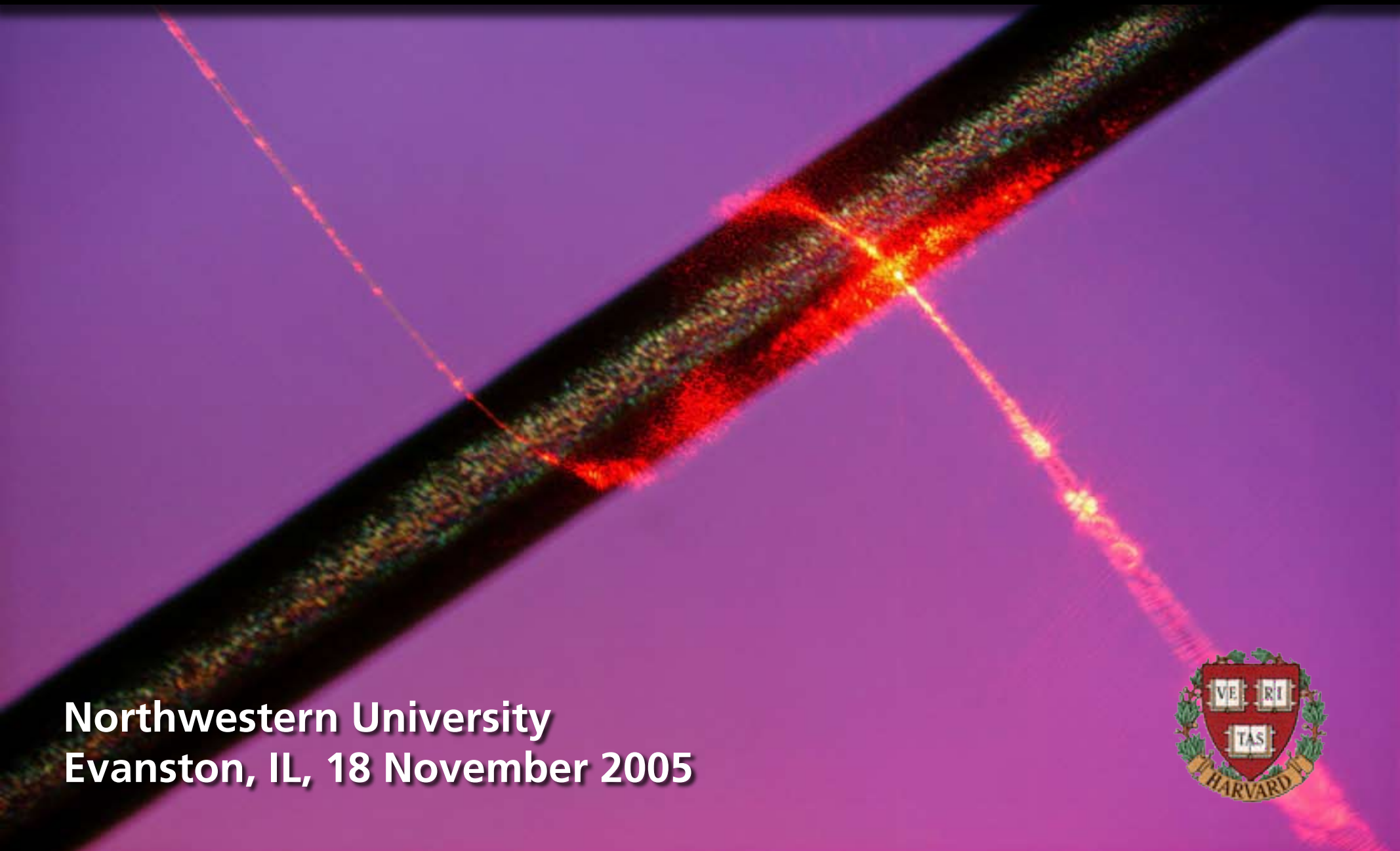
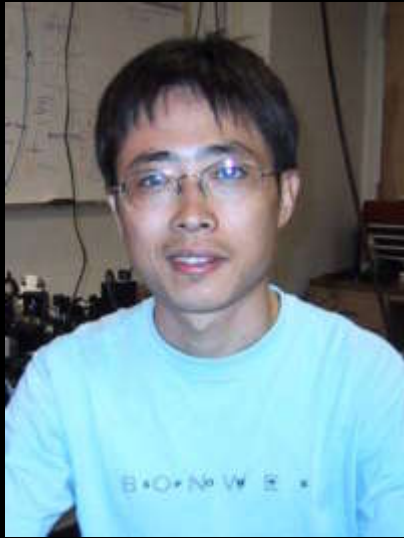


Wrapping light around a hair



Northwestern University
Evanston, IL, 18 November 2005





Limin Tong



Rafael Gattass



Geoff Svacha



Tommaso Baldacchini

and also....

at Harvard:

Jonathan Aschom

Mengyan Shen

Iva Maxwell

James Carey

Brian Tull

Dr. Yuan Lu

Dr. Richard Schalek

Prof. Federico Capasso

Prof. Cynthia Friend

and elsewhere:

Xuwen Chen (Zhejiang University)

Zhanghua Han (Zhejiang University)

Dr. Sailing He (Zhejiang University)

Prof. Igor Khrushev (Aston University)

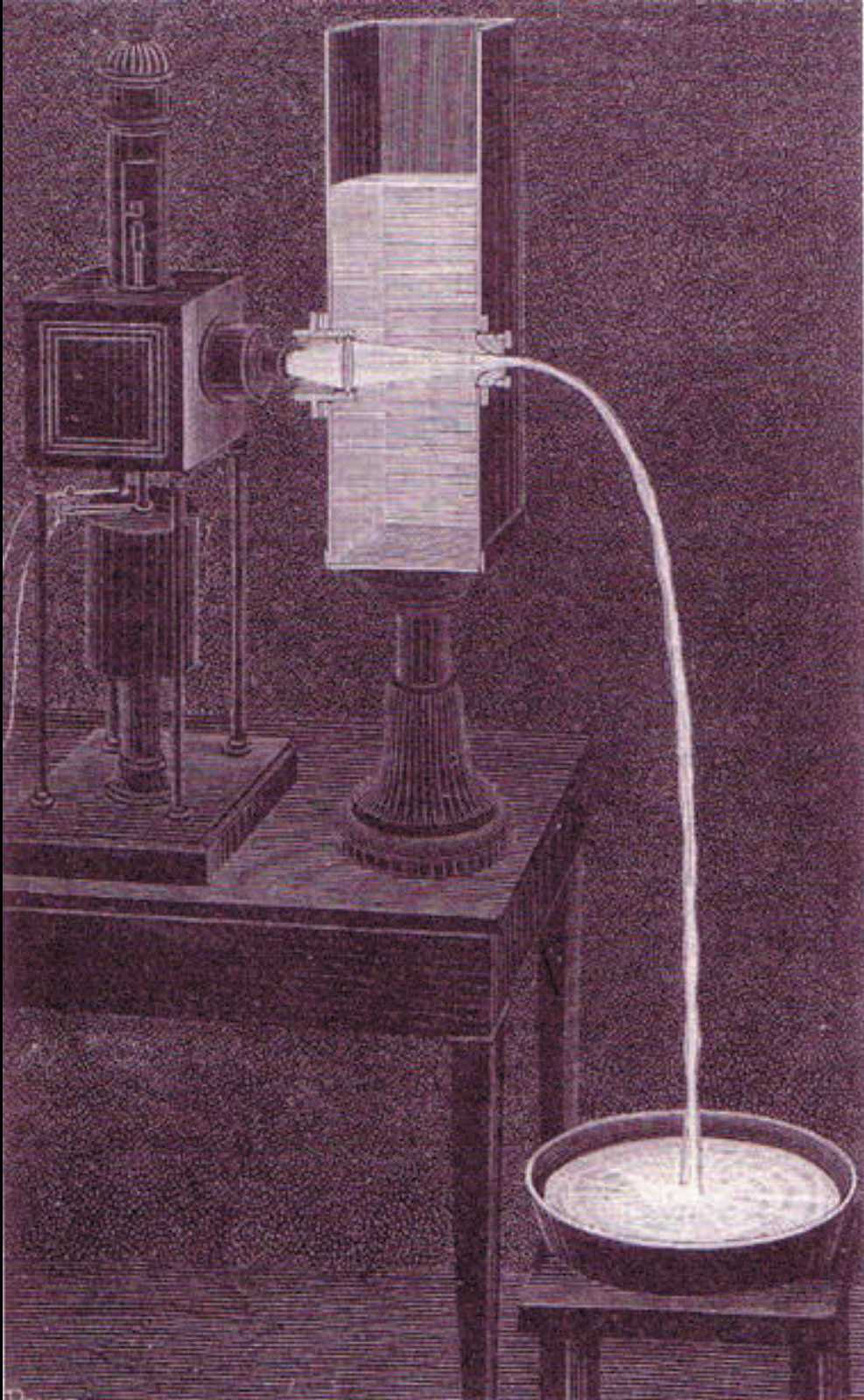
Dr. Jingyi Lou (Zhejiang University)

Dr. Ray Mariella (LLNL)

Liu Liu (Zhejiang University)

“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.

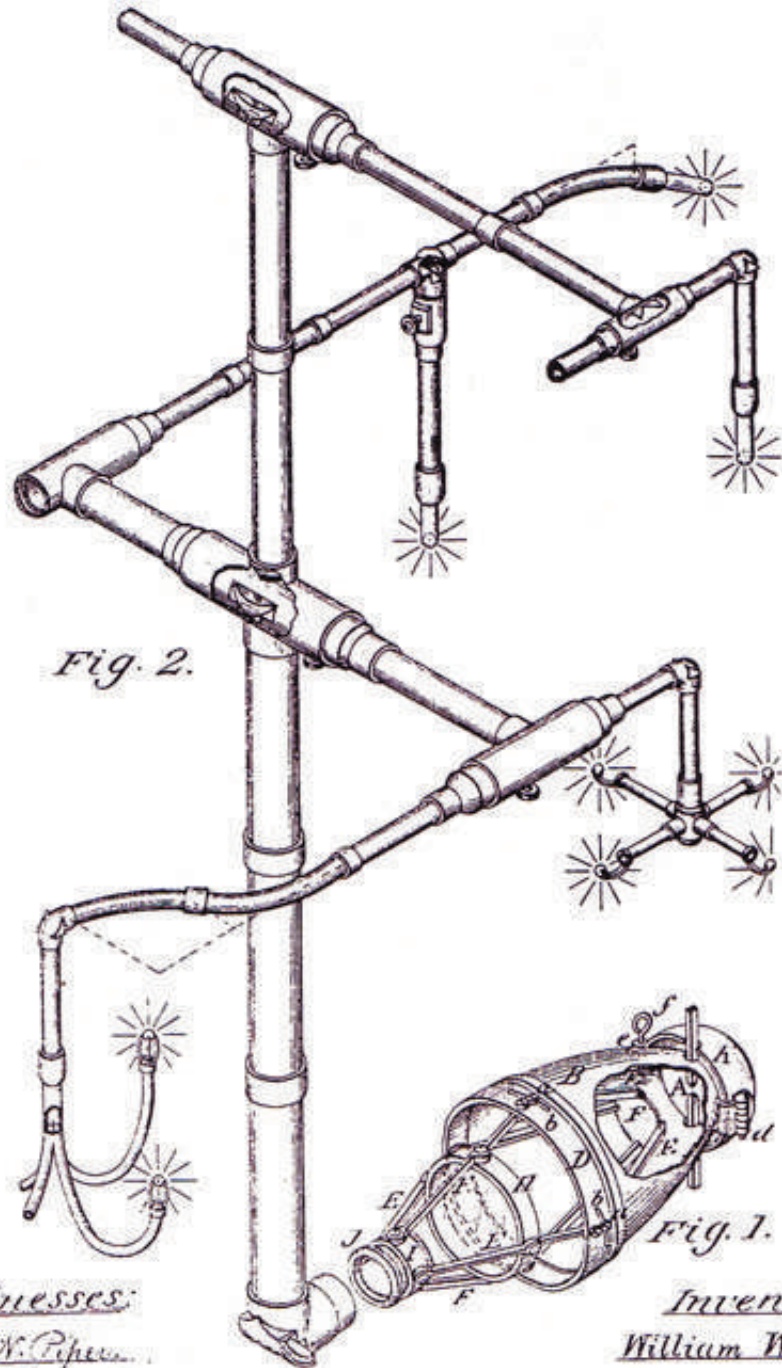


Fig. 2.

Fig. 1.

Witnesses:
J. N. Piper
E. L. [unclear]

Inventor:
William Wheeler
 by attorney
[unclear]

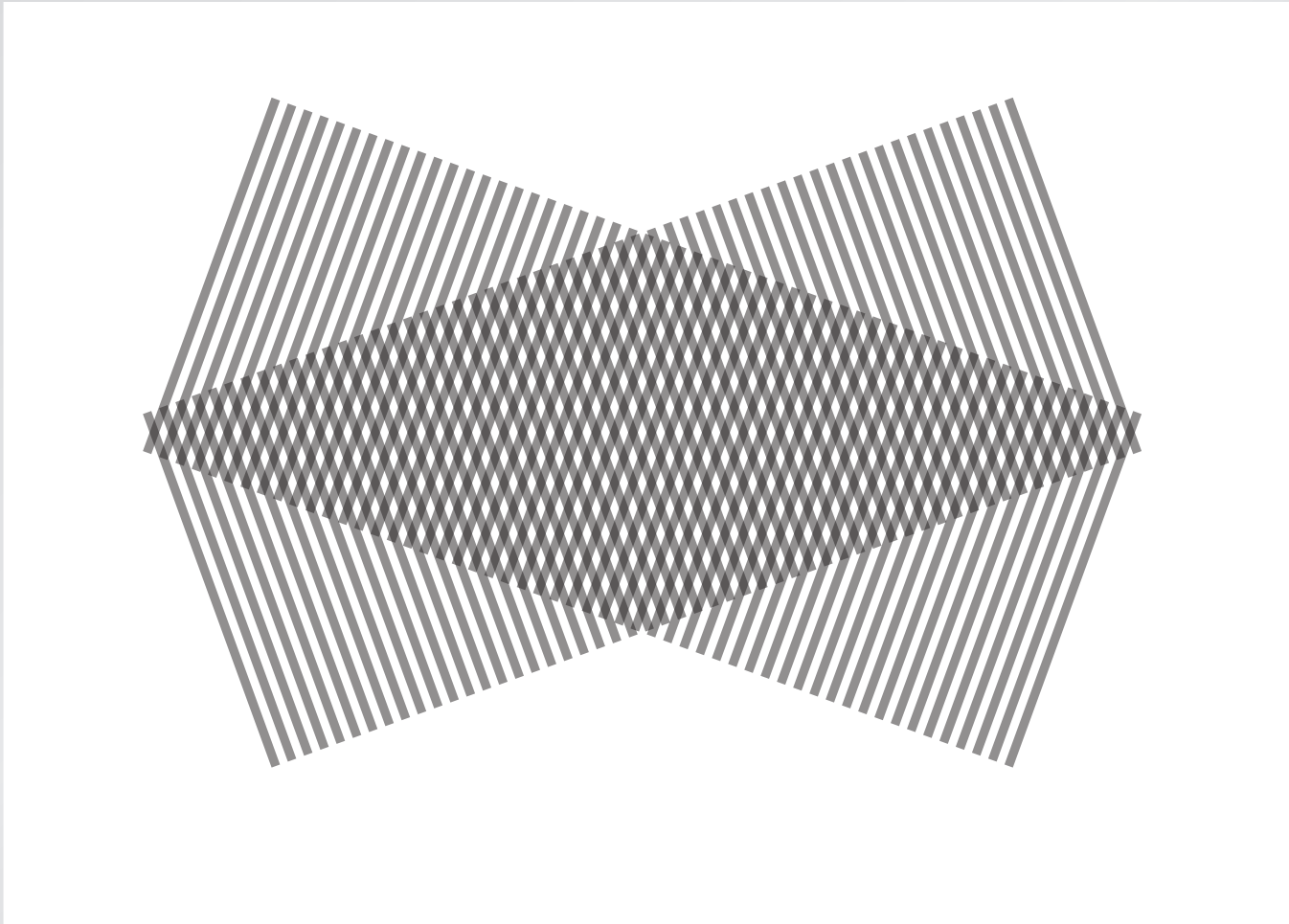
US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

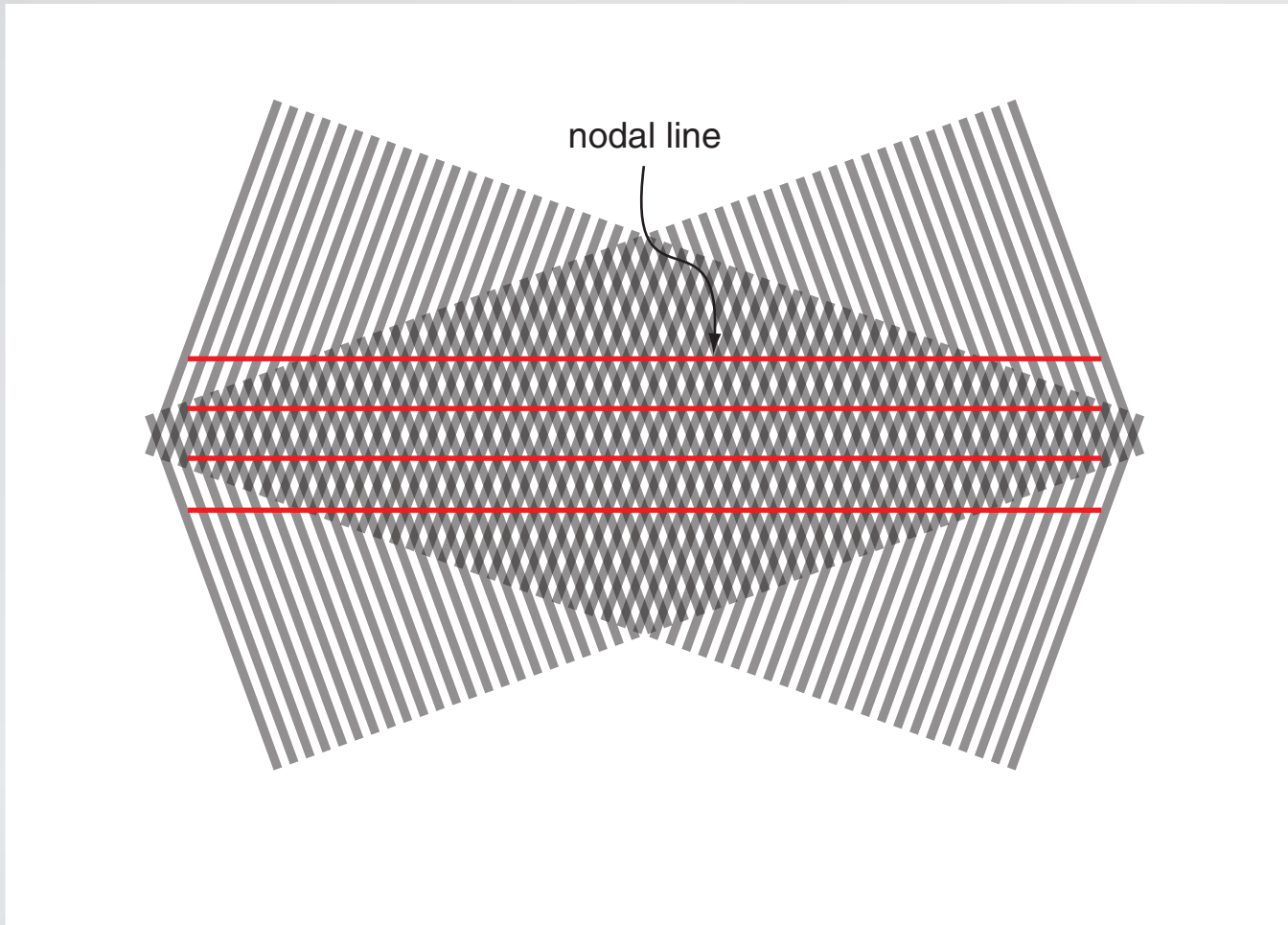
Waveguiding

two crossed planar waves...



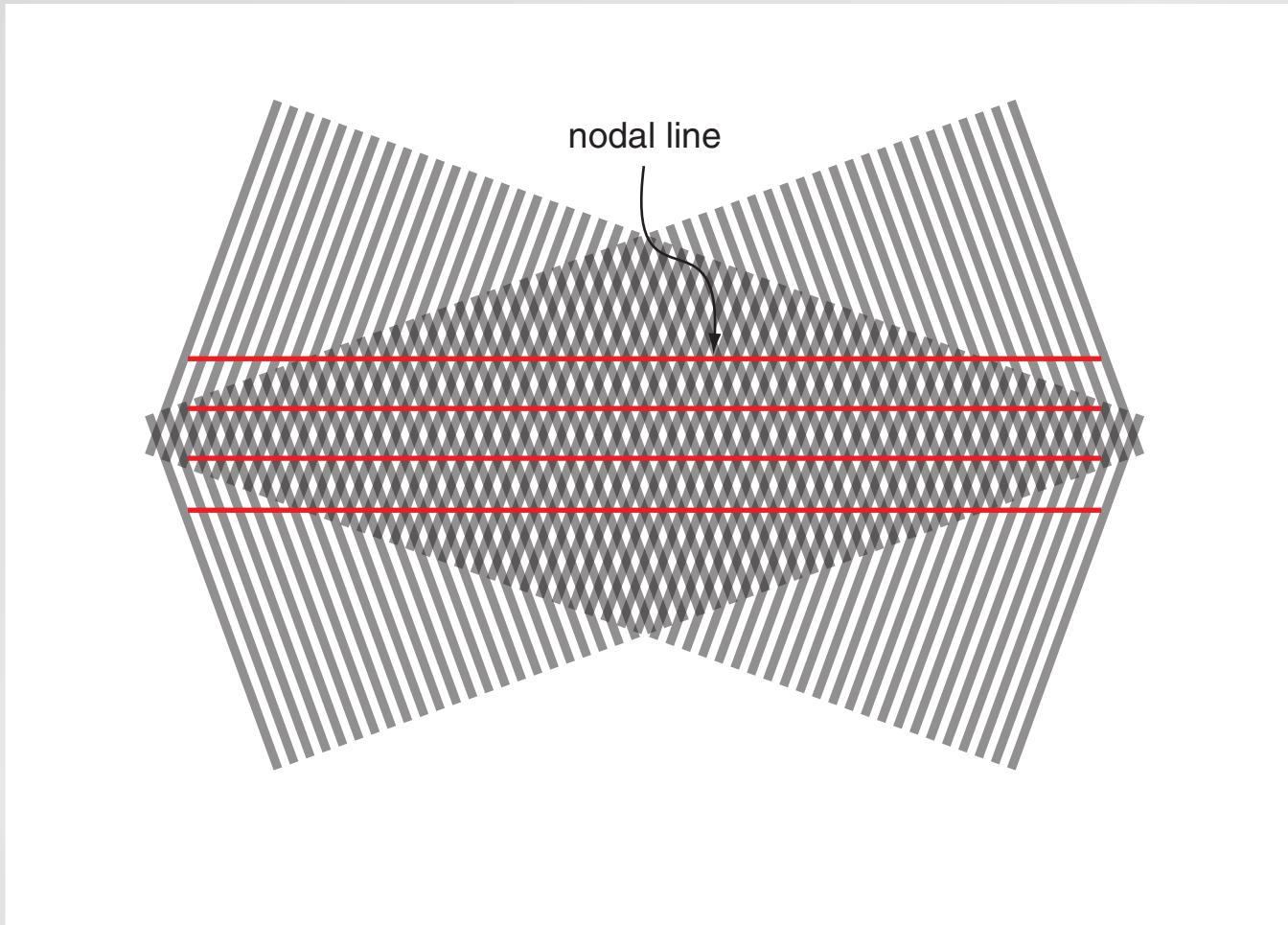
Waveguiding

...cause an interference pattern



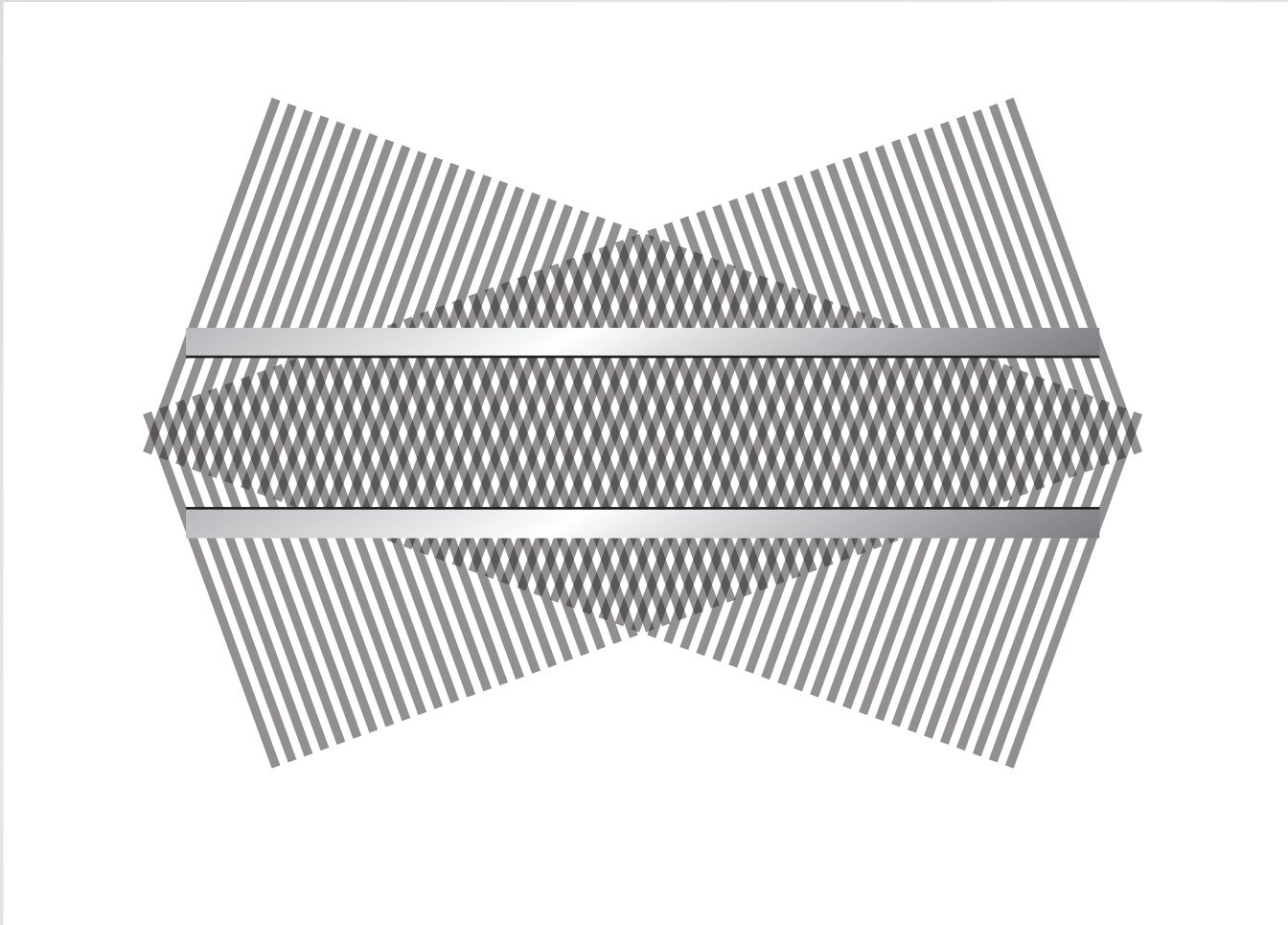
Waveguiding

$E = 0$ on the nodal lines



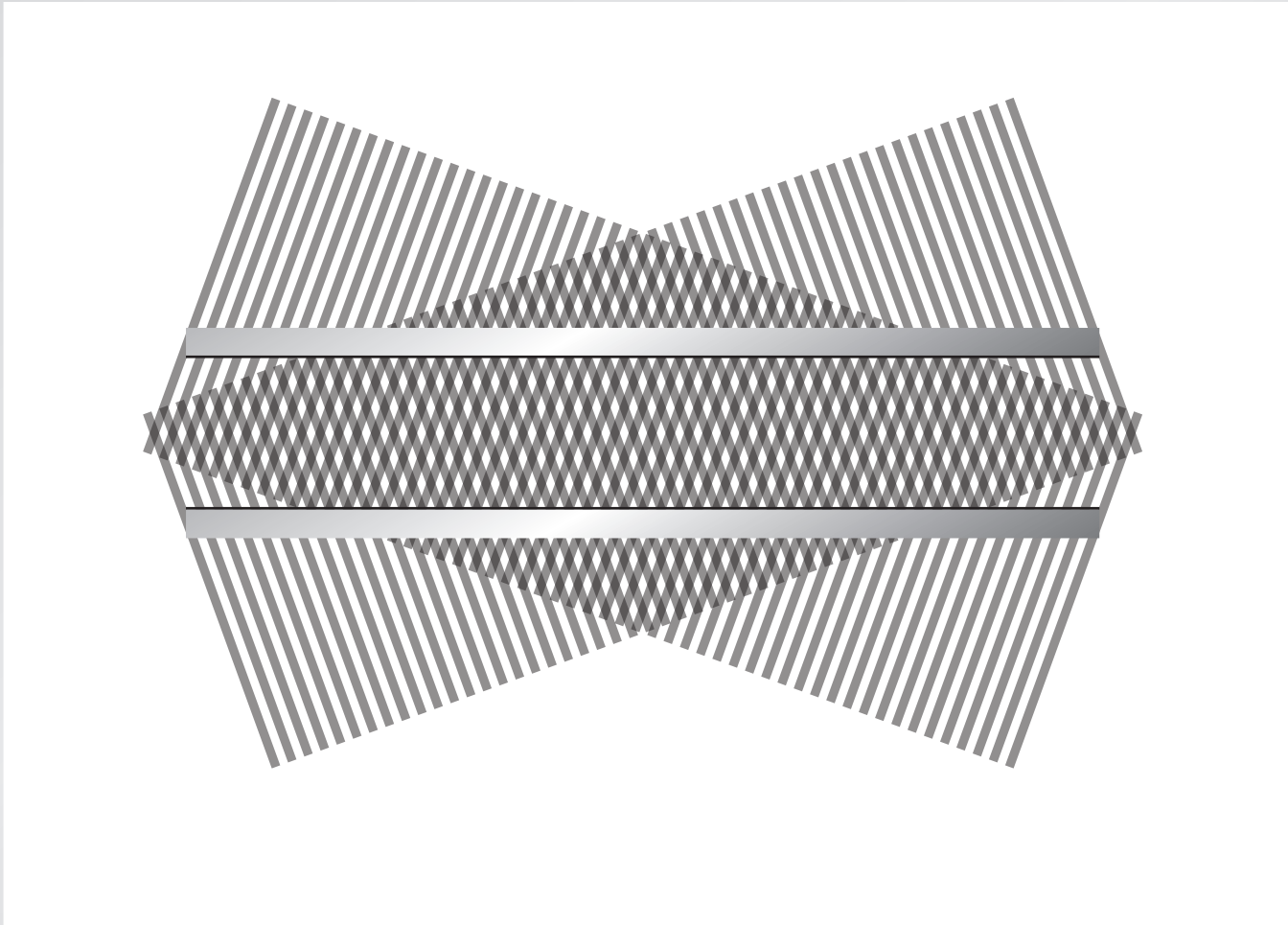
Waveguiding

...satisfying boundary conditions for planar-mirror waveguide



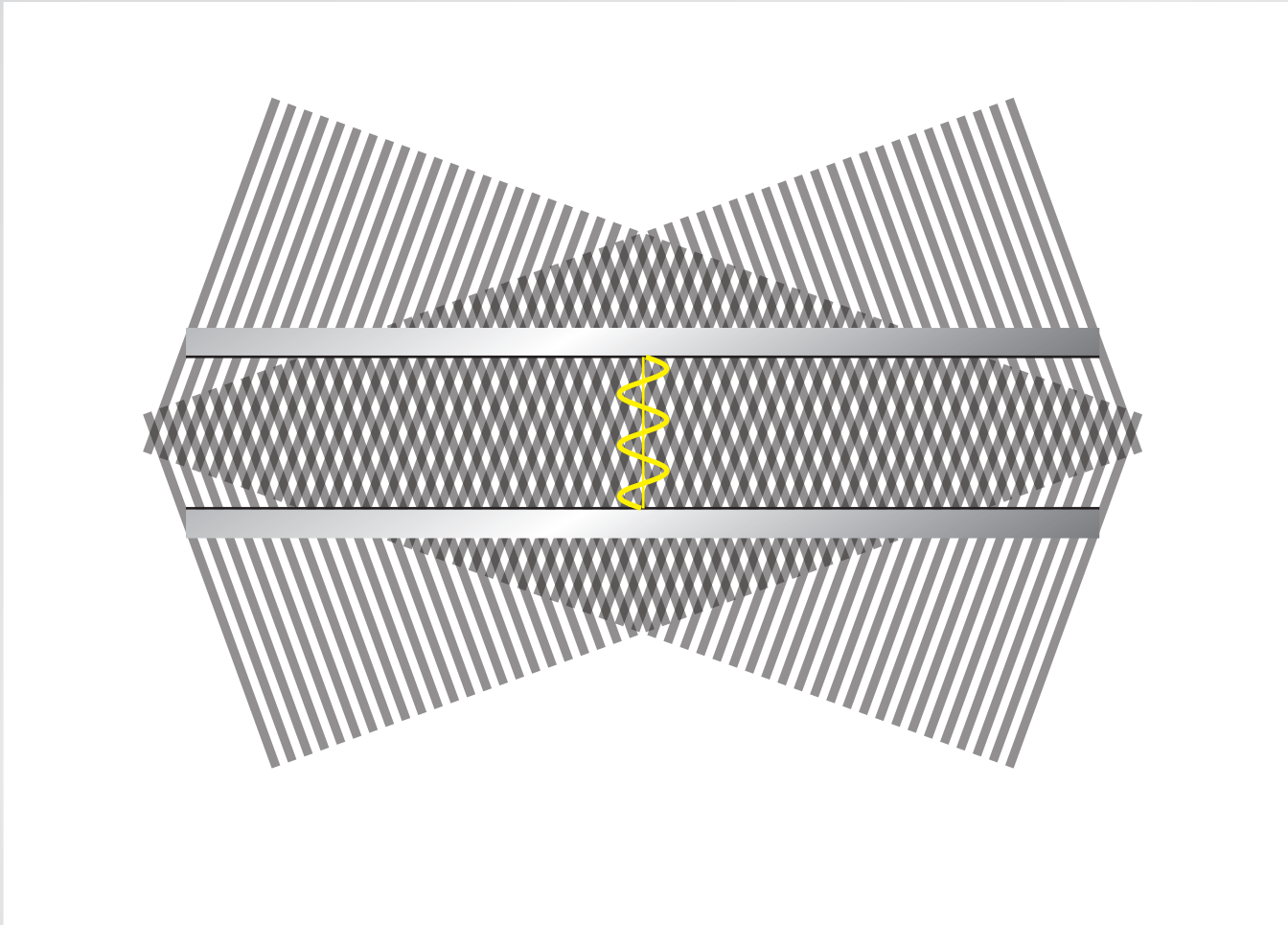
Waveguiding

transverse standing wave, traveling along axis



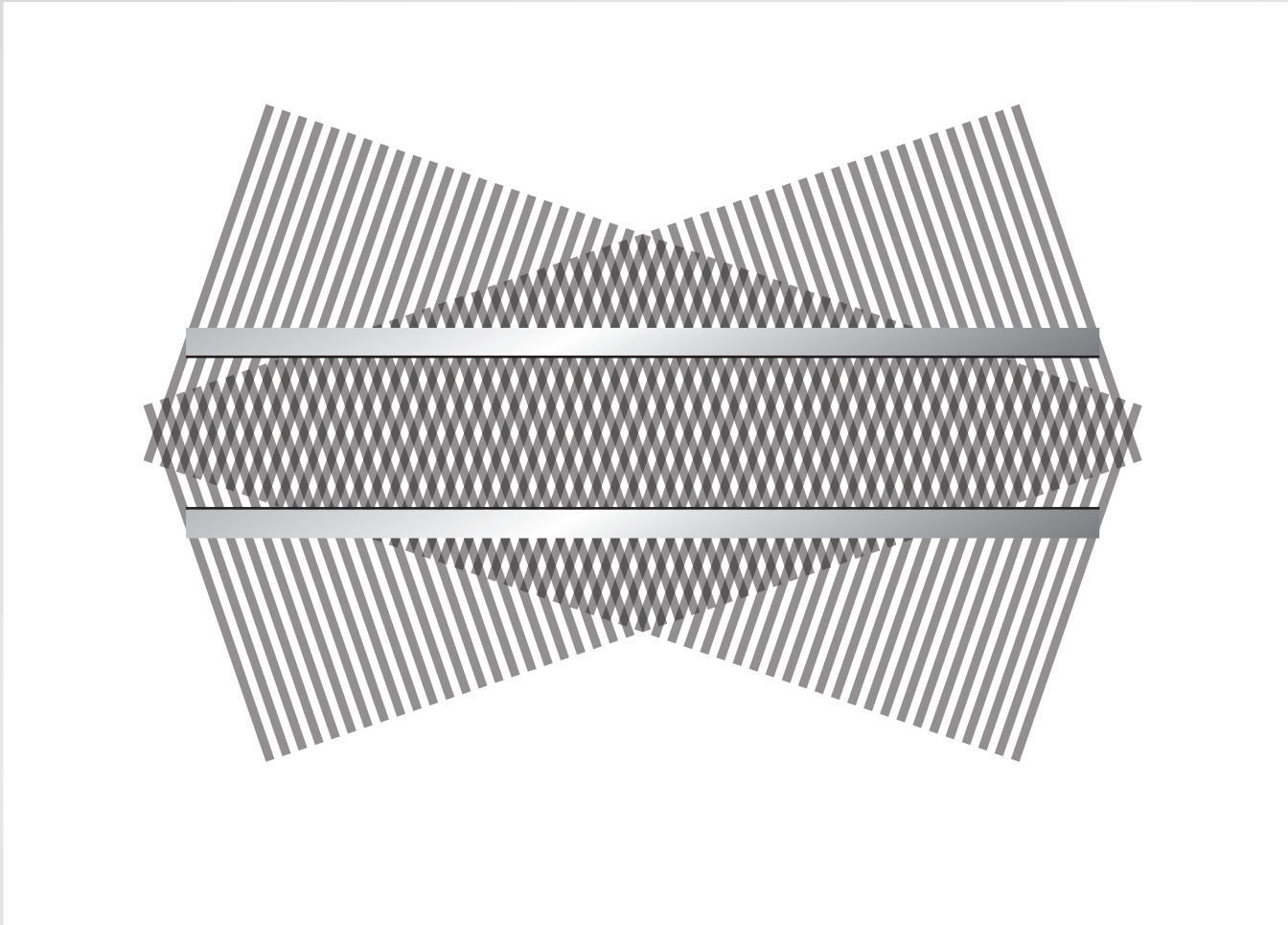
Waveguiding

transverse standing wave, traveling along axis



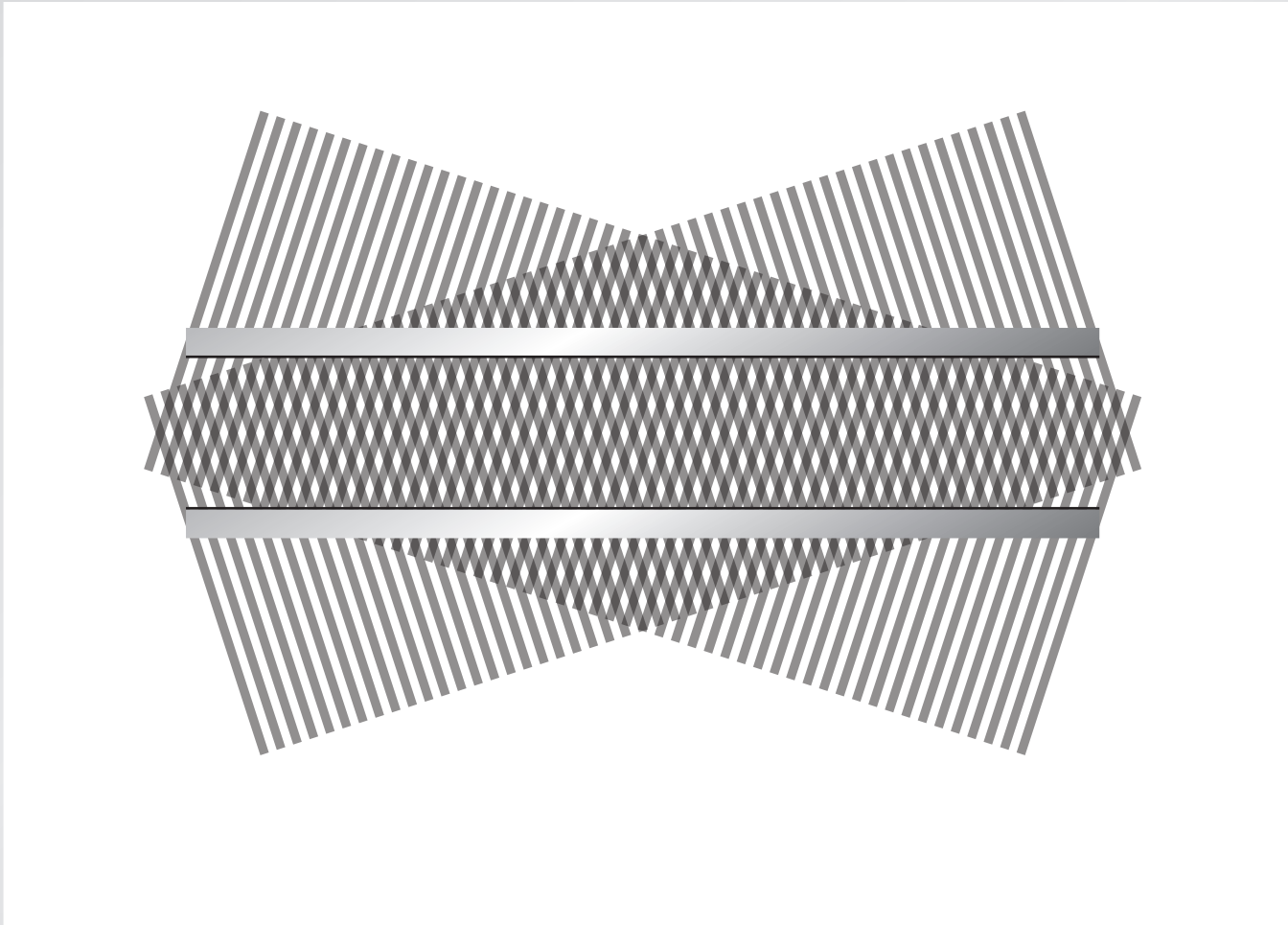
Waveguiding

change angle of incident waves...



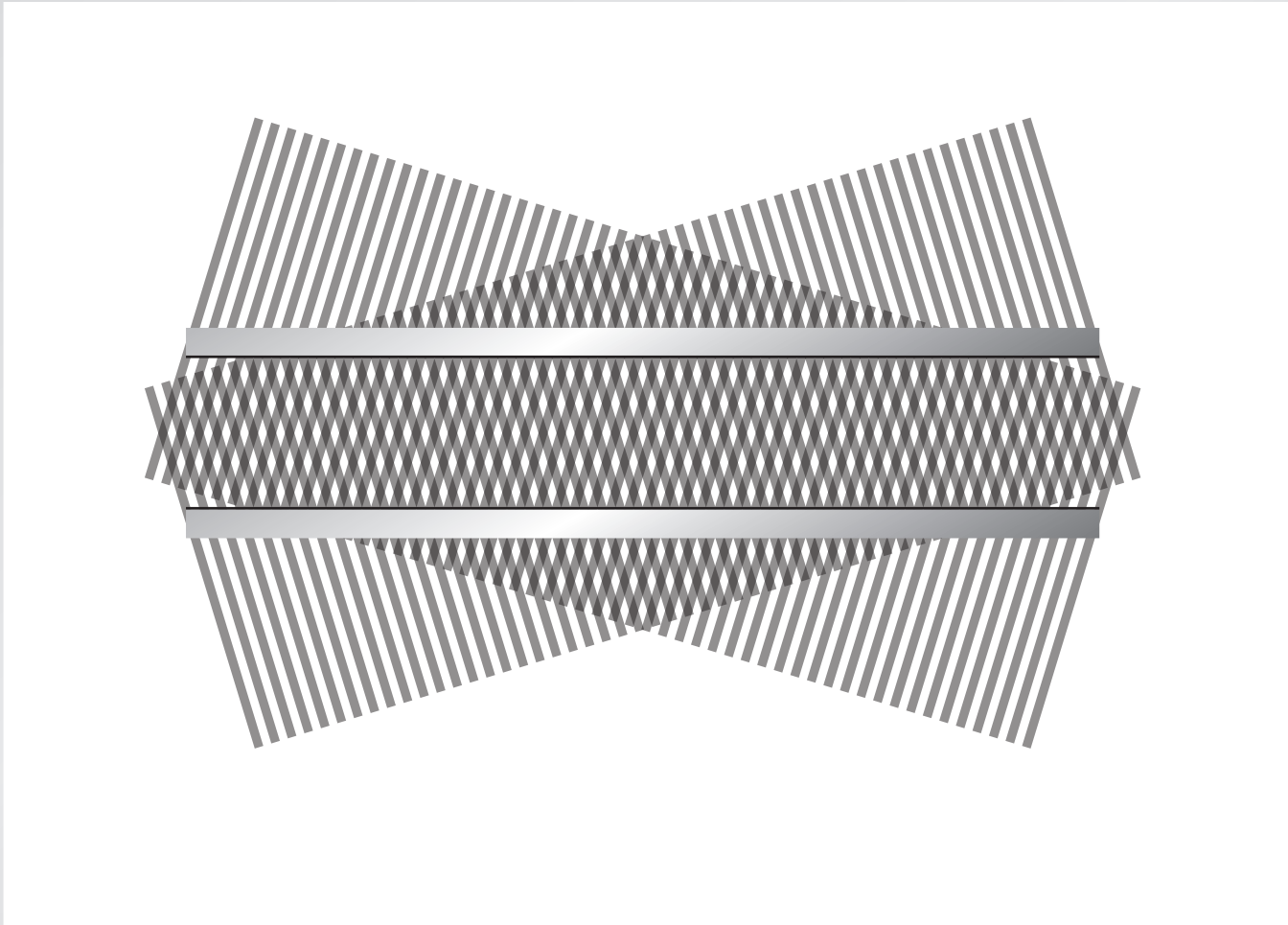
Waveguiding

change angle of incident waves...



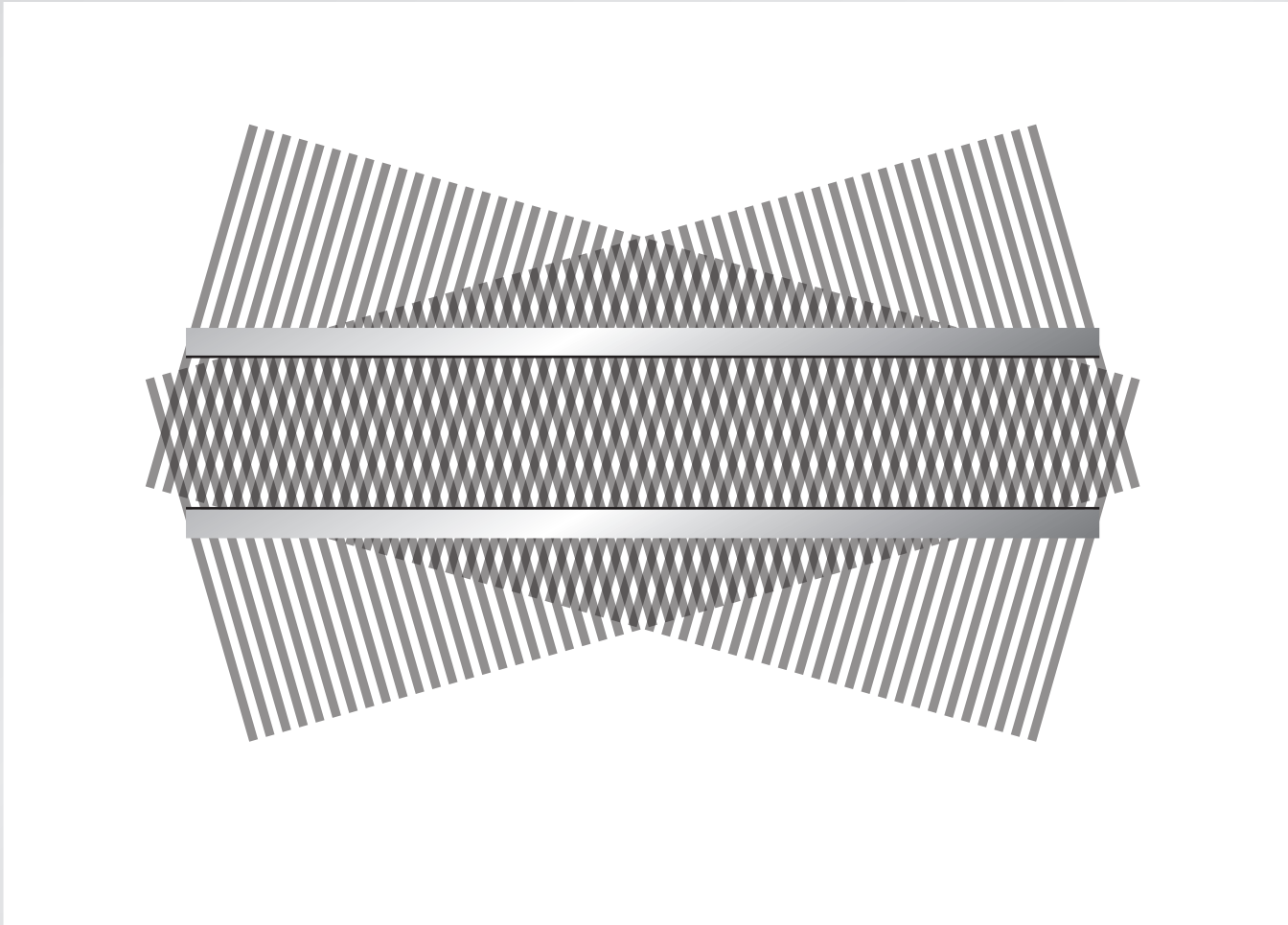
Waveguiding

change angle of incident waves...



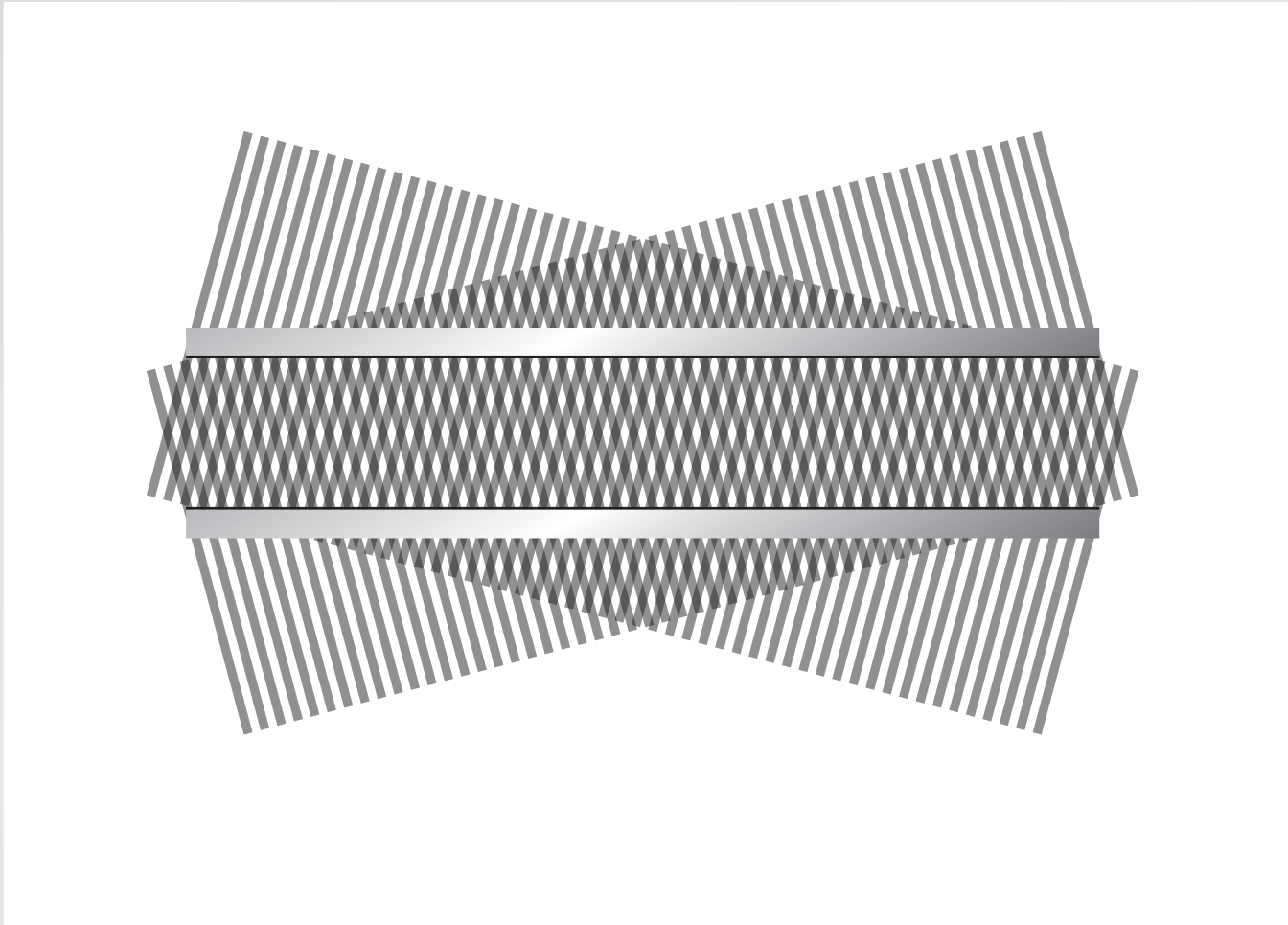
Waveguiding

change angle of incident waves...



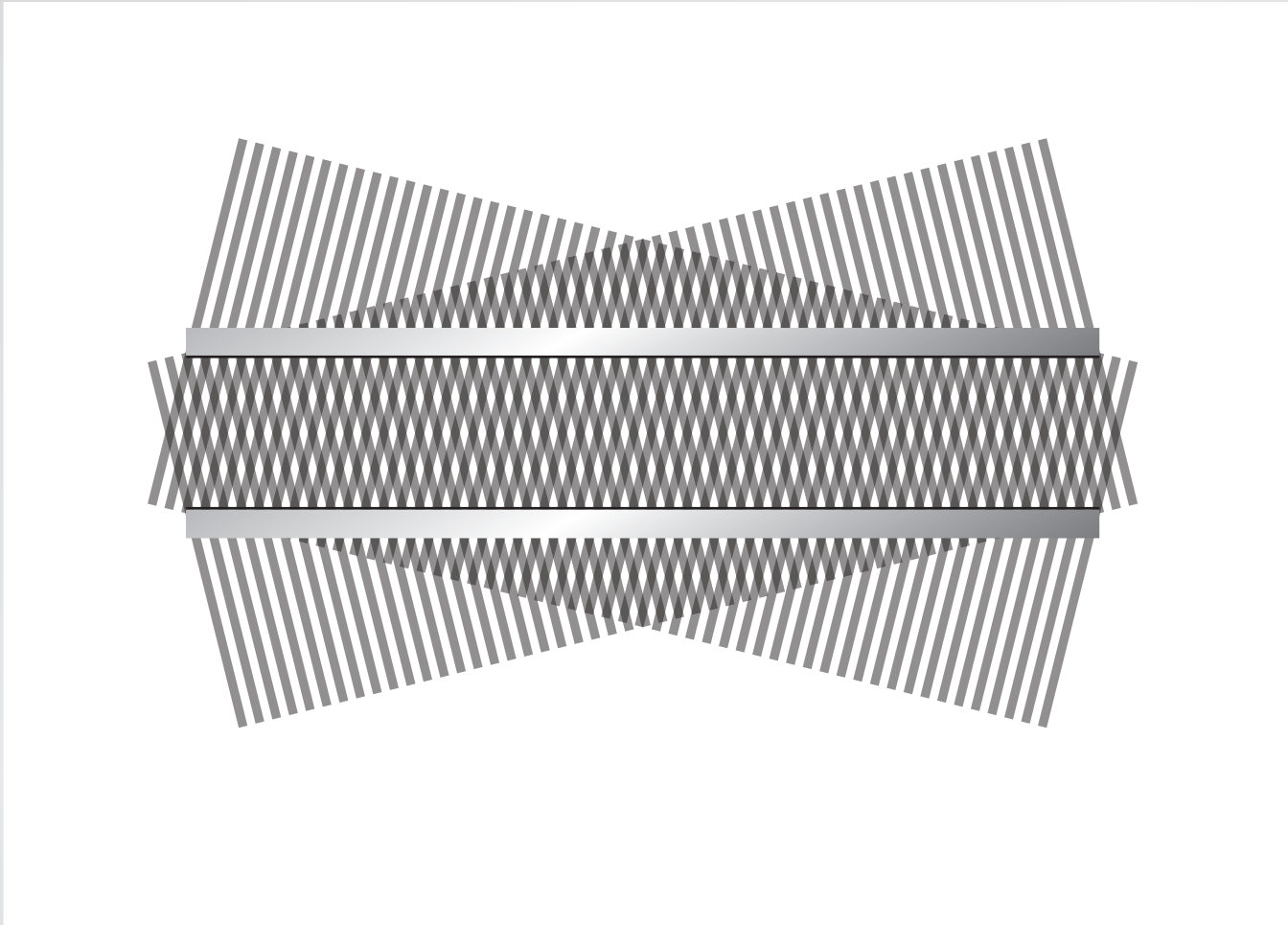
Waveguiding

change angle of incident waves...



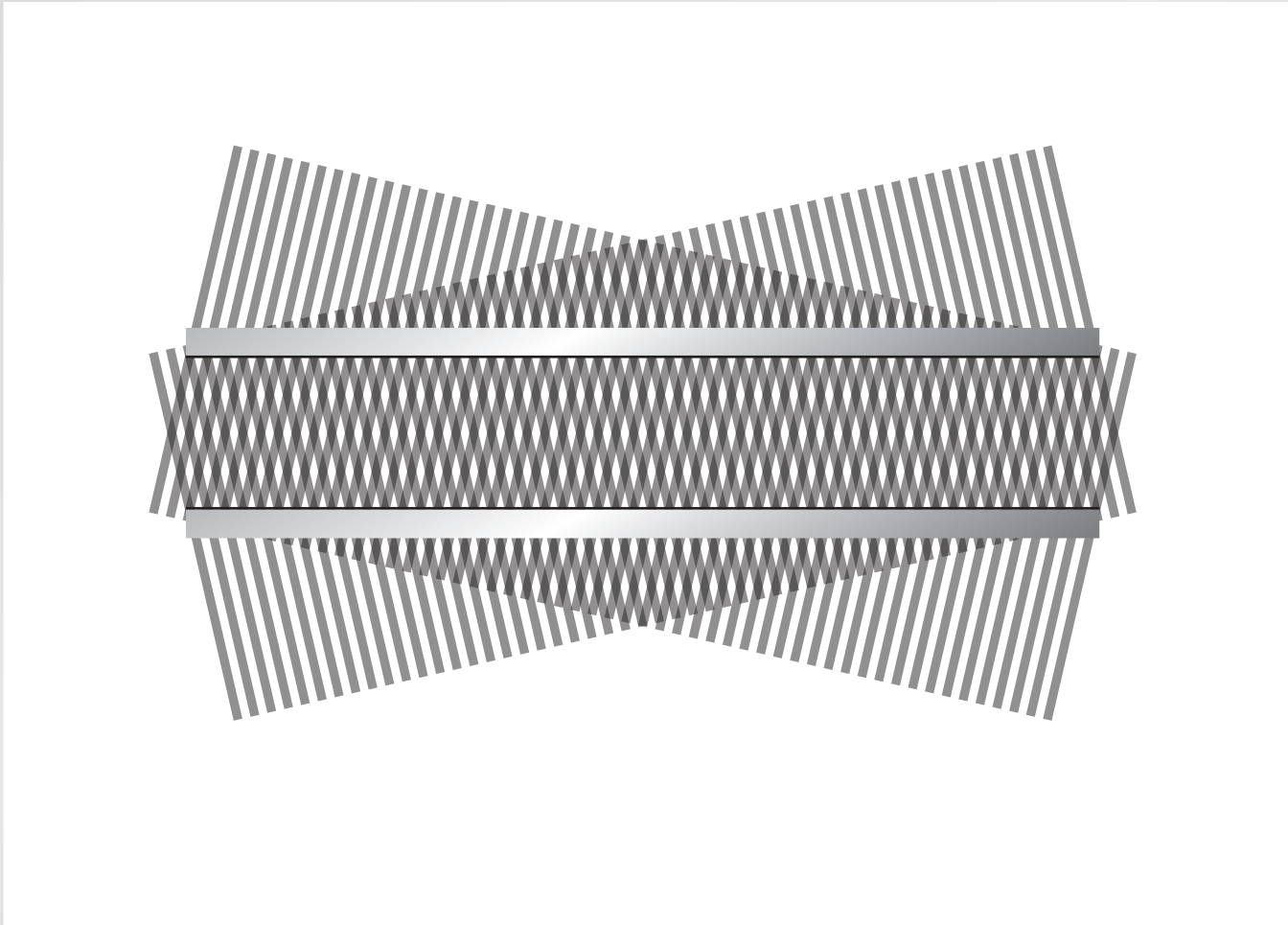
Waveguiding

change angle of incident waves...



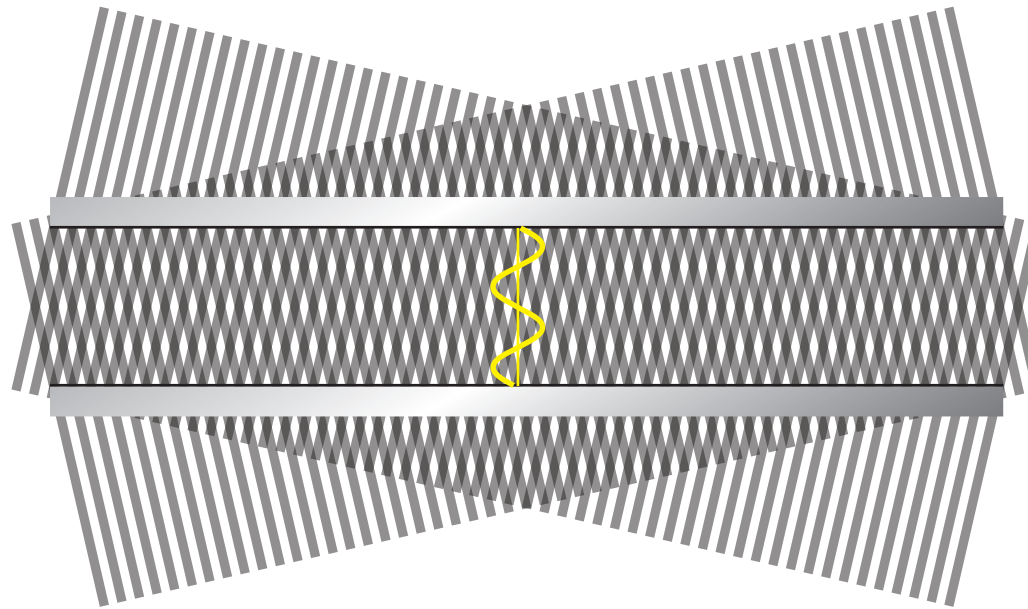
Waveguiding

change angle of incident waves...



