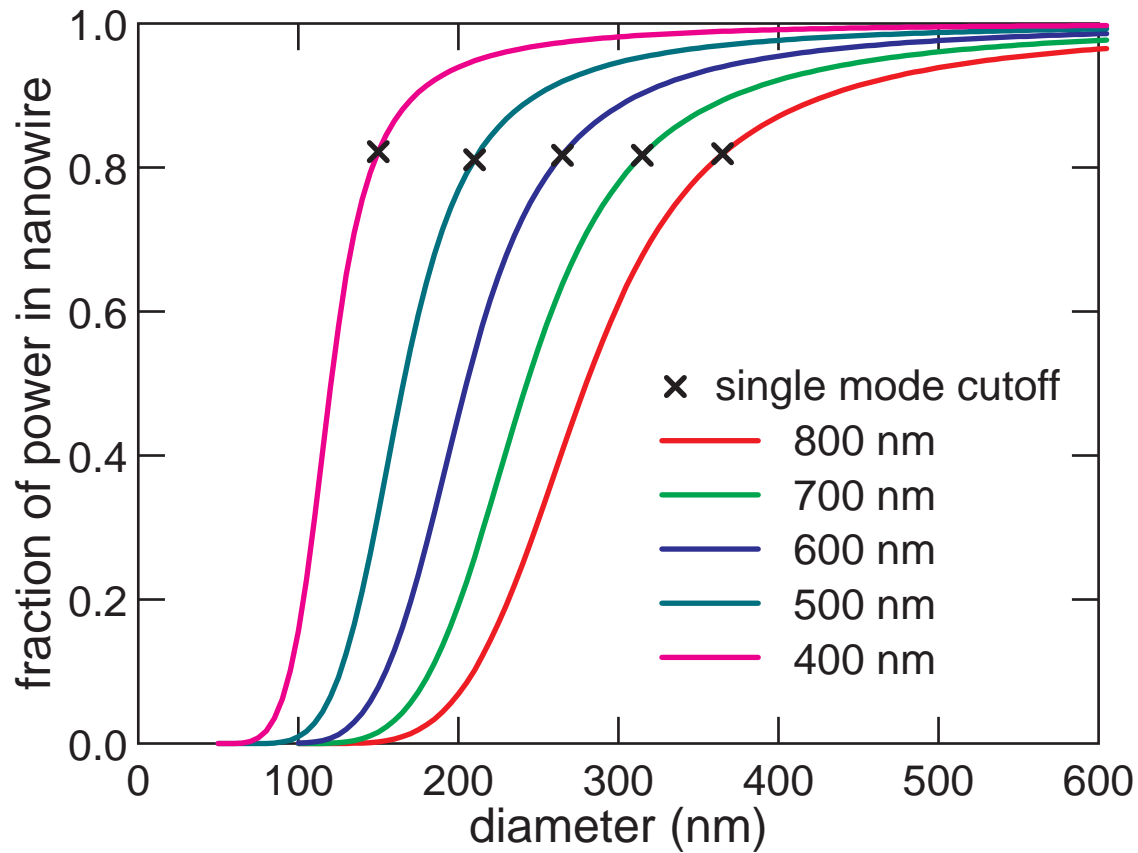
# Manipulating light at the nanoscale

## single-mode cutoff



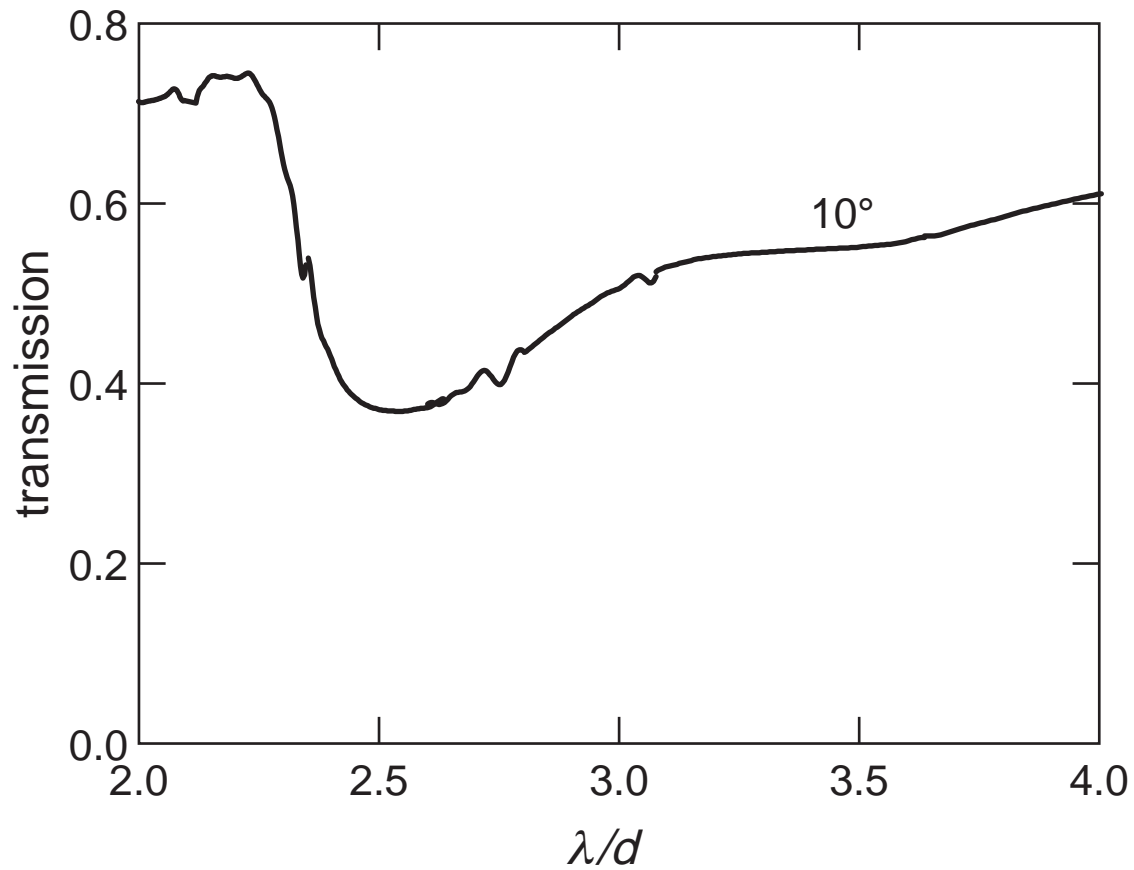
# Manipulating light at the