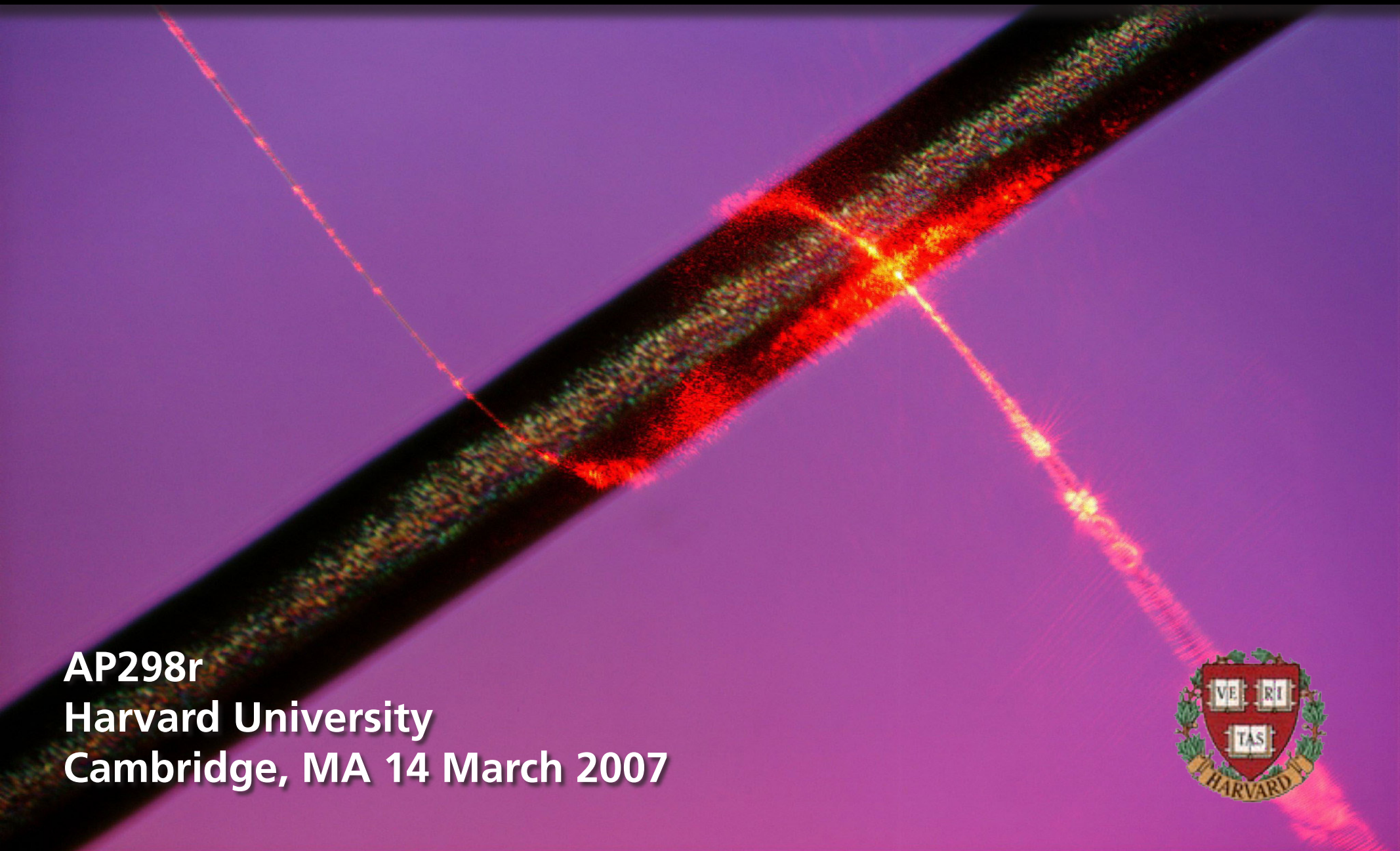
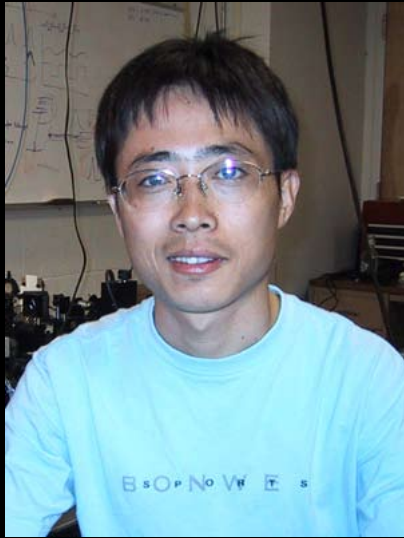


Manipulating light at the nanoscale



AP298r
Harvard University
Cambridge, MA 14 March 2007





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)

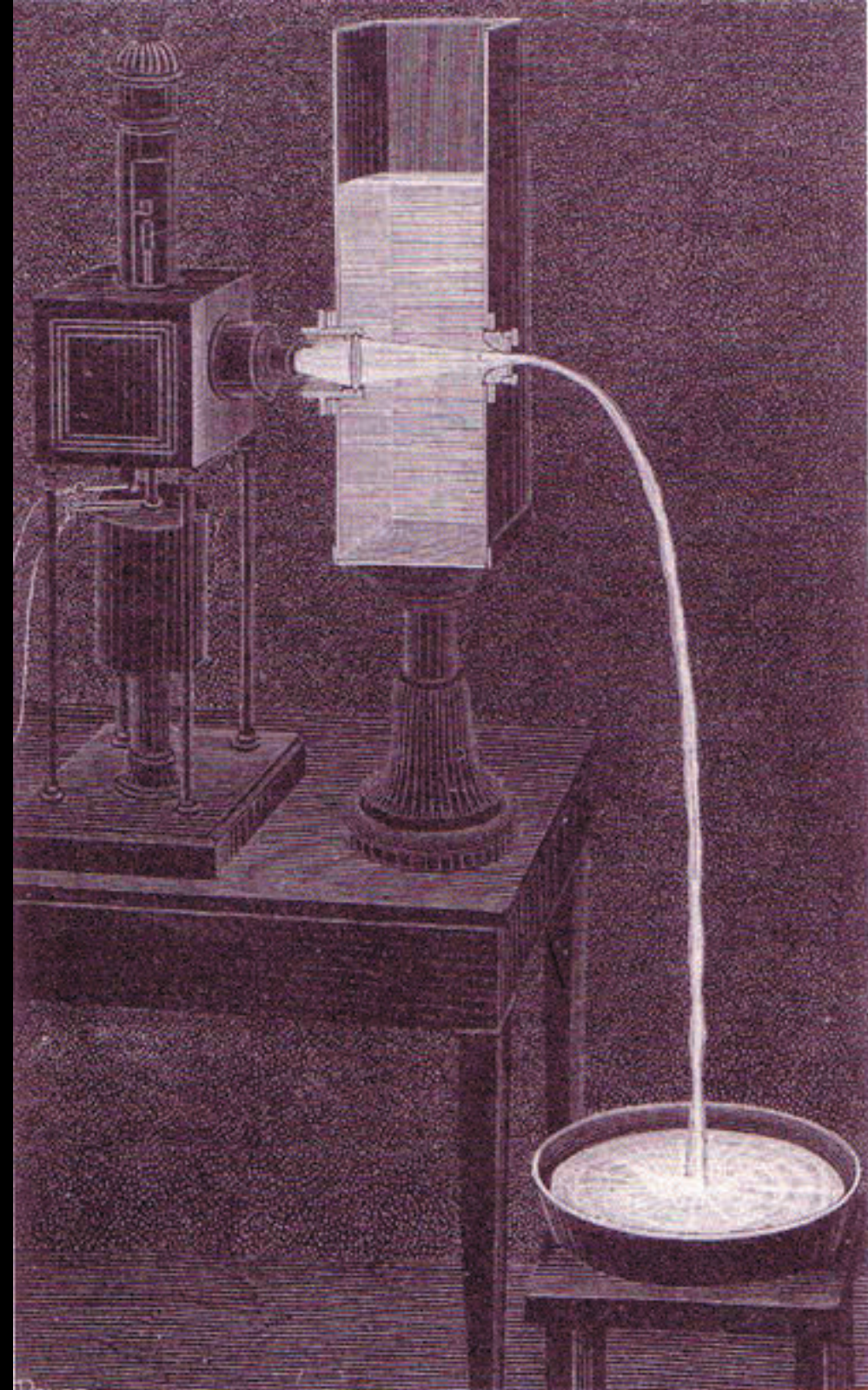
Dr. Jingyi Lou (Zhejiang University)

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.

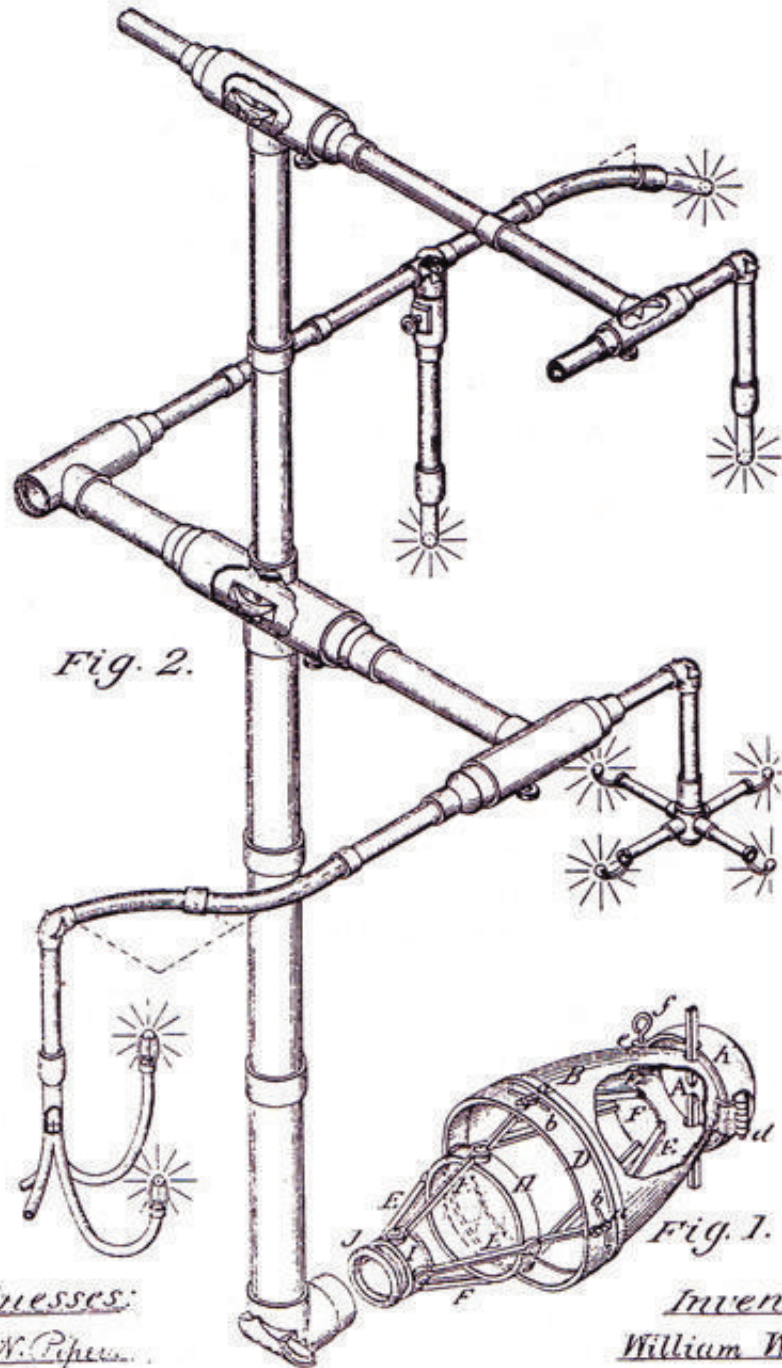


Fig. 2.

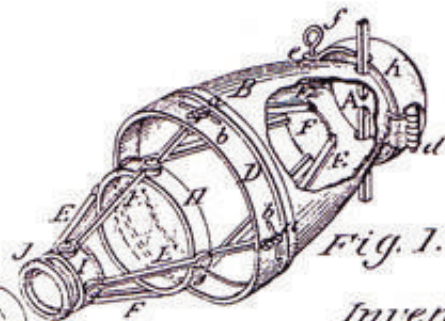


Fig. 1.

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

Inventor:
William Wheeler
 by attorney
[unclear]

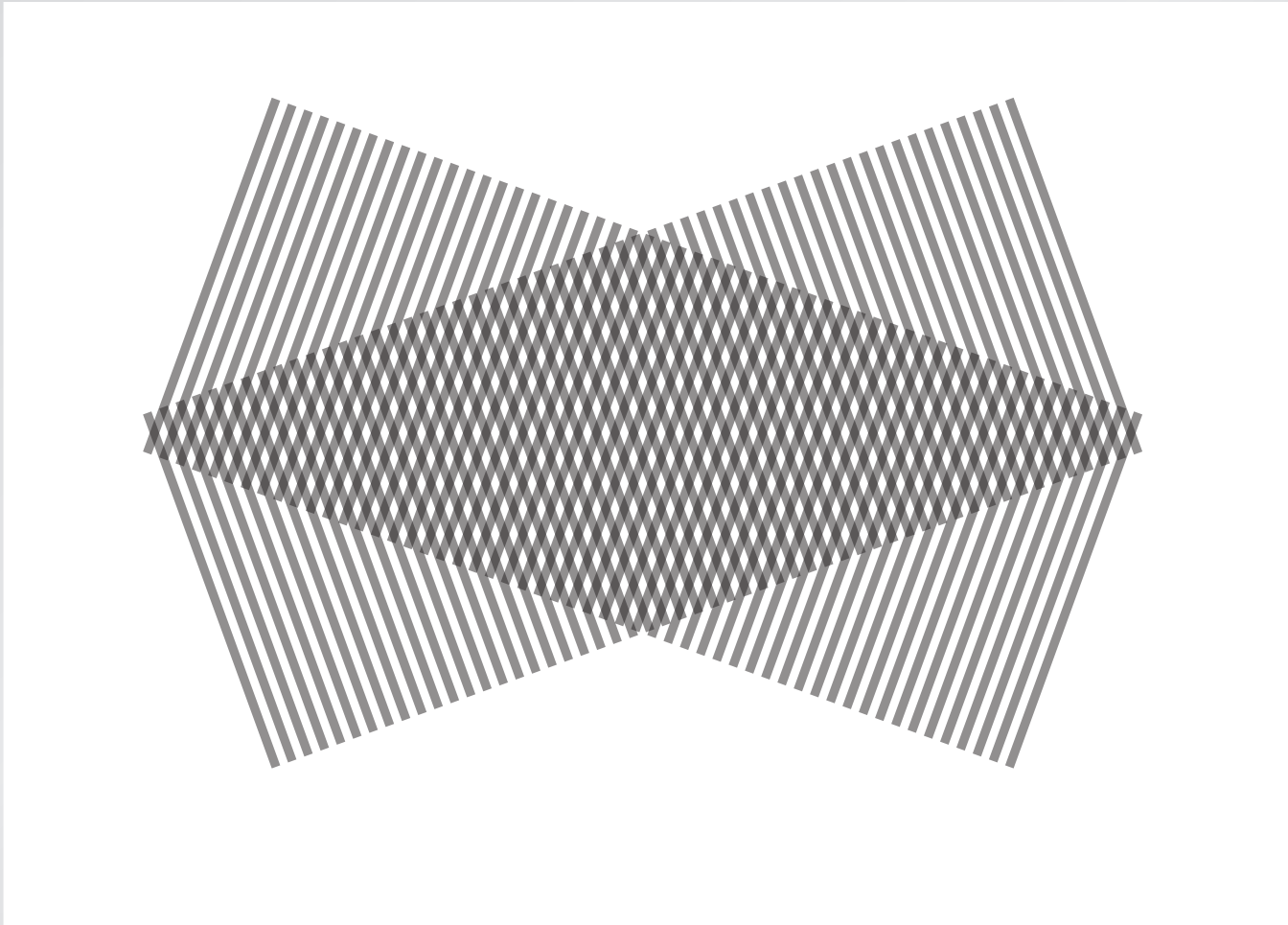
US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

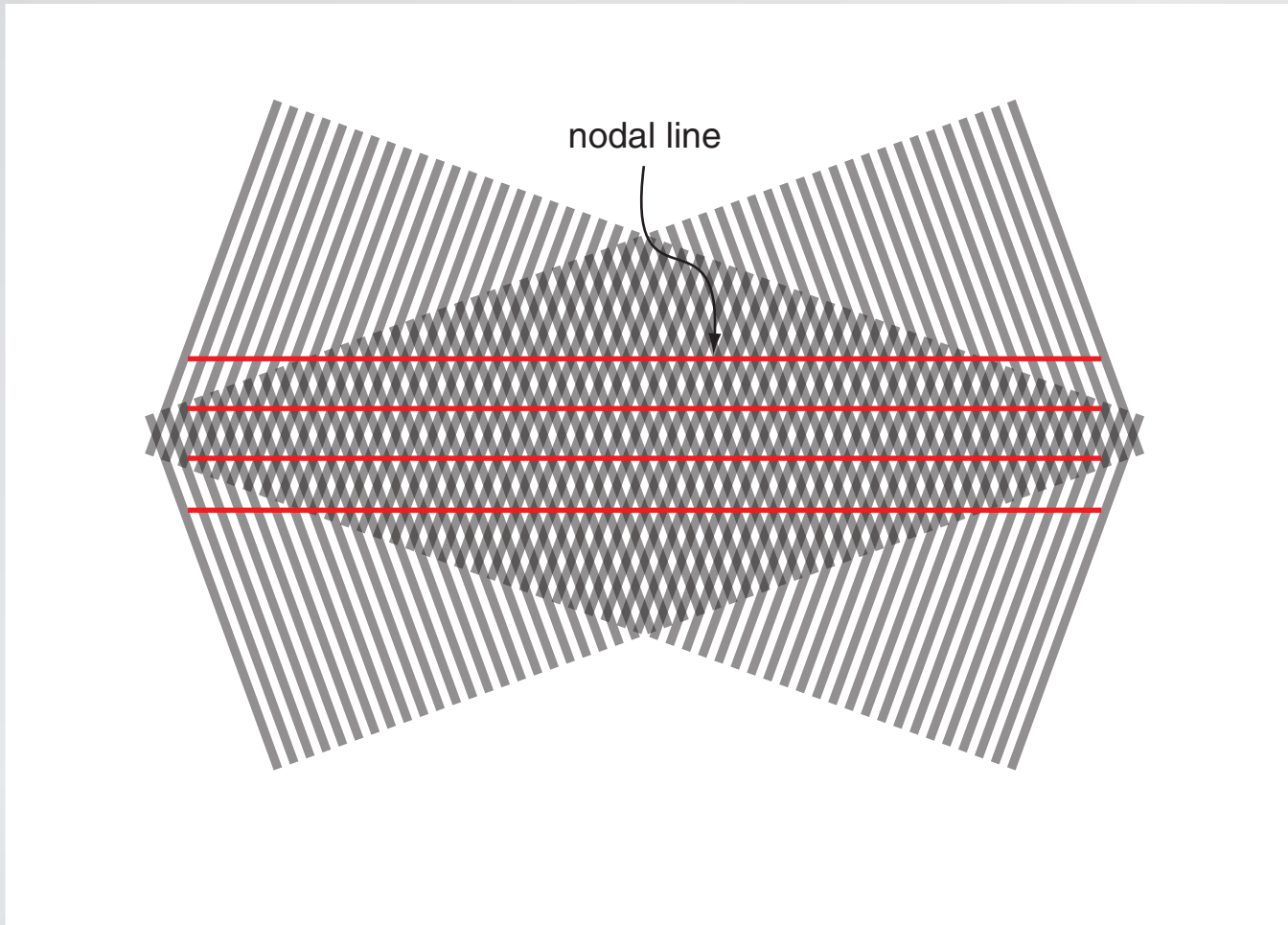
Waveguiding

two crossed planar waves...



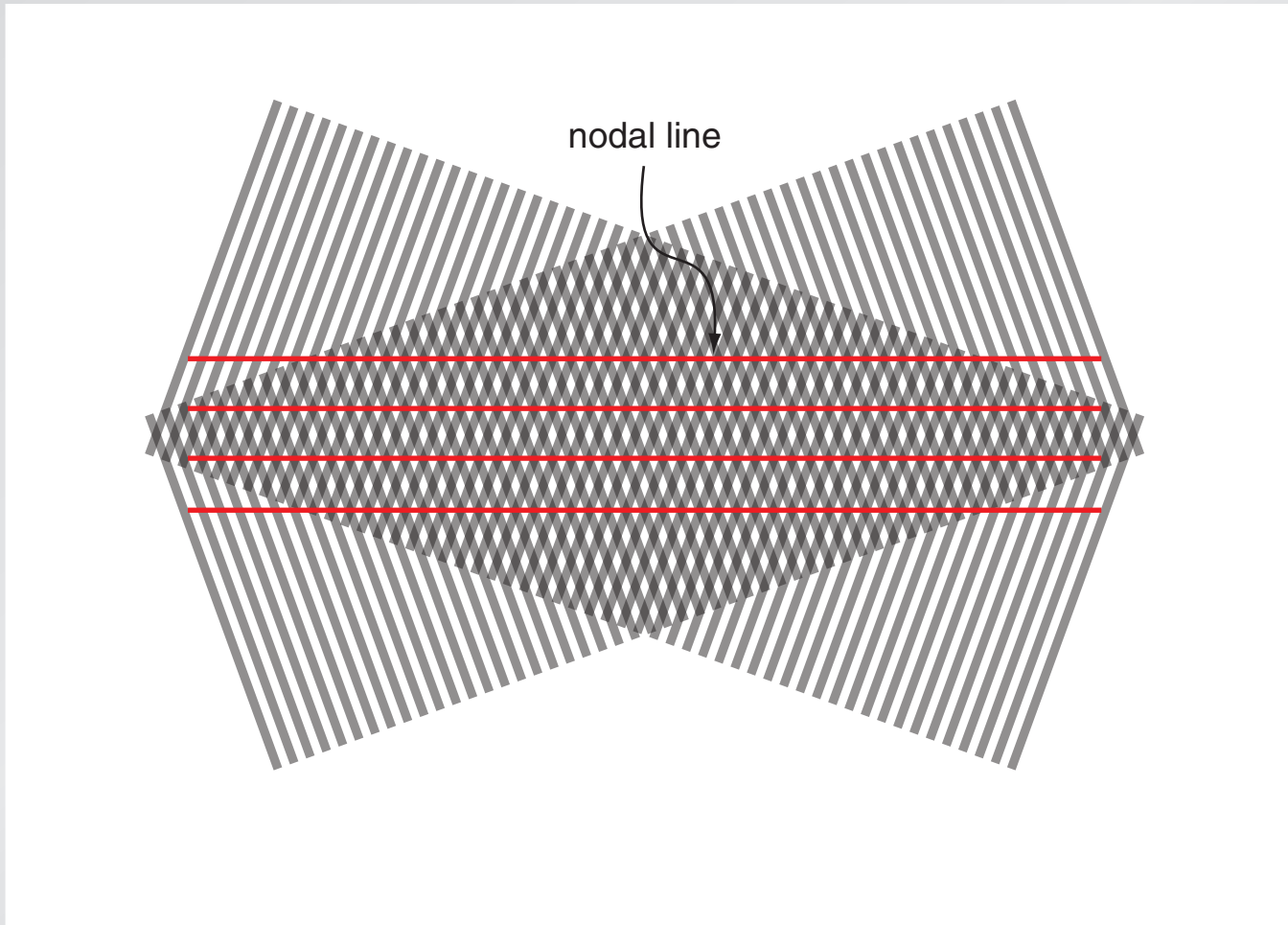
Waveguiding

...cause an interference pattern



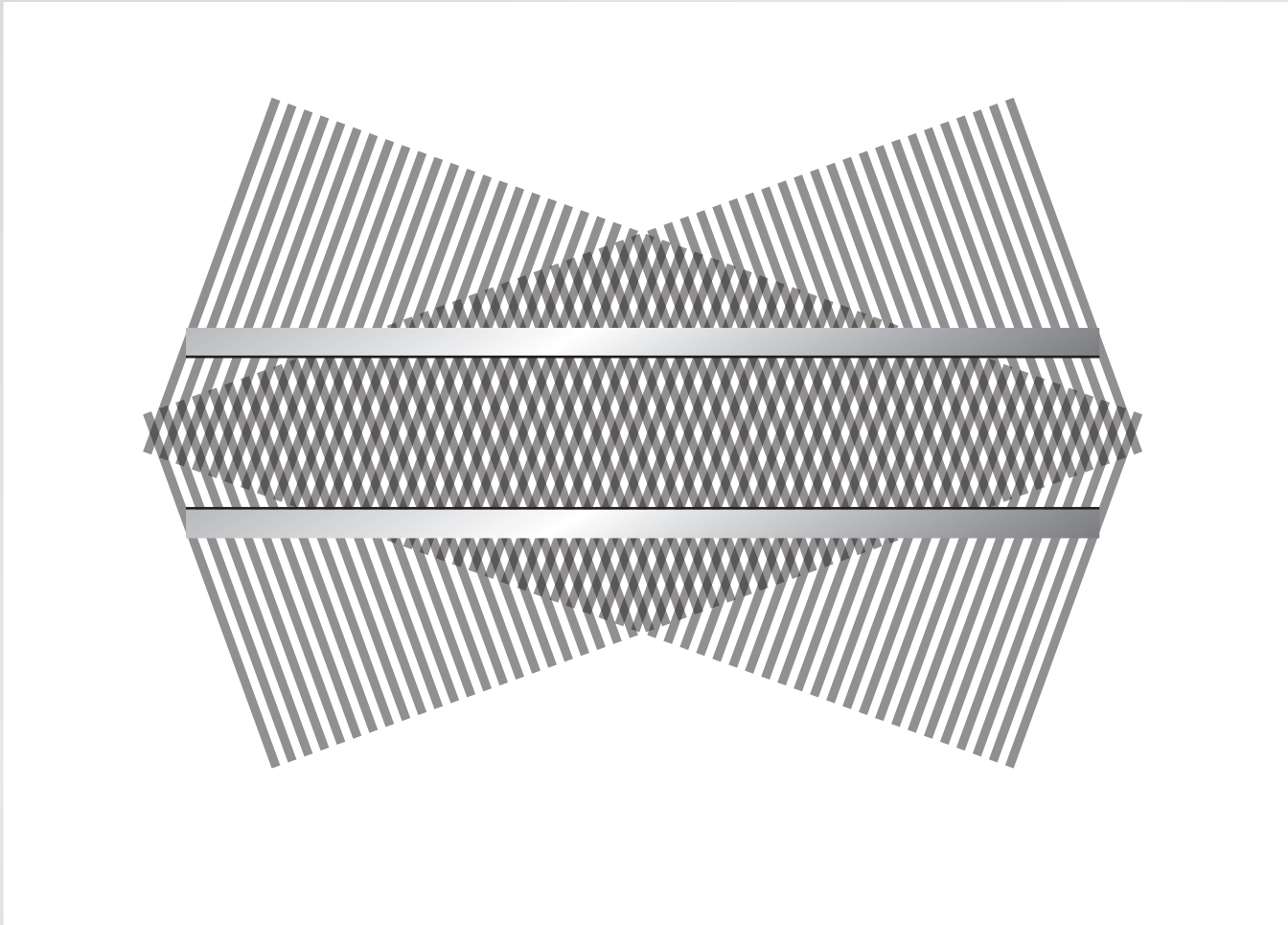
Waveguiding

$E = 0$ on the nodal lines



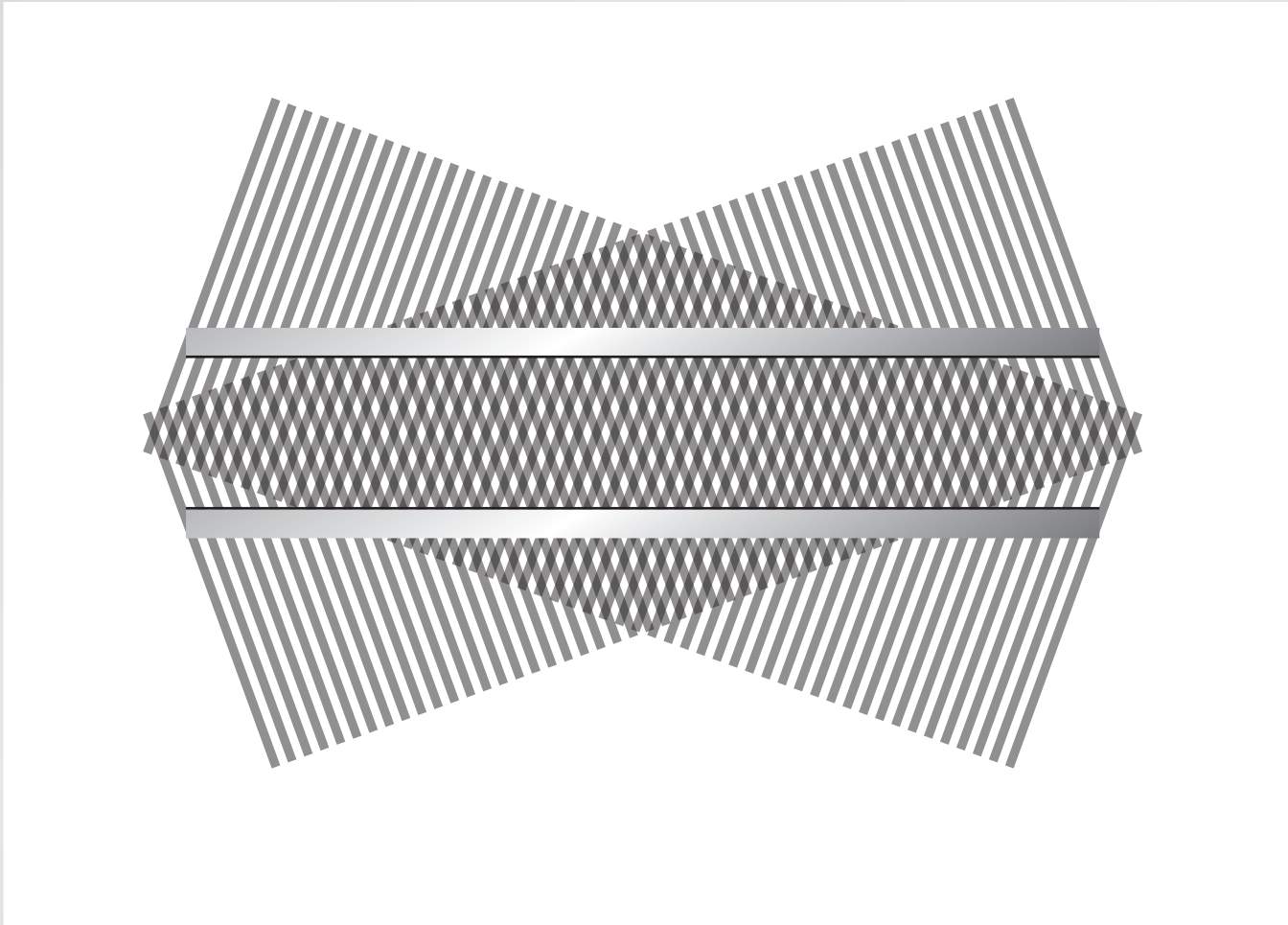
Waveguiding

...satisfying boundary conditions for planar-mirror waveguide



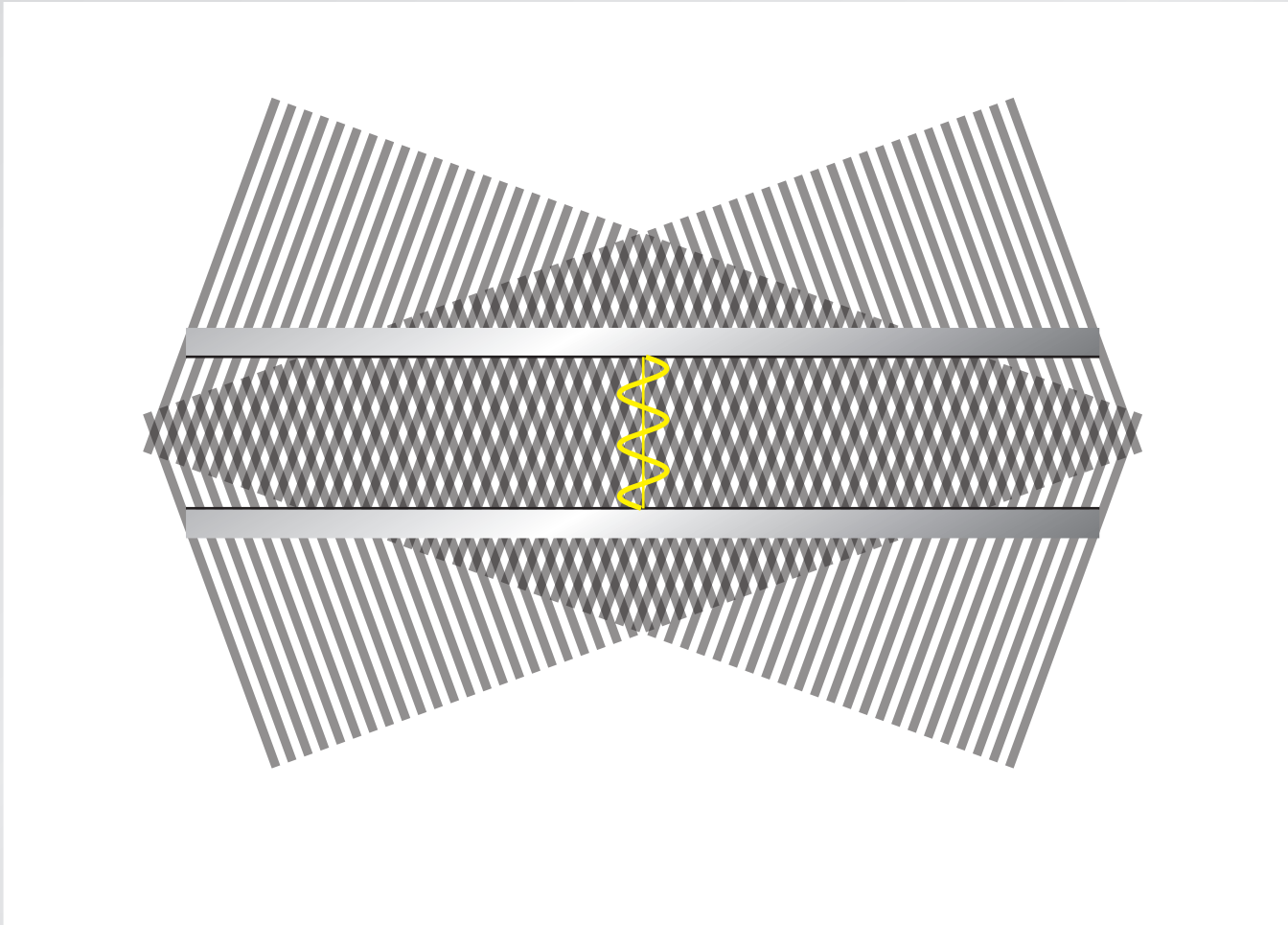
Waveguiding

transverse standing wave, traveling along axis



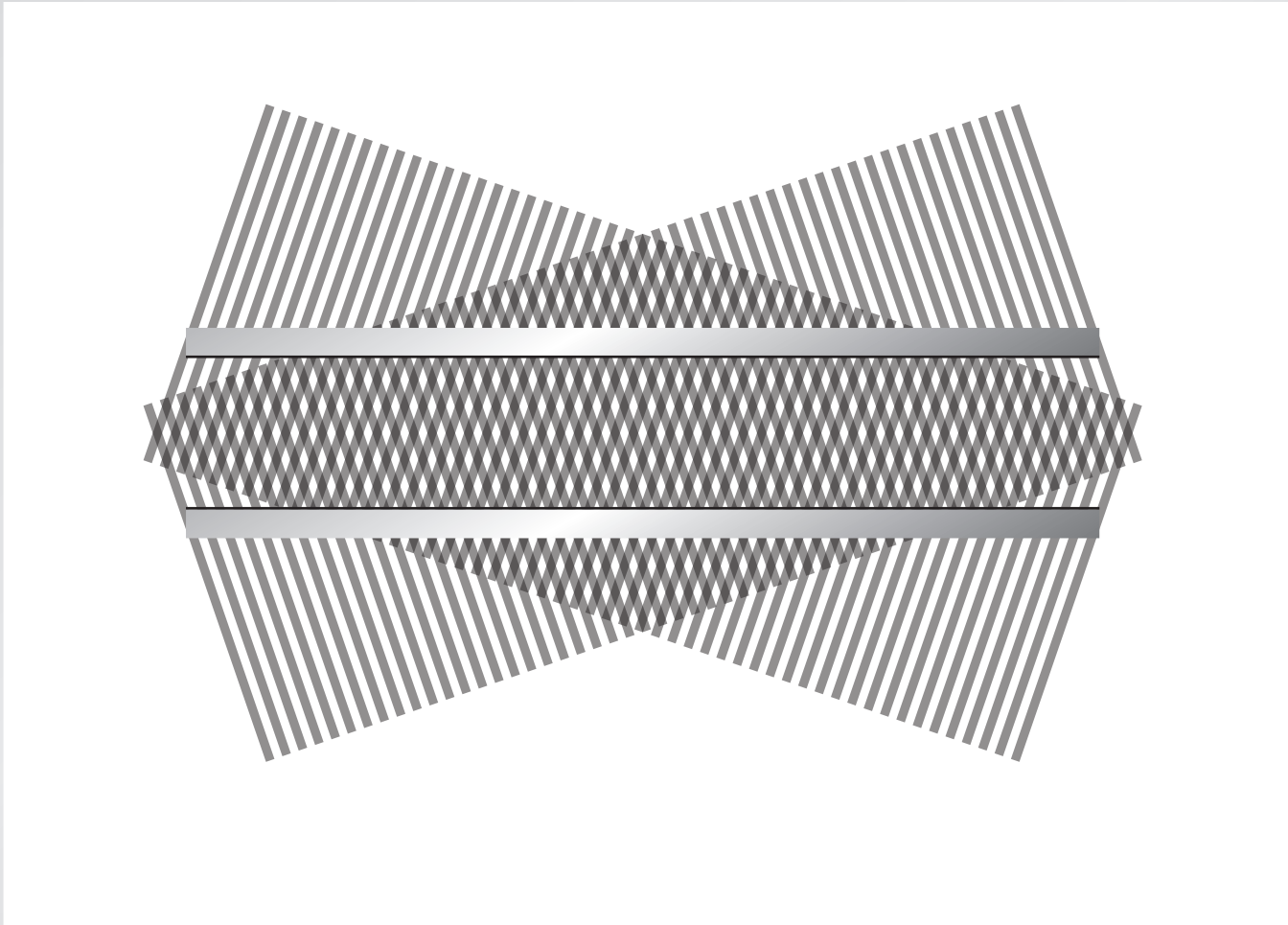
Waveguiding

transverse standing wave, traveling along axis



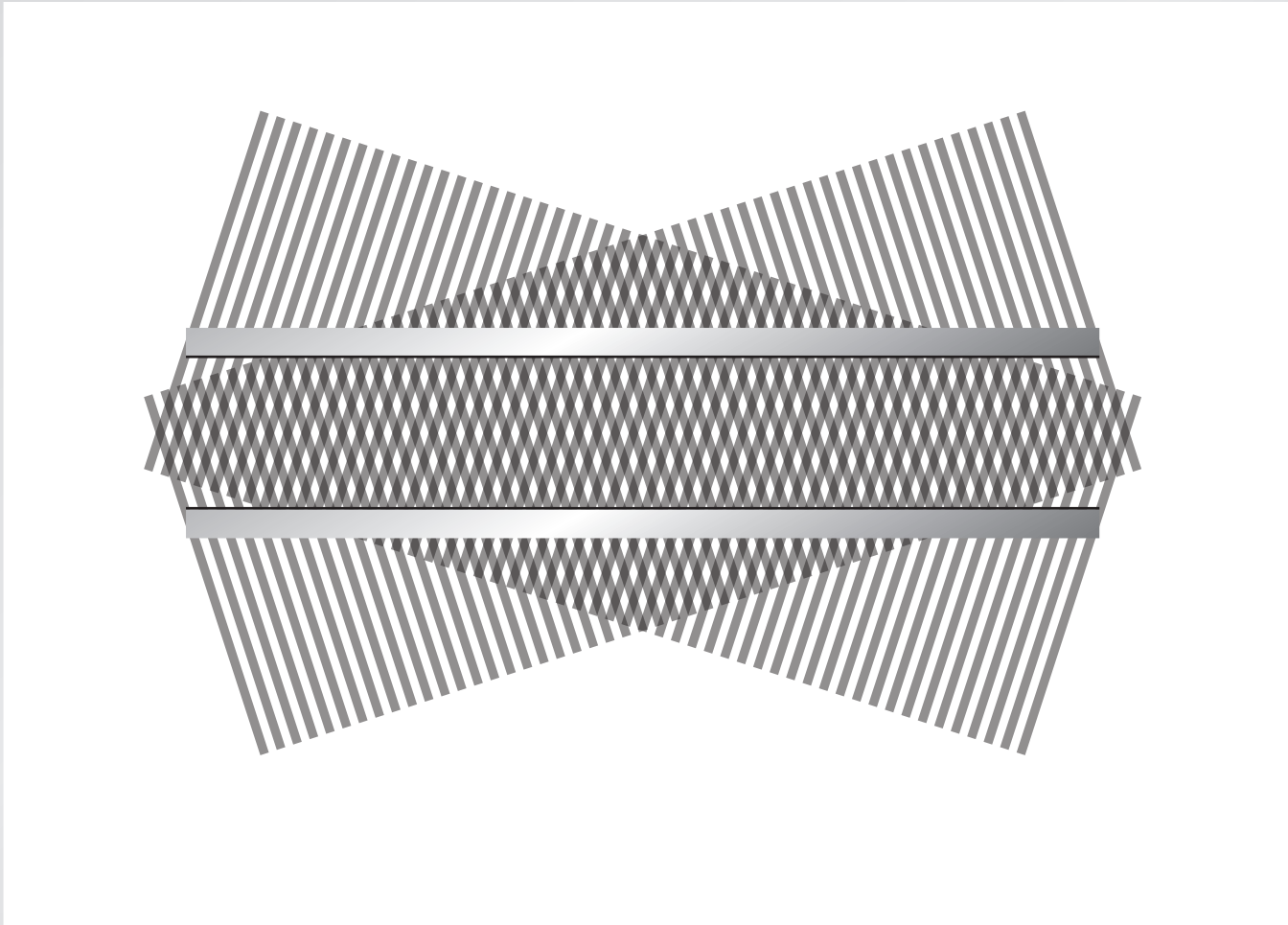
Waveguiding

change angle of incident waves...



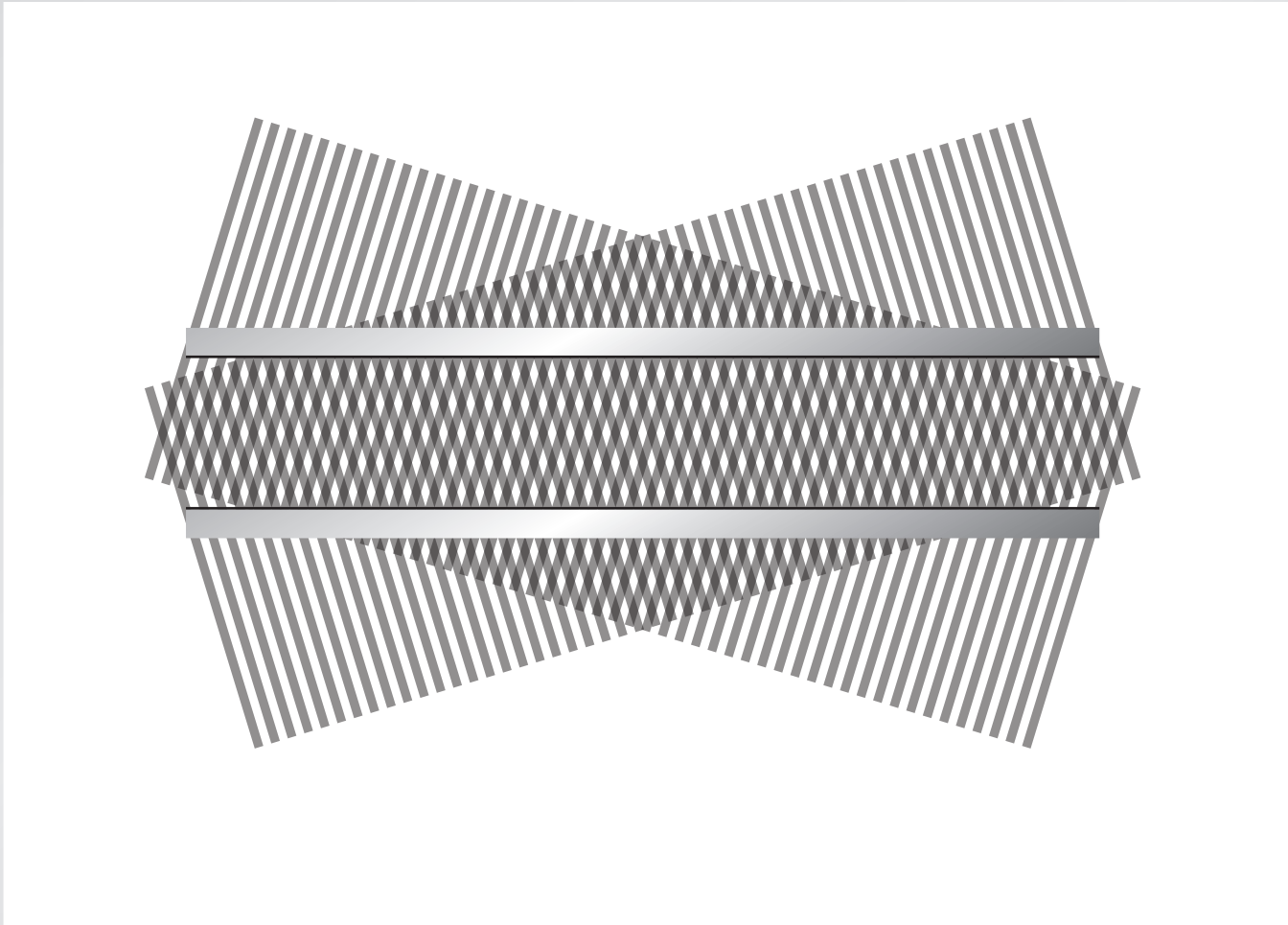
Waveguiding

change angle of incident waves...



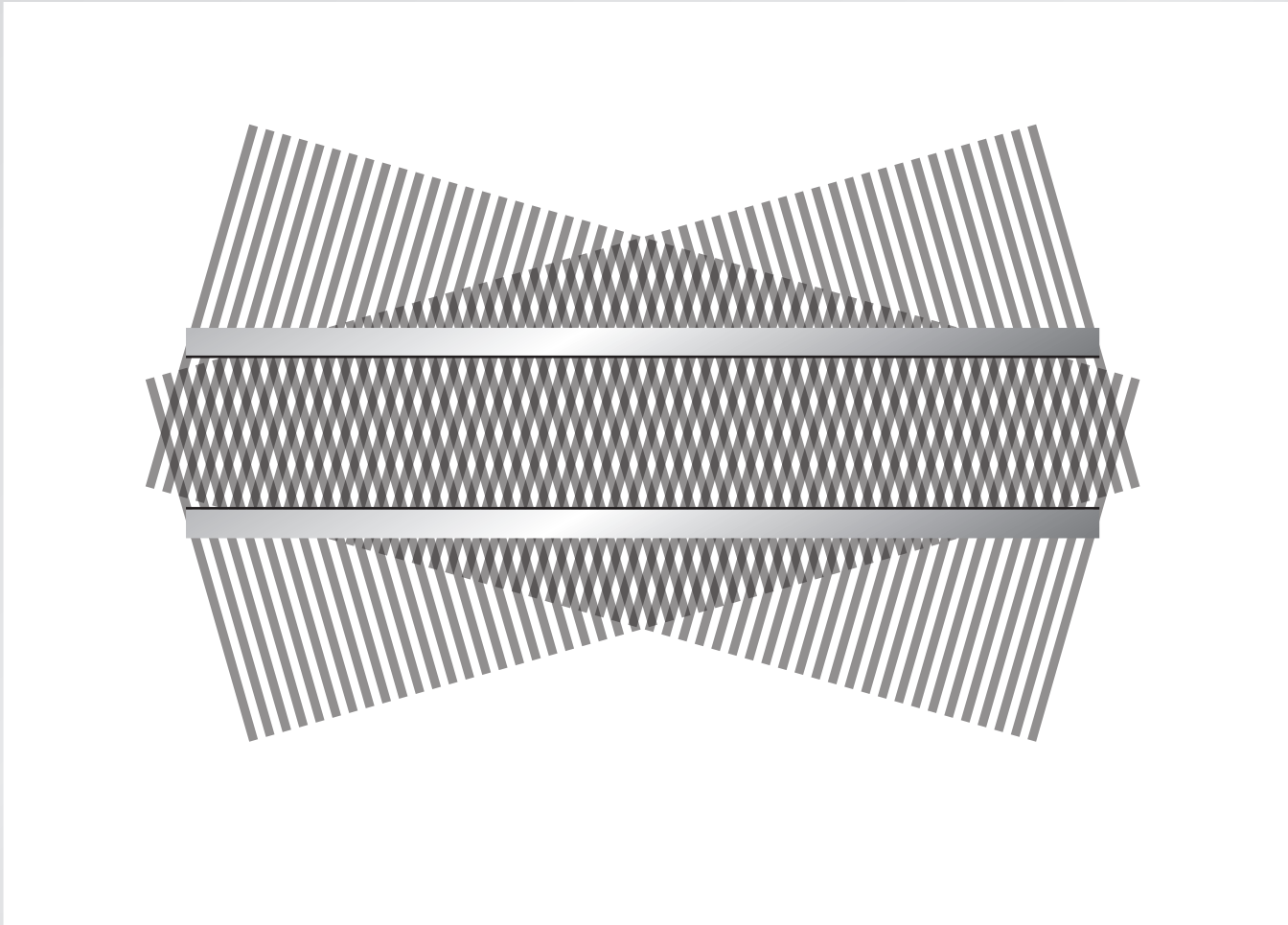
Waveguiding

change angle of incident waves...



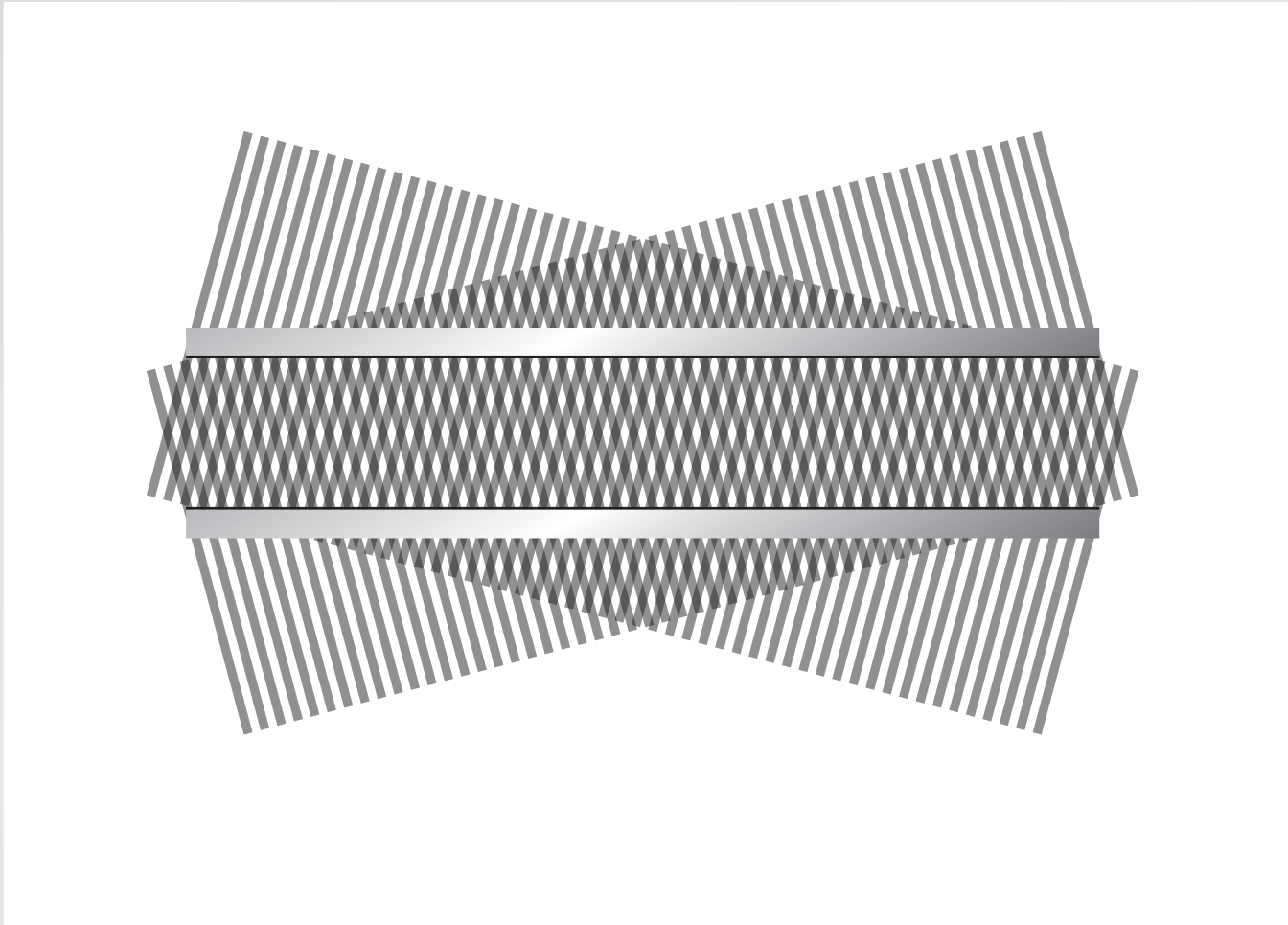
Waveguiding

change angle of incident waves...



