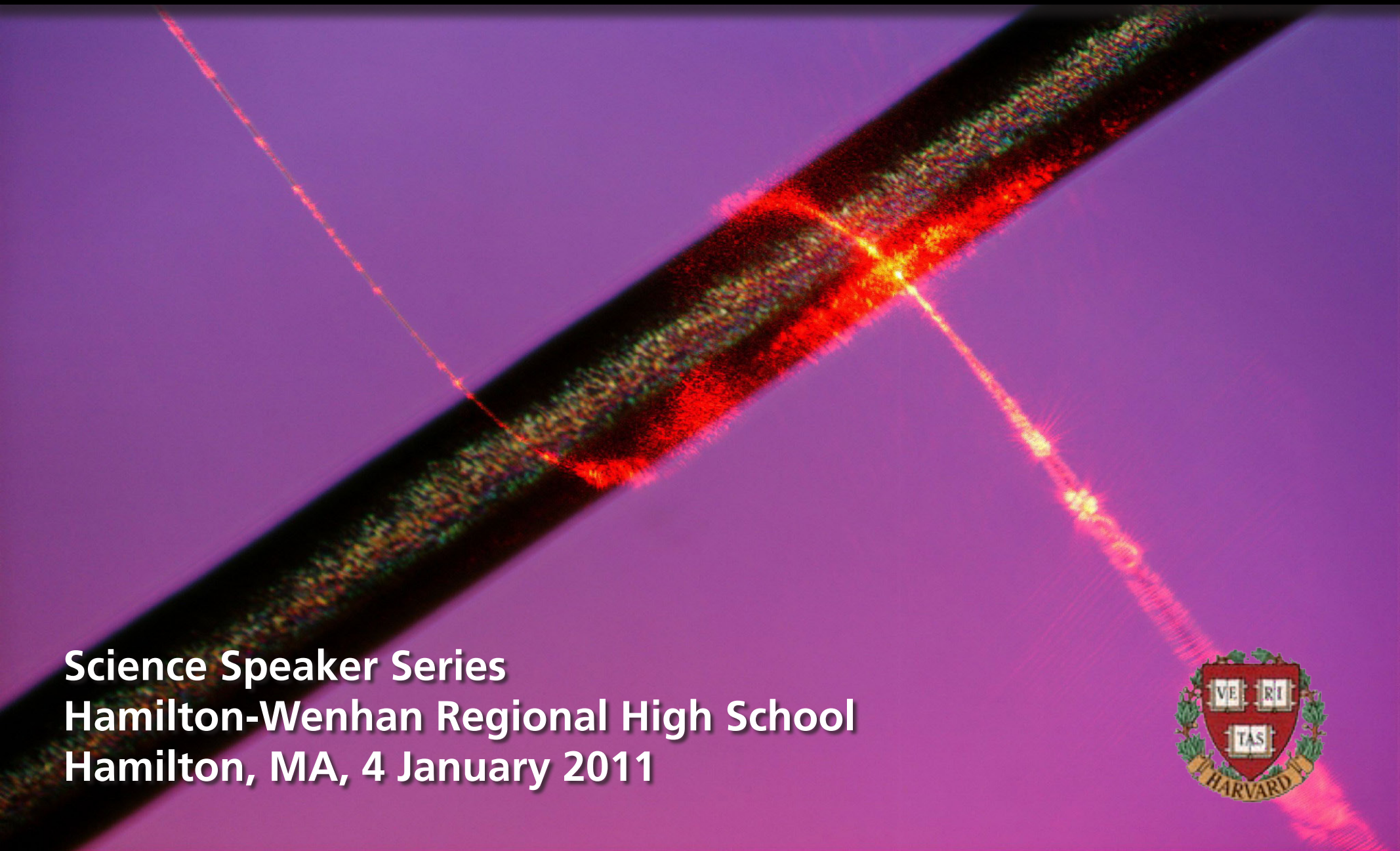
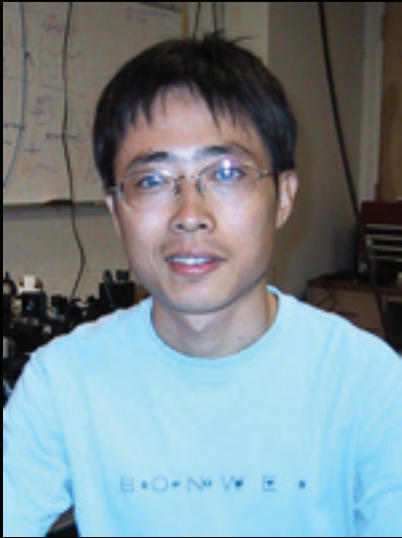


Wrapping light around a hair



Science Speaker Series
Hamilton-Wenhan Regional High School
Hamilton, MA, 4 January 2011





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

Prof. Federico Capasso

Prof. Cynthia Friend

at Zhejiang University:

Dr. Sailing He

Dr. Jingyi Lou

Xuwen Chen

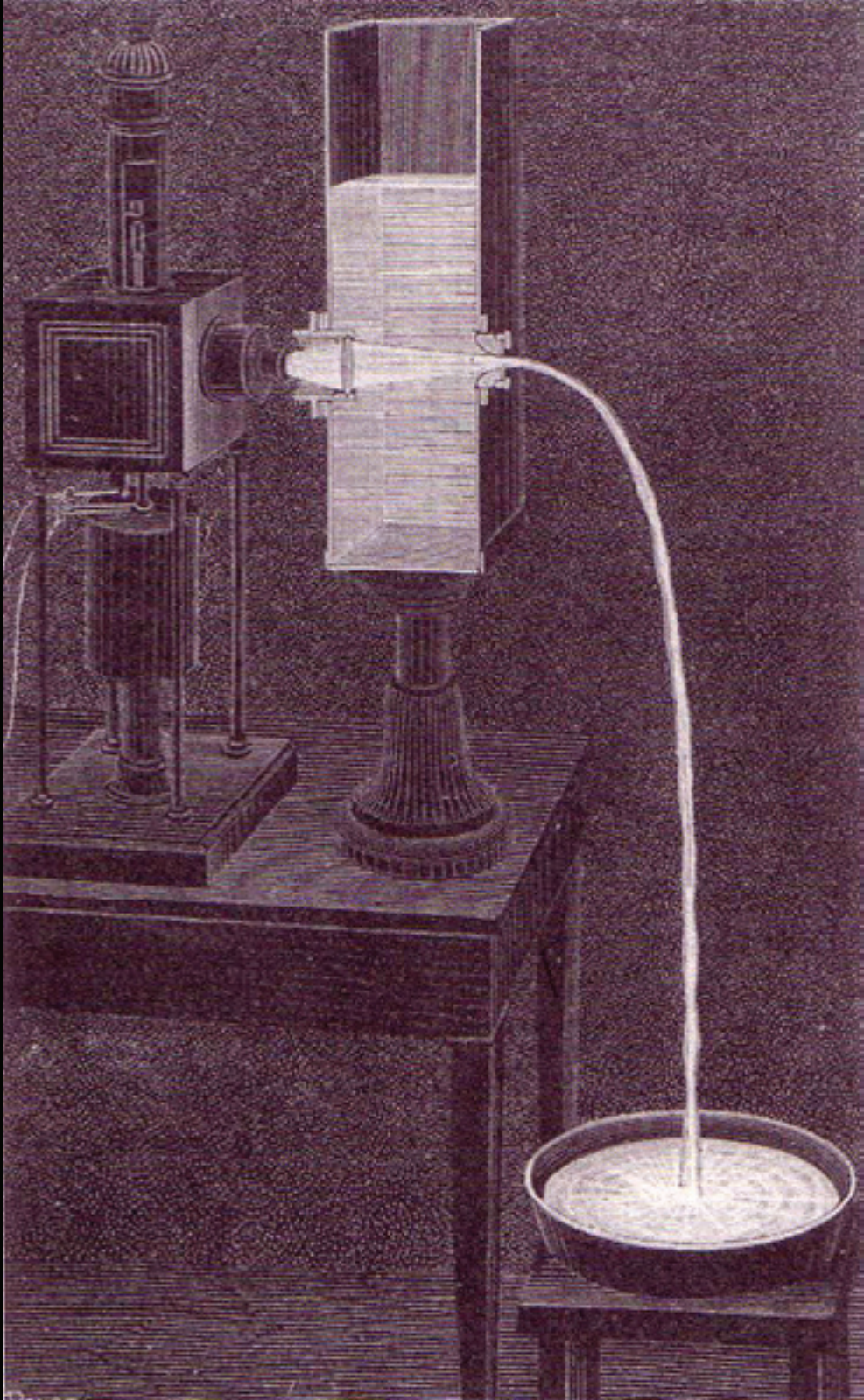
Liu Liu

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)



W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.

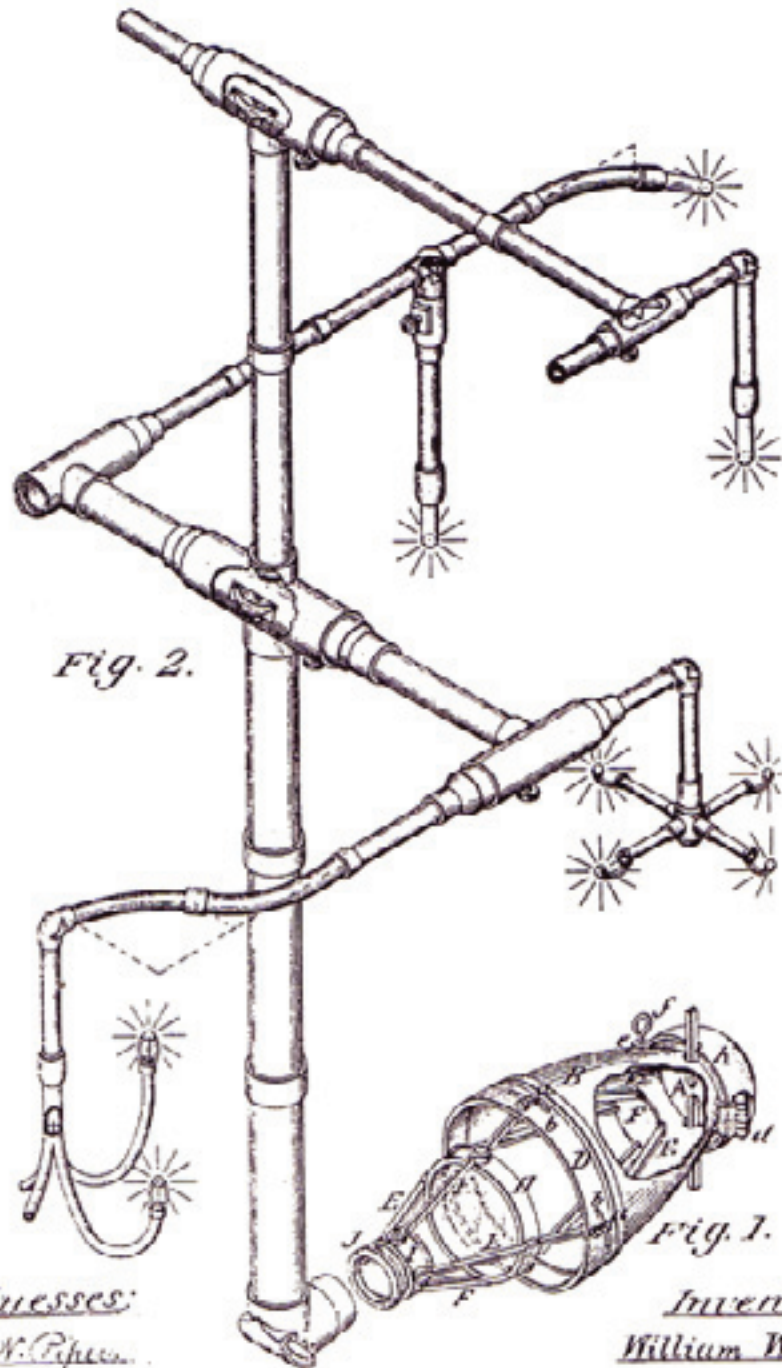


Fig. 2.

Fig. 1.

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

Inventor:
William Wheeler
 by attorney
[Signature]

US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

Waveguiding

how does water surface look from bottom?

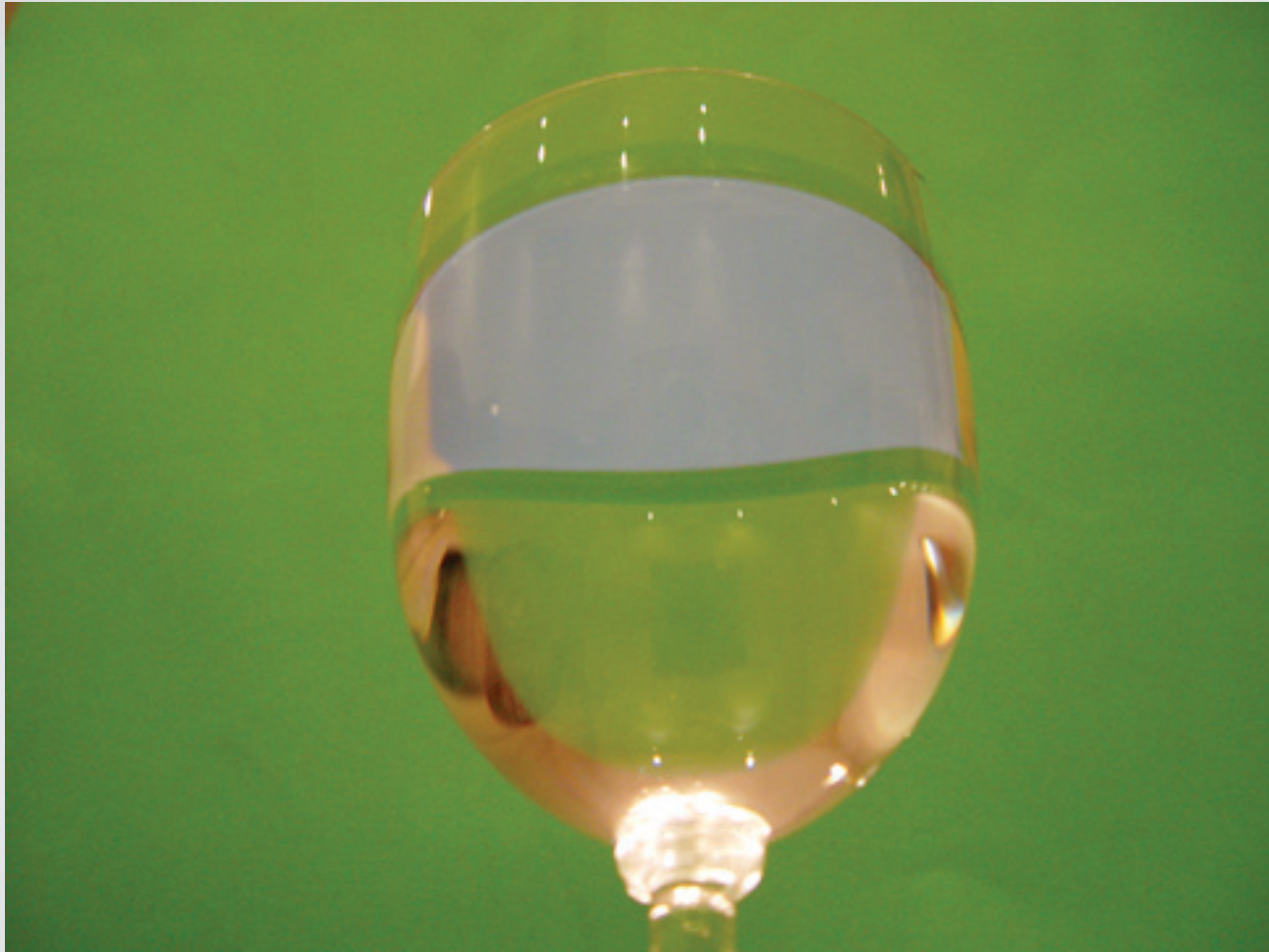


Waveguiding

from top partially transmitting!



Waveguiding

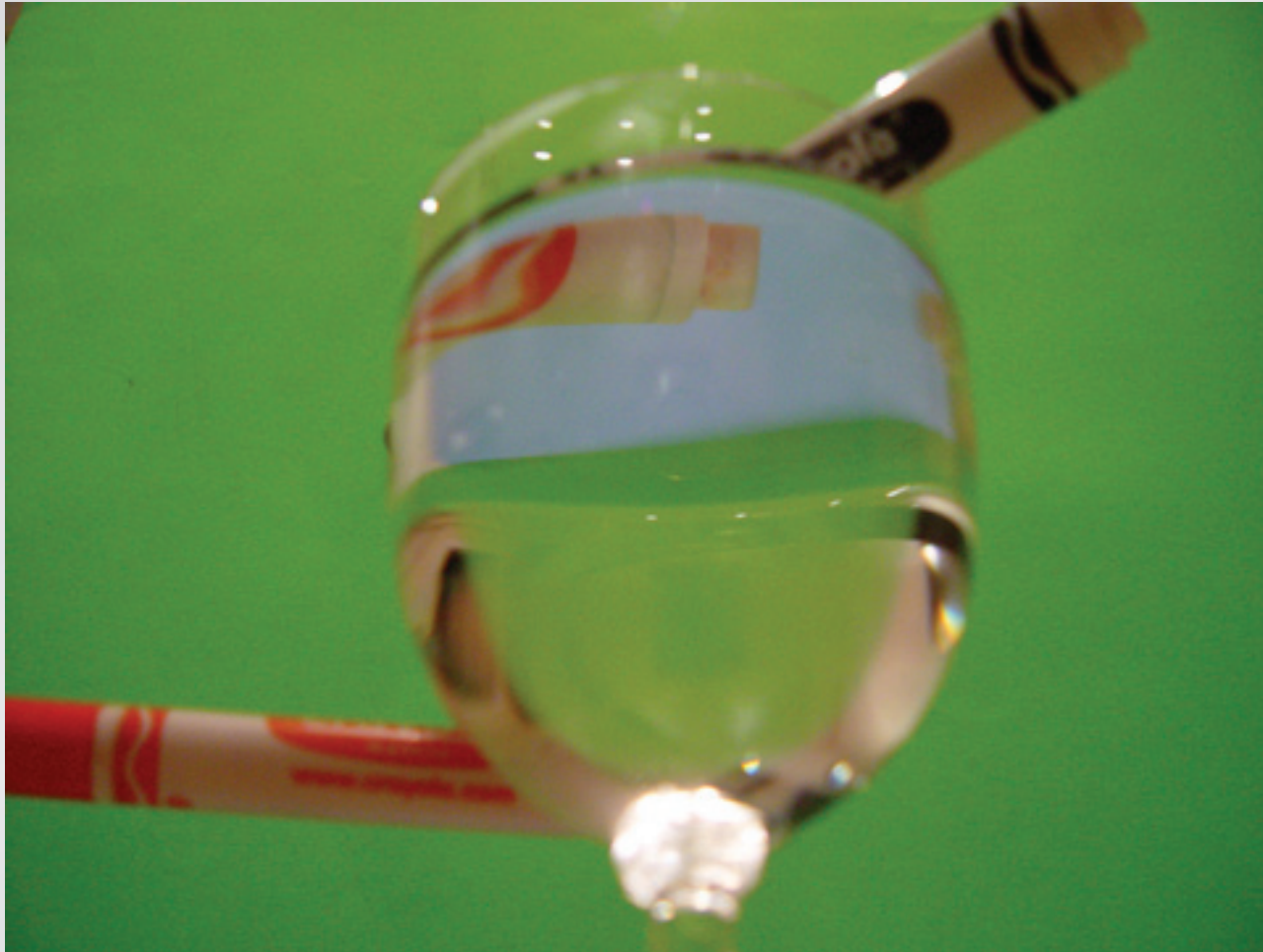


Waveguiding



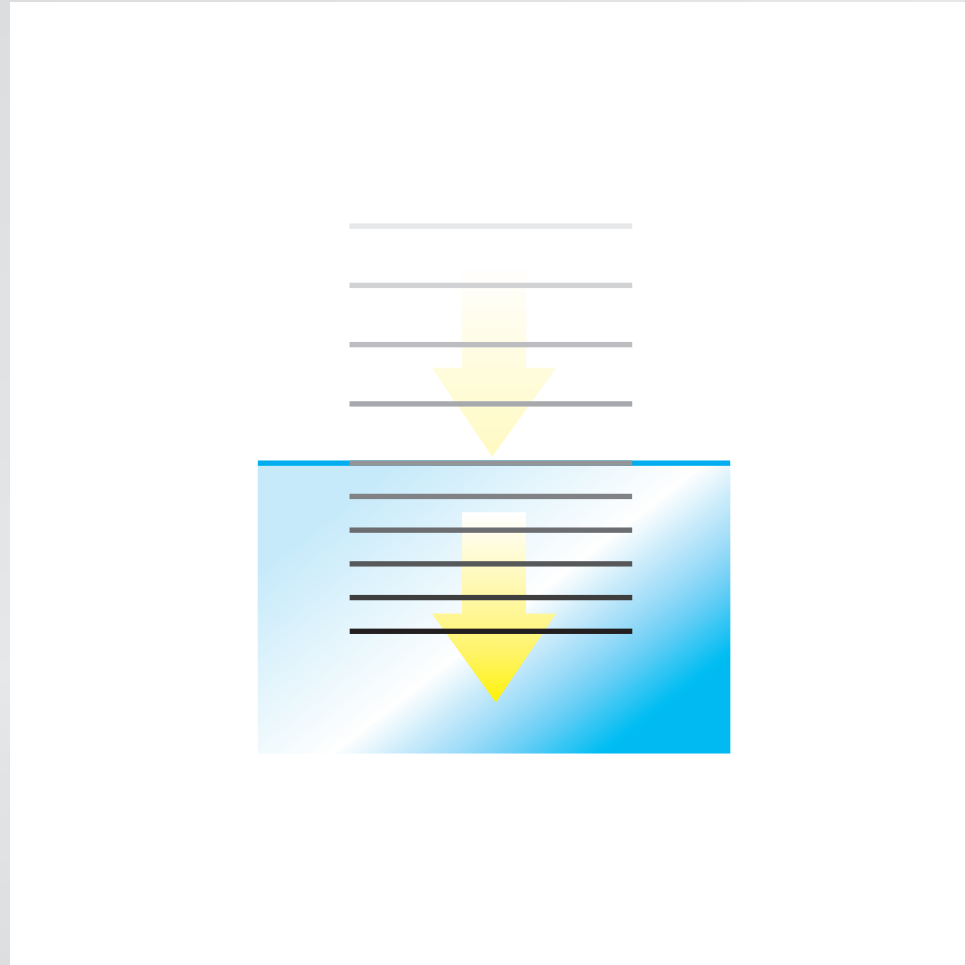
Waveguiding

water surface is perfect one-way mirror!



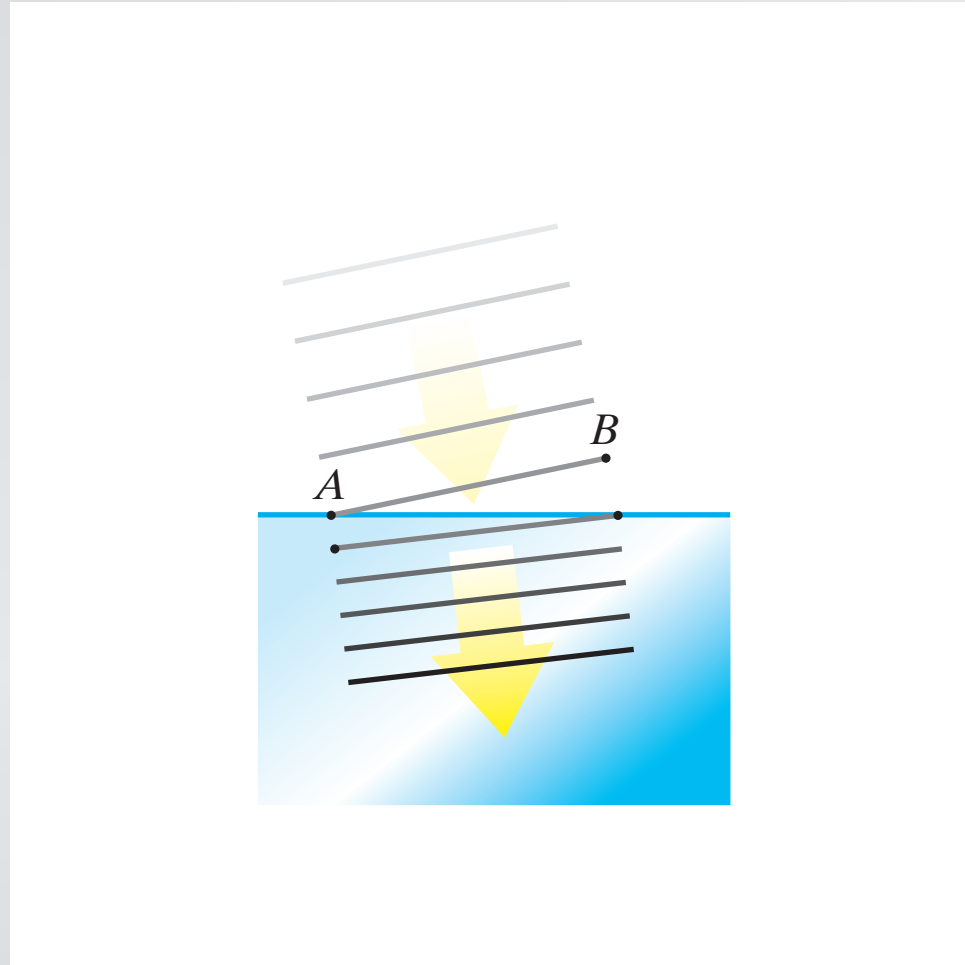
Waveguiding

Why? Because light travels more slowly in water...