nanoscale

## single-mode cutoff



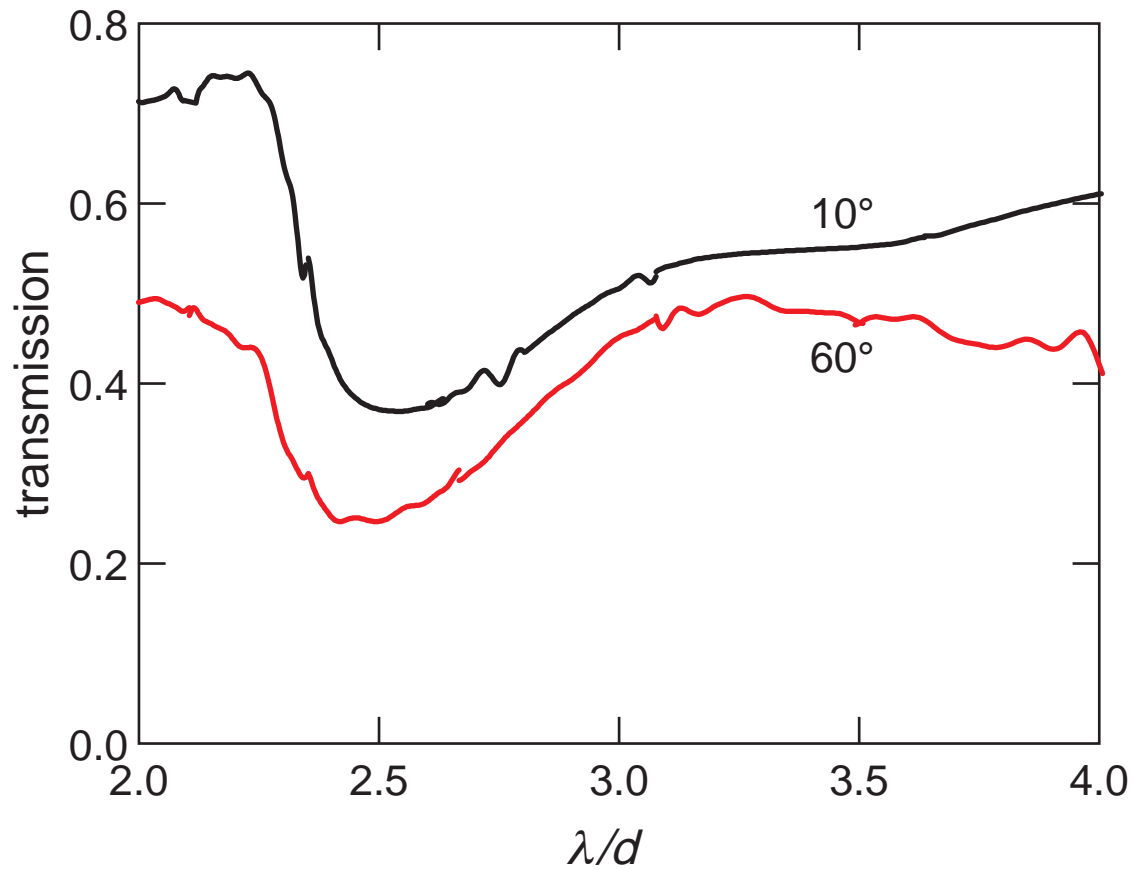
# Manipulating light at the nanoscale

## transmission spectrum



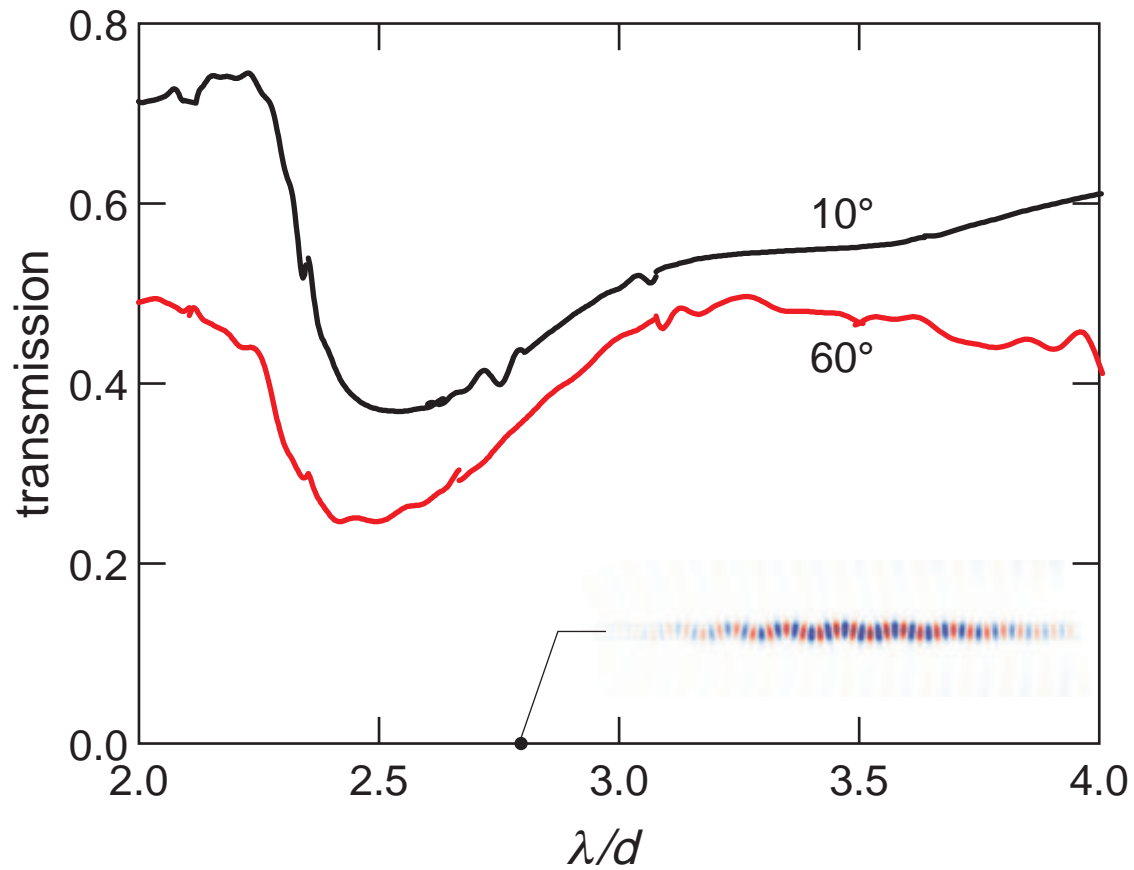
