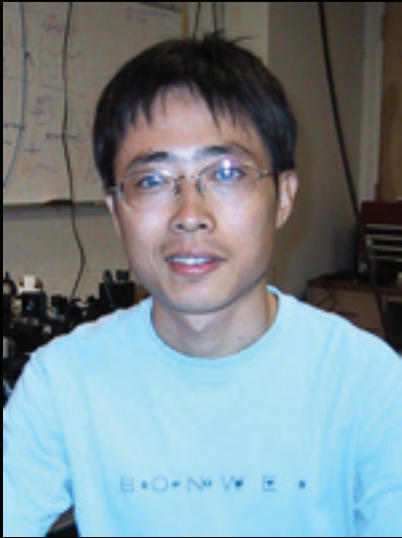


Wrapping light around a hair



Universidad Tecnológica de Panamá
Panama City, Panama, 20 marzo 2010





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

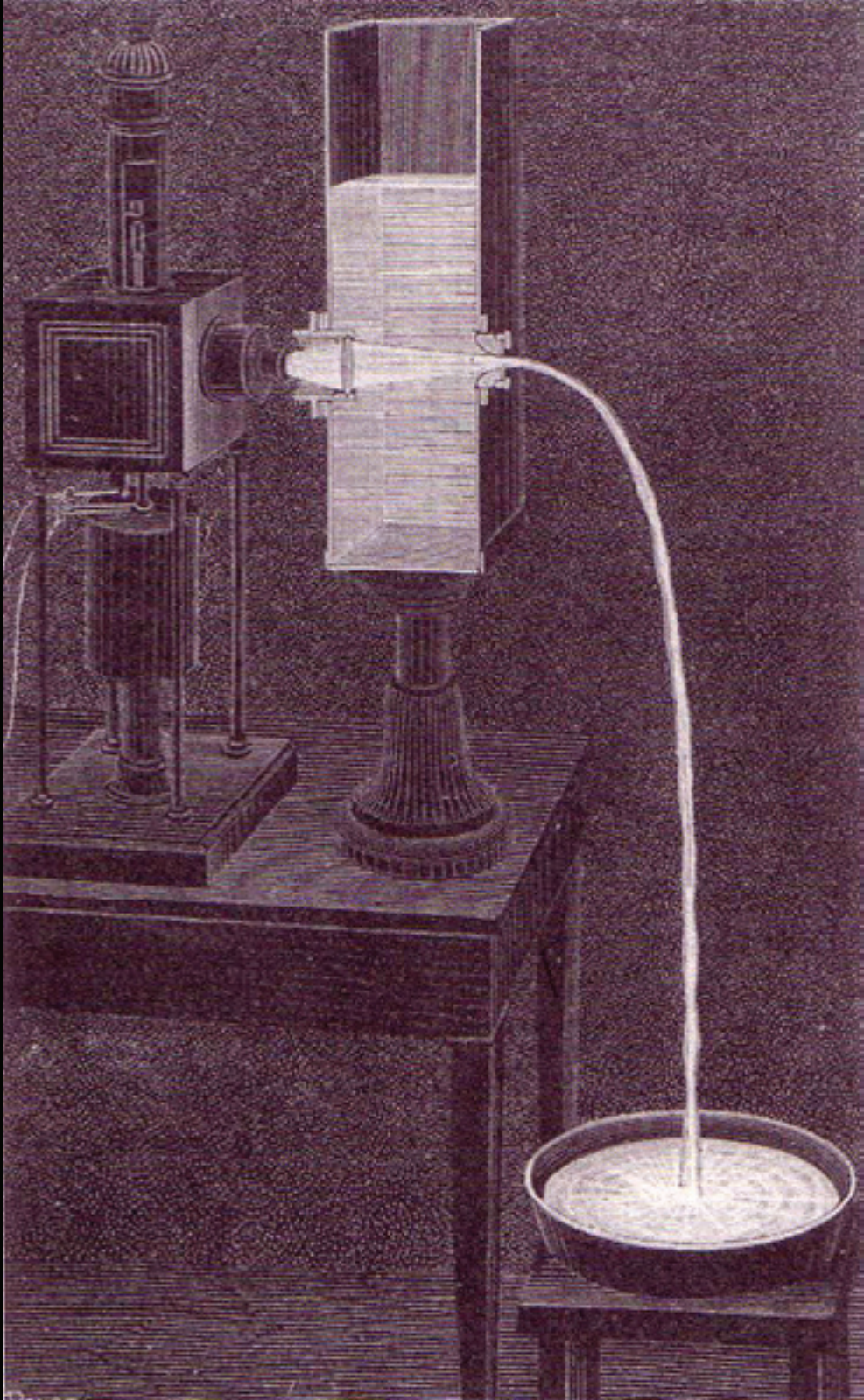
Liu Liu

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.

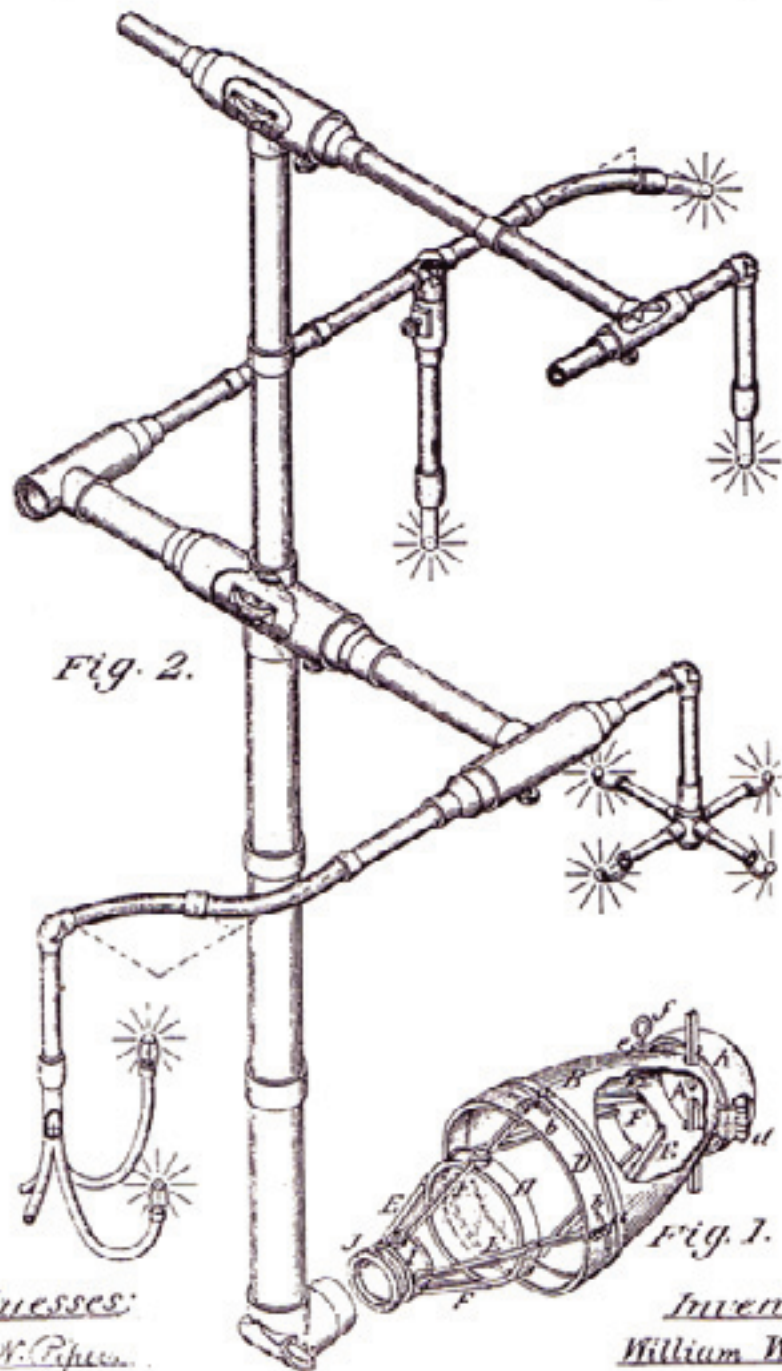


Fig. 2.

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?

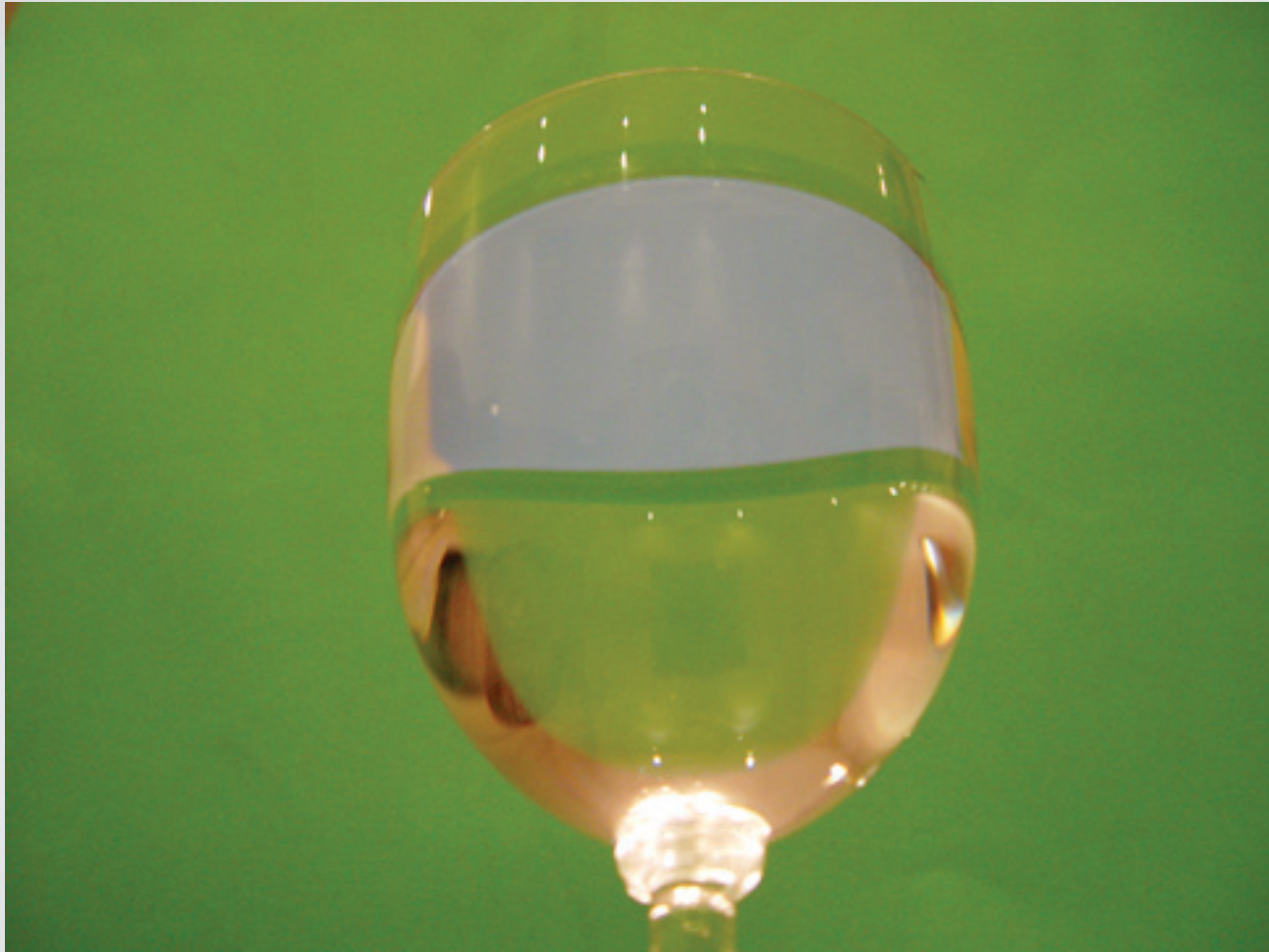


Waveguiding

from top partially transmitting!