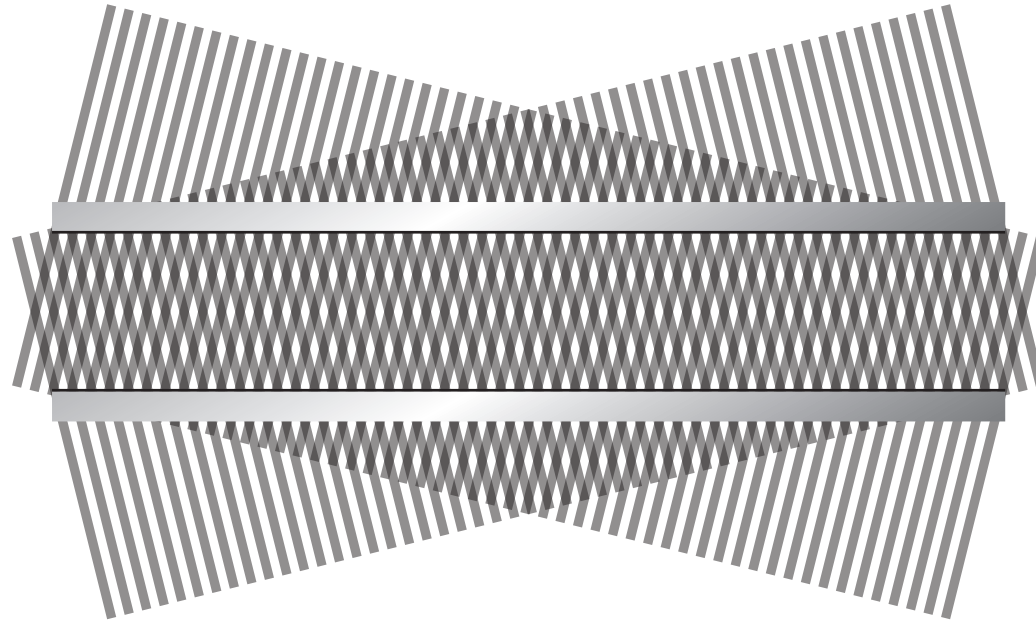
Waveguiding

change angle of incident waves...



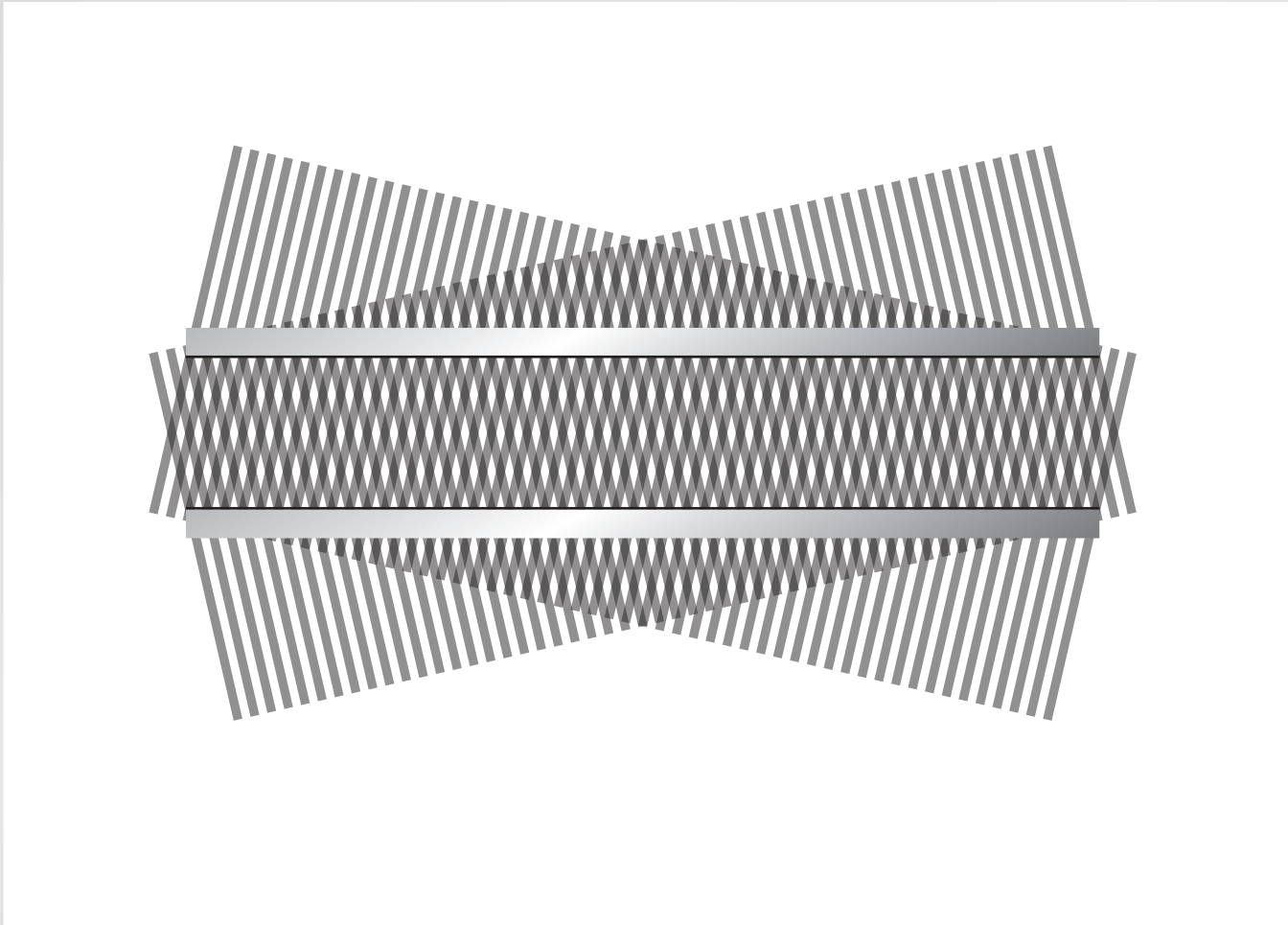
Waveguiding

change angle of incident waves...



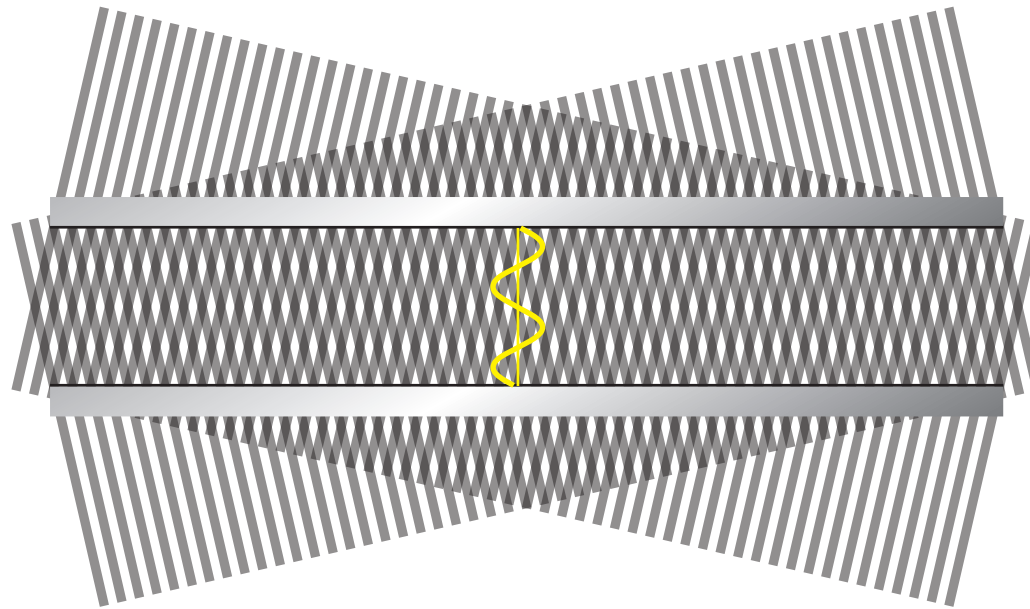
Waveguiding

change angle of incident waves...



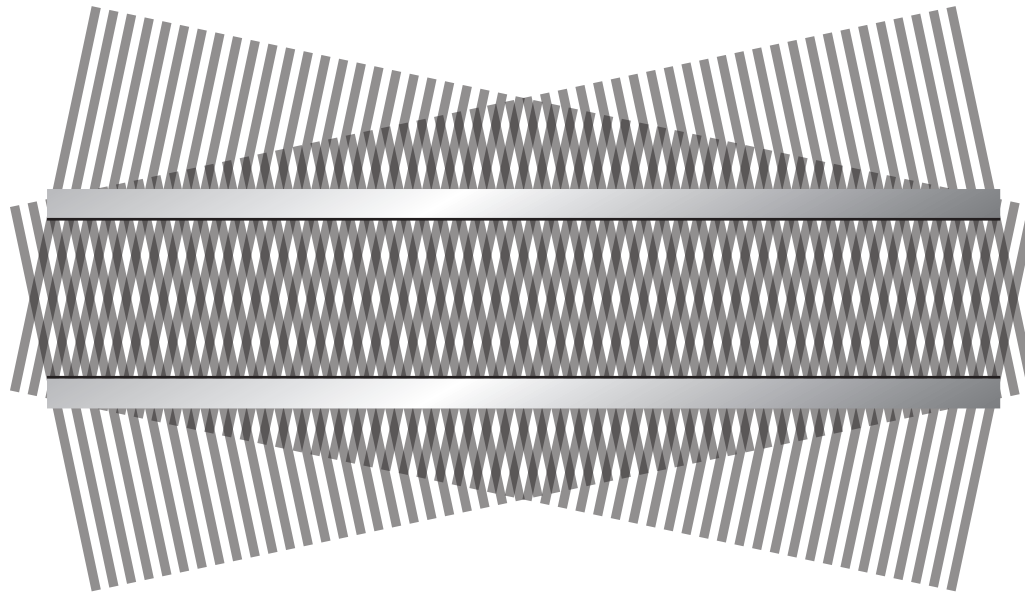
Waveguiding

change angle of incident waves...



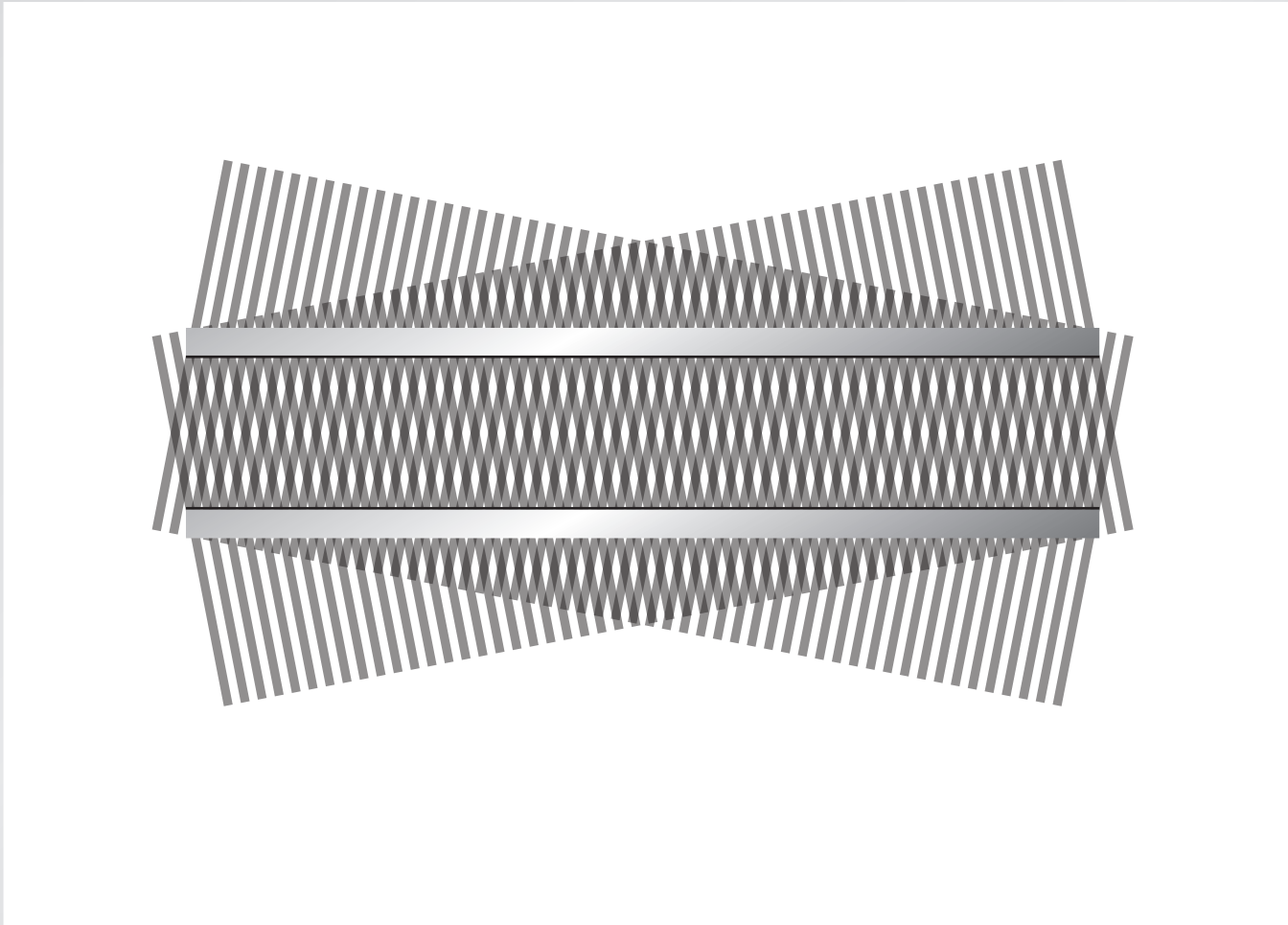
Waveguiding

change angle of incident waves...



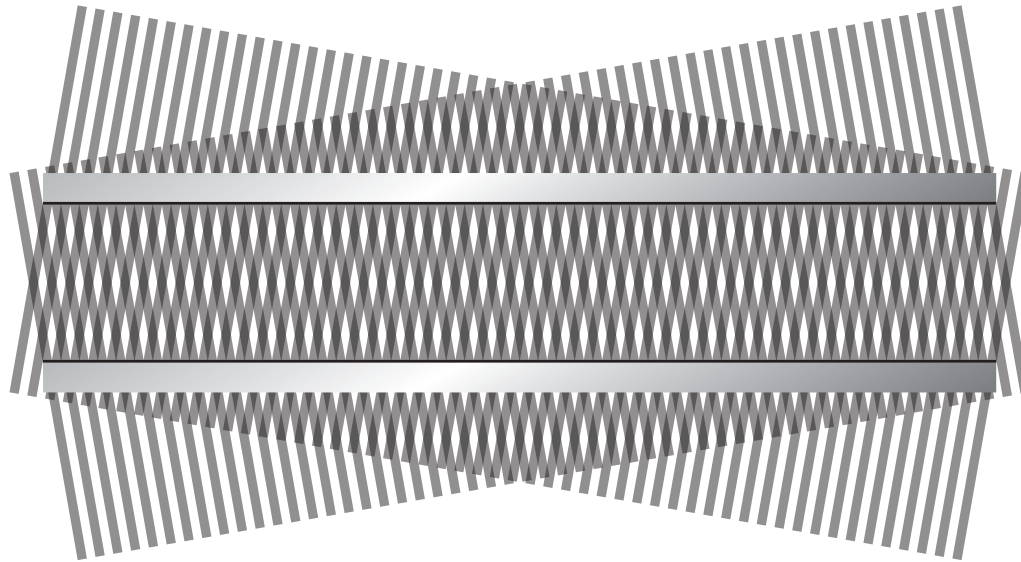
Waveguiding

change angle of incident waves...



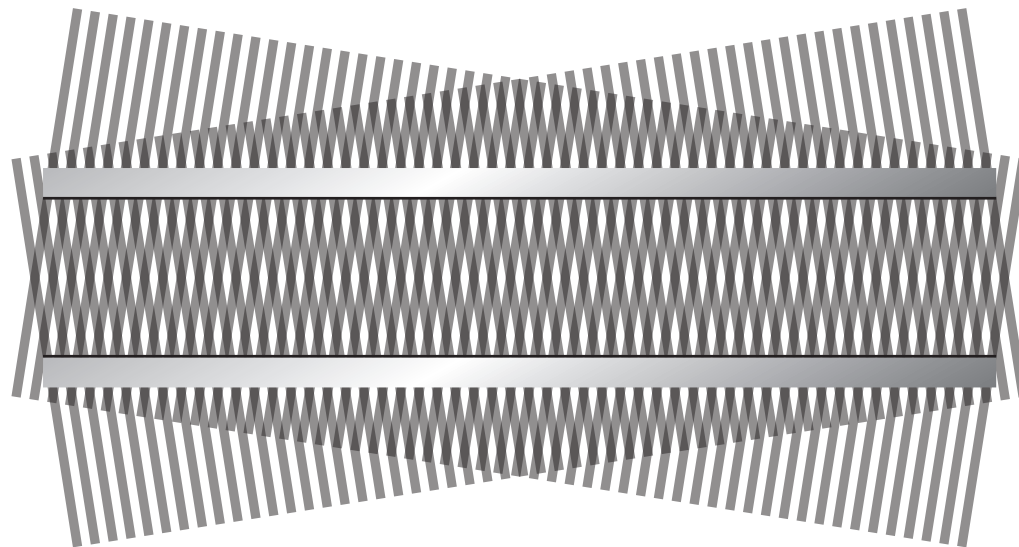
Waveguiding

change angle of incident waves...



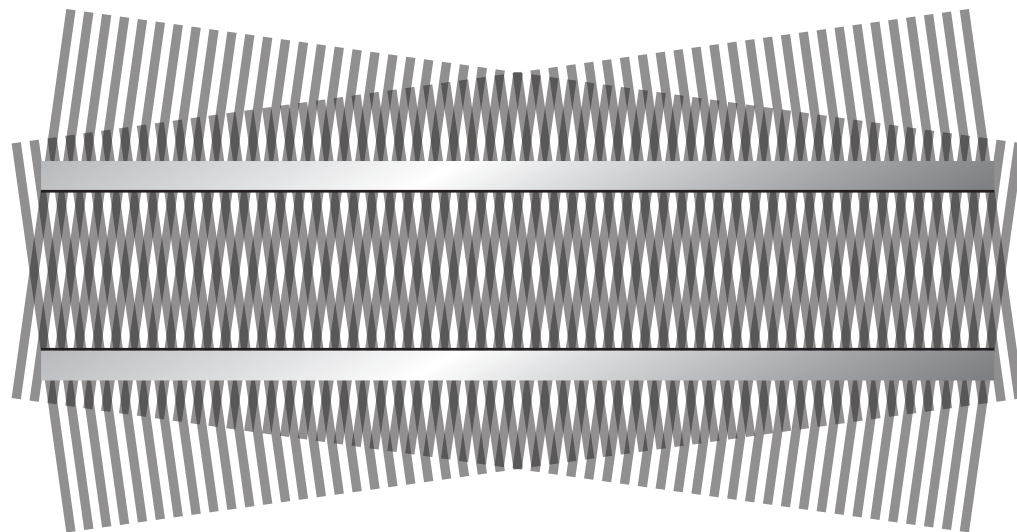
Waveguiding

change angle of incident waves...



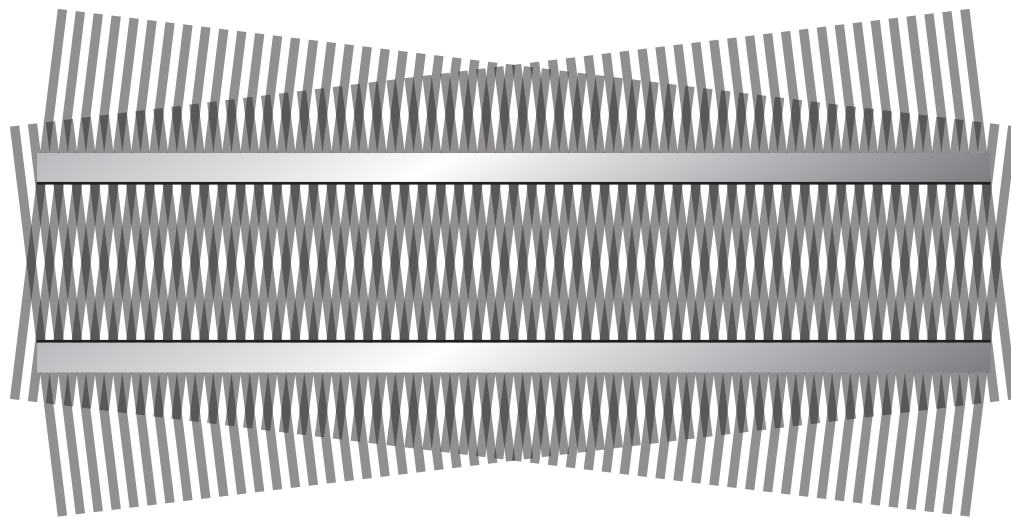
Waveguiding

change angle of incident waves...



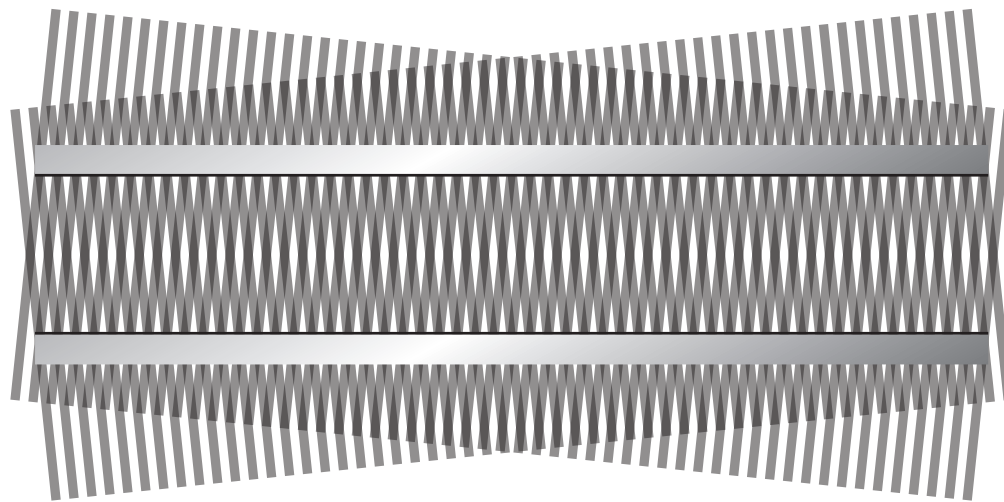
Waveguiding

change angle of incident waves...



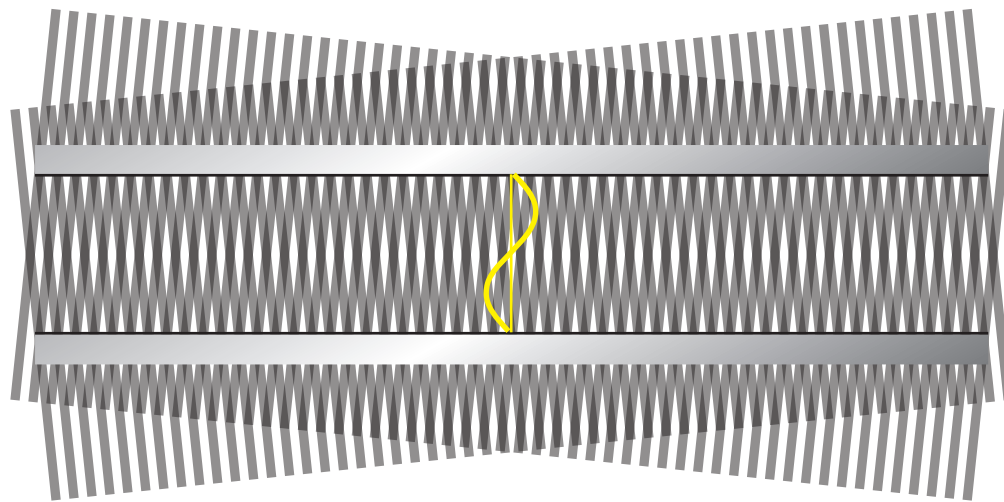
Waveguiding

change angle of incident waves...



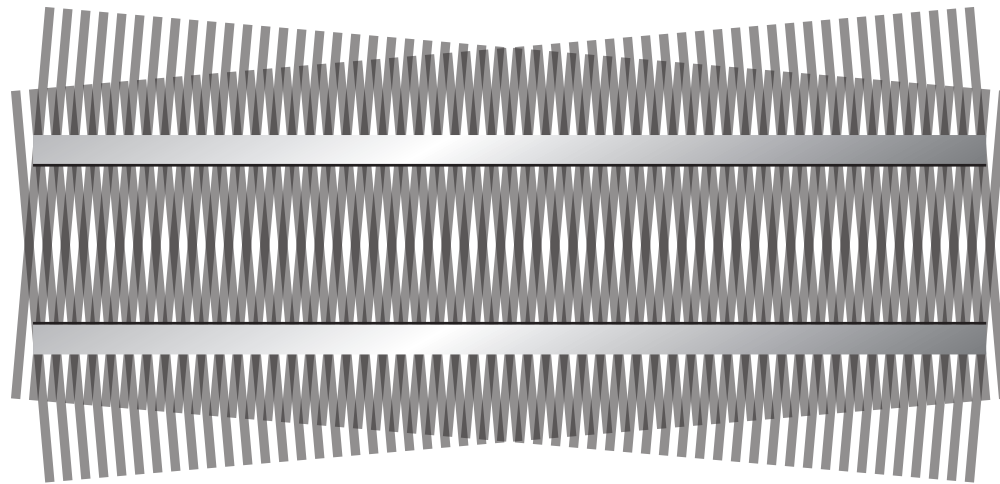
Waveguiding

change angle of incident waves...



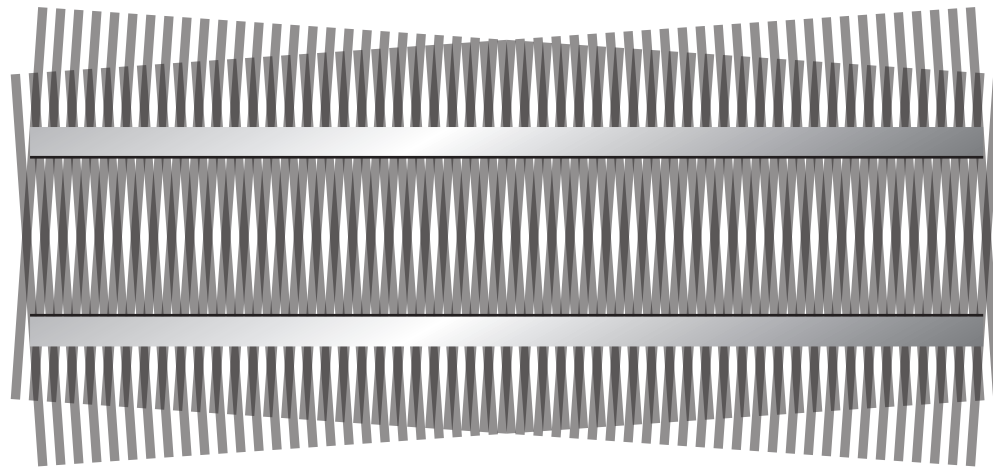
Waveguiding

change angle of incident waves...



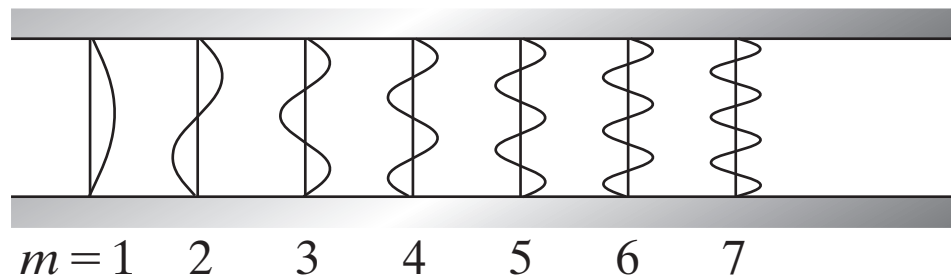
Waveguiding

change angle of incident waves...



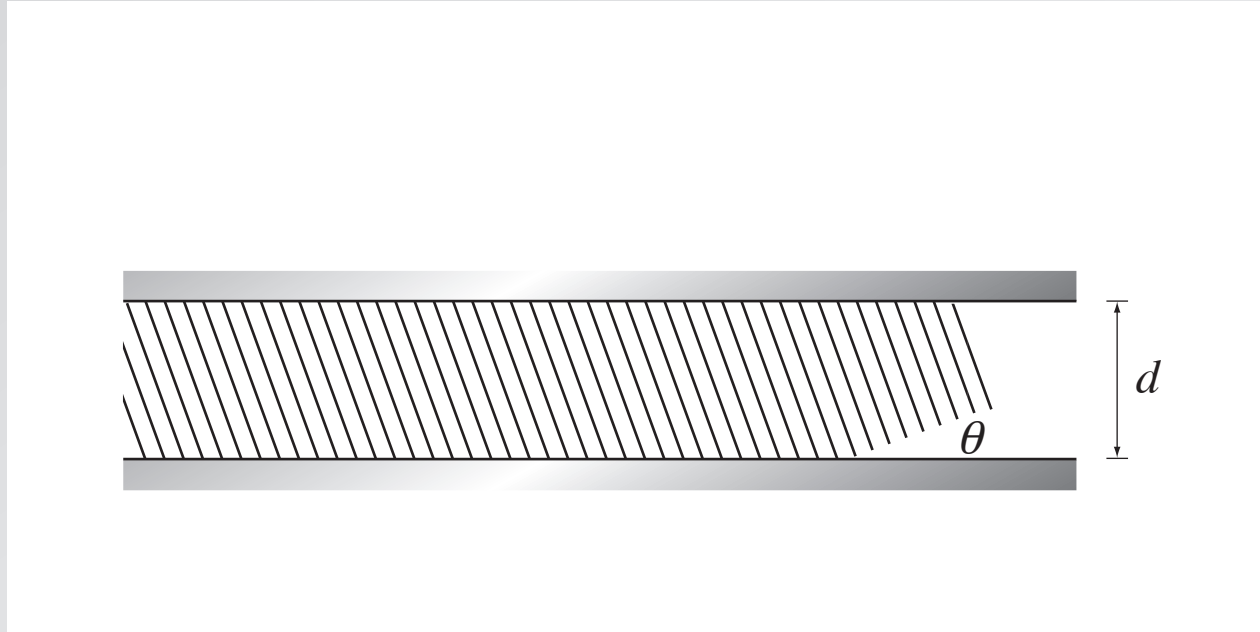
Waveguiding

boundary conditions only satisfied for certain θ



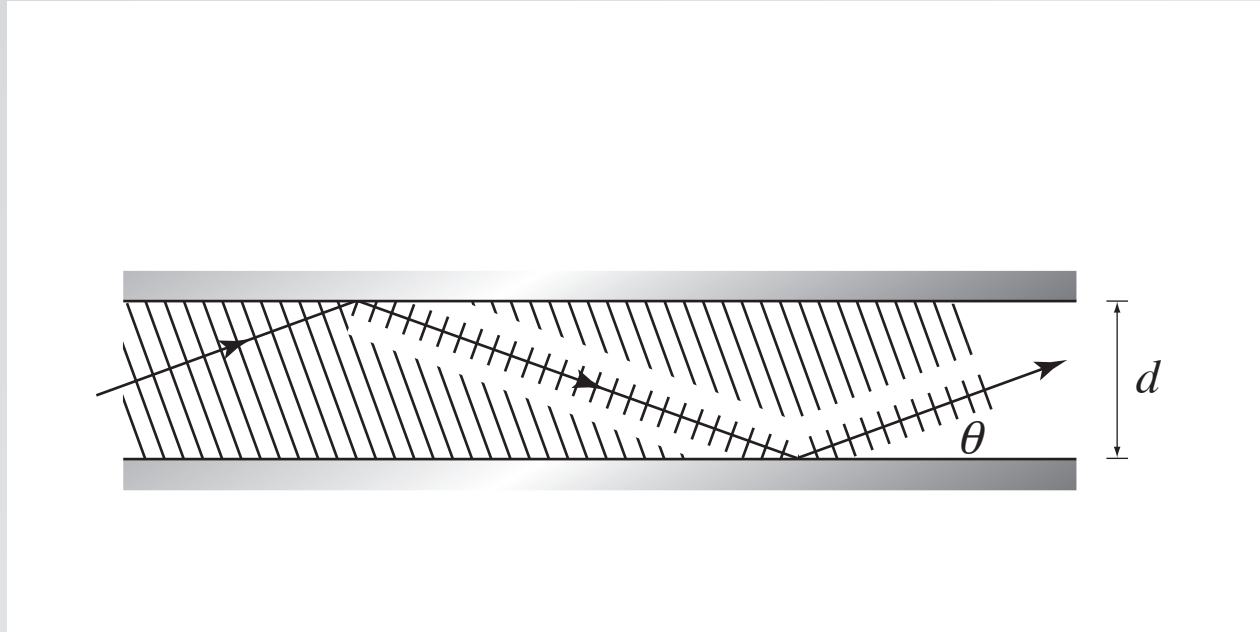
standing wave in y -direction, traveling in z -direction

Waveguiding



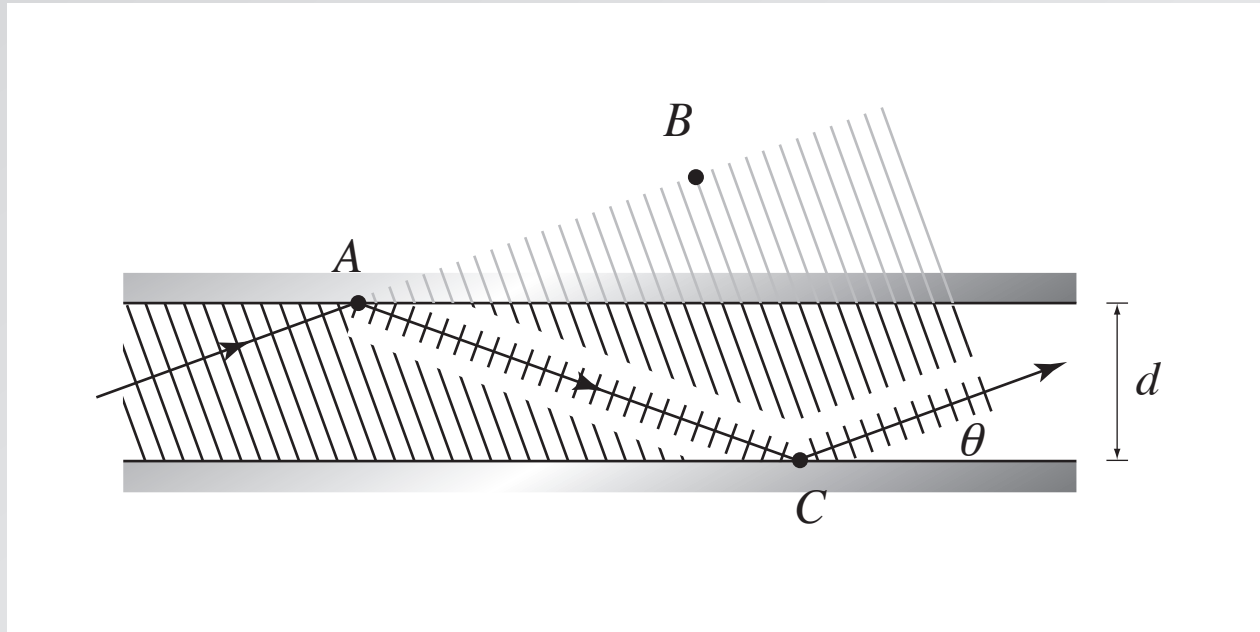
consider wave incident at angle θ

Waveguiding



twice-reflected wave

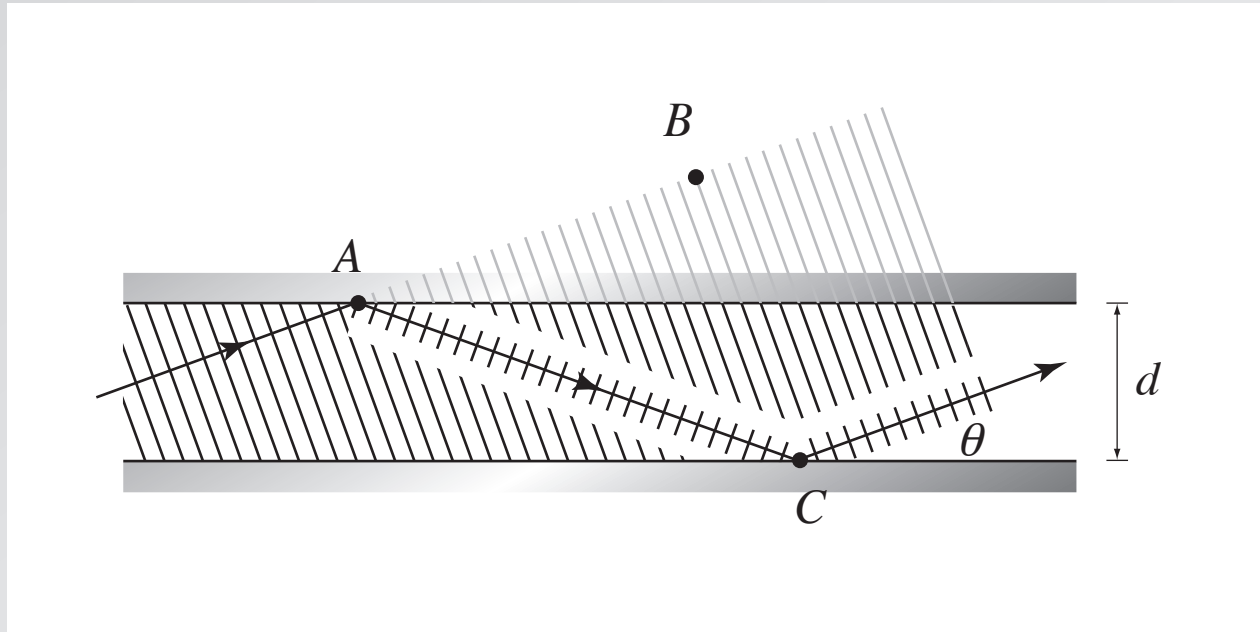
Waveguiding



self consistency:

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

Waveguiding



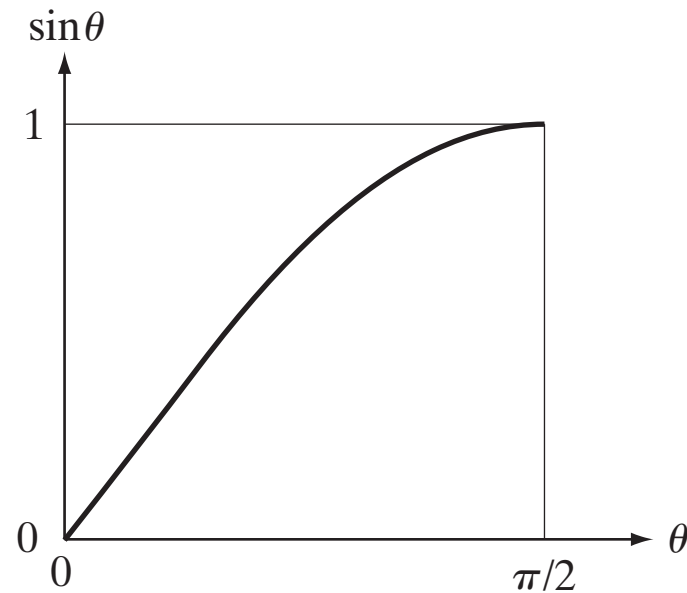
self consistency:

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

so:

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

Waveguiding



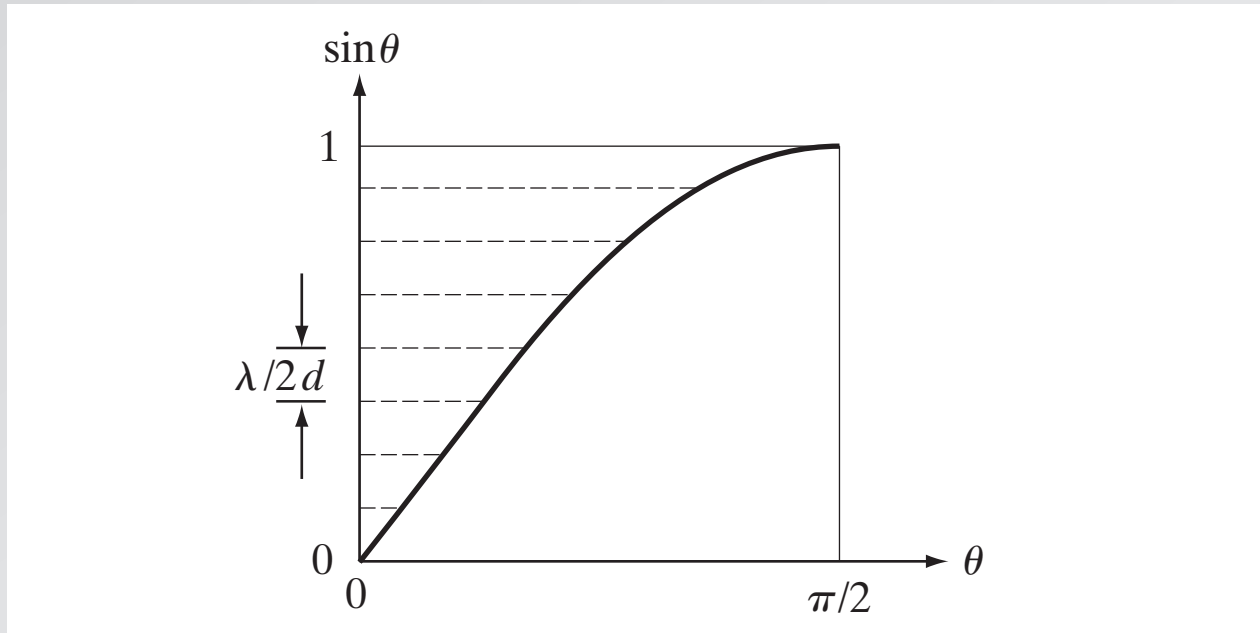
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$$AC - AB = 2d \sin \theta = m\lambda \quad (m = 1, 2, \dots)$$

so:

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

Waveguiding



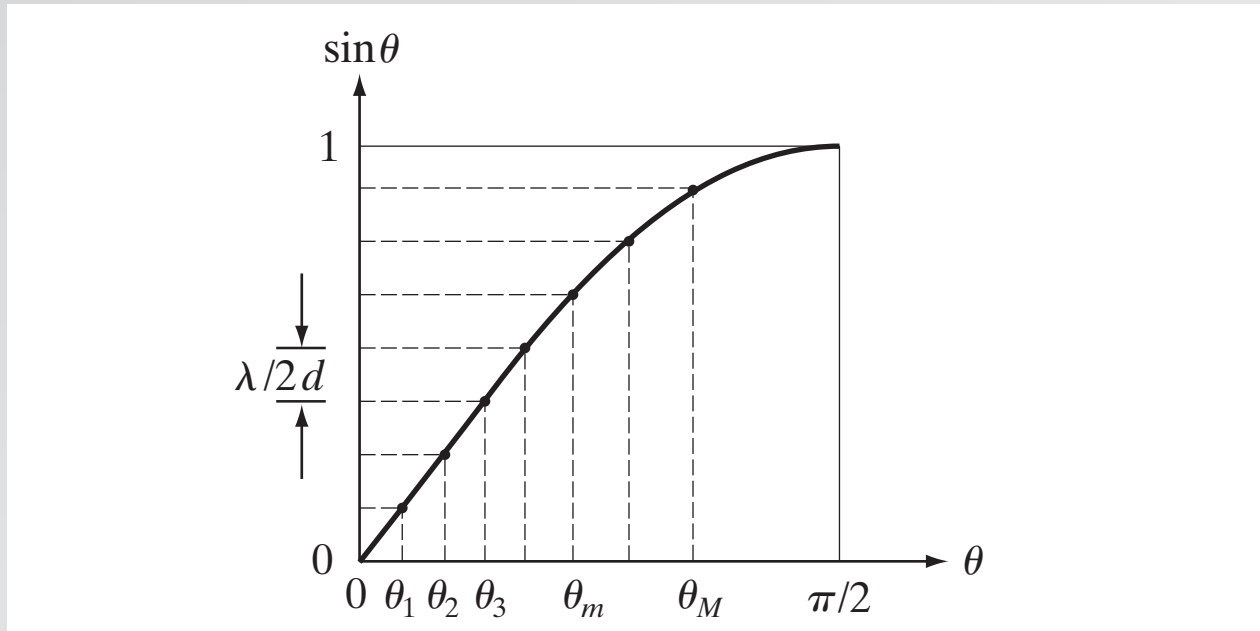
self consistency:

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

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Waveguiding



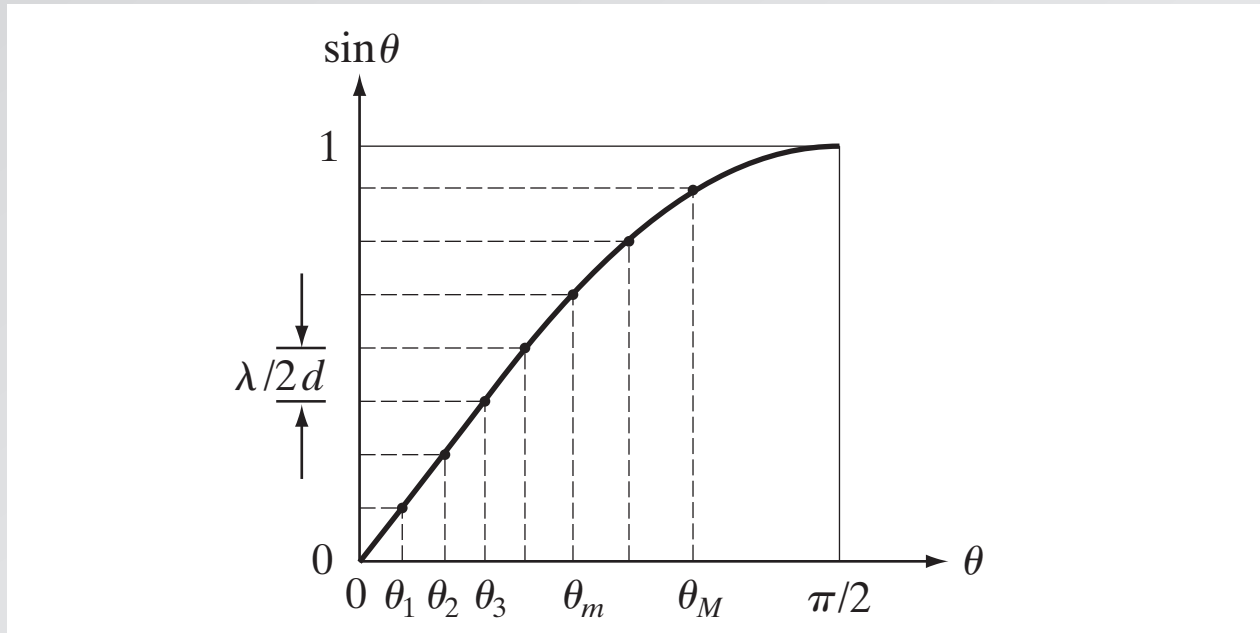
self consistency:

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

so:

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

Waveguiding



number of modes:

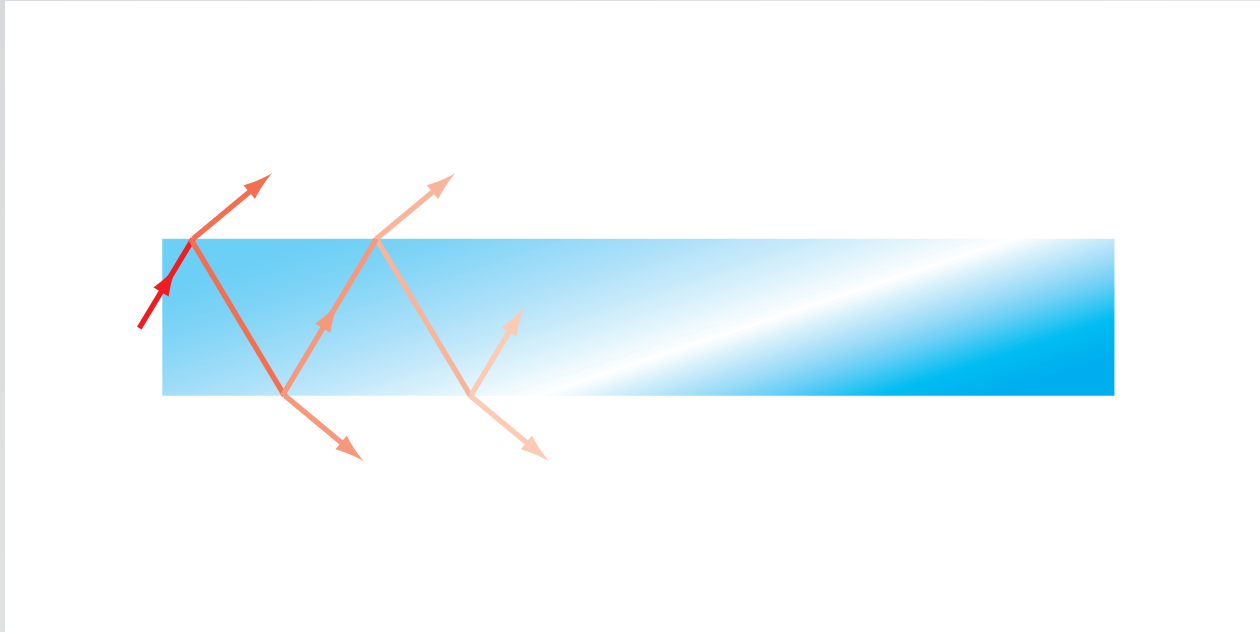
$$M = \frac{2d}{\lambda}$$

Waveguiding



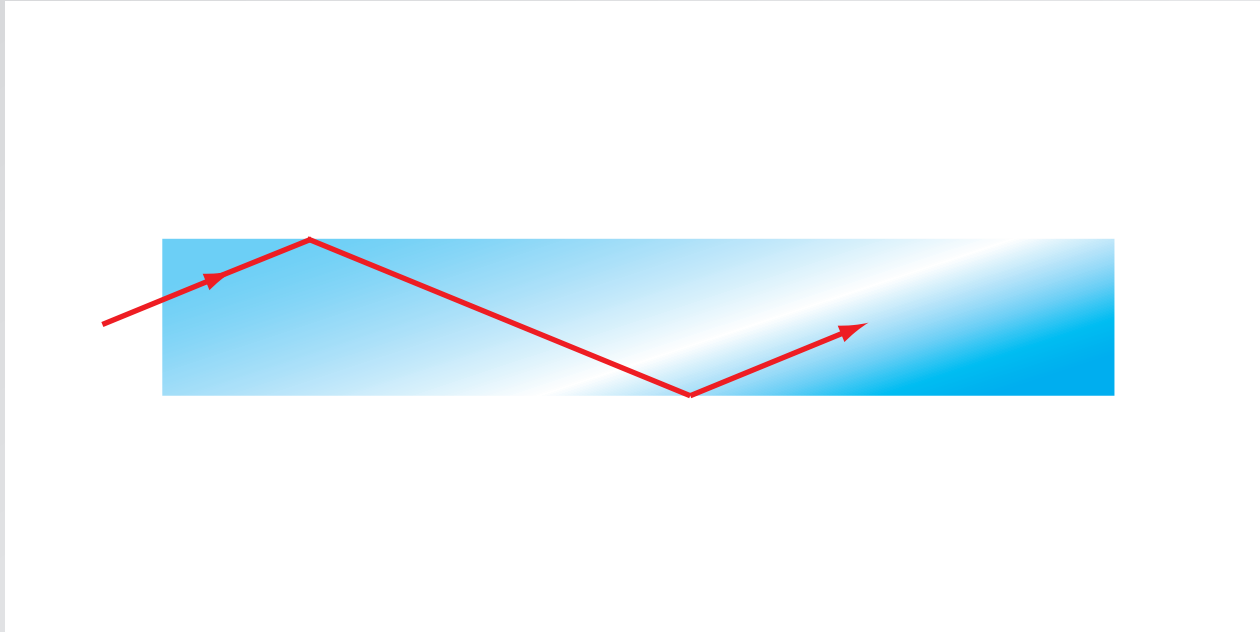
now consider a planar dielectric waveguide

Waveguiding



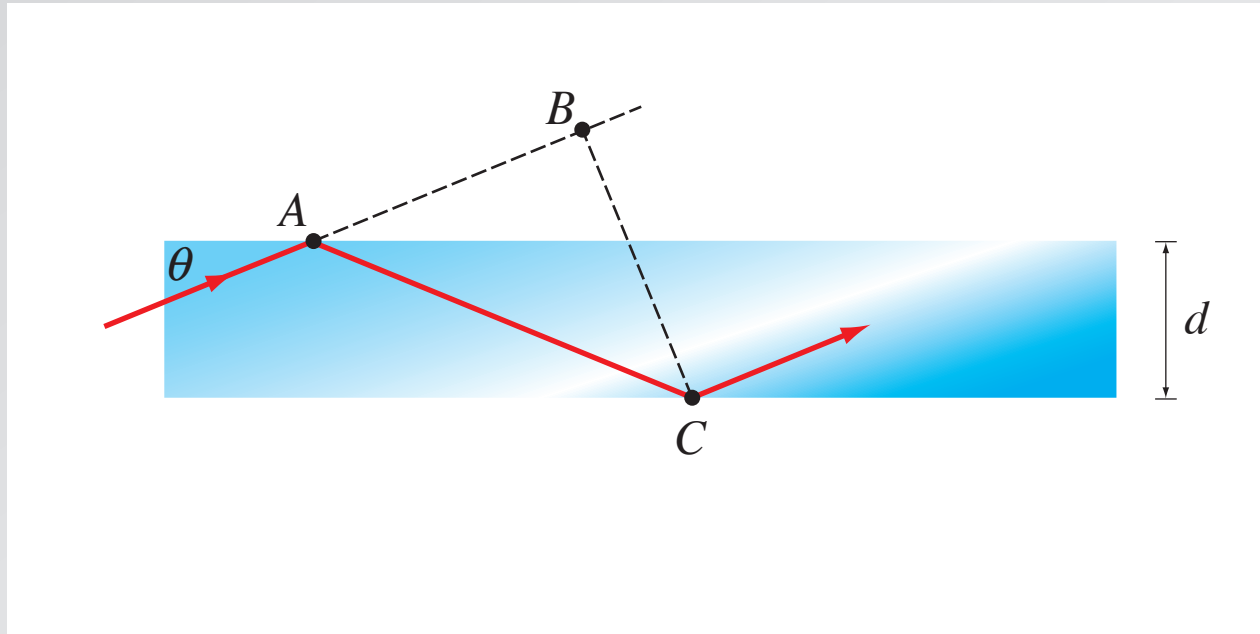
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