# Manipulating light at the nanoscale

## transmission spectrum



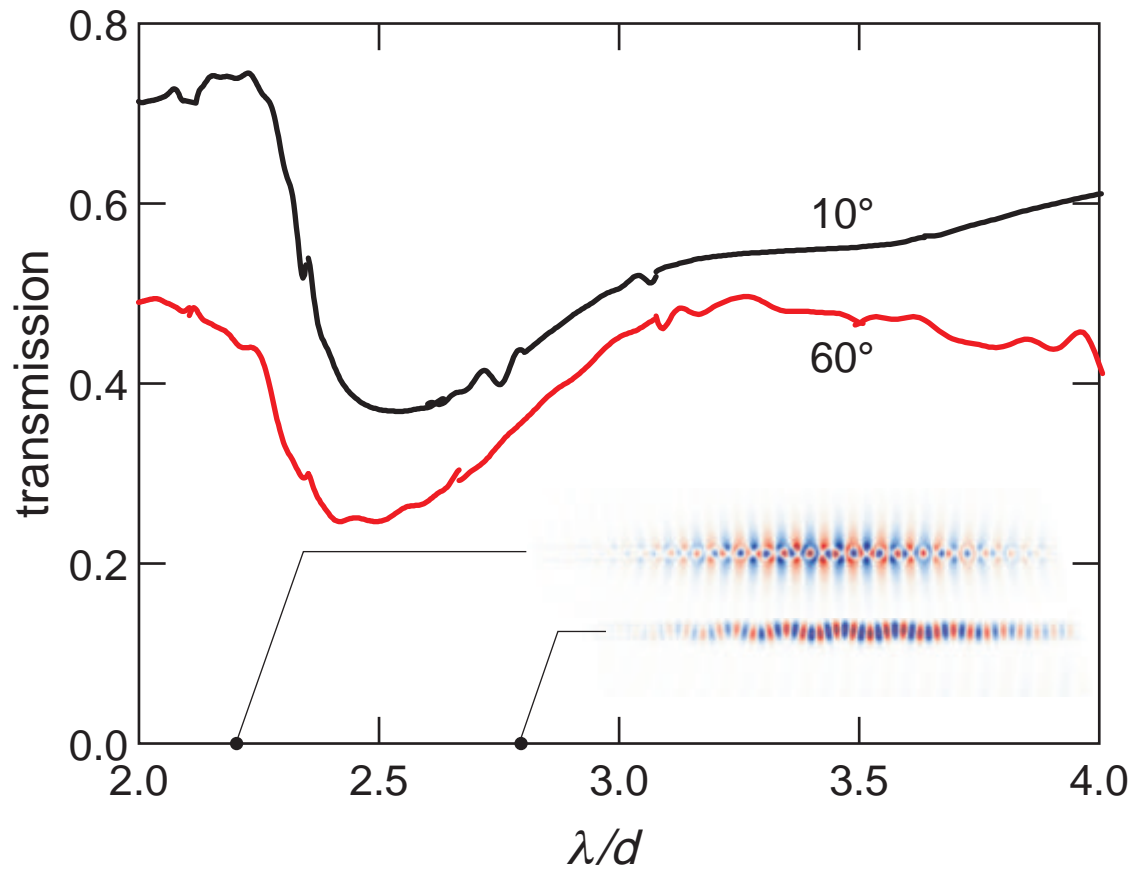
# Manipulating light at the nanoscale

## transmission spectrum