Waveguiding

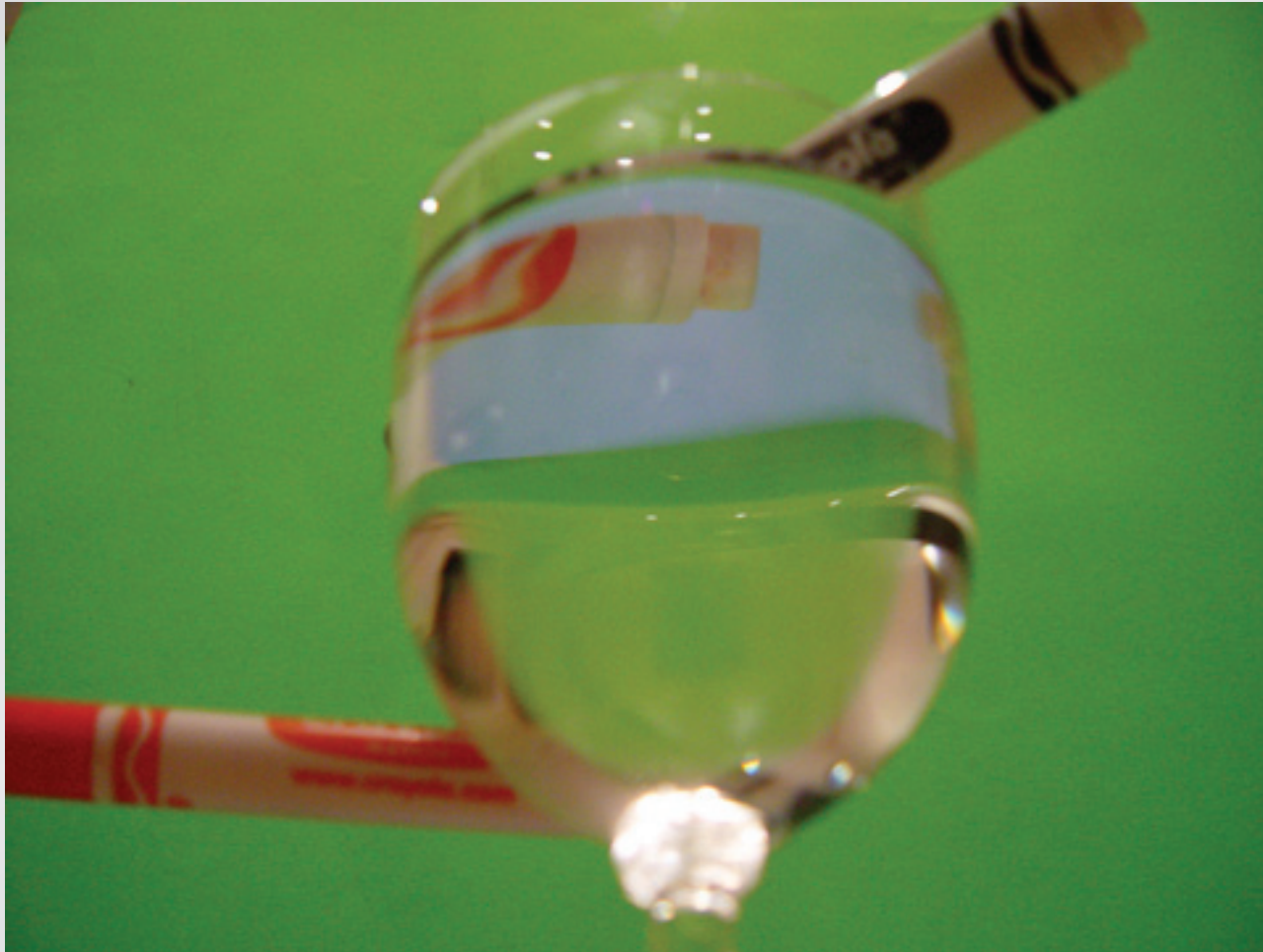


Waveguiding



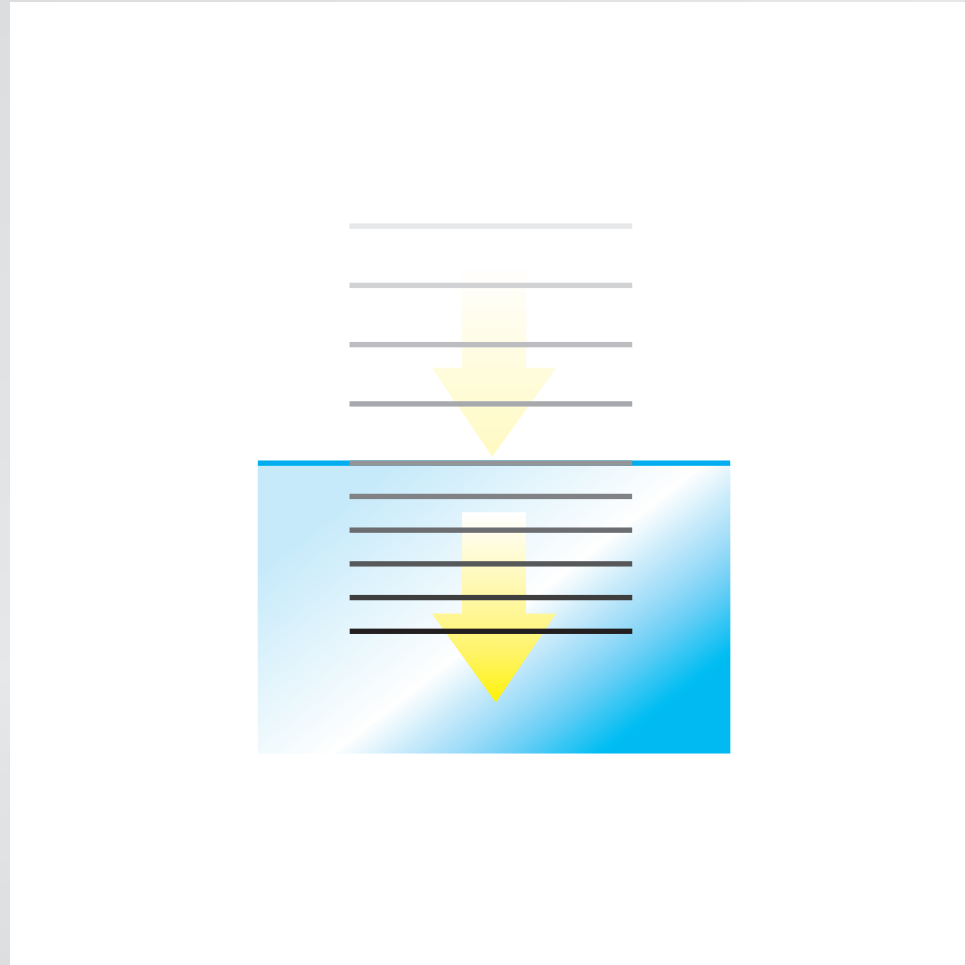
Waveguiding

water surface is perfect one-way mirror!