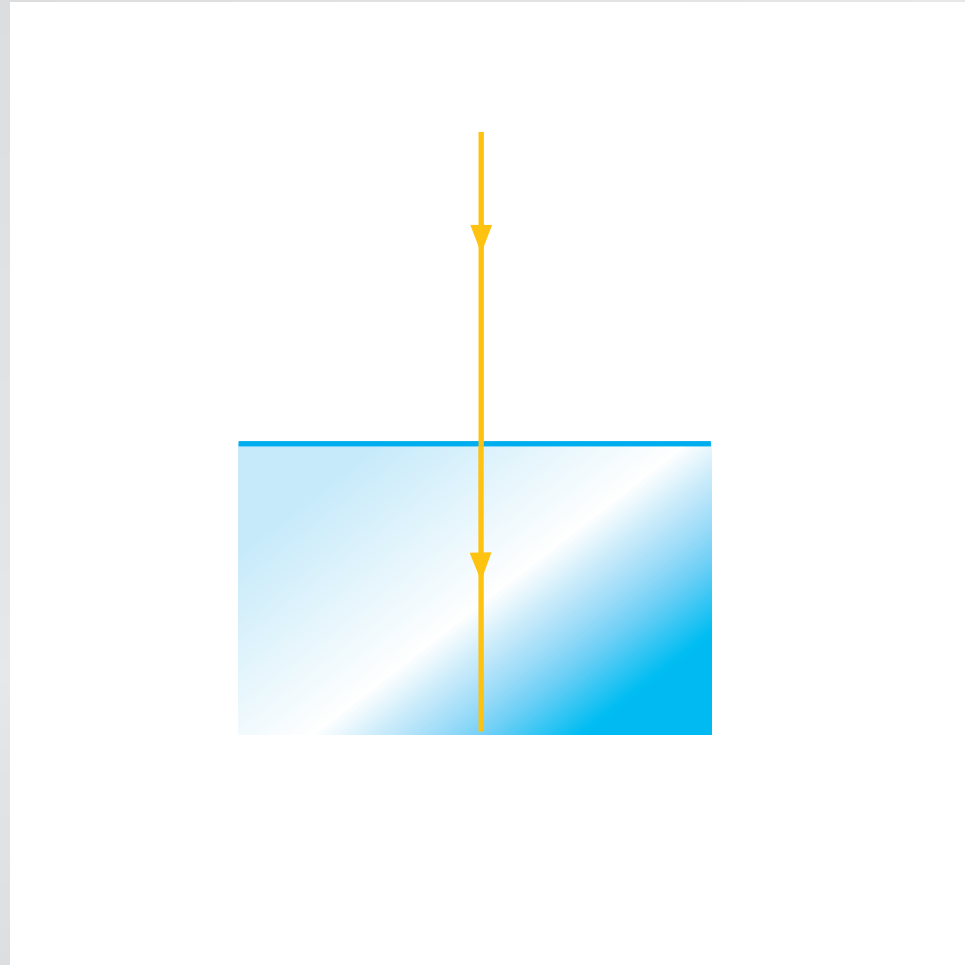
Waveguiding

...making it bend as it crosses surface



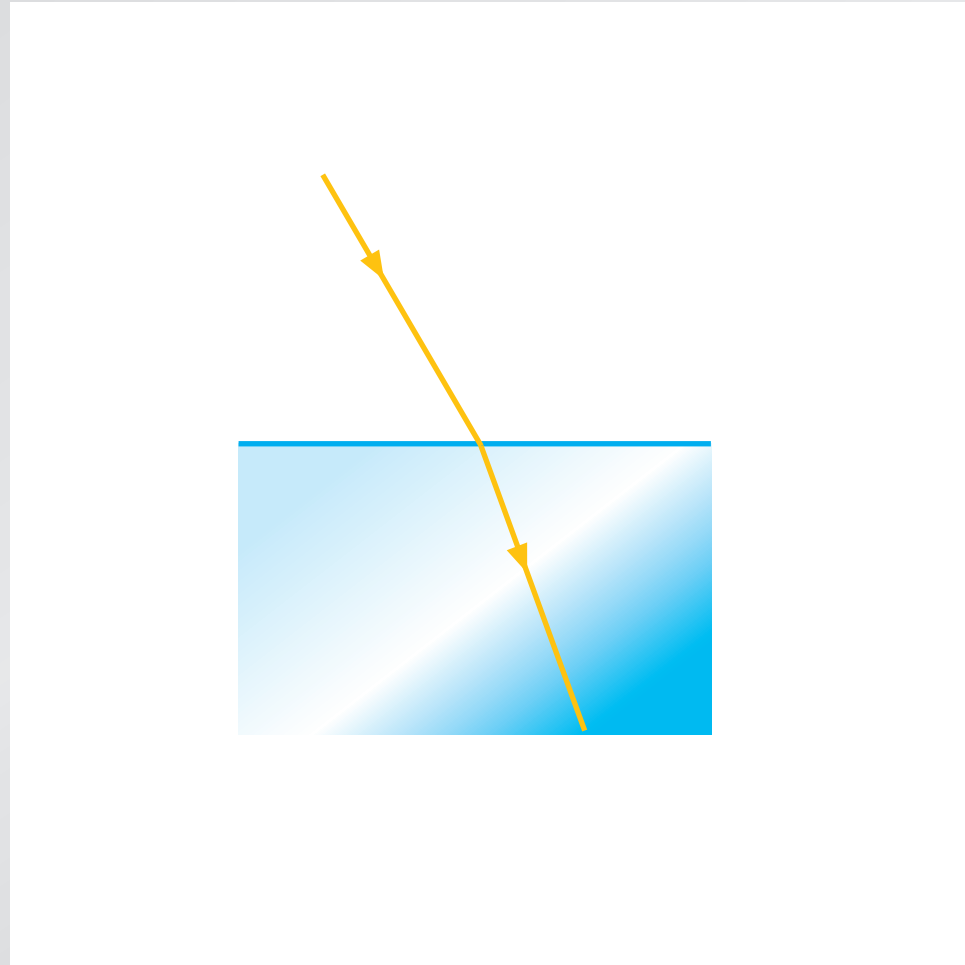
Waveguiding

The more angled the incident ray, the stronger the bending



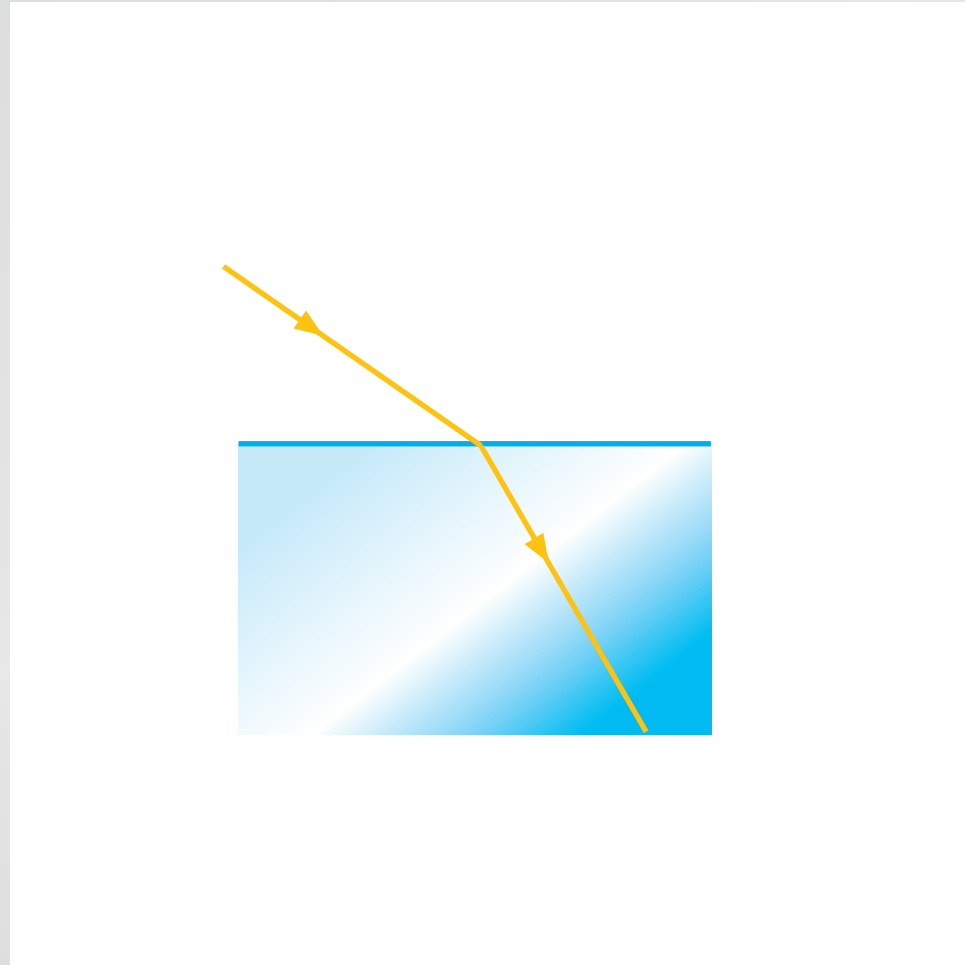
Waveguiding

The more angled the incident ray, the stronger the bending



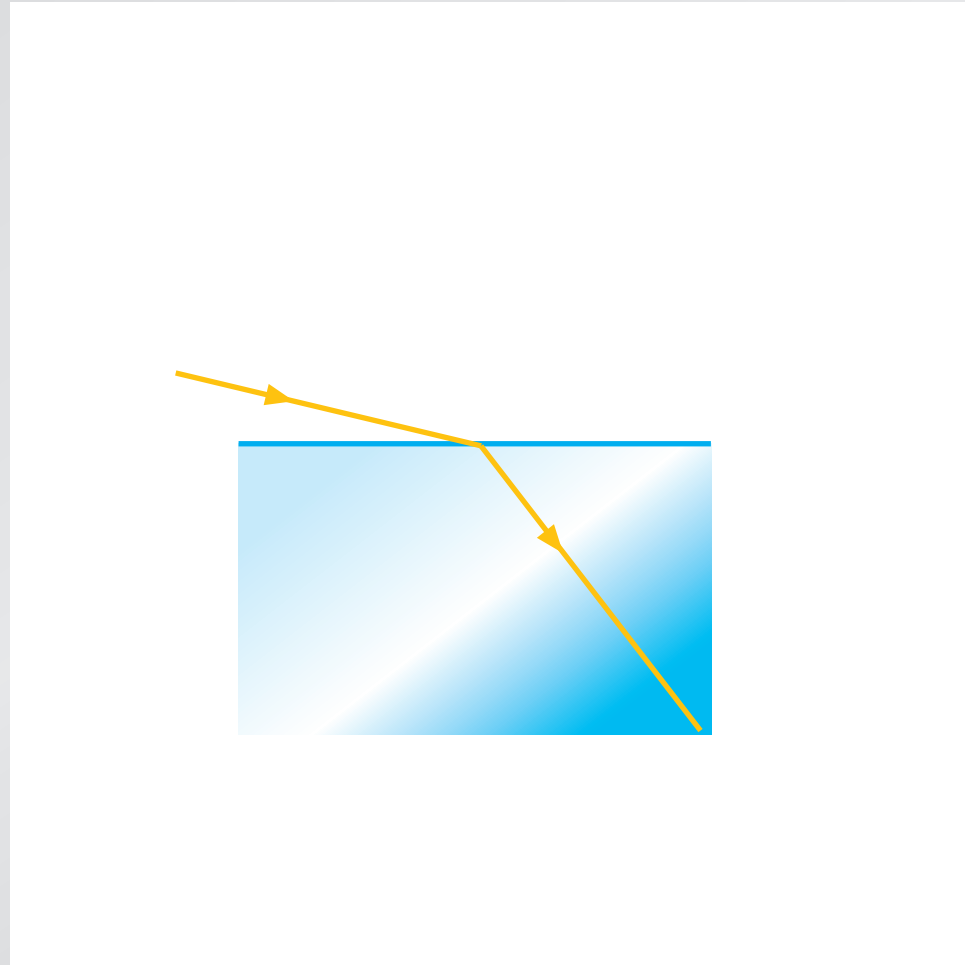
Waveguiding

The more angled the incident ray, the stronger the bending



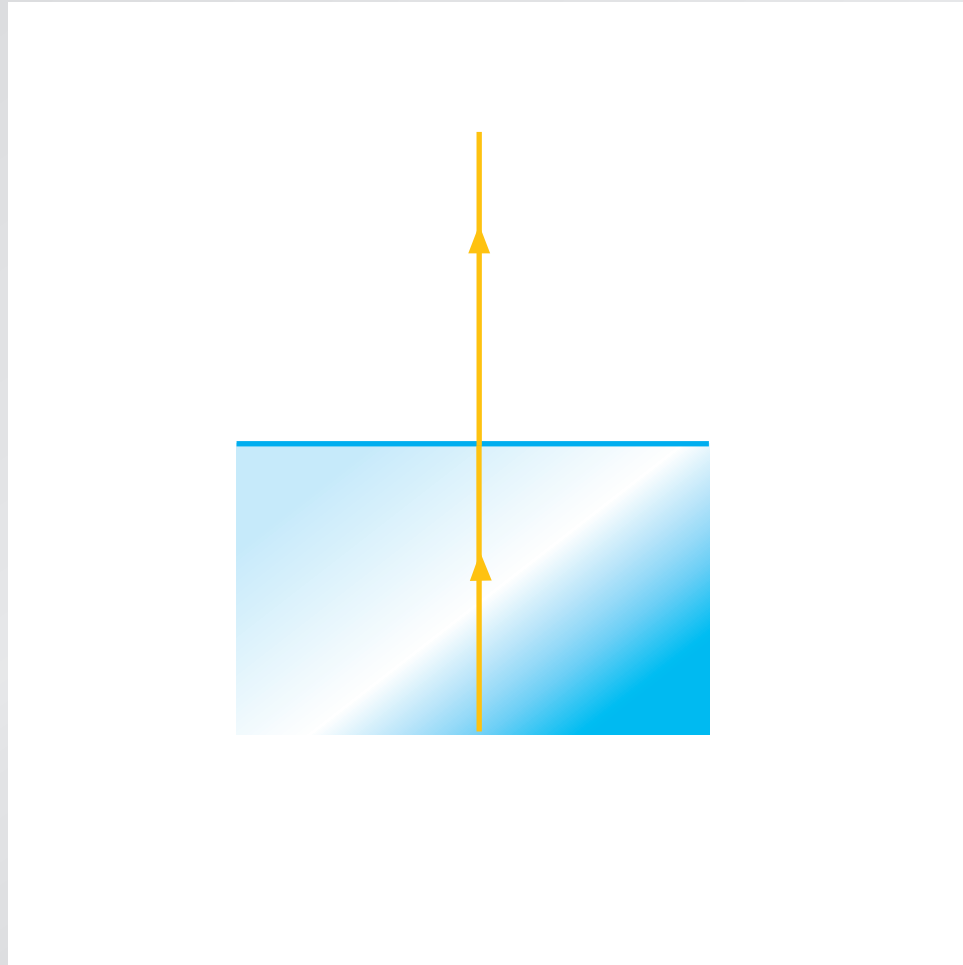
Waveguiding

The more angled the incident ray, the stronger the bending



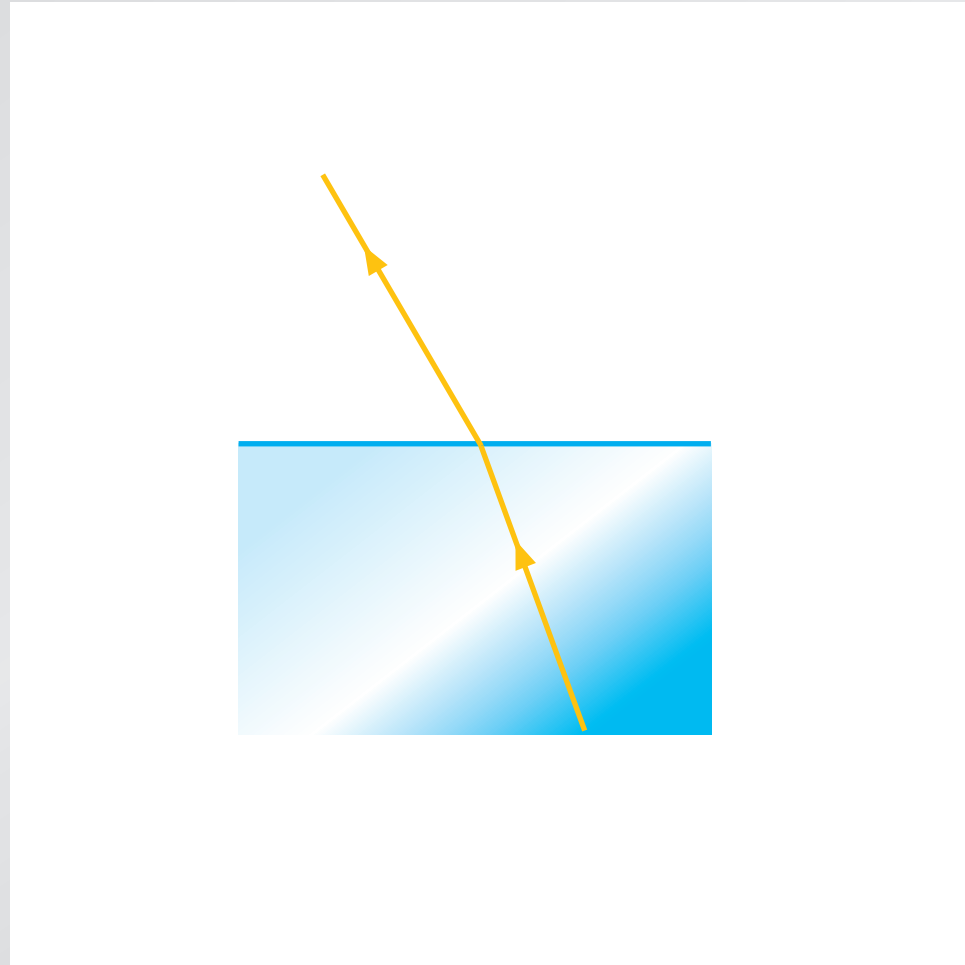
Waveguiding

The amount of bending is the same in reverse



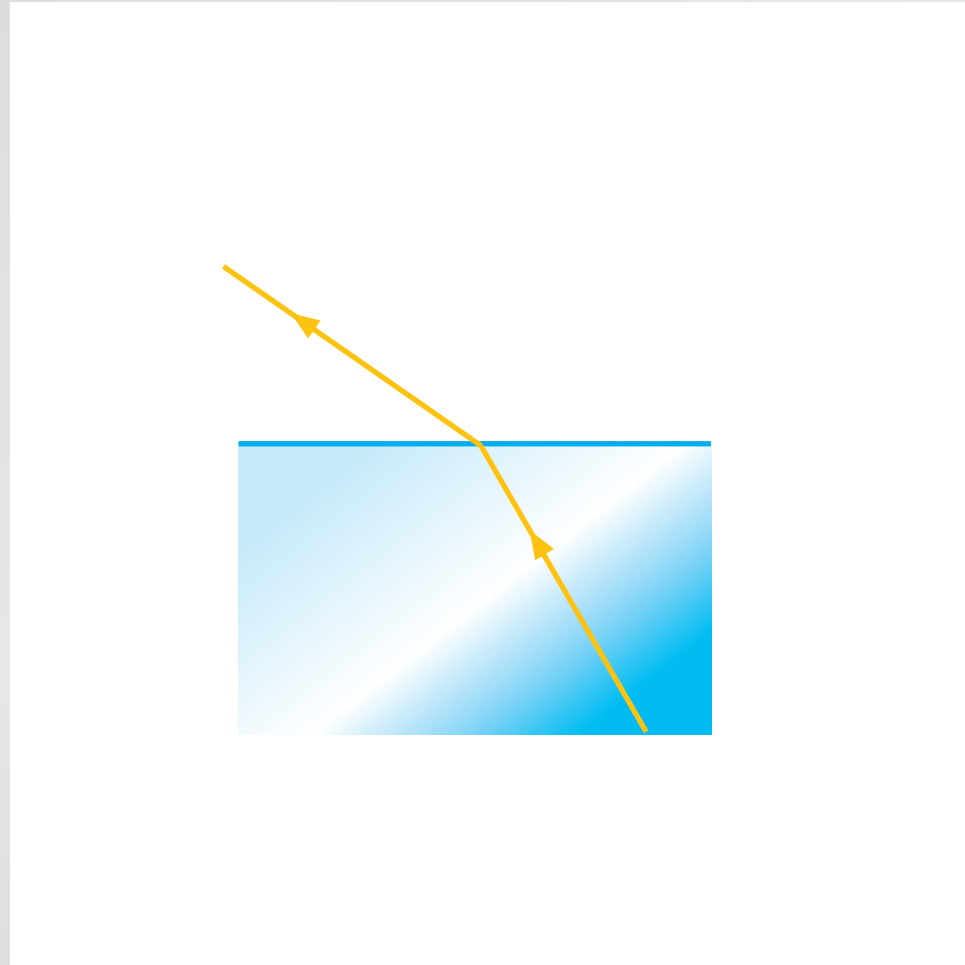
Waveguiding

The amount of bending is the same in reverse



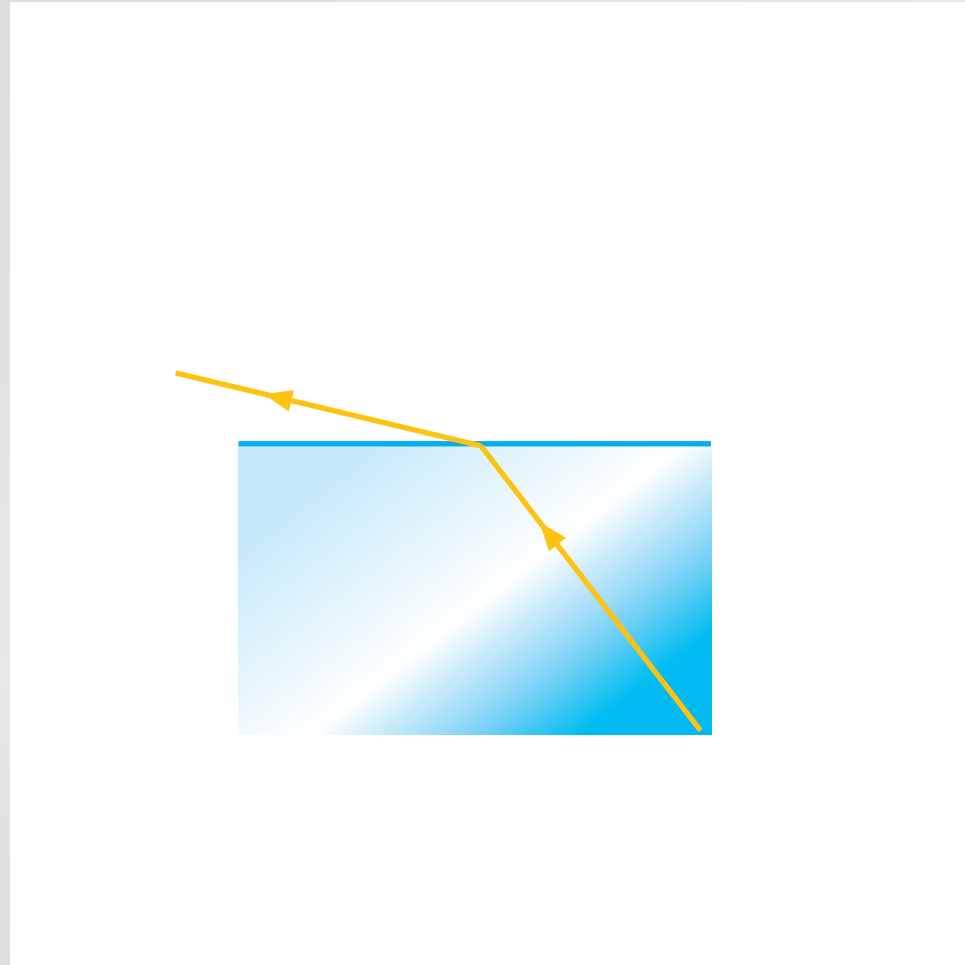
Waveguiding

The amount of bending is the same in reverse



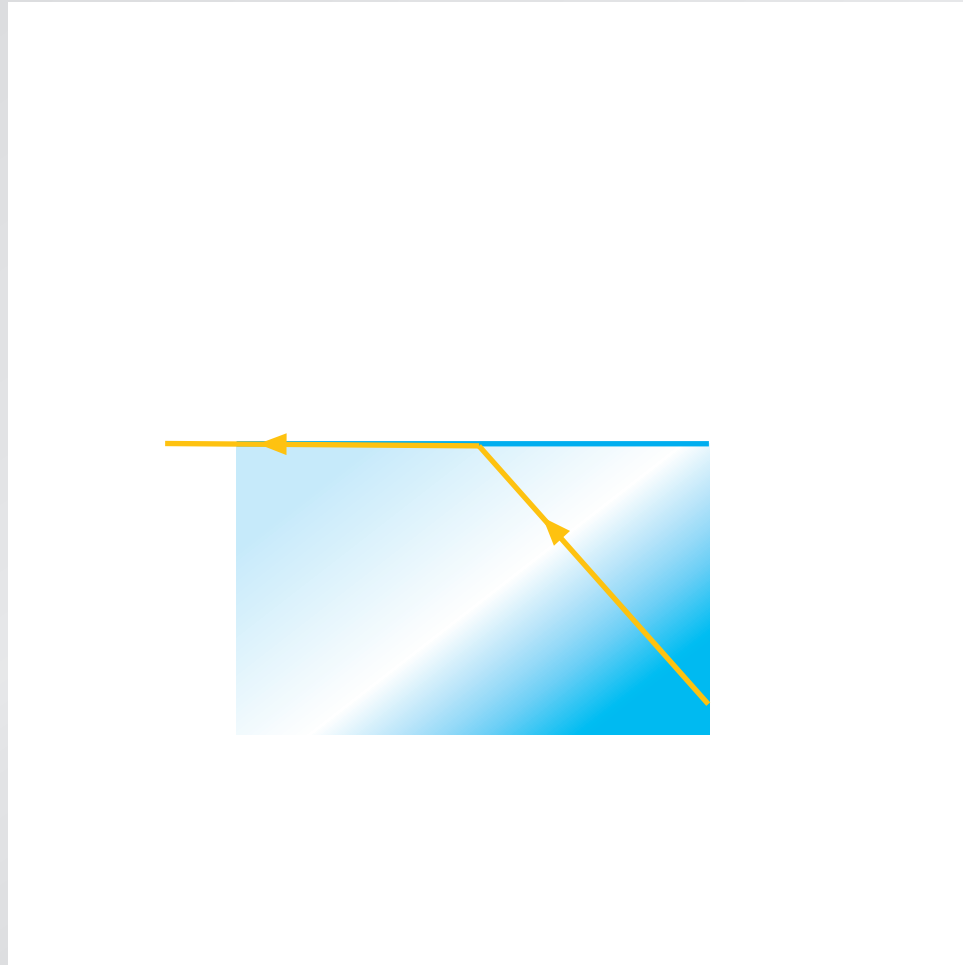
Waveguiding

The amount of bending is the same in reverse



Waveguiding

At 'critical angle' bent ray travels along surface



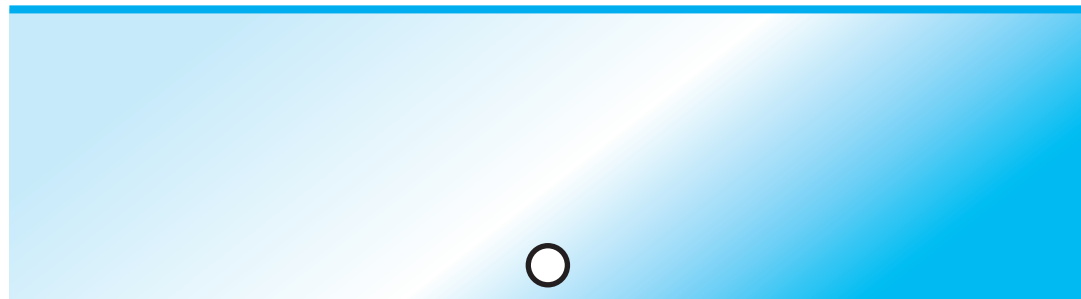
Waveguiding

Beyond 'critical angle': total internal reflection



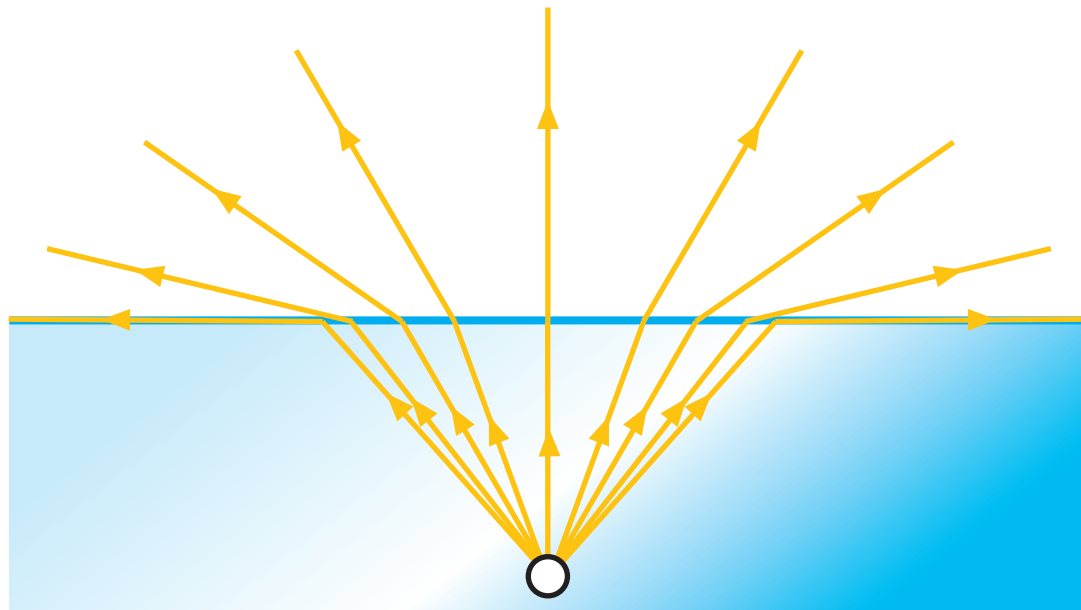
Waveguiding

seeing underwater



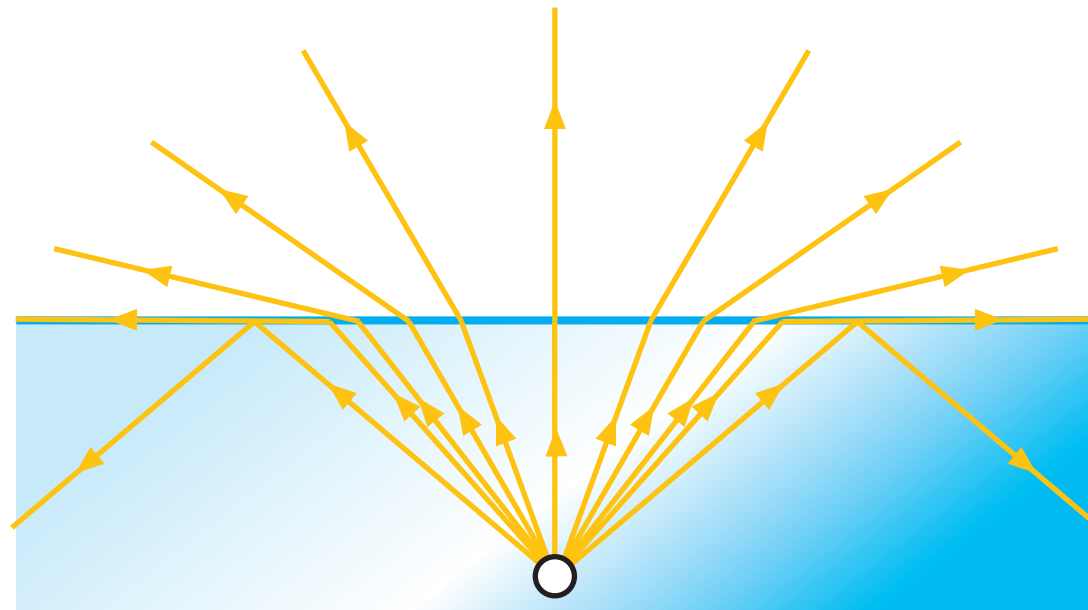
Waveguiding

seeing underwater



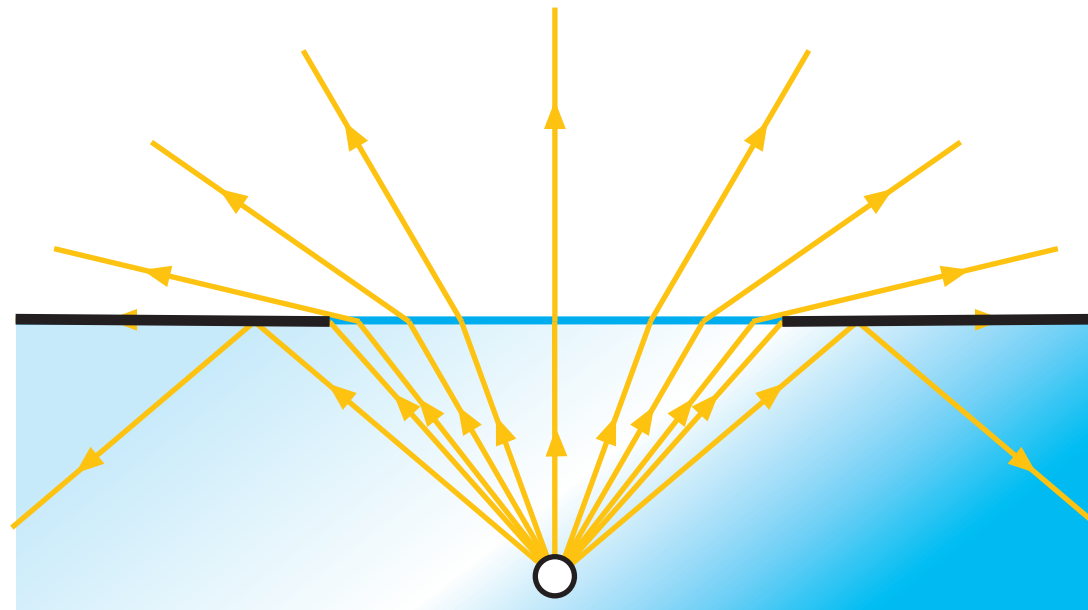
Waveguiding

seeing underwater



Waveguiding

surface looks like mirror with a circular hole



Waveguiding



Waveguiding



Waveguiding



Waveguiding

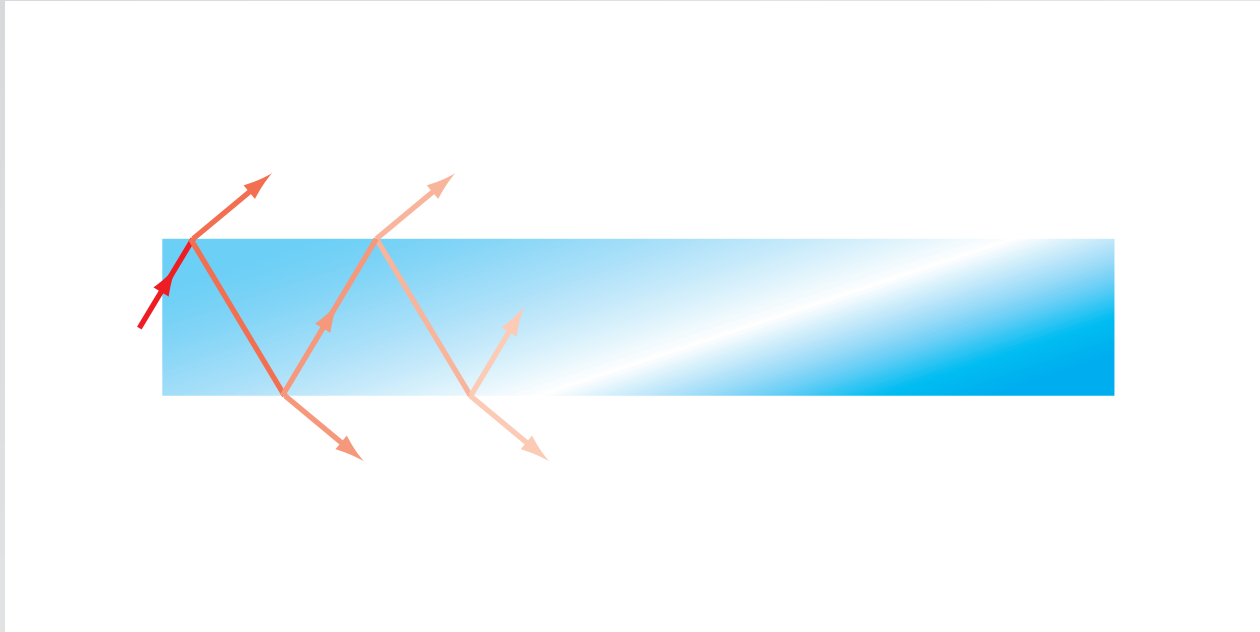


Waveguiding



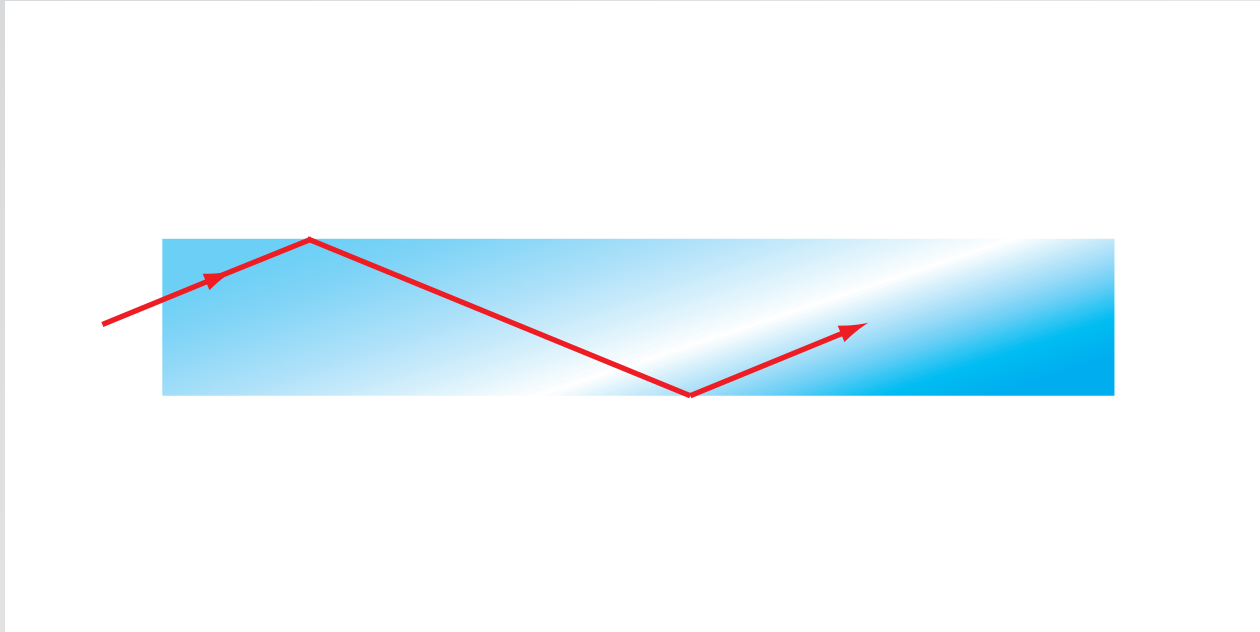
now consider a planar dielectric waveguide