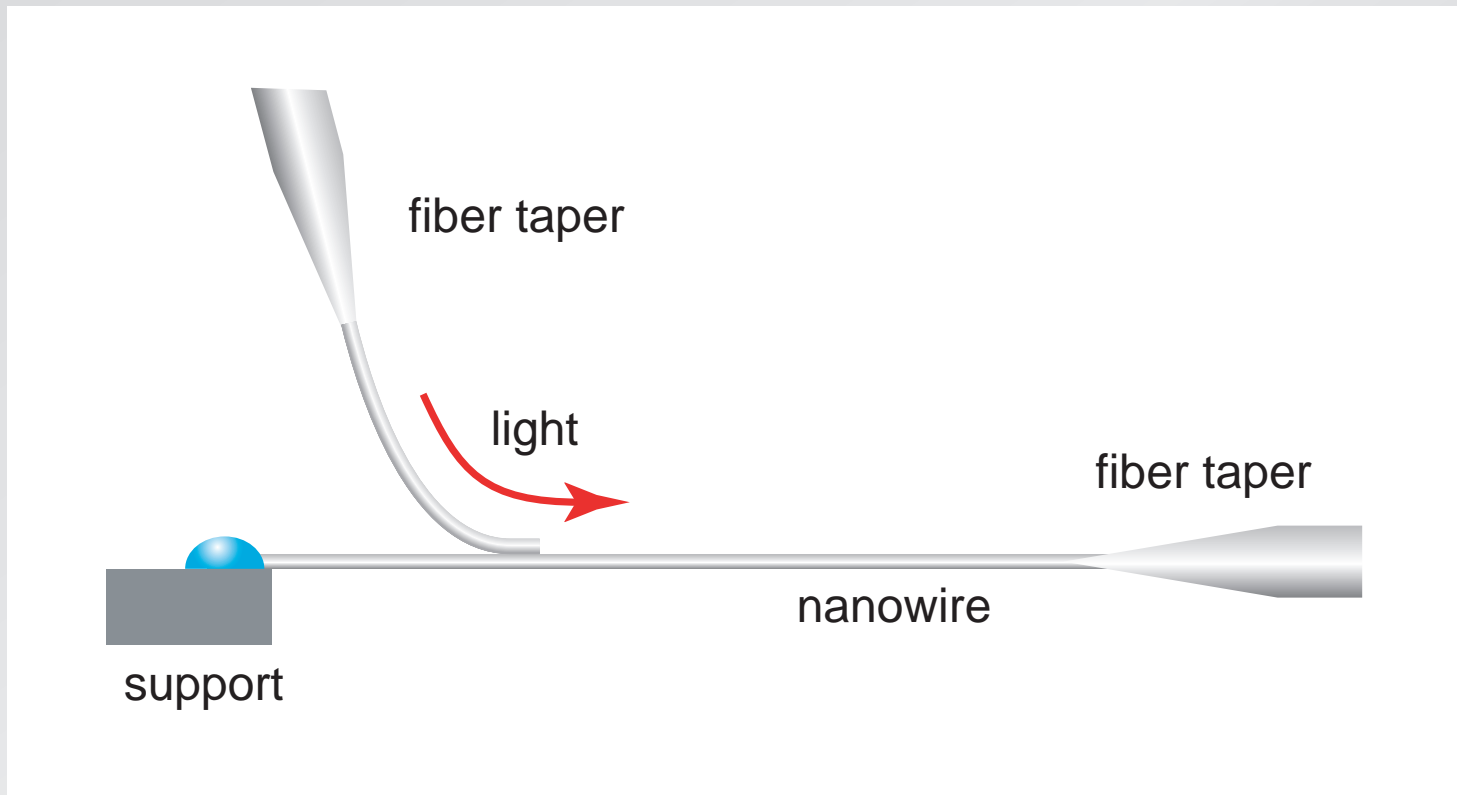
# Manipulating light at the nanoscale

## transmission spectrum



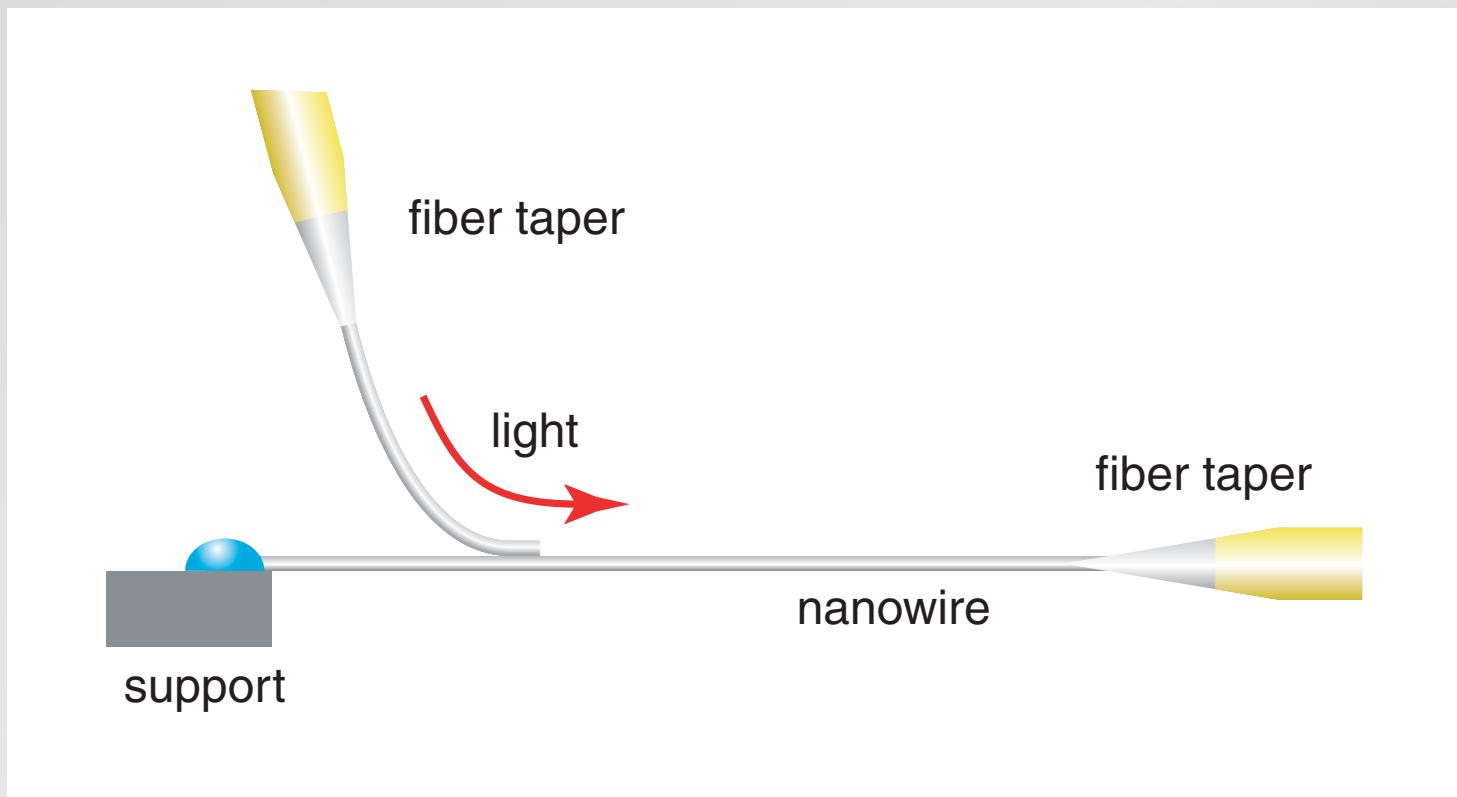
# Manipulating light at the nanoscale