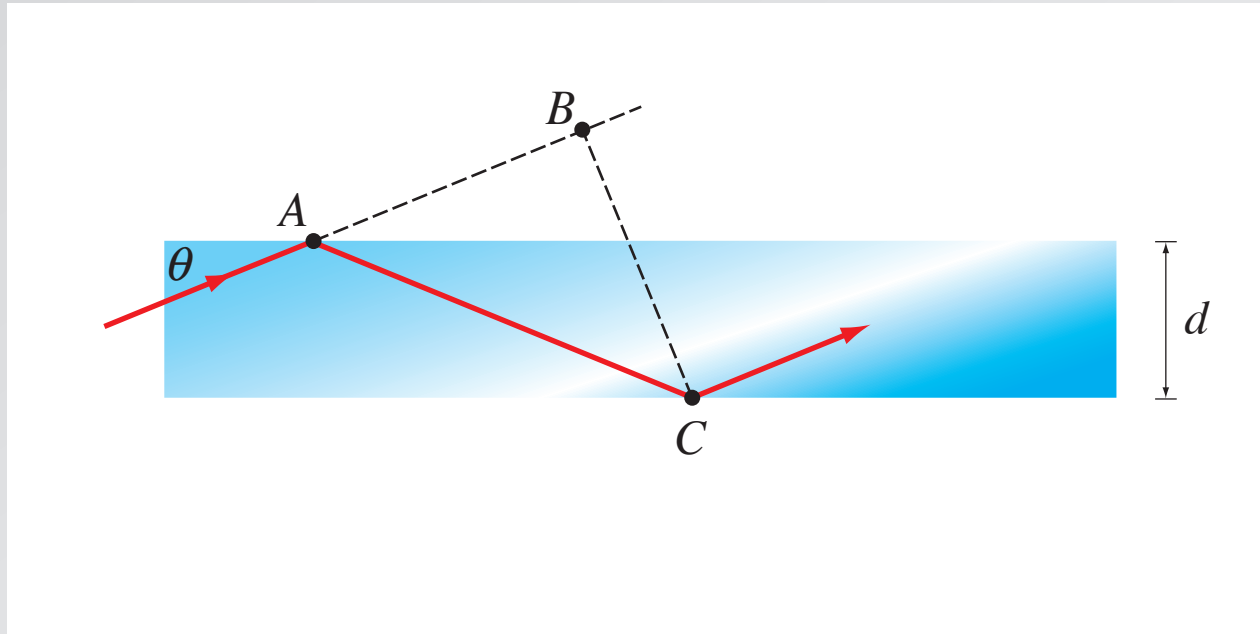
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

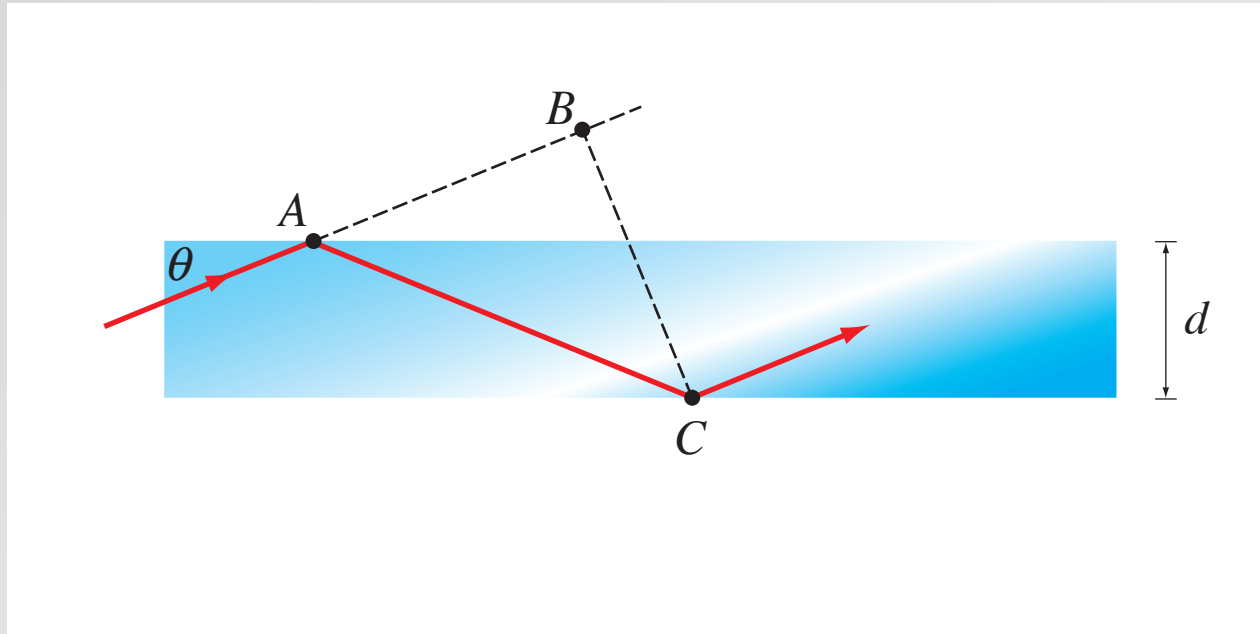
Waveguiding



self consistency:

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

Waveguiding



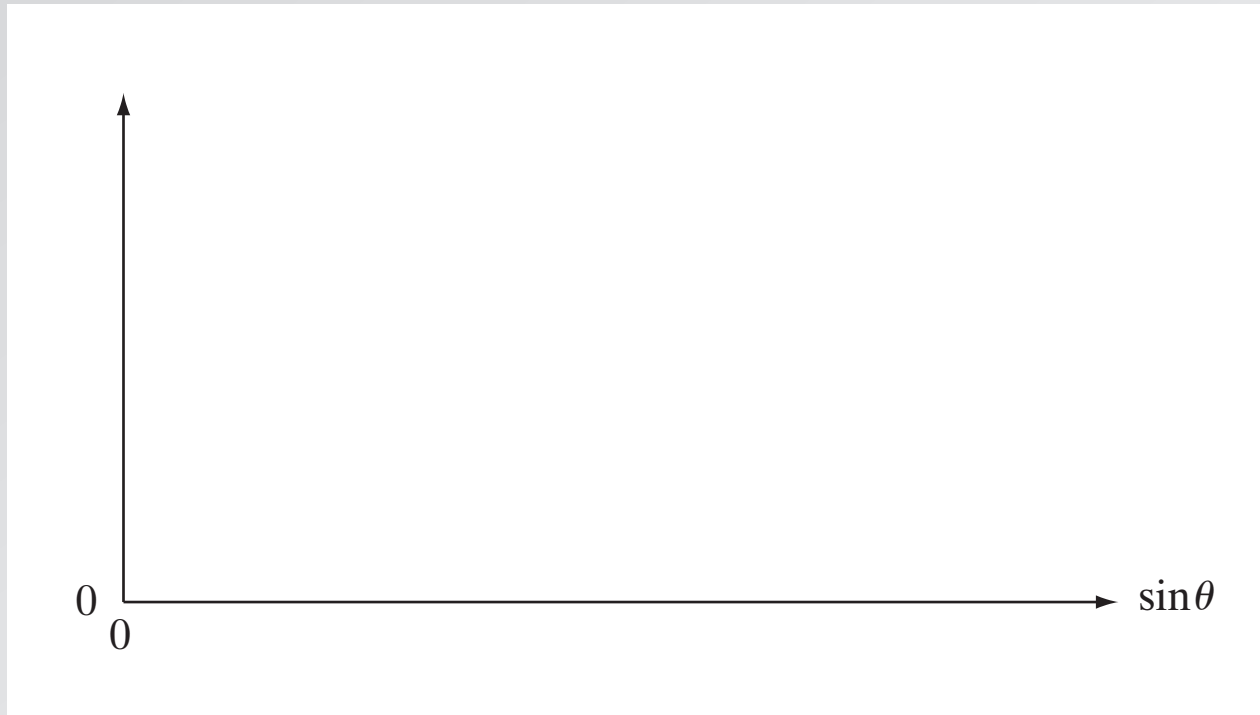
self consistency:

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

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



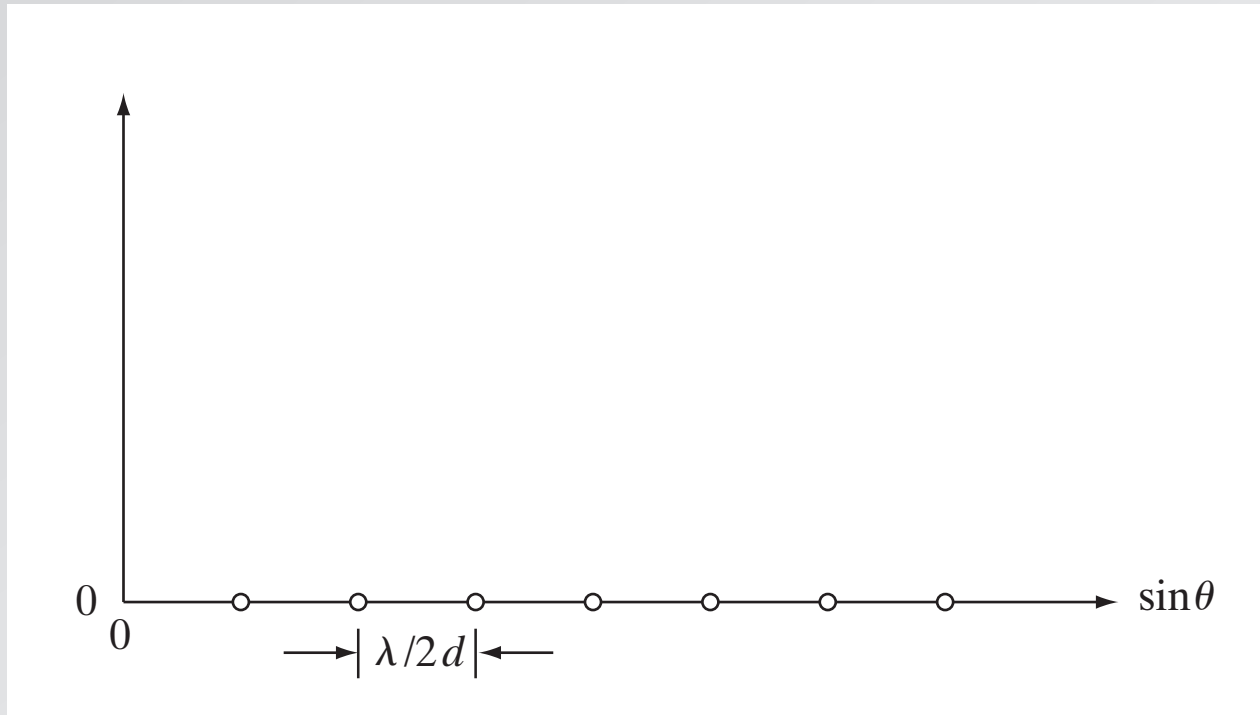
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Waveguiding



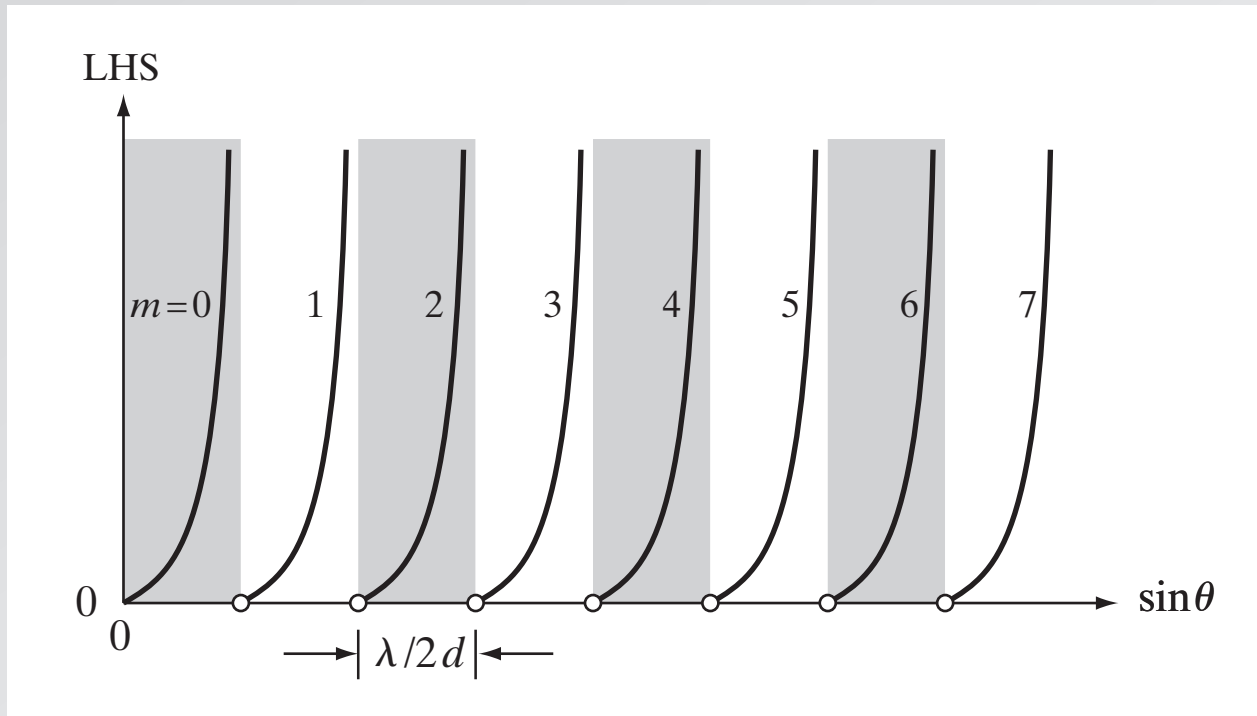
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Waveguiding



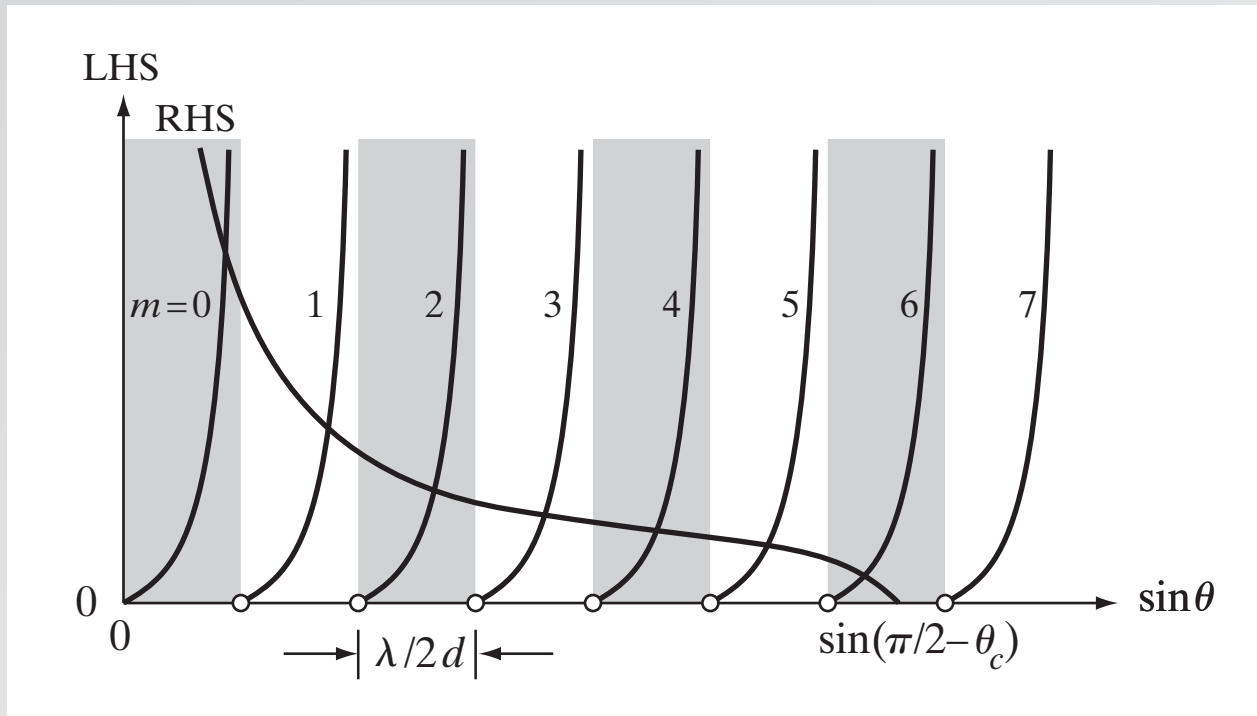
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Waveguiding



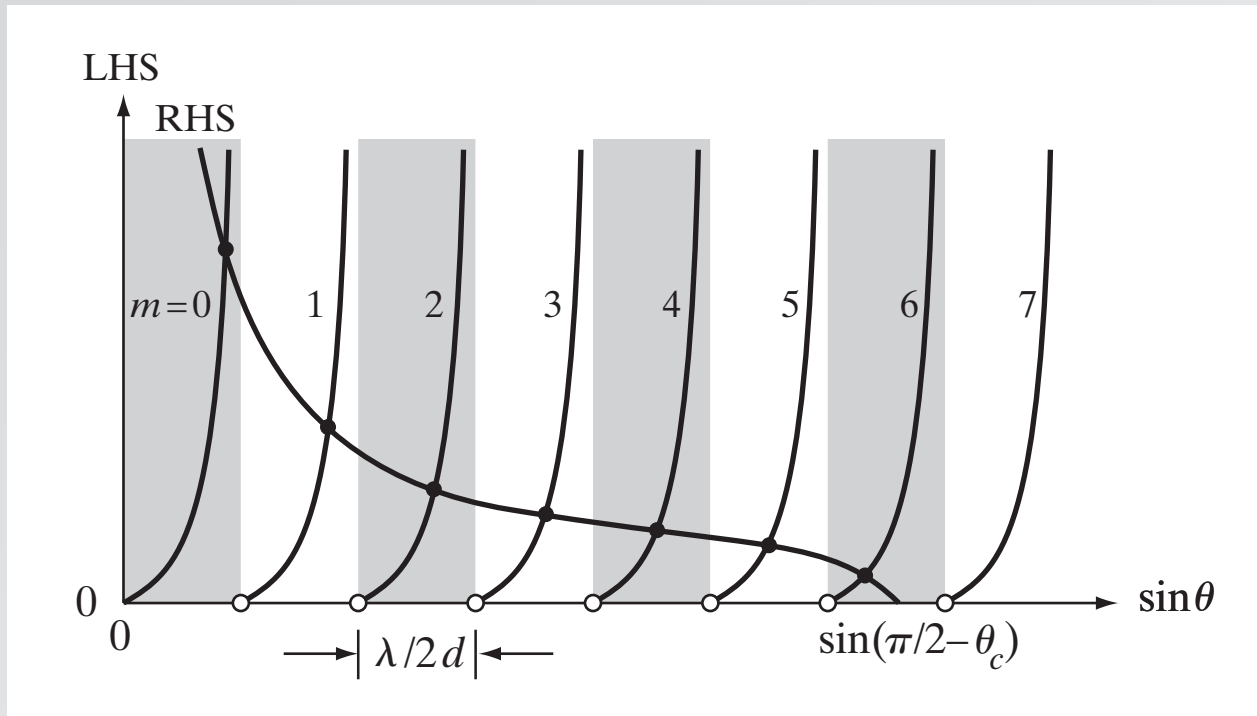
self consistency:

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

SO:

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Waveguiding



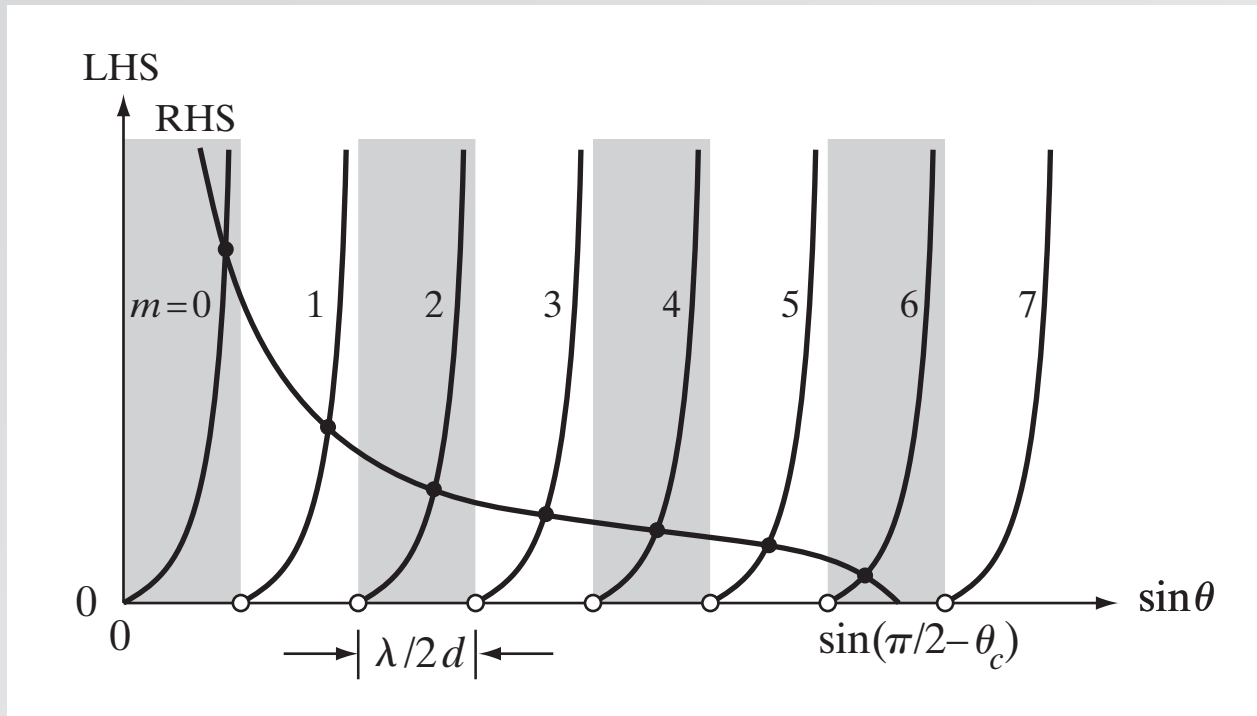
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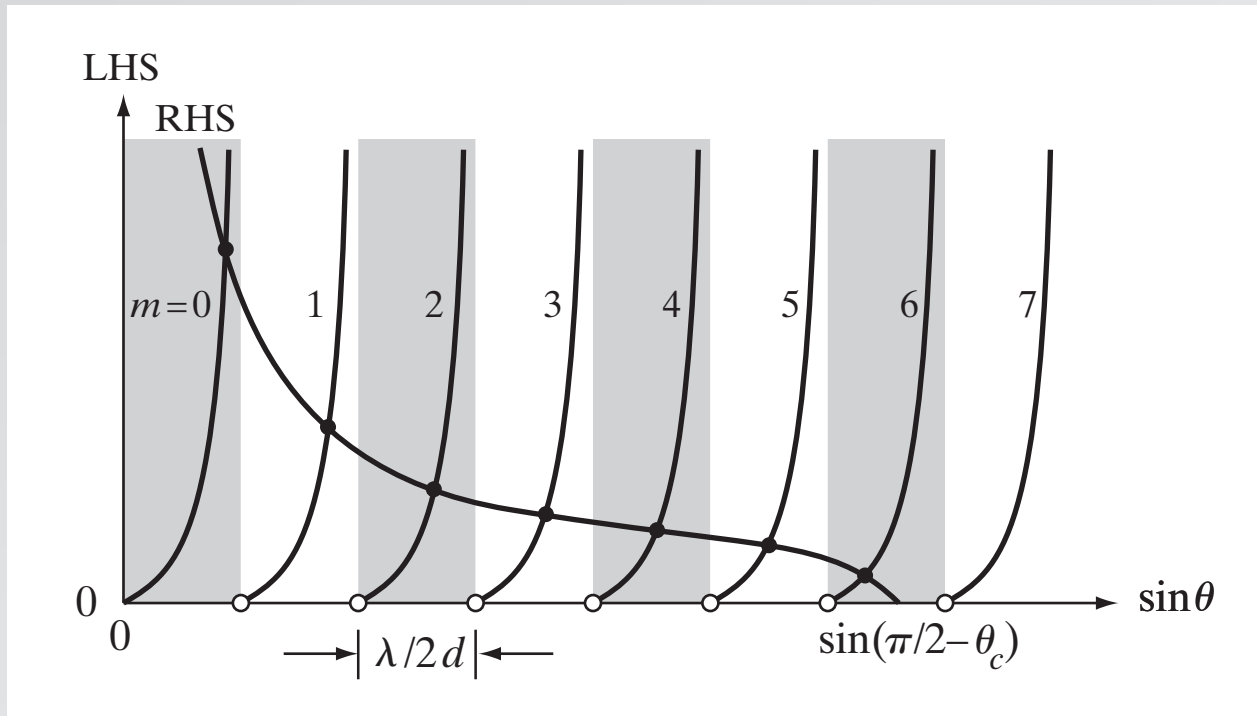
Waveguiding



number of modes:

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

Waveguiding



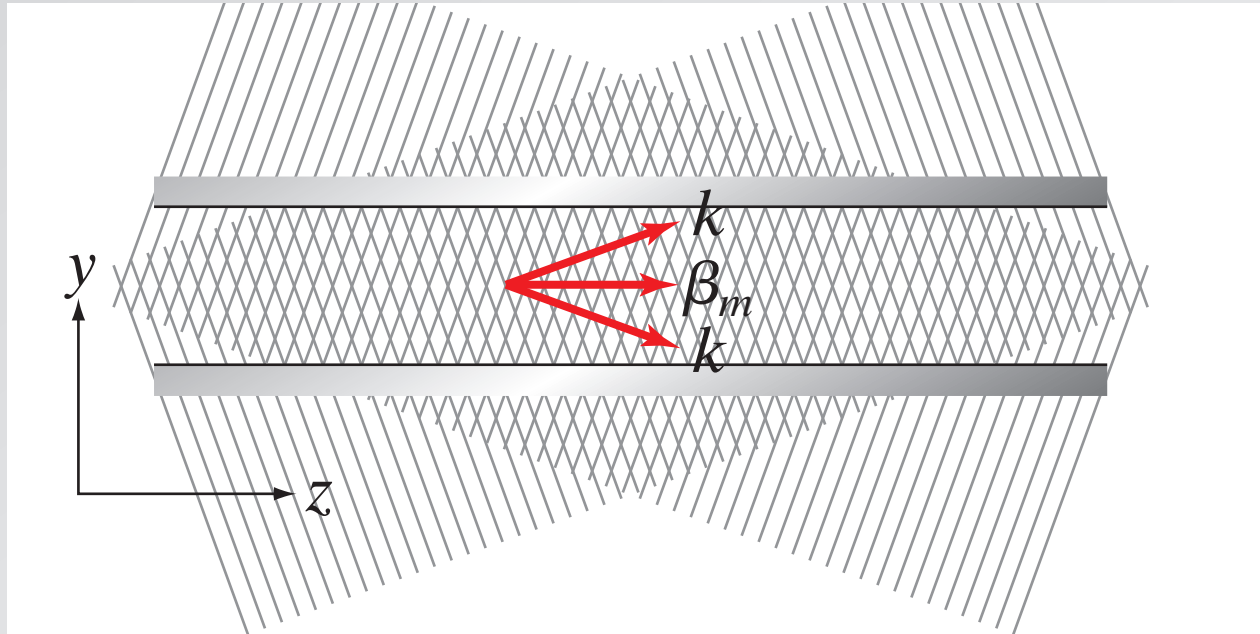
number of modes:

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

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

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

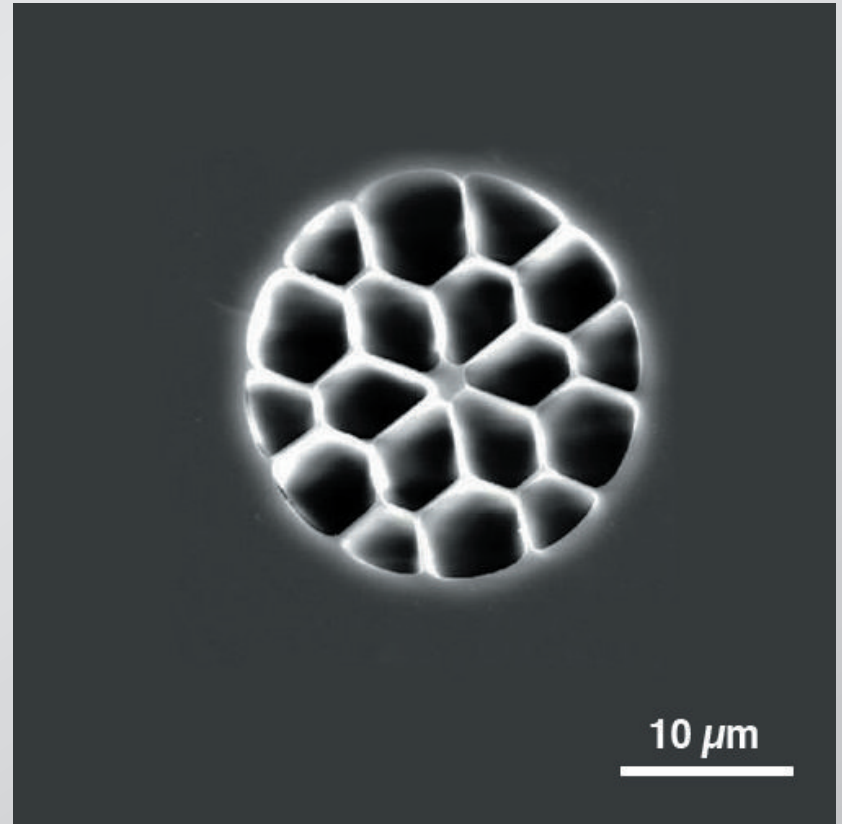
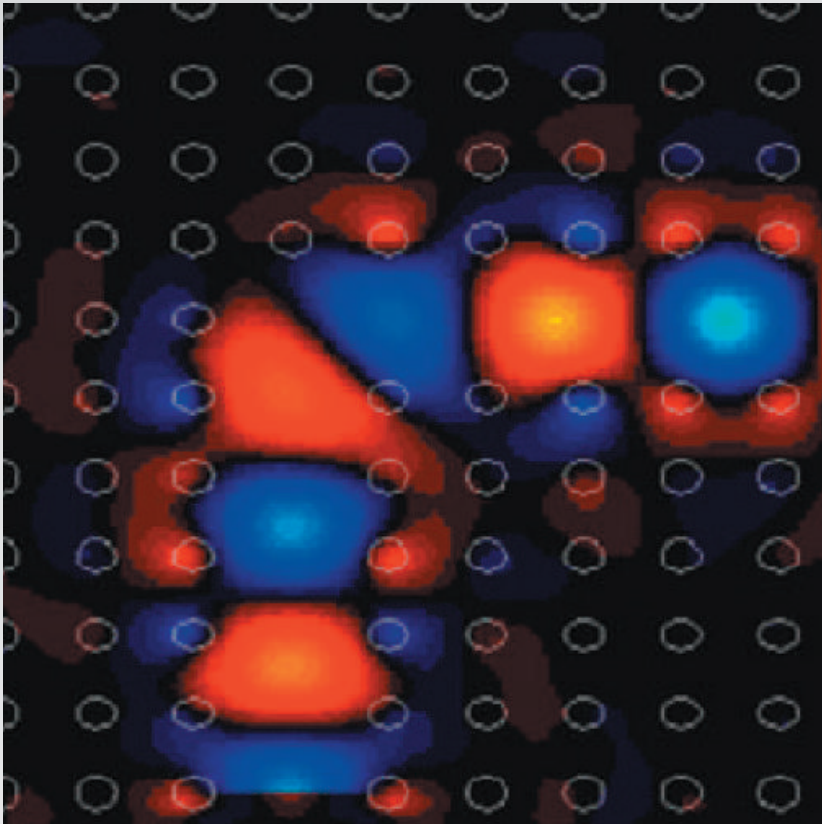
operating wavelength: $\lambda = 1310 \text{ nm}/1550 \text{ nm}$

Waveguiding

drawbacks of clad fibers:

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

Waveguiding



Outline

- waveguiding
- nanowire fabrication
- optical properties

Nanowire fabrication

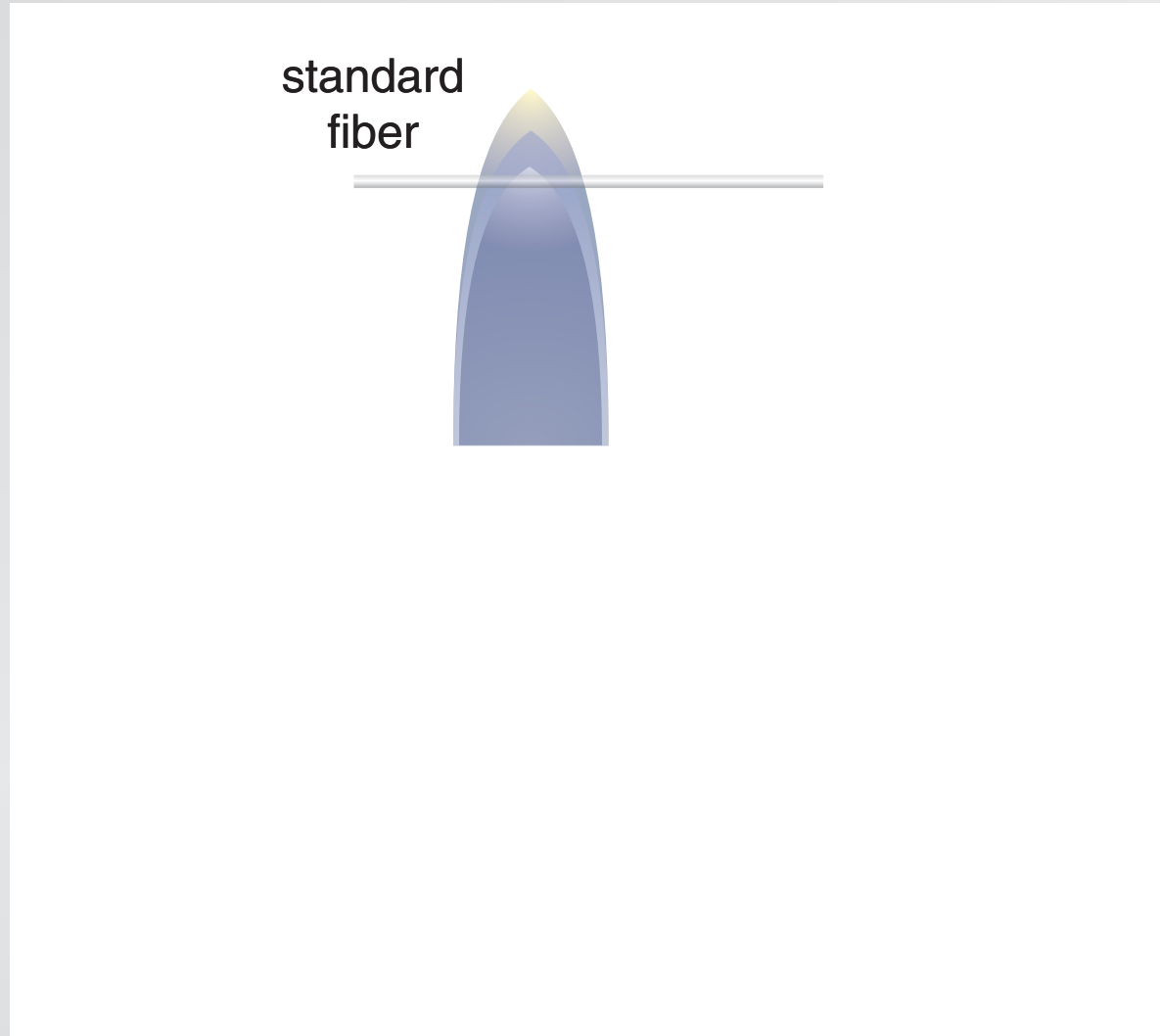
two-step drawing process

standard
fiber



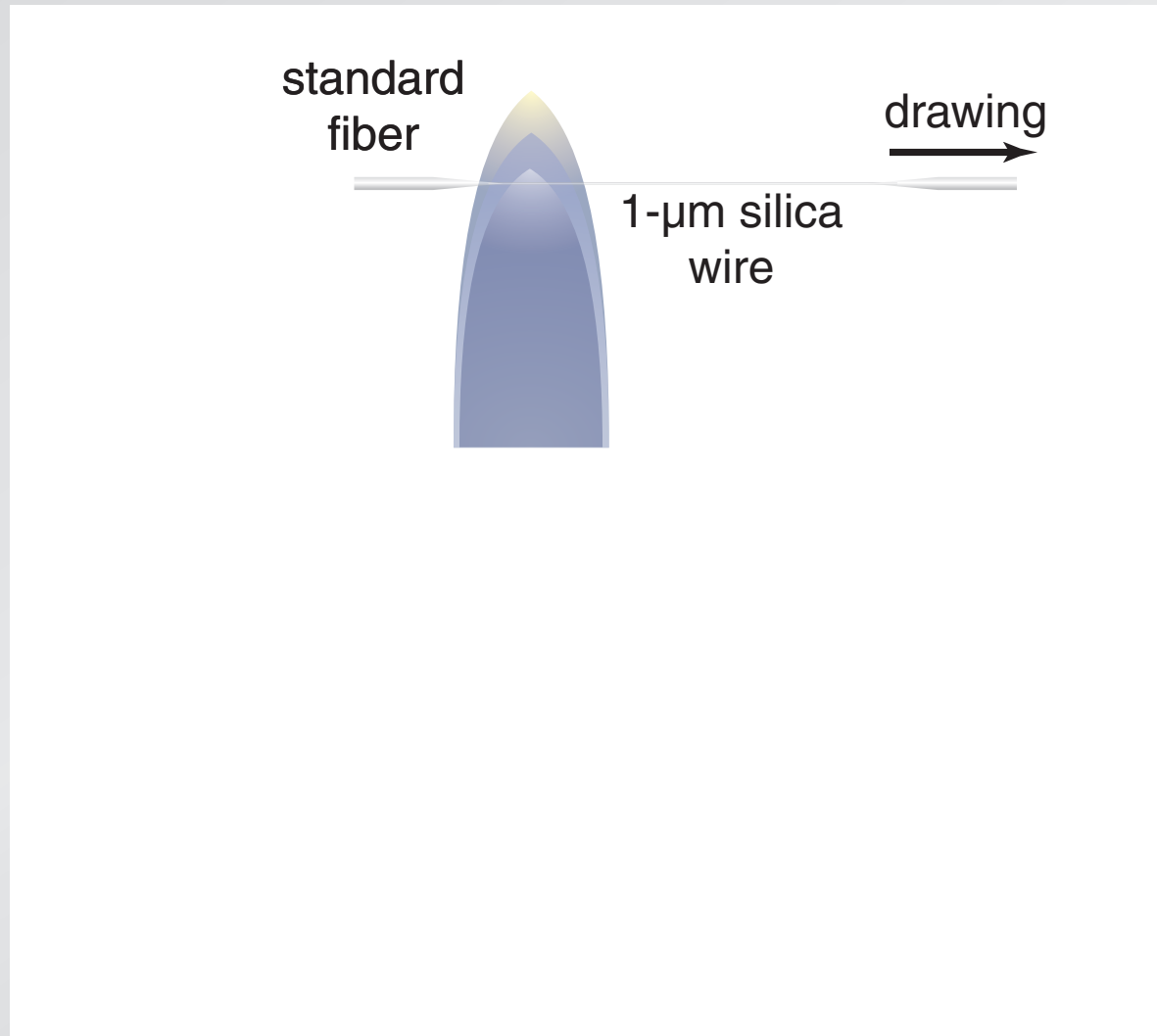
Nanowire fabrication

two-step drawing process



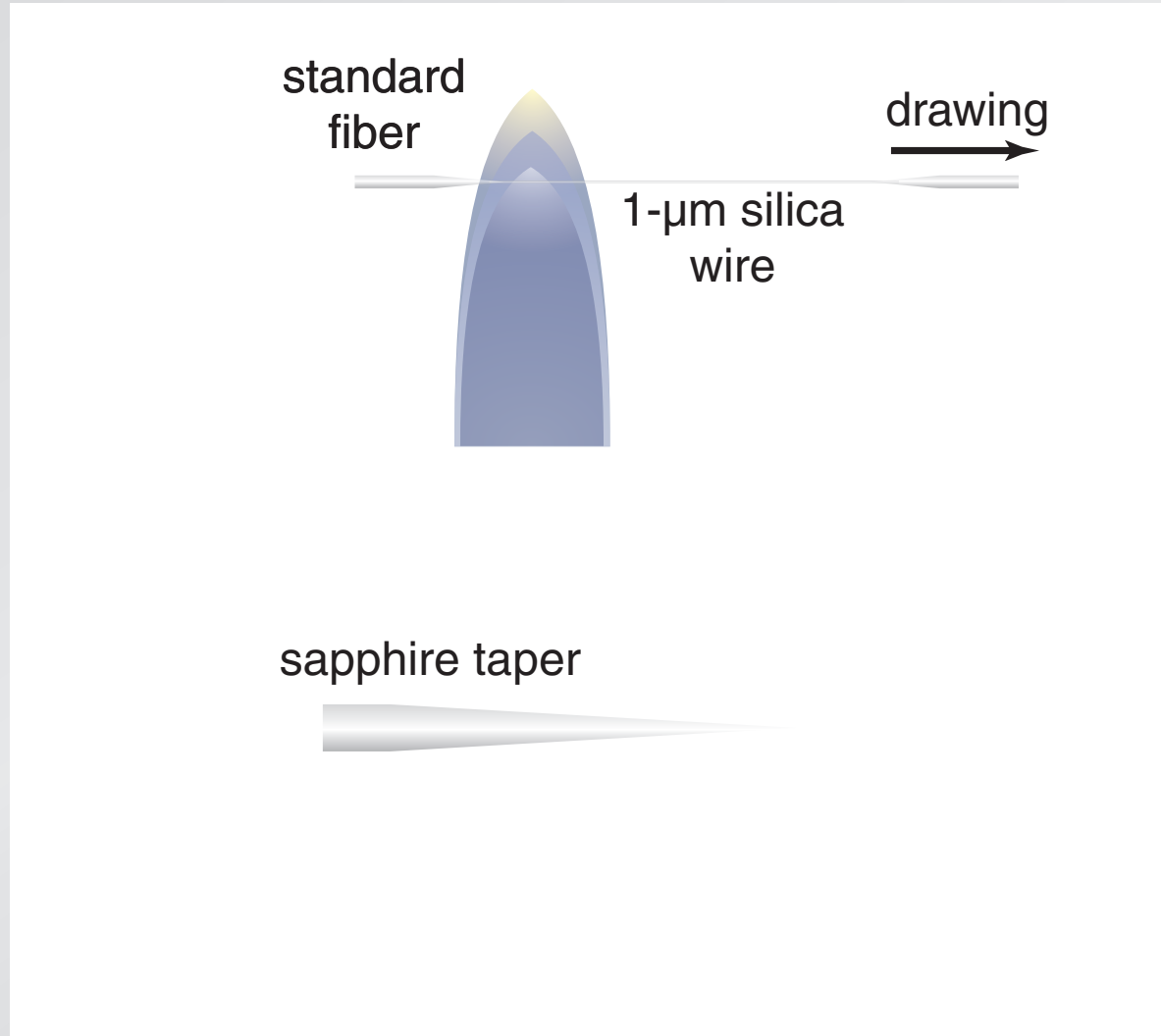
Nanowire fabrication

two-step drawing process



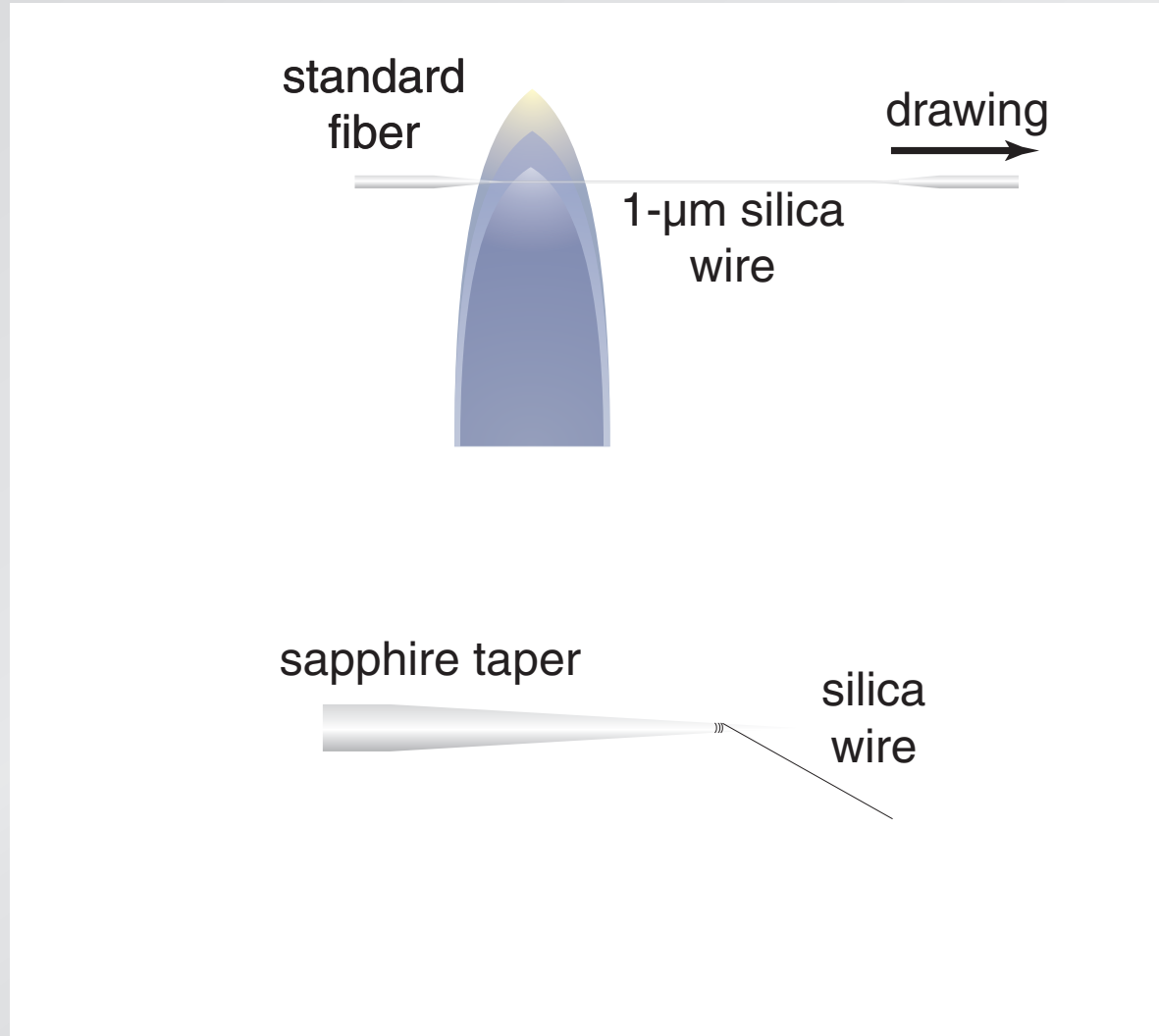
Nanowire fabrication

two-step drawing process



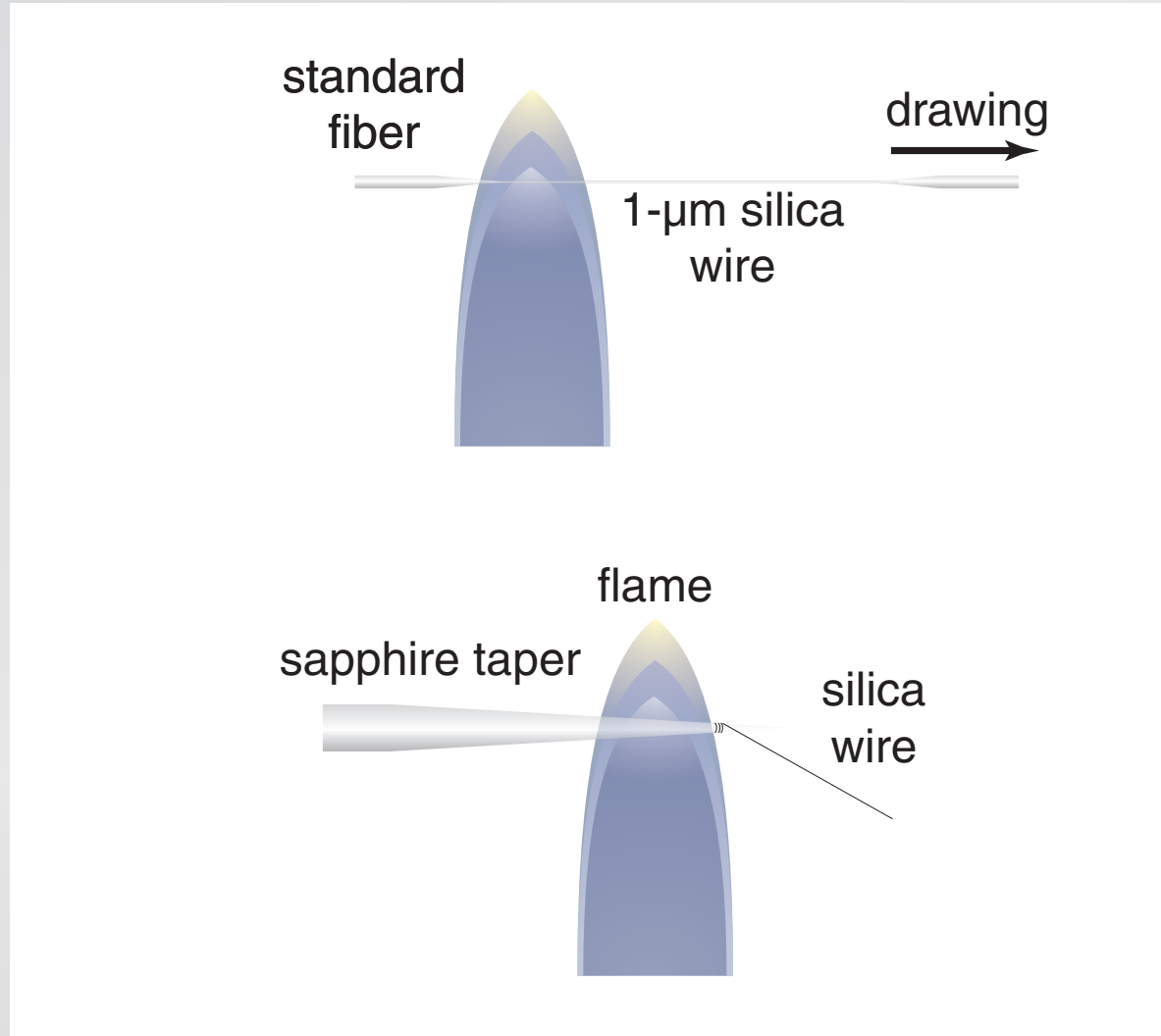
Nanowire fabrication

two-step drawing process



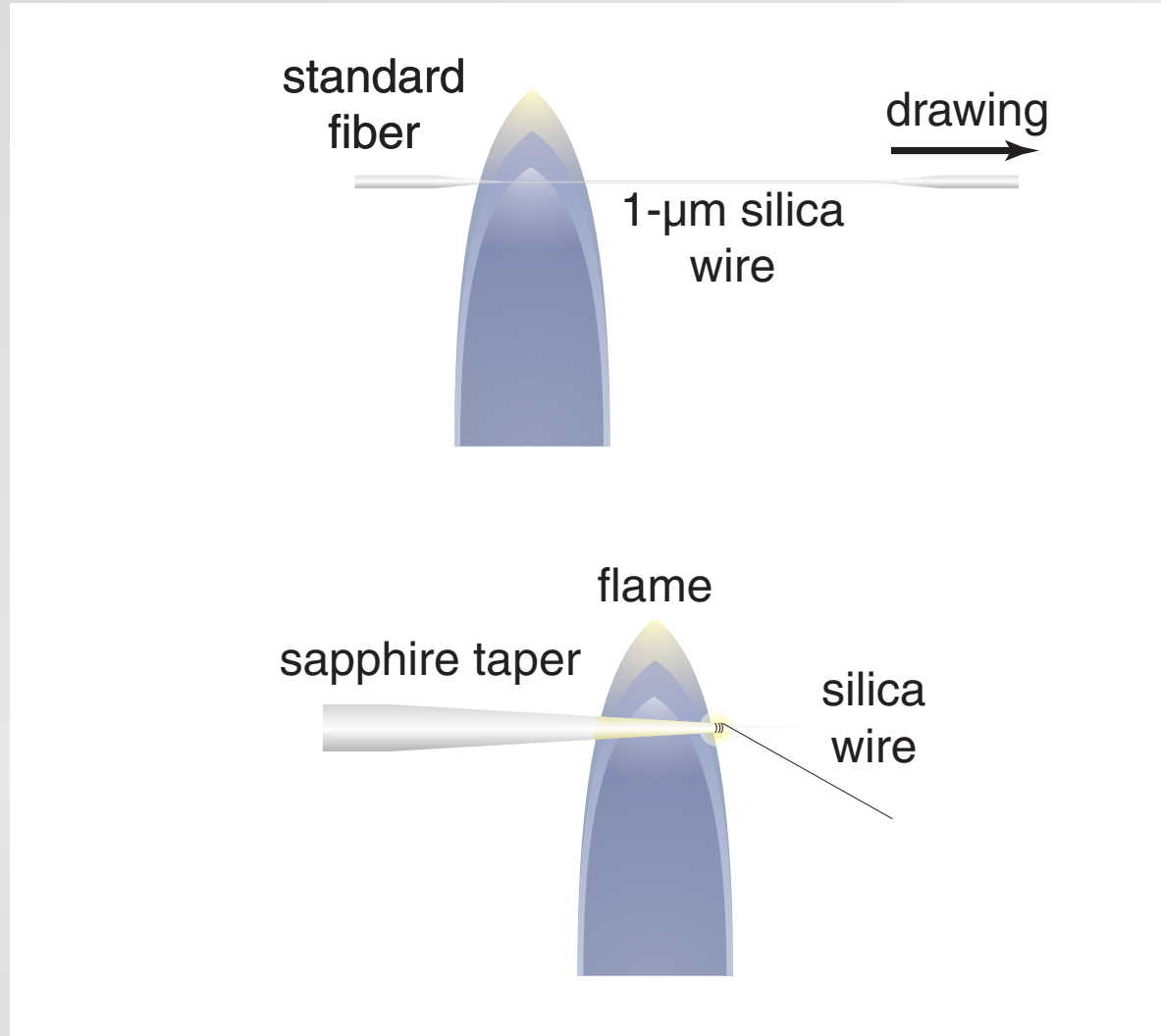
Nanowire fabrication

two-step drawing process



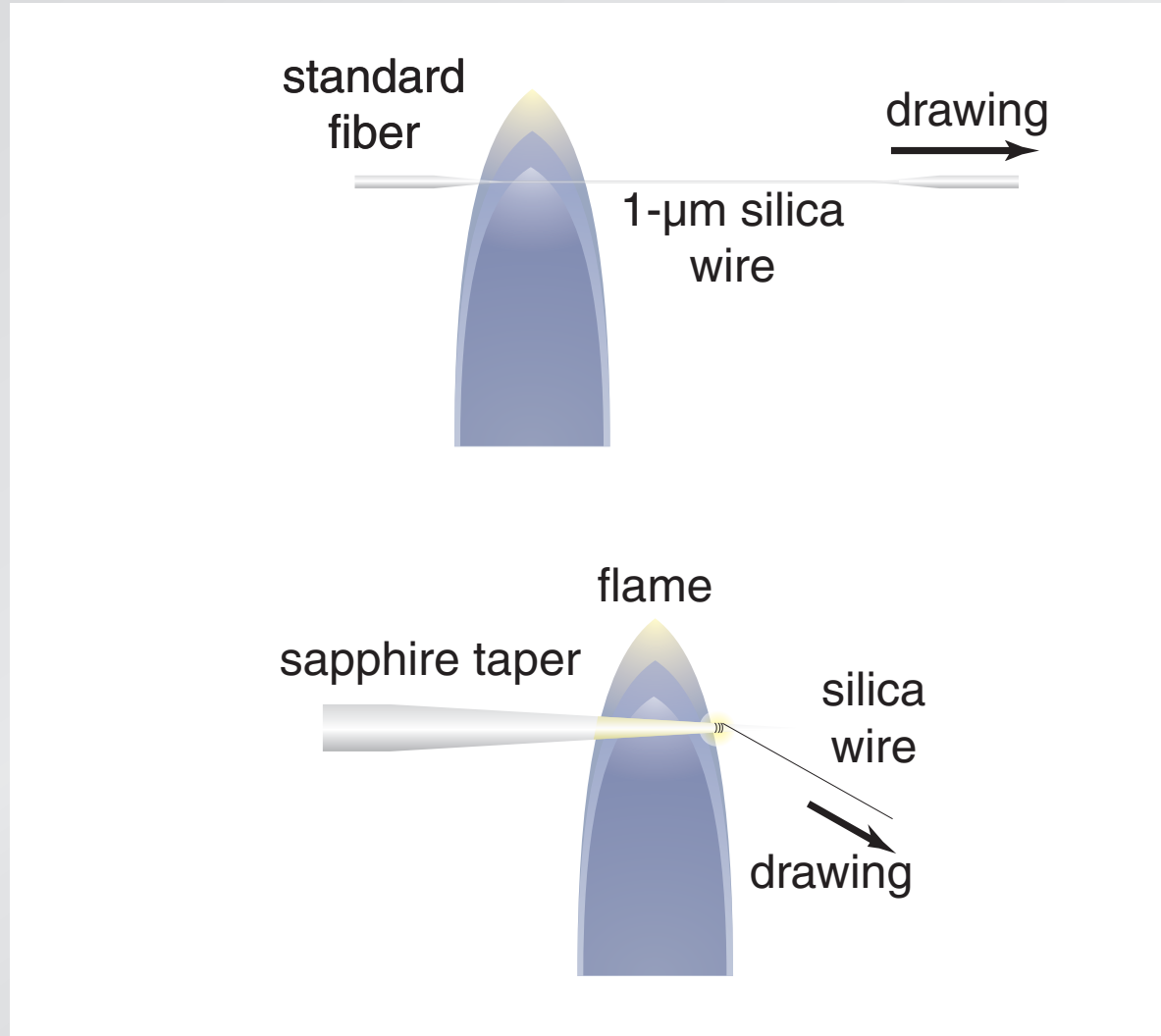
Nanowire fabrication

two-step drawing process

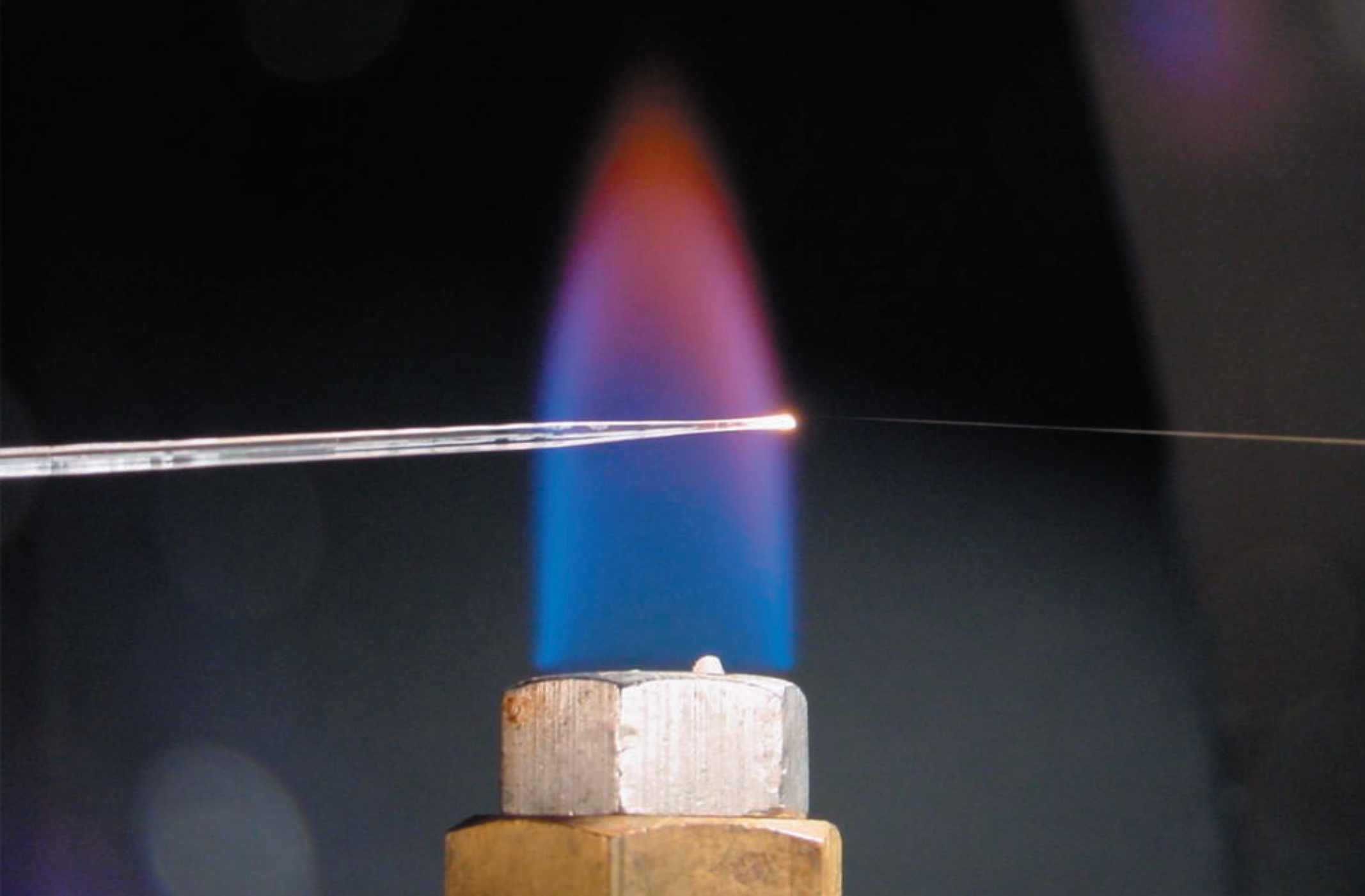


Nanowire fabrication

two-step drawing process



Nanowire fabrication



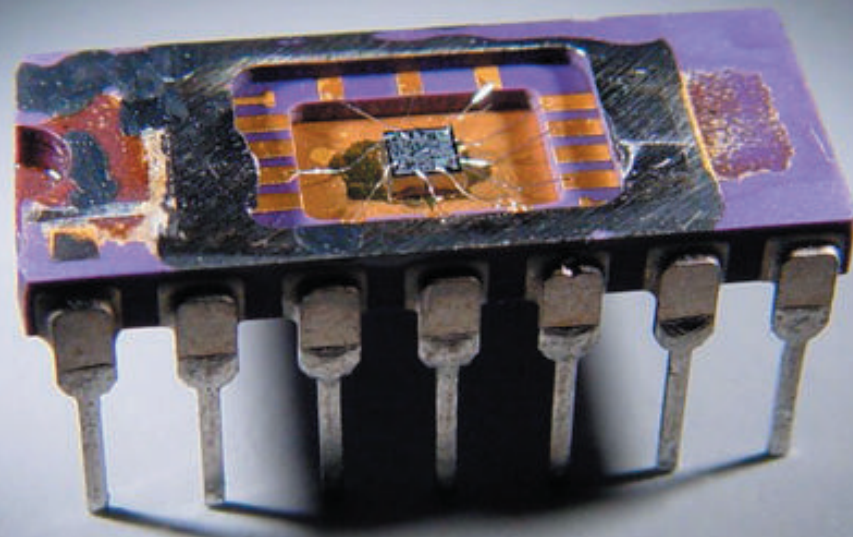
Nanowire fabrication

1 μm

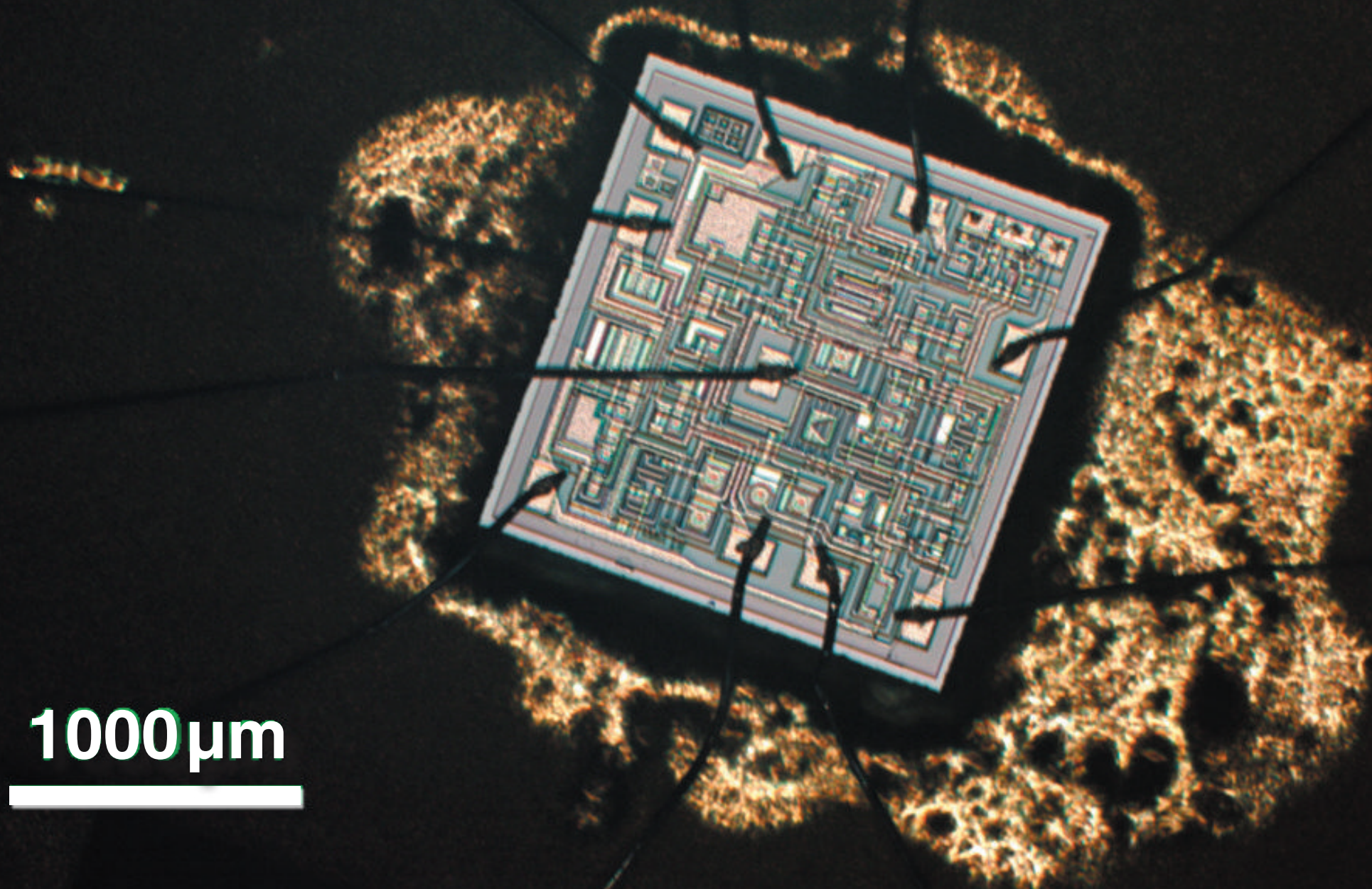


Nature, 426, 816 (2003)

Nanowire fabrication



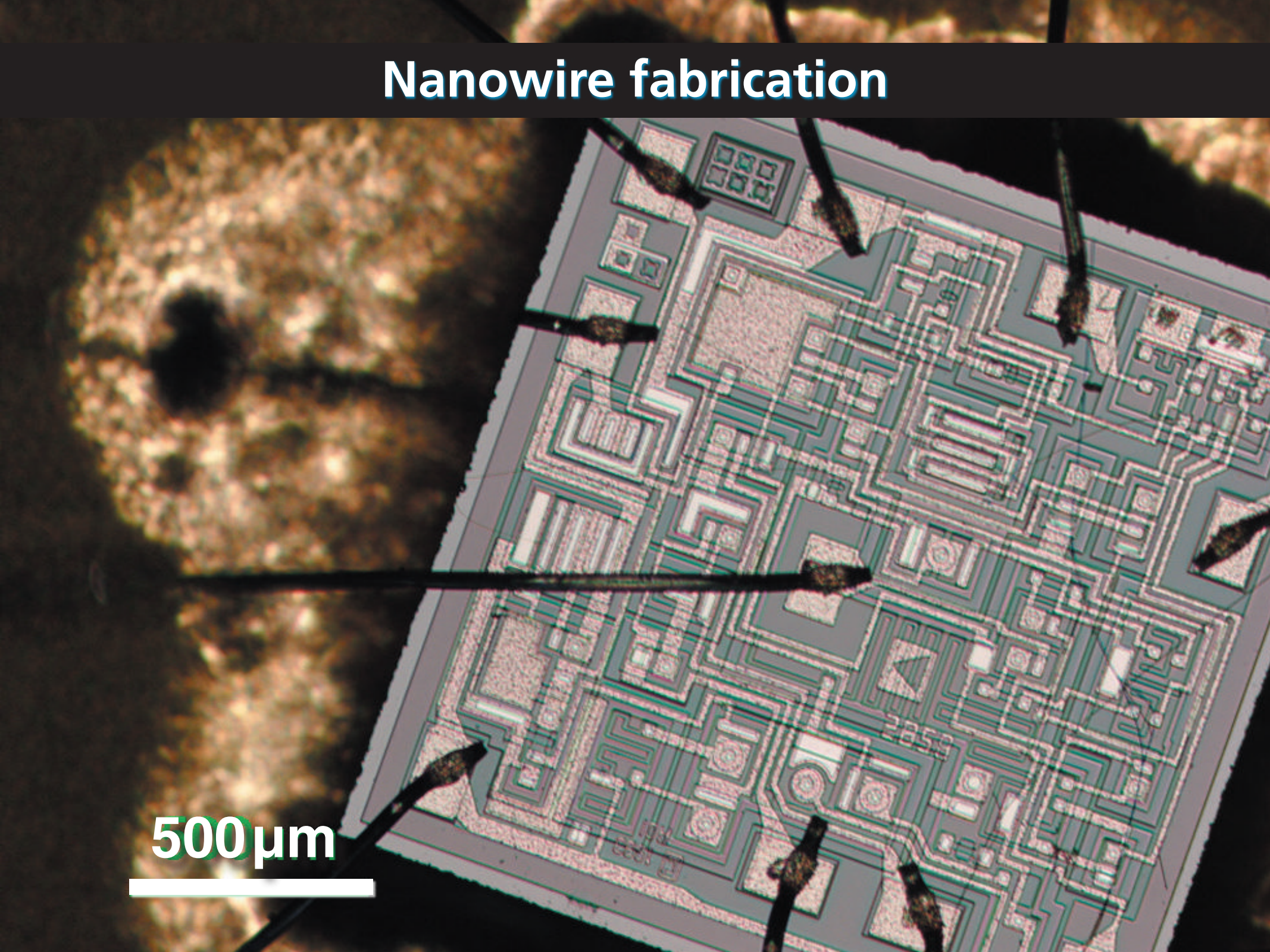
Nanowire fabrication



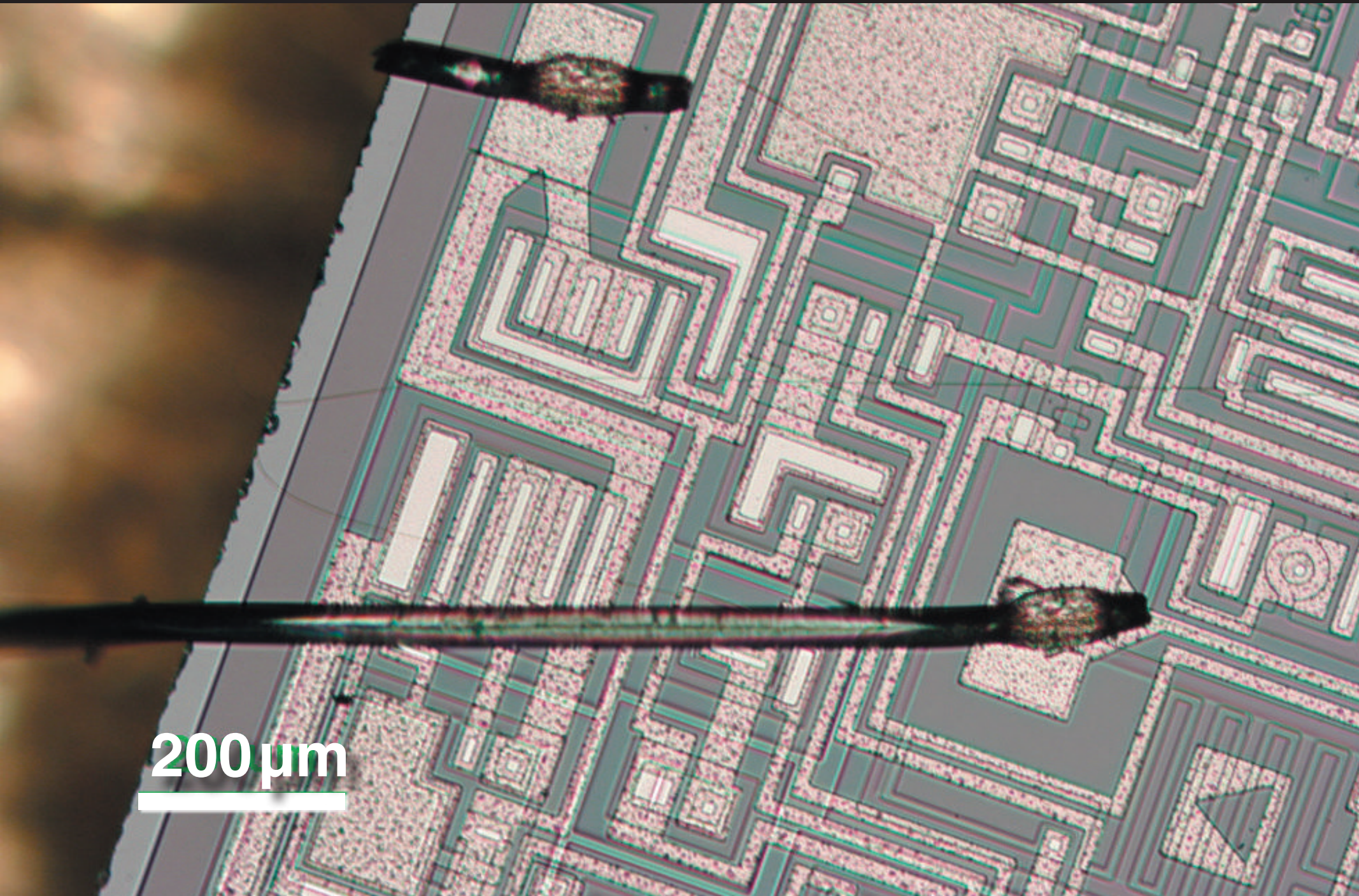
1000 μm

Nanowire fabrication

500 μm

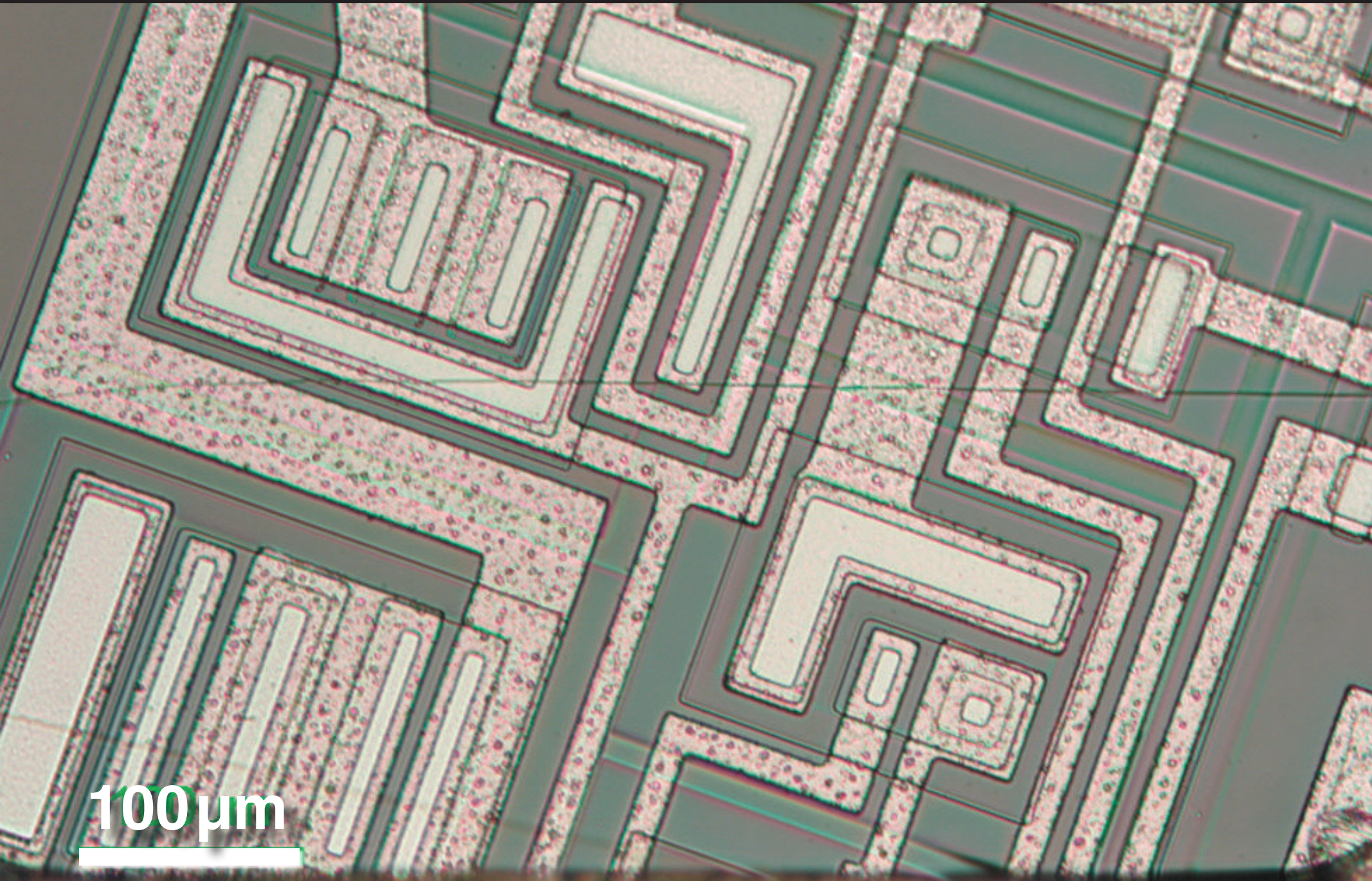


Nanowire fabrication

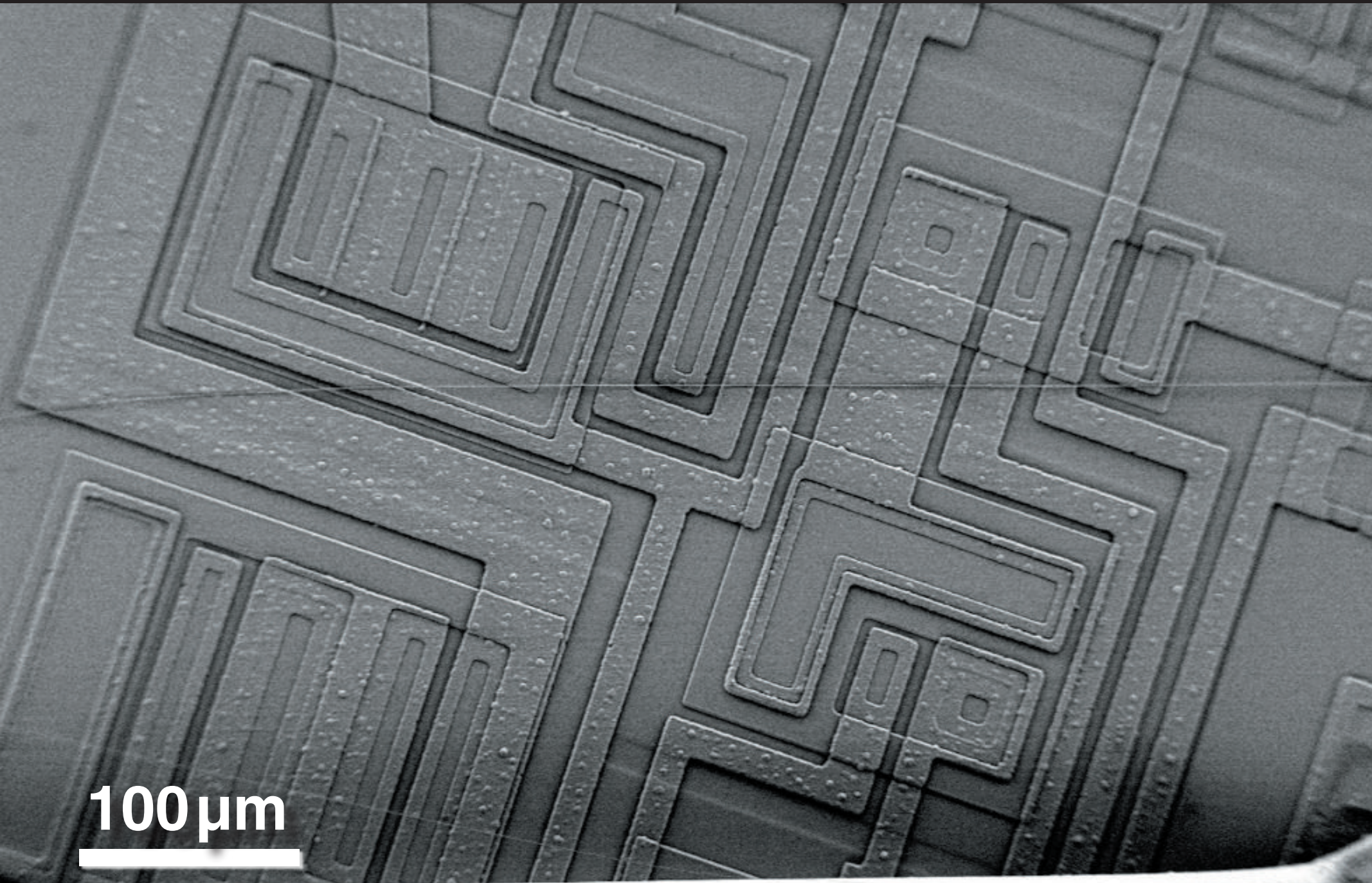


200 μm

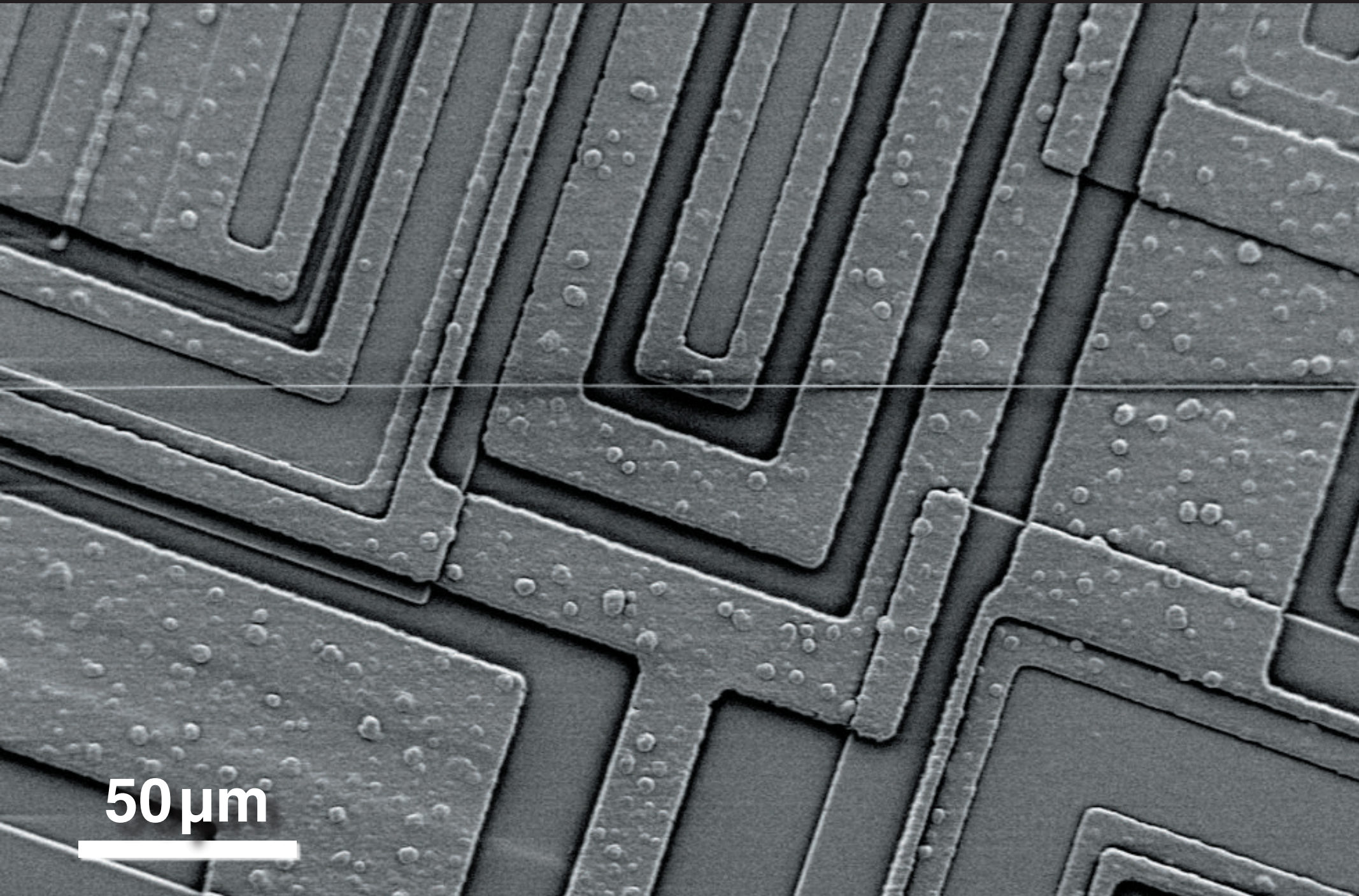
Nanowire fabrication



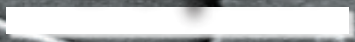
Nanowire fabrication



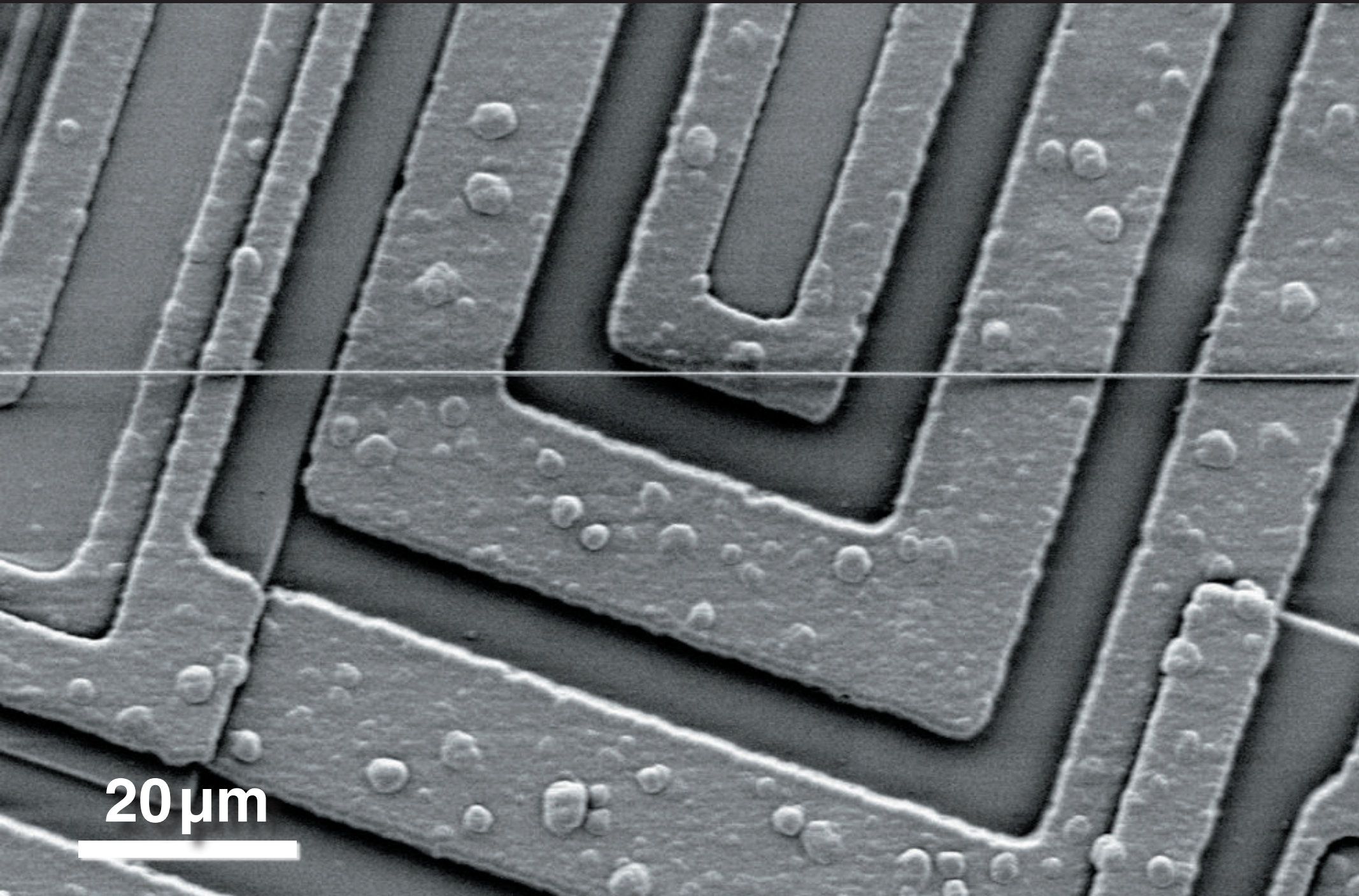
Nanowire fabrication



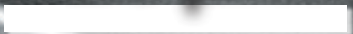
50 μm



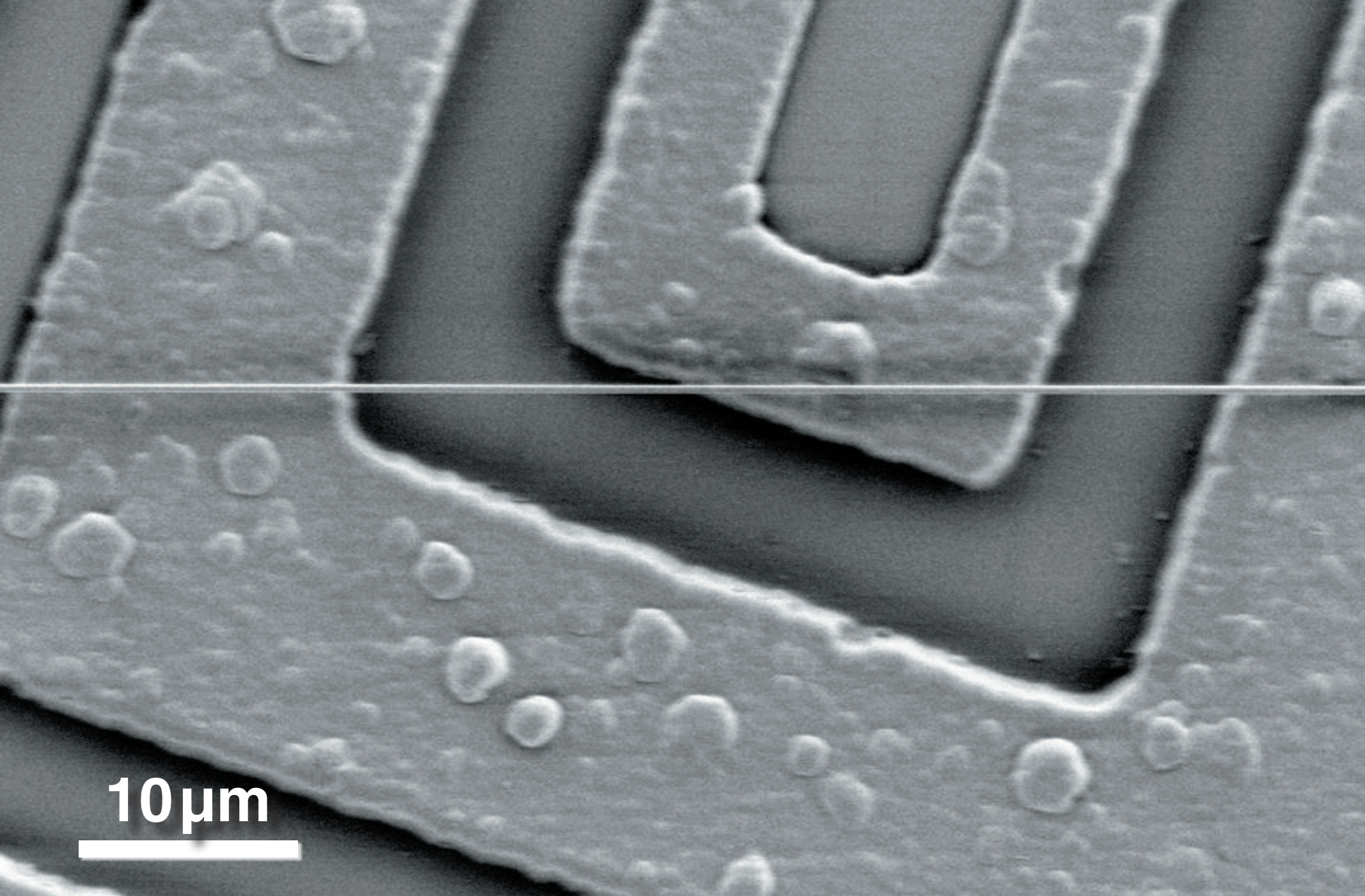
Nanowire fabrication



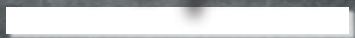
20 μm



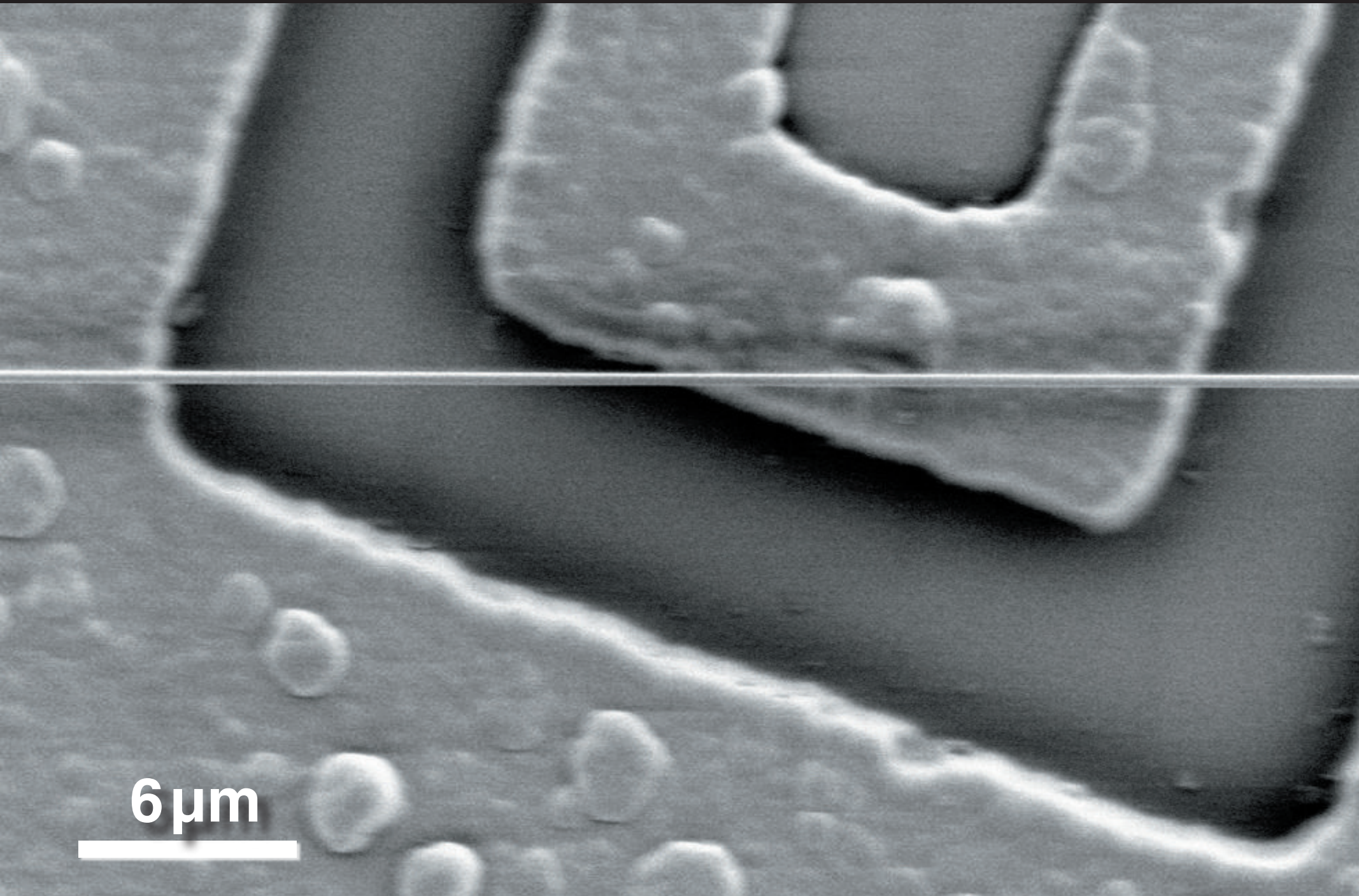
Nanowire fabrication



10 μm

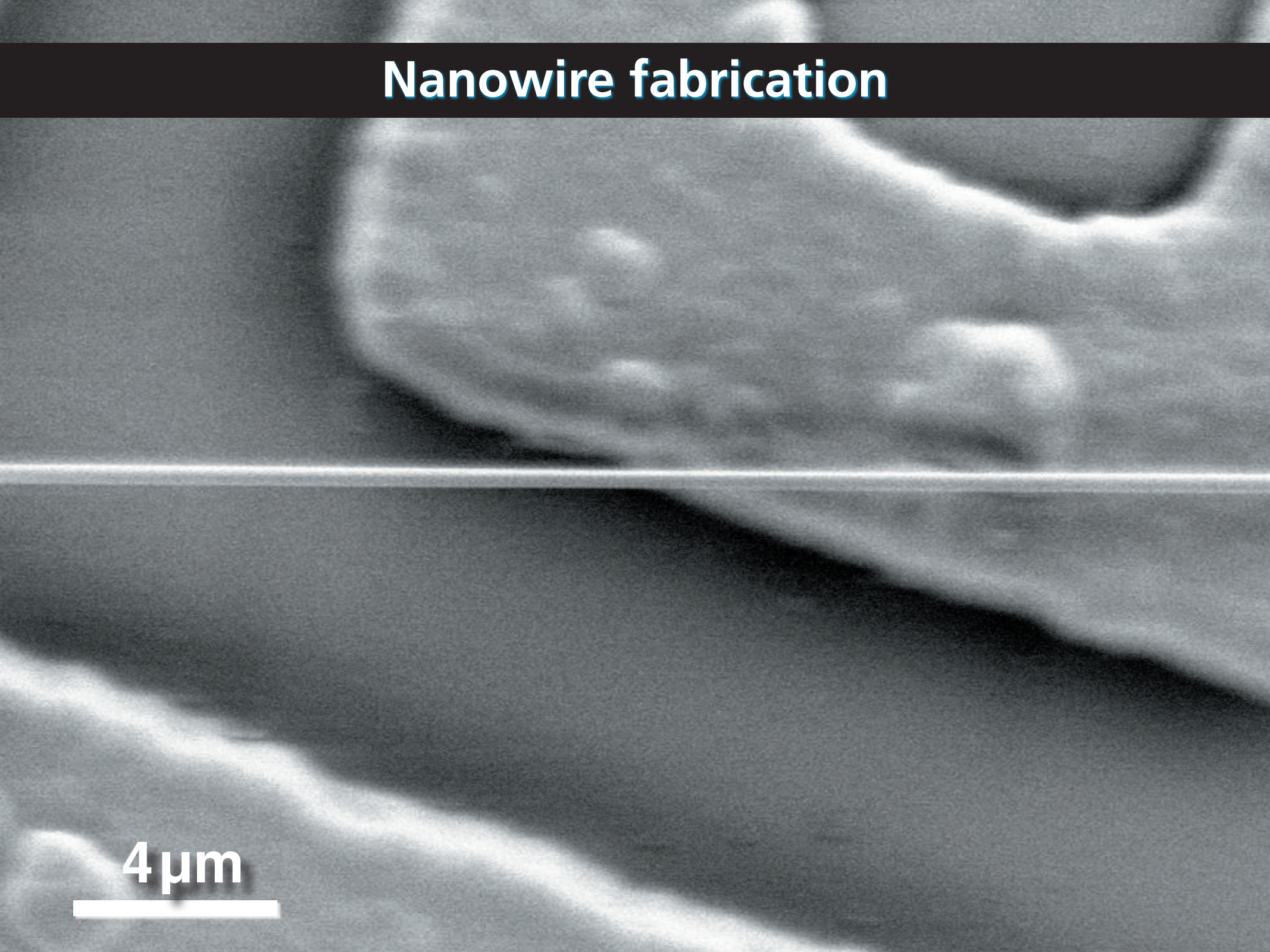


Nanowire fabrication

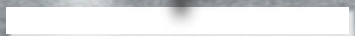


6 μm

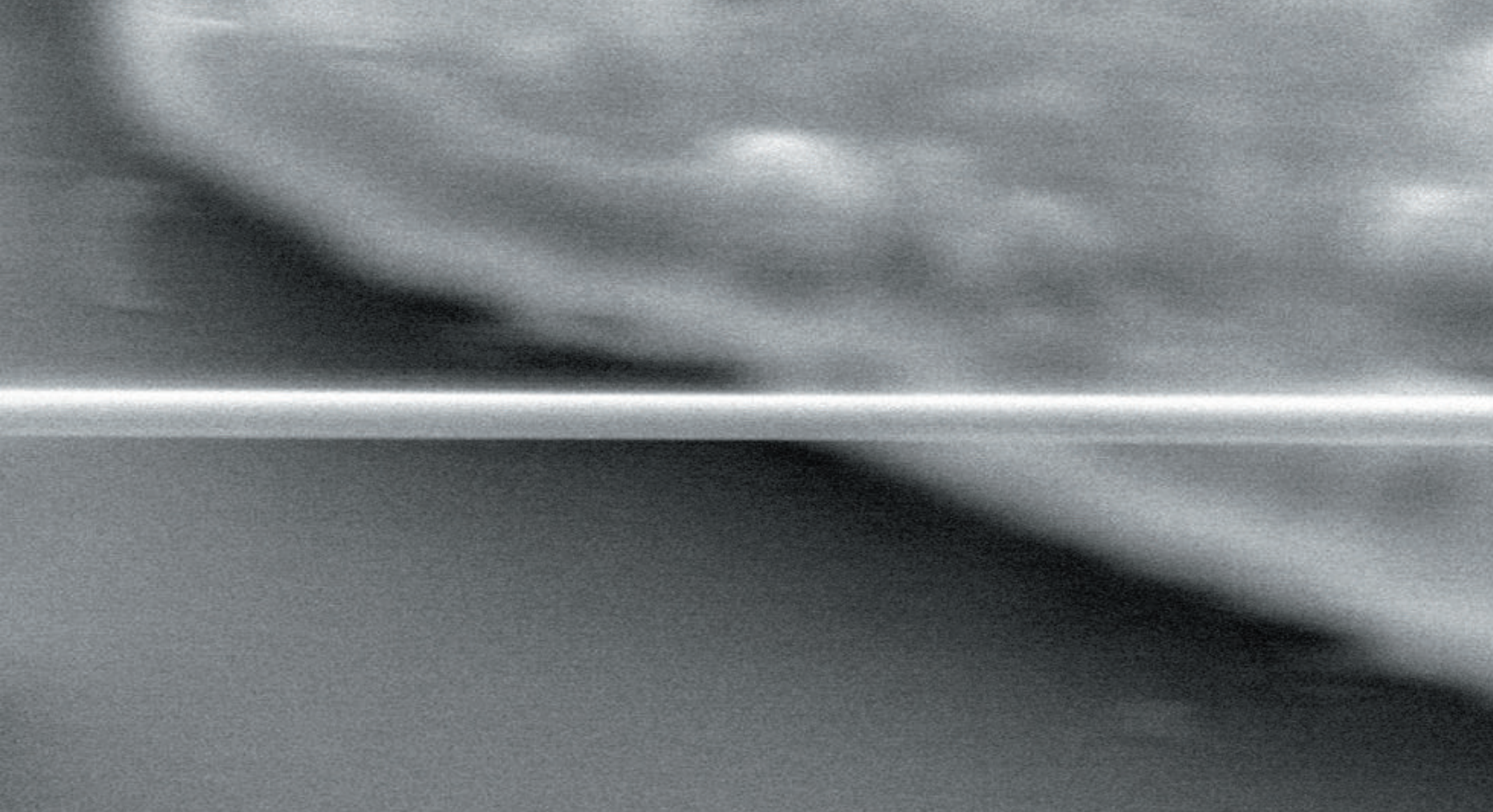
Nanowire fabrication



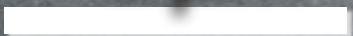
4 μm



Nanowire fabrication



2 μm



Nanowire fabrication

312 nm

A transmission electron micrograph (TEM) showing a single, long, cylindrical nanowire. The nanowire is oriented horizontally and has a uniform diameter. A vertical white line with a crossbar at the bottom is drawn across the center of the nanowire to indicate its diameter. The text "312 nm" is placed above this line. The background is dark and grainy, typical of a TEM image.

1 μm

A white horizontal scale bar located in the bottom left corner of the image. The text "1 μm" is positioned above the bar.