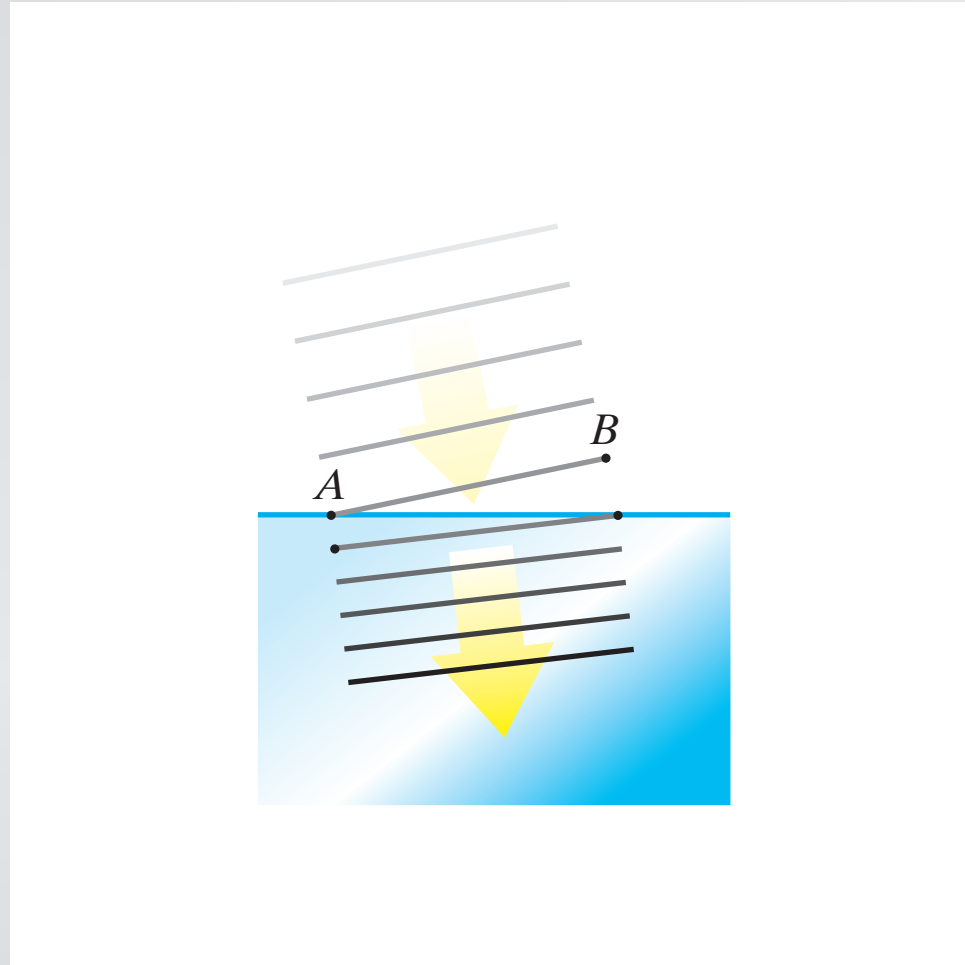
Waveguiding

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



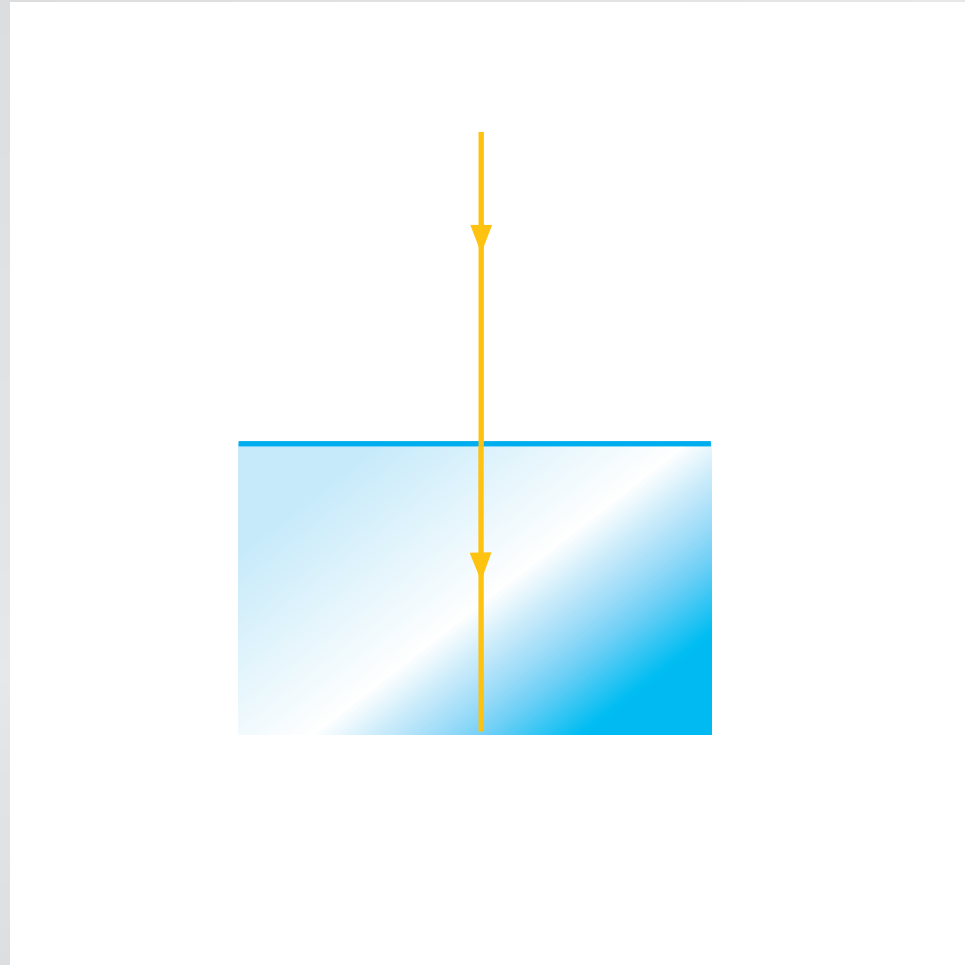
Waveguiding

...making it bend as it crosses surface



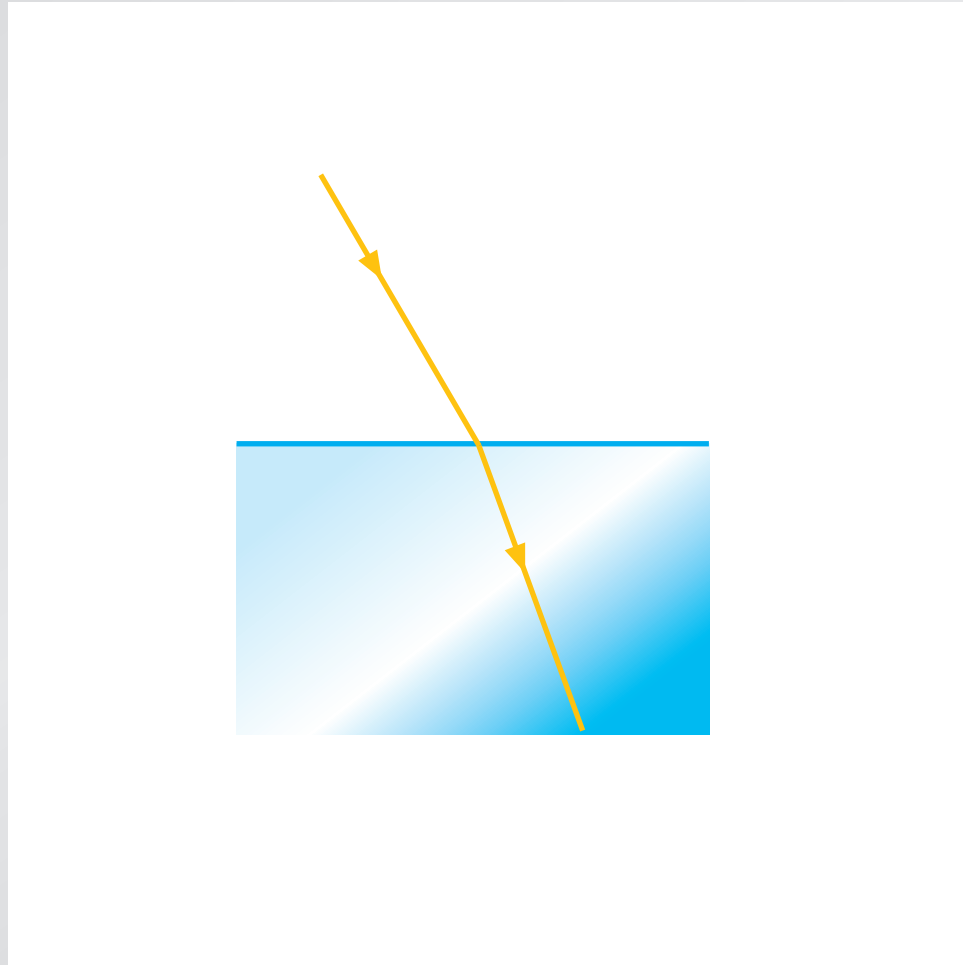
Waveguiding

The more angled the incident ray, the stronger the bending



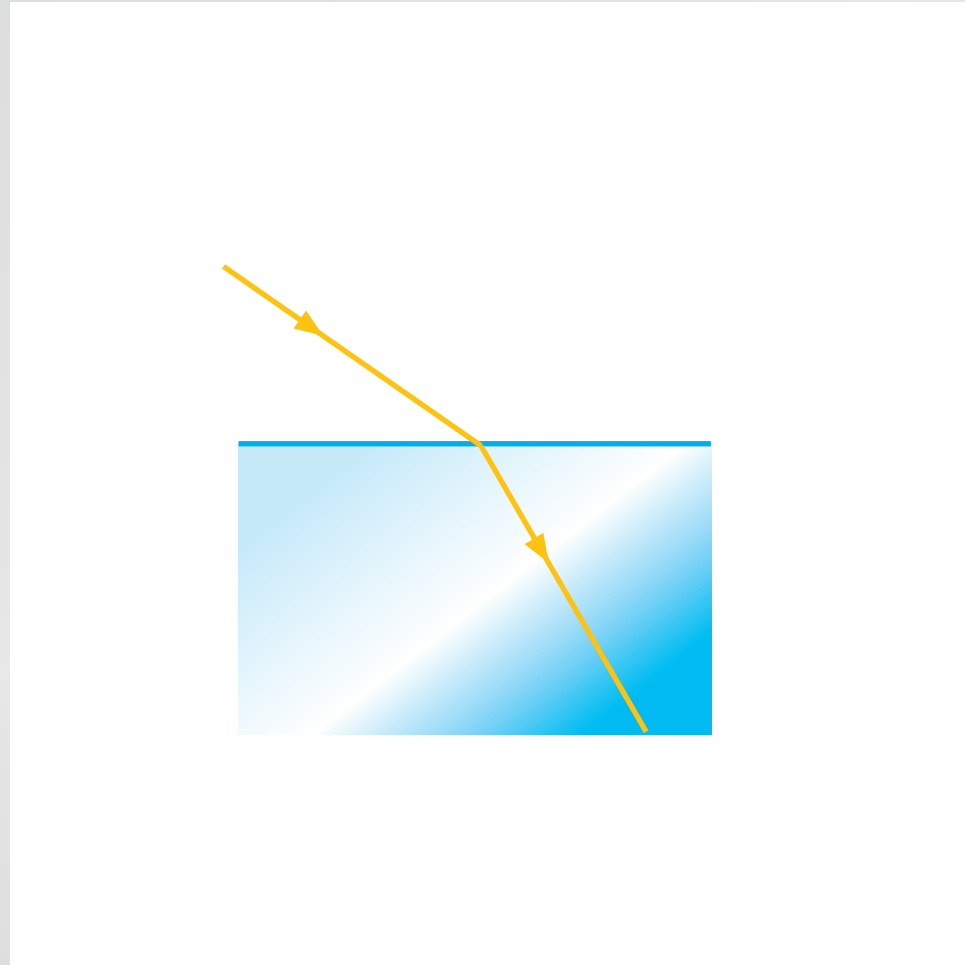
Waveguiding

The more angled the incident ray, the stronger the bending



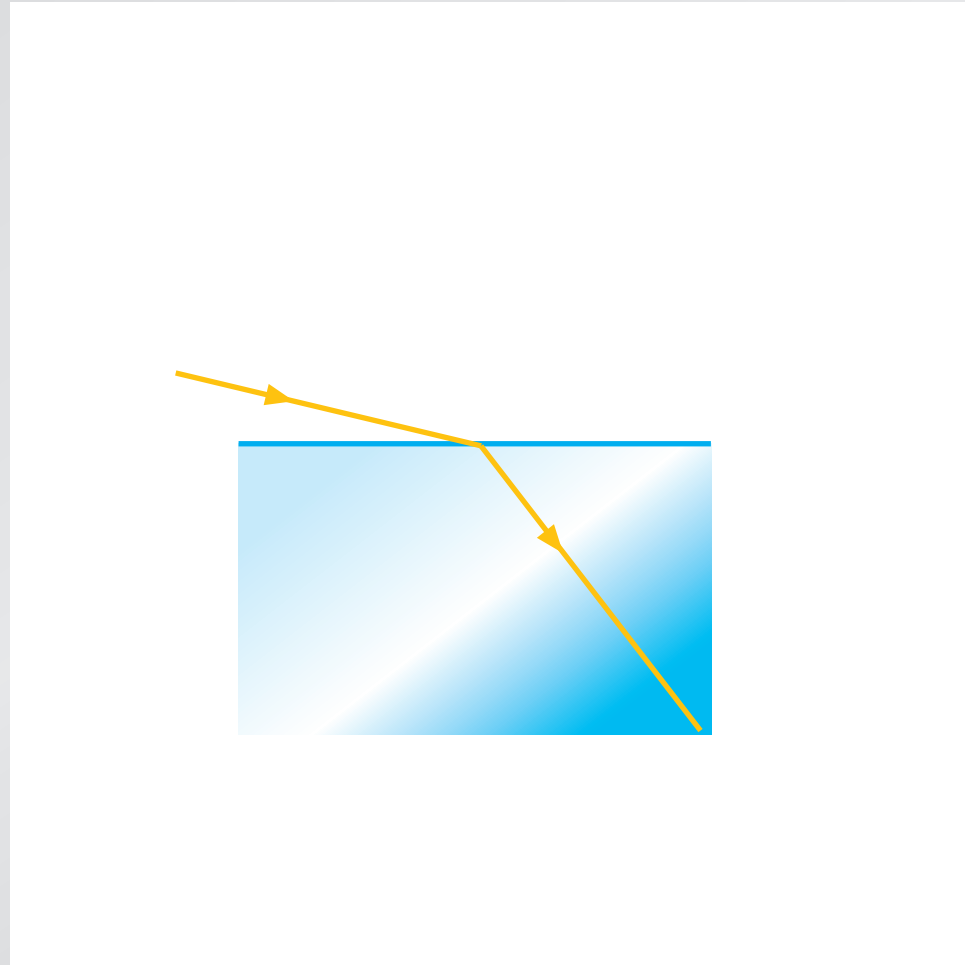
Waveguiding

The more angled the incident ray, the stronger the bending



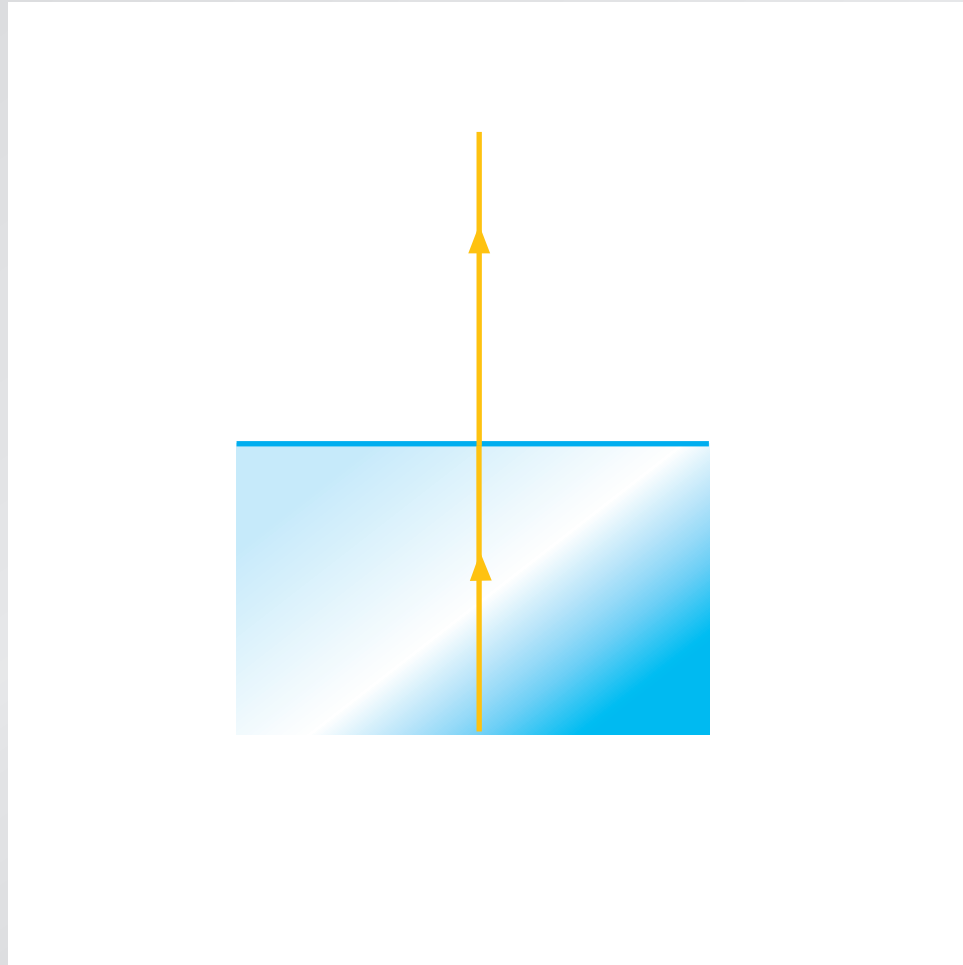