## loss measurement



# Manipulating light at the nanoscale

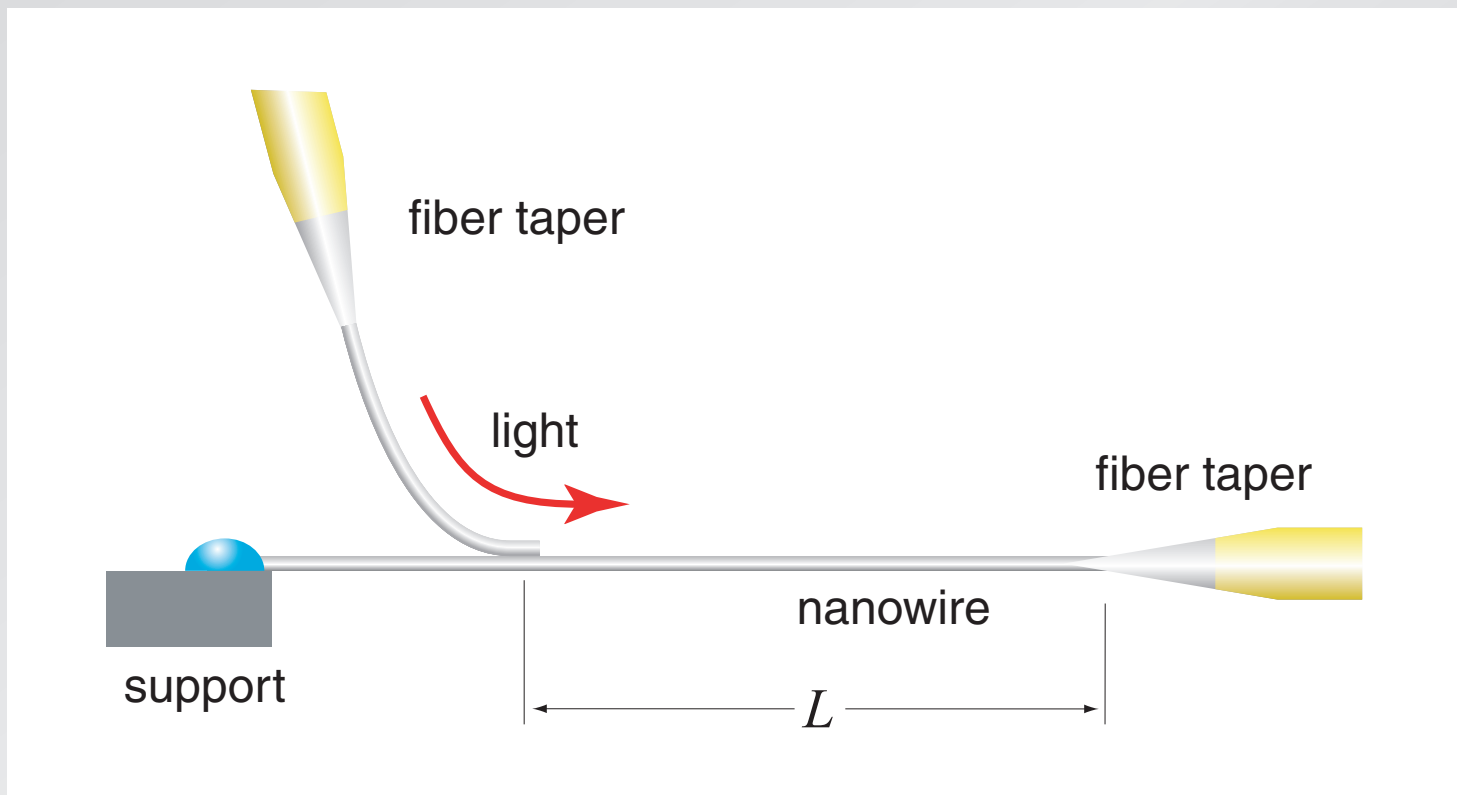
## loss measurement





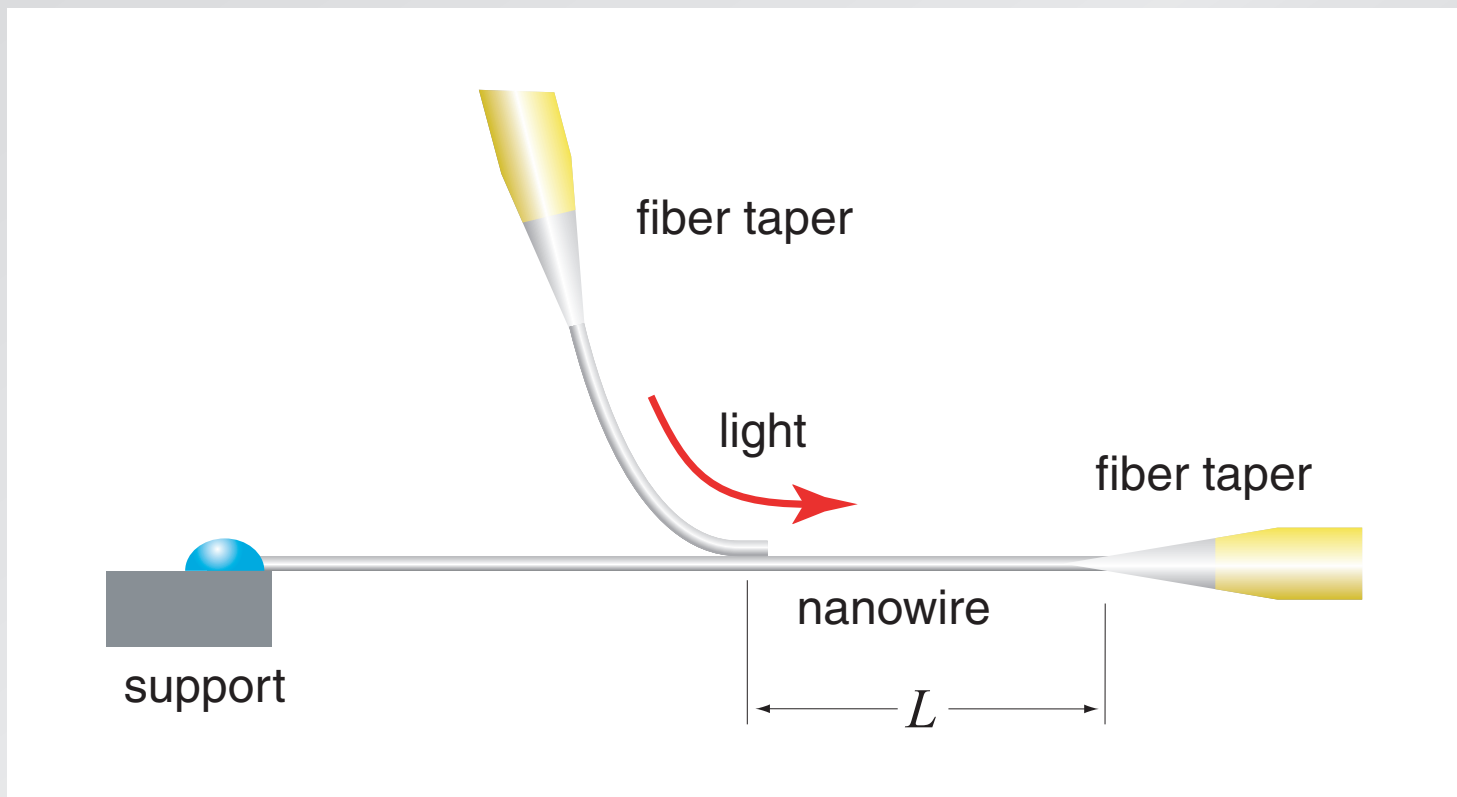