Waveguiding

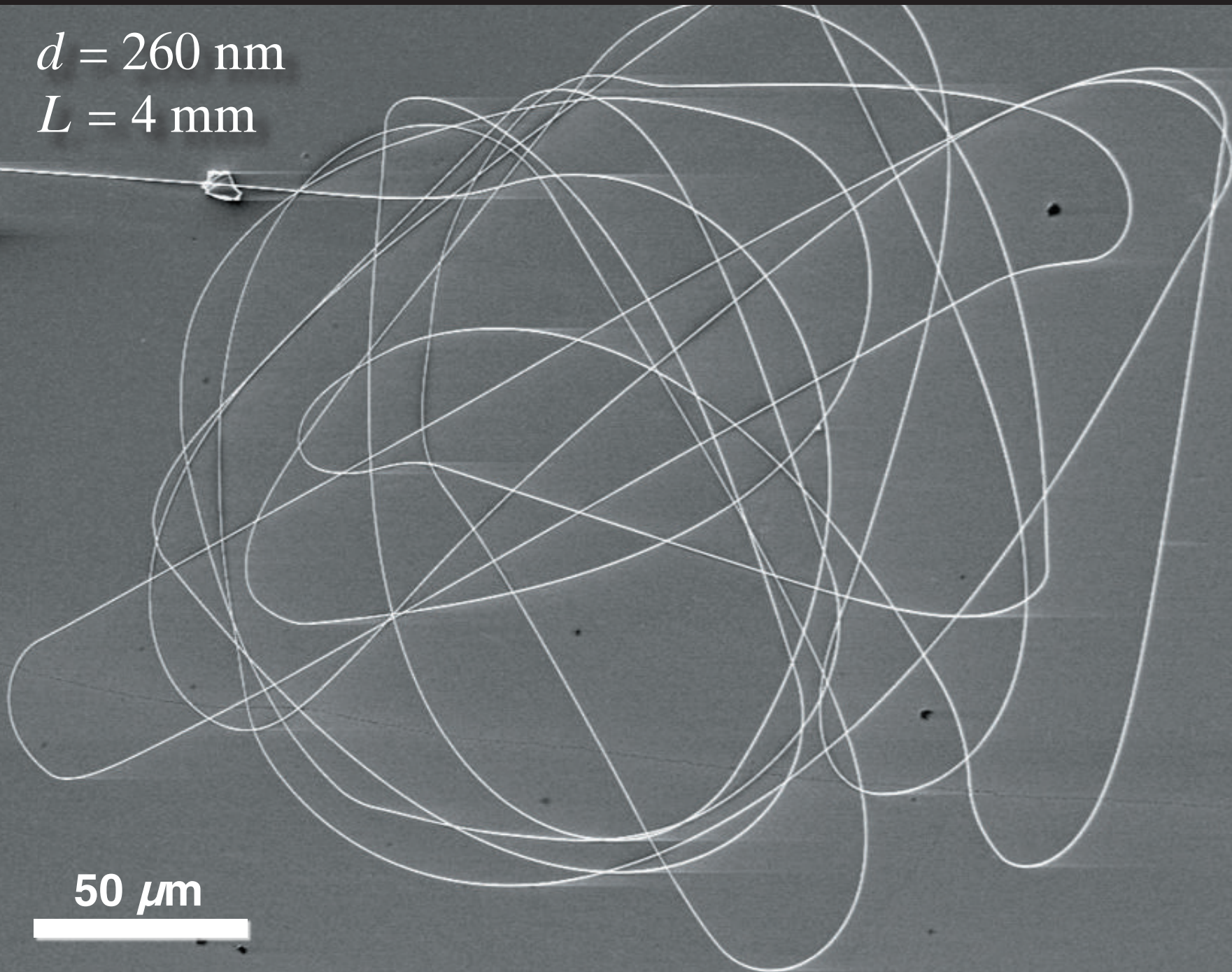
Specifications

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

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50 μm

Nanowire fabrication

240-nm wire

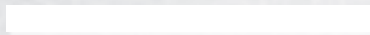
200 nm



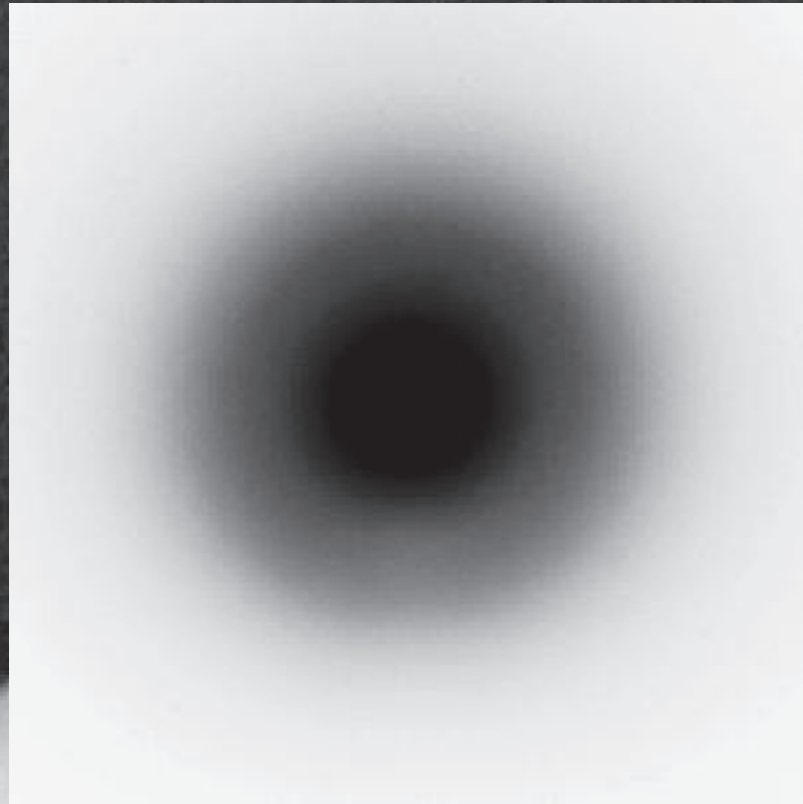
Nanowire fabrication

RMS roughness < 0.5 nm

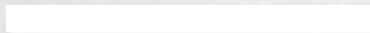
20 nm



Nanowire fabrication



20 nm



Nanowire fabrication

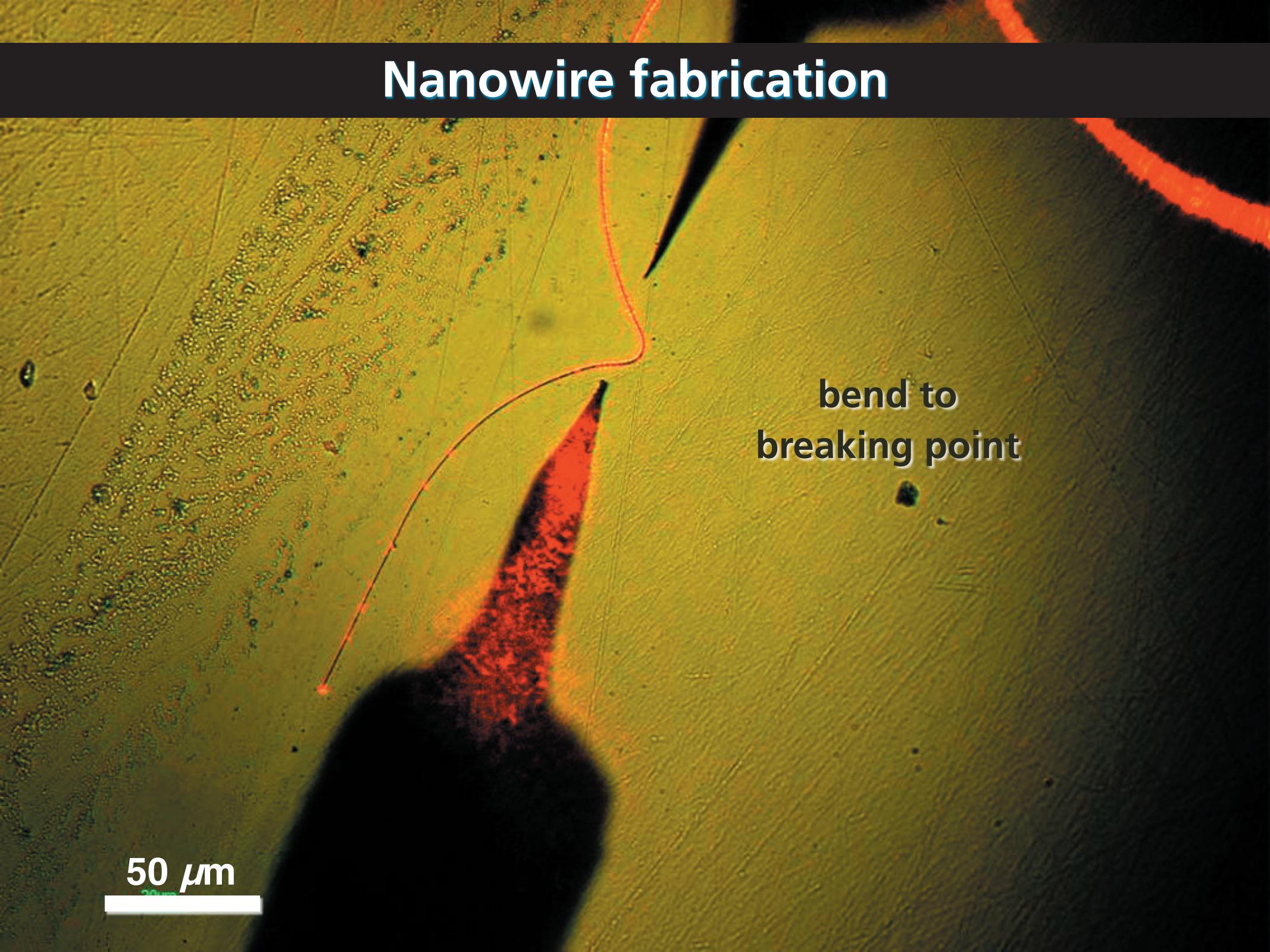
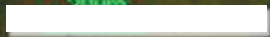
measure tensile stress
at breaking point



Nanowire fabrication

bend to
breaking point

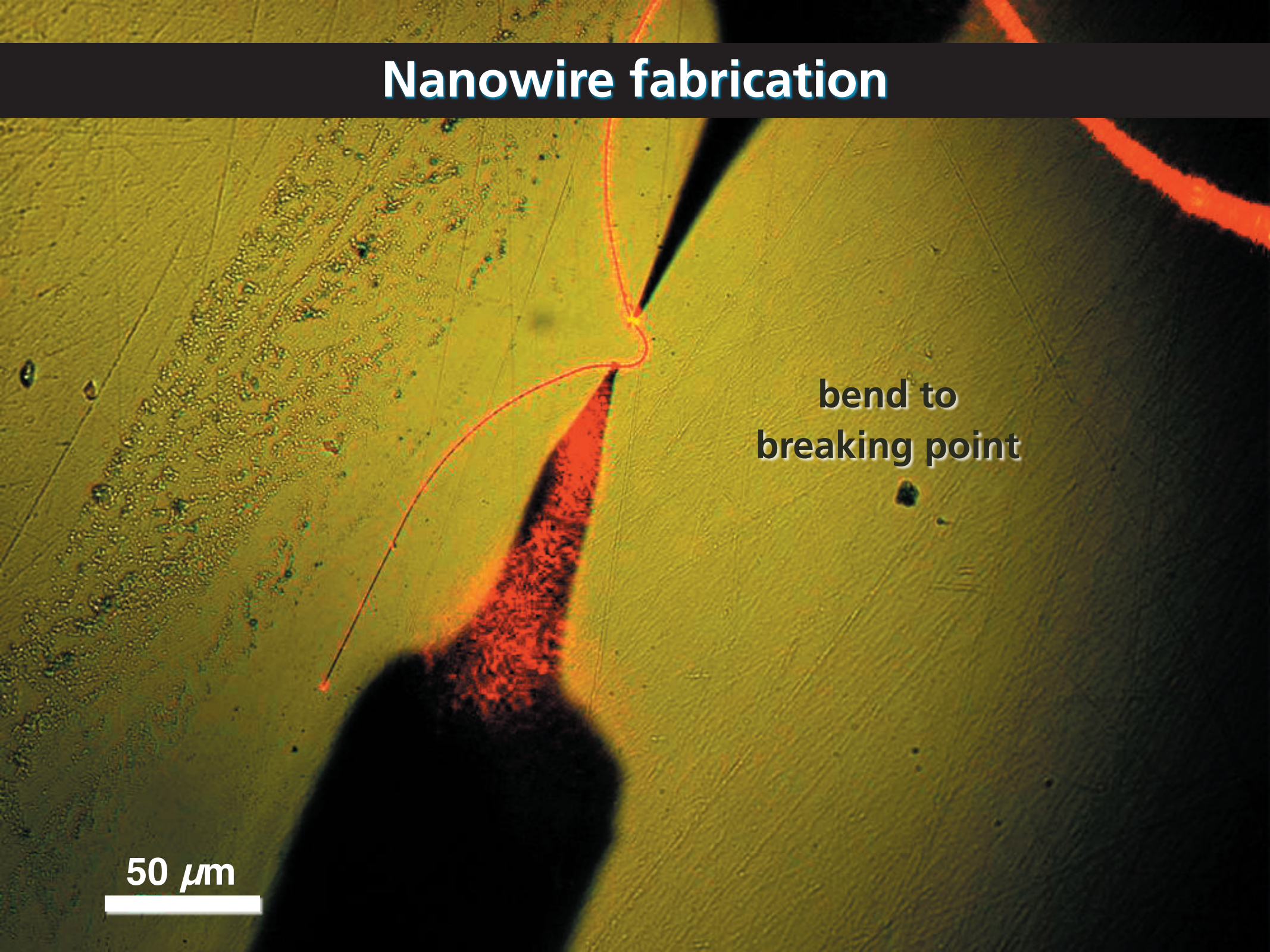
50 μm



Nanowire fabrication

bend to
breaking point

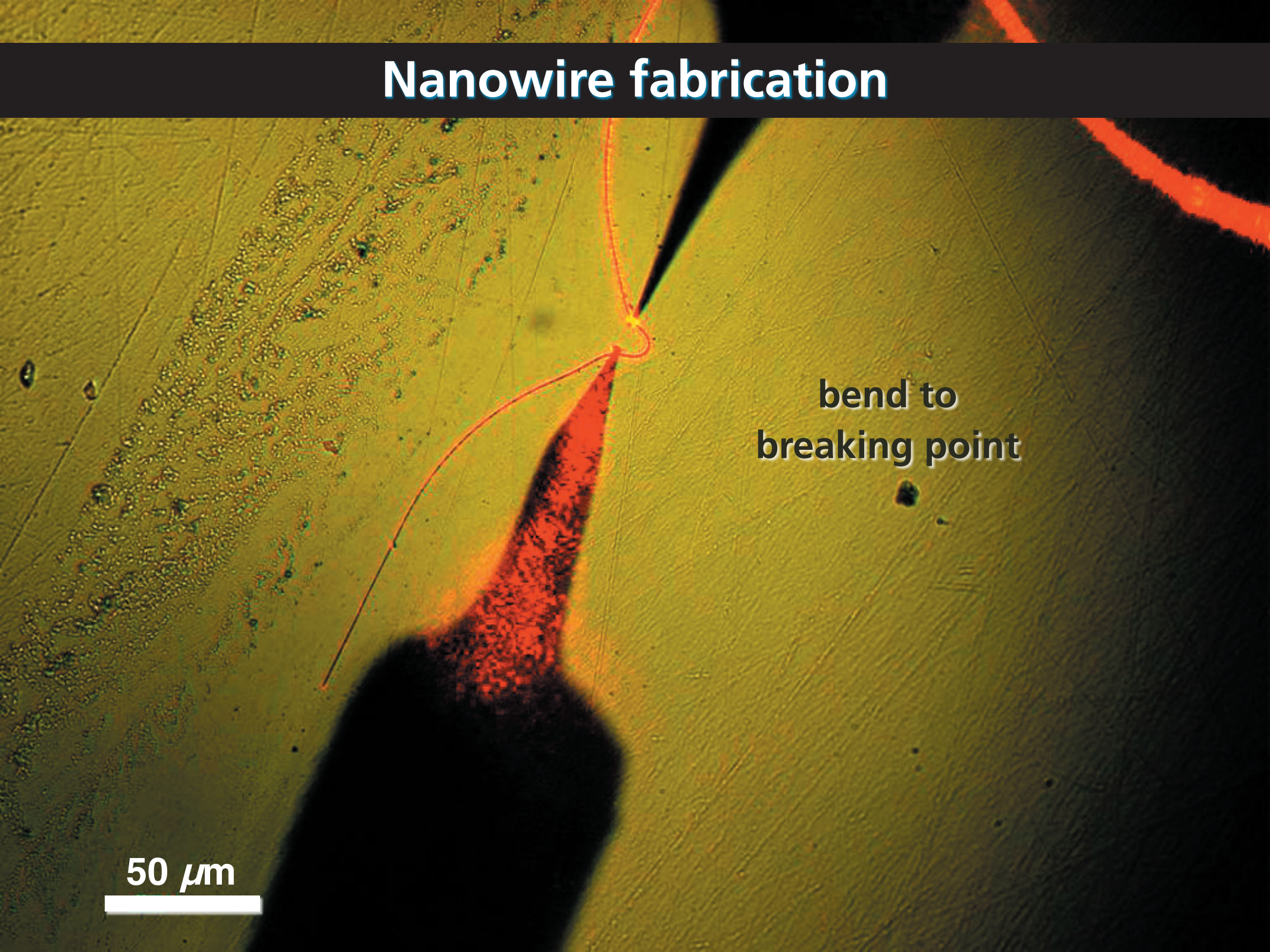
50 μm



Nanowire fabrication

bend to
breaking point

50 μm



Nanowire fabrication



minimum bending radius R_{EB}
gives tensile stress:

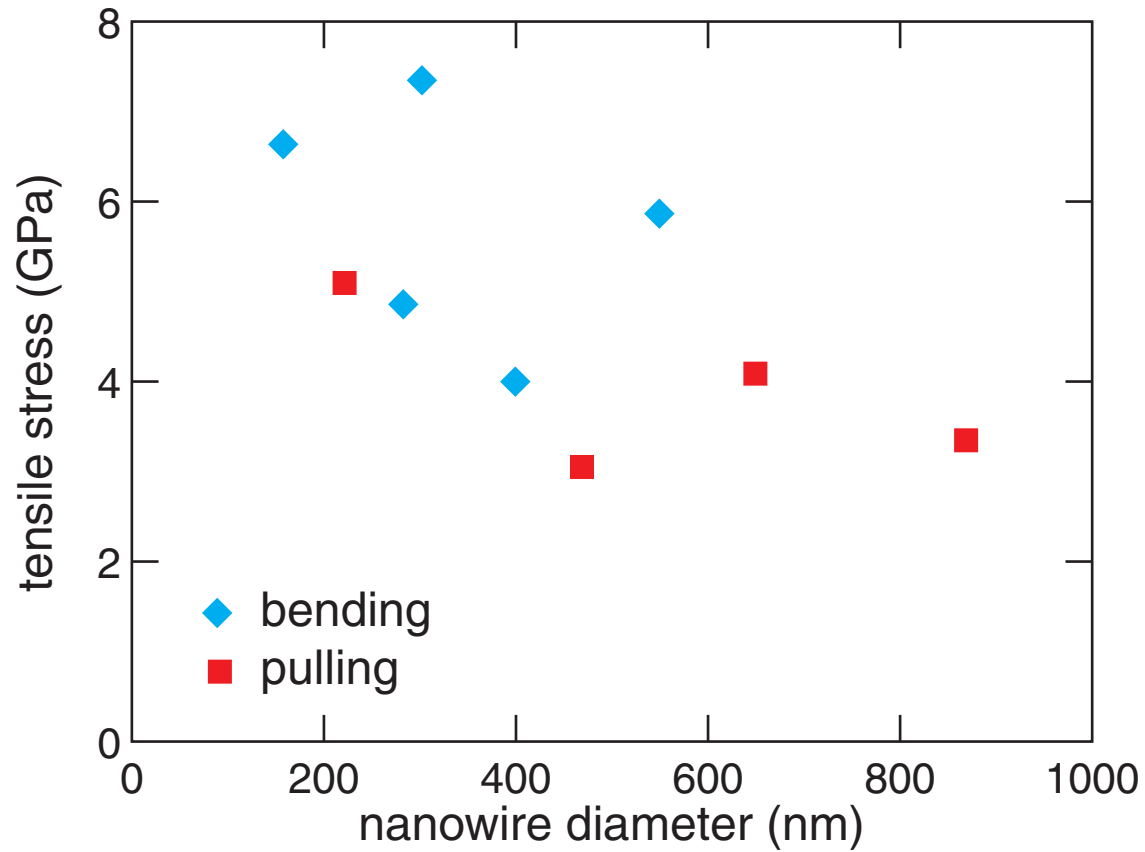
$$\sigma = \frac{ED}{2R_{EB}}$$

E = Young's modulus

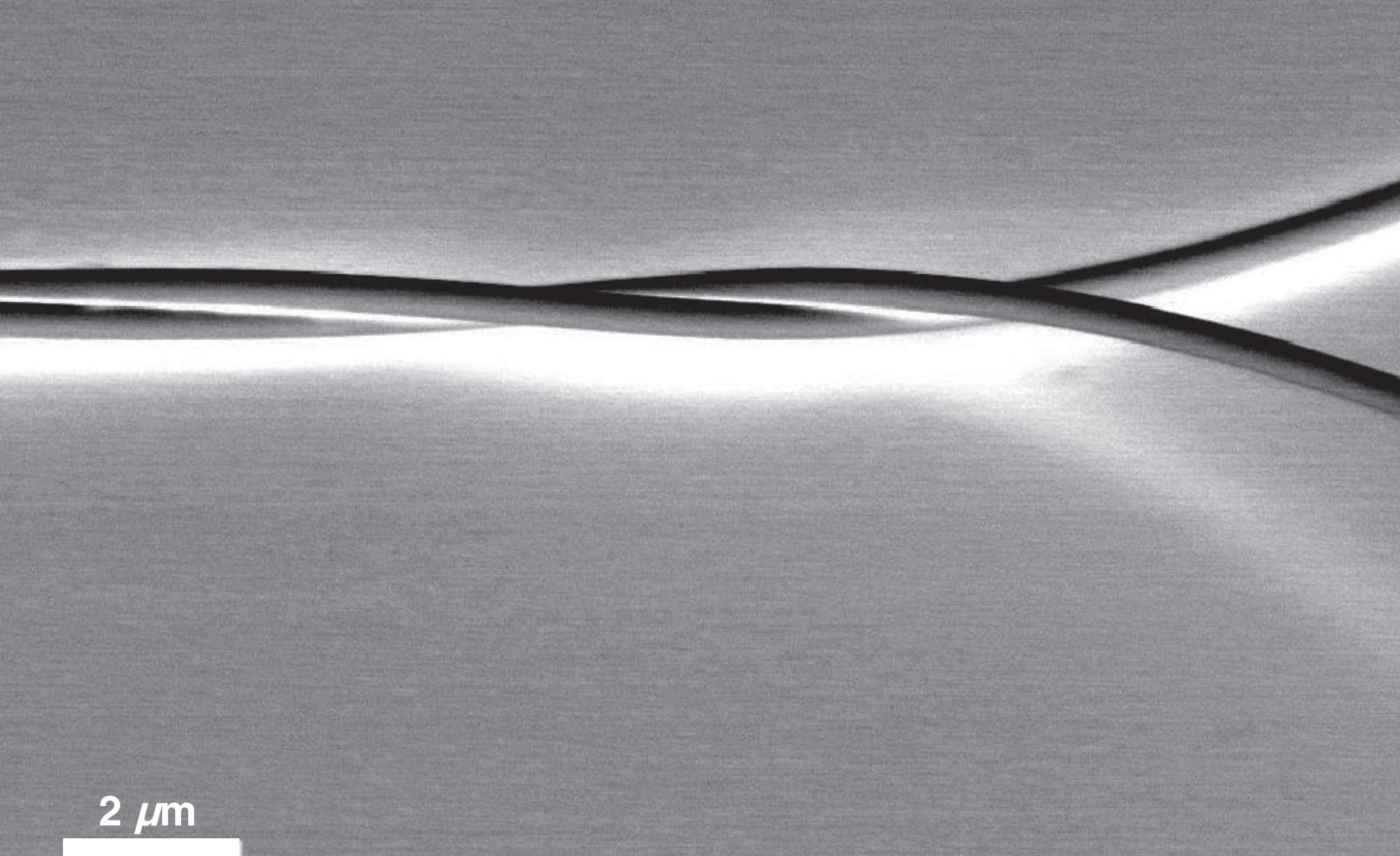
D = wire diameter

Waveguiding

tensile strength

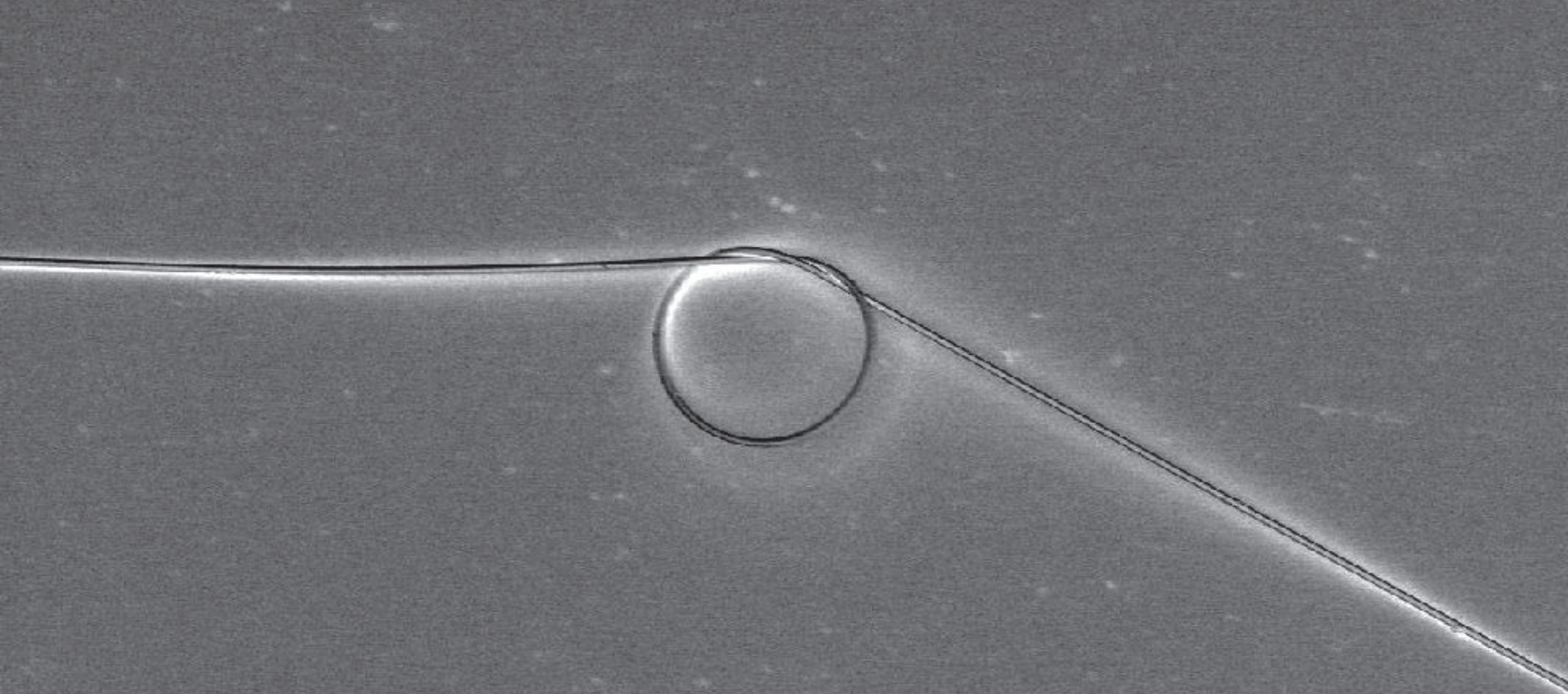


Nanowire fabrication



2 μm

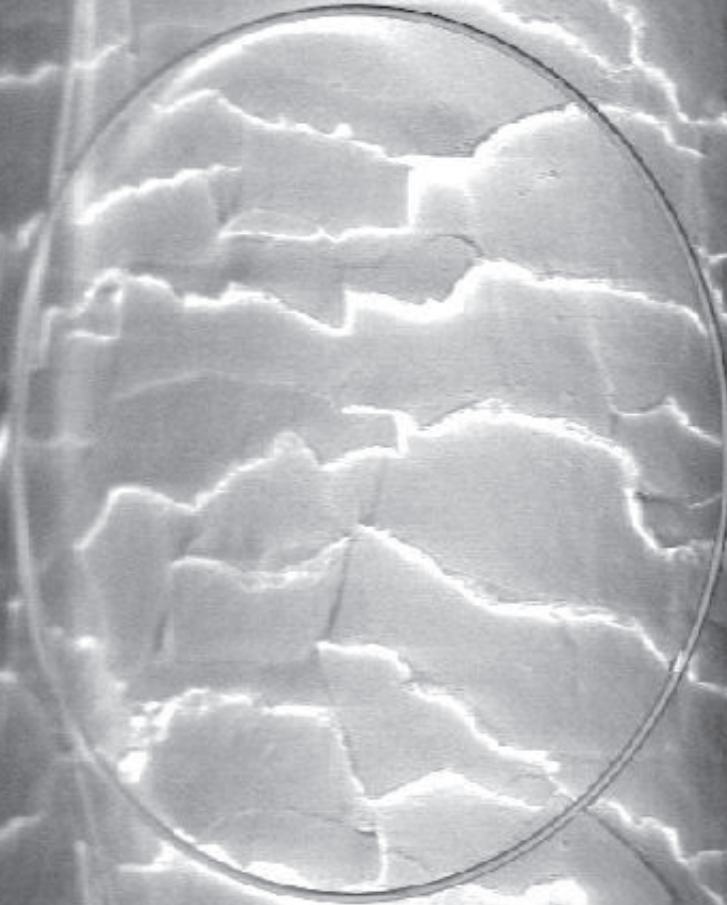
Nanowire fabrication



20 μm



Nanowire fabrication



20 μm

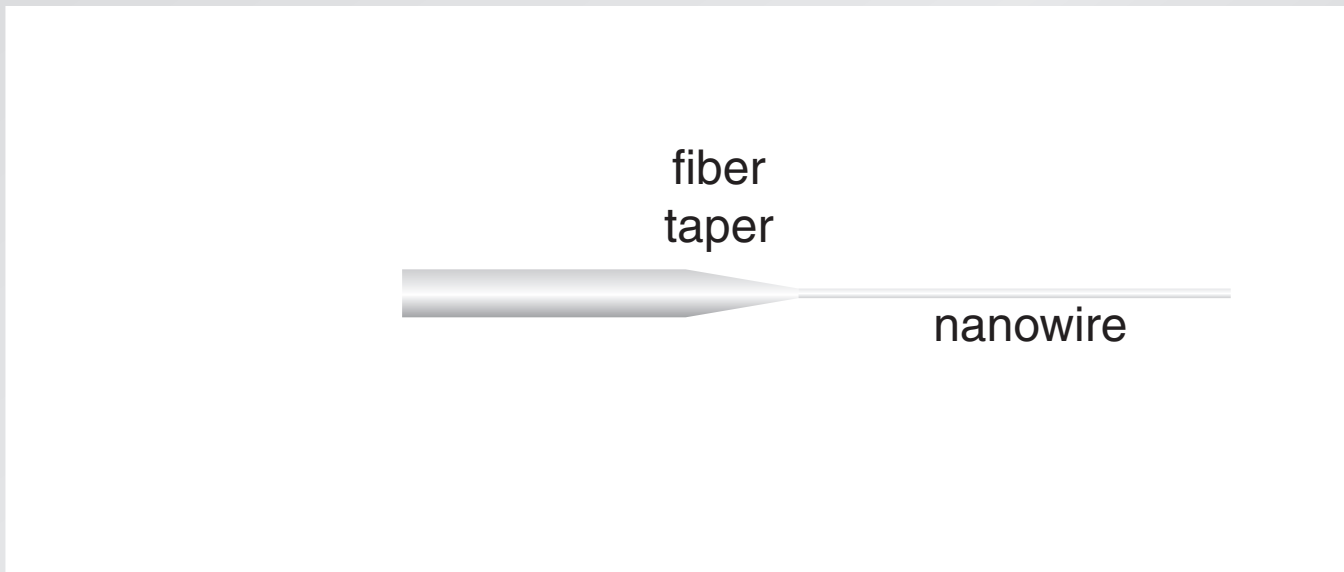


Outline

- waveguiding
- nanowire fabrication
- optical properties

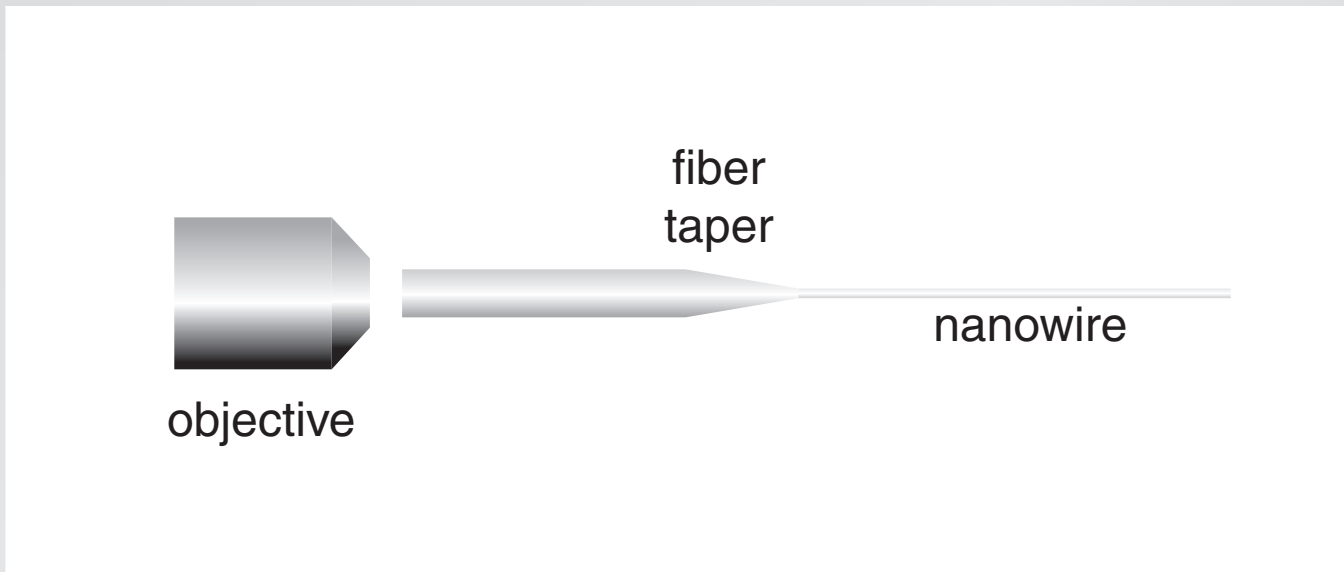
Optical properties

coupling light into nanowires



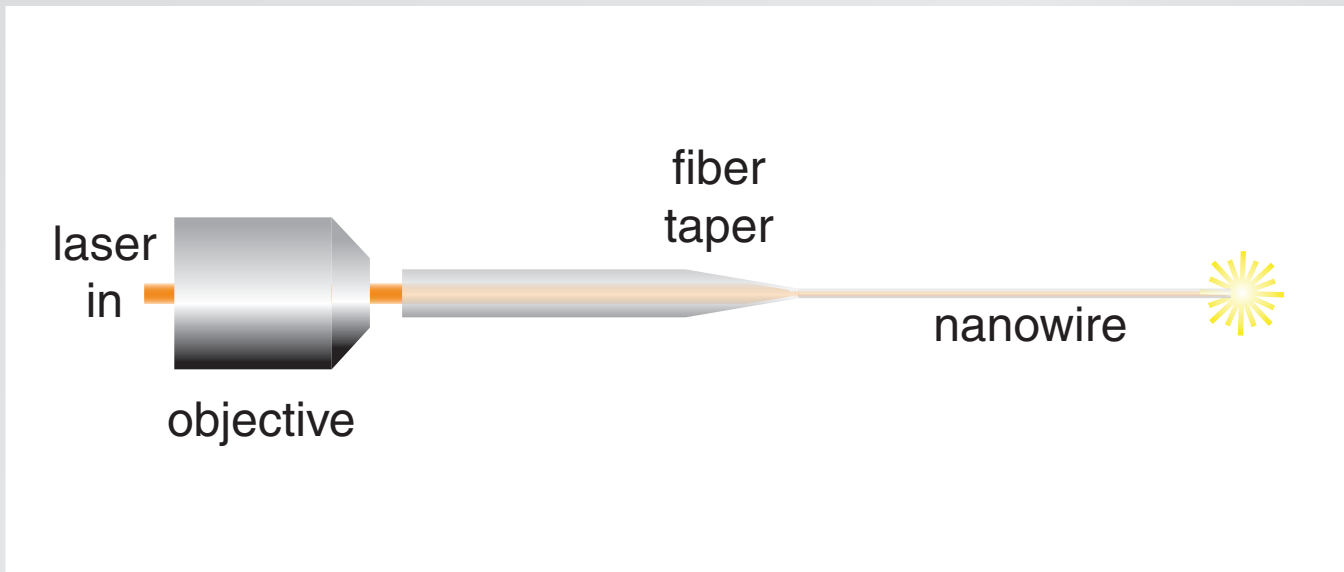
Optical properties

coupling light into nanowires



Optical properties

coupling light into nanowires



Optical properties

280-nm nanowire



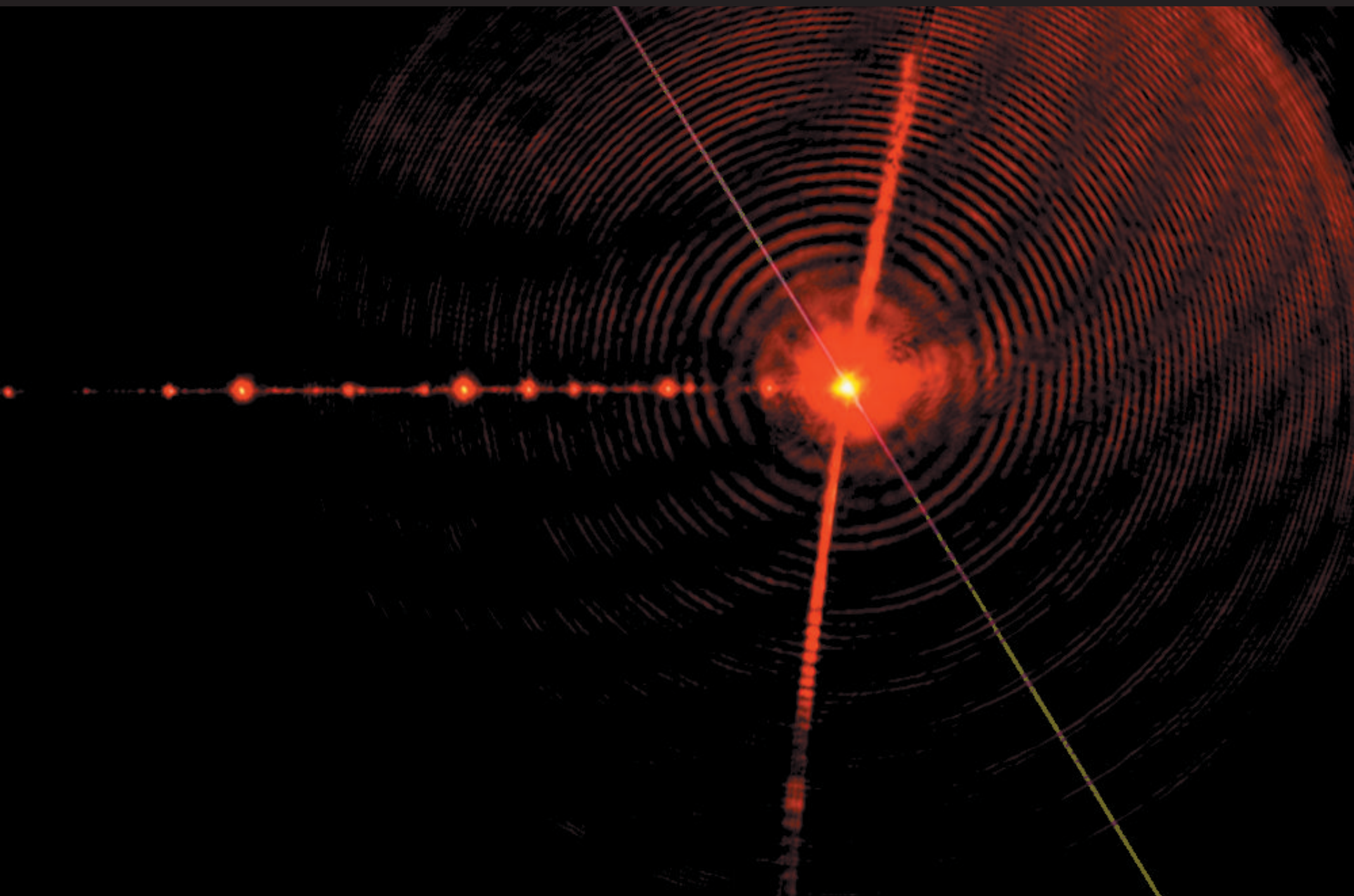
360 nm



450 nm



Optical properties

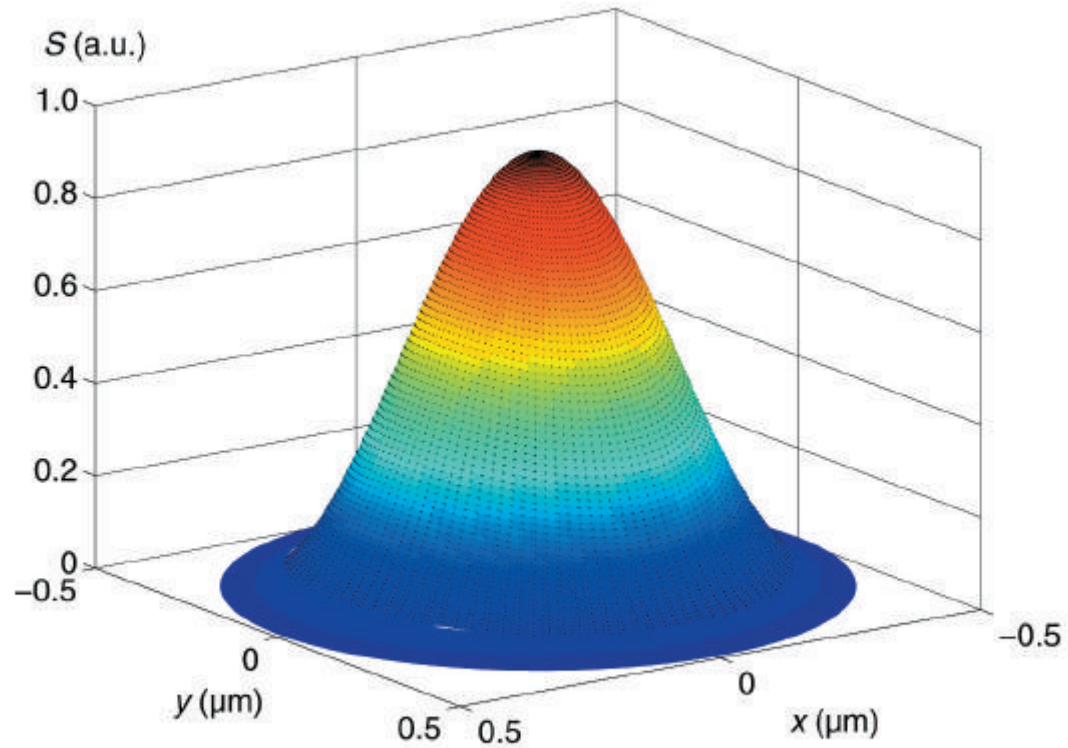


Optical properties



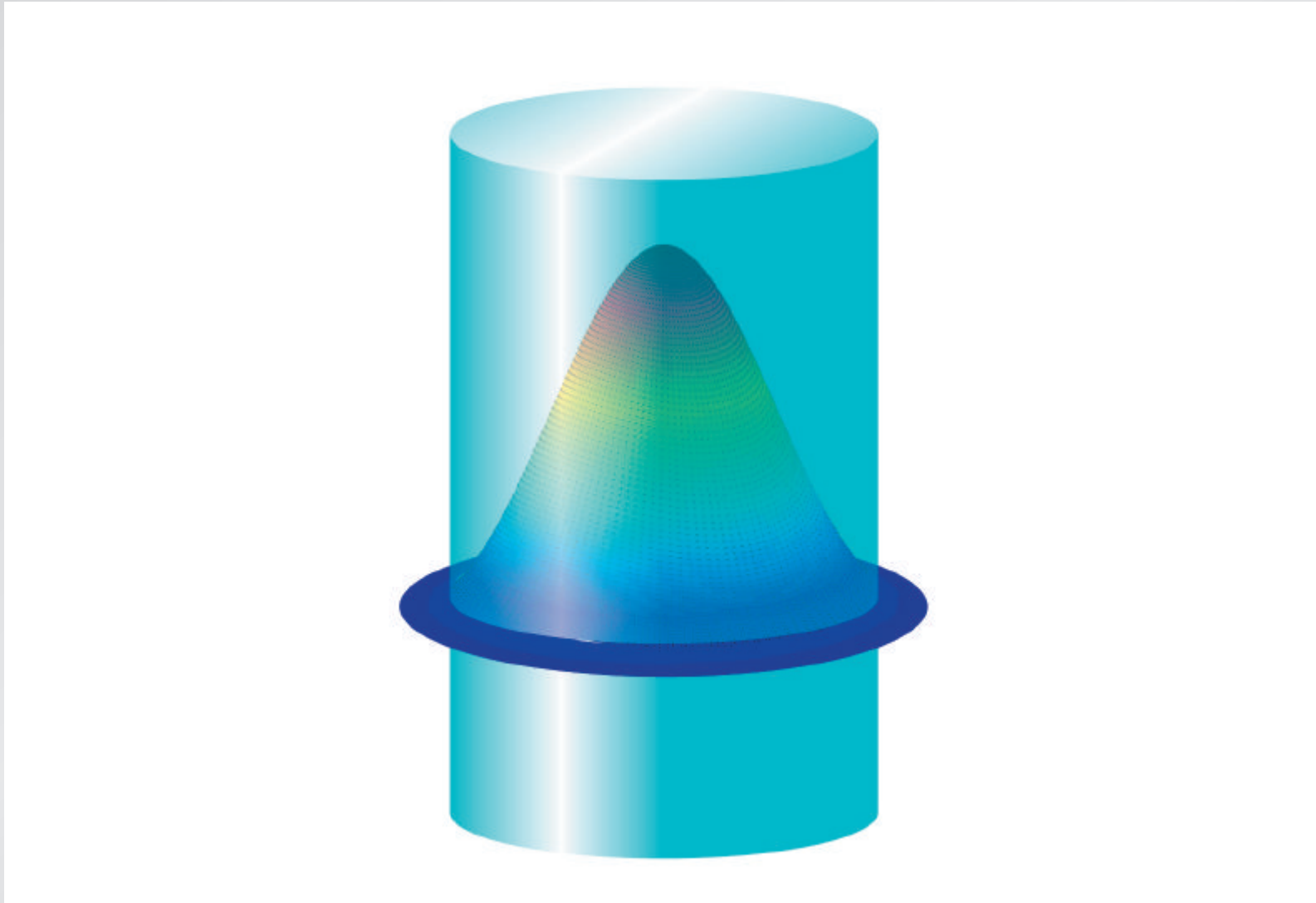
Optical properties

Poynting vector profile for 800-nm nanowire



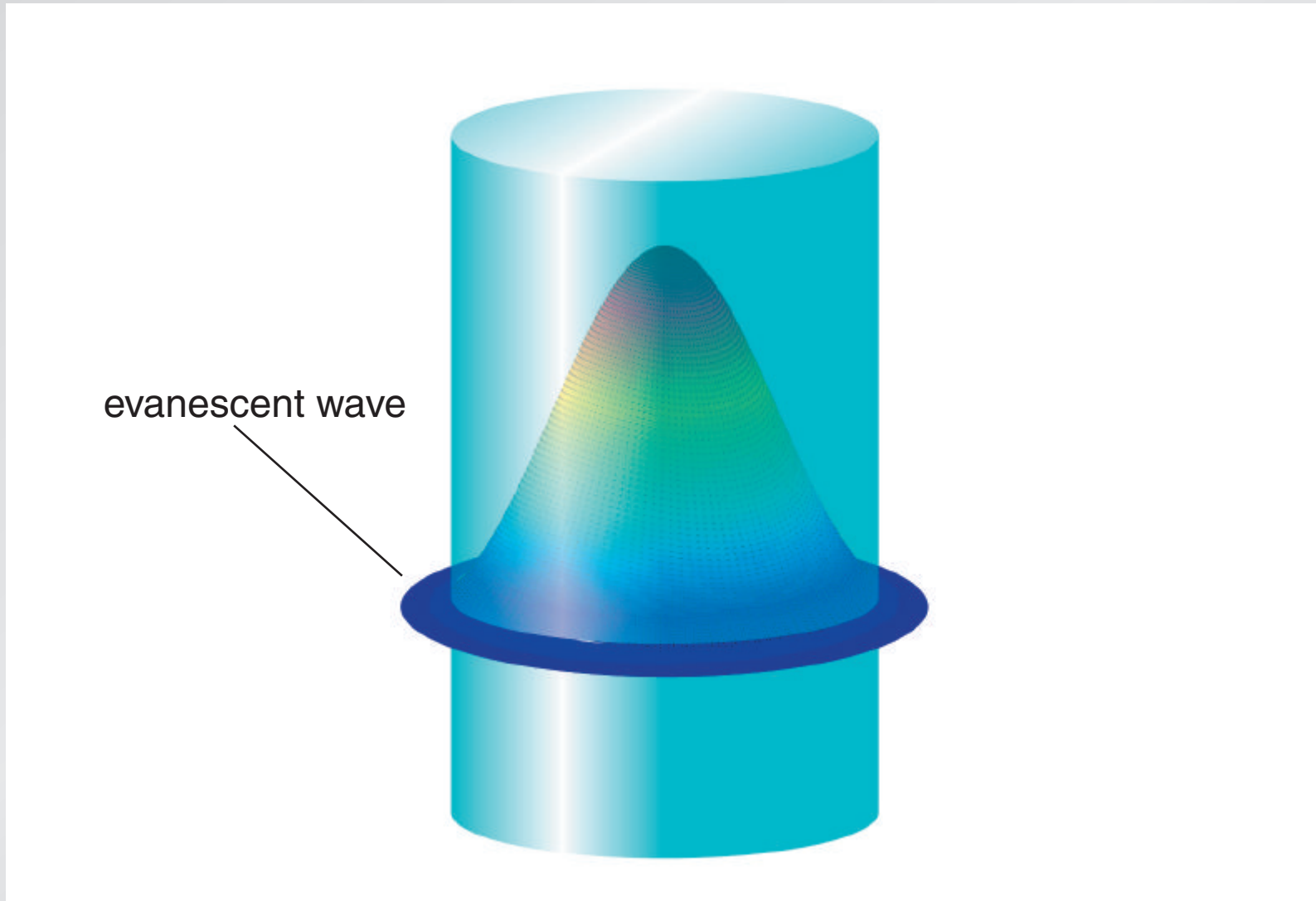
Optical properties

Poynting vector profile for 800-nm nanowire



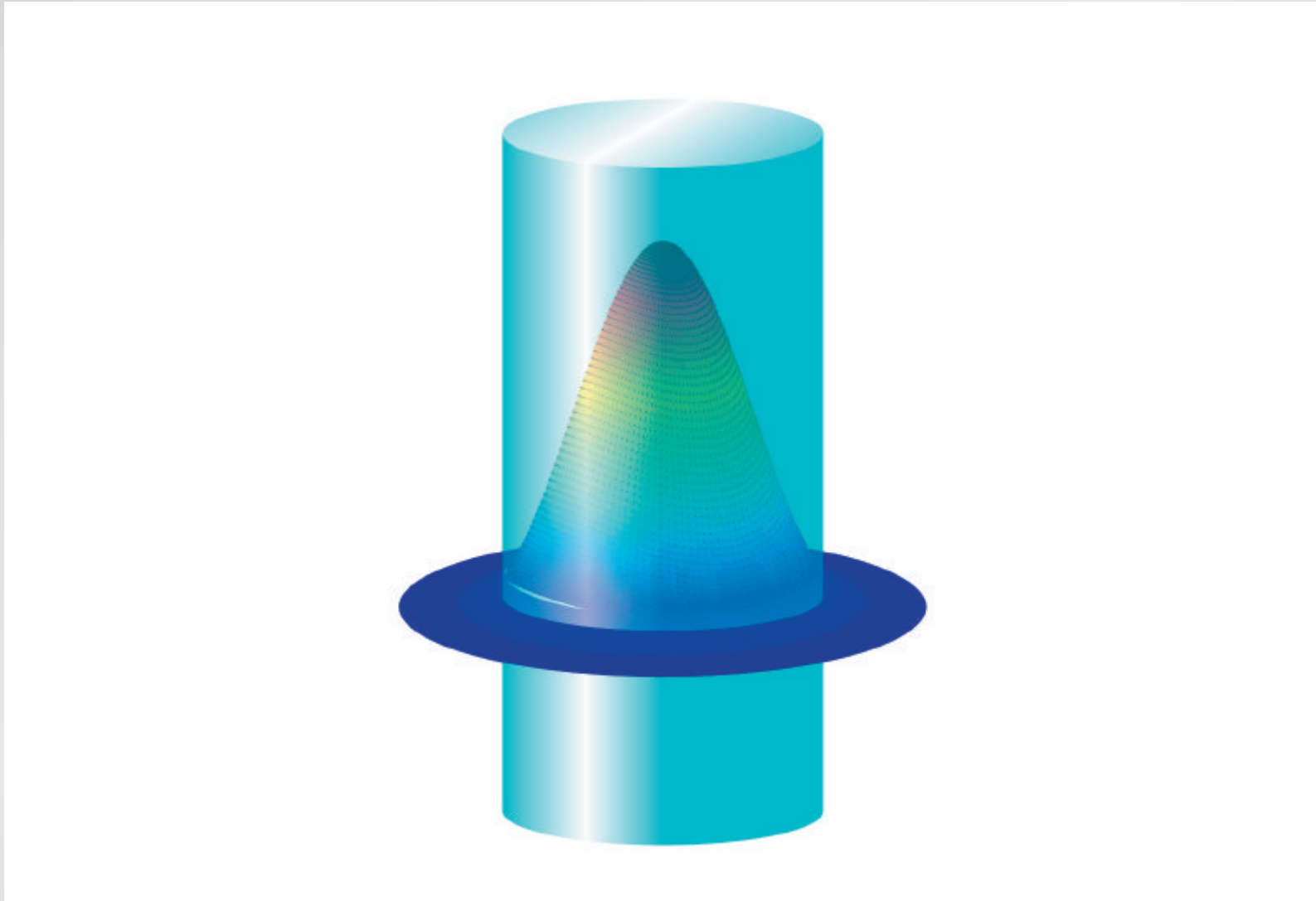
Optical properties

Poynting vector profile for 800-nm nanowire



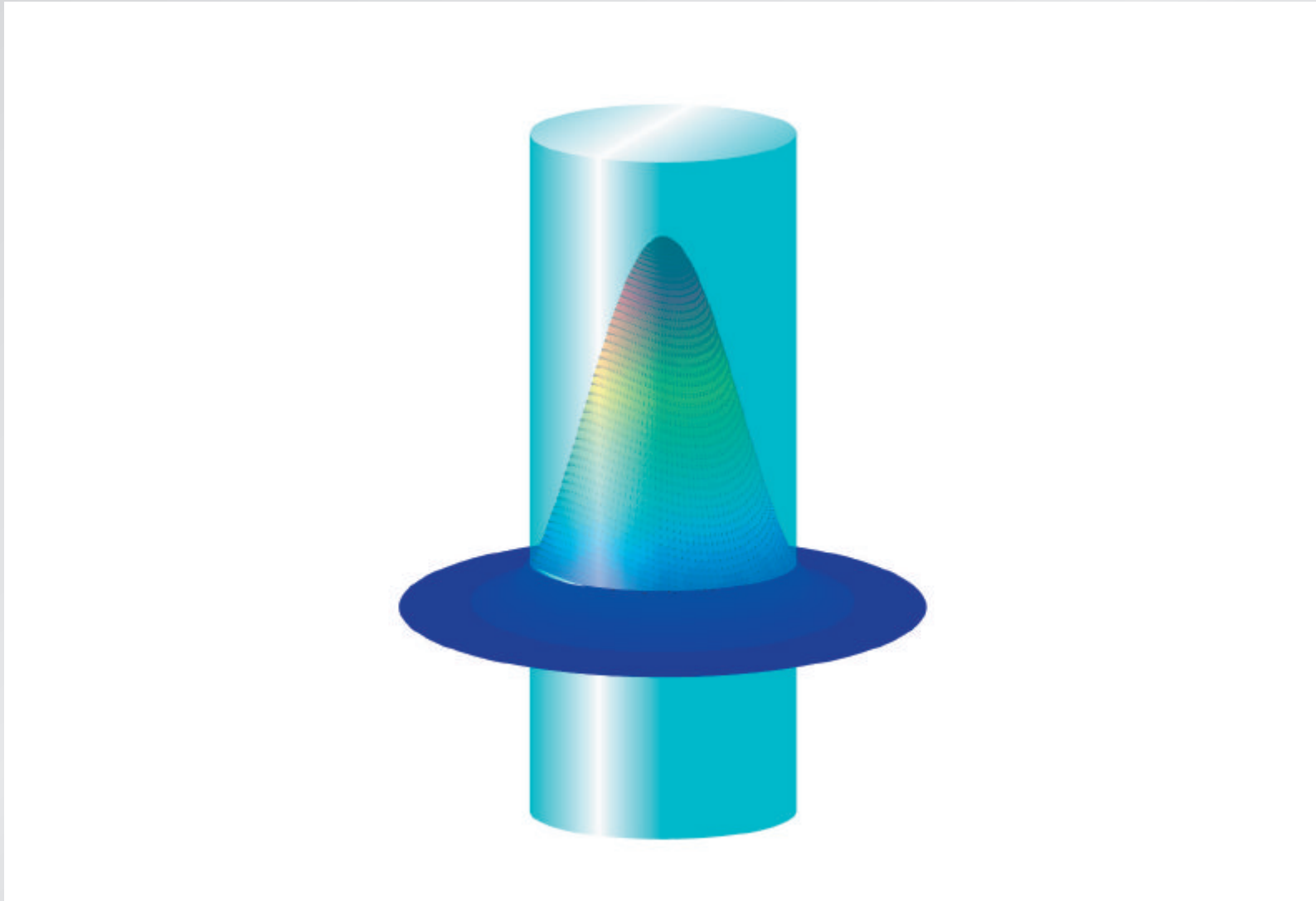
Optical properties

Poynting vector profile for 600-nm nanowire



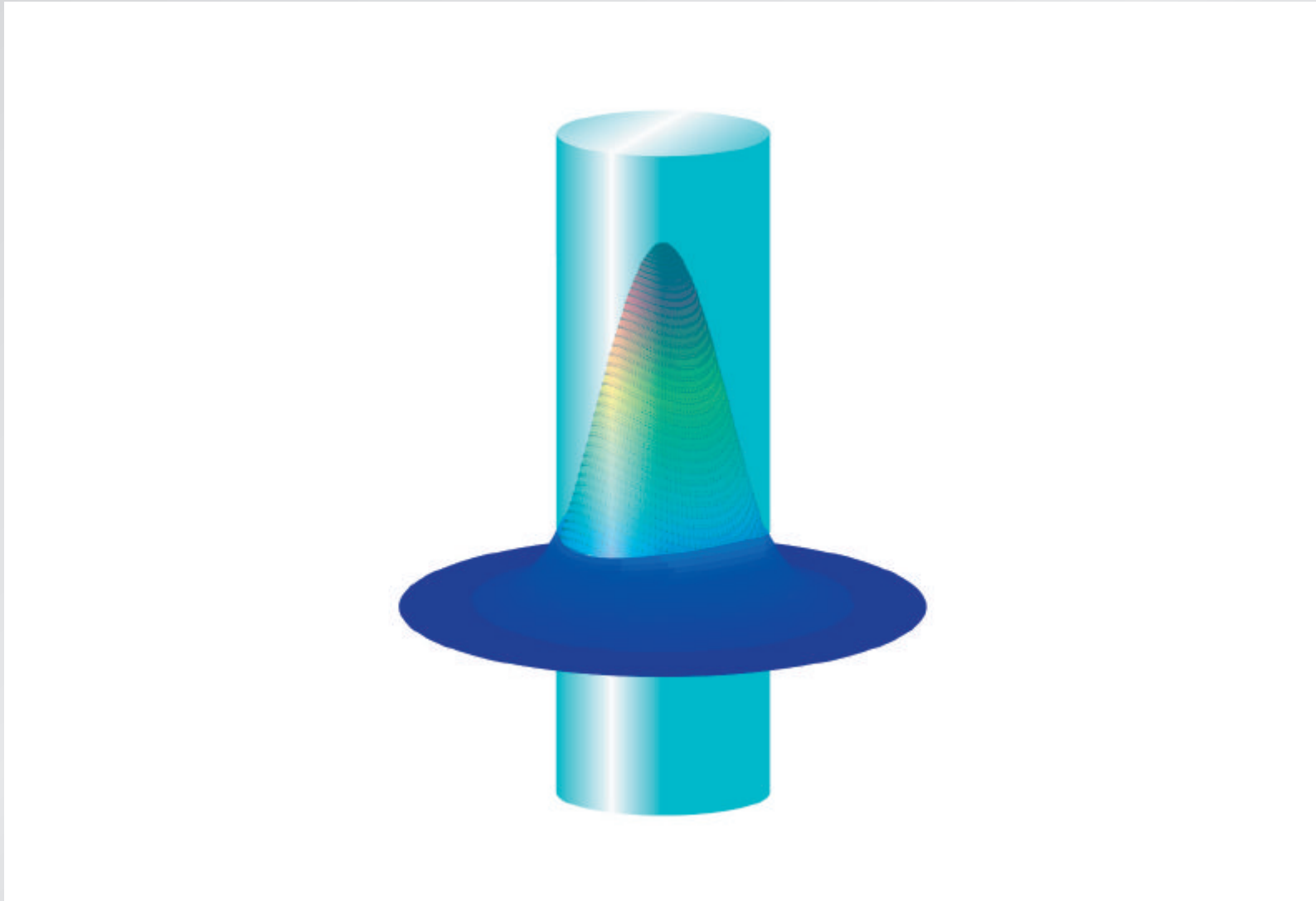
Optical properties

Poynting vector profile for 500-nm nanowire



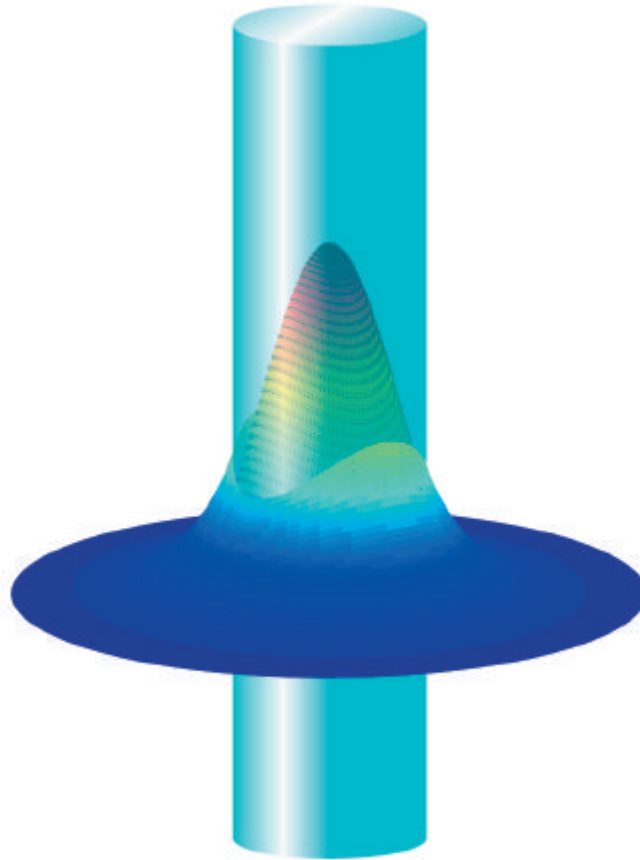
Optical properties

Poynting vector profile for 400-nm nanowire



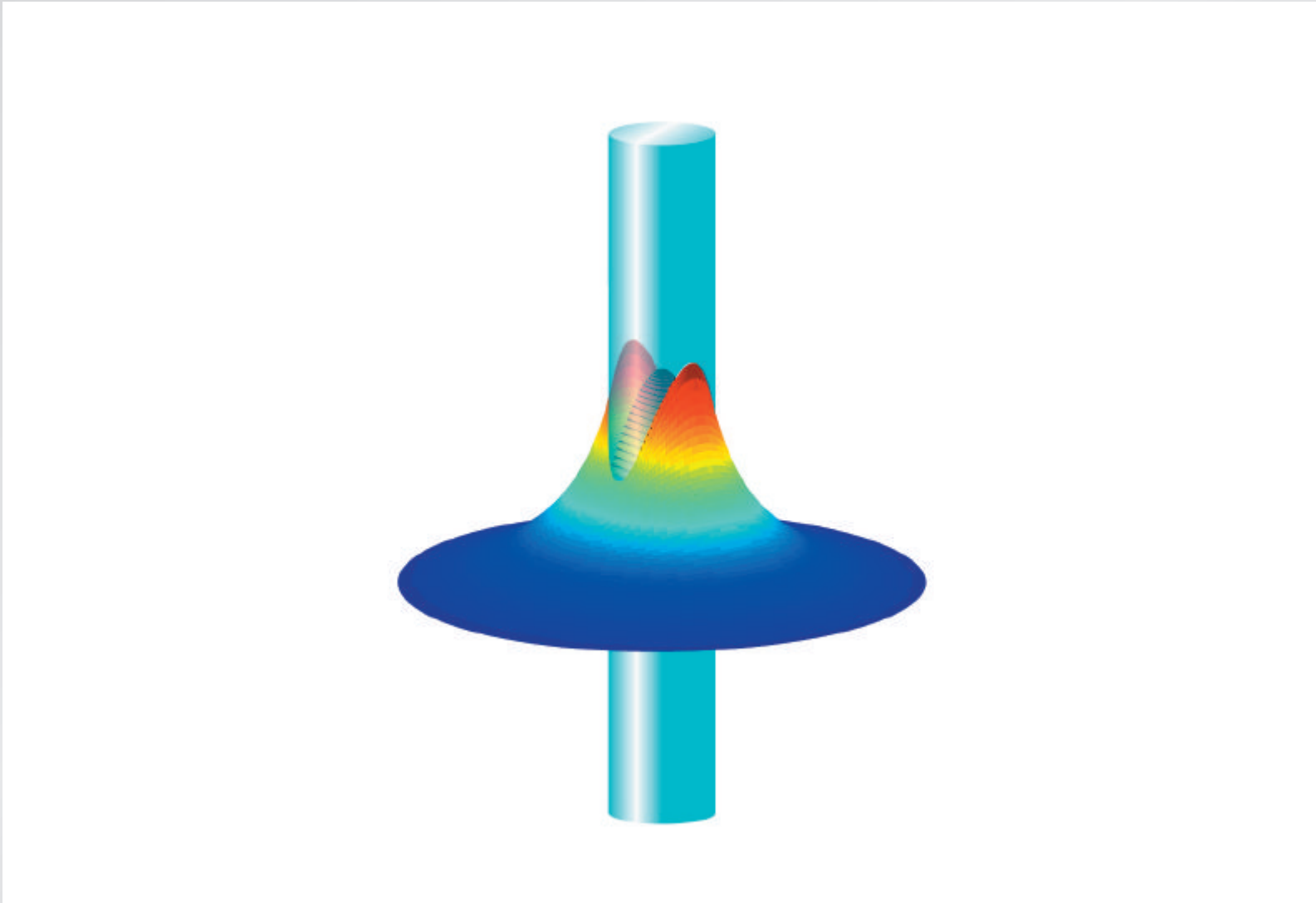
Optical properties

Poynting vector profile for 300-nm nanowire



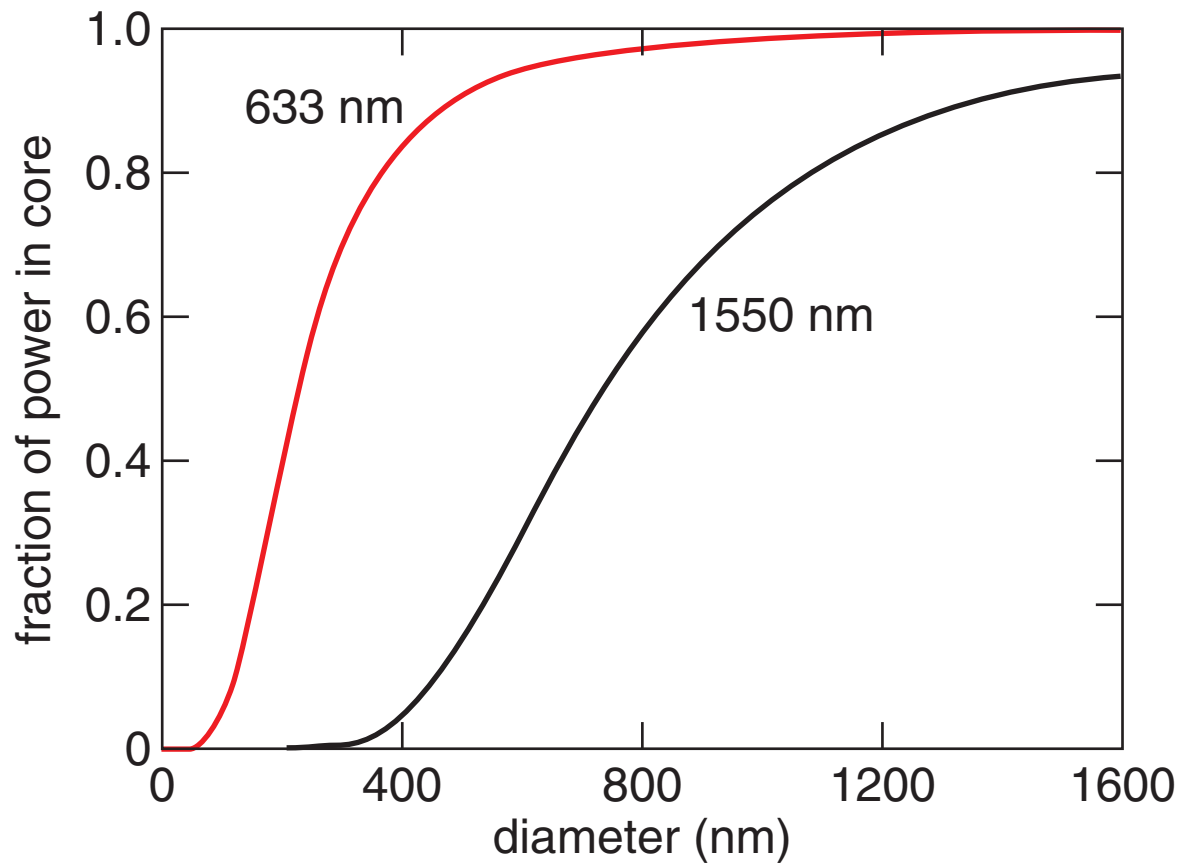
Optical properties

Poynting vector profile for 200-nm nanowire



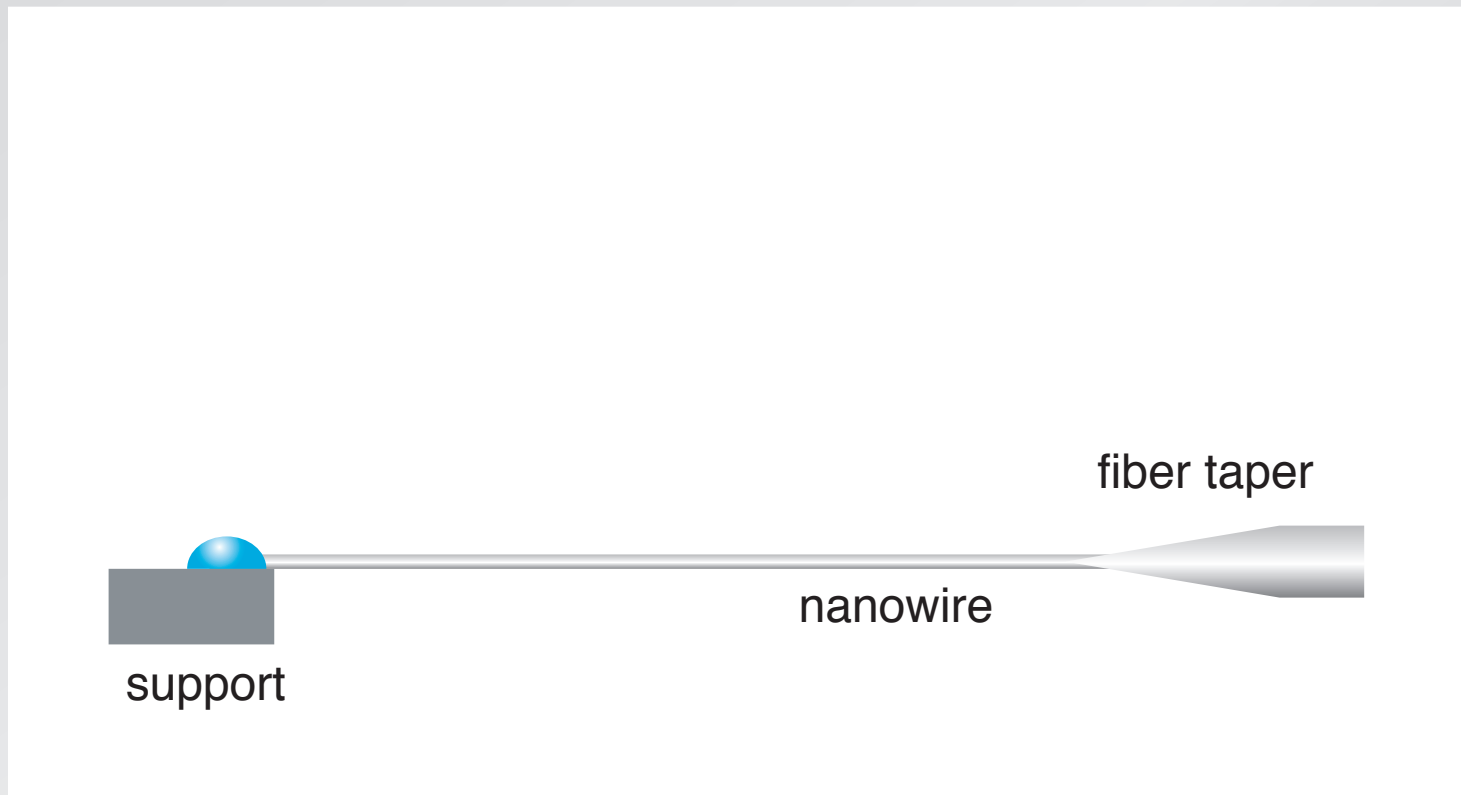
Waveguiding

fraction of power carried in core



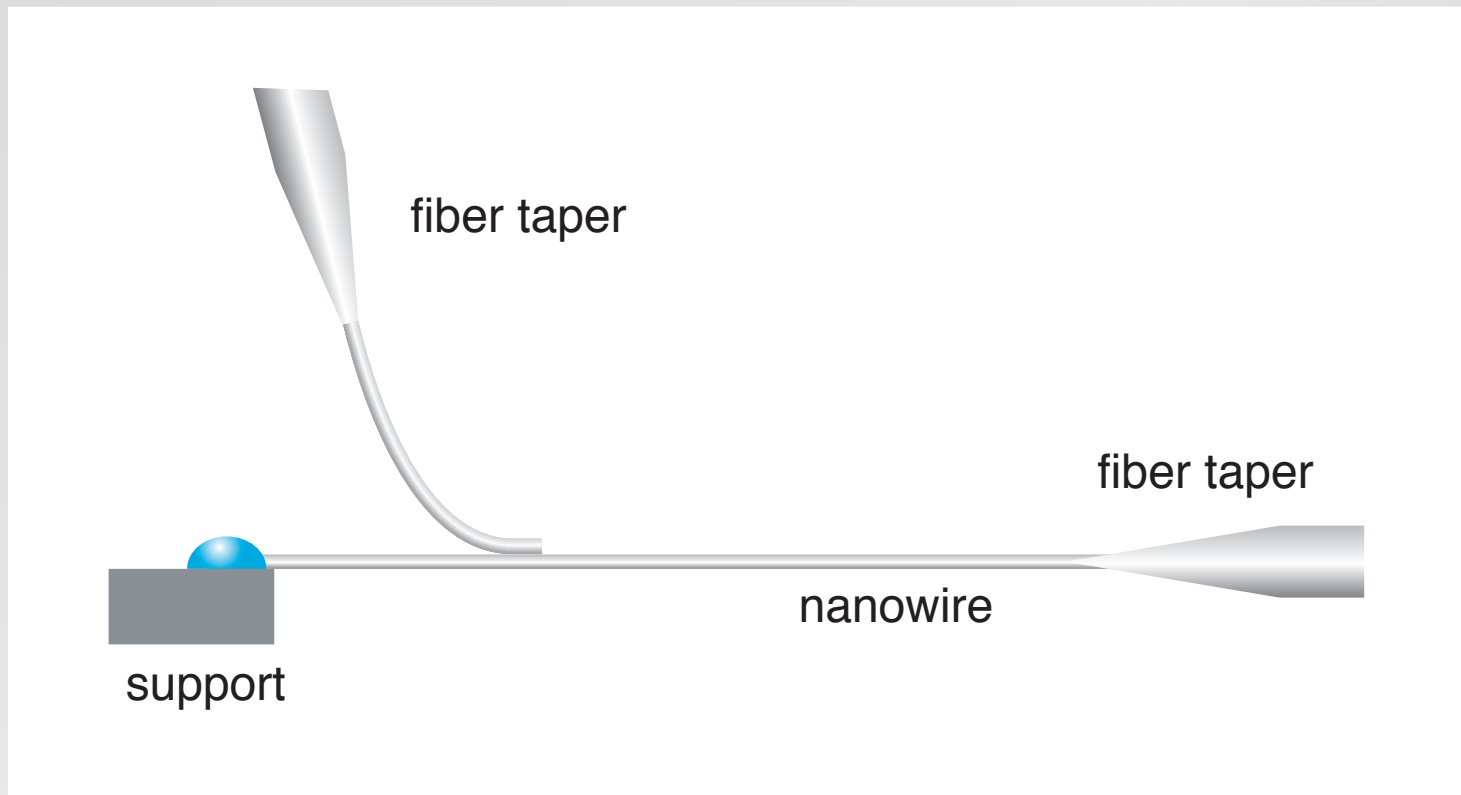
Optical properties

coupling light between nanowires



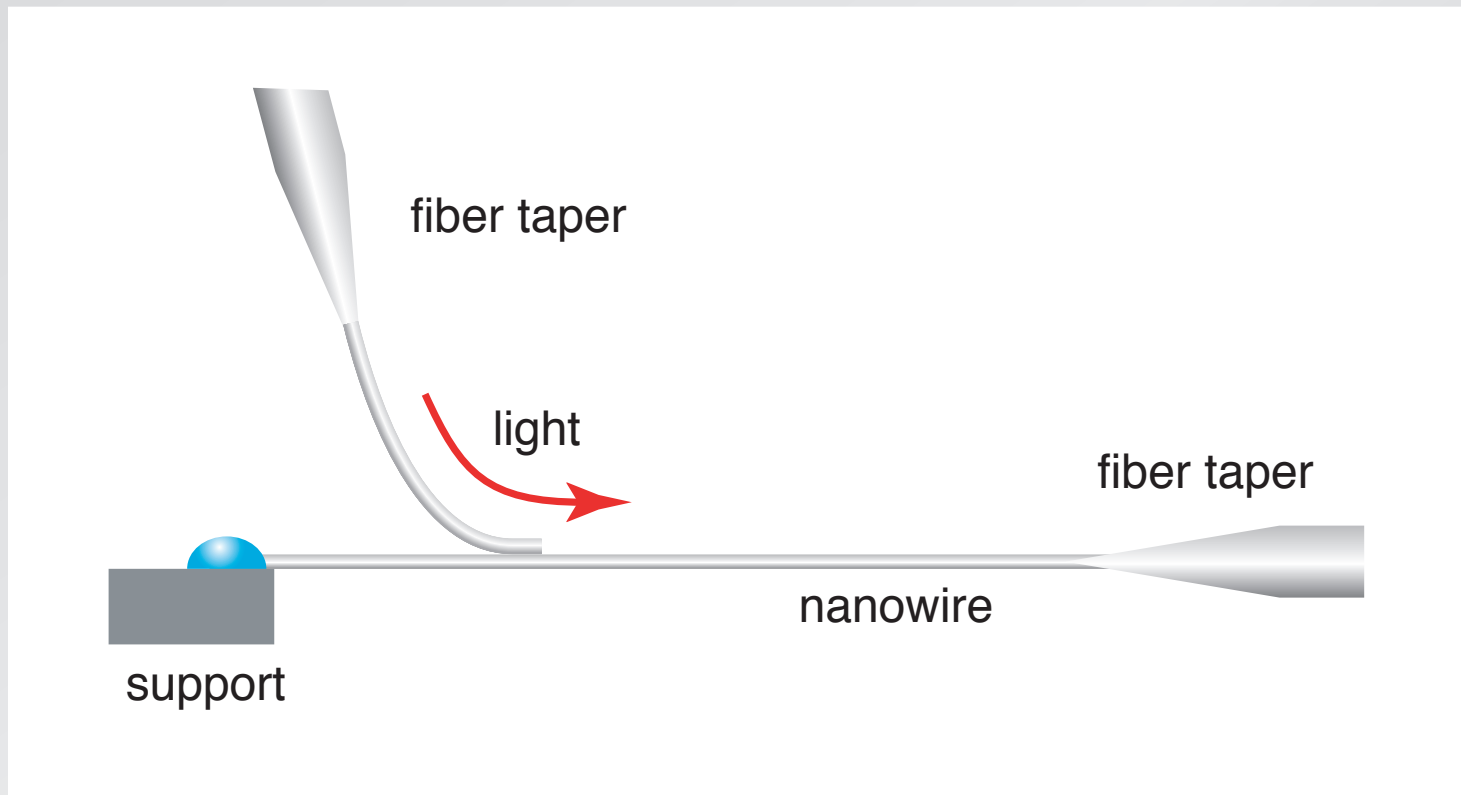
Optical properties

coupling light between nanowires



Optical properties

coupling light between nanowires



Optical properties



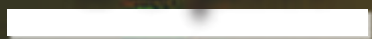
50 μm



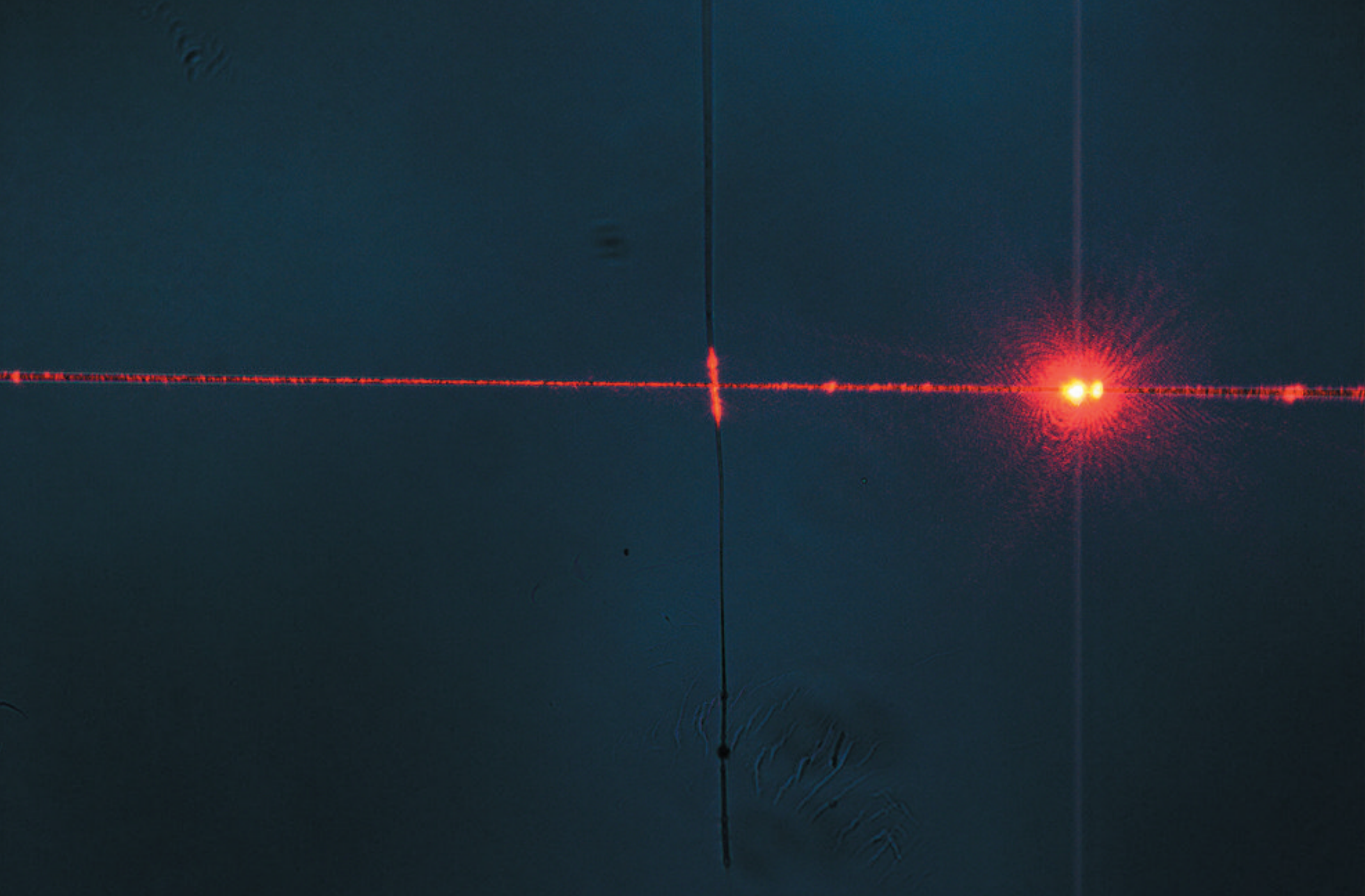
Optical properties



50 μm

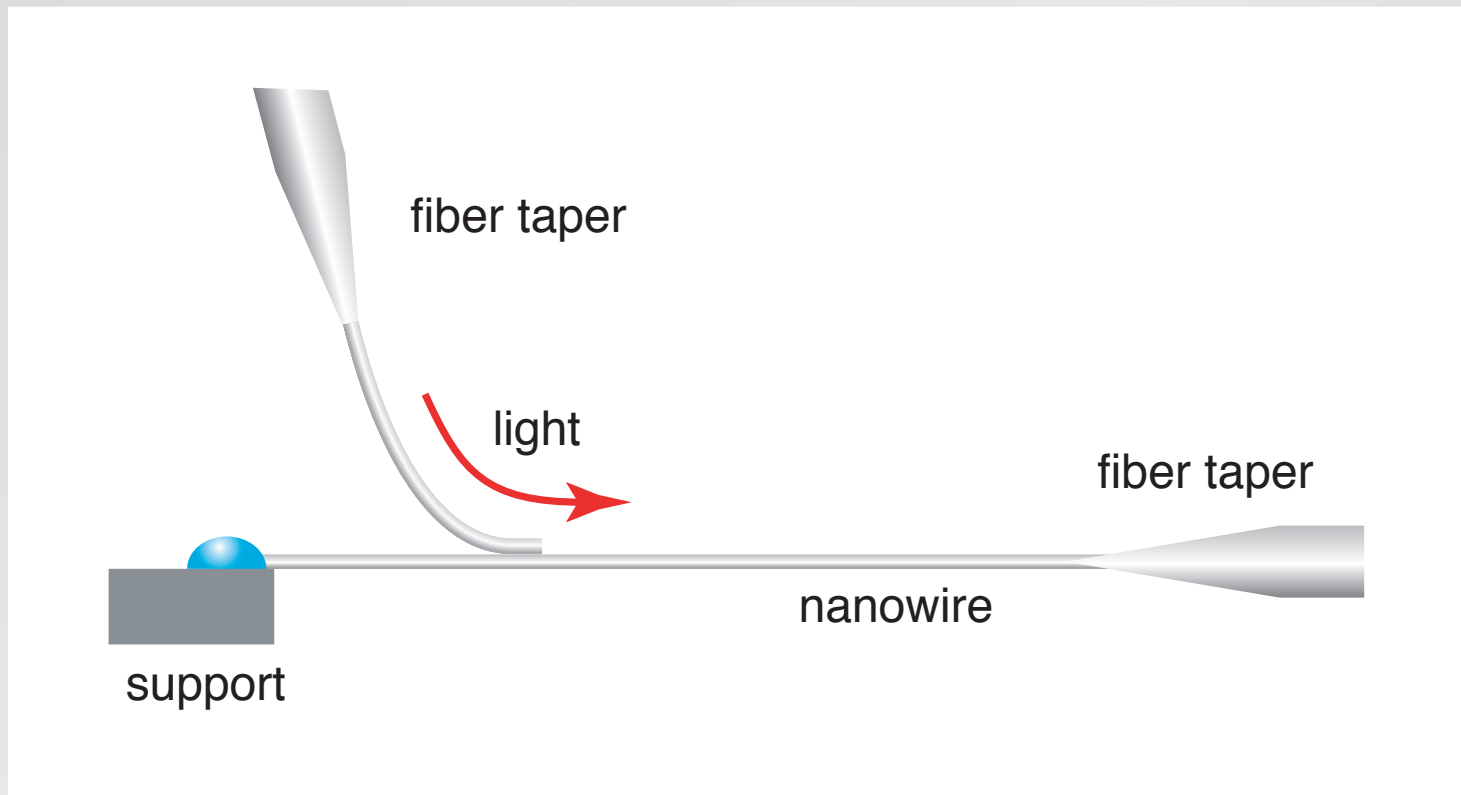


Optical properties



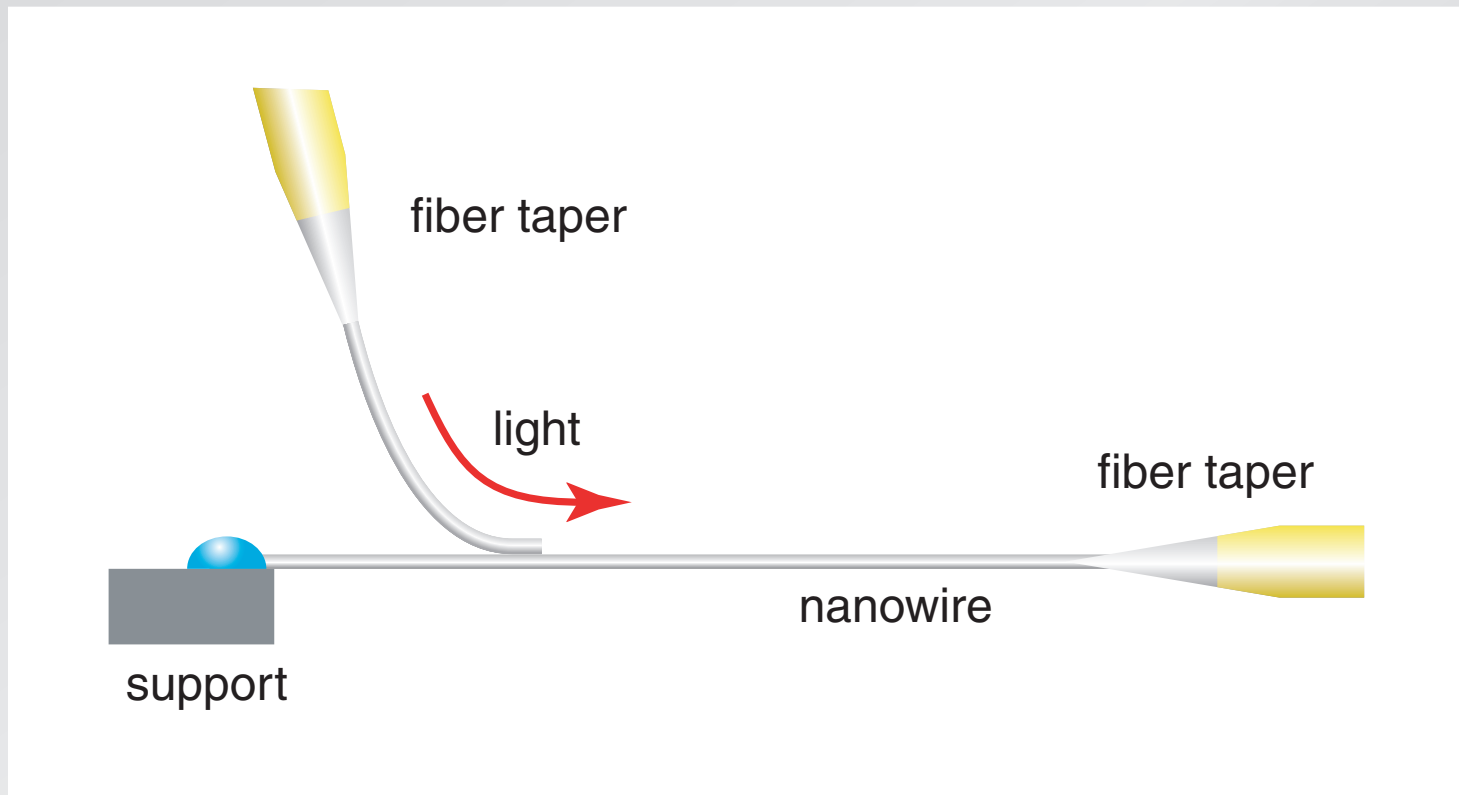
Optical properties

loss measurement



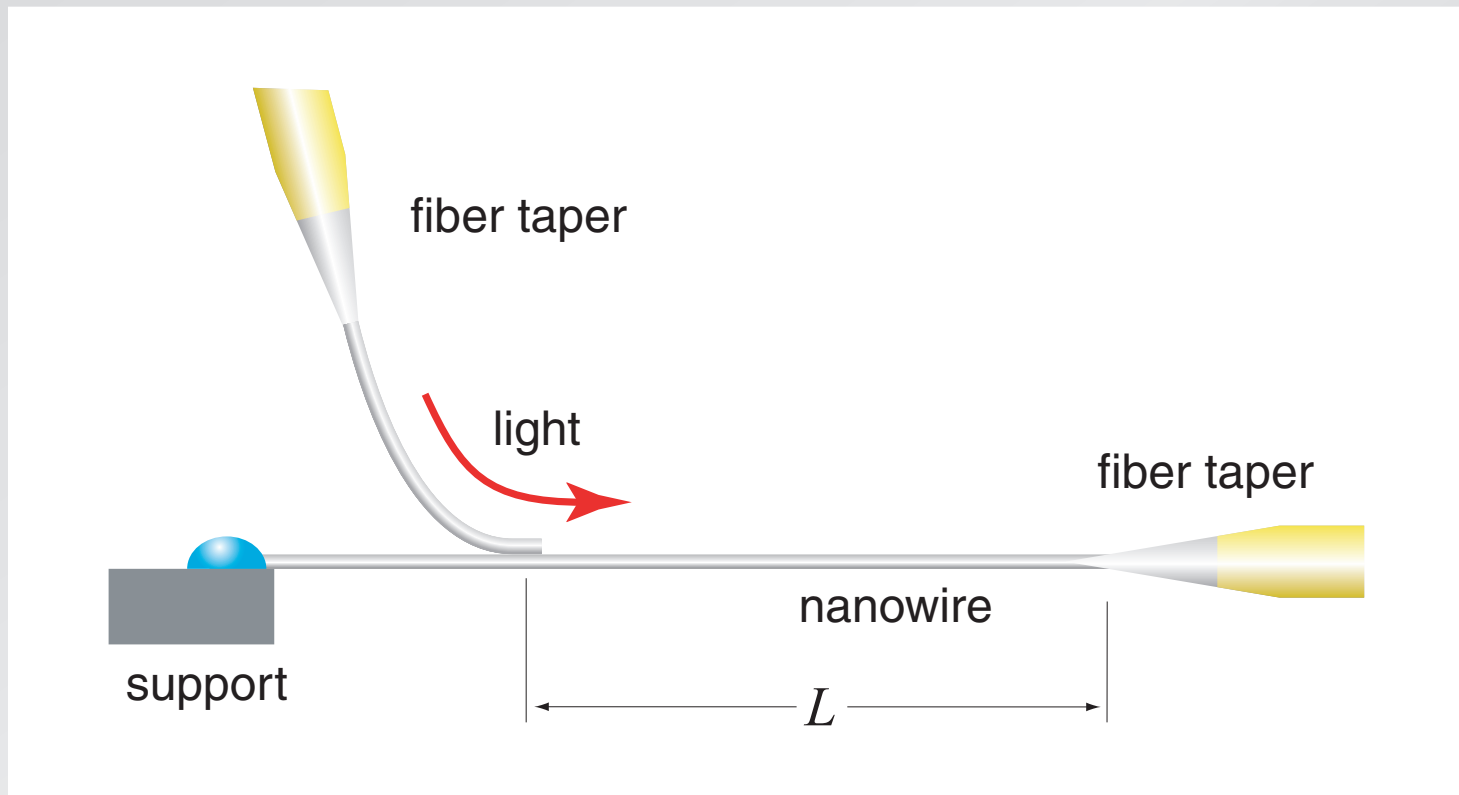
Optical properties

loss measurement



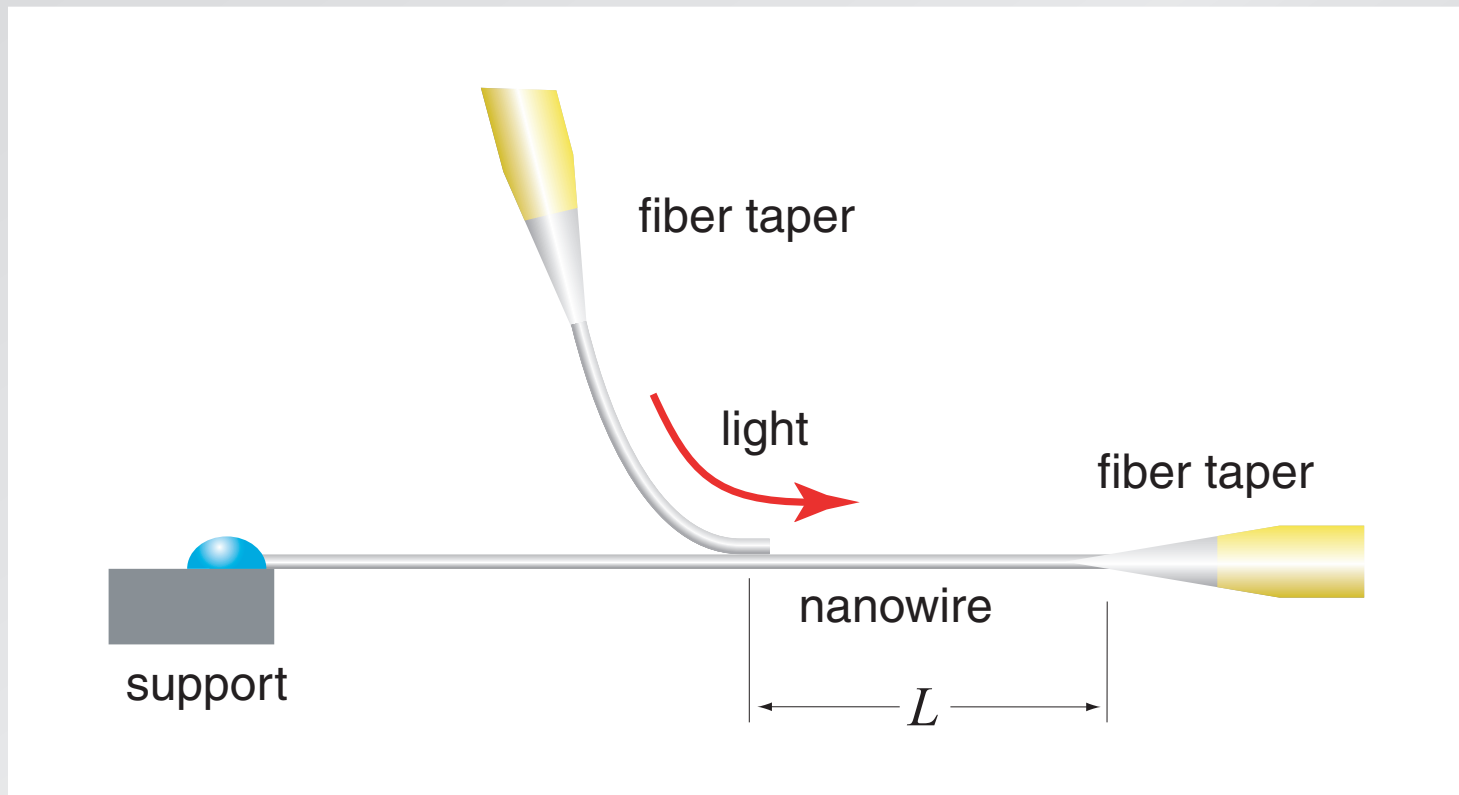
Optical properties

loss measurement



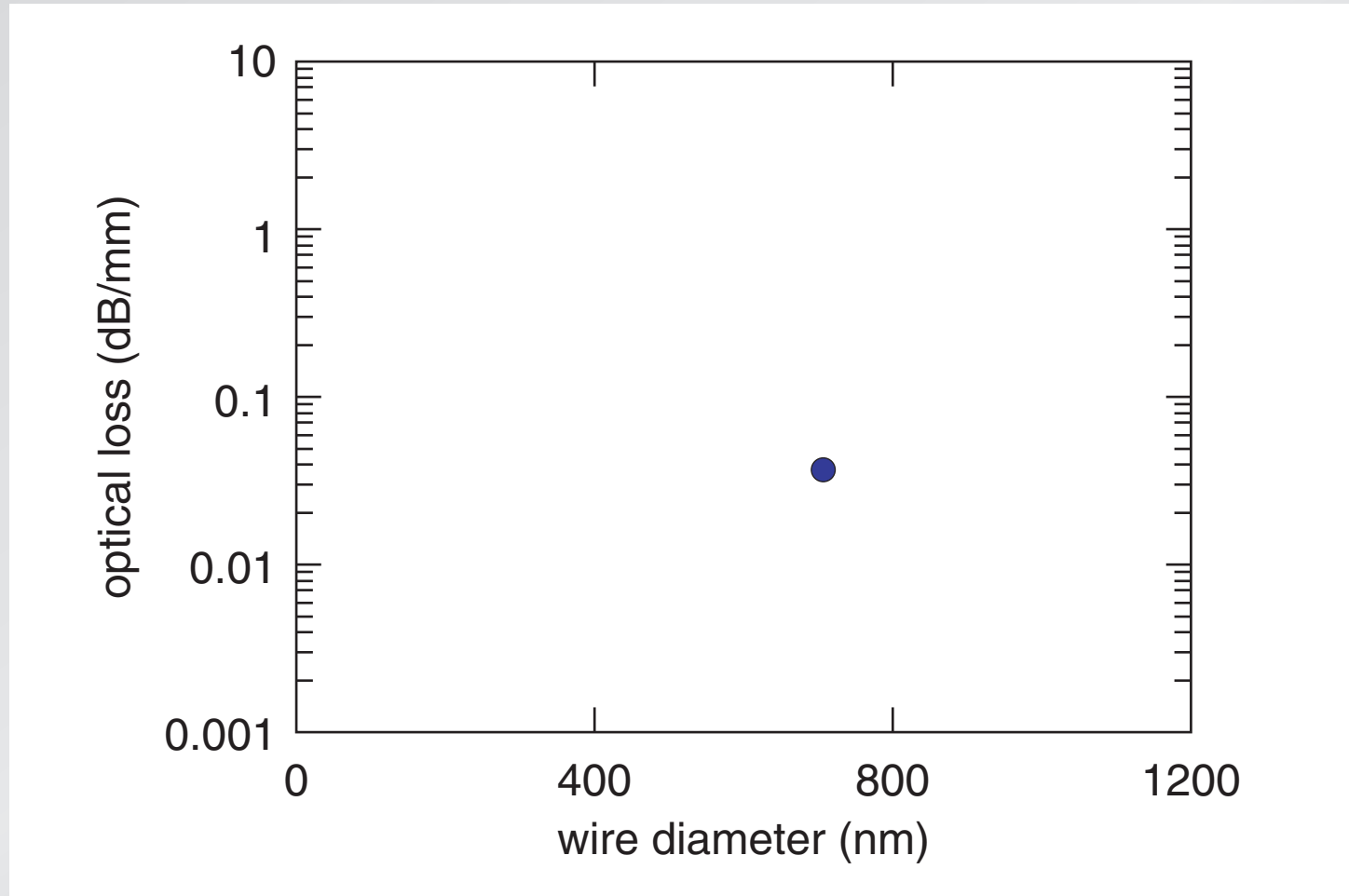
Optical properties

loss measurement



Optical properties

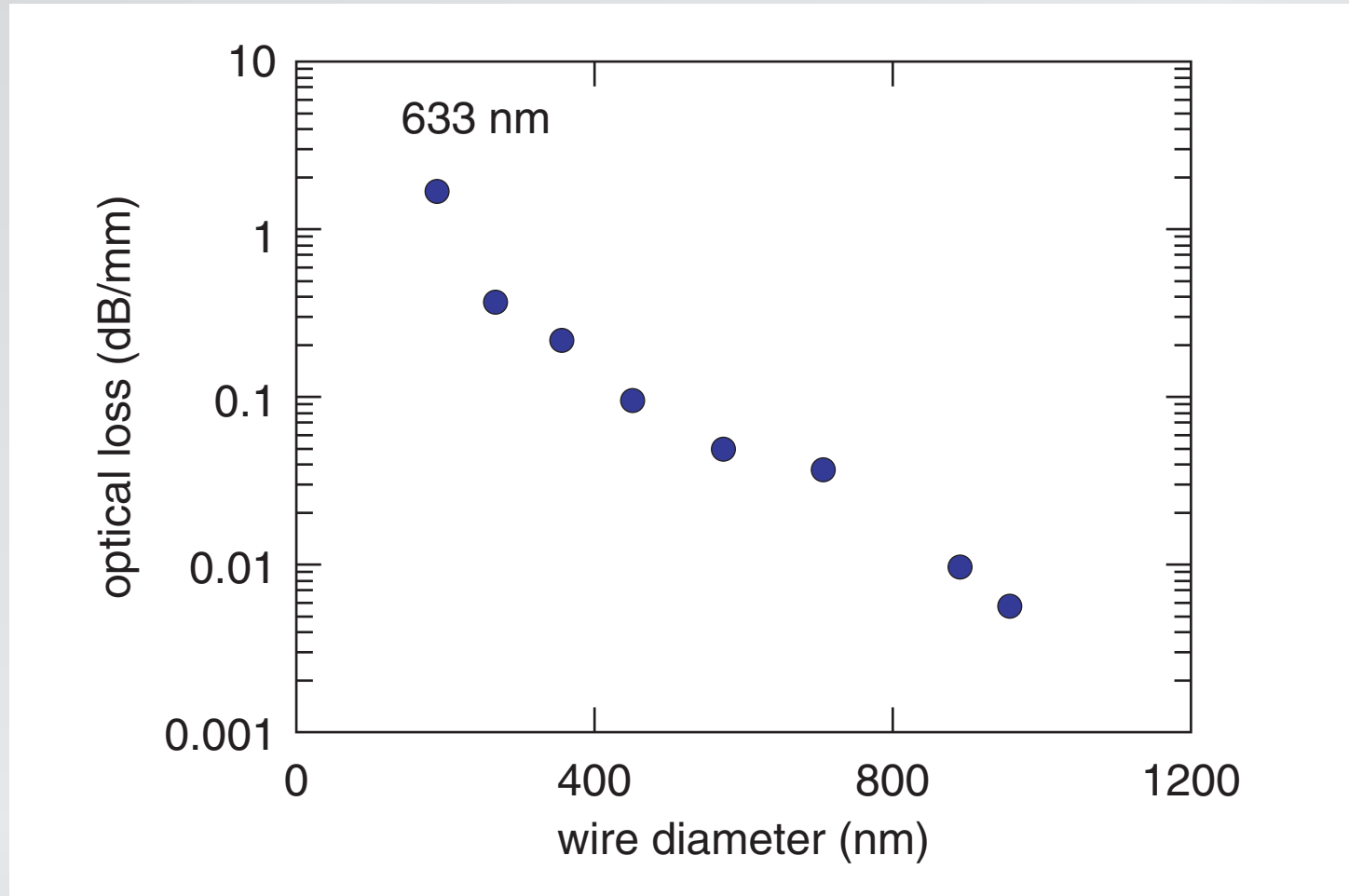
loss measurement



Nature, 426, 816 (2003)