Waveguiding

The more angled the incident ray, the stronger the bending



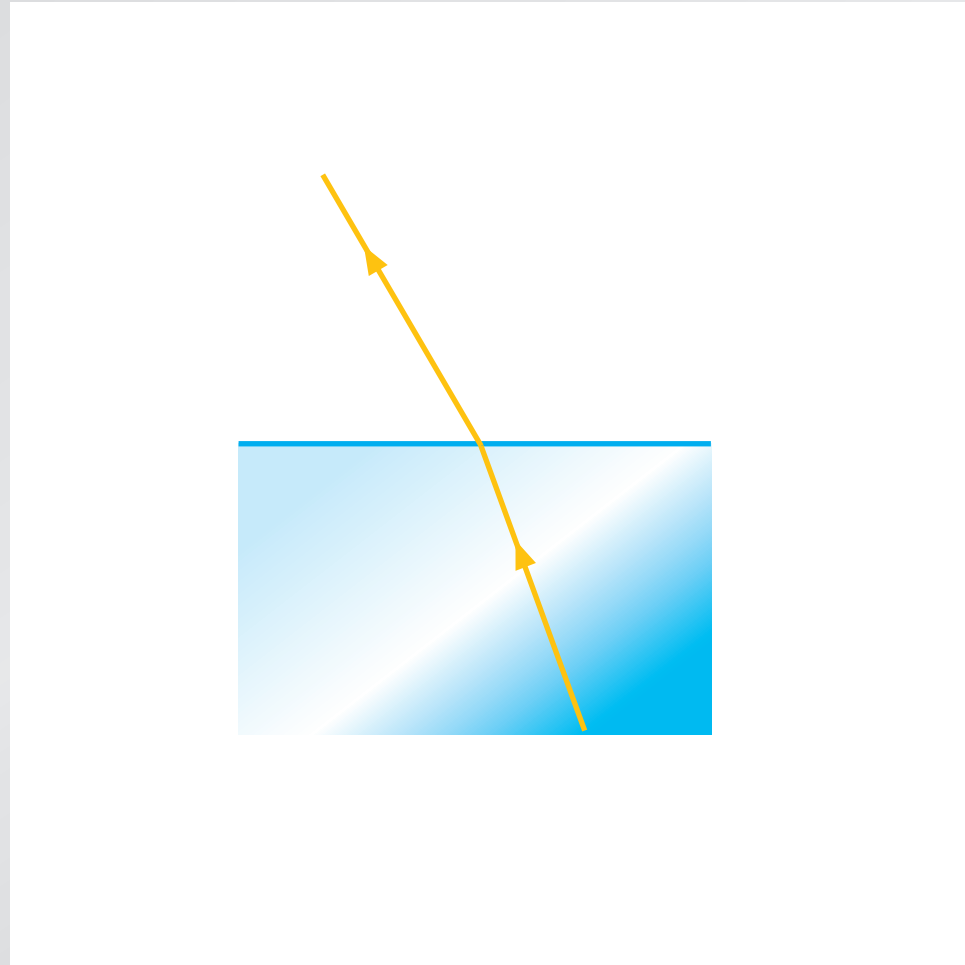
Waveguiding

The amount of bending is the same in reverse



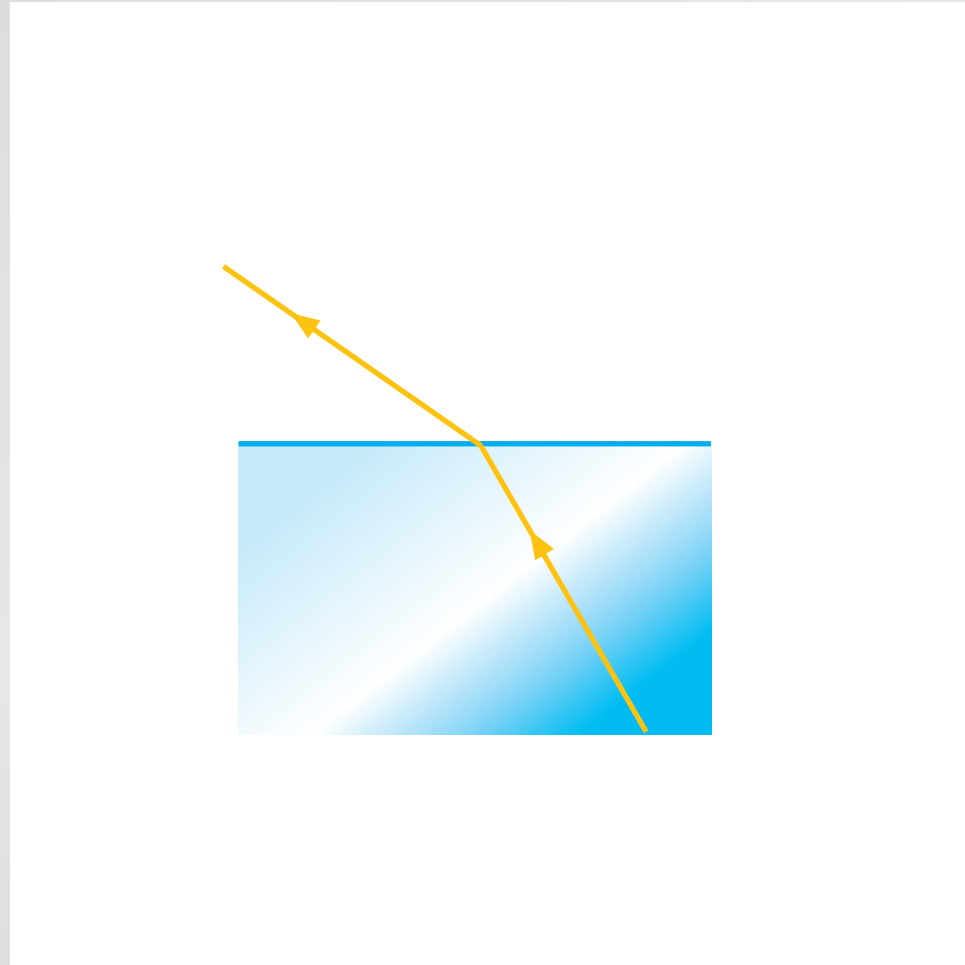
Waveguiding

The amount of bending is the same in reverse



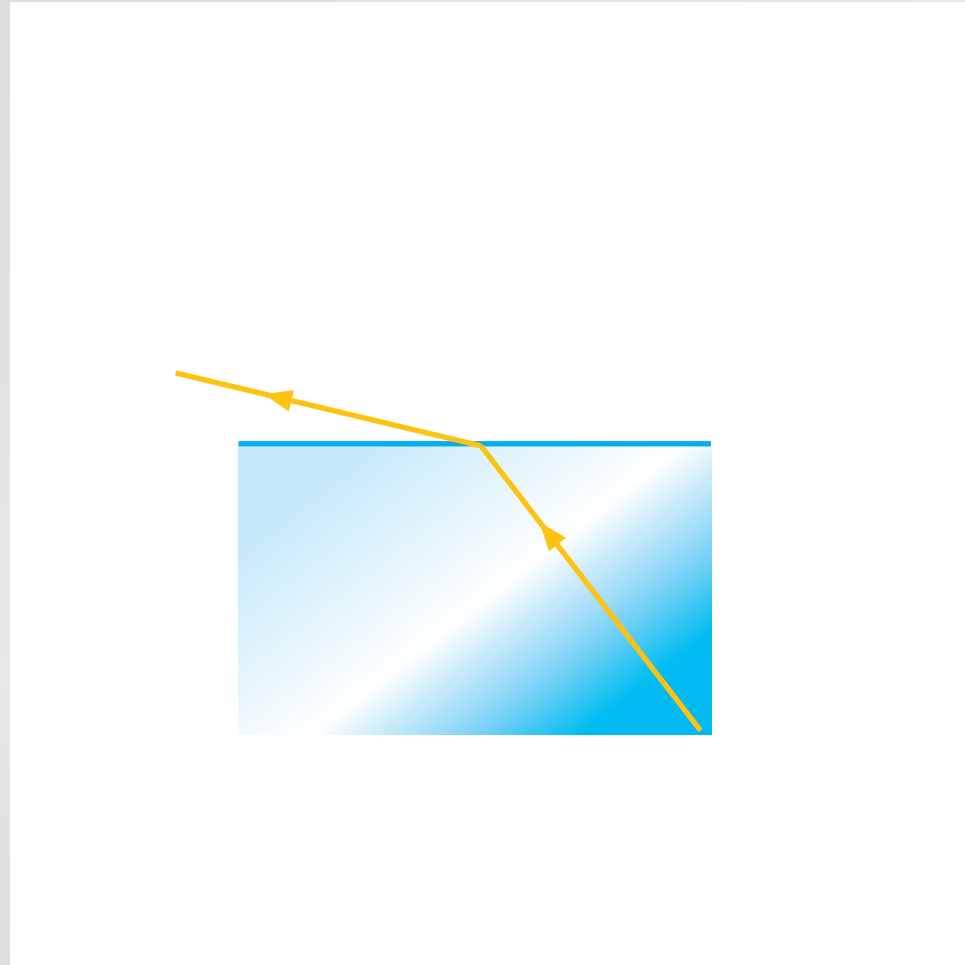
Waveguiding

The amount of bending is the same in reverse



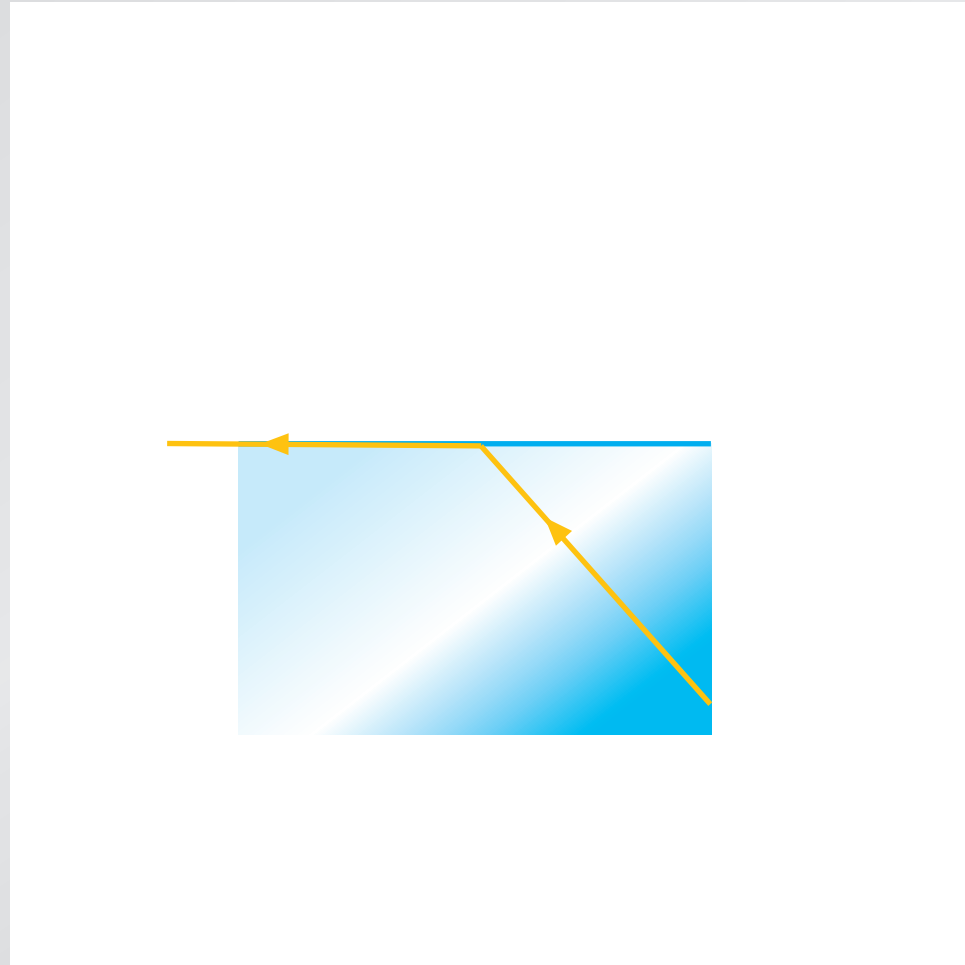
Waveguiding

The amount of bending is the same in reverse



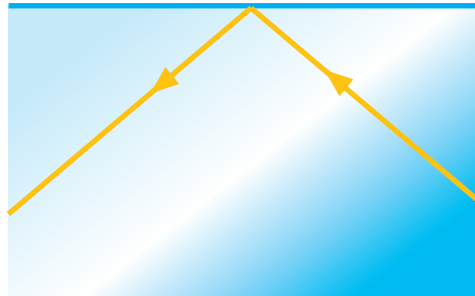
Waveguiding

At 'critical angle' bent ray travels along surface