Waveguiding



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

Waveguiding



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

Waveguiding



Outline

- waveguiding
- nanowire fabrication
- optical properties

Nanowire fabrication

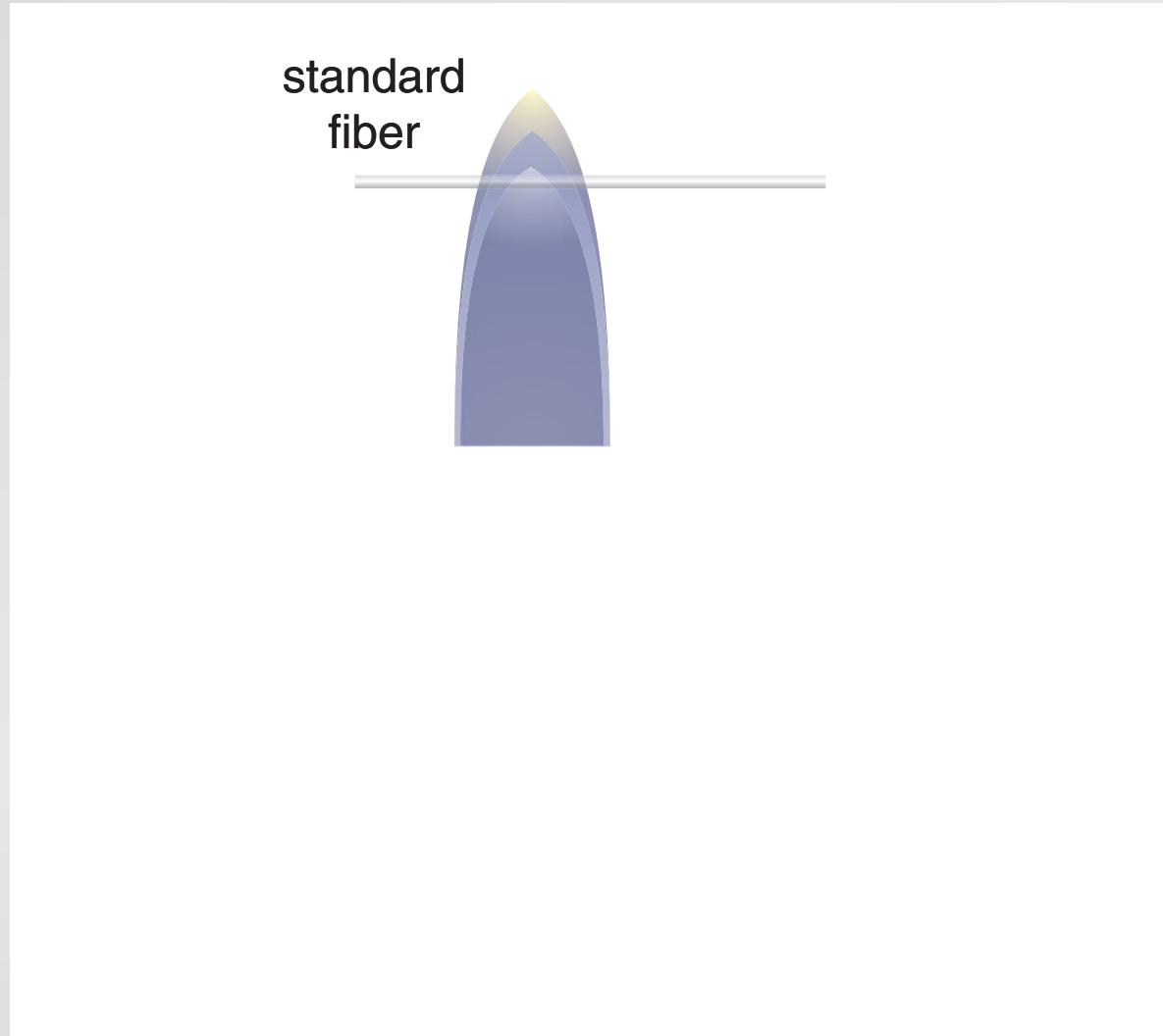
two-step drawing process

standard
fiber



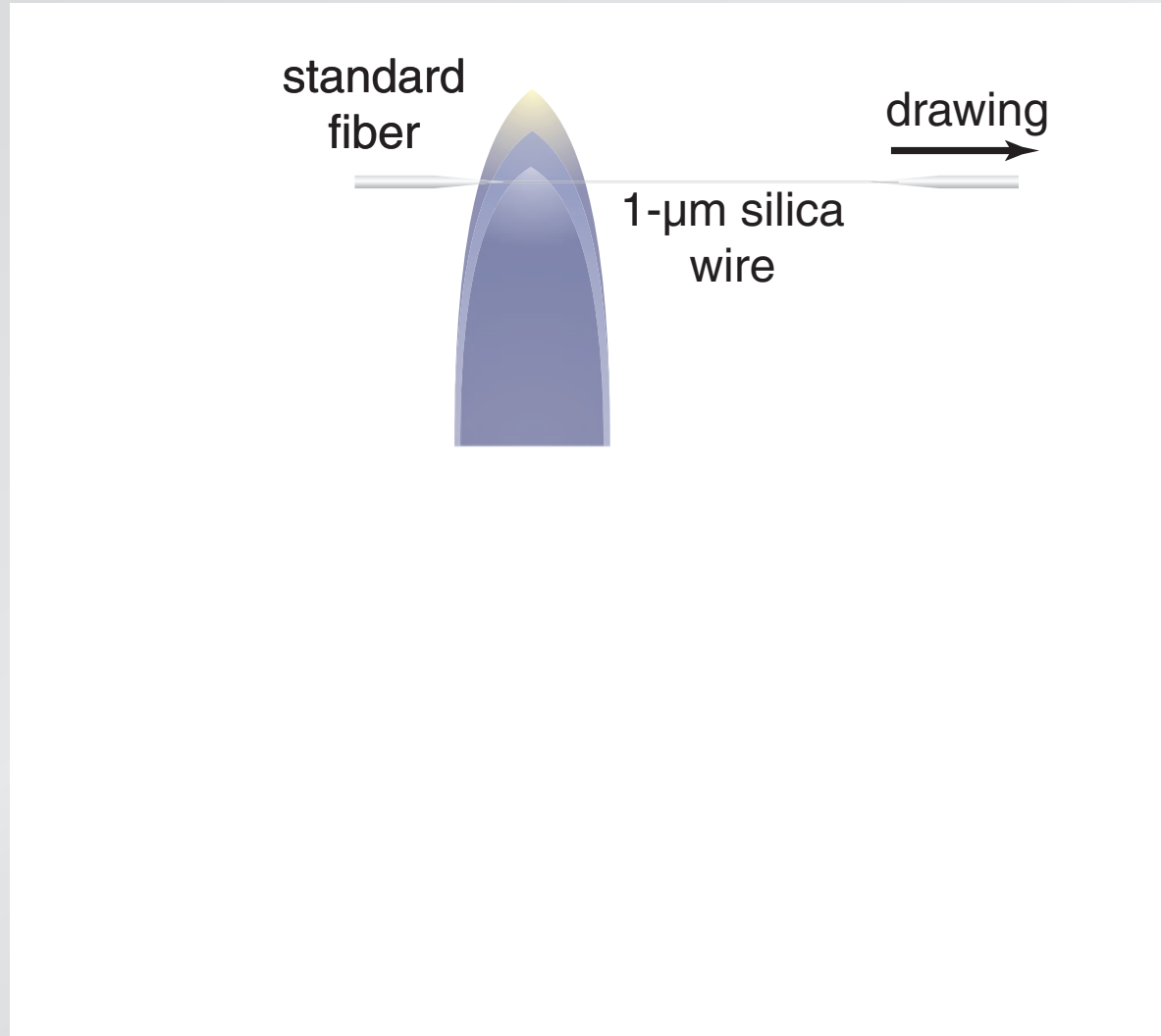
Nanowire fabrication

two-step drawing process



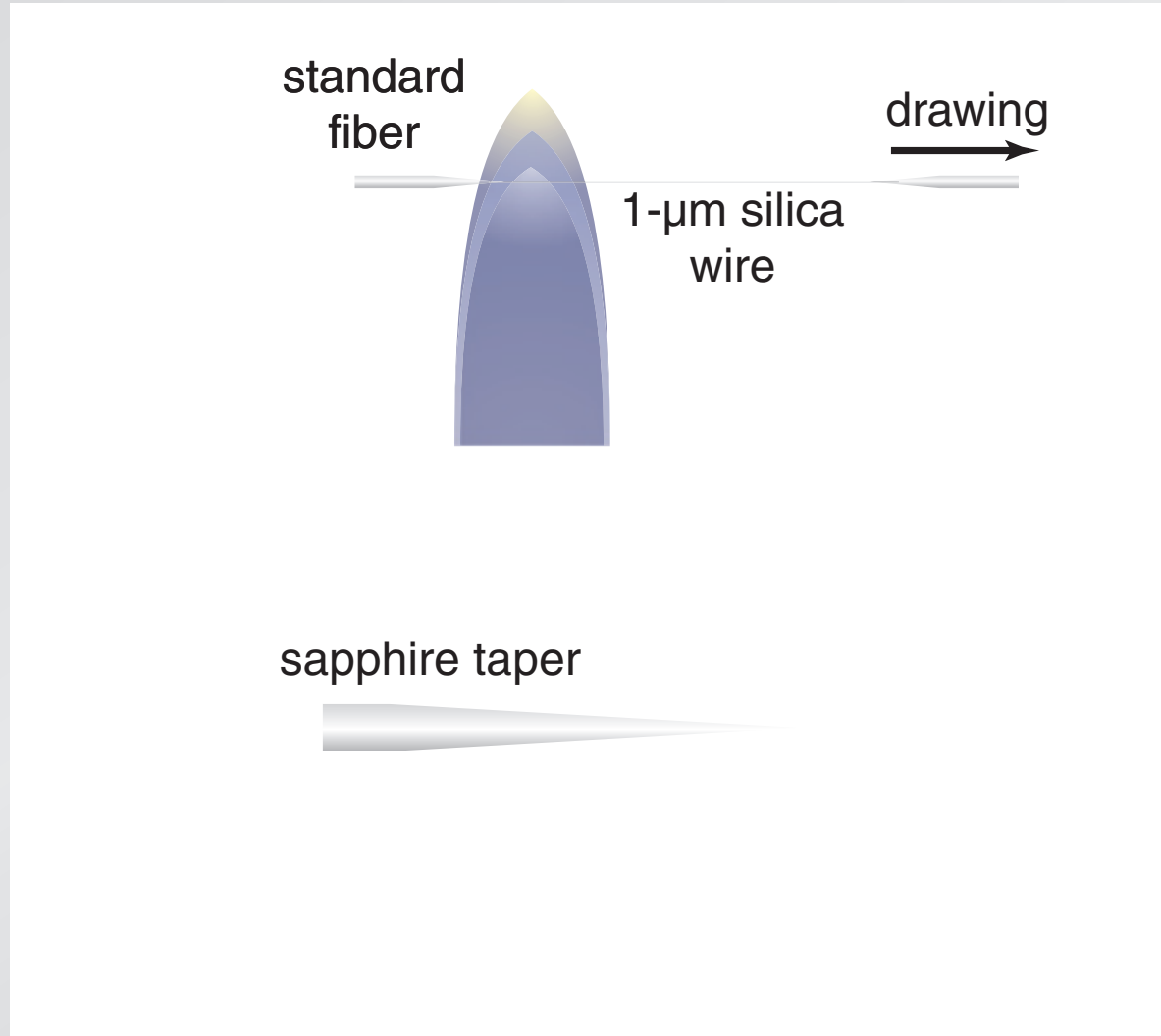
Nanowire fabrication

two-step drawing process



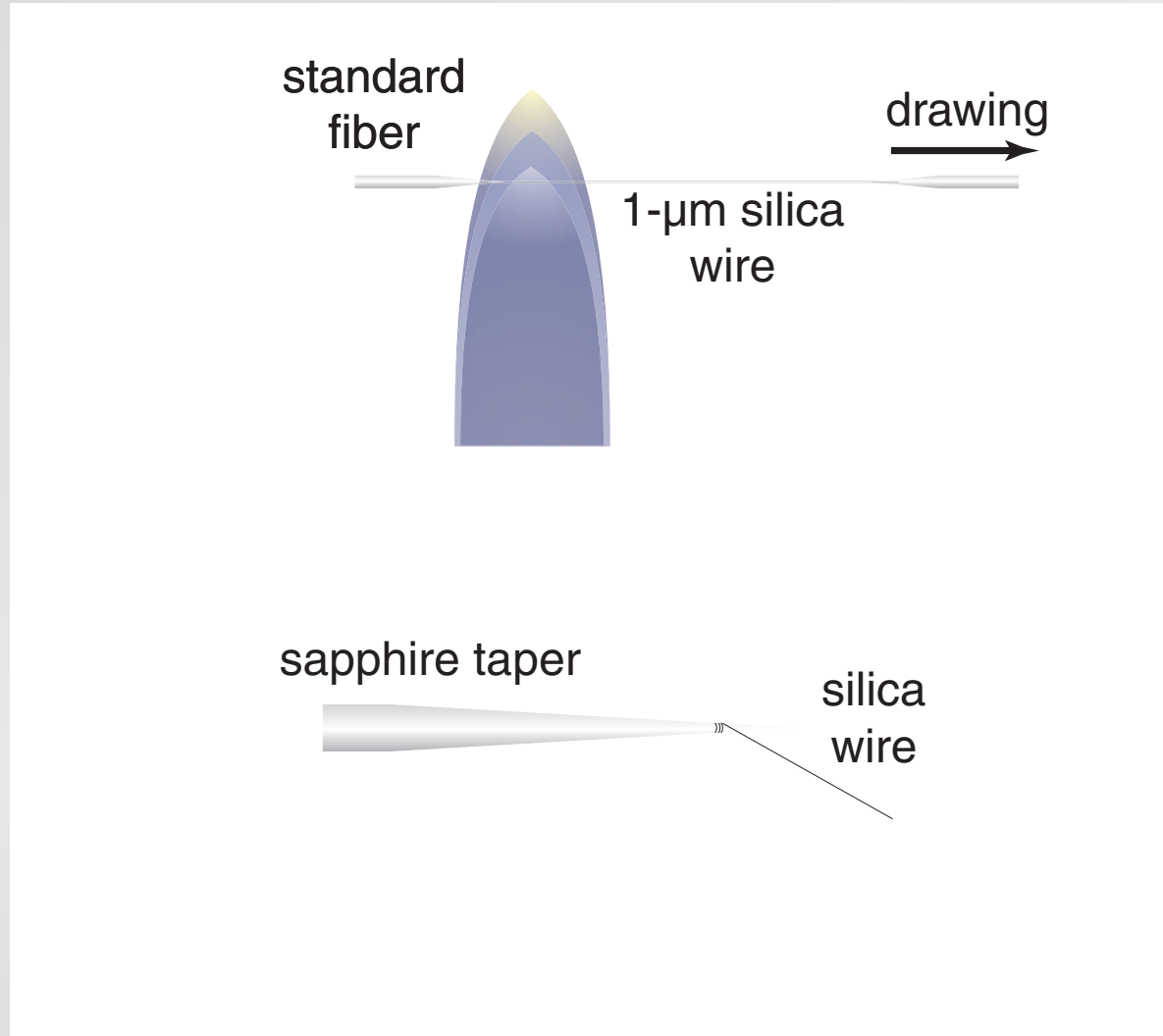
Nanowire fabrication

two-step drawing process



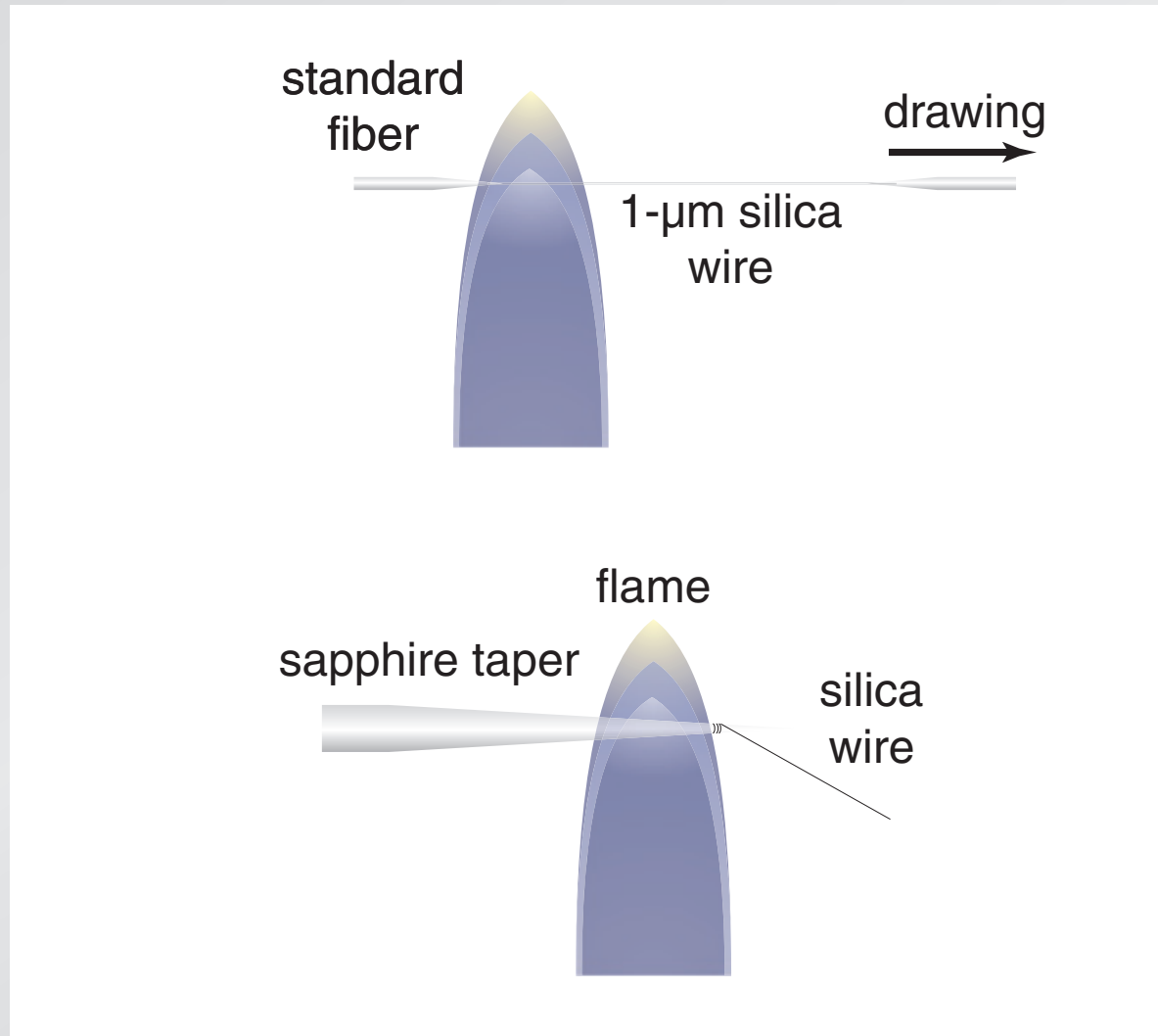
Nanowire fabrication

two-step drawing process



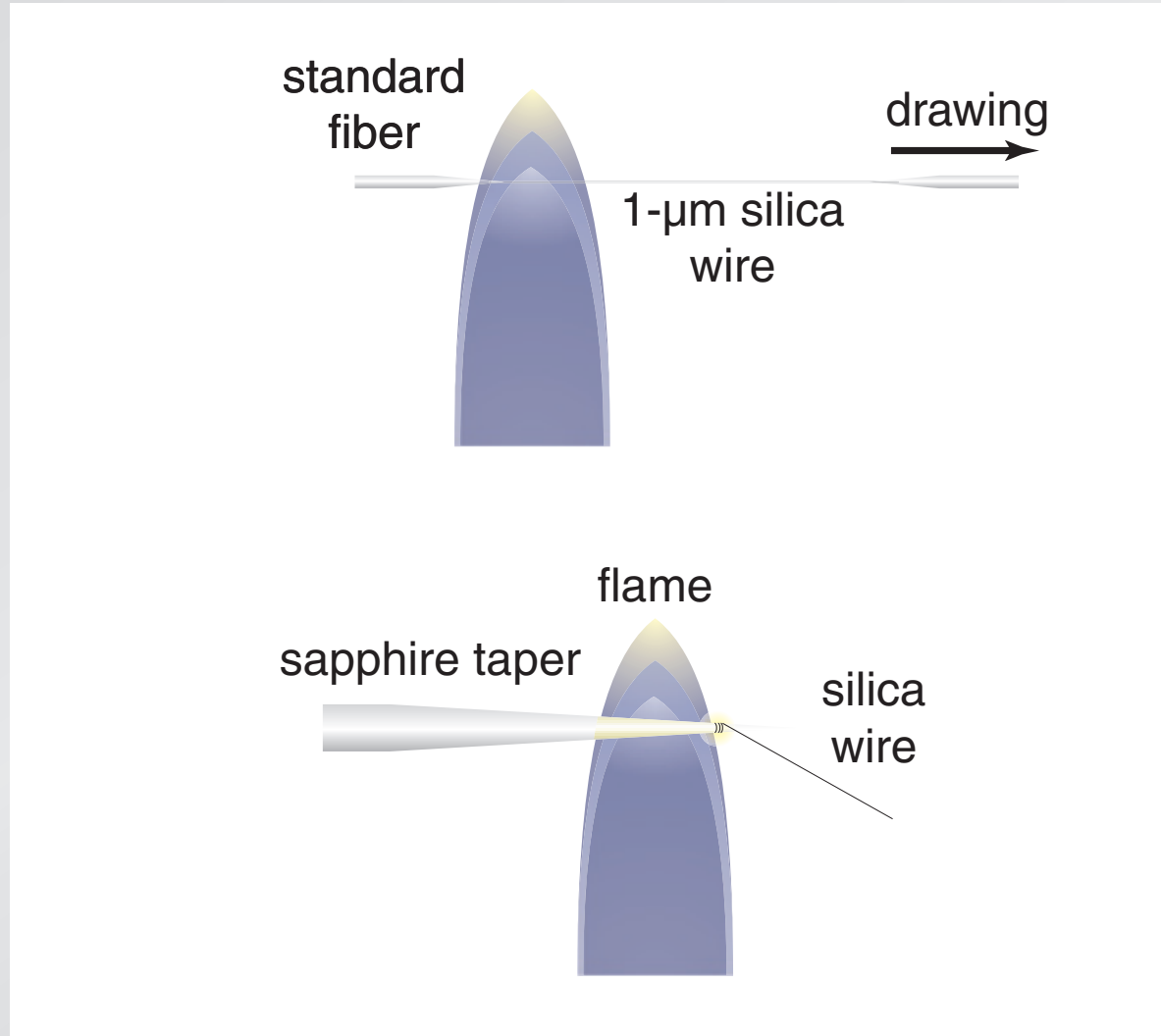
Nanowire fabrication

two-step drawing process



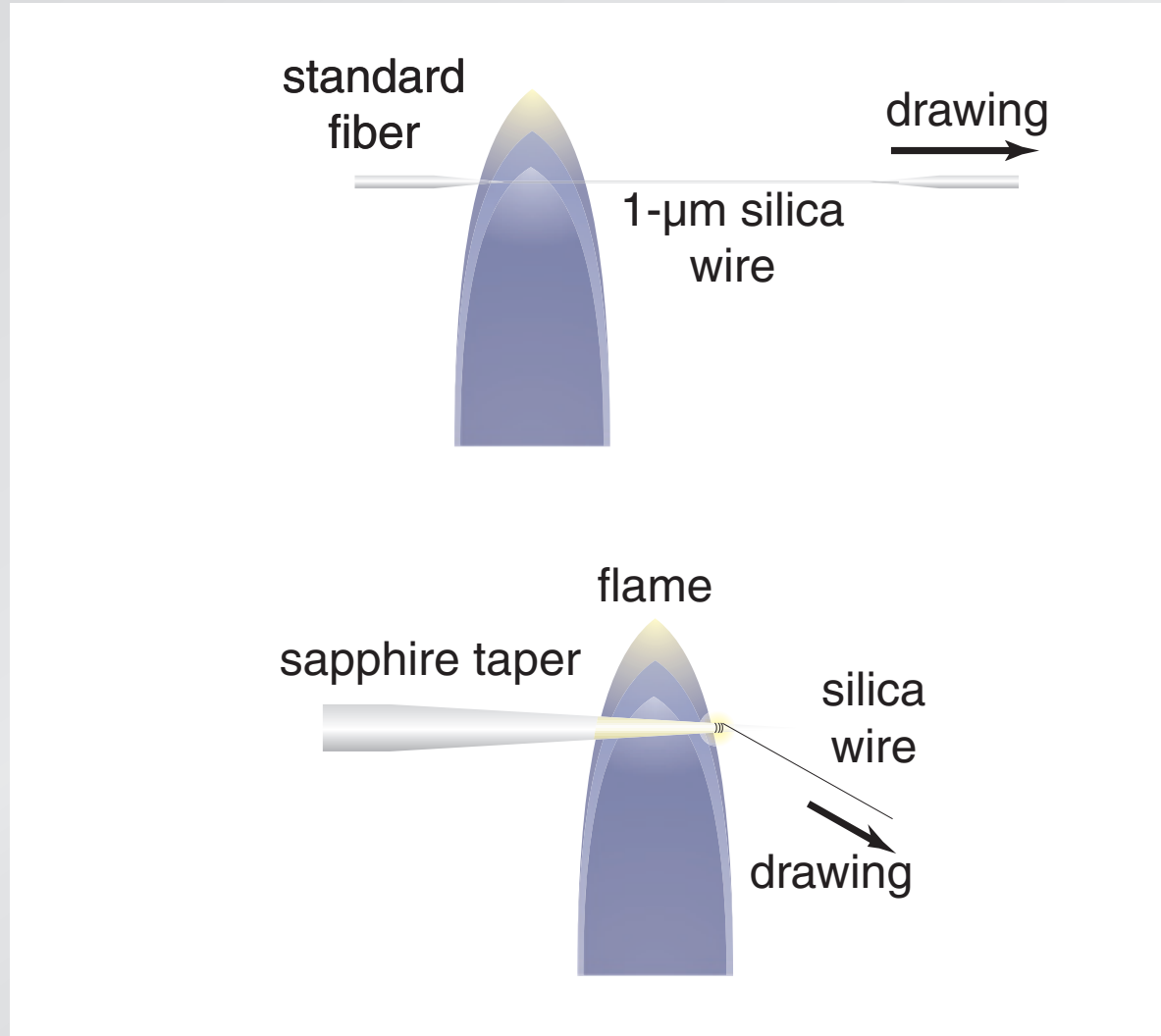
Nanowire fabrication

two-step drawing process

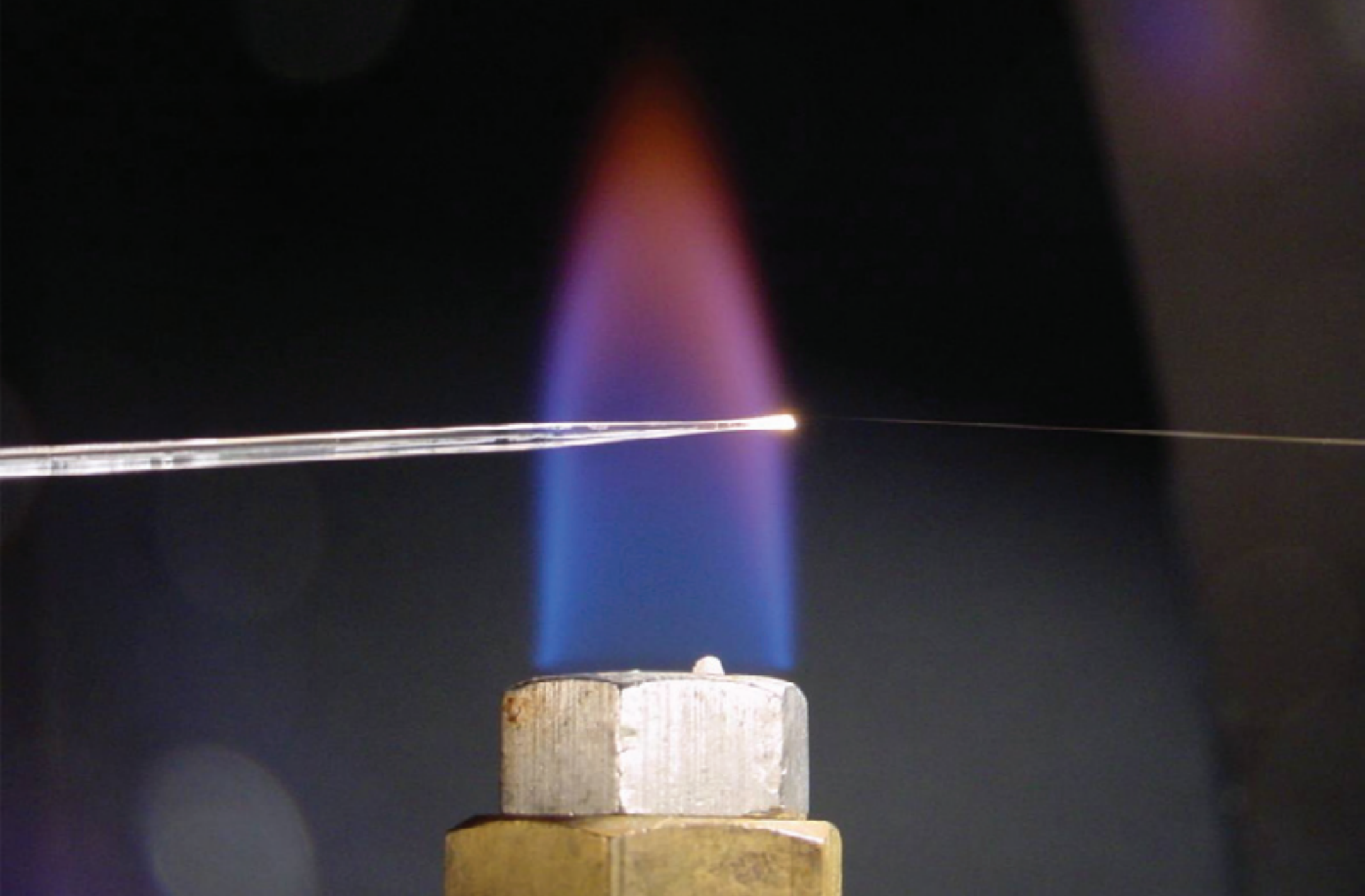


Nanowire fabrication

two-step drawing process



Nanowire fabrication



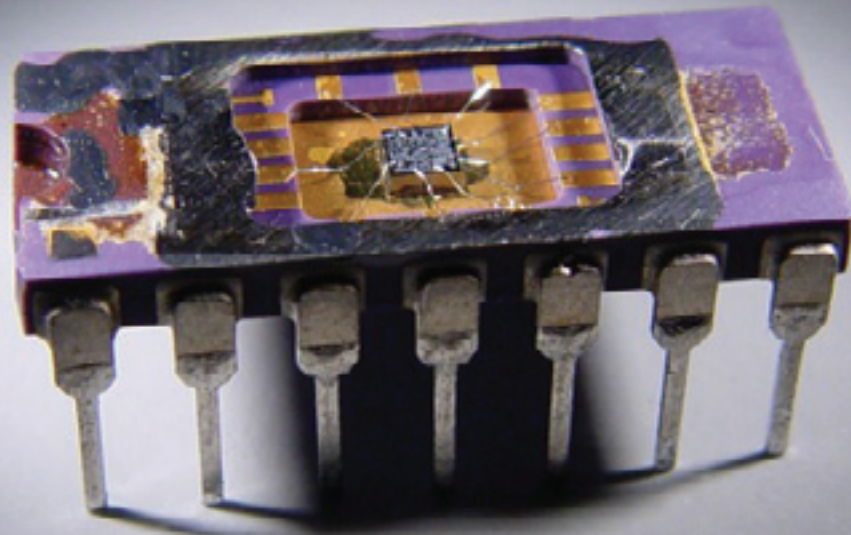
Nanowire fabrication

1 μm

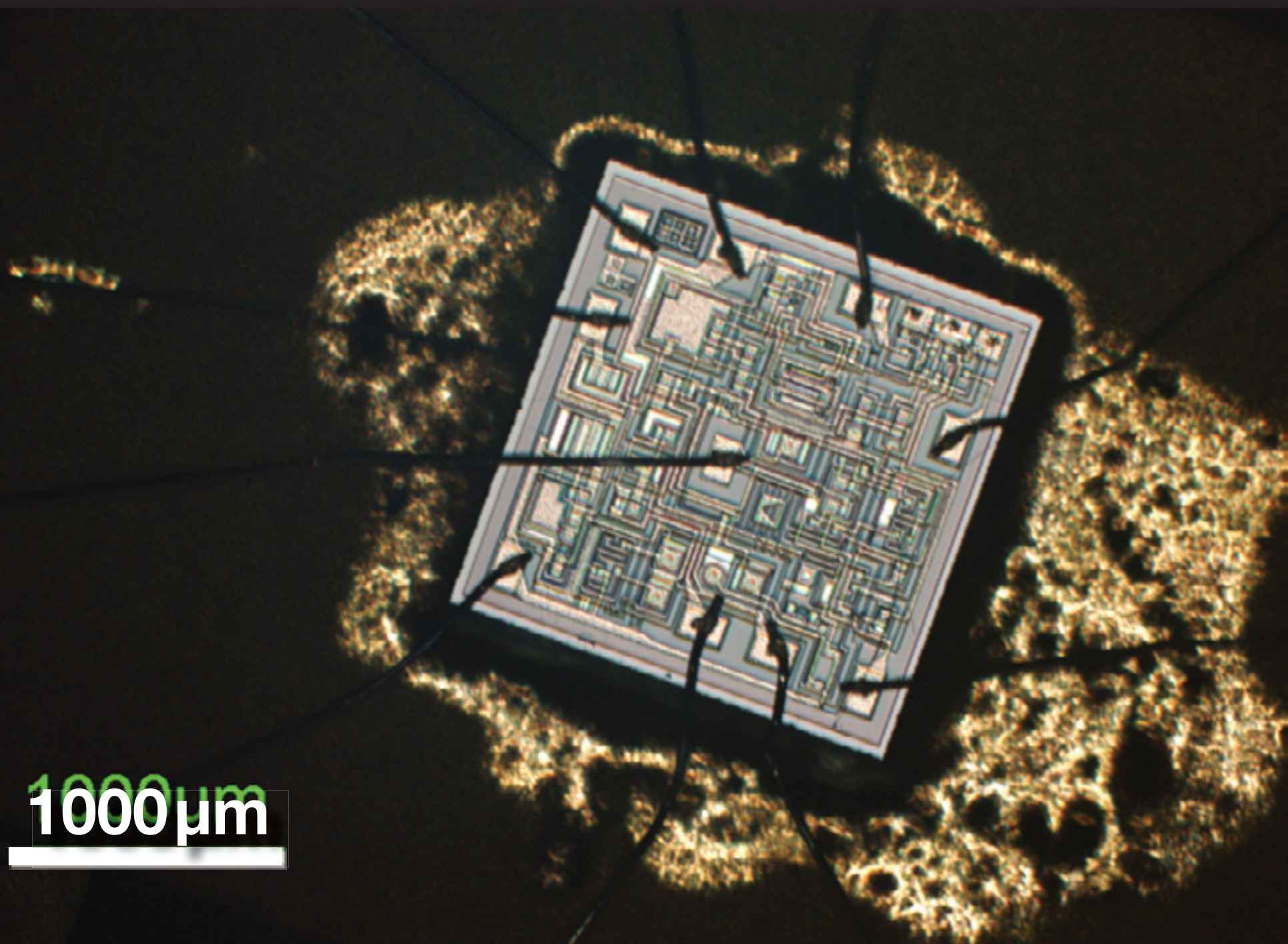


Nature, 426, 816 (2003)