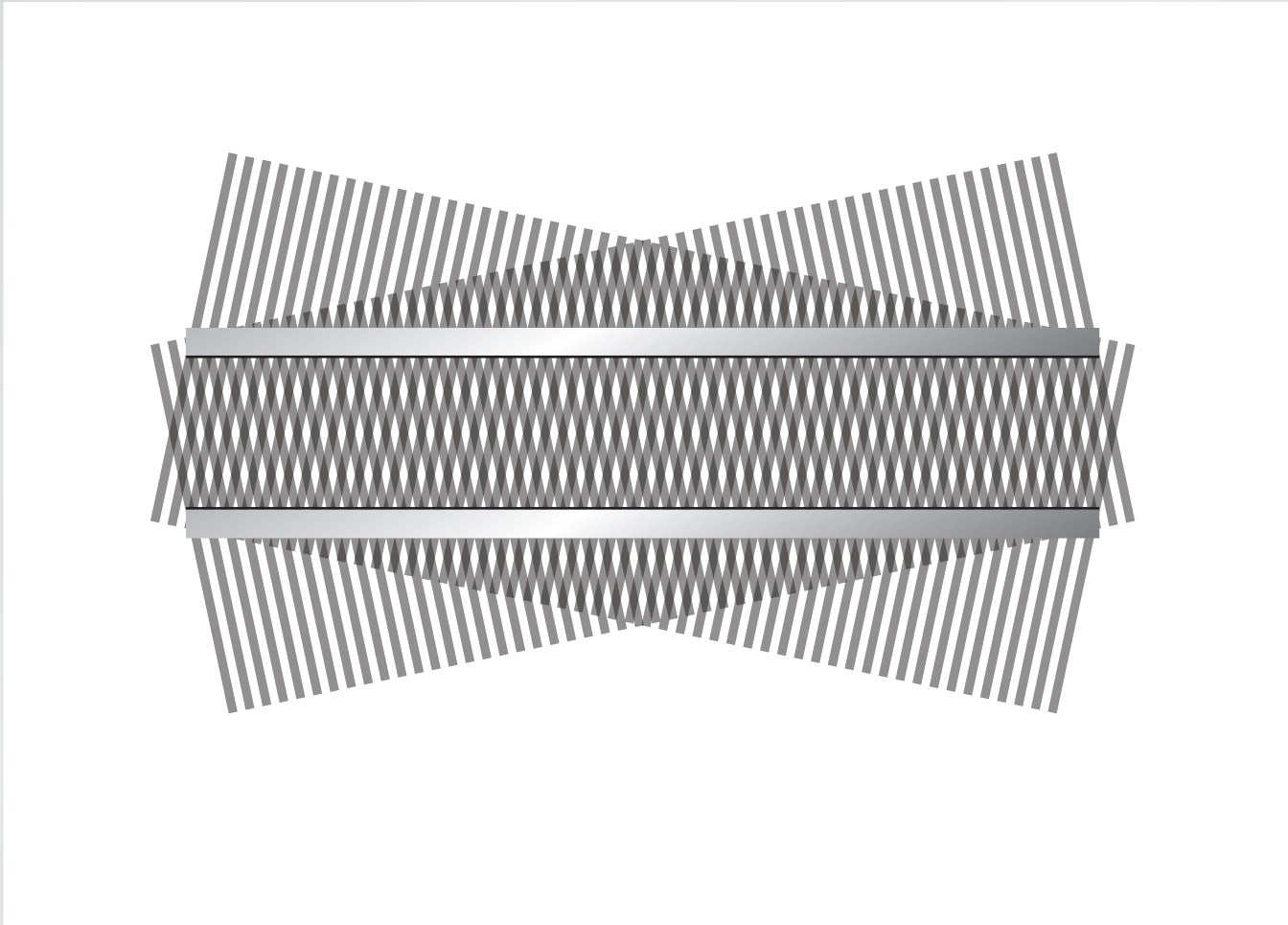
Waveguiding

change angle of incident waves...



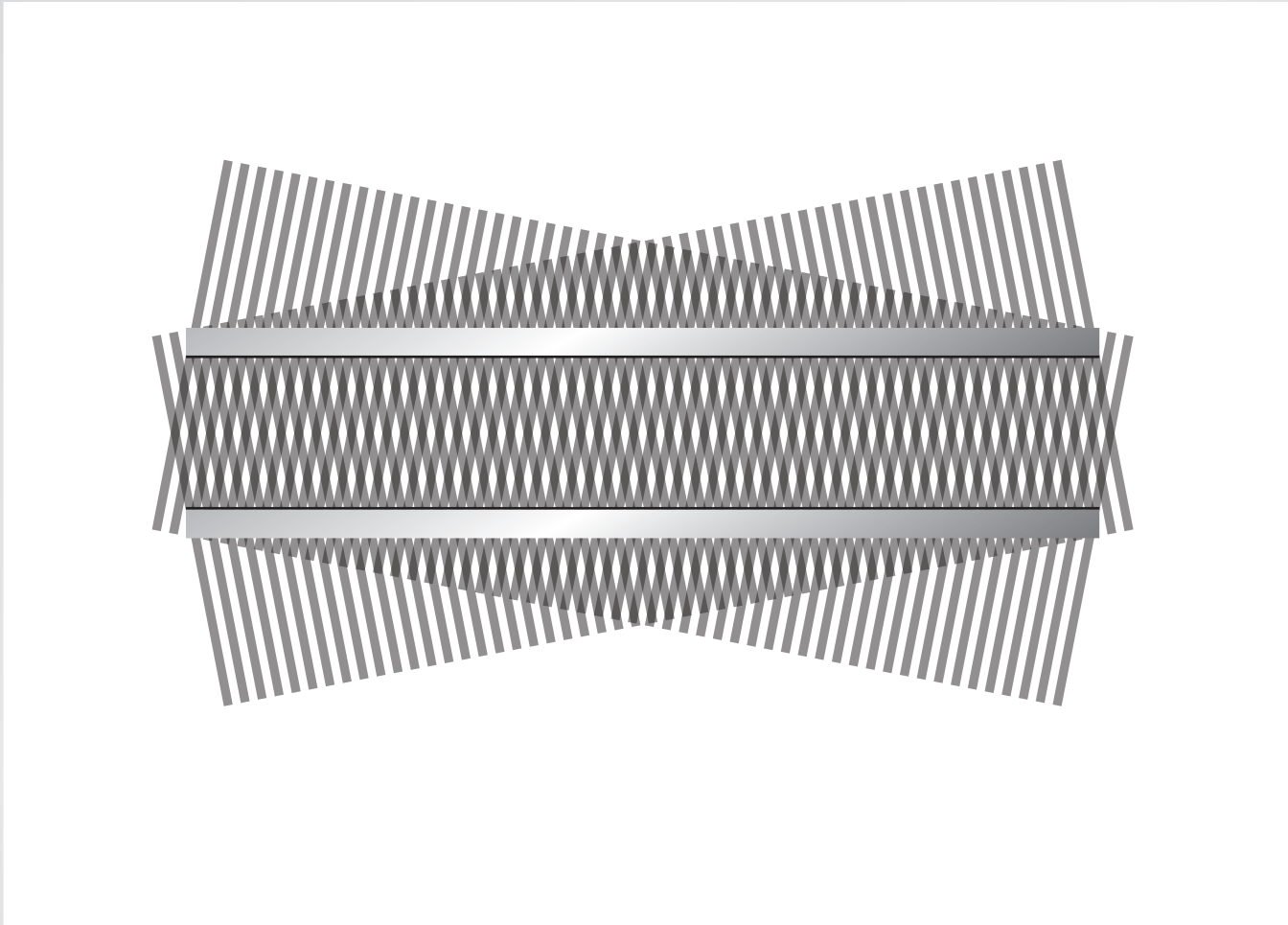
Waveguiding

change angle of incident waves...



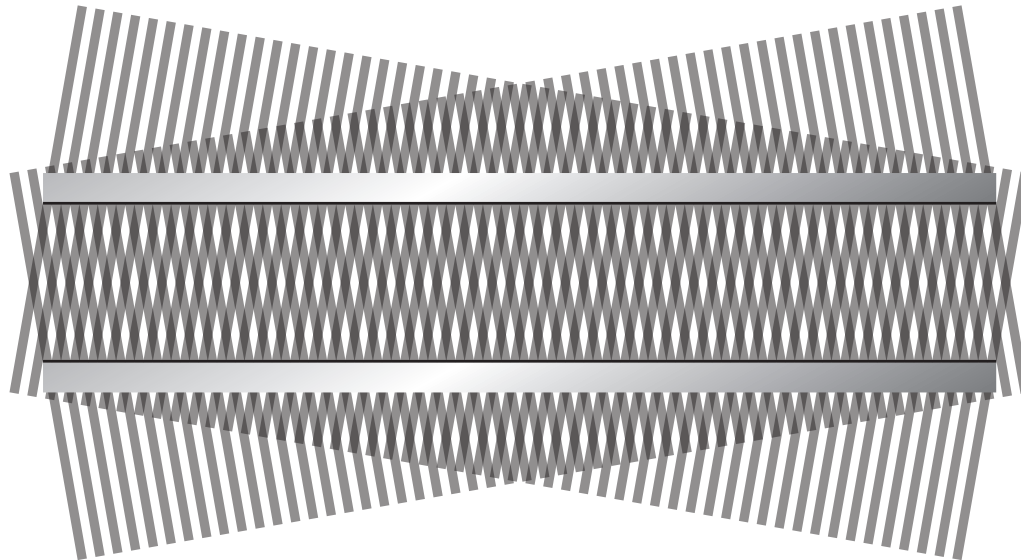
Waveguiding

change angle of incident waves...



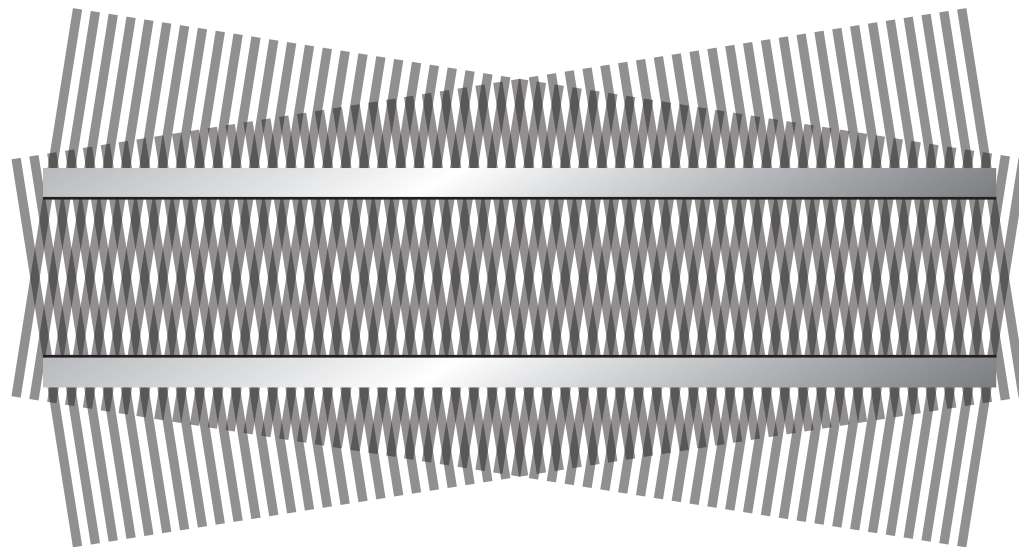
Waveguiding

change angle of incident waves...



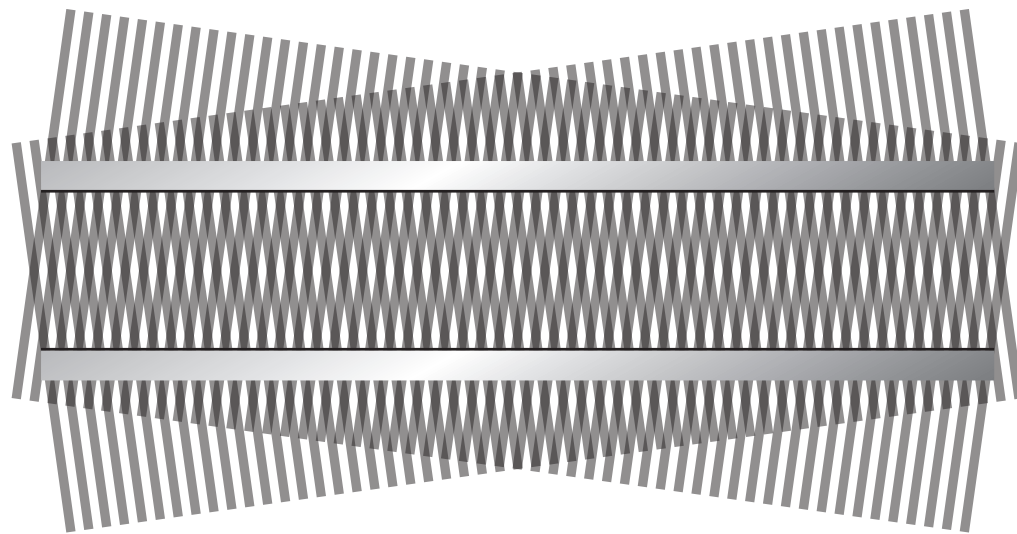
Waveguiding

change angle of incident waves...



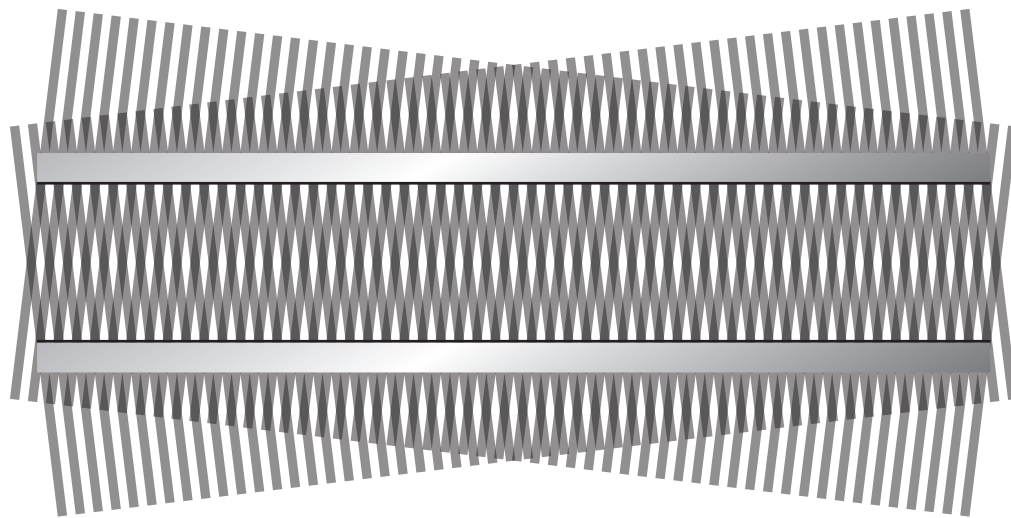
Waveguiding

change angle of incident waves...



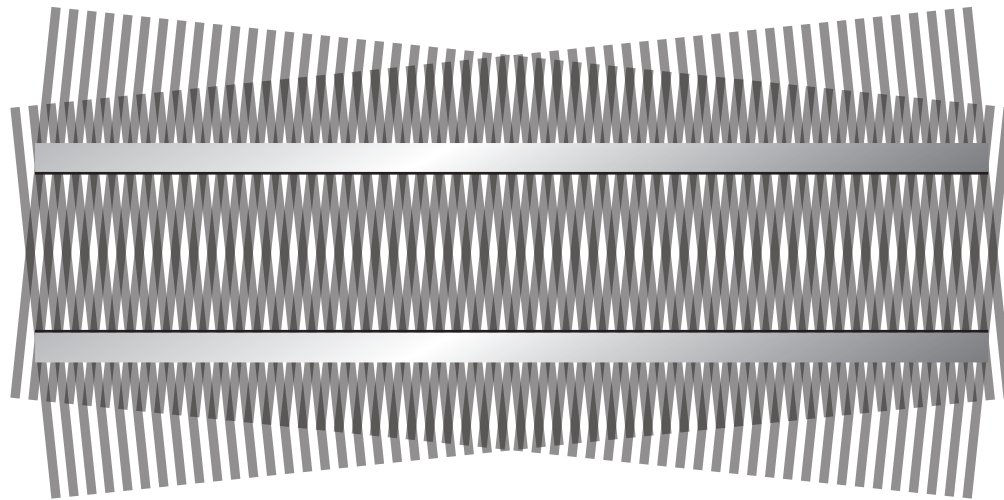
Waveguiding

change angle of incident waves...



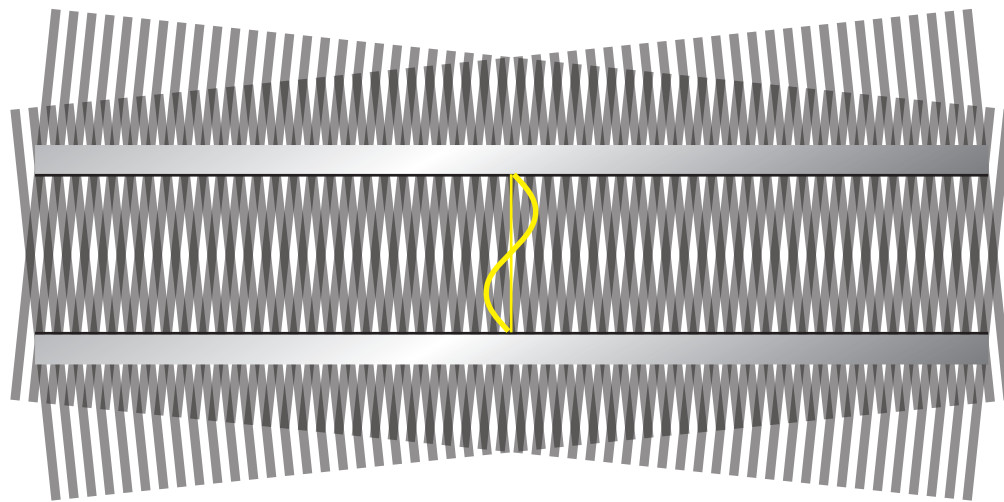
Waveguiding

change angle of incident waves...



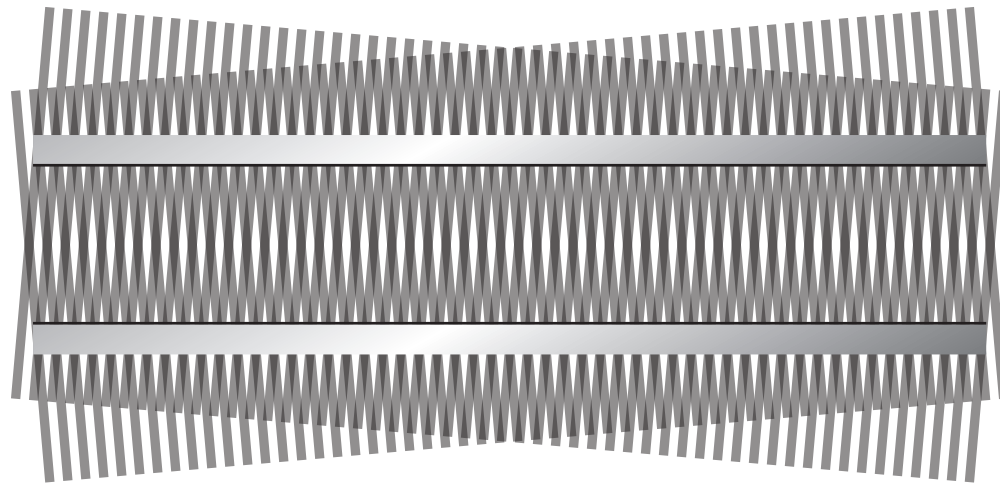
Waveguiding

change angle of incident waves...



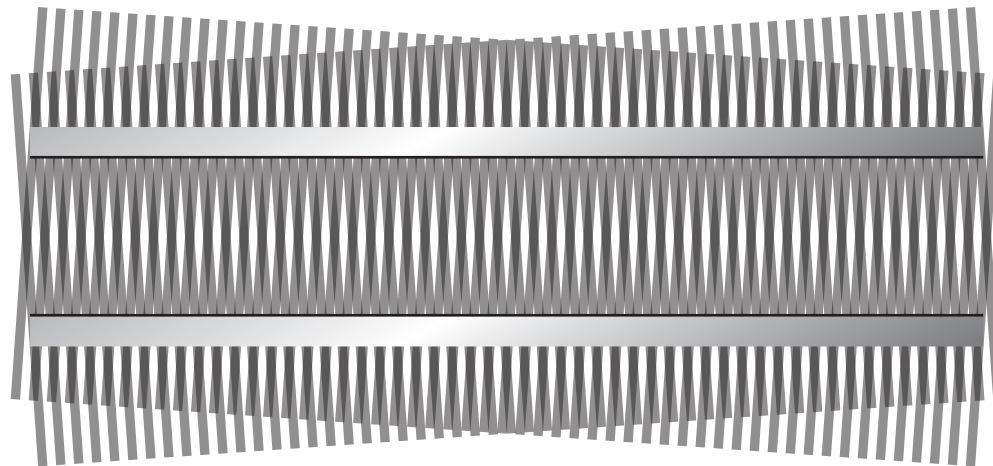
Waveguiding

change angle of incident waves...



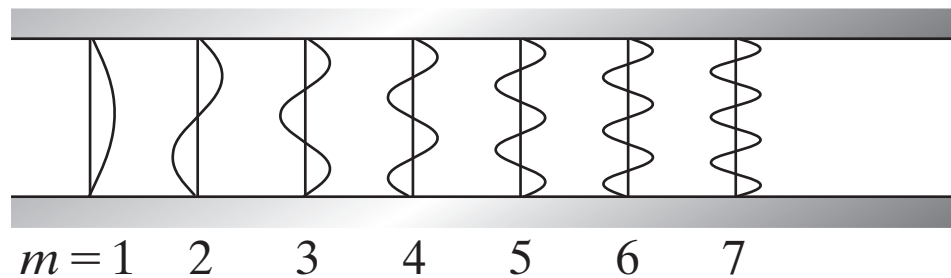
Waveguiding

change angle of incident waves...



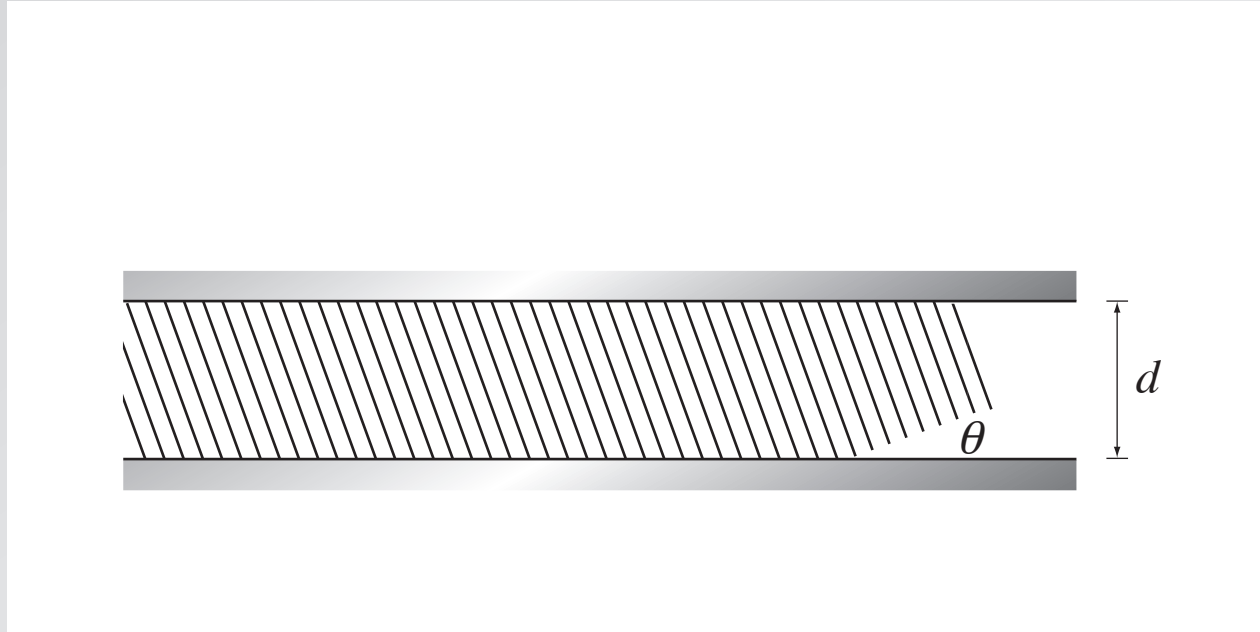
Waveguiding

boundary conditions only satisfied for certain θ



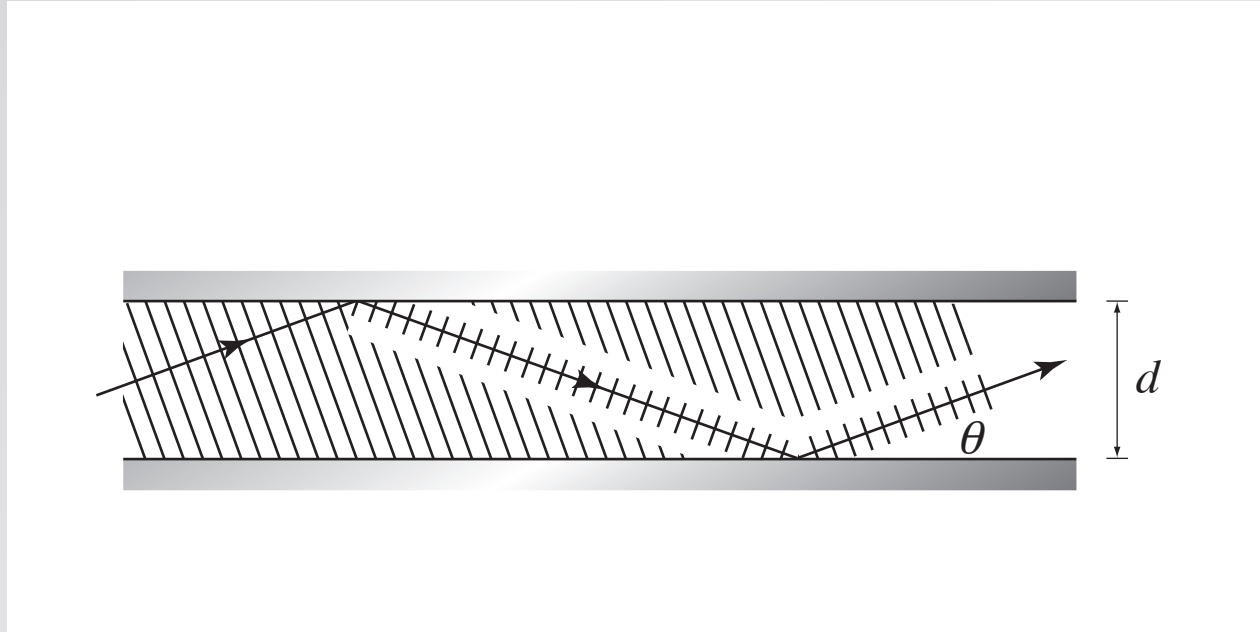
standing wave in y -direction, traveling in z -direction

Waveguiding



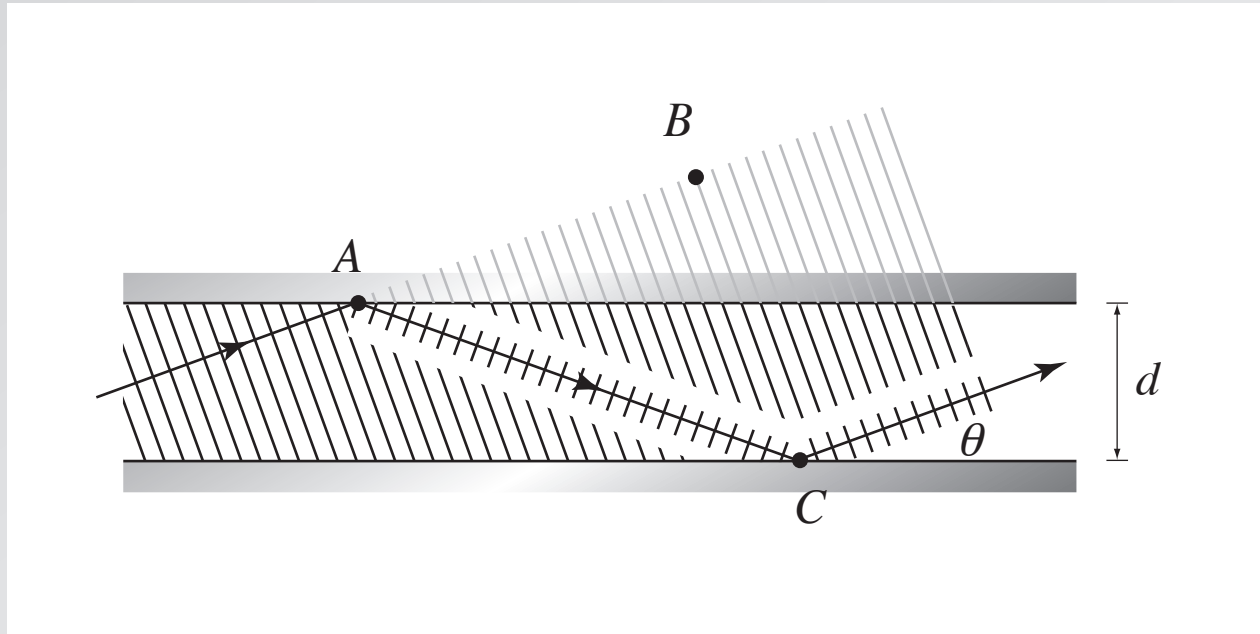
consider wave incident at angle θ

Waveguiding



twice-reflected wave

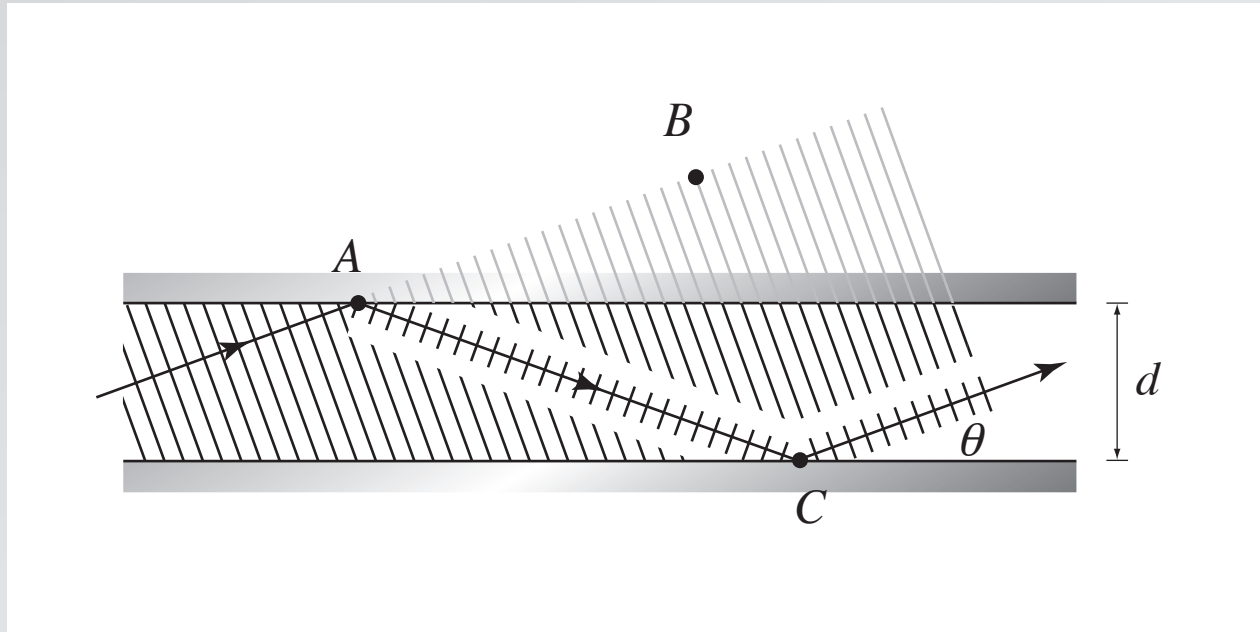
Waveguiding



self consistency:

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

Waveguiding



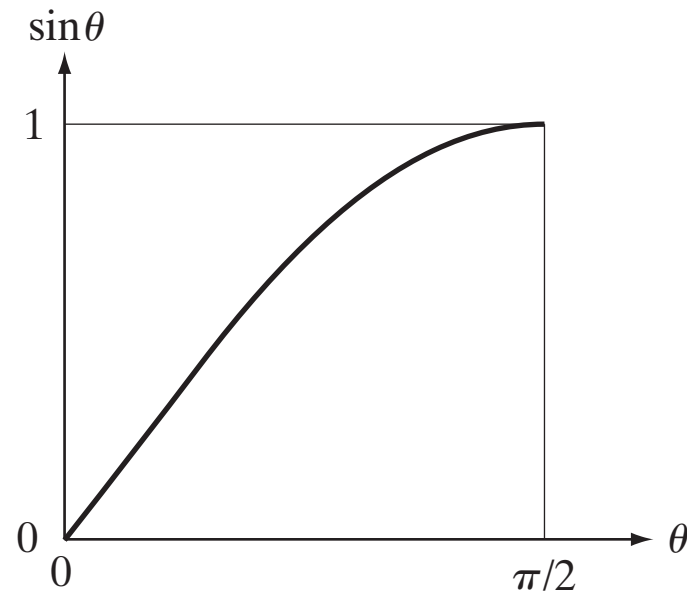
self consistency:

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

so:

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

Waveguiding



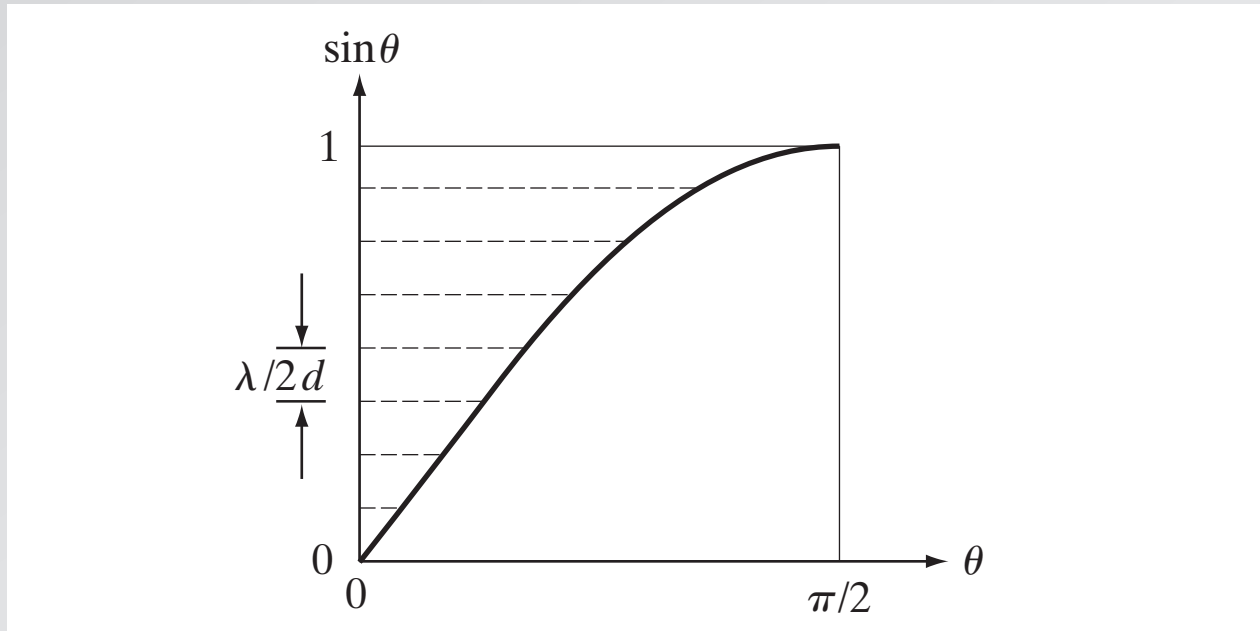
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$$\sin \theta_m = m \frac{\lambda}{2d}$$

Waveguiding



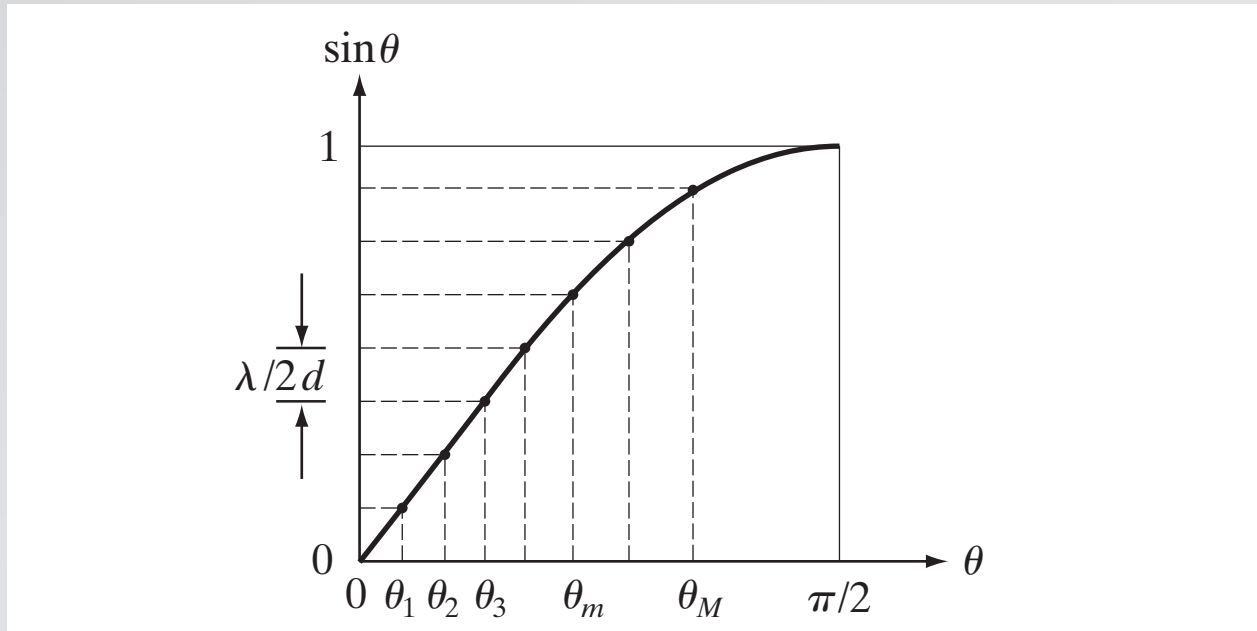
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Waveguiding



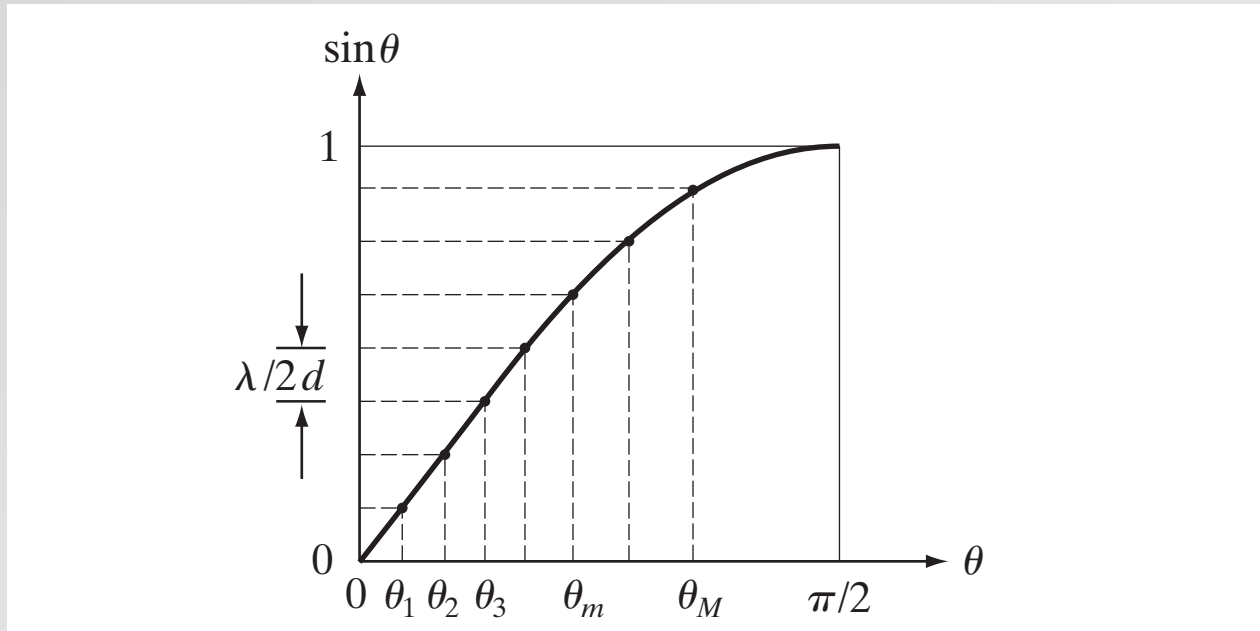
self consistency:

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

so:

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

Waveguiding



number of modes:

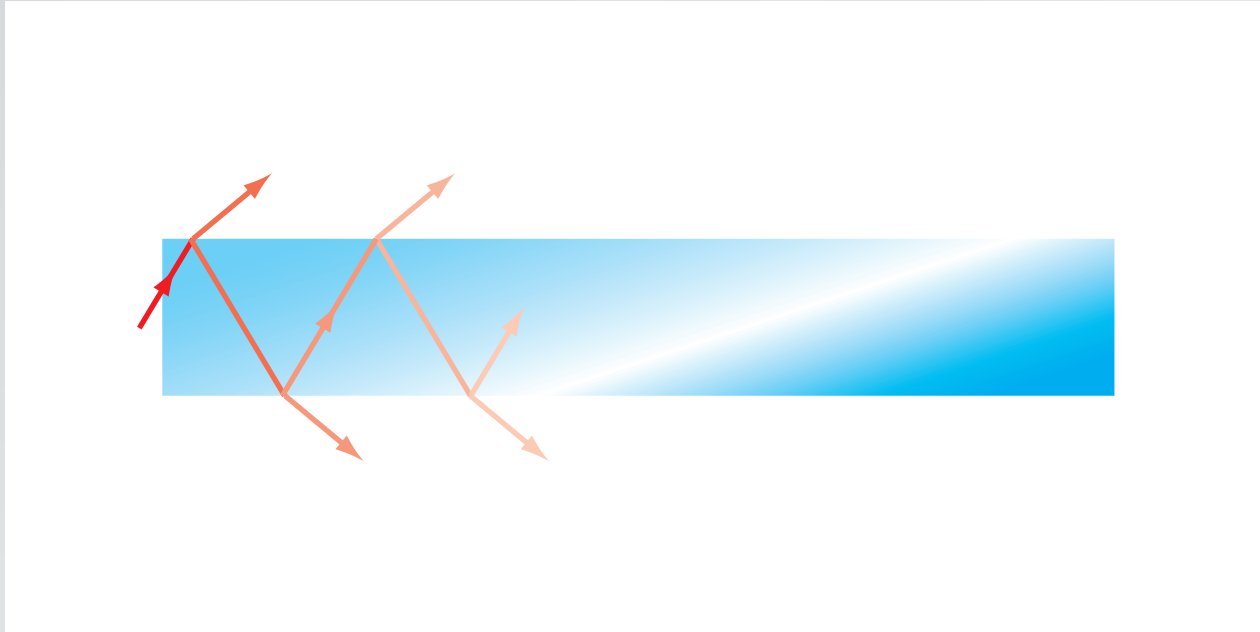
$$M = \frac{2d}{\lambda}$$

Waveguiding



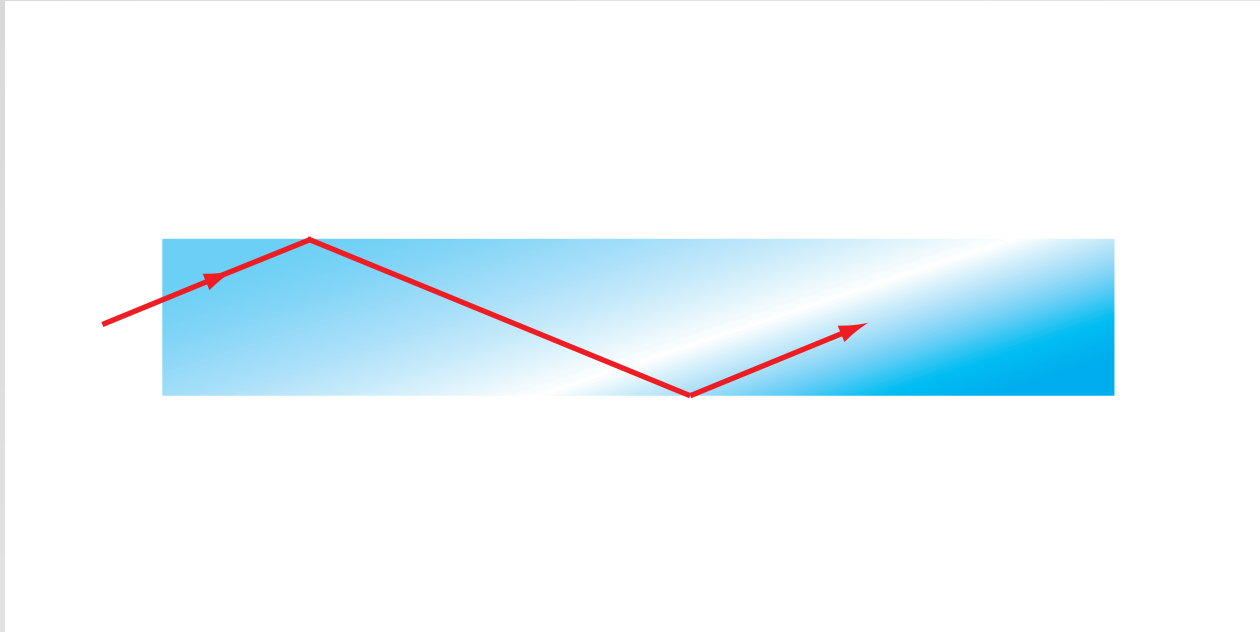
now consider a planar dielectric waveguide

Waveguiding



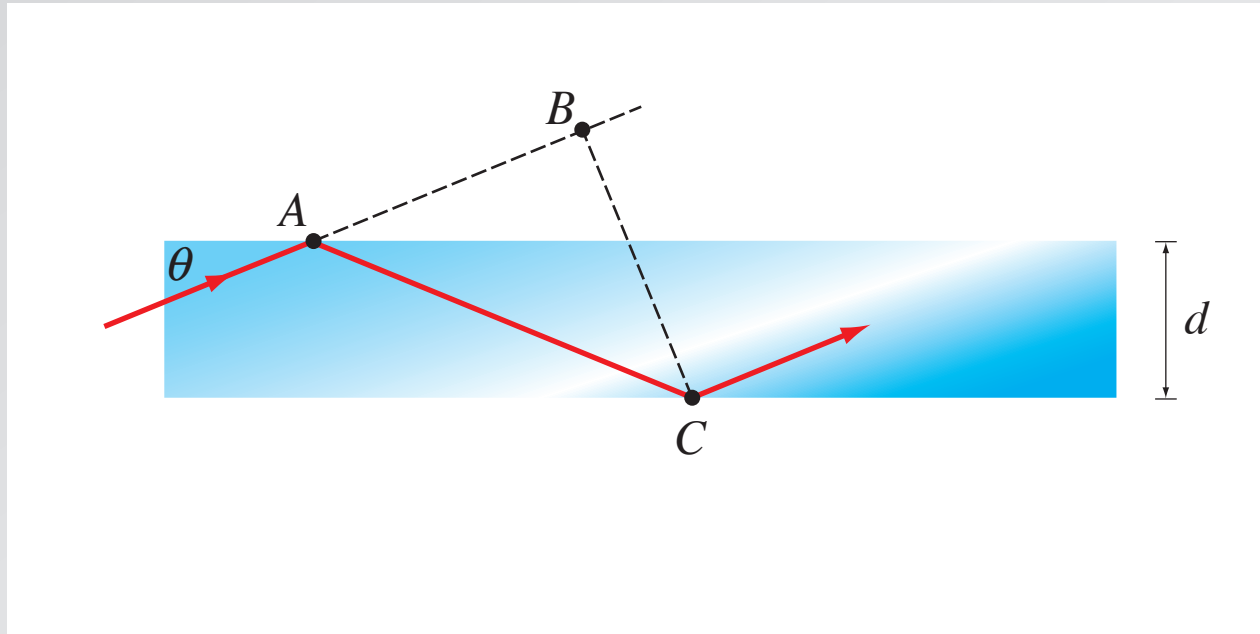
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



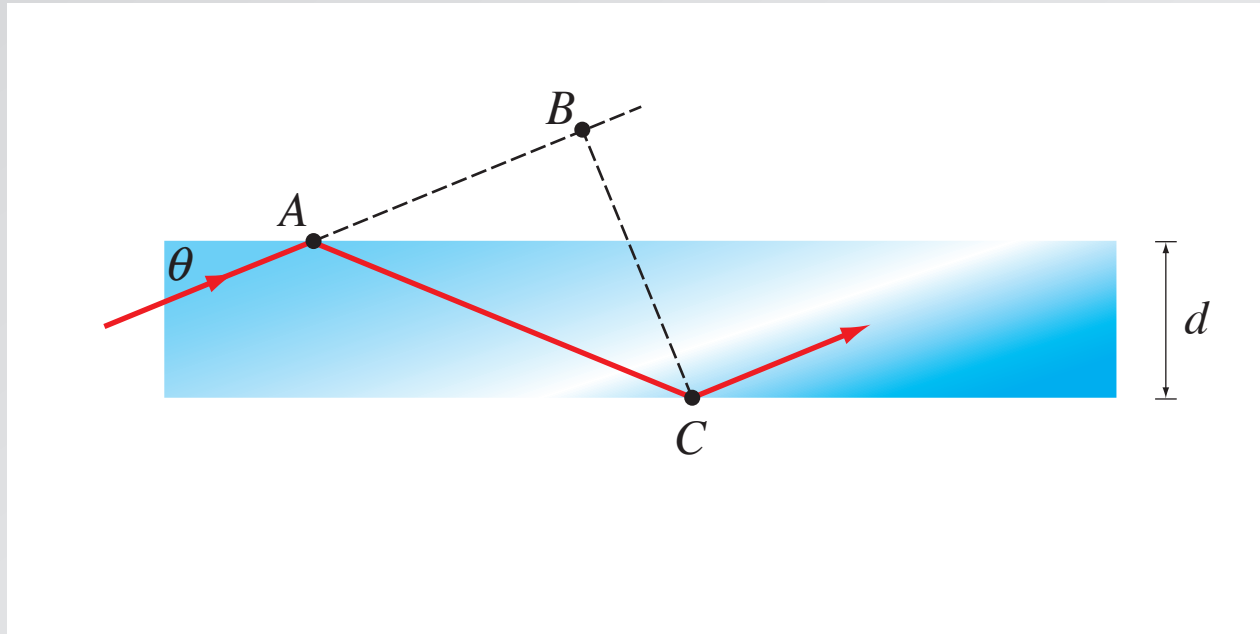
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

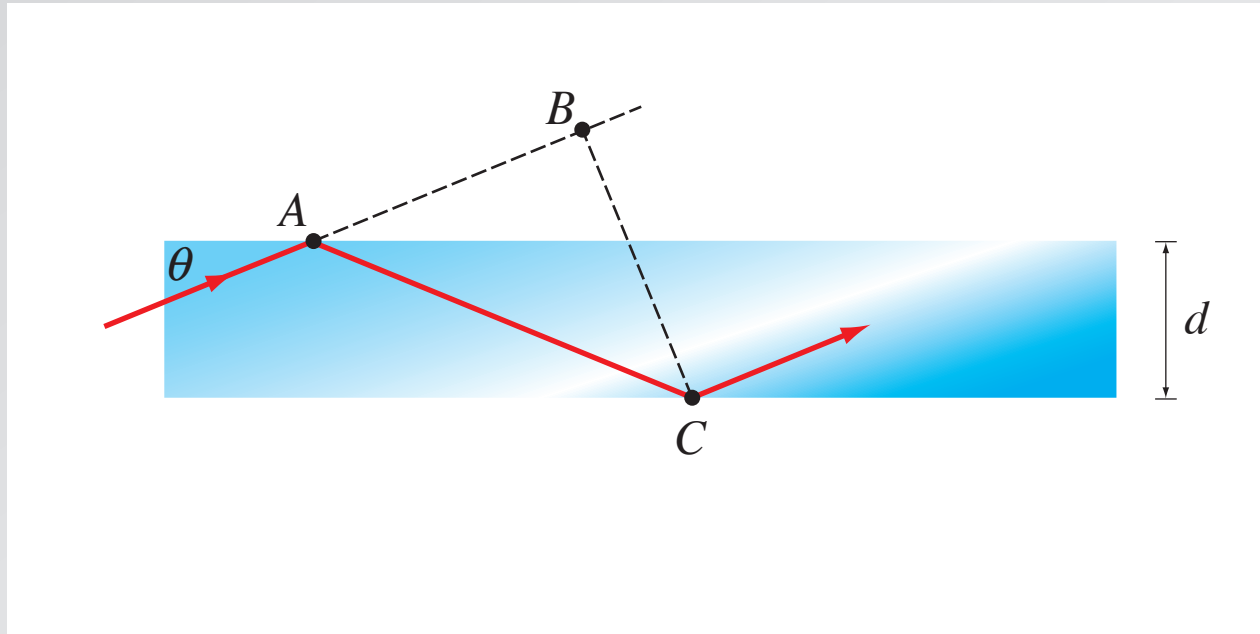
Waveguiding



self consistency:

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

Waveguiding



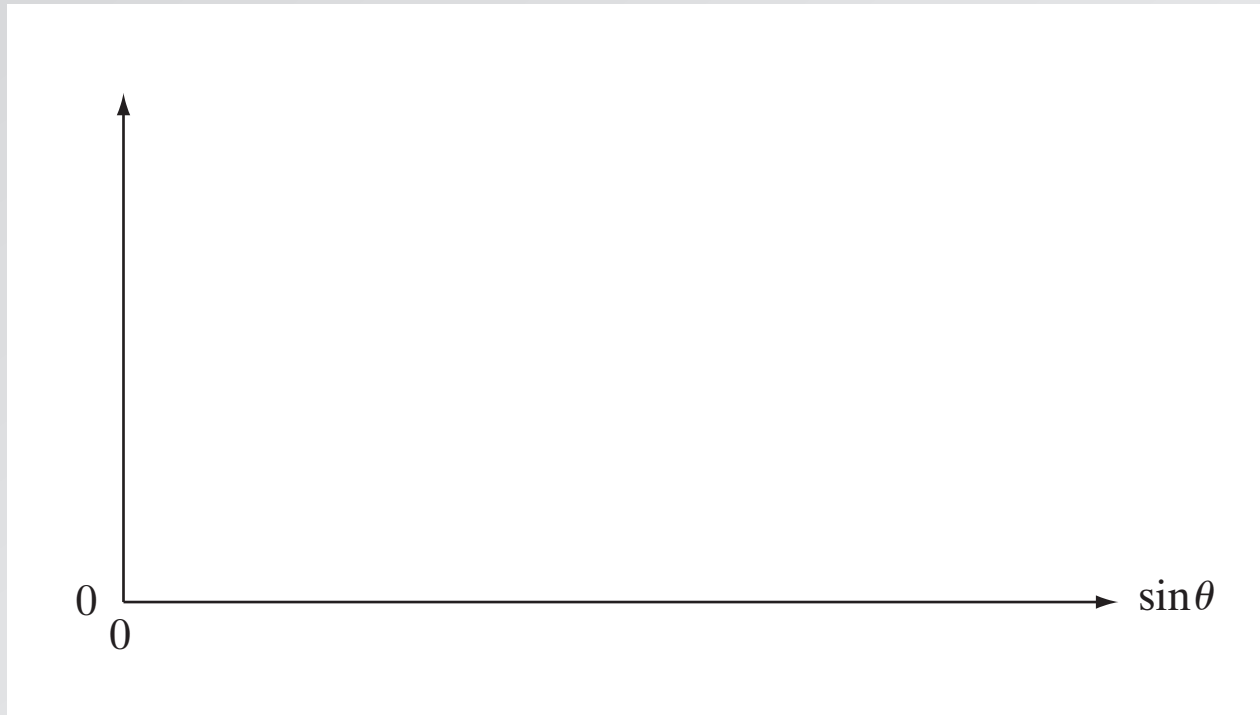
self consistency:

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

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



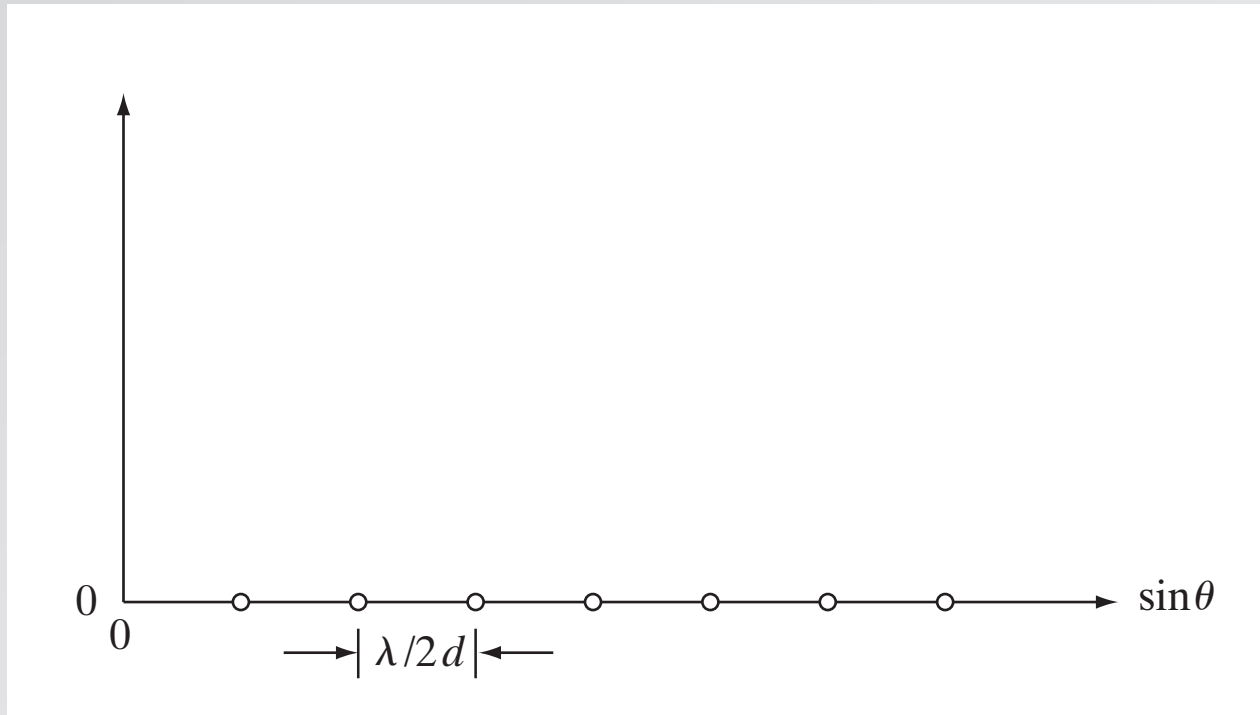
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Waveguiding



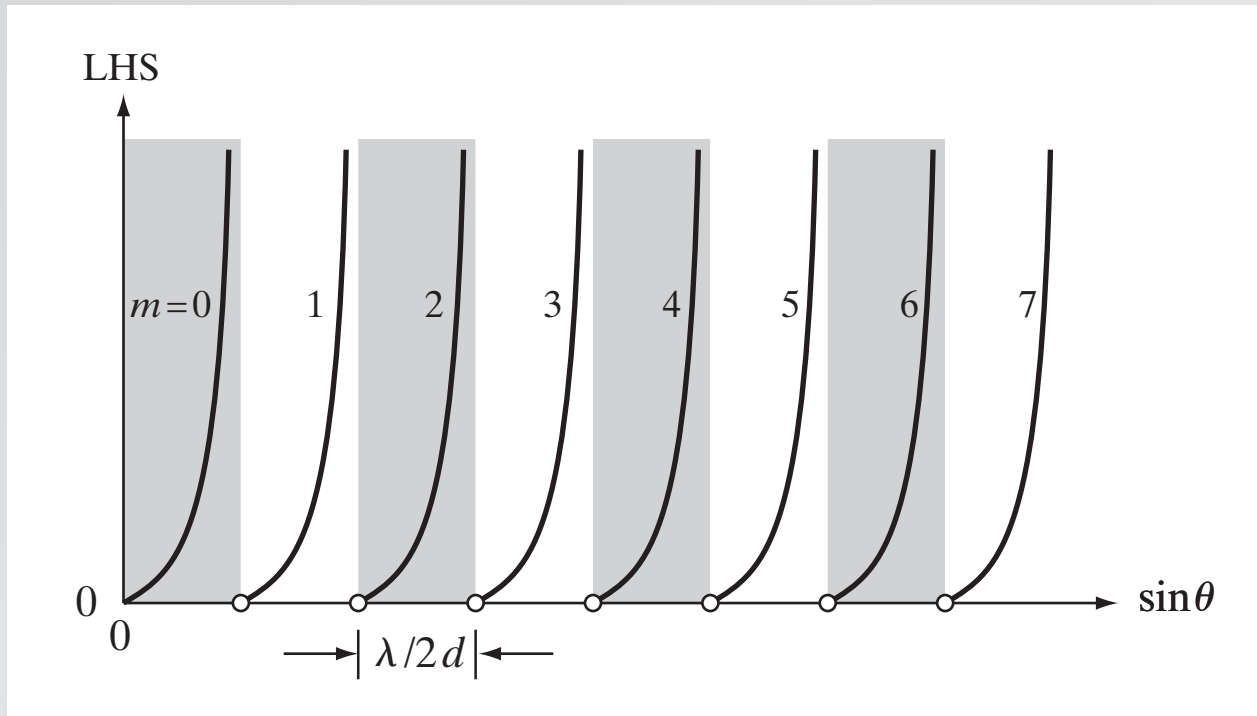
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Waveguiding



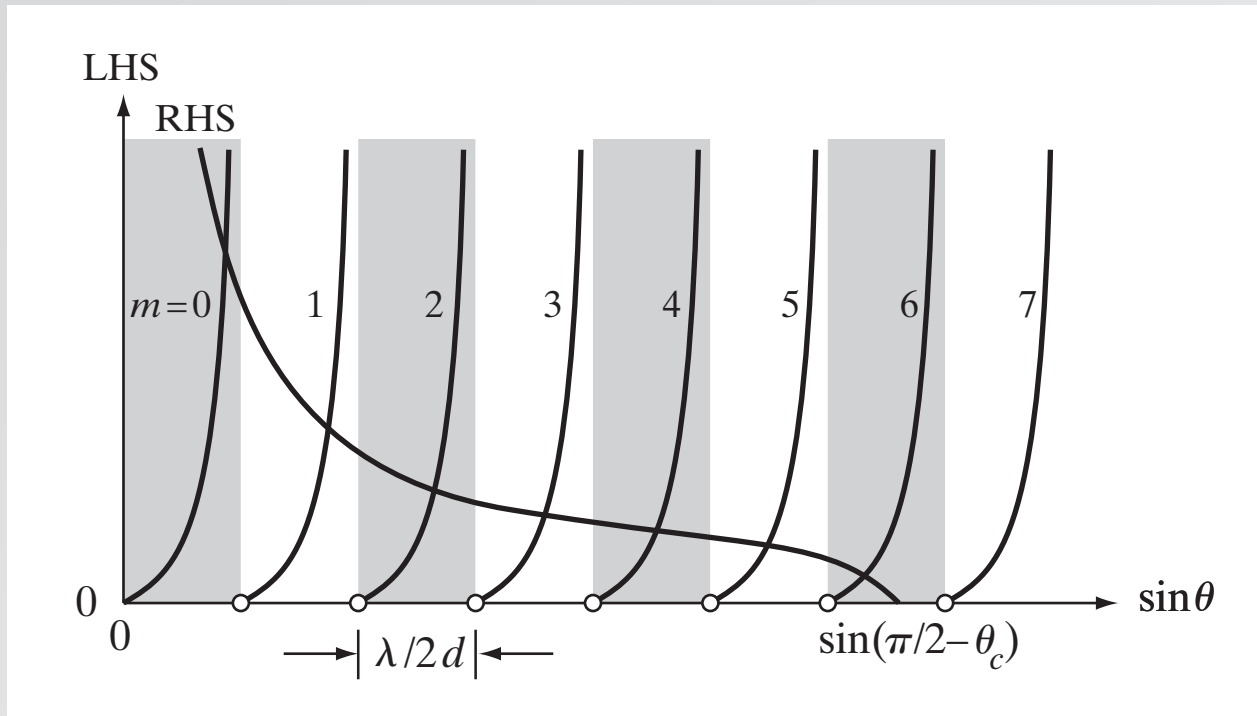
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Waveguiding



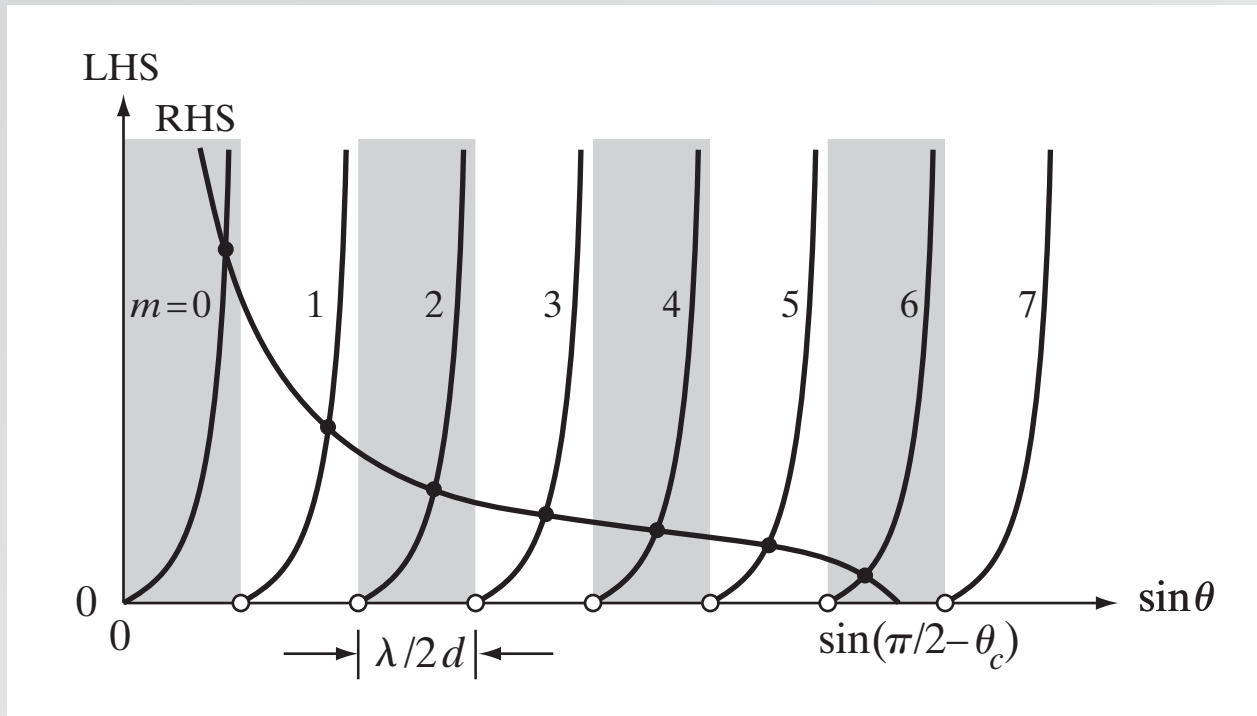
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Waveguiding



