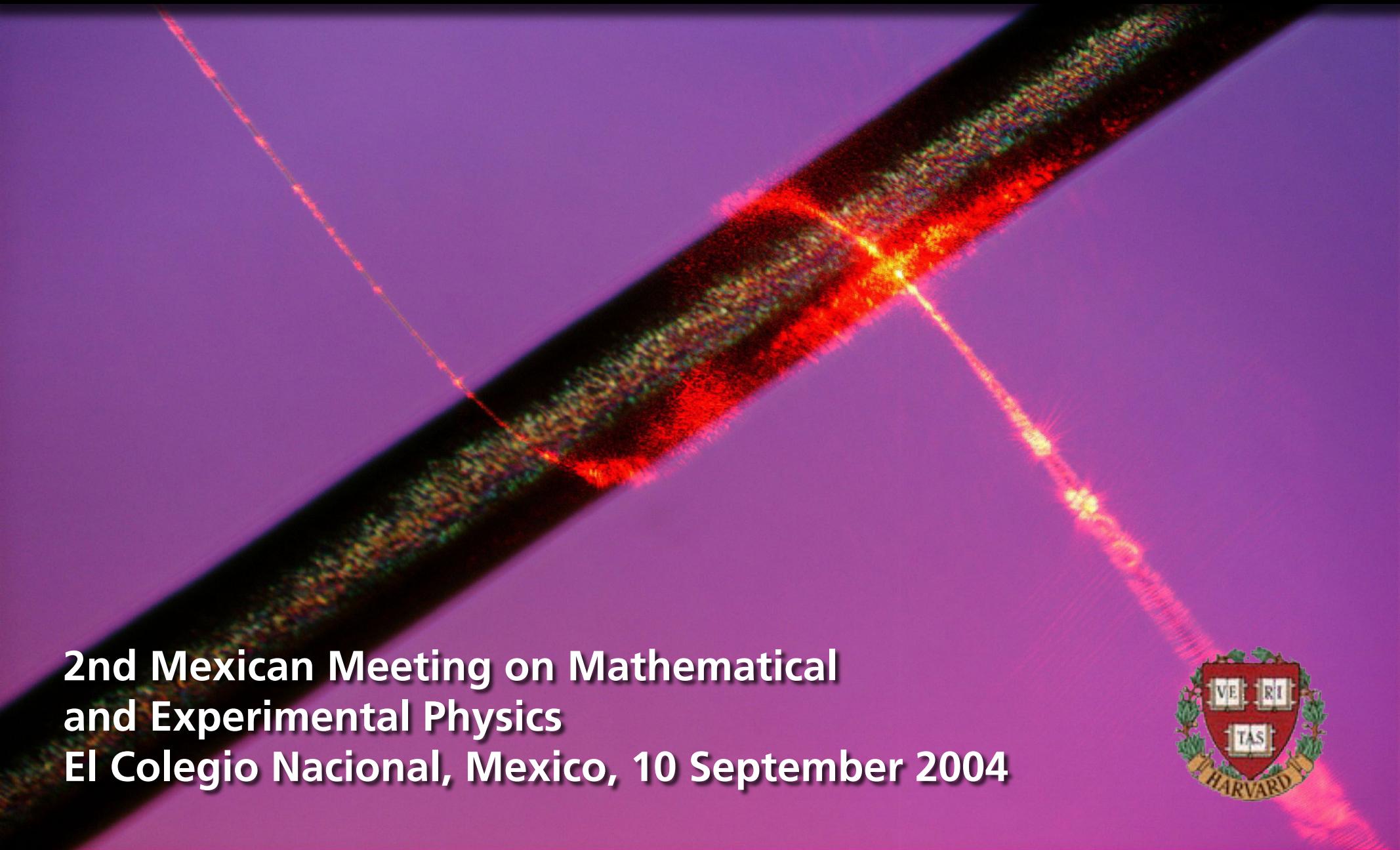
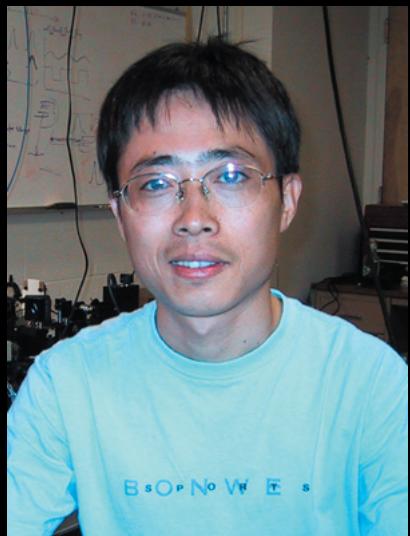


Wrapping light around a hair



2nd Mexican Meeting on Mathematical
and Experimental Physics
El Colegio Nacional, Mexico, 10 September 2004





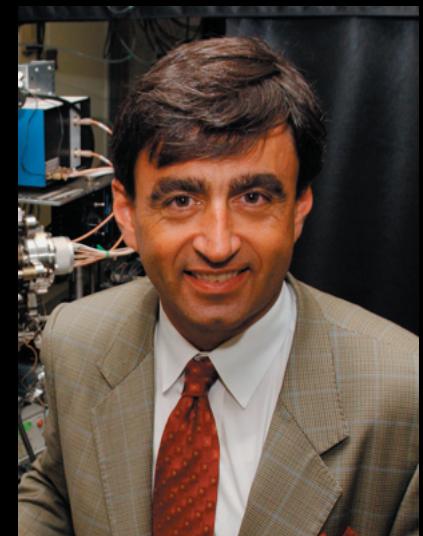
Limin Tong



Rafael Gattass



Geoff Svacha



Eric Mazur

and also....

at Harvard:

Jonathan Aschom

Mengyan Shen

Iva Maxwell

James Carey

Brian Tull

Dr. Yuan Lu

Dr. Richard Schalek

at Zhejiang University:

Dr. Sailing He

Dr. Jingyi Lou

Xuewen Chen

Liu Liu

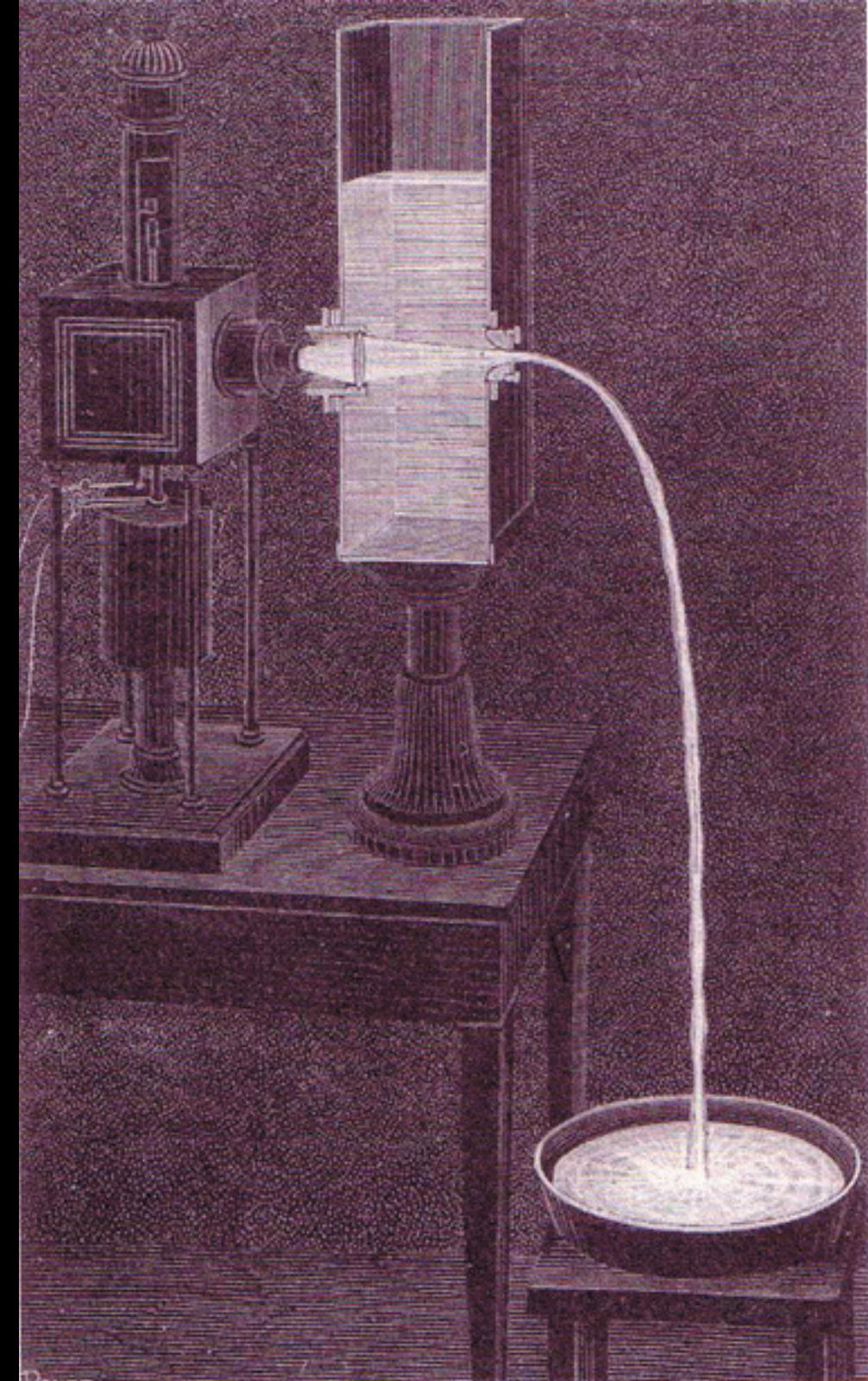
Zhanghua Han

Dr. Ray Mariella (LLNL)

"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)





(nu model.)

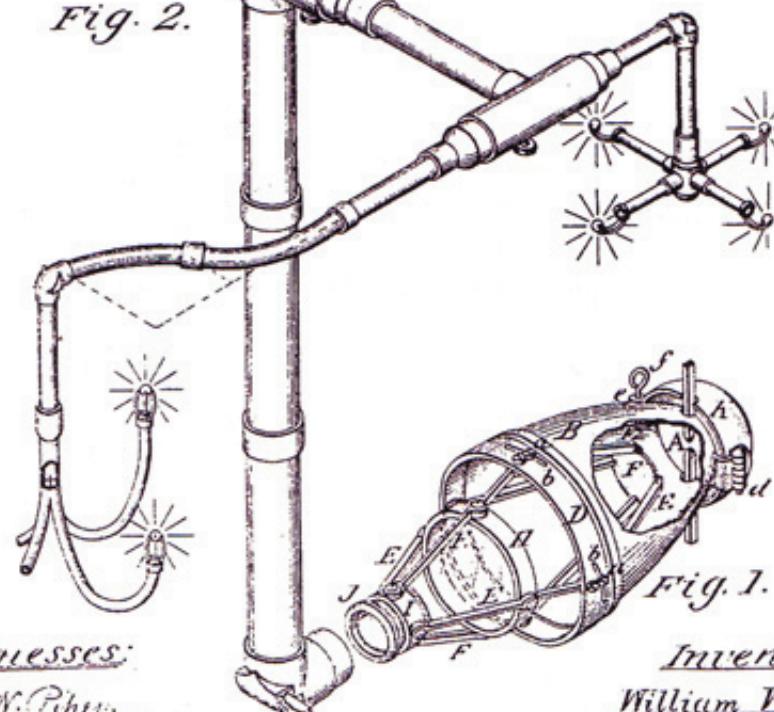
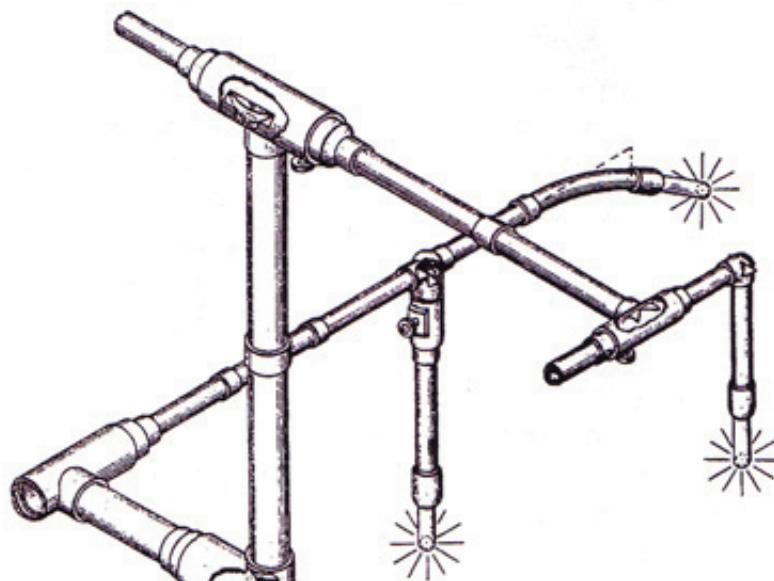
4 Sheets—Sheet

W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.



Witnesses:

S. N. Piper

E. L. Pease

Inventor:

William Wheeler

by attorney

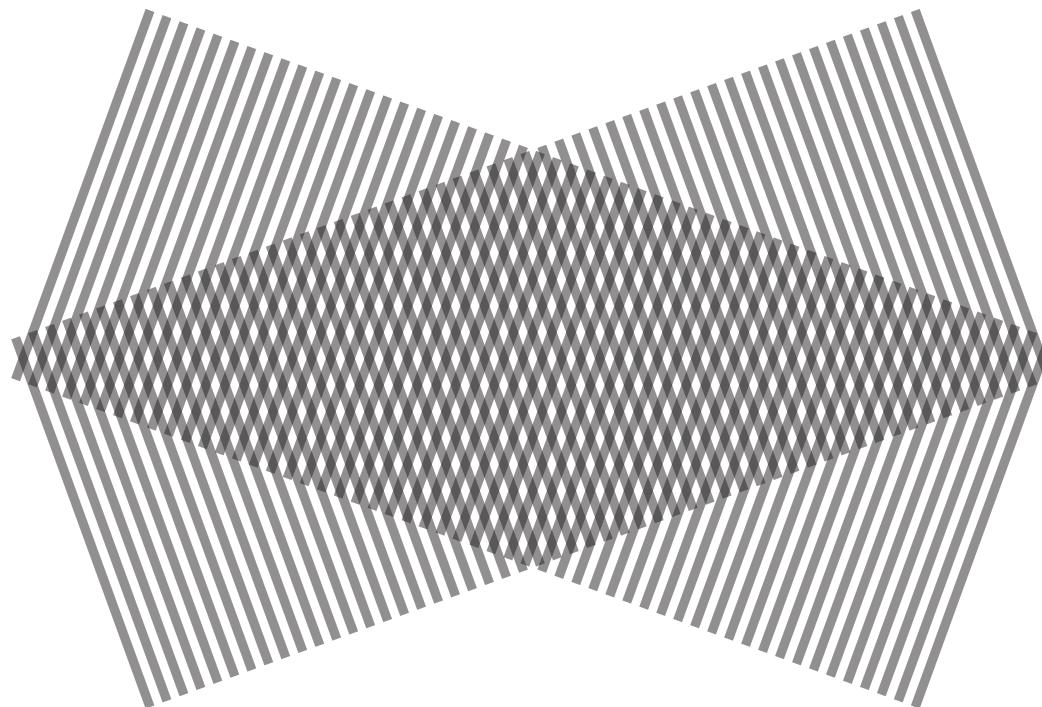
US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

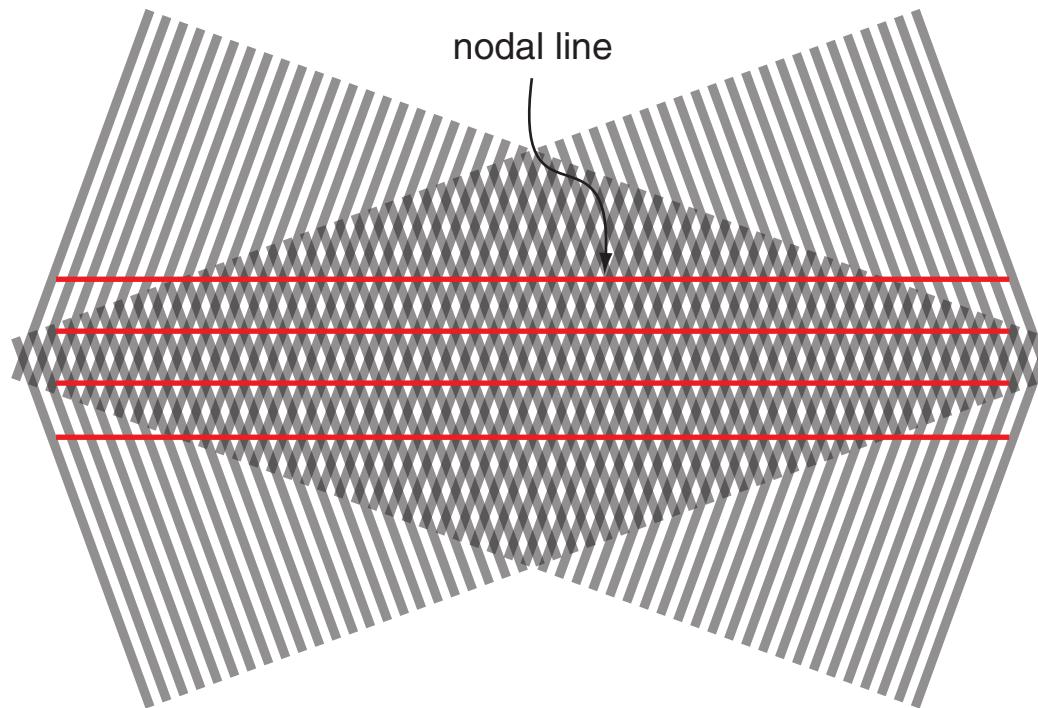
Waveguiding

two crossed planar waves...



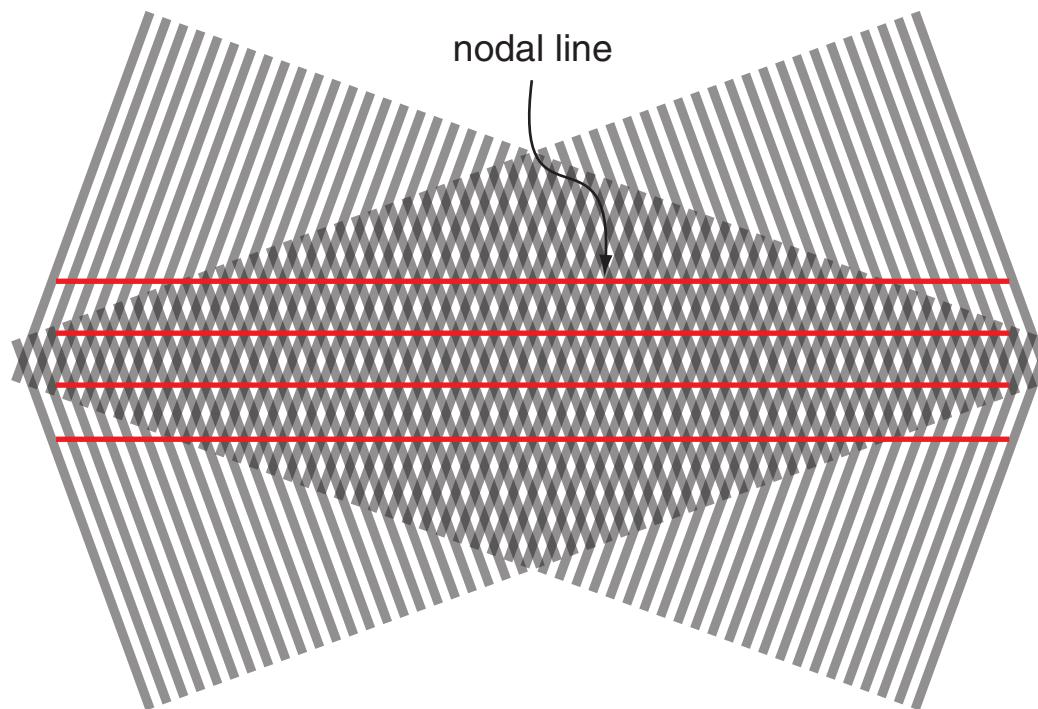
Waveguiding

...cause an interference pattern



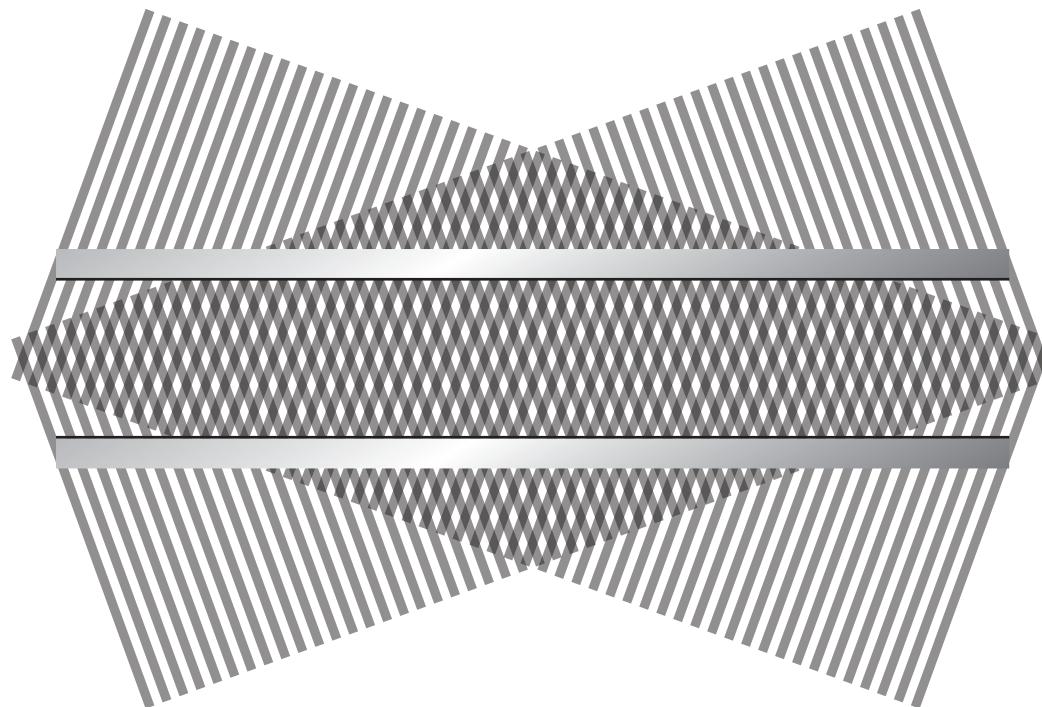
Waveguiding

$E = 0$ on the nodal lines



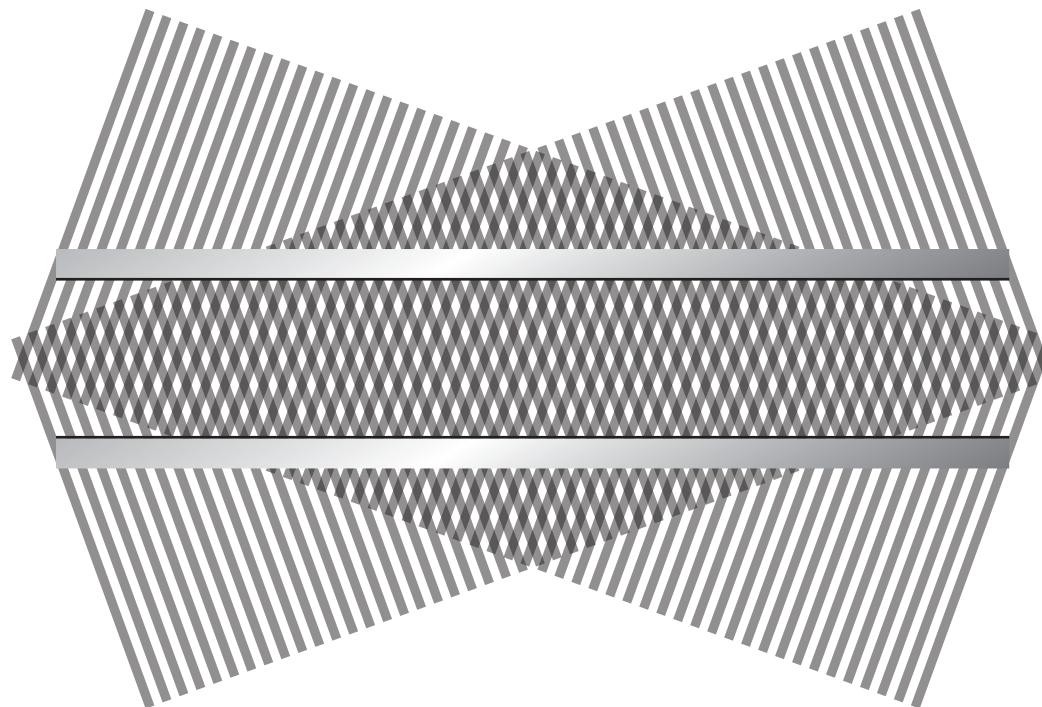
Waveguiding

...satisfying boundary conditions for planar-mirror waveguide



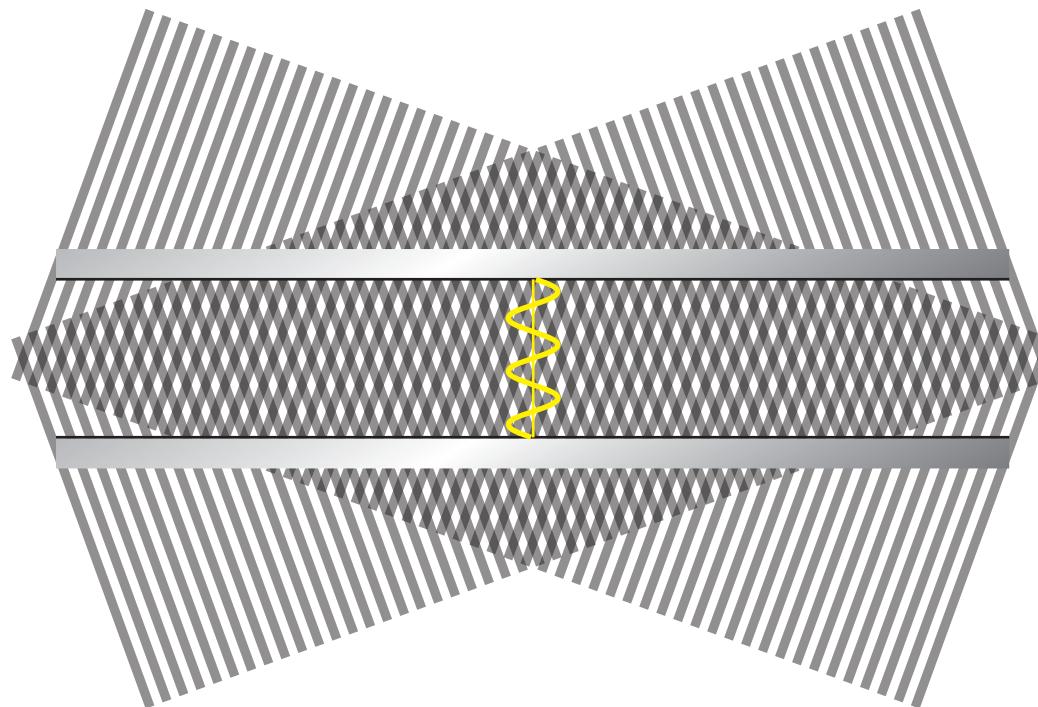
Waveguiding

transverse standing wave, traveling along axis



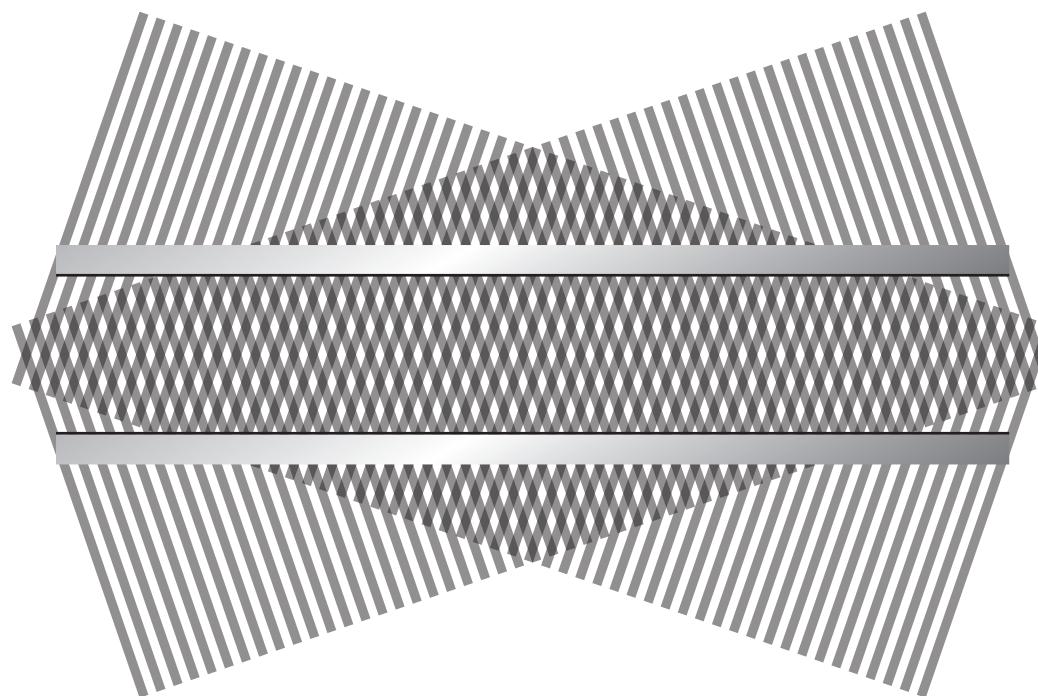
Waveguiding

transverse standing wave, traveling along axis



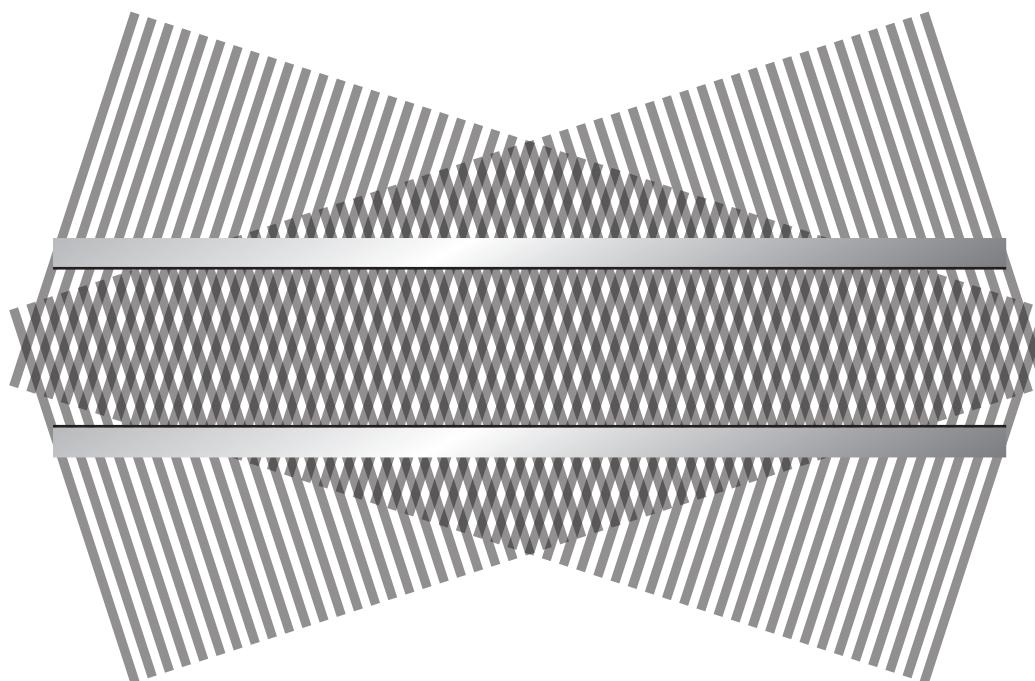
Waveguiding

change angle of incident waves...



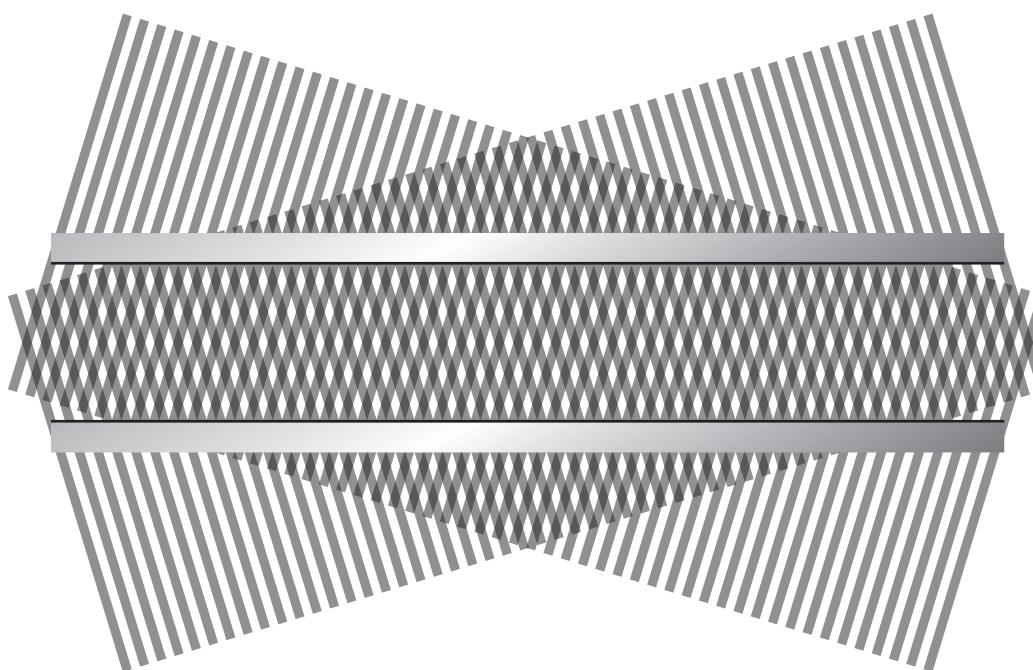
Waveguiding

change angle of incident waves...



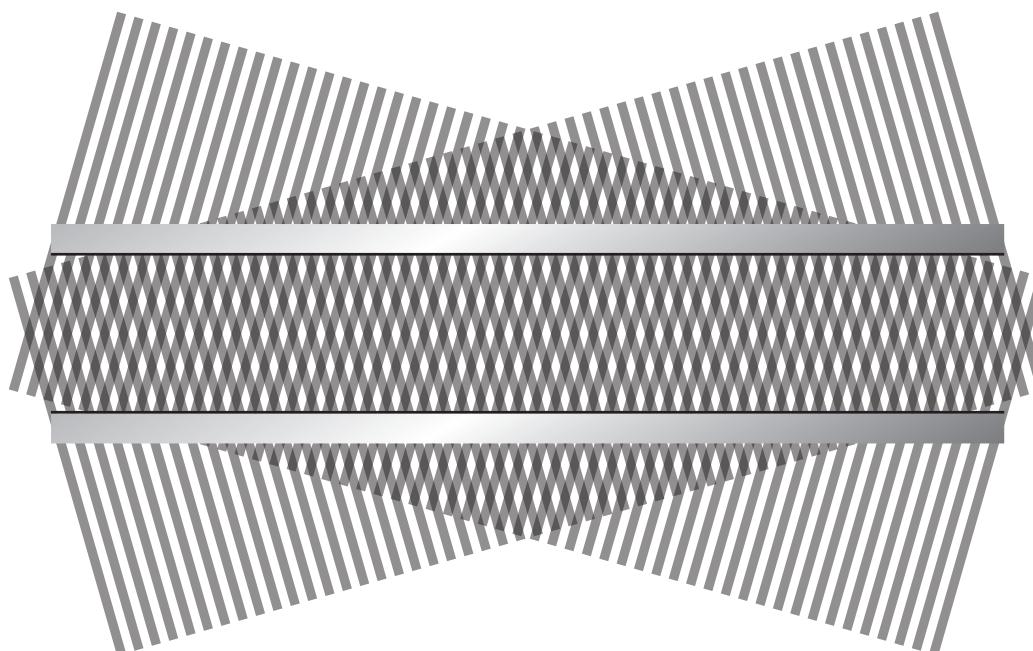
Waveguiding

change angle of incident waves...



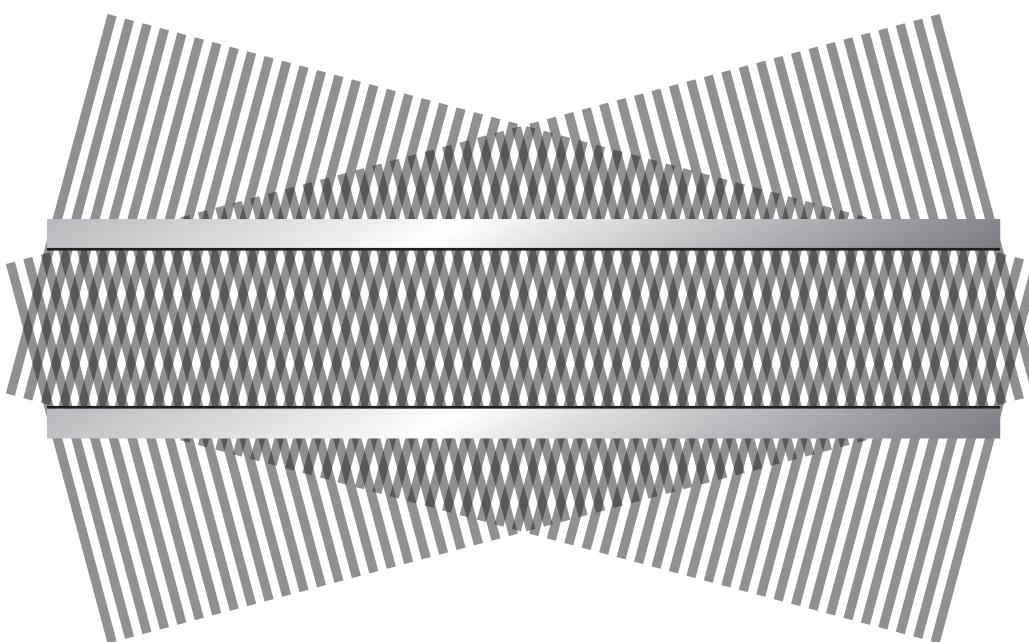
Waveguiding

change angle of incident waves...



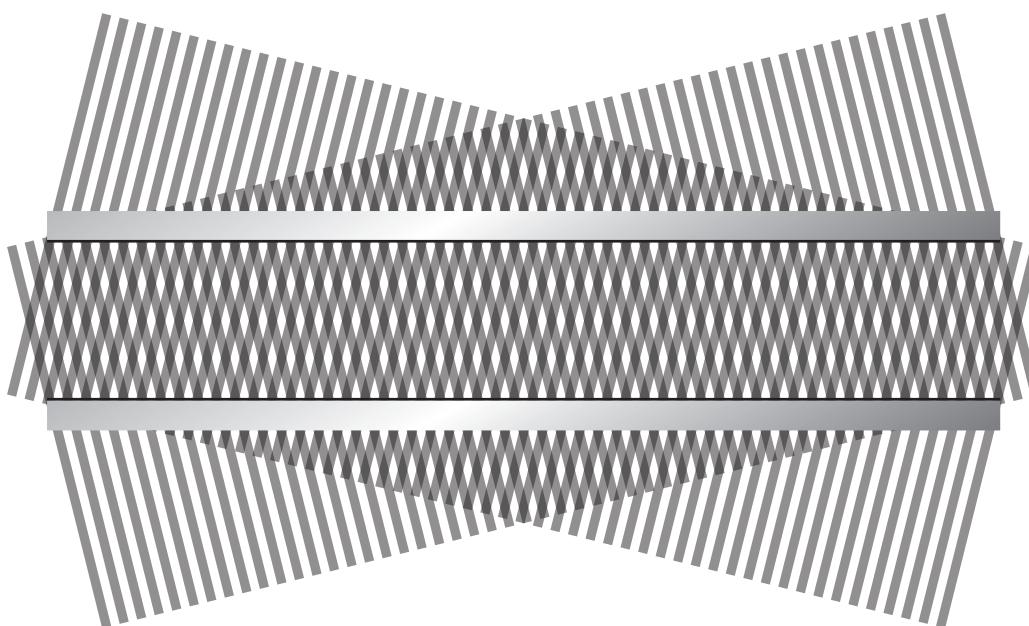
Waveguiding

change angle of incident waves...



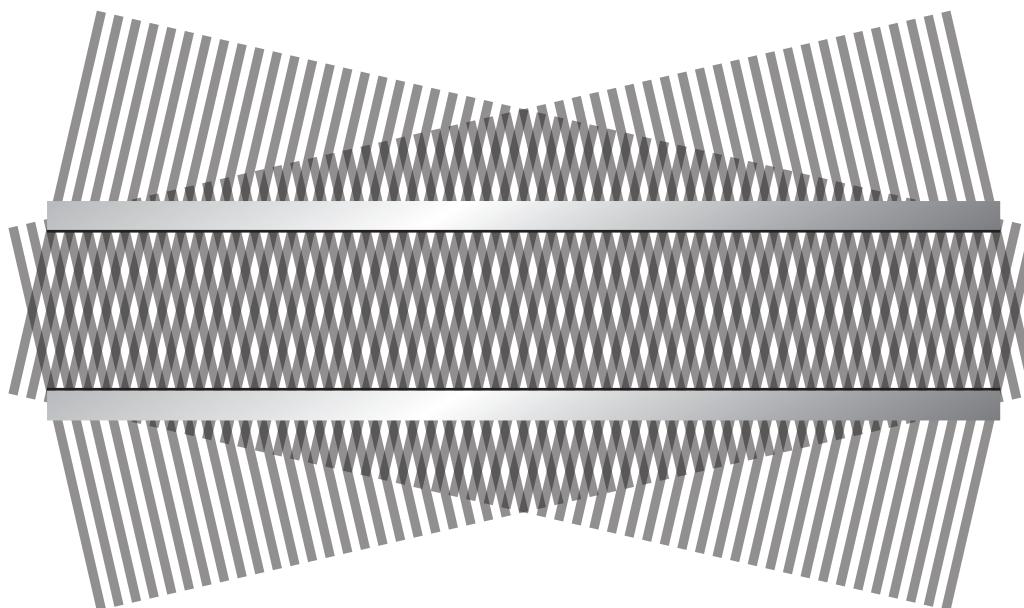
Waveguiding

change angle of incident waves...



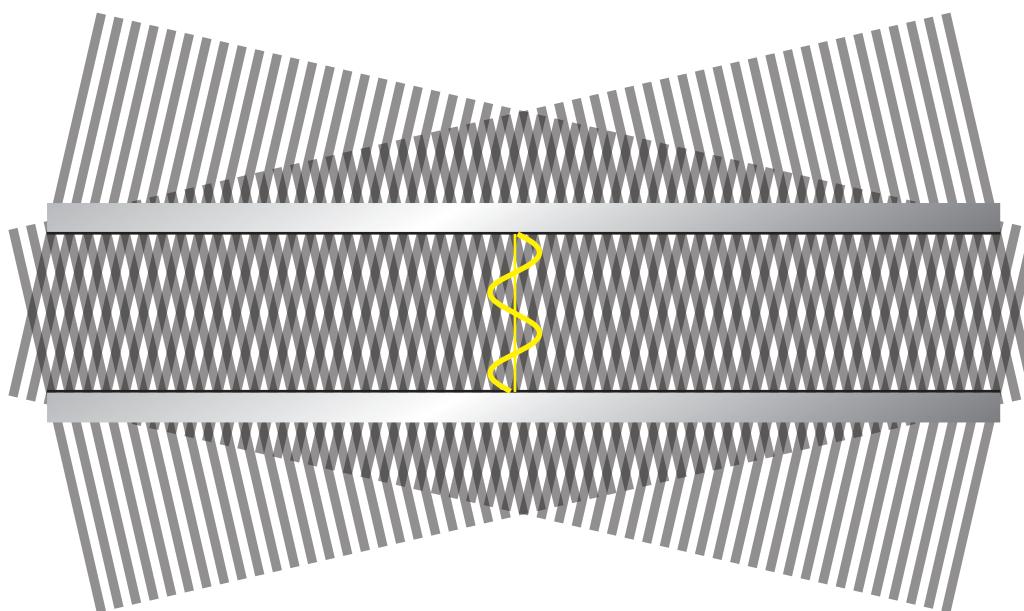
Waveguiding

change angle of incident waves...



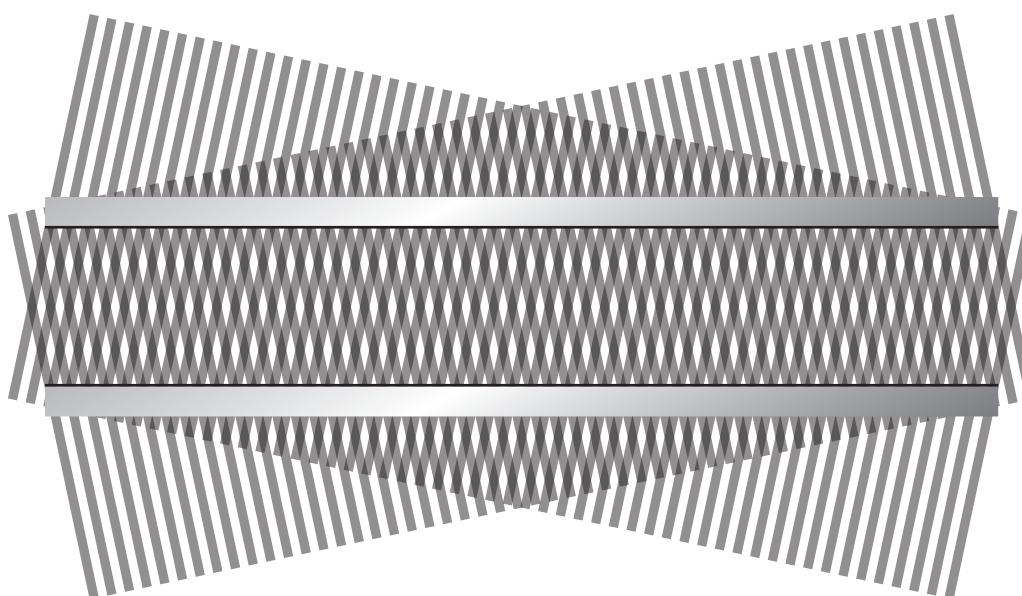
Waveguiding

change angle of incident waves...



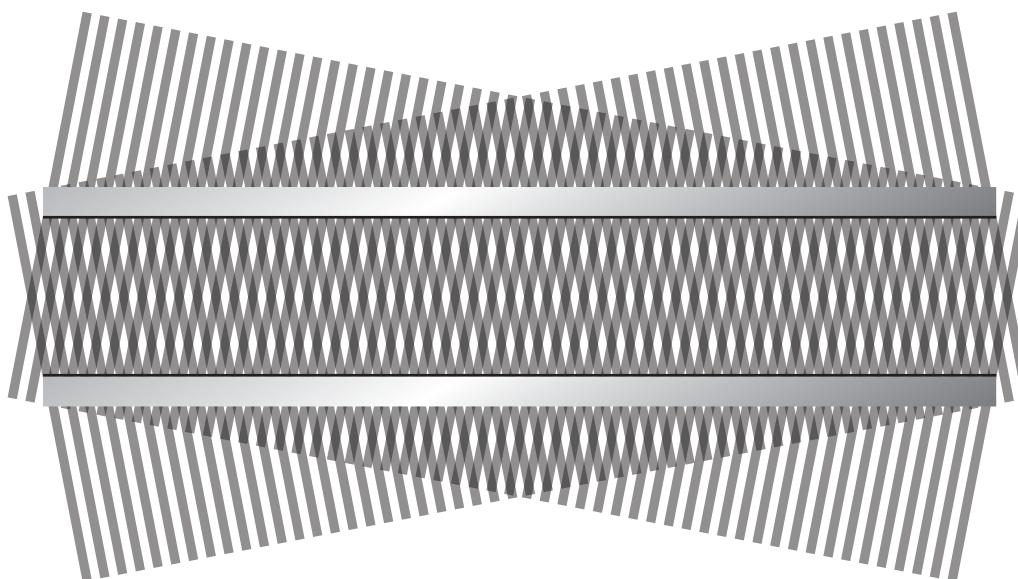
Waveguiding

change angle of incident waves...



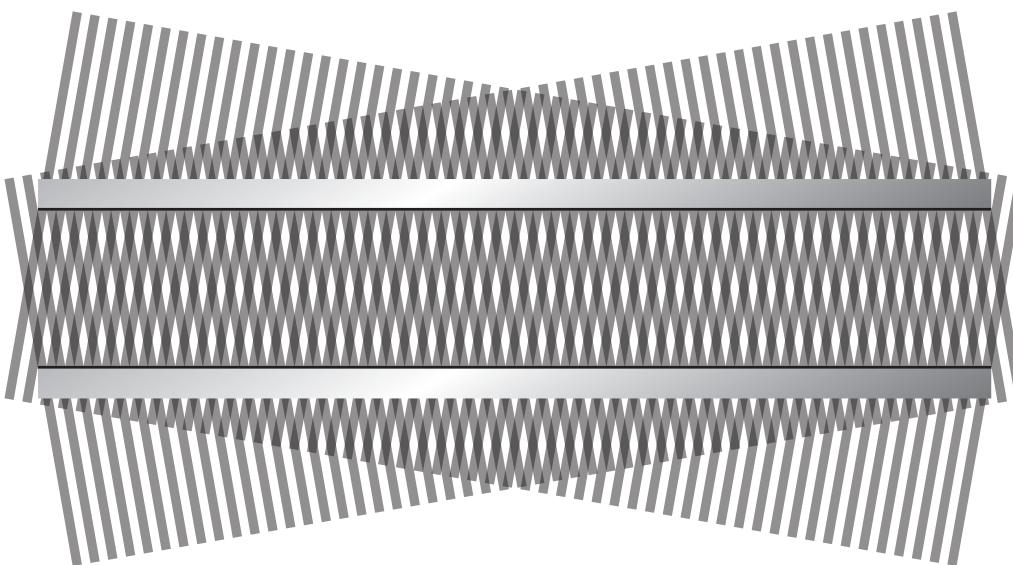
Waveguiding

change angle of incident waves...



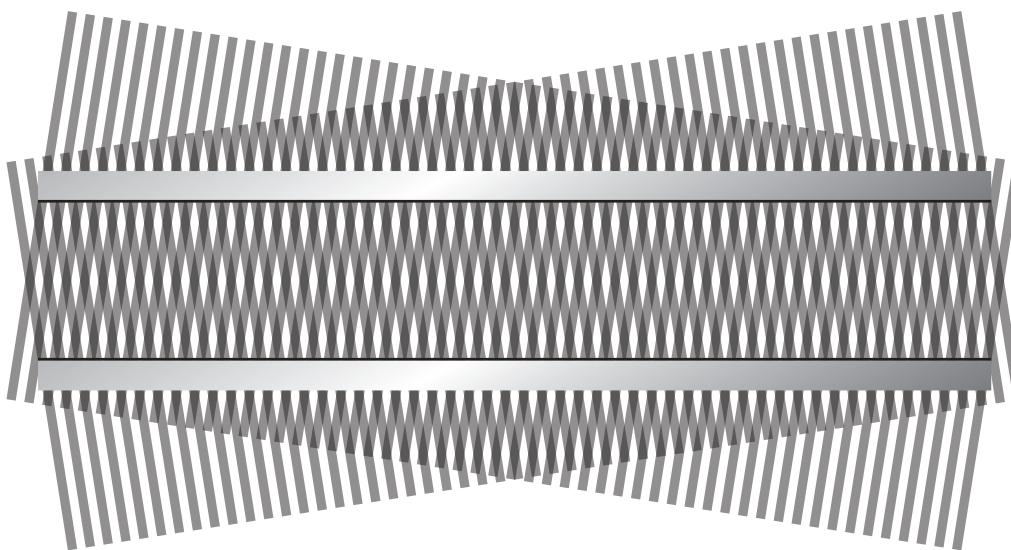
Waveguiding

change angle of incident waves...