Nanowire fabrication



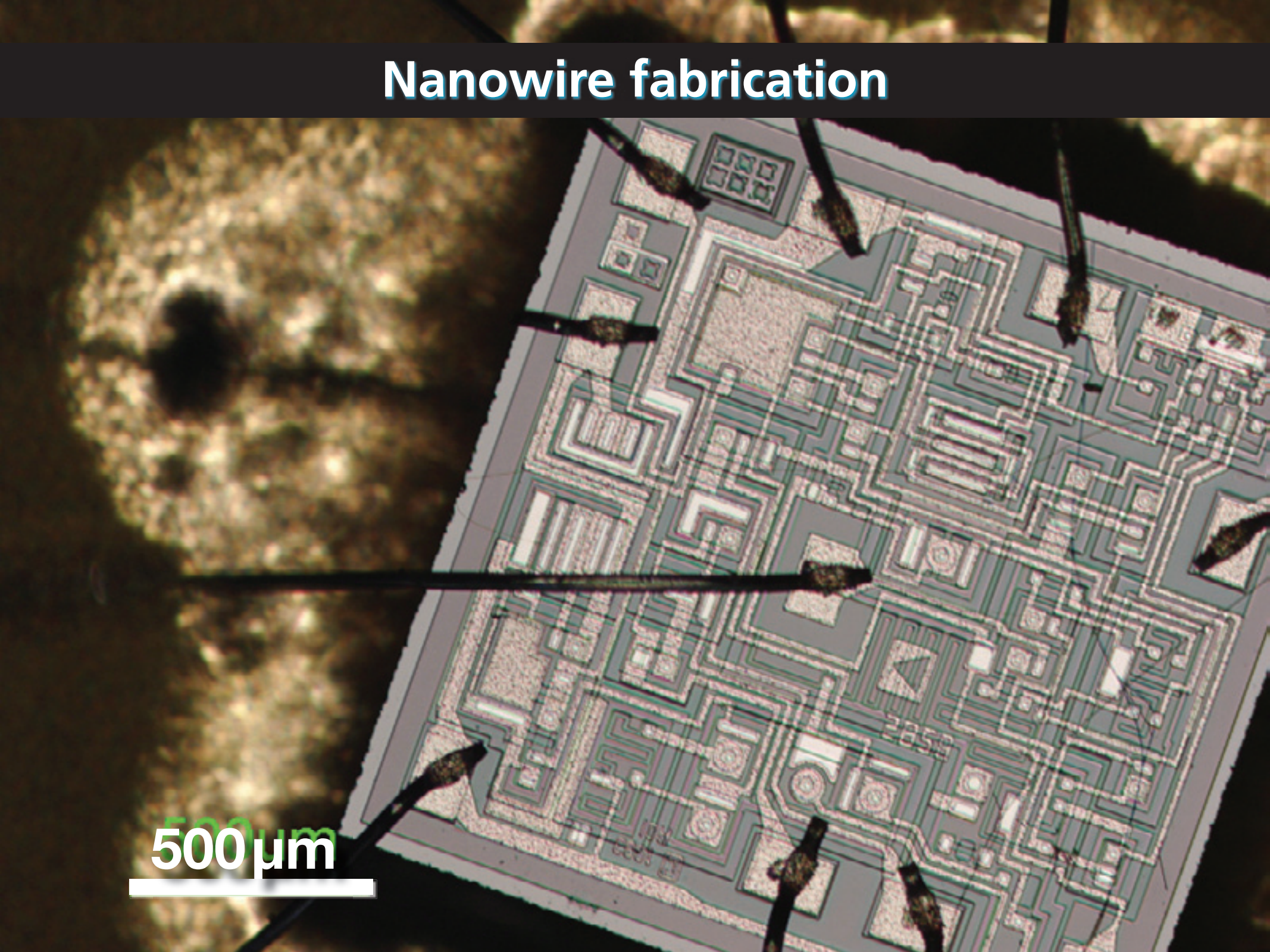
Nanowire fabrication



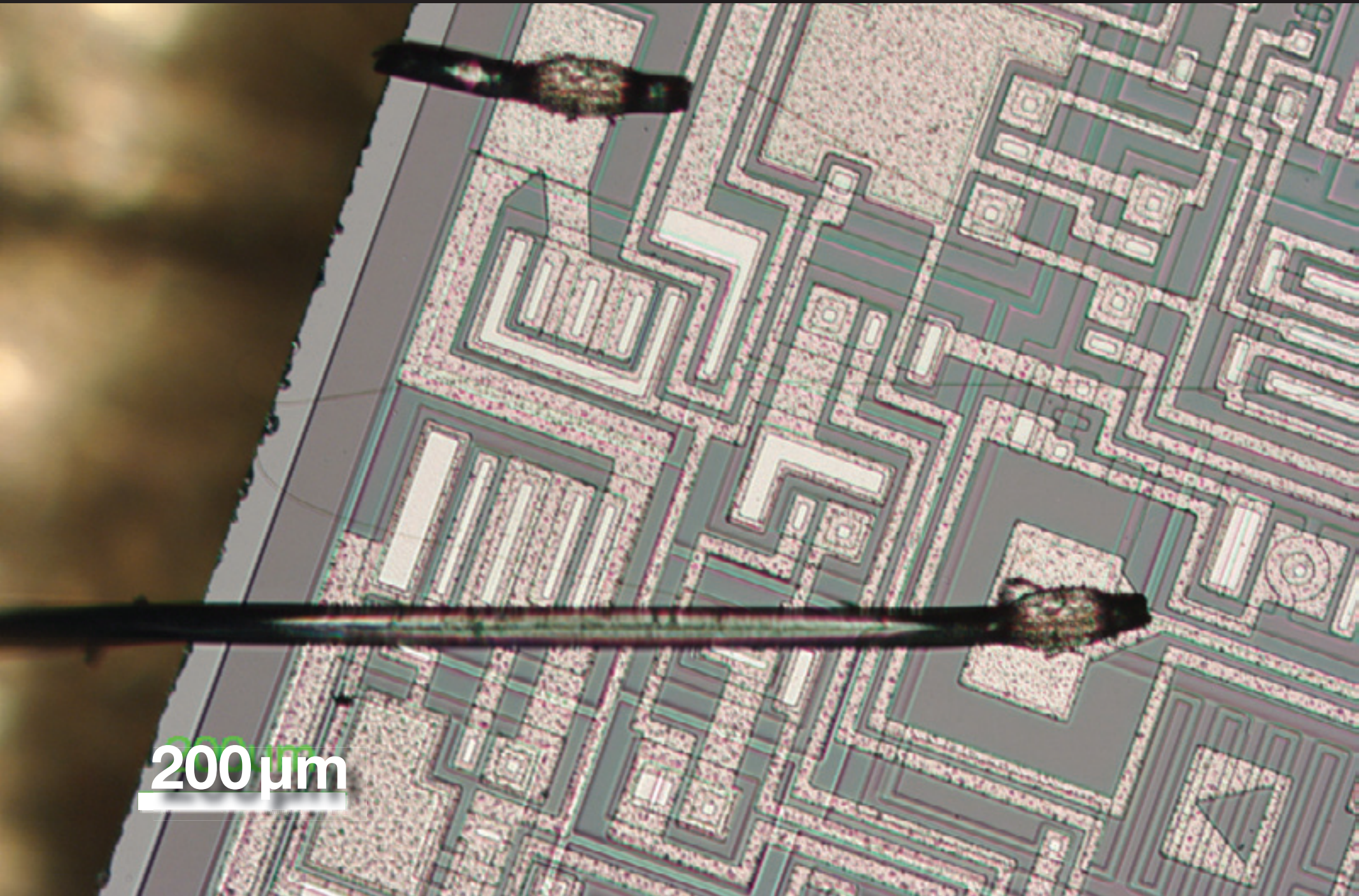
1000 μm

Nanowire fabrication

500 μm

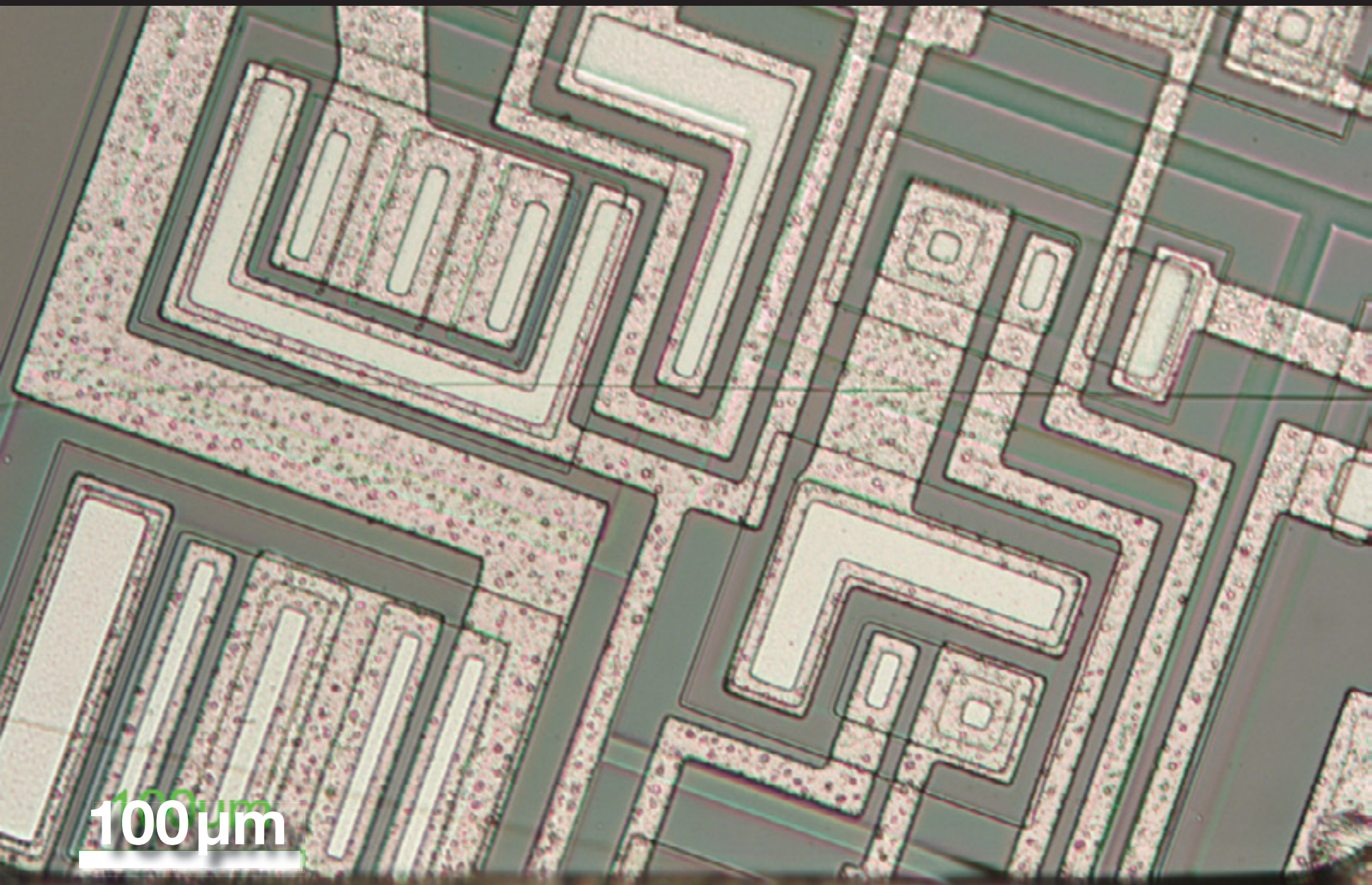


Nanowire fabrication

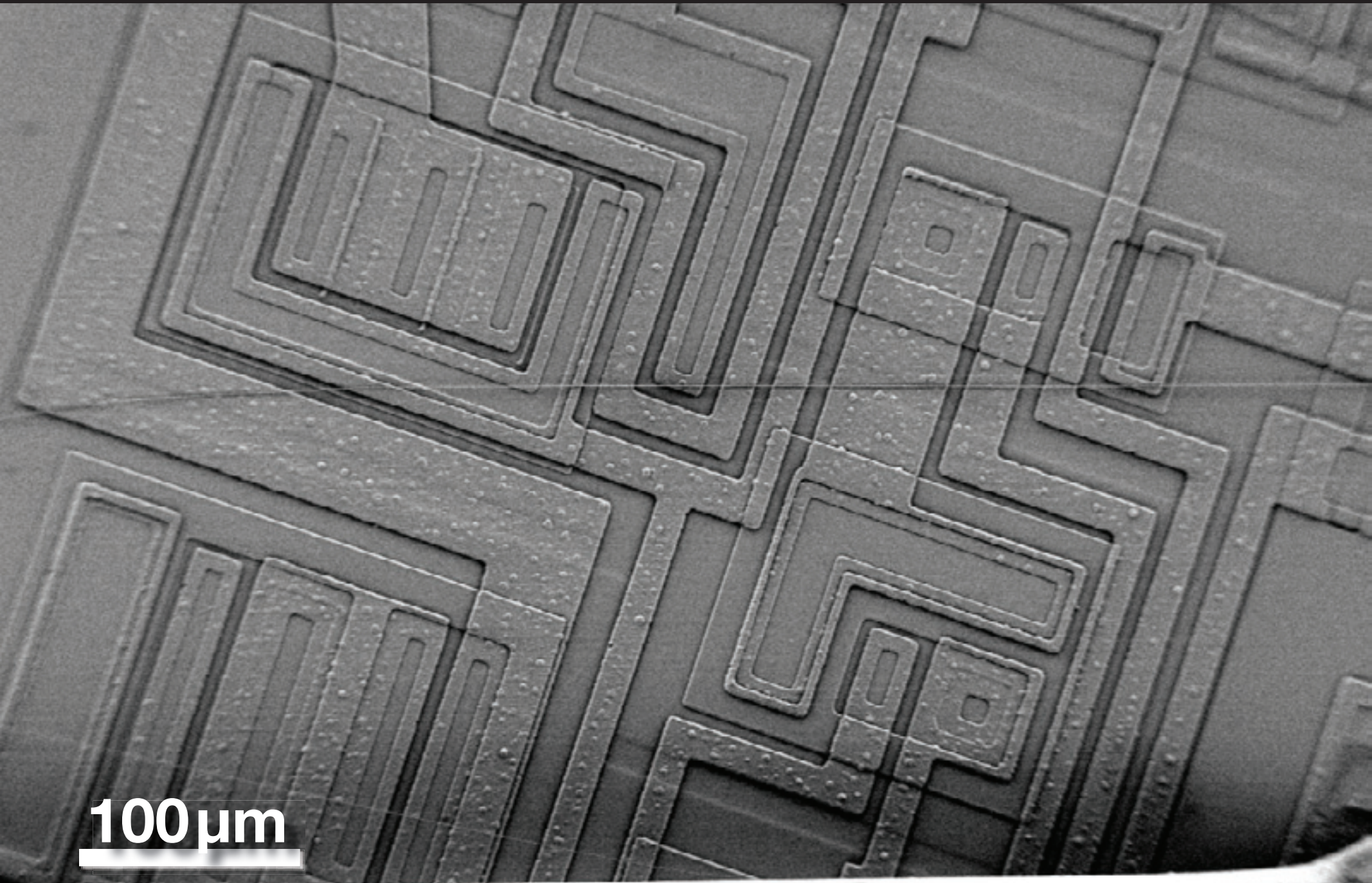


200 μm

Nanowire fabrication

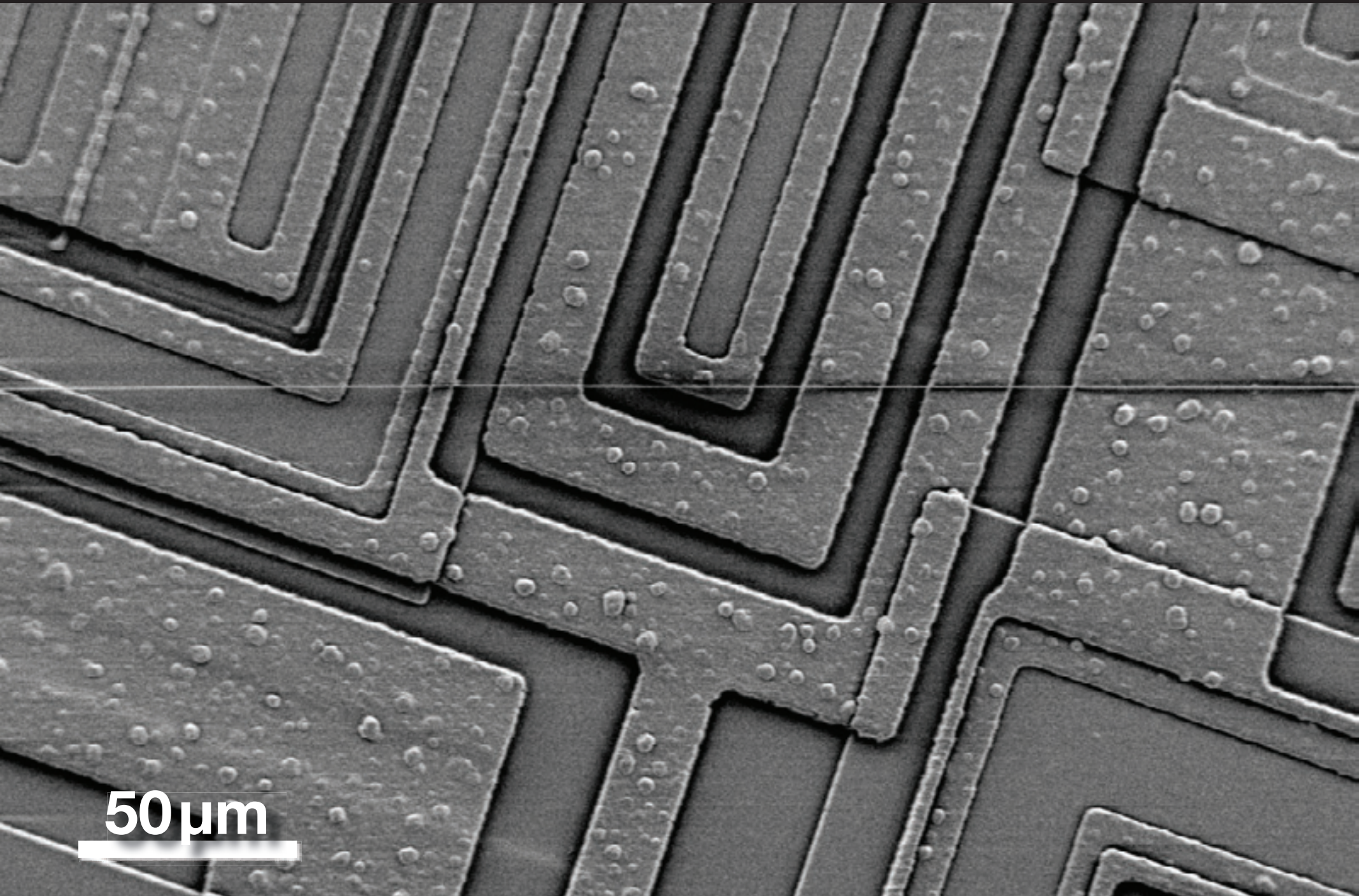


Nanowire fabrication



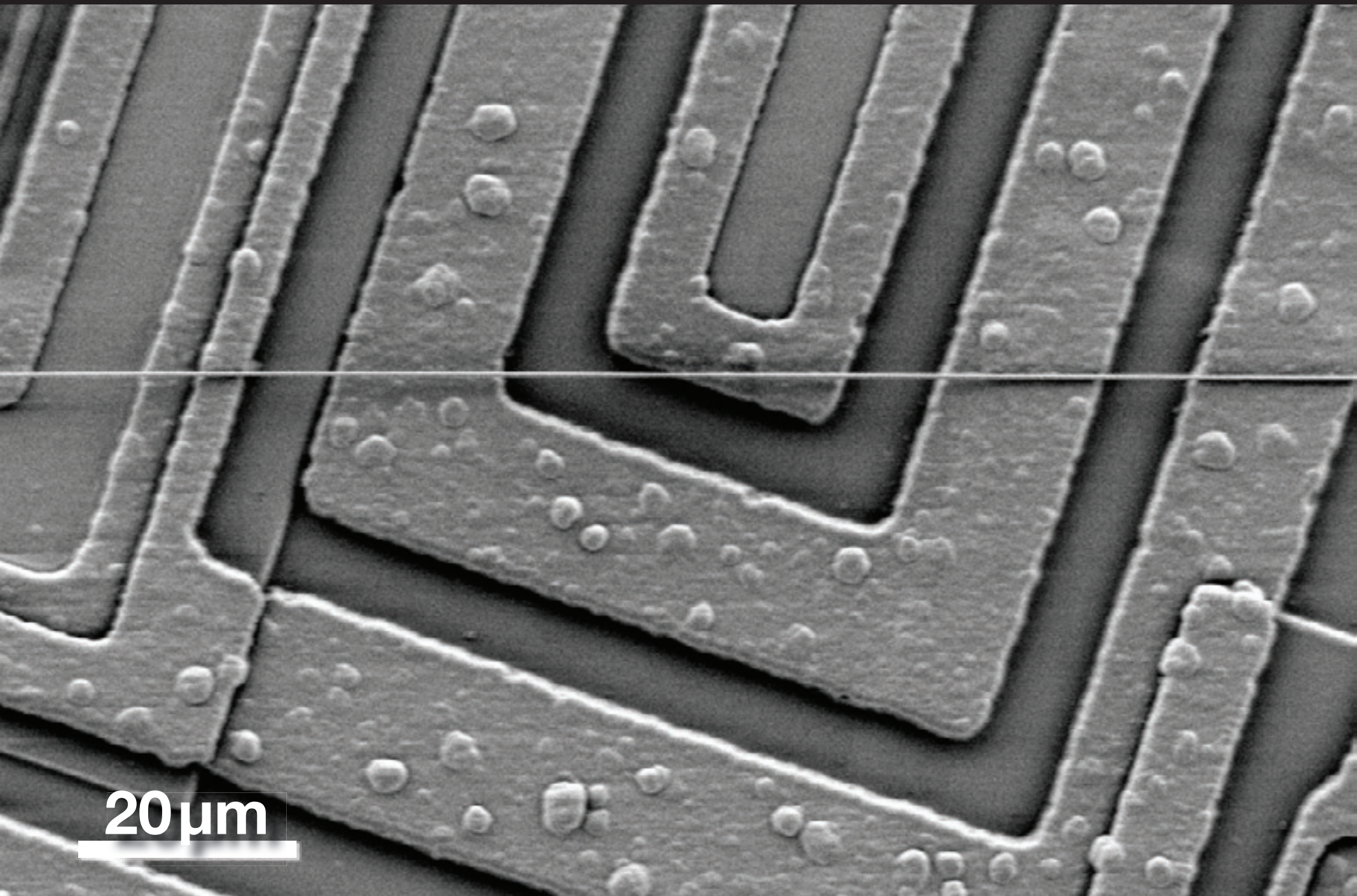
100 μm

Nanowire fabrication



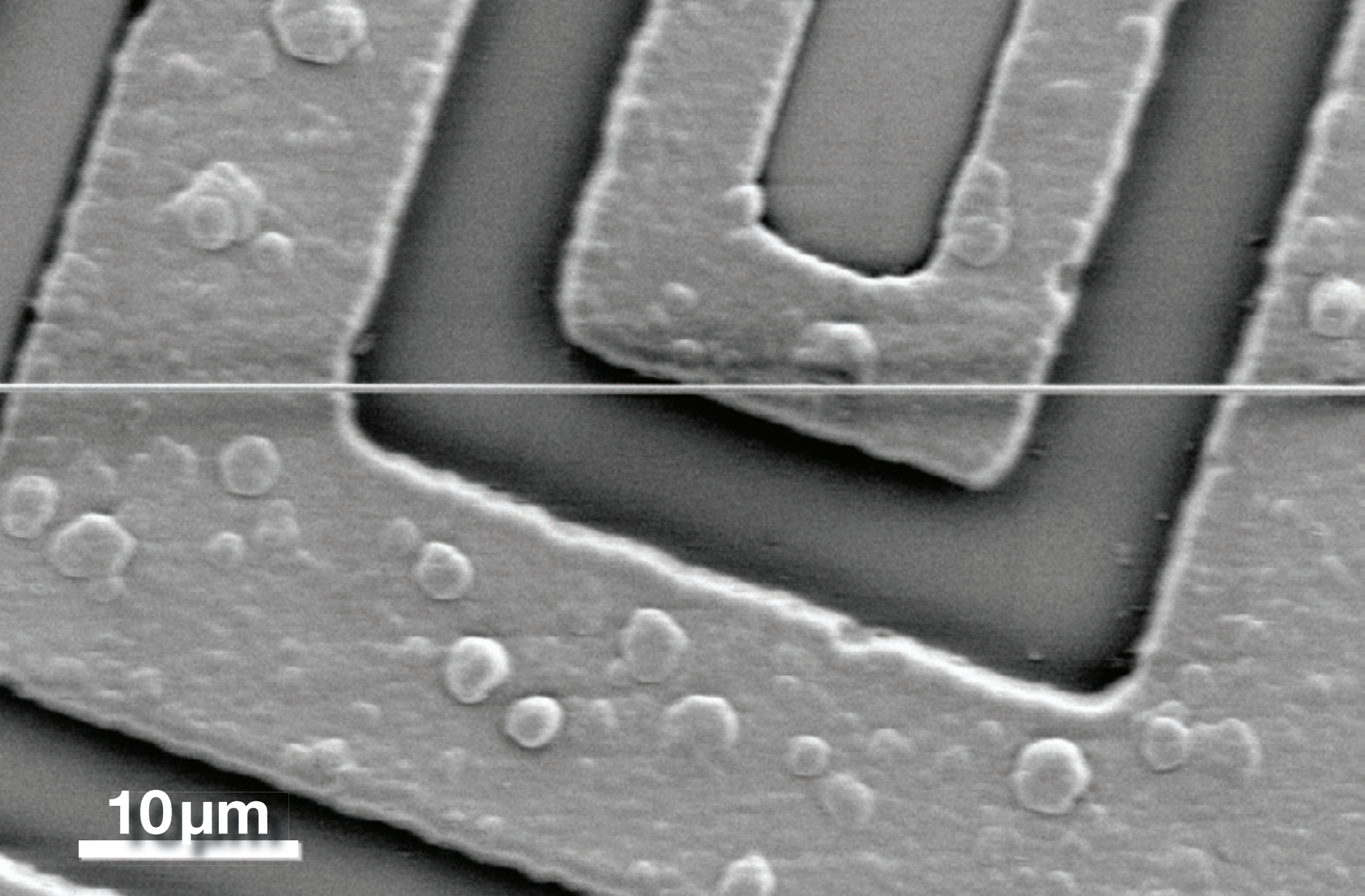
50 μm

Nanowire fabrication



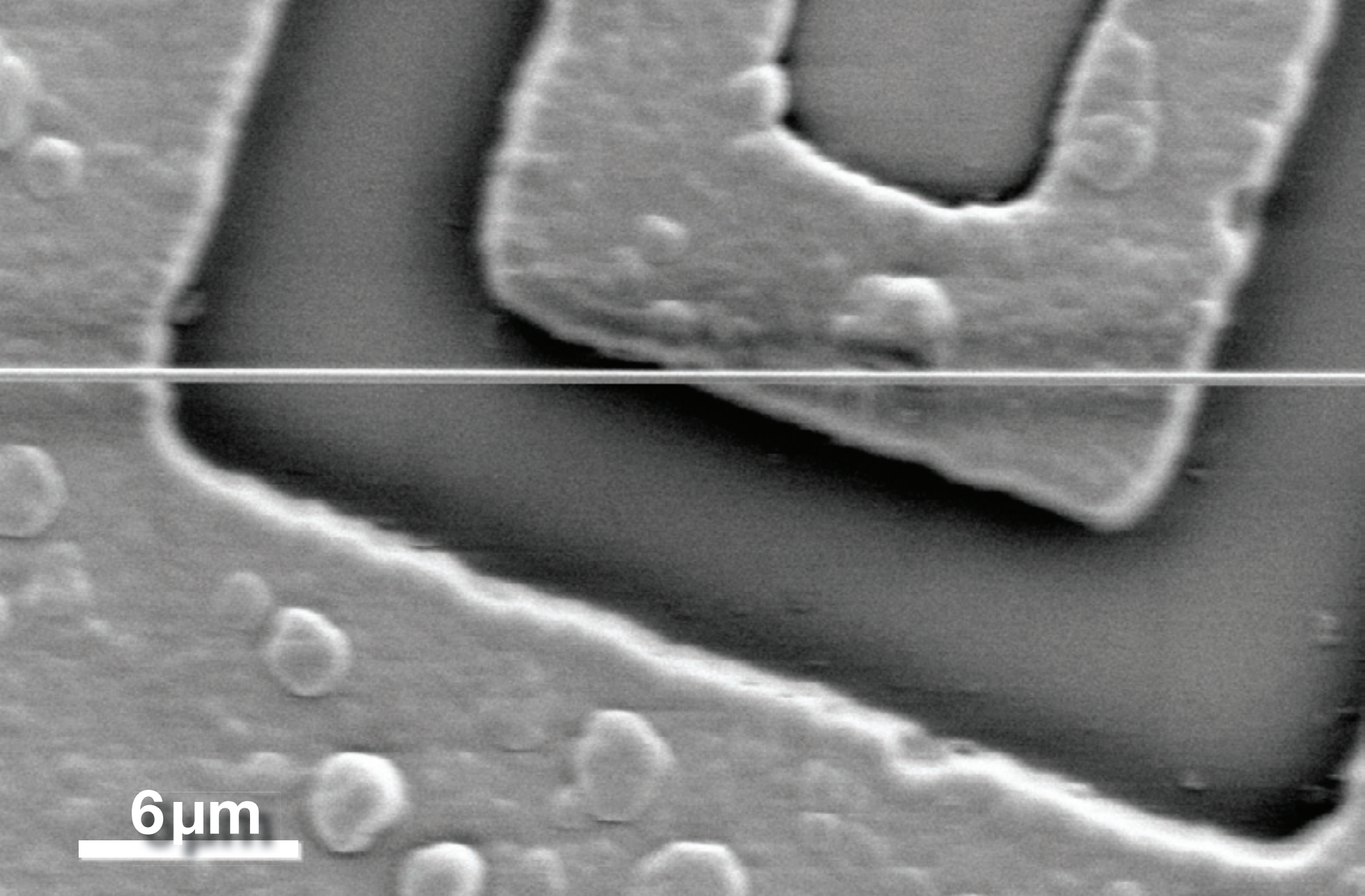
20 μm

Nanowire fabrication



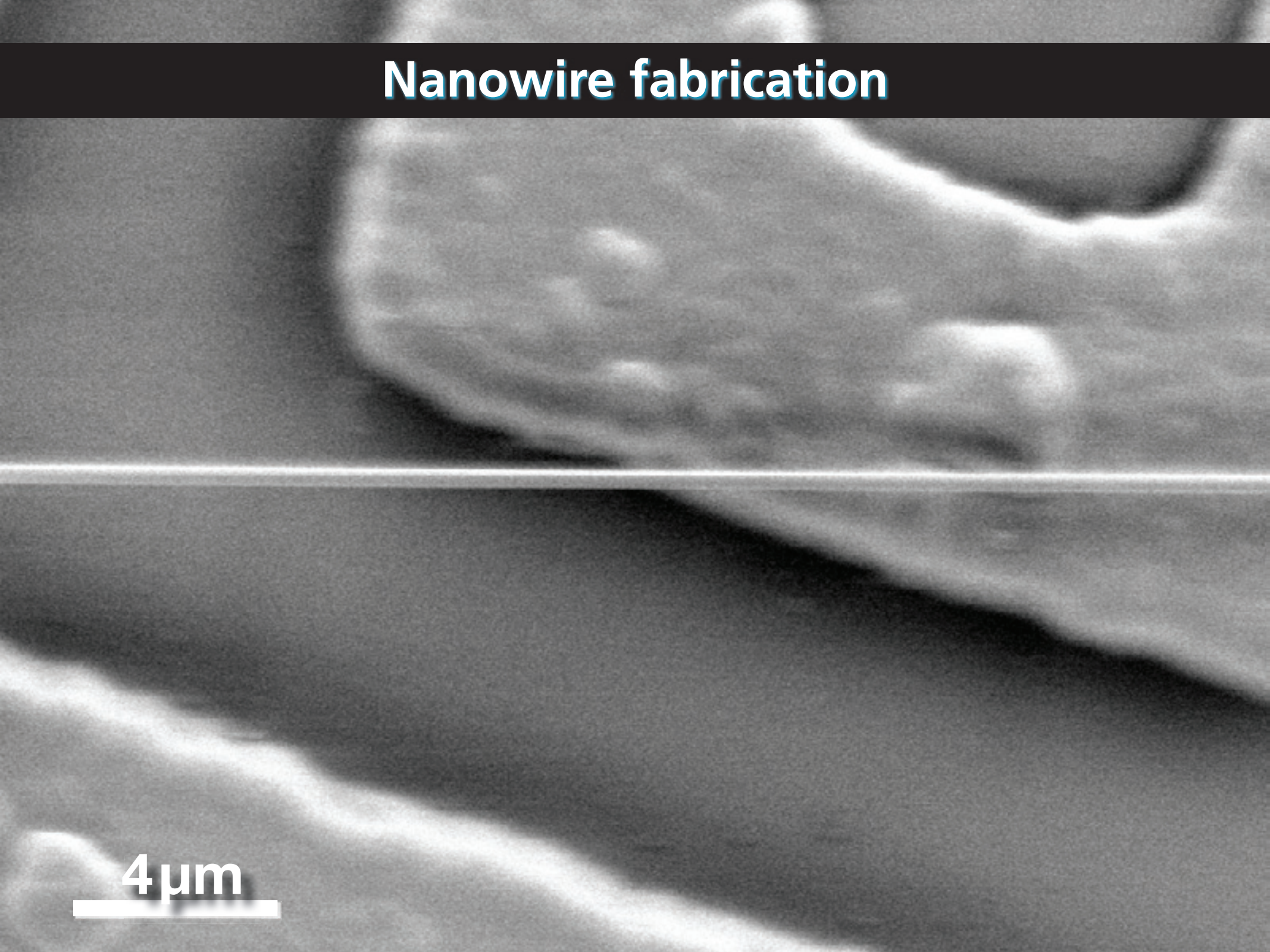
10 μm

Nanowire fabrication



6 μm

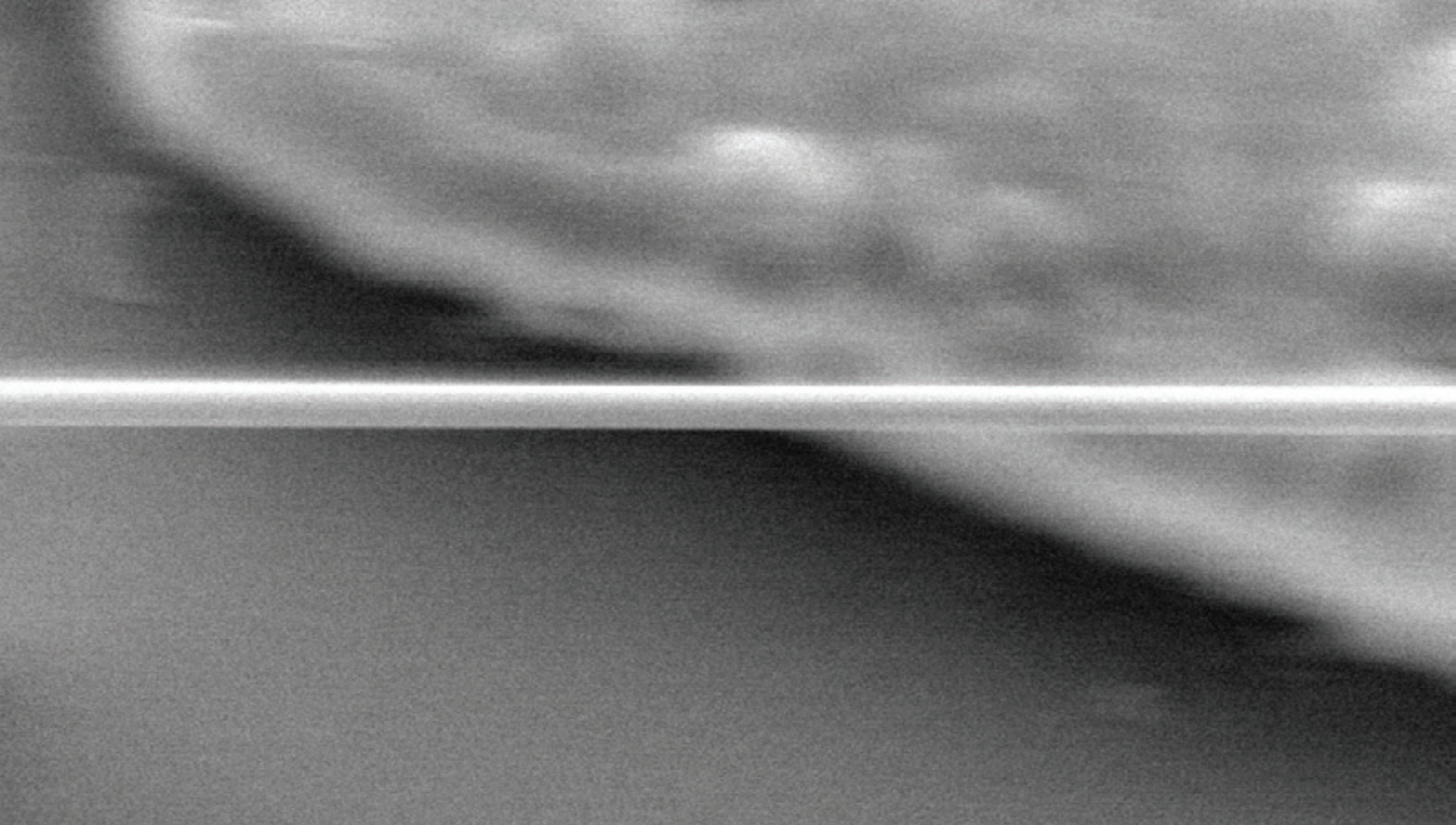
Nanowire fabrication



4 μm



Nanowire fabrication



2 μm



Nanowire fabrication

312 nm

A transmission electron micrograph (TEM) showing a single, long, cylindrical nanowire. The nanowire is oriented horizontally and appears as a bright, uniform line against a dark background. A vertical white line with a crossbar at the bottom indicates the diameter of the nanowire, which is labeled as 312 nm. The background shows some faint, diffuse patterns, likely from the surrounding material or the imaging process.