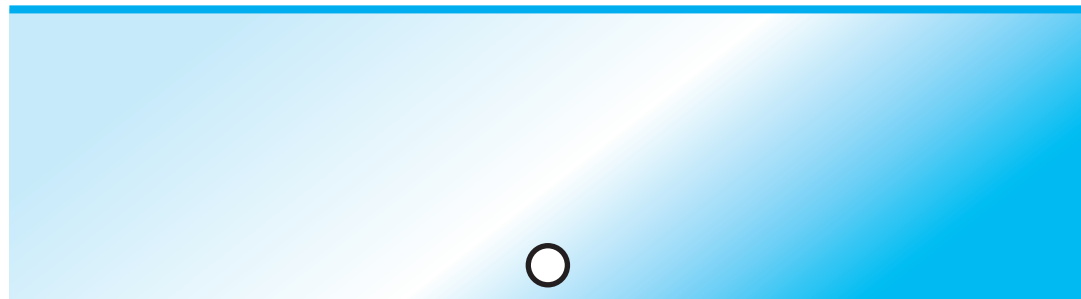
Waveguiding

Beyond 'critical angle': total internal reflection



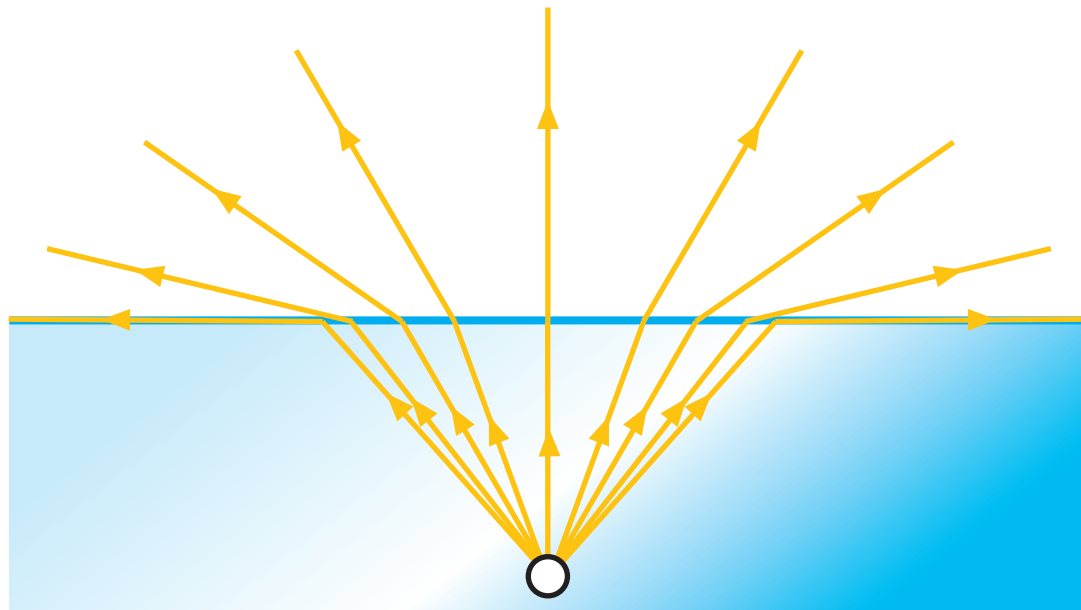
Waveguiding

seeing underwater



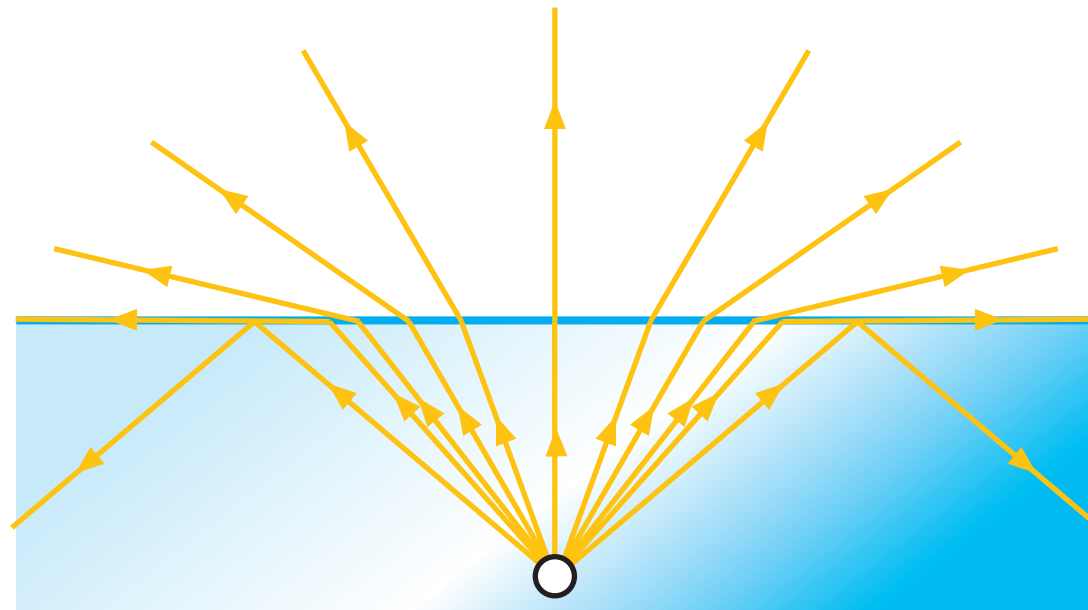
Waveguiding

seeing underwater



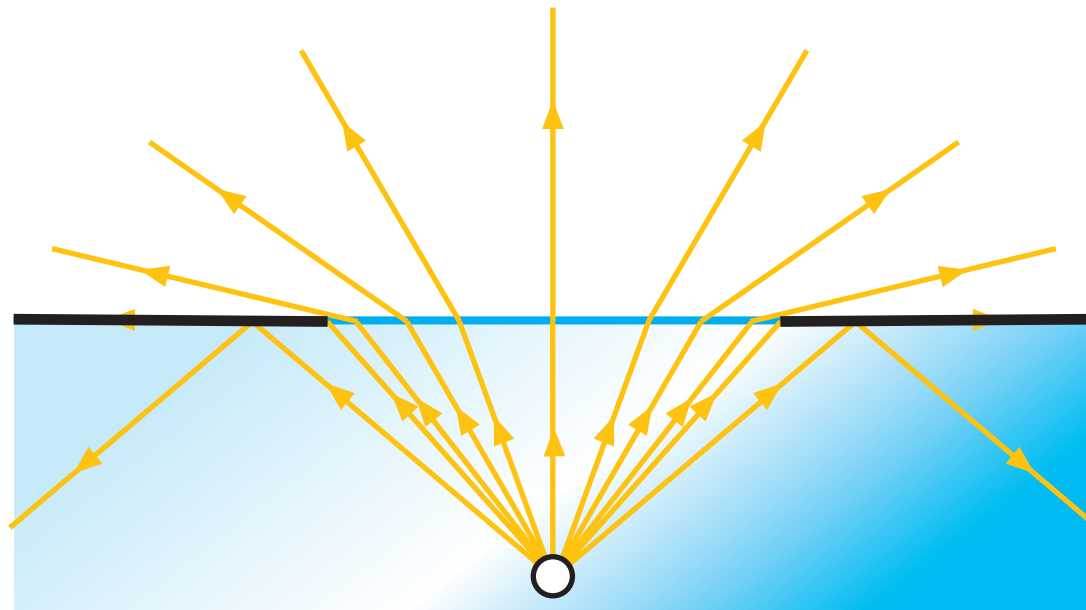
Waveguiding

seeing underwater



Waveguiding

surface looks like mirror with a circular hole



Waveguiding



Waveguiding



Waveguiding



Waveguiding

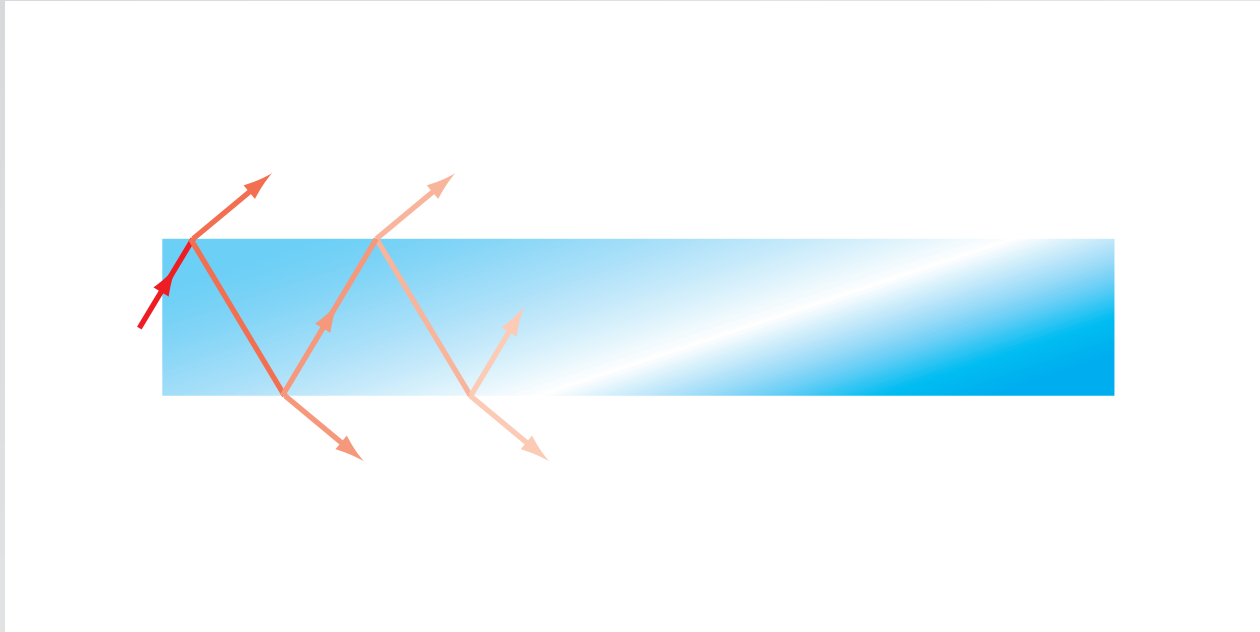


Waveguiding



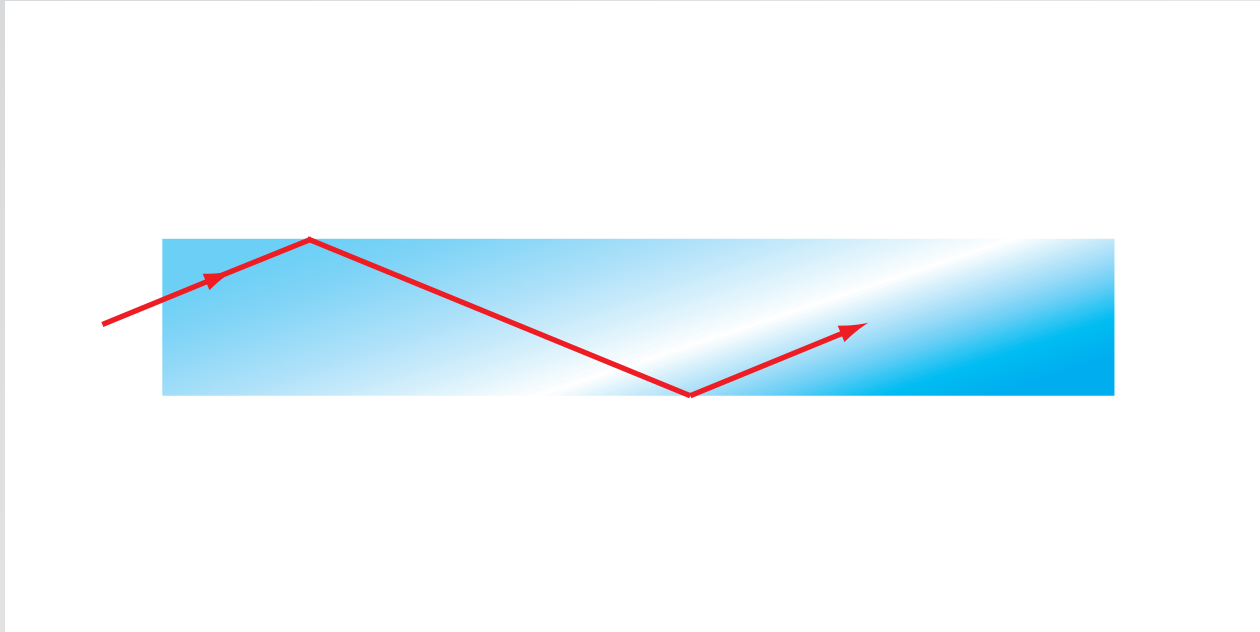
now consider a planar dielectric waveguide