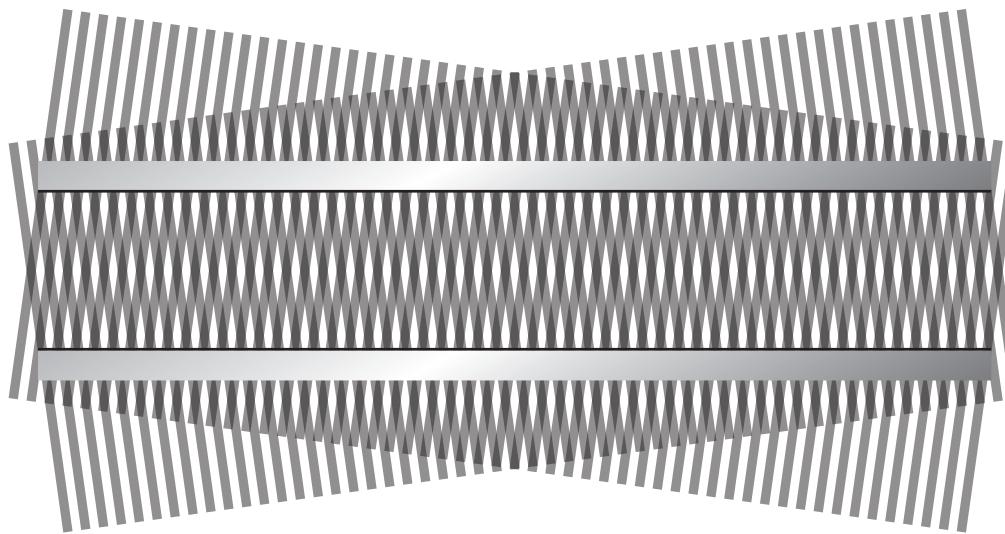
Waveguiding

change angle of incident waves...



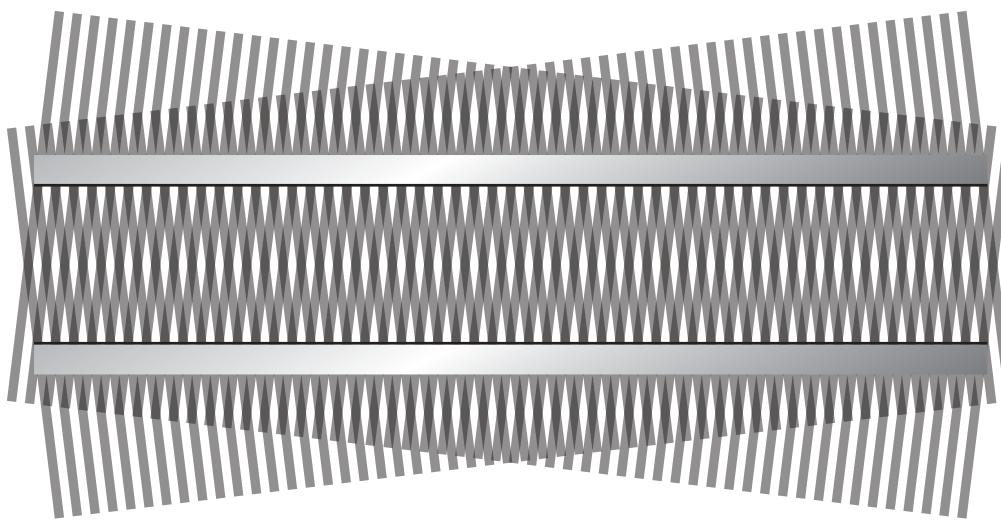
Waveguiding

change angle of incident waves...



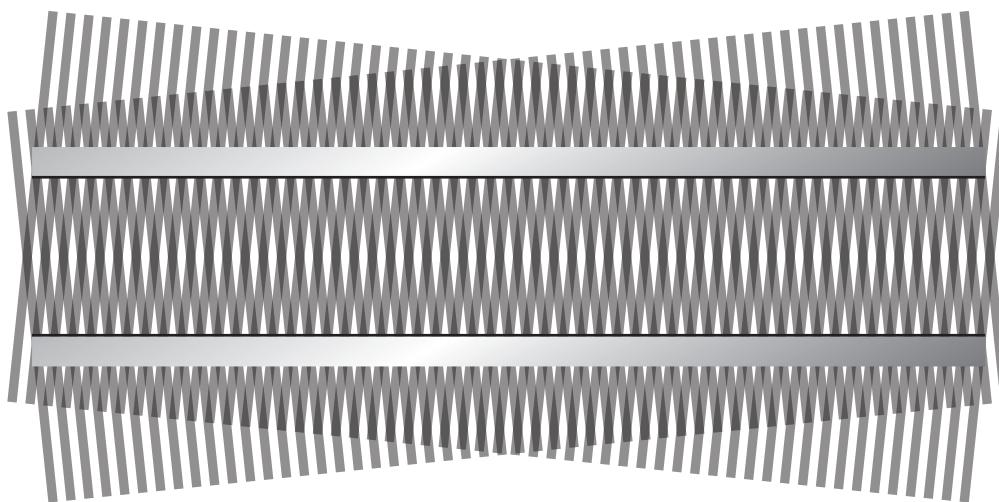
Waveguiding

change angle of incident waves...



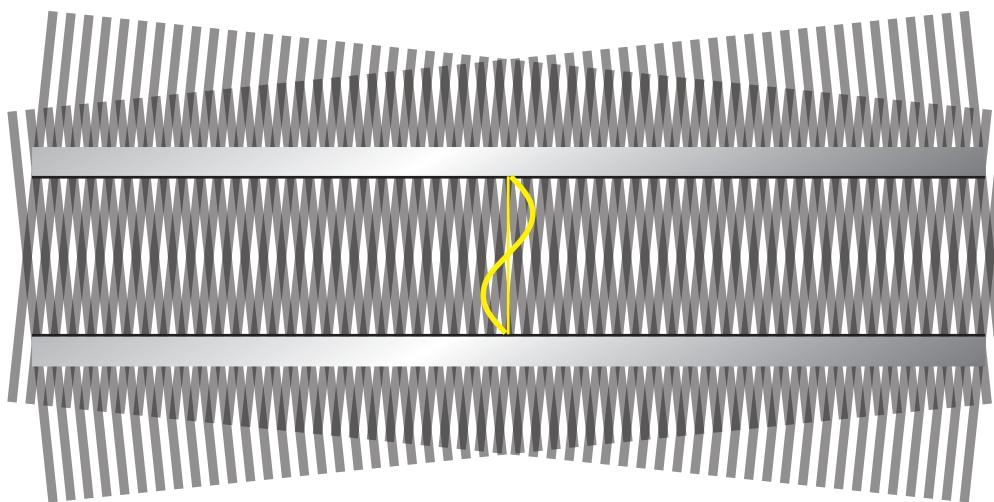
Waveguiding

change angle of incident waves...



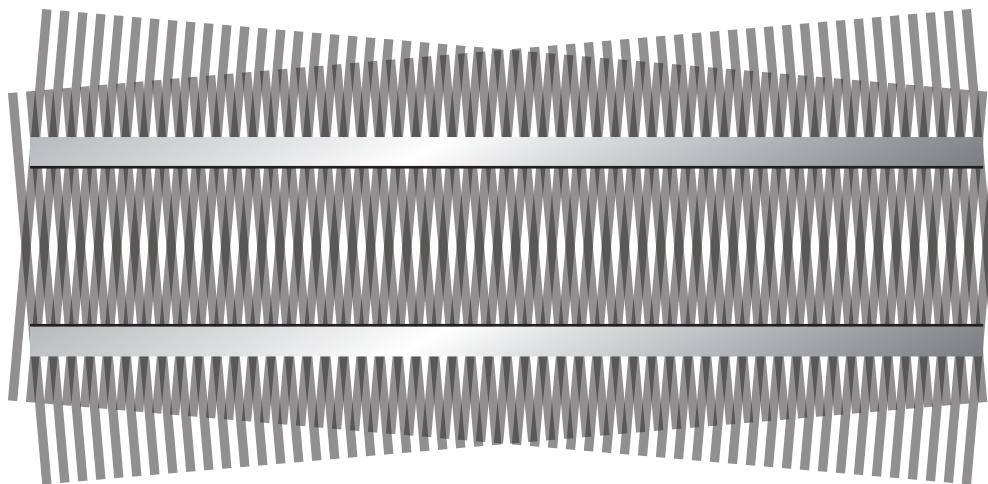
Waveguiding

change angle of incident waves...



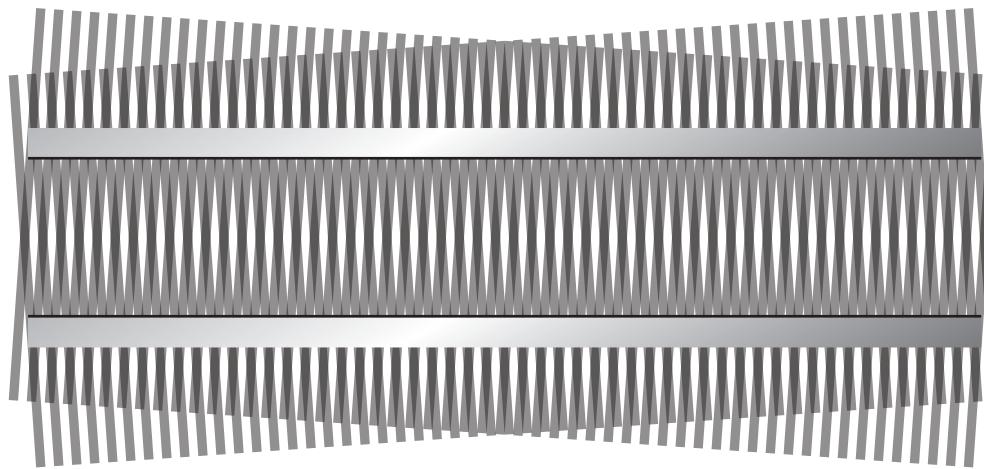
Waveguiding

change angle of incident waves...



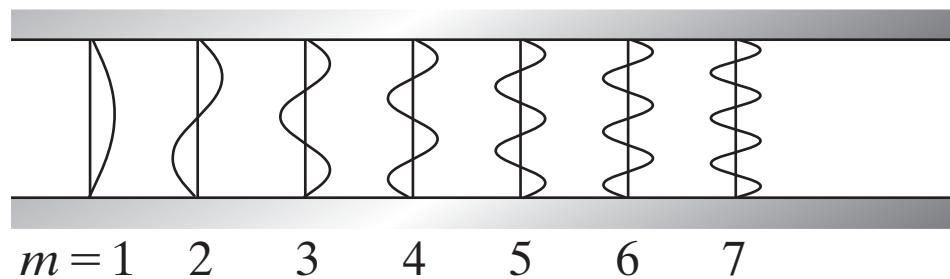
Waveguiding

change angle of incident waves...



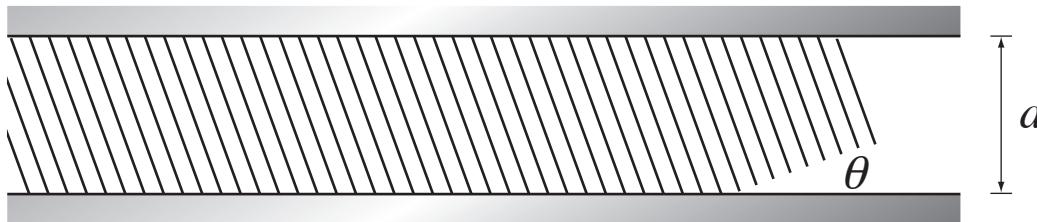
Waveguiding

boundary conditions only satisfied for certain θ



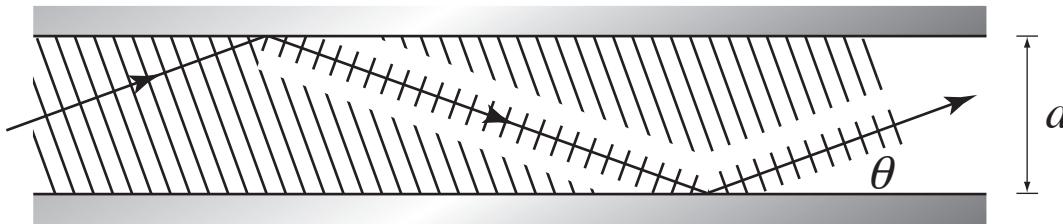
standing wave in y -direction, traveling in z -direction

Waveguiding



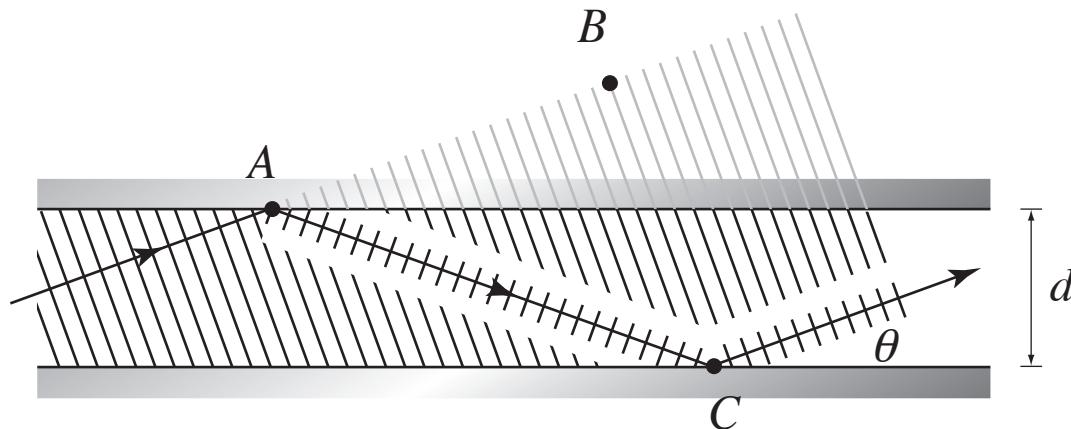
consider wave incident at angle θ

Waveguiding



twice-reflected wave

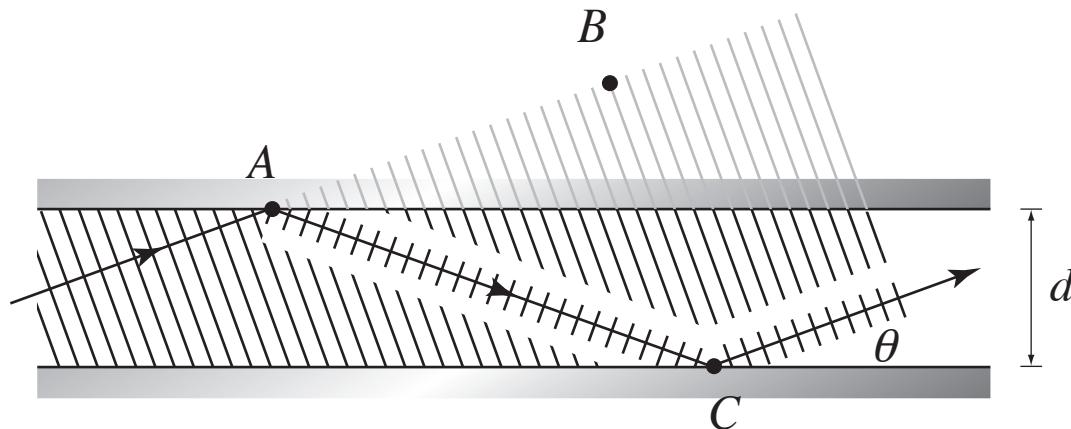
Waveguiding



self consistency:

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

Waveguiding



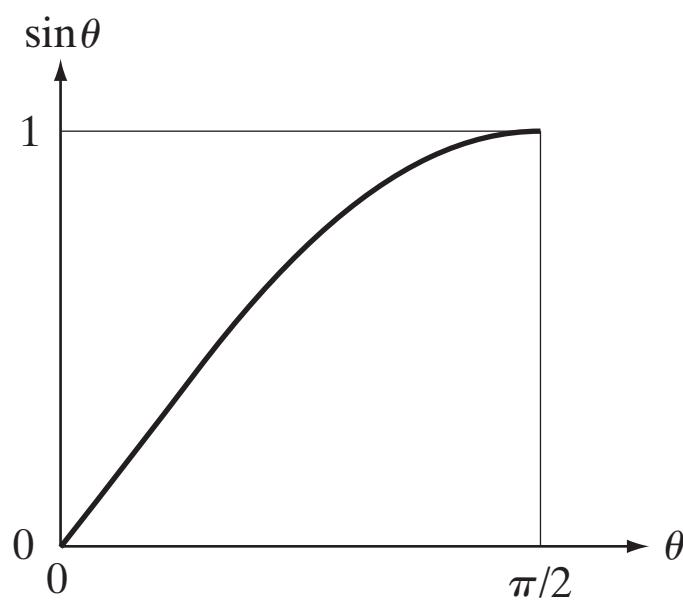
self consistency:

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

so:

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

Waveguiding



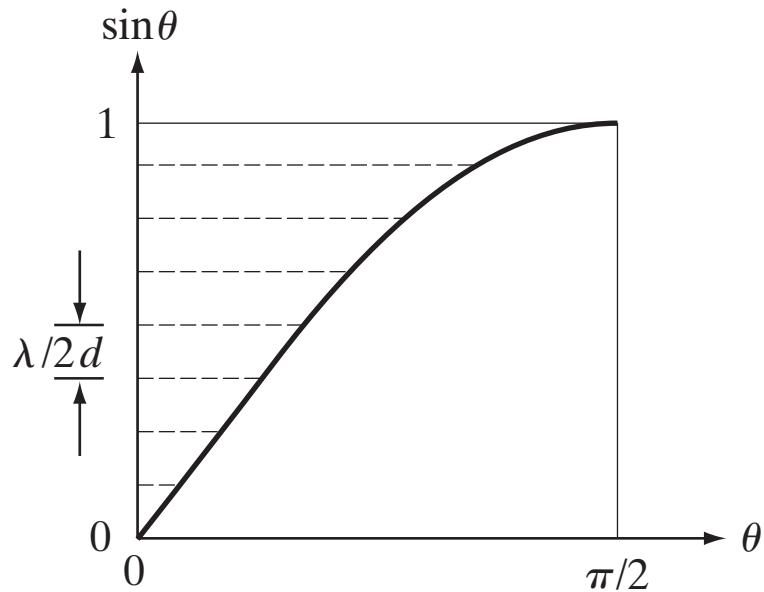
self consistency:

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

so:

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Waveguiding



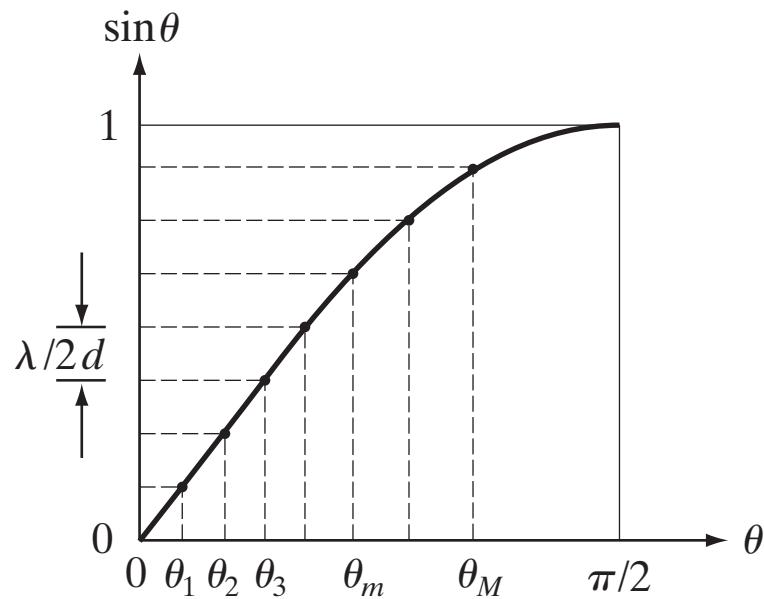
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$$AC - AB = 2d \sin \theta = m\lambda \quad (m = 1, 2, \dots)$$

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Waveguiding



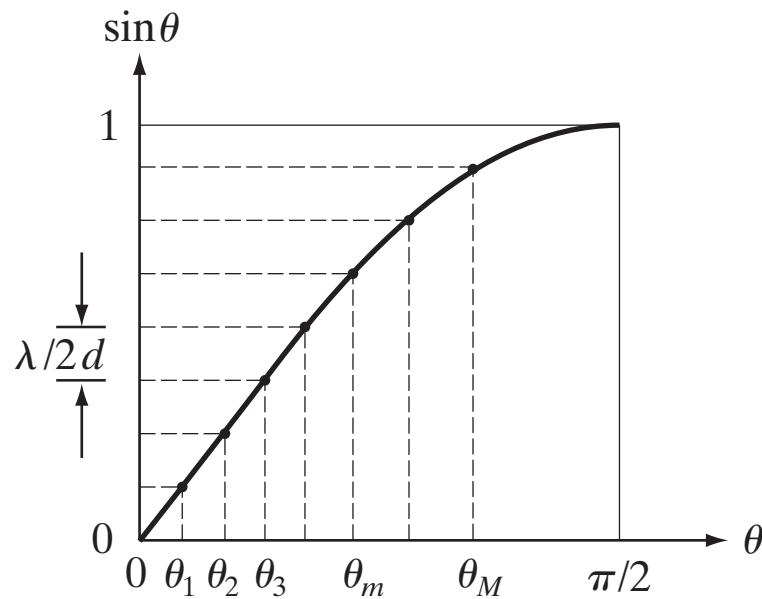
self consistency:

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

so:

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

Waveguiding



number of modes:

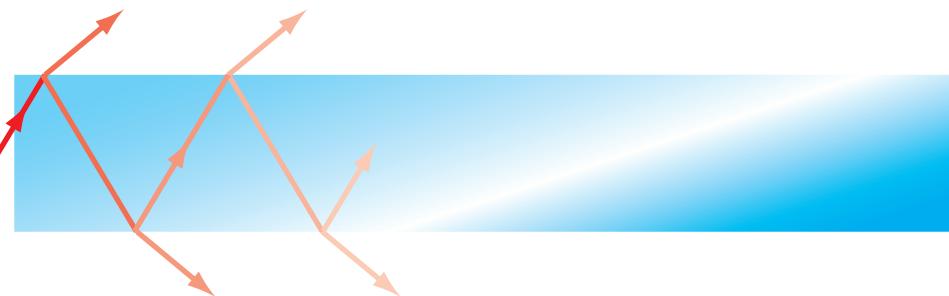
$$M \doteq \frac{2d}{\lambda}$$

Waveguiding



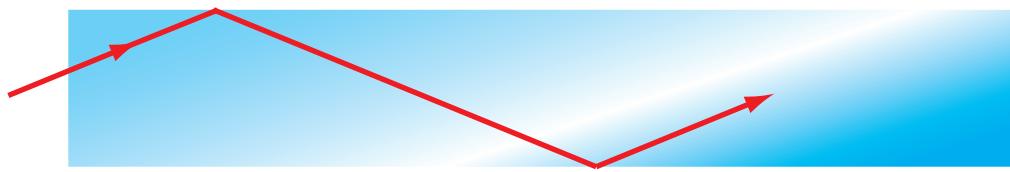
now consider a planar dielectric waveguide

Waveguiding



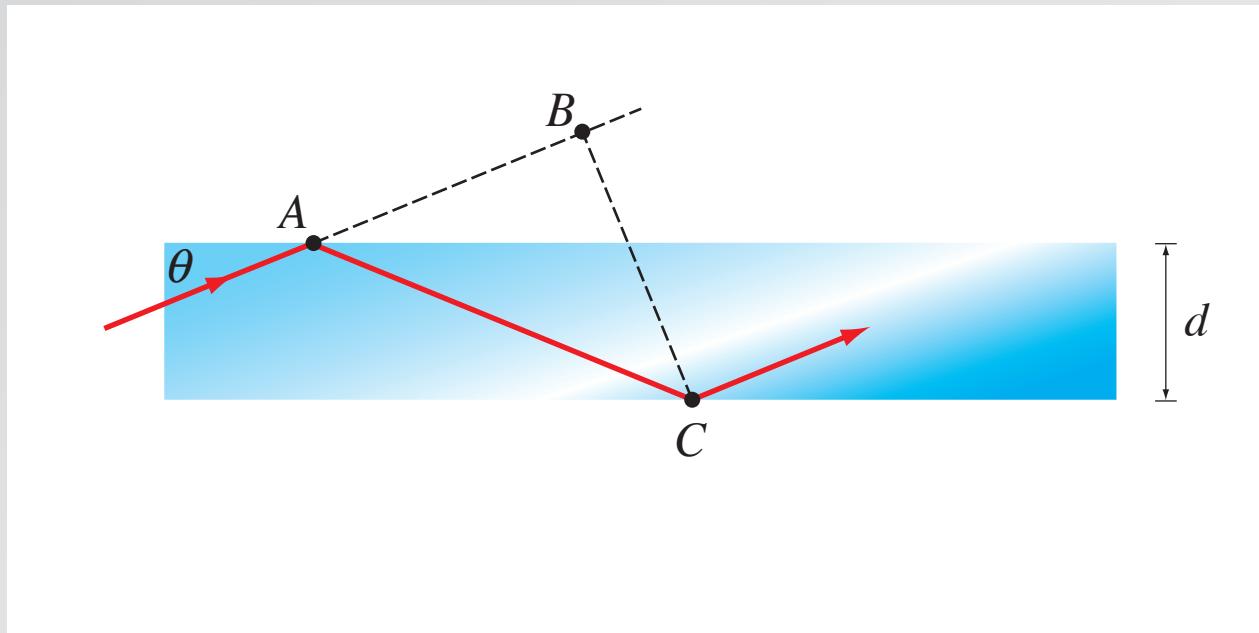
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



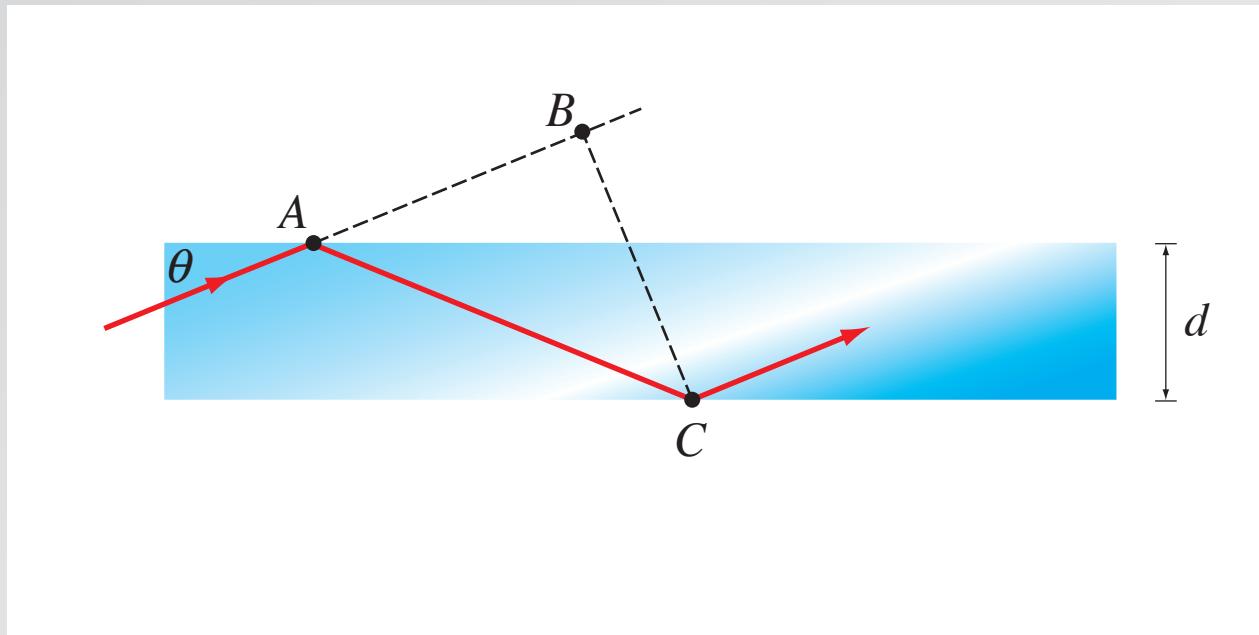
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

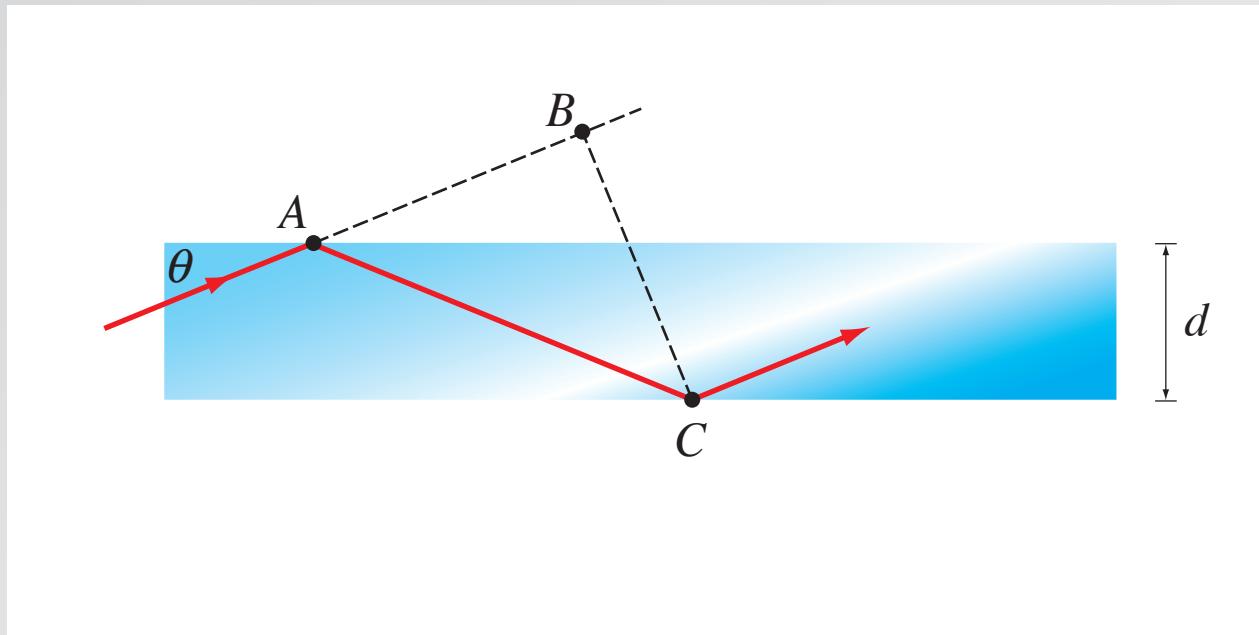
Waveguiding



self consistency:

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

Waveguiding



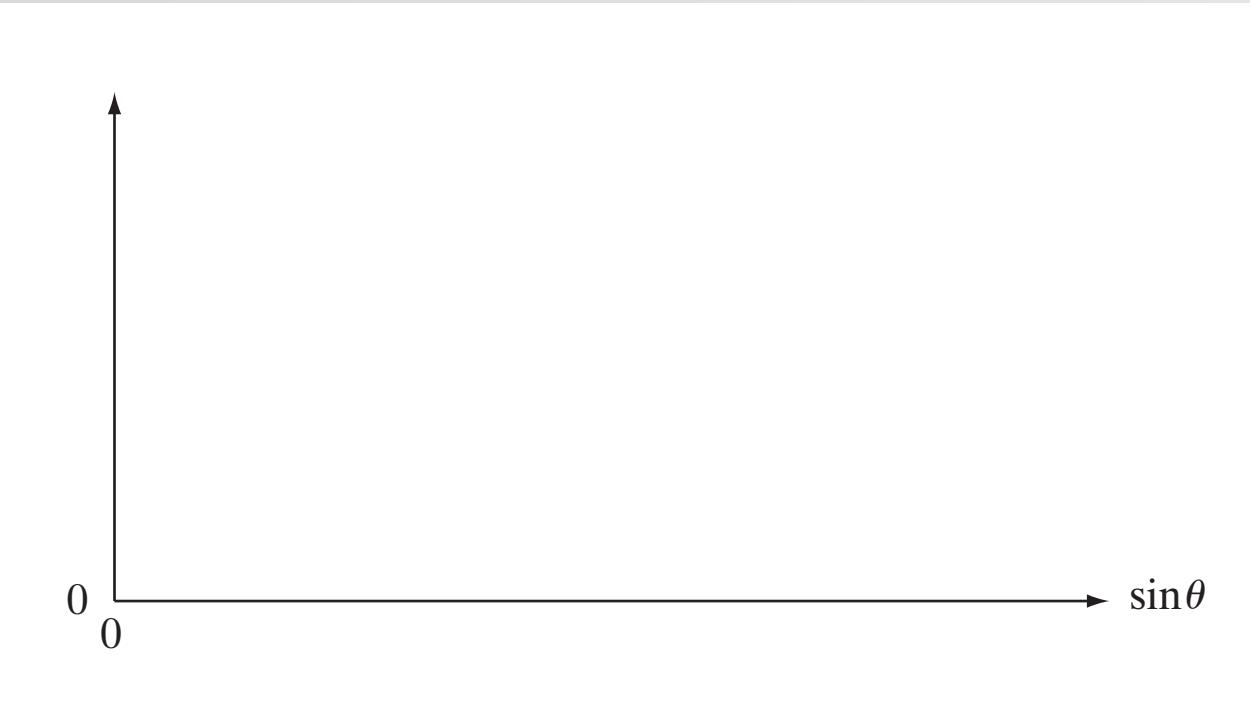
self consistency:

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

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



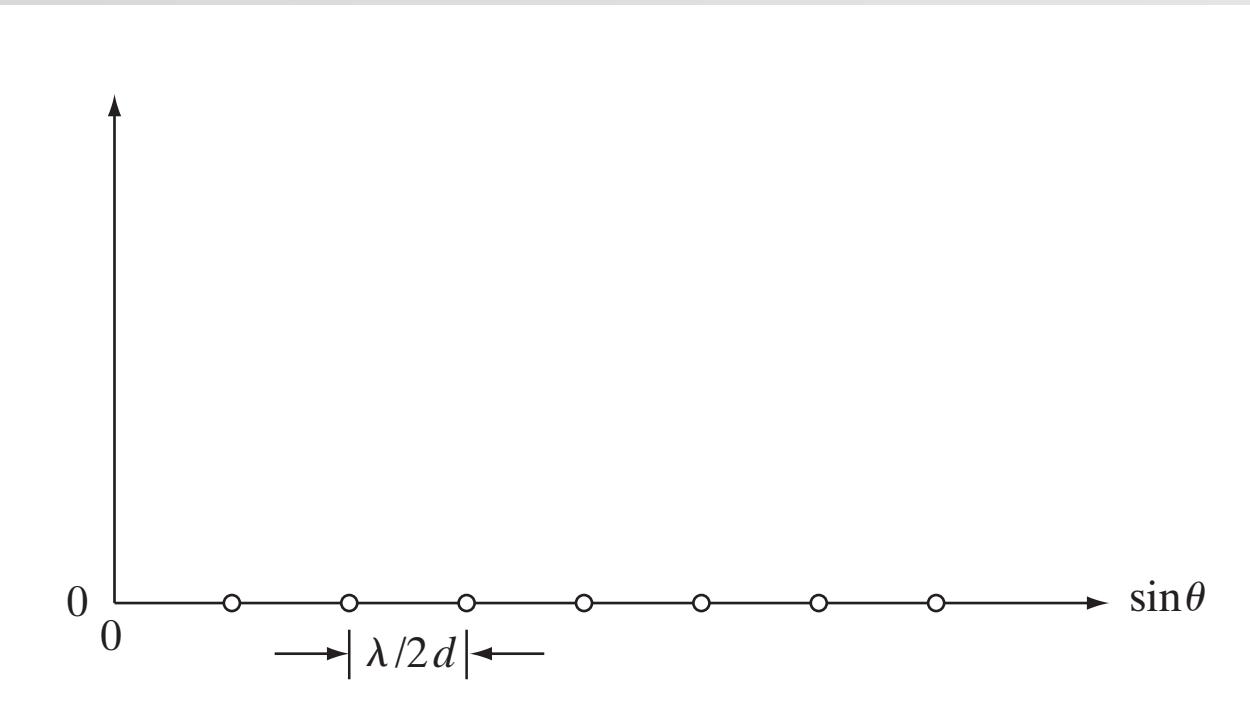
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$$AC - AB = 2d \sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\dots)$$

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Waveguiding



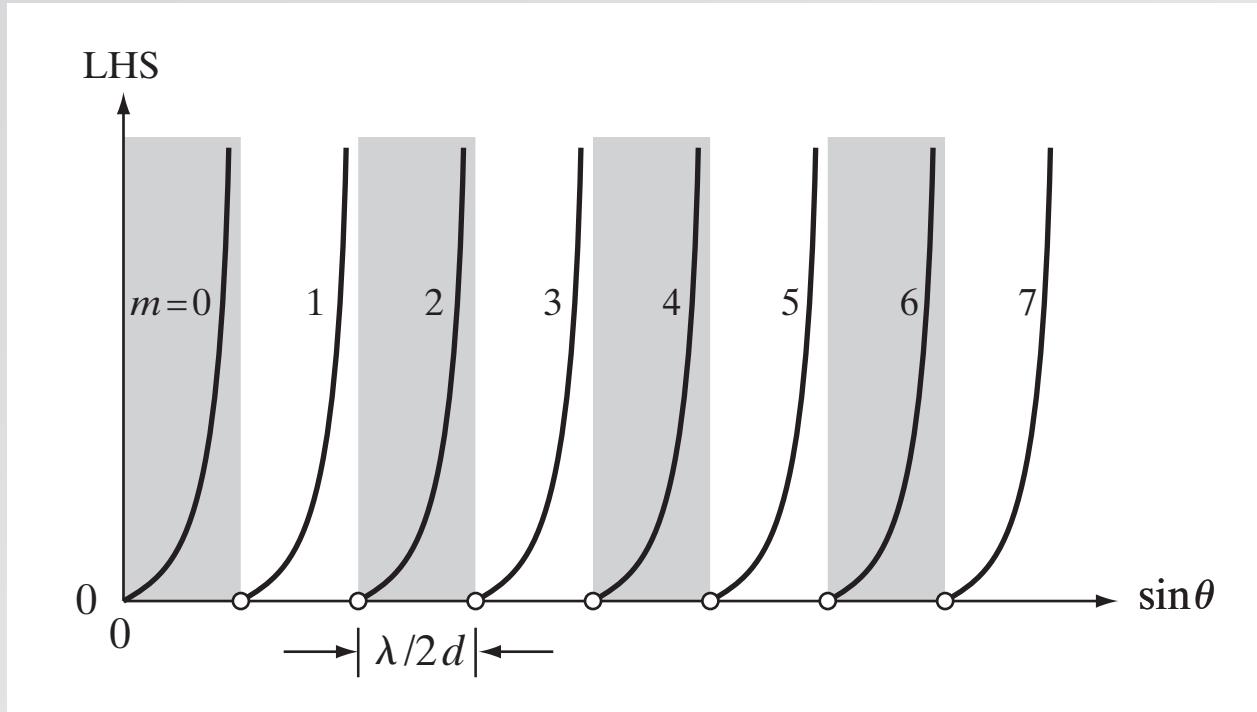
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Waveguiding



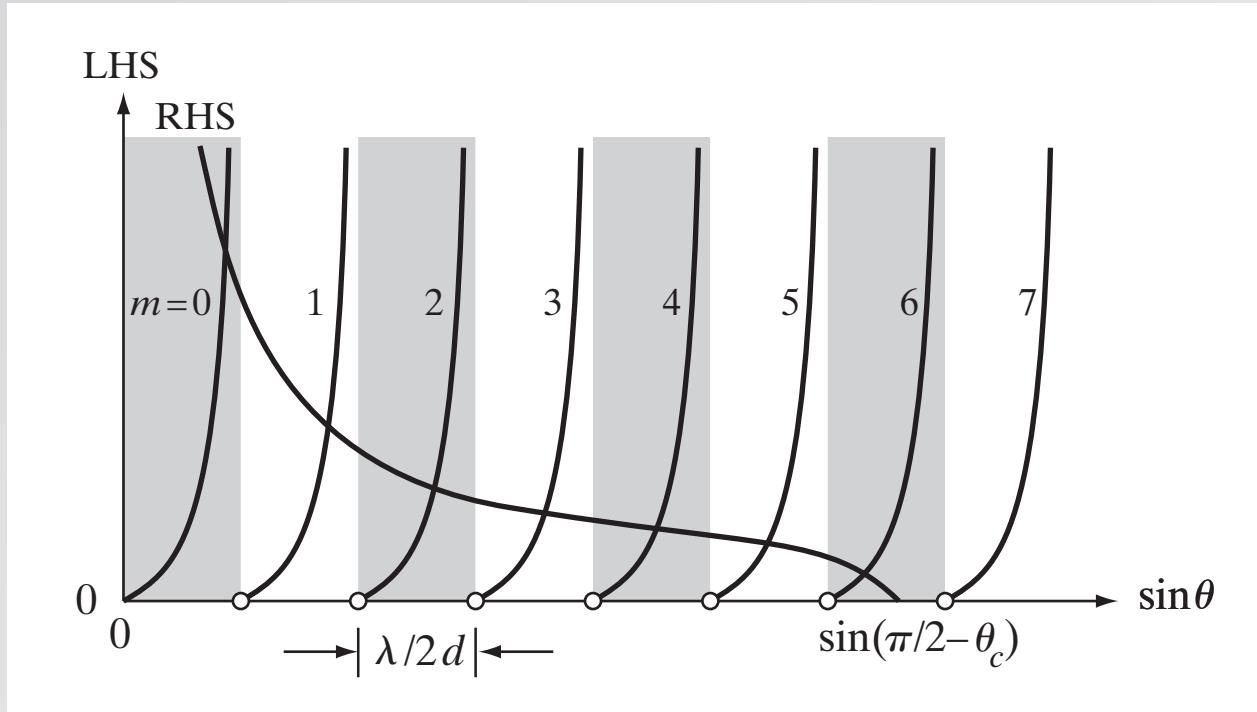
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Waveguiding



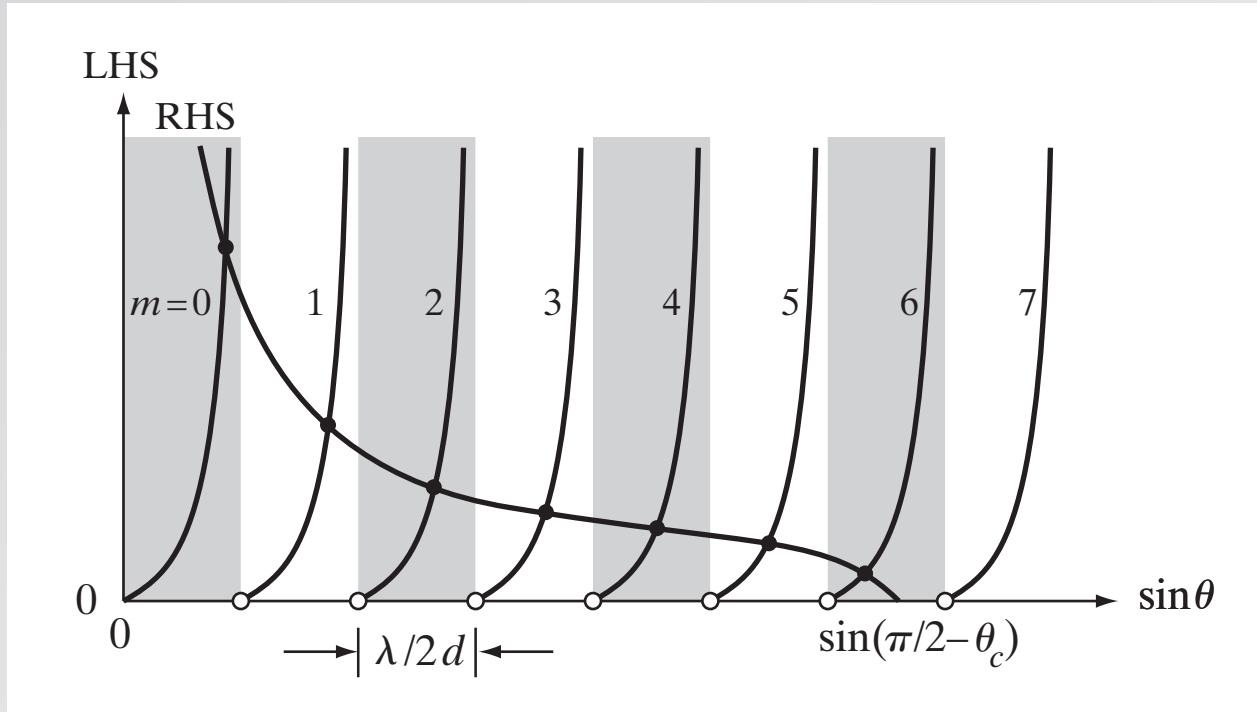
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Waveguiding



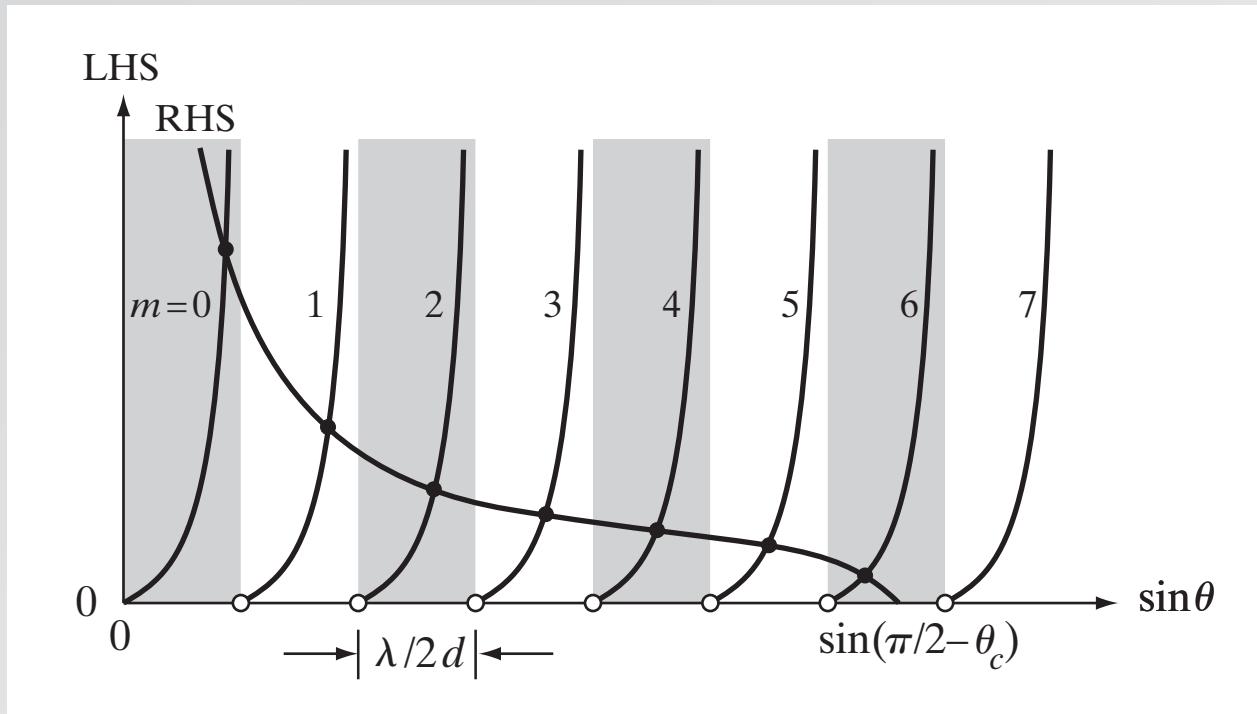
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$$AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m\lambda \quad (m = 0, 1, 2\dots)$$

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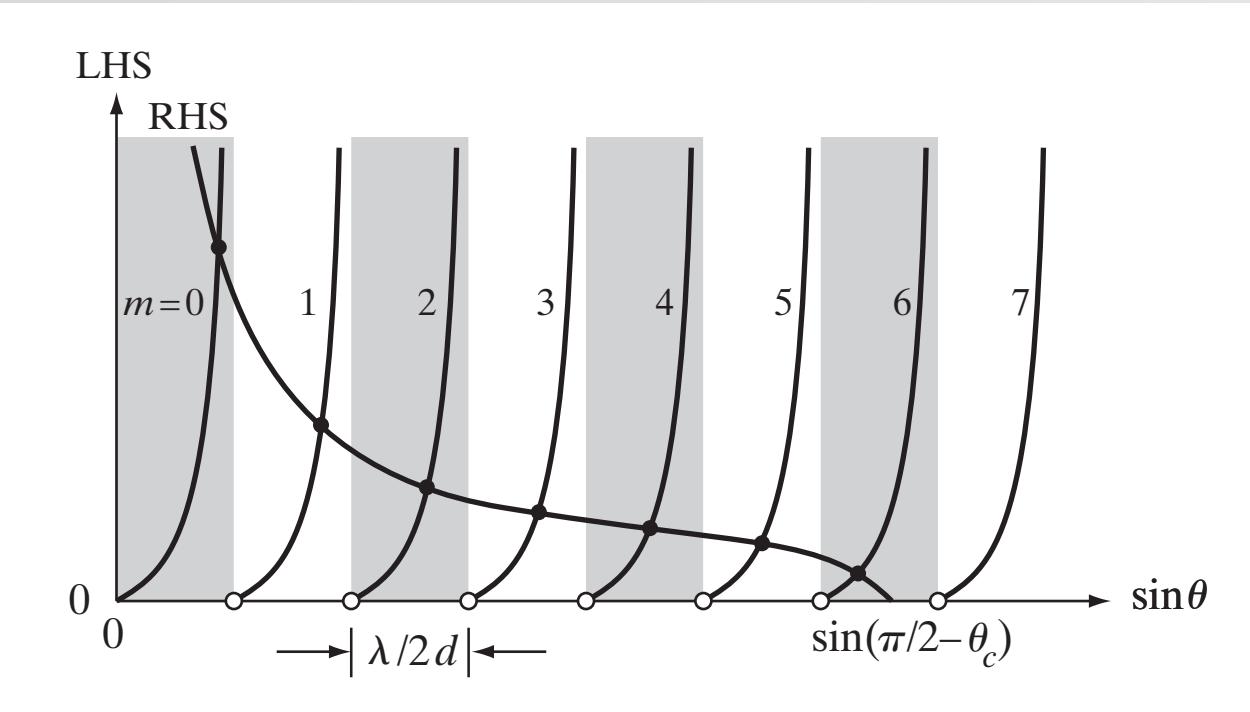
Waveguiding



number of modes:

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

Waveguiding



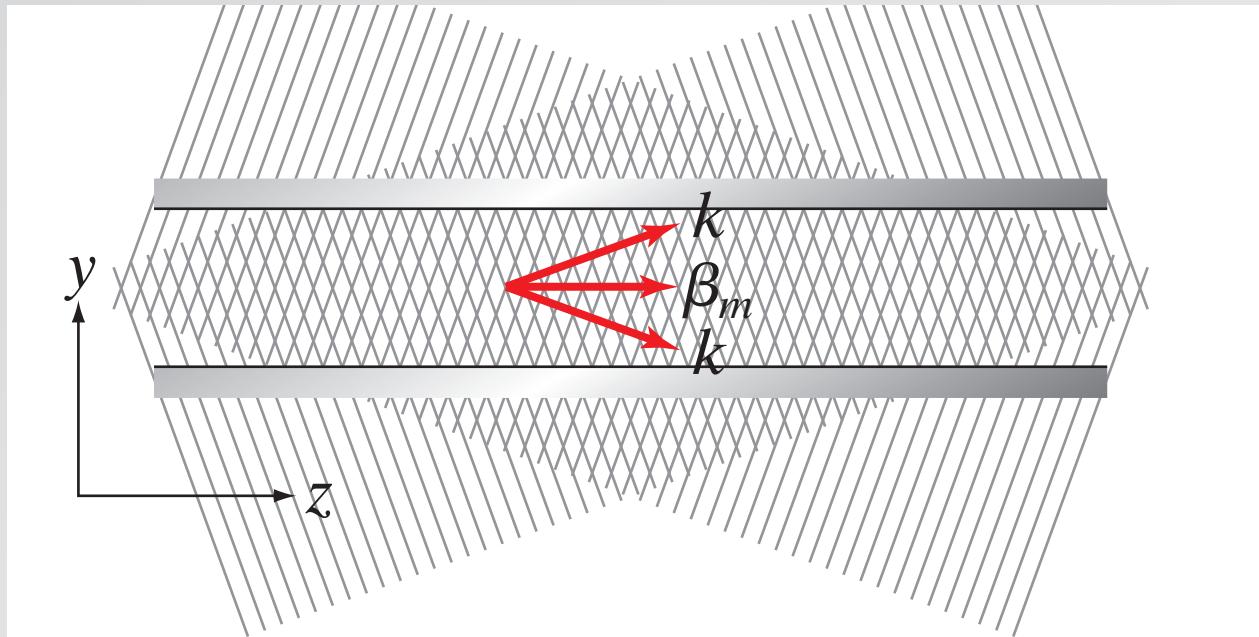
number of modes:

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

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

$$M \doteq \frac{2d}{\lambda} \quad 300 < d < 600 \text{ nm}$$

dielectric

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

Waveguiding

single mode condition for 600-nm light:

planar mirror

$$M \doteq \frac{2d}{\lambda} \quad 300 < d < 600 \text{ nm}$$

dielectric

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

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:

$$\nabla^2 \vec{A} + \omega^2 \mu_0 \epsilon \vec{A} = 0$$

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

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

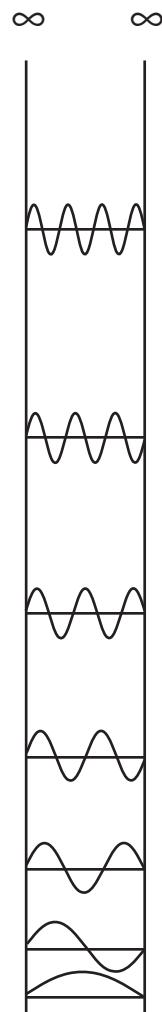
yields:

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

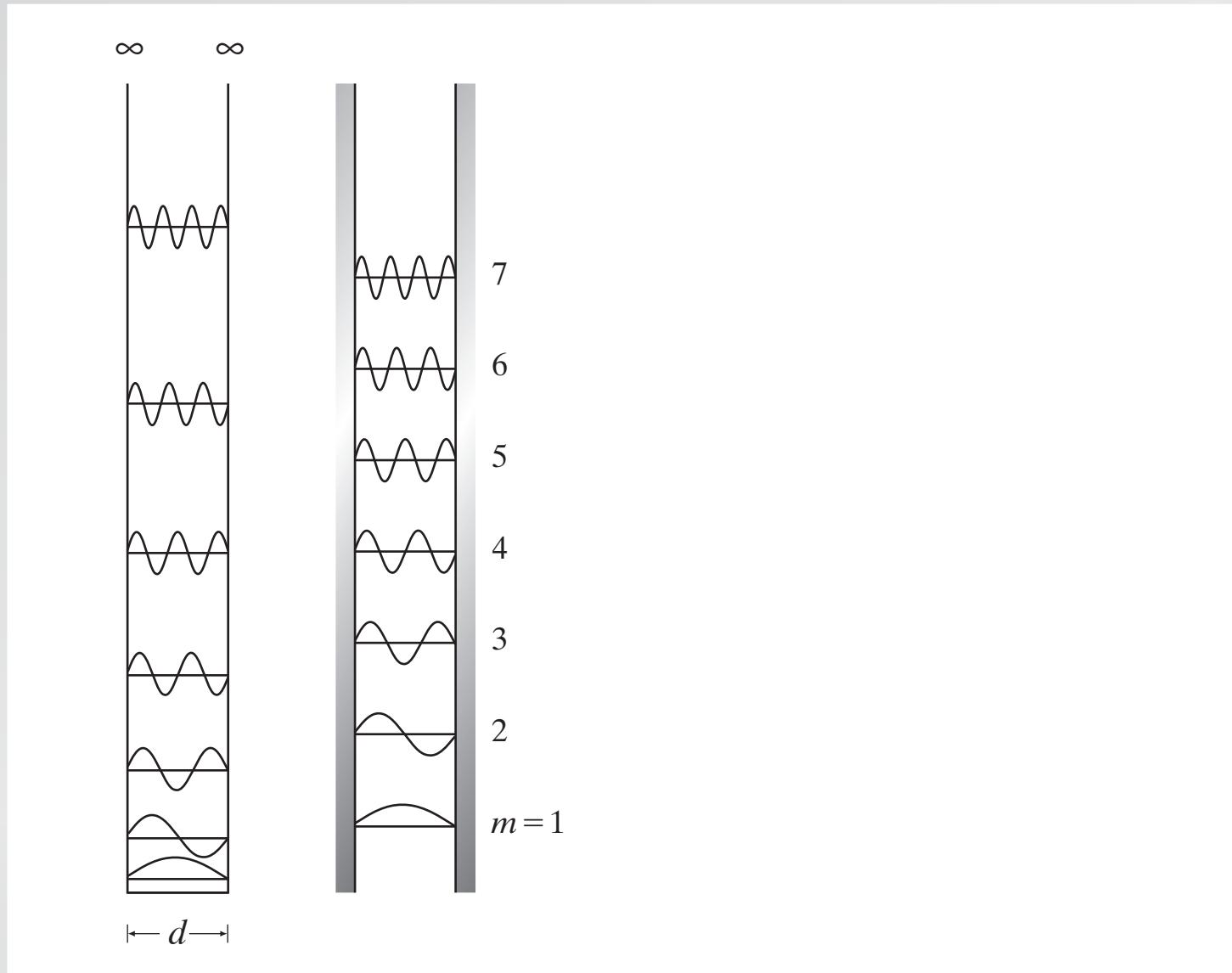
Compare to time-independent Schrödinger equation:

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

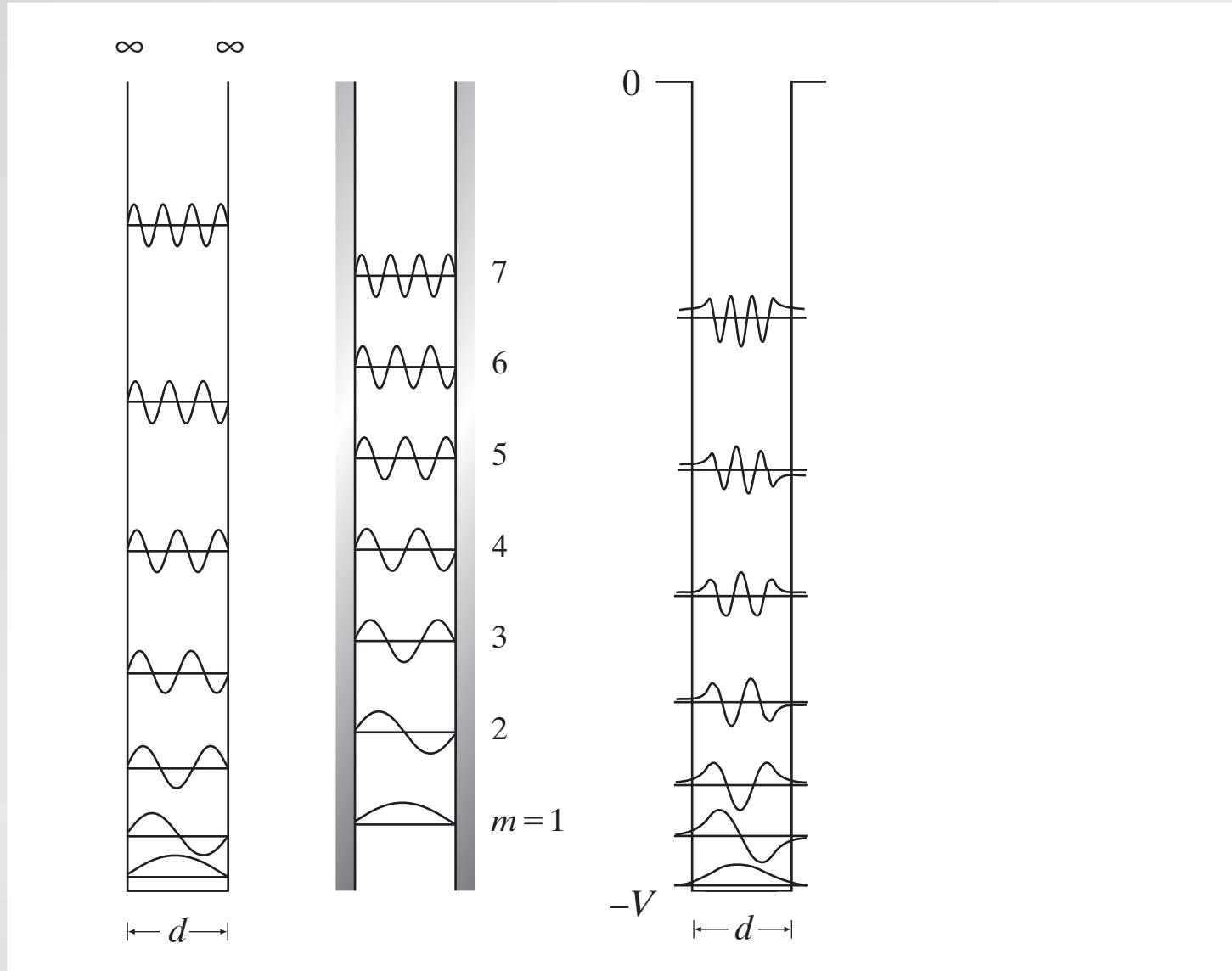
Waveguiding



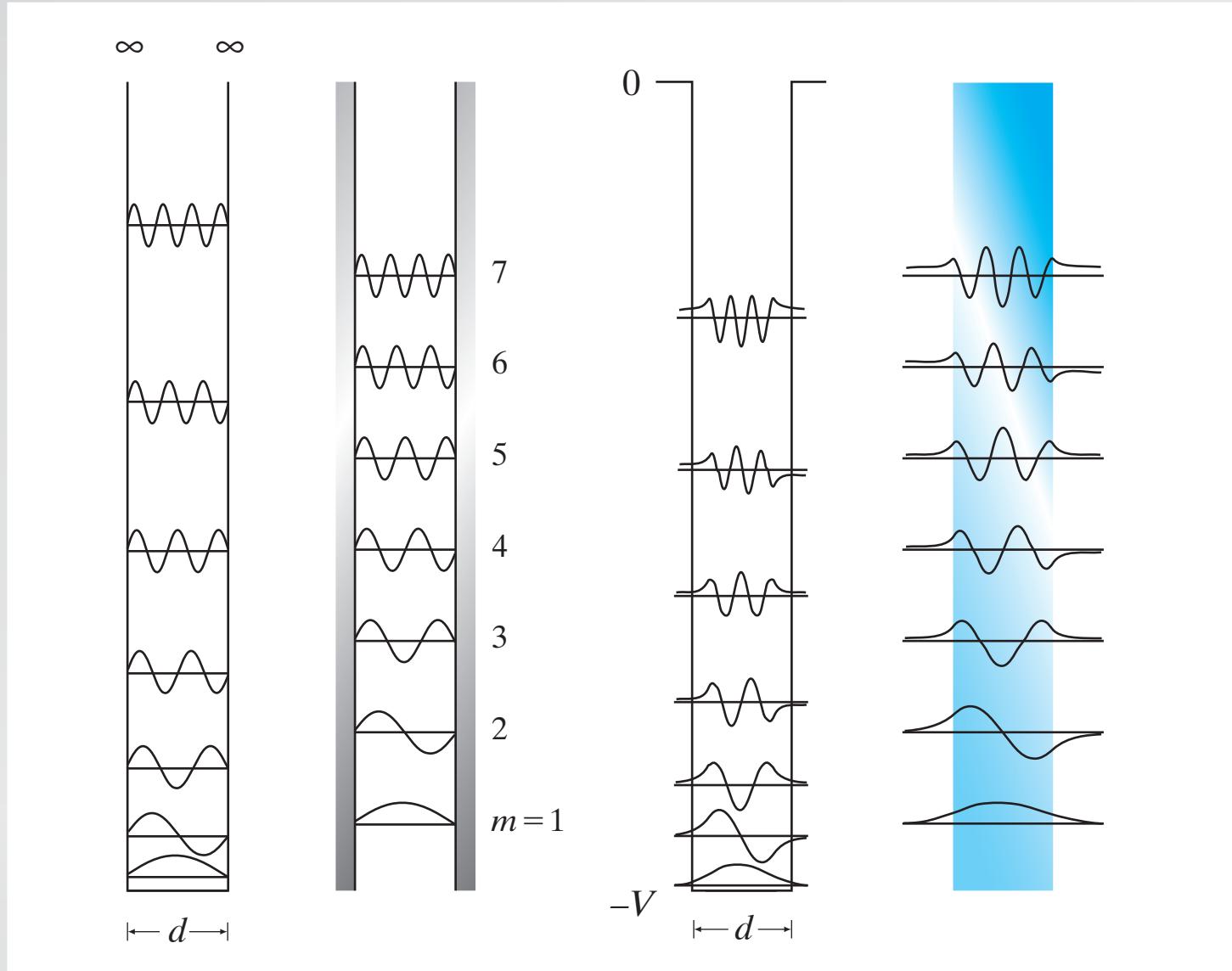
Waveguiding



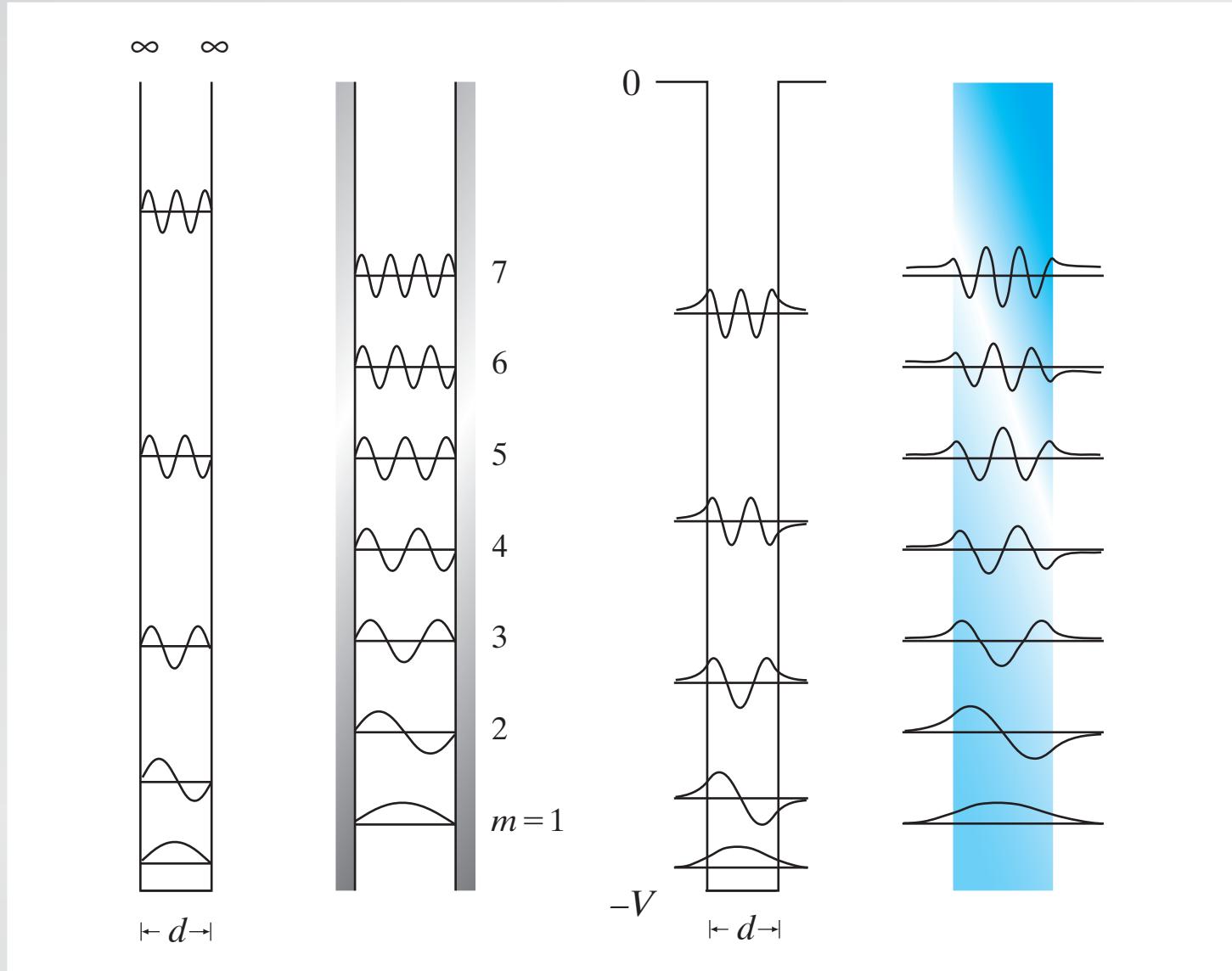
Waveguiding



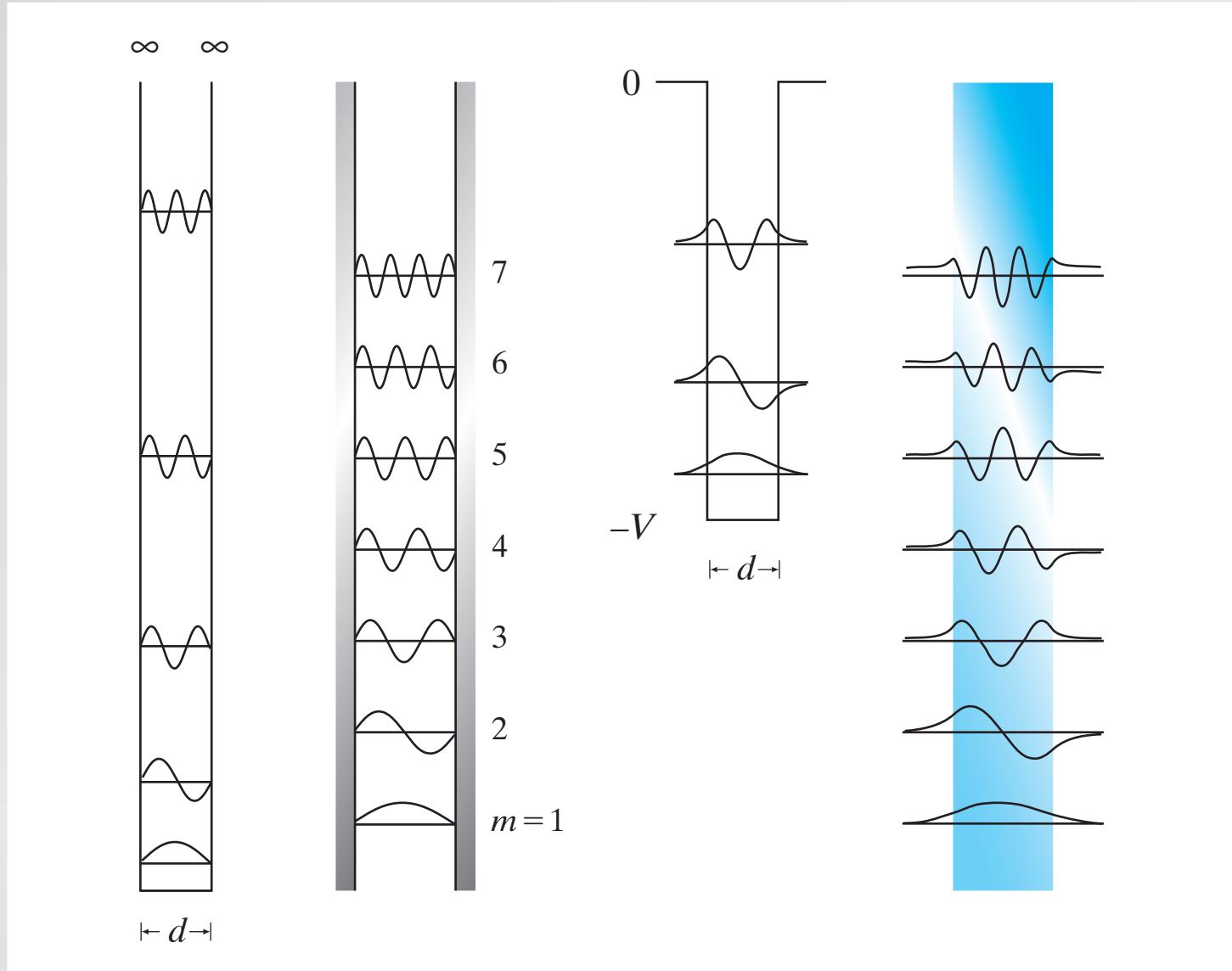
Waveguiding



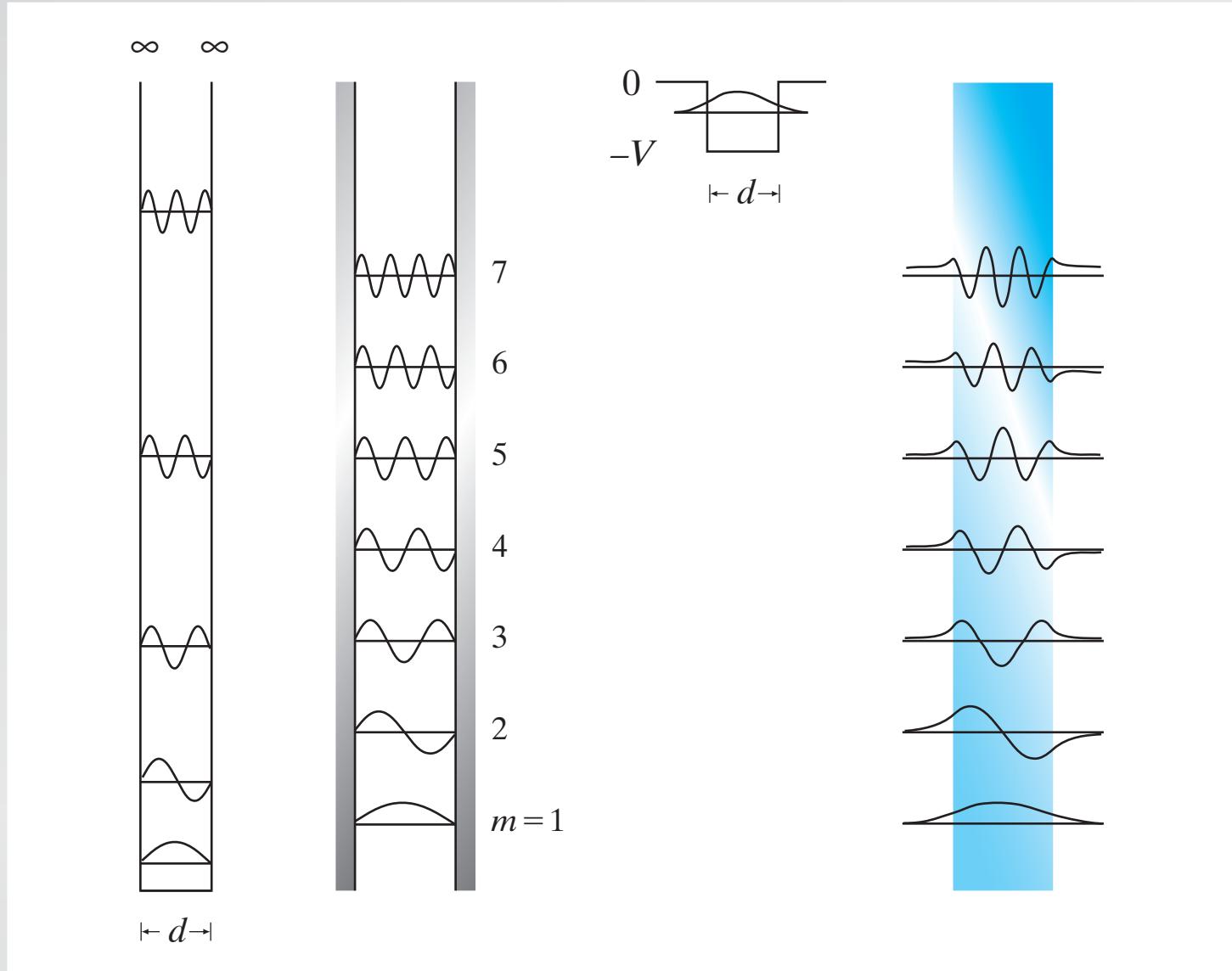
Waveguiding



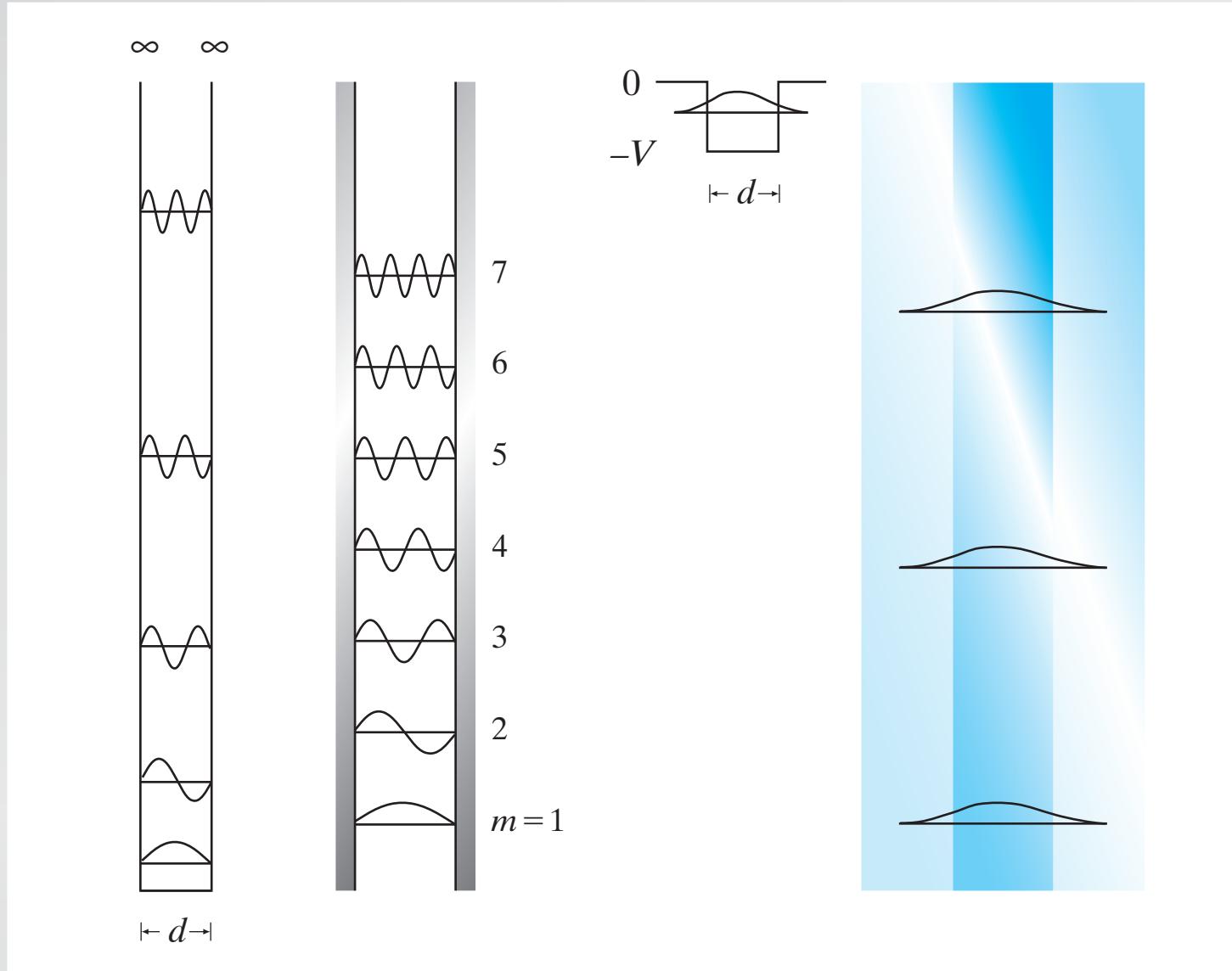
Waveguiding



Waveguiding



Waveguiding



Waveguiding

single mode condition for 600-nm light:

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

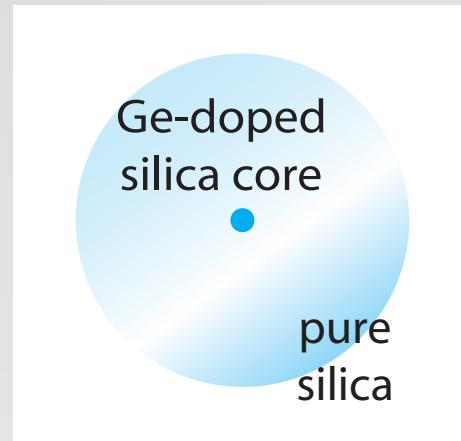
without cladding: $d < 268 \text{ nm}$

Add cladding with 0.4% index difference:

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

Waveguiding

commercial single-mode fiber (Corning Titan®)



core

cladding

index

$n_1 = 1.468$

$n_2 = 1.462$

diameter:

$8.3 \mu\text{m}$

$125.0 \pm 1.0 \mu\text{m}$

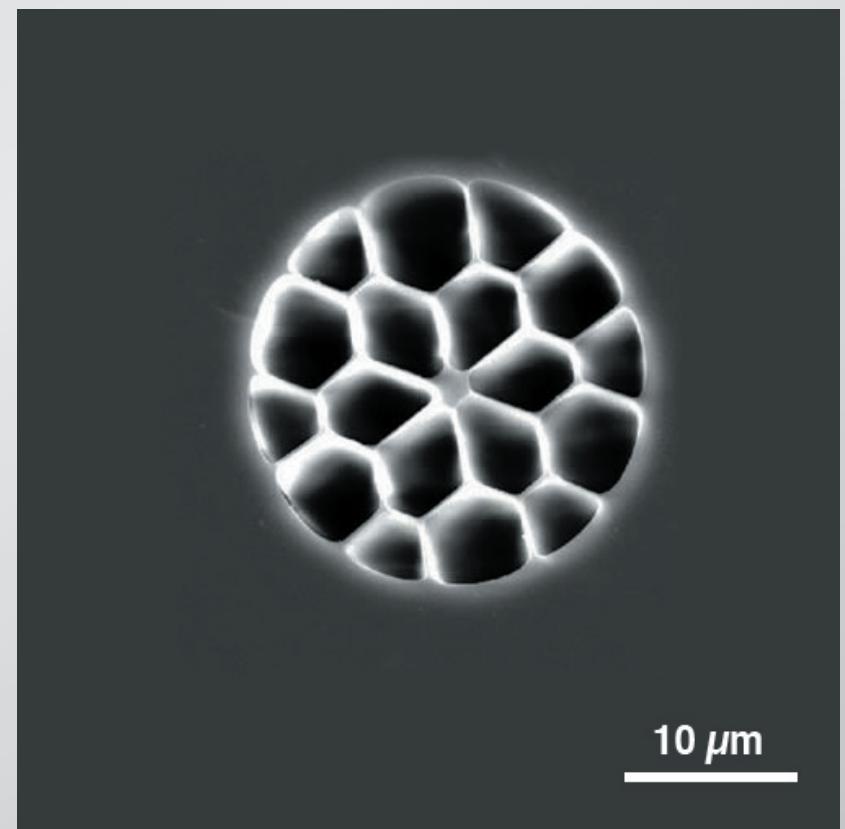
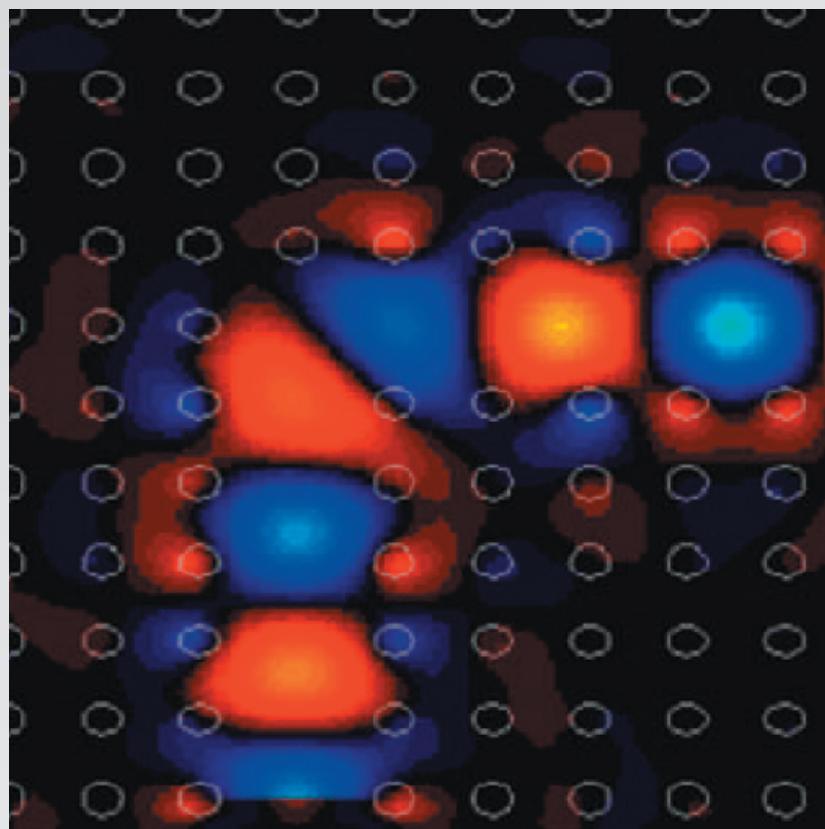
operating wavelength: $\lambda = 1310 \text{ nm}/1550 \text{ nm}$

Waveguiding

drawbacks of clad fibers:

- weak confinement
- no tight bending
- coupling requires splicing

Waveguiding



Outline

- waveguiding
- nanowire fabrication
- optical properties

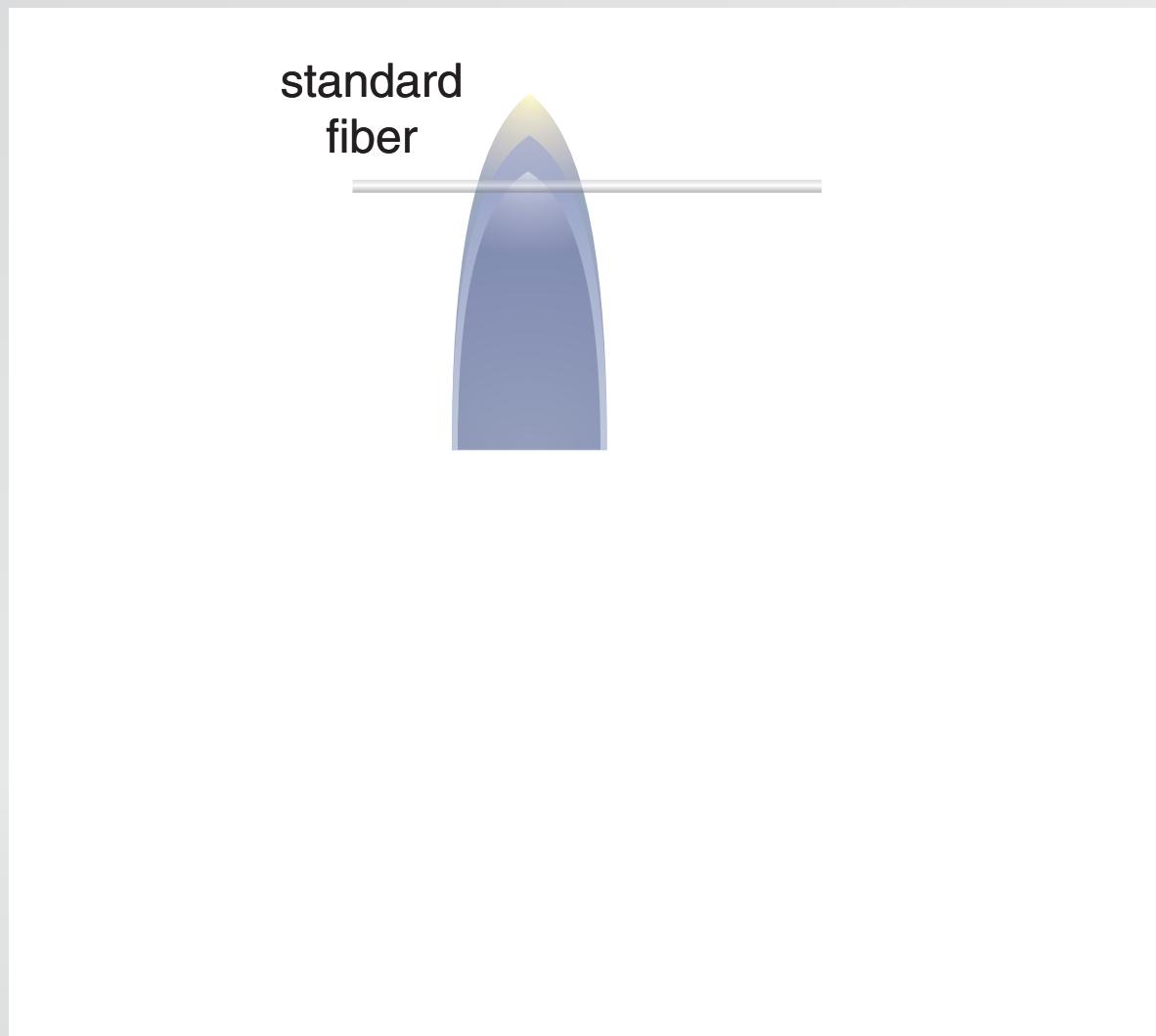
Nanowire fabrication

two-step drawing process

standard
fiber

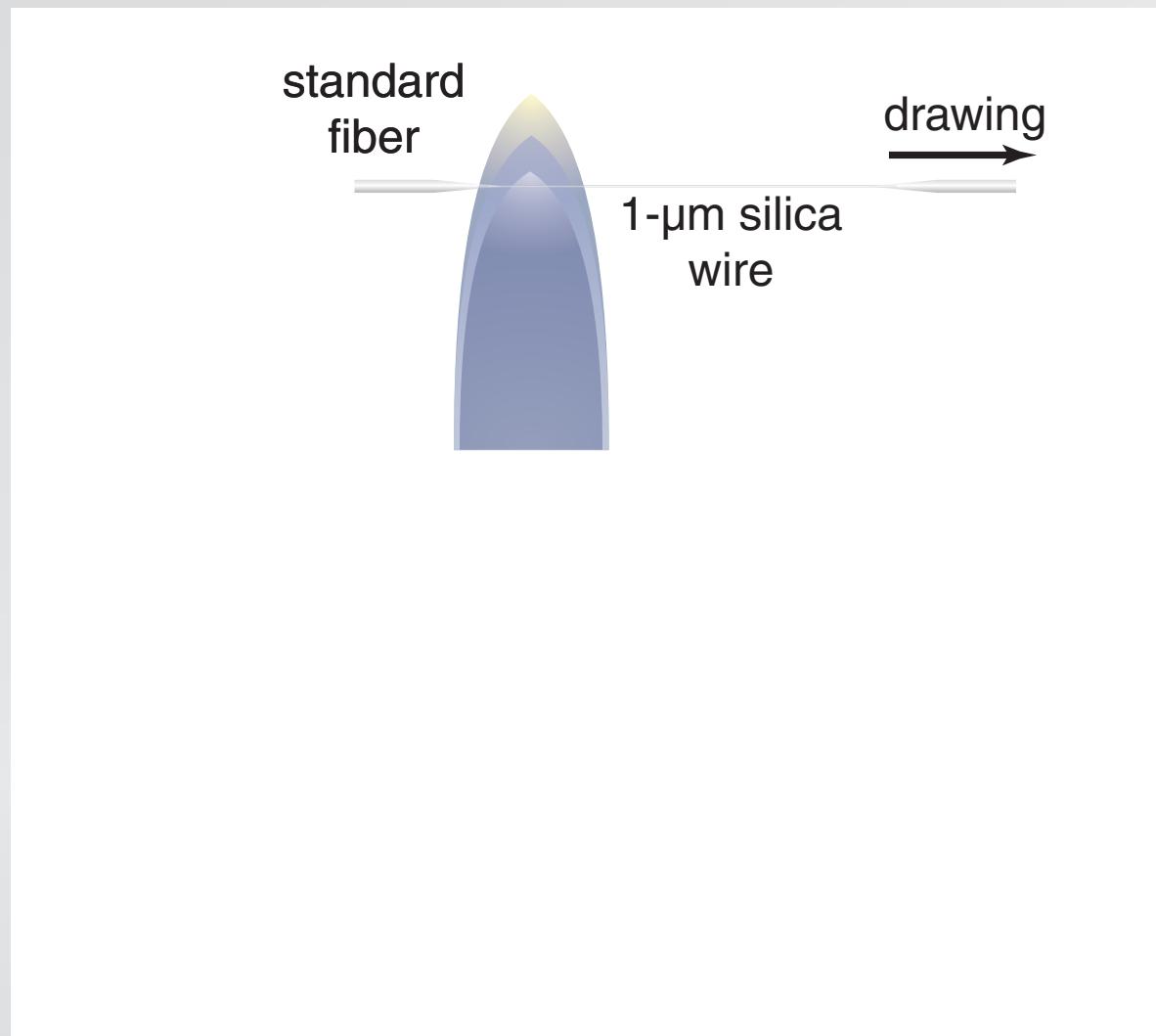
Nanowire fabrication

two-step drawing process



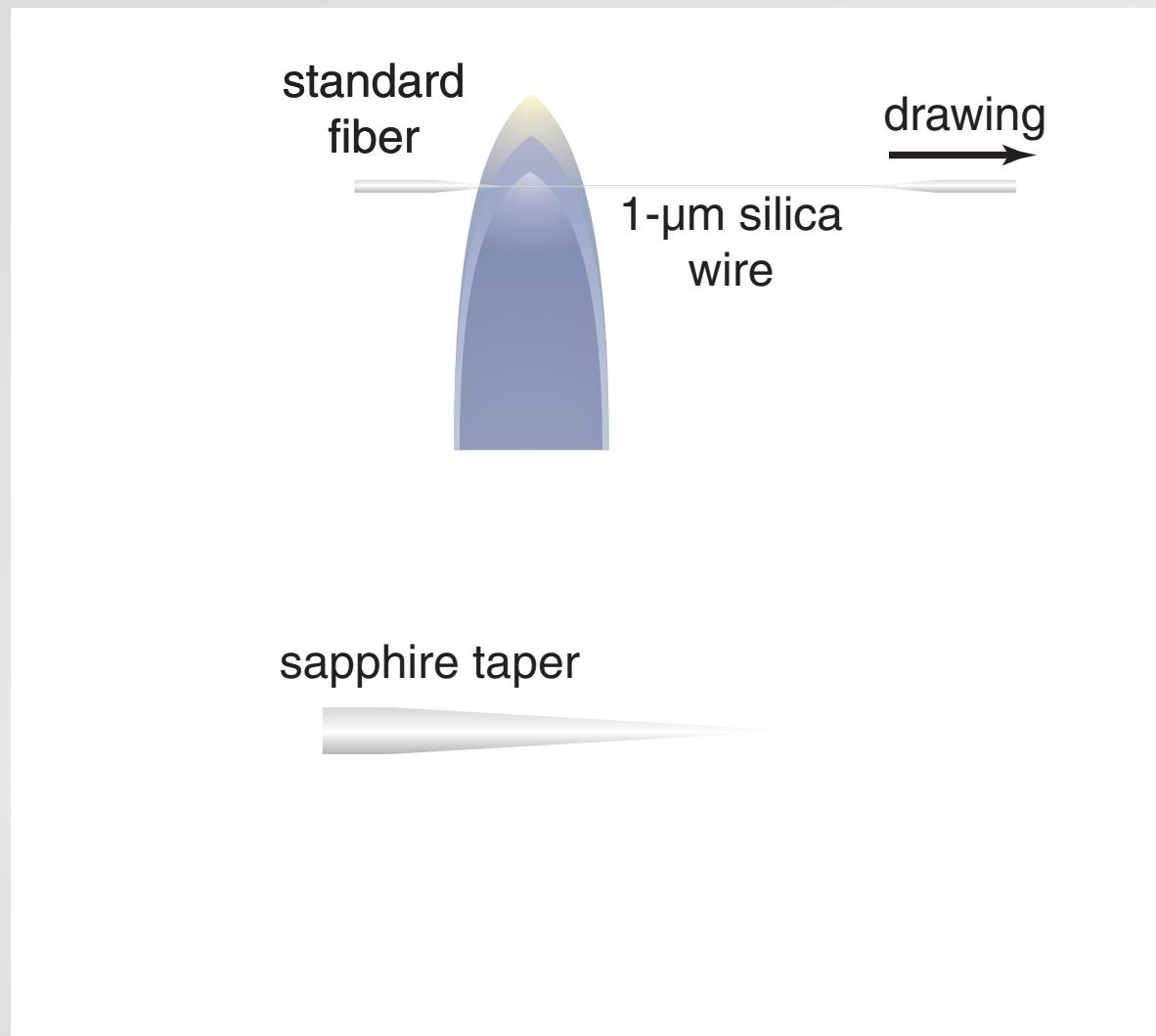
Nanowire fabrication

two-step drawing process



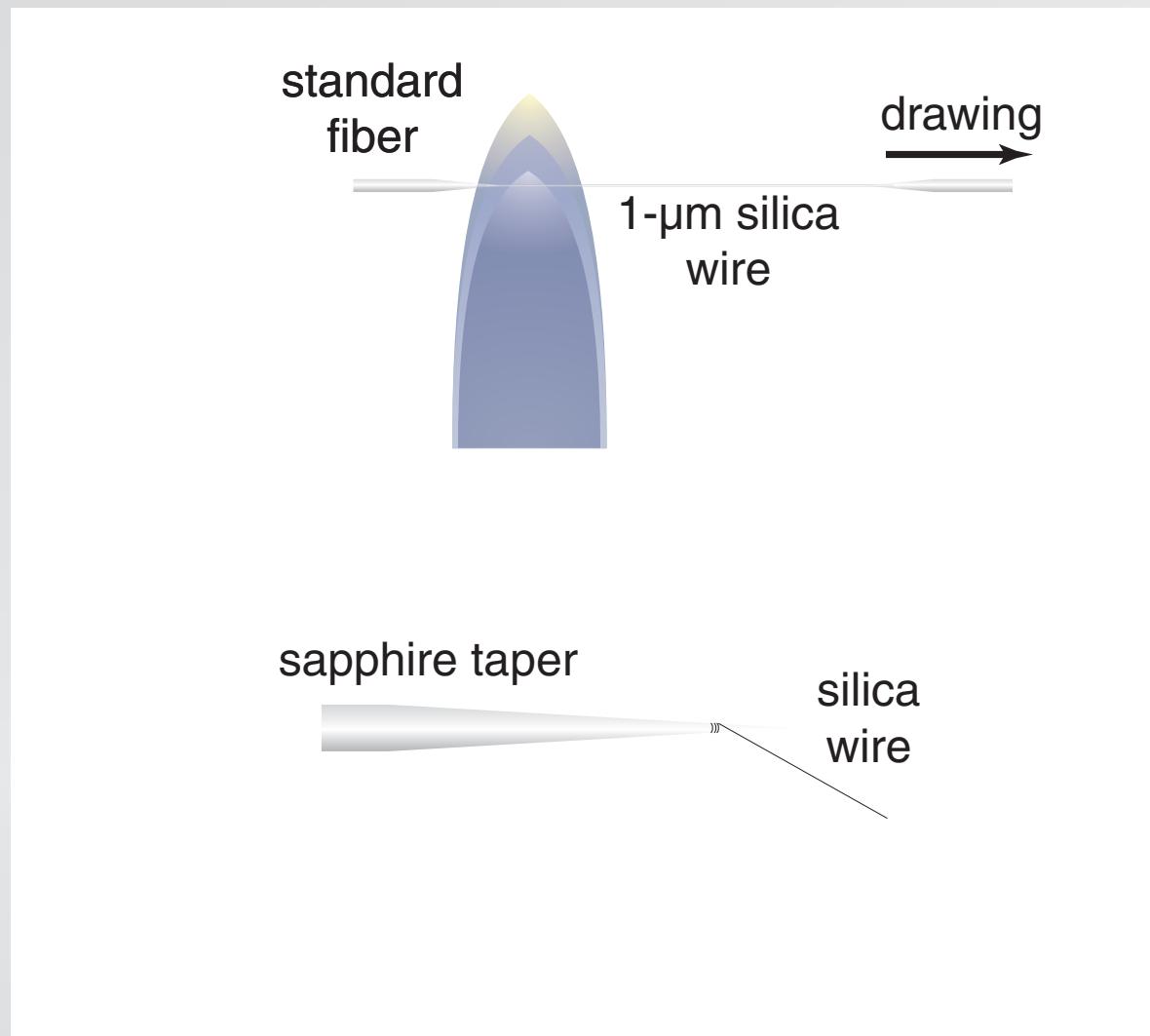
Nanowire fabrication

two-step drawing process



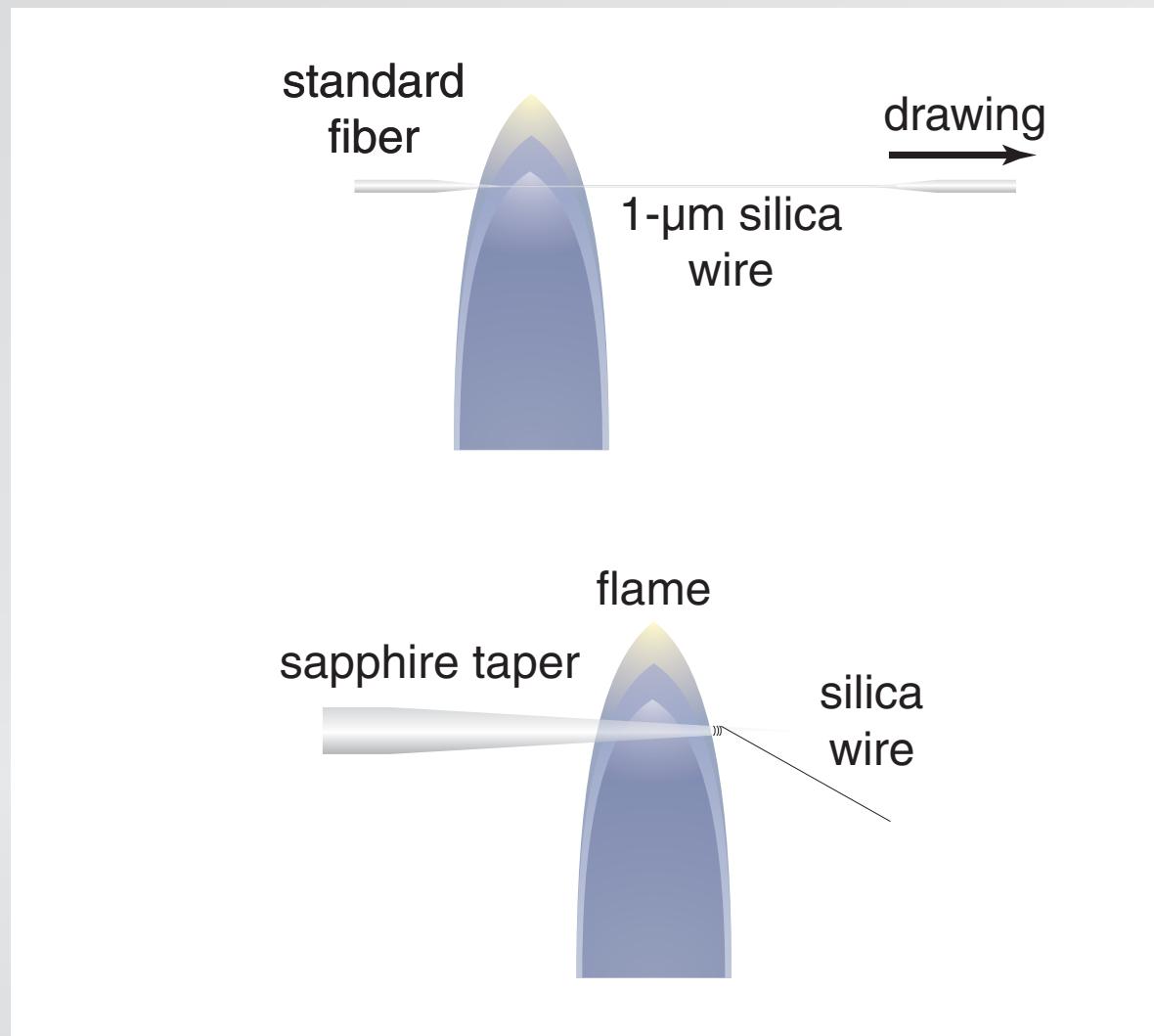
Nanowire fabrication

two-step drawing process



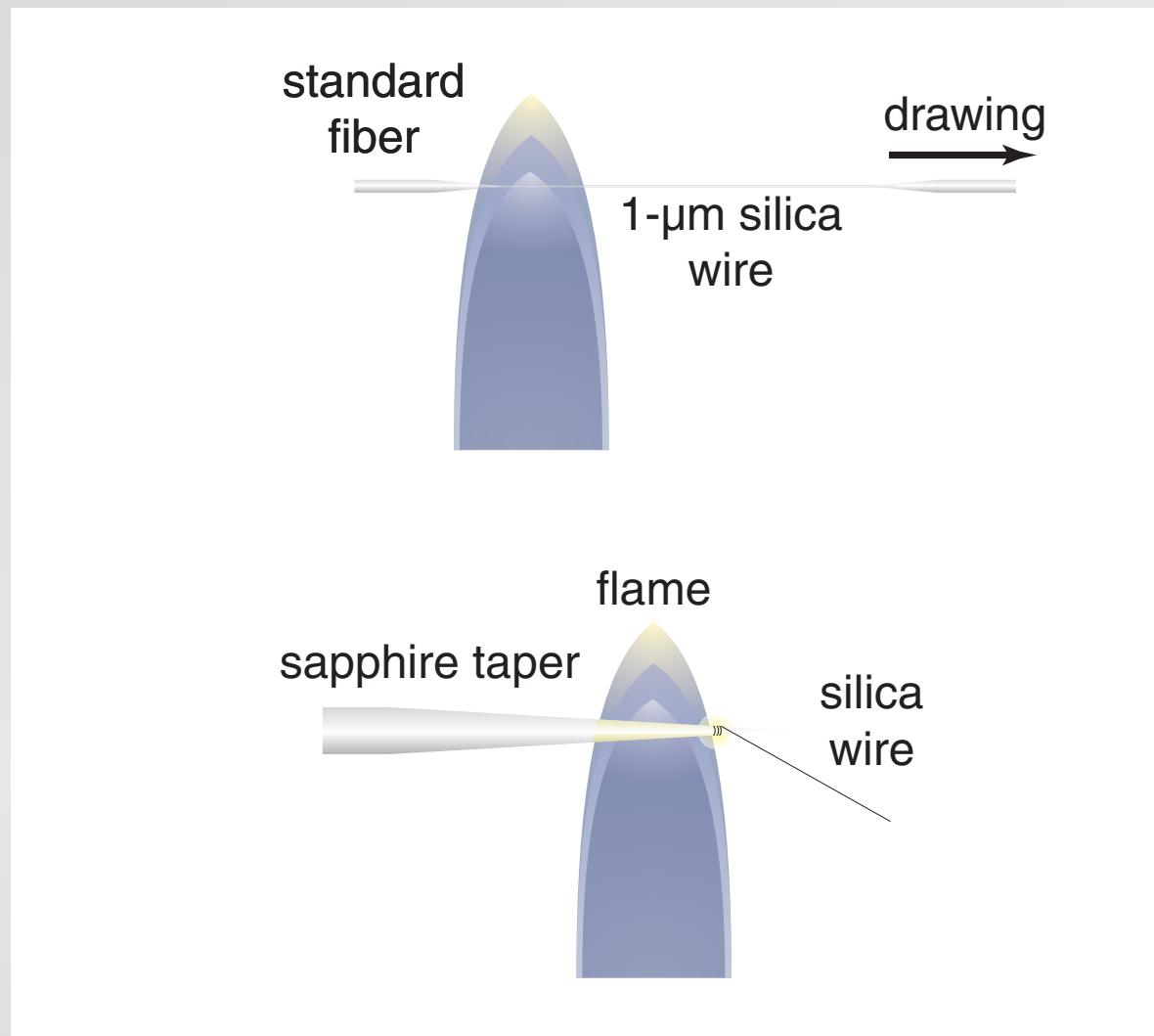
Nanowire fabrication

two-step drawing process



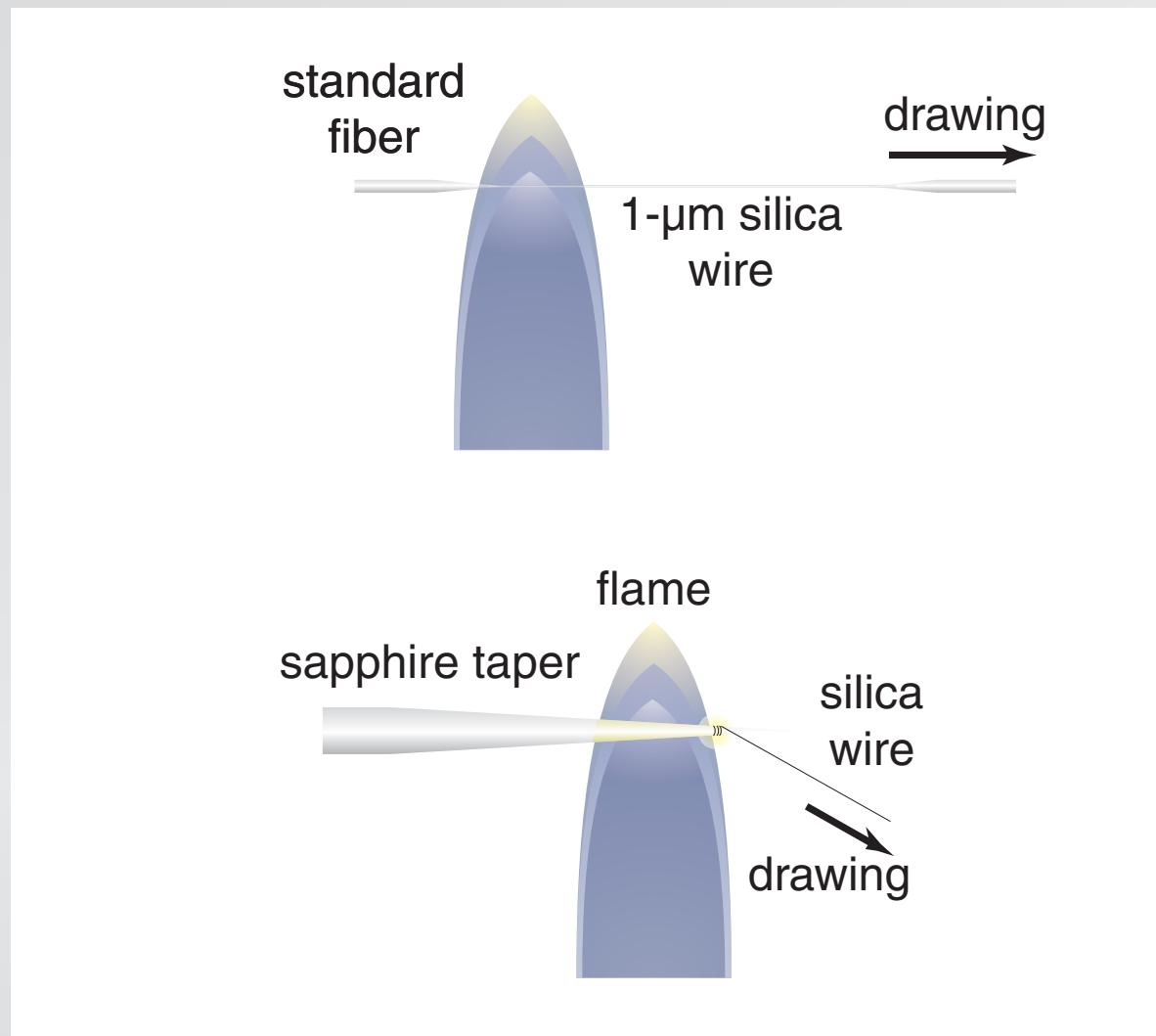
Nanowire fabrication

two-step drawing process

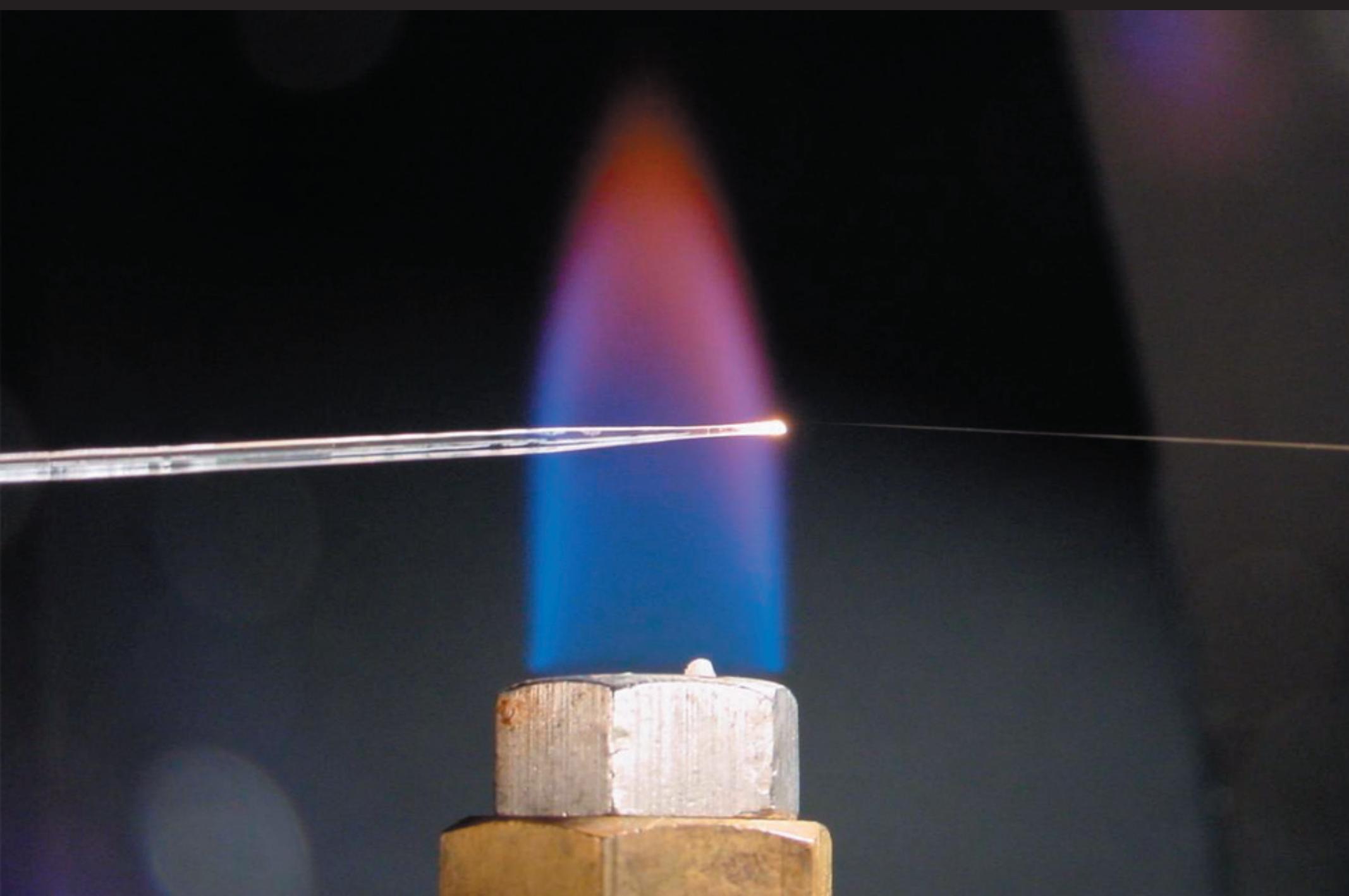


Nanowire fabrication

two-step drawing process



Nanowire fabrication

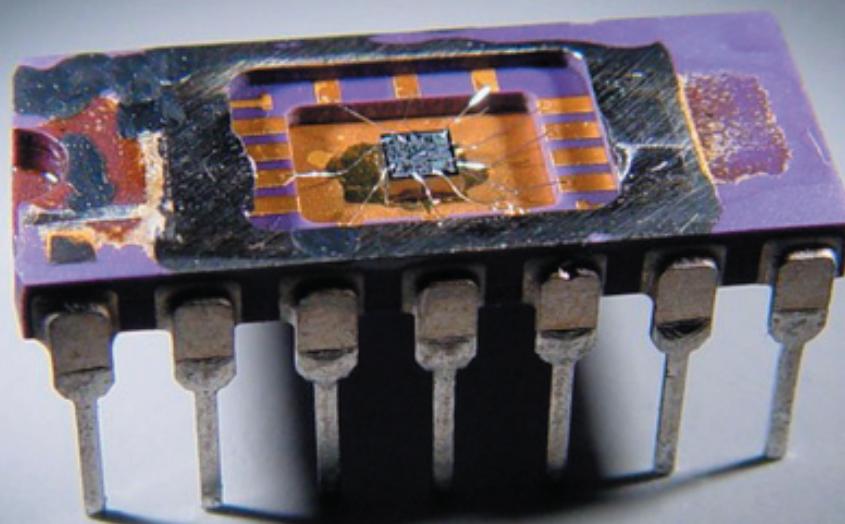


Nanowire fabrication

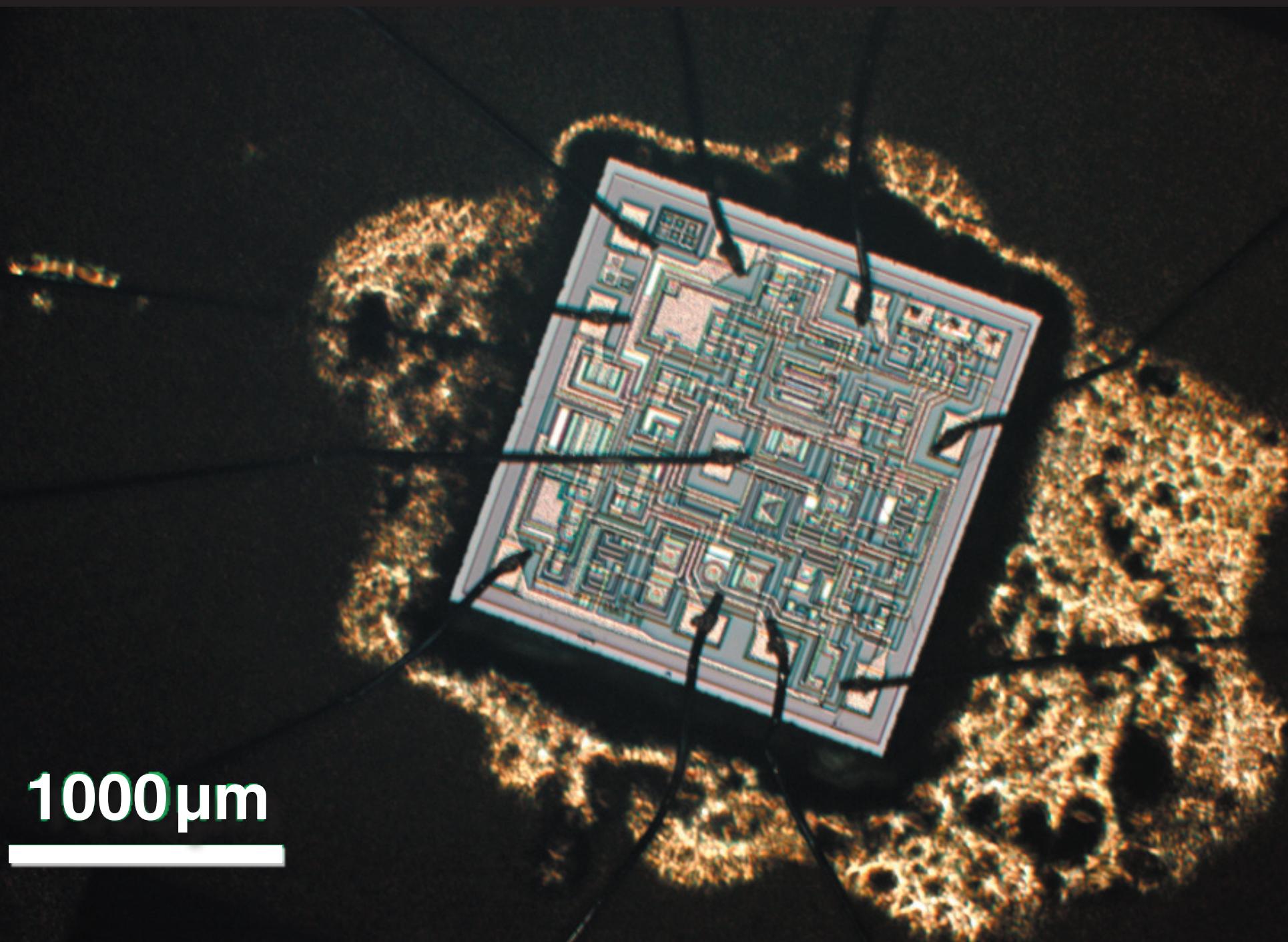
Nature, 426, 816 (2003)

1 μm

Nanowire fabrication



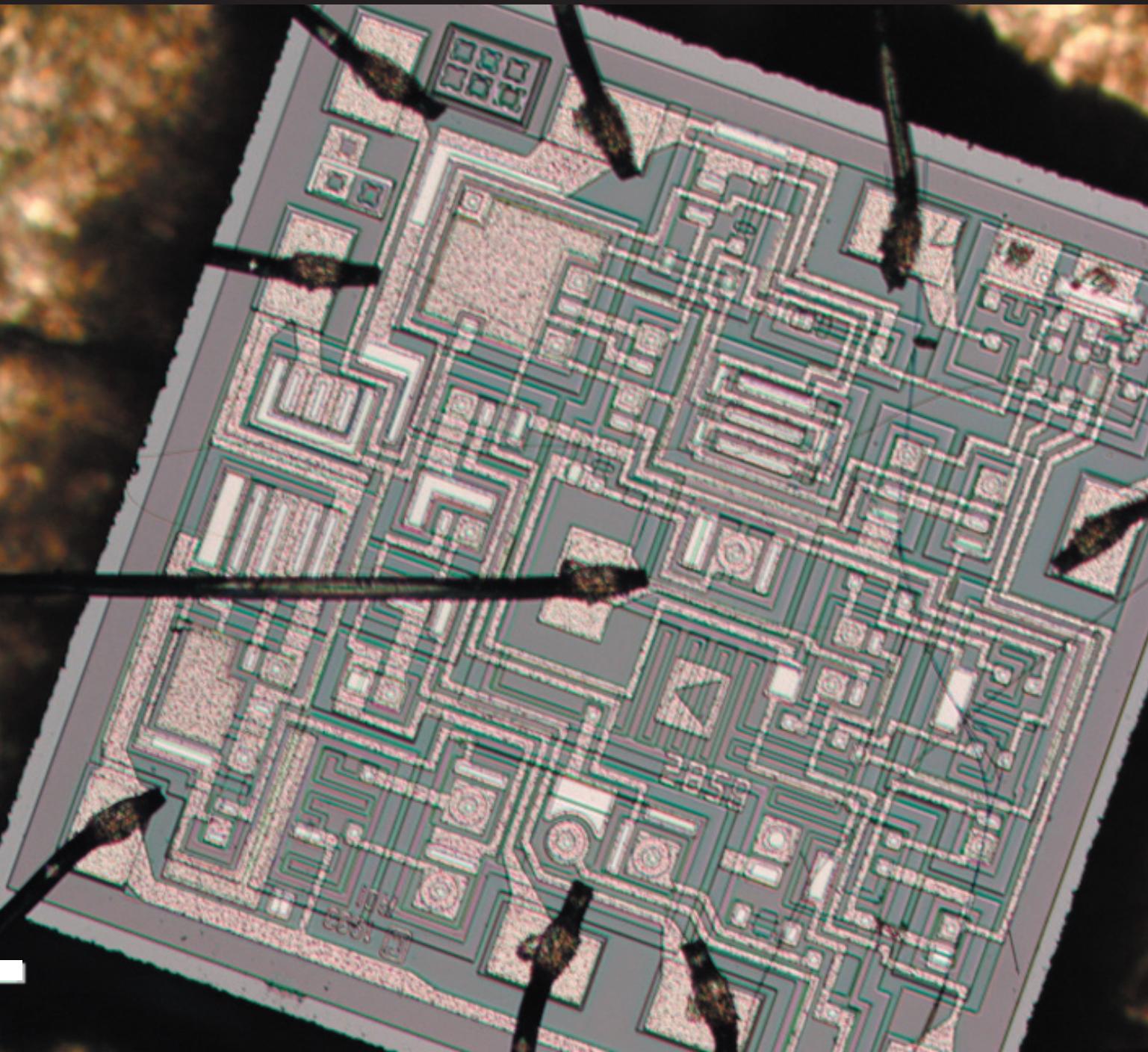
Nanowire fabrication



1000 μm

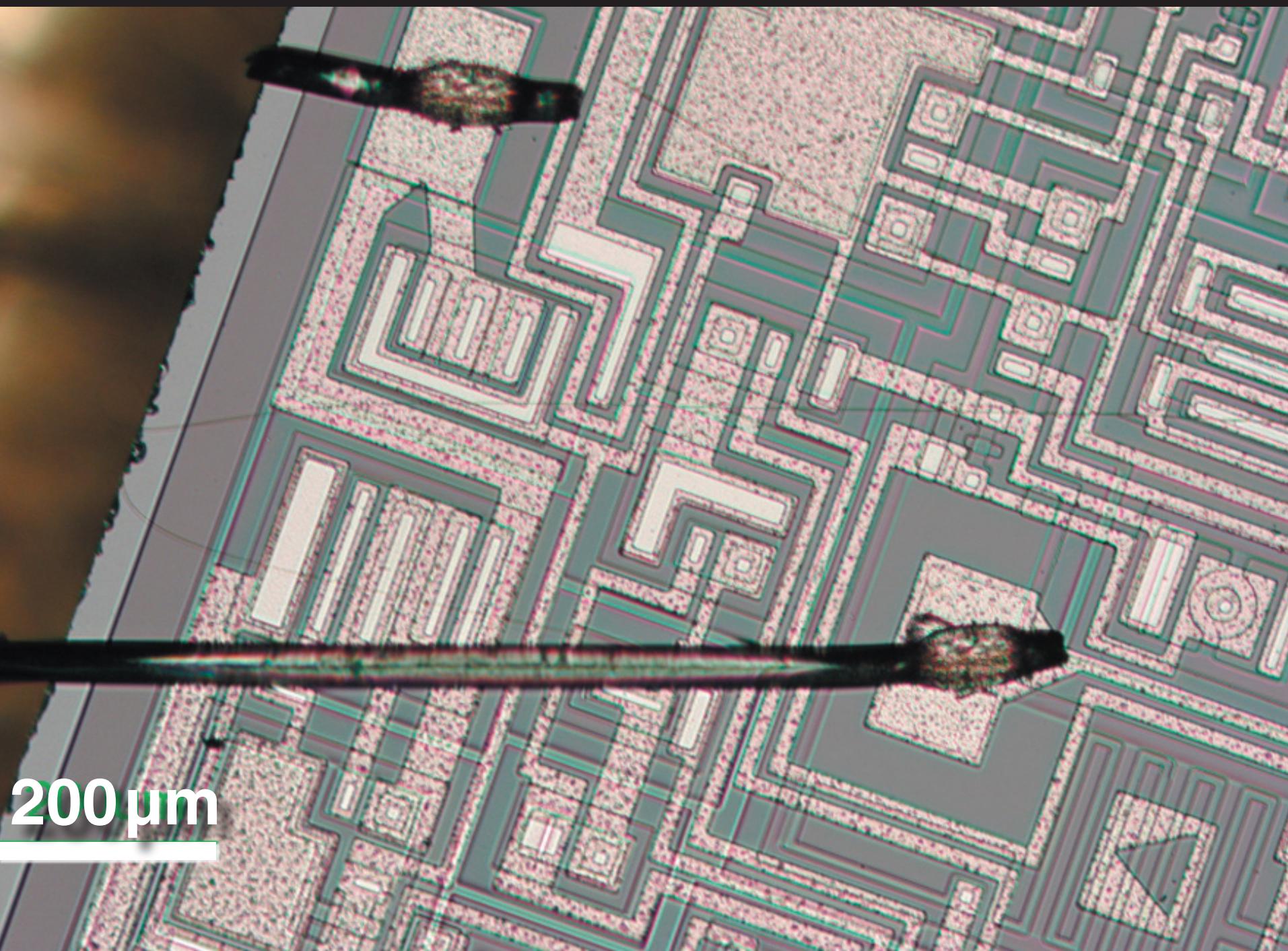
Nanowire fabrication

500 μm

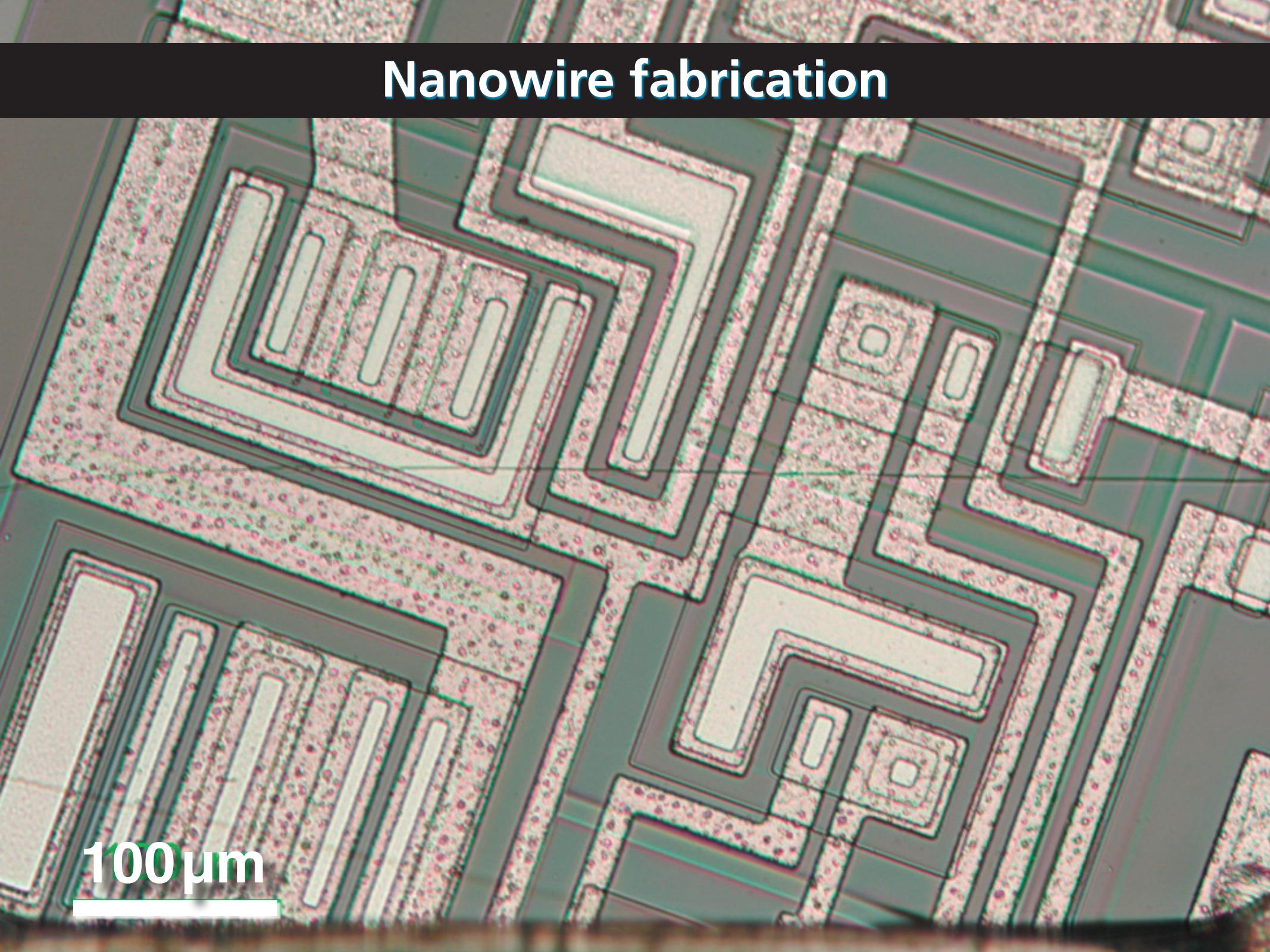


Nanowire fabrication

200 μm

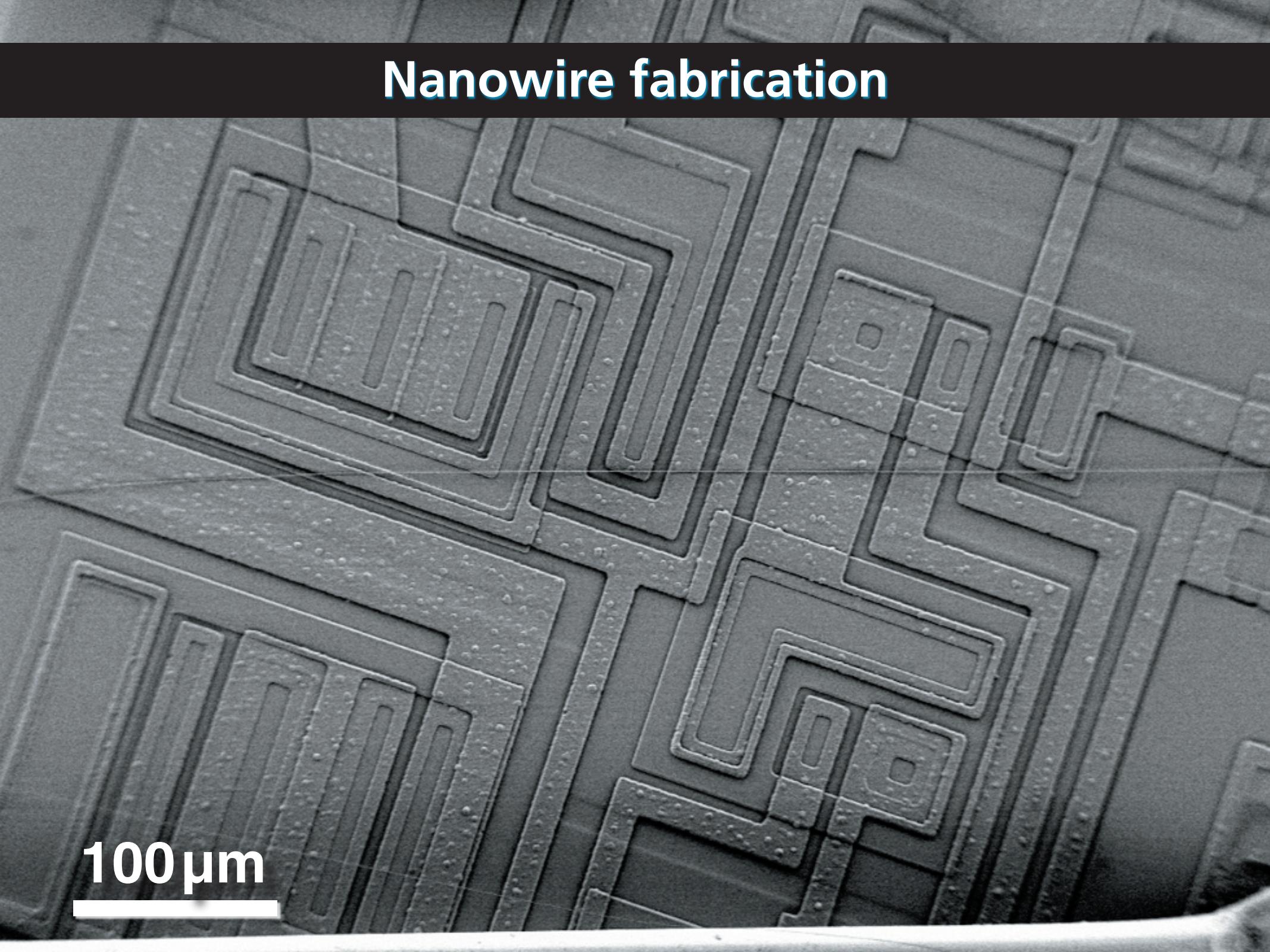


Nanowire fabrication



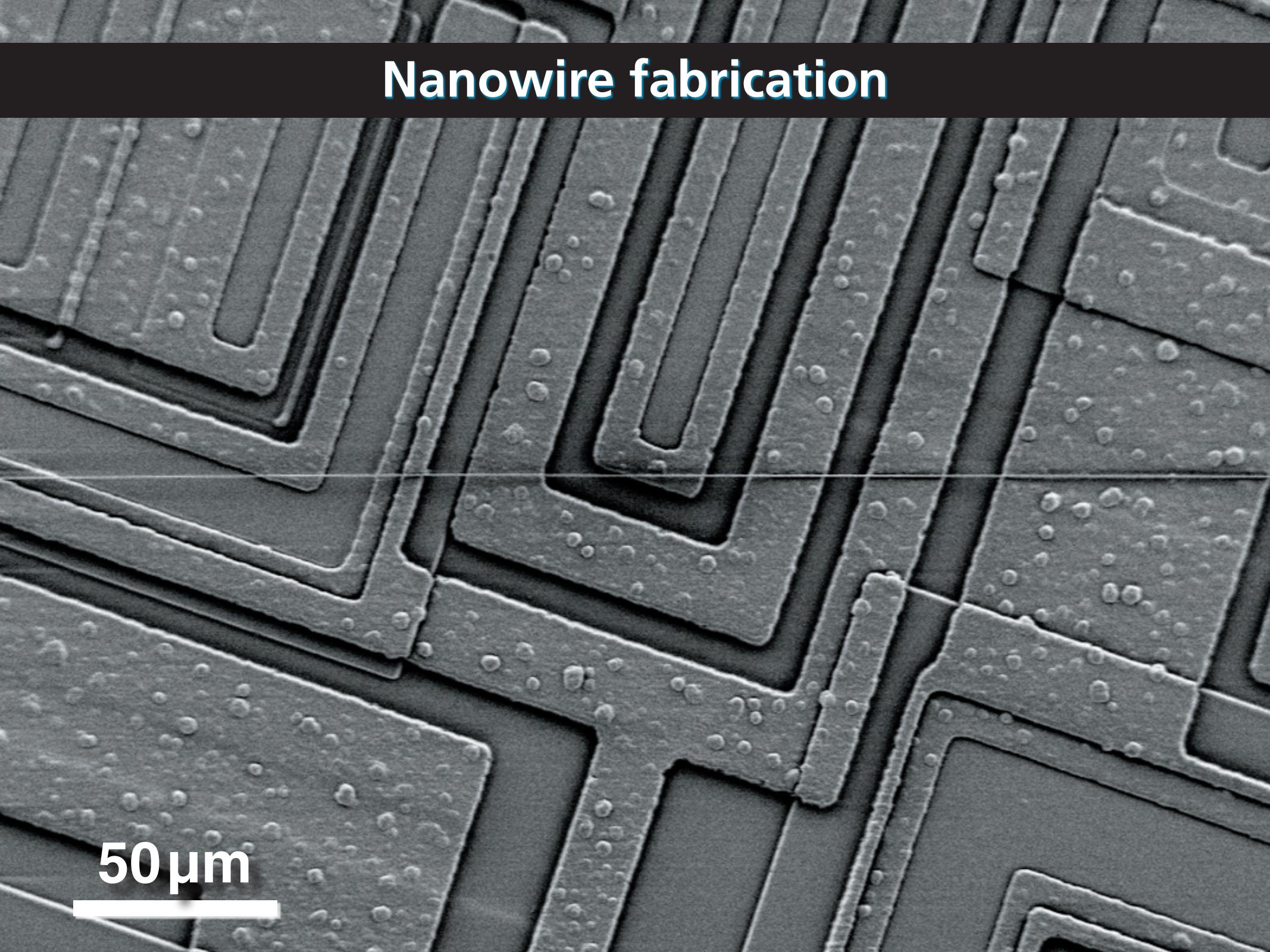
100 μ m

Nanowire fabrication



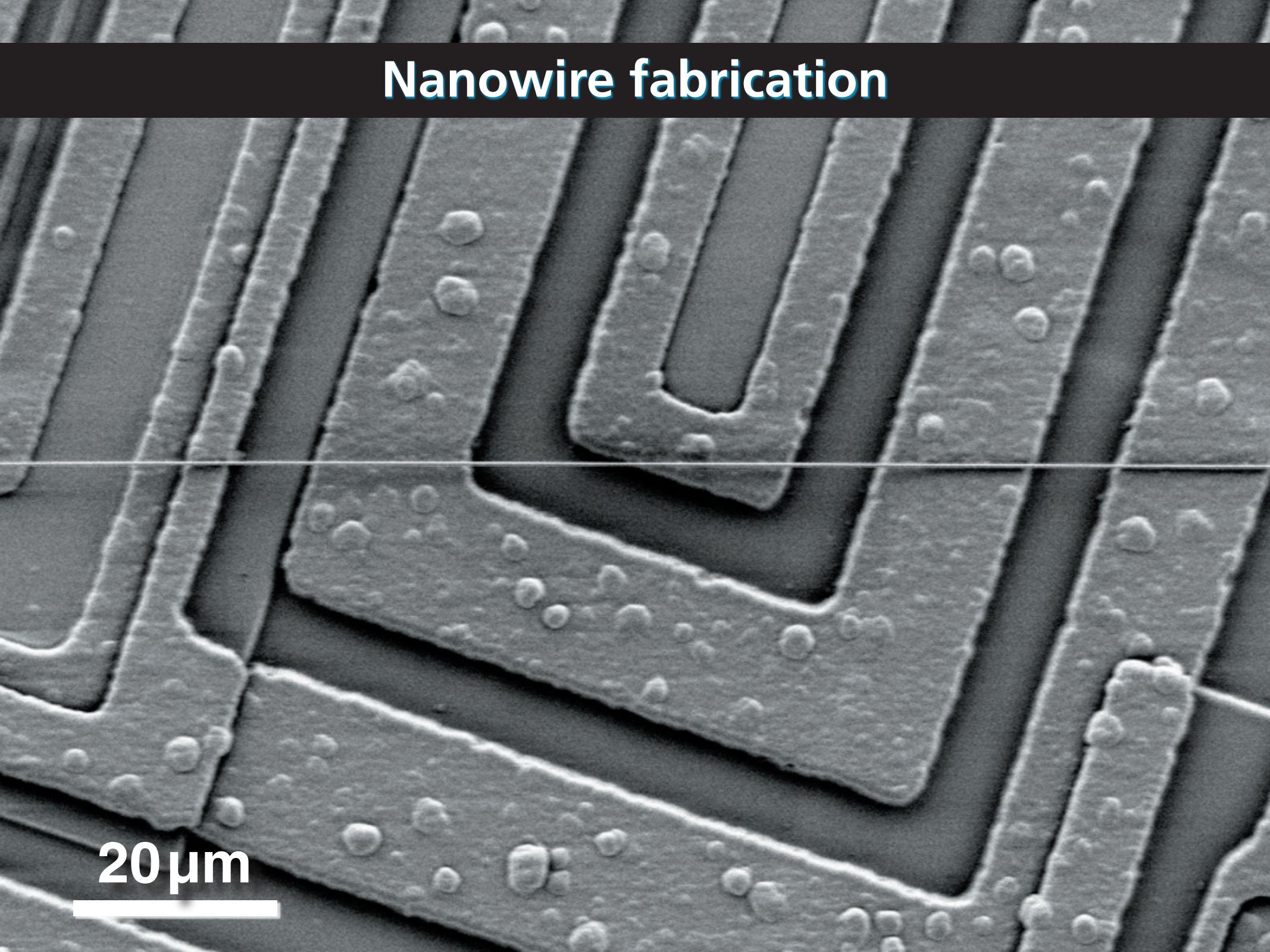
100 μm

Nanowire fabrication



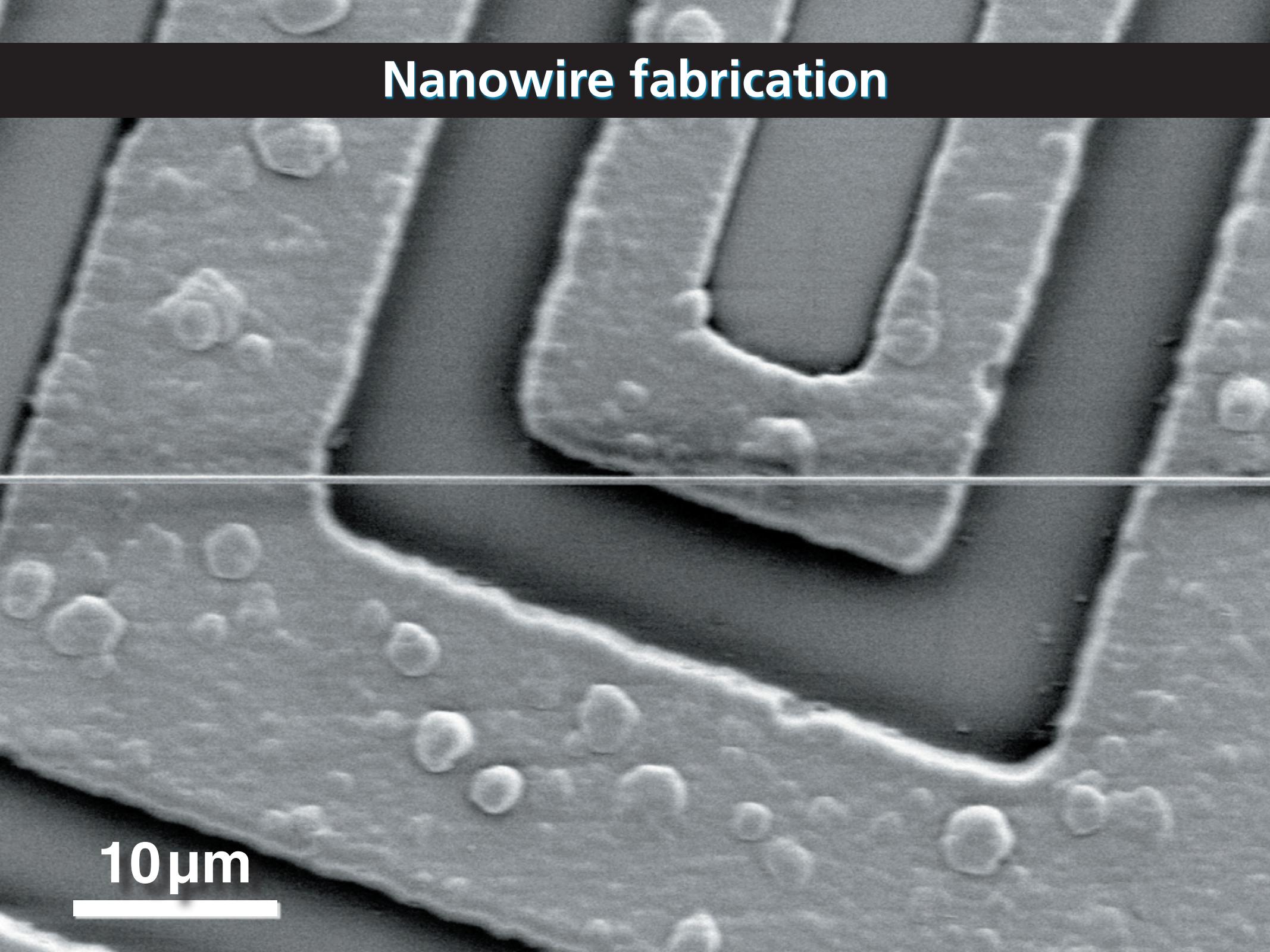
50 μm

Nanowire fabrication



20 μm

Nanowire fabrication



10 μm

Nanowire fabrication

6 μ m

Nanowire fabrication

4 μm

Nanowire fabrication

2 μm

Nanowire fabrication

312 nm



1 μ m



Waveguiding

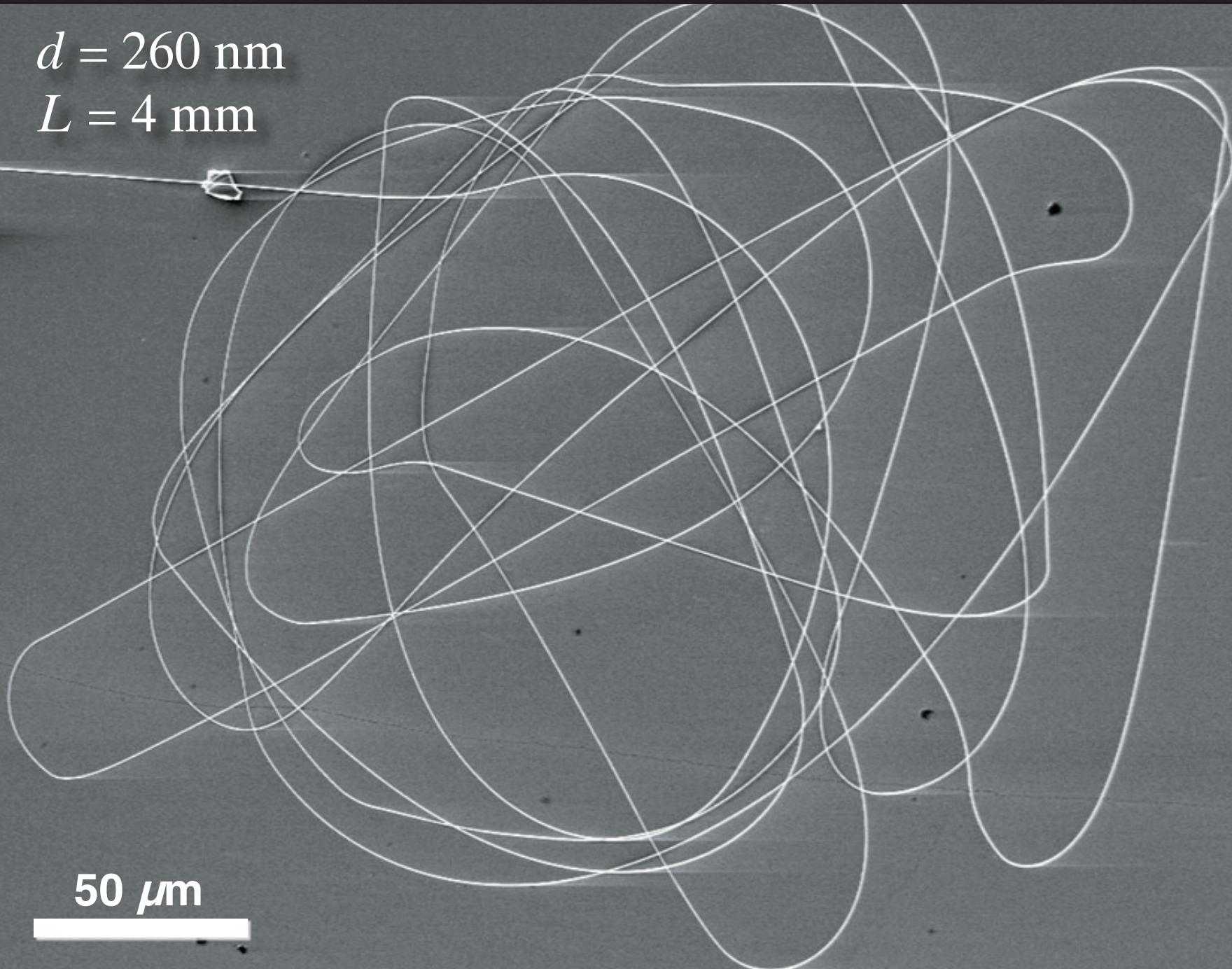
Specifications

diameter D:	down to 50 nm
length L:	up to 40 mm
aspect ratio D/L:	up to 2×10^5
diameter uniformity $\Delta D/L$:	2×10^{-6}