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

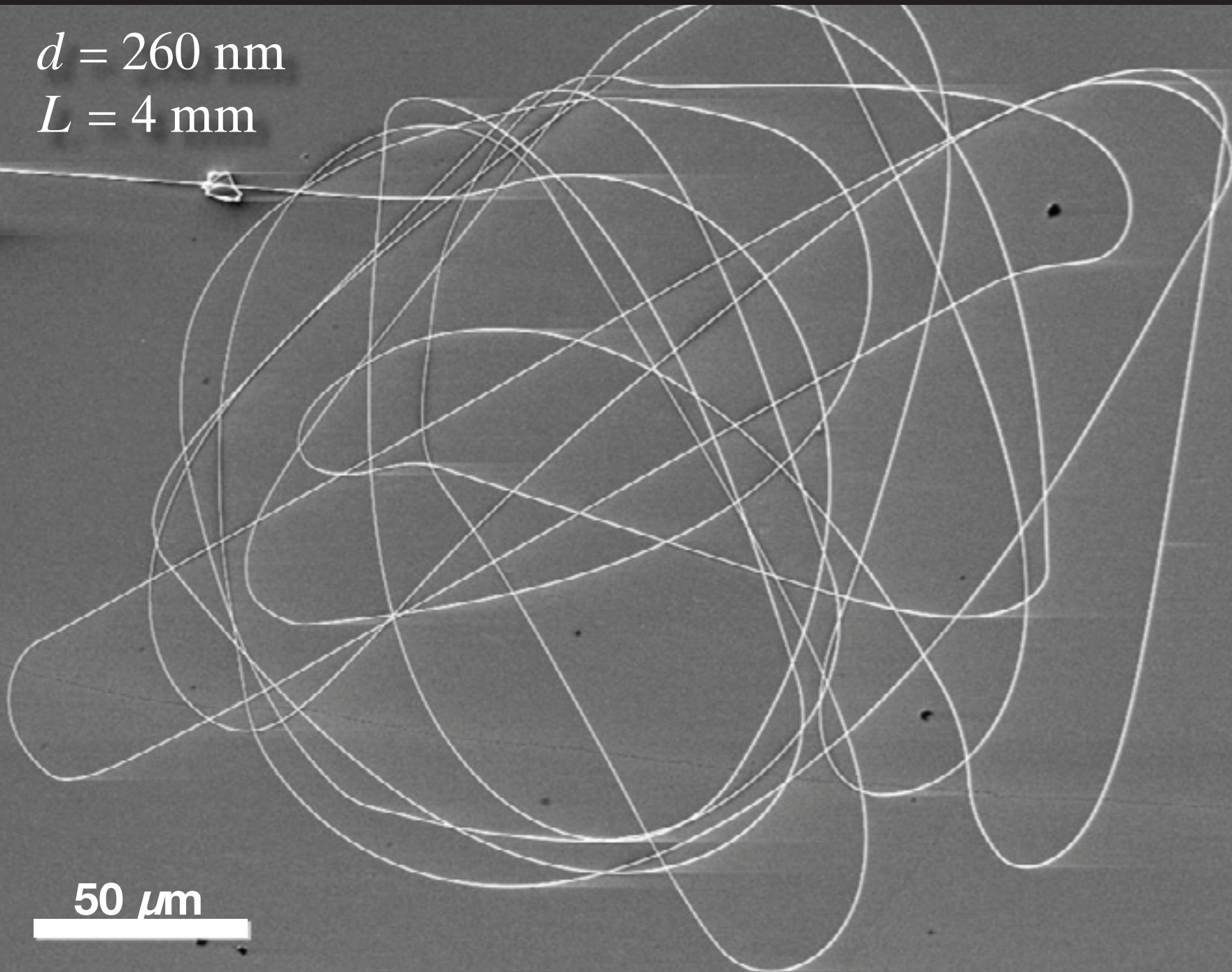
aspect ratio D/L : up to 10^6

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

A transmission electron micrograph (TEM) showing a single, dark, cylindrical nanowire oriented diagonally across the frame. The wire has a uniform diameter and is set against a light gray, textured background. A scale bar in the bottom right corner indicates a length of 200 nm.

Nanowire fabrication

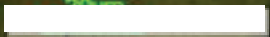
RMS roughness < 0.5 nm

20 nm



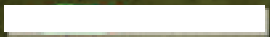
Nanowire fabrication

bend to
breaking point



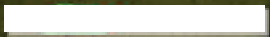
Nanowire fabrication

bend to
breaking point

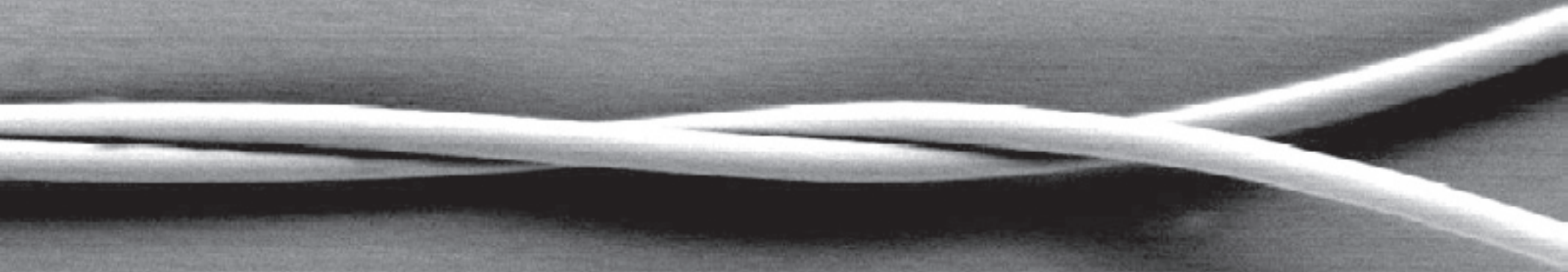


Nanowire fabrication

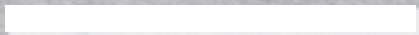
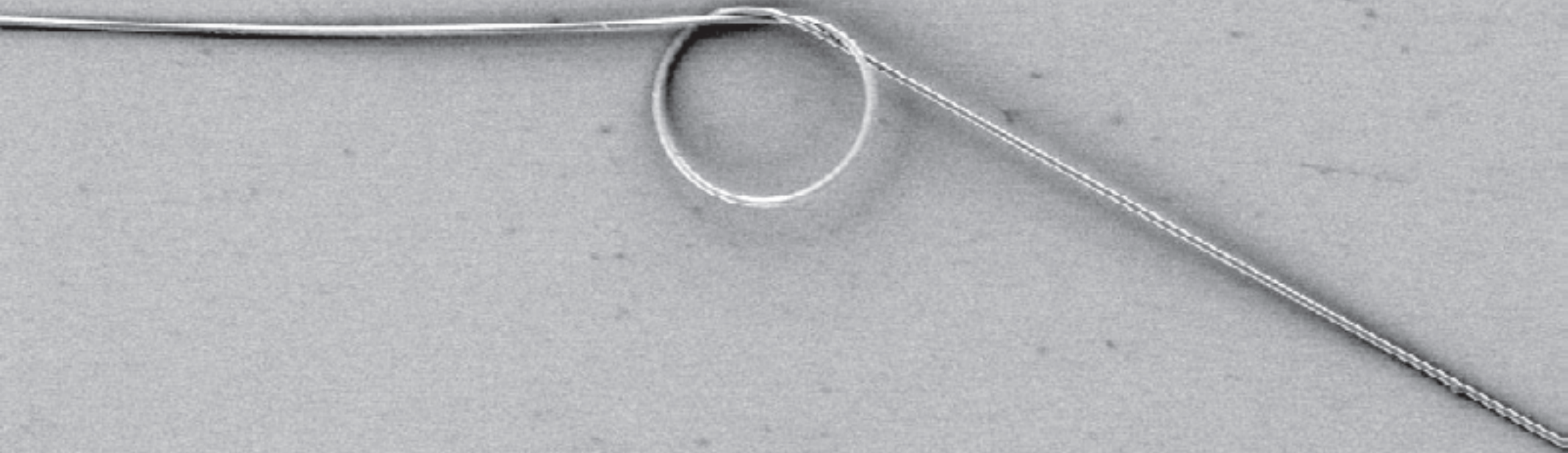
bend to
breaking point