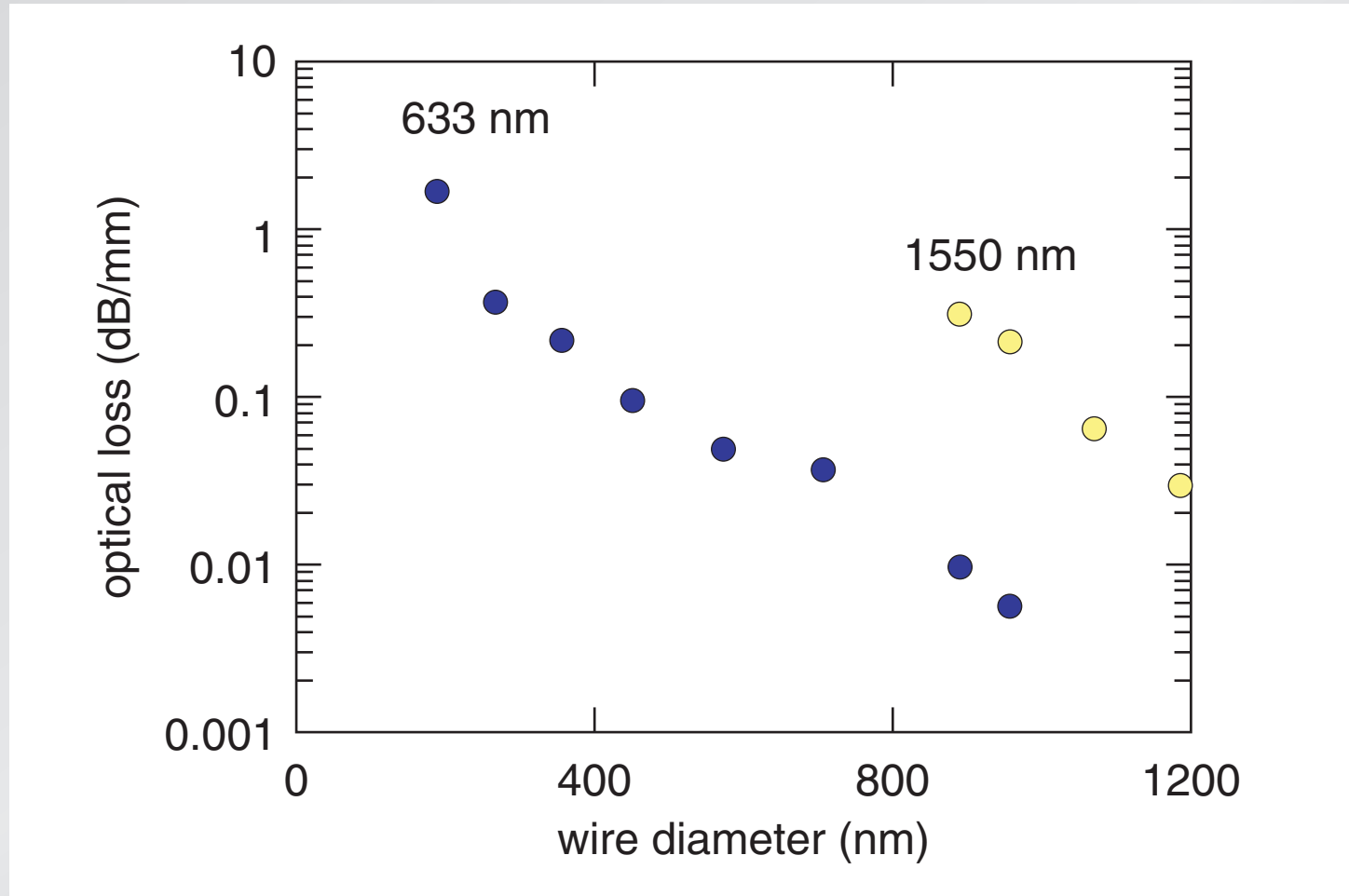
Optical properties

loss measurement



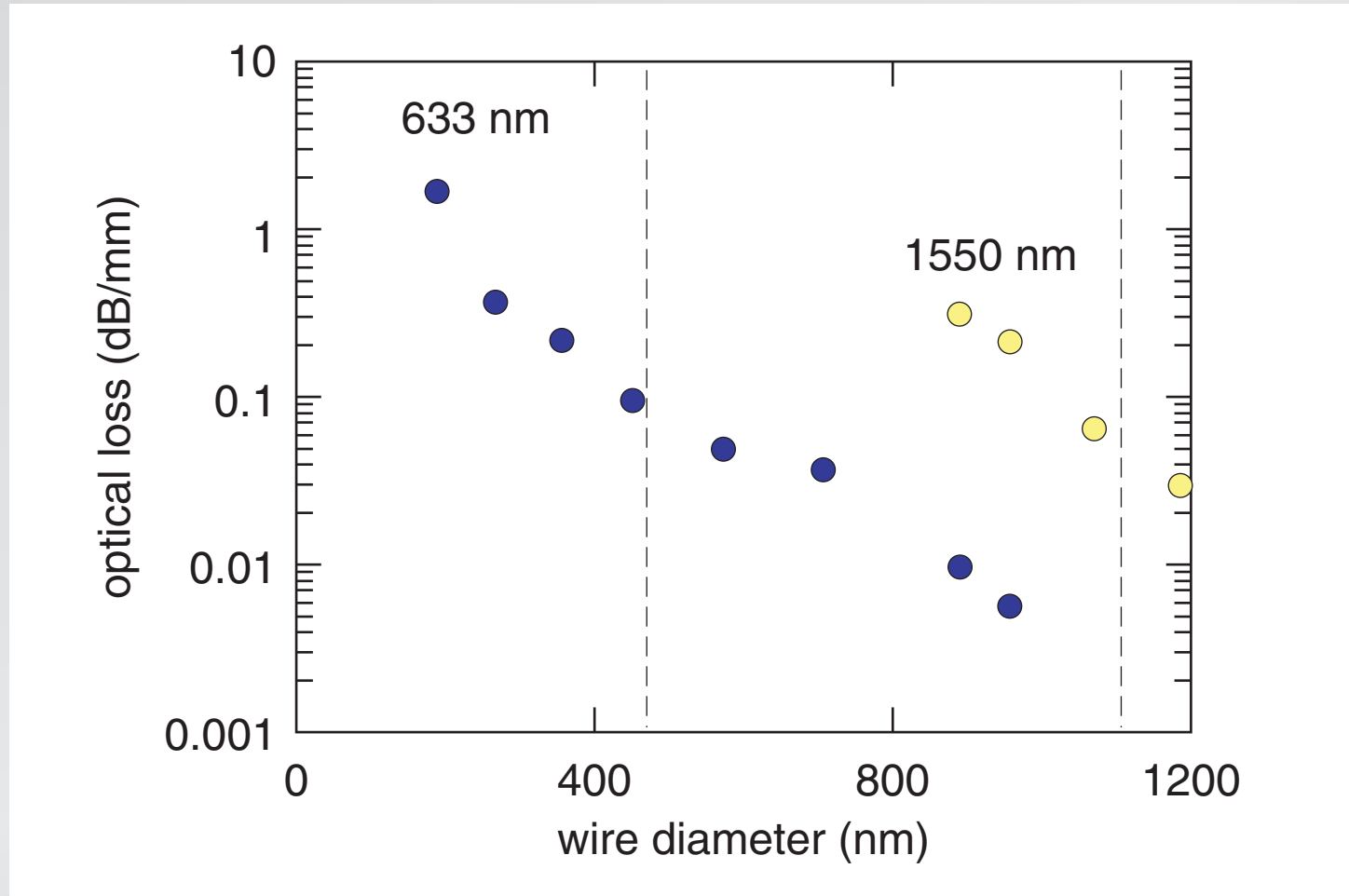
Optical properties

loss measurement

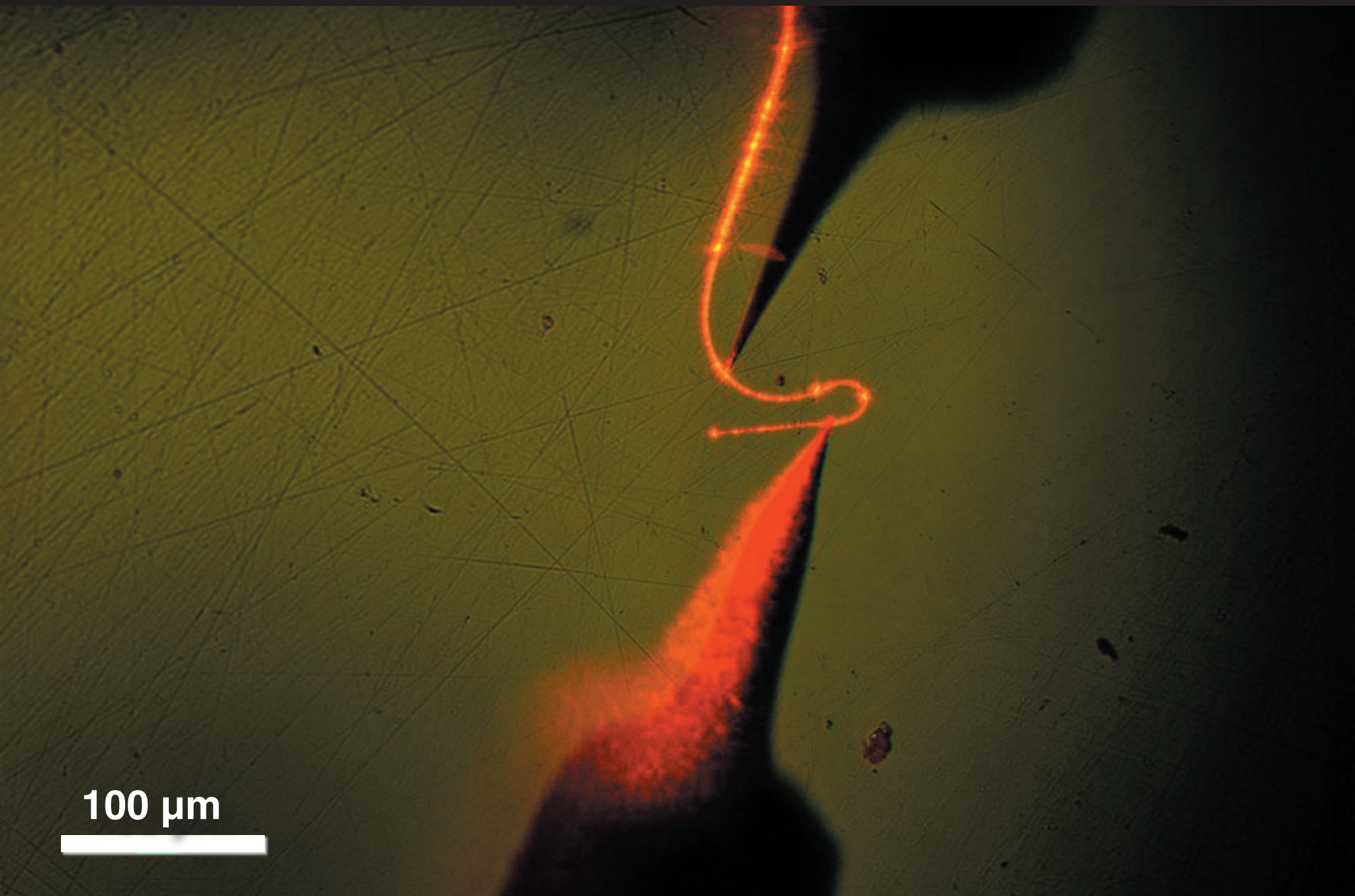


Optical properties

loss a single-mode diameter < 0.1 dB/mm

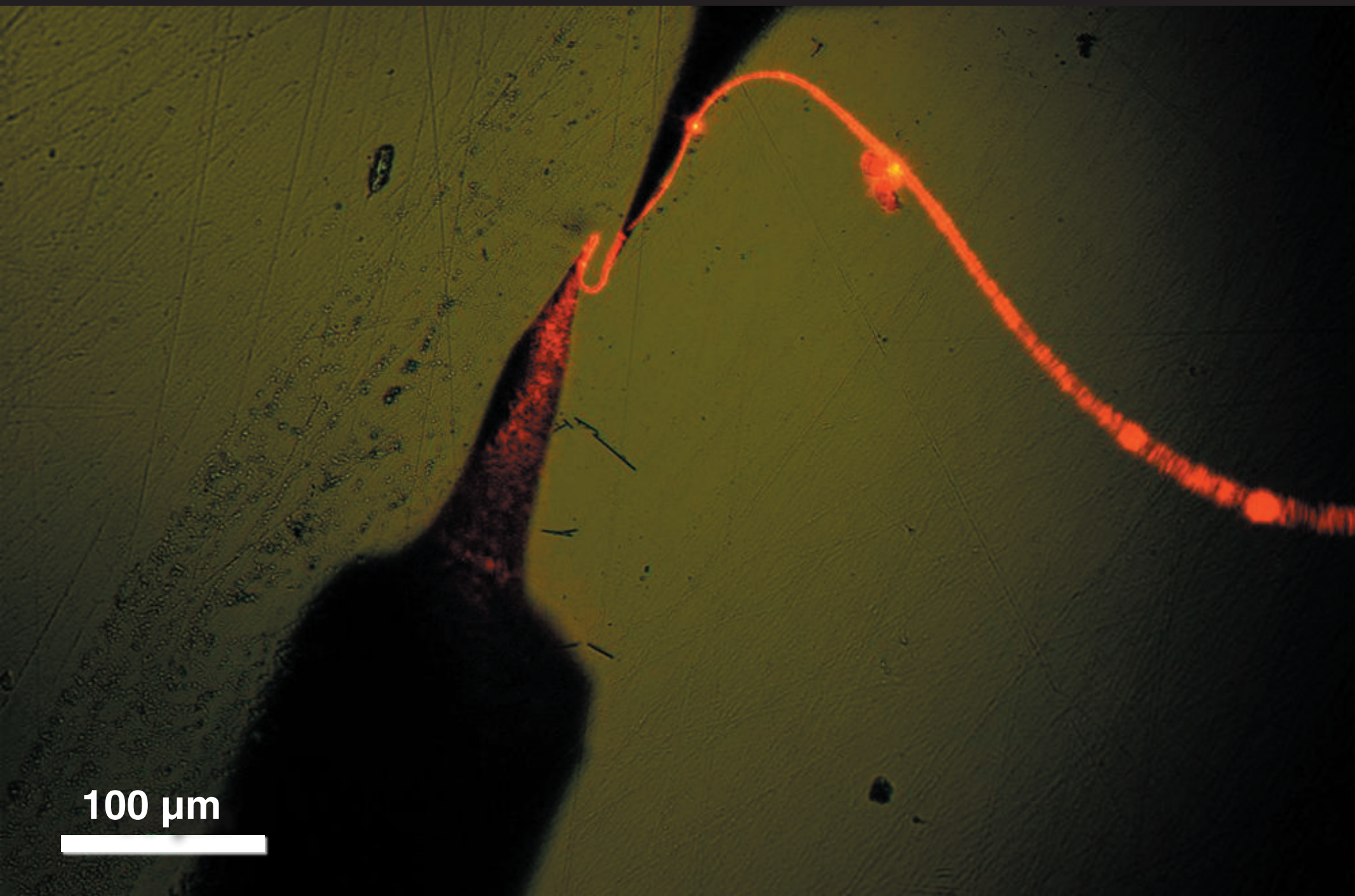


Optical properties



100 μm

Optical properties

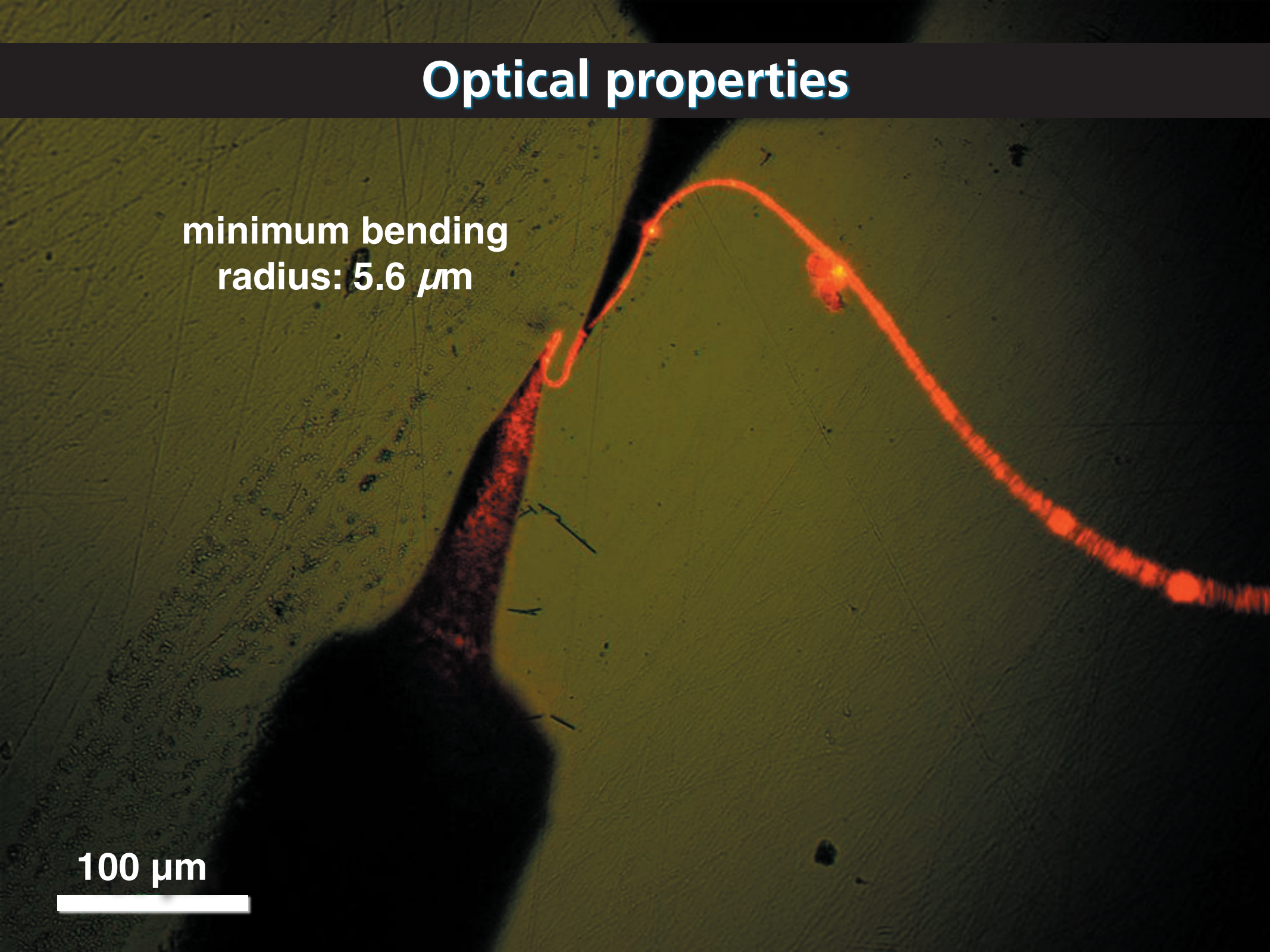


100 μm

Optical properties

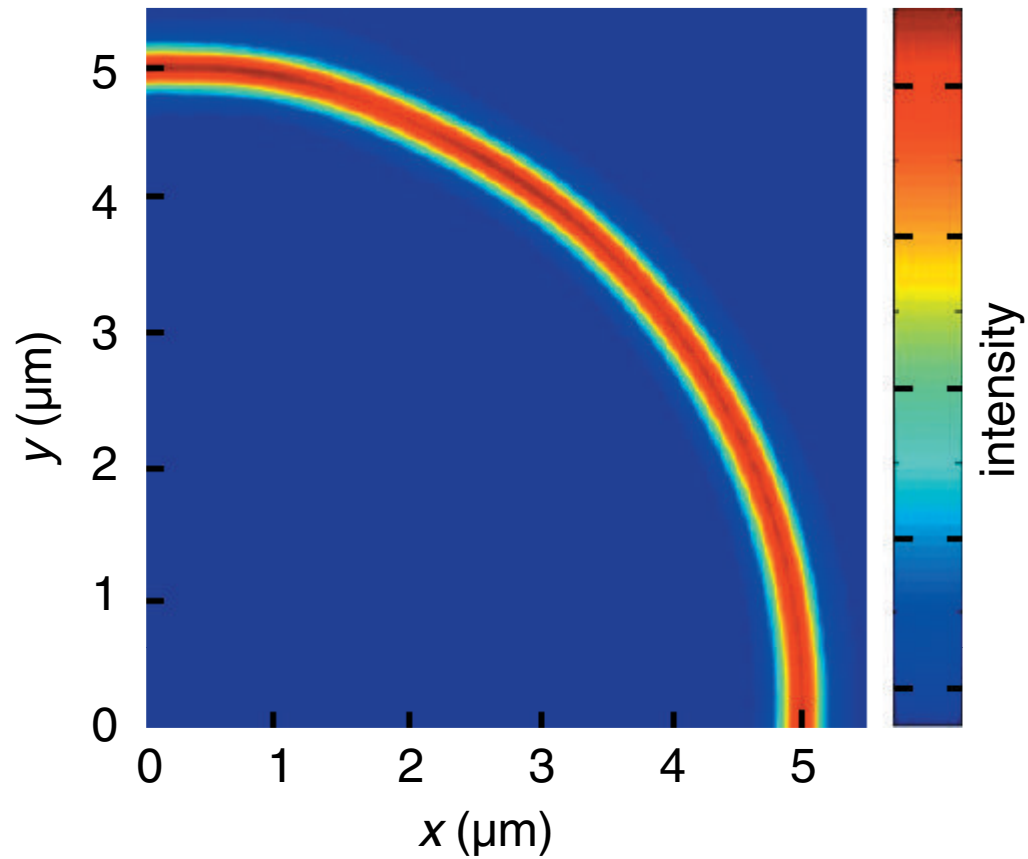
minimum bending
radius: $5.6 \mu\text{m}$

100 μm



Optical properties

virtually no loss through 5 μm corner!



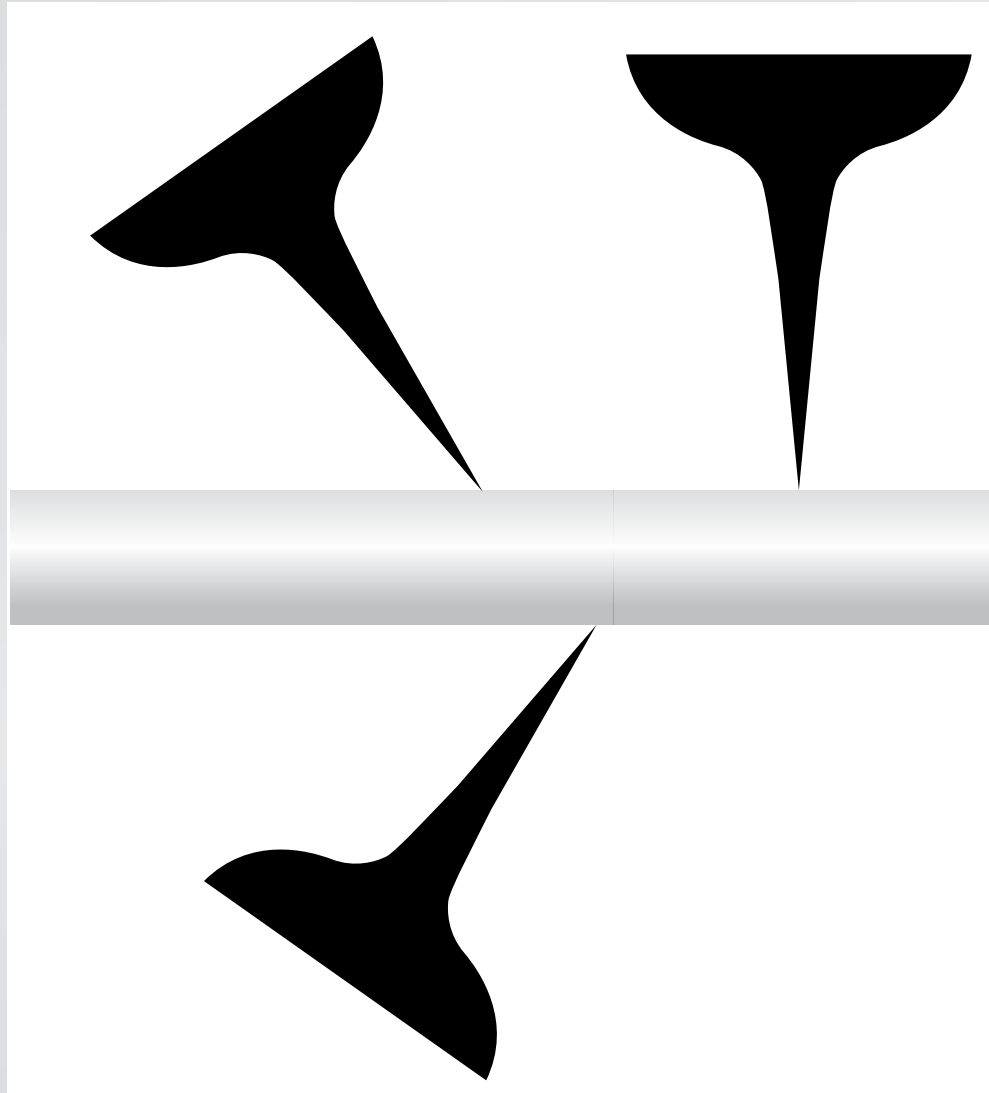
Optical properties

microphotonic components



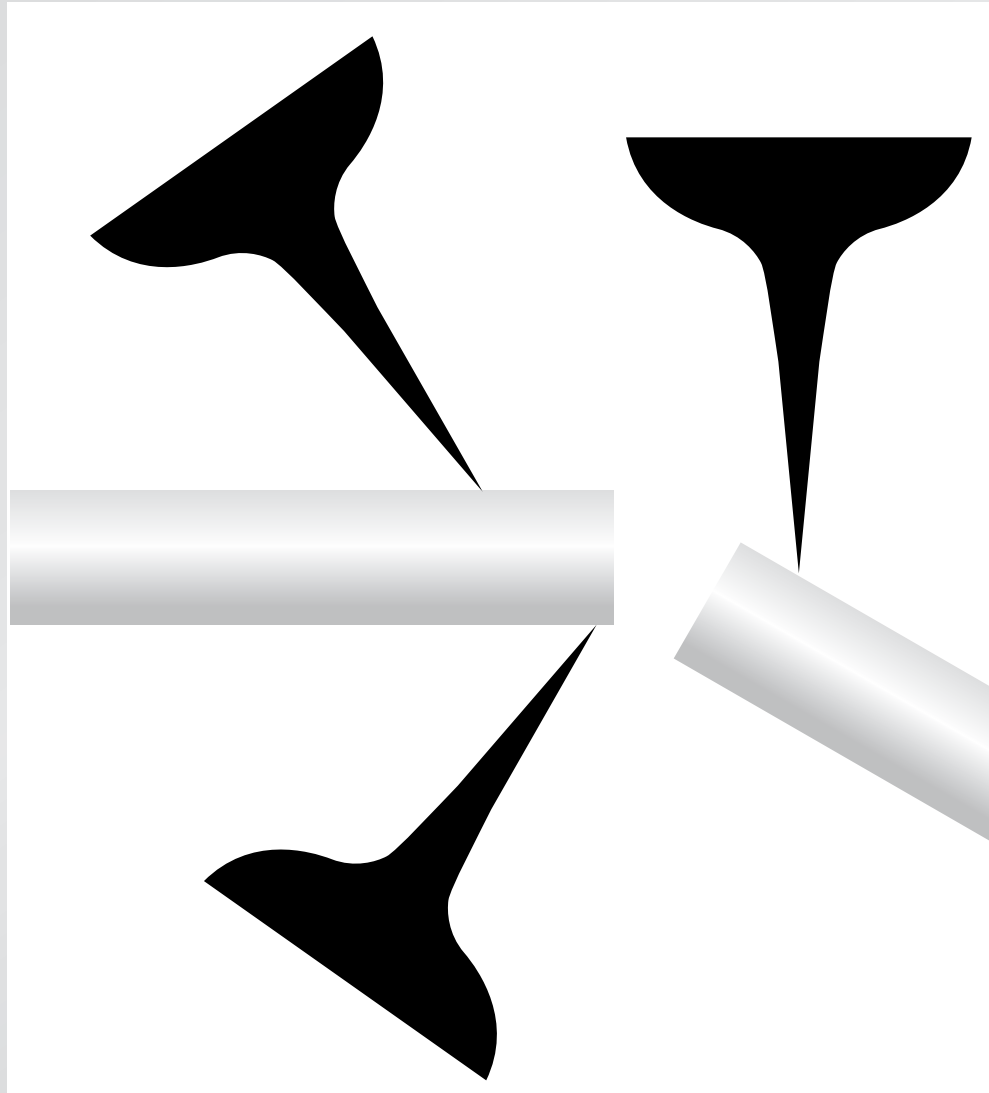
Optical properties

microphotonic components



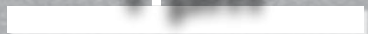
Optical properties

microphotonic components



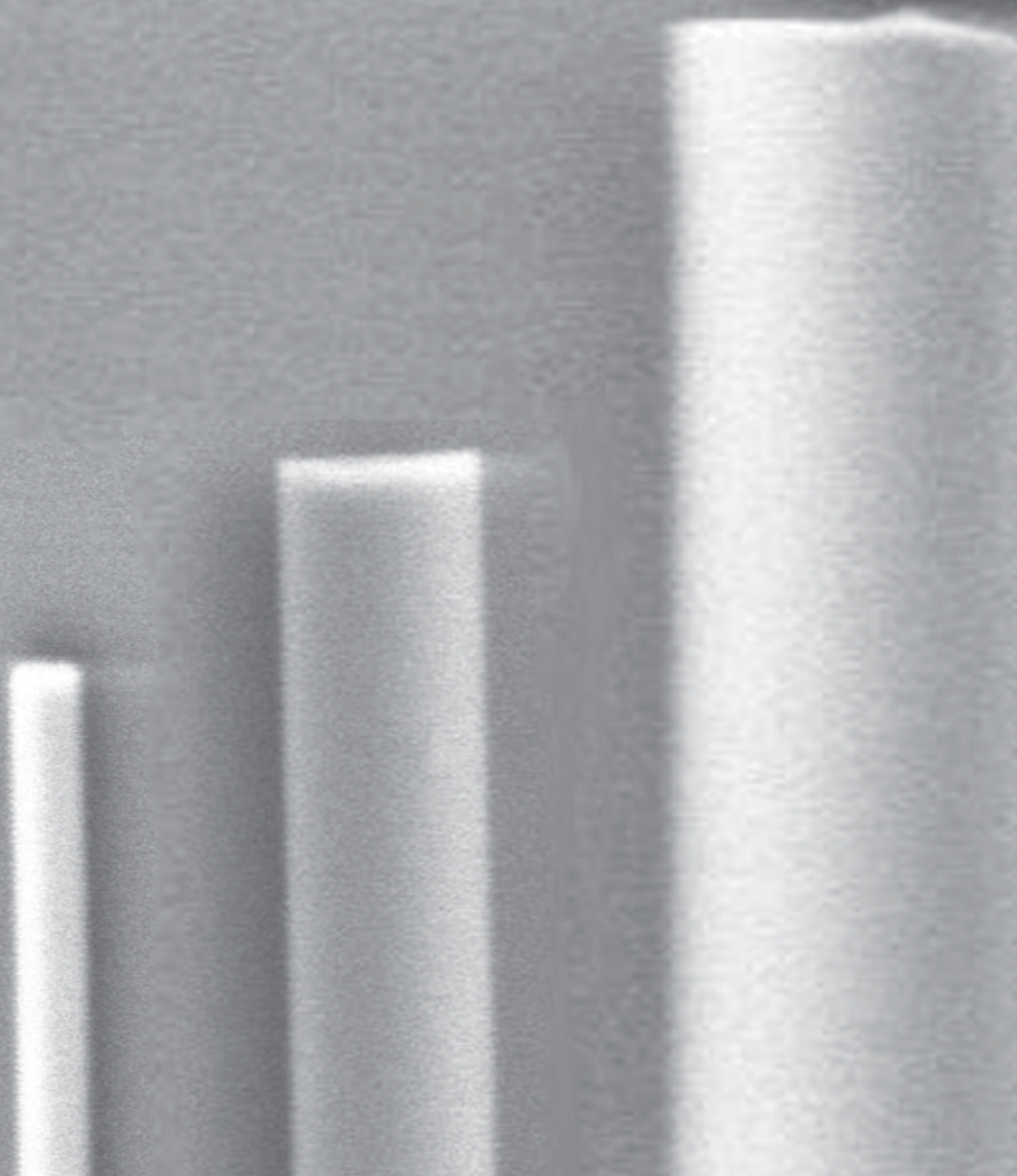
Optical properties

1 μm

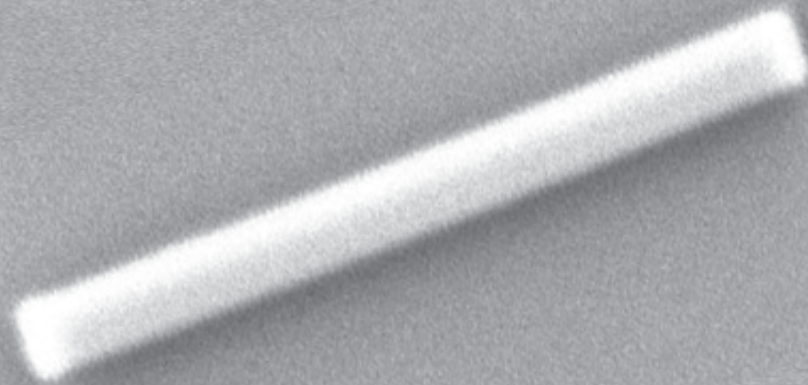


Optical properties

500 nm



Optical properties



500 nm

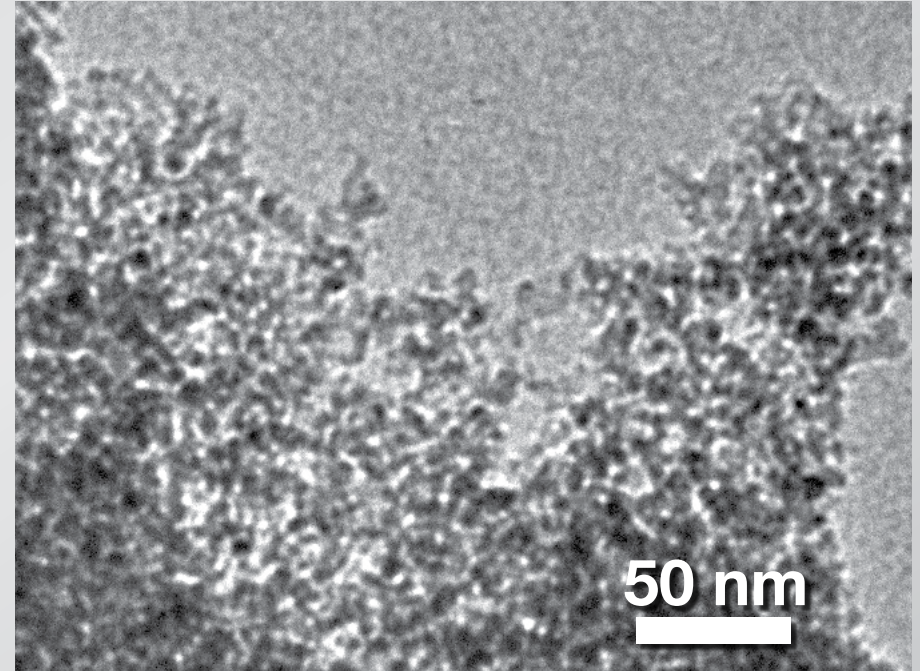
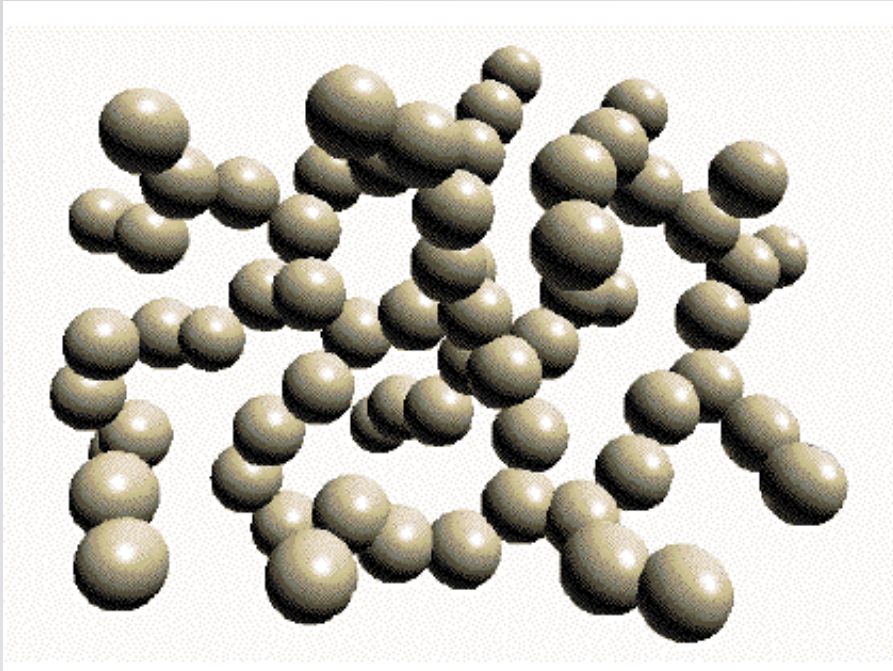


Optical properties



Optical properties

Aerogel



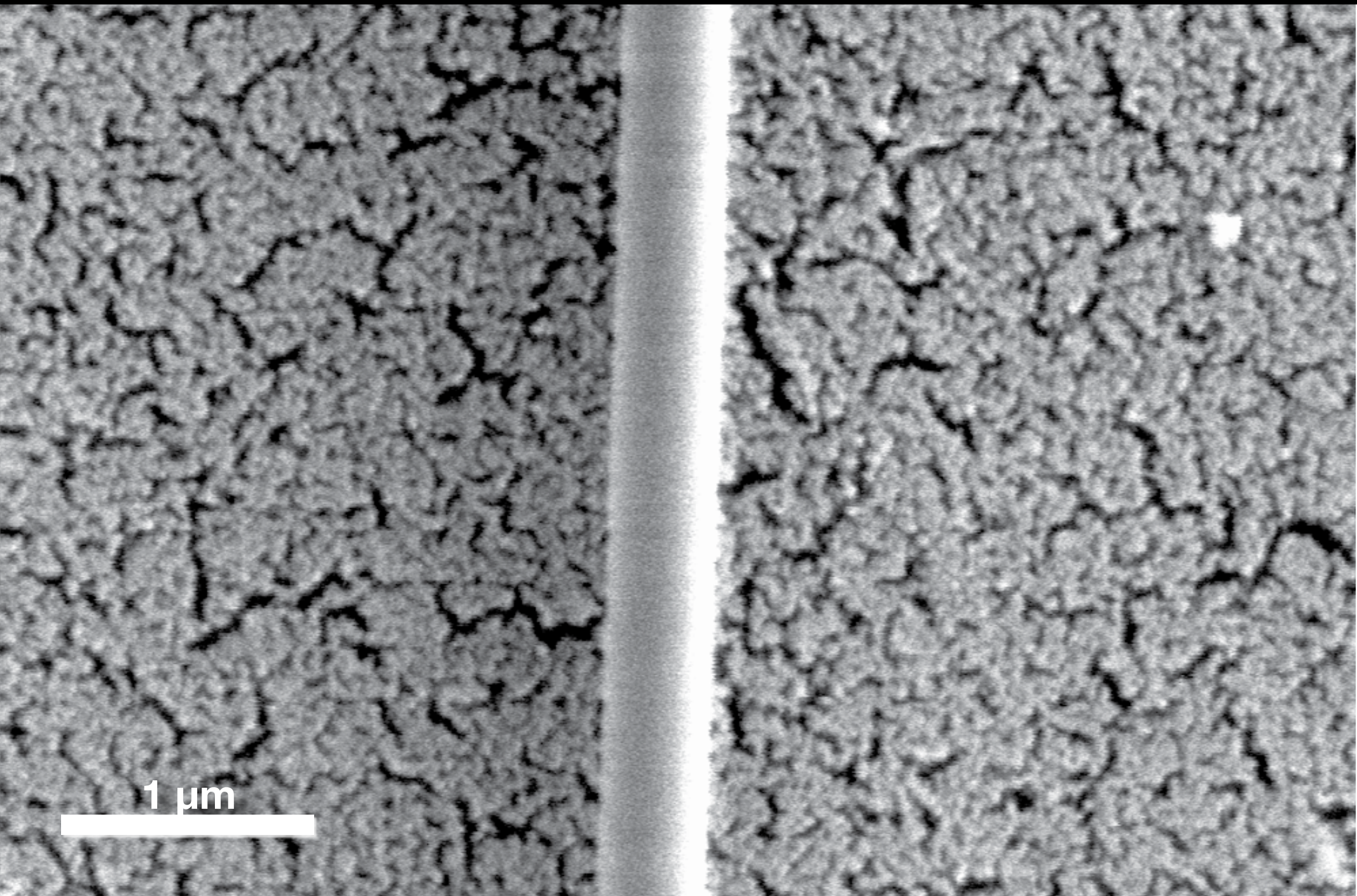
density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Optical properties



Optical properties

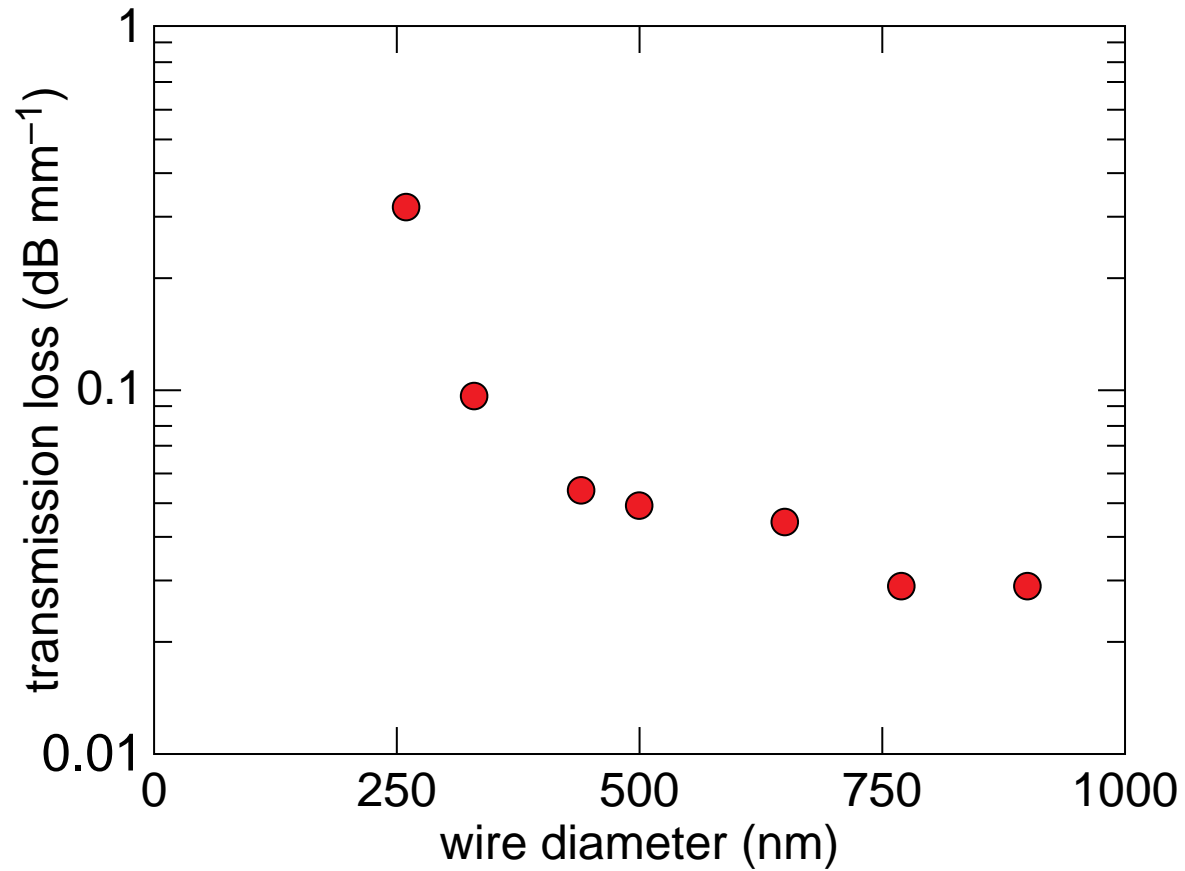


1 μm



Optical properties

loss measurement @ 633 nm



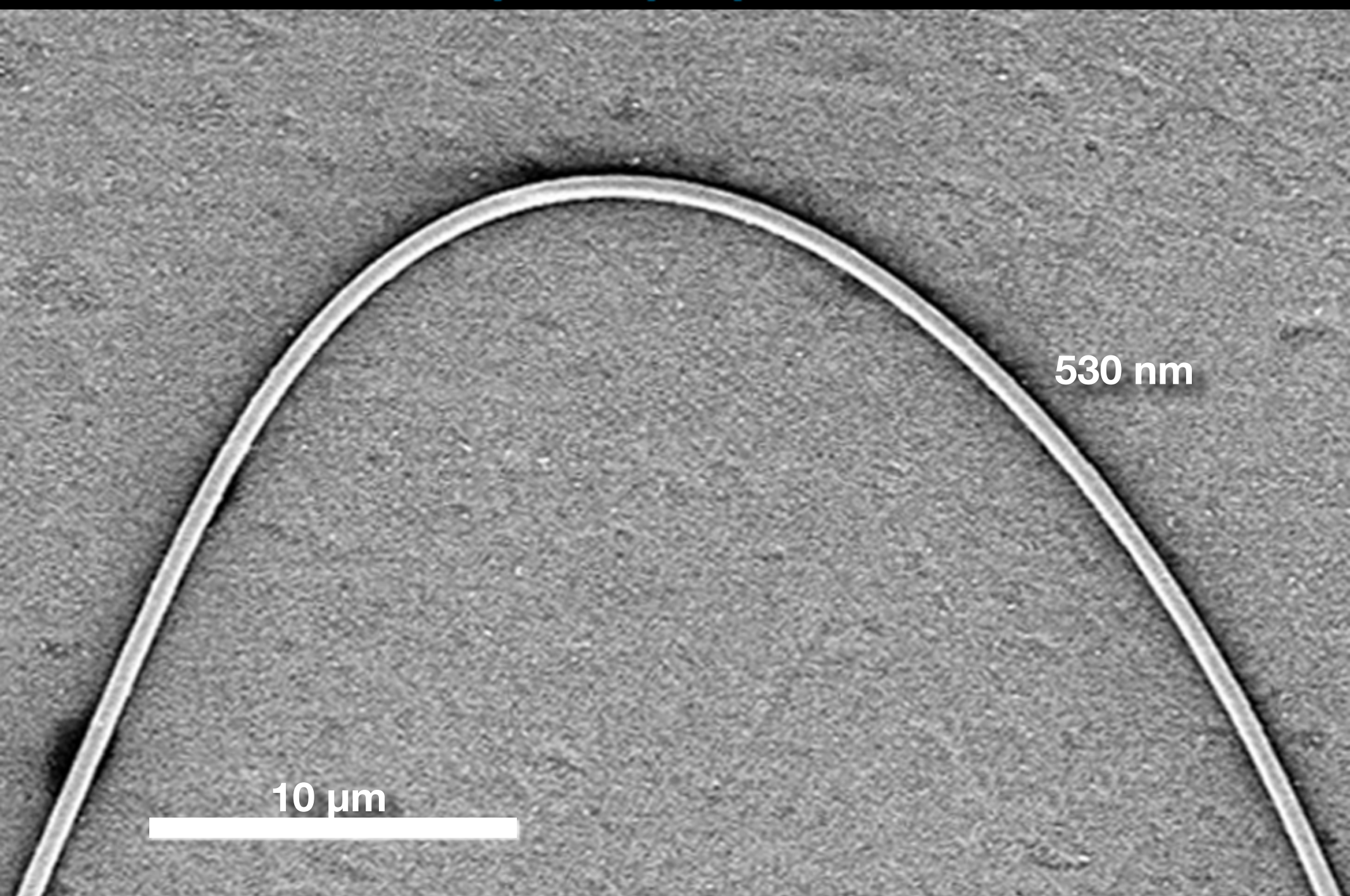
Optical properties

530 nm

The image shows a brown, textured background with a prominent red fluorescent ring structure. The ring is composed of many small, bright red spots, forming a continuous loop. In the bottom left corner, there is a white horizontal scale bar. The text '530 nm' is positioned above the ring, and '50 μm' is positioned above the scale bar.