Nanowire fabrication

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



Nanowire fabrication

240-nm wire

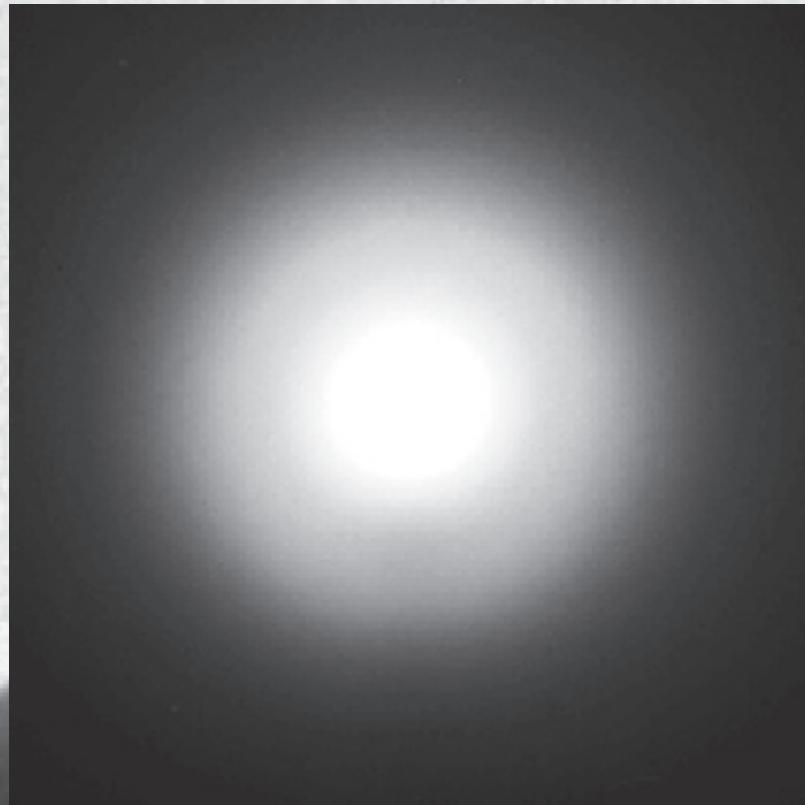
200 nm

Nanowire fabrication

RMS roughness < 0.5 nm

20 nm

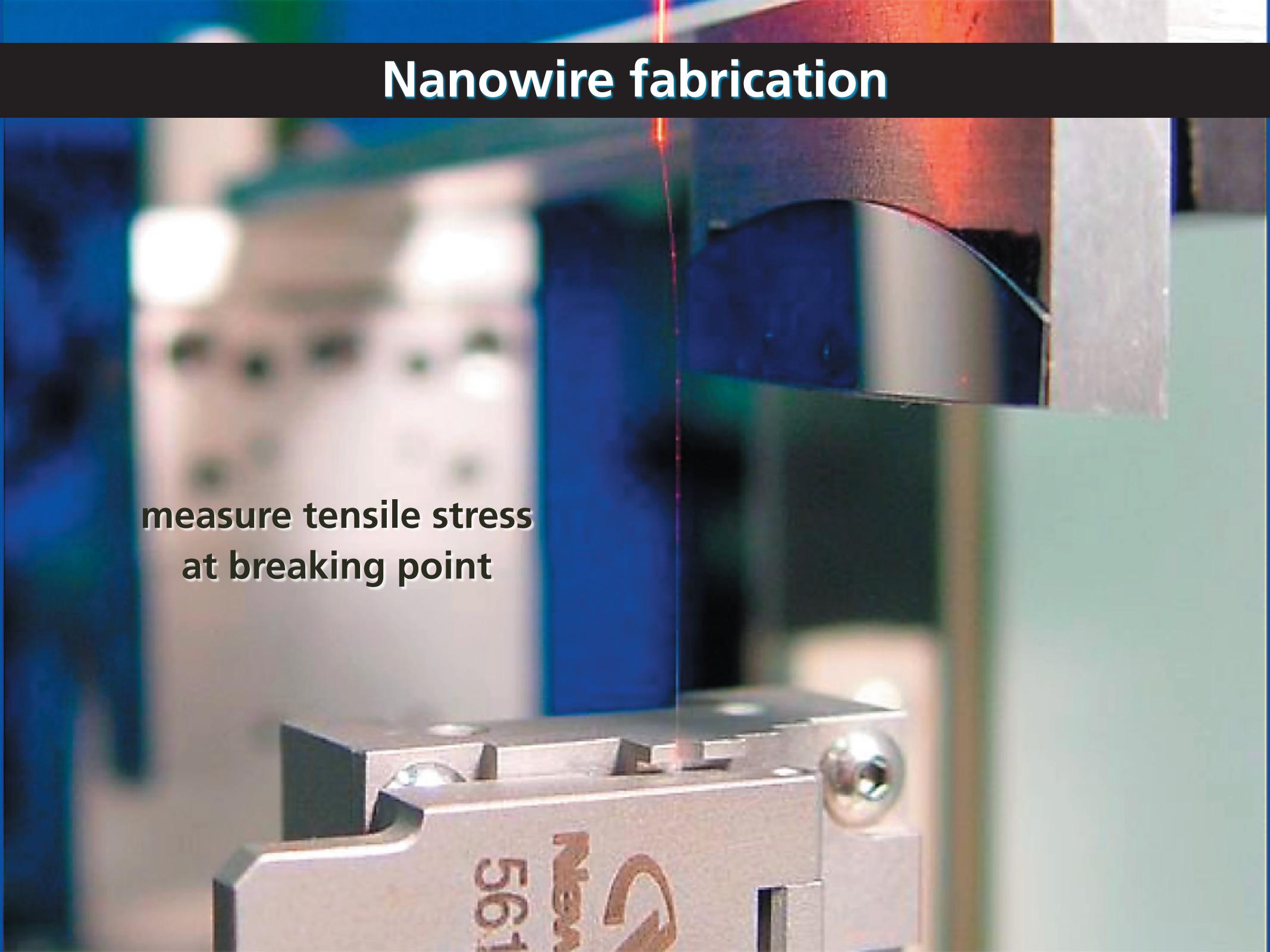
Nanowire fabrication



20 nm

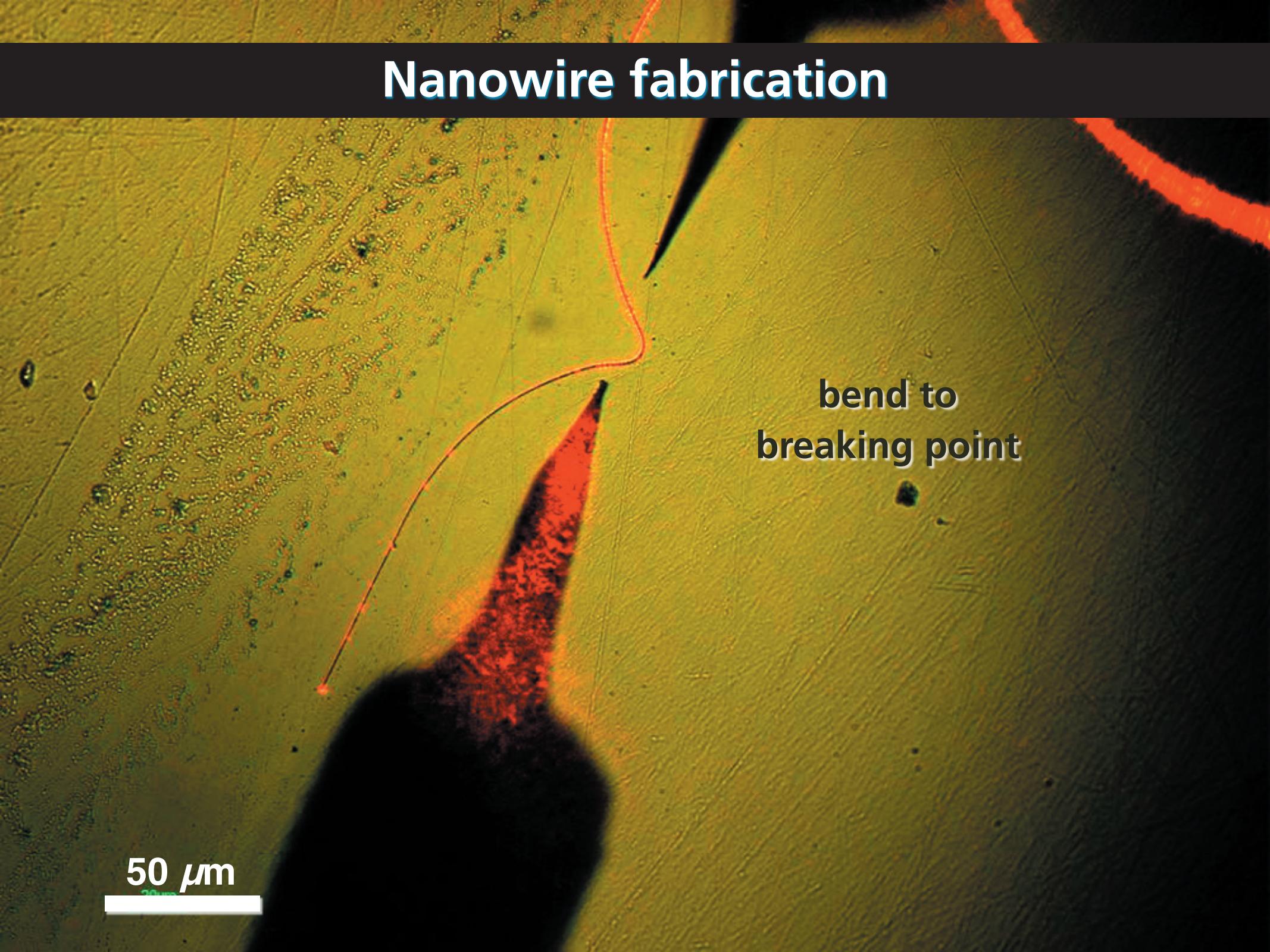


Nanowire fabrication



measure tensile stress
at breaking point

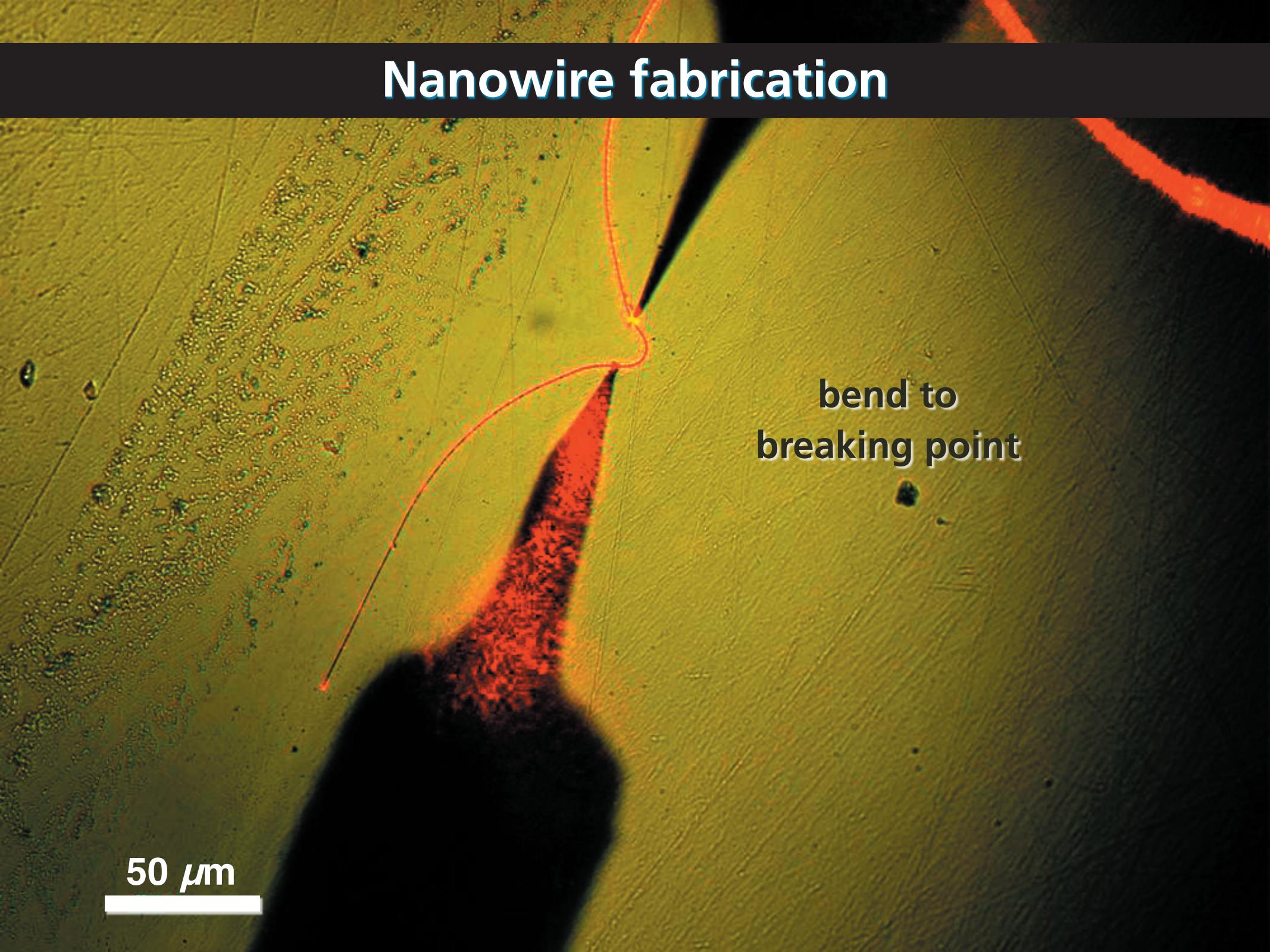
Nanowire fabrication

A scanning electron micrograph showing the fabrication of a nanowire. A red line traces the path of the nanowire as it is being pulled from a source at the bottom left. The nanowire is highly crystalline and exhibits a bright, granular texture. It is being bent sharply to its breaking point, which is indicated by a black arrowhead pointing to a dark, irregularly shaped area where the wire has snapped. The background shows a textured surface with some small, dark, isolated spots.

bend to
breaking point

50 μm

Nanowire fabrication

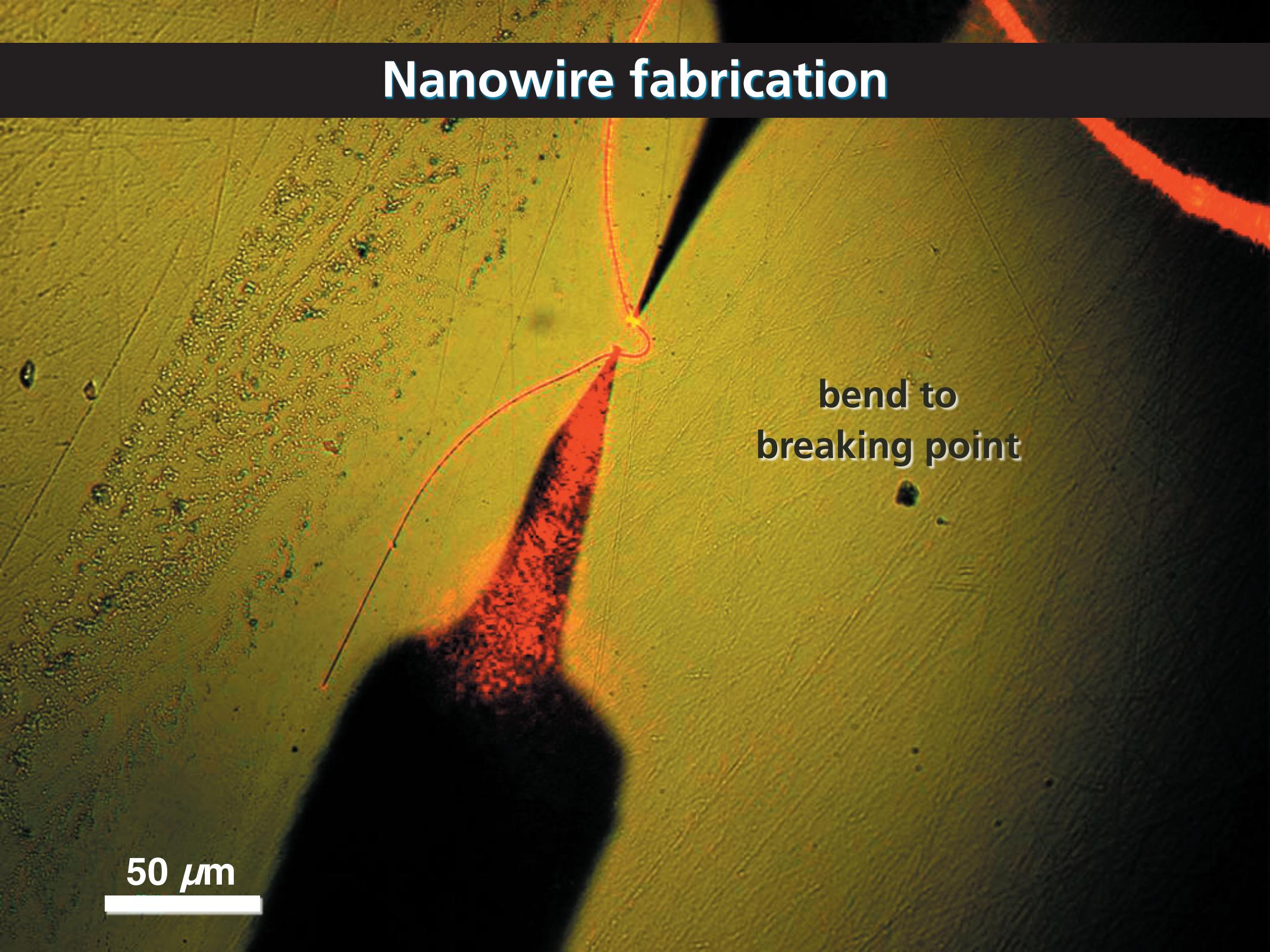


A fluorescence micrograph showing the fabrication of a nanowire. A red laser beam traces a curved path across a greenish-yellow substrate. A bright yellow spot marks the point where the nanowire bends to its breaking point. The background shows some small, scattered fluorescent spots. A large black shadow of the experimental setup is visible at the bottom left.

bend to
breaking point

50 μm

Nanowire fabrication

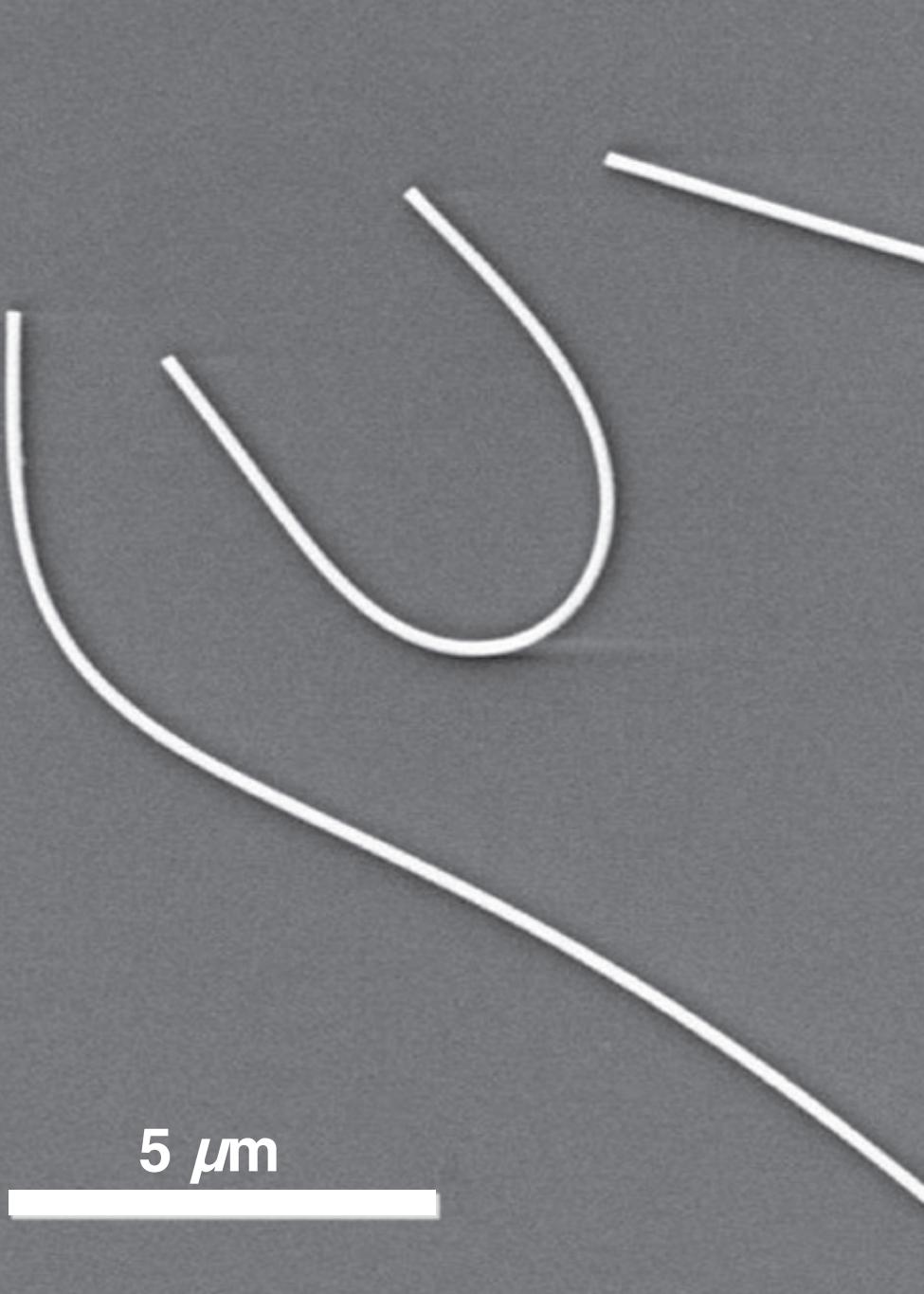


A scanning electron micrograph showing the fabrication of a nanowire. A red line traces the path of the nanowire as it is being pulled from a source area on the left. The nanowire is highly elongated and tapers to a point. A black arrow points to the breaking point of the nanowire. The background shows a textured surface with some greenish-yellow staining. A scale bar in the bottom left corner indicates 50 μm.

bend to
breaking point

50 μm

Nanowire fabrication



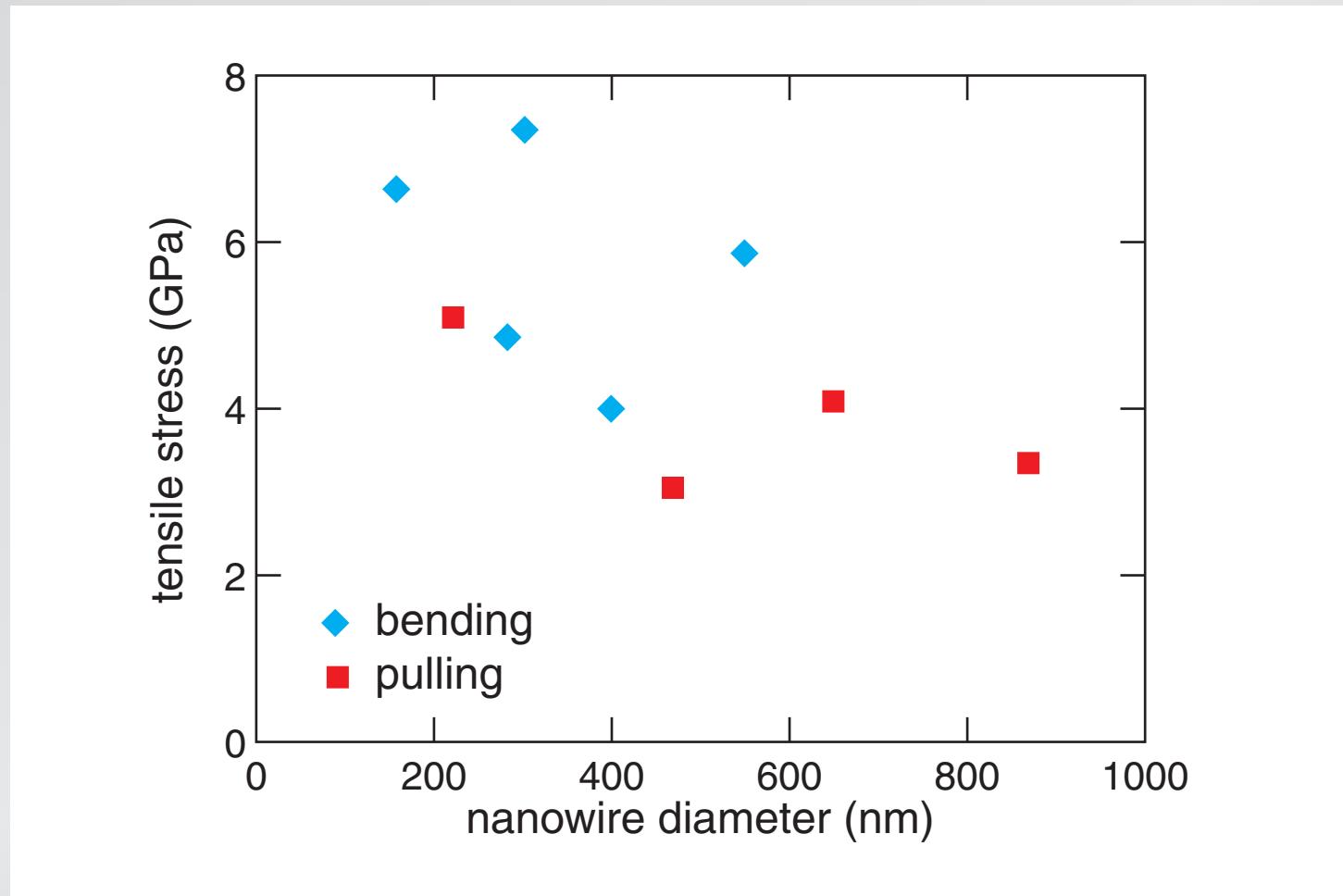
minimum bending radius R_{EB}
gives tensile stress:

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

E = Young's modulus
 D = wire diameter

Waveguiding

tensile strength



Nanowire fabrication

2 μm

Nanowire fabrication

20 μm

Nanowire fabrication



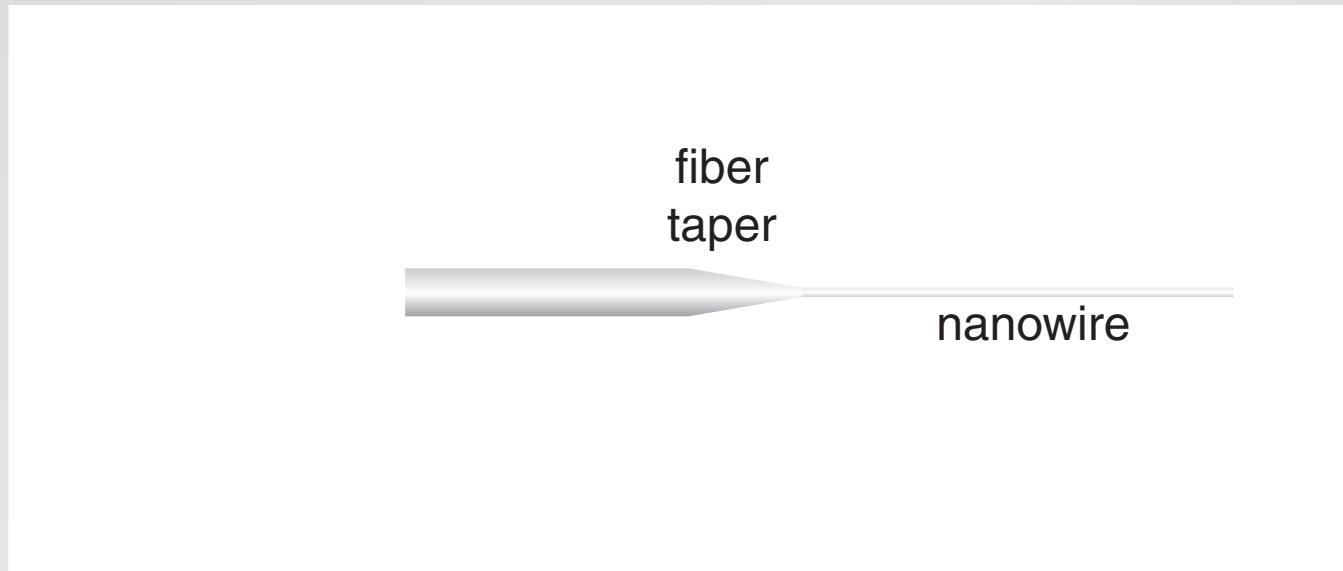
20 μm

Outline

- waveguiding
- nanowire fabrication
- optical properties

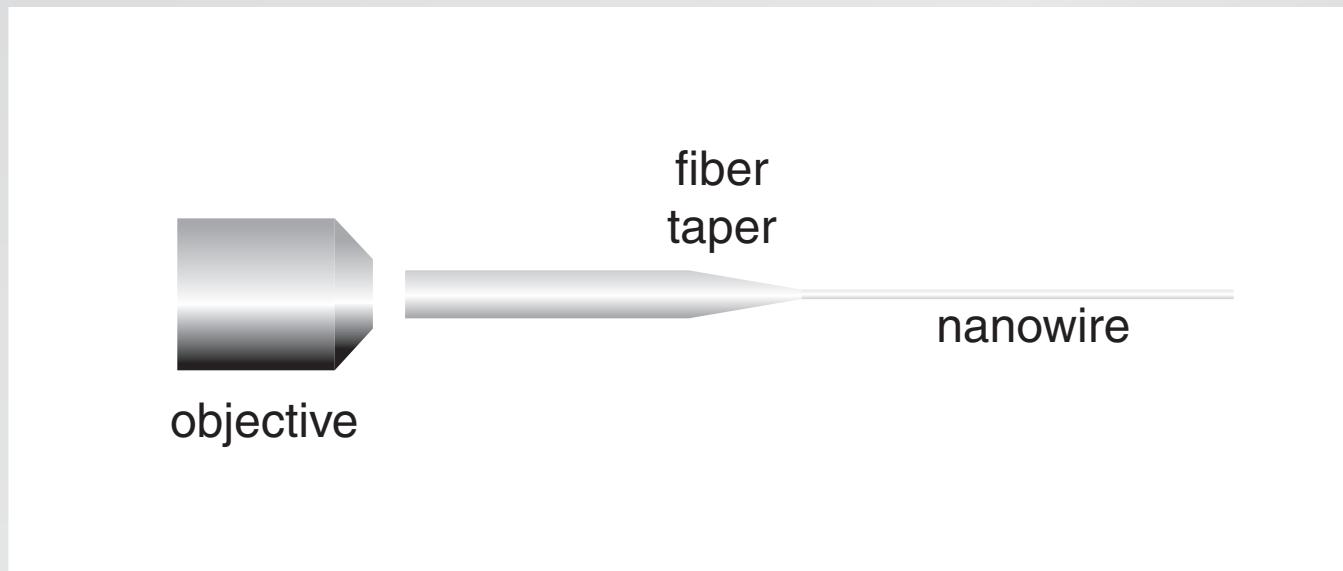
Optical properties

coupling light into nanowires



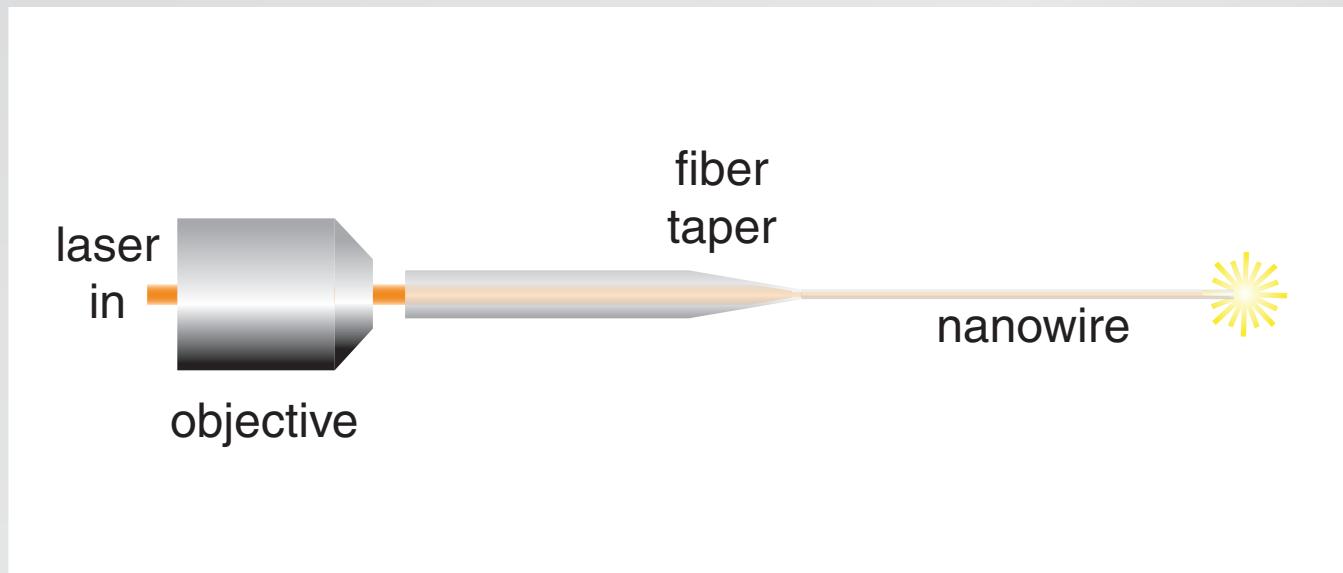
Optical properties

coupling light into nanowires



Optical properties

coupling light into nanowires



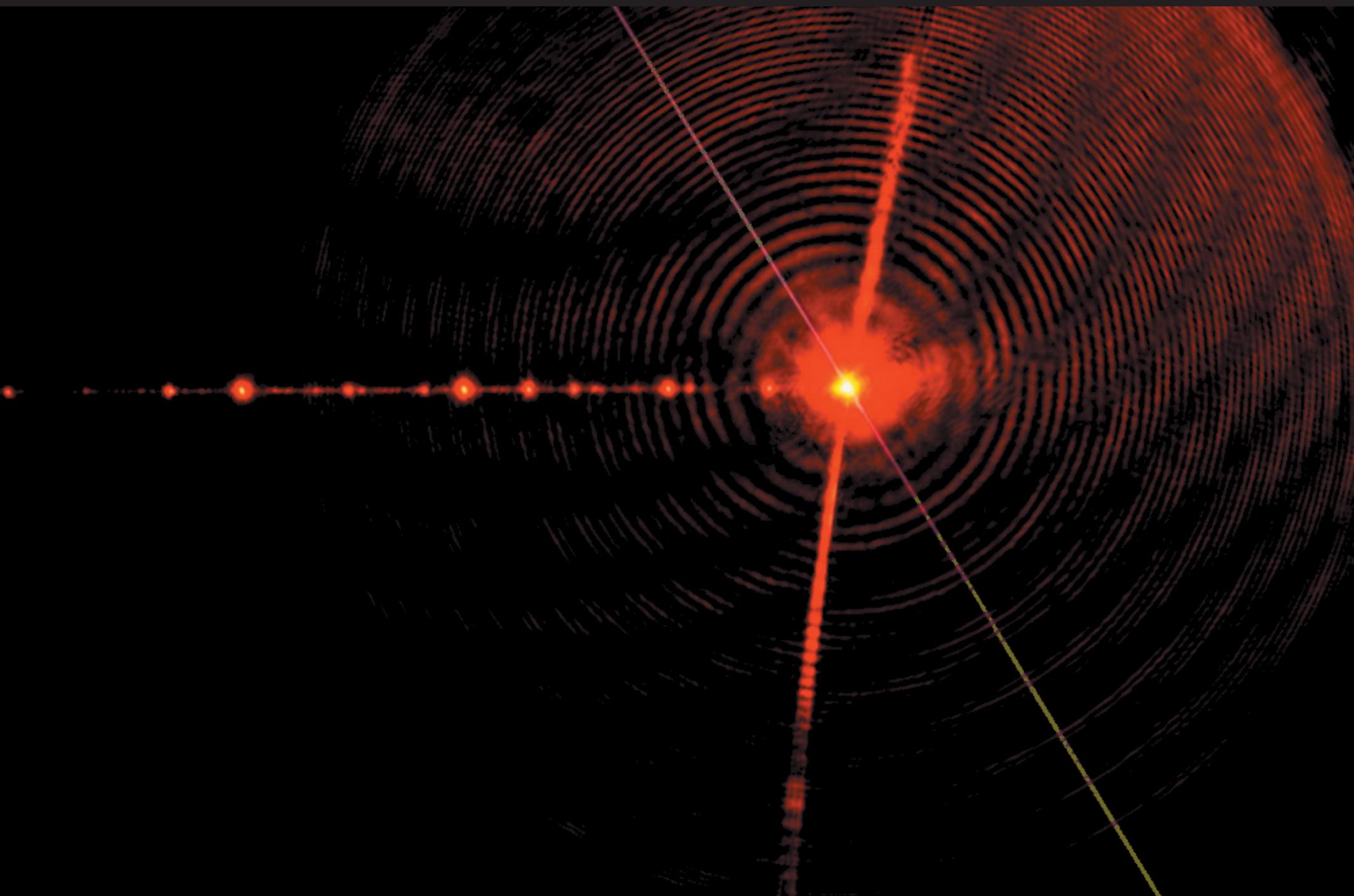
Optical properties

280-nm nanowire

360 nm

450 nm

Optical properties

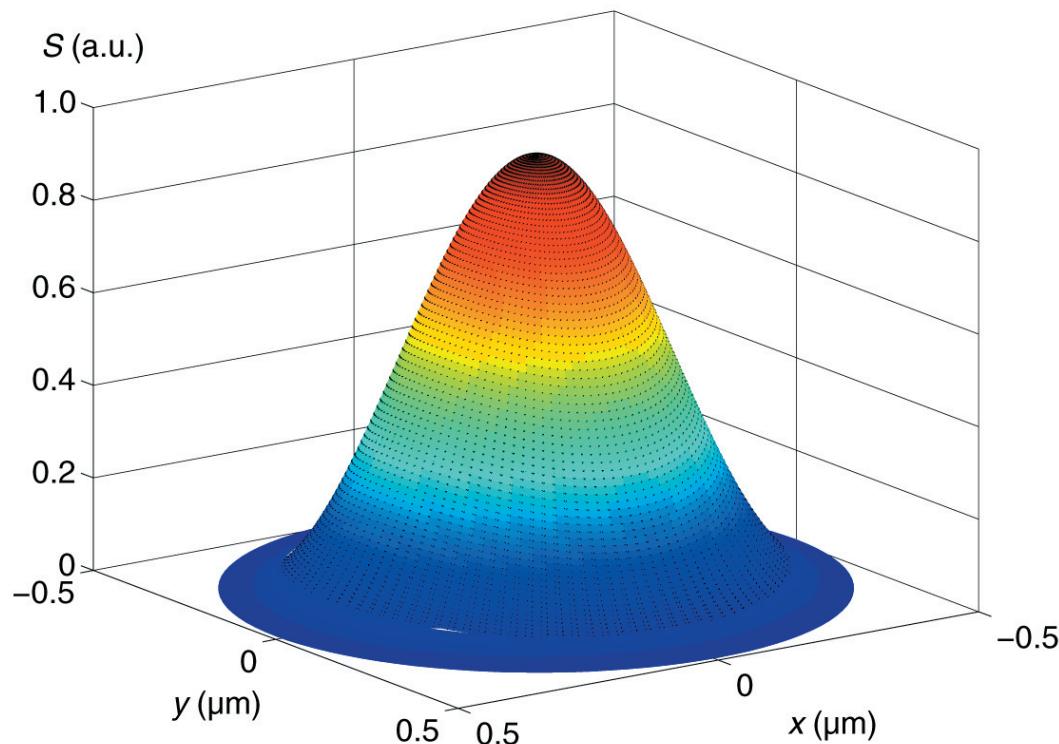


Optical properties



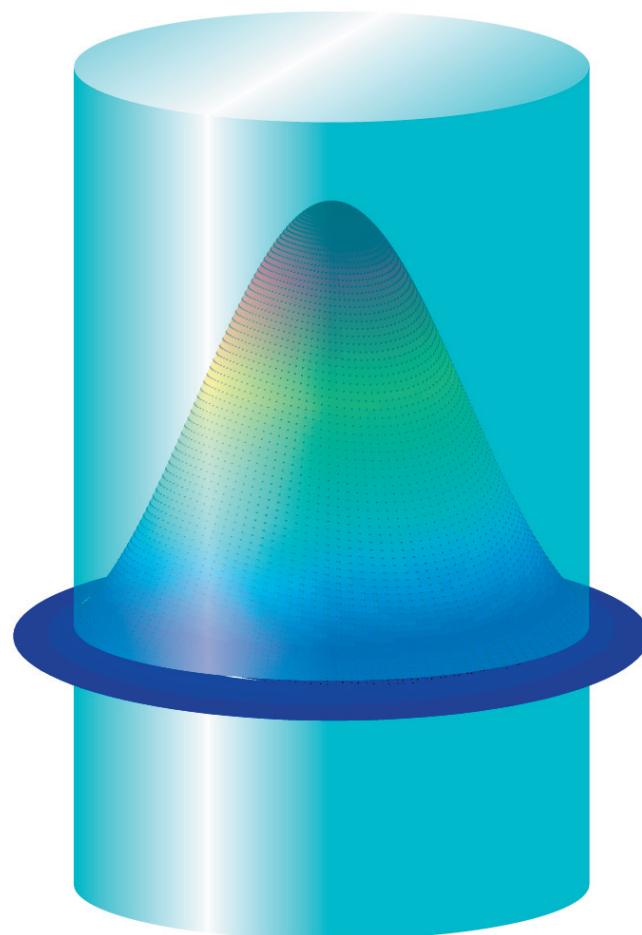
Optical properties

Poynting vector profile for 800-nm nanowire



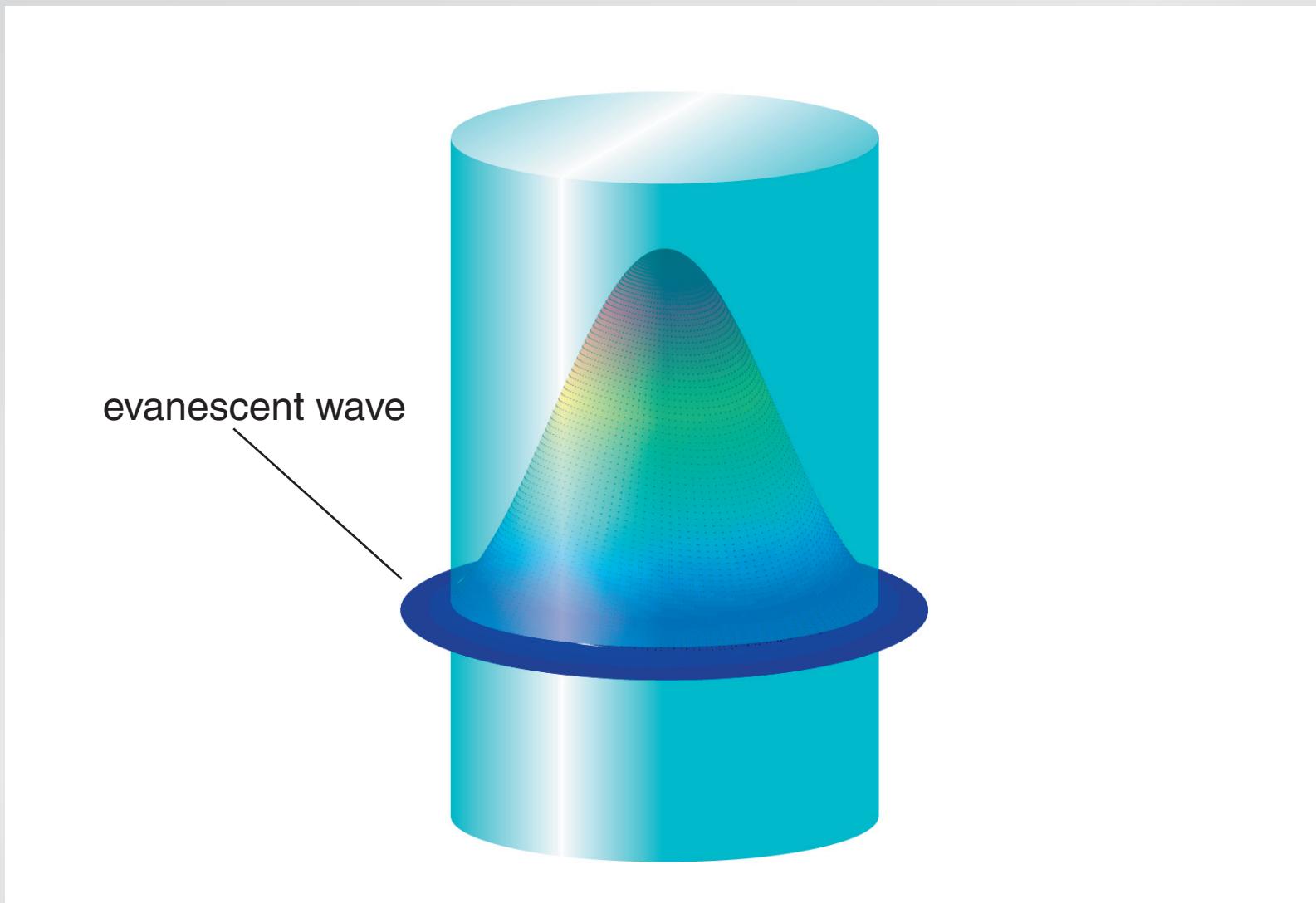
Optical properties

Poynting vector profile for 800-nm nanowire



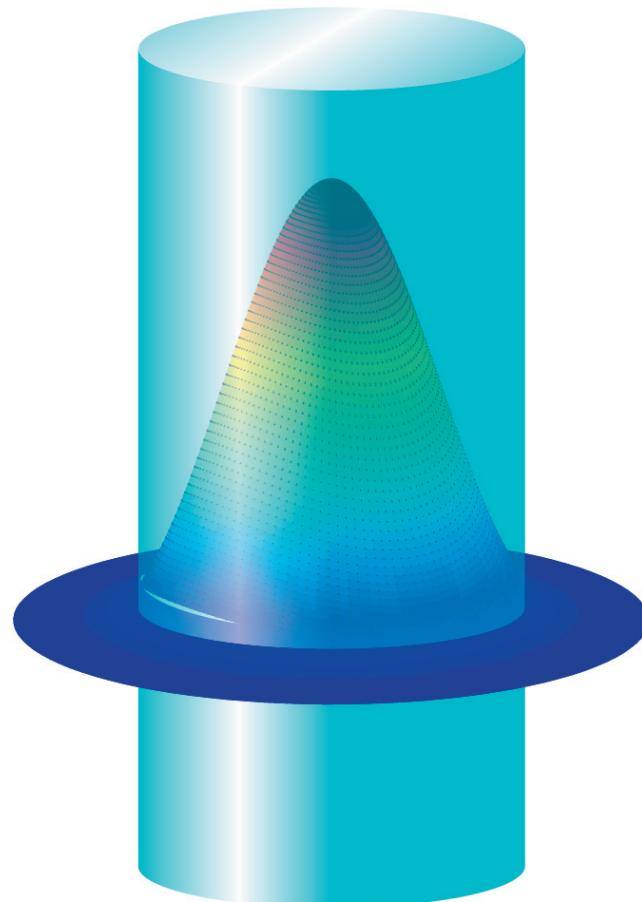
Optical properties

Poynting vector profile for 800-nm nanowire



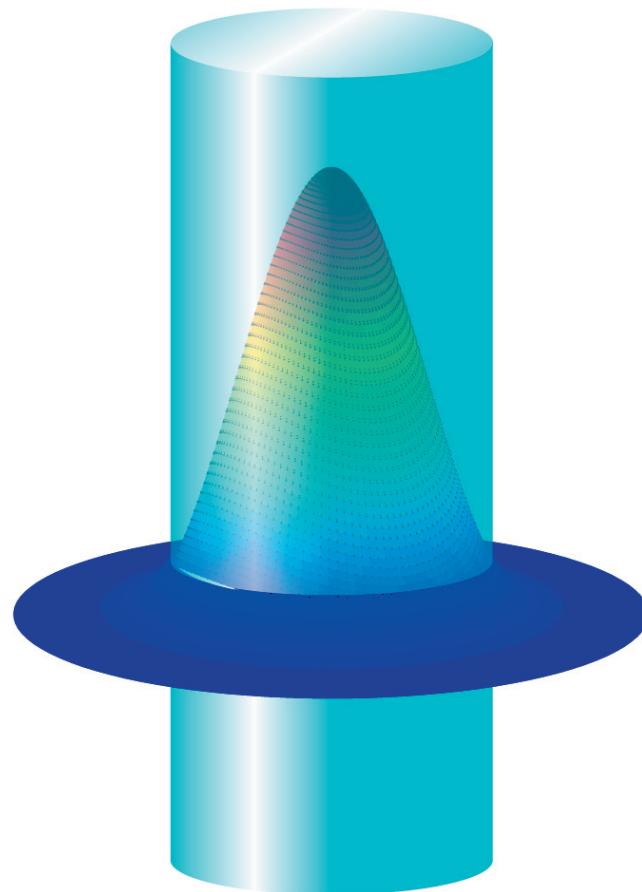
Optical properties

Poynting vector profile for 600-nm nanowire



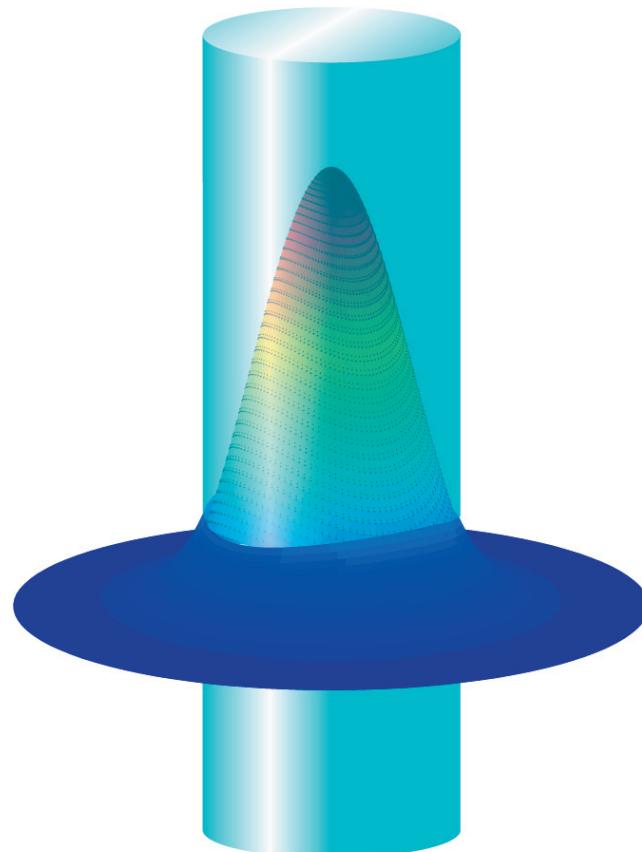
Optical properties

Poynting vector profile for 500-nm nanowire



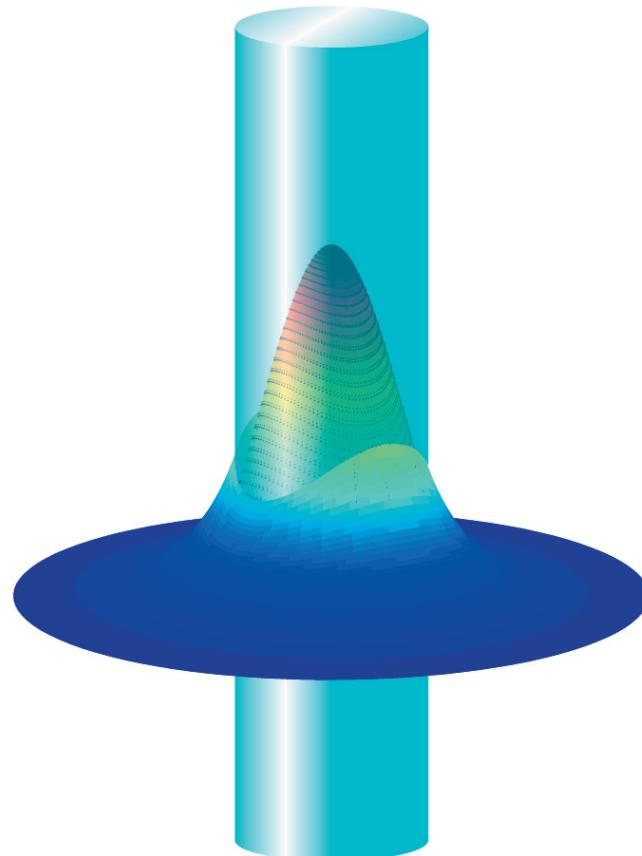
Optical properties

Poynting vector profile for 400-nm nanowire



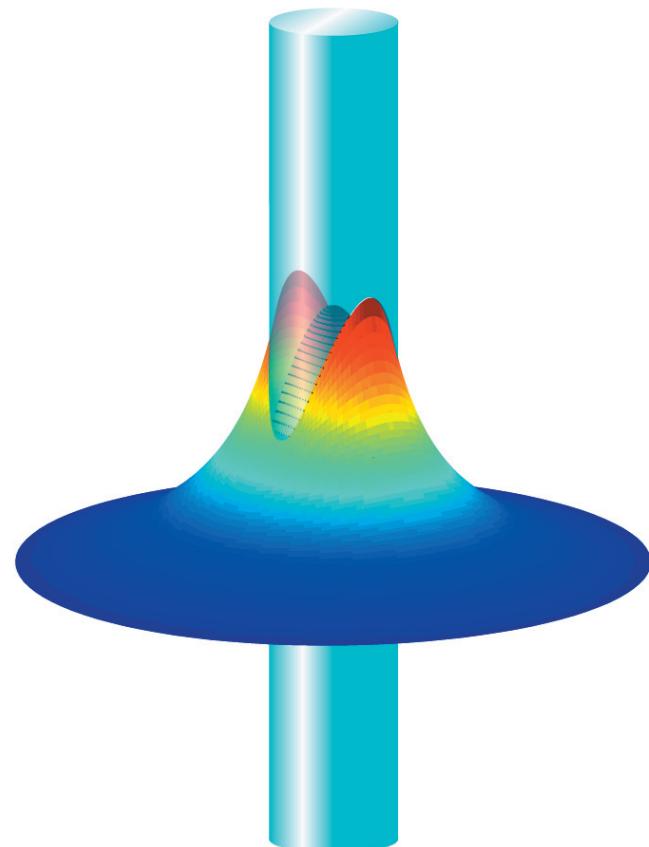
Optical properties

Poynting vector profile for 300-nm nanowire



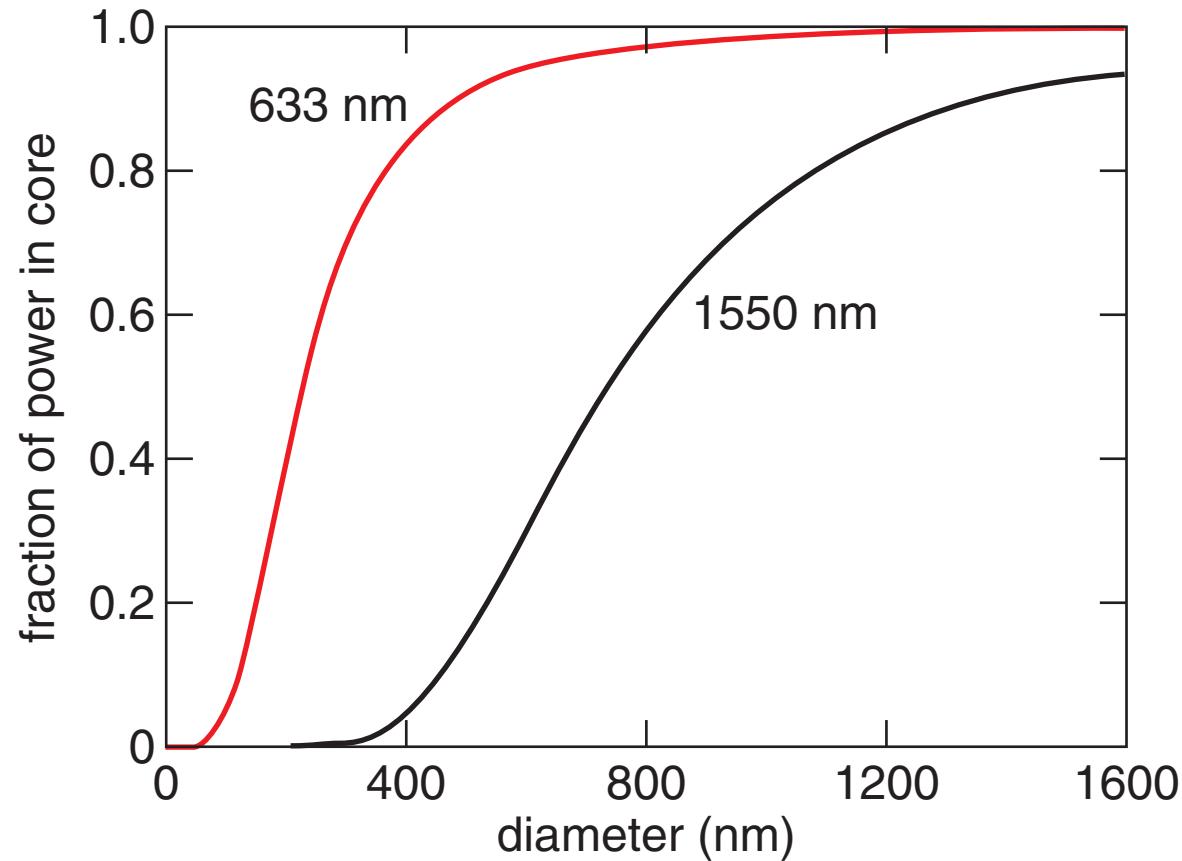
Optical properties

Poynting vector profile for 200-nm nanowire

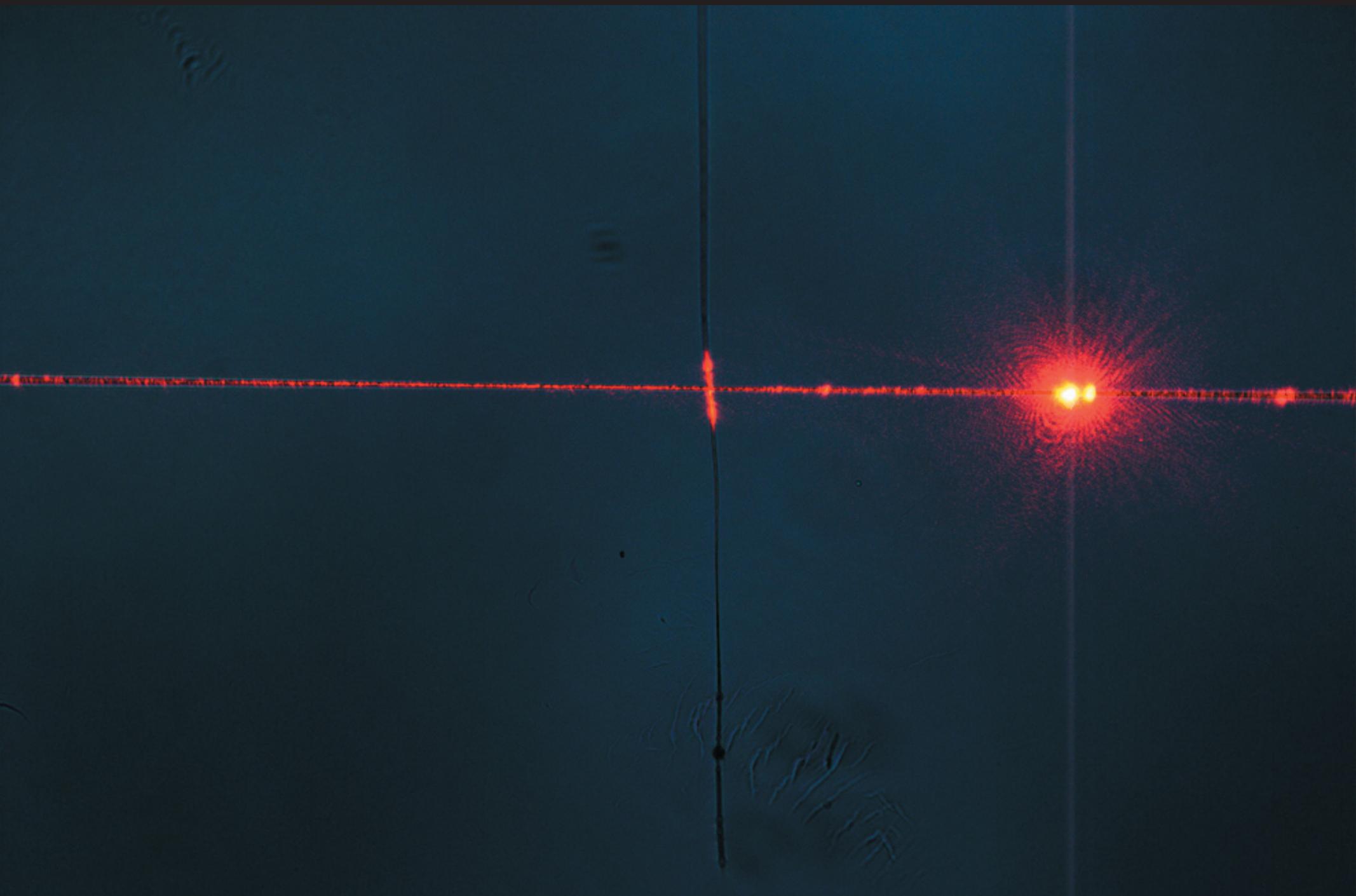


Waveguiding

fraction of power carried in core

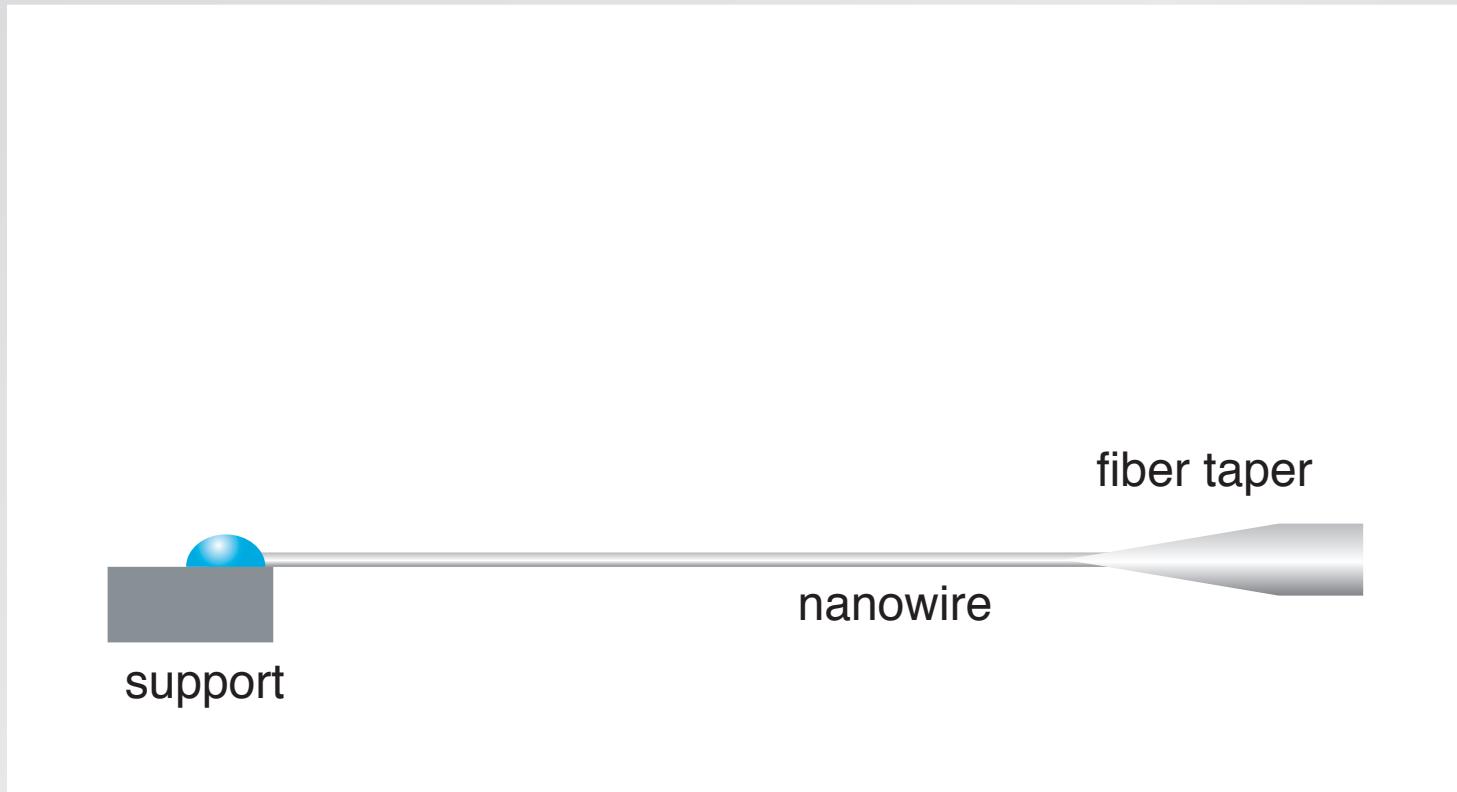