# Manipulating light at the nanoscale

## loss measurement



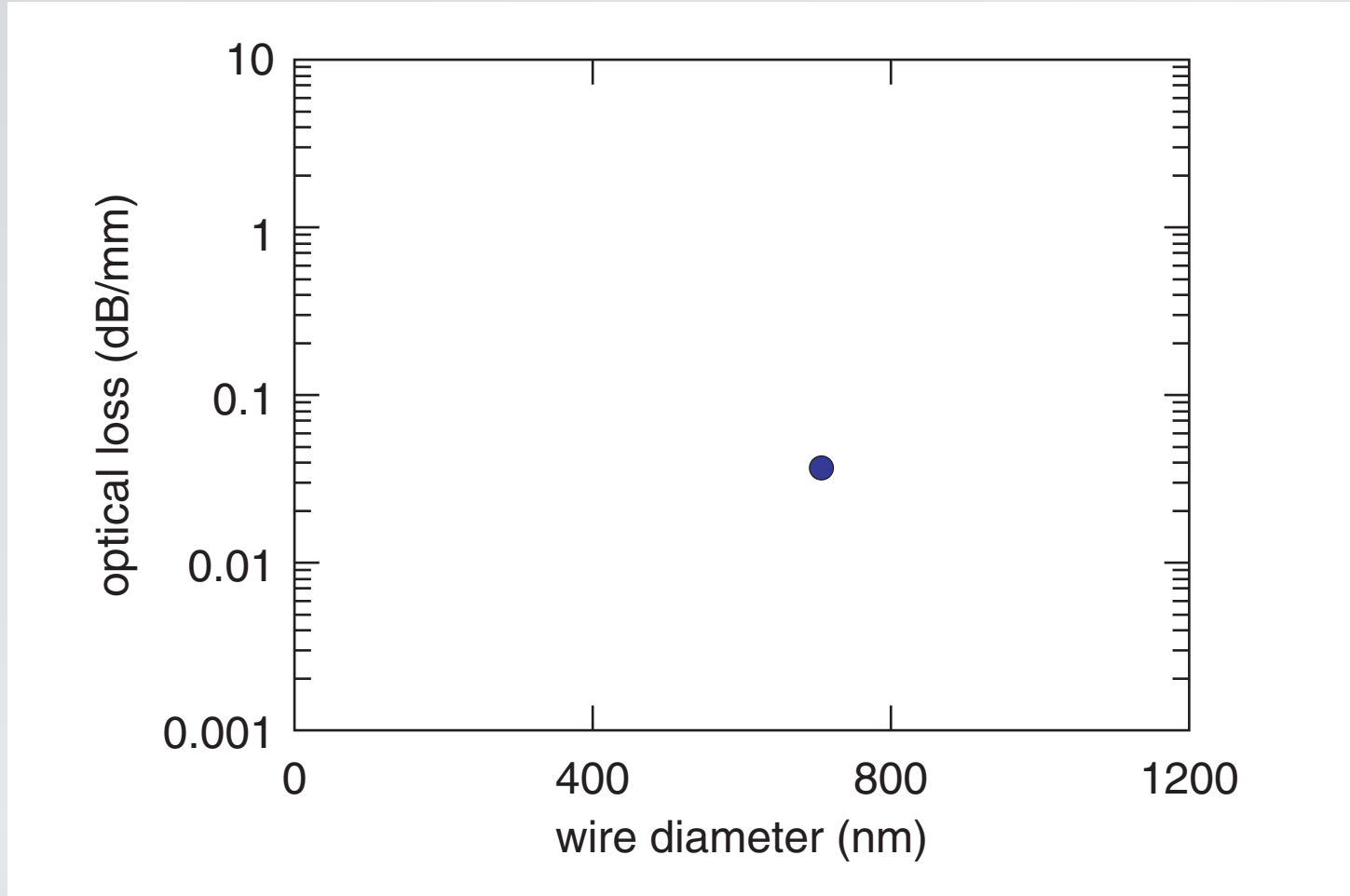
# Manipulating light at the nanoscale

## loss measurement



# Manipulating light