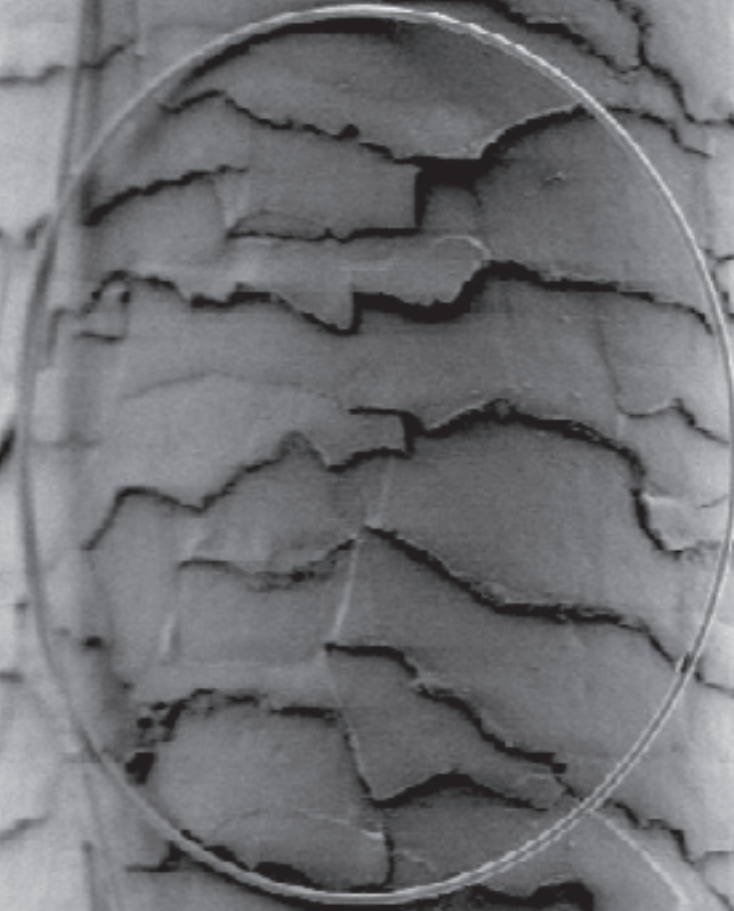
Nanowire fabrication



Nanowire fabrication



Nanowire fabrication

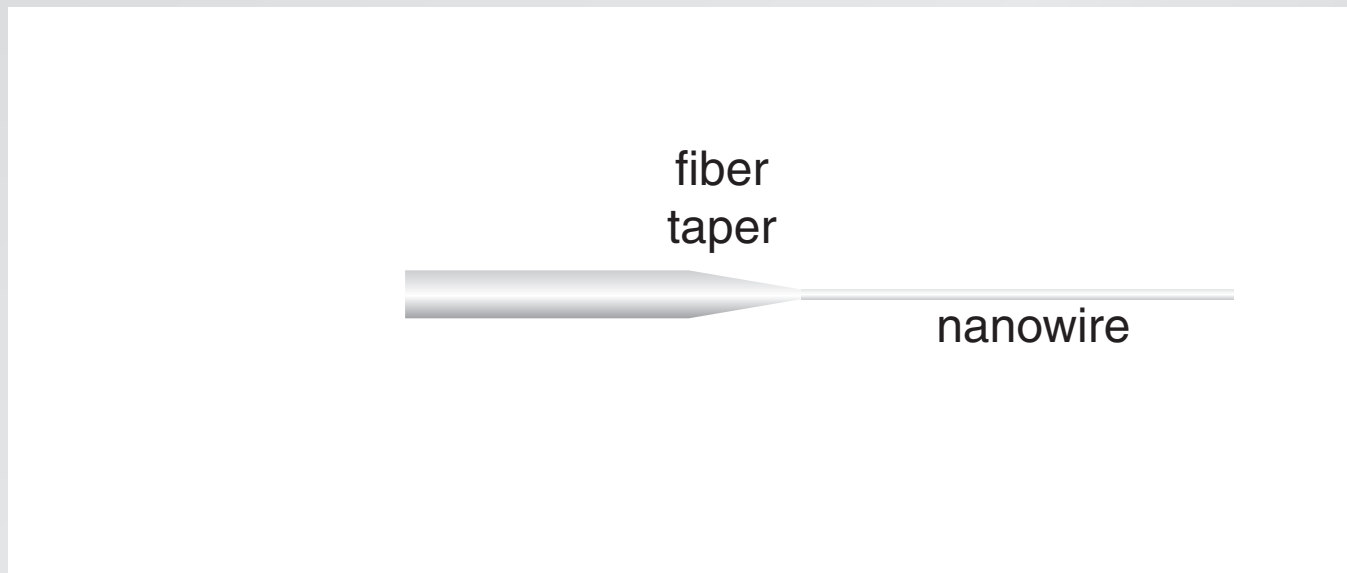


Outline

- waveguiding
- nanowire fabrication
- optical properties

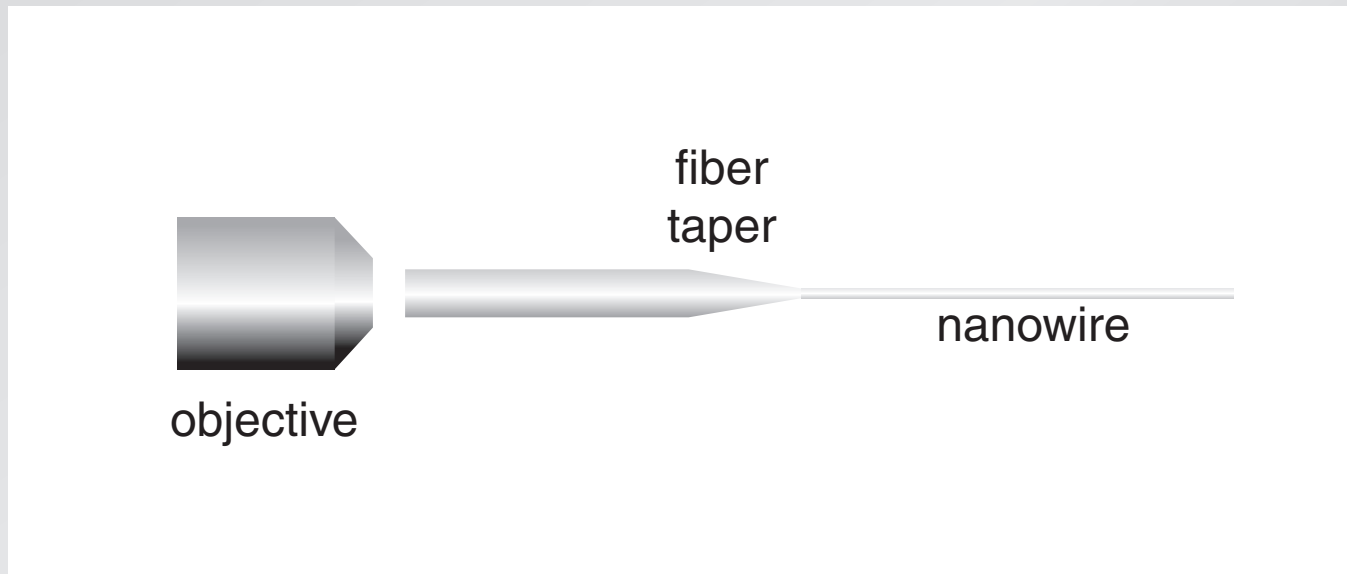
Optical properties

coupling light into nanowires



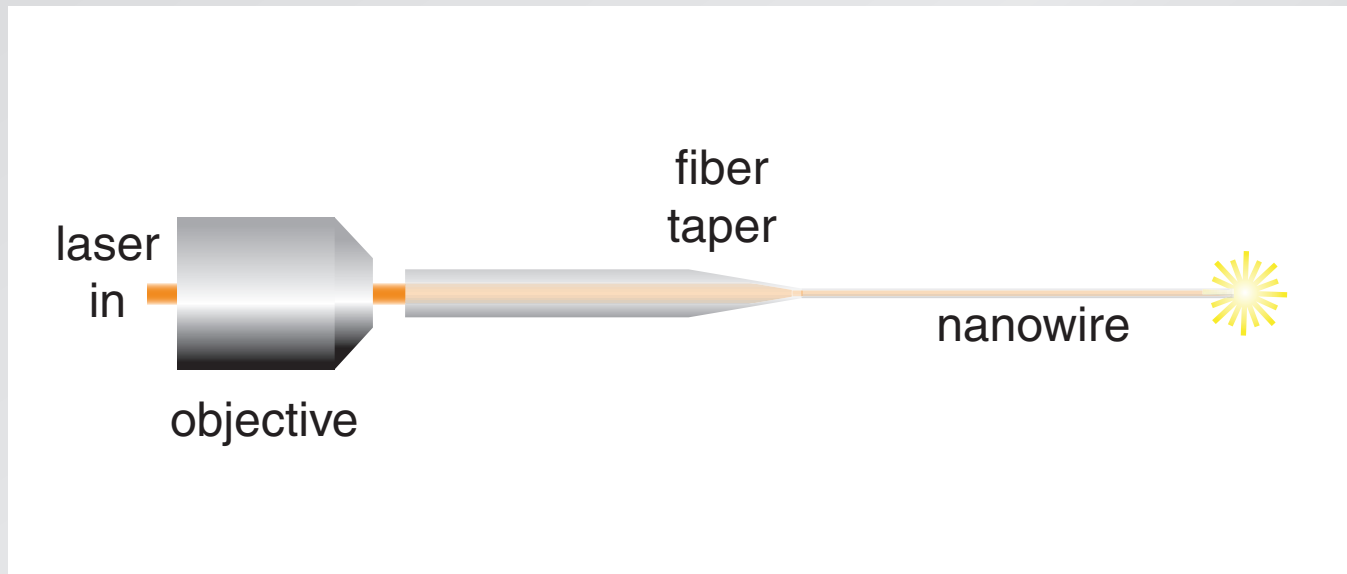
Optical properties

coupling light into nanowires

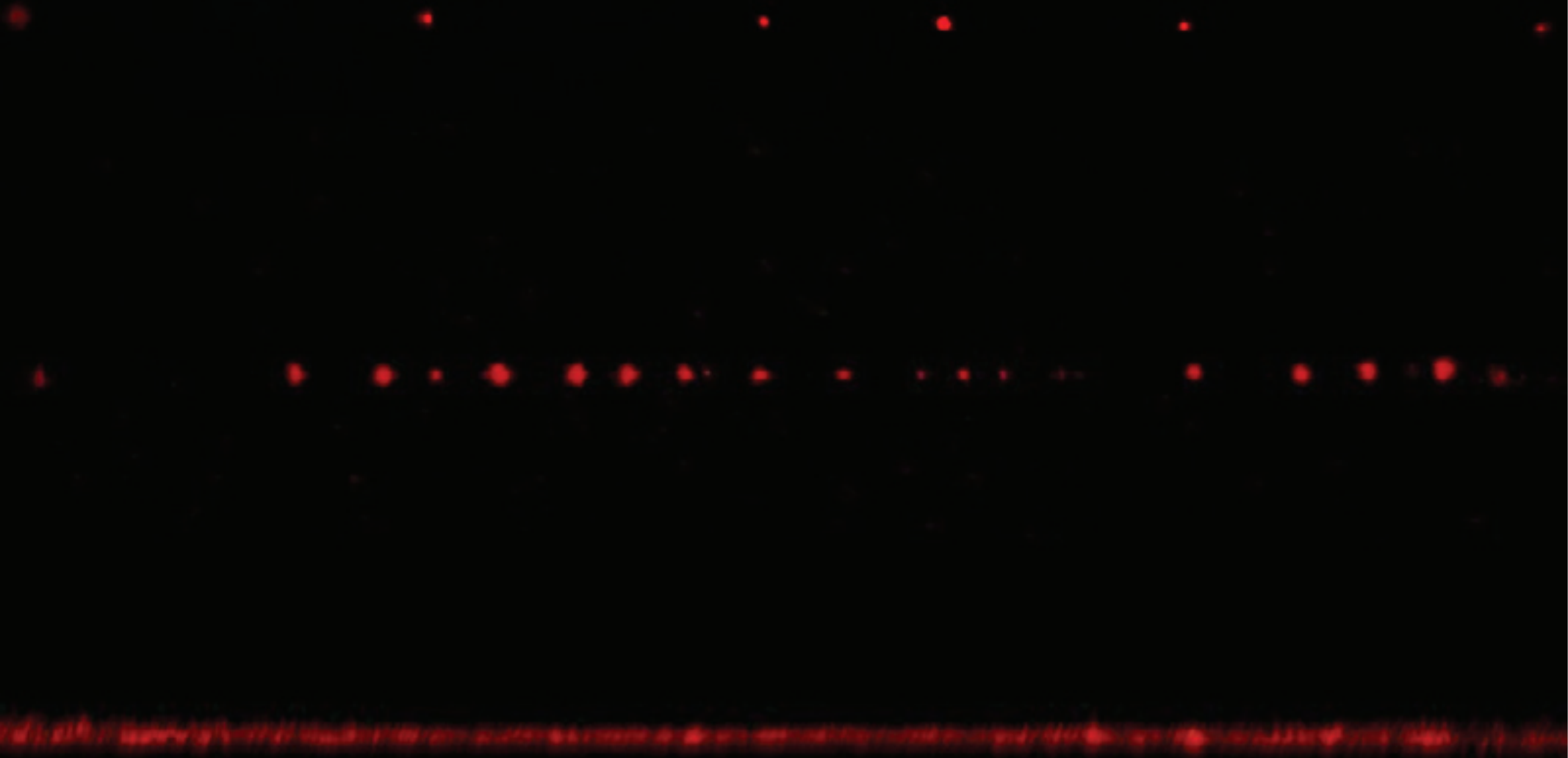


Optical properties

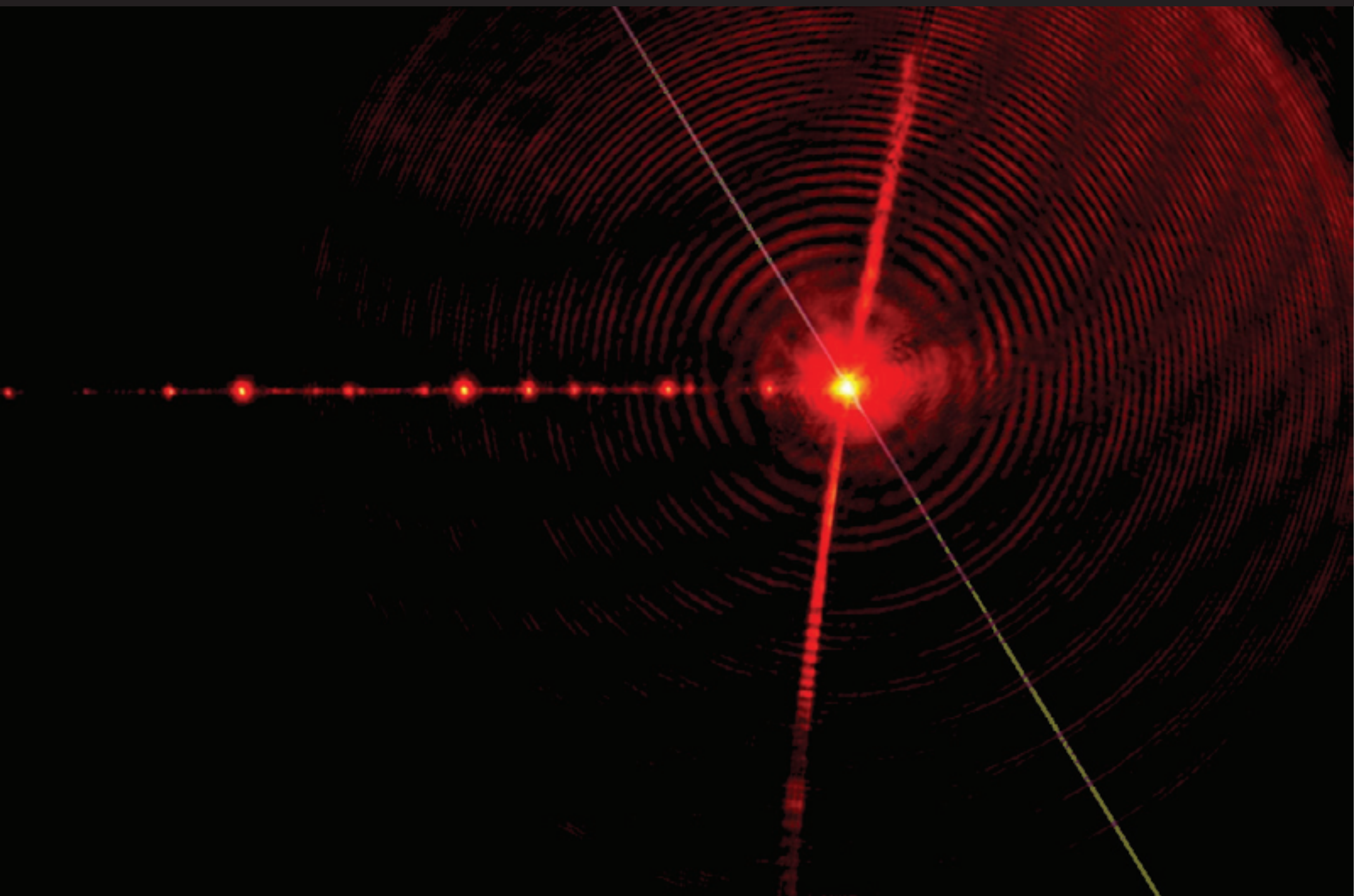
coupling light into nanowires



Optical properties



Optical properties

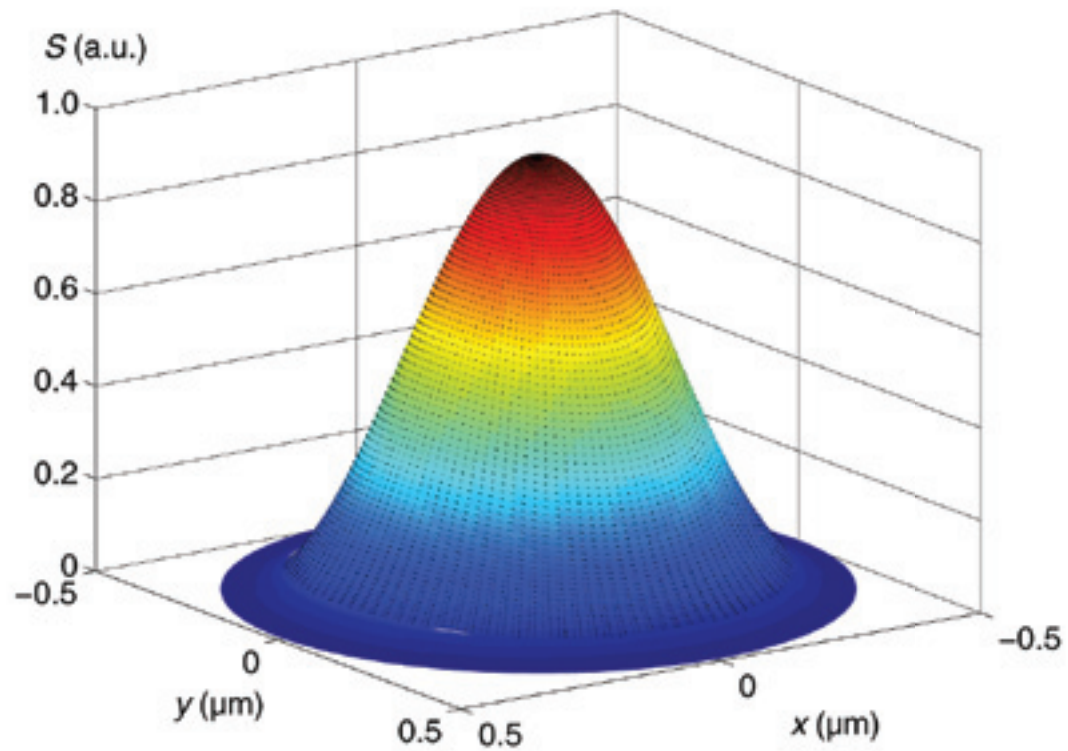


Optical properties



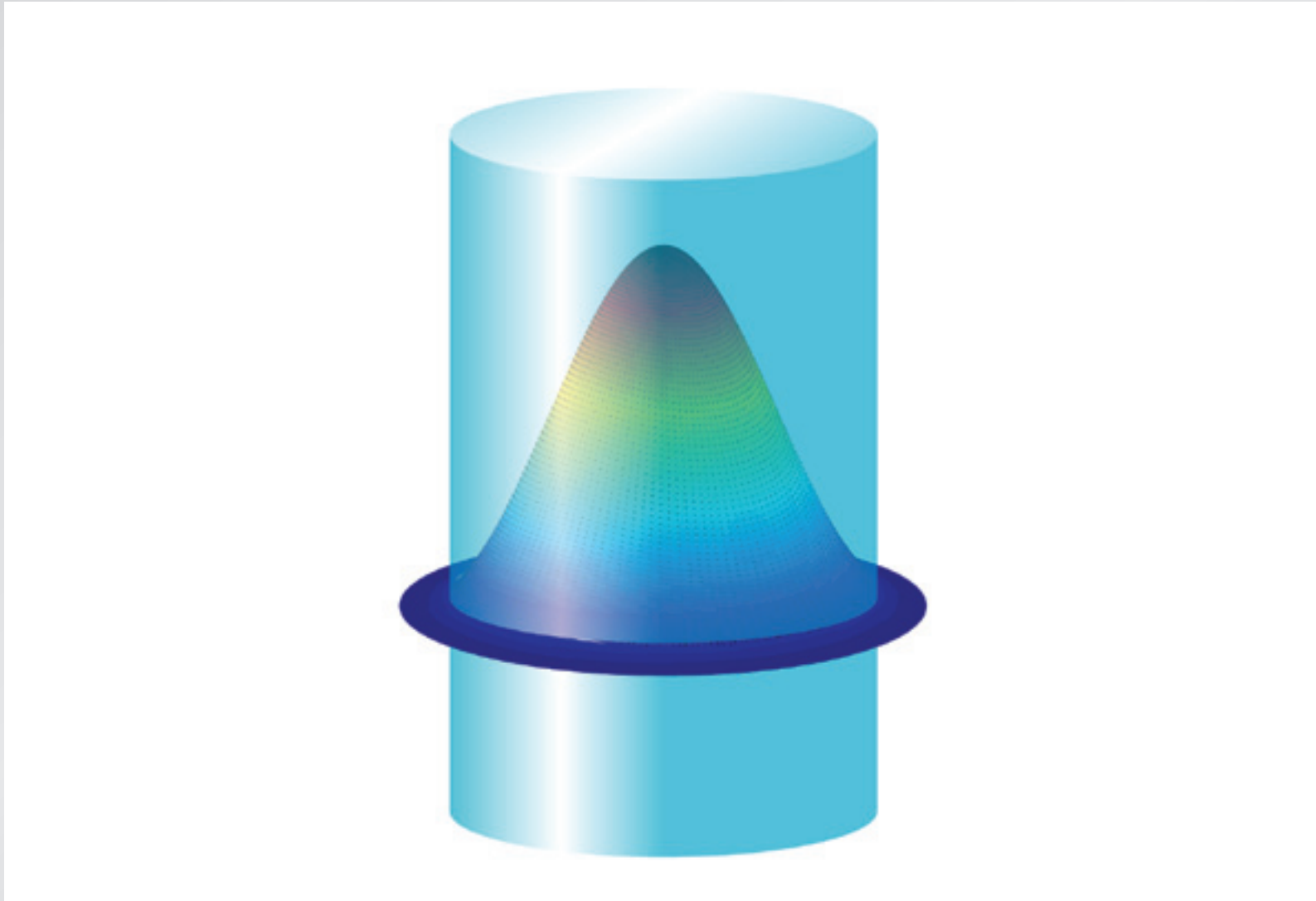
Optical properties

Poynting vector profile for 800-nm nanowire



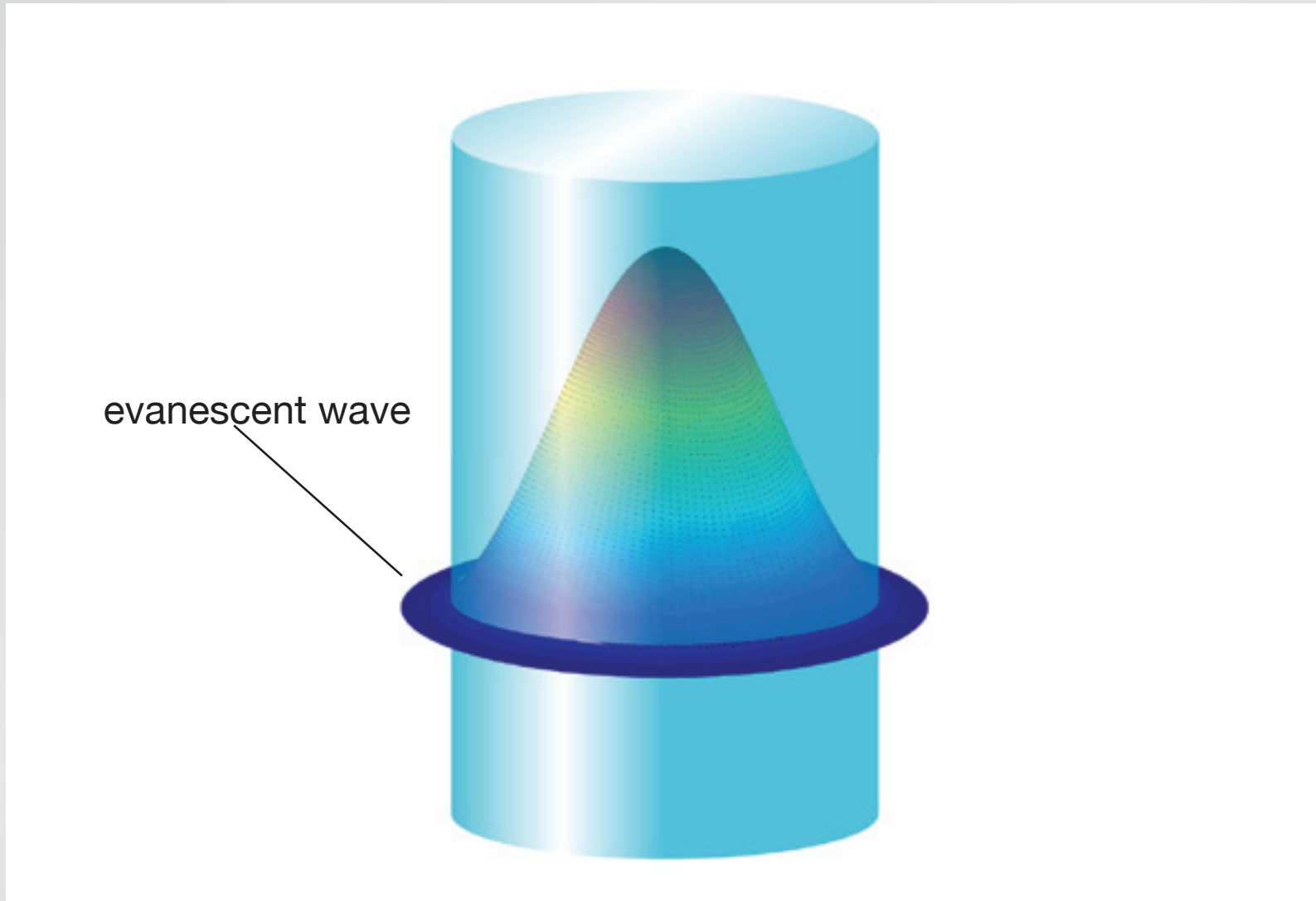
Optical properties

Poynting vector profile for 800-nm nanowire



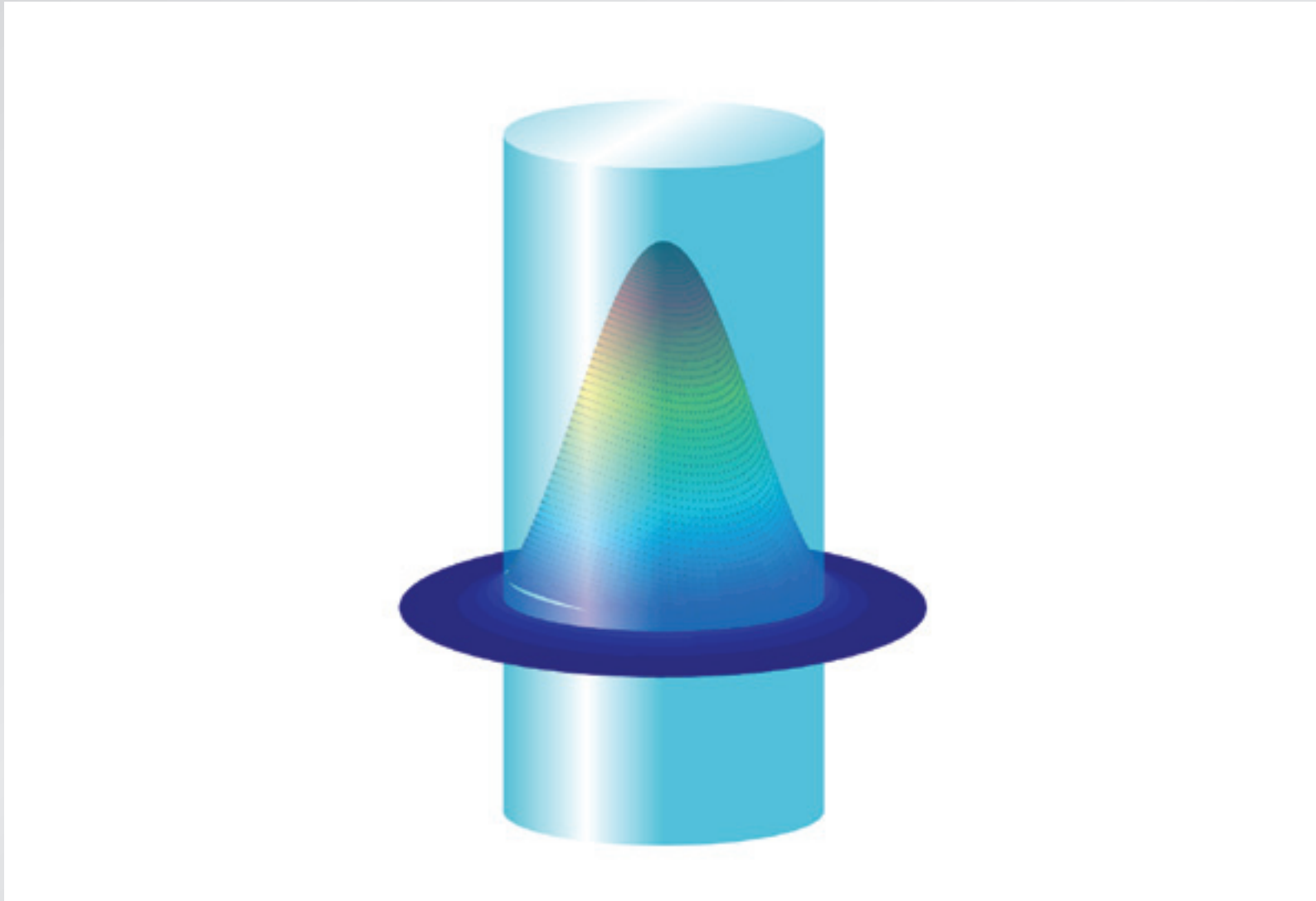
Optical properties

Poynting vector profile for 800-nm nanowire



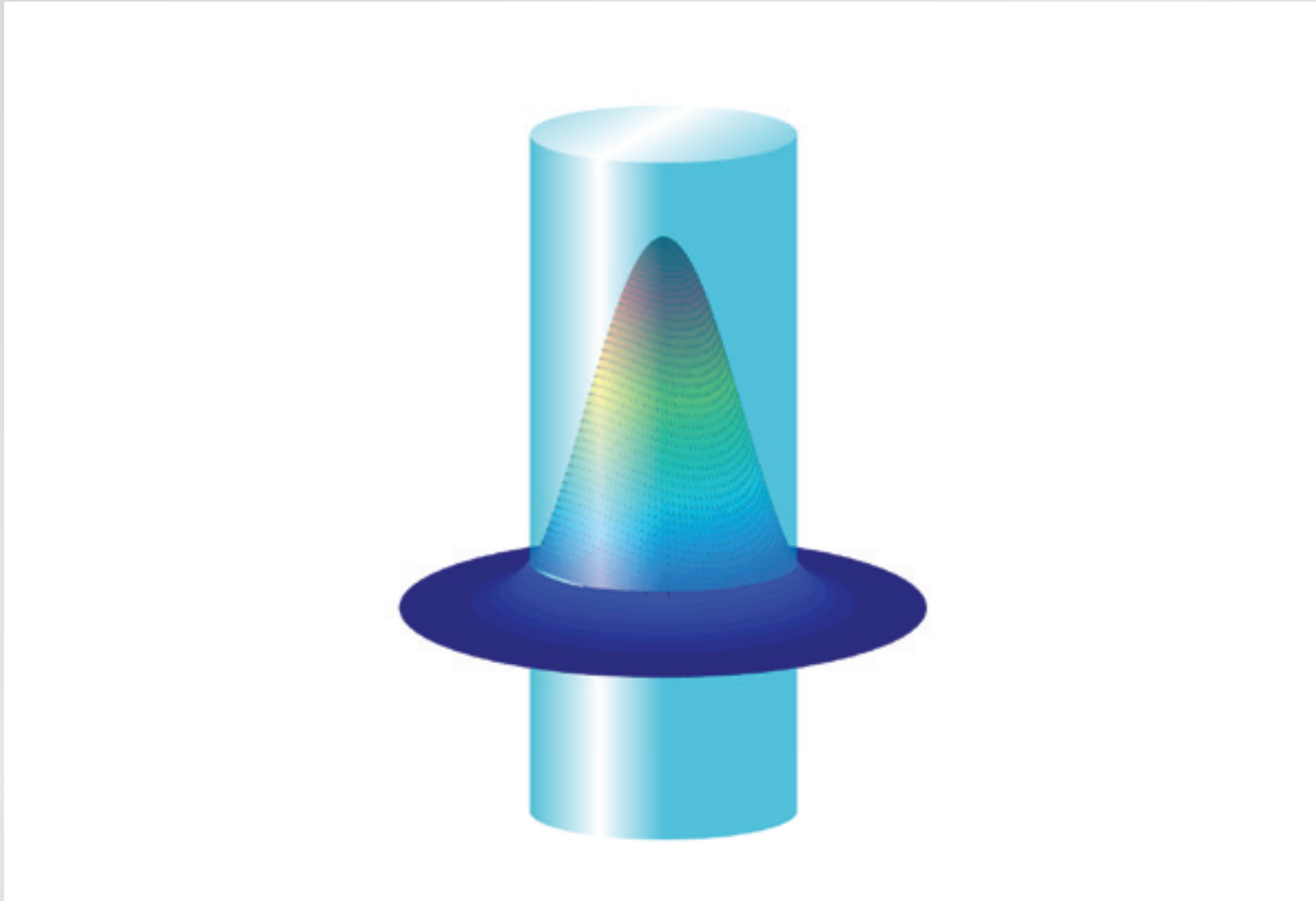
Optical properties

Poynting vector profile for 600-nm nanowire



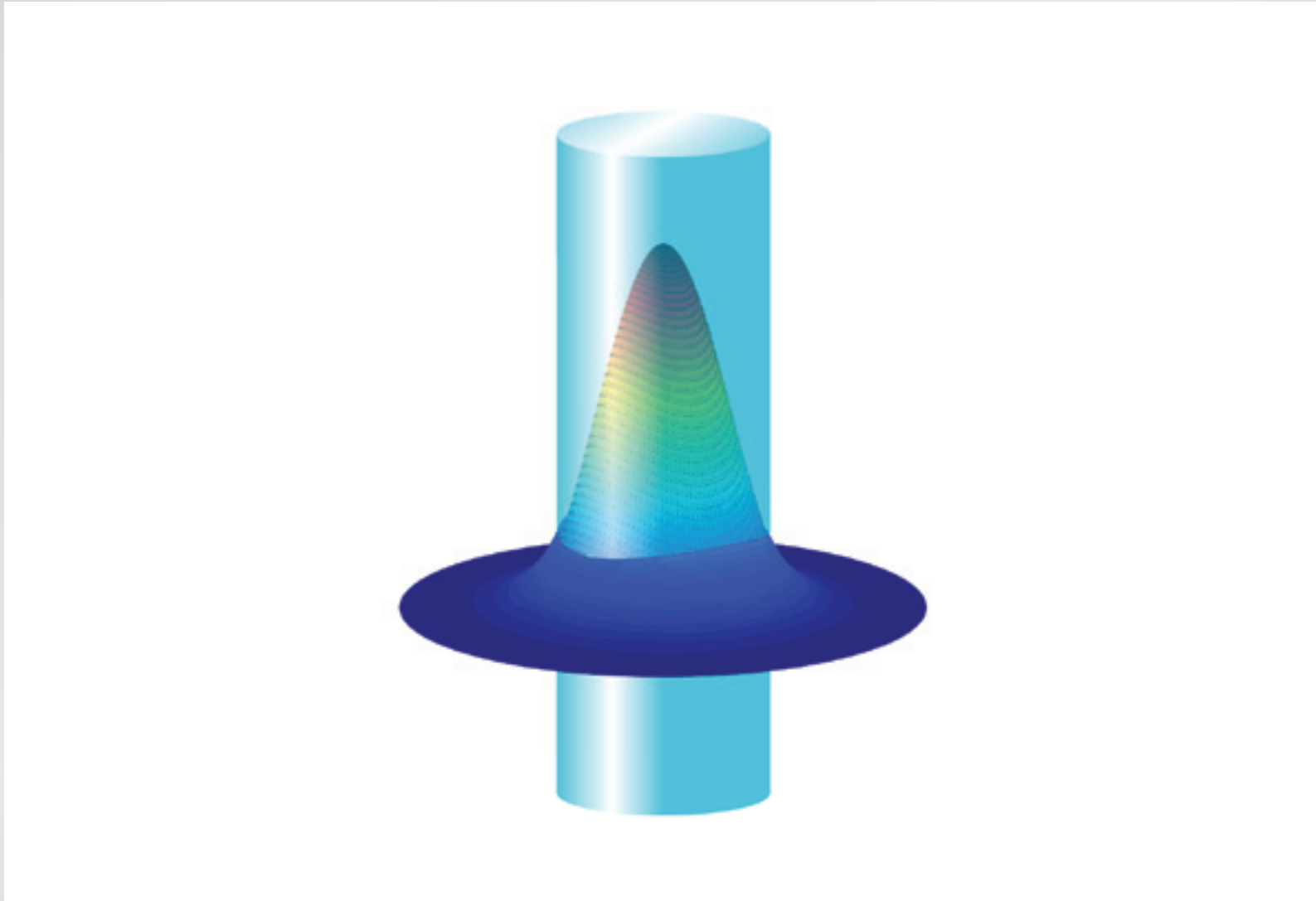
Optical properties

Poynting vector profile for 500-nm nanowire



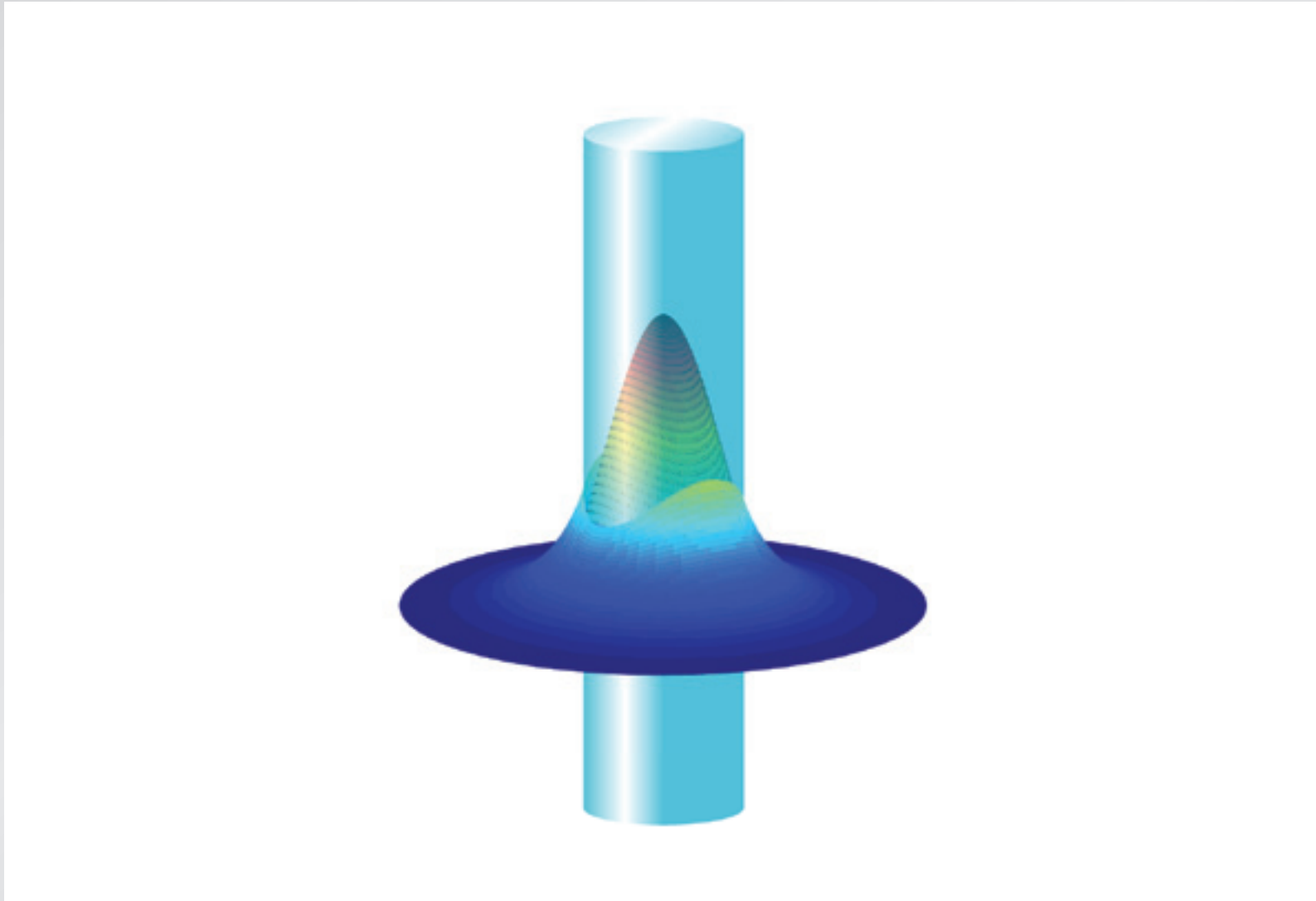
Optical properties

Poynting vector profile for 400-nm nanowire



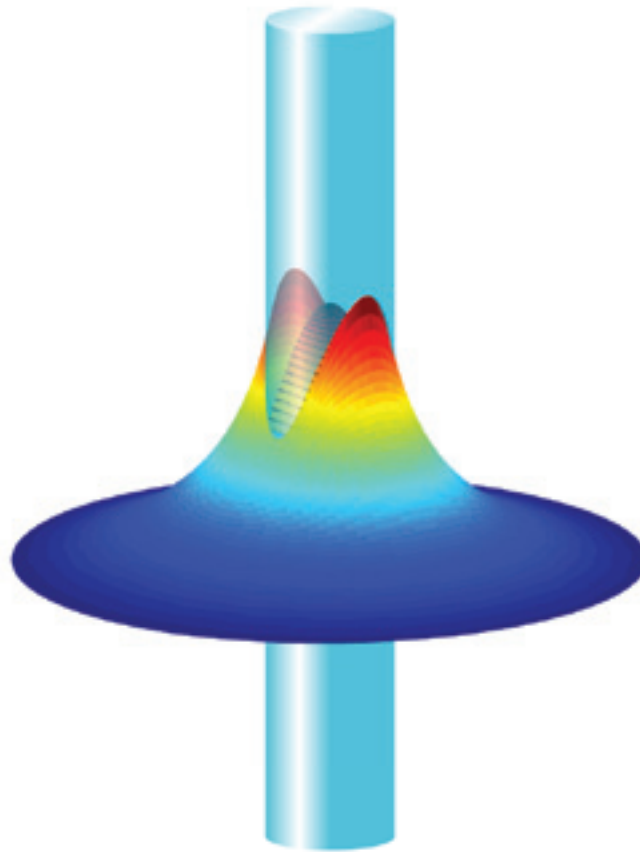
Optical properties

Poynting vector profile for 300-nm nanowire



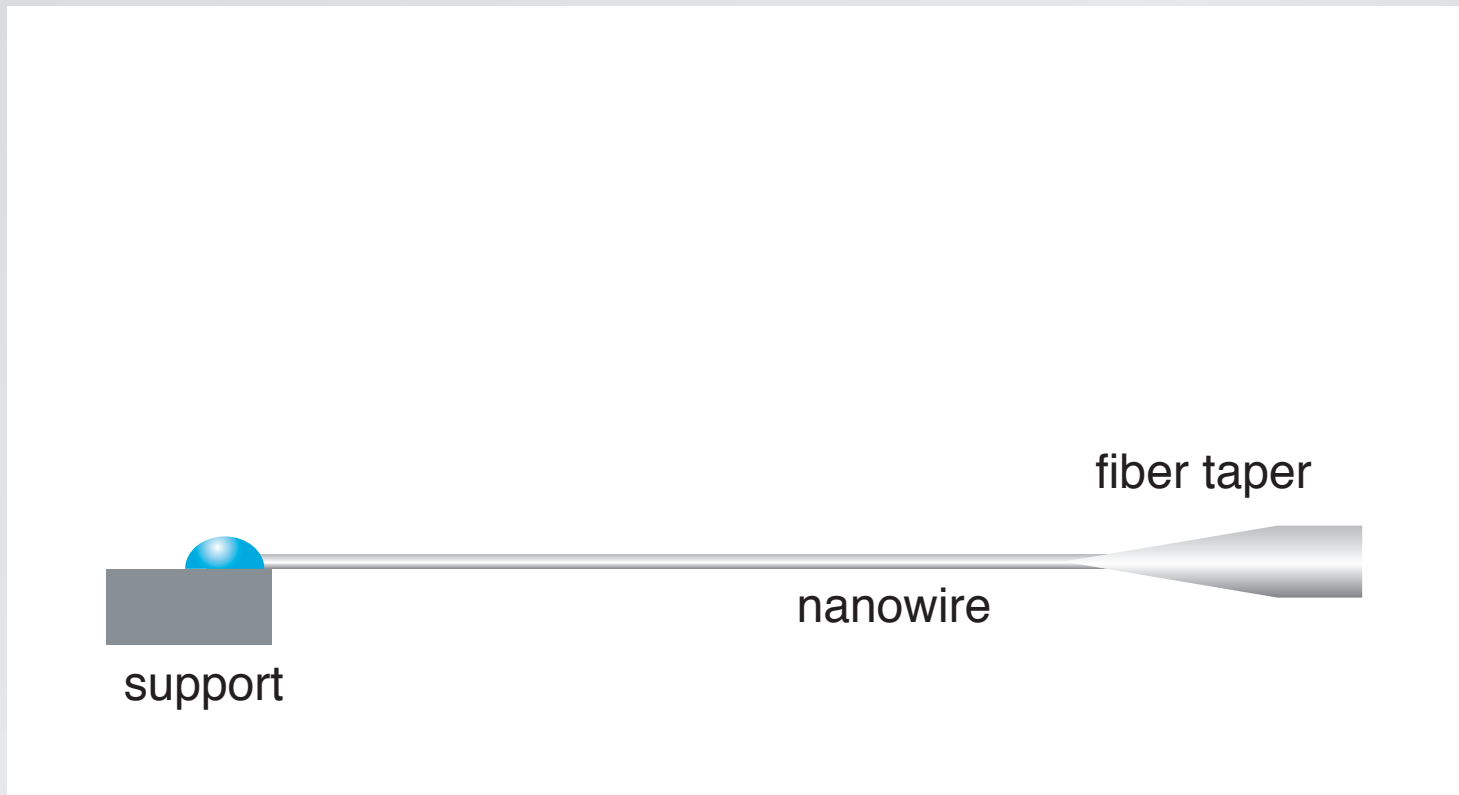
Optical properties