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

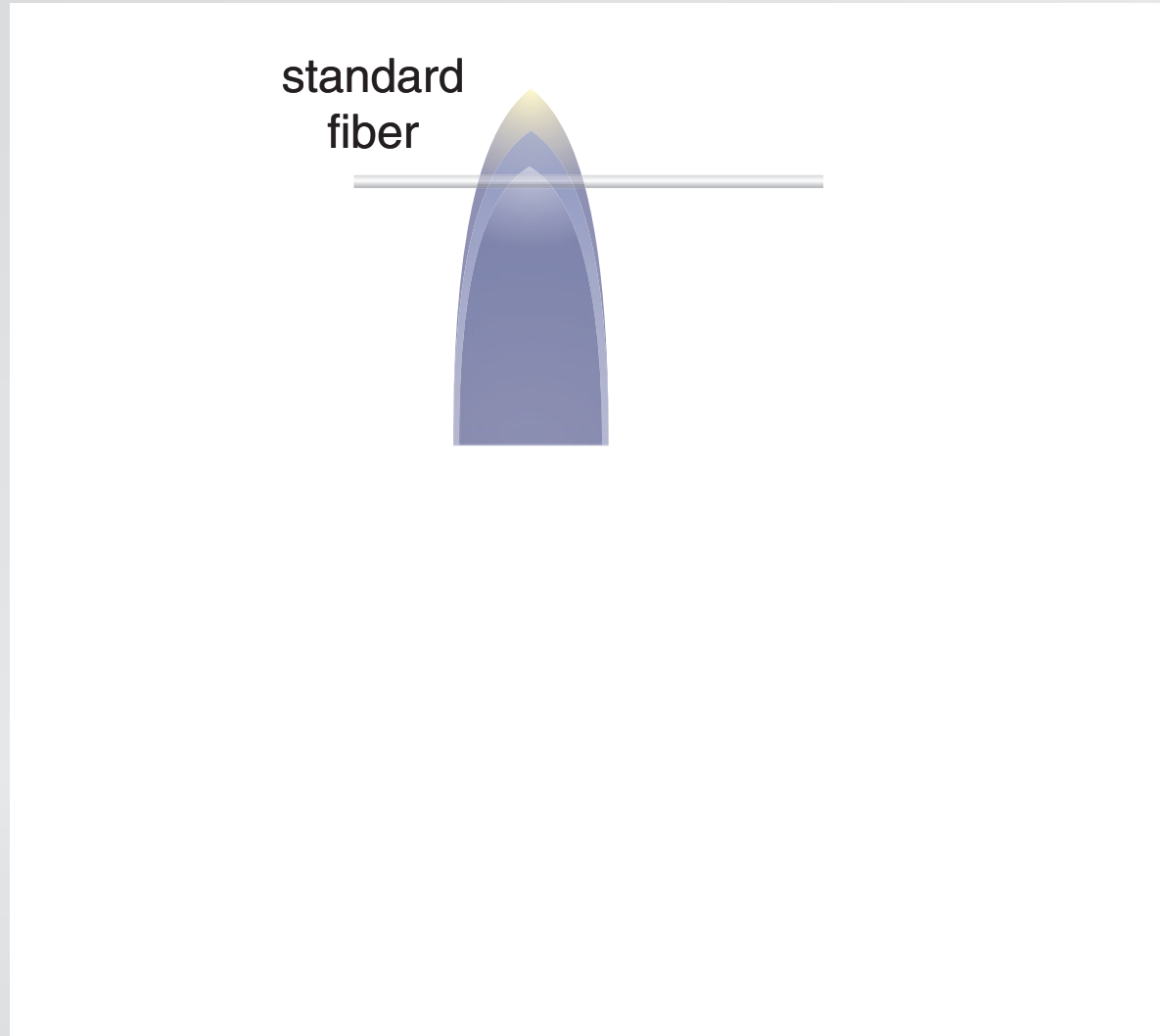
two-step drawing process

standard
fiber



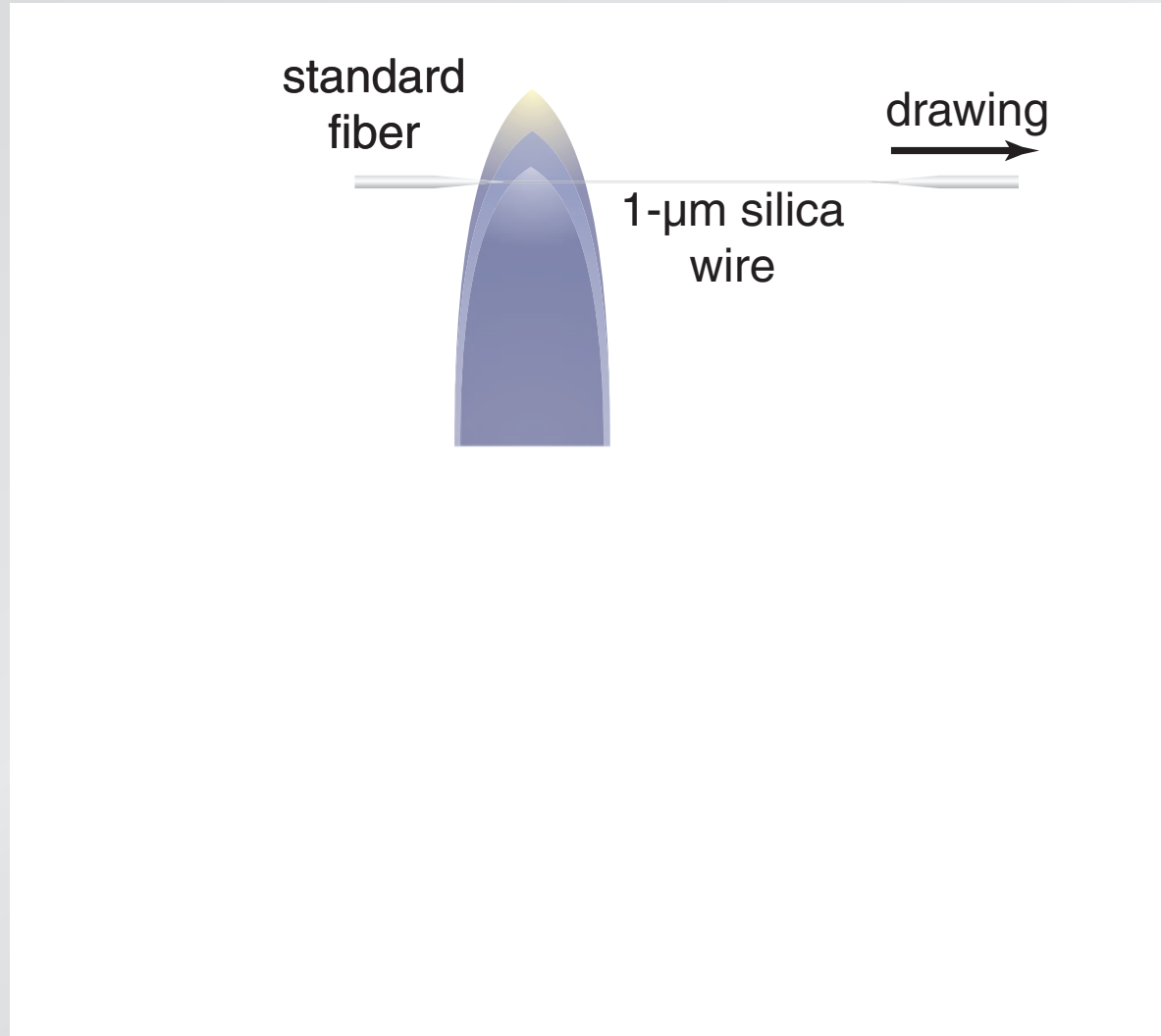
Nanowire fabrication

two-step drawing process



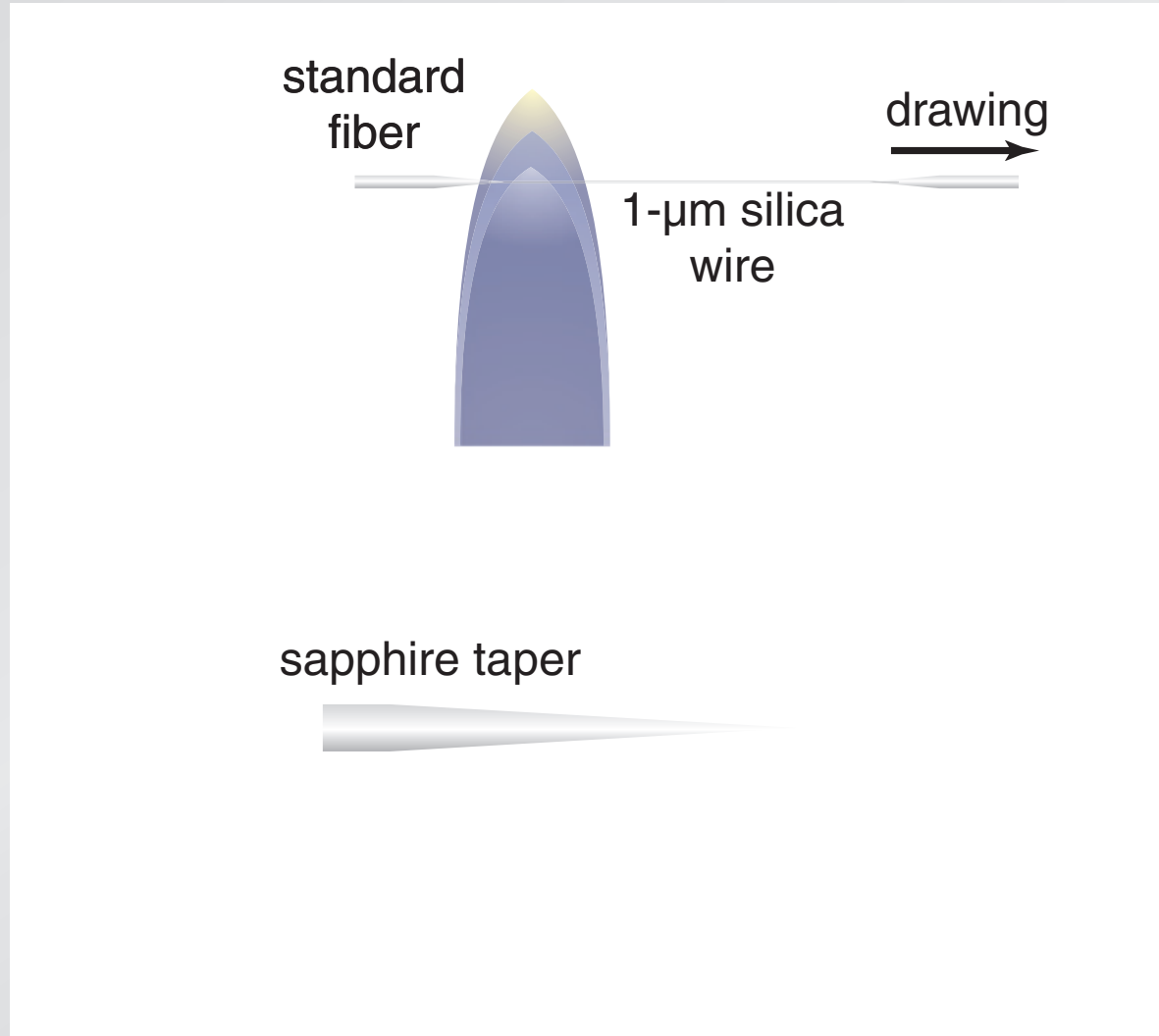
Nanowire fabrication

two-step drawing process



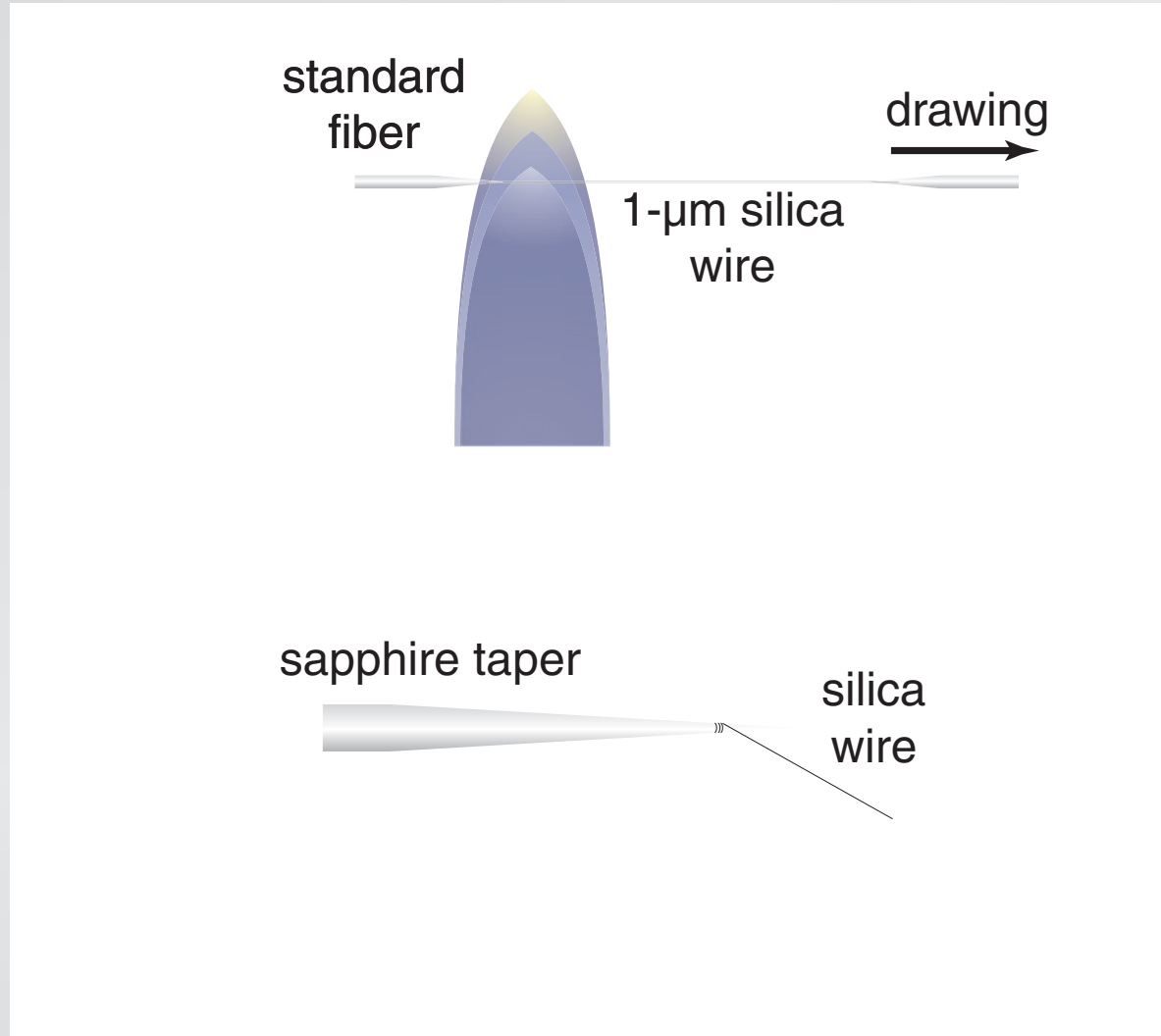
Nanowire fabrication

two-step drawing process



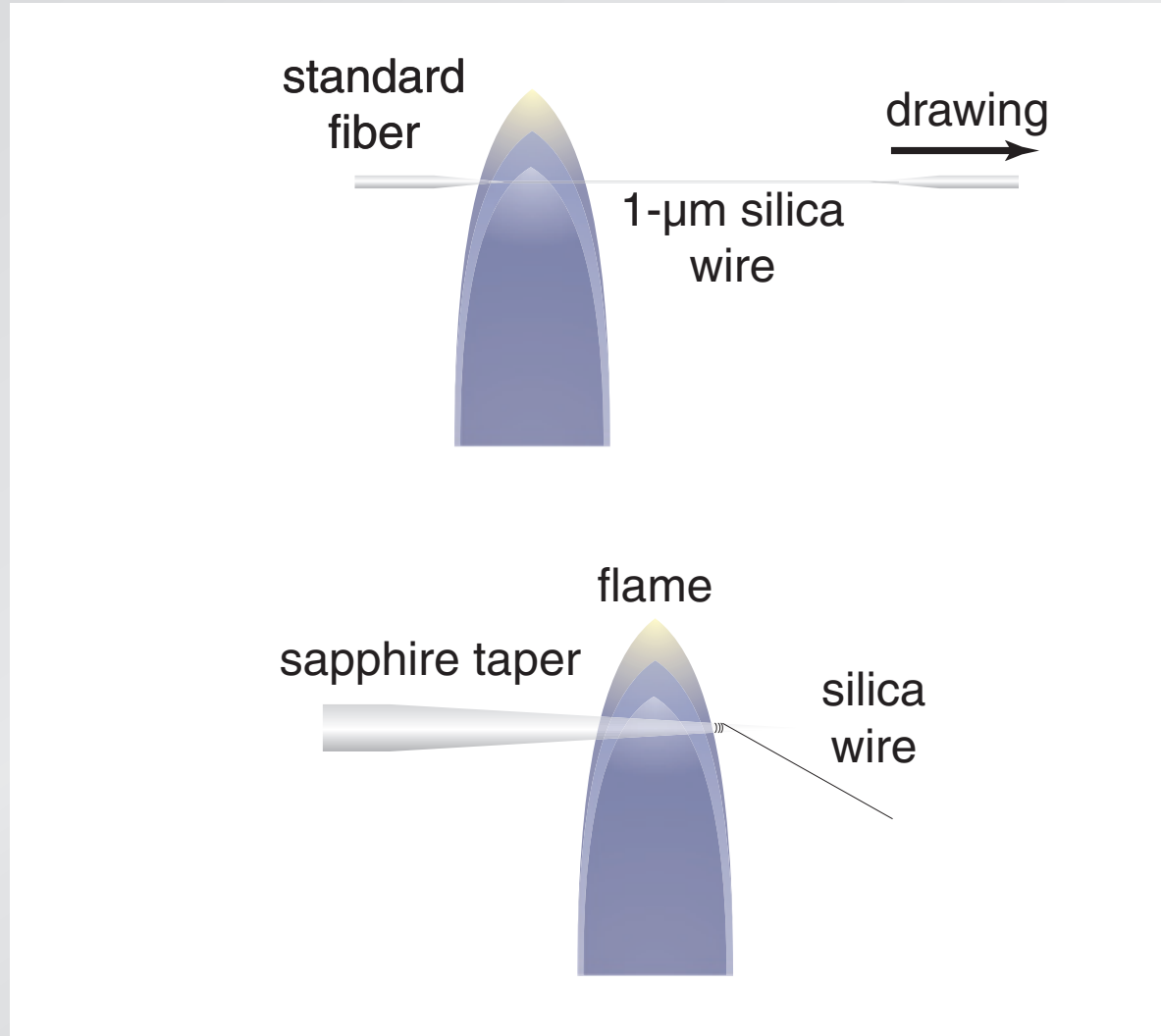
Nanowire fabrication