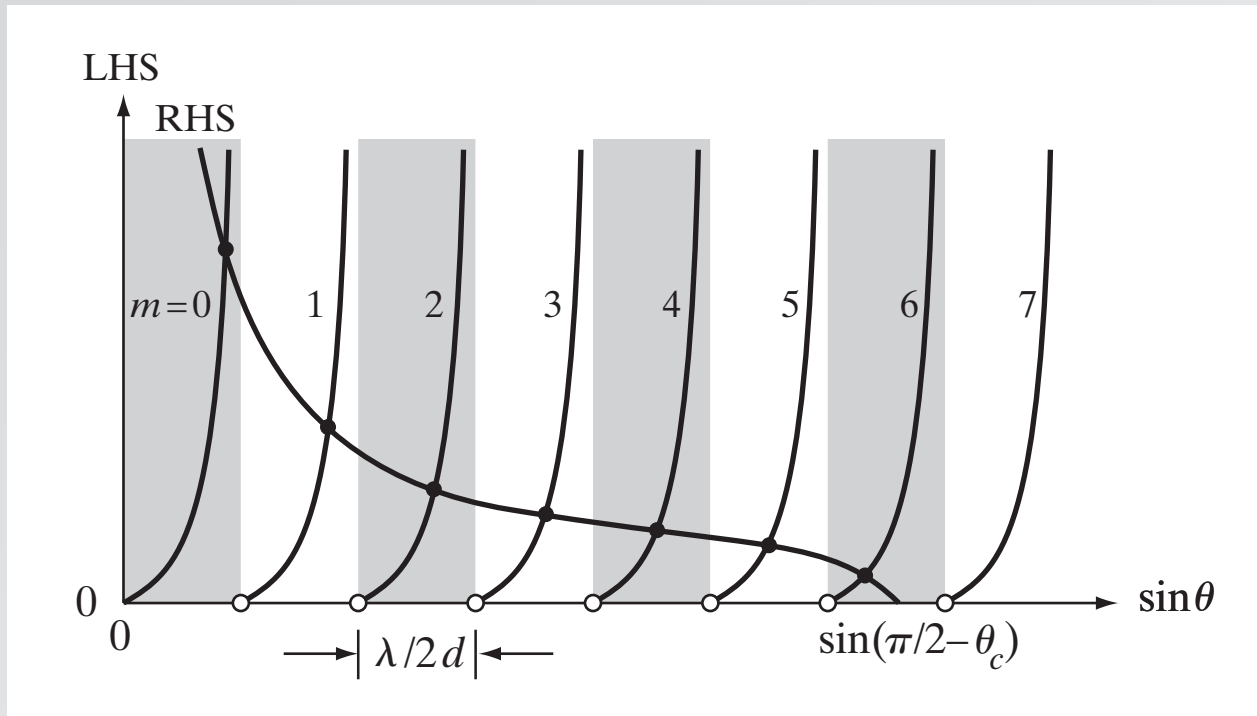
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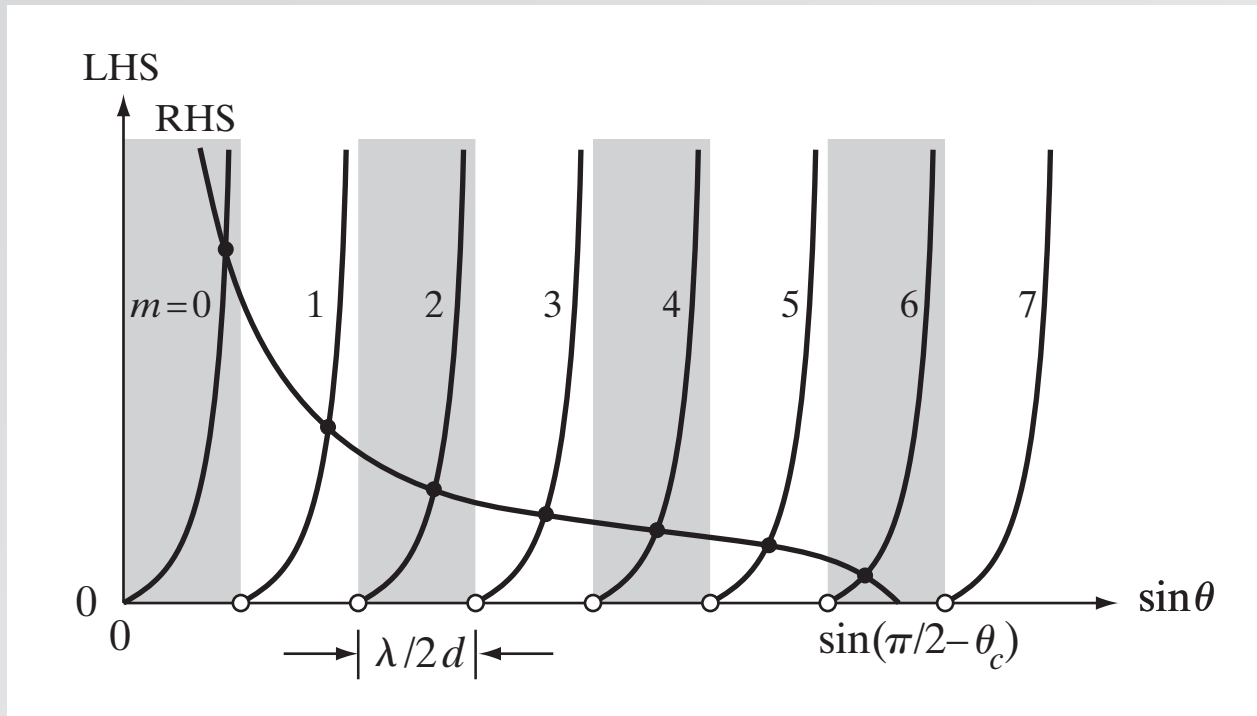
Waveguiding



number of modes:

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

Waveguiding



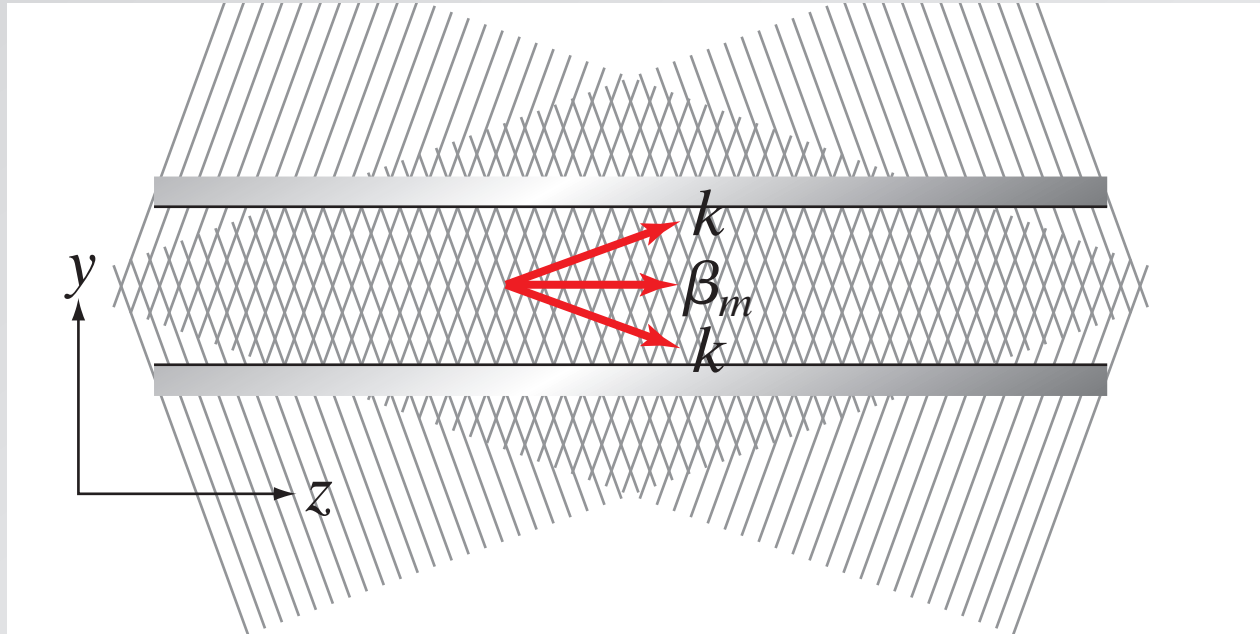
number of modes:

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

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

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

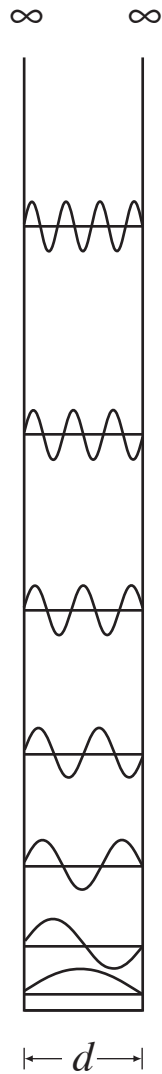
yields:

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

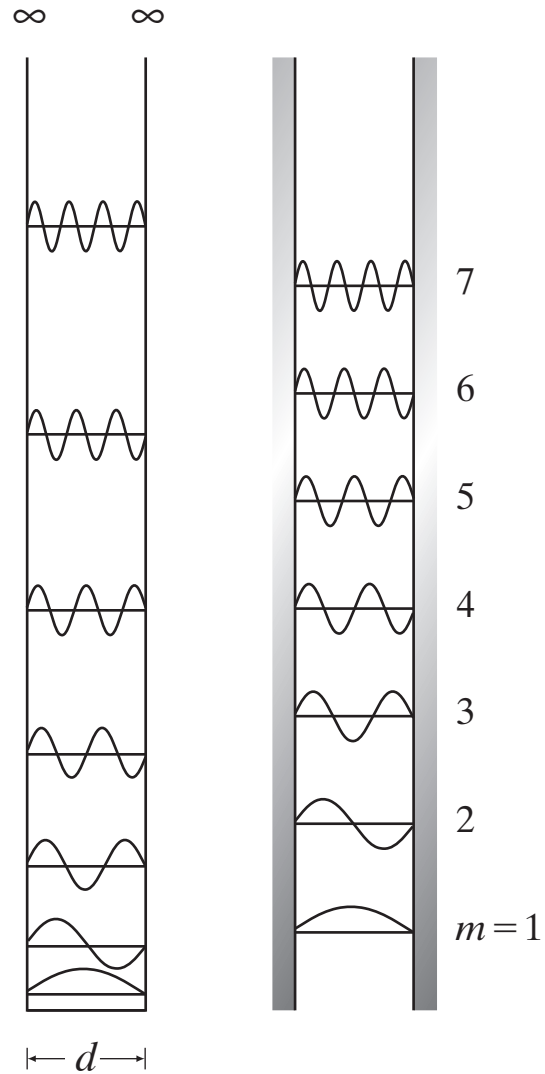
Compare to time-independent Schrödinger equation:

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

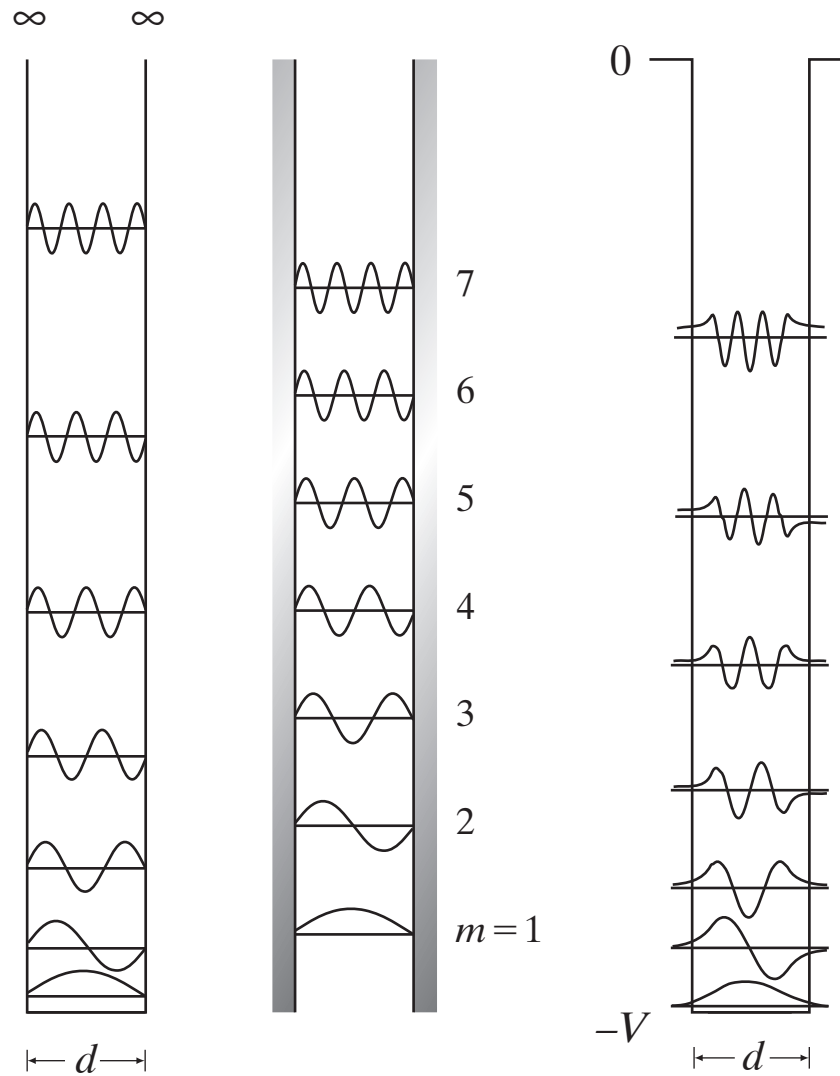
Waveguiding



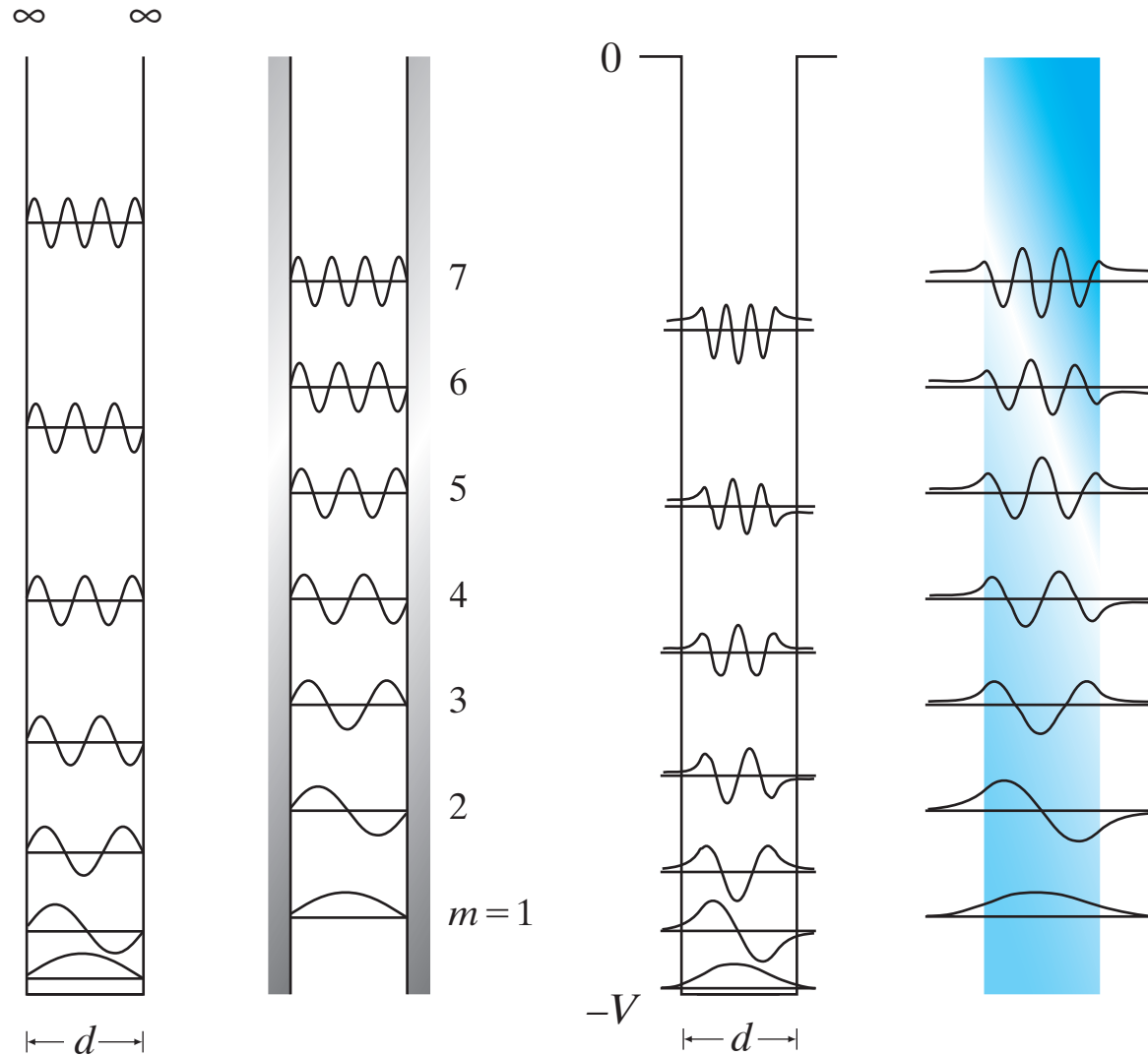
Waveguiding



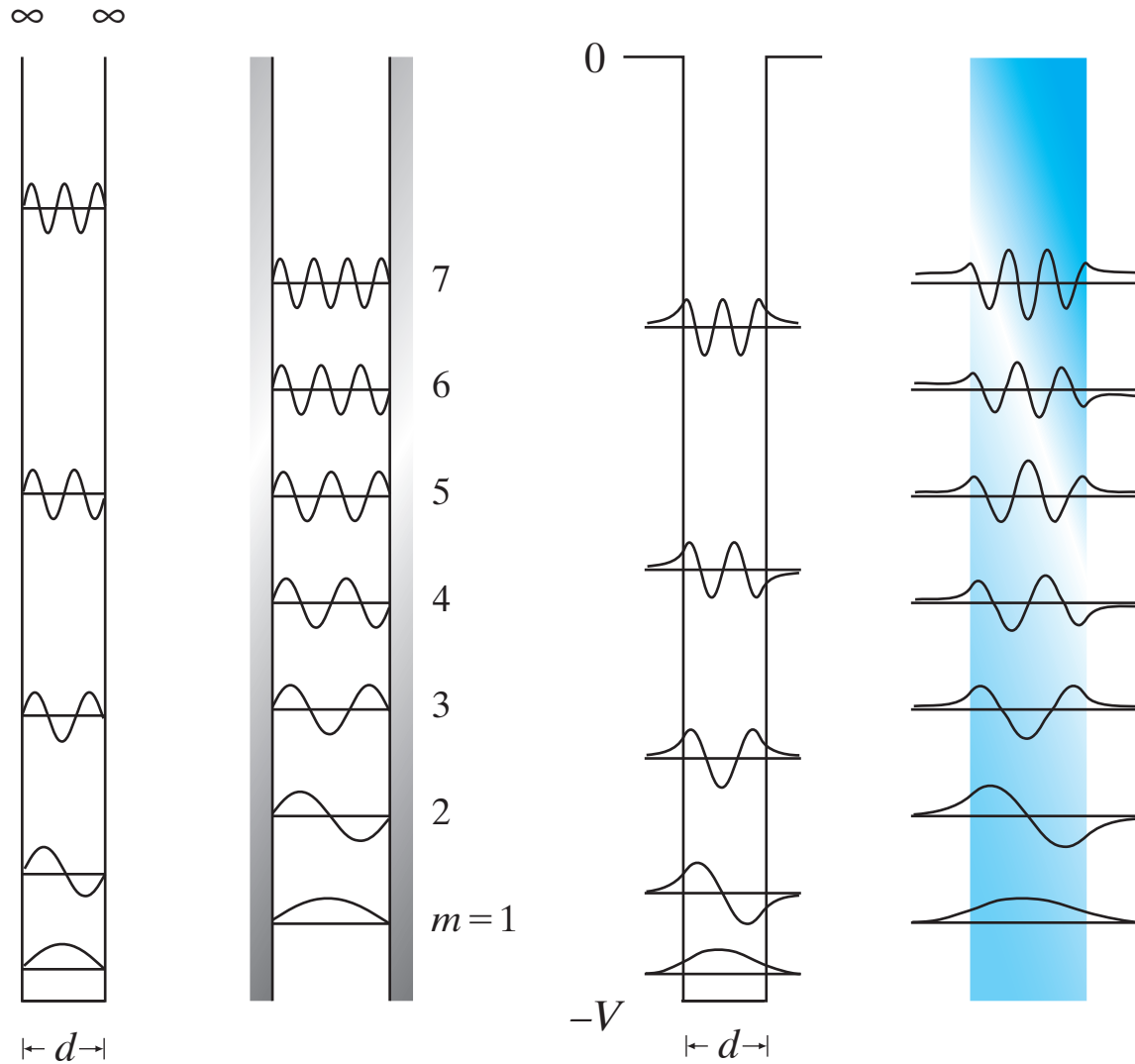
Waveguiding



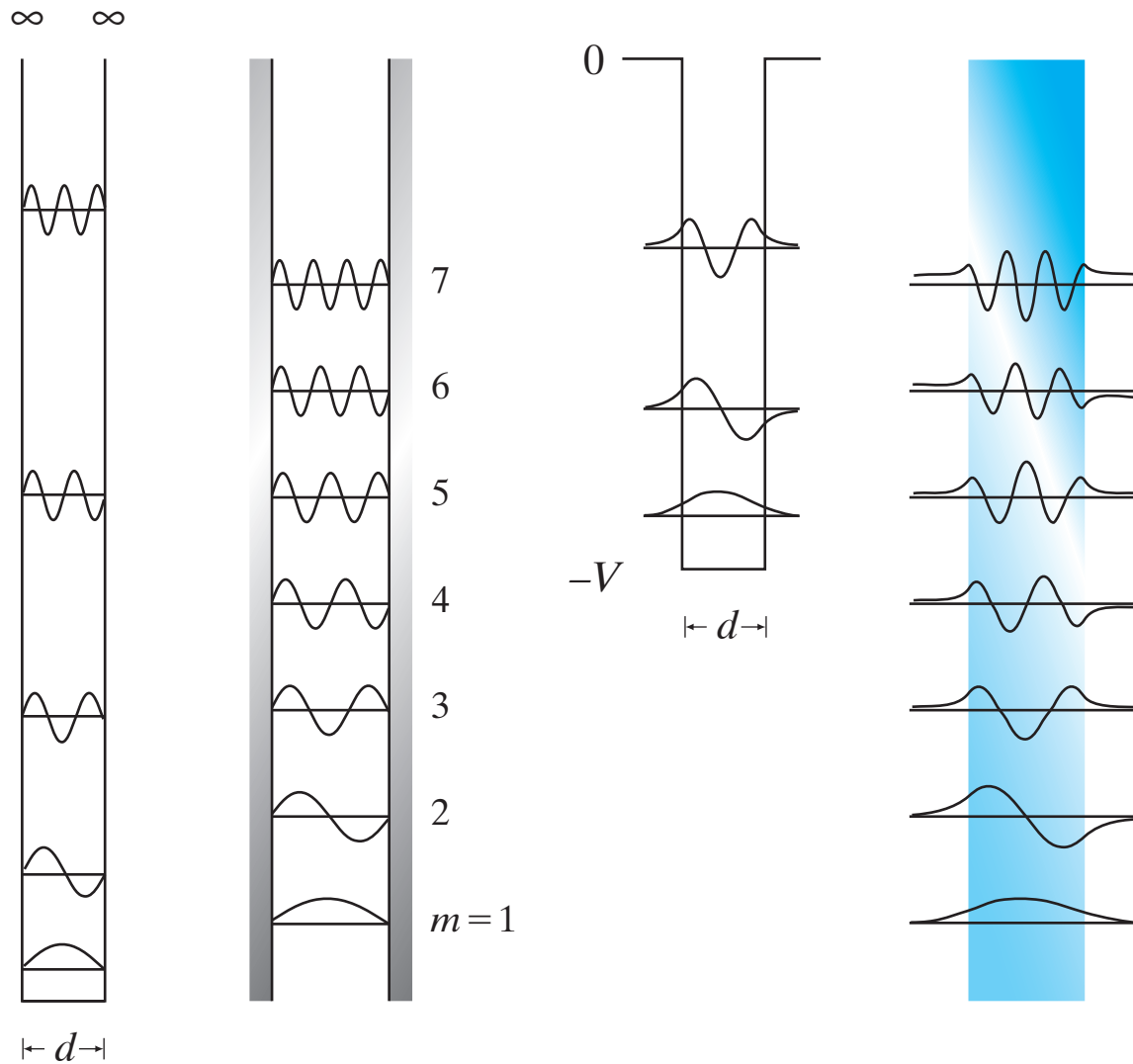
Waveguiding



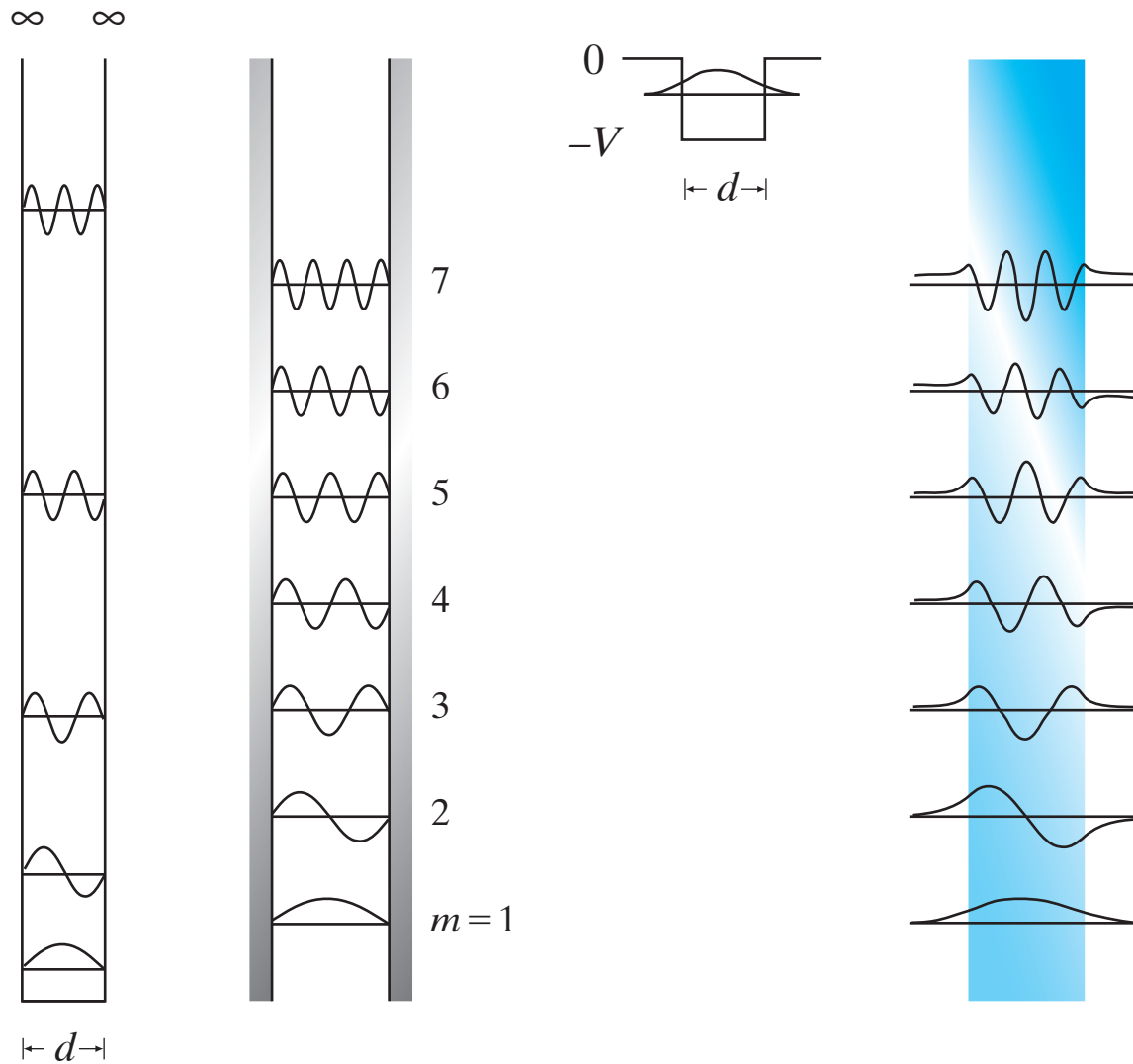
Waveguiding



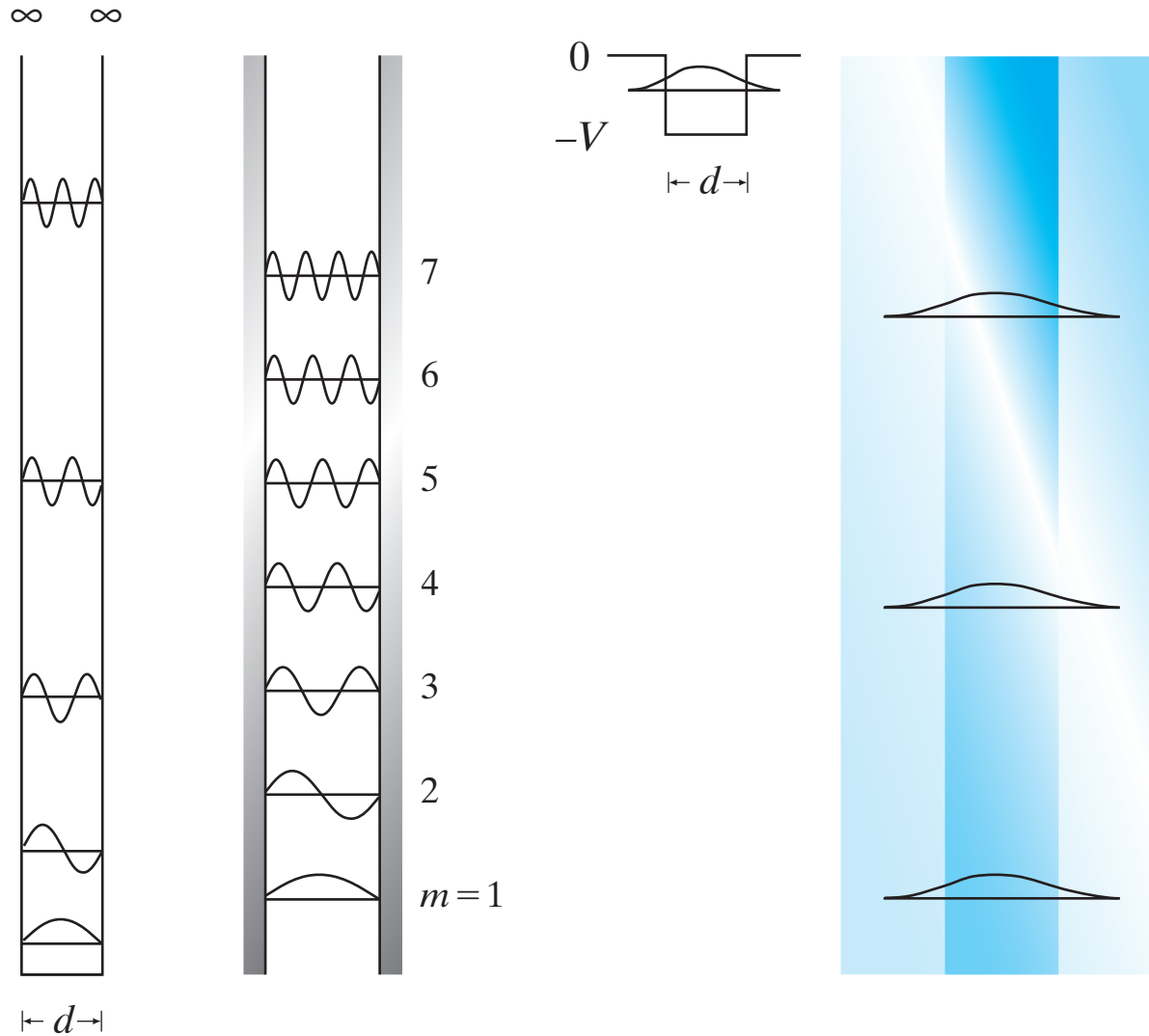
Waveguiding



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: | $8.3 \mu\text{m}$ | $125.0 \pm 1.0 \mu\text{m}$ |

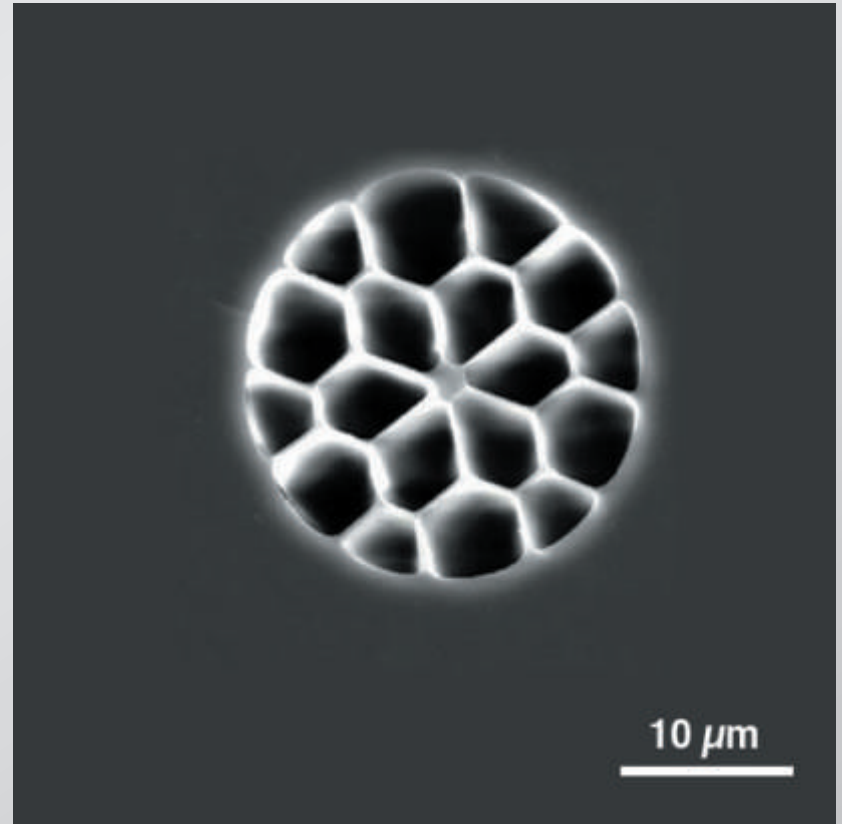
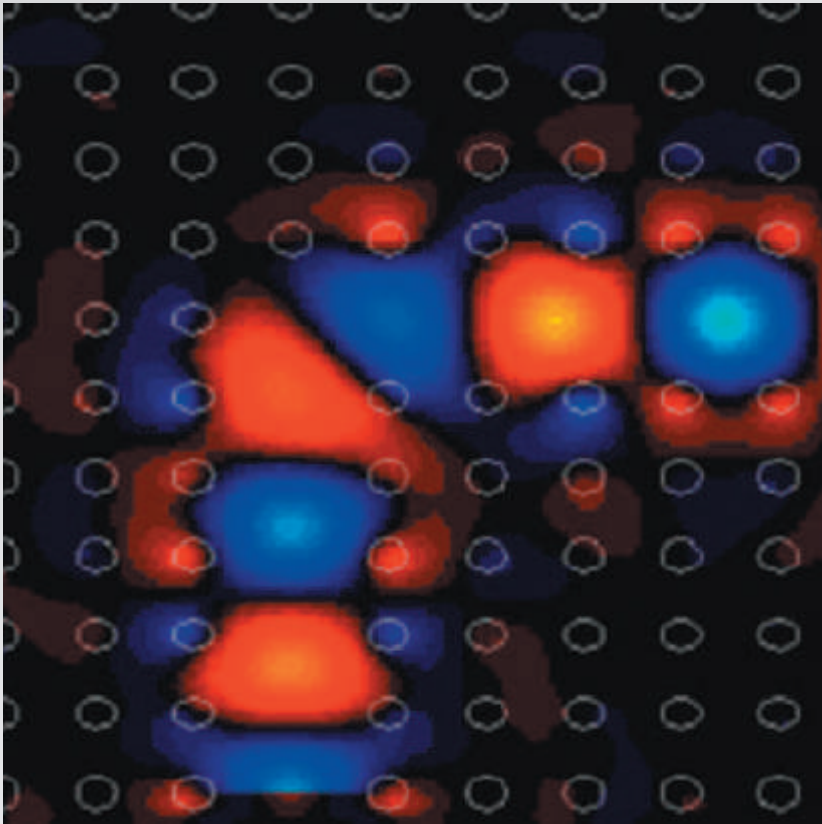
operating wavelength: $\lambda = 1310 \text{ nm}/1550 \text{ nm}$

Waveguiding

drawbacks of clad fibers:

- **weak confinement**
- **no tight bending**
- **coupling requires splicing**

Waveguiding



Outline

- waveguiding
- nanowire fabrication
- optical properties

Nanowire fabrication

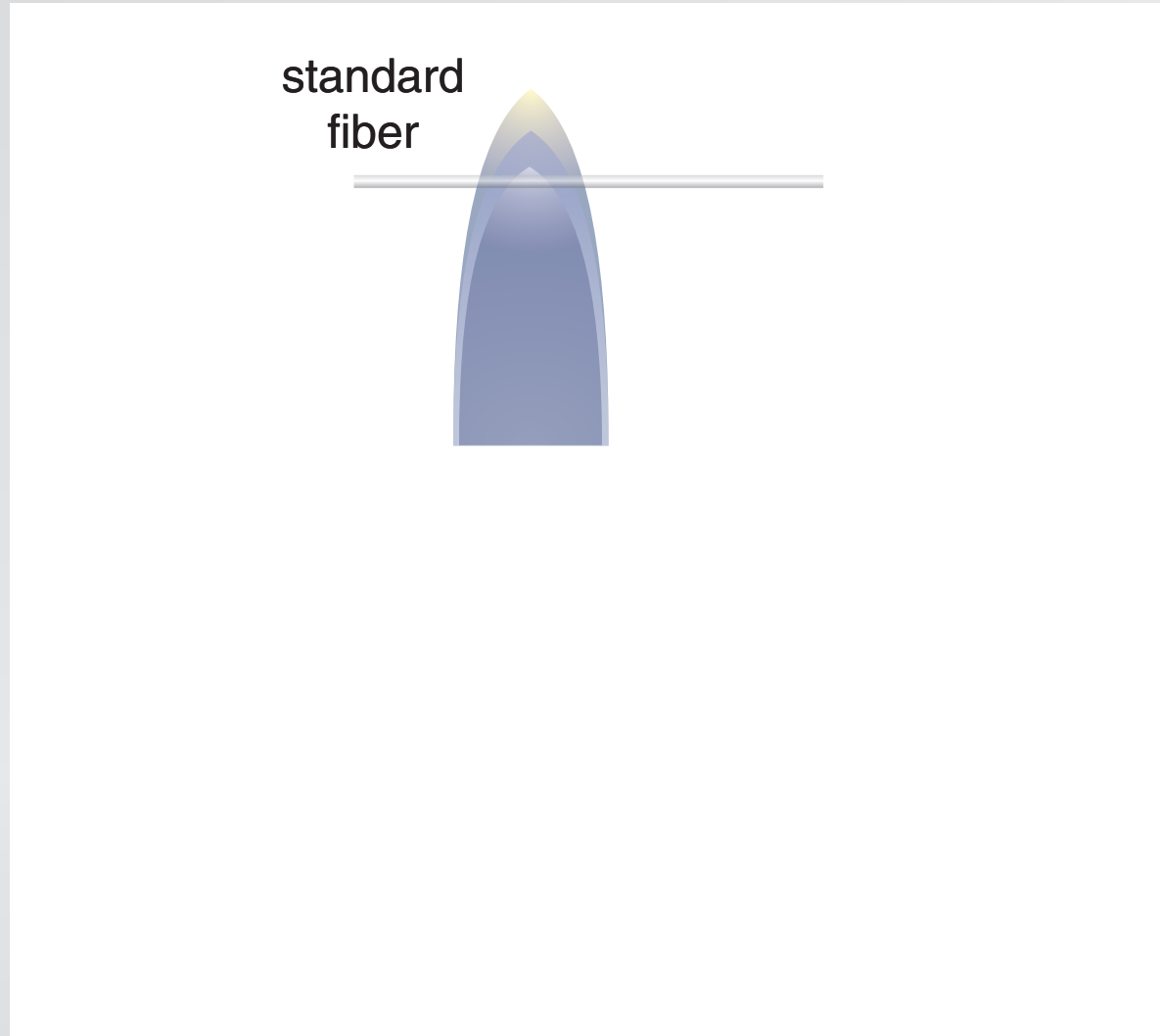
two-step drawing process

standard
fiber



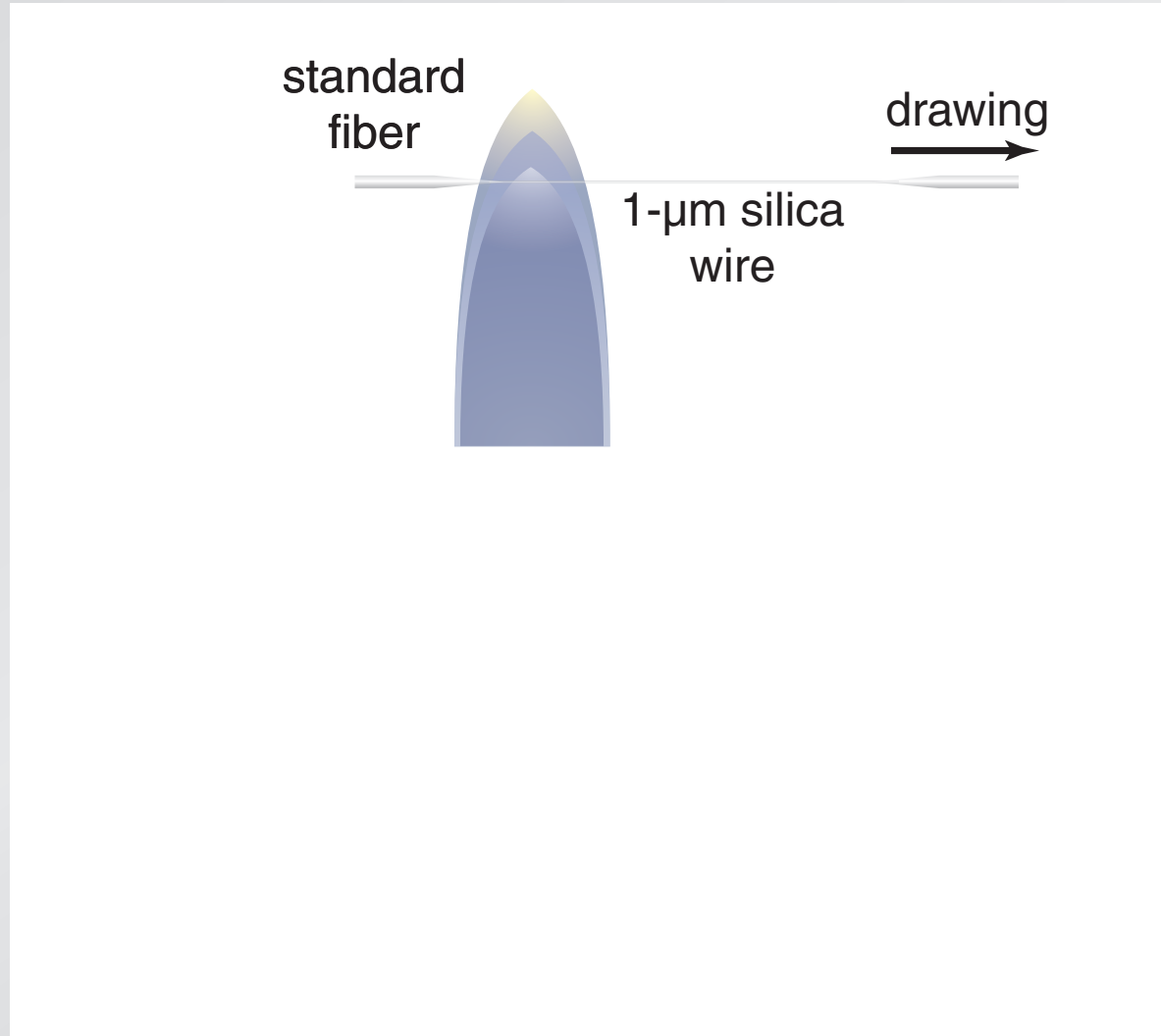
Nanowire fabrication

two-step drawing process



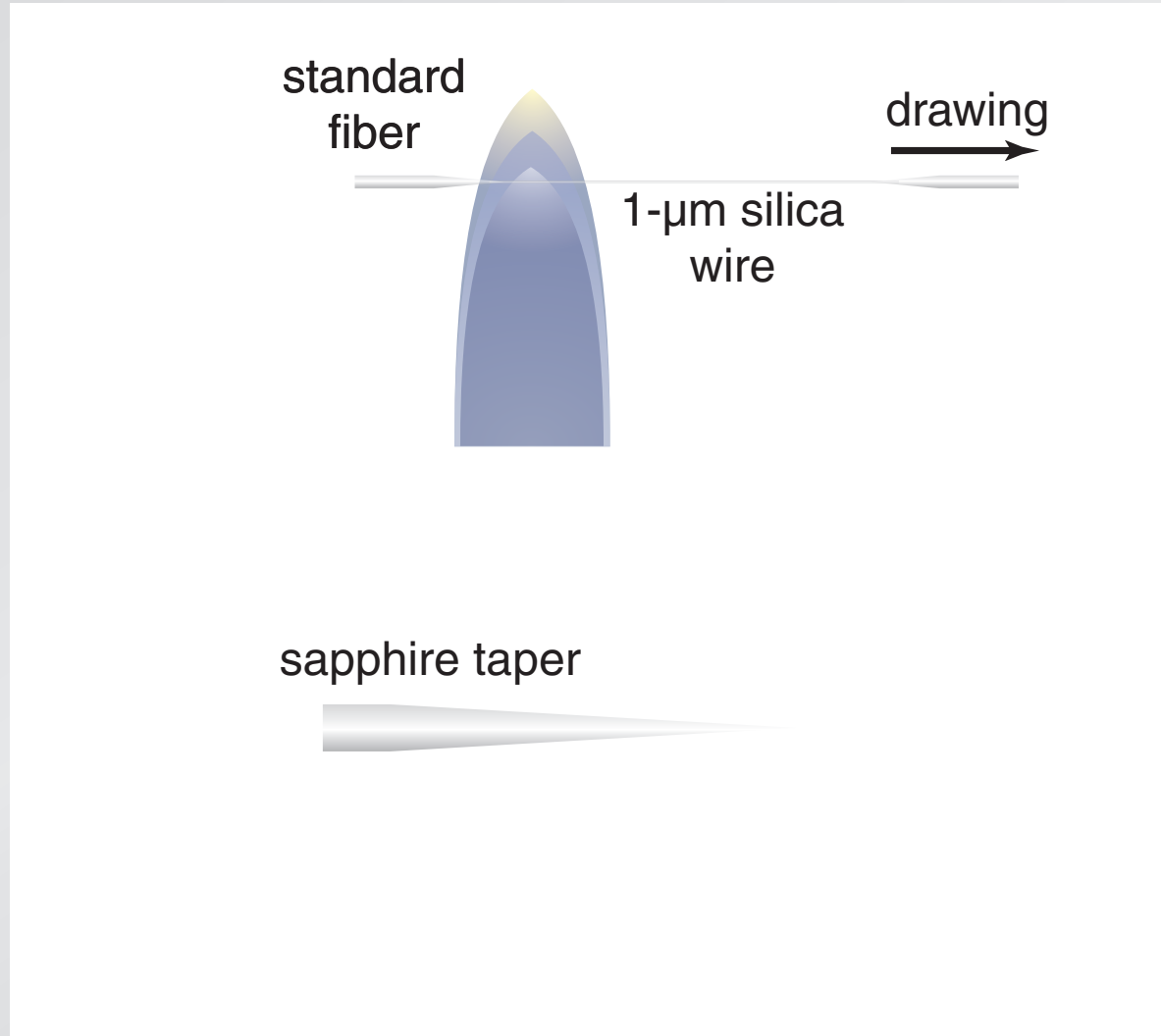
Nanowire fabrication

two-step drawing process



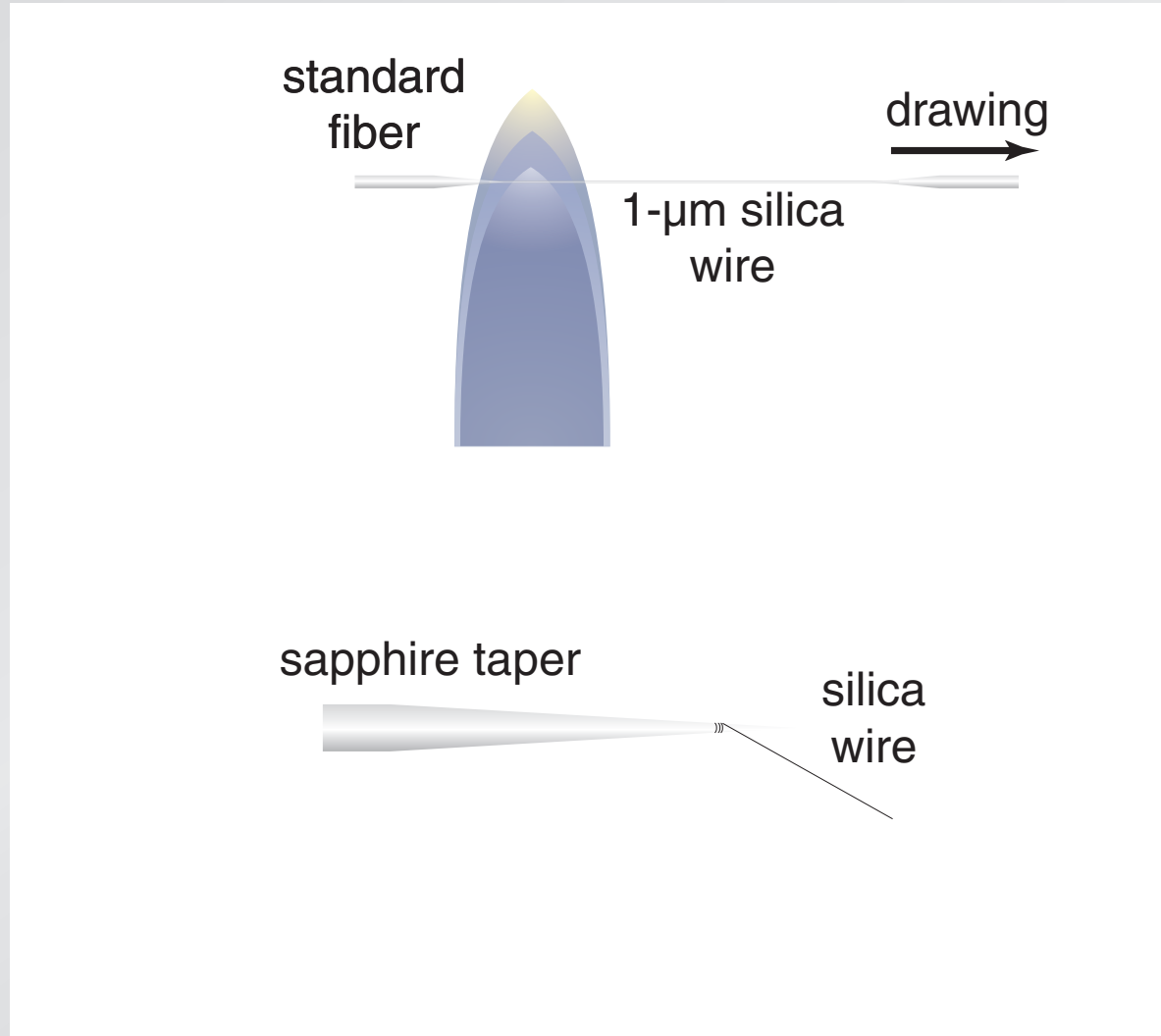
Nanowire fabrication

two-step drawing process



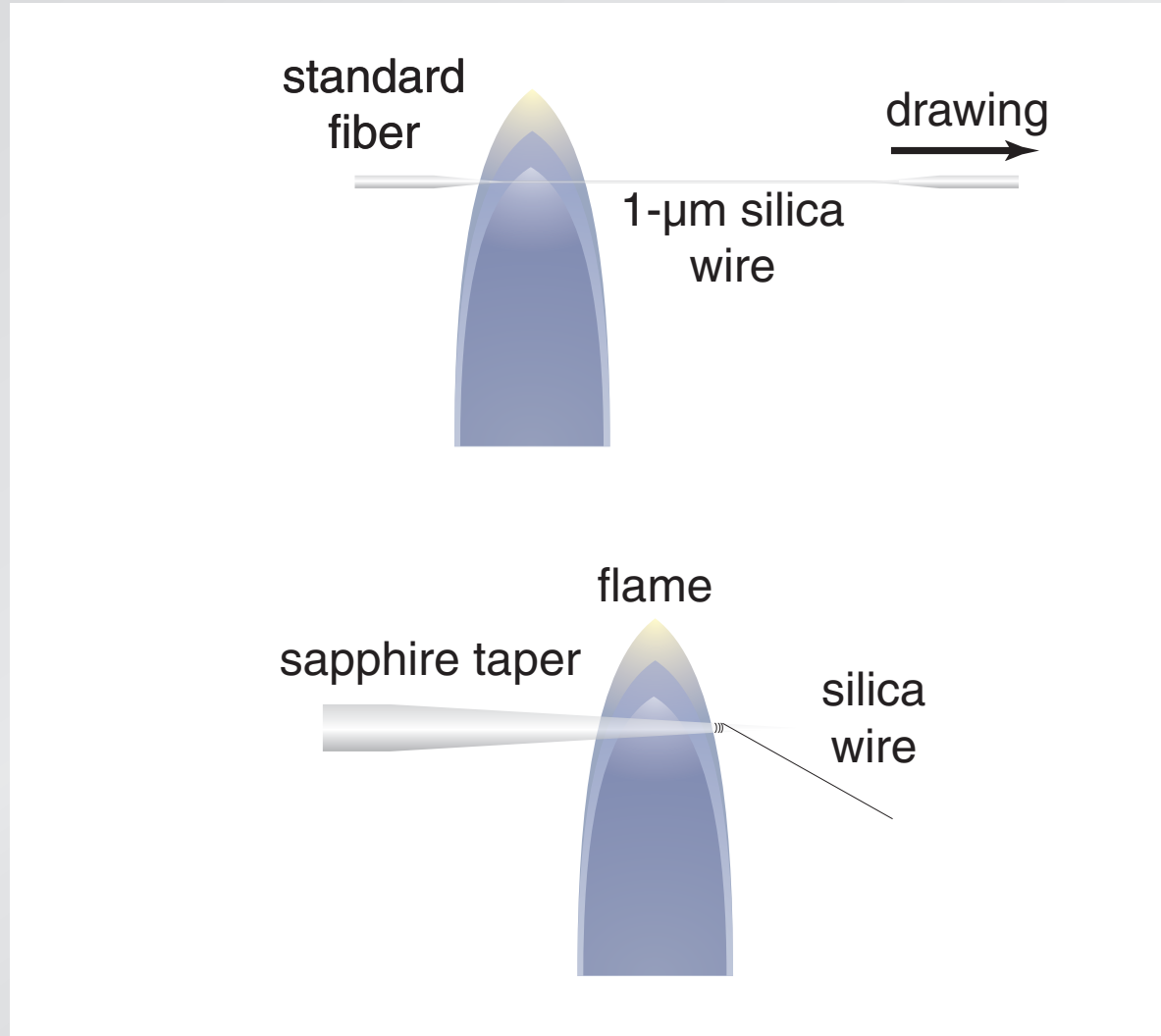
Nanowire fabrication

two-step drawing process



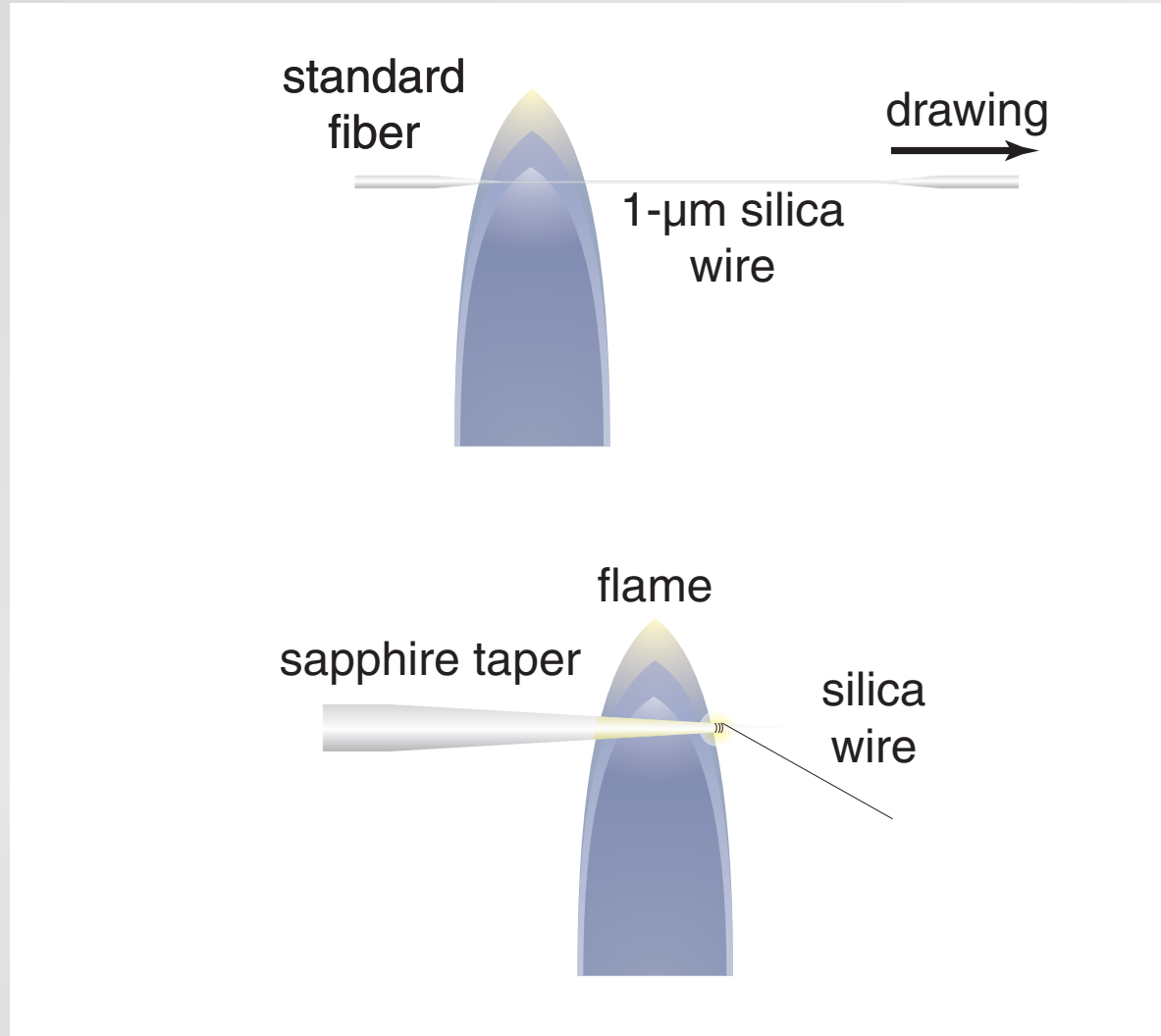
Nanowire fabrication

two-step drawing process



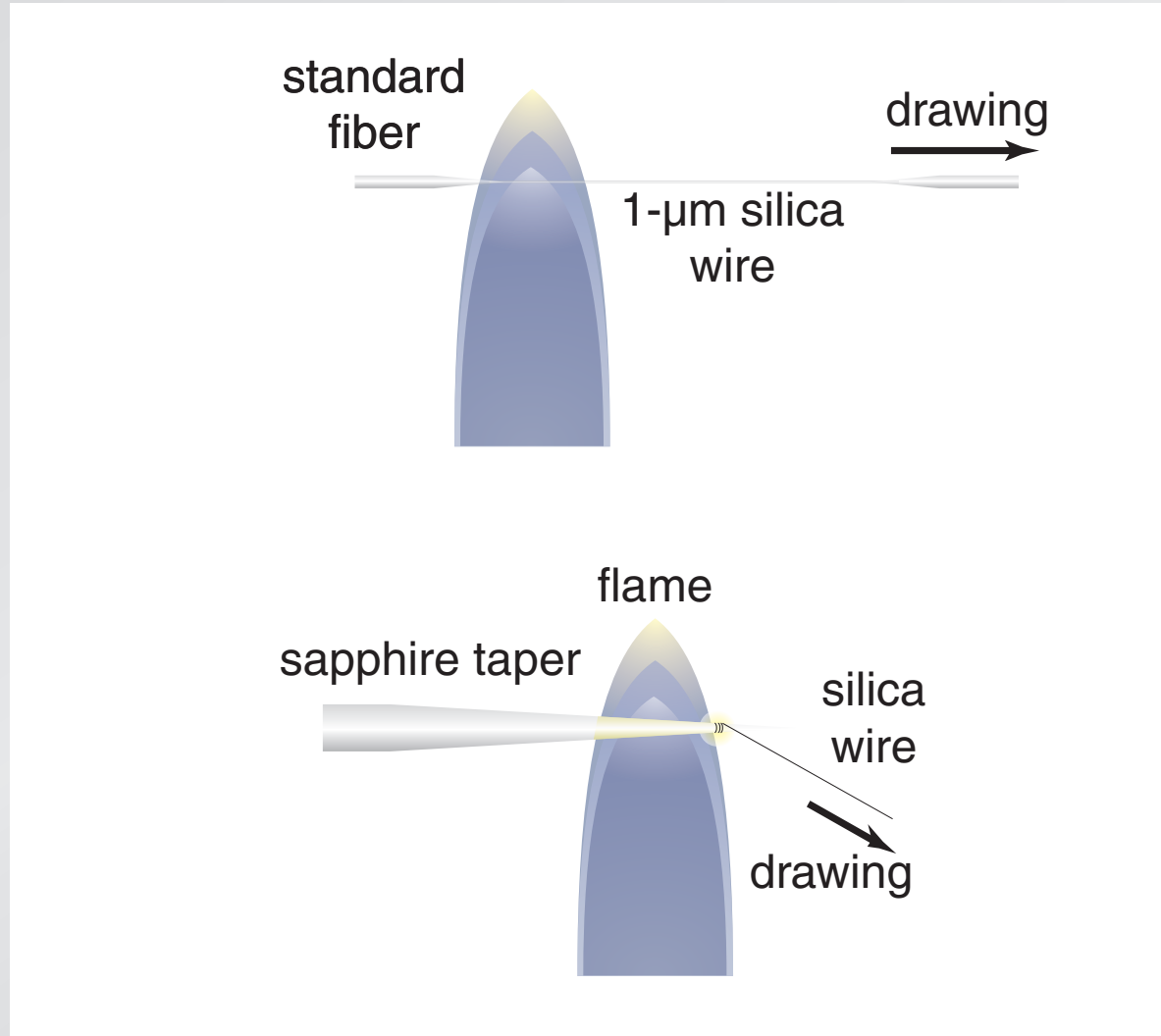
Nanowire fabrication

two-step drawing process

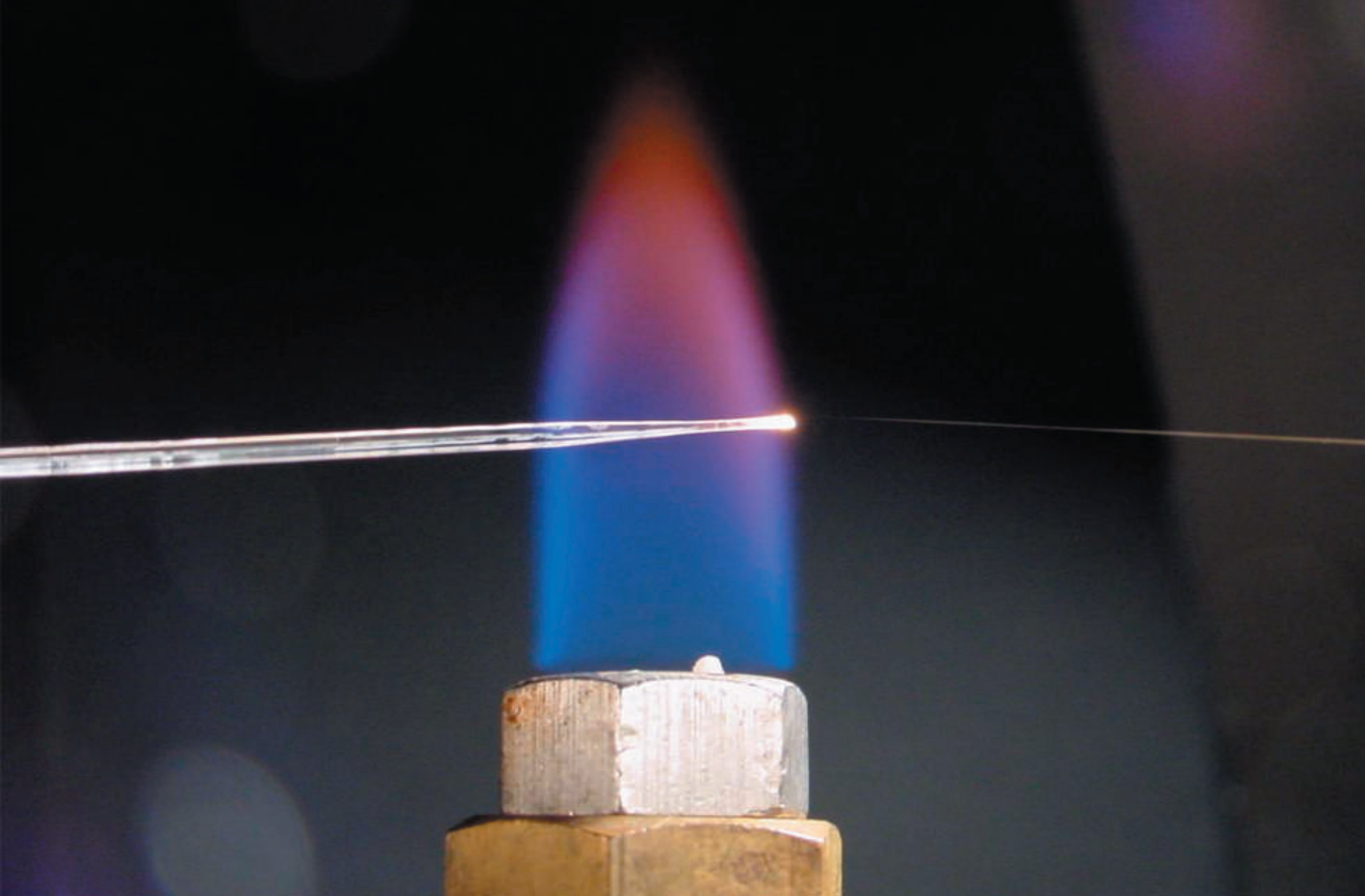


Nanowire fabrication

two-step drawing process



Nanowire fabrication



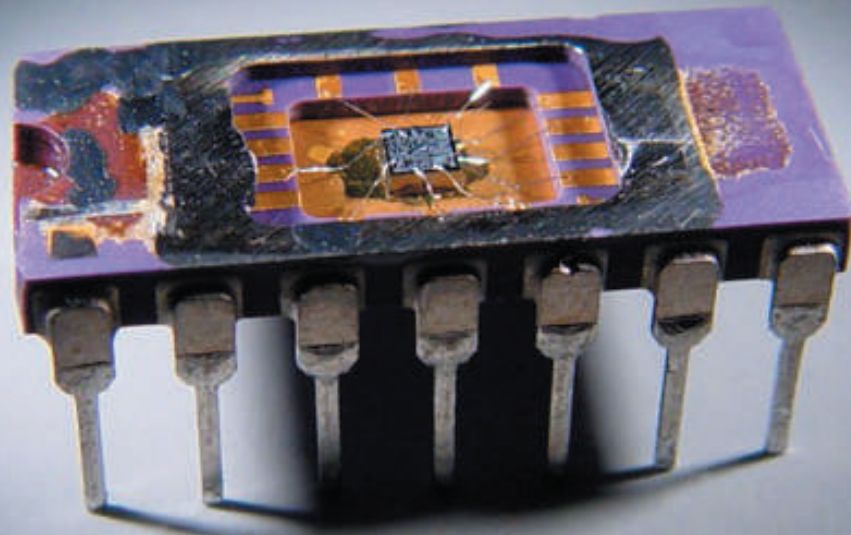
Nanowire fabrication

1 μm

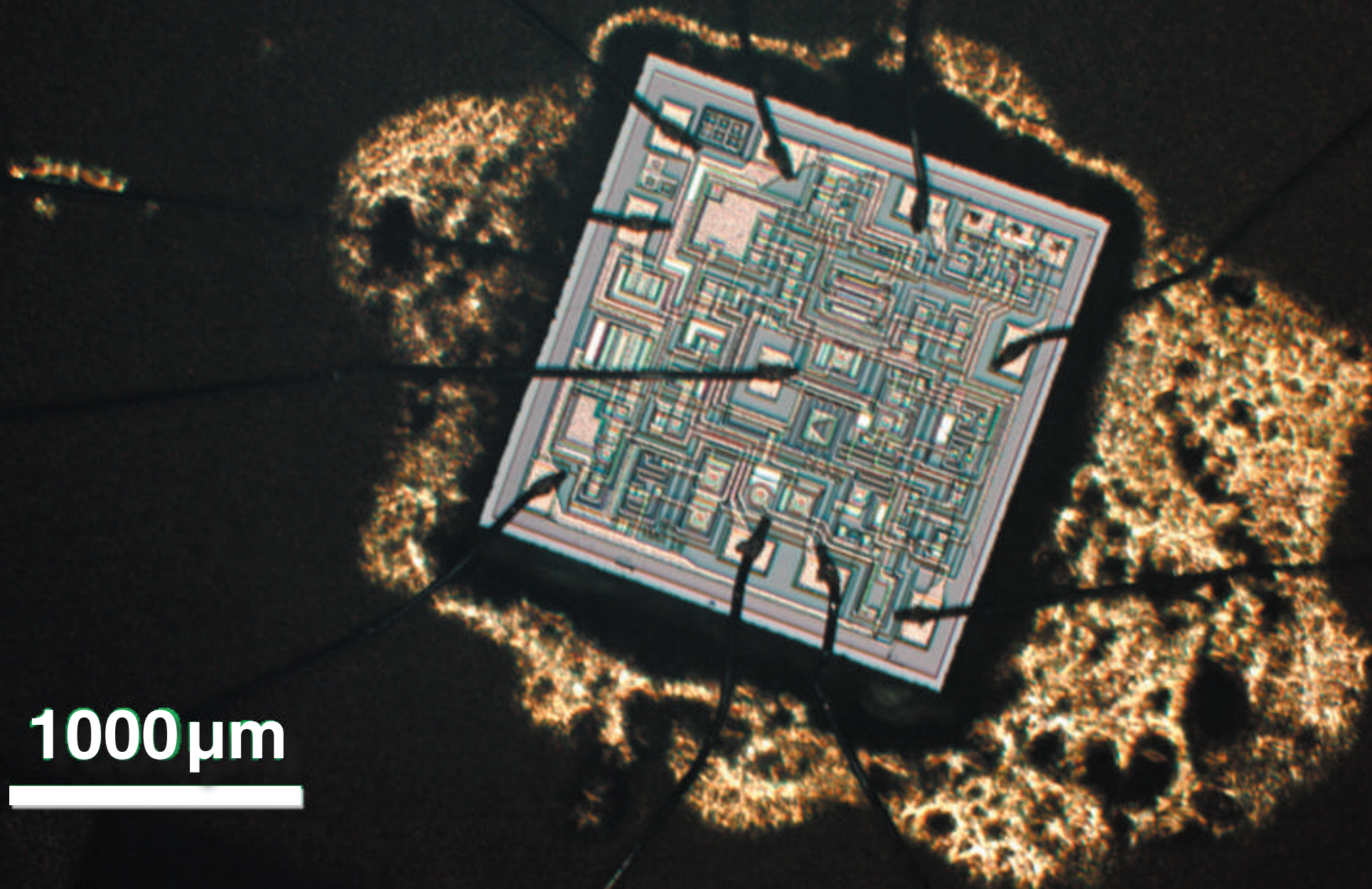


Nature, 426, 816 (2003)