Optical properties



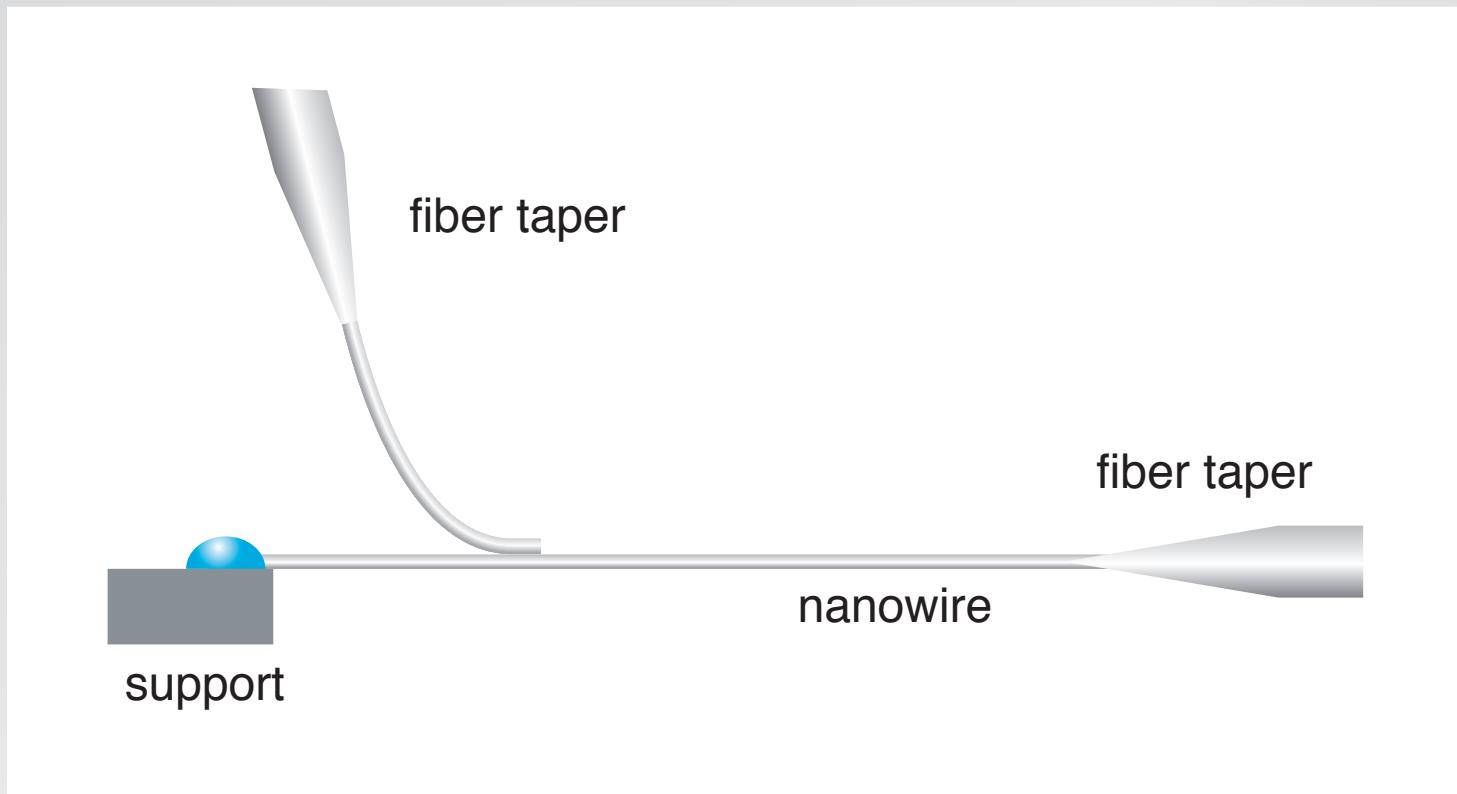
Optical properties

coupling light between nanowires



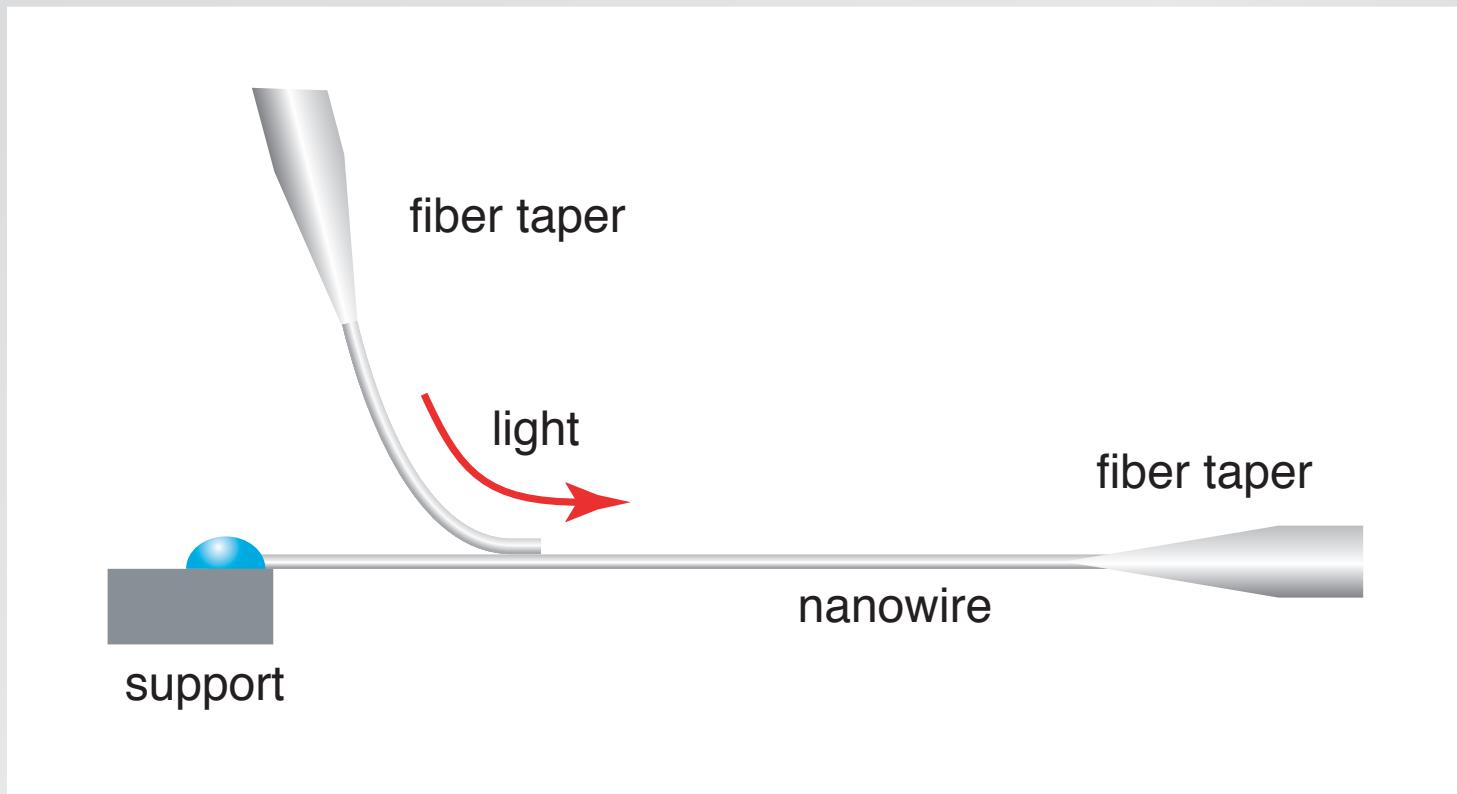
Optical properties

coupling light between nanowires



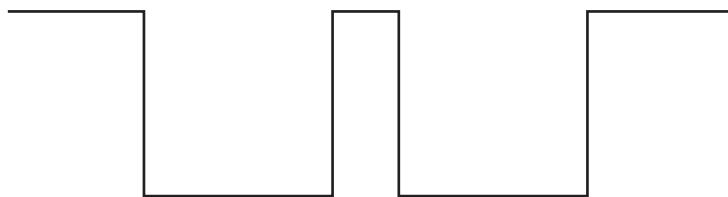
Optical properties

coupling light between nanowires



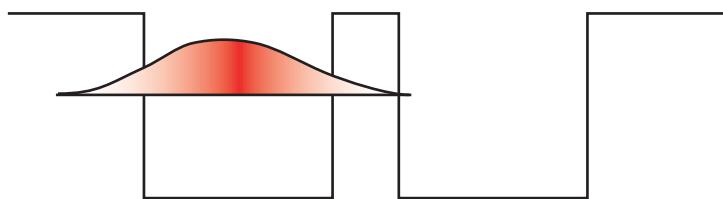
Optical properties

coupling light between nanowires



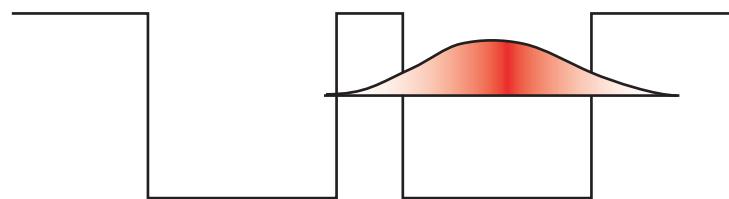
Optical properties

coupling light between nanowires



Optical properties

“tunneling” of light



Optical properties

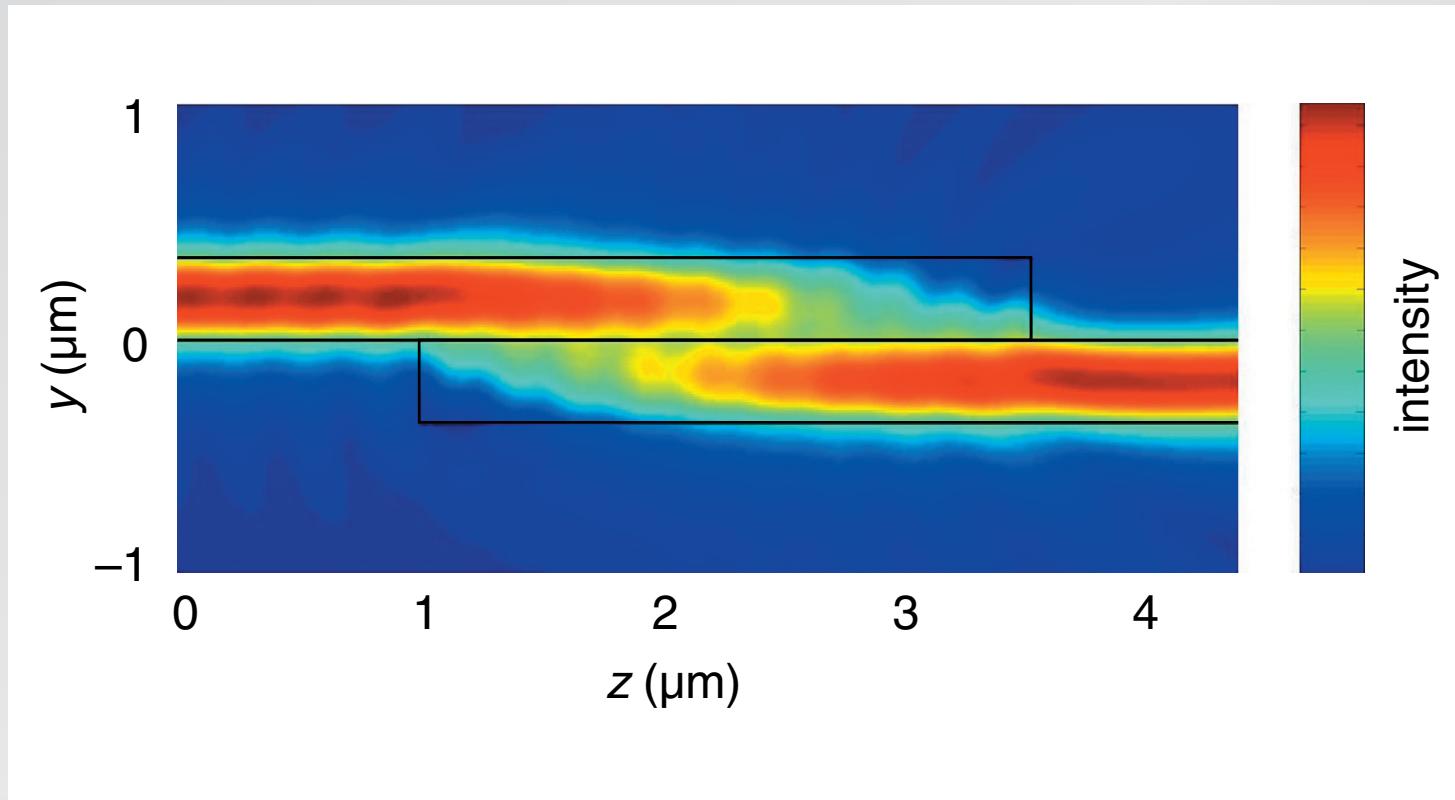
50µm

Optical properties



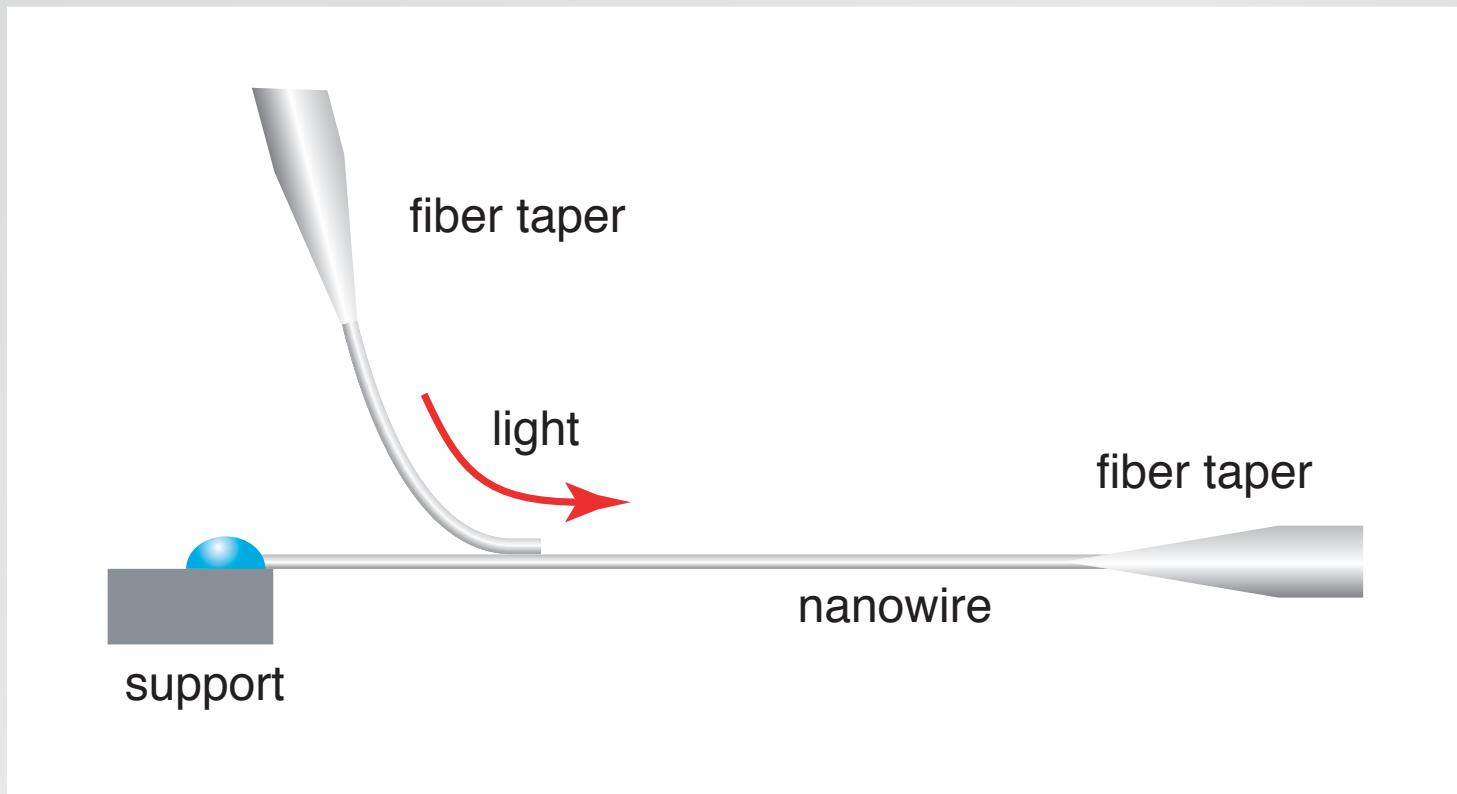
Optical properties

intensity distribution



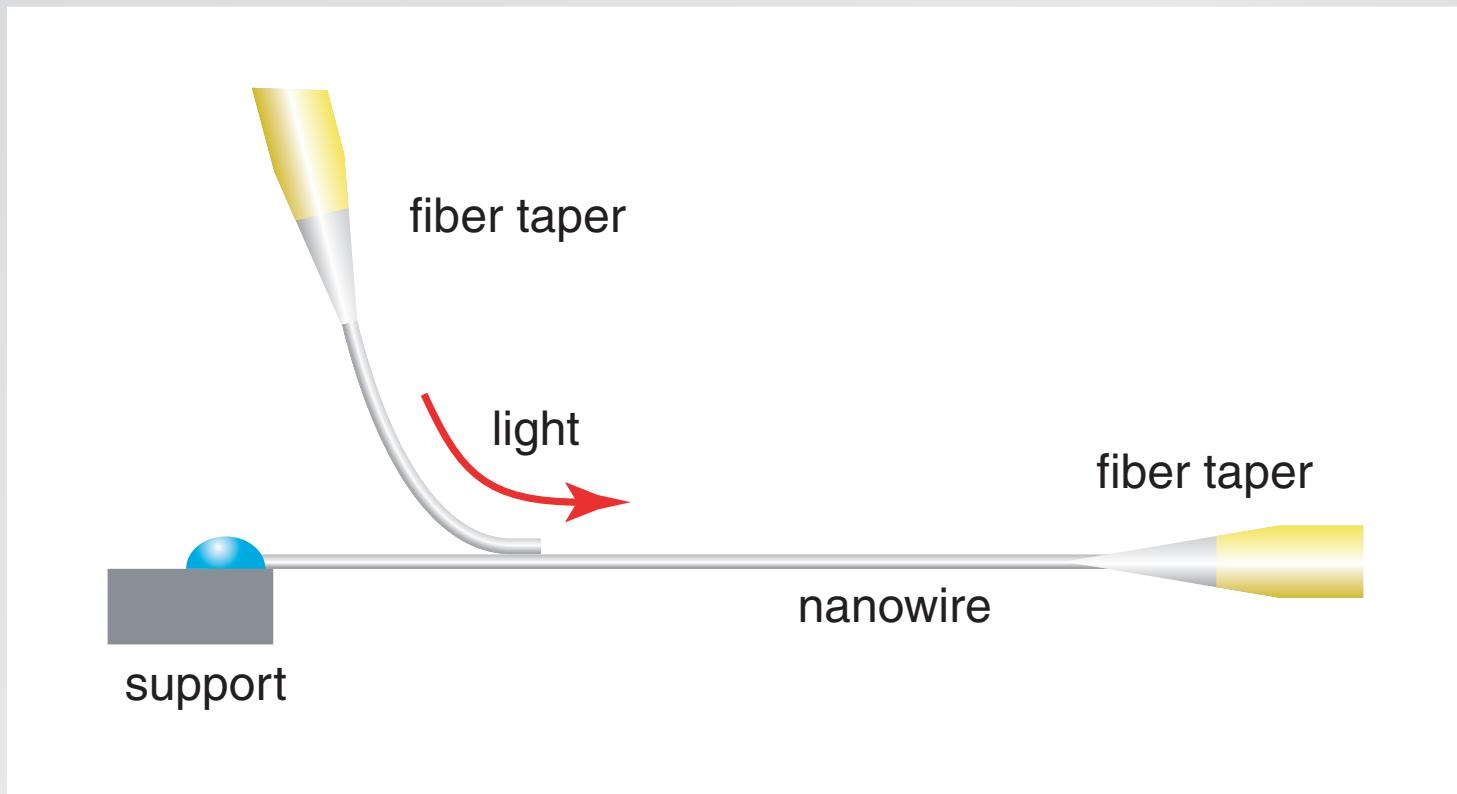
Optical properties

loss measurement



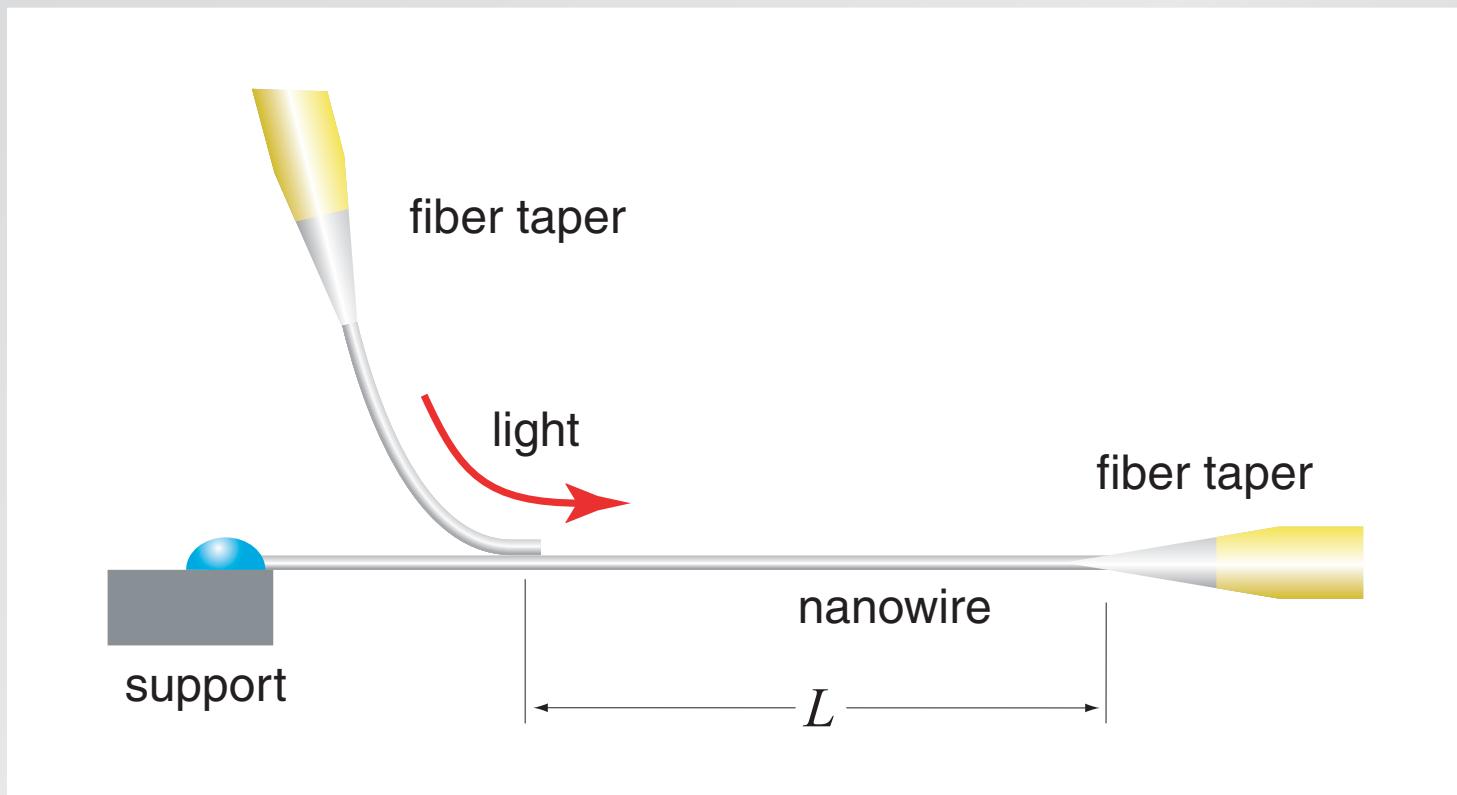
Optical properties

loss measurement



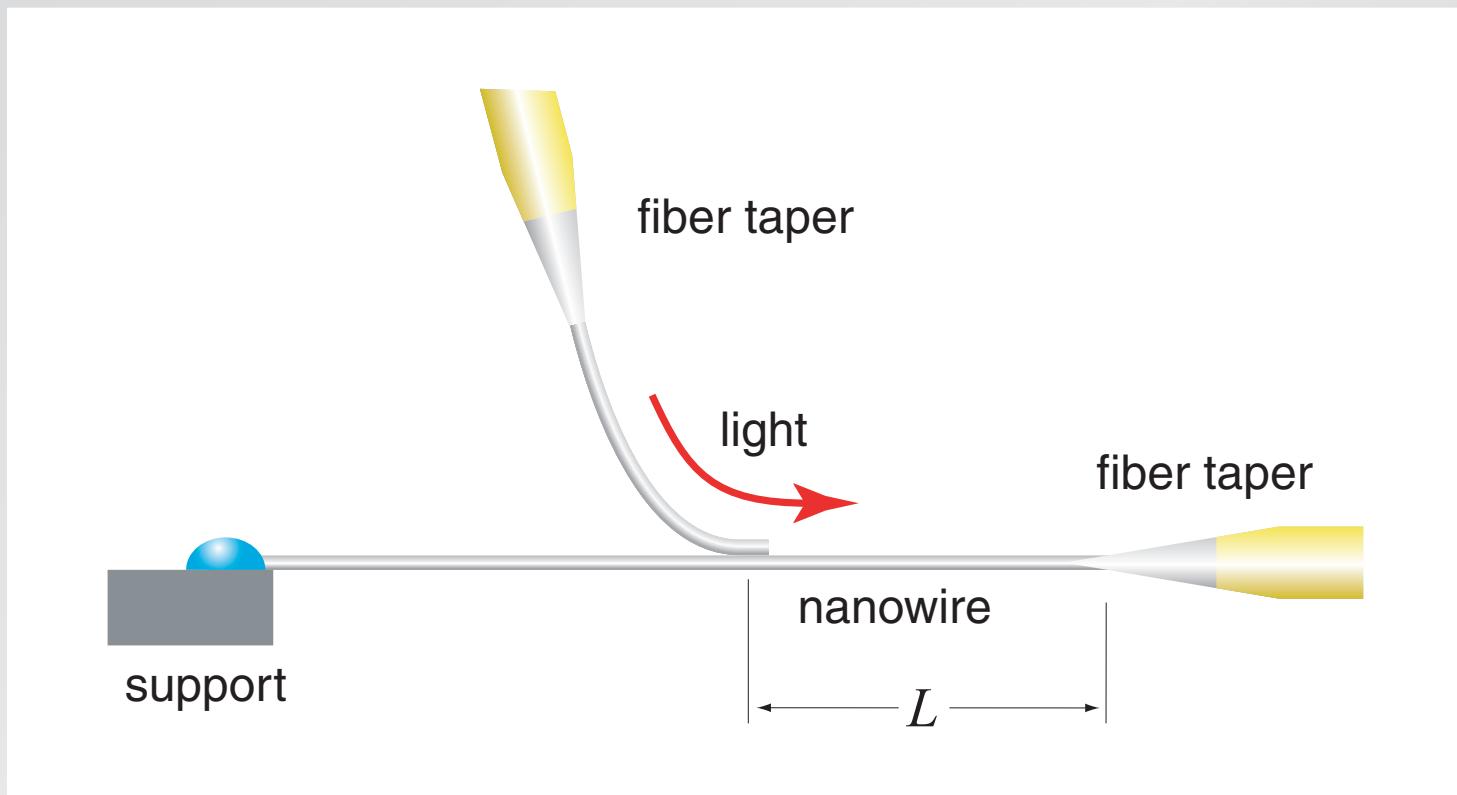
Optical properties

loss measurement



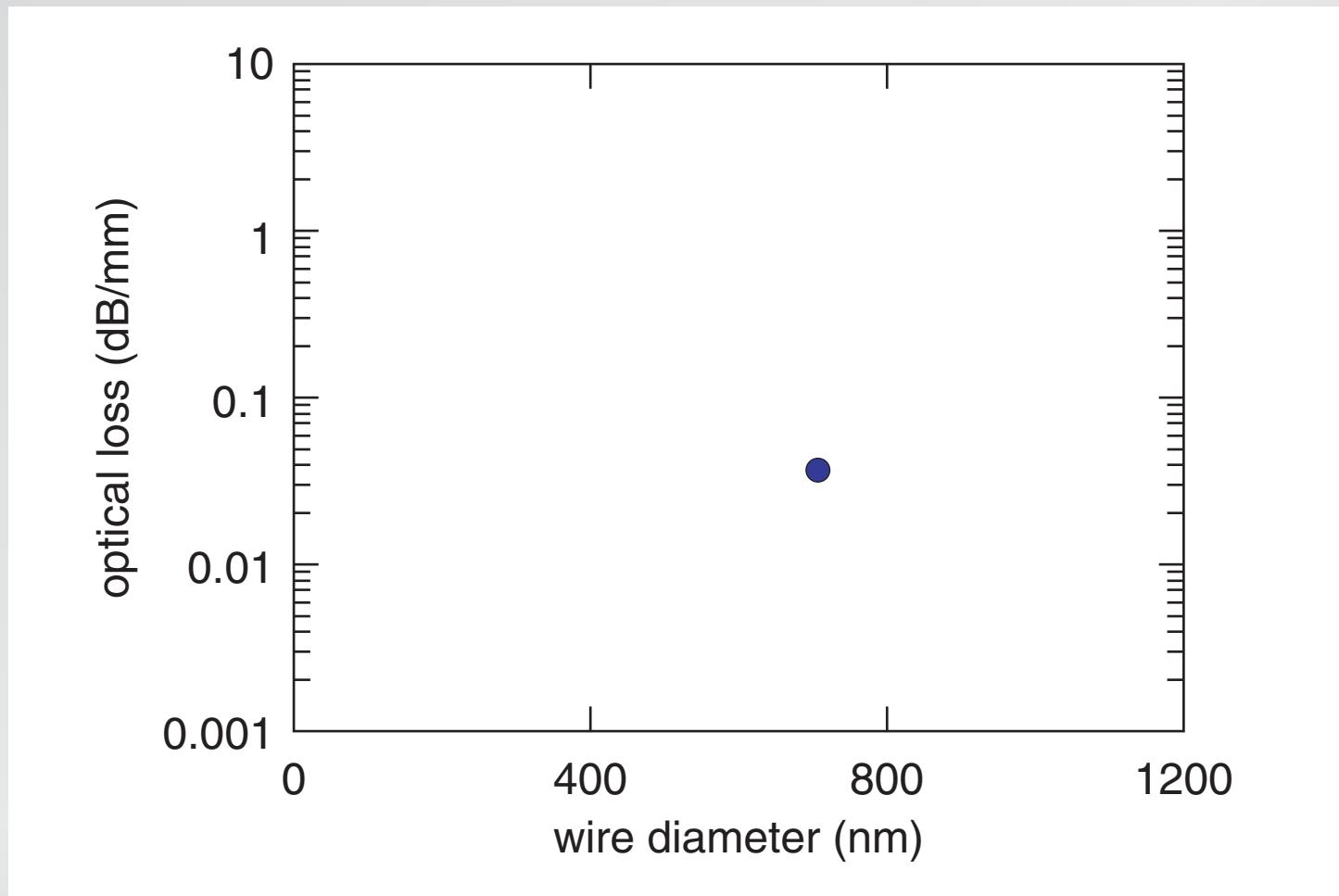
Optical properties

loss measurement



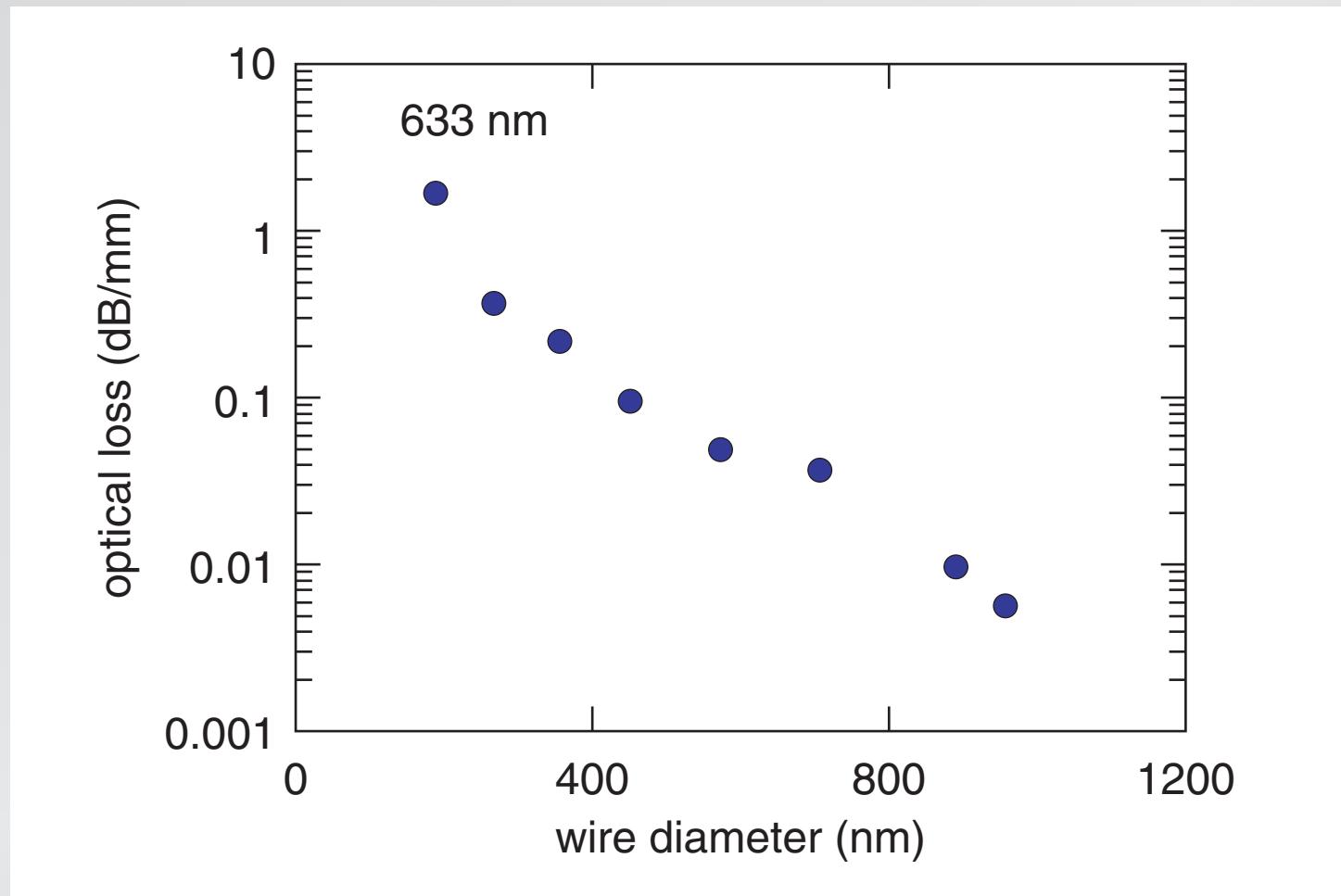
Optical properties

loss measurement



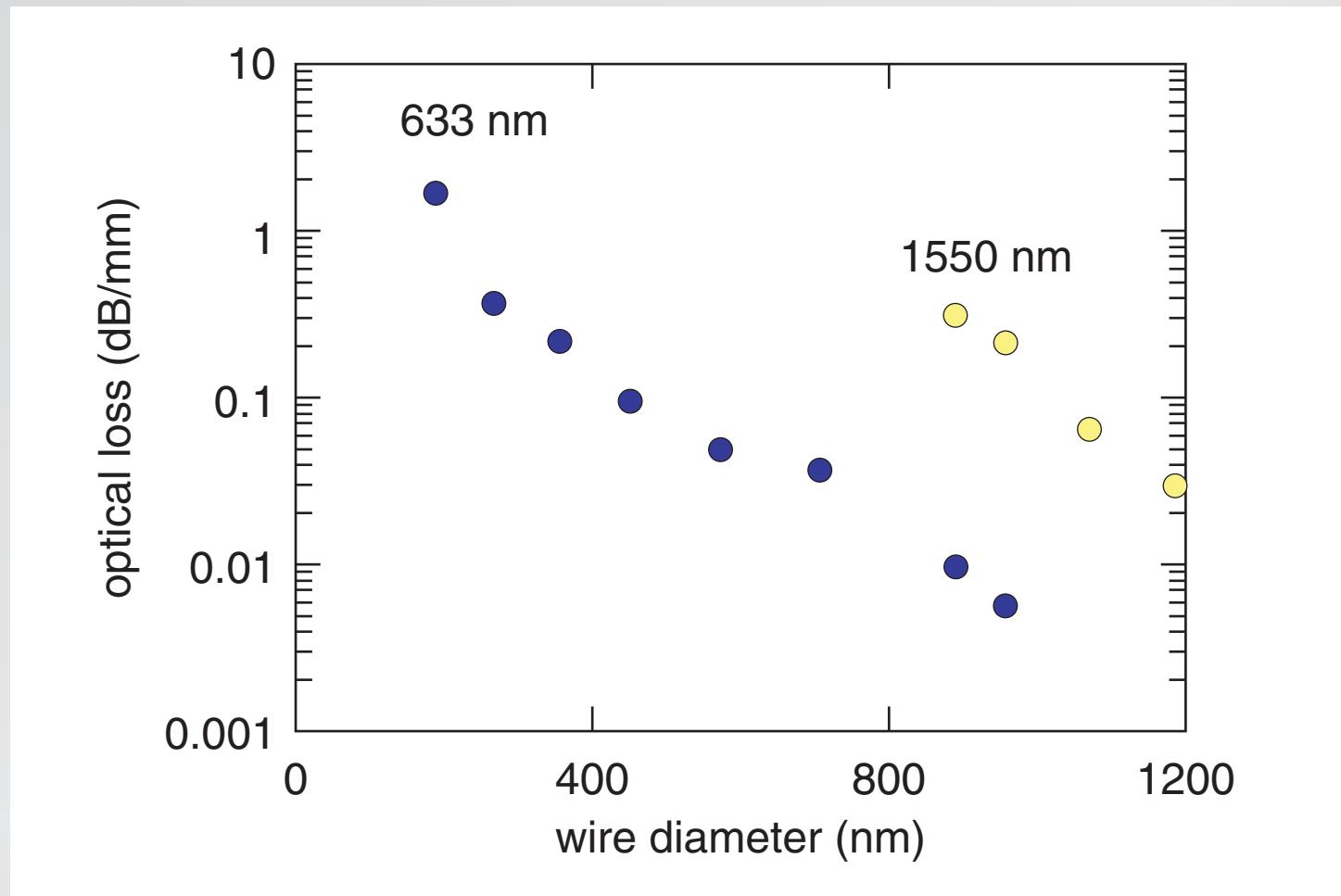
Optical properties

loss measurement



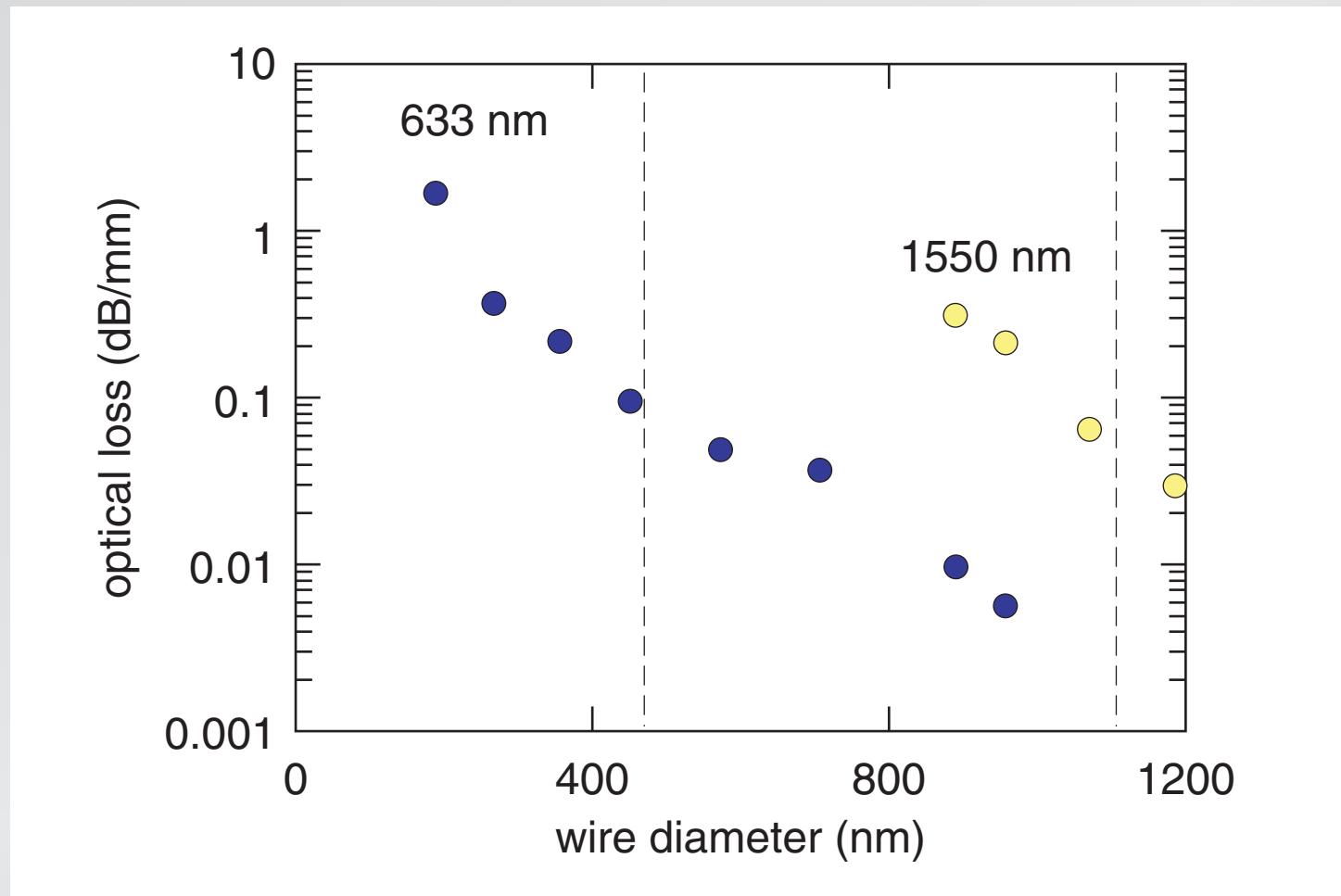
Optical properties

loss measurement

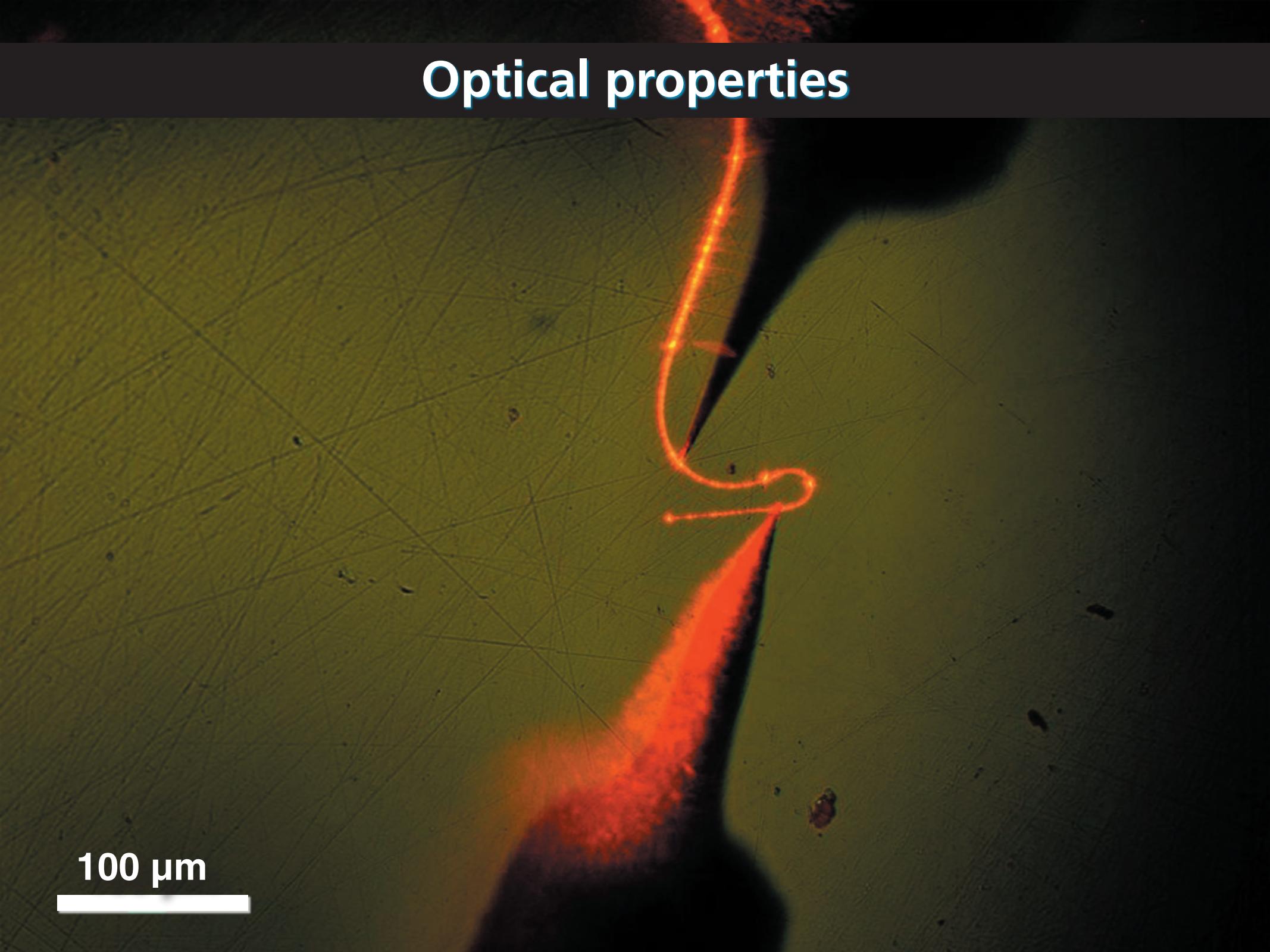


Optical properties

loss at single-mode diameter < 0.1 dB/mm

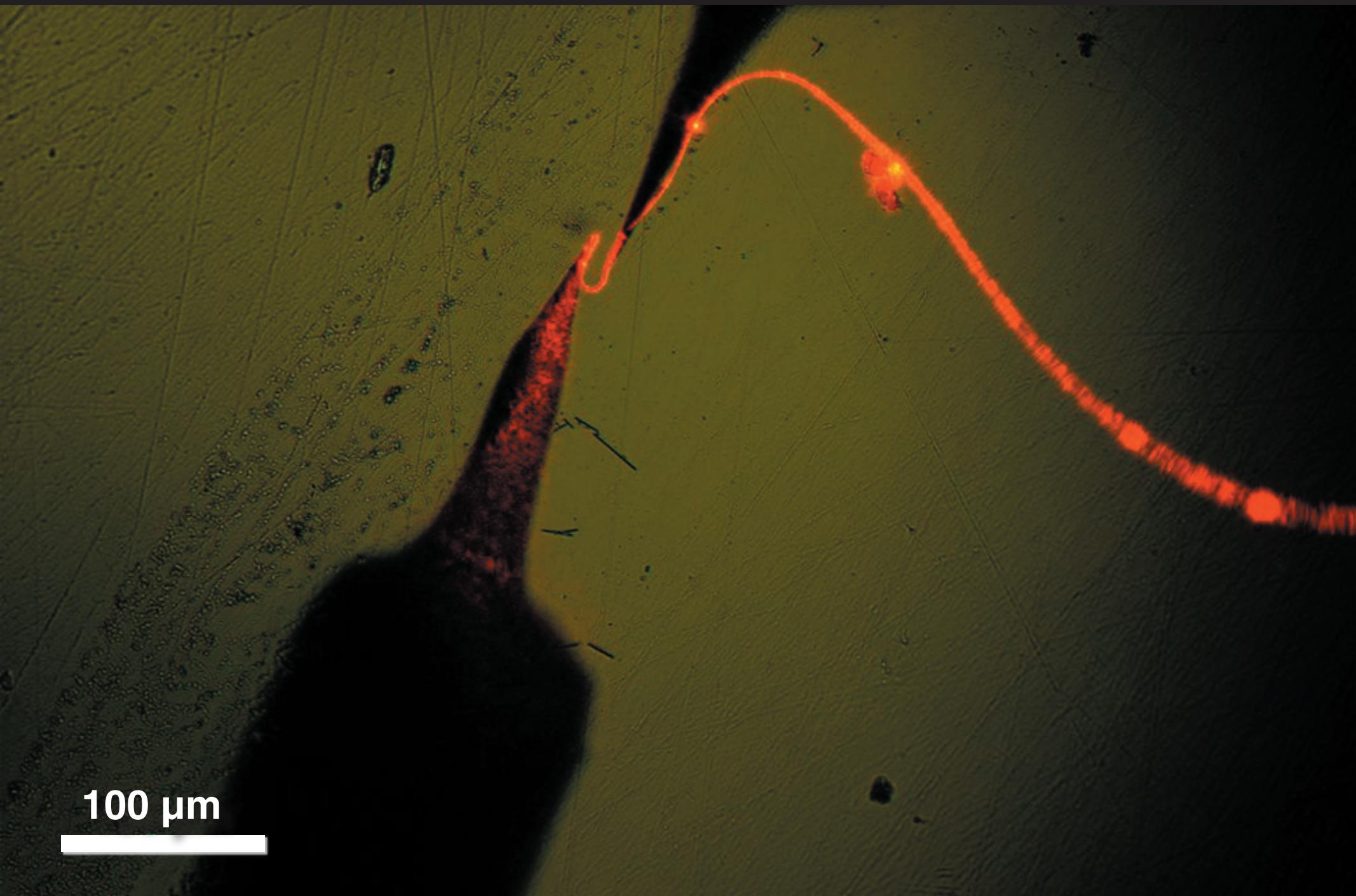


Optical properties



100 μm

Optical properties



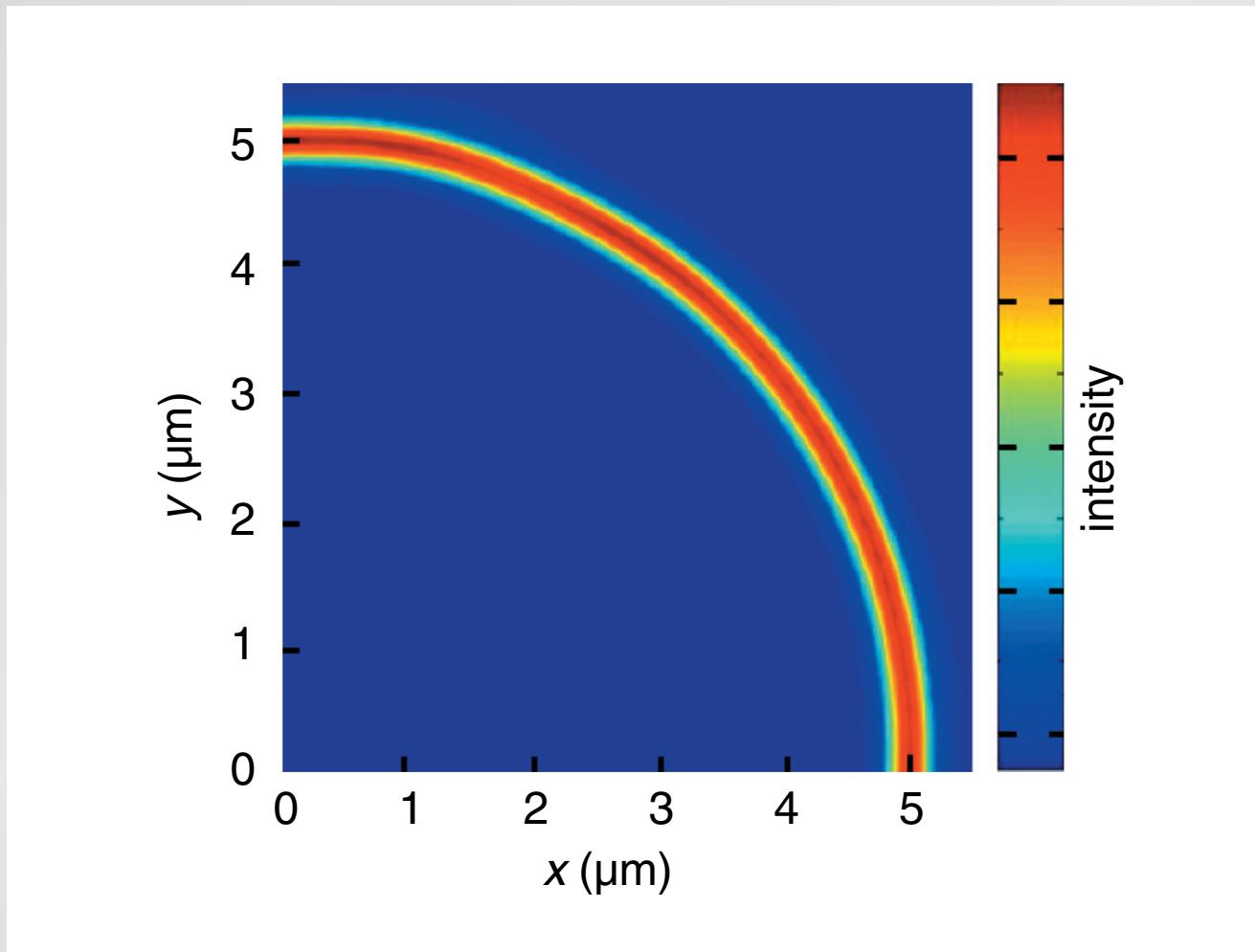
Optical properties

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

100 μm

Optical properties

virtually no loss through 5 μm corner!



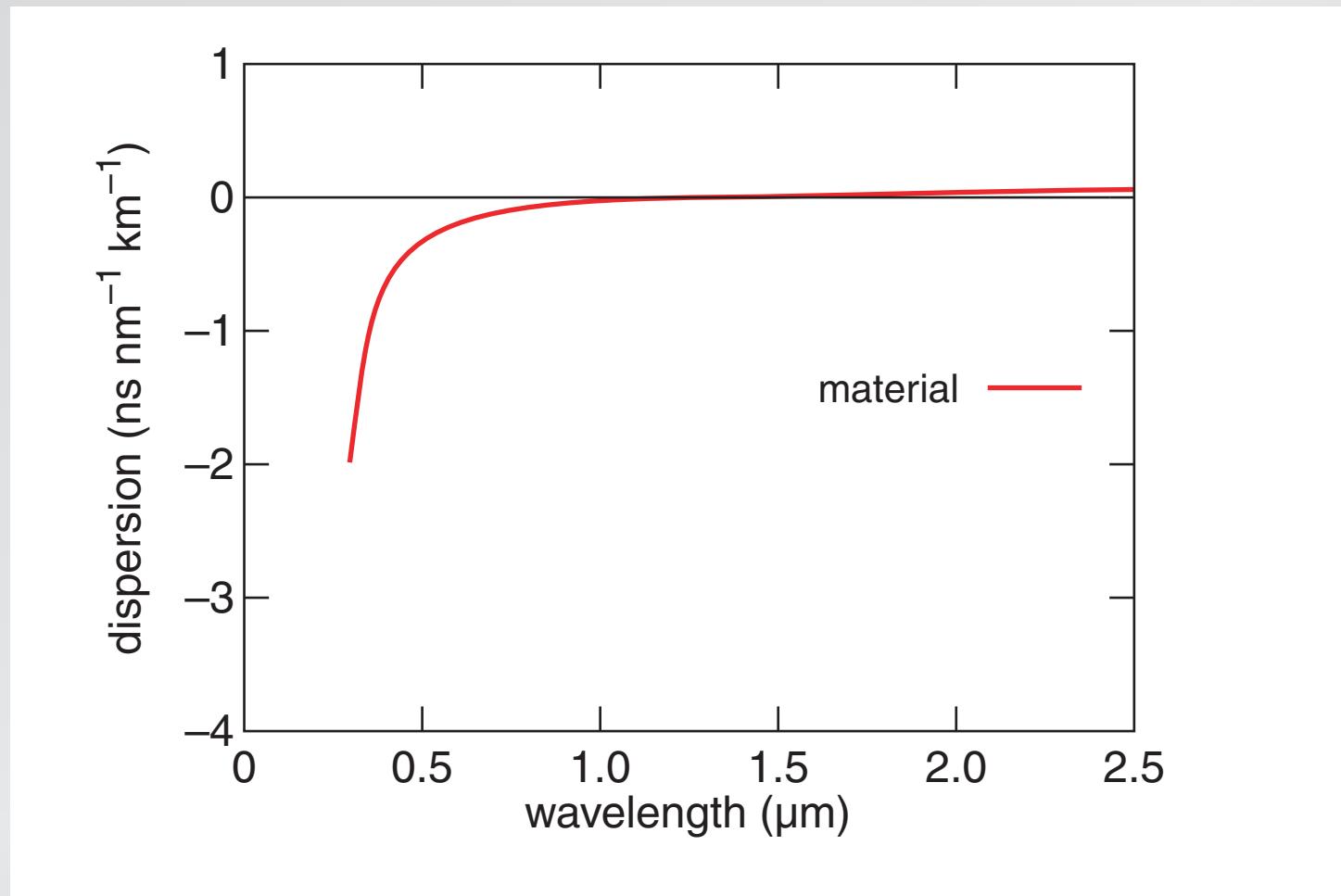
Optical properties

dispersion:

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

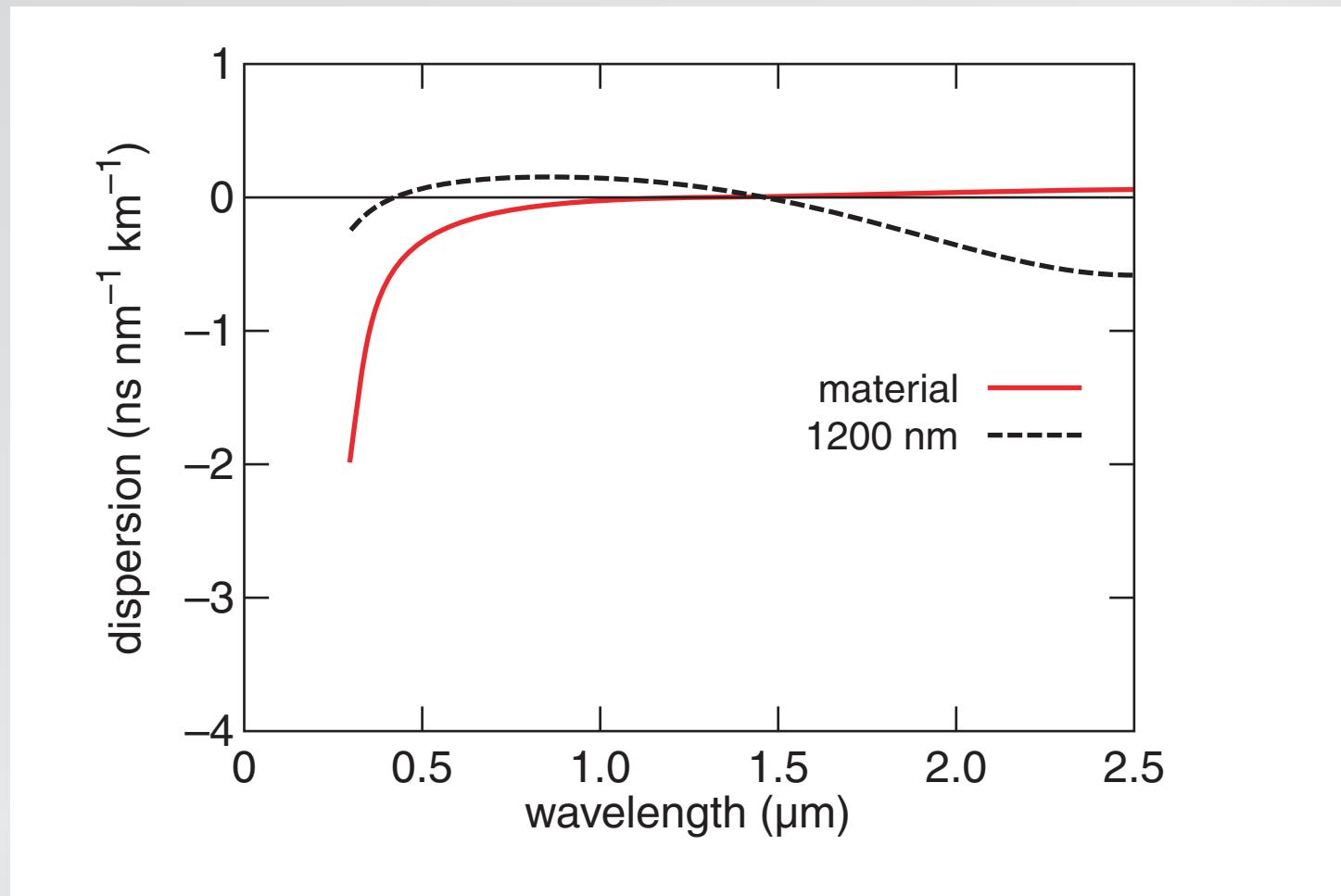
Optical properties

waveguide dispersion



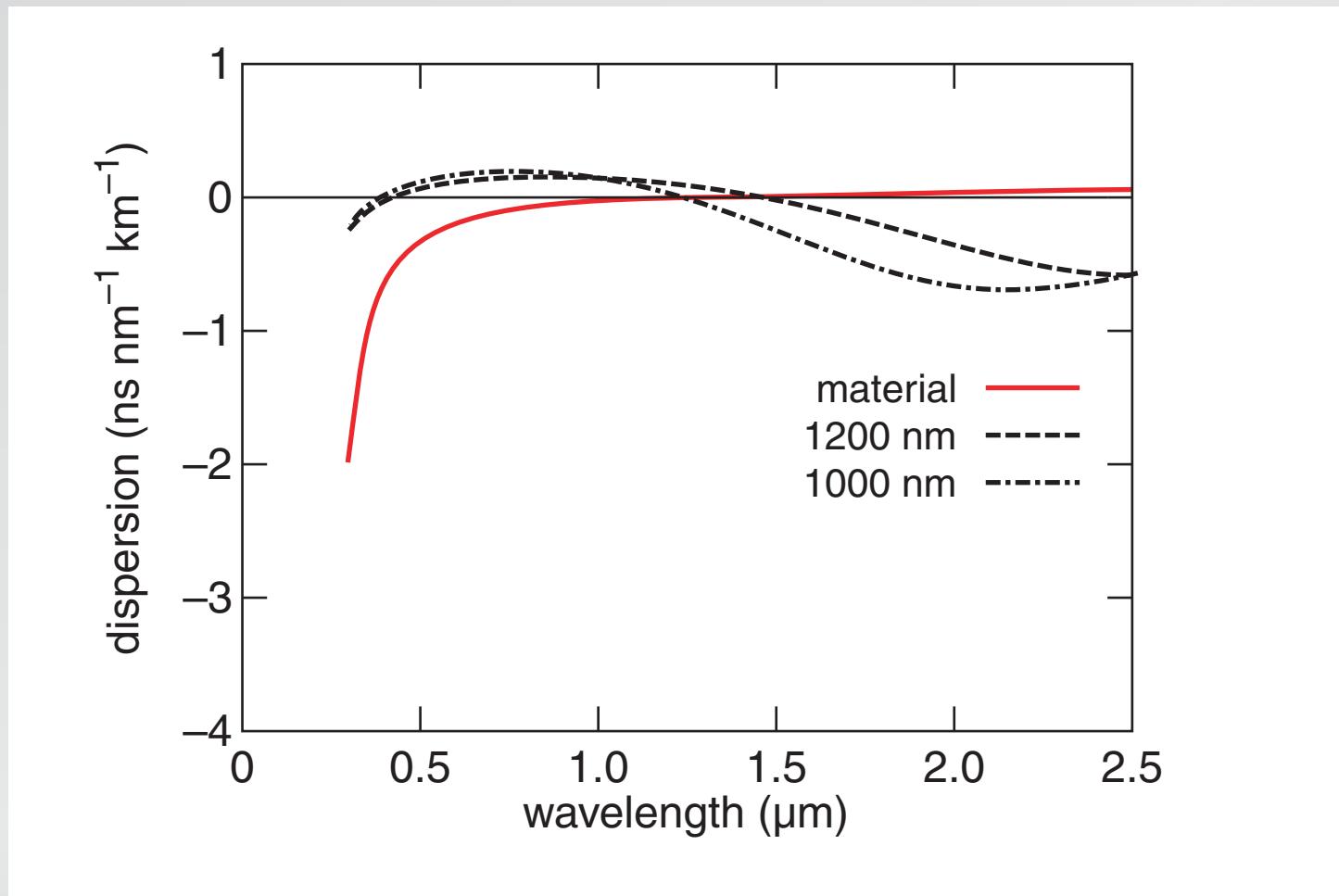
Optical properties

waveguide dispersion



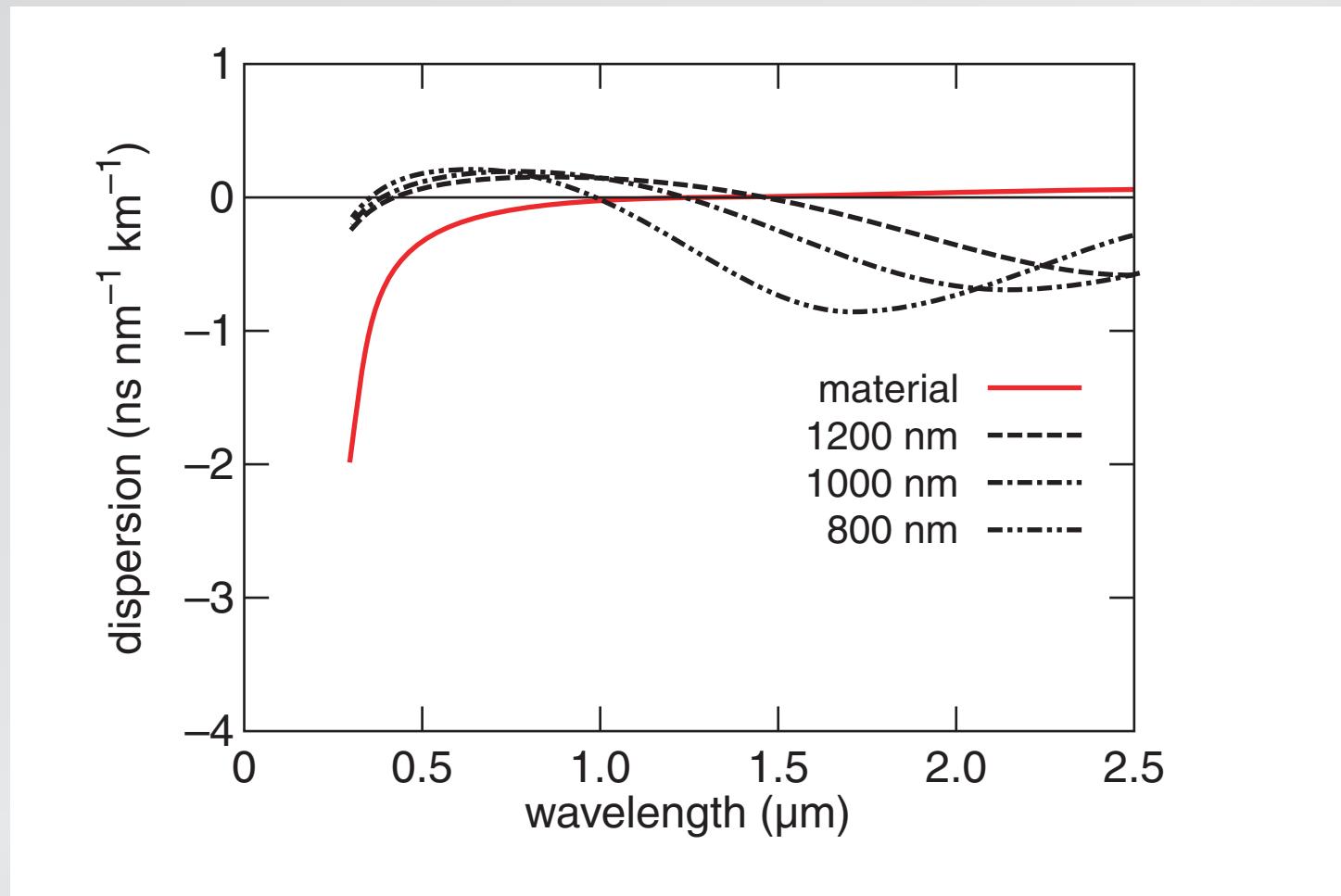
Optical properties

waveguide dispersion



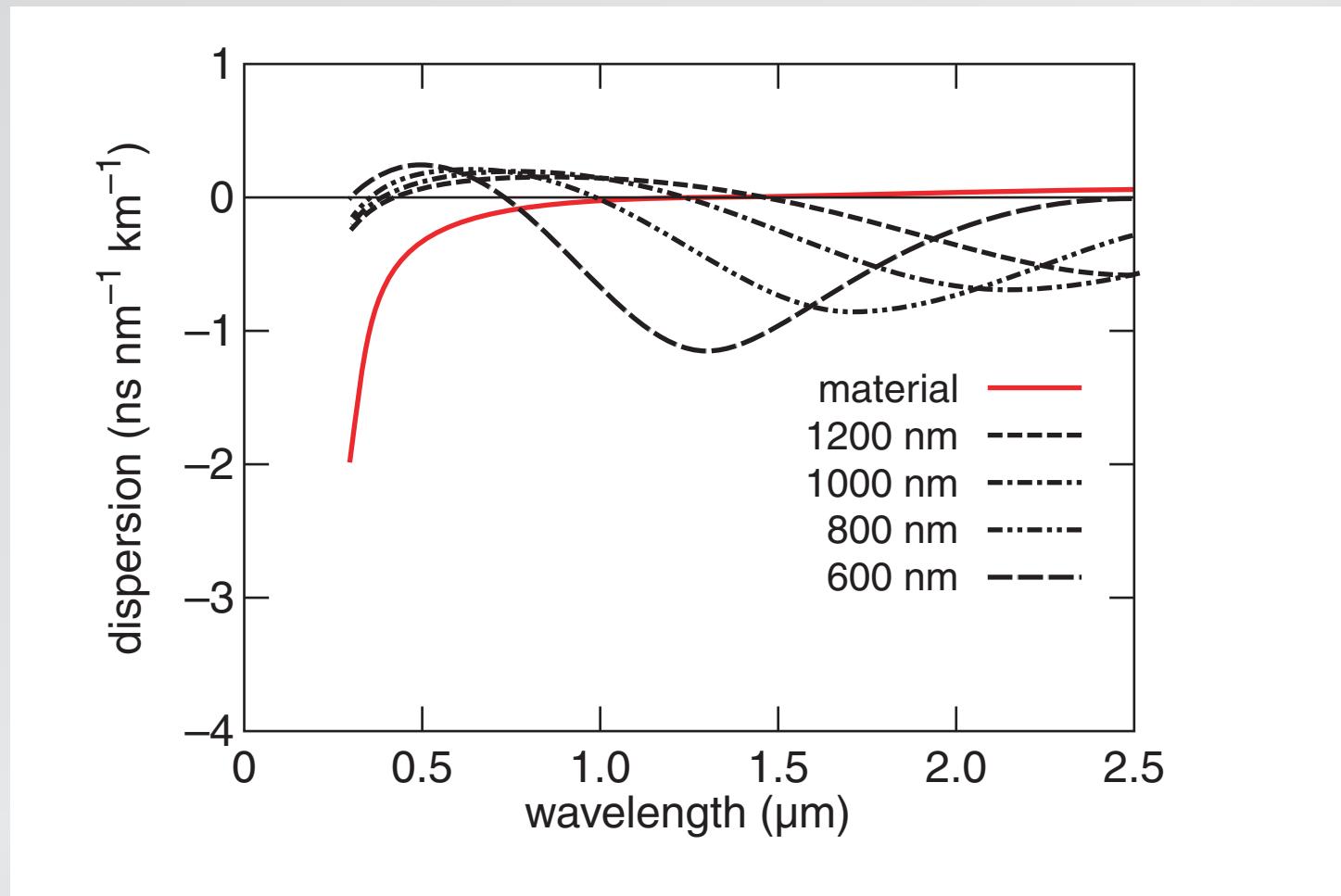
Optical properties

waveguide dispersion



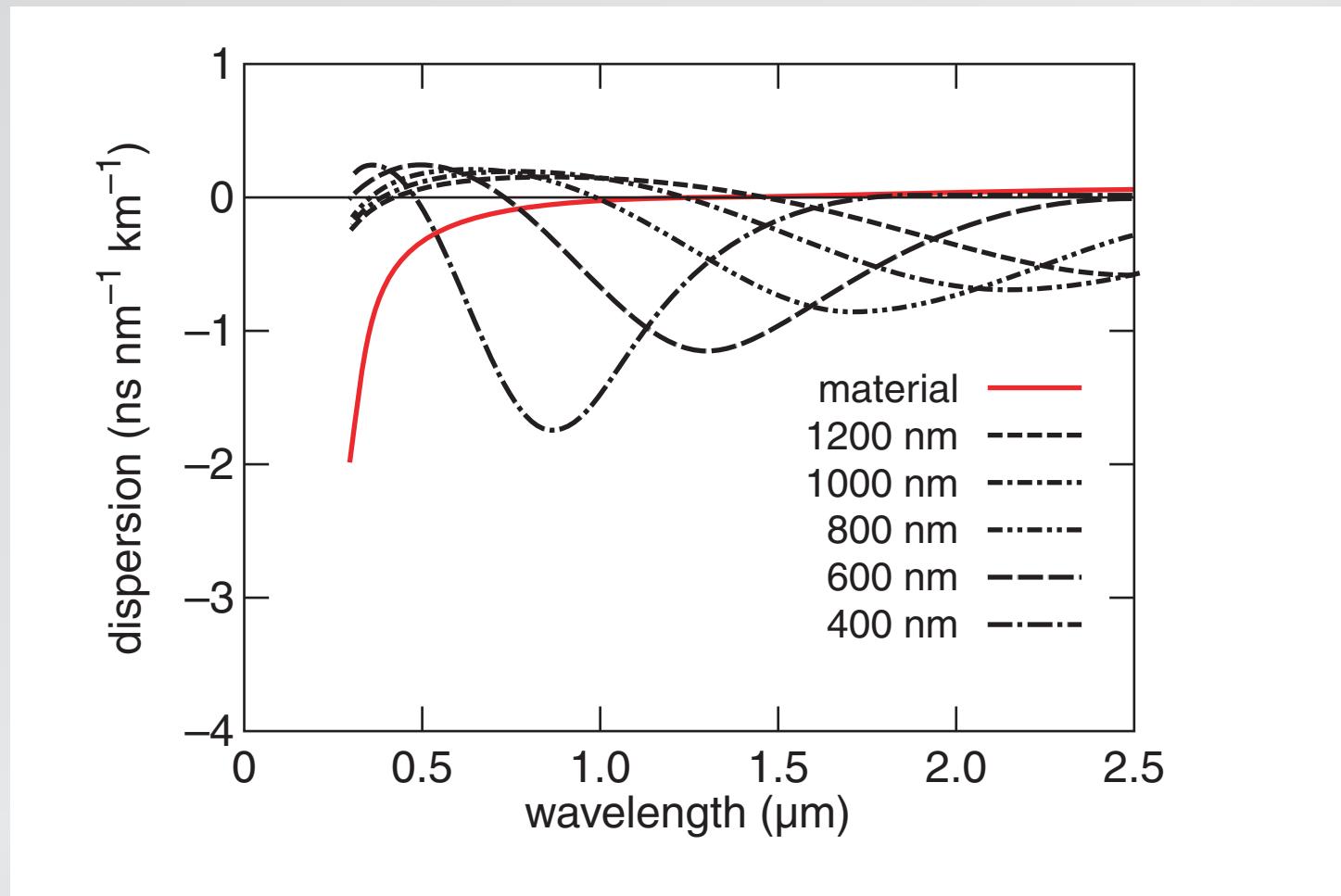
Optical properties

waveguide dispersion



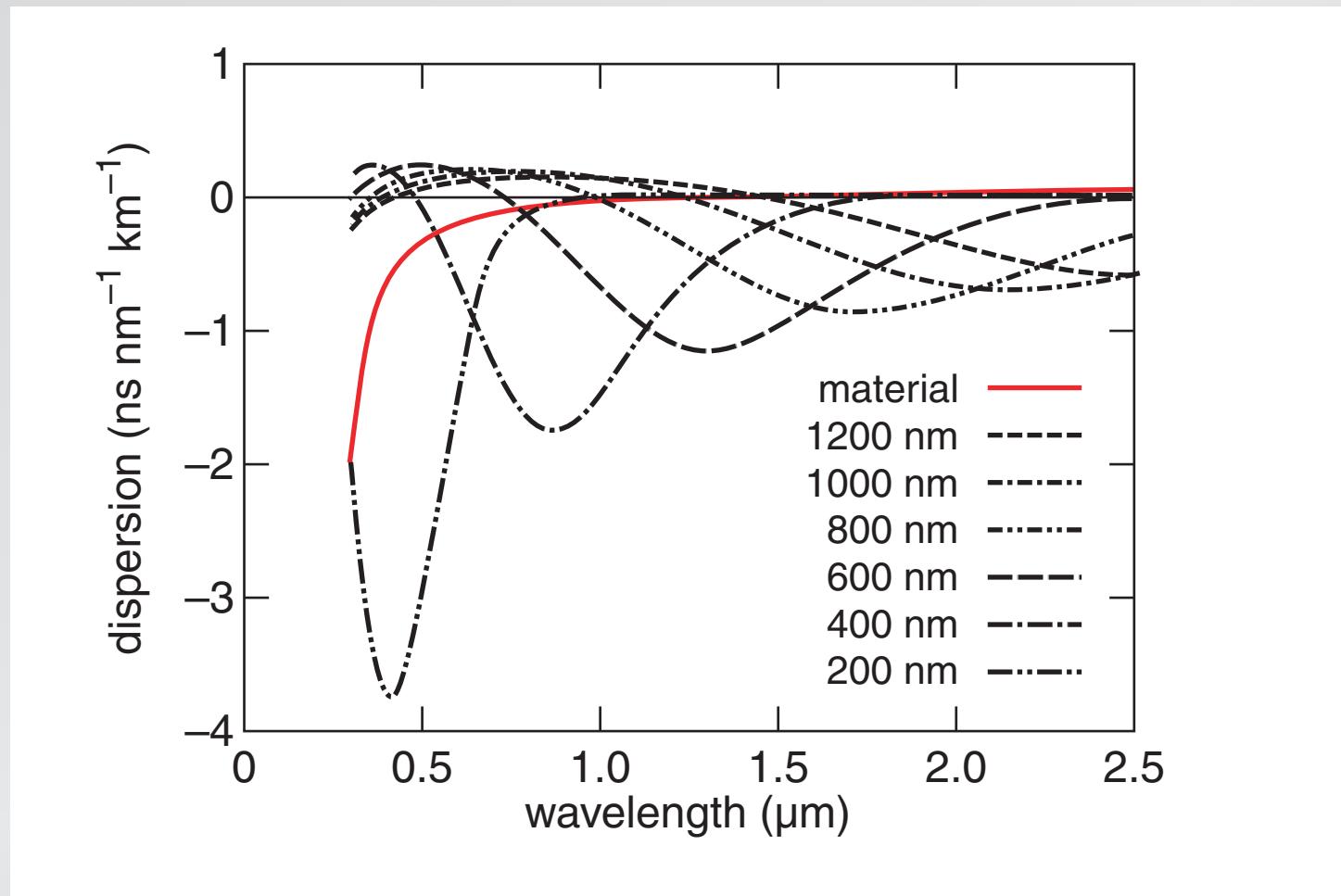
Optical properties

waveguide dispersion



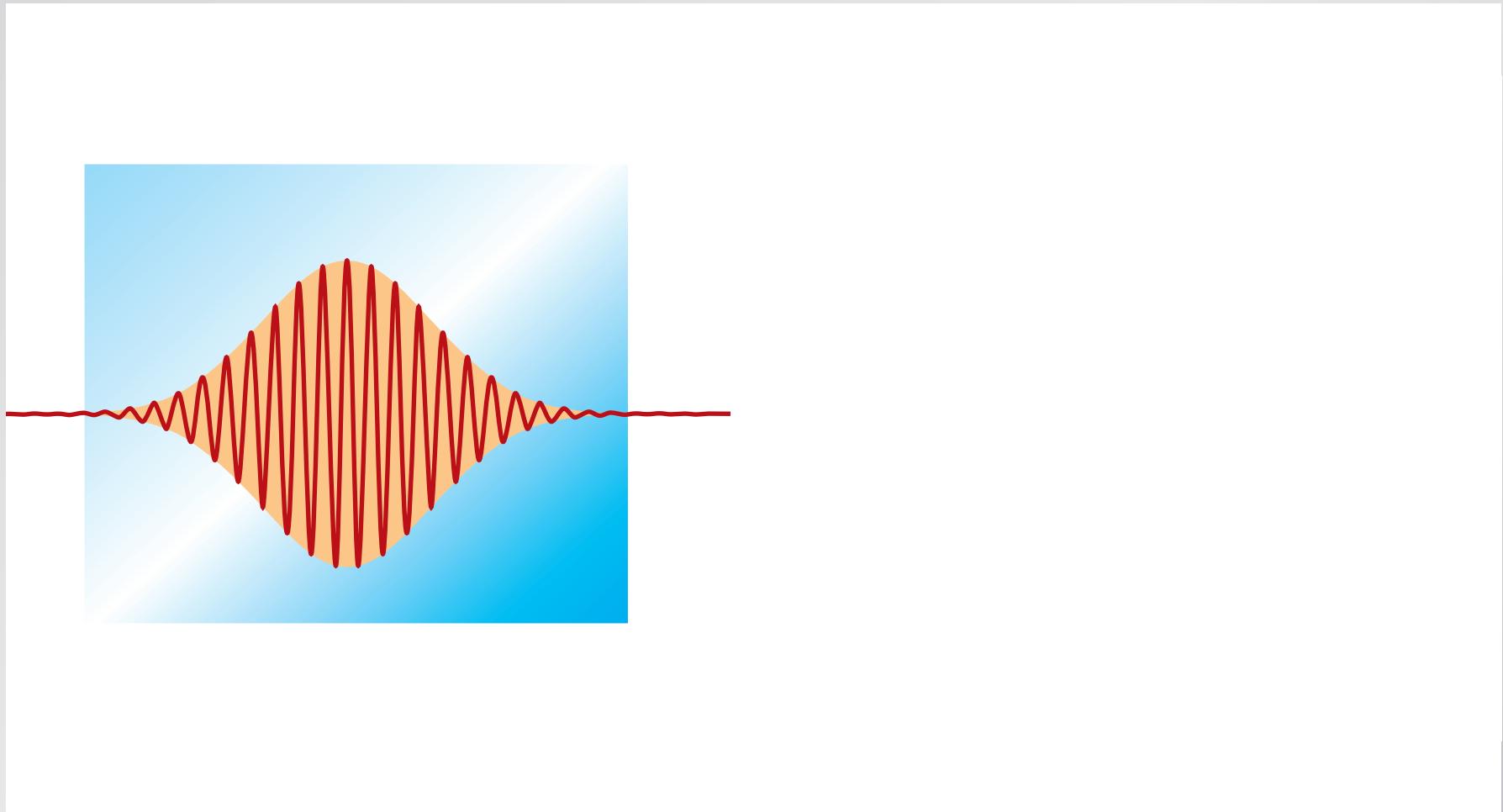
Optical properties

waveguide dispersion



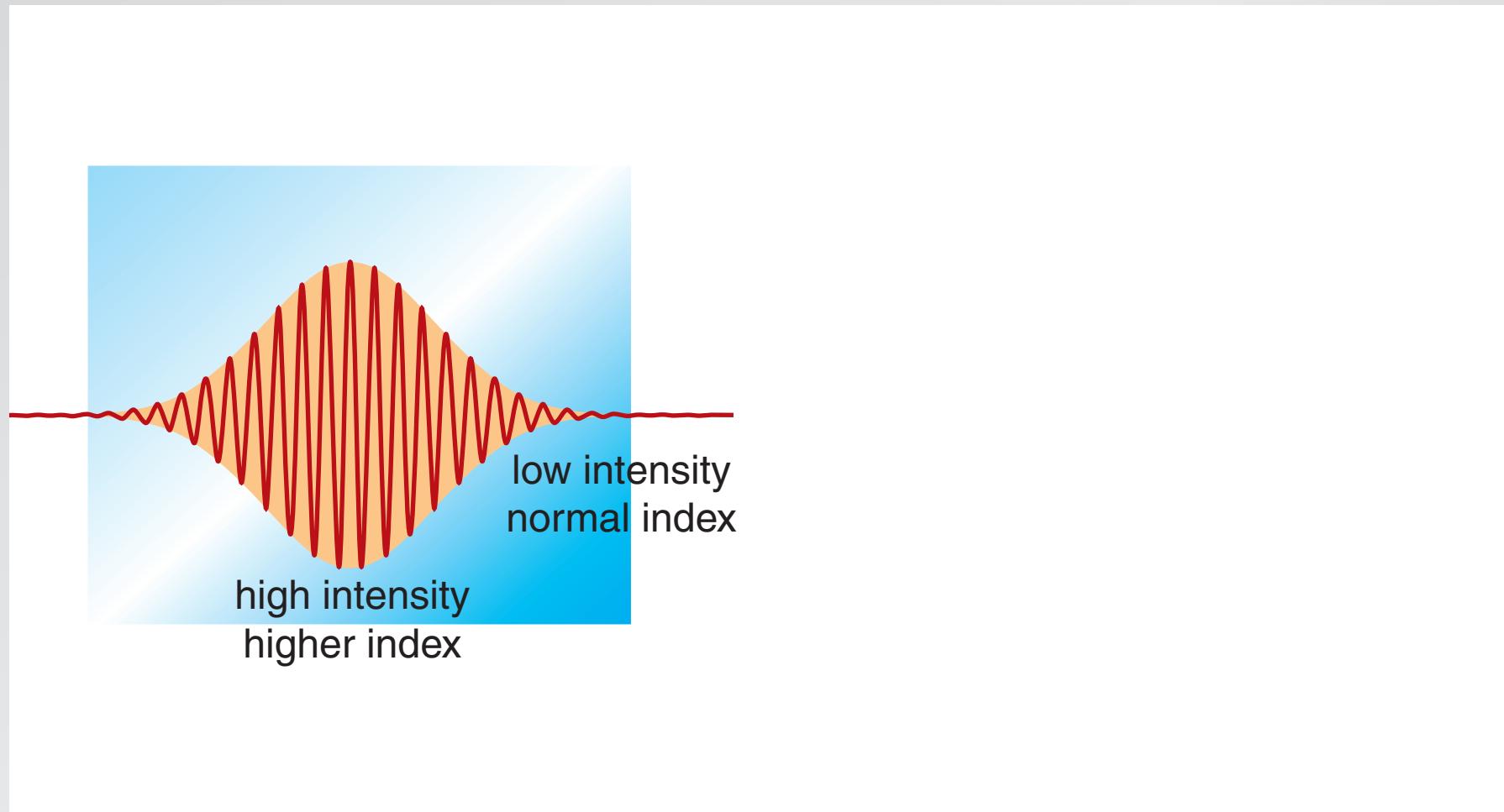
Optical properties

nonlinear dispersion: $n = n_0 + n_2 I$



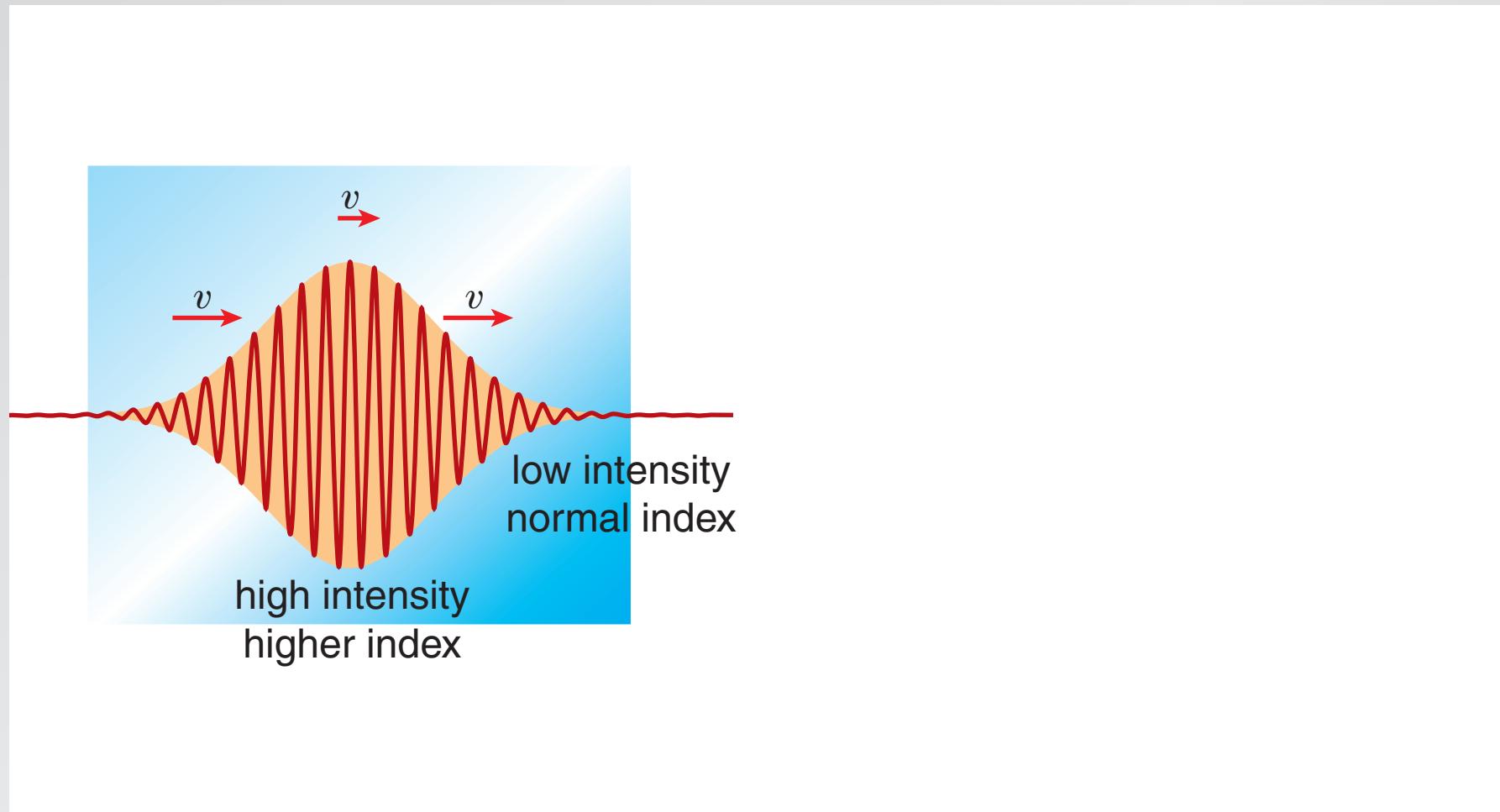
Optical properties

nonlinear dispersion: $n = n_0 + n_2 I$



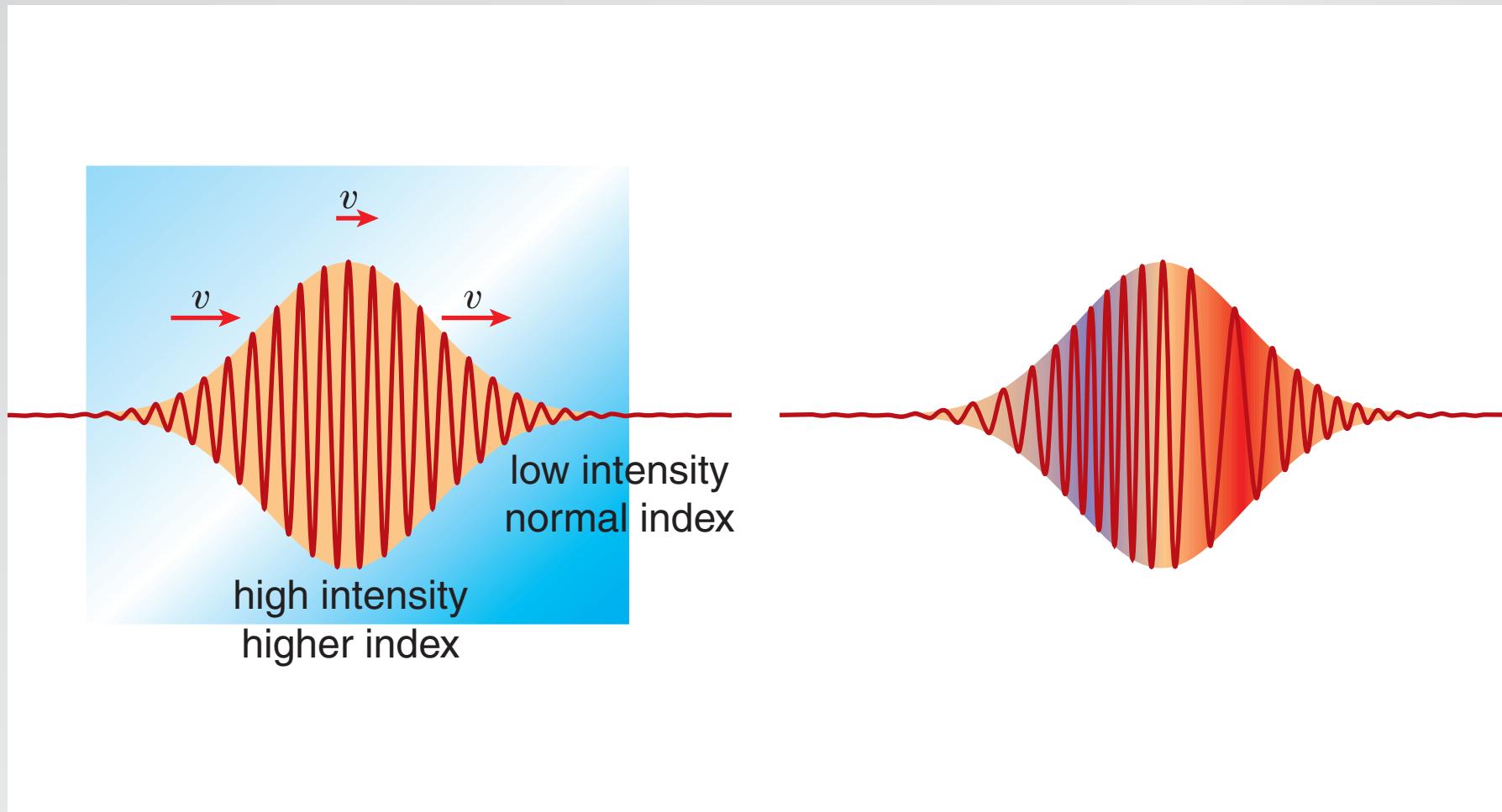
Optical properties

nonlinear dispersion: $n = n_0 + n_2 I$



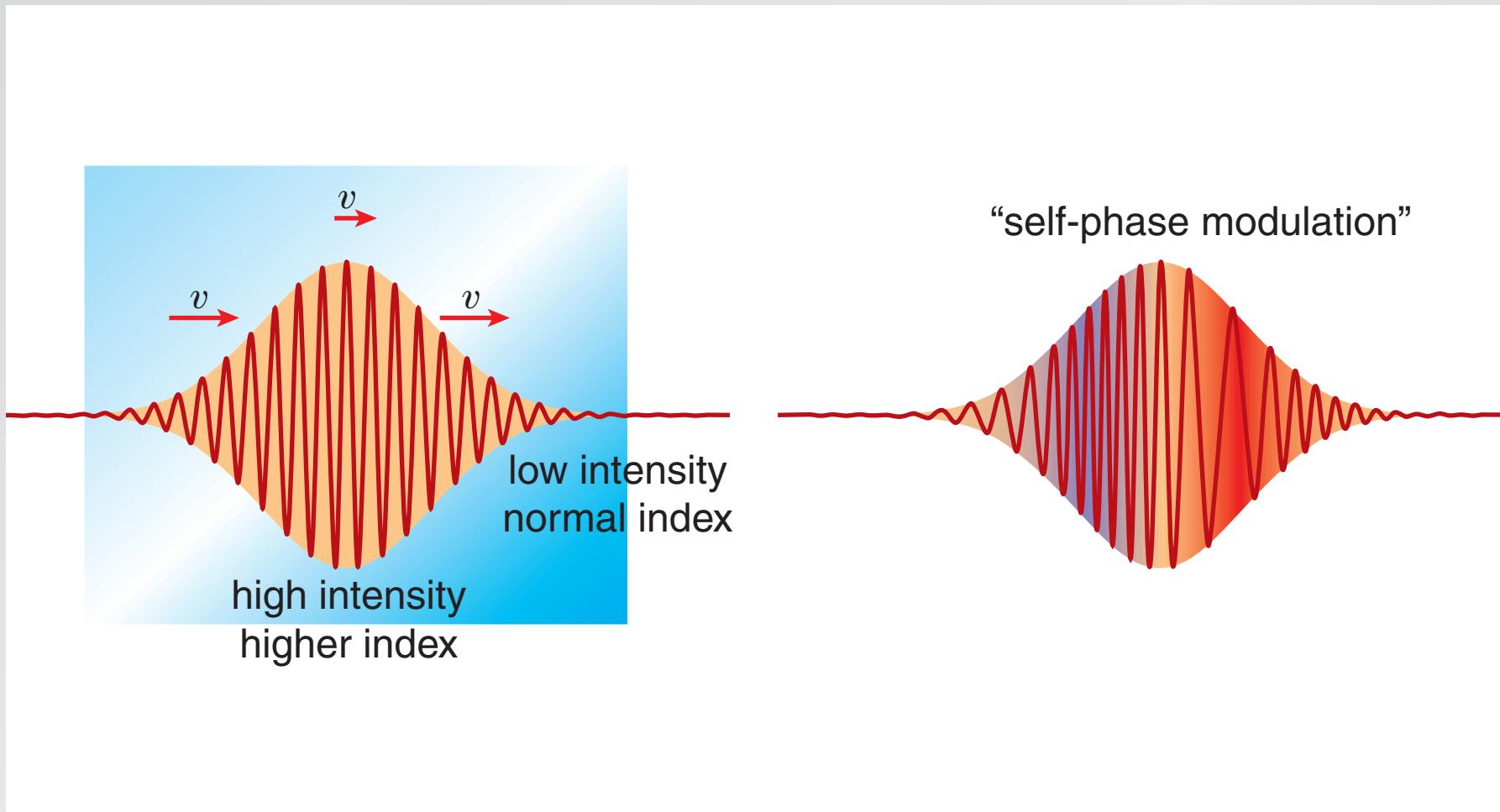
Optical properties

nonlinear dispersion: $n = n_0 + n_2 I$

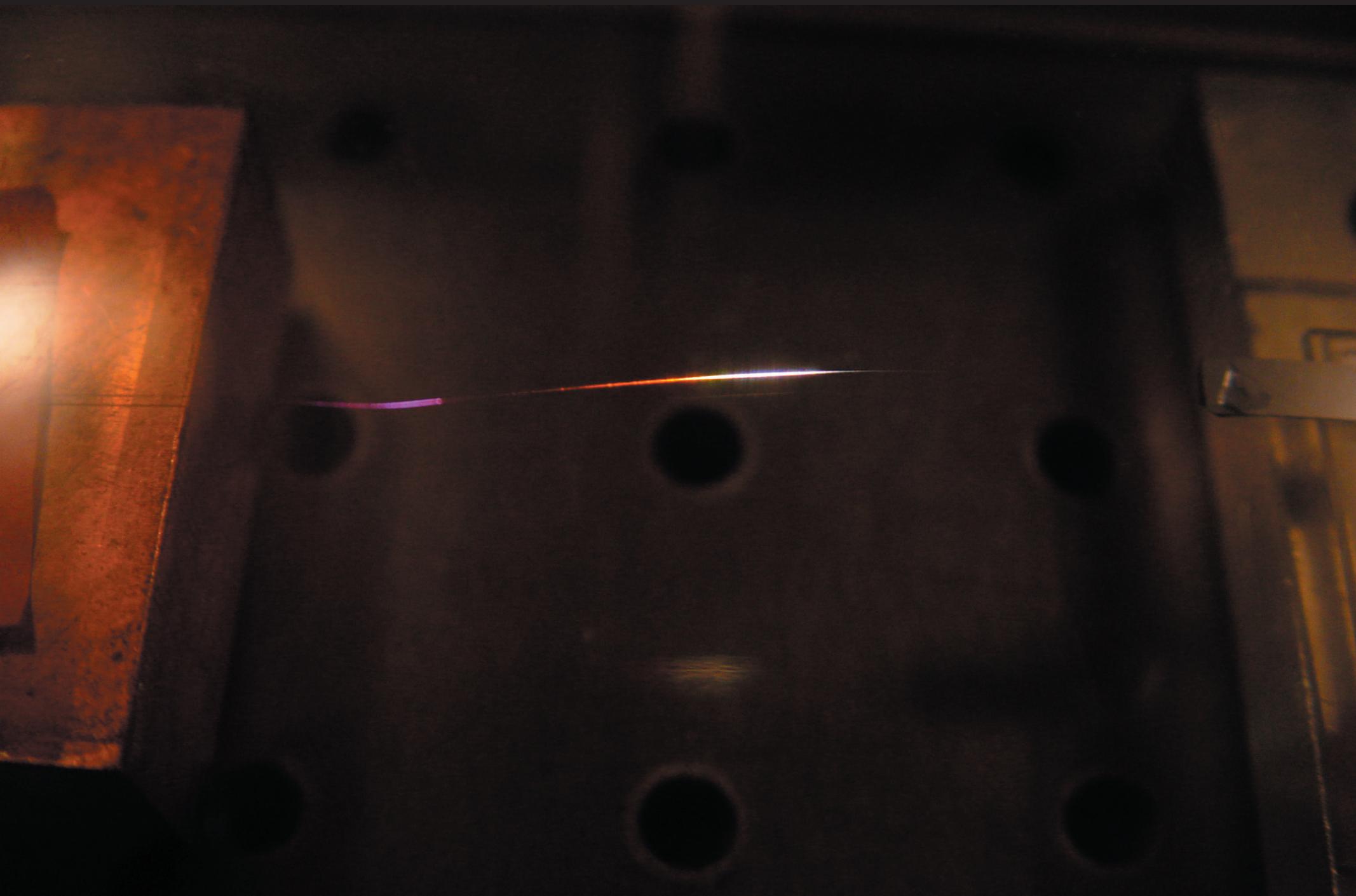


Optical properties

nonlinear dispersion: $n = n_0 + n_2 I$



Optical properties

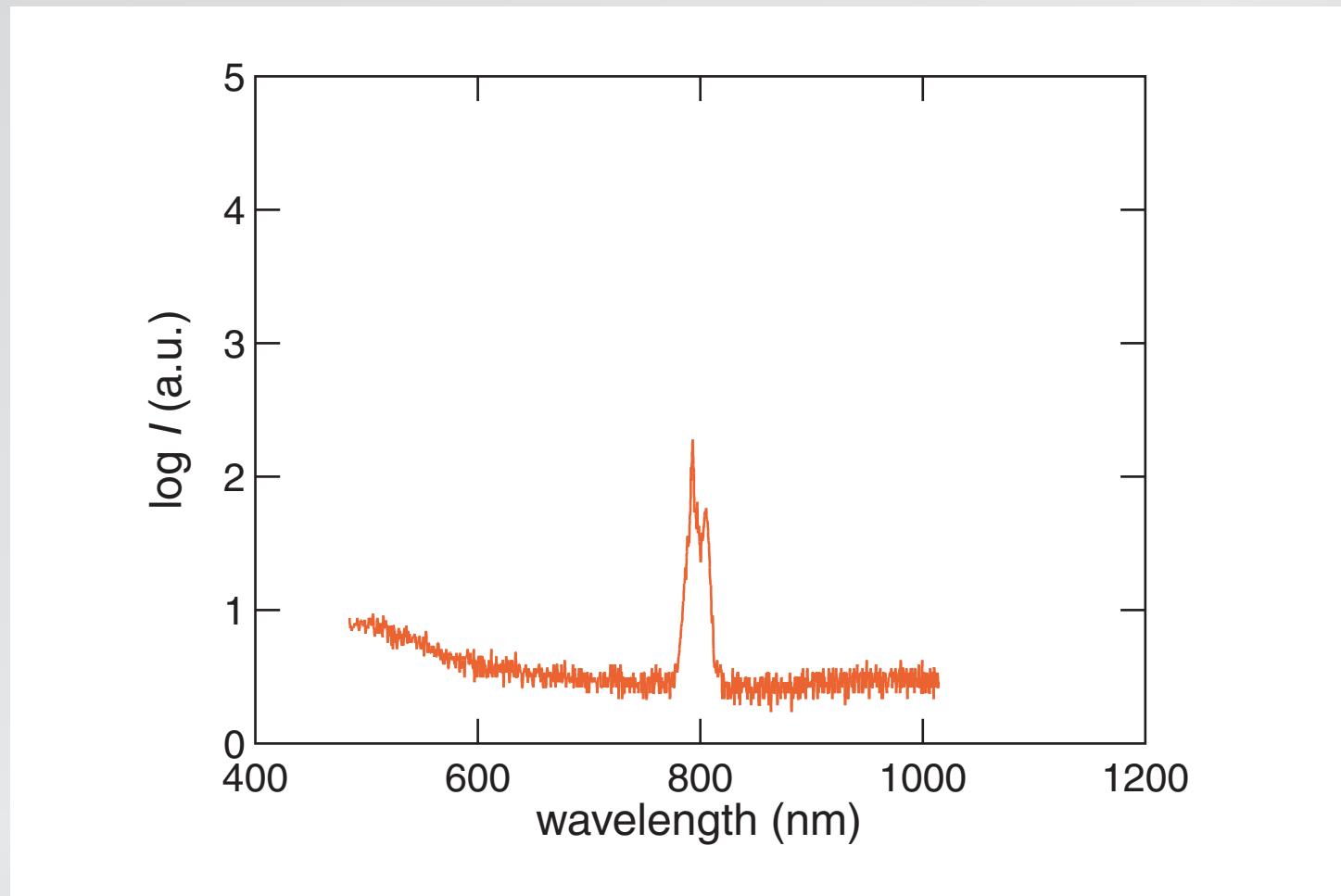


Optical properties



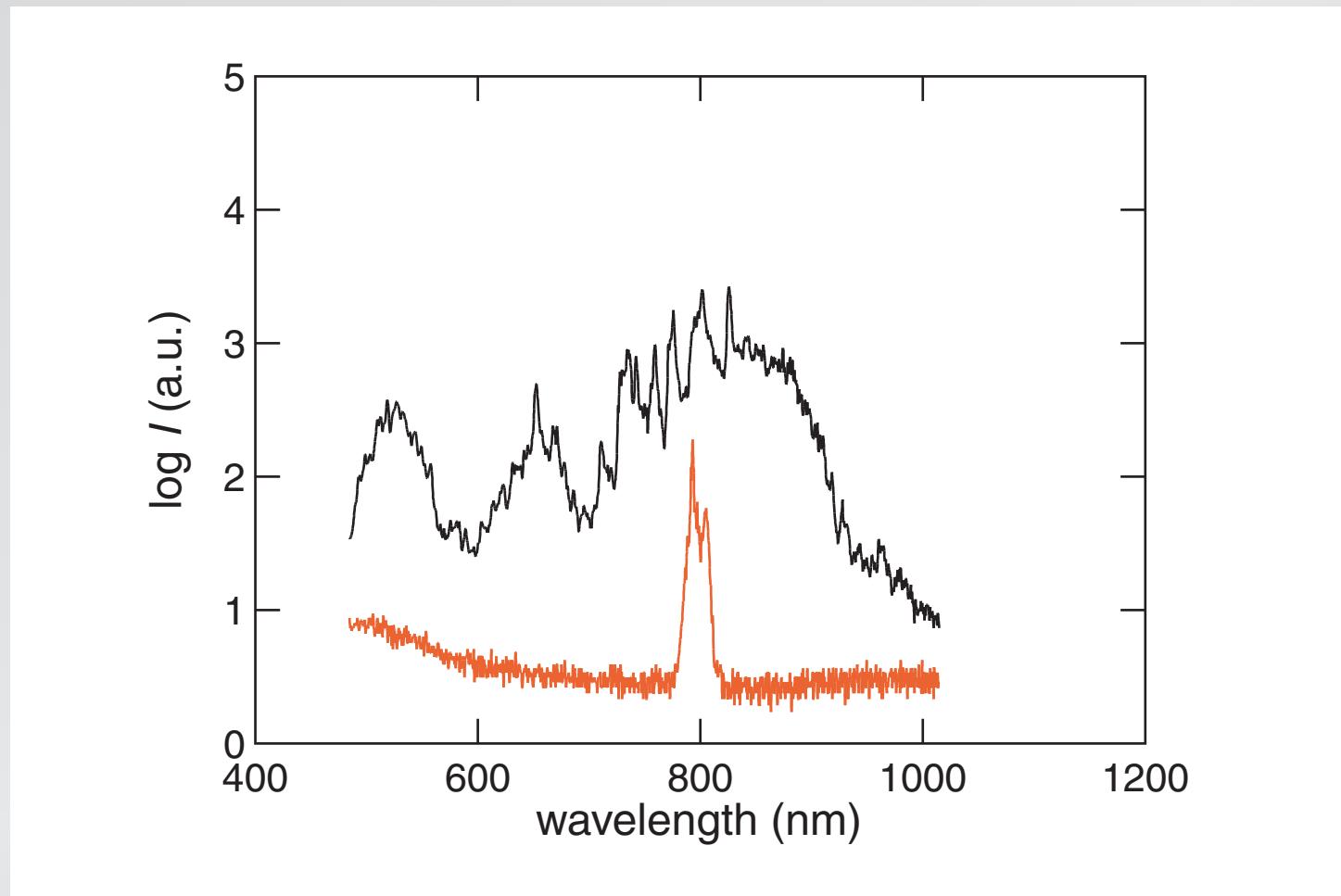
Optical properties

self-phase modulation



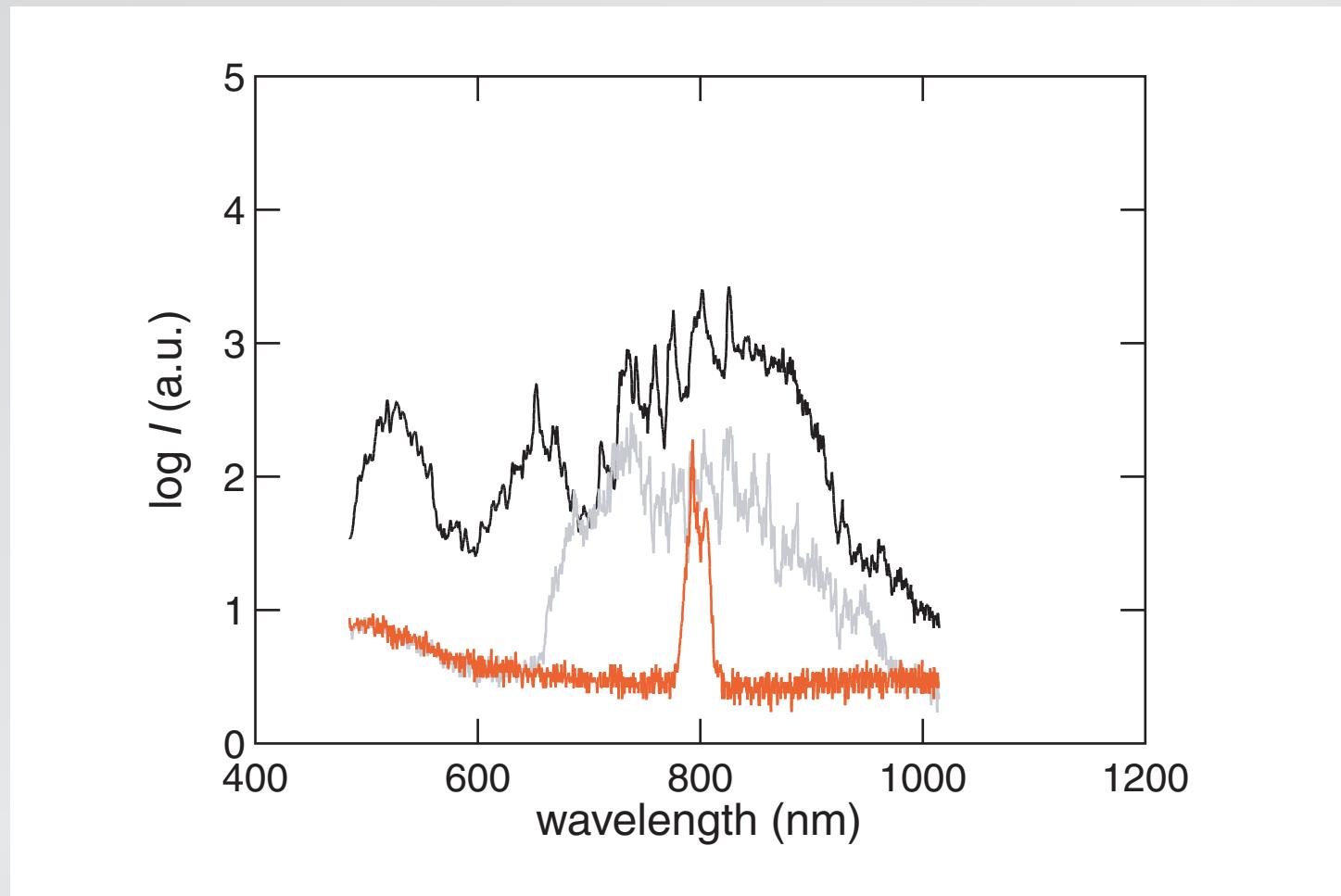
Optical properties

self-phase modulation

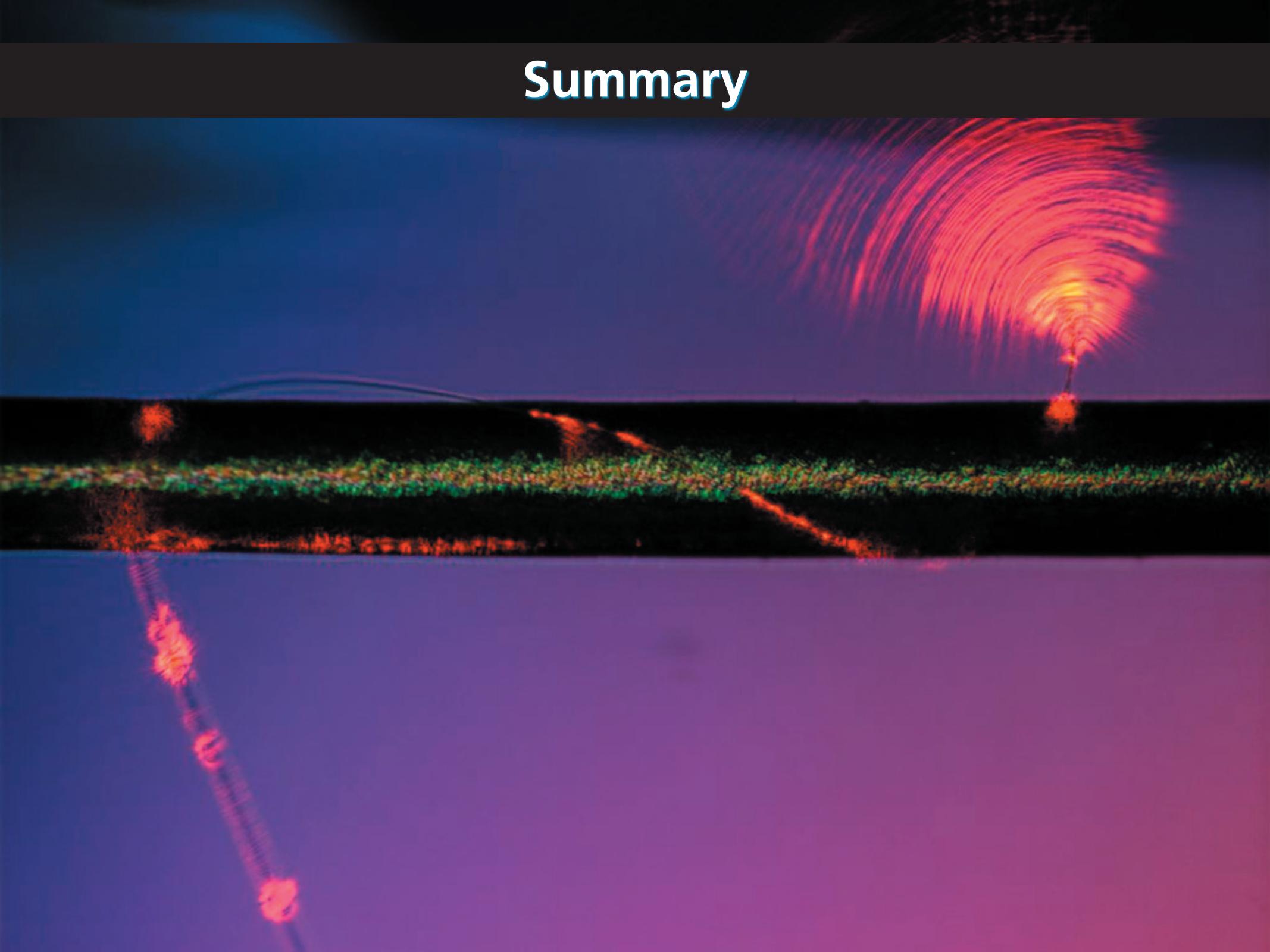


Optical properties

self-phase modulation



Summary



Summary

- strong confinement
- very tight bending
- large evanescent wave

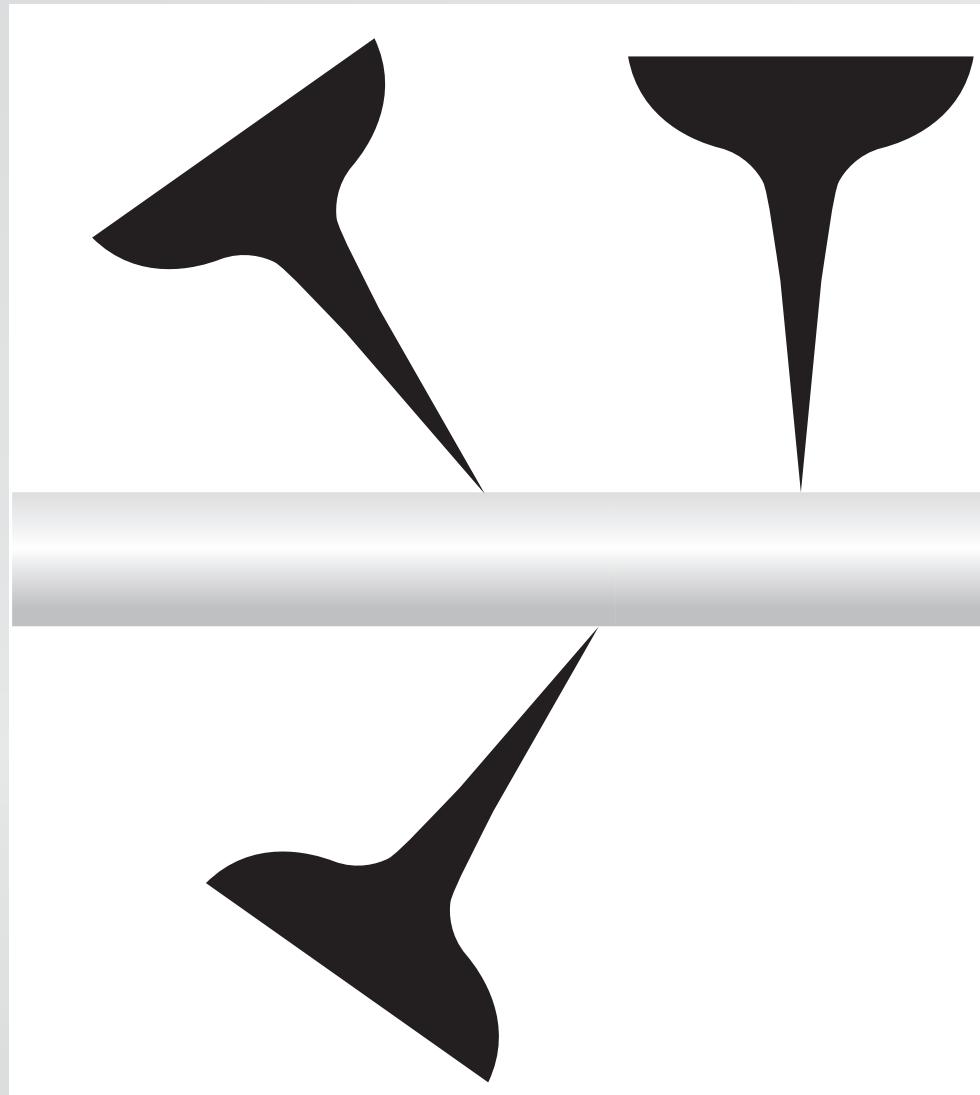
Outlook

microphtonic components



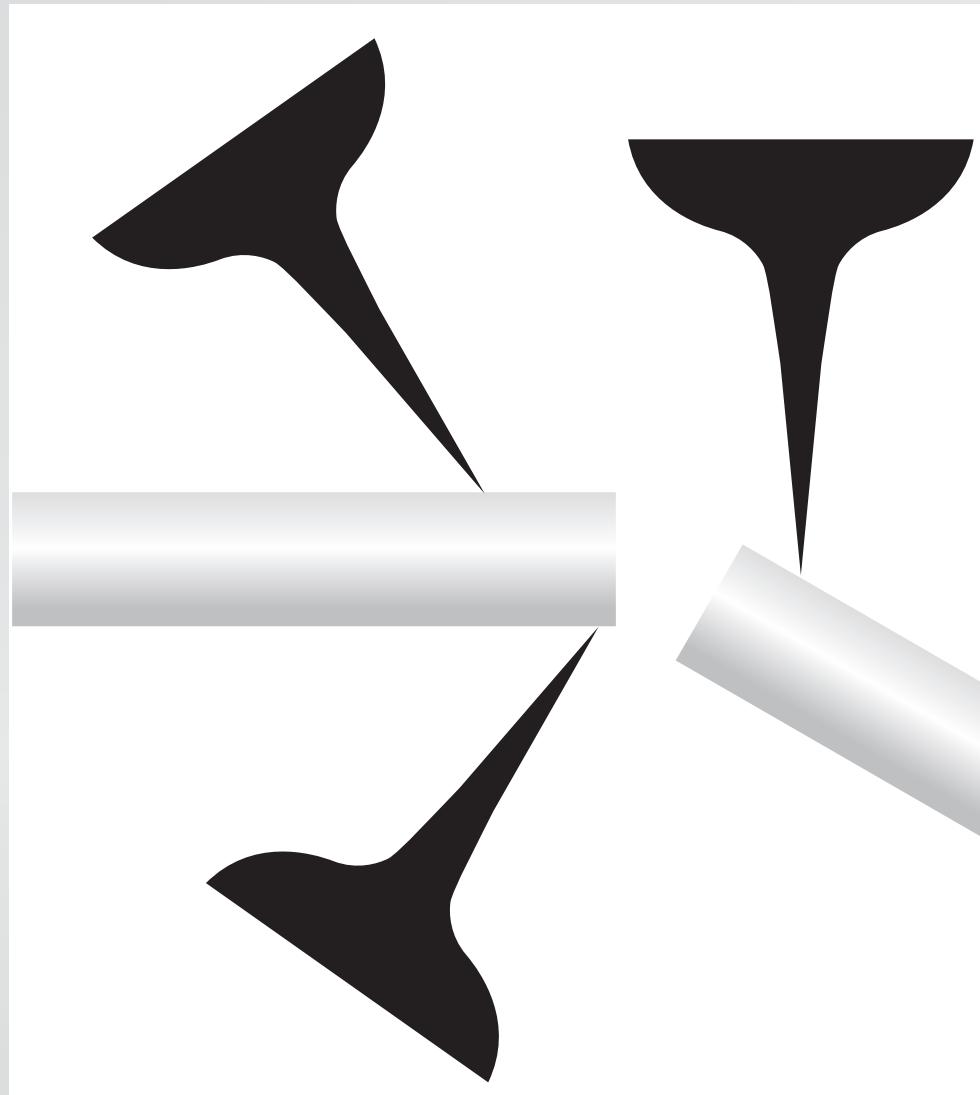
Outlook

microphotonic components



Outlook

microphotonic components



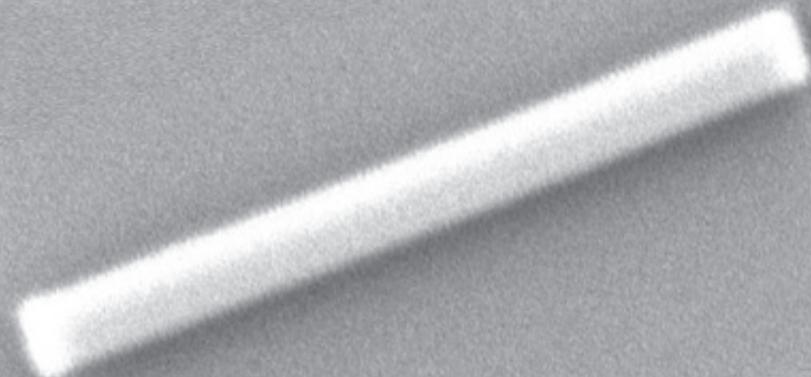
Outlook

1 μm

Outlook

500 nm

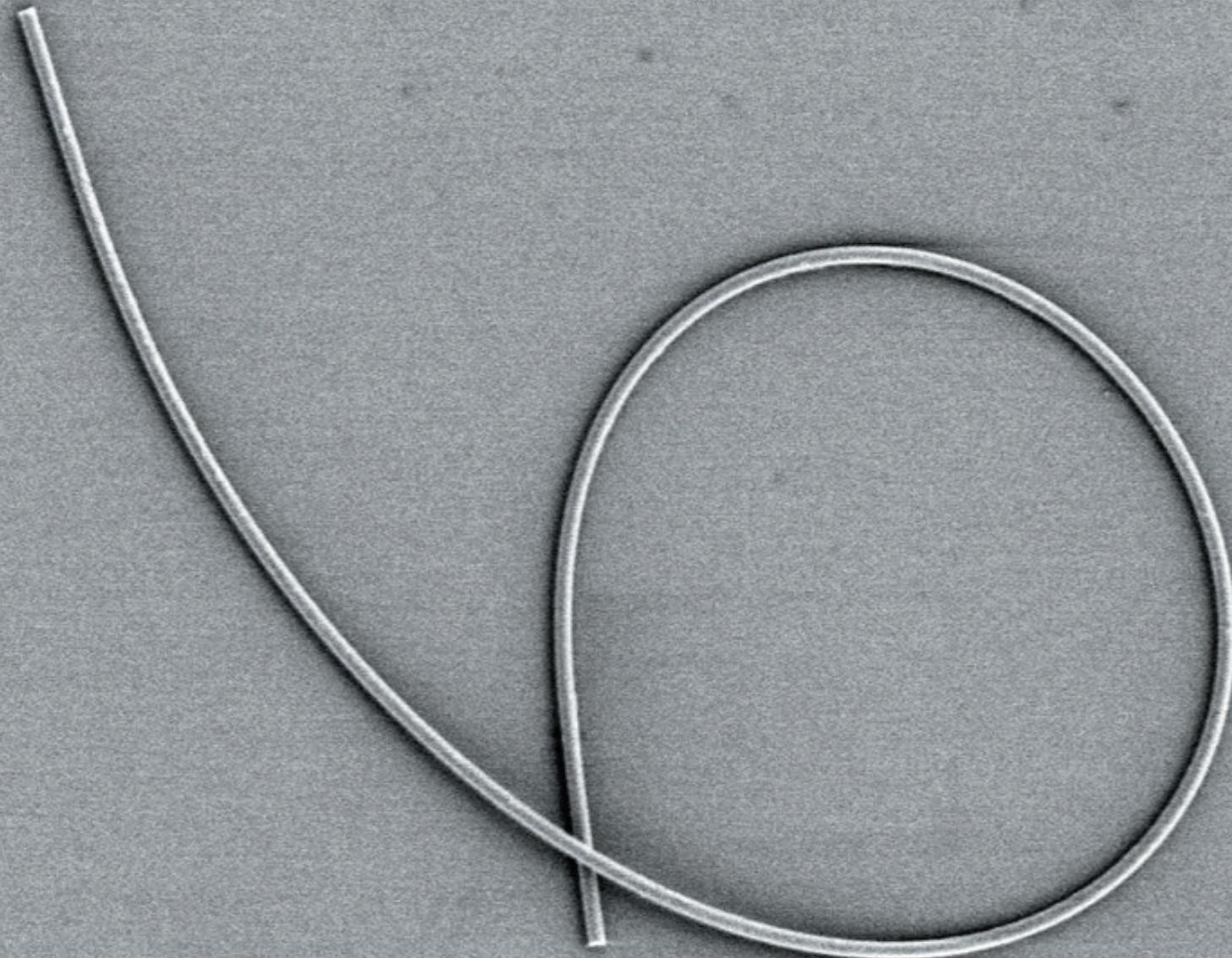
Outlook



500 nm

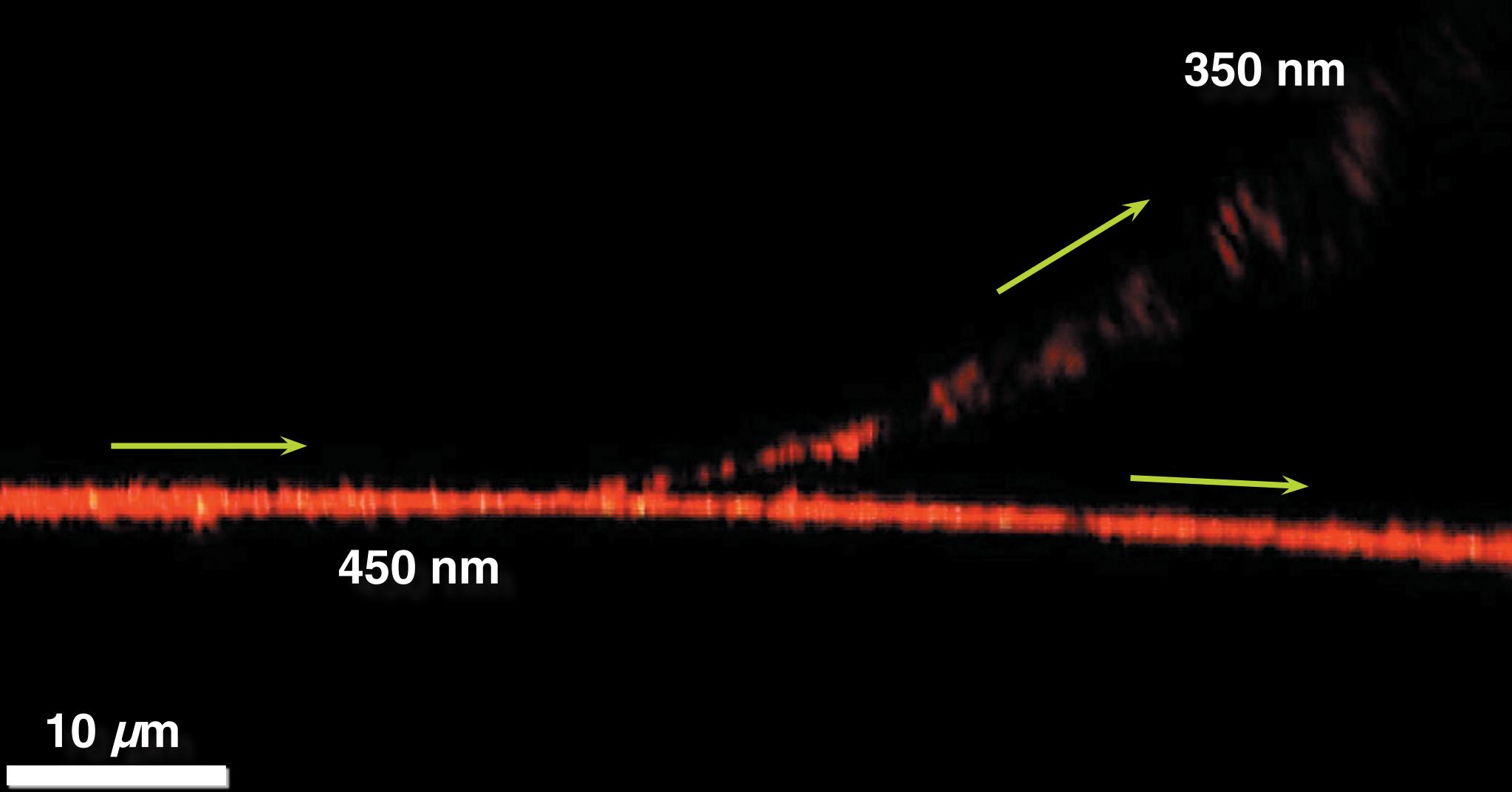


Outlook



3 μm

Outlook



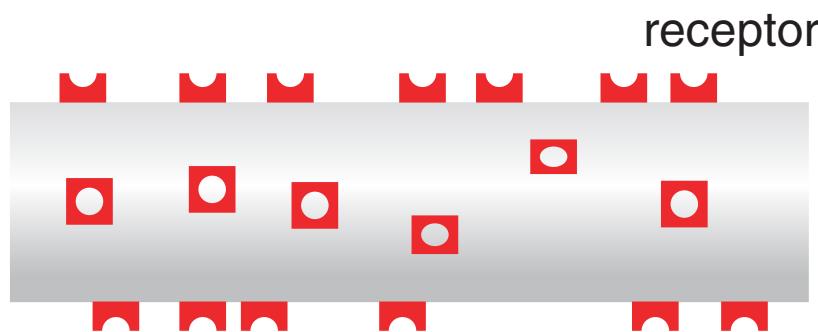
Outlook

biosensor



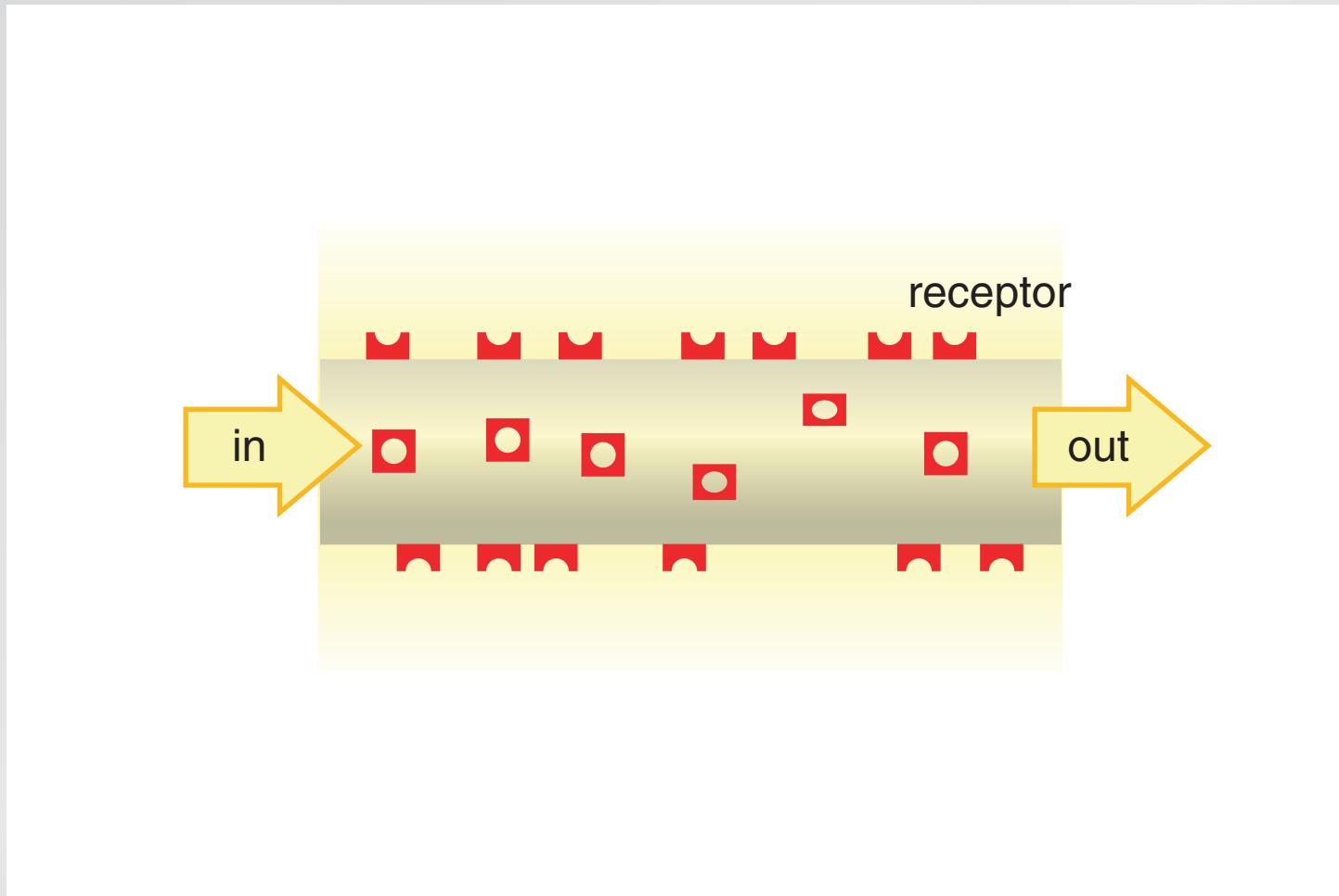
Outlook

biosensor



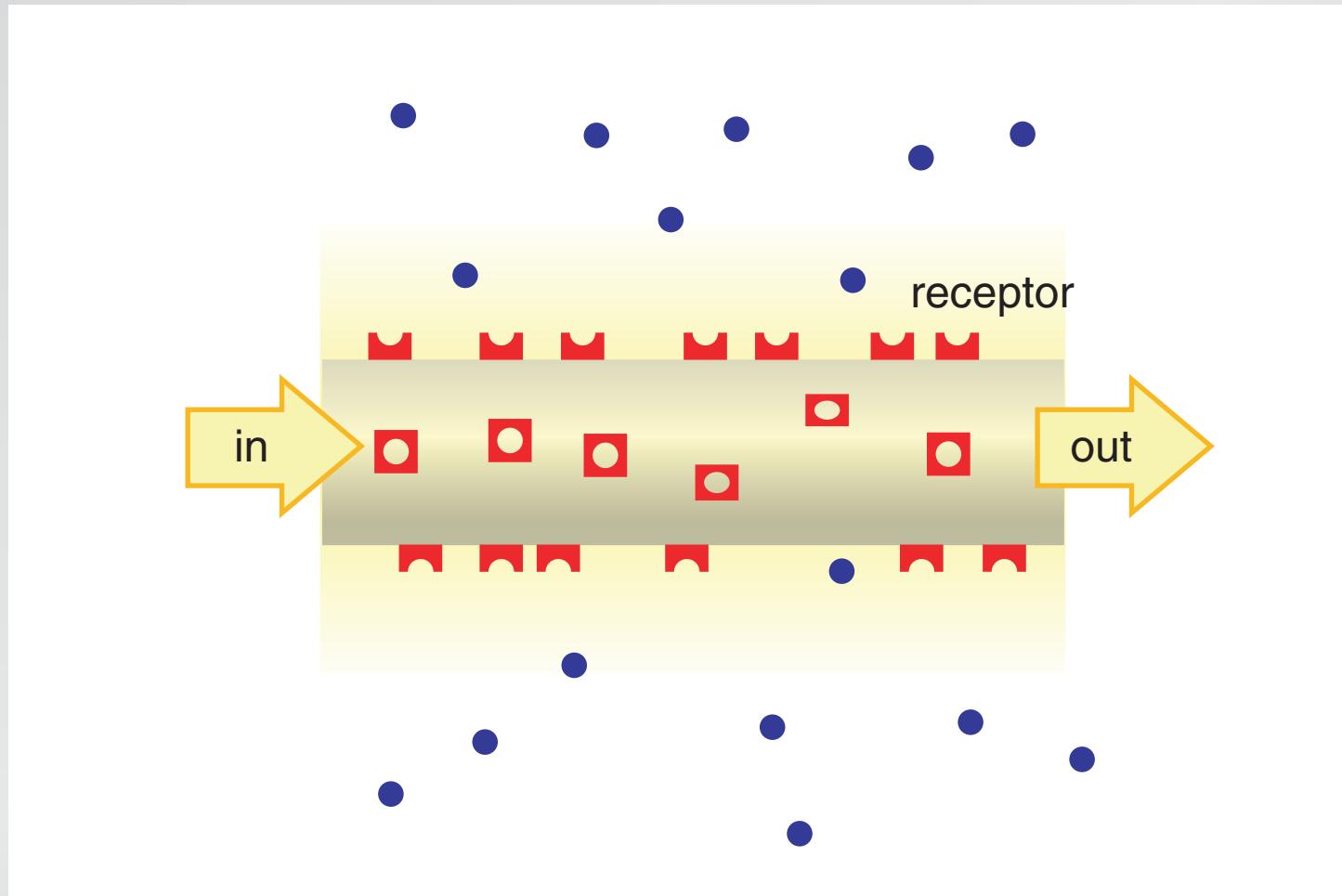
Outlook

biosensor



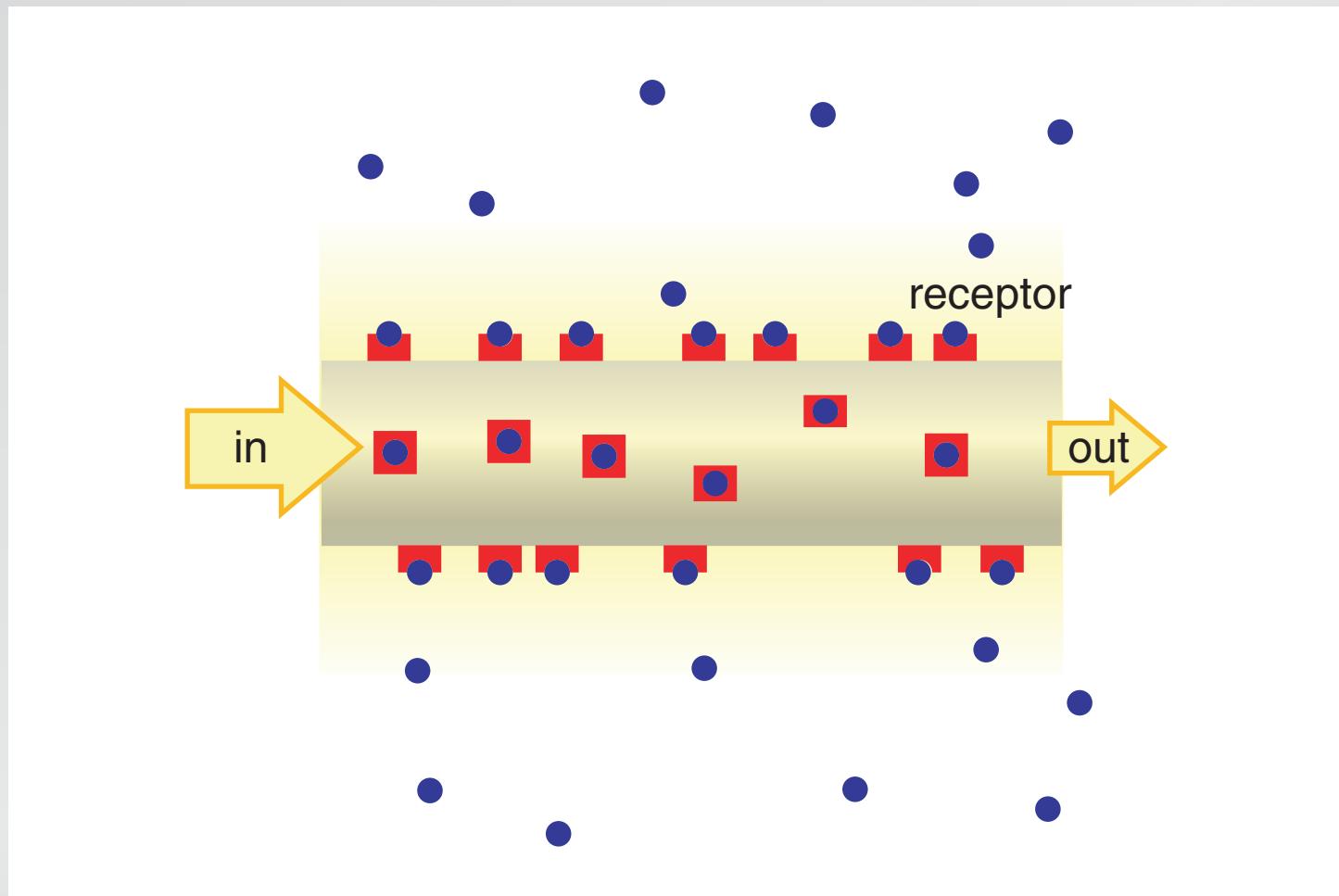
Outlook

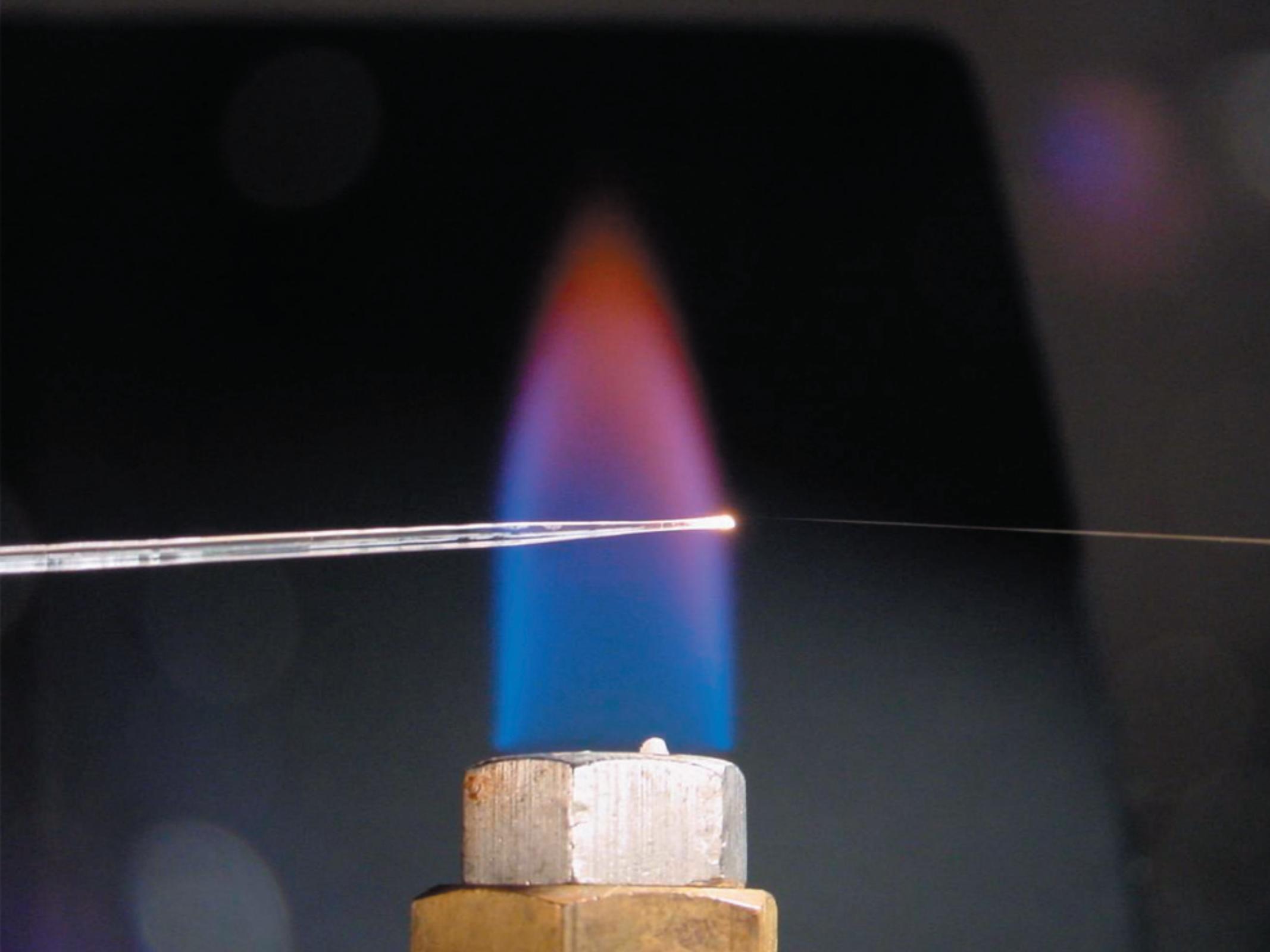
biosensor



Outlook

biosensor









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