Poynting vector profile for 200-nm nanowire



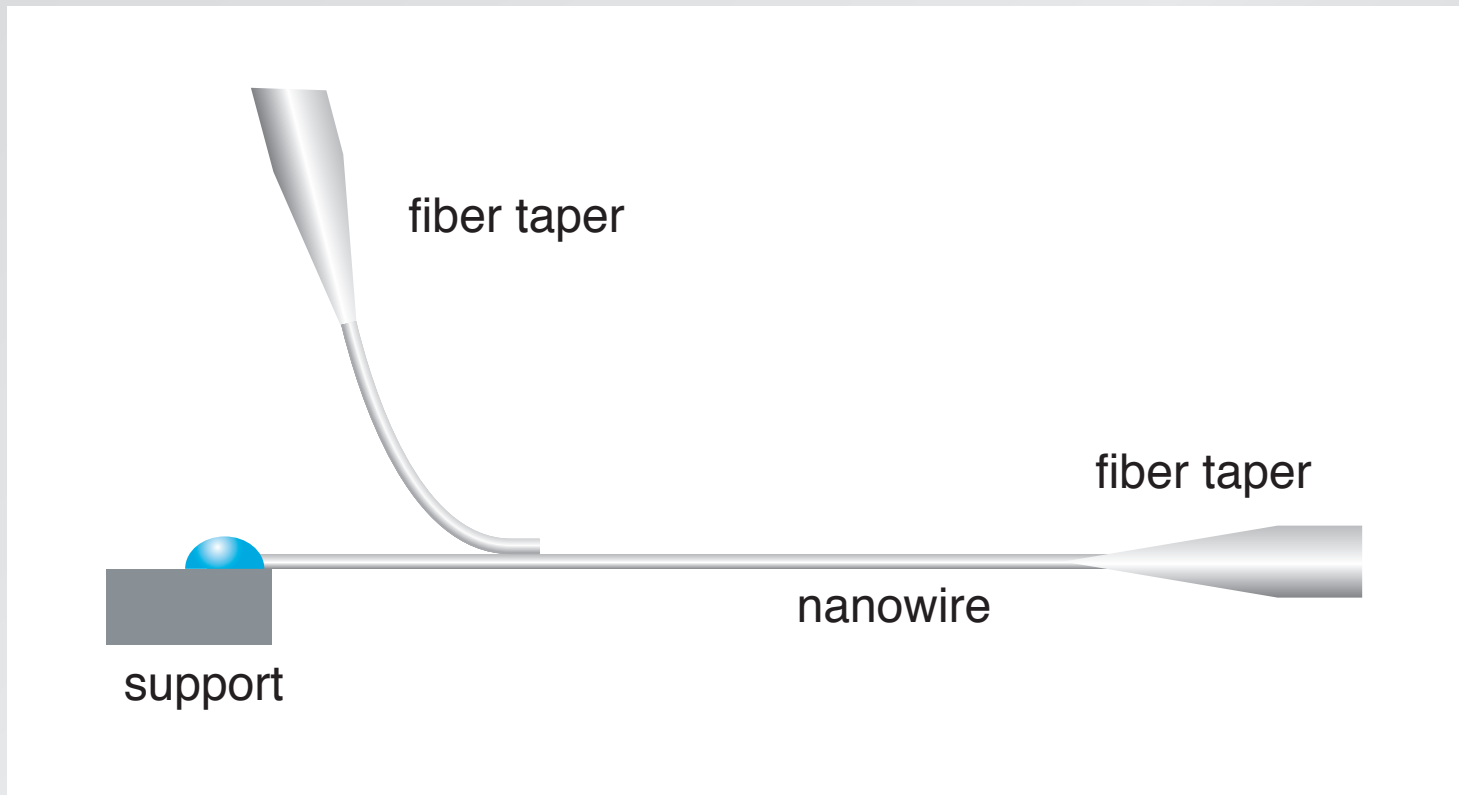
Optical properties

coupling light between nanowires



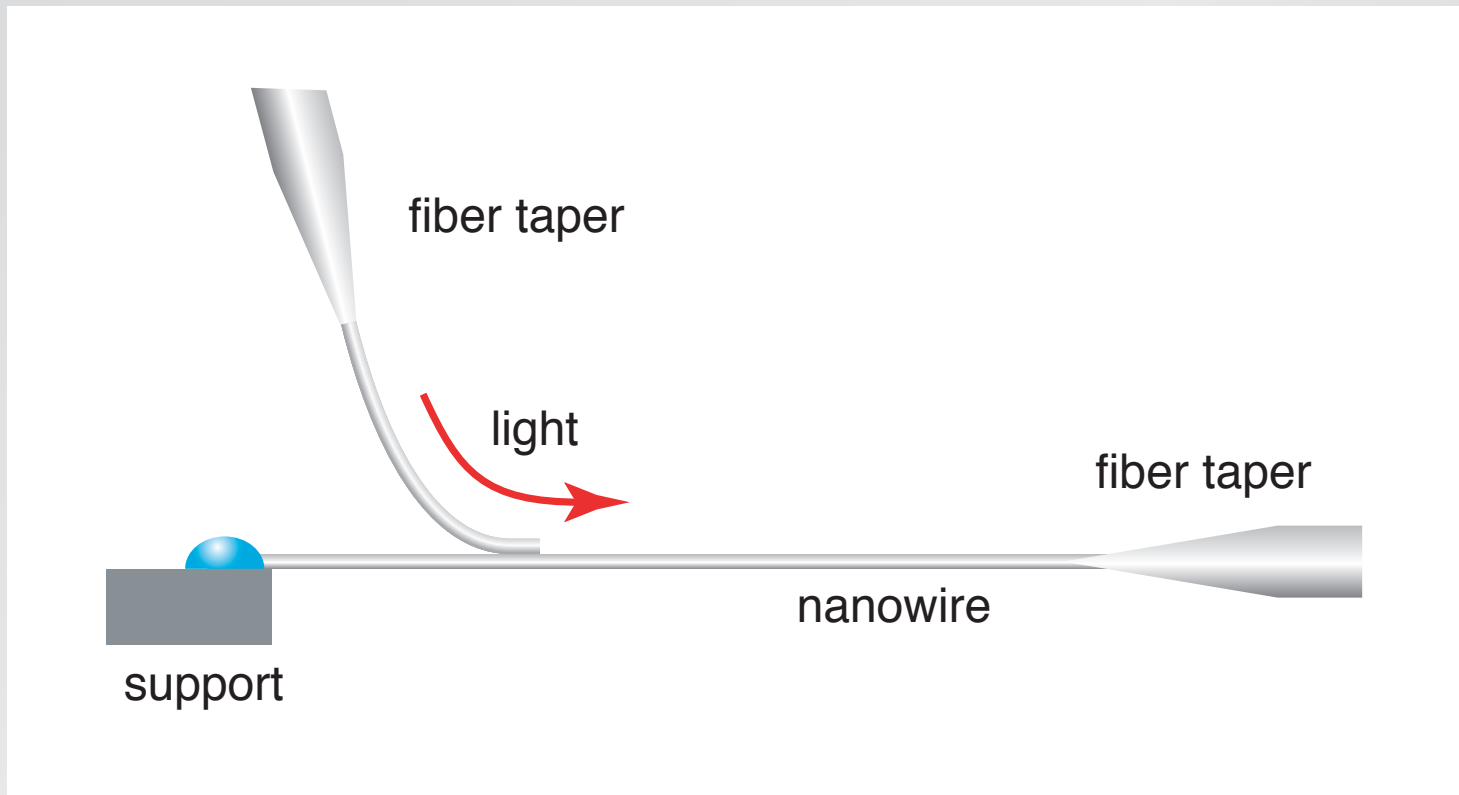
Optical properties

coupling light between nanowires

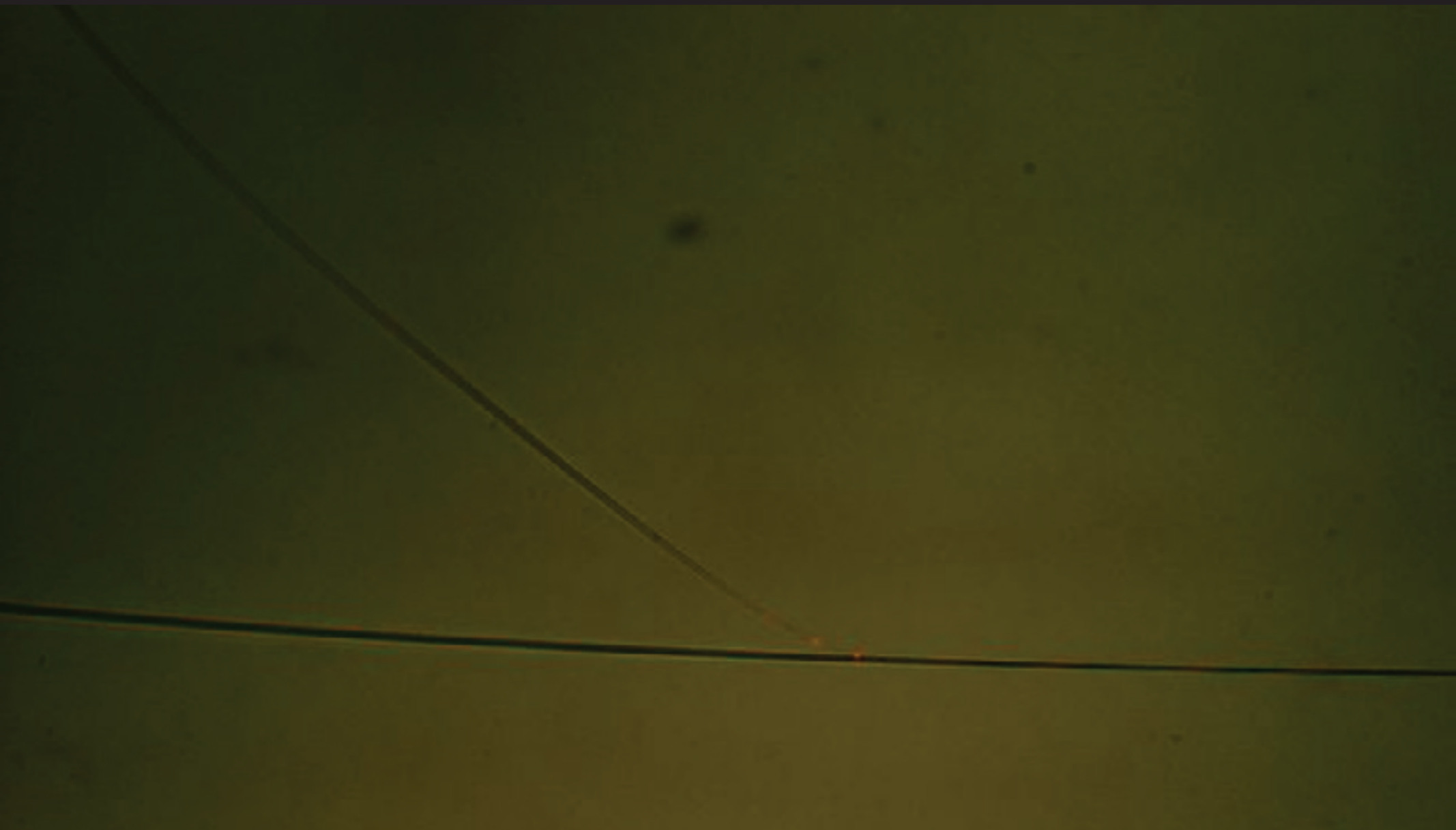


Optical properties

coupling light between nanowires



Optical properties



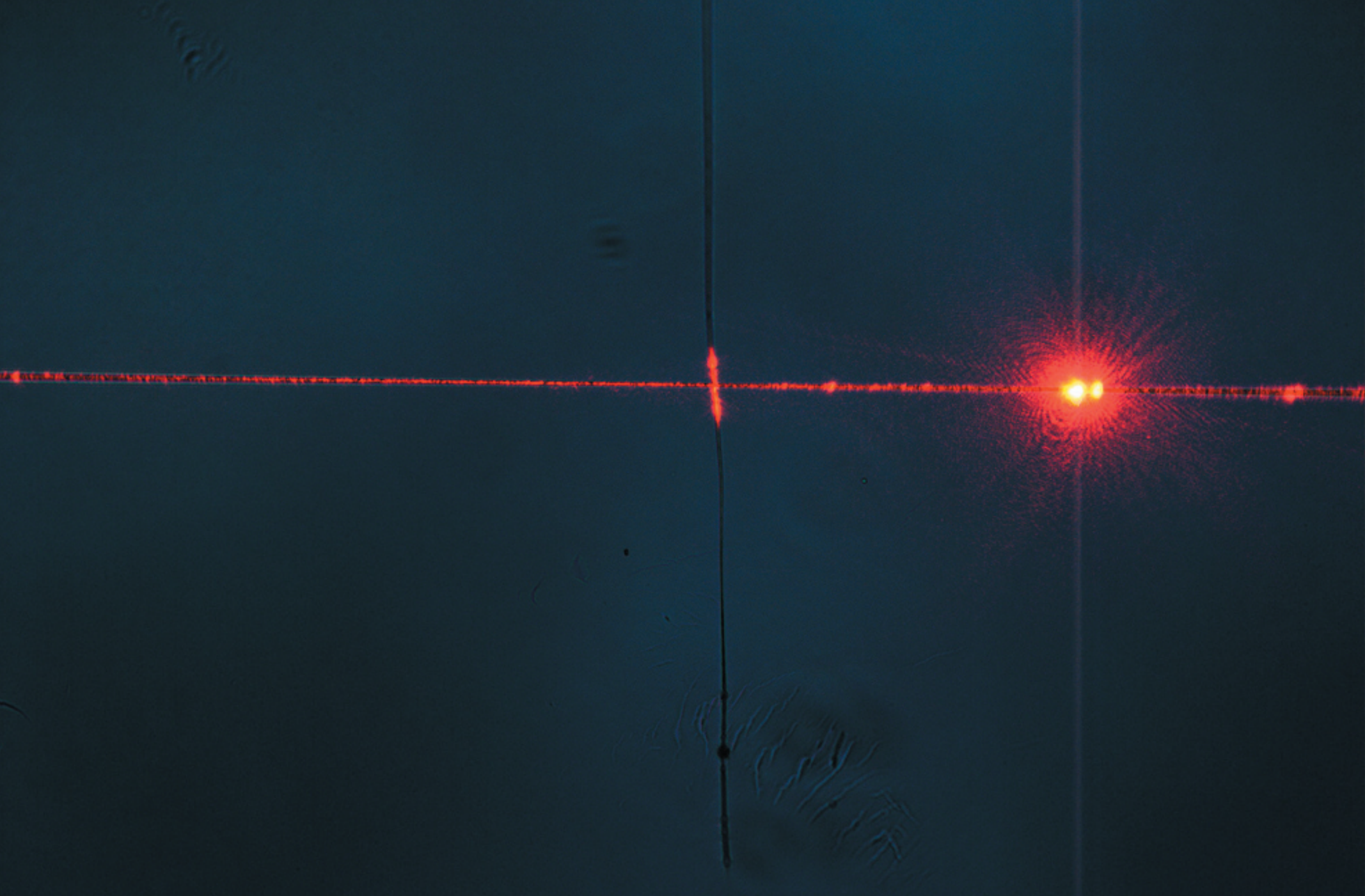
50 μm

Optical properties

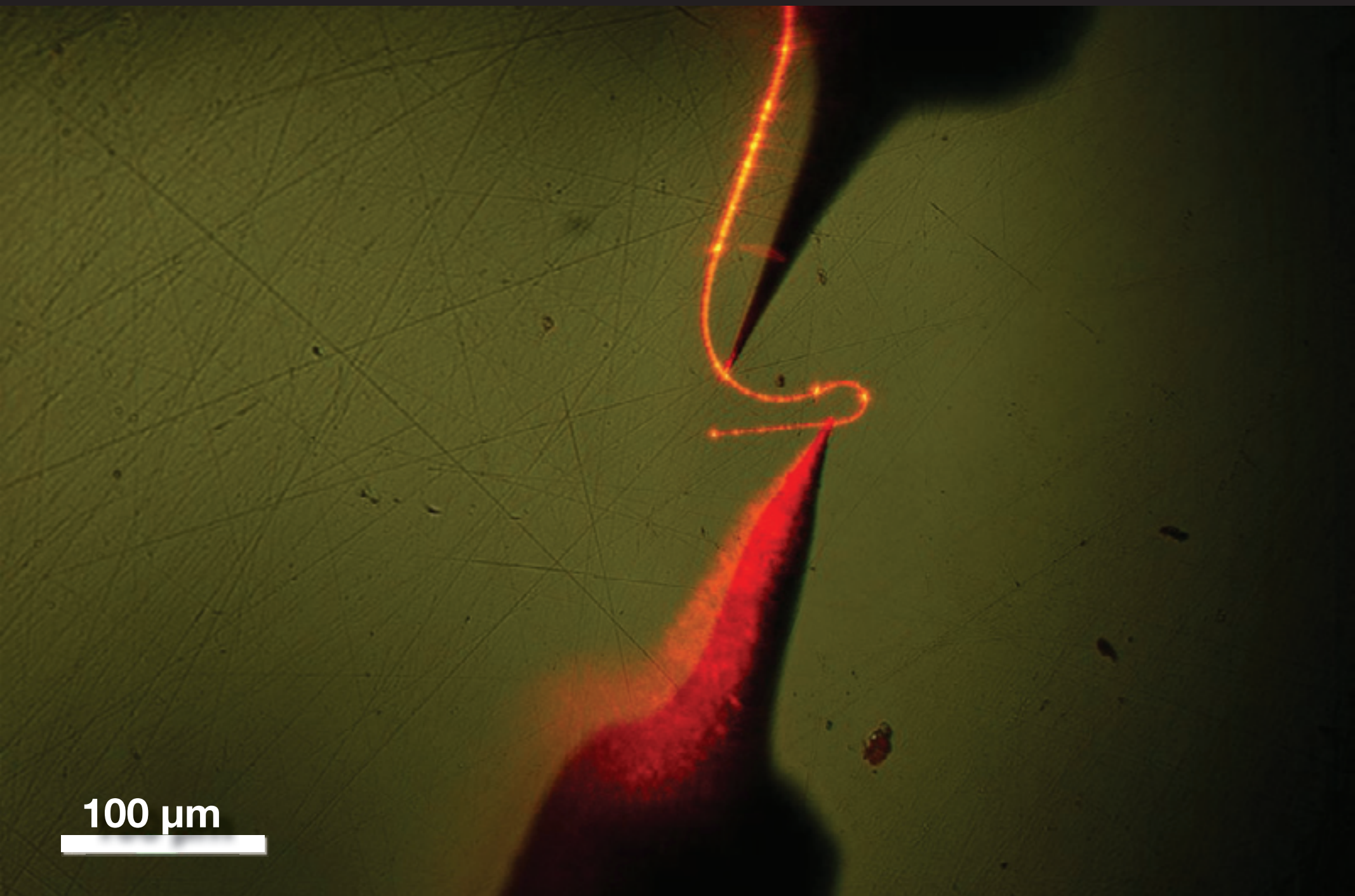


50 μm

Optical properties

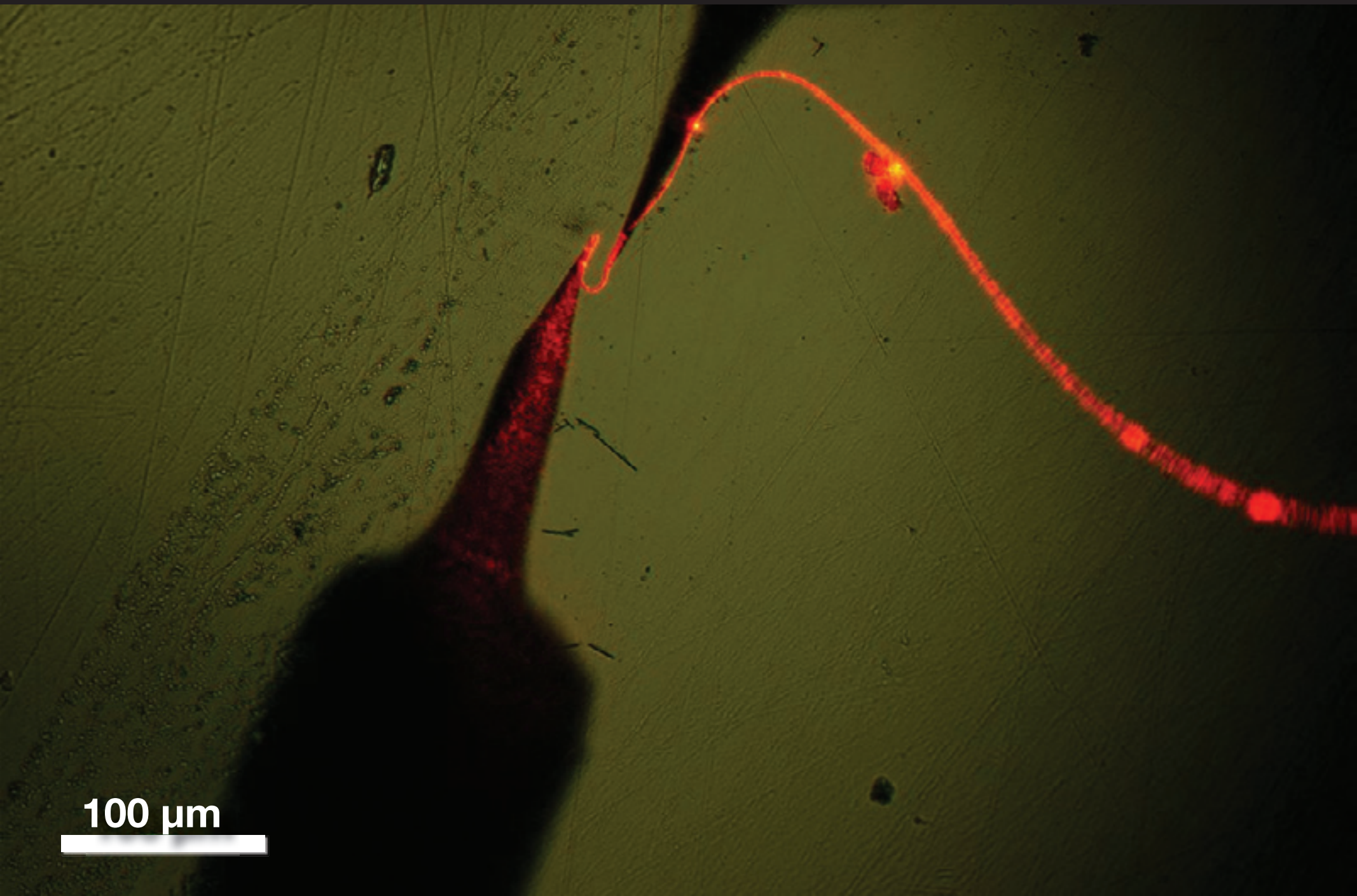


Optical properties



100 μm

Optical properties



100 μm

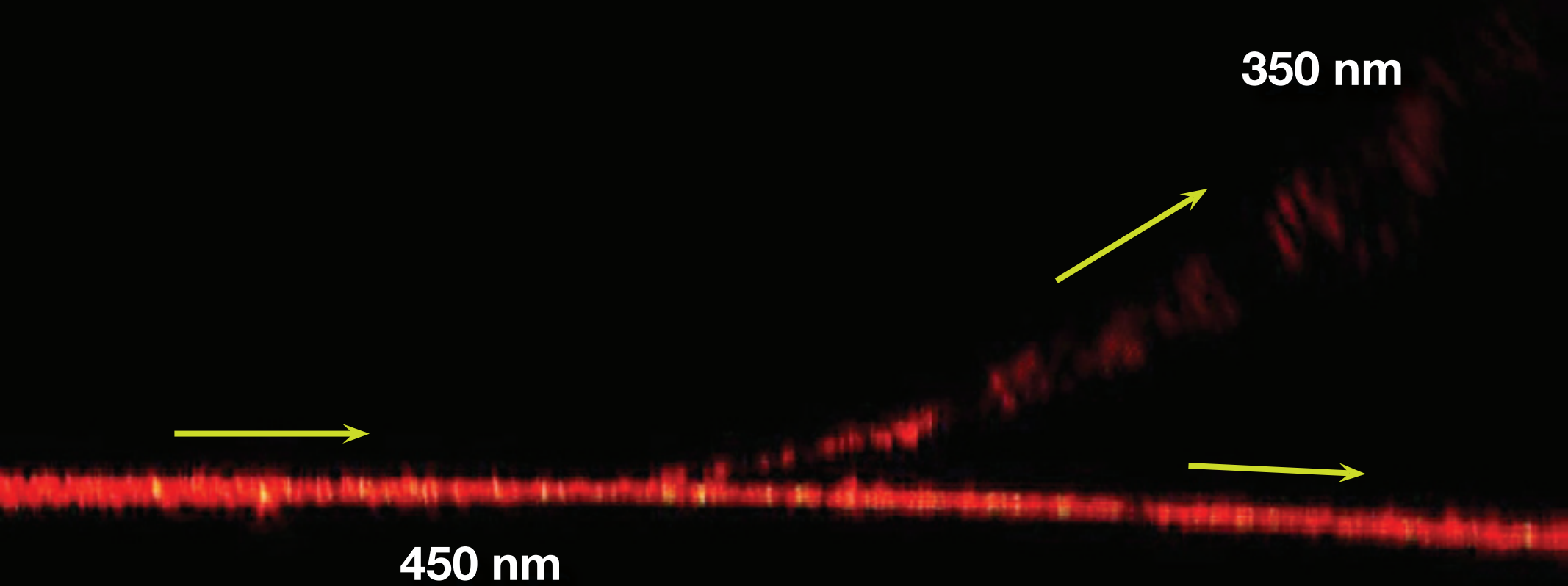
Optical properties

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

100 μm



Outlook



10 μm

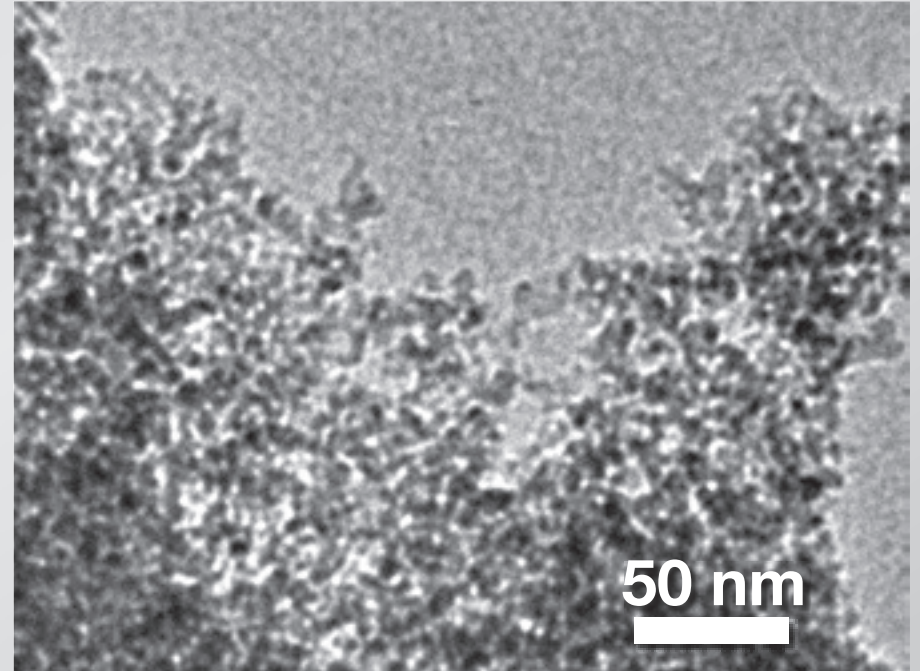
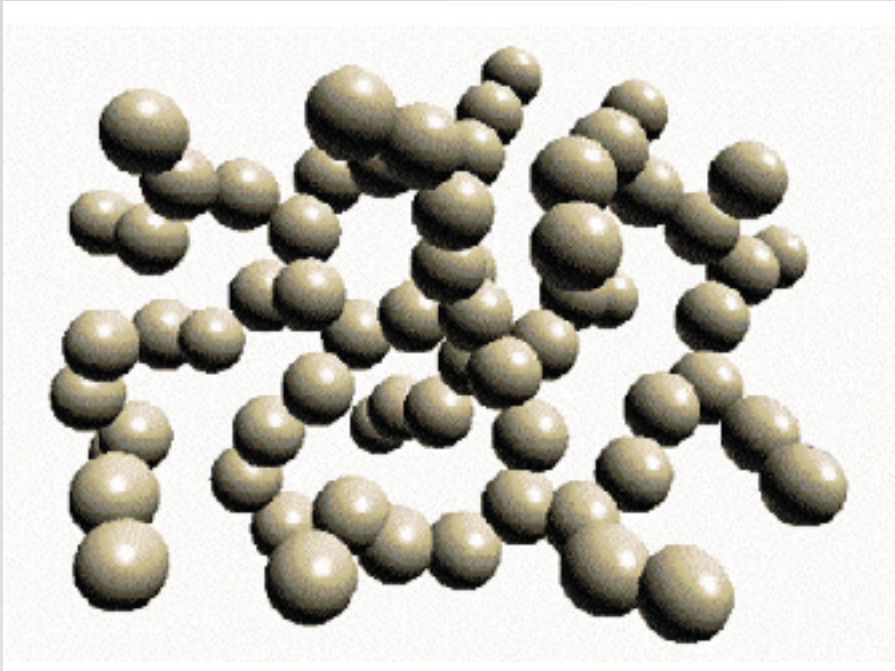


Outlook



Outlook

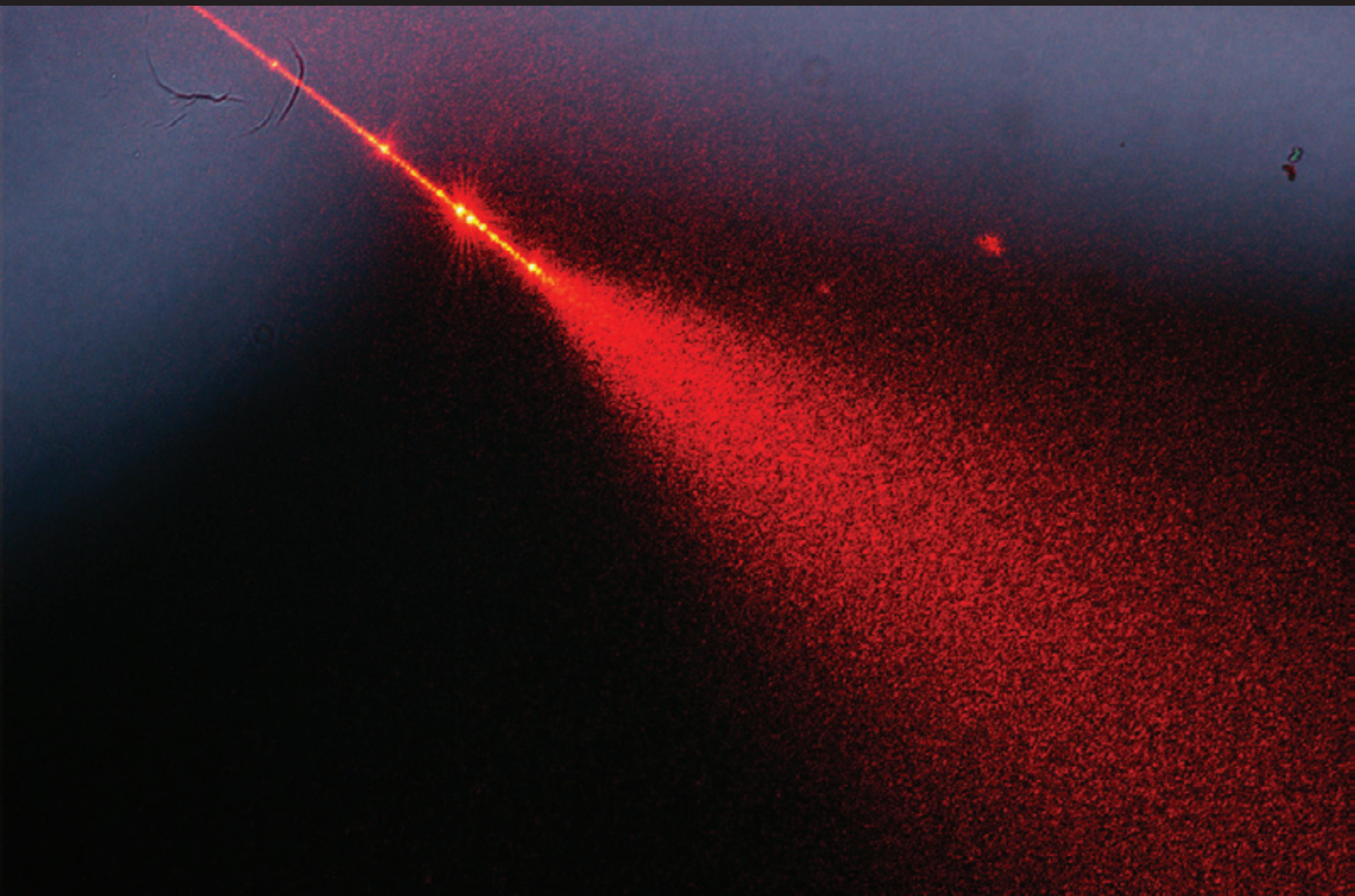
Aerogel



density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Outlook



Outlook

1 μm



Outlook

530 nm

50 μm

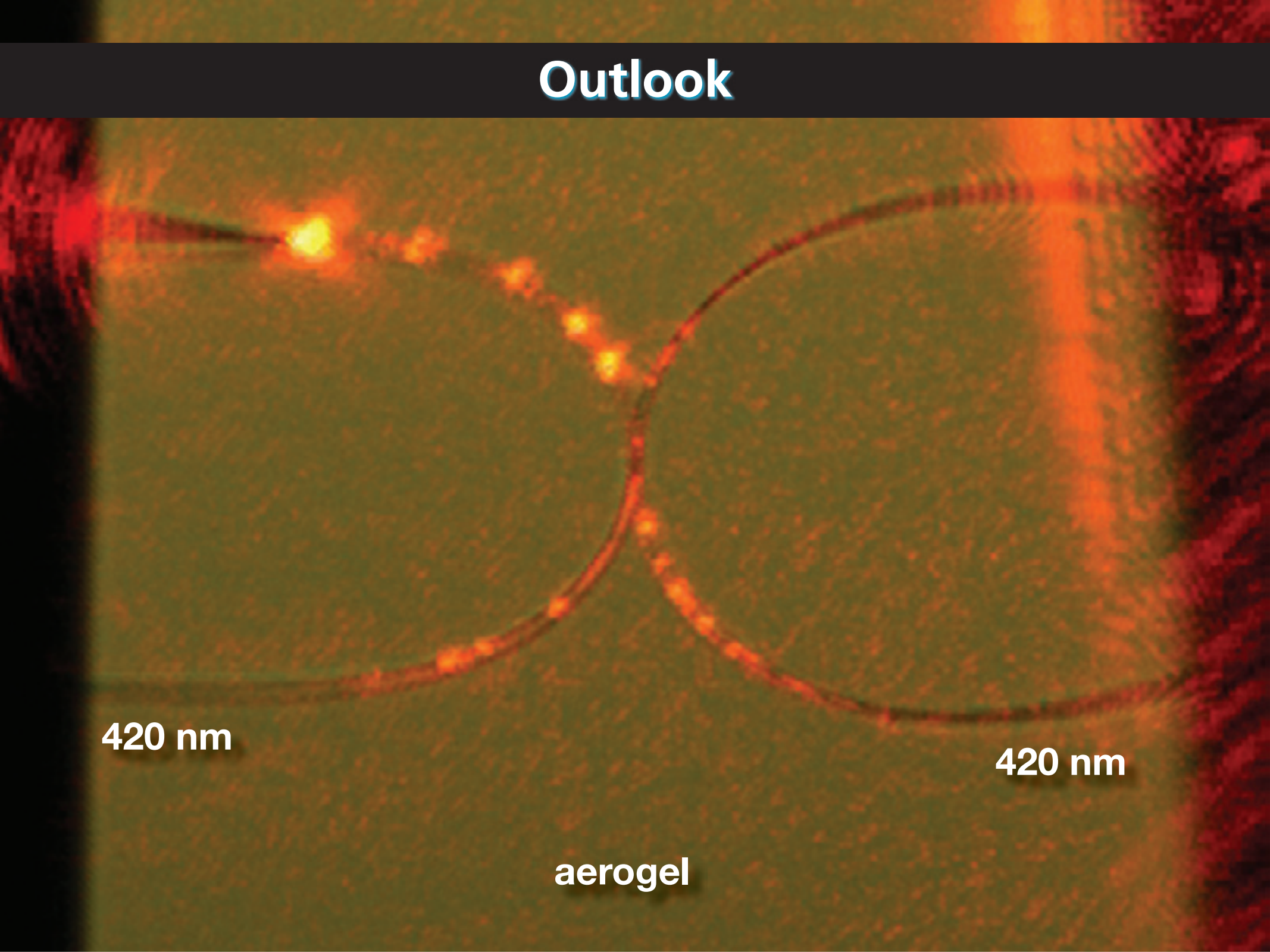
A fluorescence microscopy image showing a red fluorescent structure on a dark background. The structure is elongated and has a rounded, bulbous end. A white scale bar is located in the bottom left corner. The text '530 nm' is positioned above the structure, and '50 μm' is positioned above the scale bar. The background is dark brown with some faint, curved lines and a small, bright spot in the lower right quadrant.