Nanowire fabrication

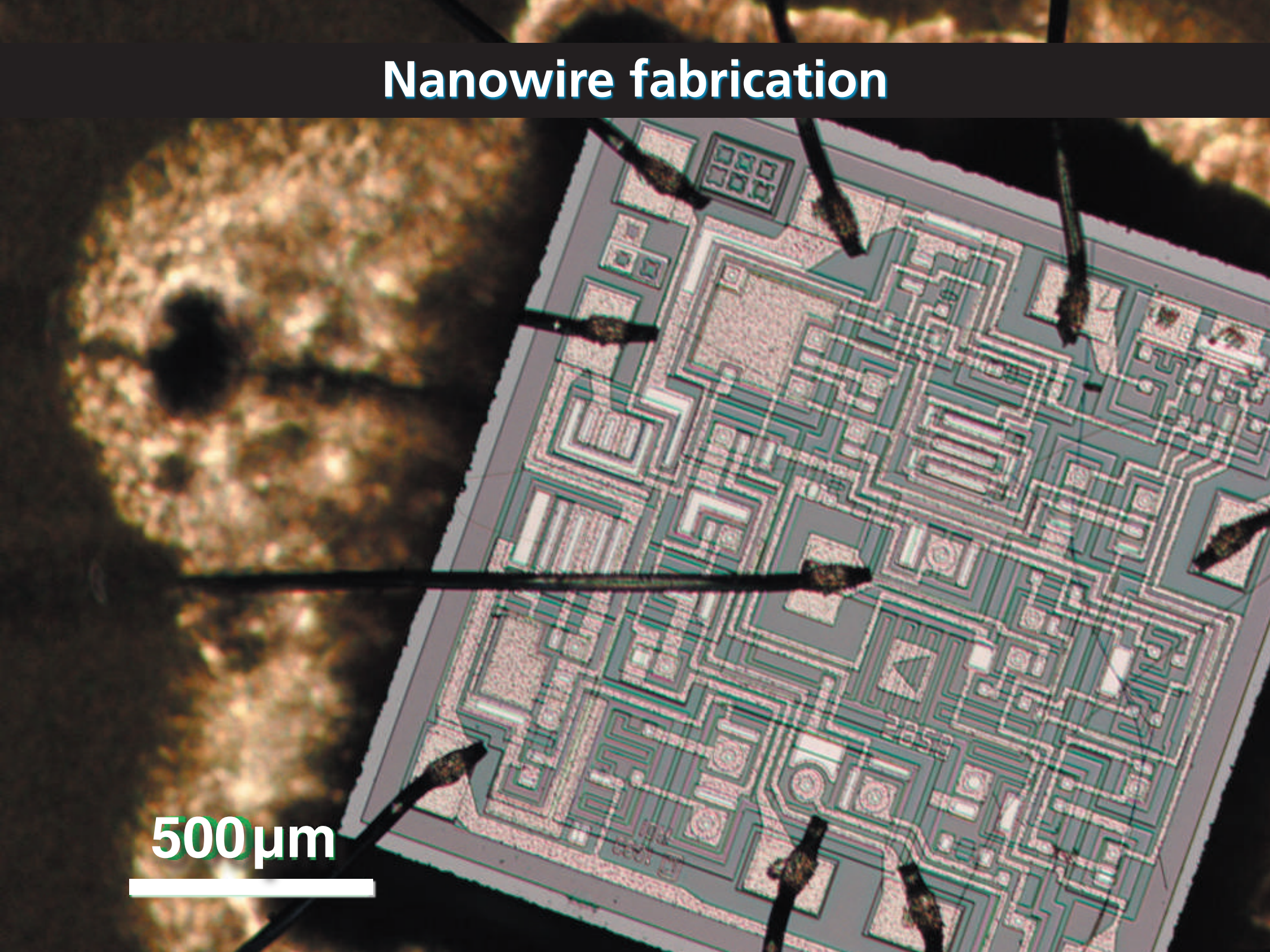


Nanowire fabrication

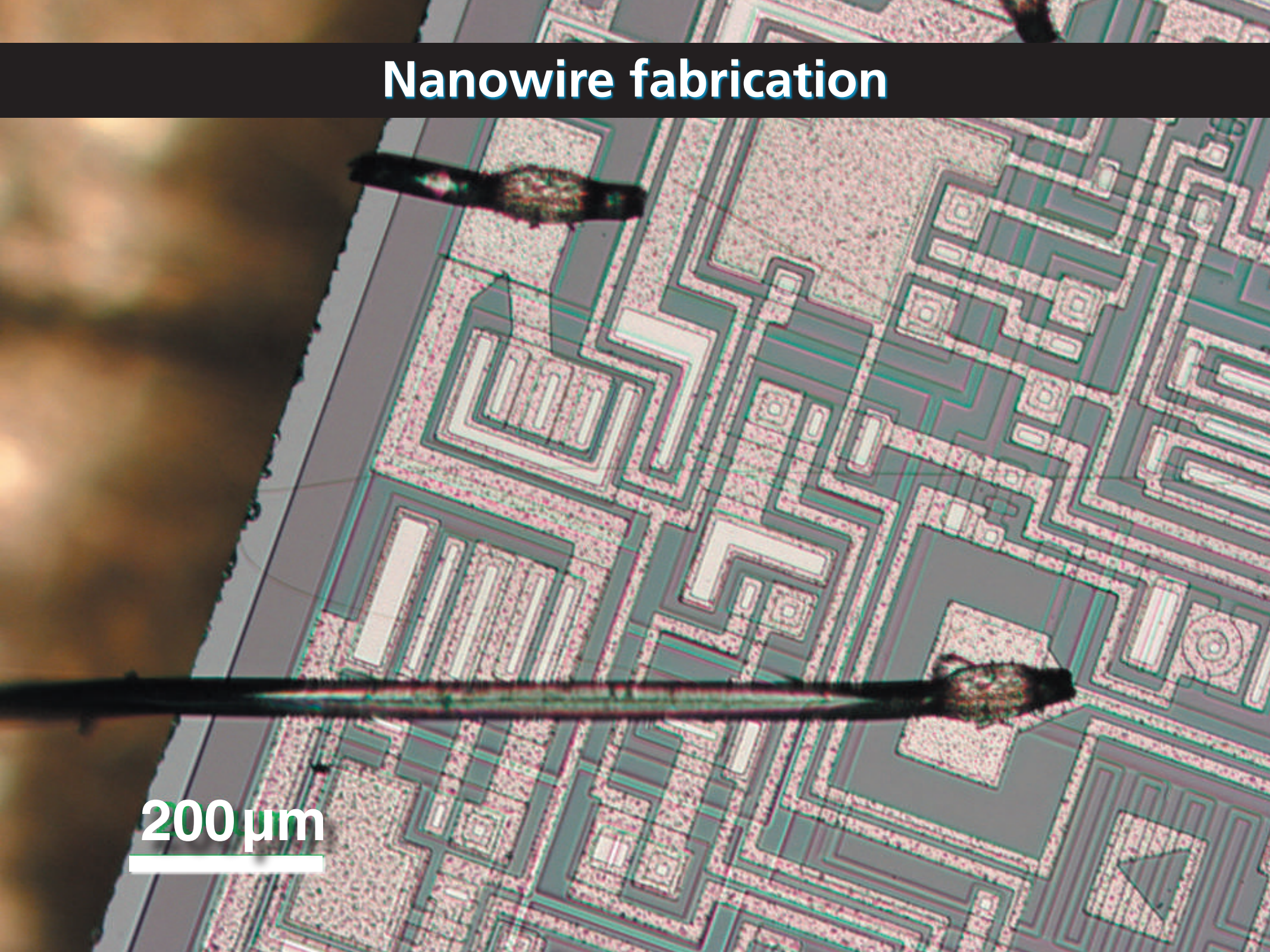


Nanowire fabrication

500 μm

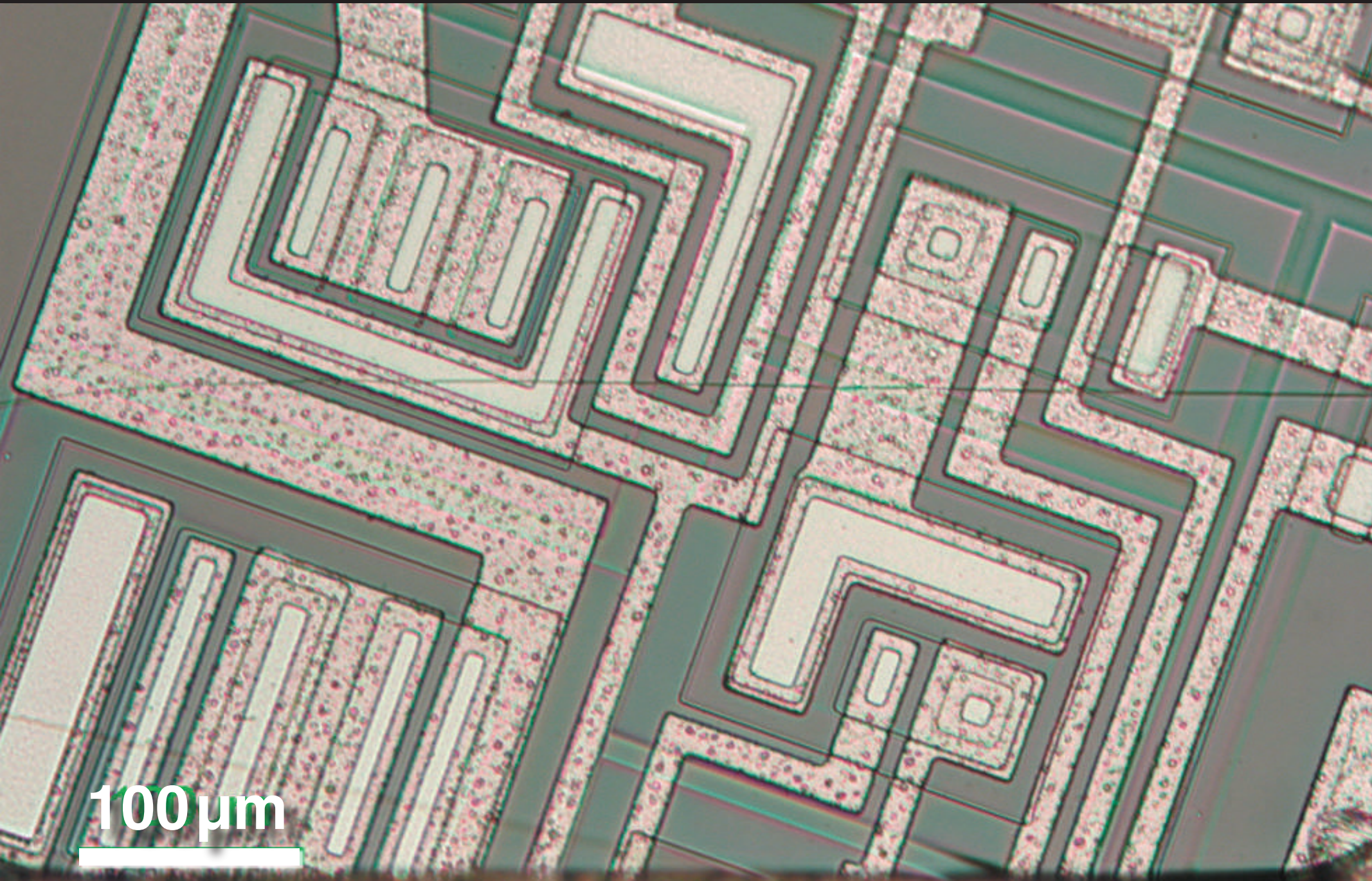


Nanowire fabrication

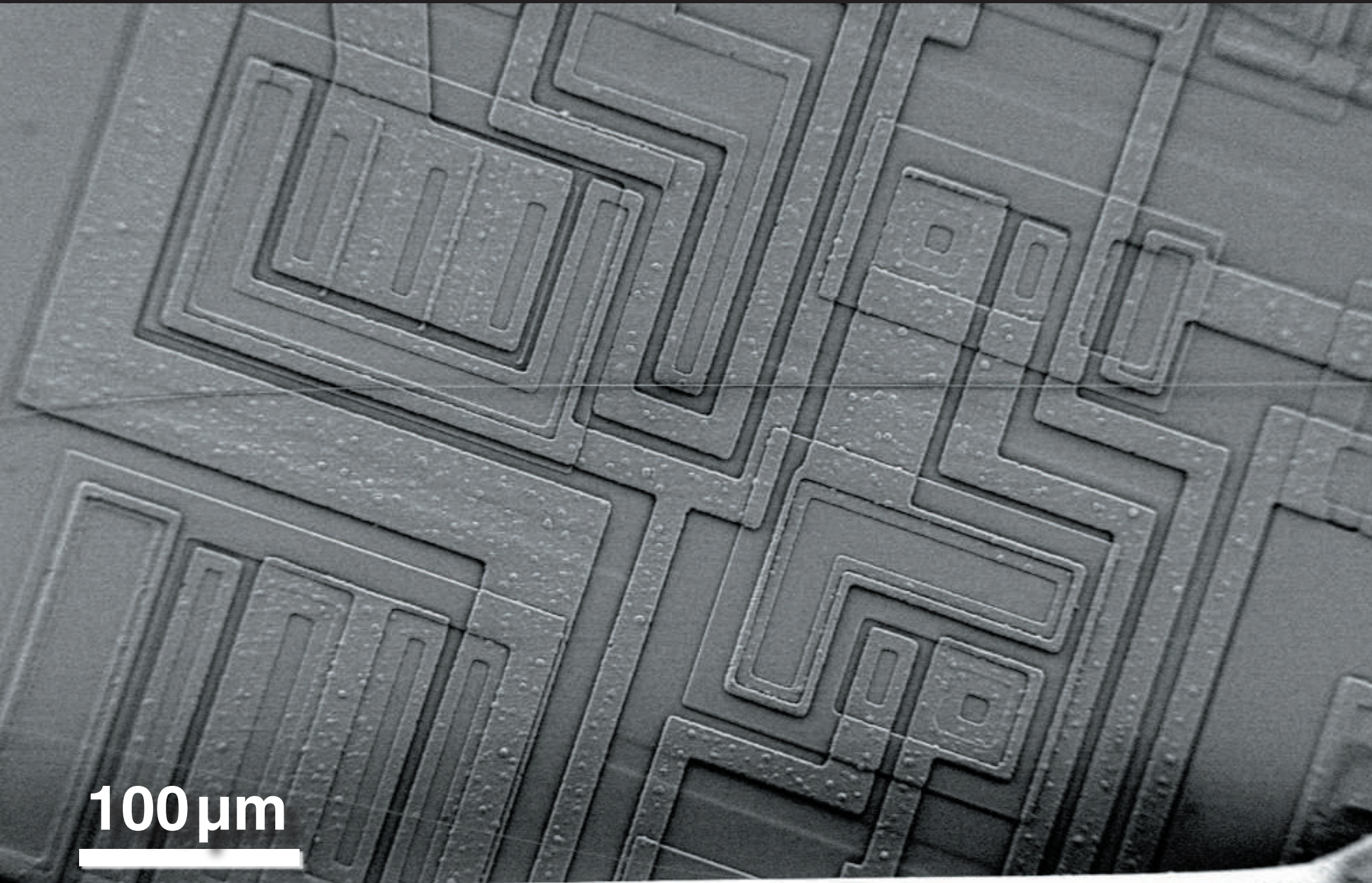


200 μm

Nanowire fabrication



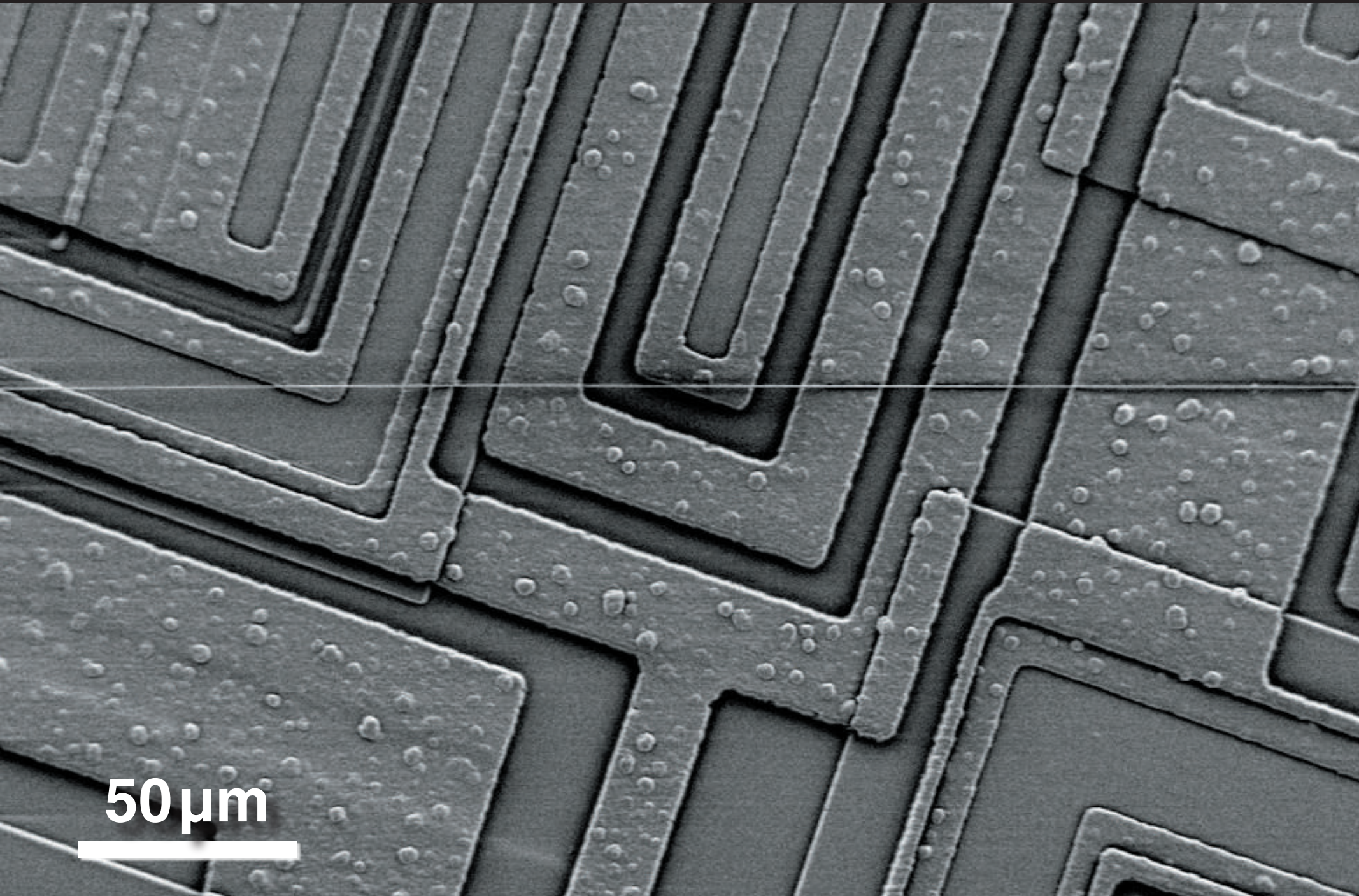
Nanowire fabrication



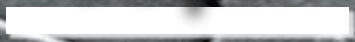
100 μm



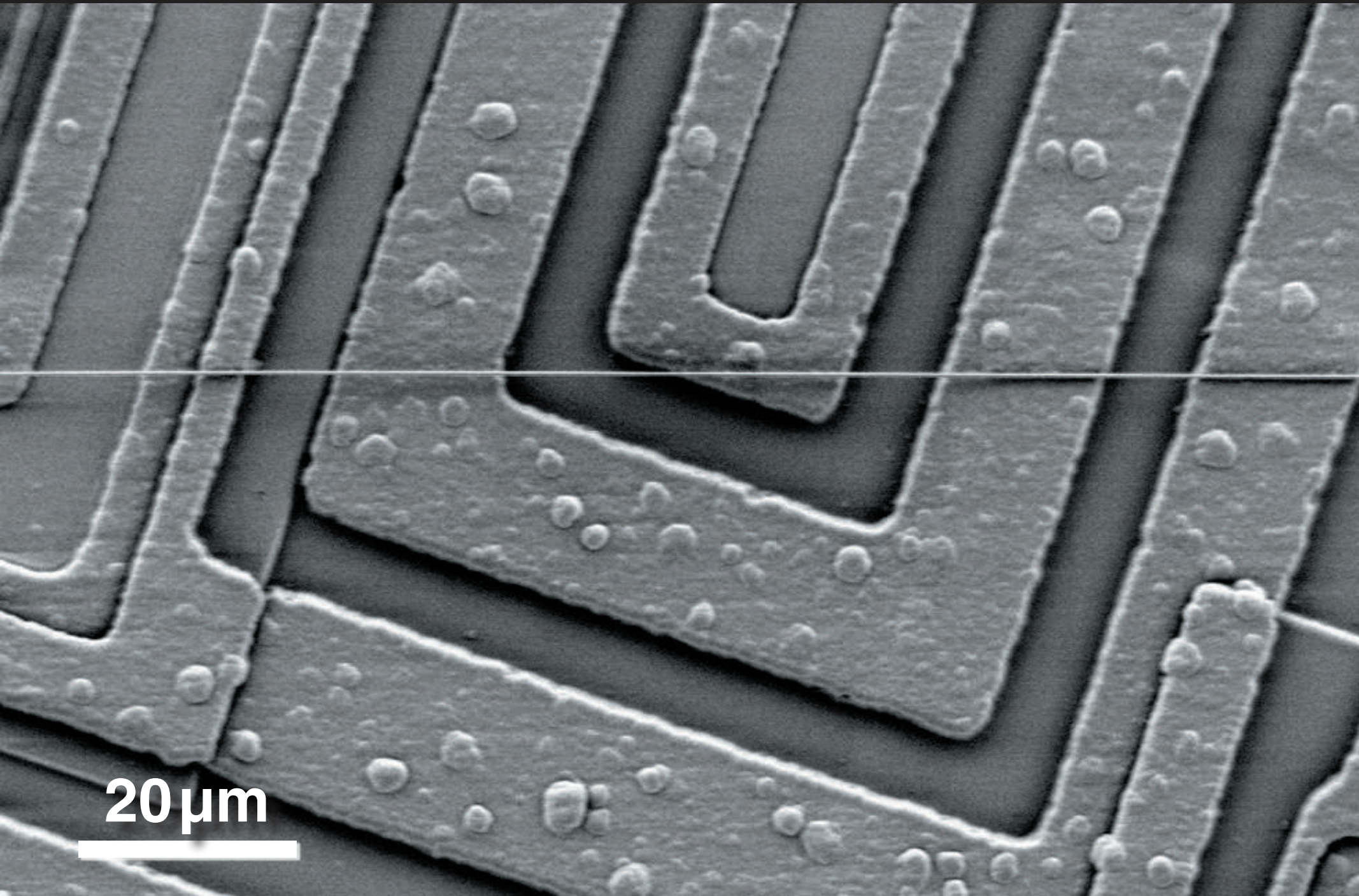
Nanowire fabrication



50 μm

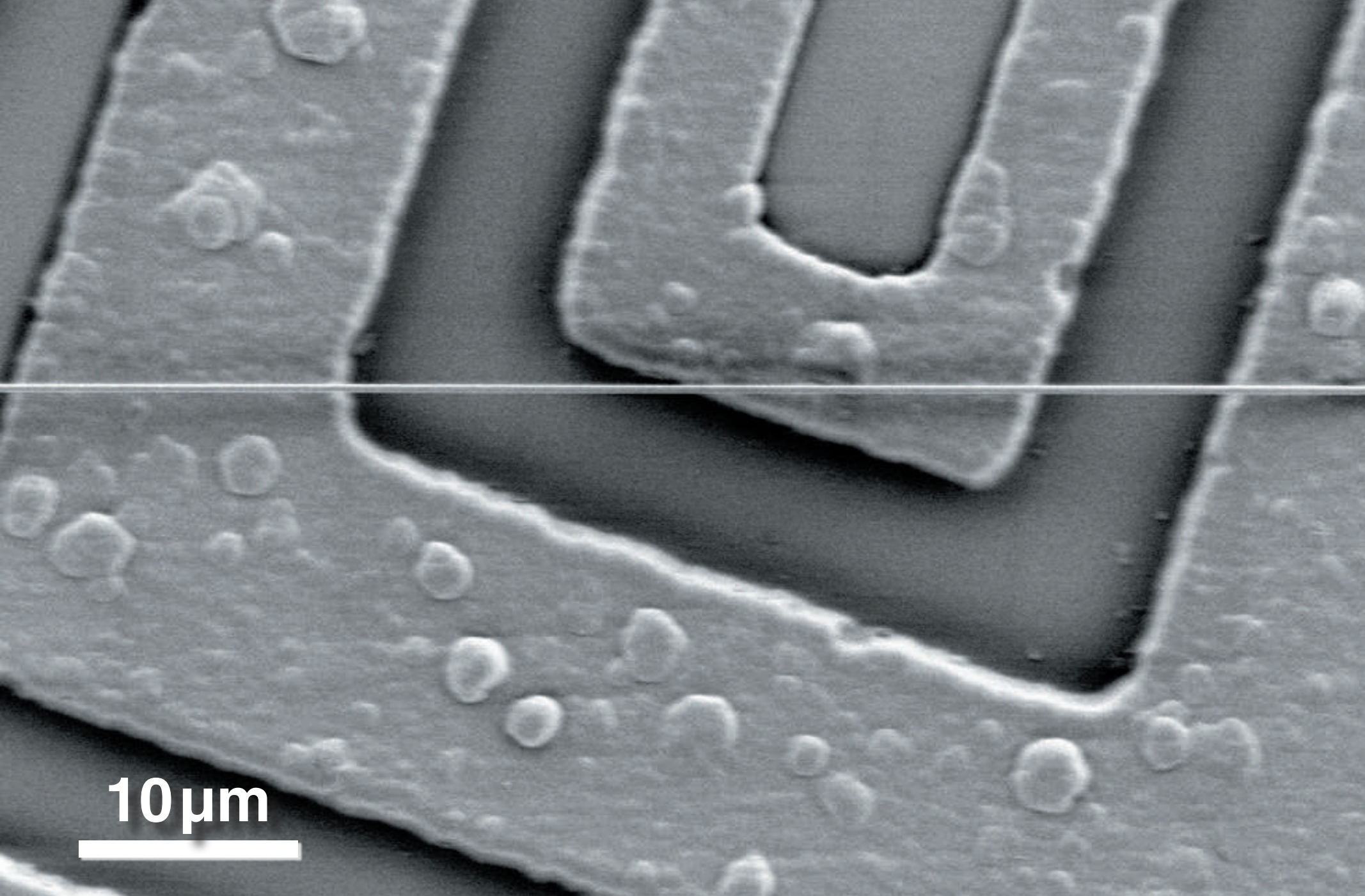


Nanowire fabrication

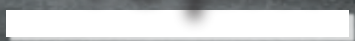


20 μm

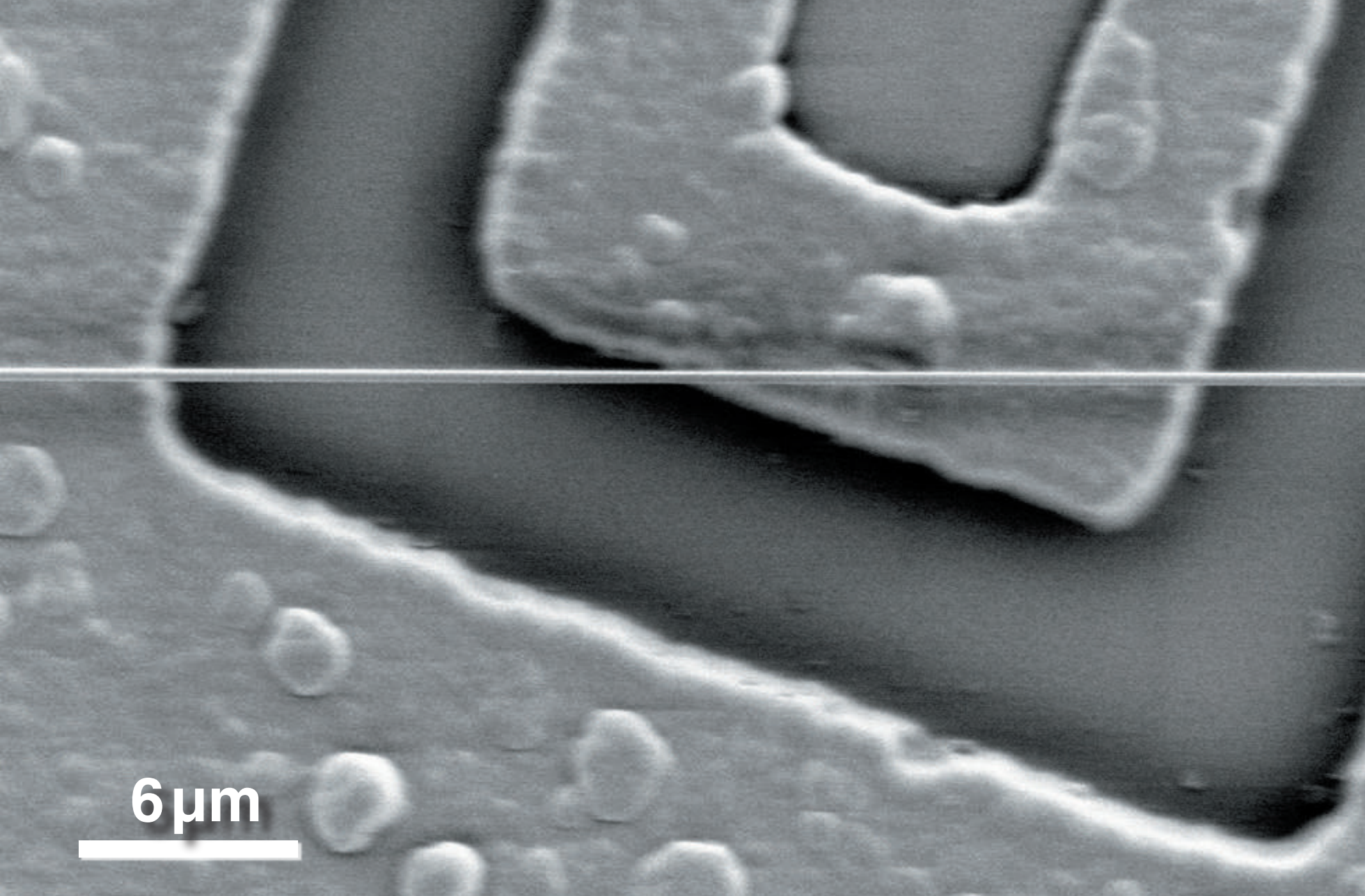
Nanowire fabrication



10 μm



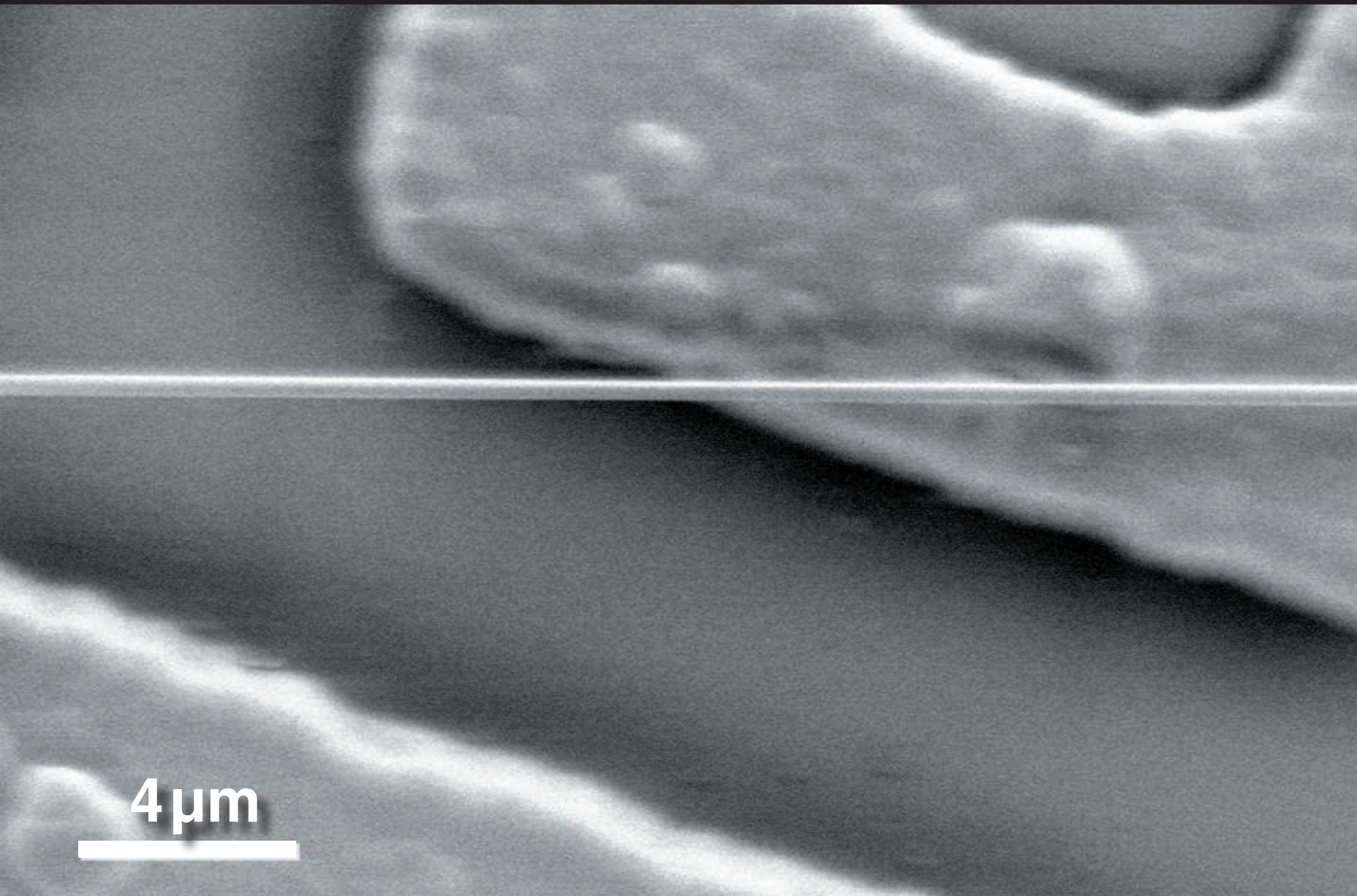
Nanowire fabrication



6 μm



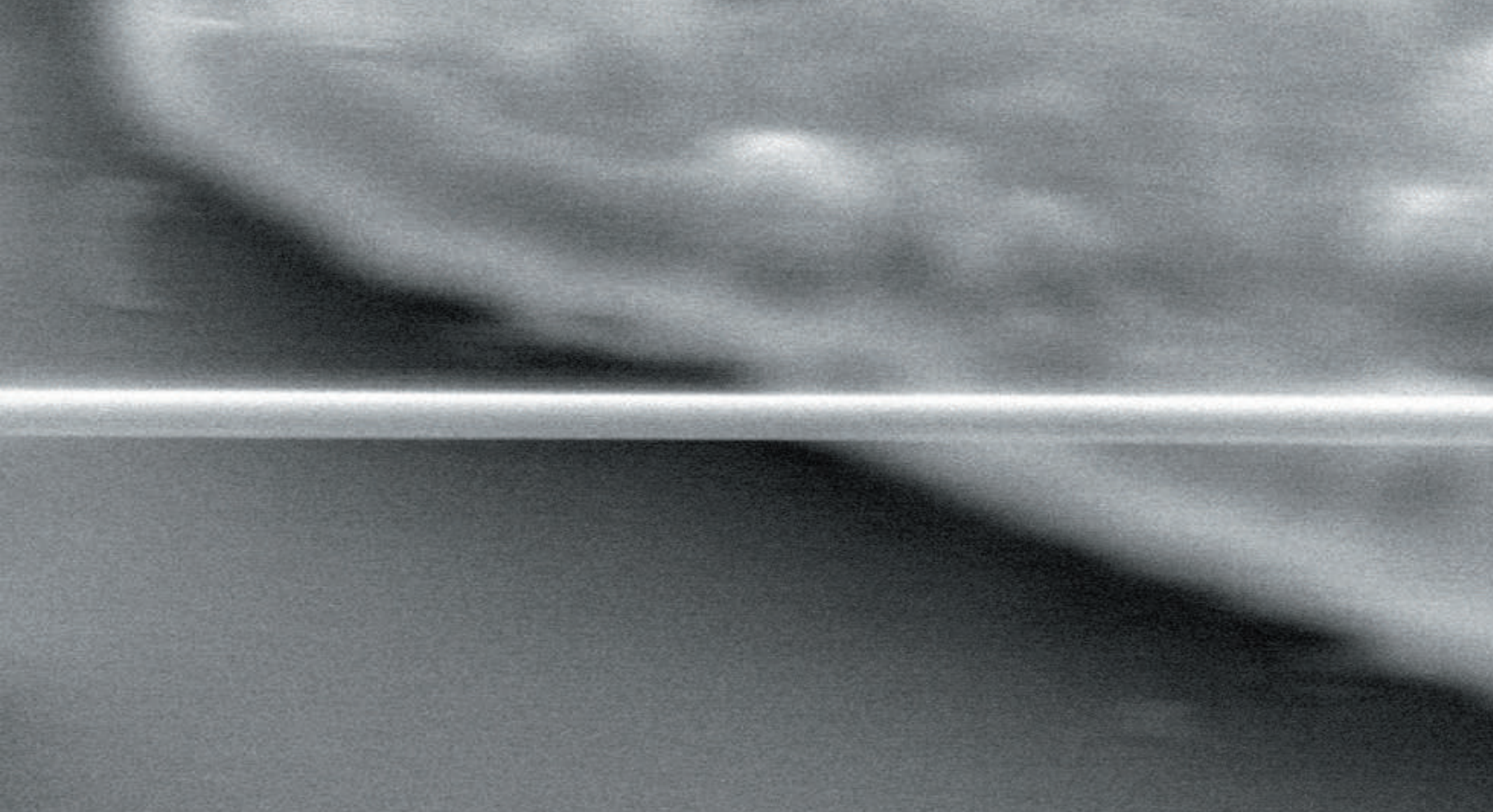
Nanowire fabrication



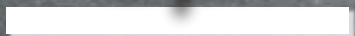
4 μm



Nanowire fabrication



2 μm



Nanowire fabrication

312 nm

A transmission electron micrograph (TEM) showing a single nanowire. The nanowire is a bright, horizontal line against a dark background. A vertical white line with a crossbar at the bottom indicates the diameter of the nanowire, which is labeled as 312 nm. The nanowire has a slightly irregular, textured appearance.

1 μm

A white horizontal scale bar located in the bottom left corner of the image, representing a length of 1 micrometer.

Waveguiding

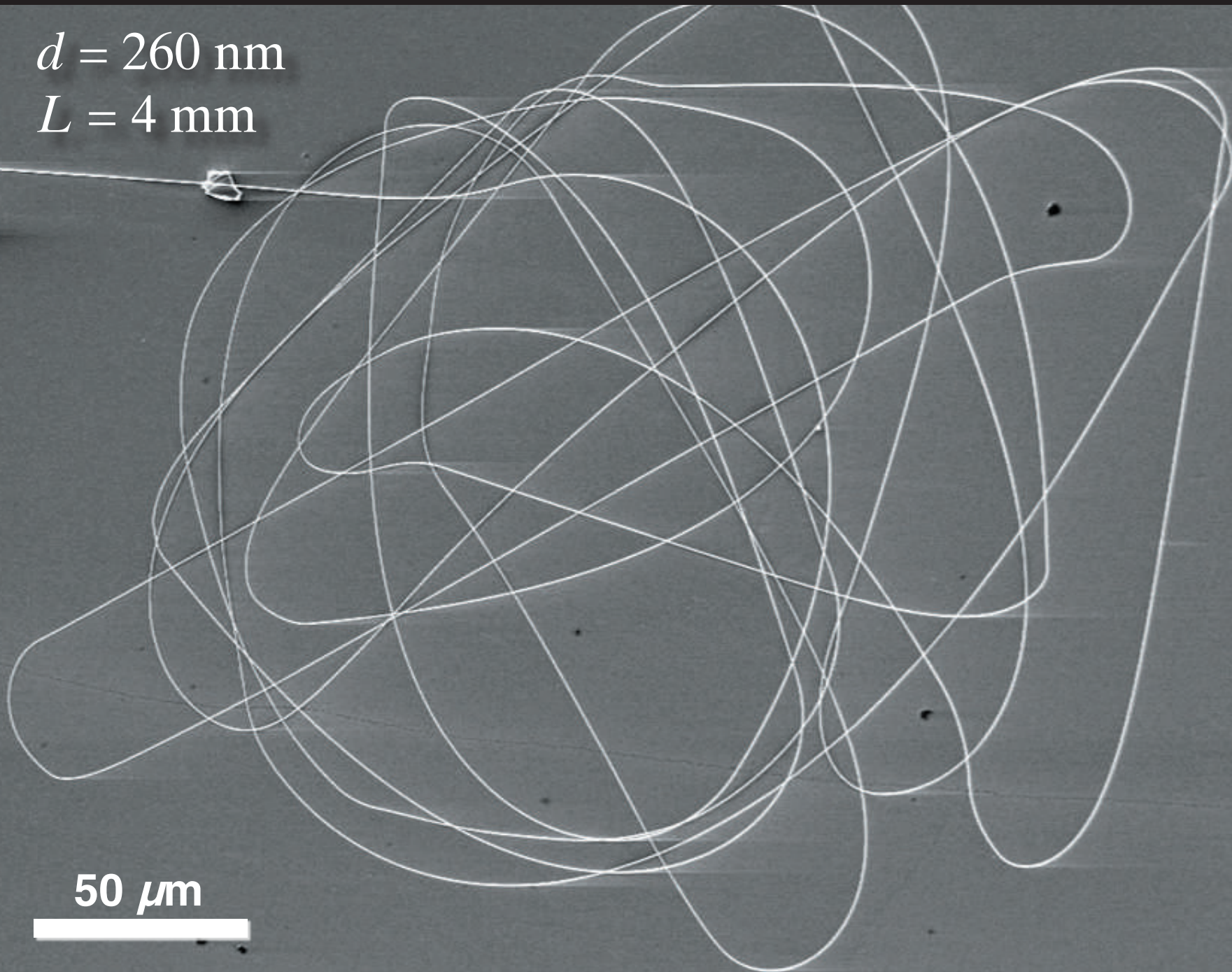
Specifications

| | |
|------------------------------------|--------------------|
| 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} |

Nanowire fabrication

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



Nanowire fabrication

240-nm wire

200 nm



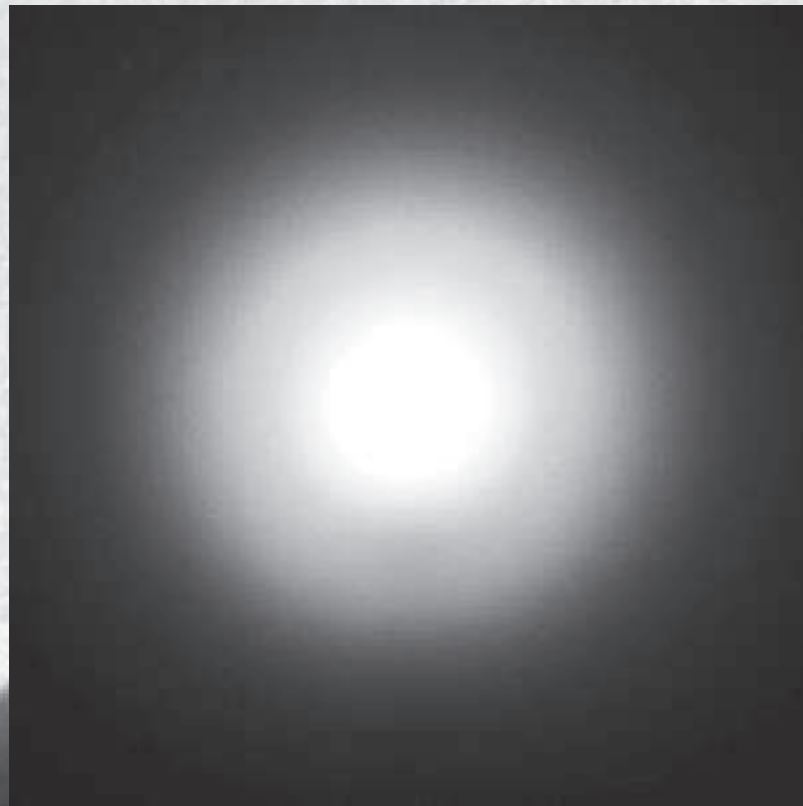
Nanowire fabrication

RMS roughness < 0.5 nm

20 nm



Nanowire fabrication



20 nm



Nanowire fabrication

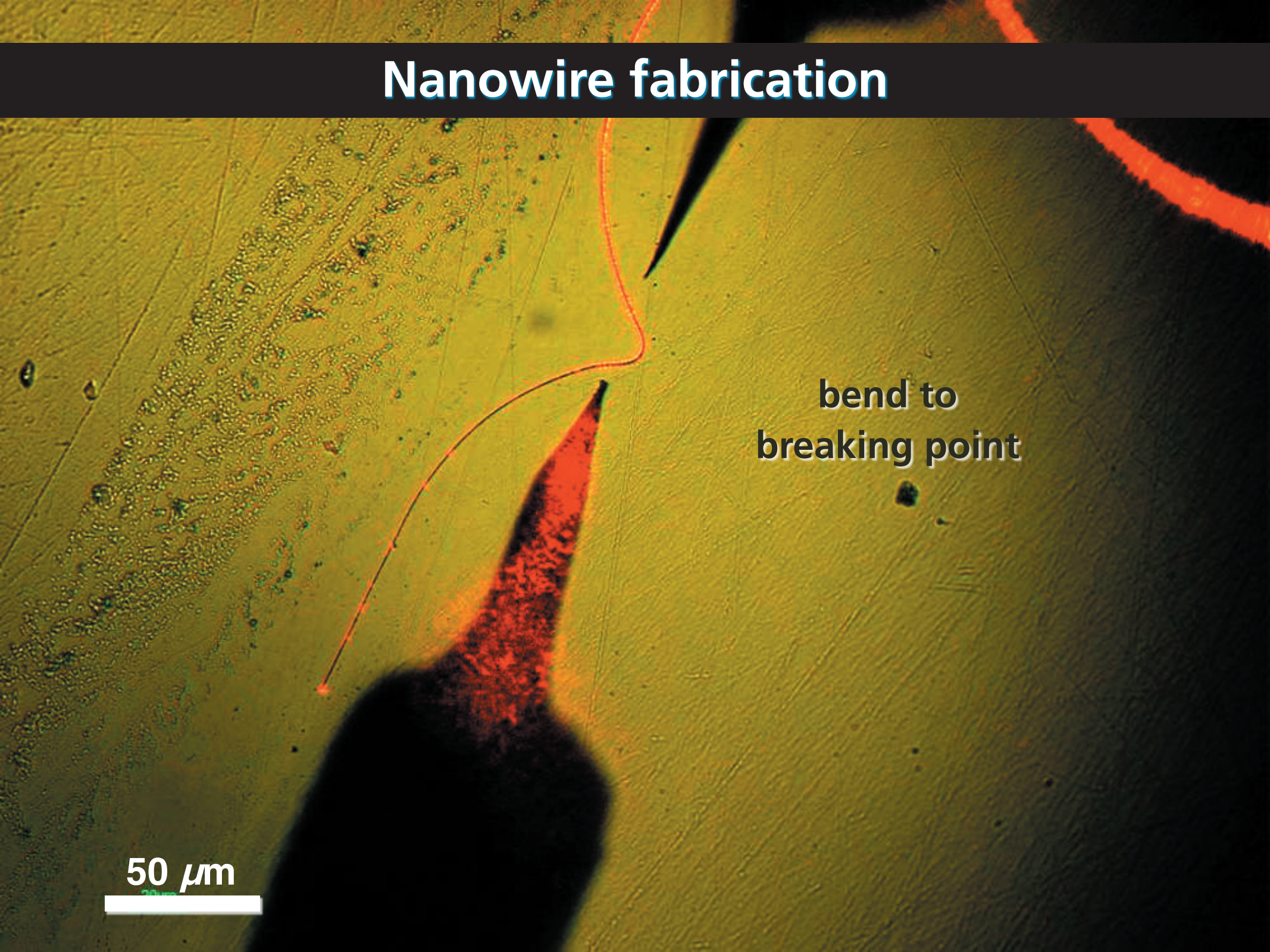
measure tensile stress
at breaking point



Nanowire fabrication

bend to
breaking point

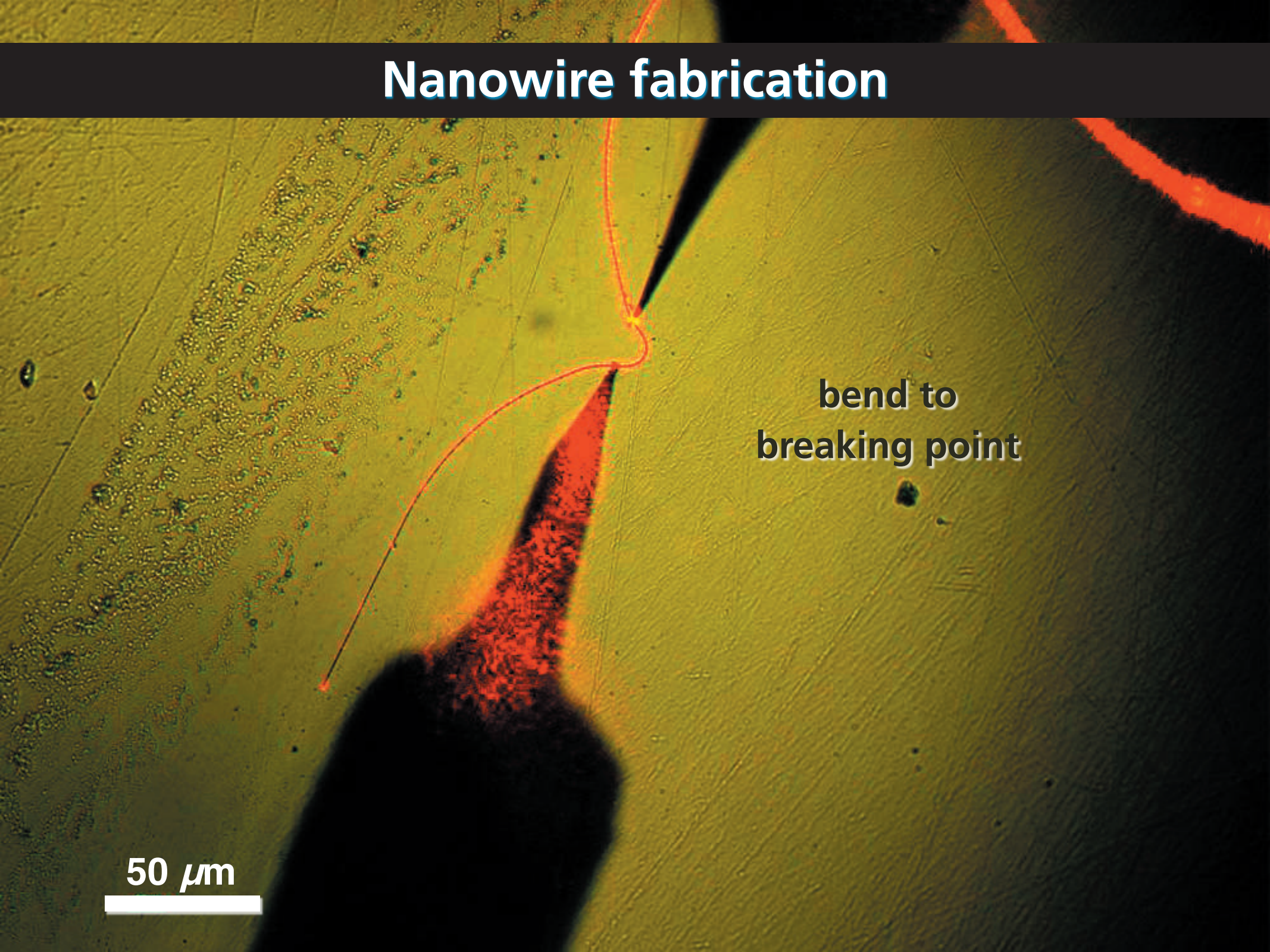
50 μm



Nanowire fabrication

bend to
breaking point

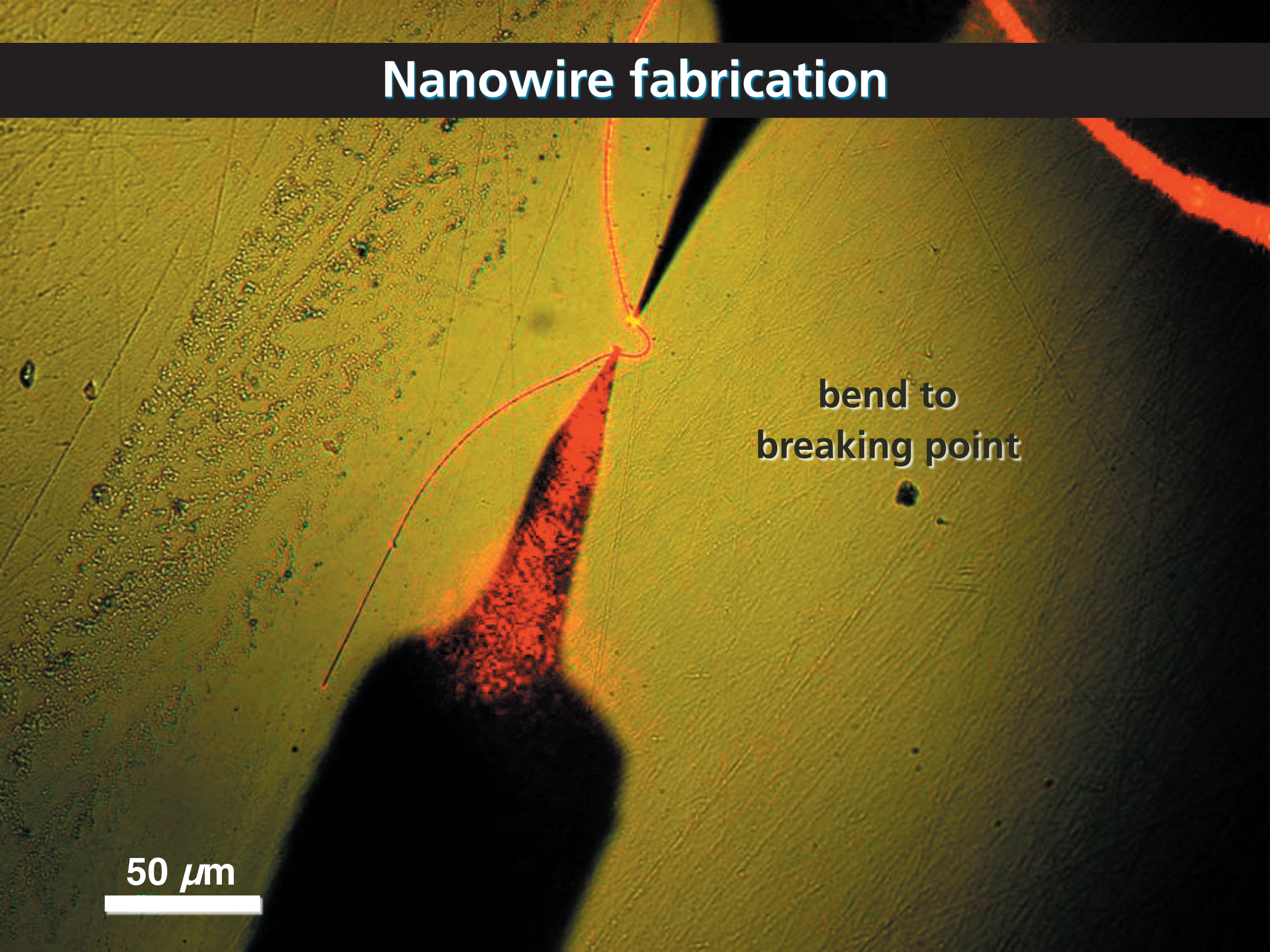
50 μm



Nanowire fabrication

bend to
breaking point

50 μm



Nanowire fabrication



minimum bending radius R_{EB}
gives tensile stress:

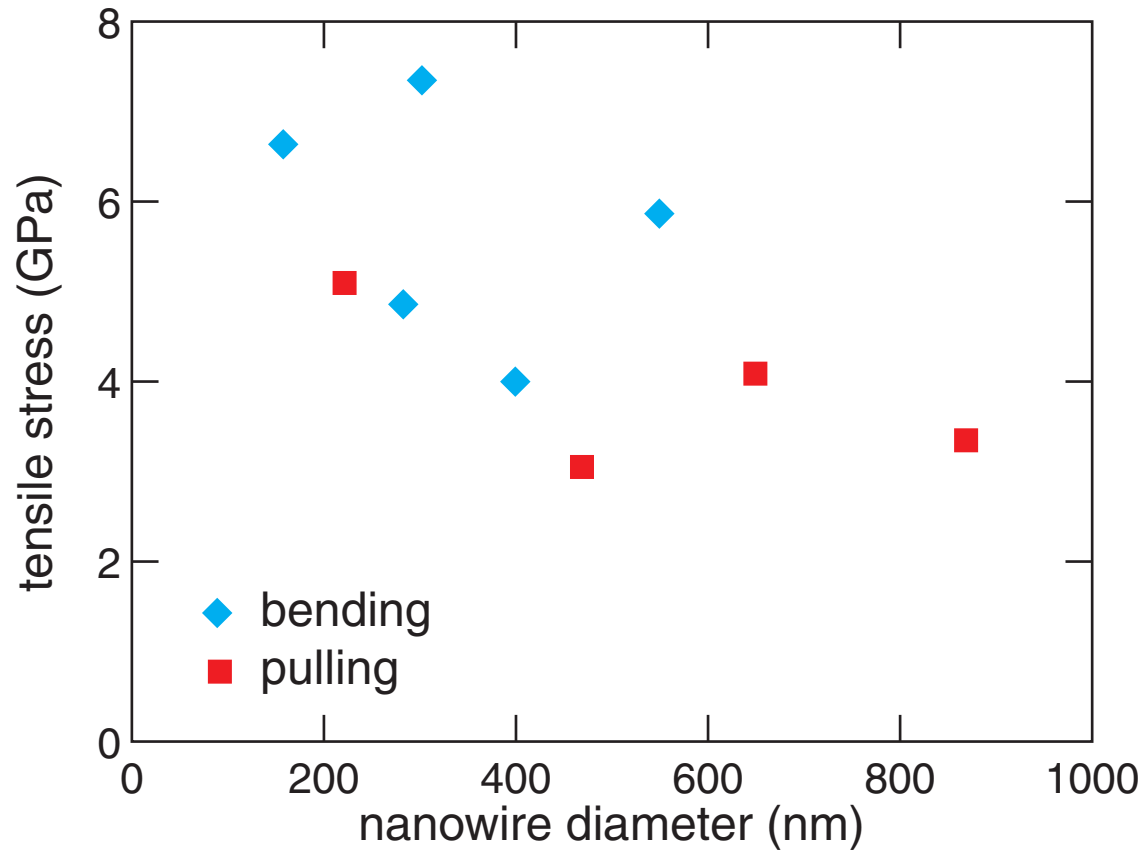
$$\sigma = \frac{ED}{2R_{EB}}$$

E = Young's modulus

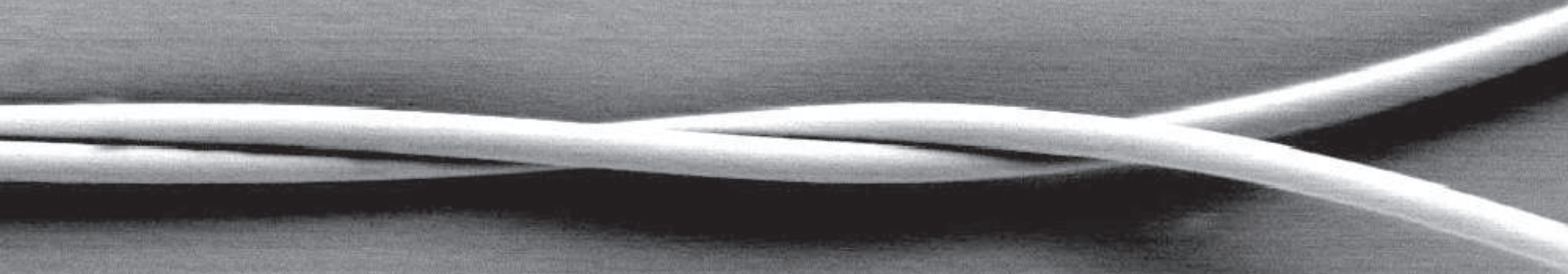
D = wire diameter

Waveguiding

tensile strength



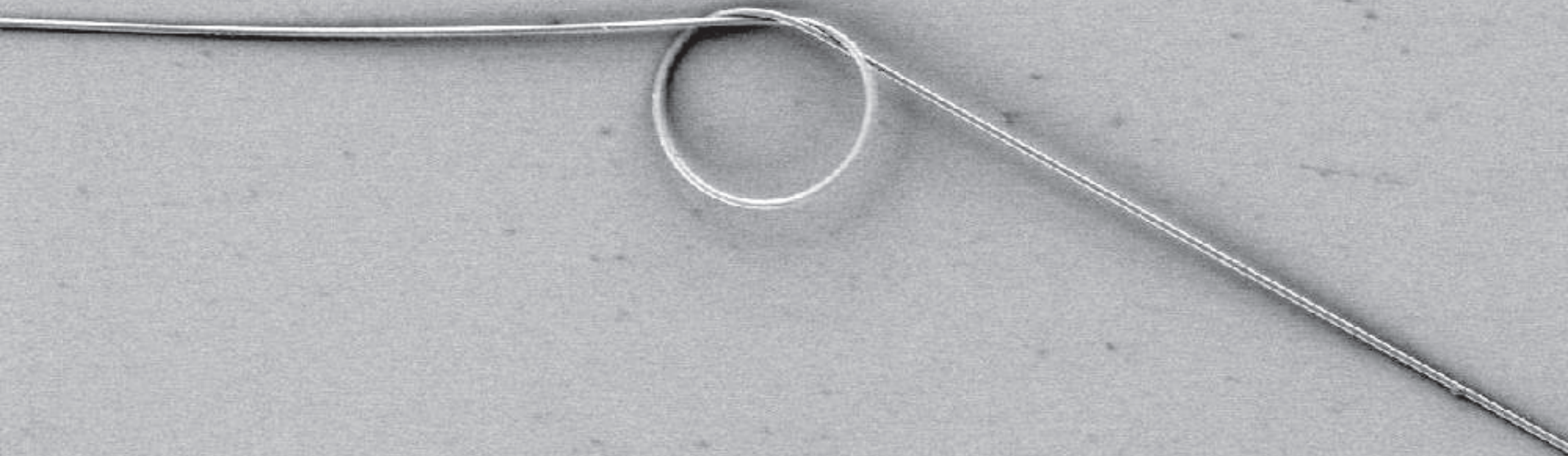
Nanowire fabrication



2 μm



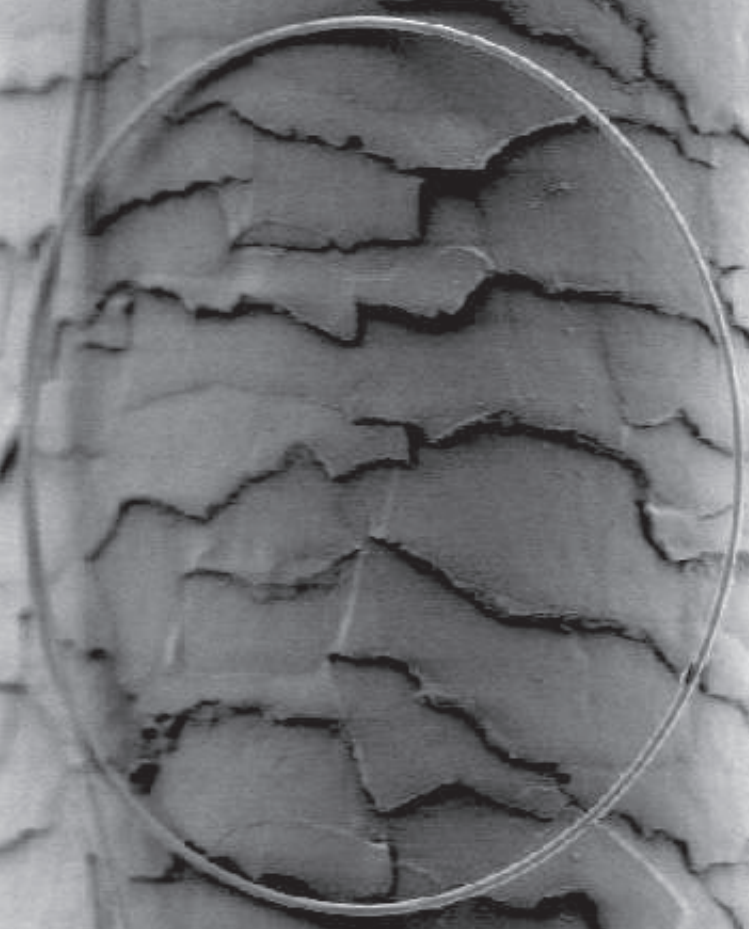
Nanowire fabrication



20 μm



Nanowire fabrication



20 μm

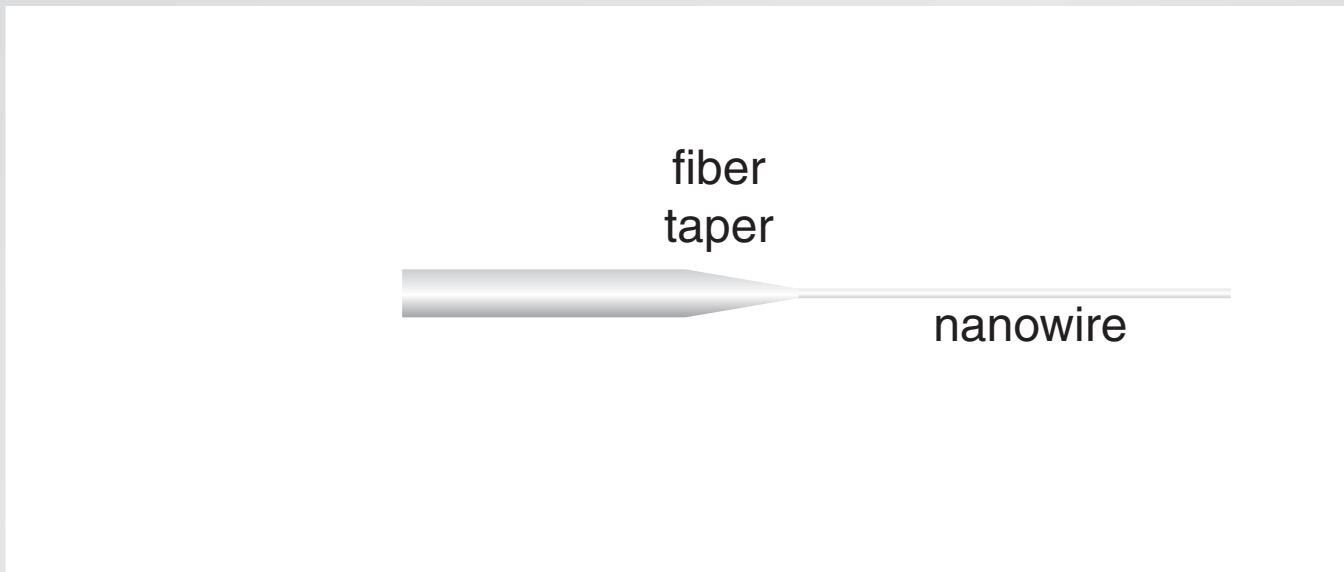


Outline

- waveguiding
- nanowire fabrication
- optical properties

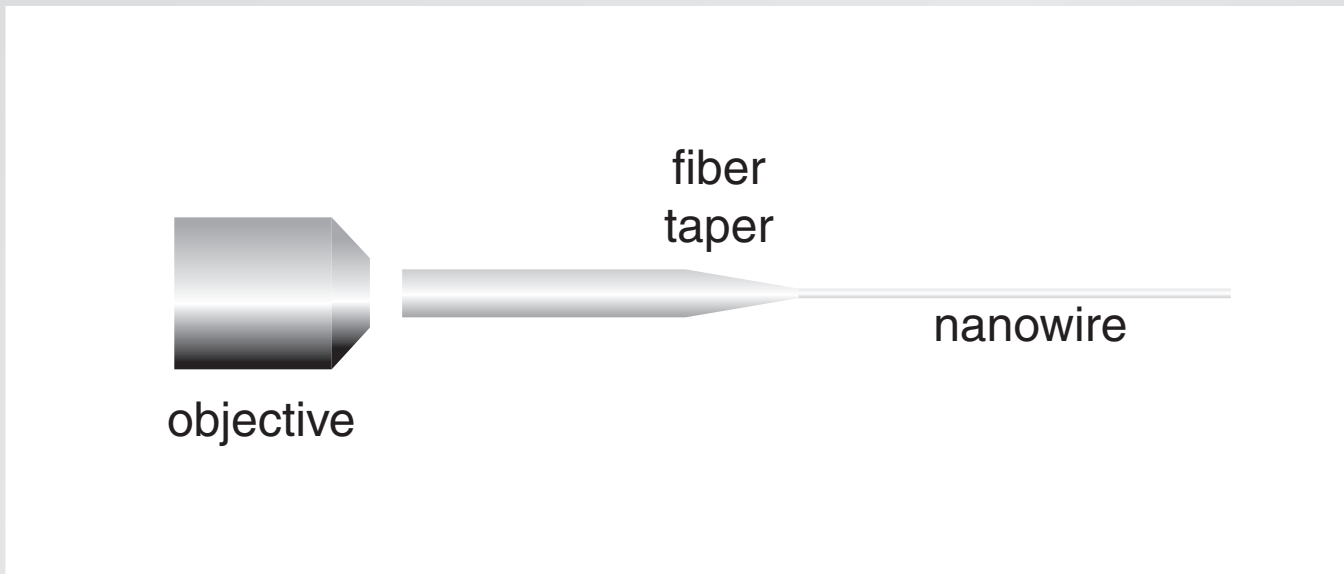
Optical properties

coupling light into nanowires



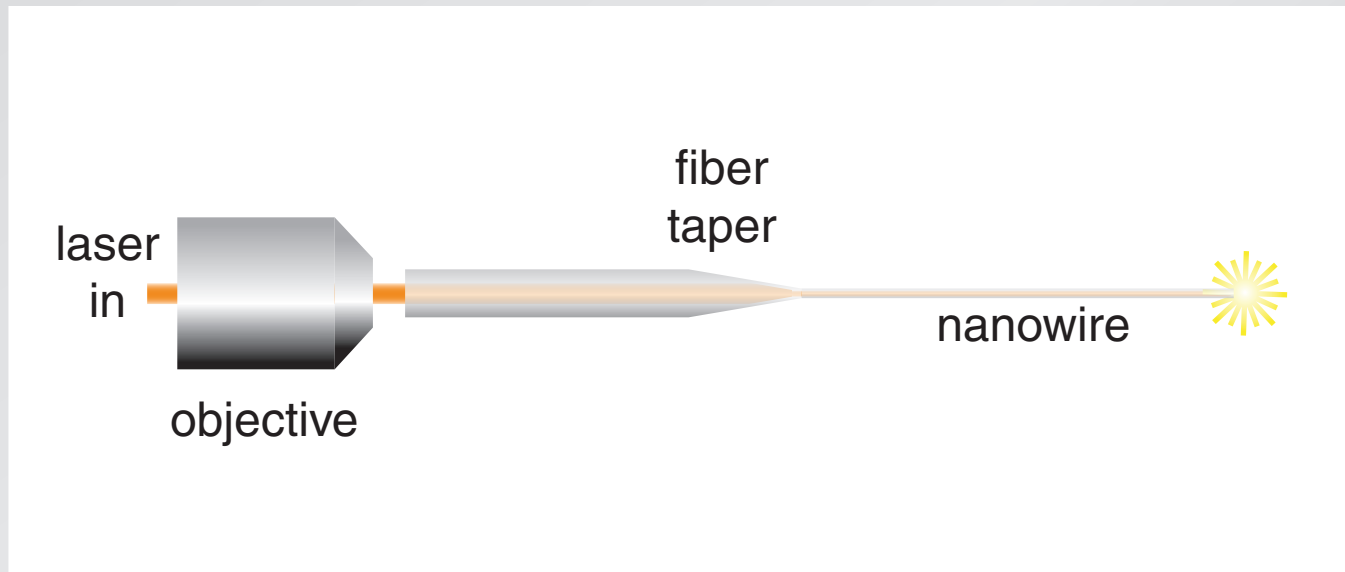
Optical properties

coupling light into nanowires



Optical properties

coupling light into nanowires



Optical properties

280-nm nanowire



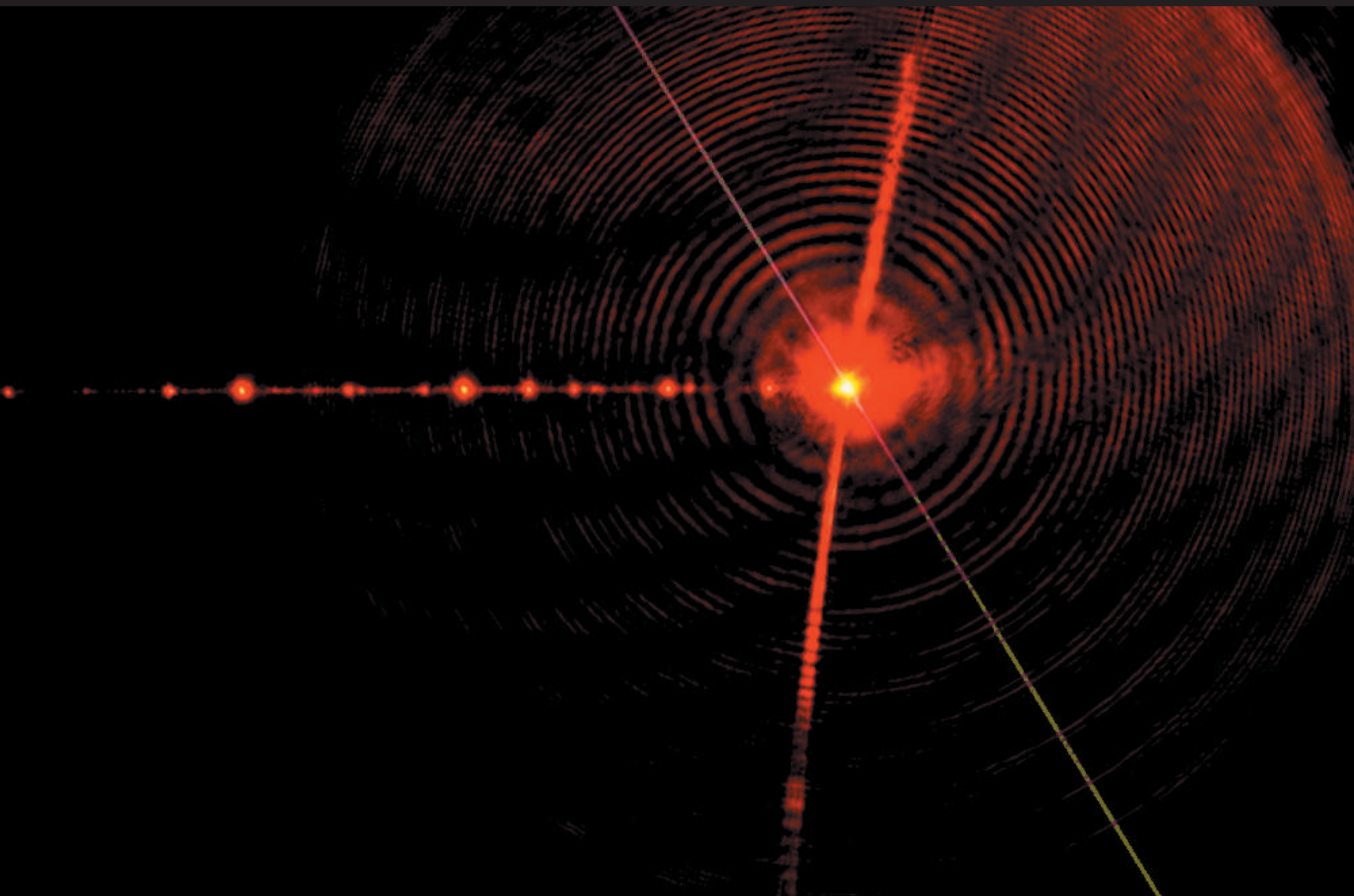
360 nm



450 nm



Optical properties

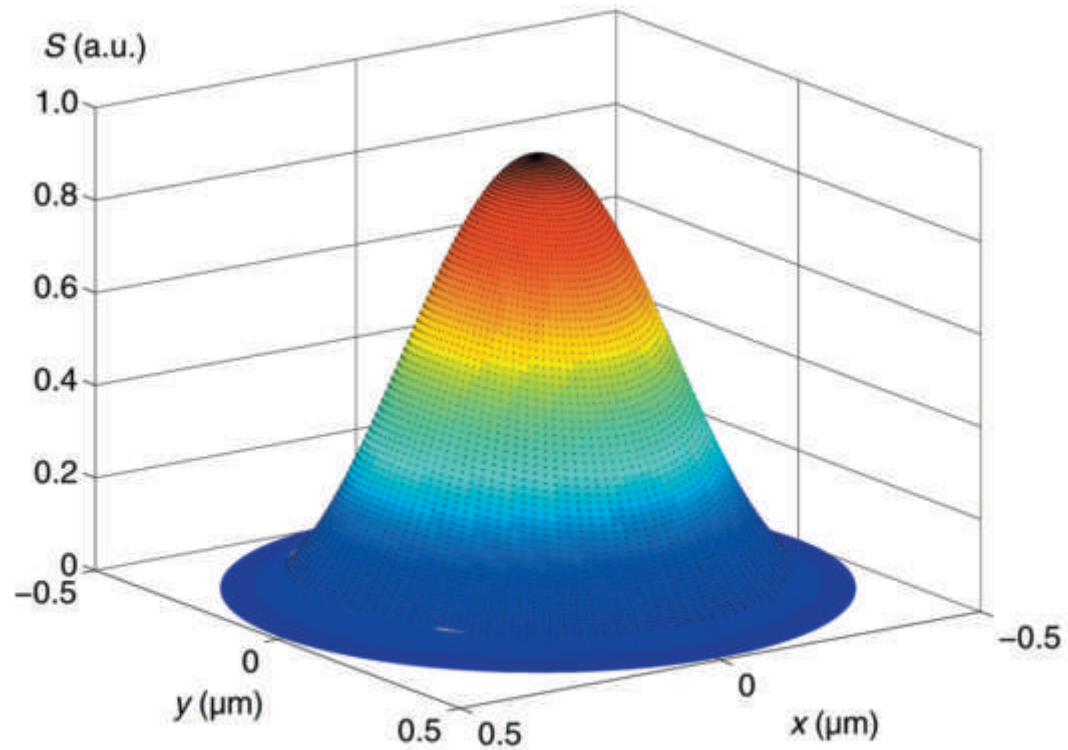


Optical properties



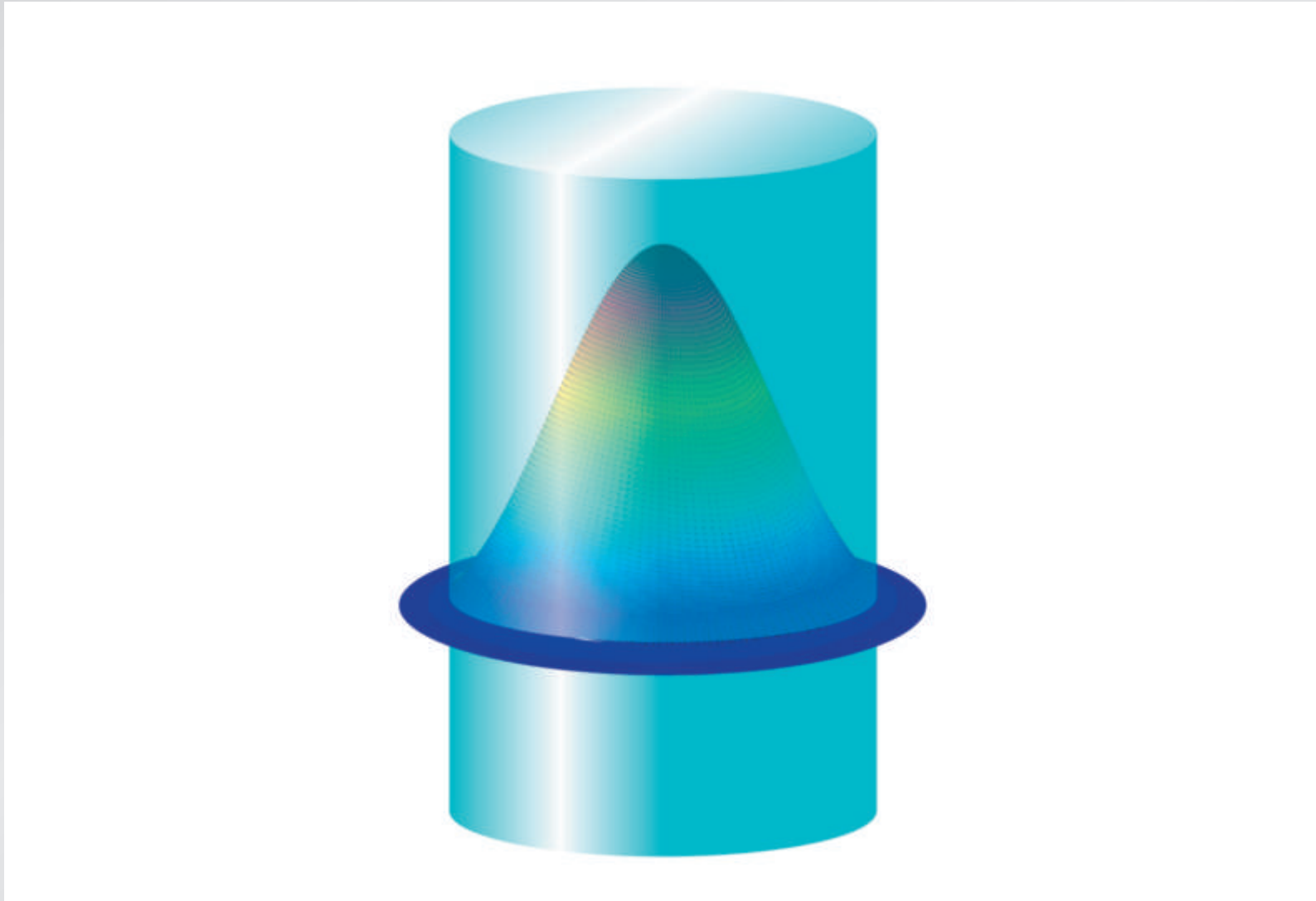
Optical properties

Poynting vector profile for 800-nm nanowire



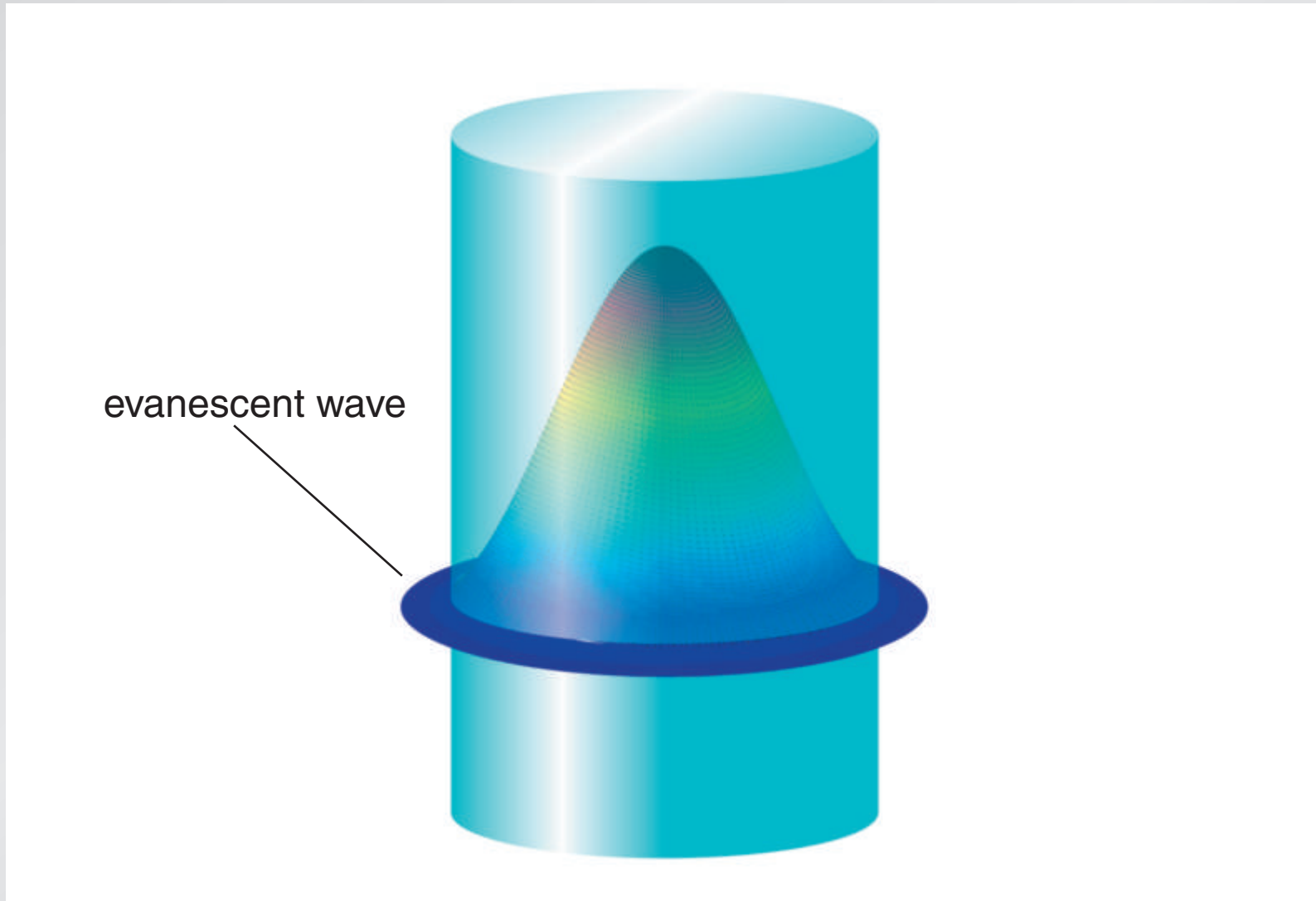
Optical properties

Poynting vector profile for 800-nm nanowire



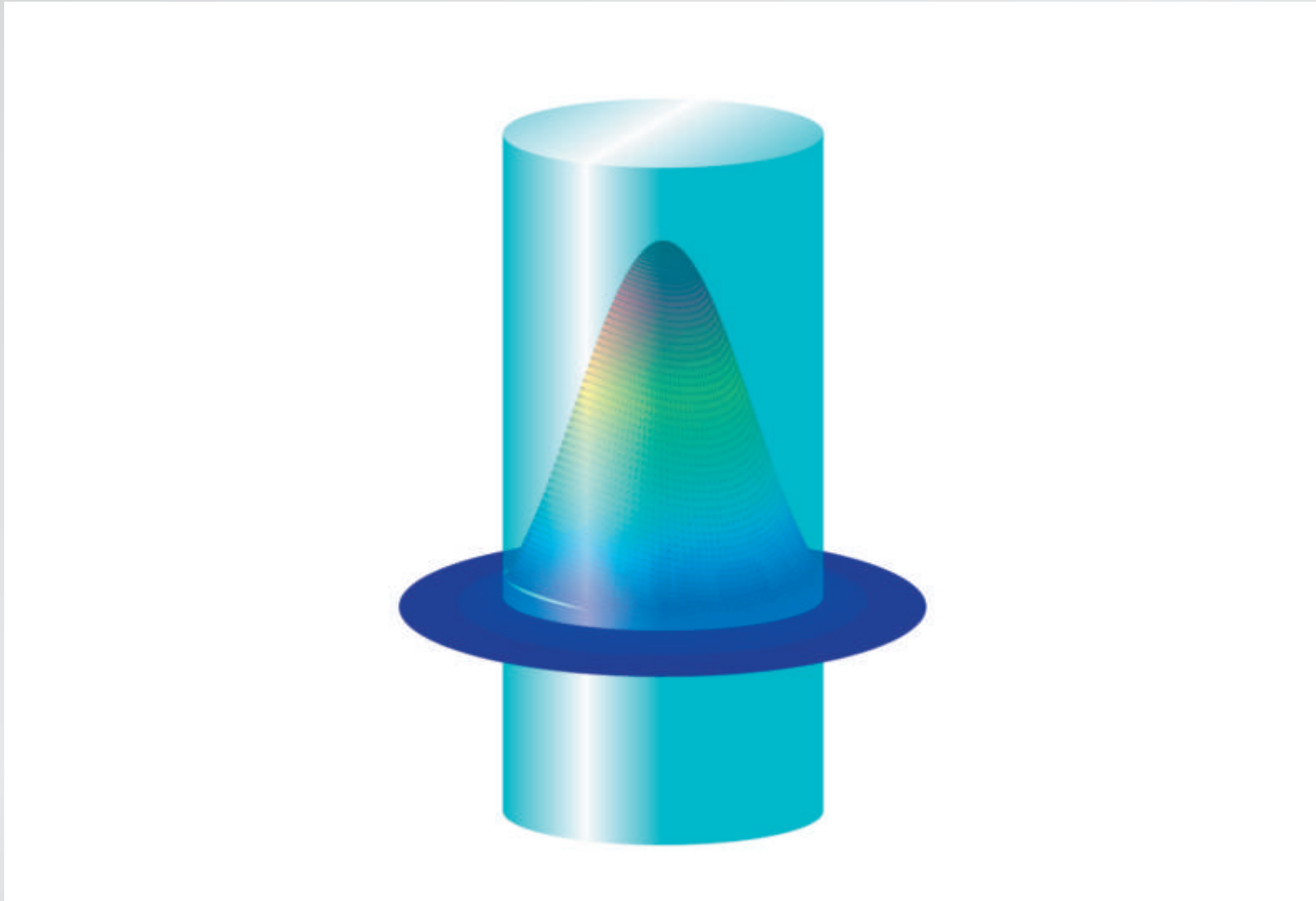
Optical properties

Poynting vector profile for 800-nm nanowire



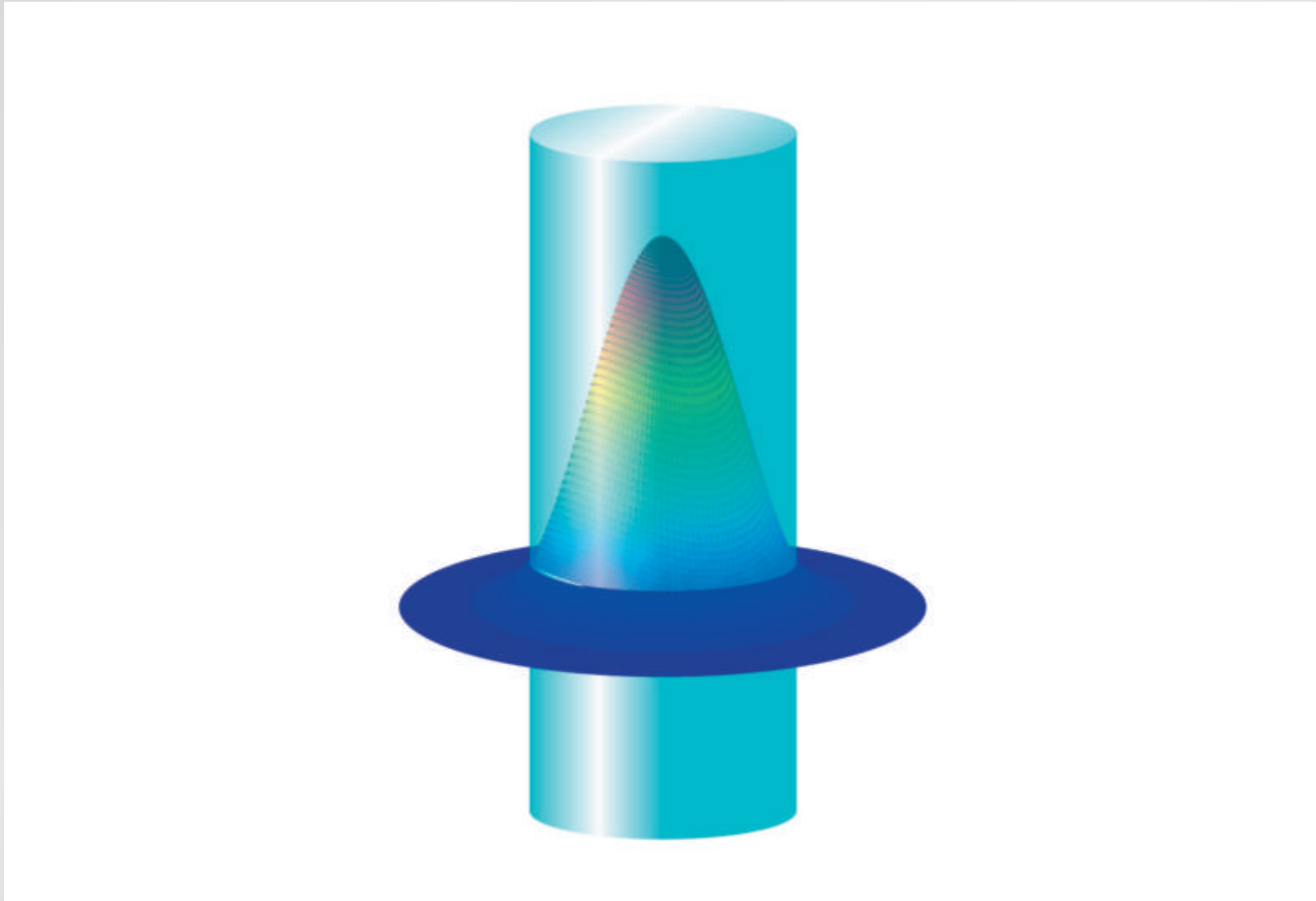
Optical properties

Poynting vector profile for 600-nm nanowire



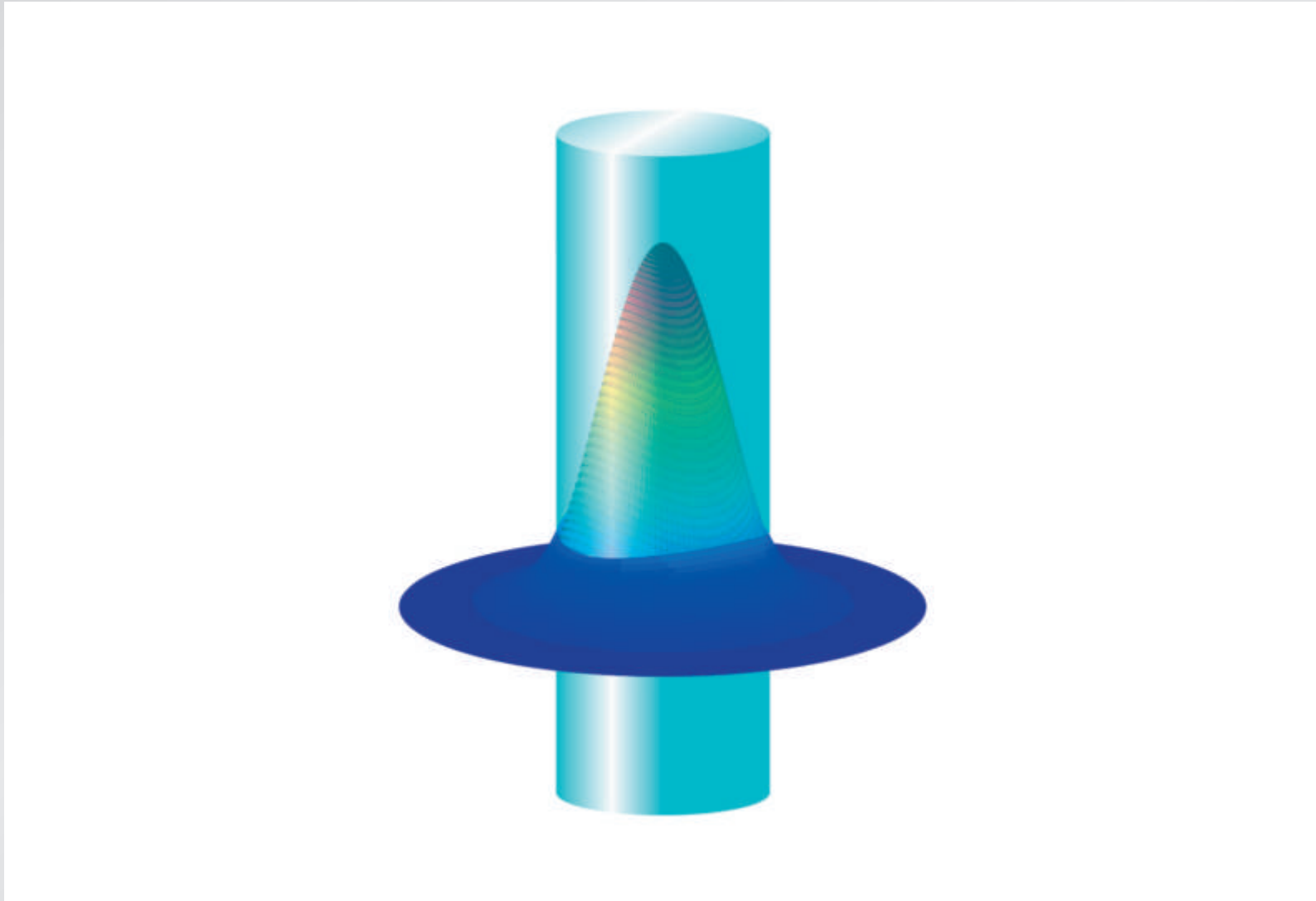
Optical properties

Poynting vector profile for 500-nm nanowire



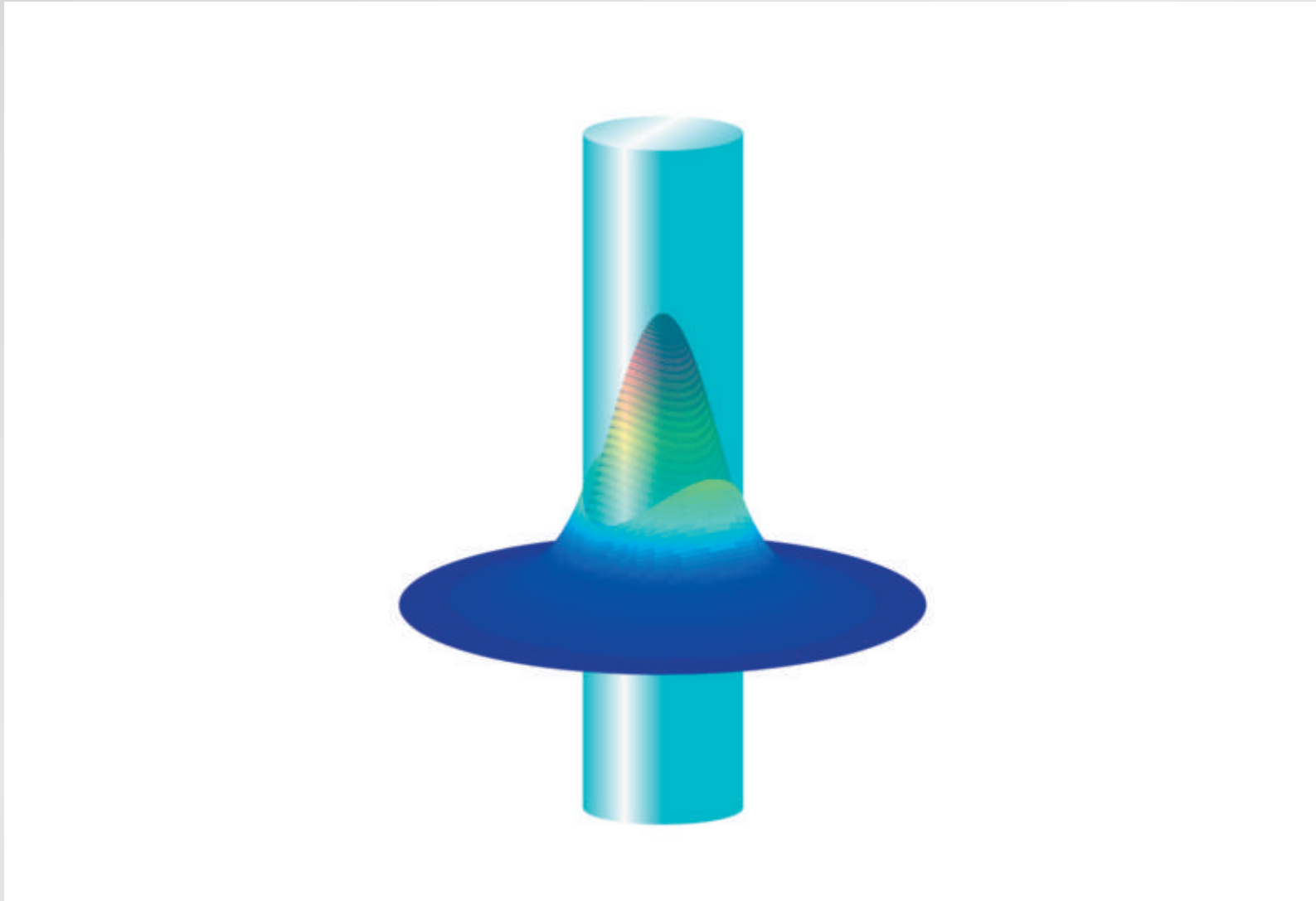
Optical properties

Poynting vector profile for 400-nm nanowire



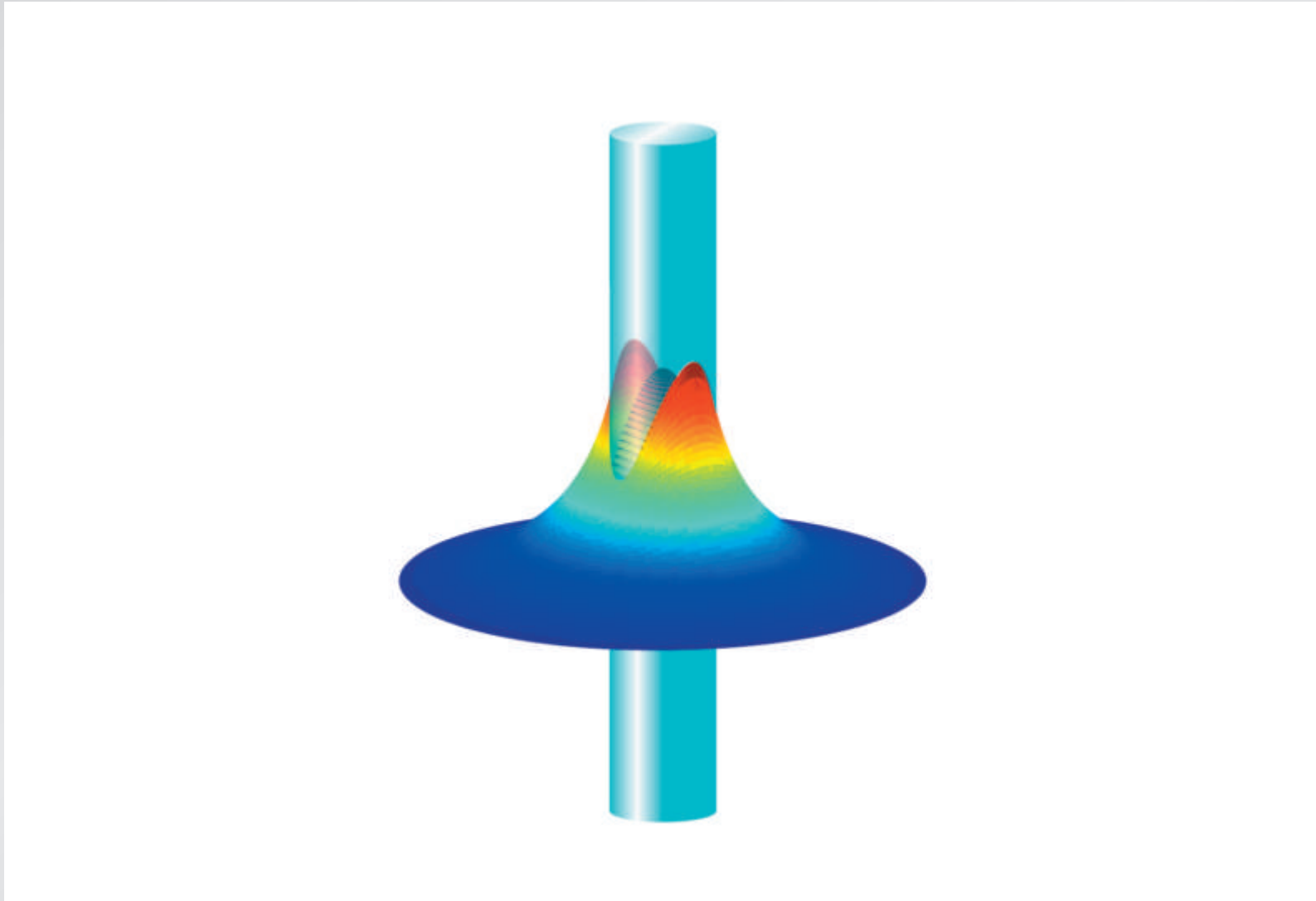
Optical properties

Poynting vector profile for 300-nm nanowire



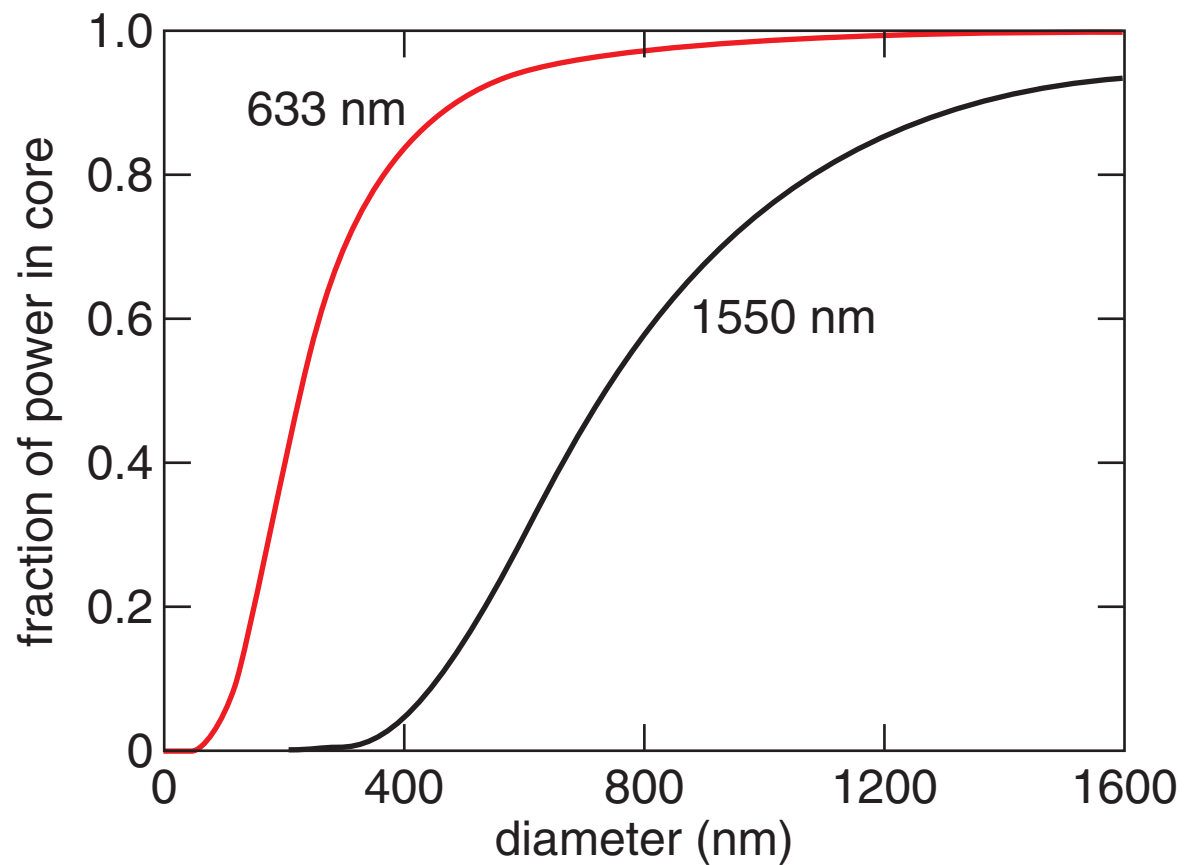
Optical properties

Poynting vector profile for 200-nm nanowire



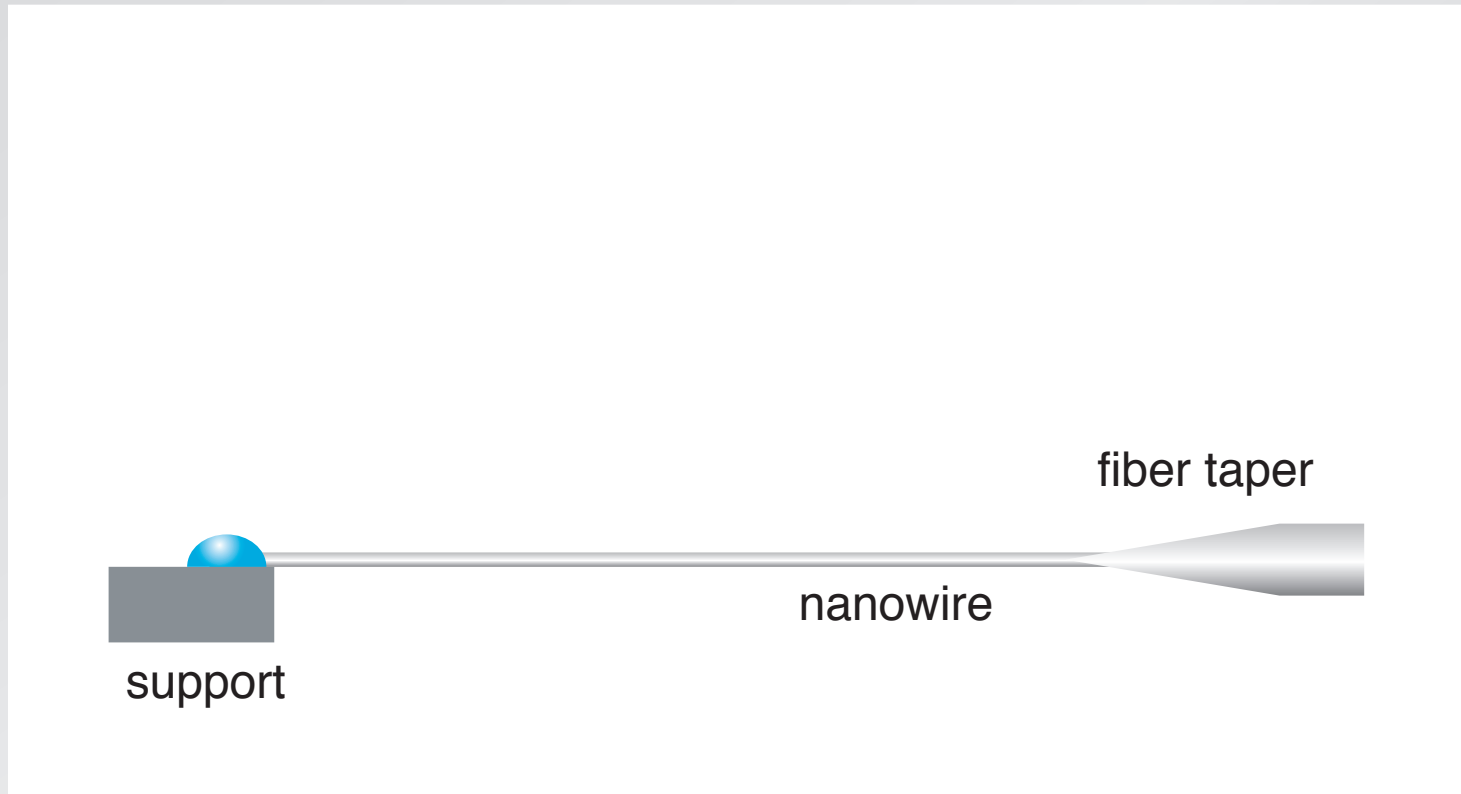
Waveguiding

fraction of power carried in core



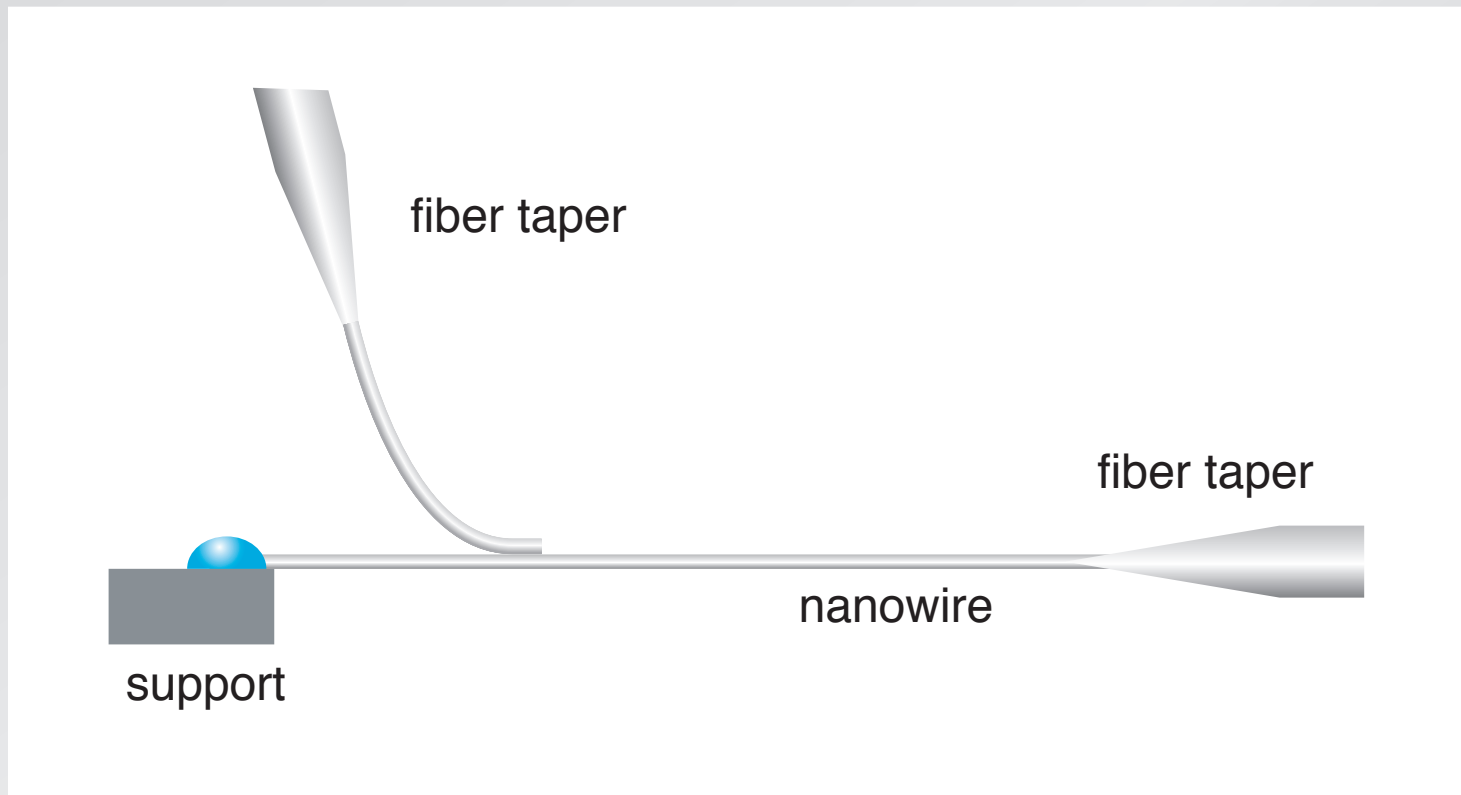
Optical properties

coupling light between nanowires



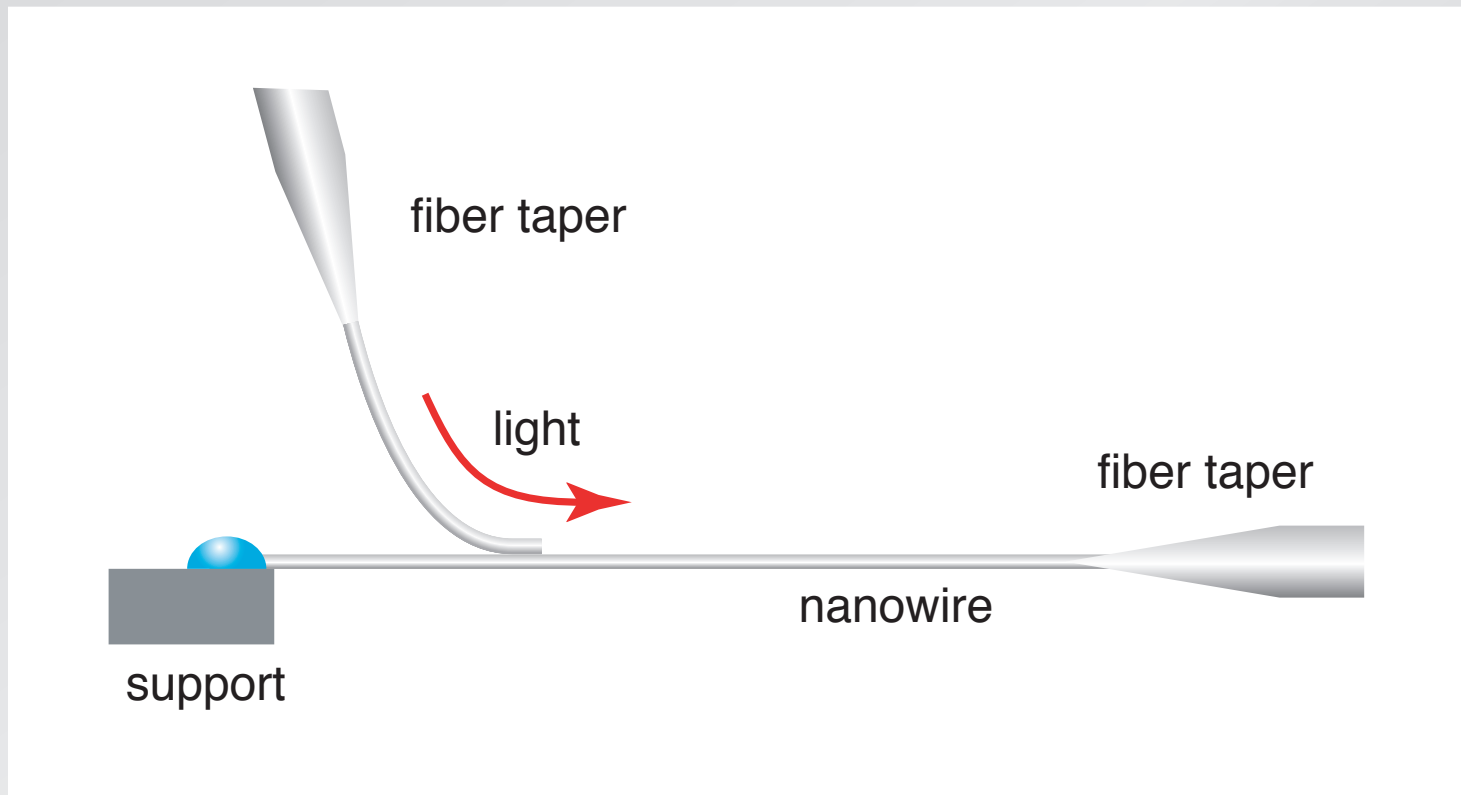
Optical properties

coupling light between nanowires

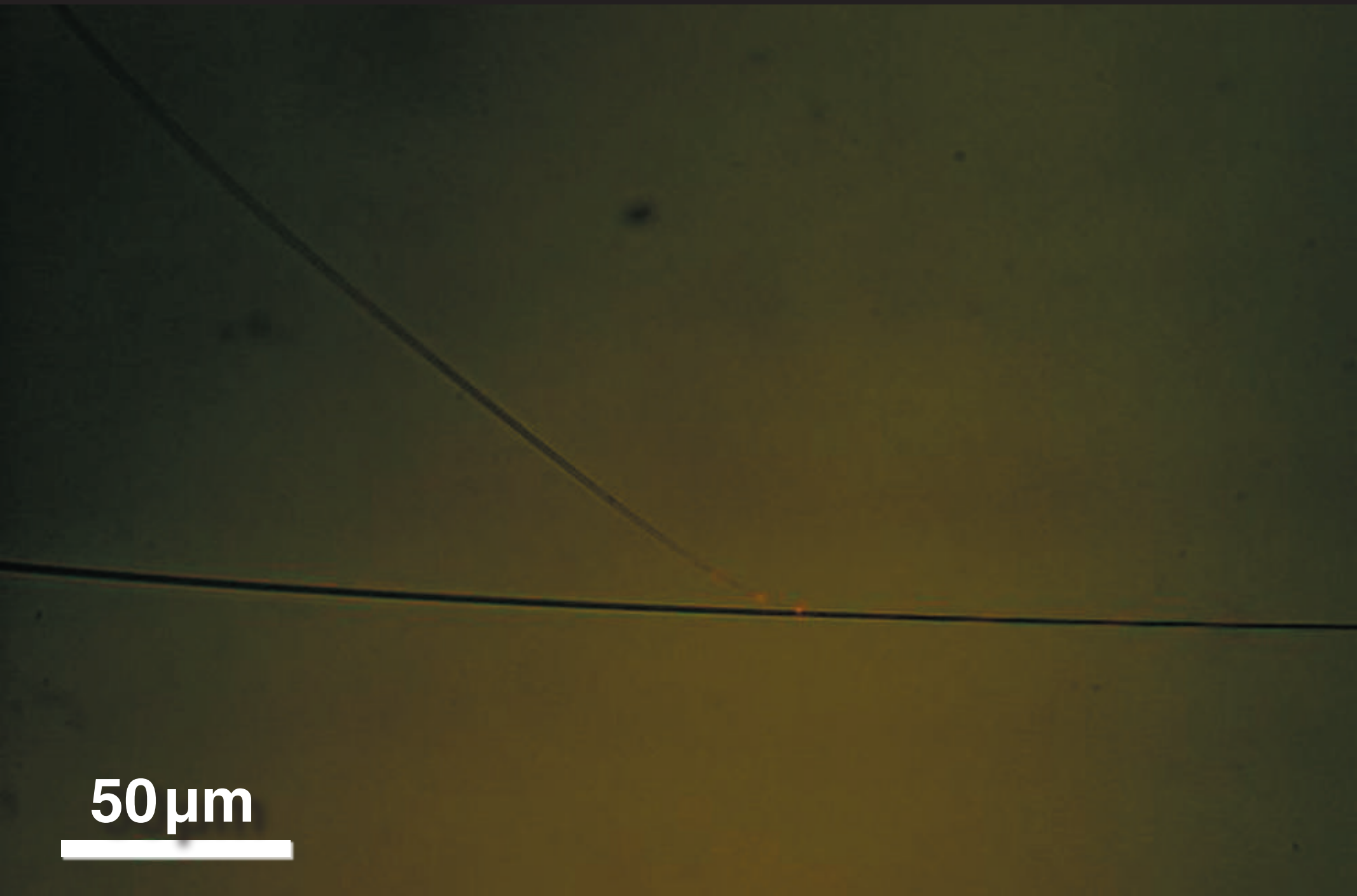