at the nanoscale

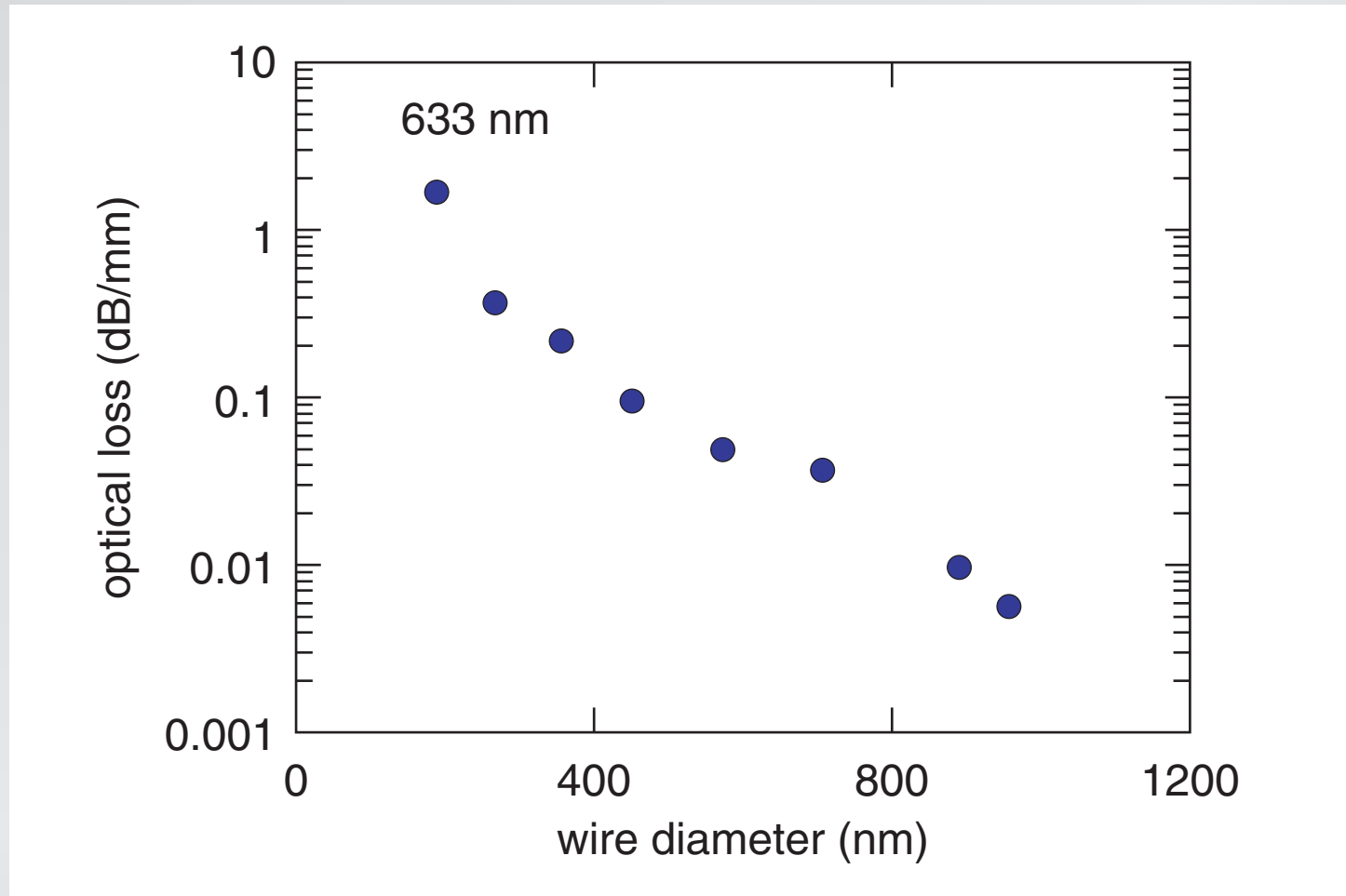
## loss measurement



*Nature*, 426, 816 (2003)

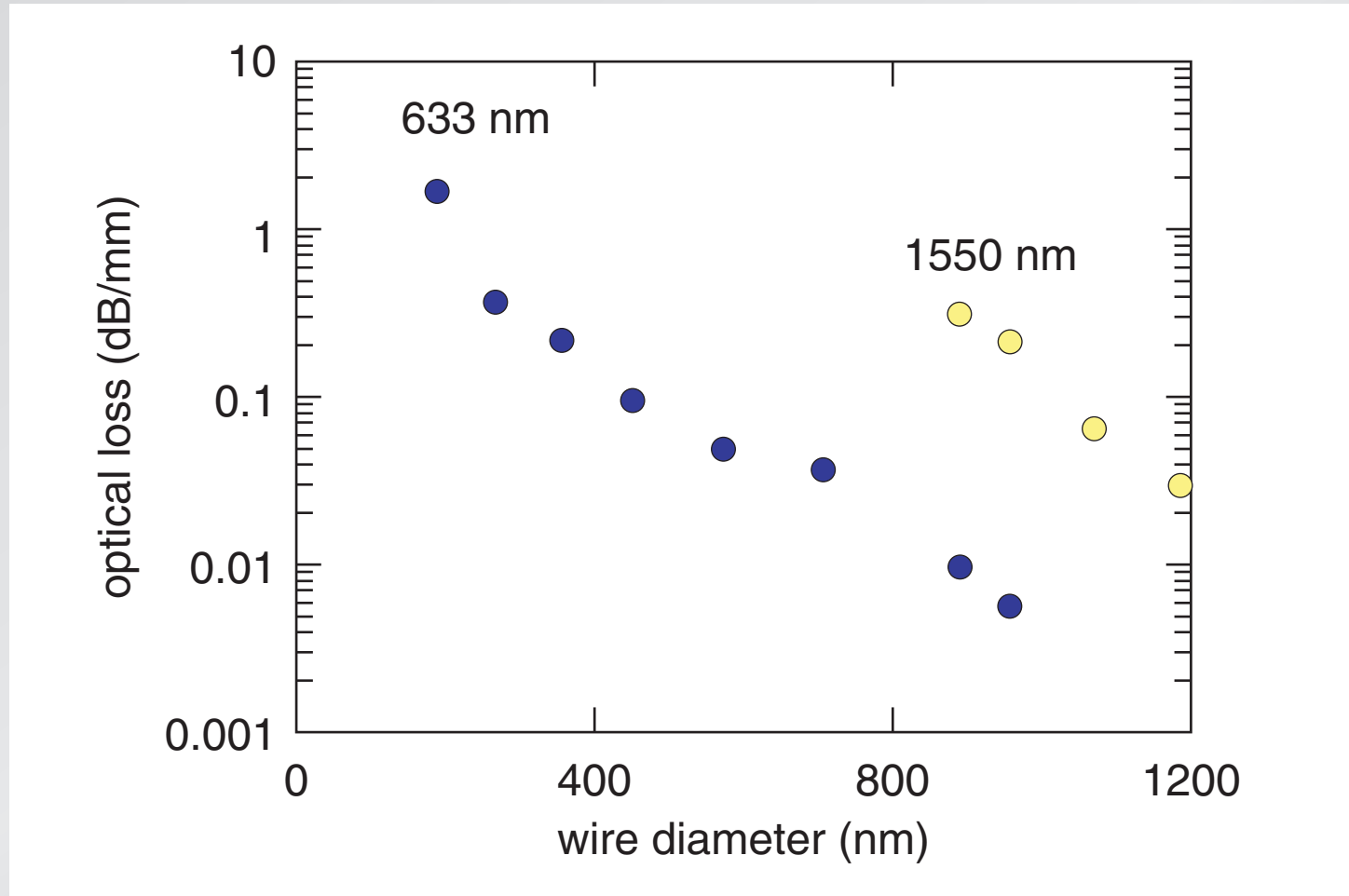
# Manipulating light at the nanoscale

## loss measurement



# Manipulating light at the nanoscale

## loss measurement



# Manipulating light at the nanoscale

loss at single-mode diameter  $< 0.1$  dB/mm