50 μm

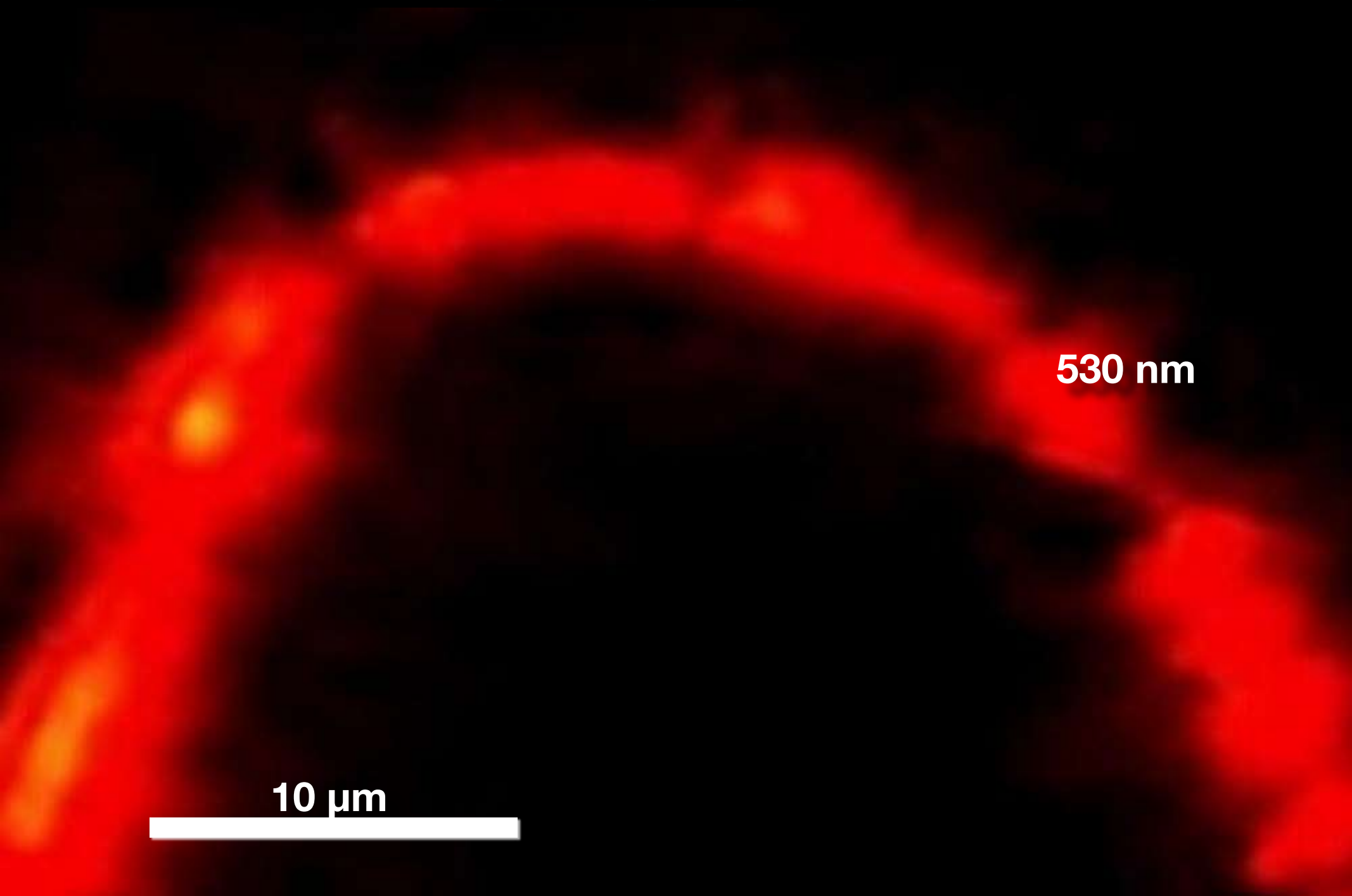
Optical properties



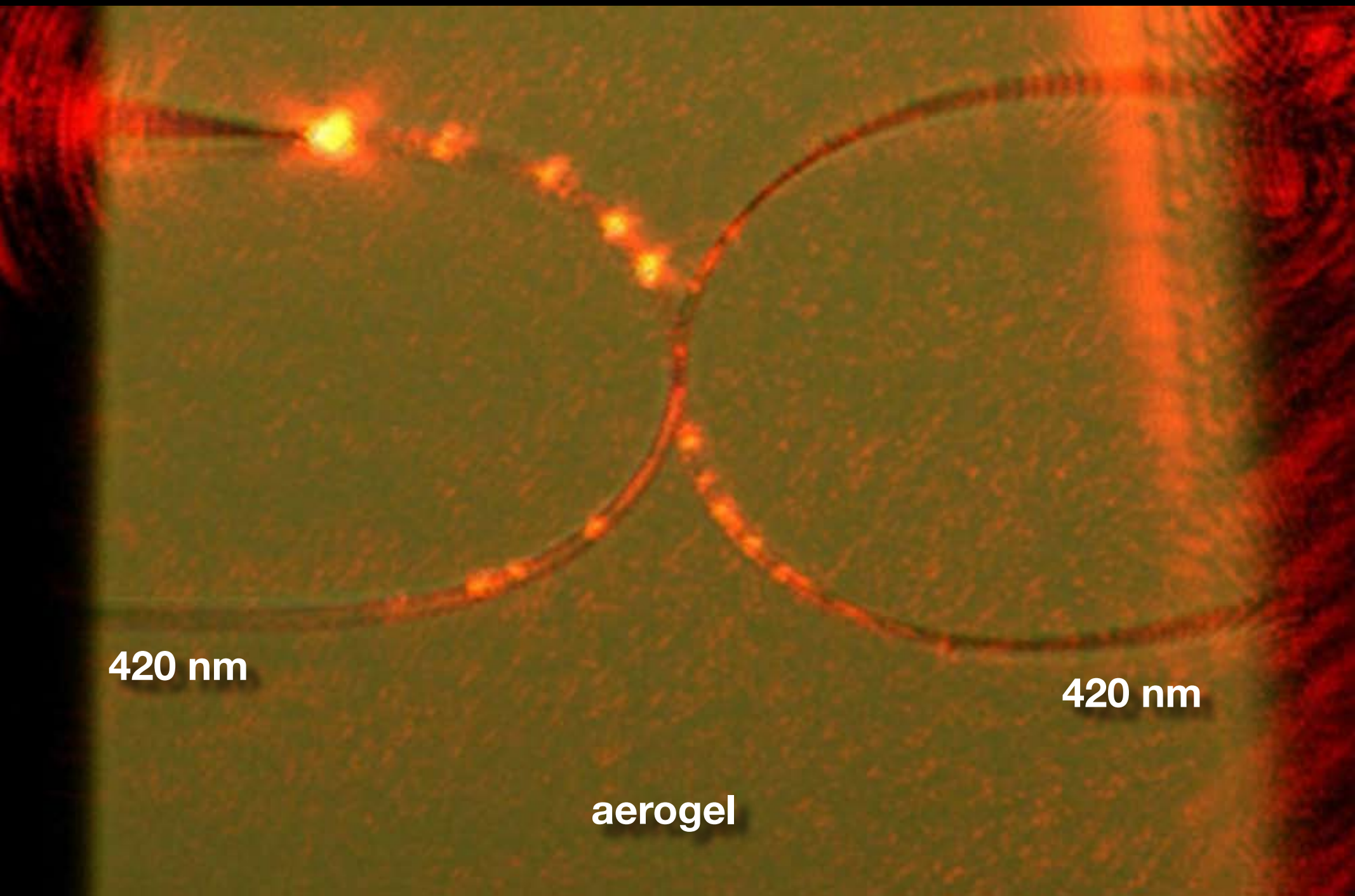
10 μm

530 nm

Optical properties



Optical properties

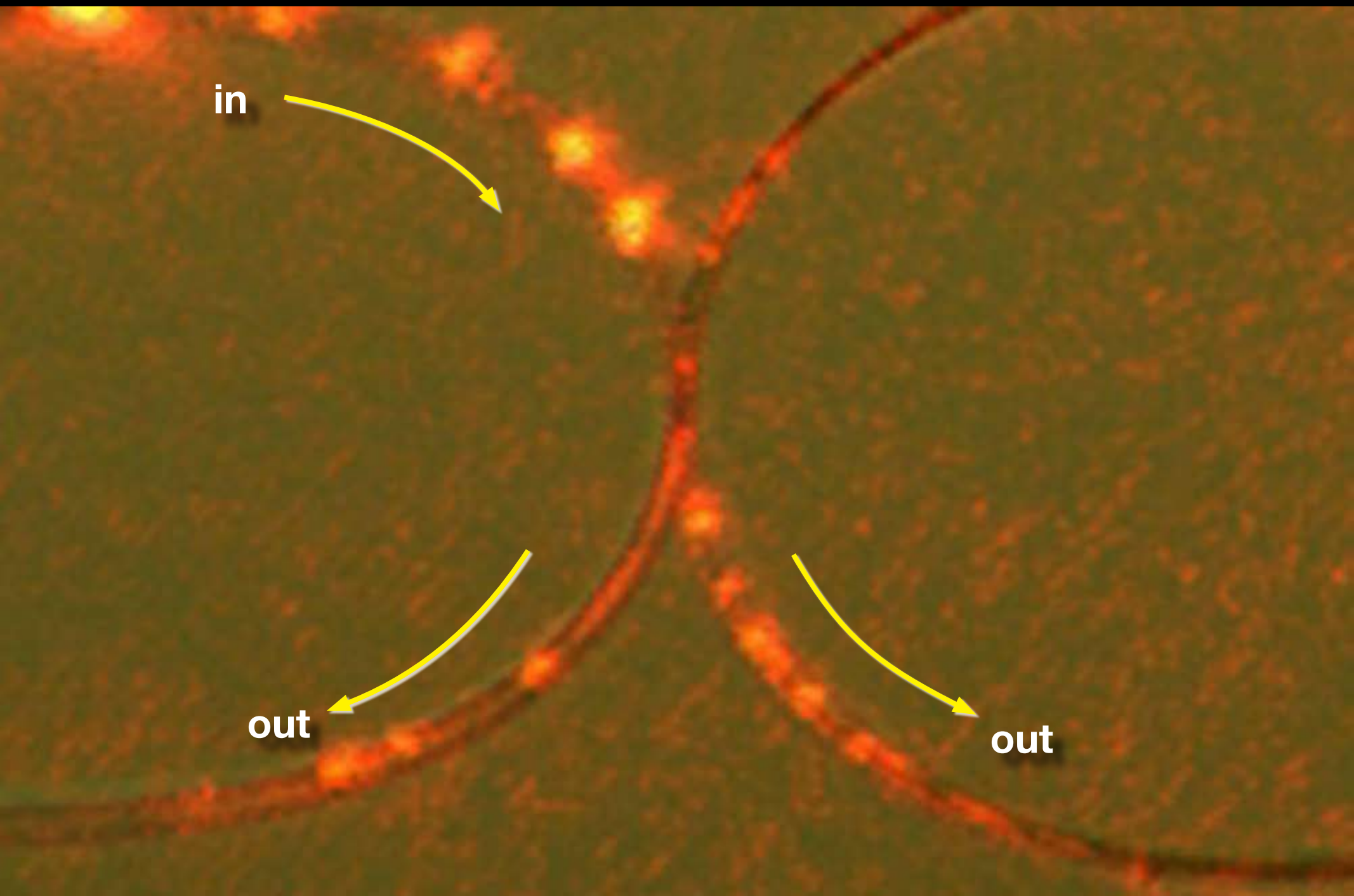


420 nm

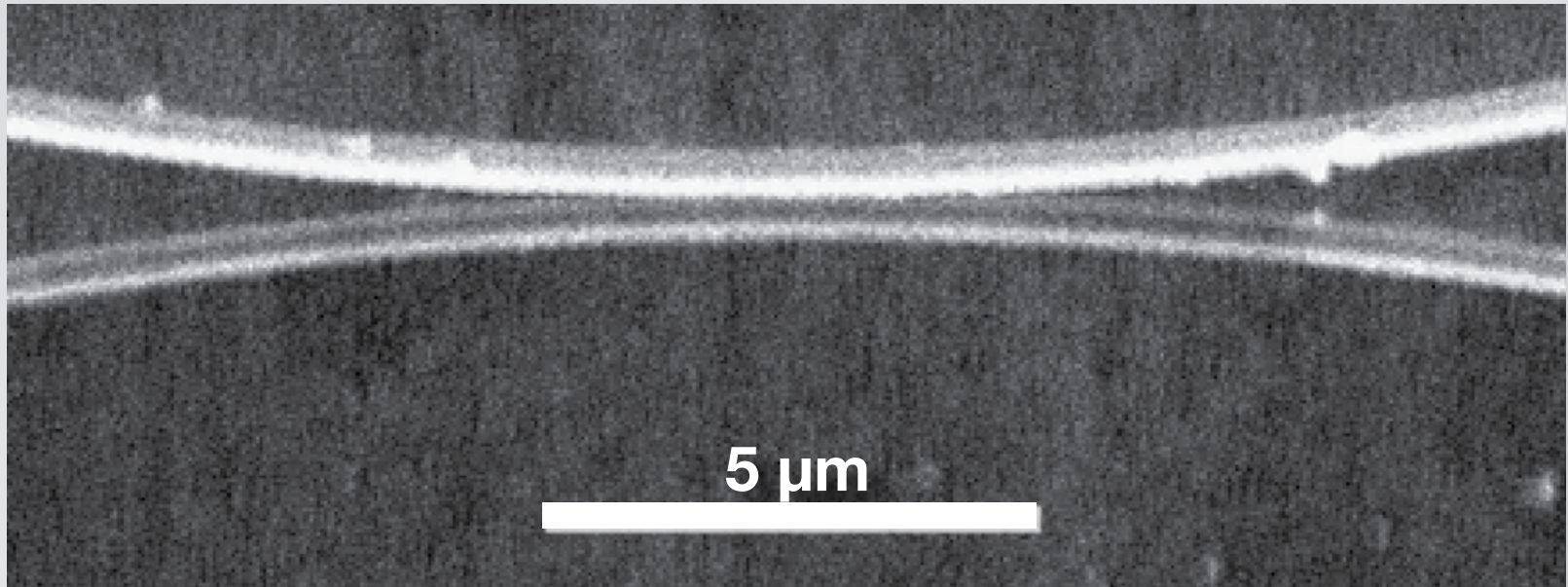
420 nm

aerogel

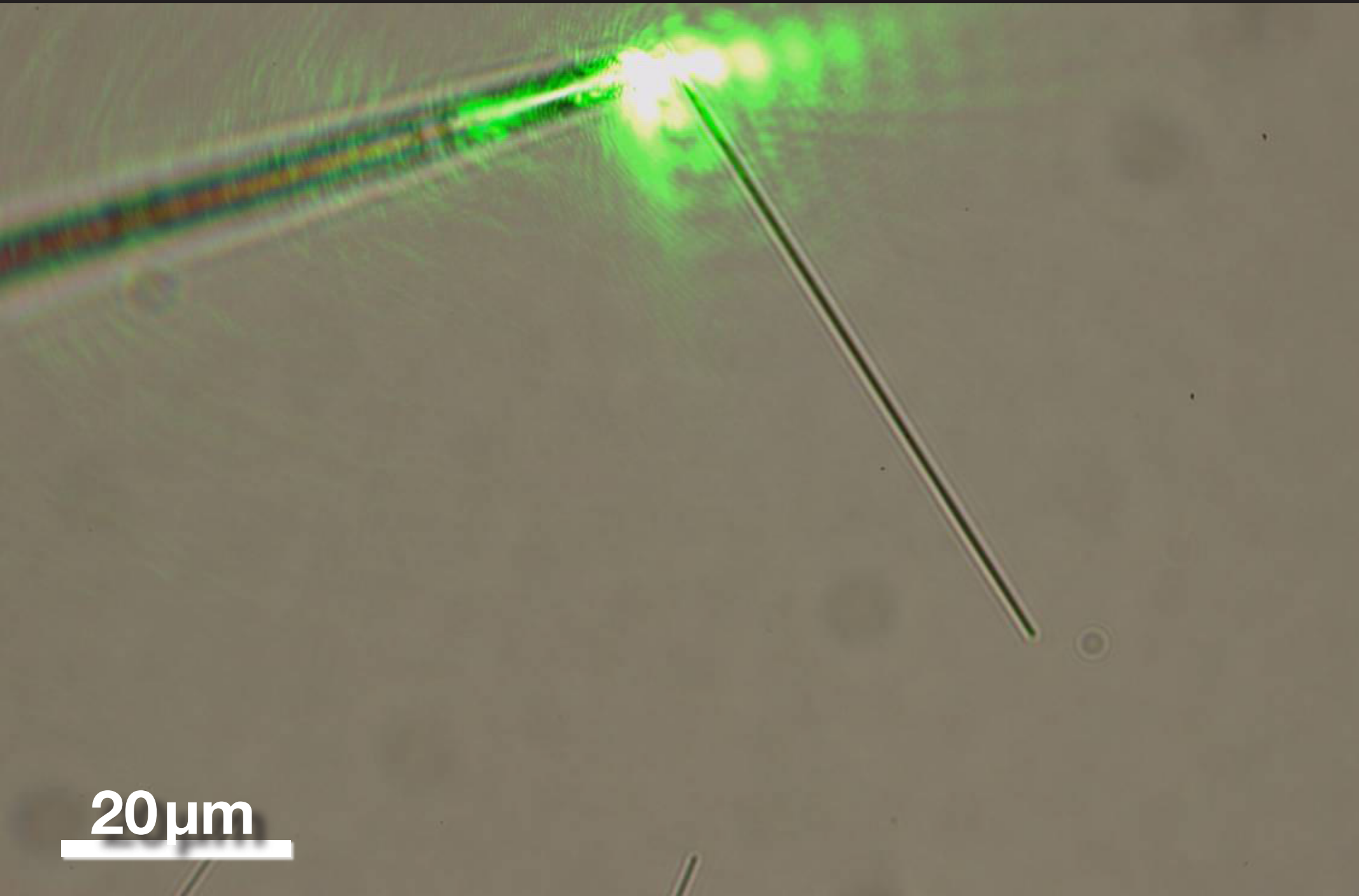
Optical properties



Optical properties

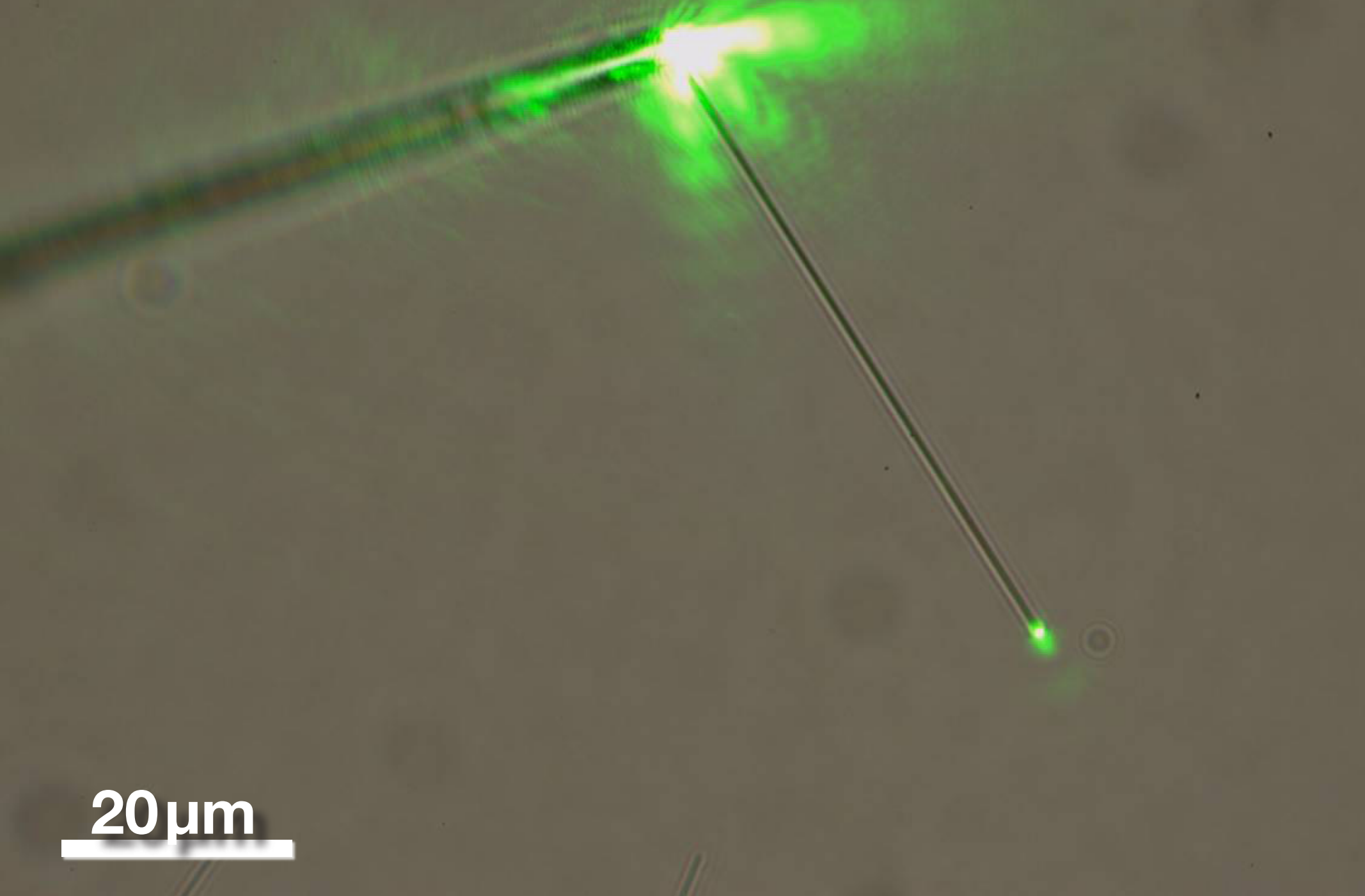


Coupling with semiconductor nanowires



20 μm

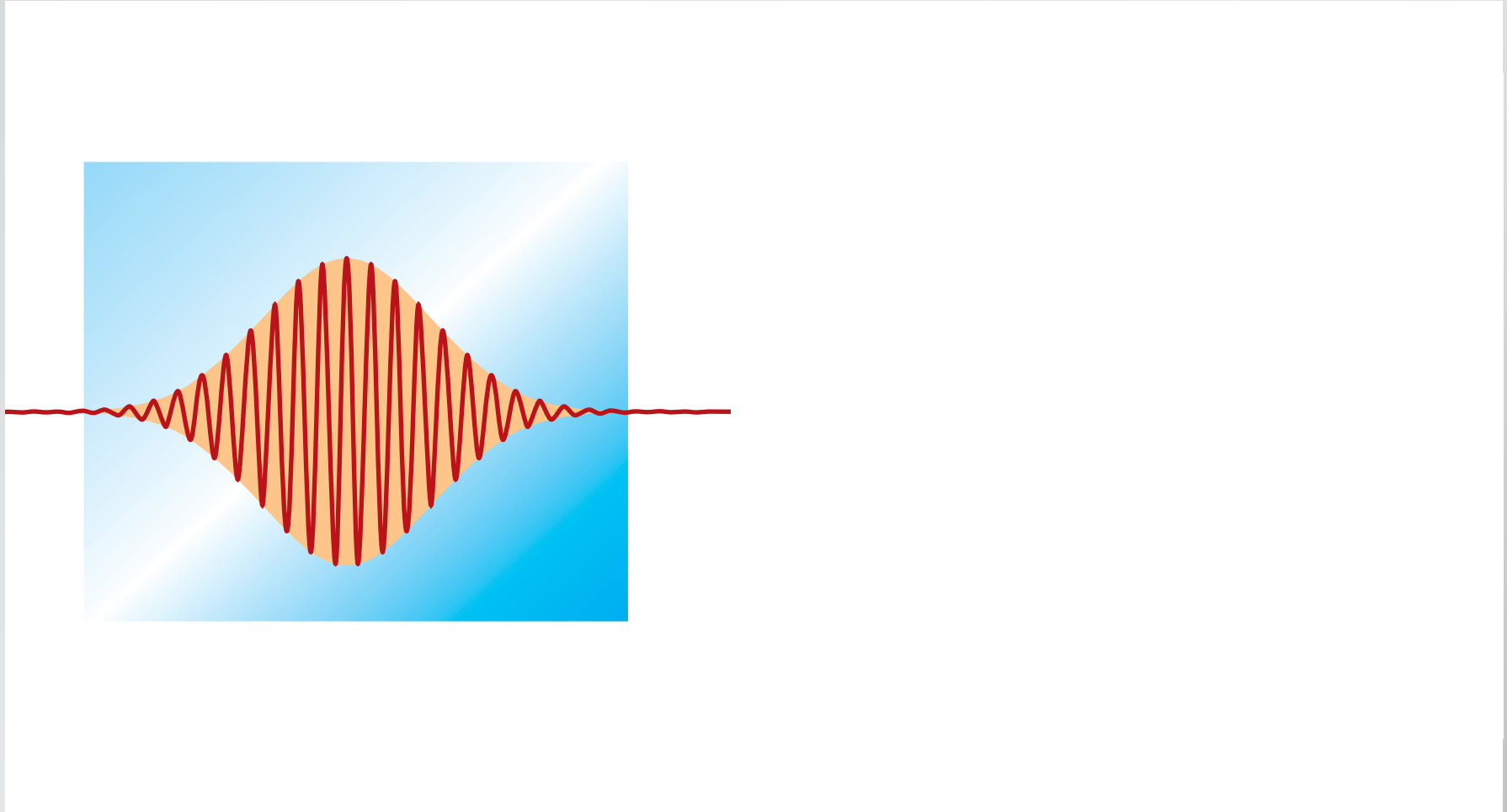
Coupling with semiconductor nanowires



20 μm

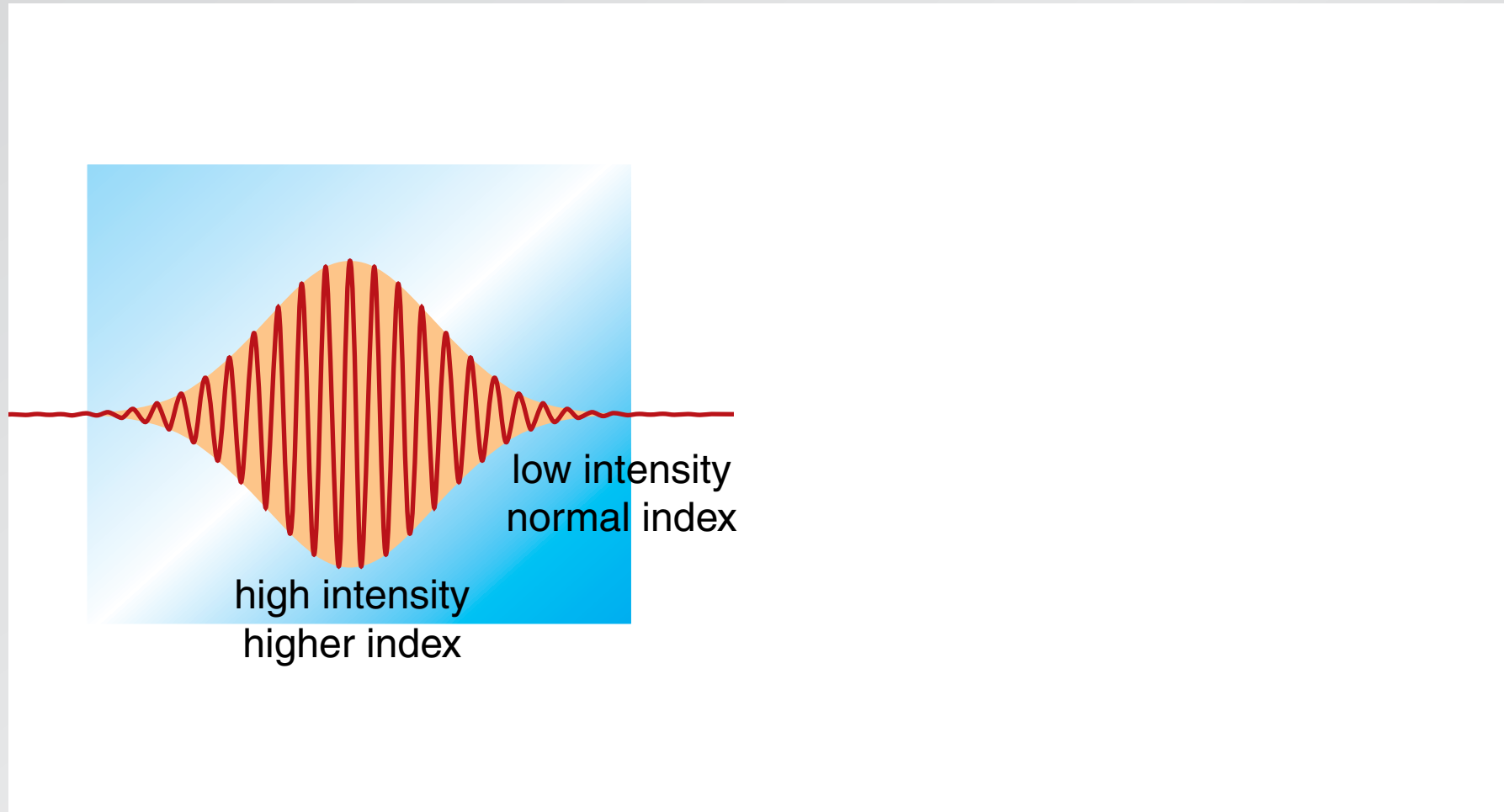
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



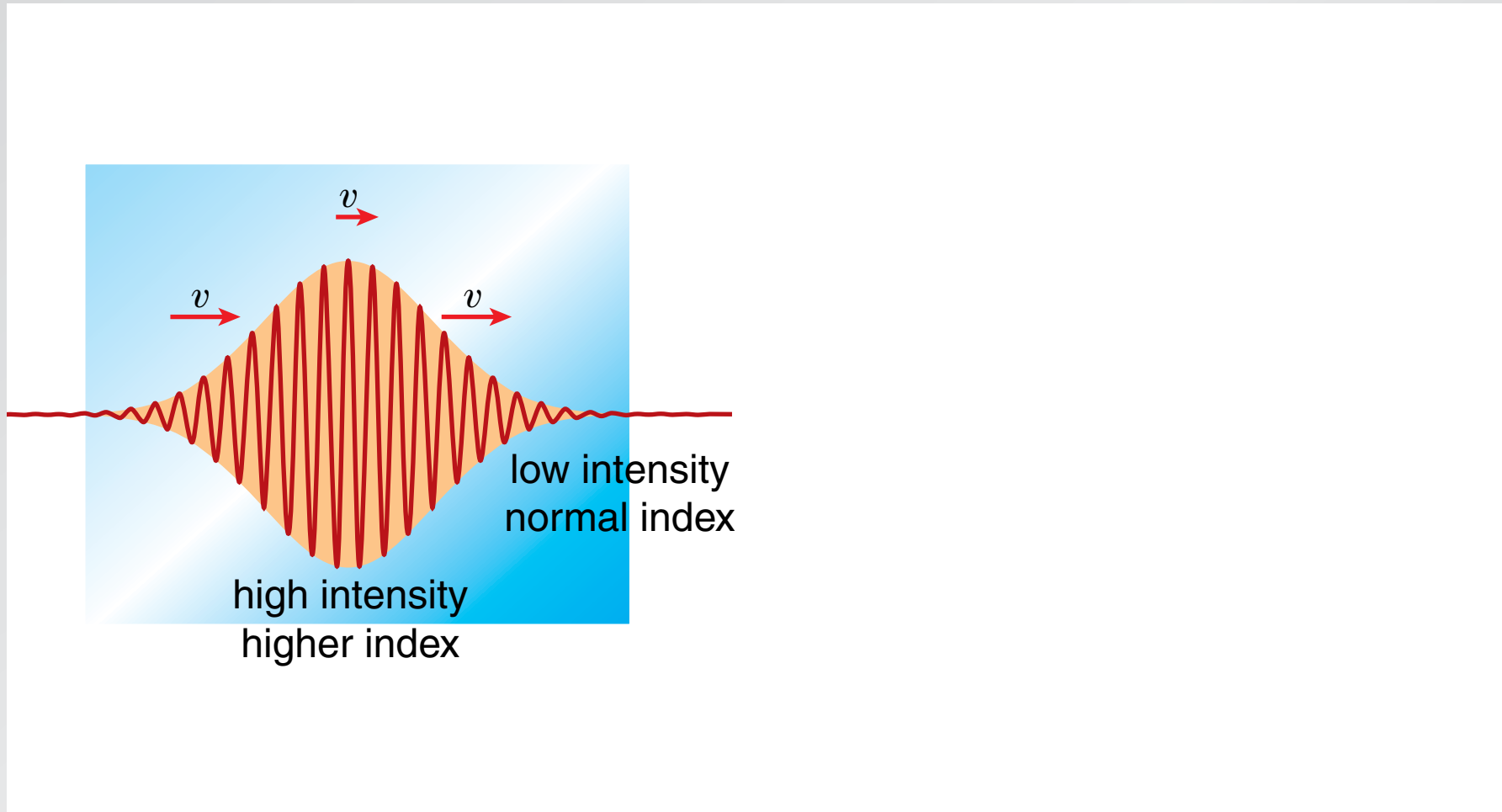
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



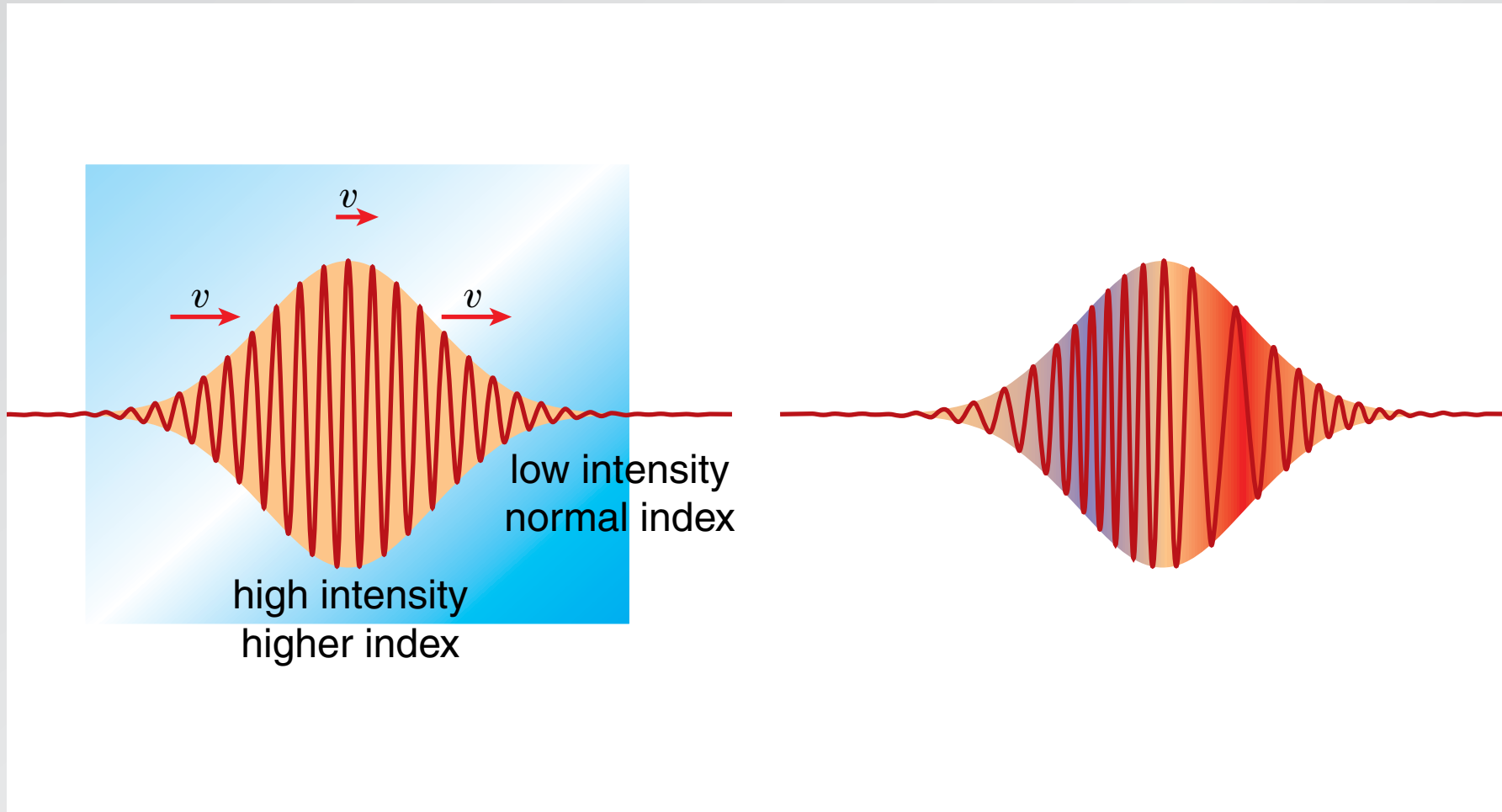
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



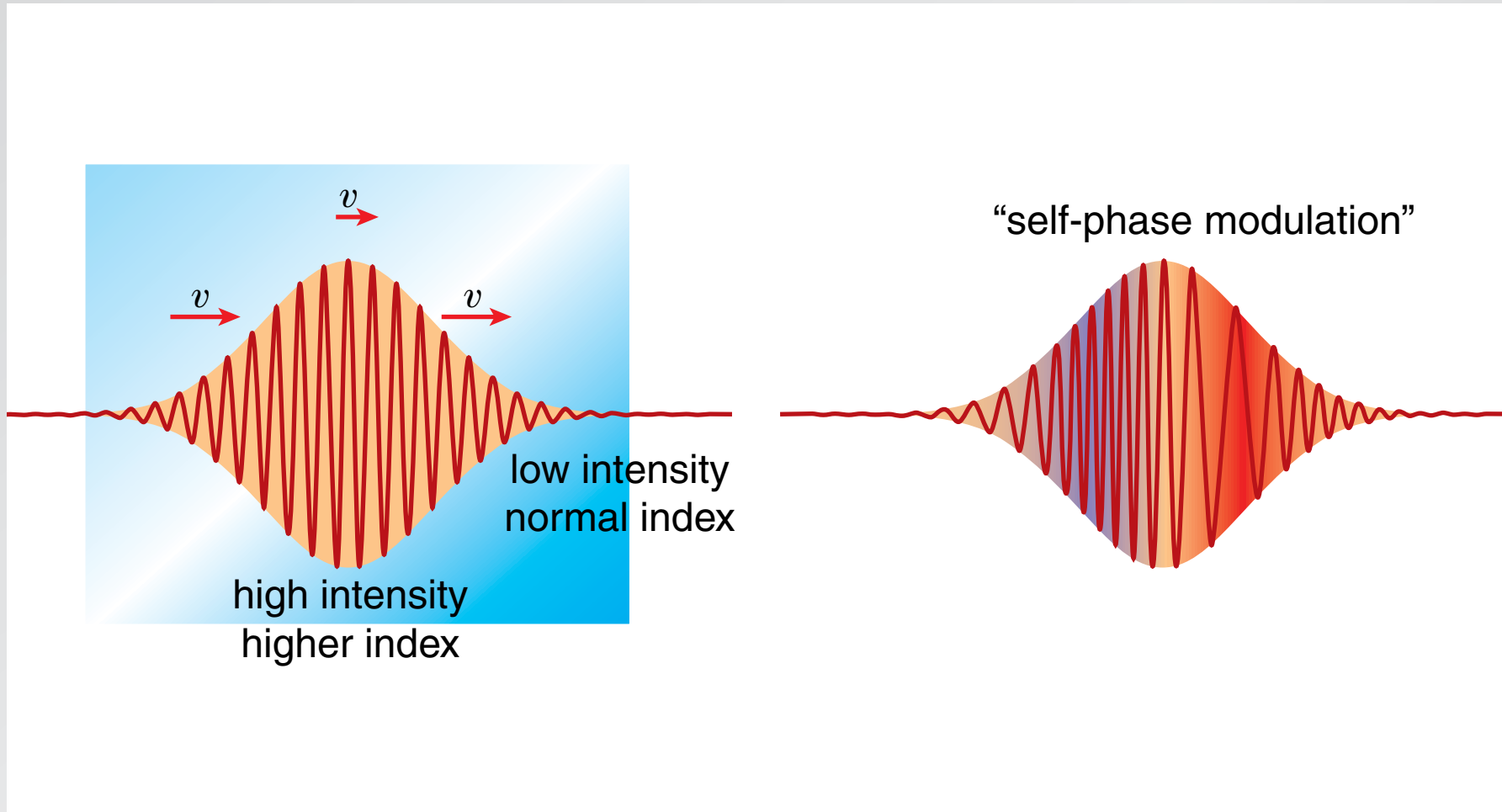
Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$

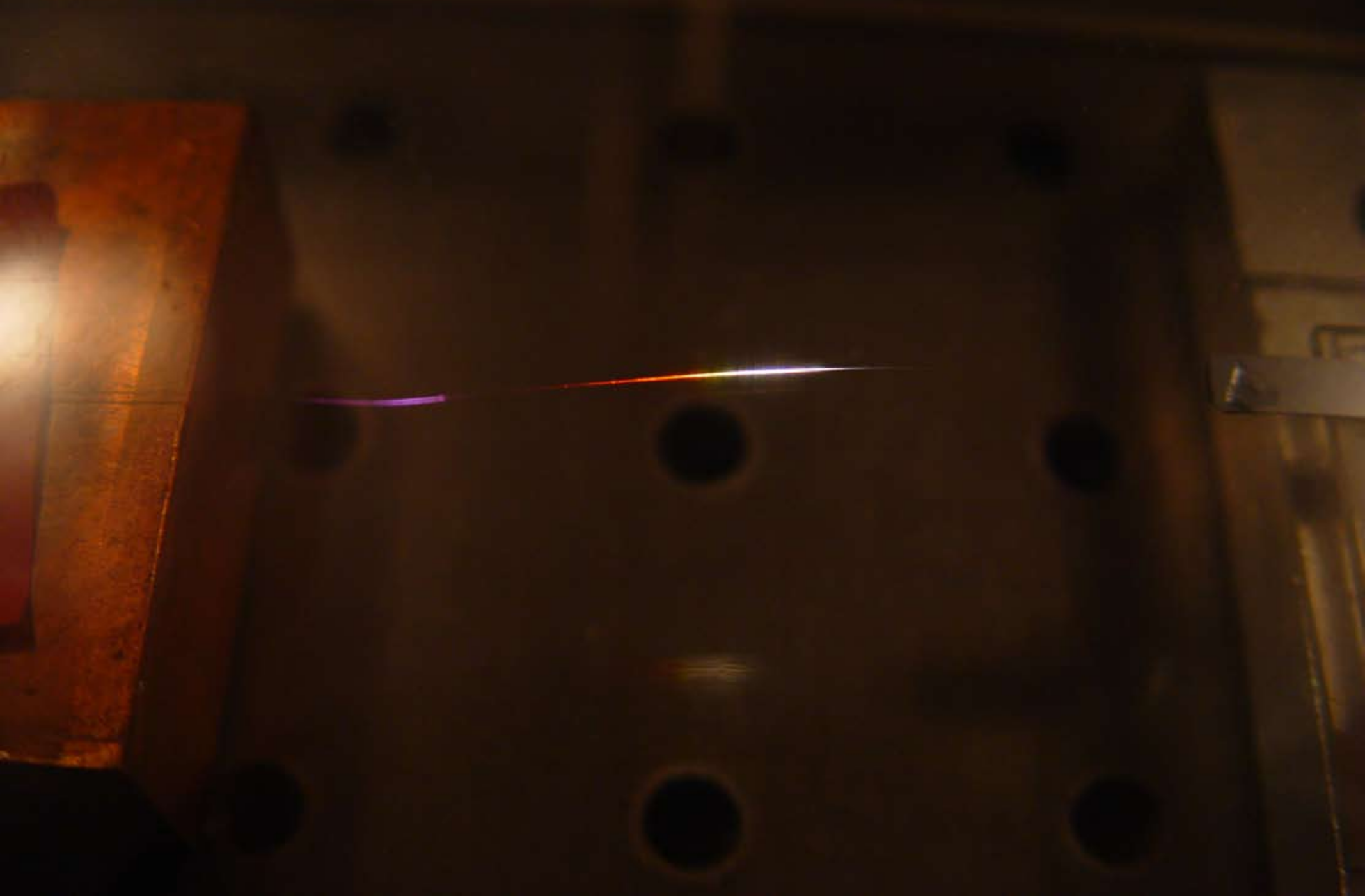


Nonlinear properties

nonlinear dispersion: $n = n_0 + n_2 I$



Nonlinear properties



Nonlinear properties

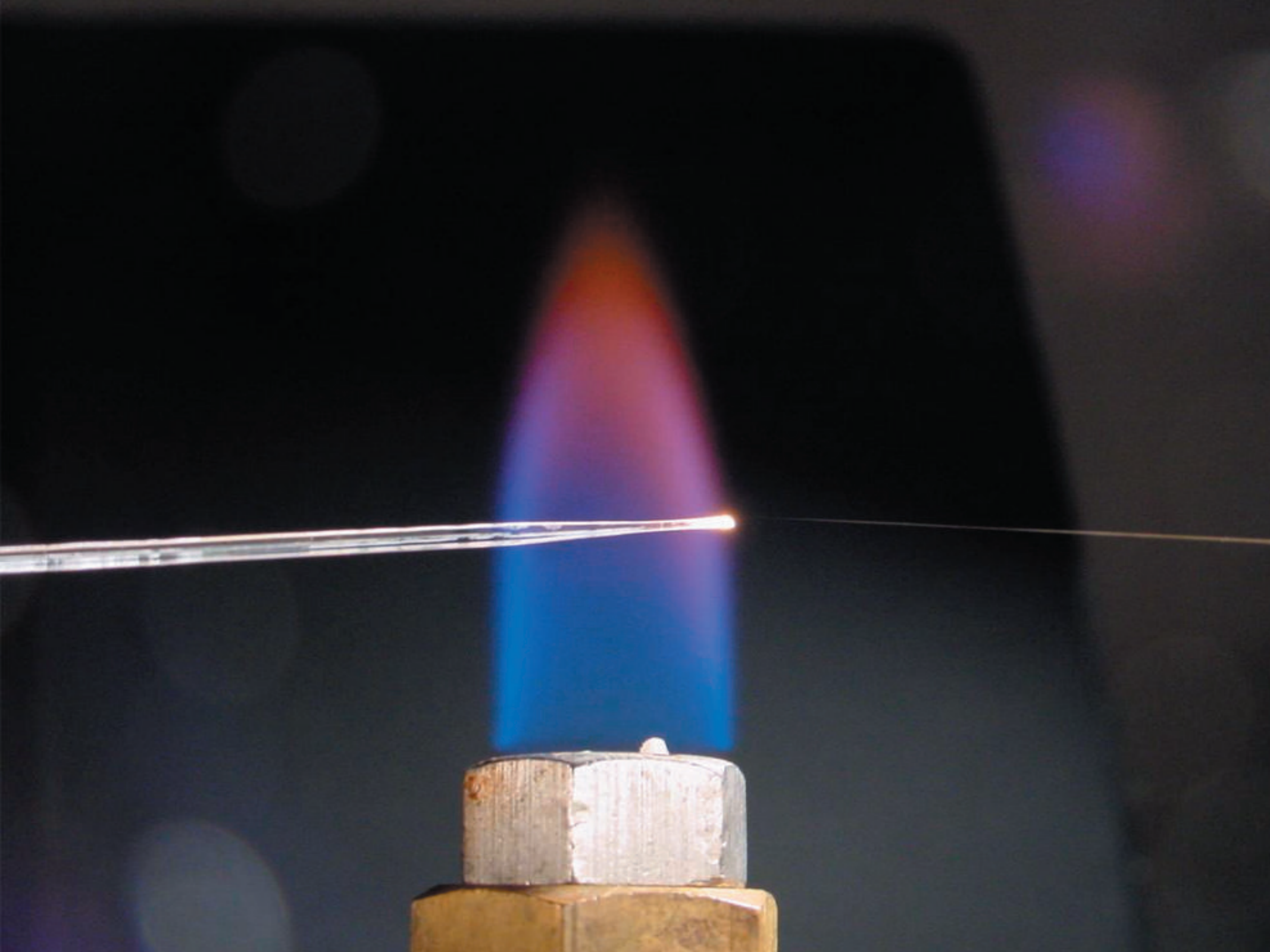


Nonlinear properties

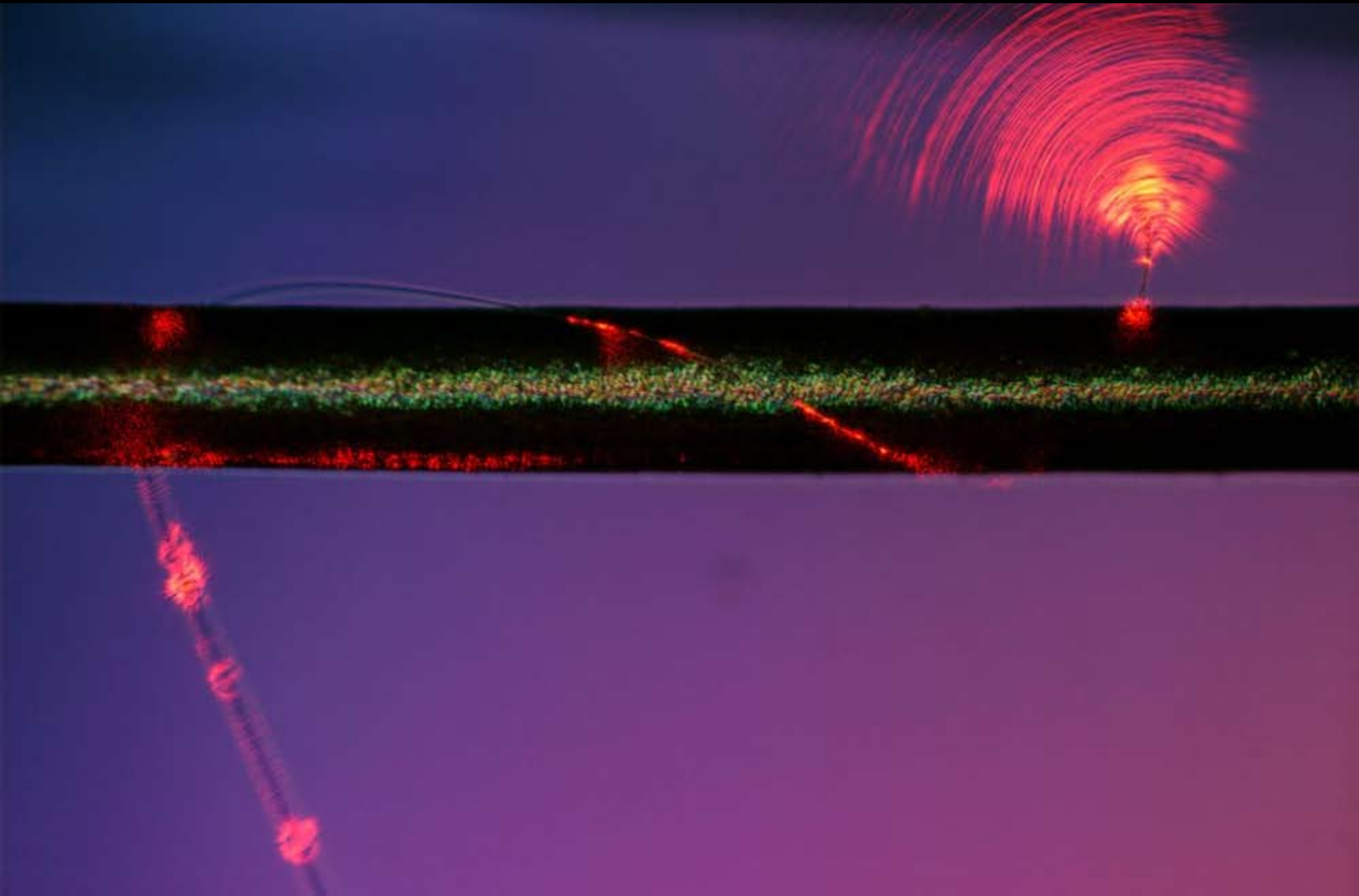
strong confinement \longrightarrow **high intensity**

Nonlinear properties

energy in nanowire < 100 pJ!

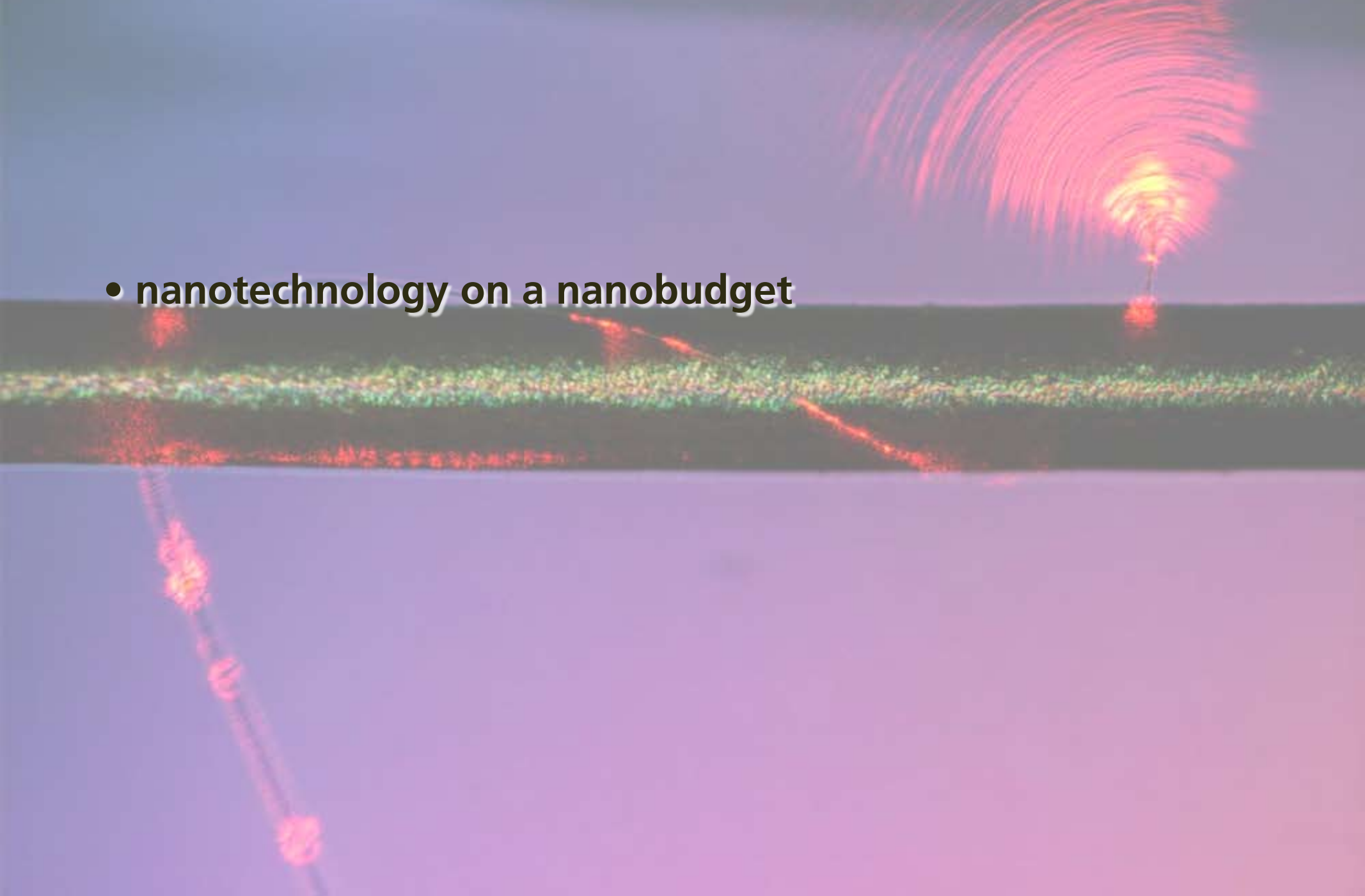


Summary



Summary

- nanotechnology on a nanobudget

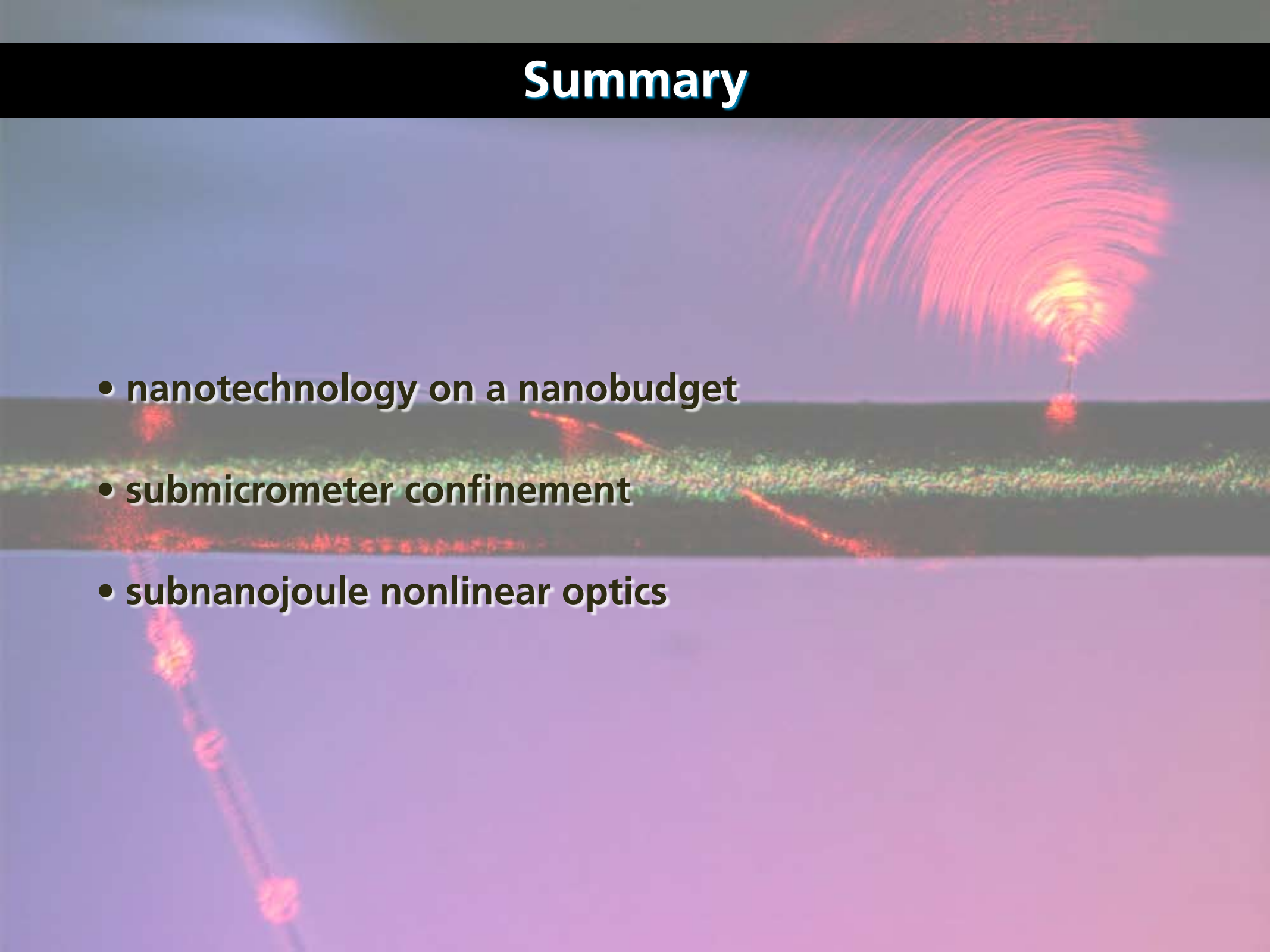


Summary

- nanotechnology on a nanobudget
- submicrometer confinement



Summary

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





Funding:

**Harvard Center for Imaging and Mesoscopic Structures
National Science Foundation
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