Outlook

420 nm

420 nm

aerogel



Outlook

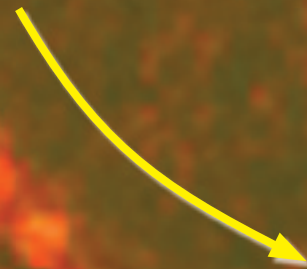
in



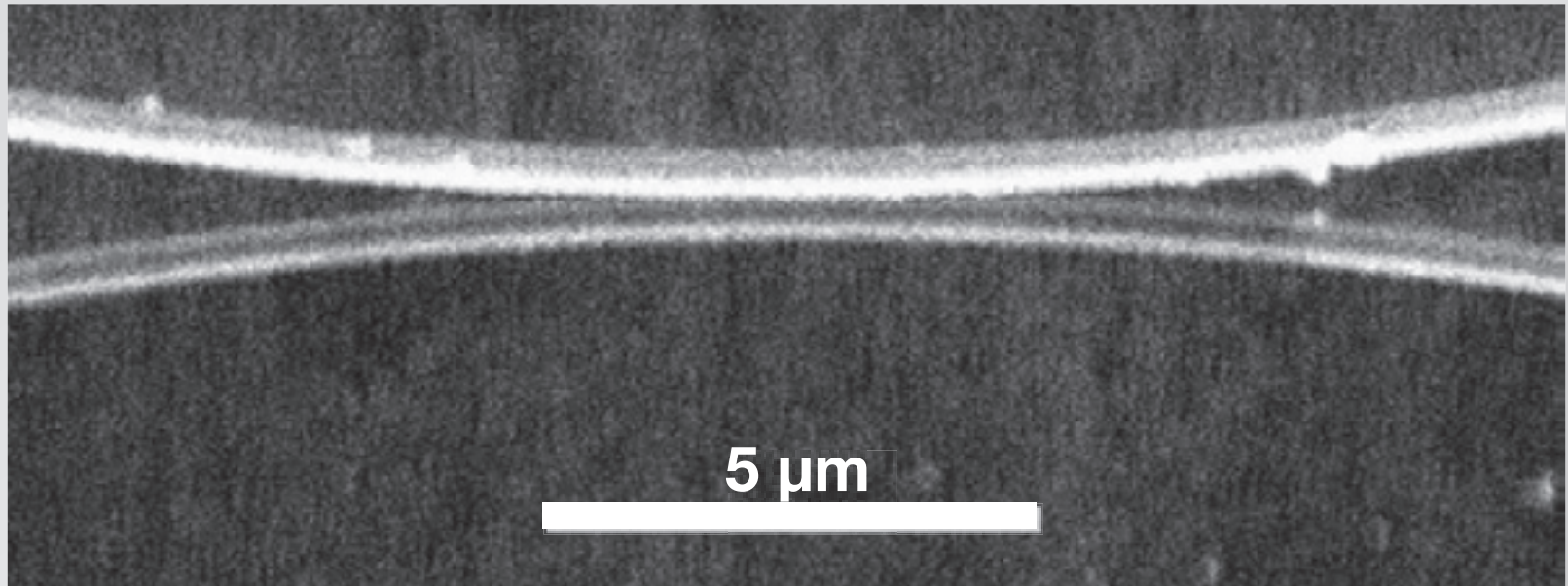
out



out

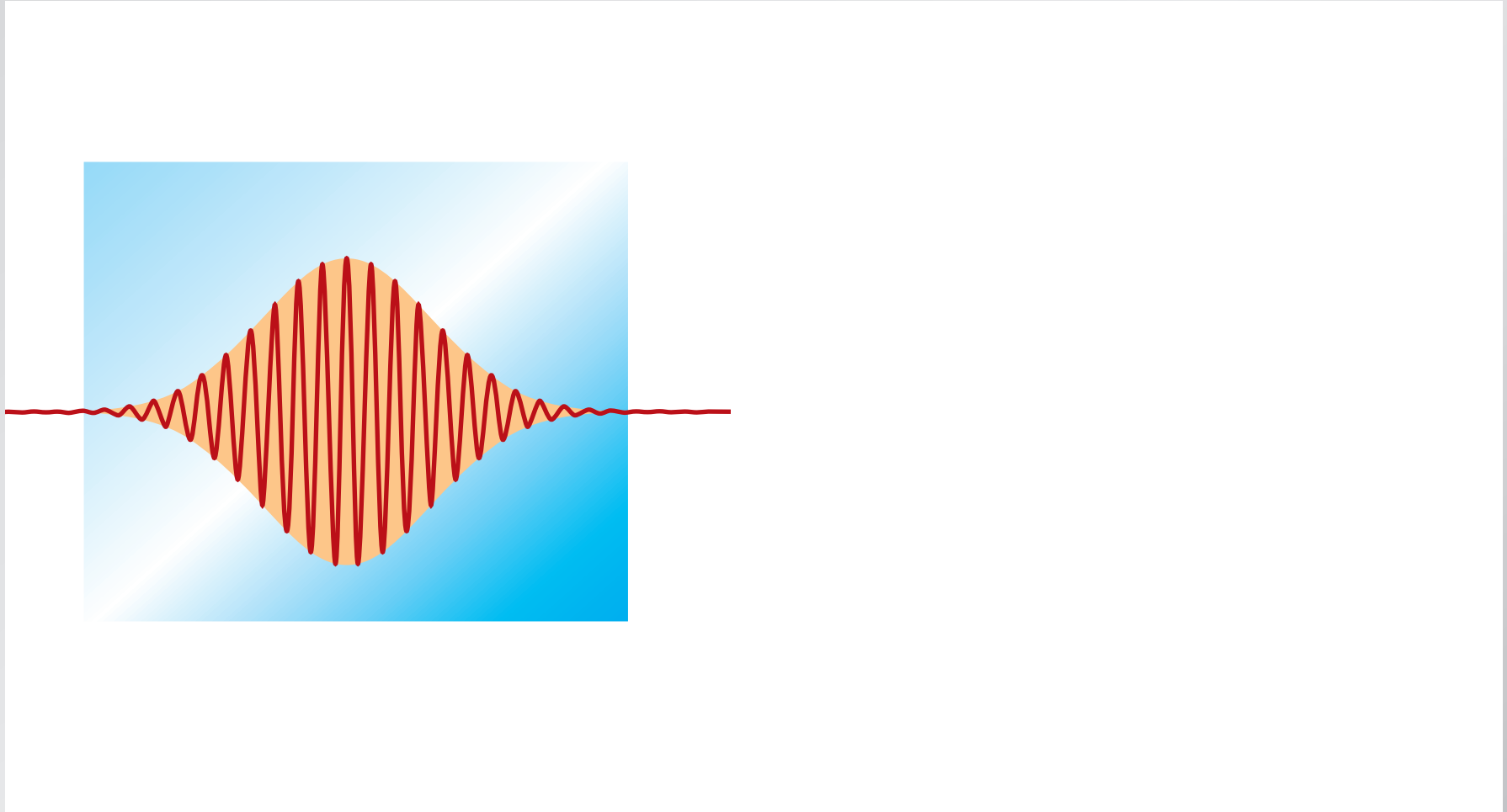


Outlook



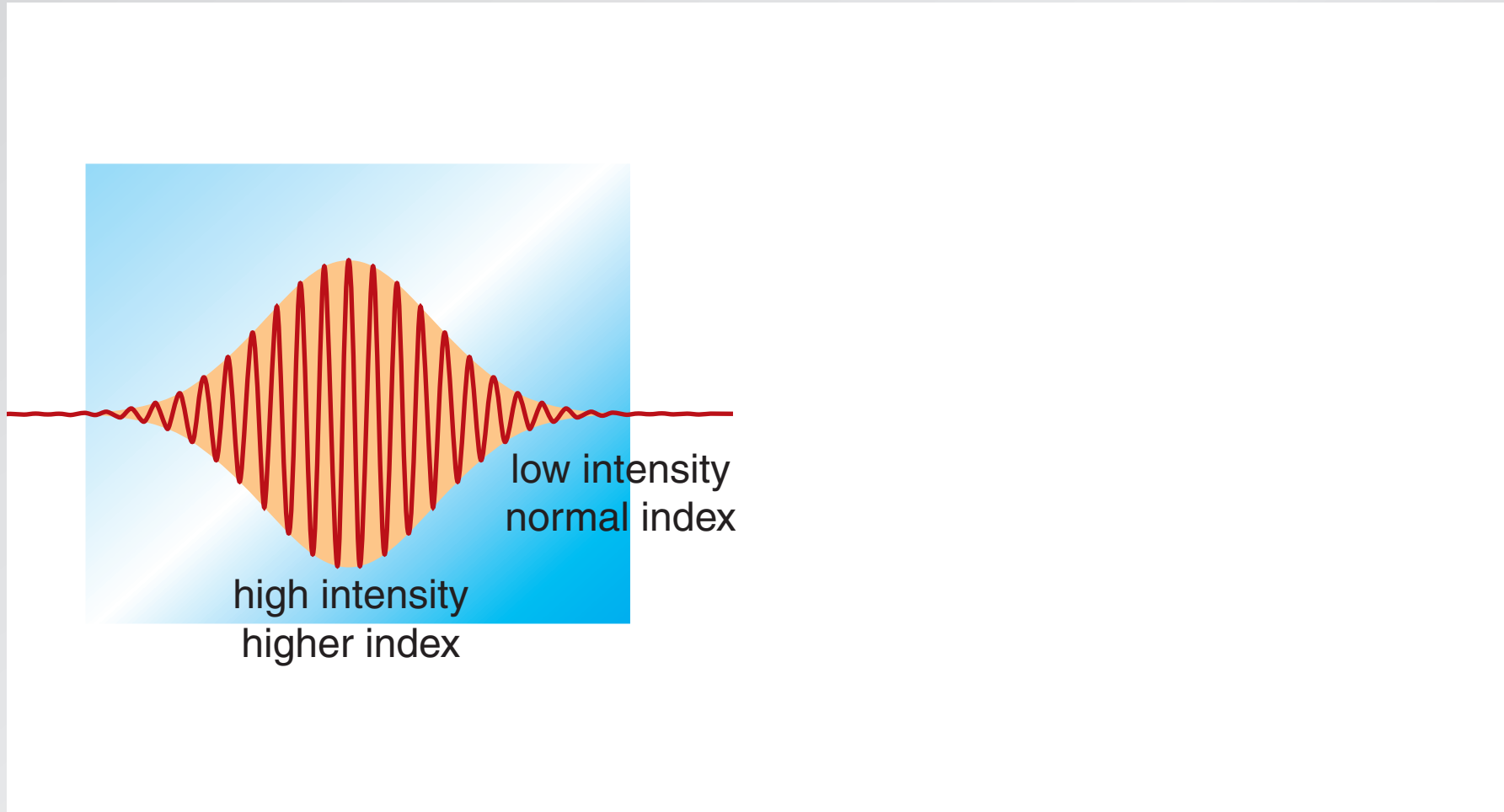
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



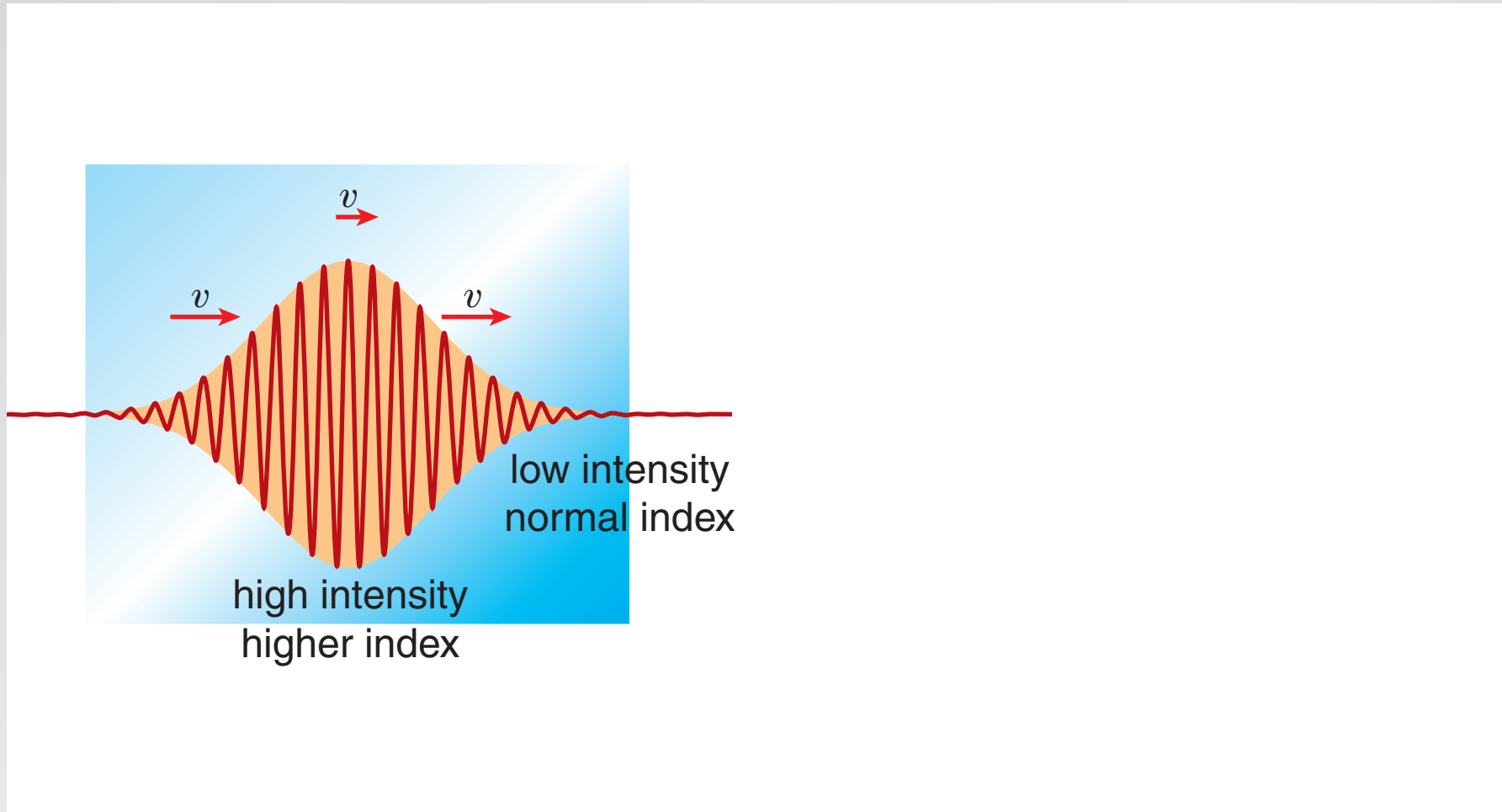
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



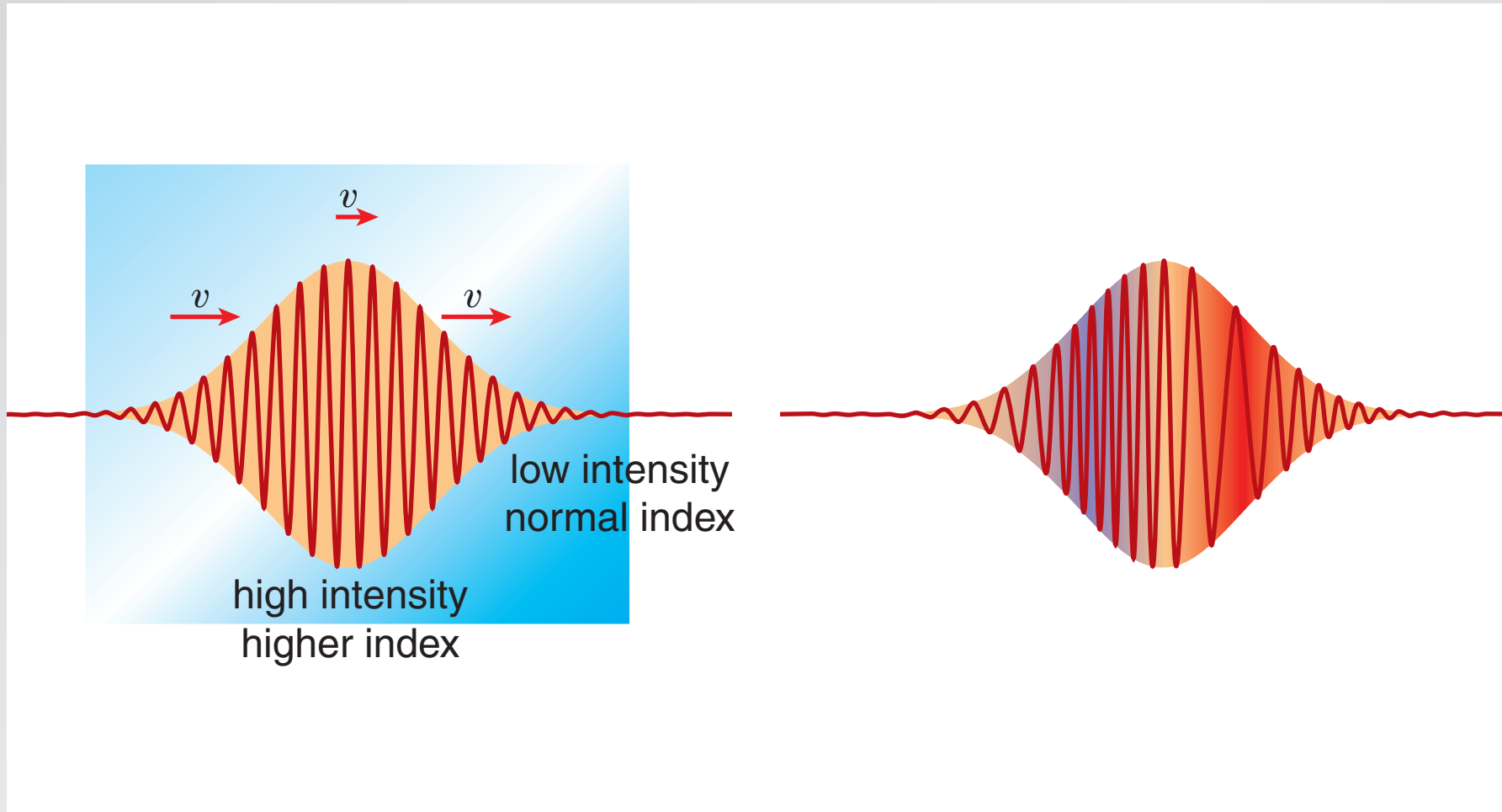
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



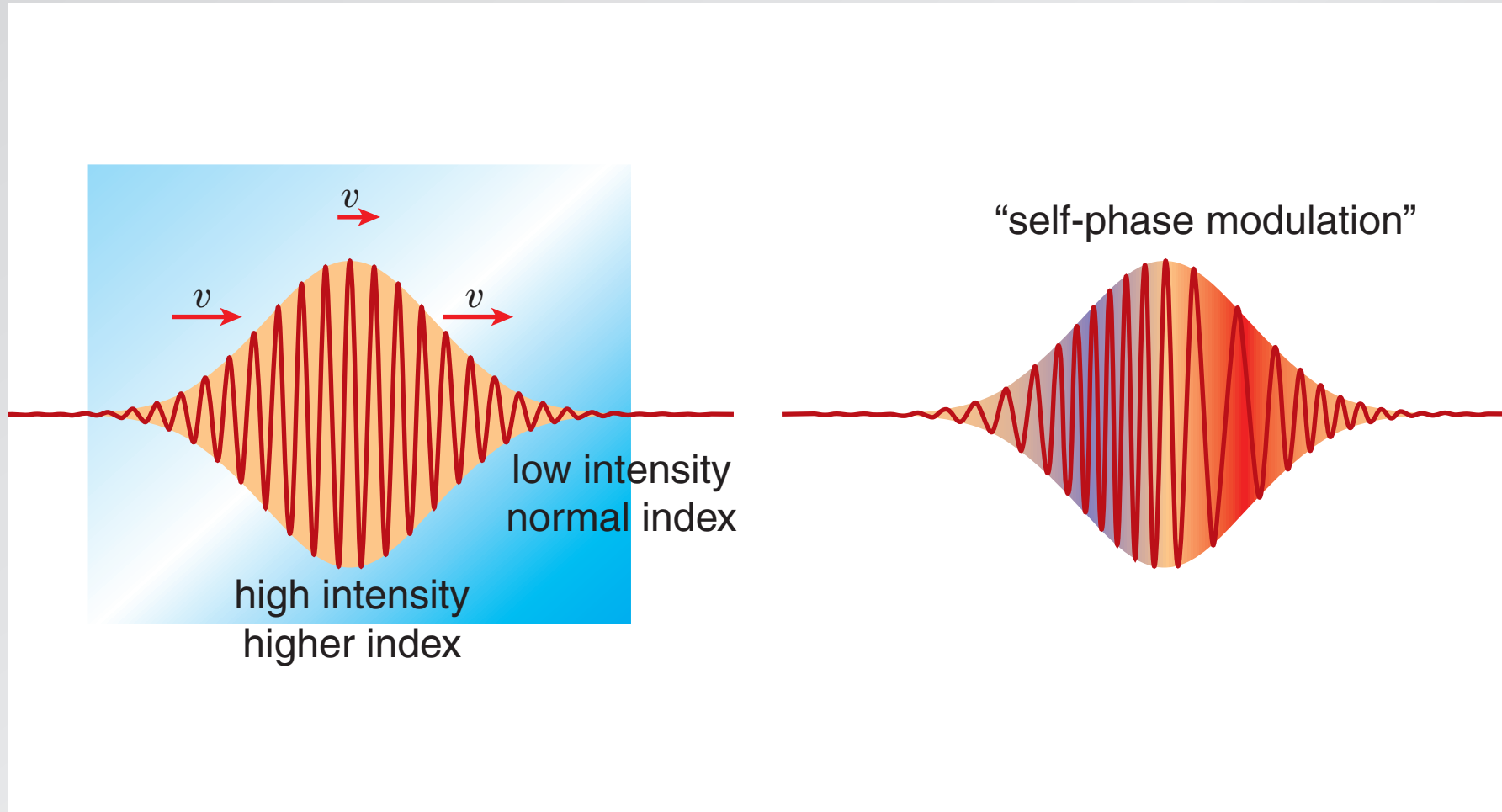
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



Nanoscale nonlinear optics

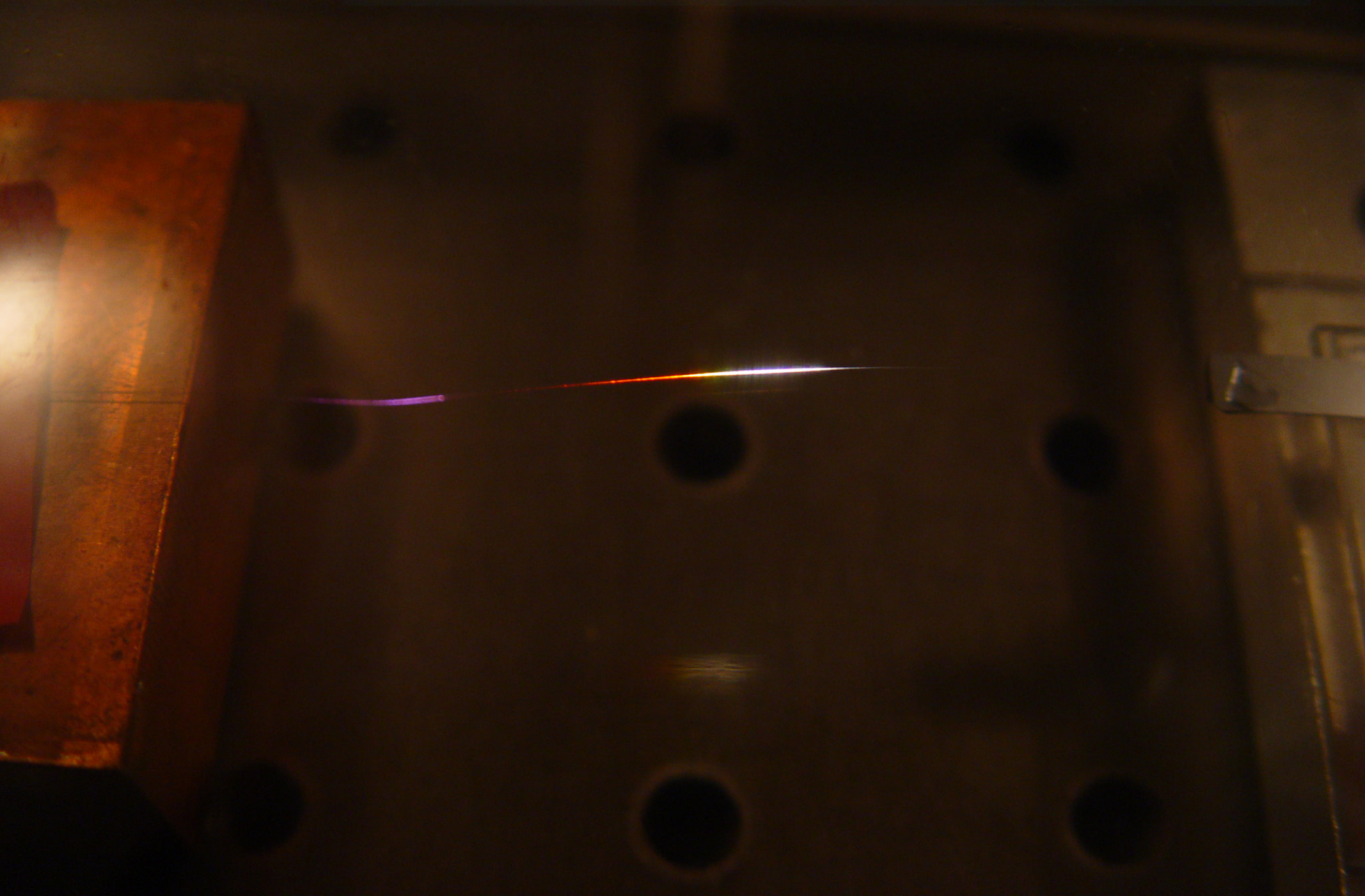
nonlinear dispersion: $n = n_0 + n_2 I$



Nanoscale nonlinear optics

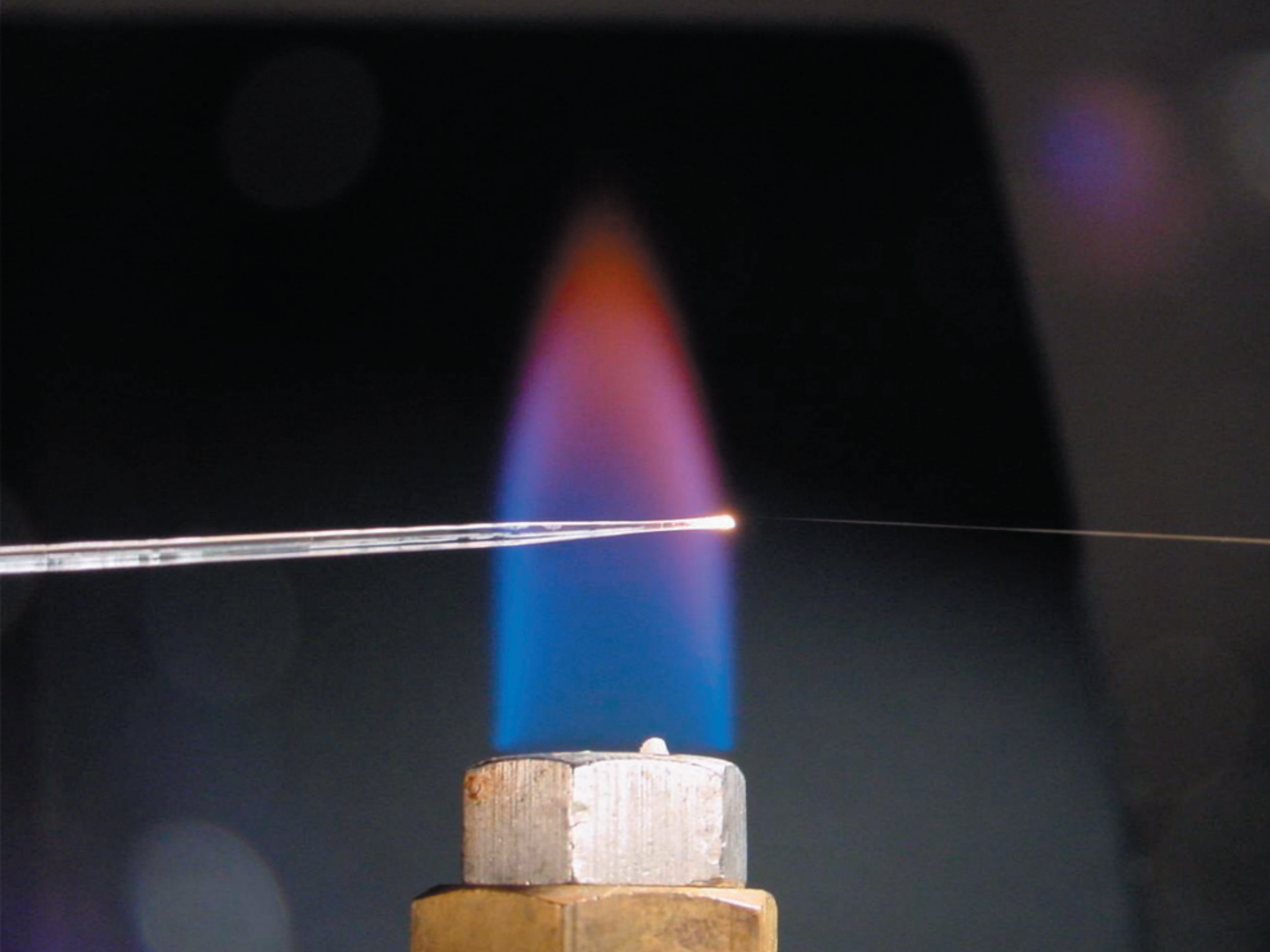
strong confinement \longrightarrow **high intensity**

Nanoscale nonlinear optics

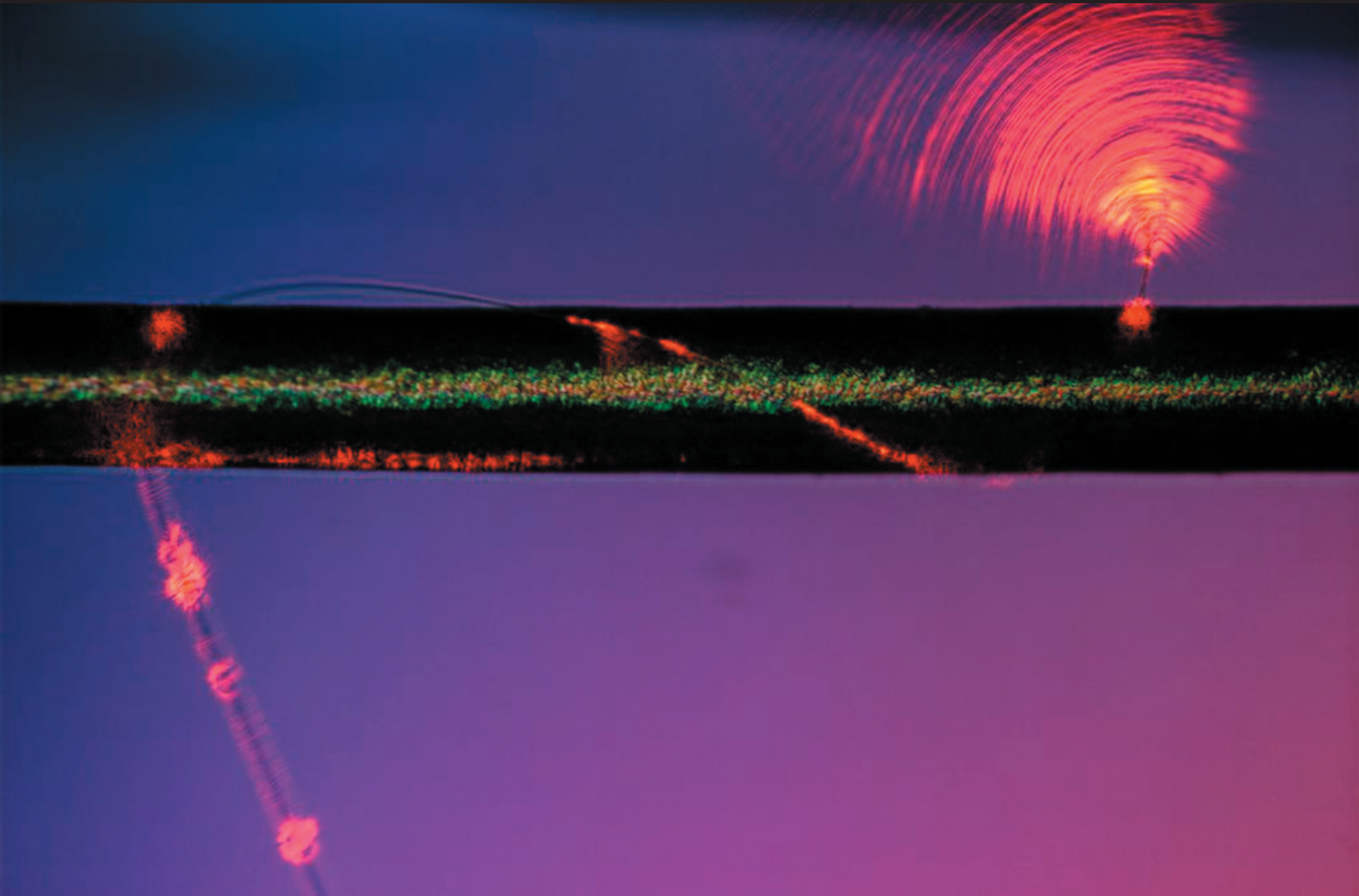


Nanoscale nonlinear optics

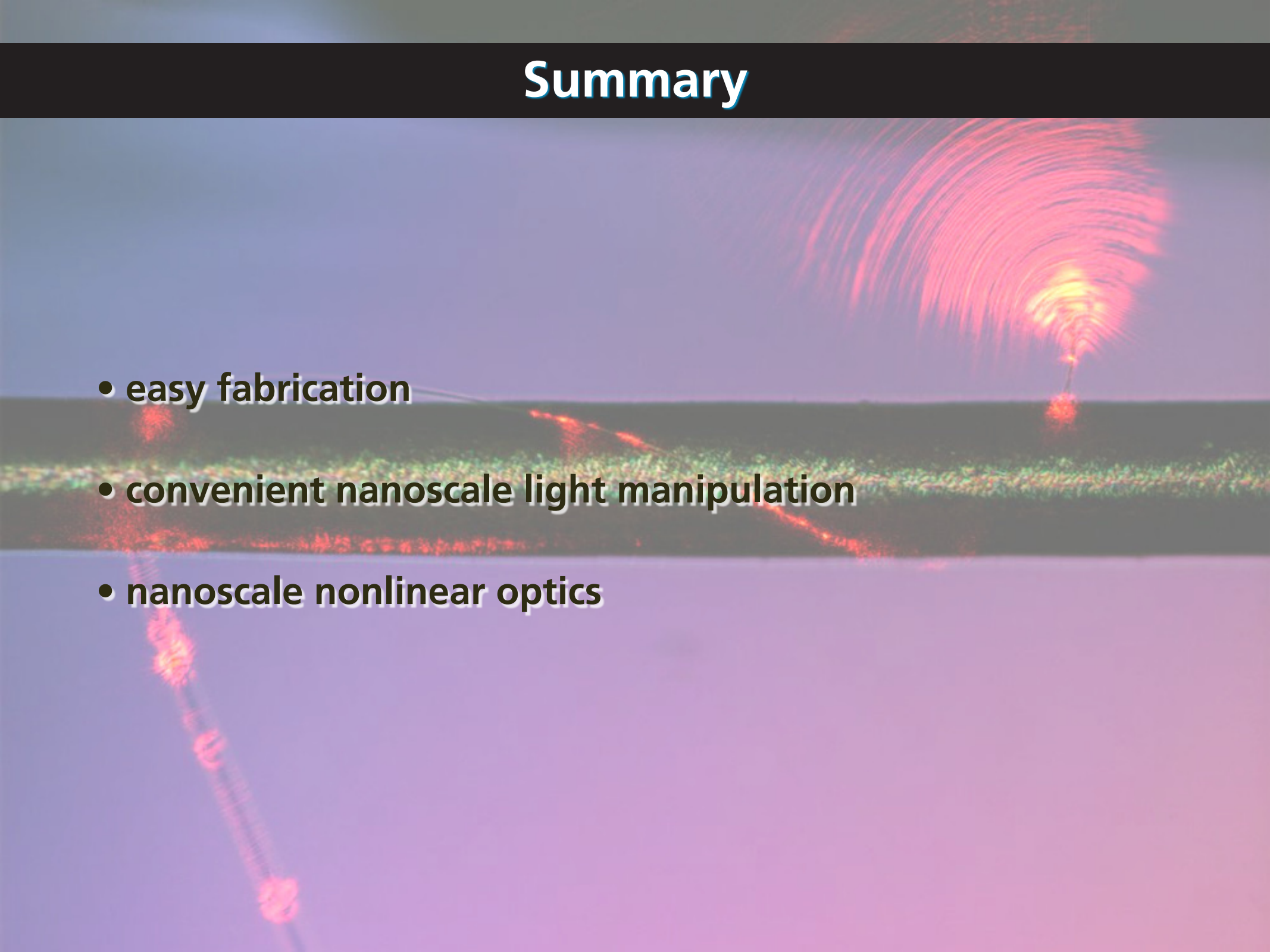




Summary



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- **easy fabrication**
 - **convenient nanoscale light manipulation**
 - **nanoscale nonlinear optics**
- 



Funding:

Harvard Center for Imaging and Mesoscopic Structures

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