two-step drawing process



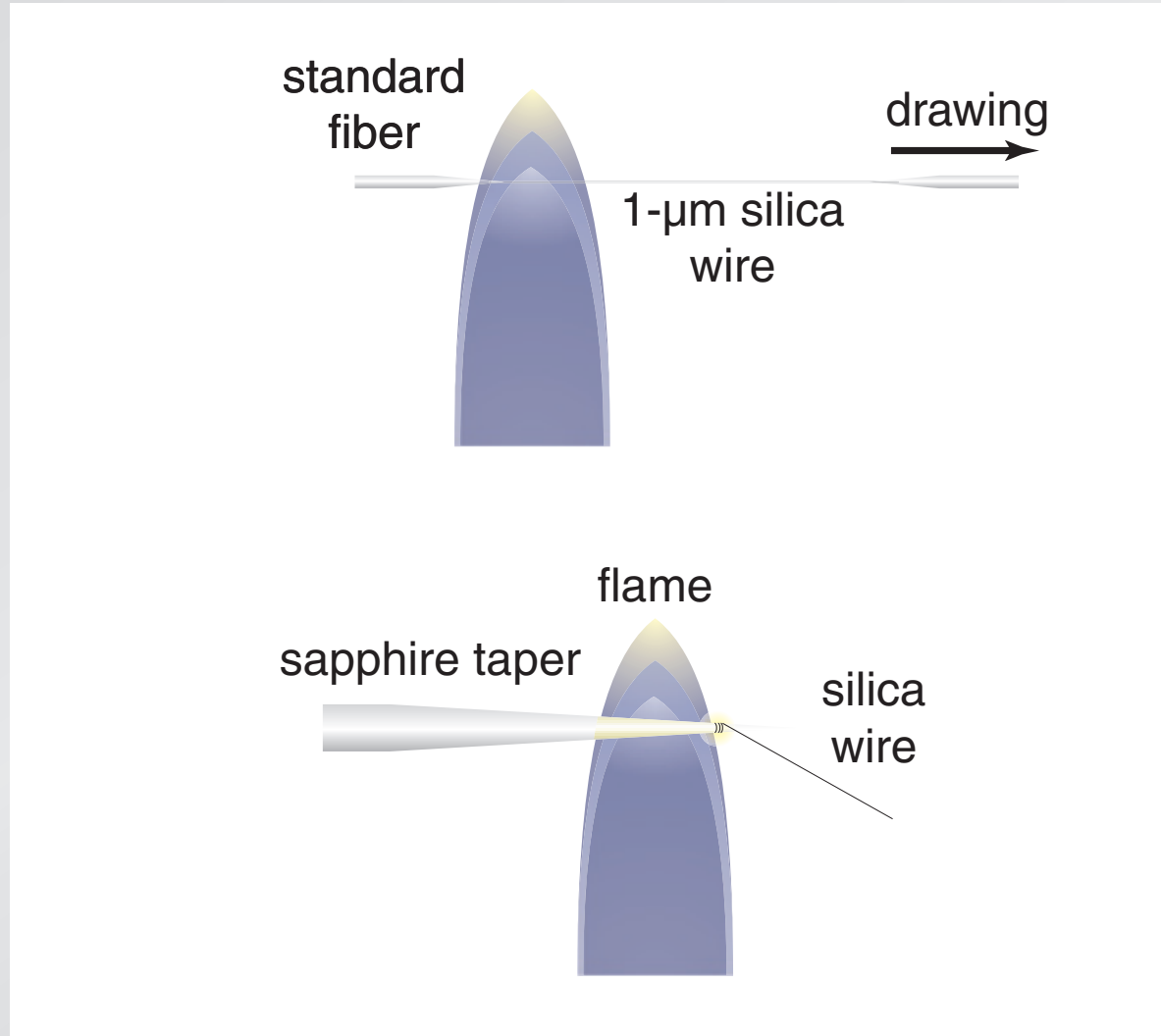
Nanowire fabrication

two-step drawing process



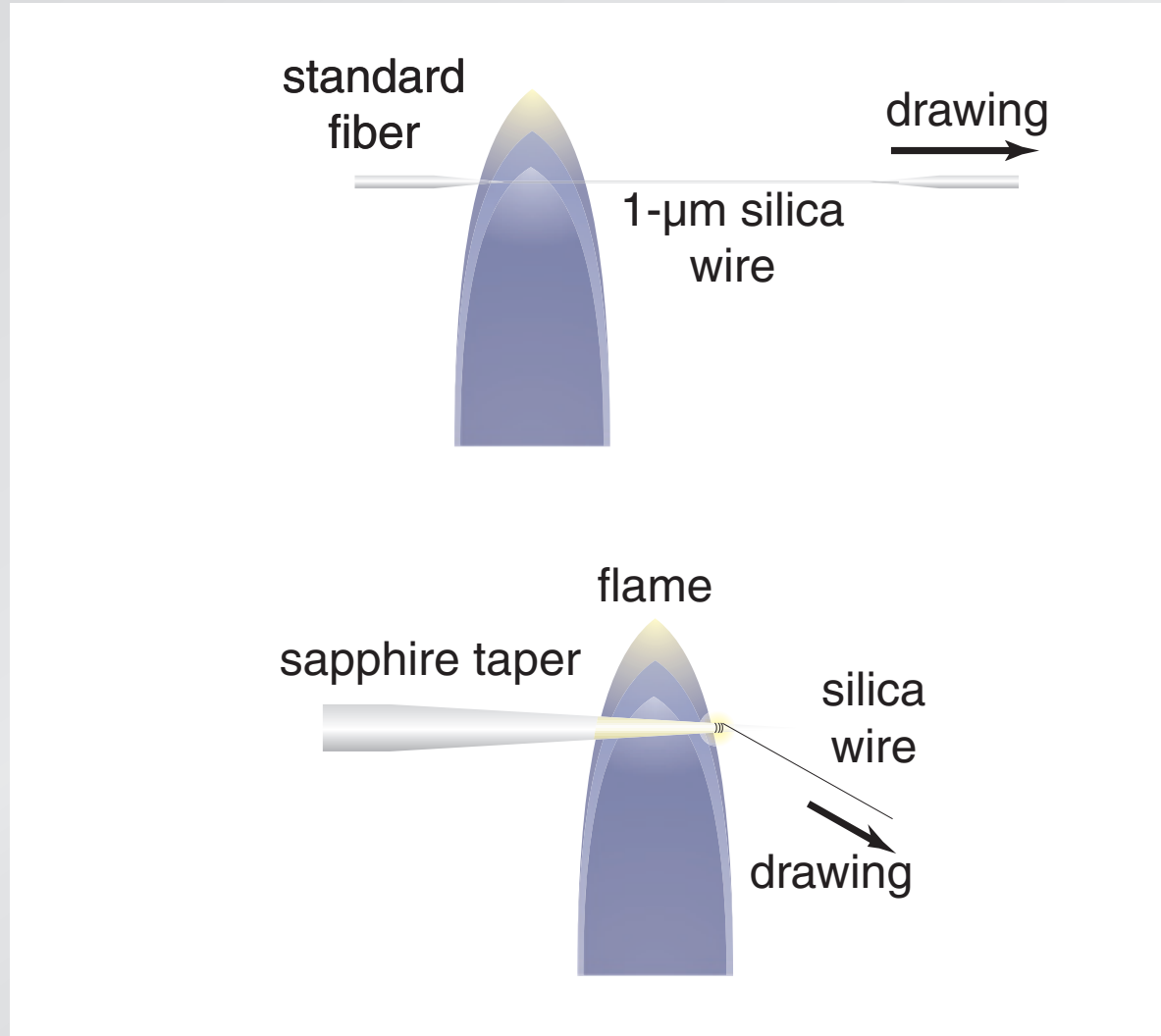
Nanowire fabrication

two-step drawing process

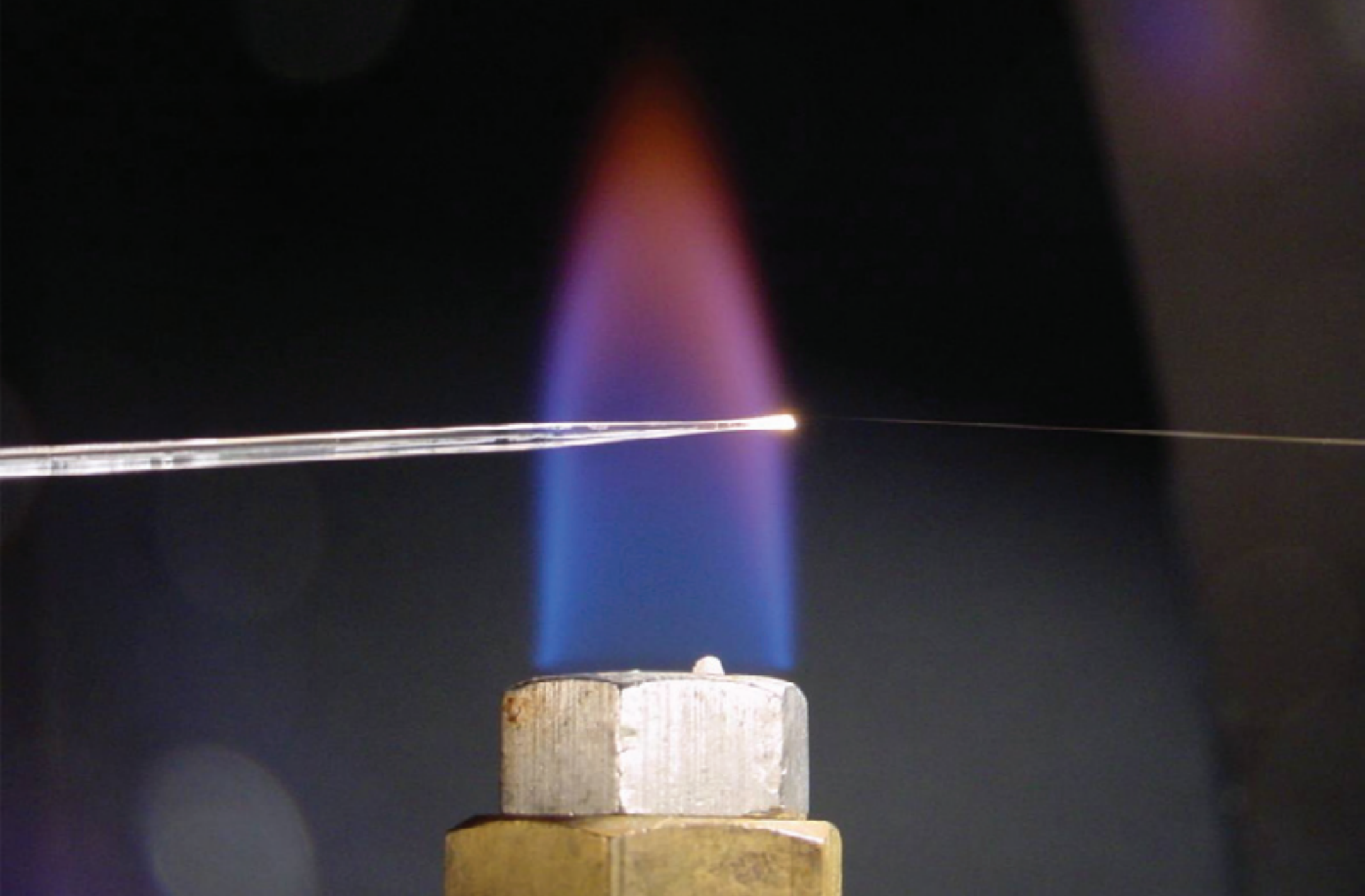


Nanowire fabrication

two-step drawing process



Nanowire fabrication



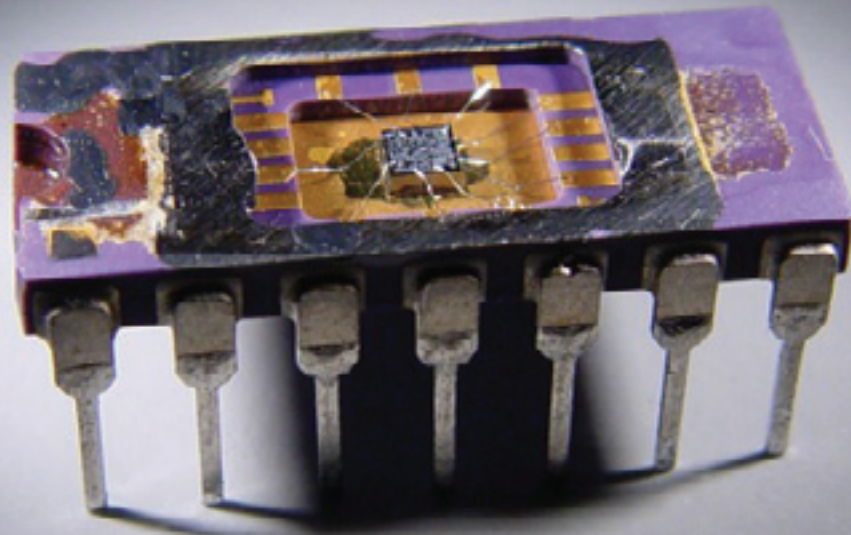
Nanowire fabrication

1 μm

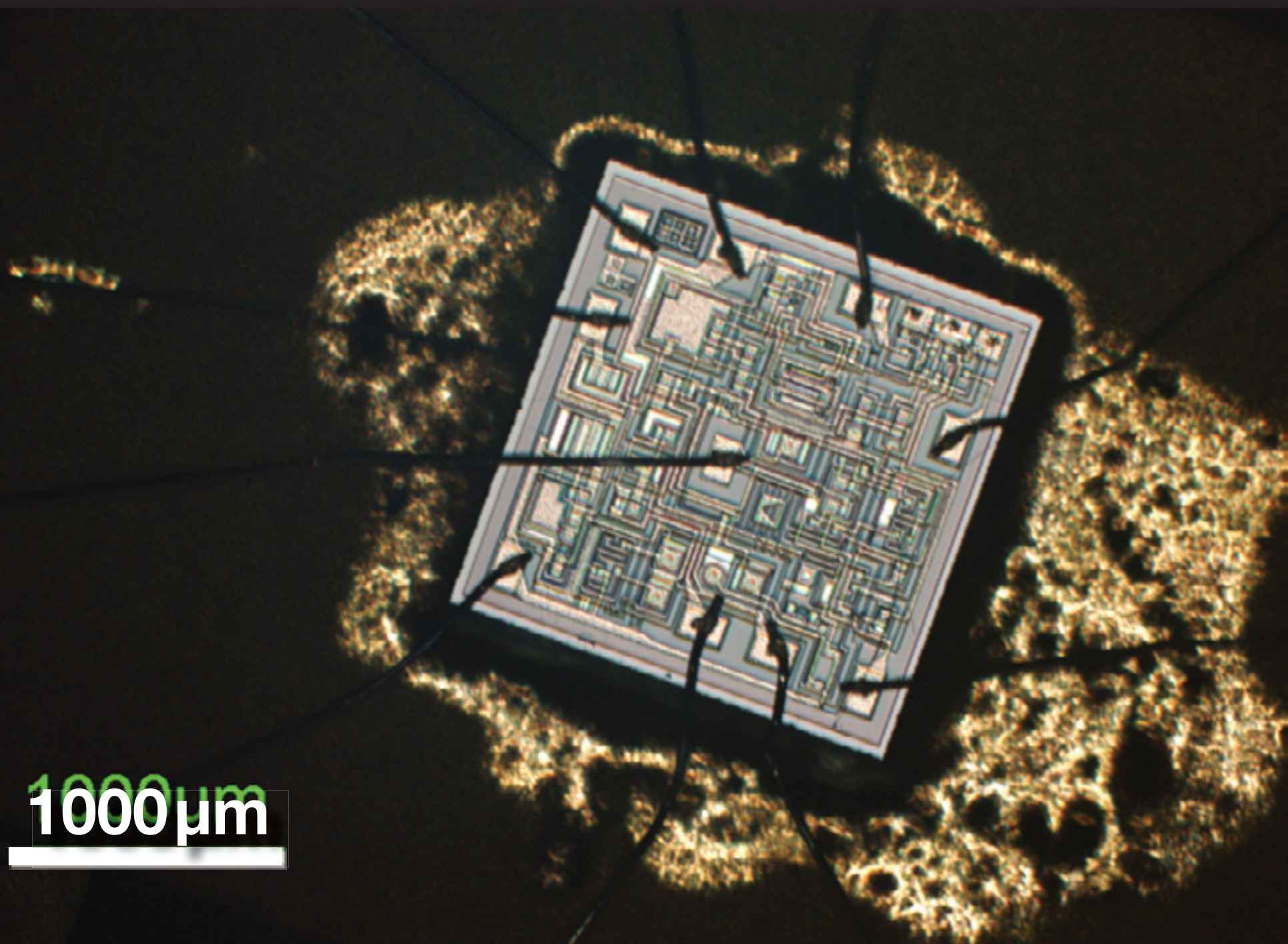


Nature, 426, 816 (2003)