Optical properties

coupling light between nanowires



Optical properties



50 μm

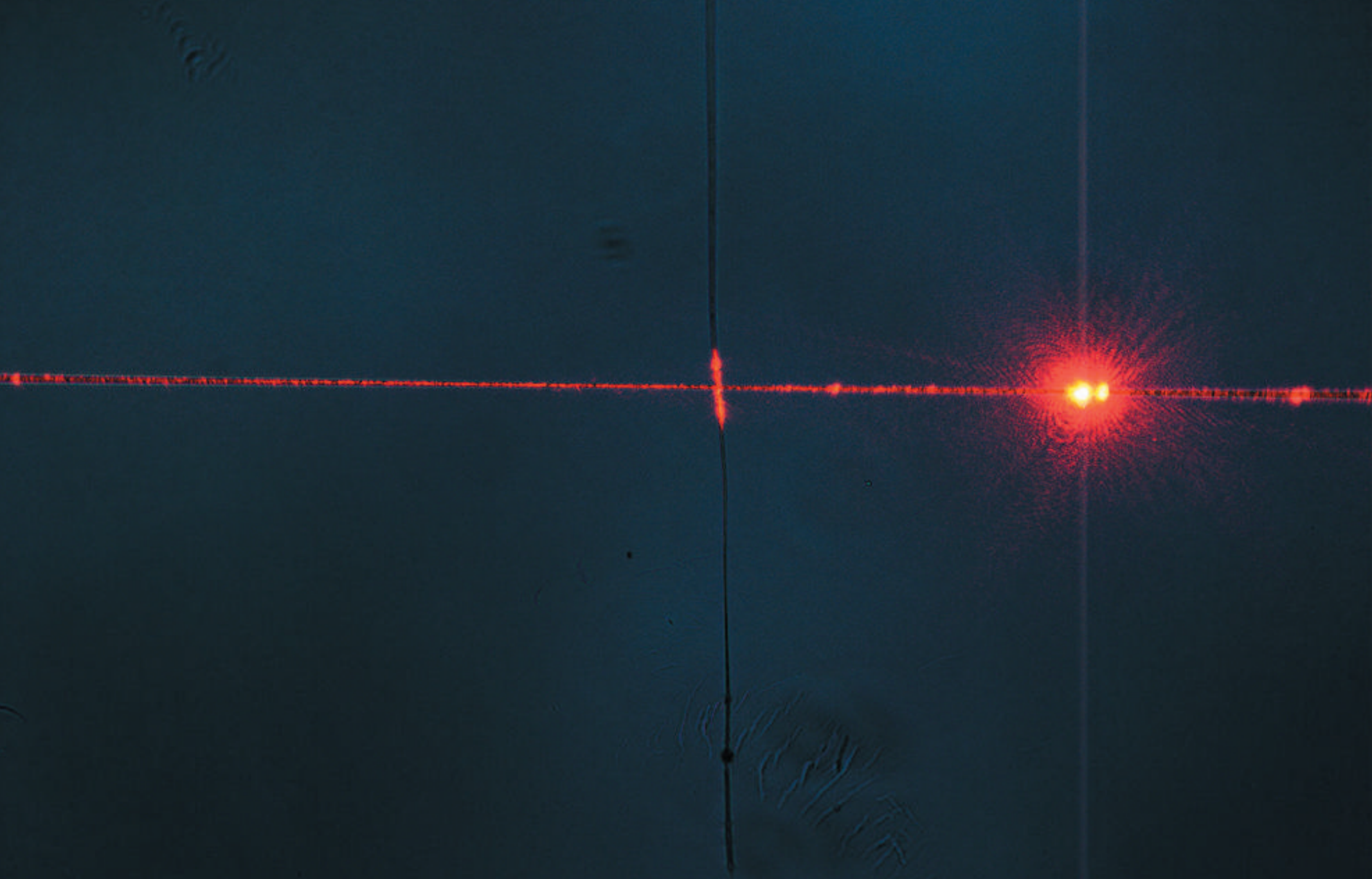
Optical properties



50 μm

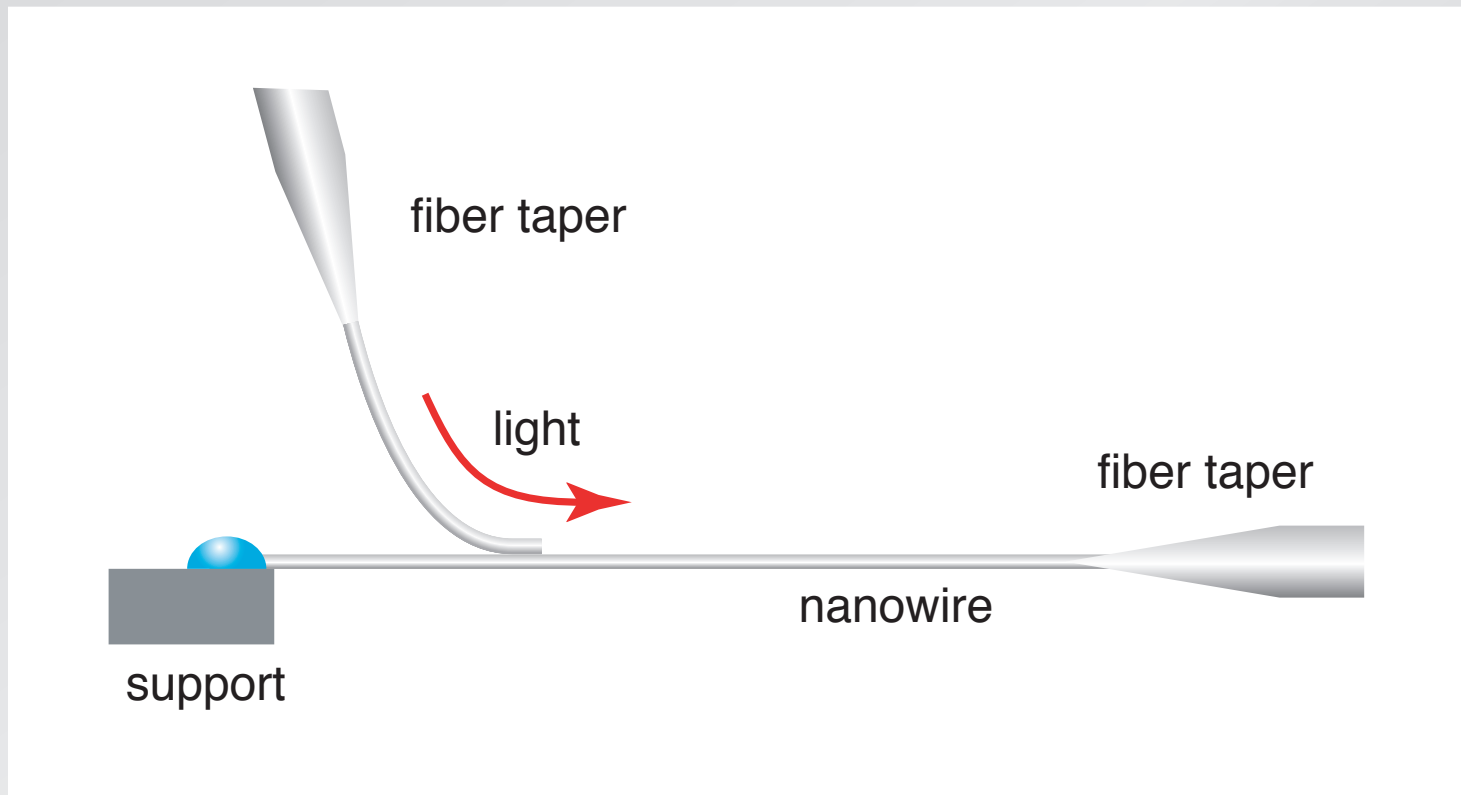


Optical properties



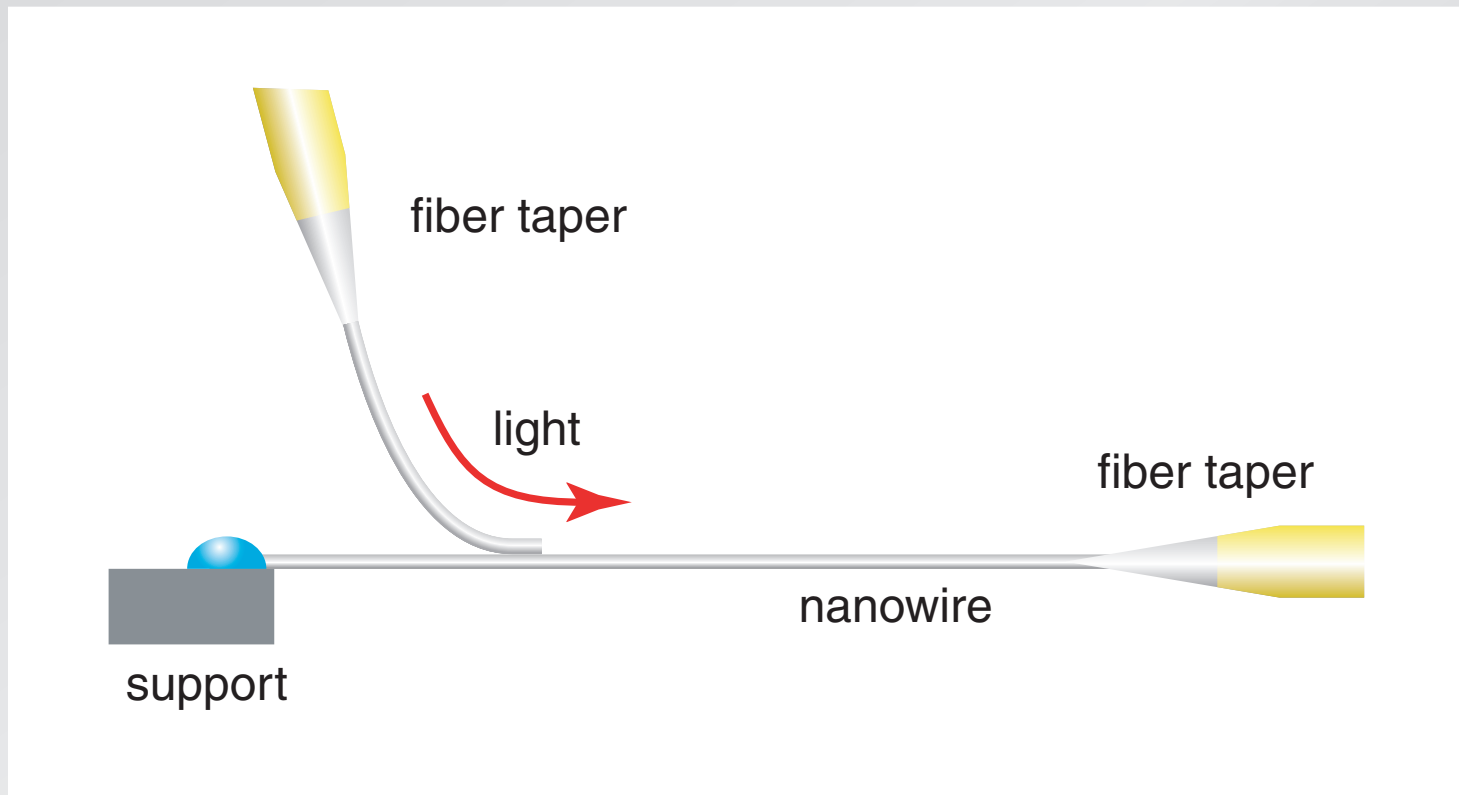
Optical properties

loss measurement



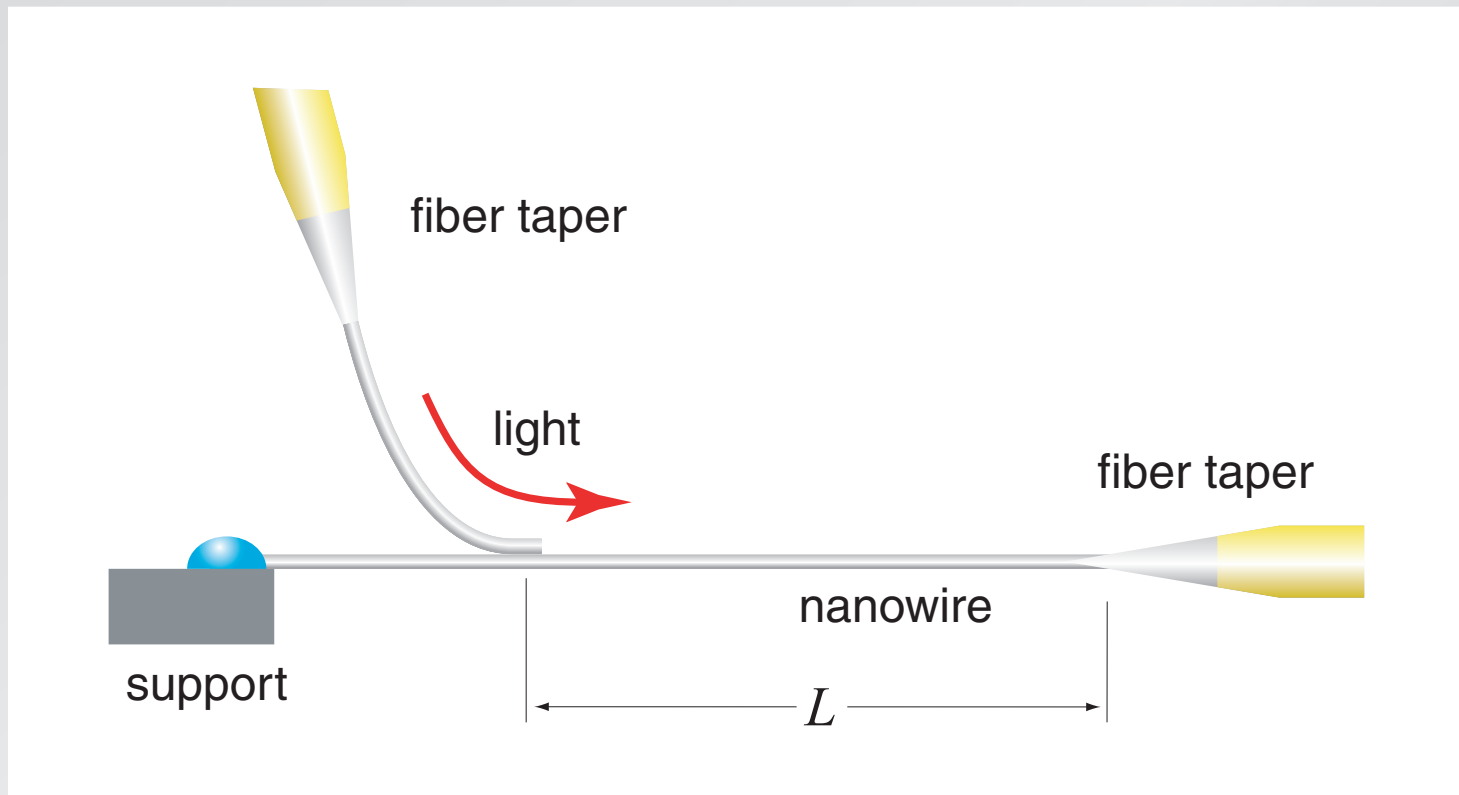
Optical properties

loss measurement



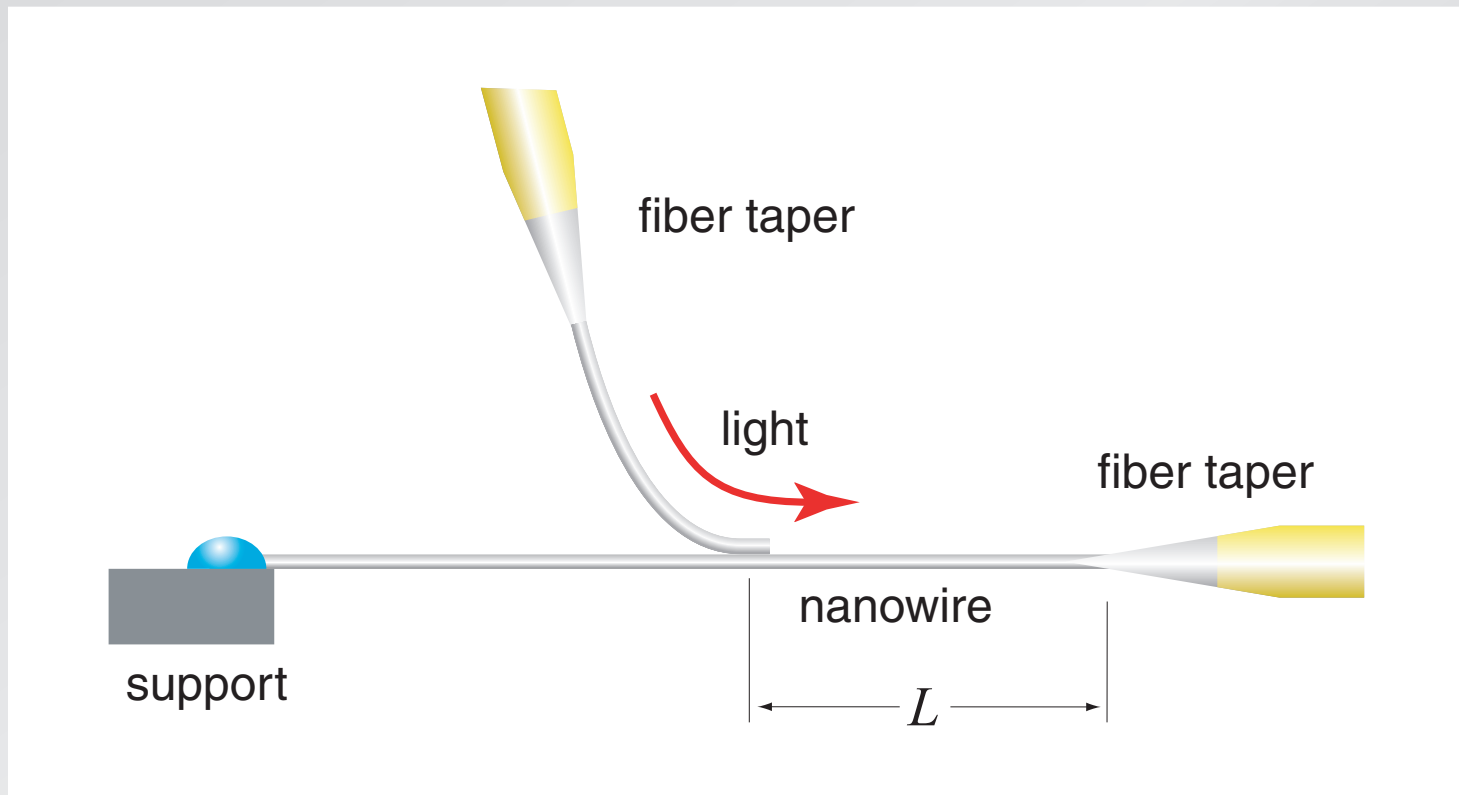
Optical properties

loss measurement



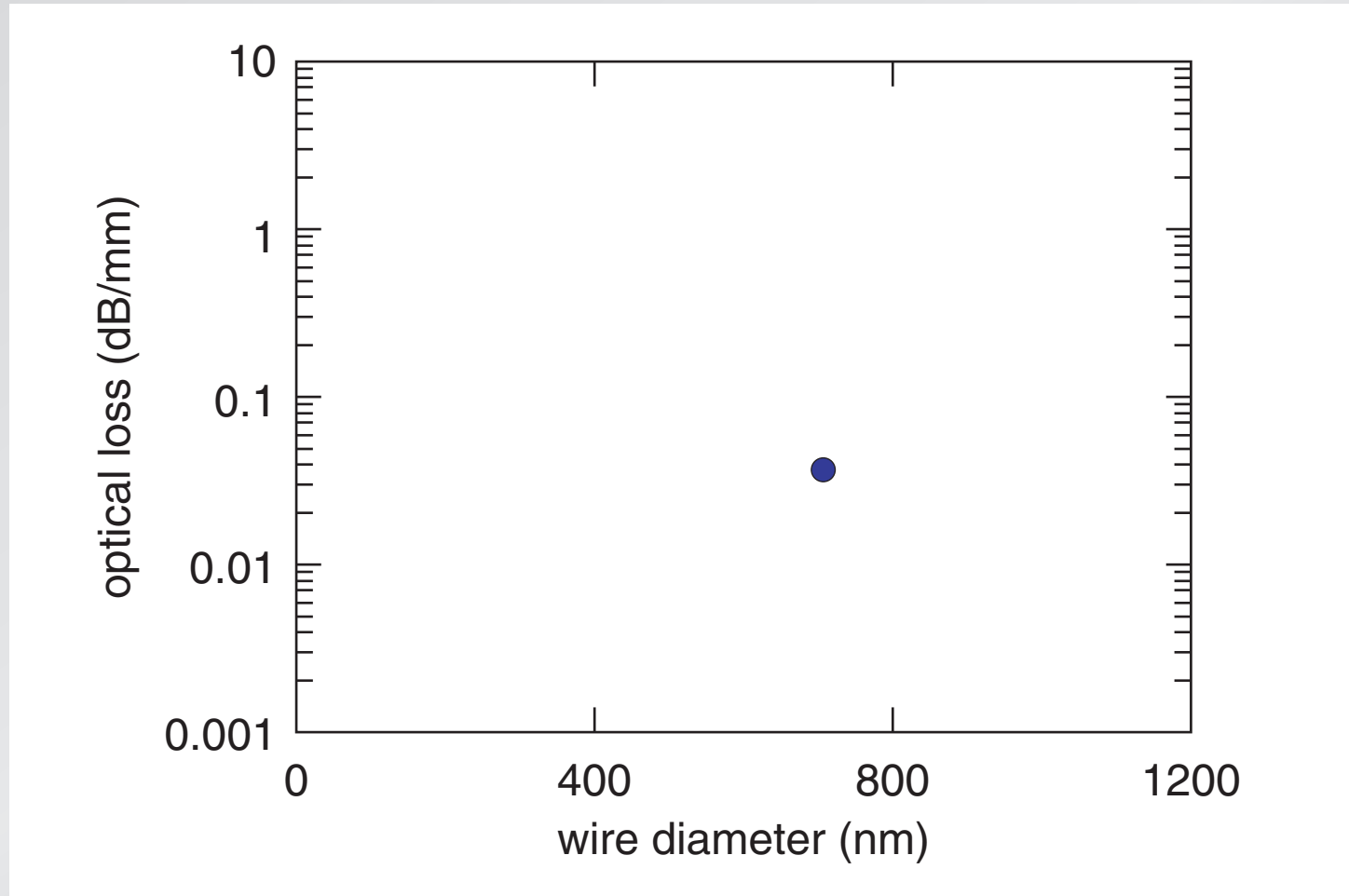
Optical properties

loss measurement



Optical properties

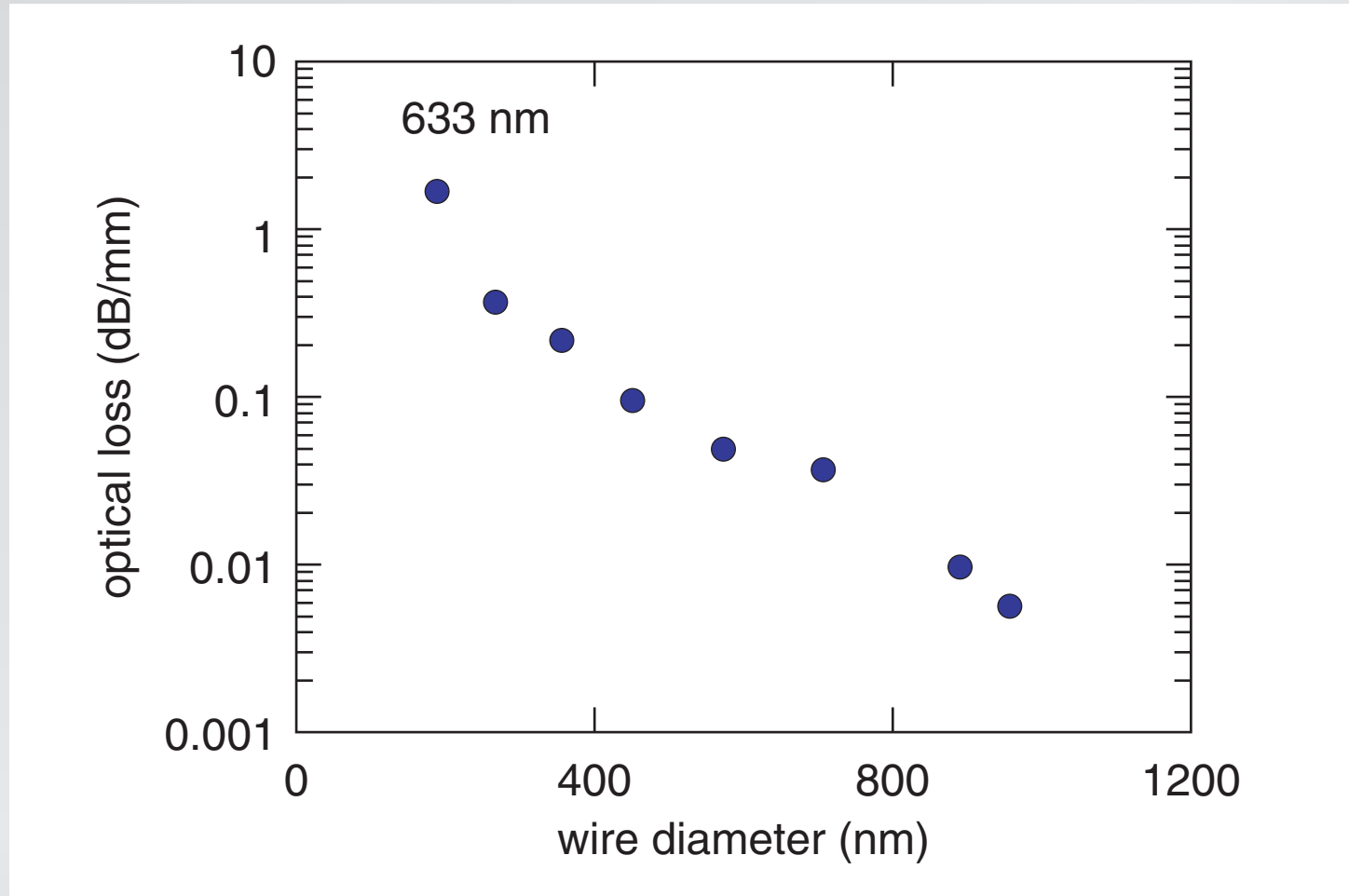
loss measurement



Nature, 426, 816 (2003)

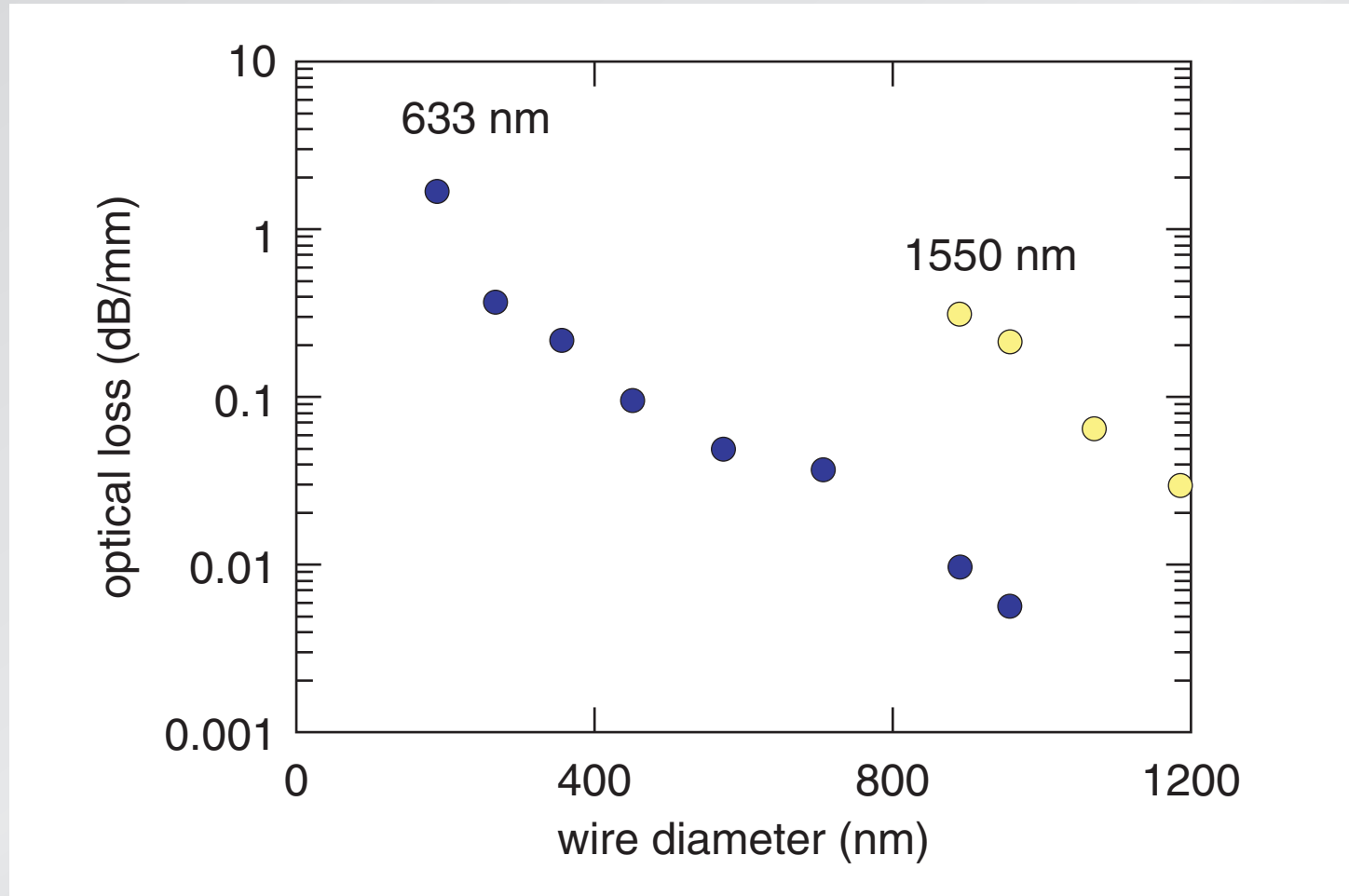
Optical properties

loss measurement



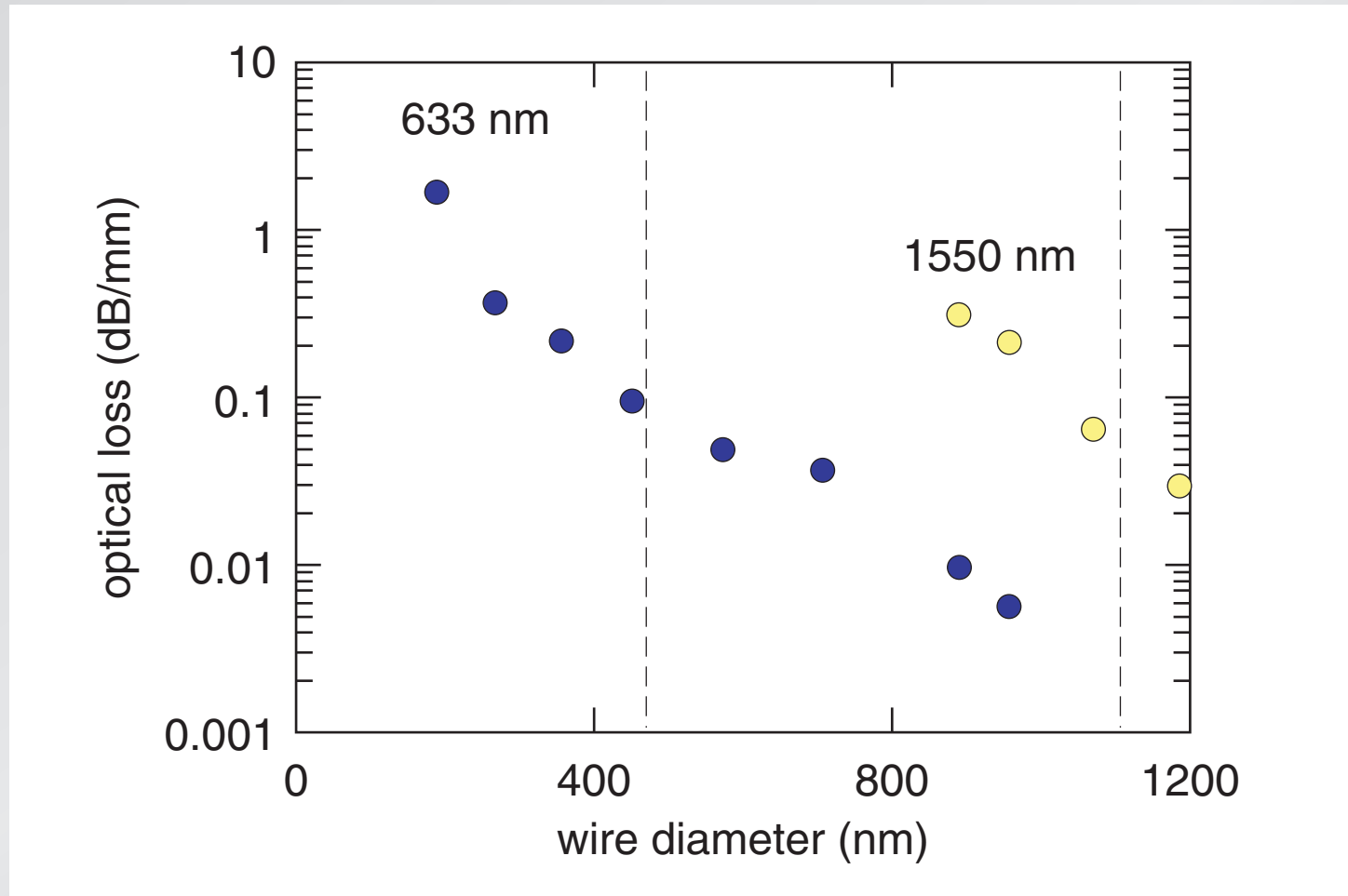
Optical properties

loss measurement



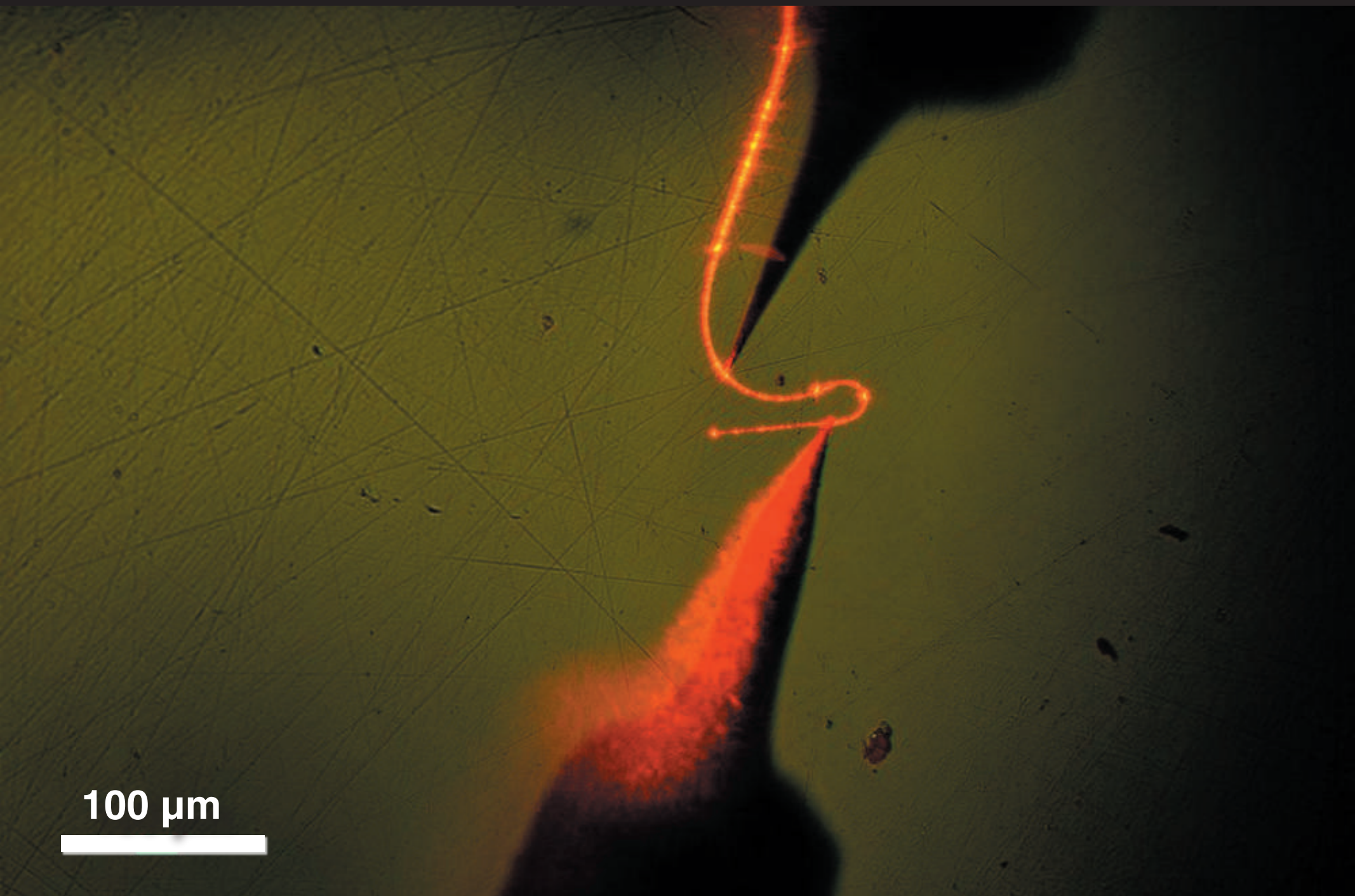
Optical properties

loss a single-mode diameter < 0.1 dB/mm



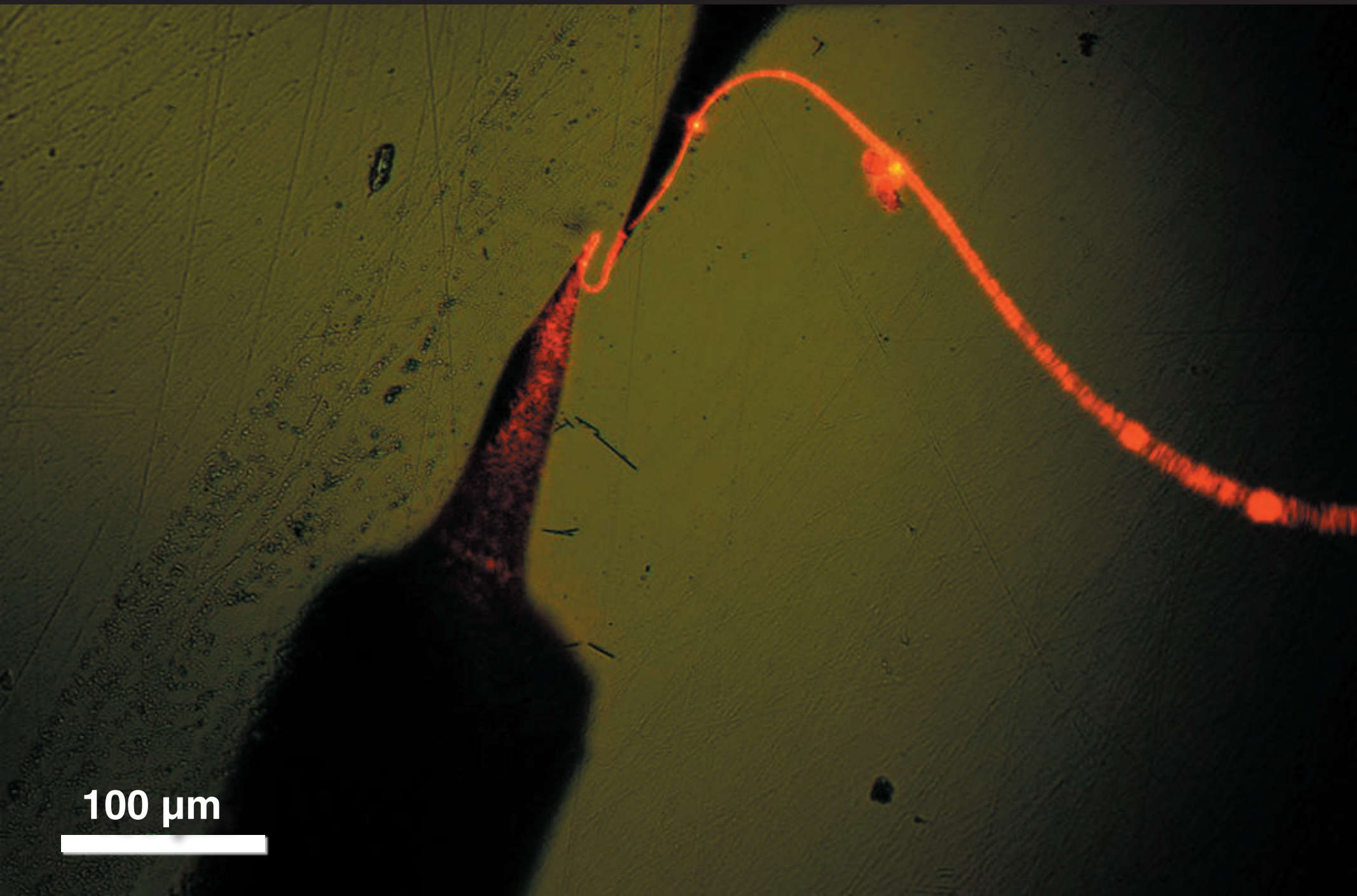
Nature, 426, 816 (2003)

Optical properties



100 μm

Optical properties



100 μm

Optical properties

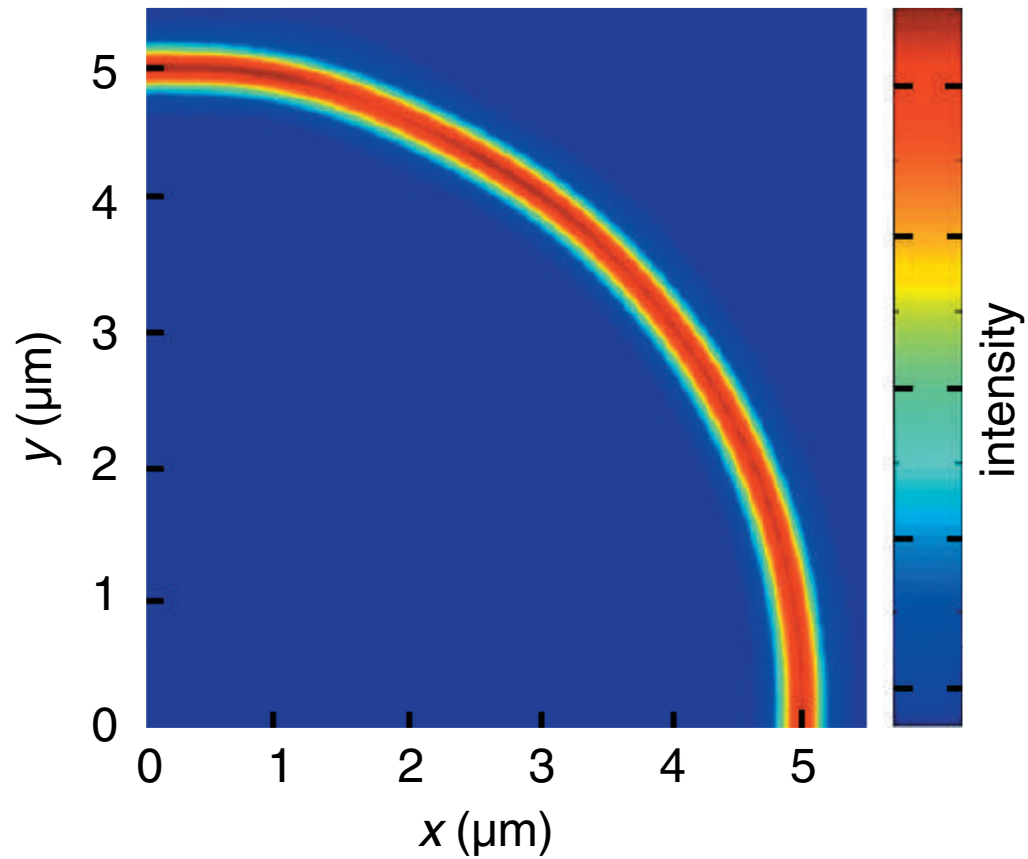
minimum bending
radius: $5.6 \mu\text{m}$

100 μm



Optical properties

virtually no loss through 5 μm corner!



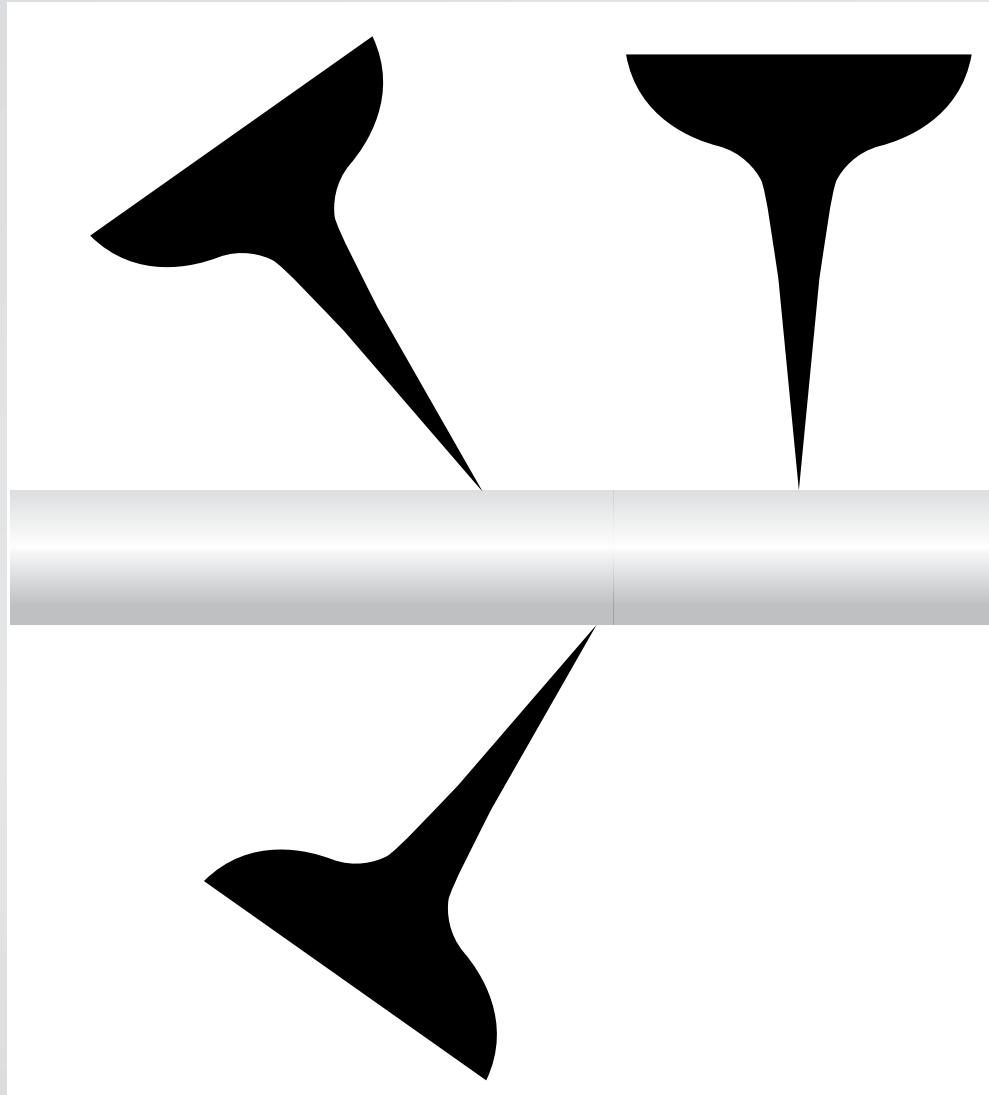
Optical properties

microphotonic components



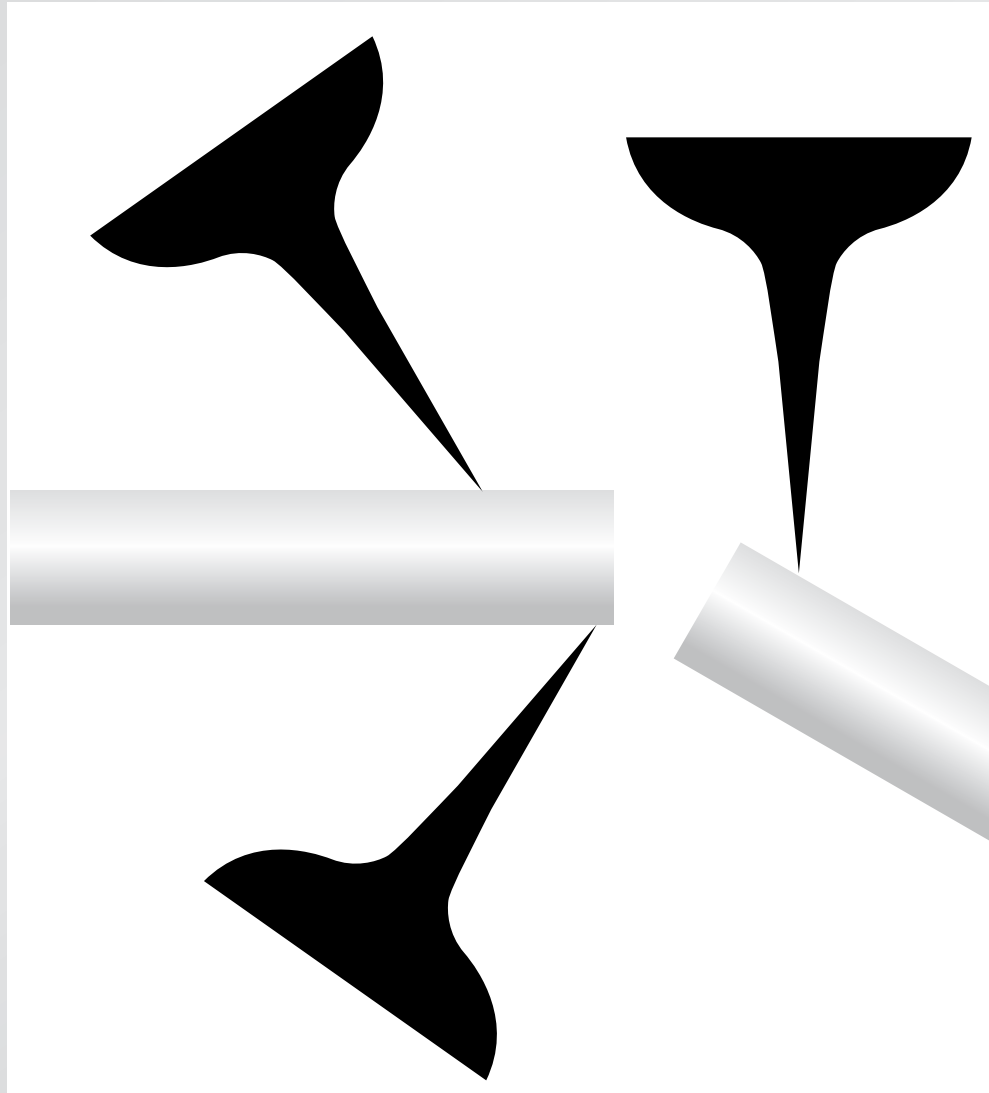
Optical properties

microphotonic components



Optical properties

microphotonic components



Optical properties

1 μm

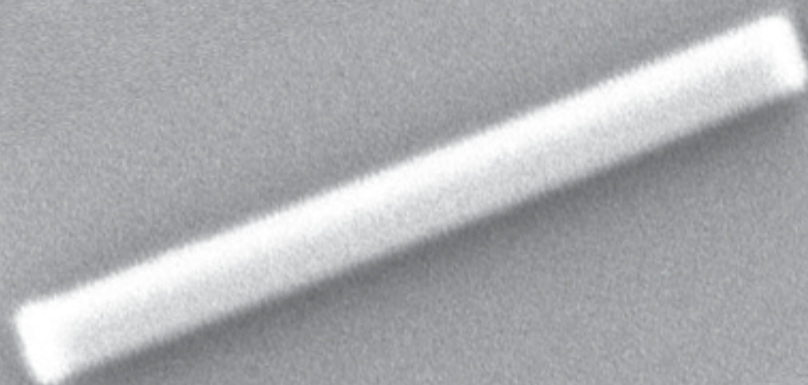


Optical properties

500 nm

A grayscale micrograph showing three vertical nanowires of increasing diameter from left to right. The nanowires are positioned in the lower half of the frame. A white horizontal scale bar is located in the bottom-left corner, with the text '500 nm' positioned above it.

Optical properties



500 nm

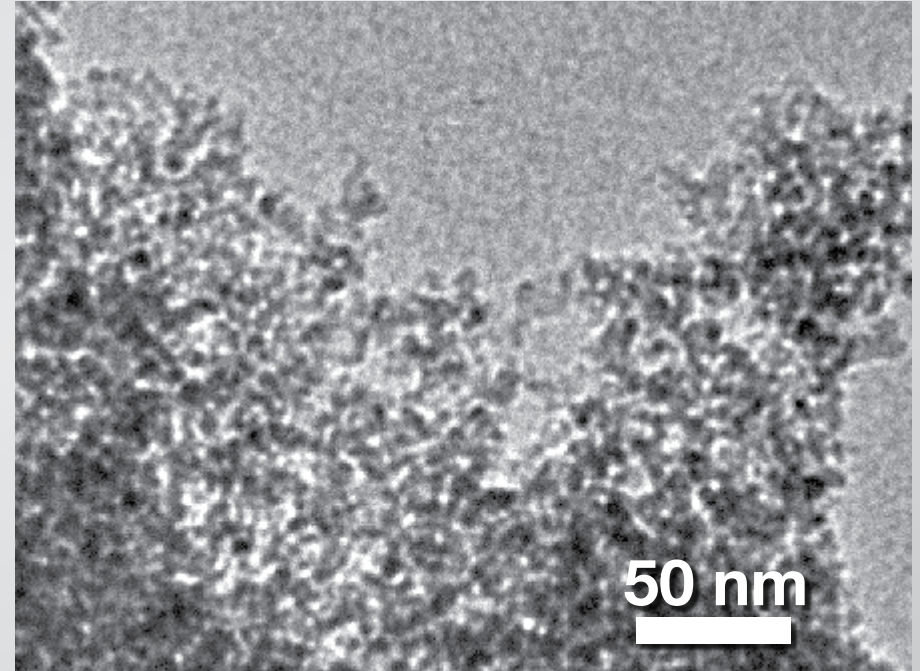
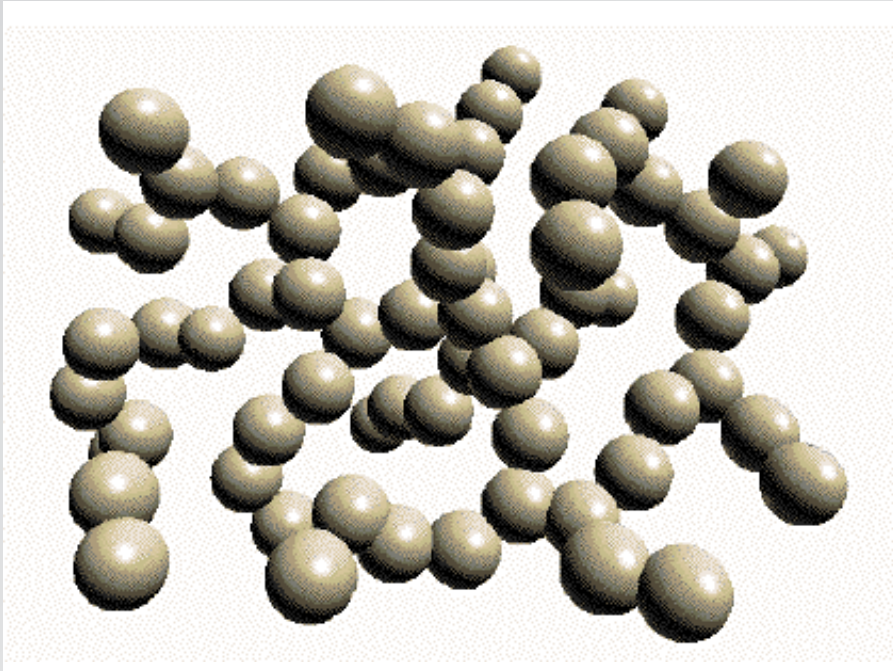


Optical properties



Optical properties

Aerogel



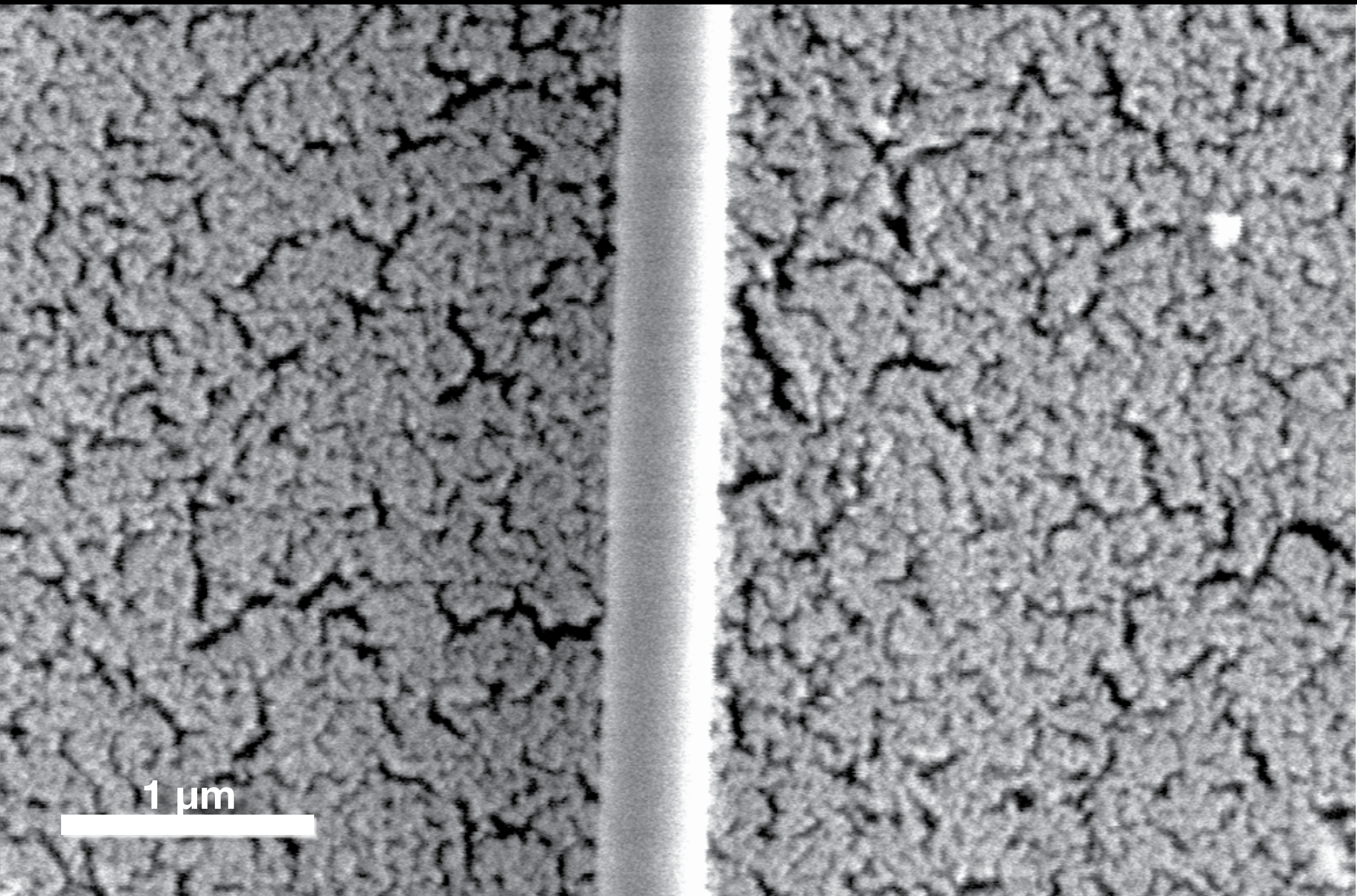
density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Optical properties



Optical properties

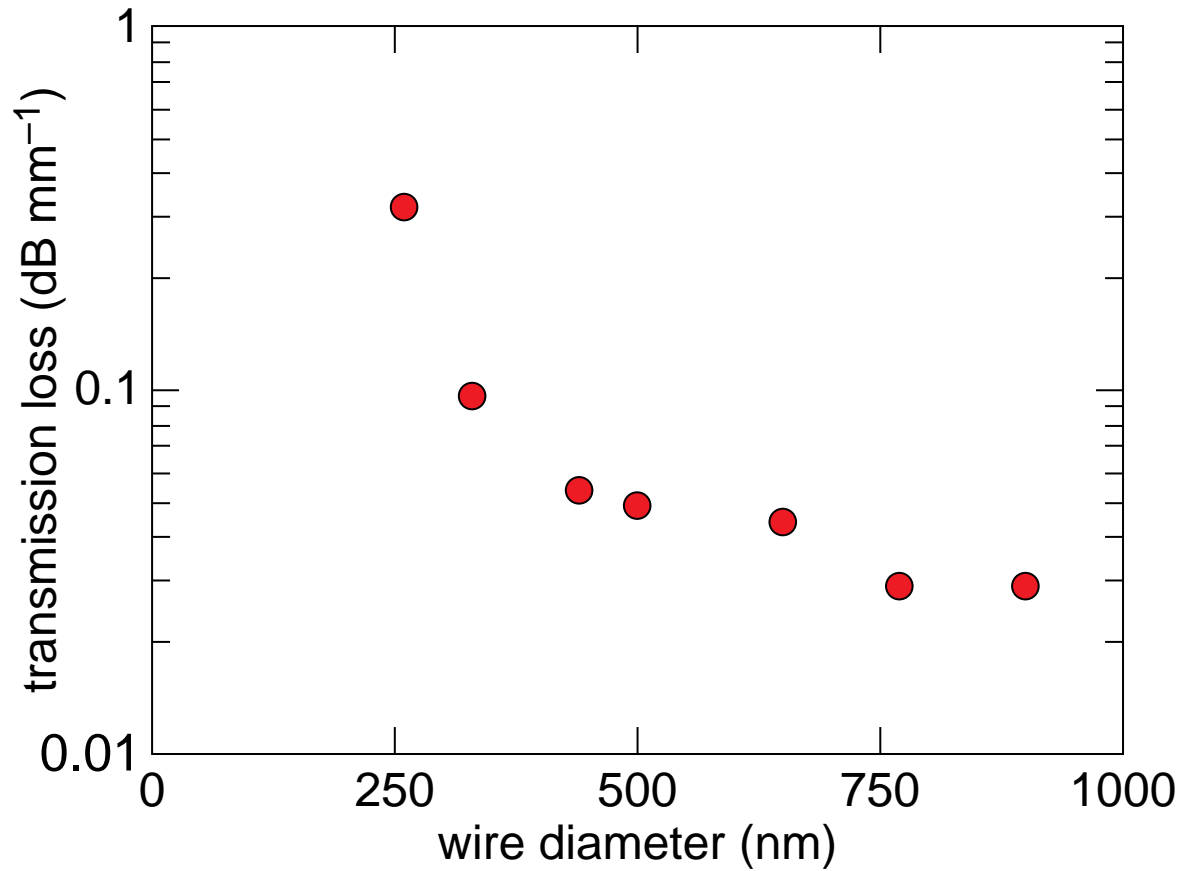


1 μm



Optical properties

loss measurement @ 633 nm

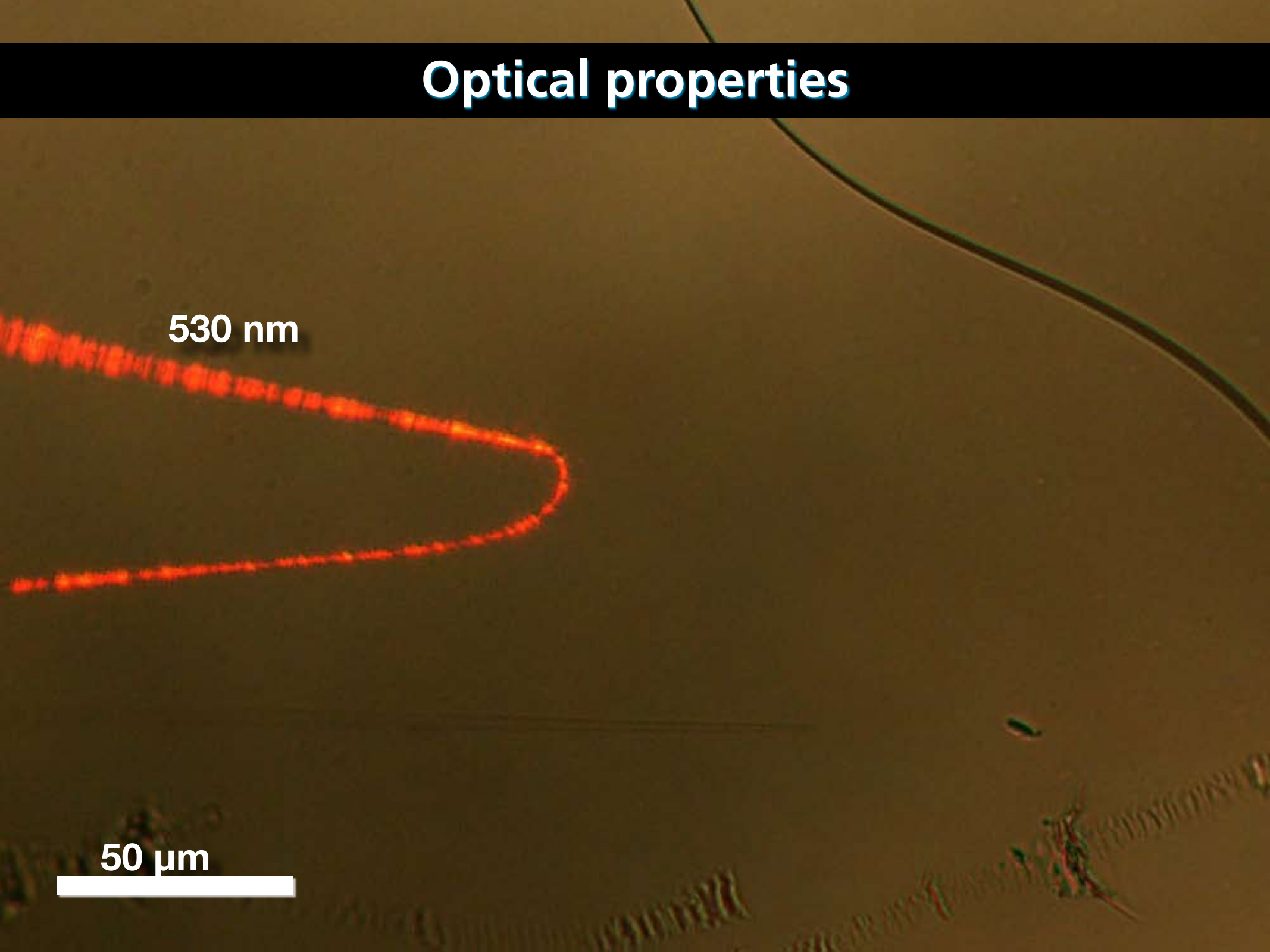


Nano Lett., 5, 259–262 (2005)

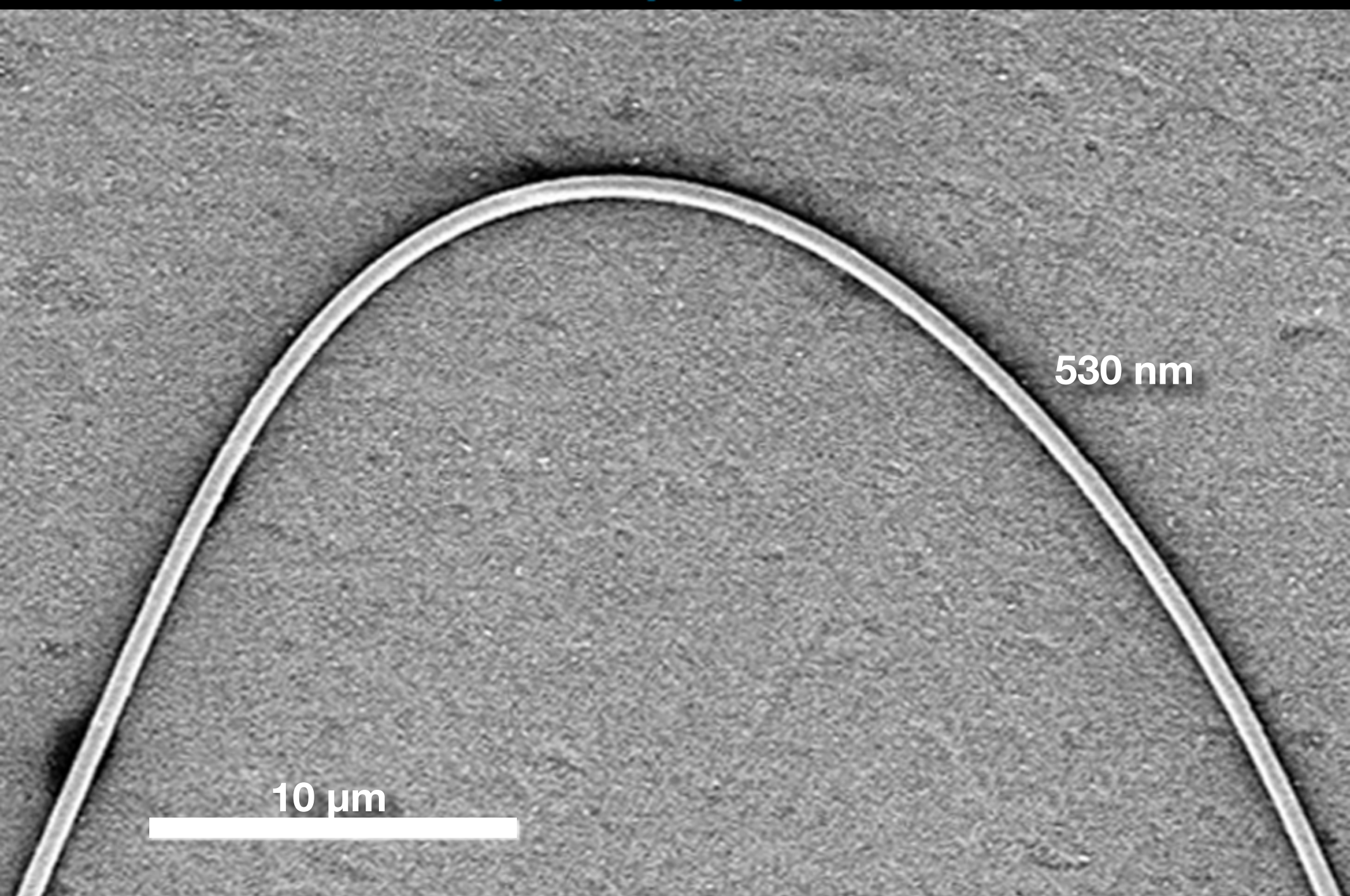
Optical properties

530 nm

50 μm



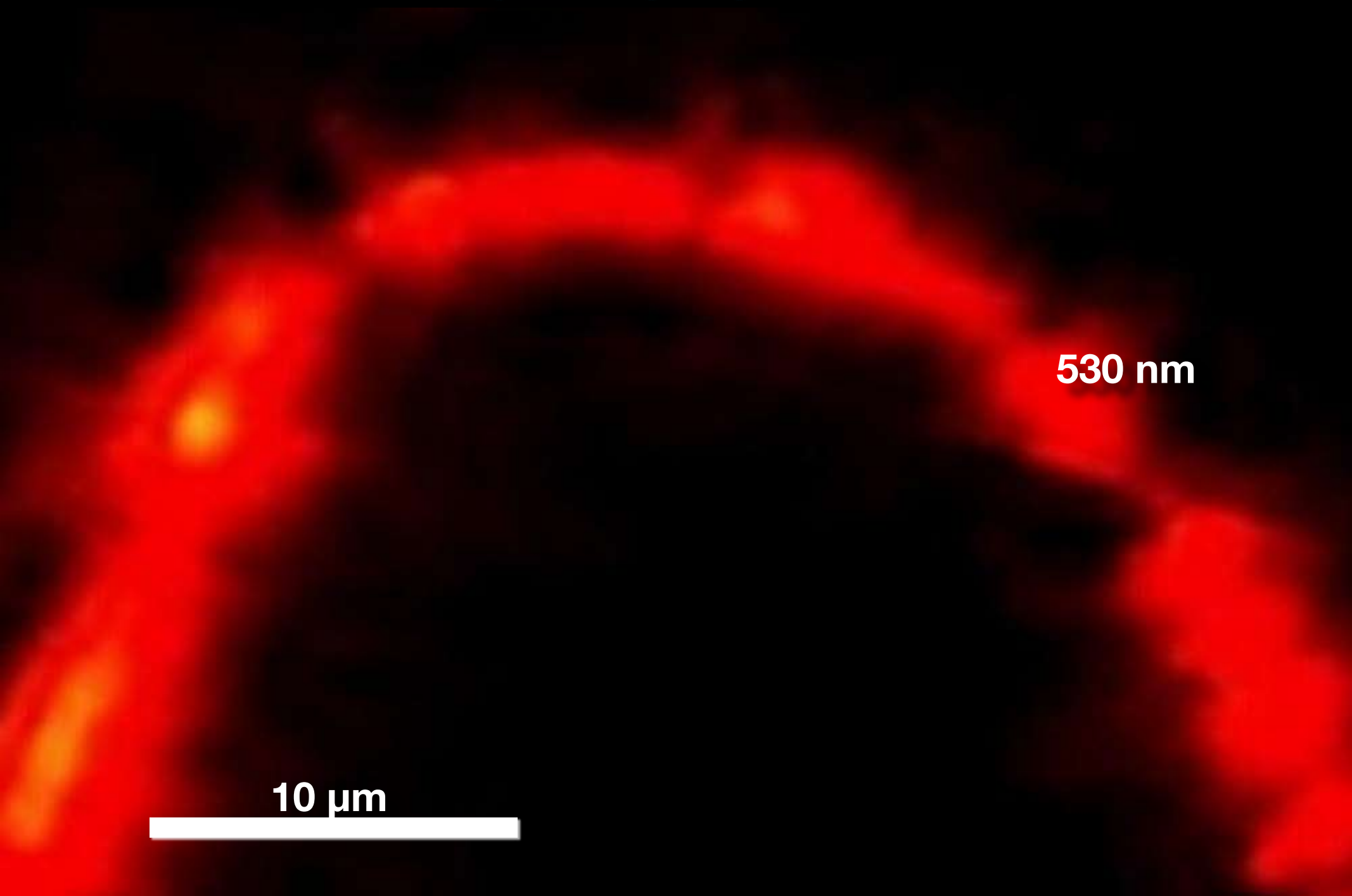
Optical properties



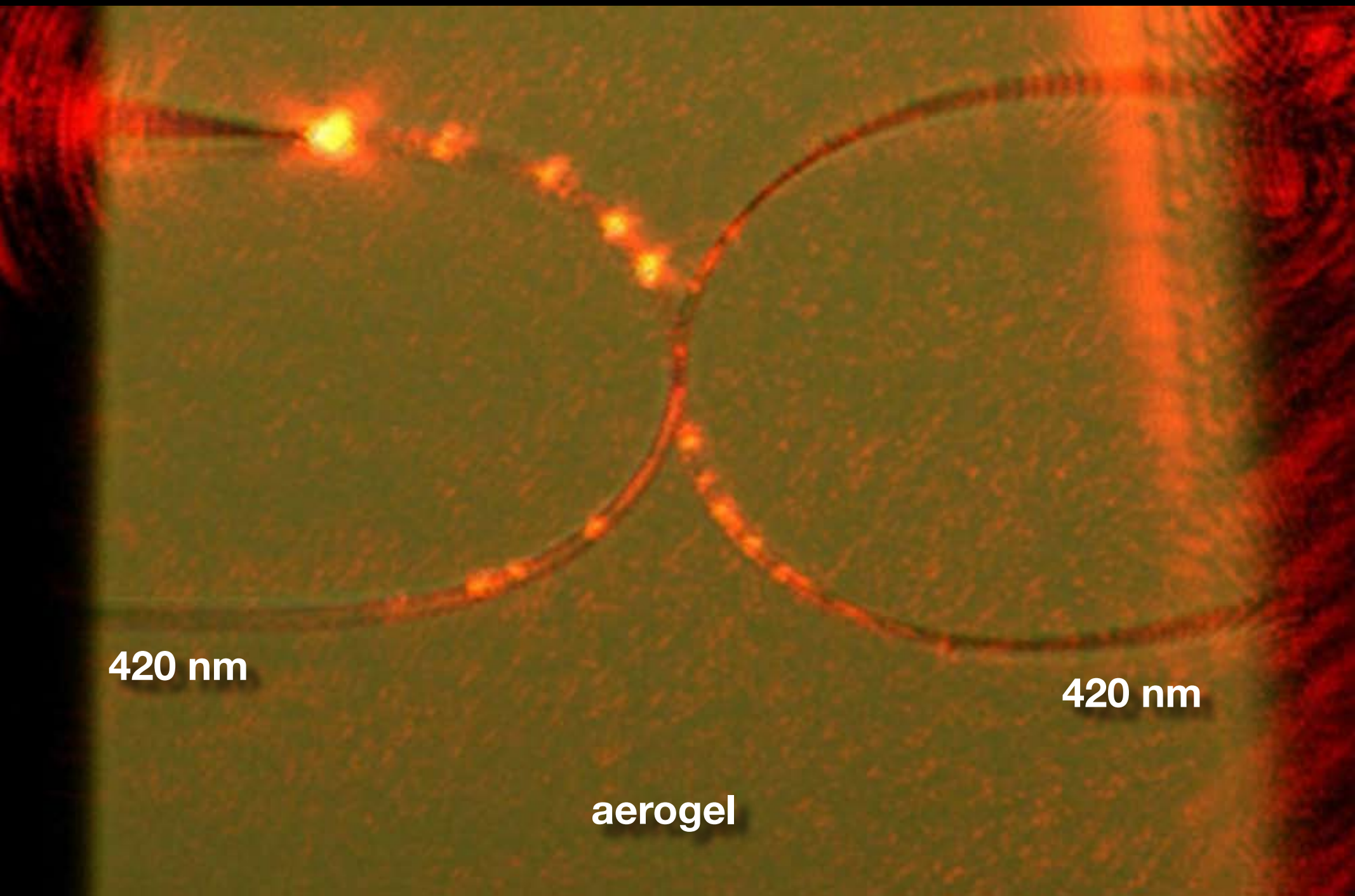
530 nm

10 μm

Optical properties



Optical properties

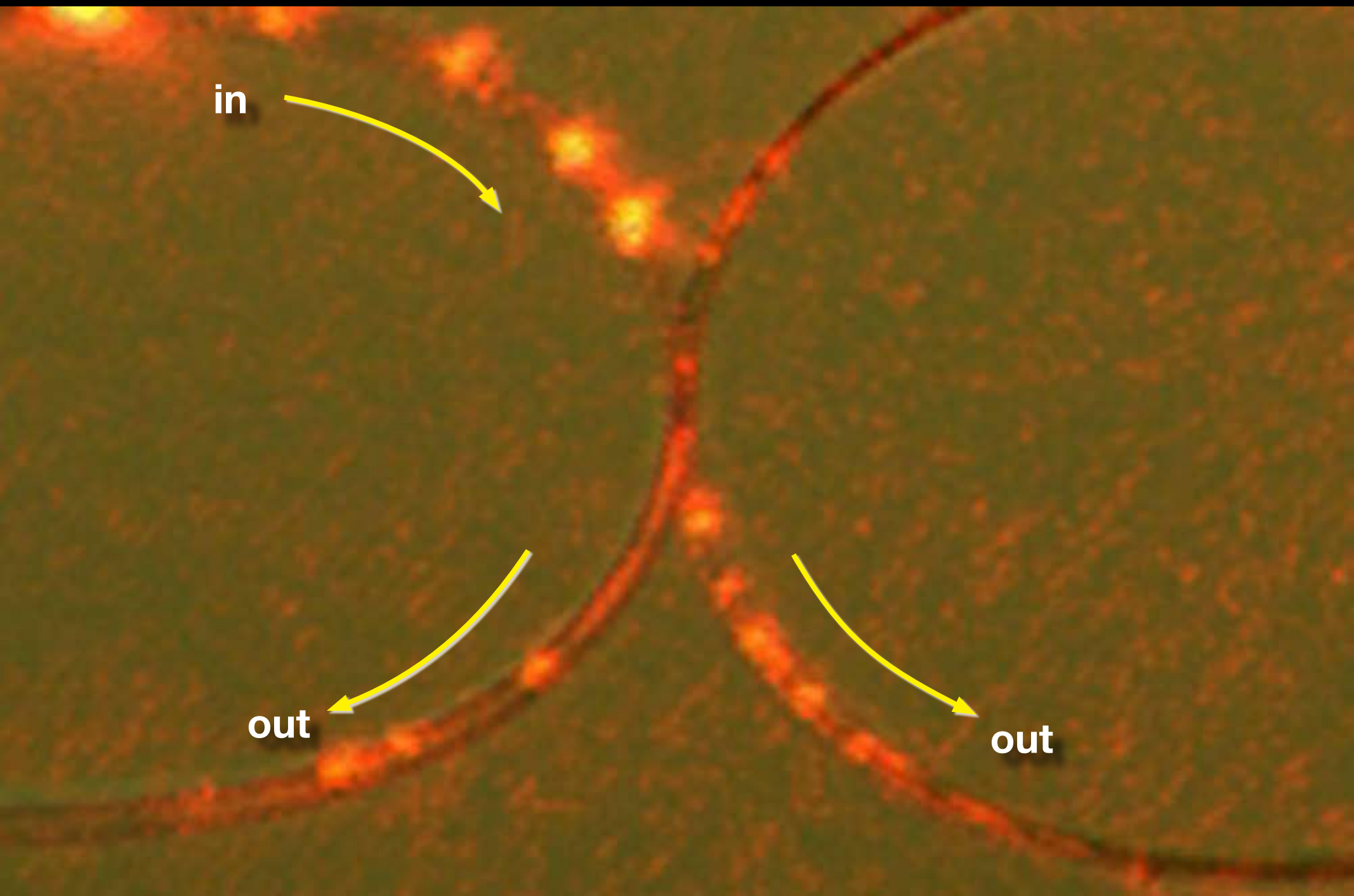


420 nm

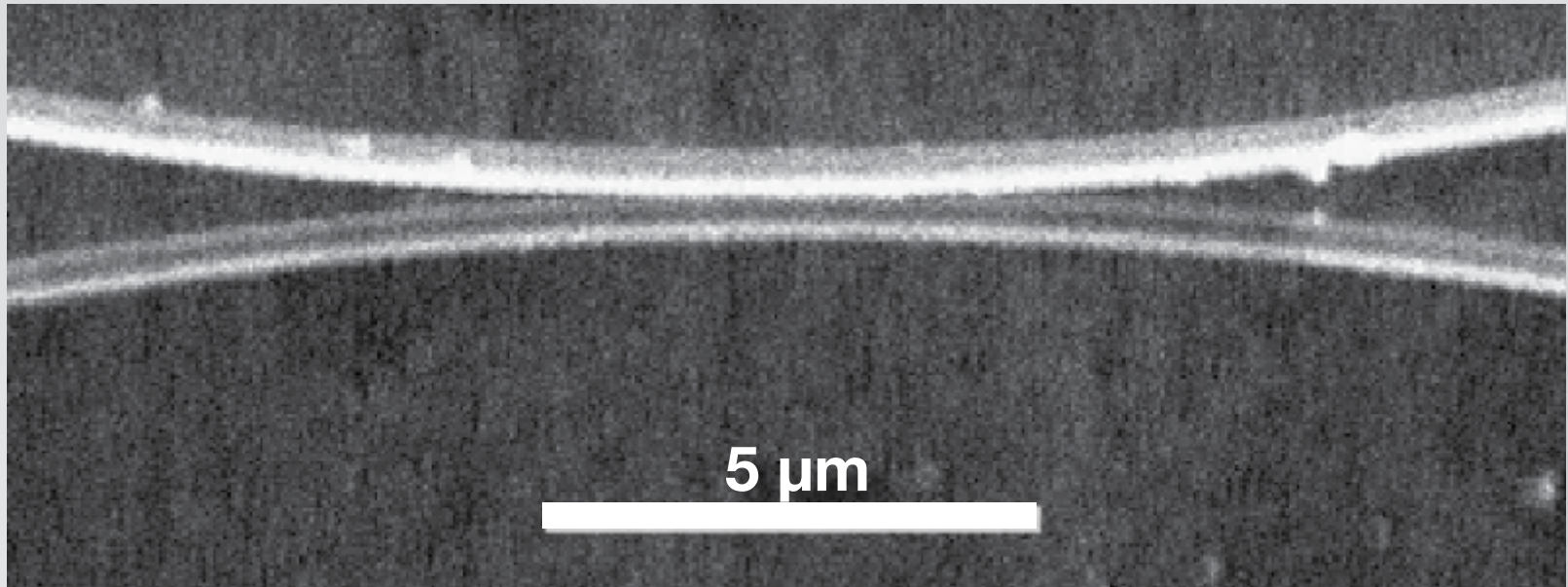
420 nm

aerogel

Optical properties

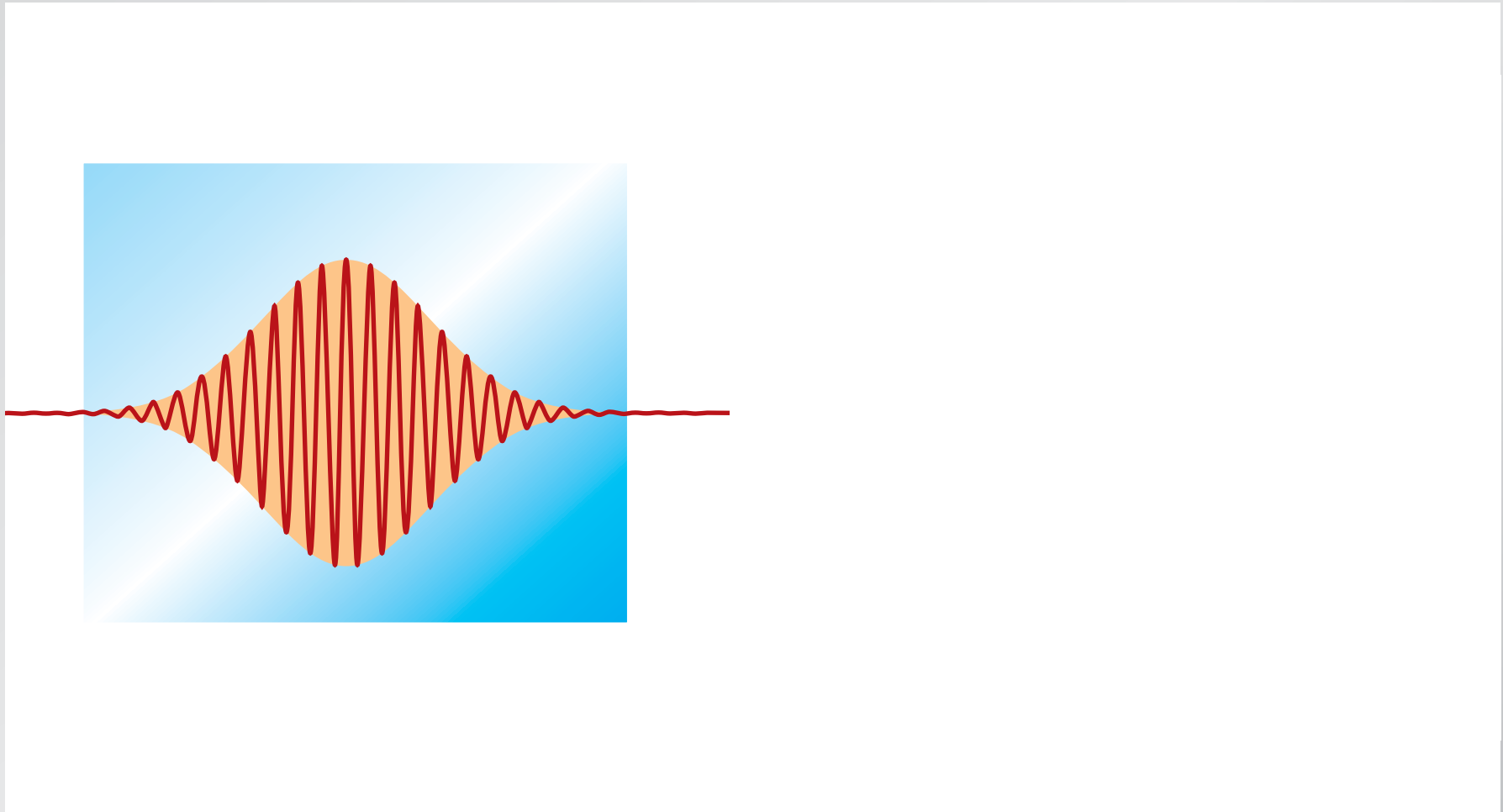


Optical properties



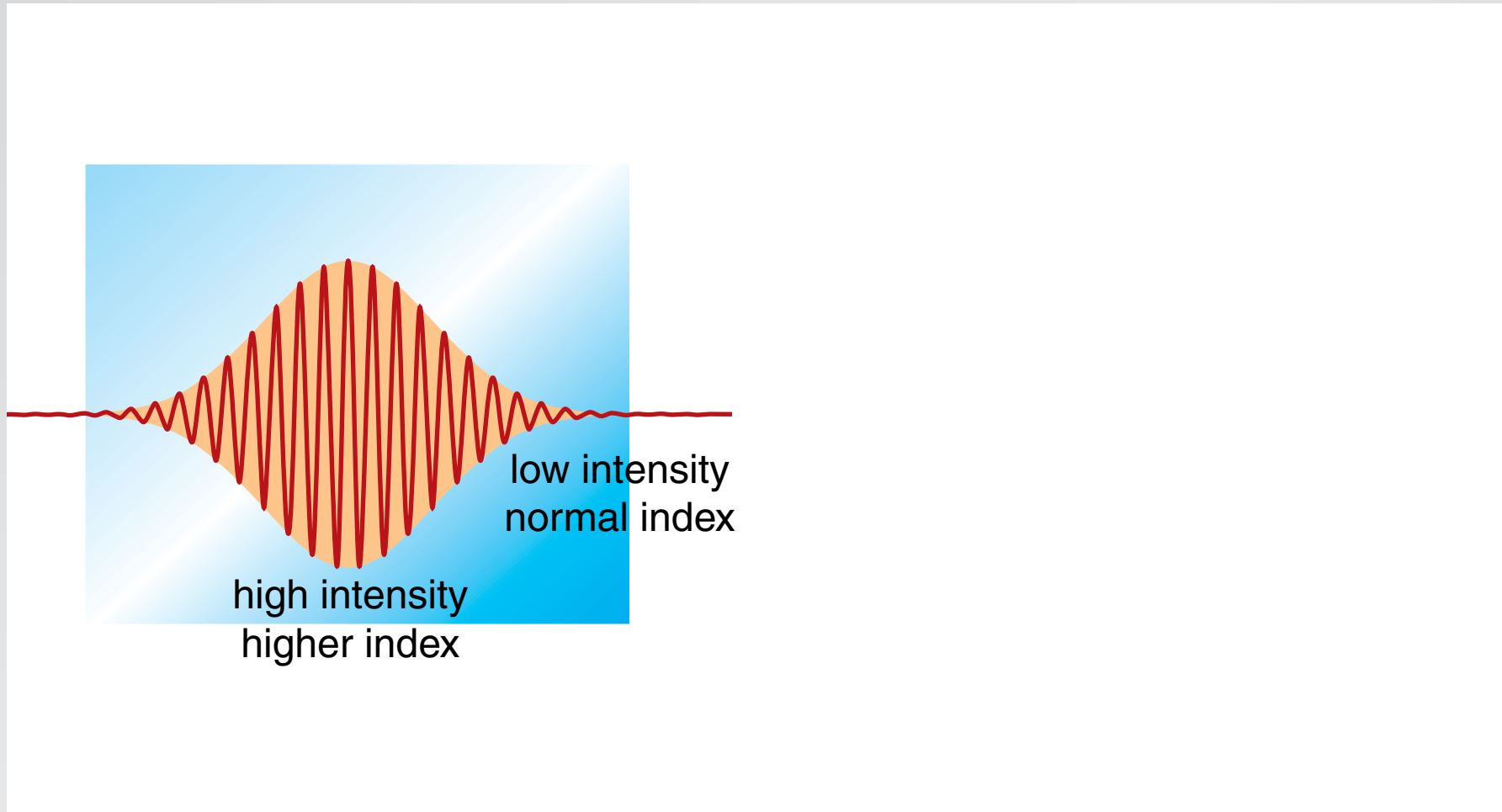
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



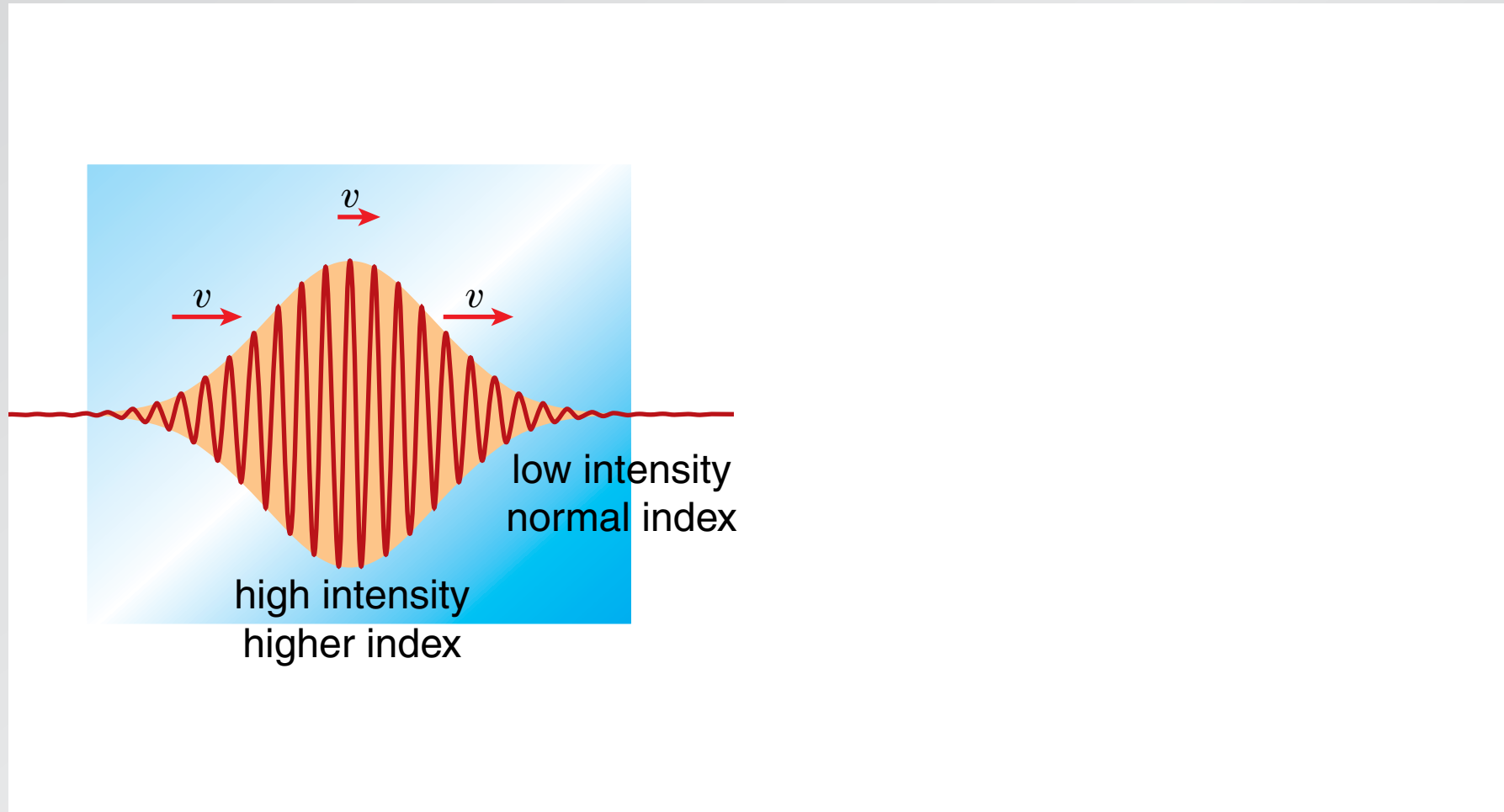
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



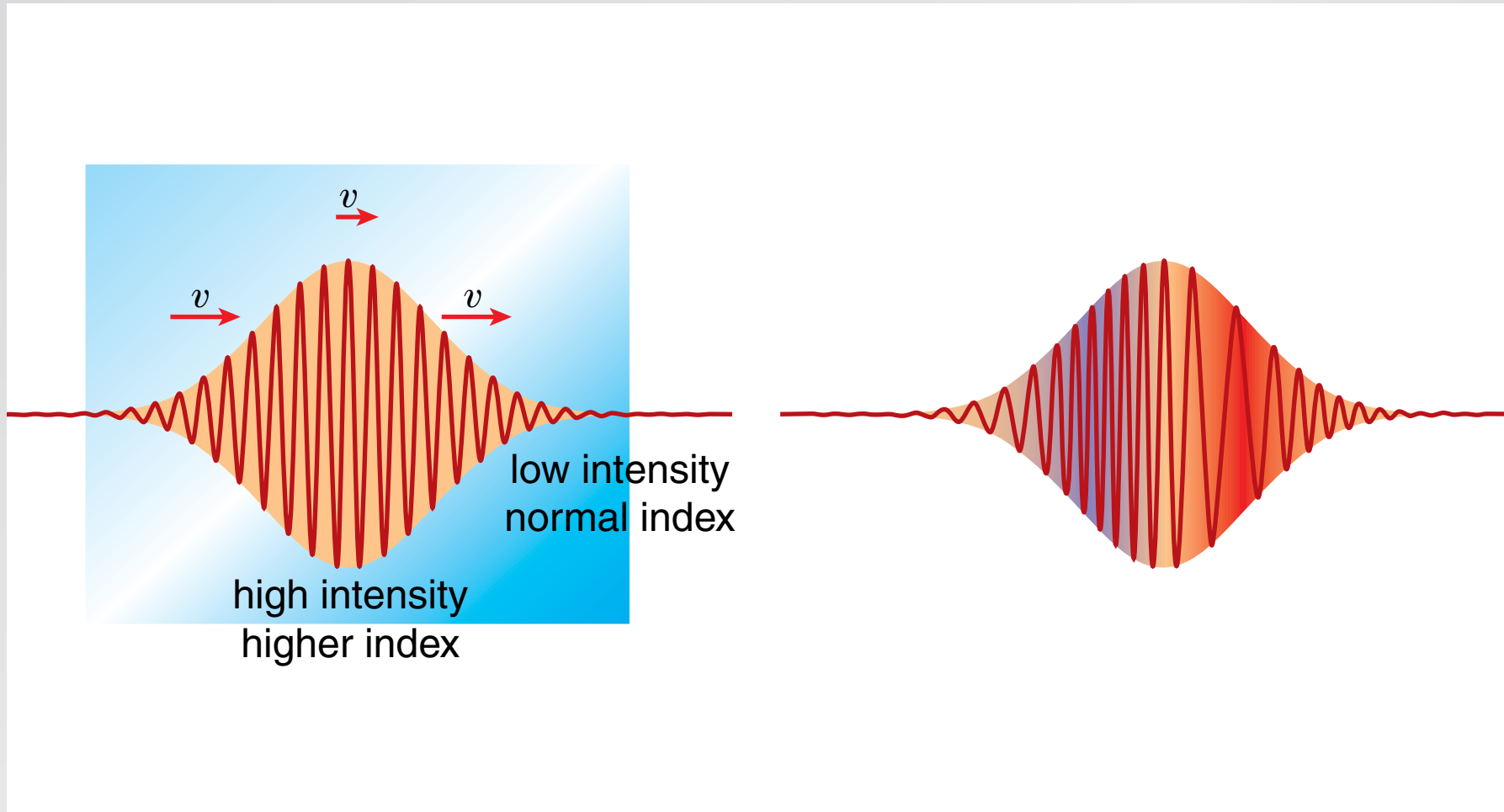
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



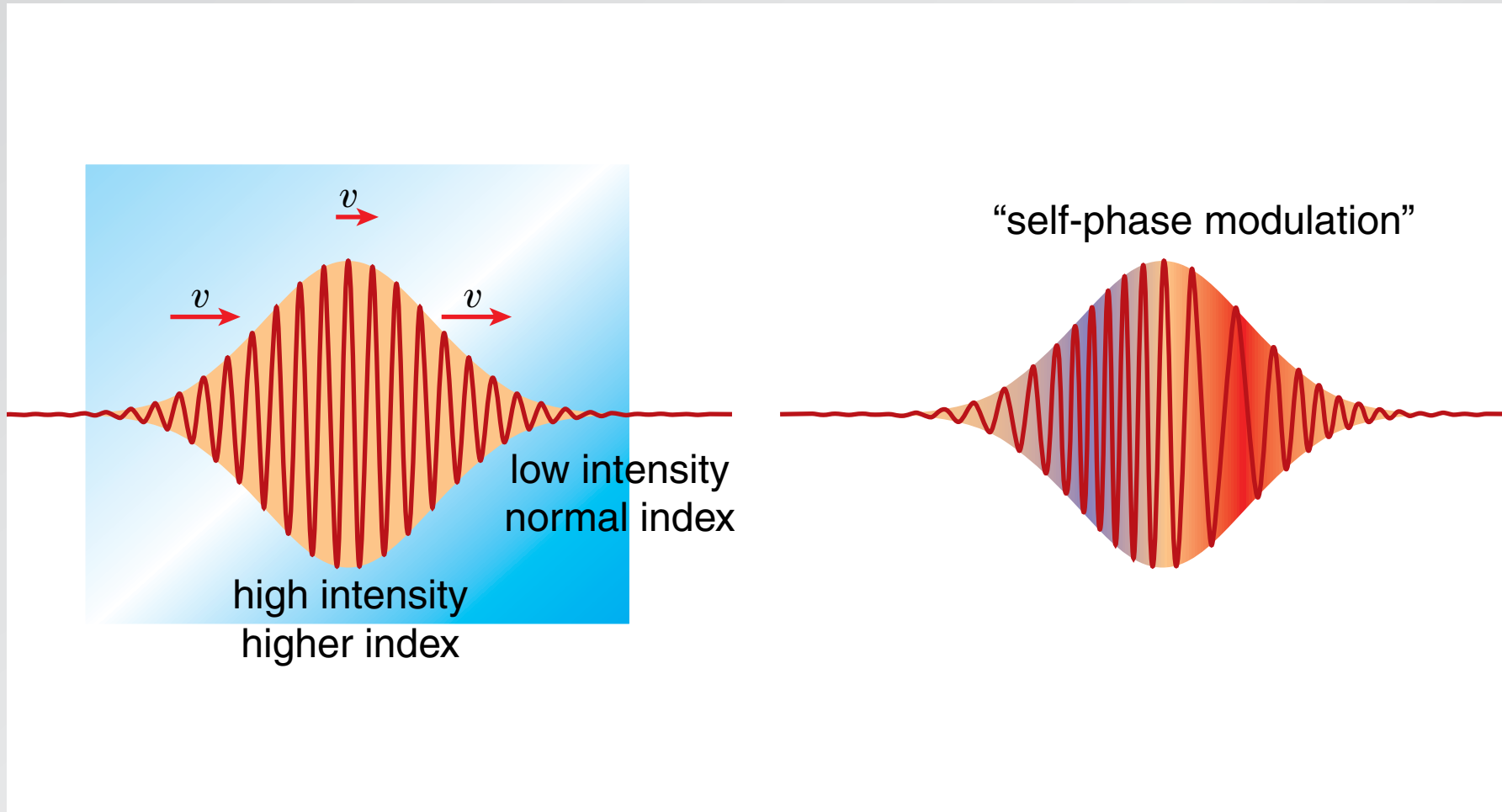
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$

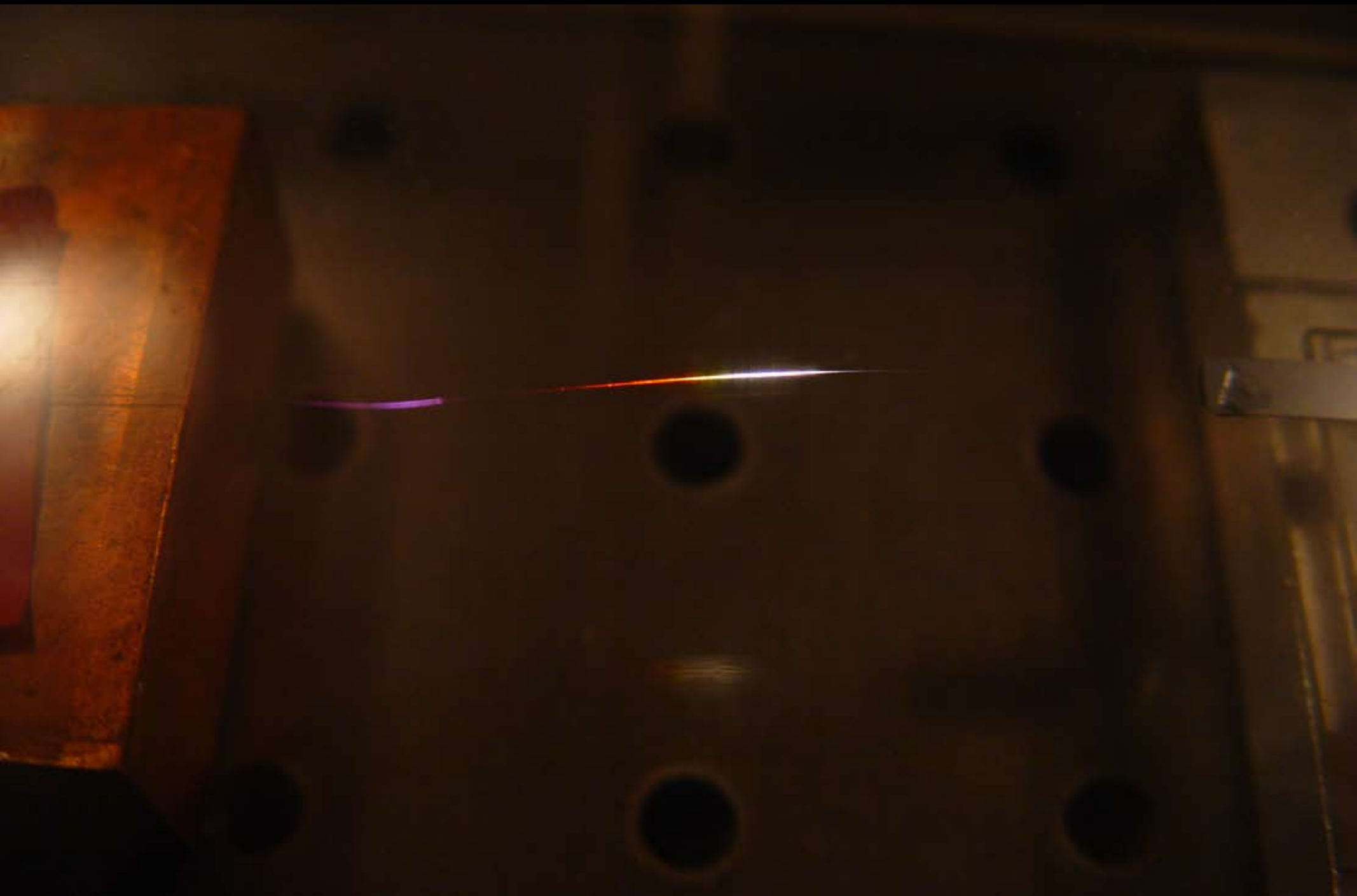


Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



Nonlinear properties



Nonlinear properties

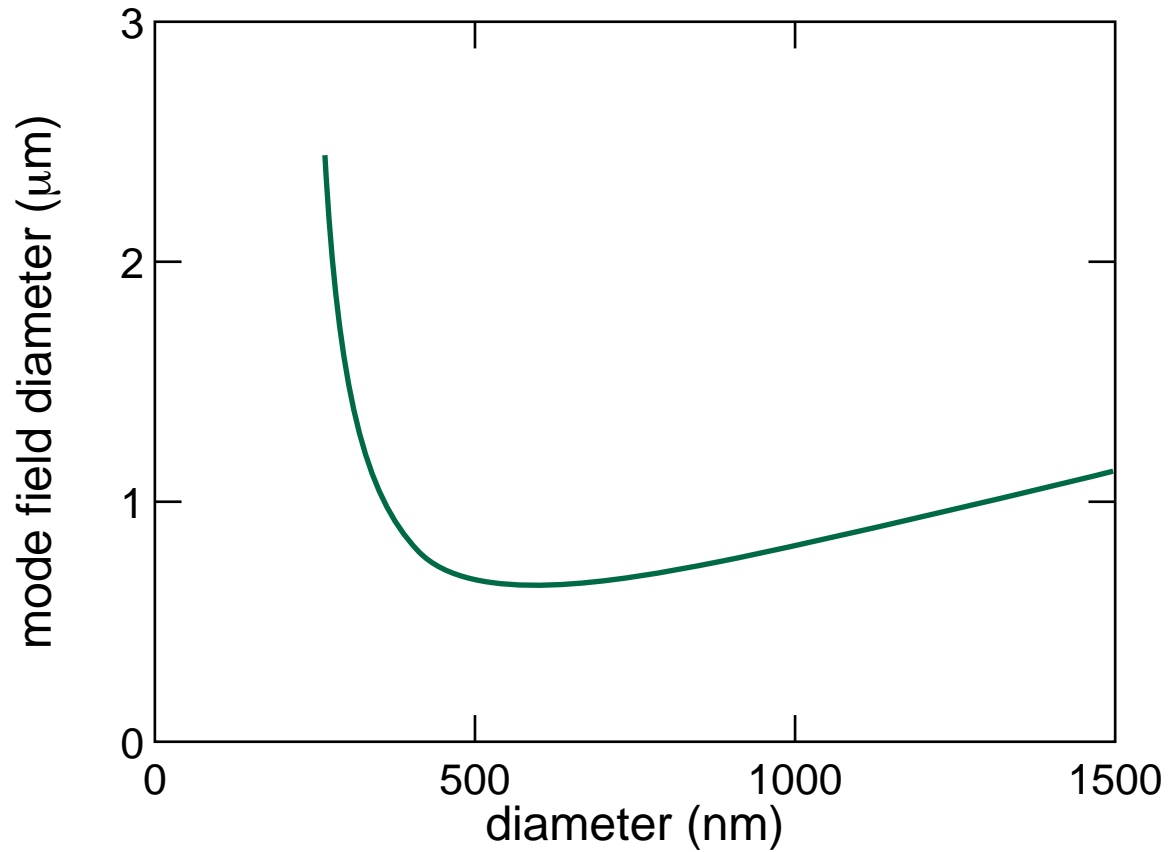


Nonlinear properties

strong confinement \longrightarrow **high intensity**

Nonlinear properties

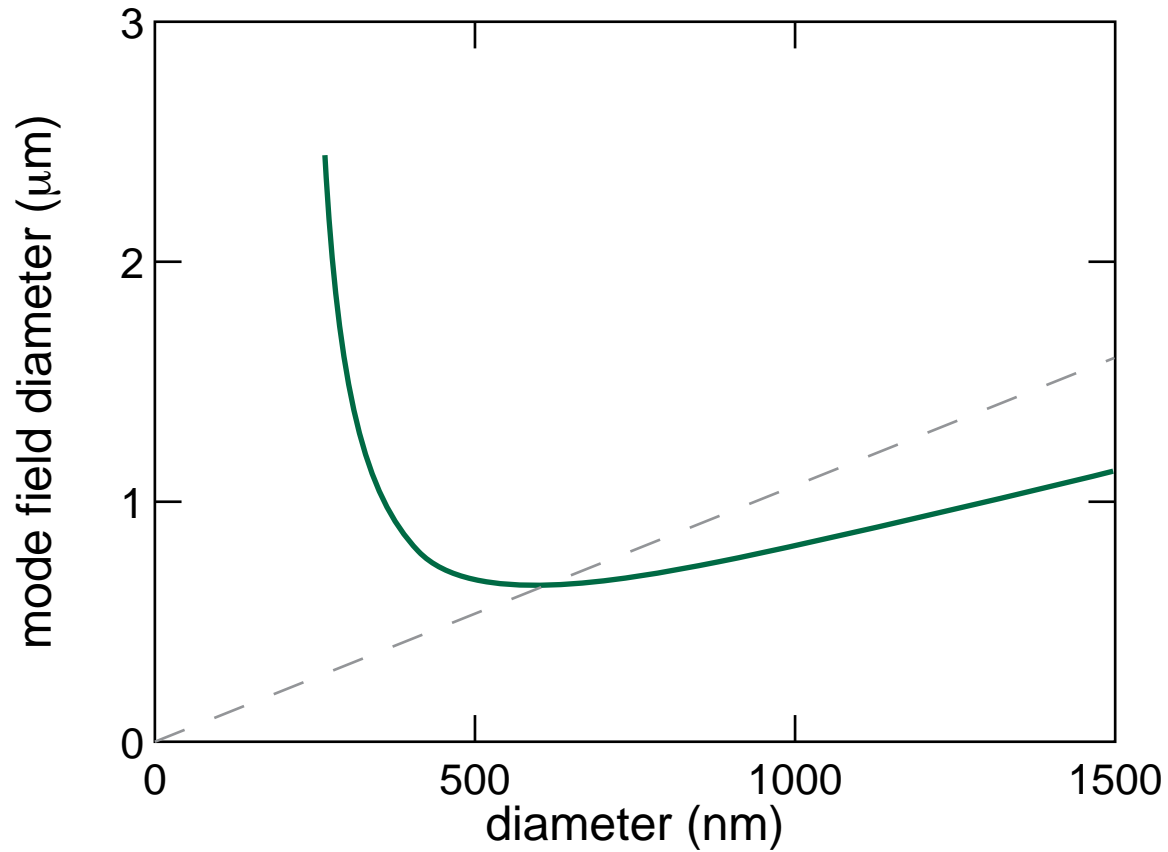
mode field diameter ($\lambda = 800$ nm)



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

Nonlinear properties

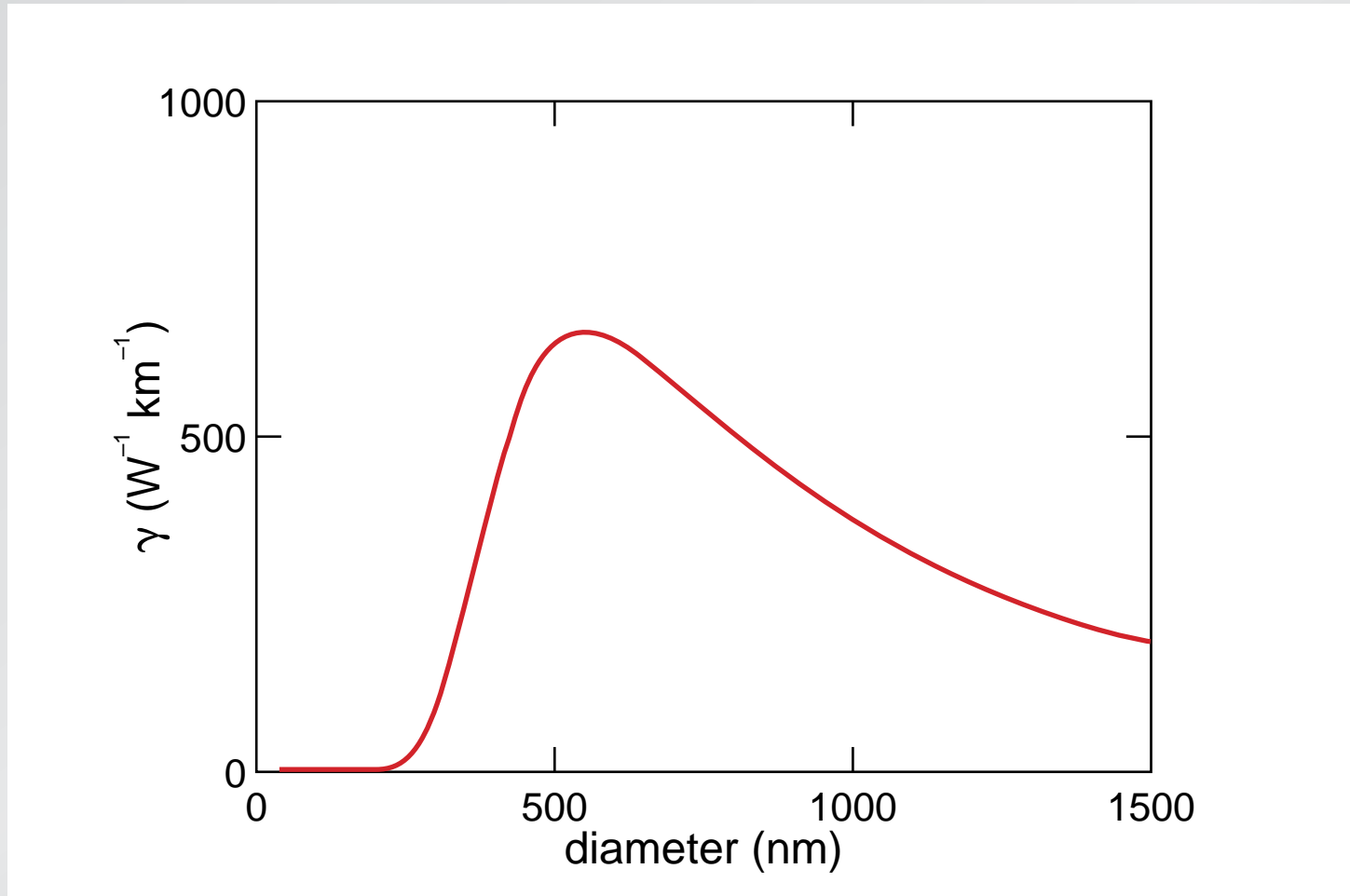
mode field diameter ($\lambda = 800$ nm)



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

Nonlinear properties

nonlinear parameter



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

Nonlinear properties

dispersion important!

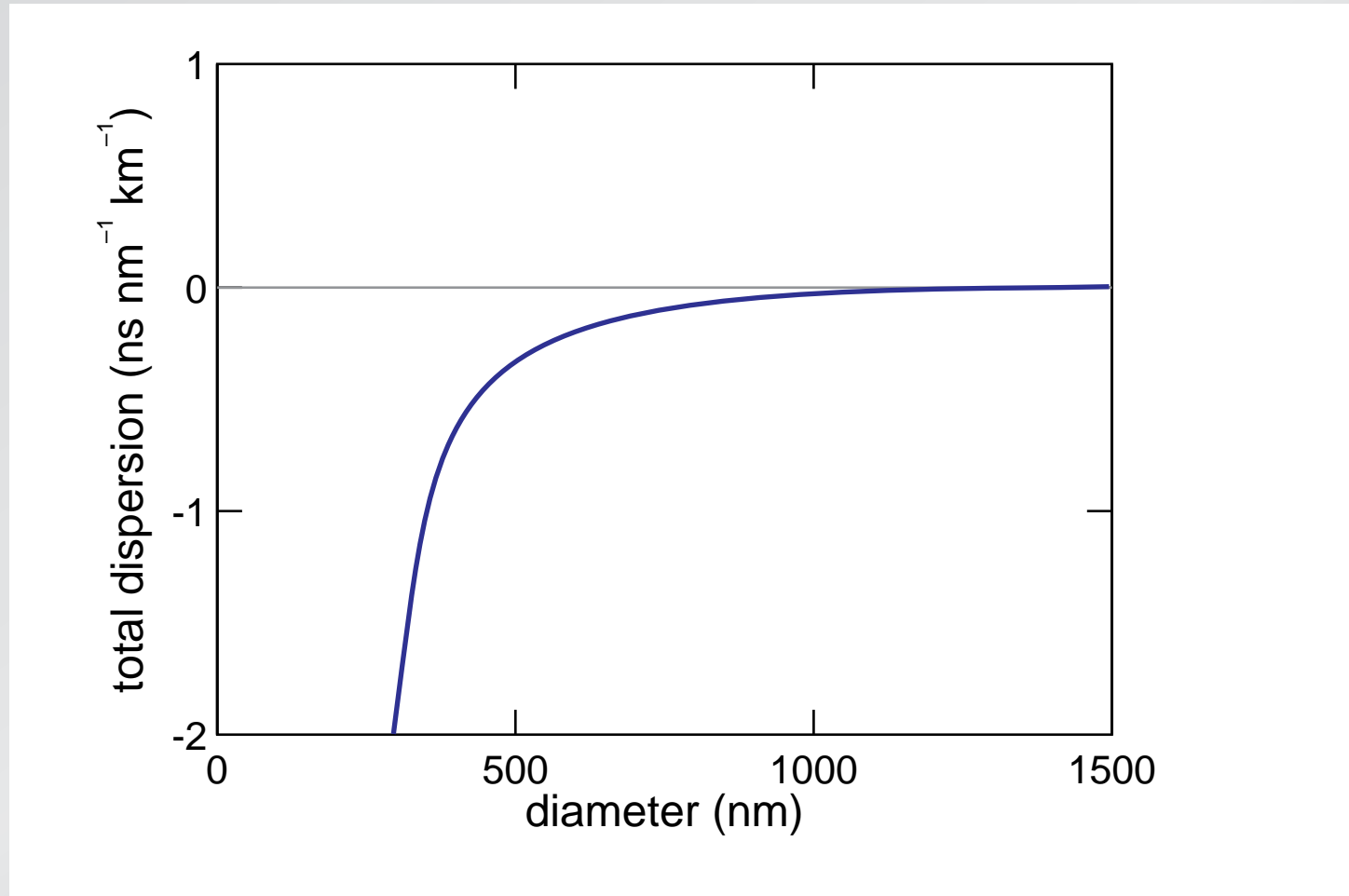
Nonlinear properties

dispersion:

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

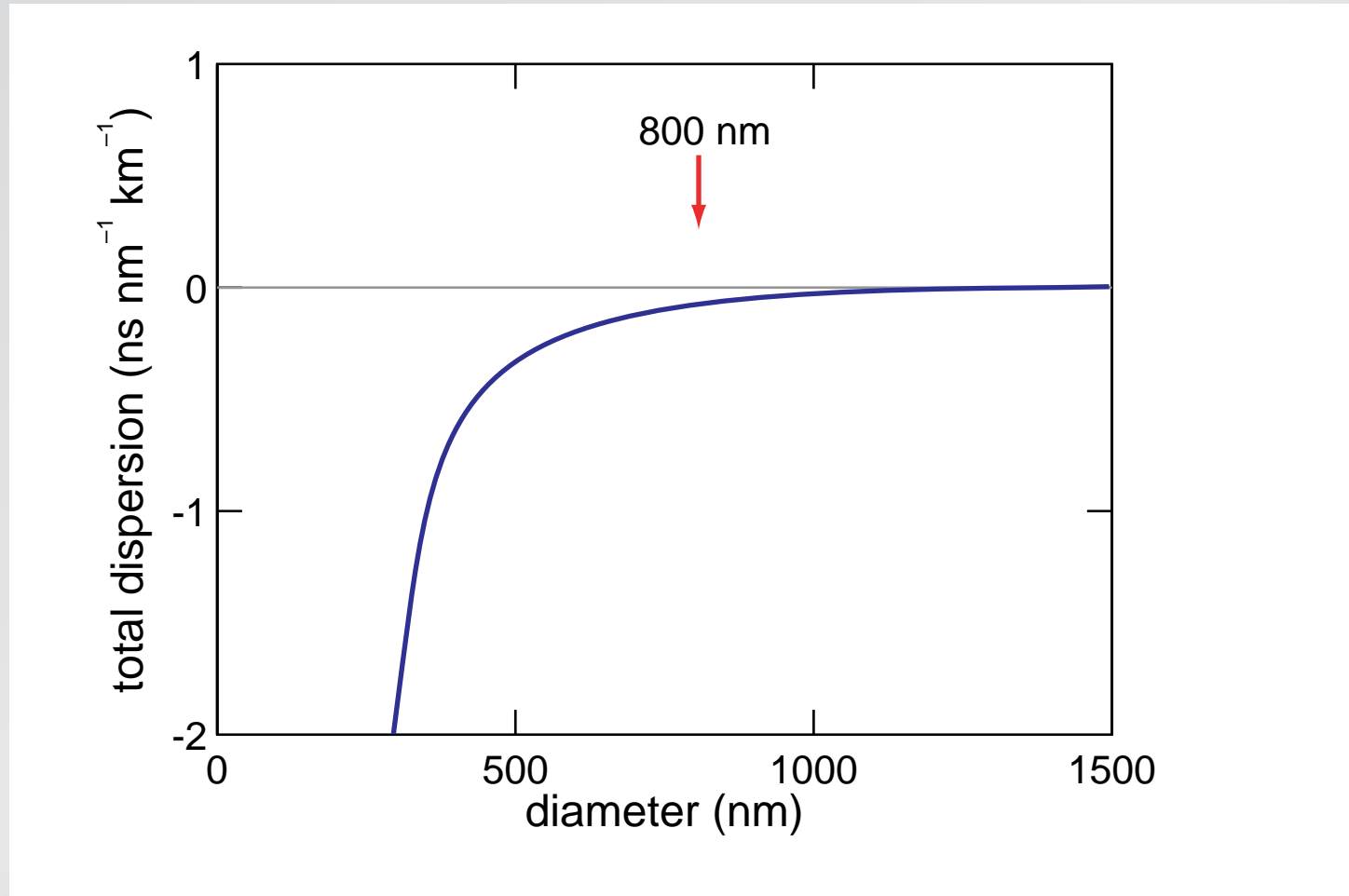
Nonlinear properties

waveguide dispersion



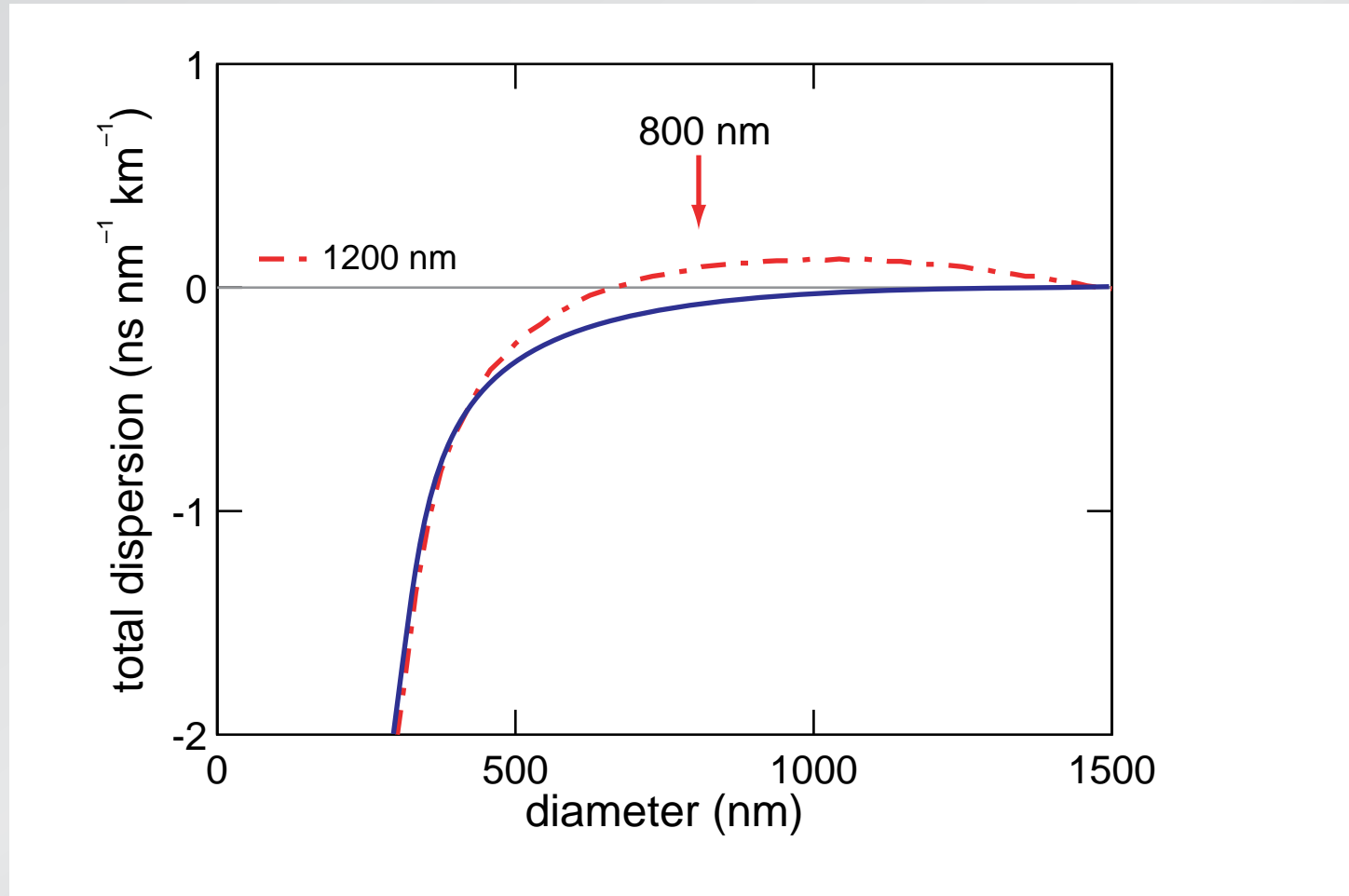
Nonlinear properties

waveguide dispersion



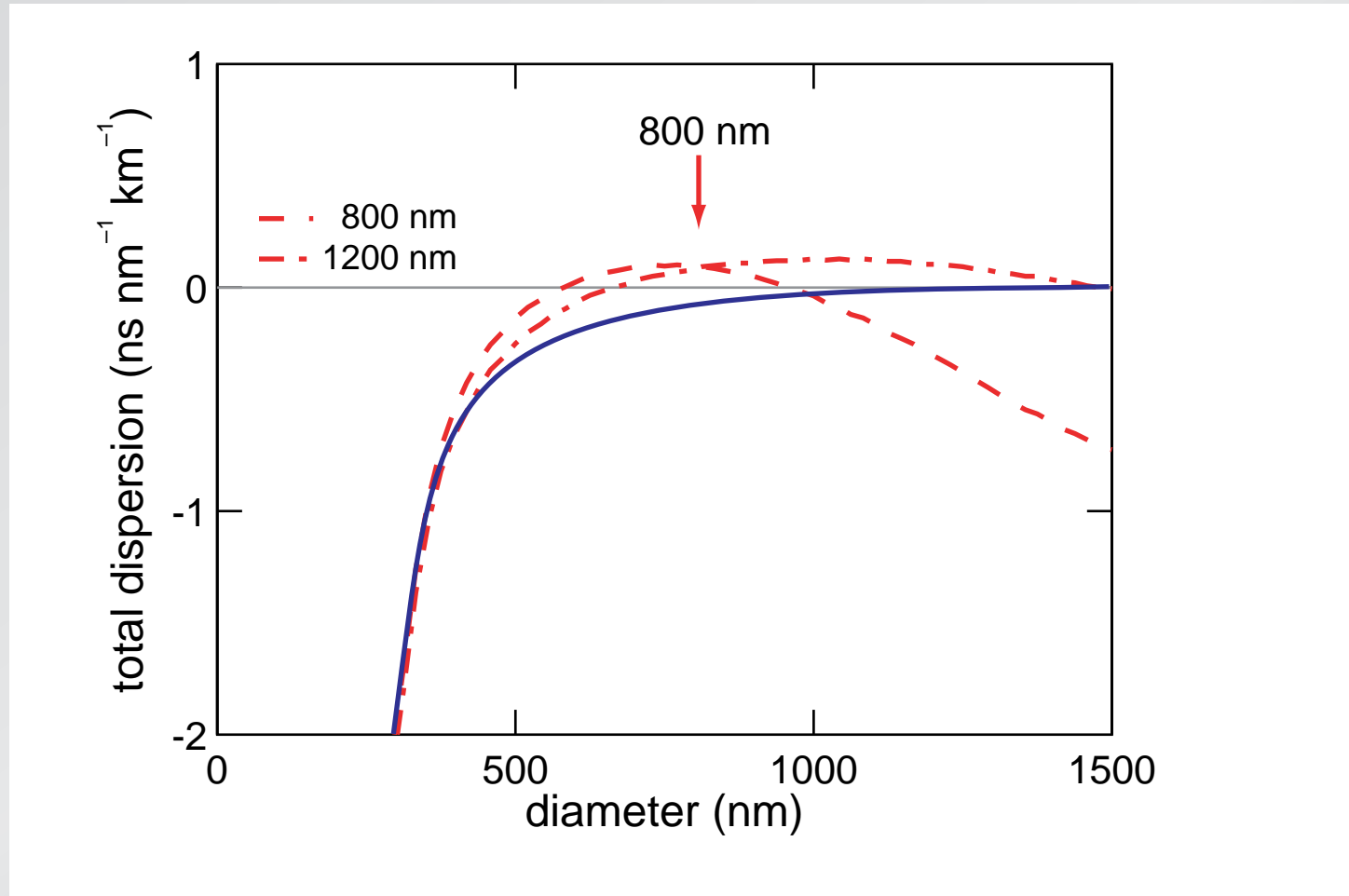
Nonlinear properties

waveguide dispersion



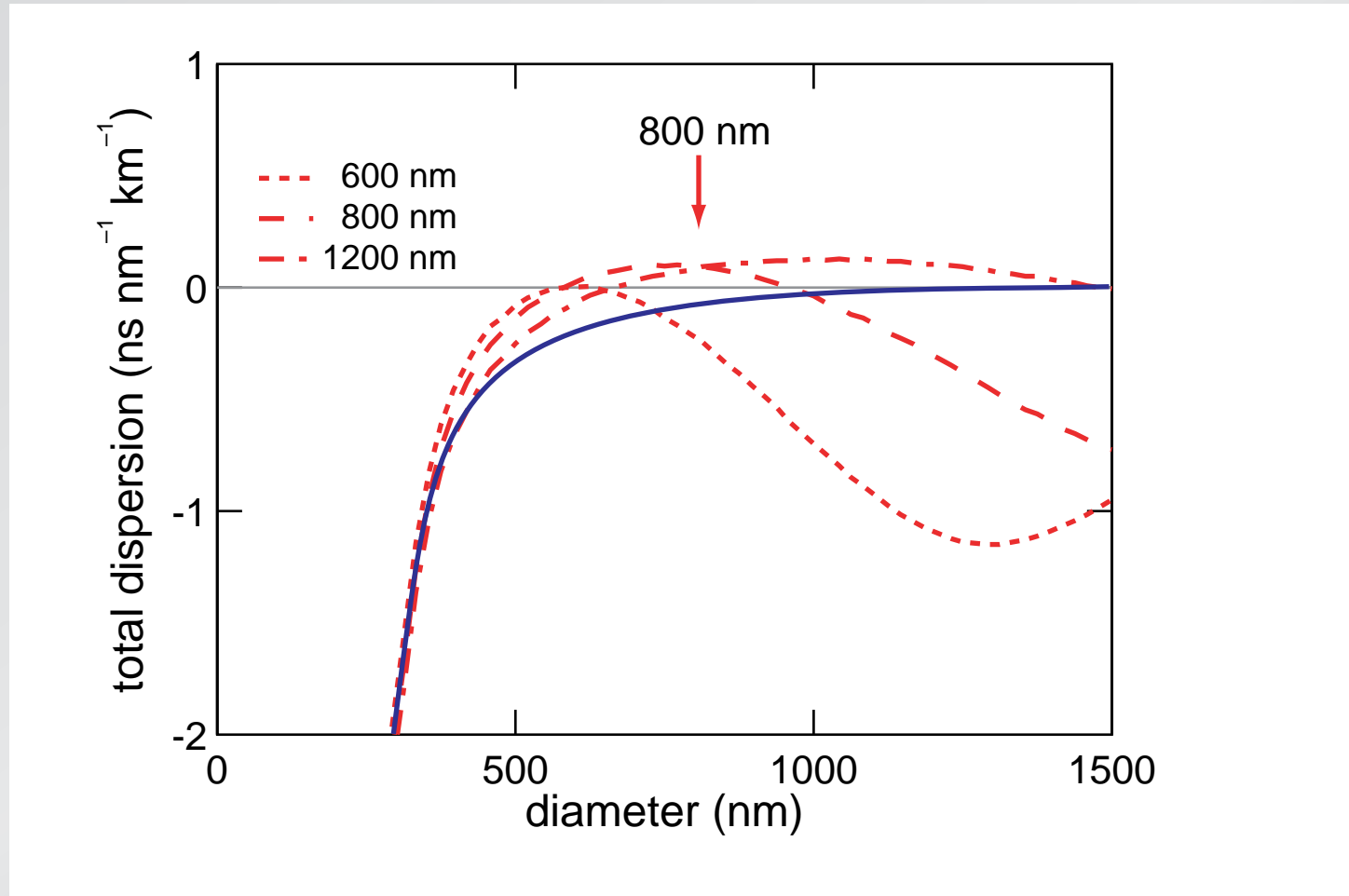
Nonlinear properties

waveguide dispersion



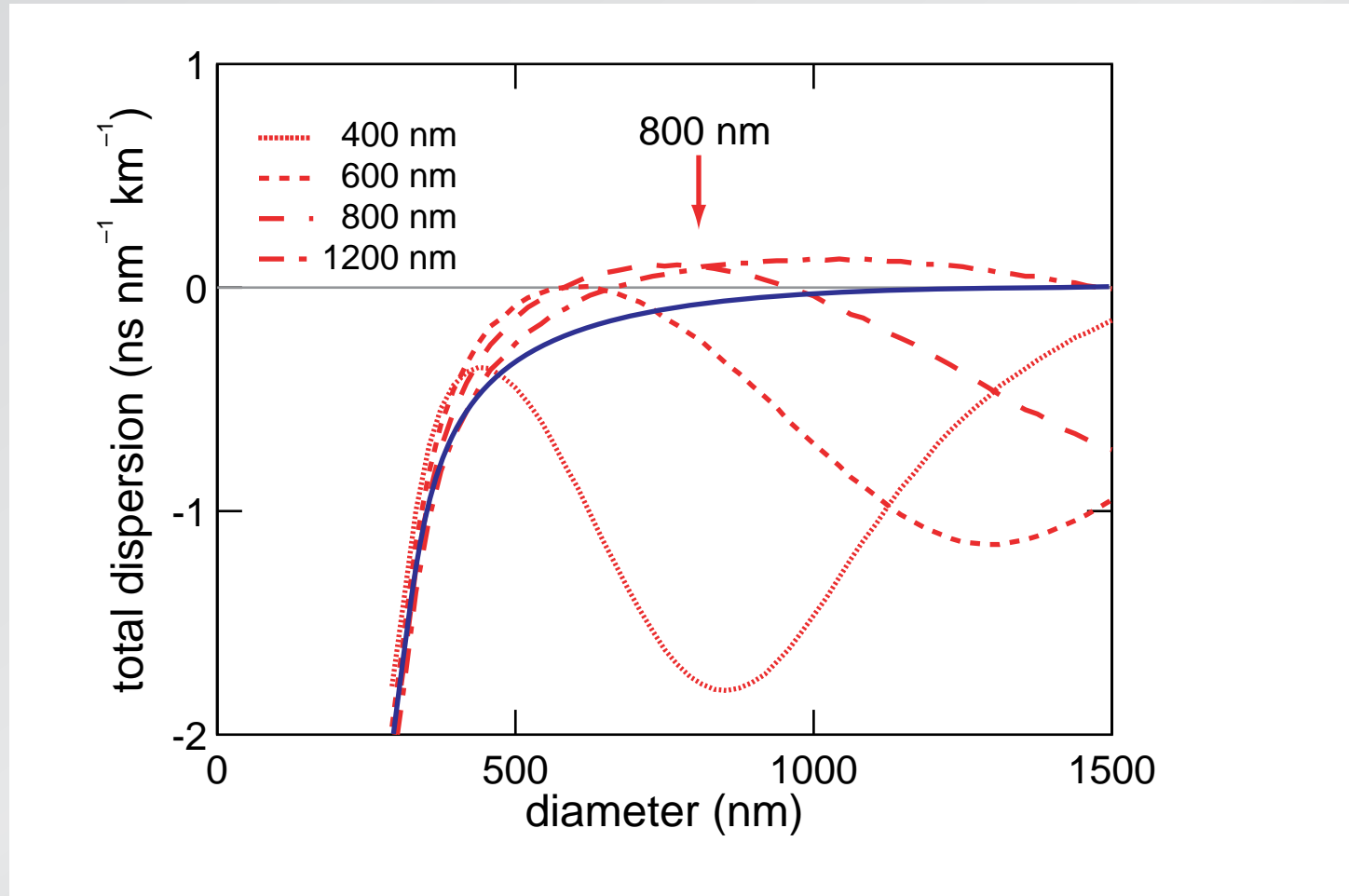
Nonlinear properties

waveguide dispersion



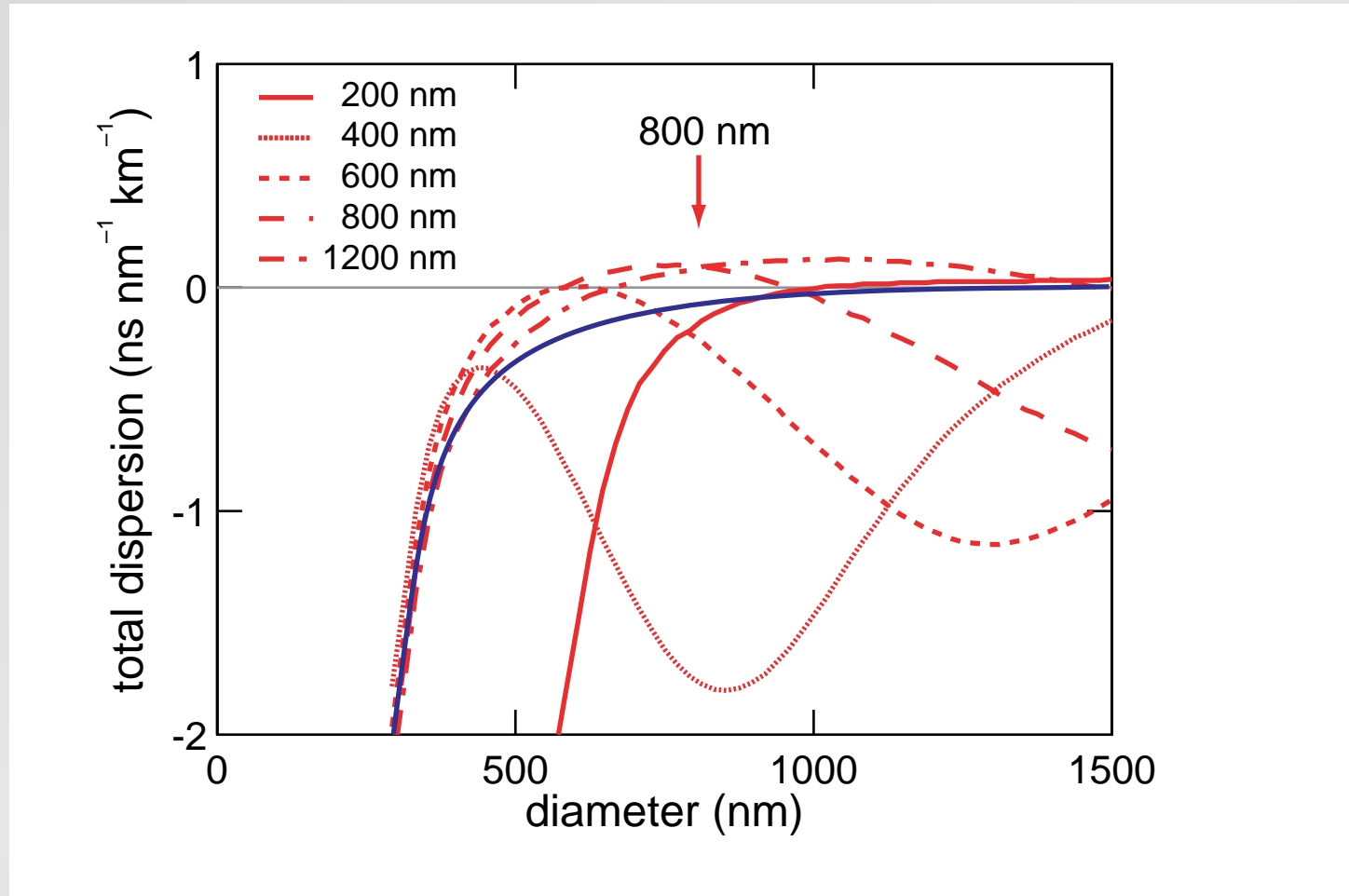
Nonlinear properties

waveguide dispersion



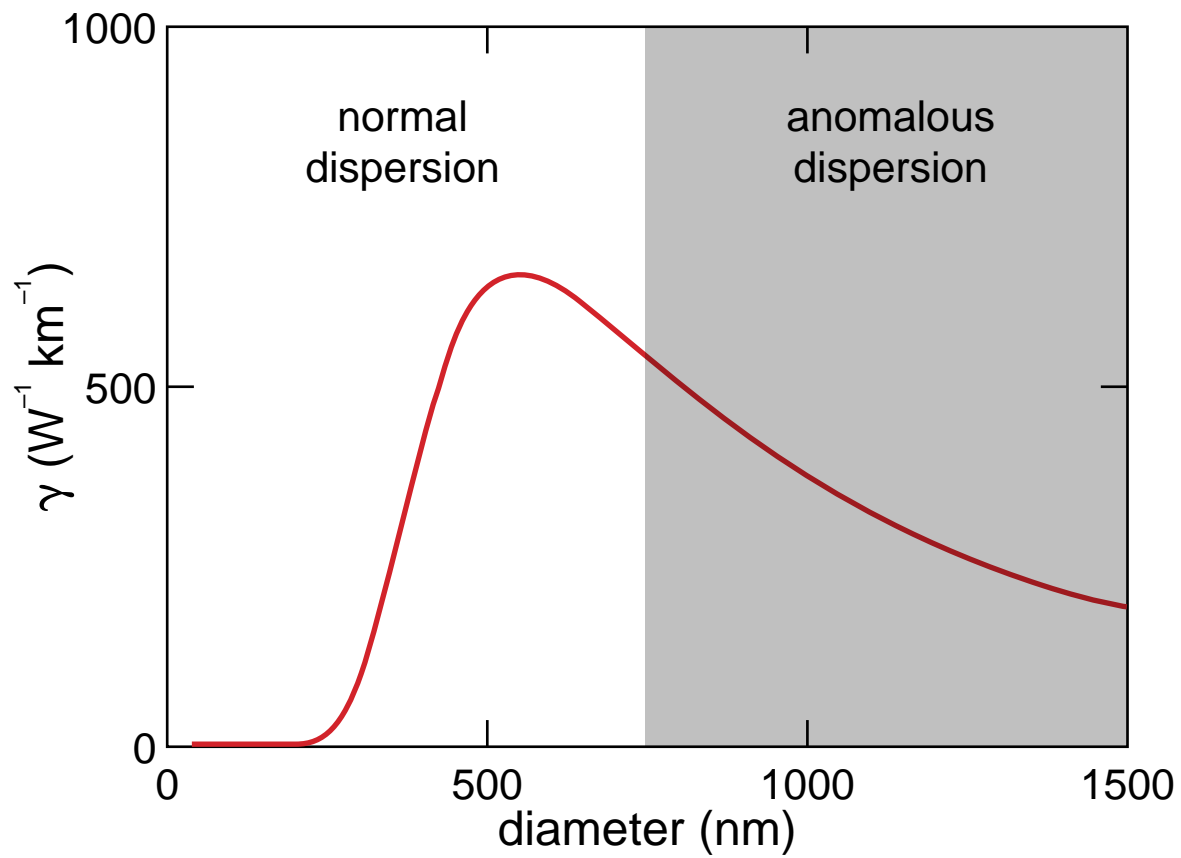
Nonlinear properties

waveguide dispersion



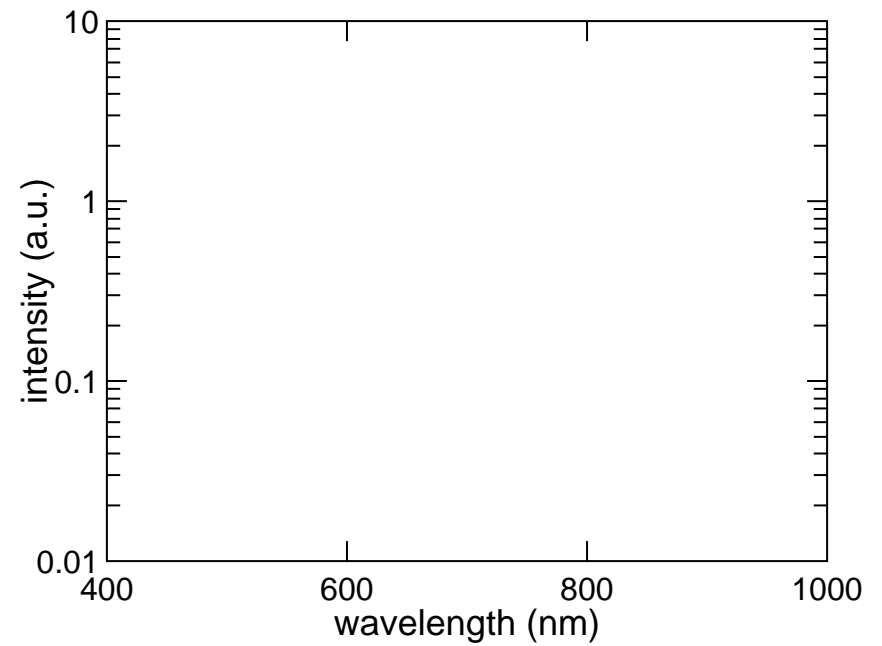
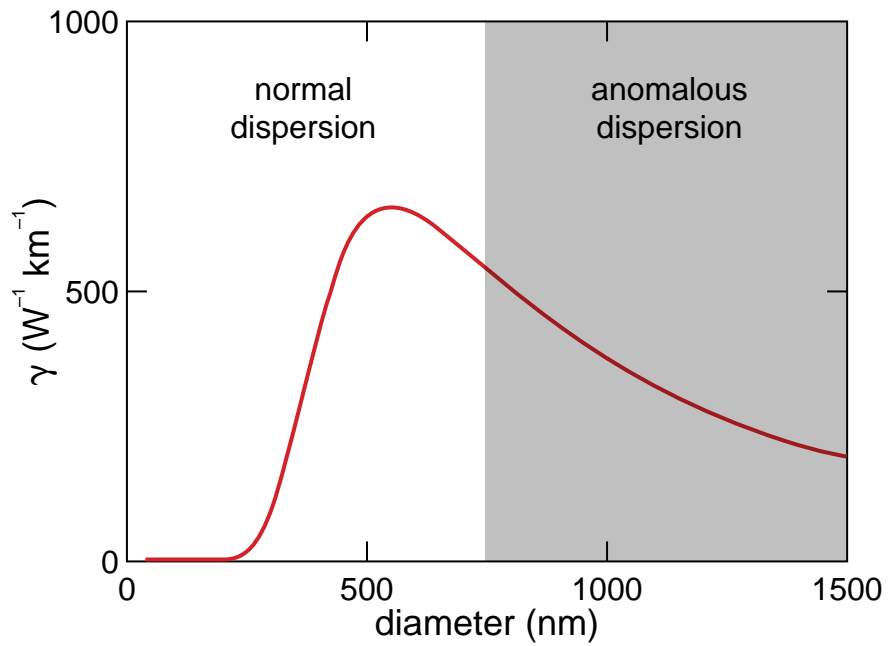
Nonlinear properties

nonlinear parameter



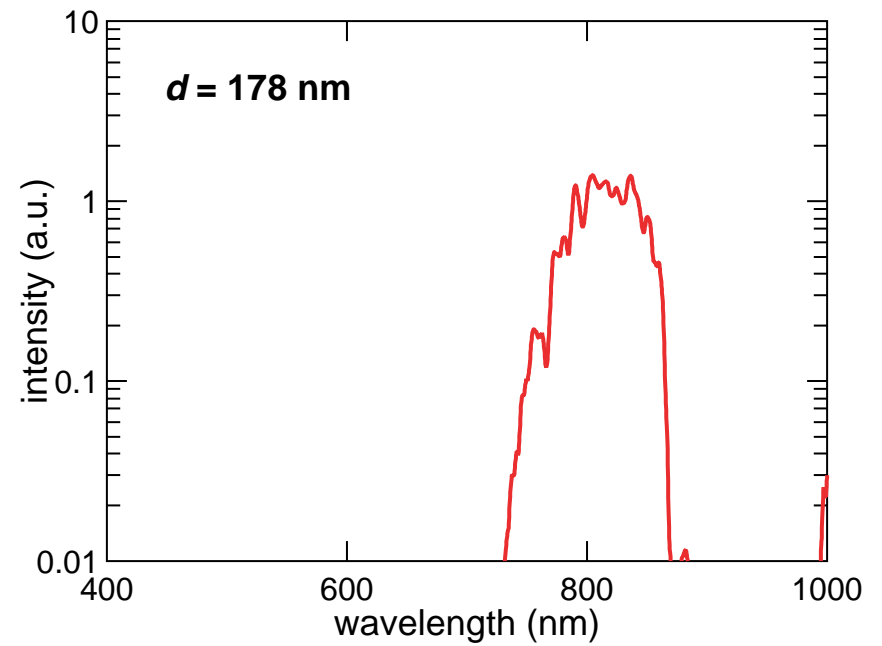
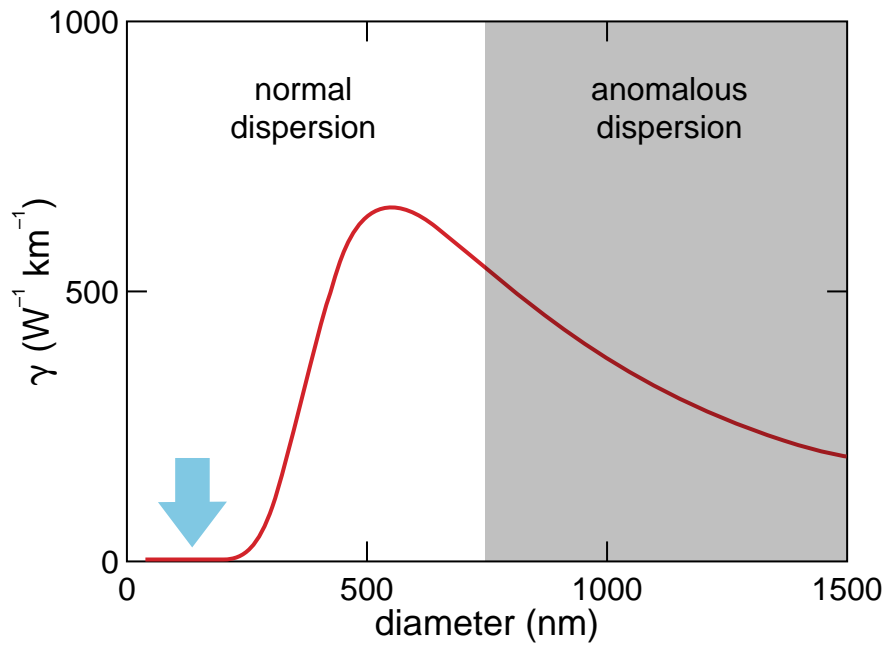
Nonlinear properties

nanowire continuum generation



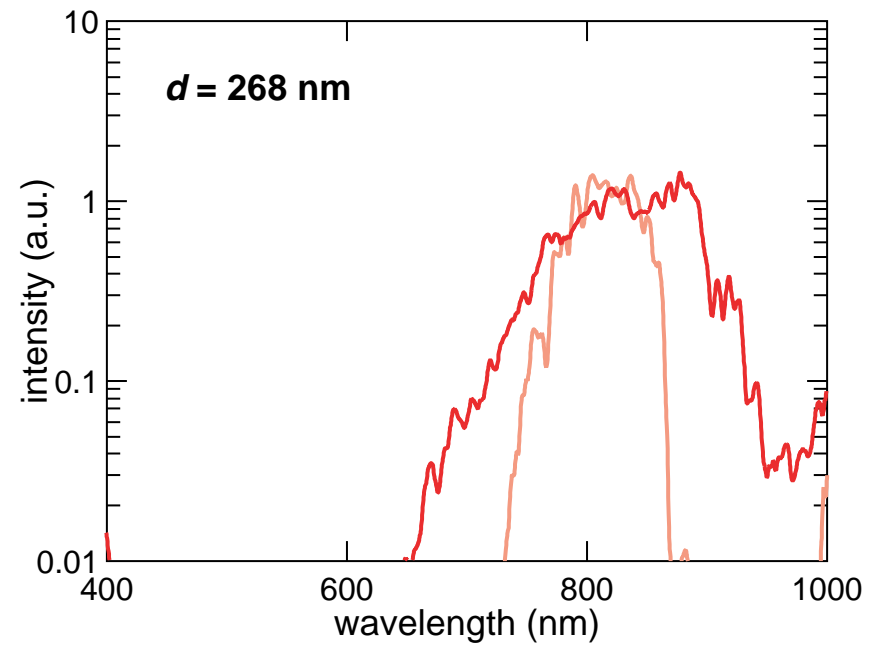
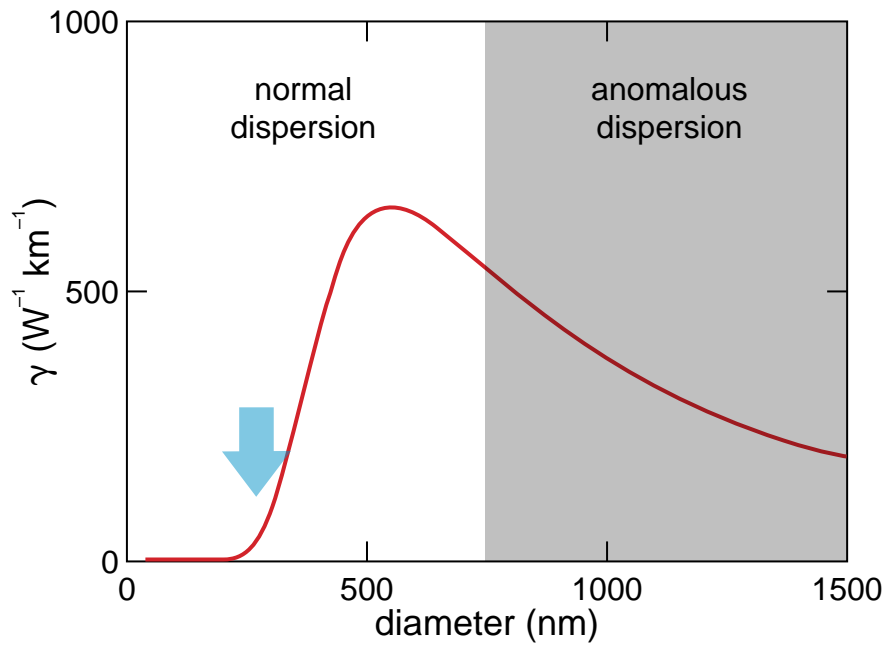
Nonlinear properties

nanowire continuum generation



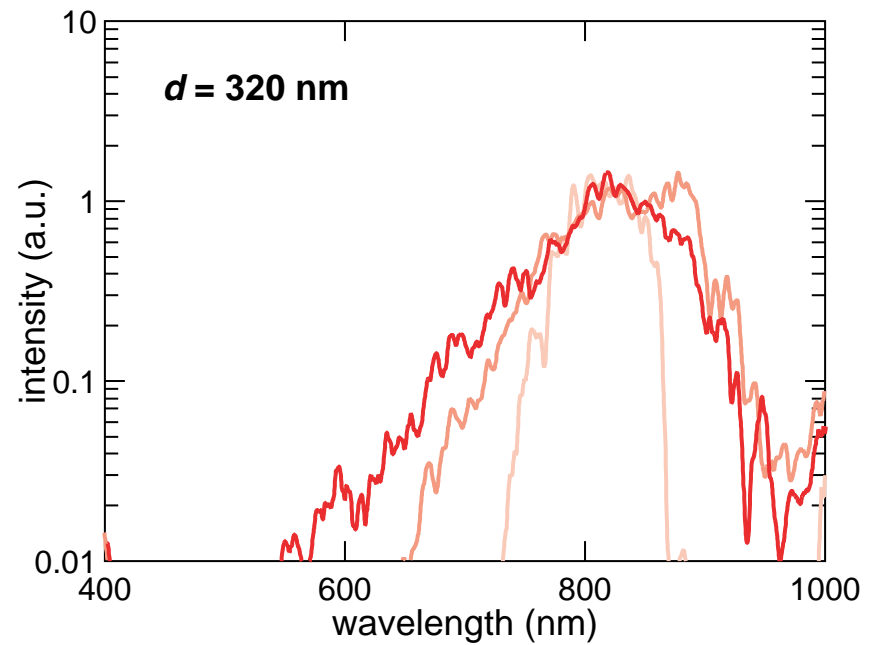
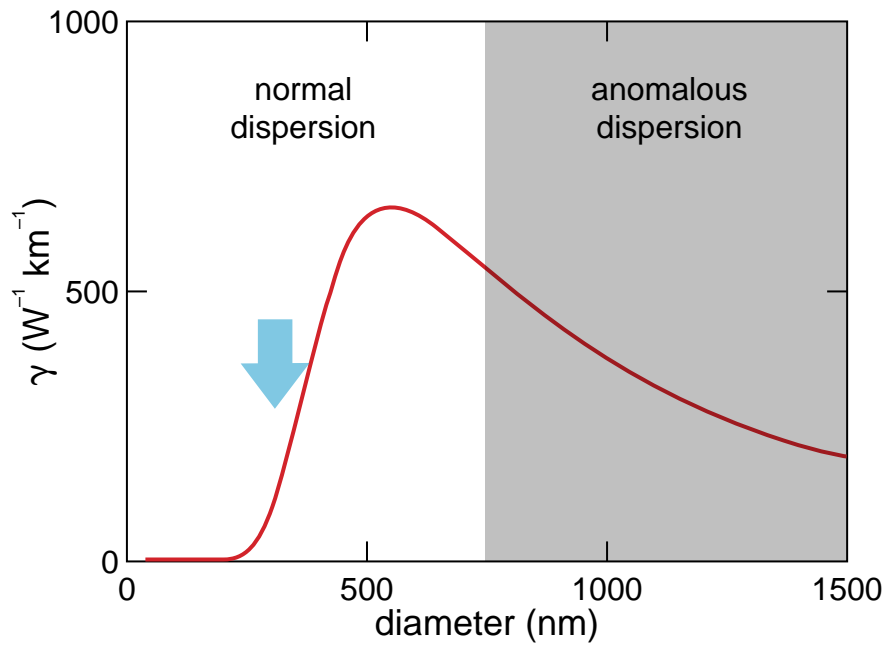
Nonlinear properties

nanowire continuum generation



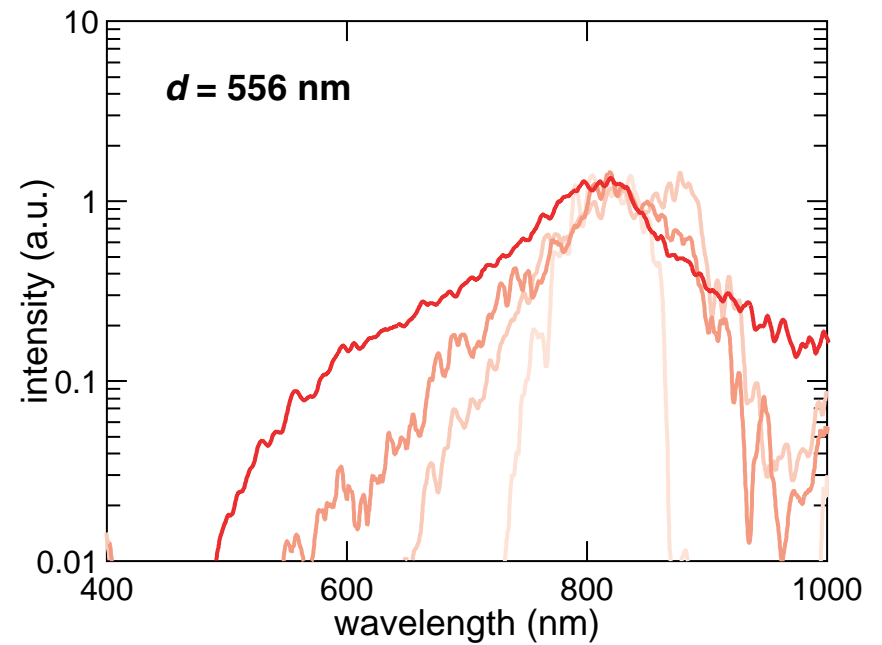
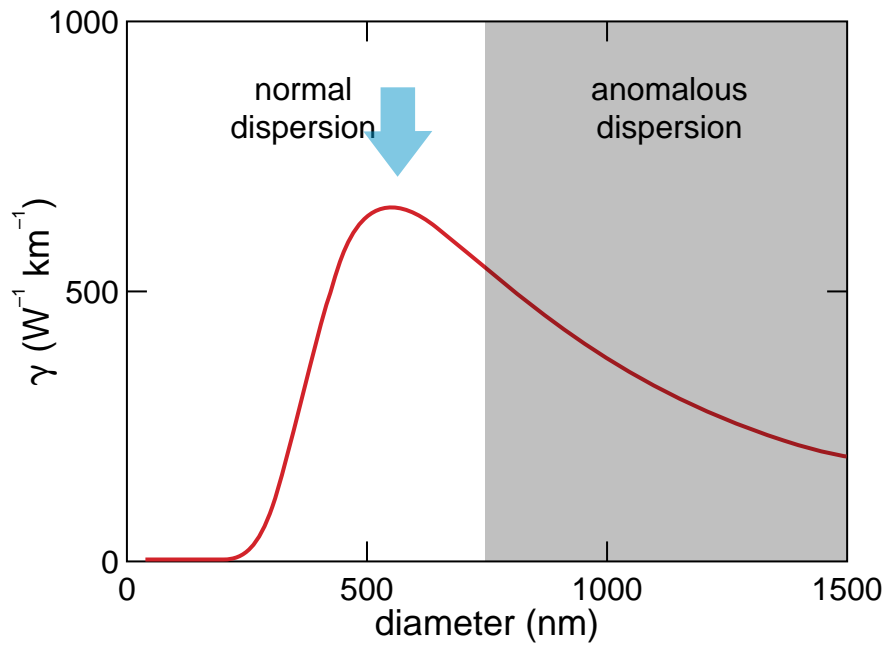
Nonlinear properties

nanowire continuum generation



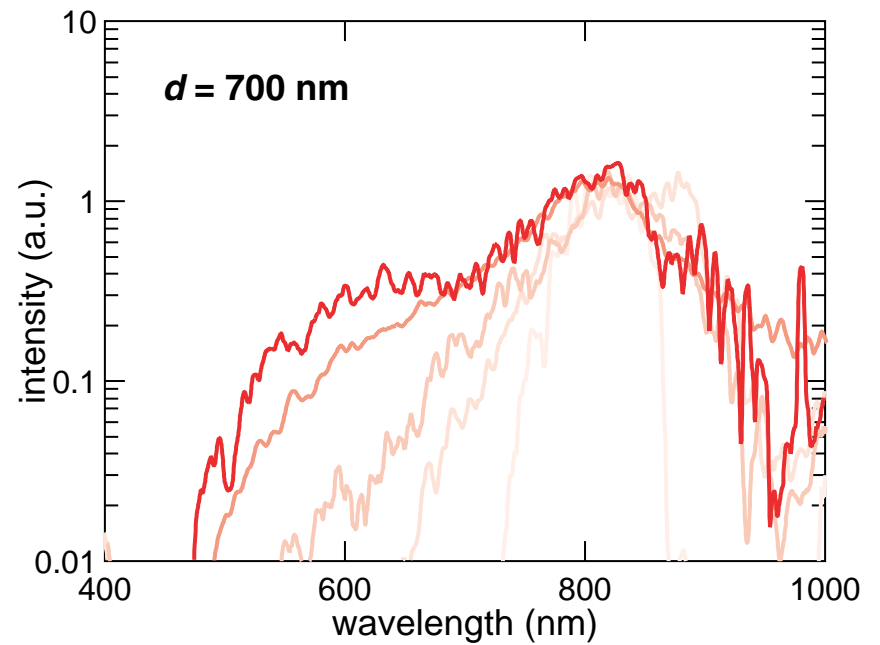
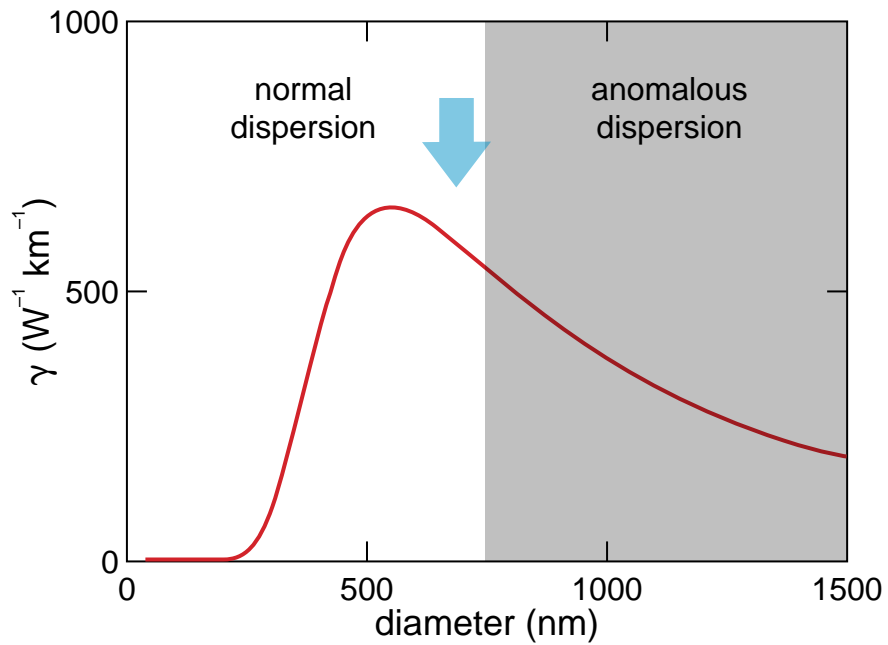
Nonlinear properties

nanowire continuum generation



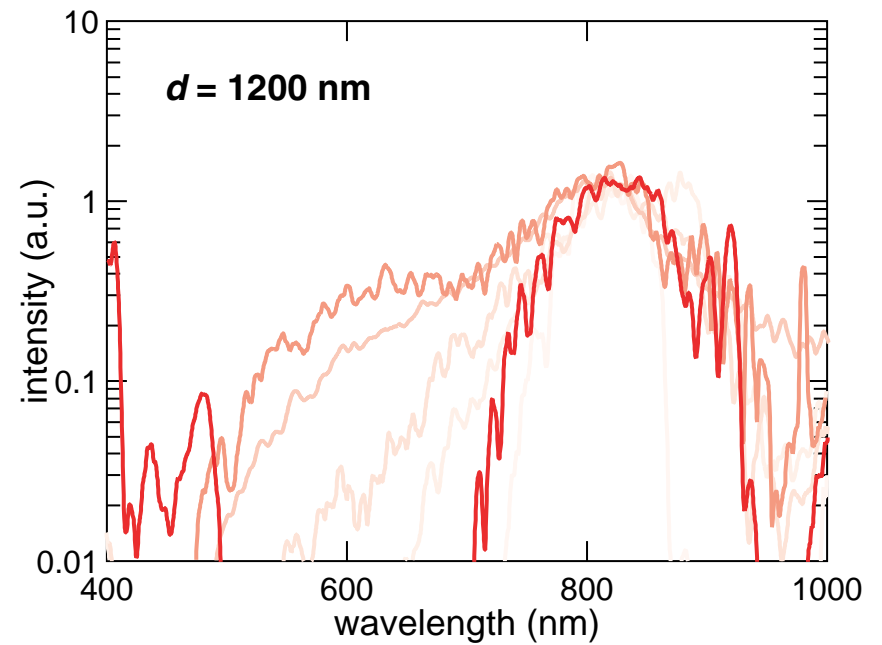
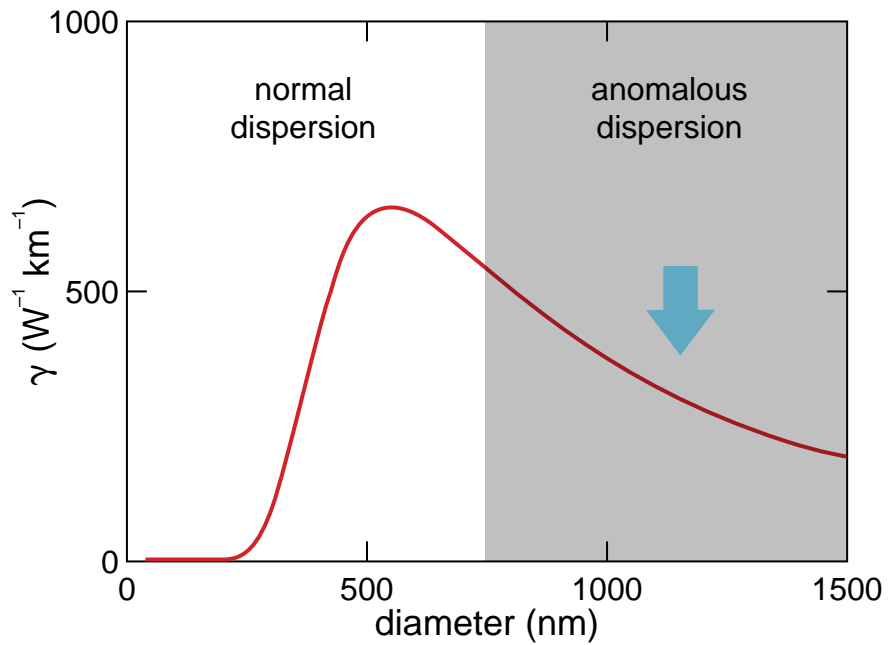
Nonlinear properties

nanowire continuum generation



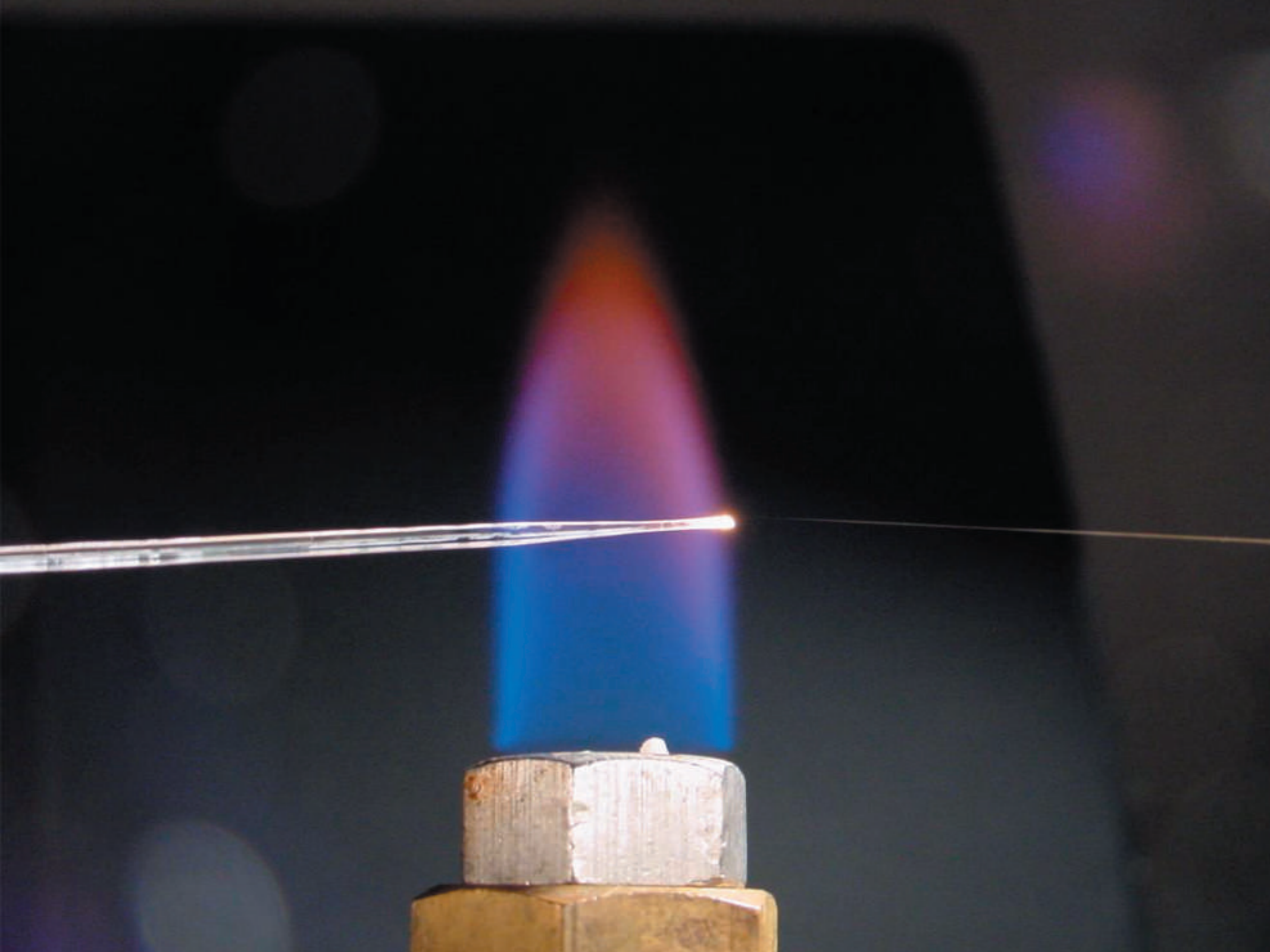
Nonlinear properties

nanowire continuum generation

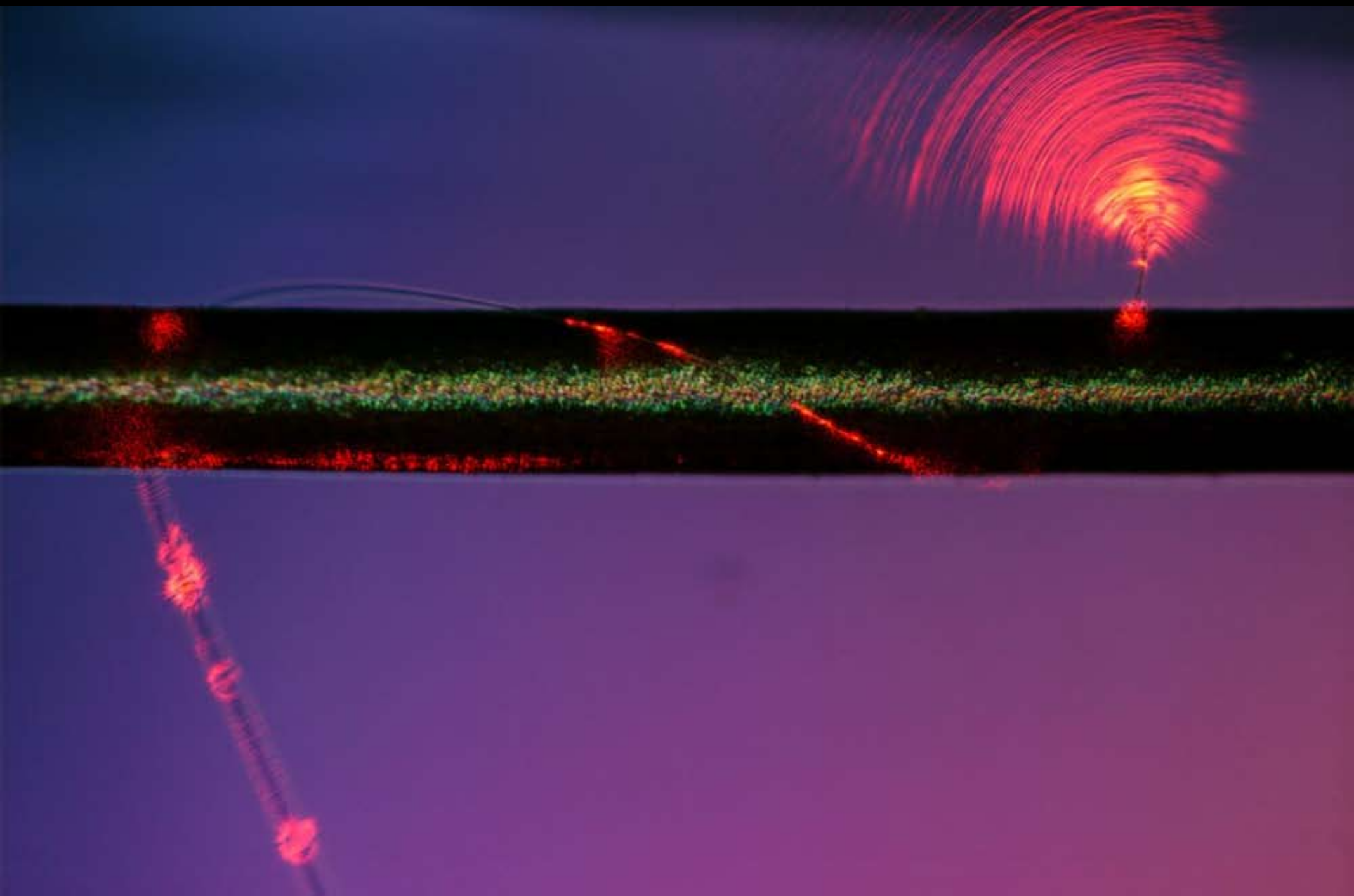


Nonlinear properties

energy in nanowire < 100 pJ!

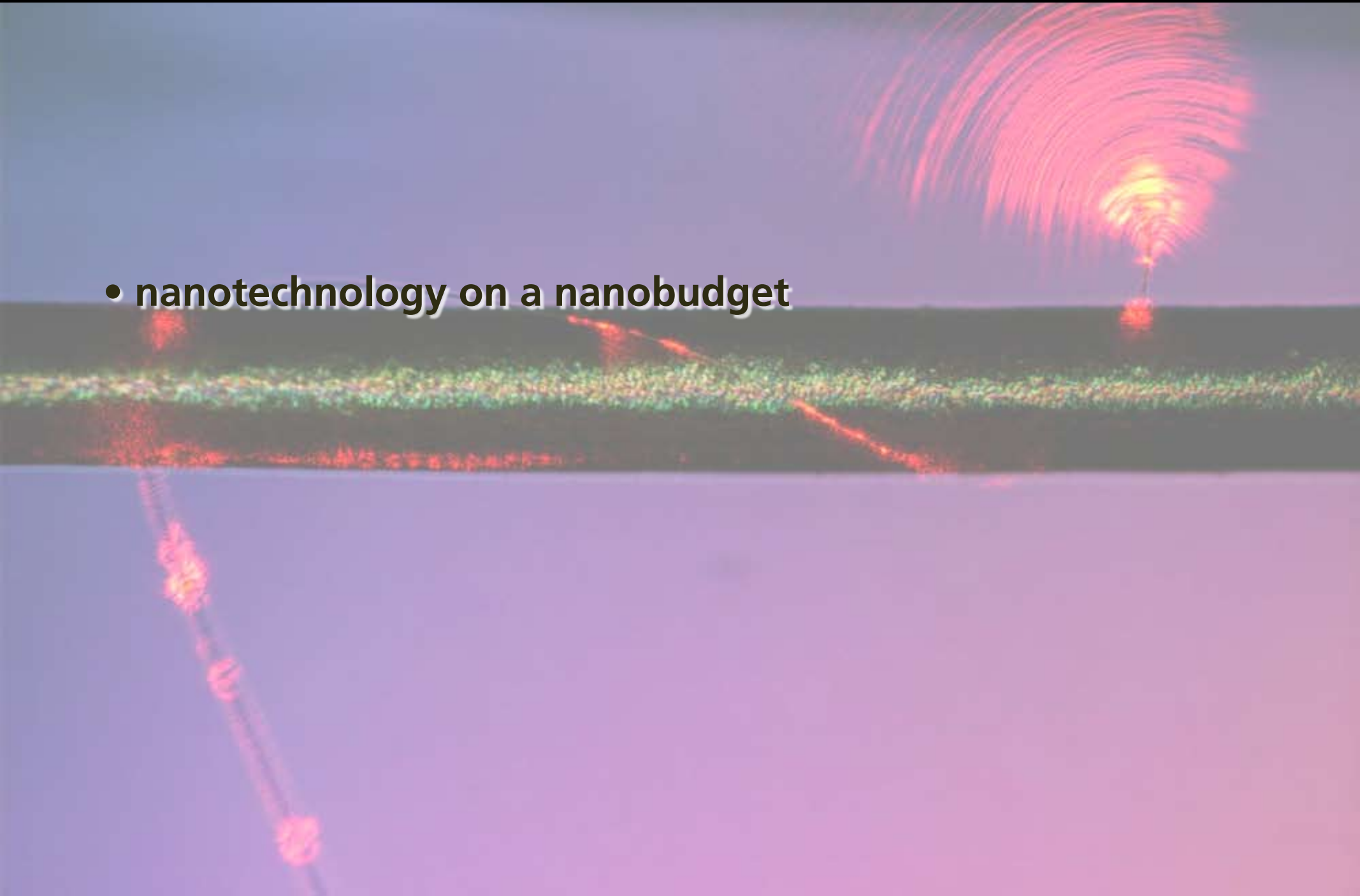


Summary



Summary

- nanotechnology on a nanobudget



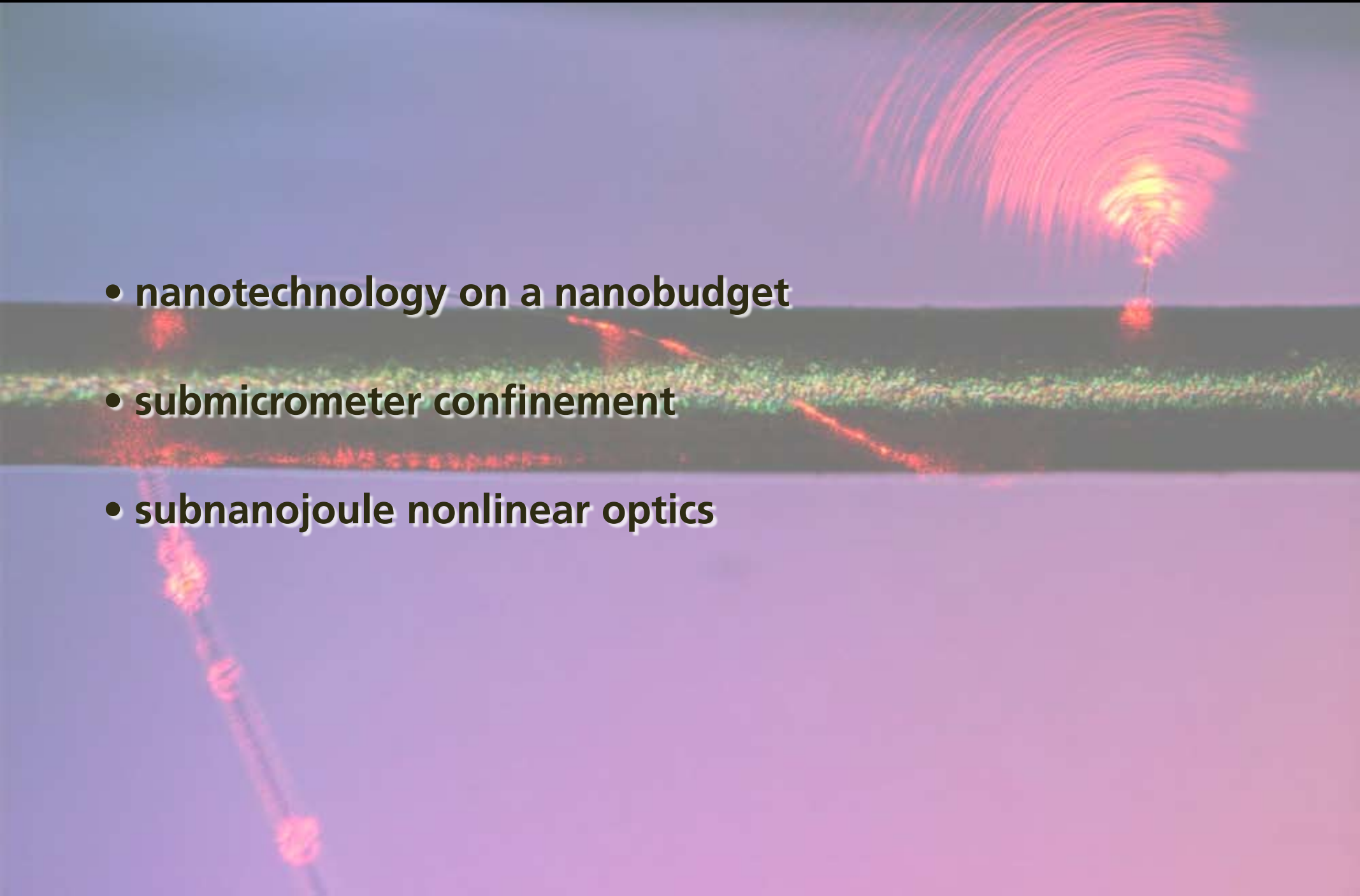
Summary

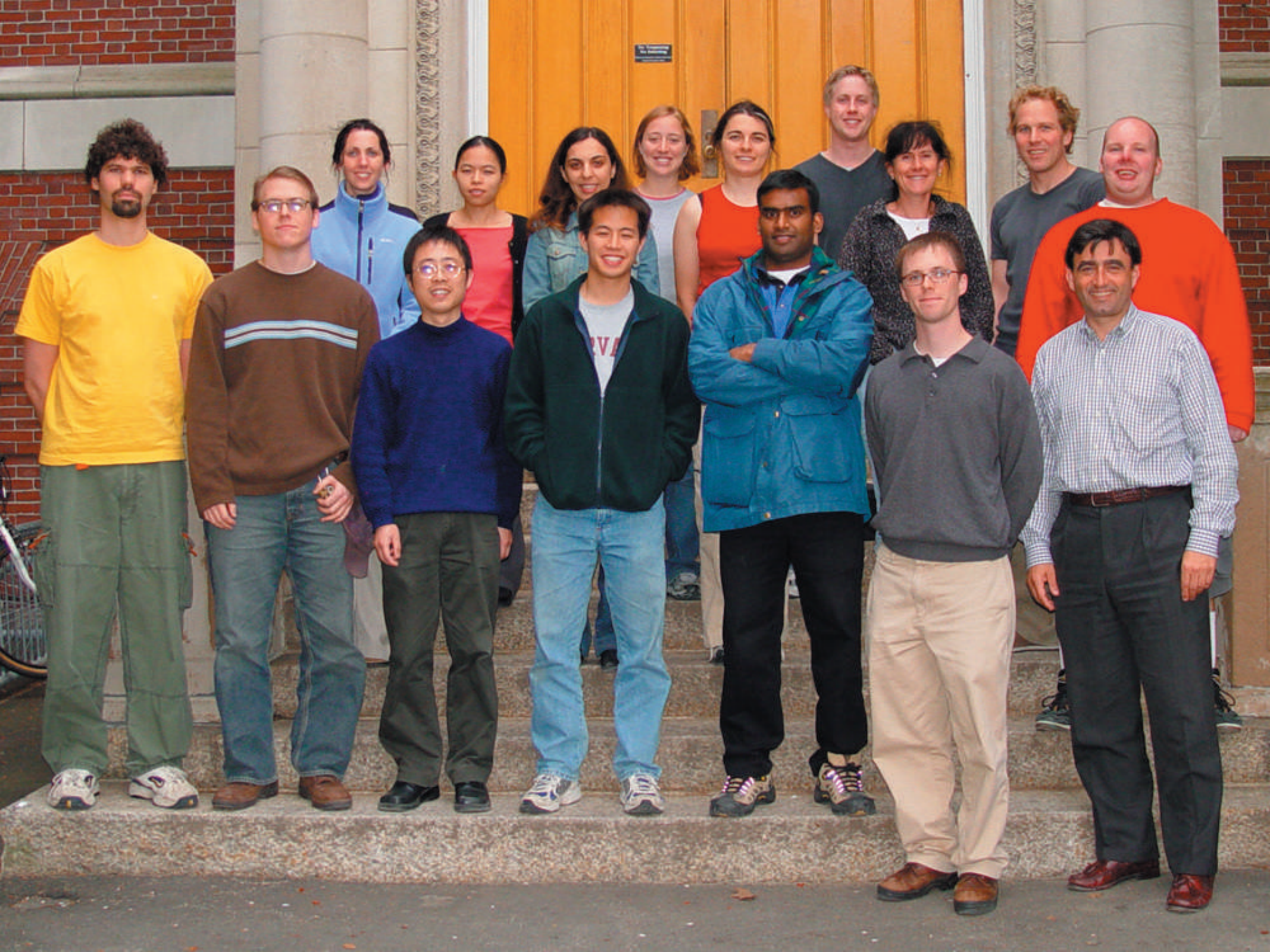
- nanotechnology on a nanobudget
- submicrometer confinement



Summary

- nanotechnology on a nanobudget
- submicrometer confinement
- subnanojoule nonlinear optics







Funding:

**Harvard Center for Imaging and Mesoscopic Structures
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