Nanowire fabrication

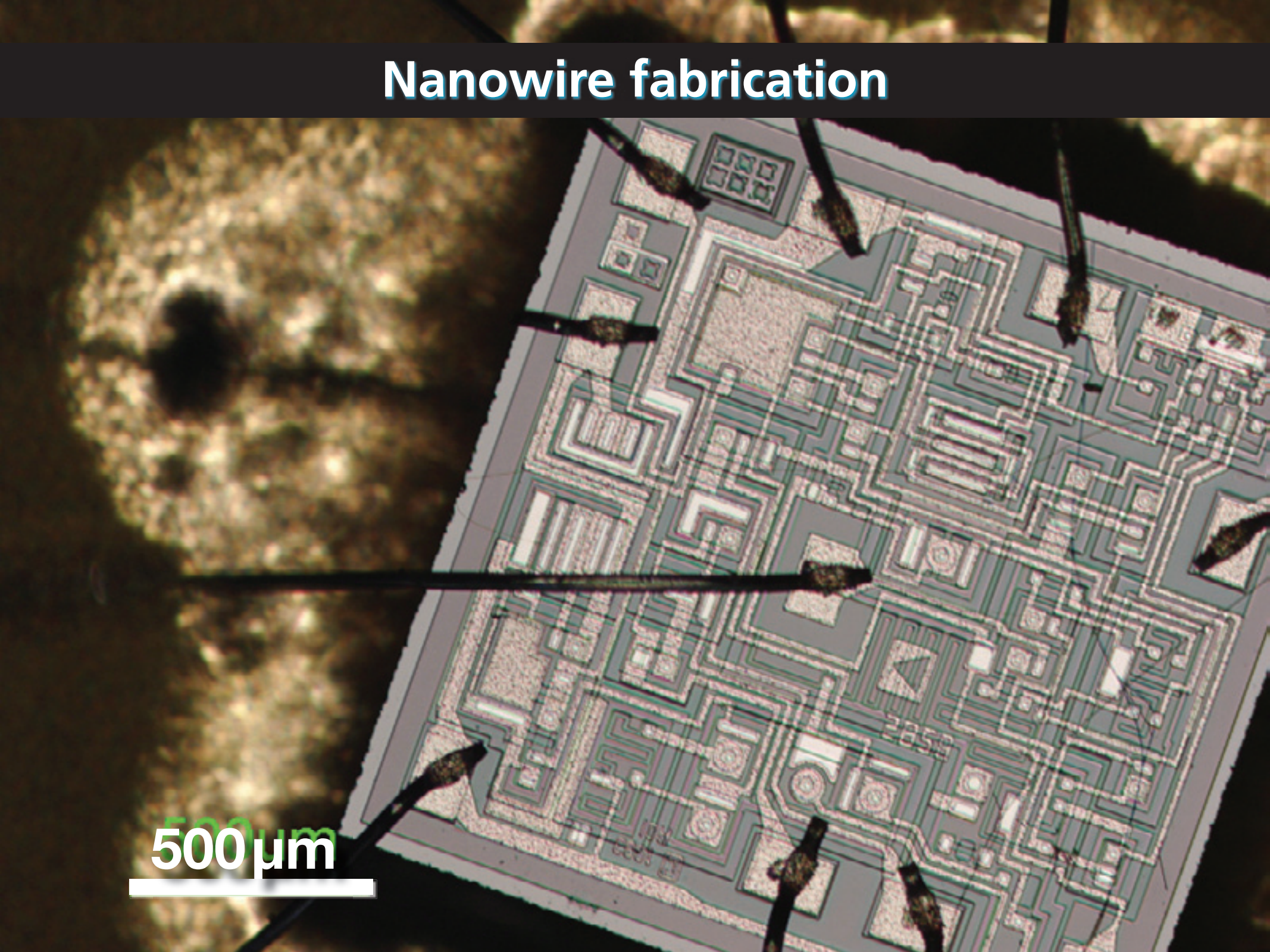


Nanowire fabrication

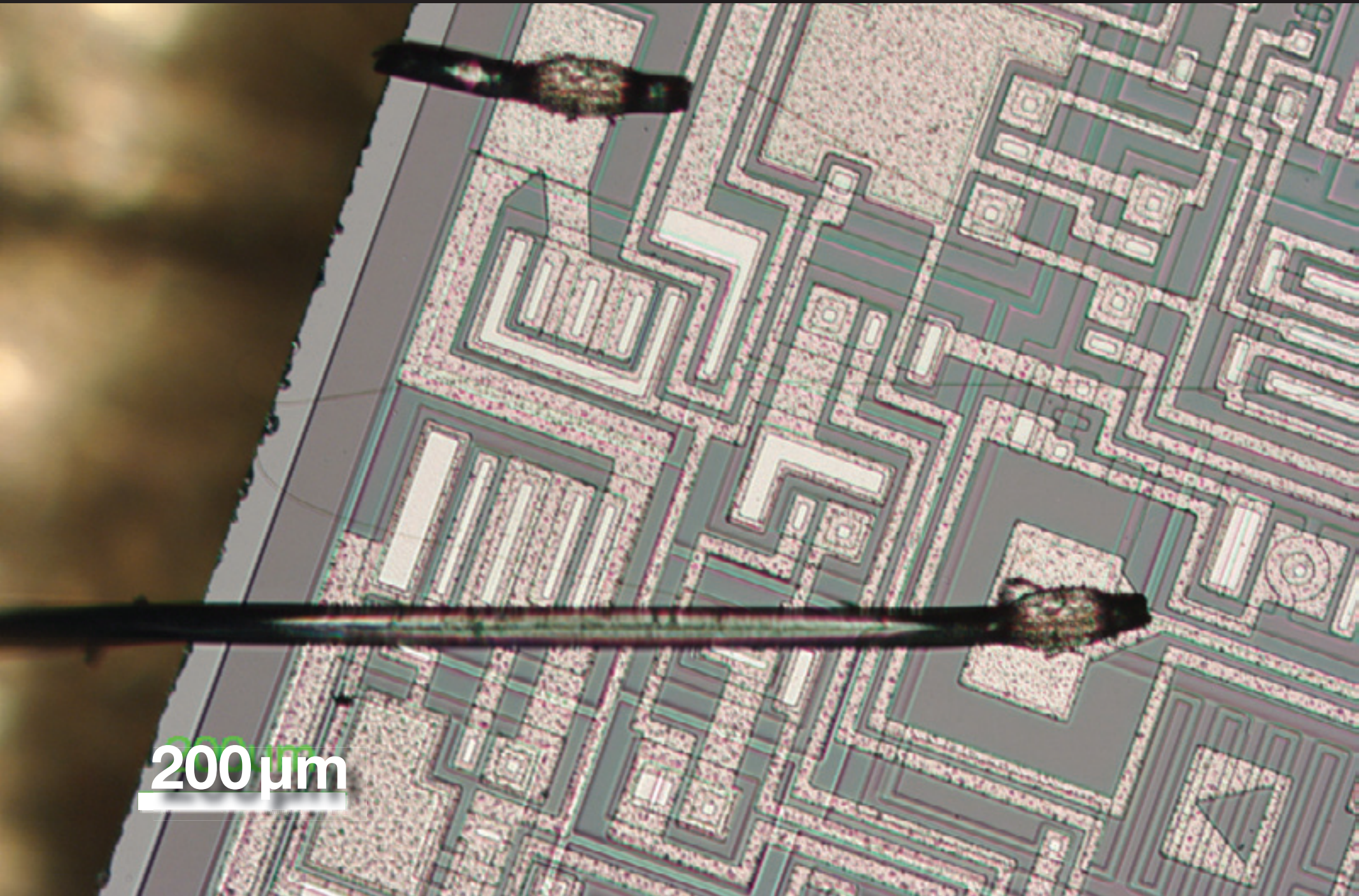


Nanowire fabrication

500 μm

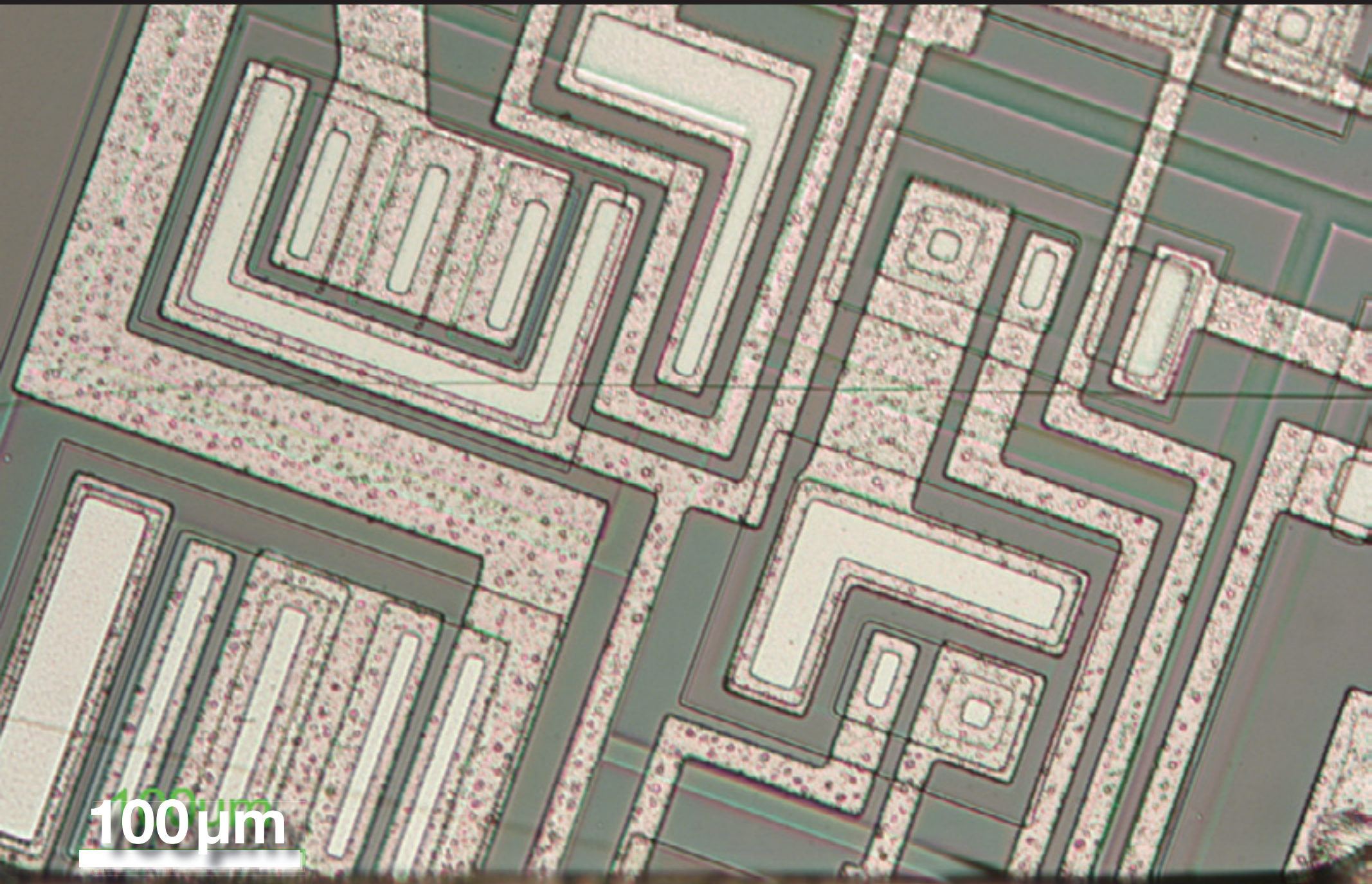


Nanowire fabrication

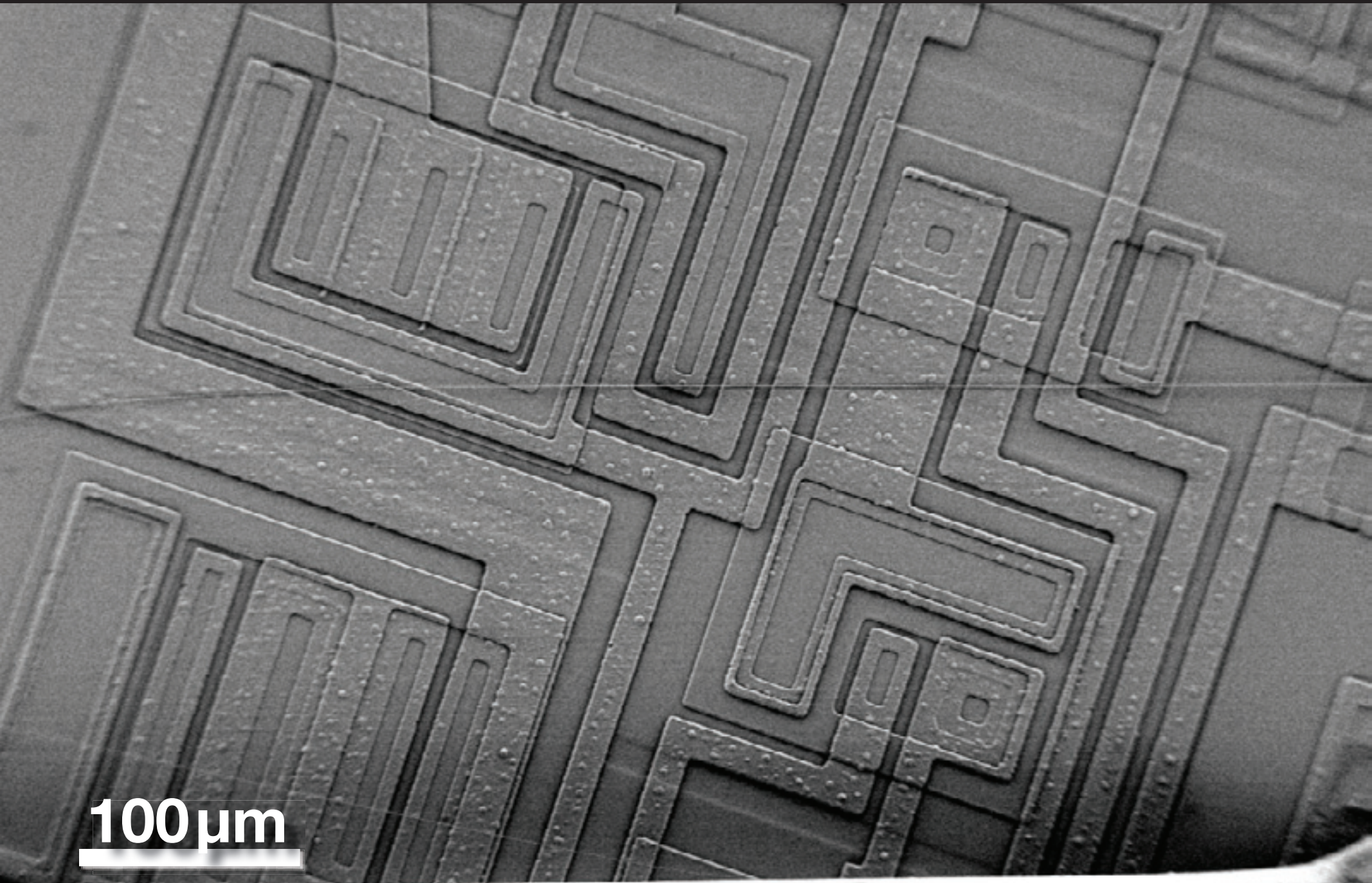


200 μm

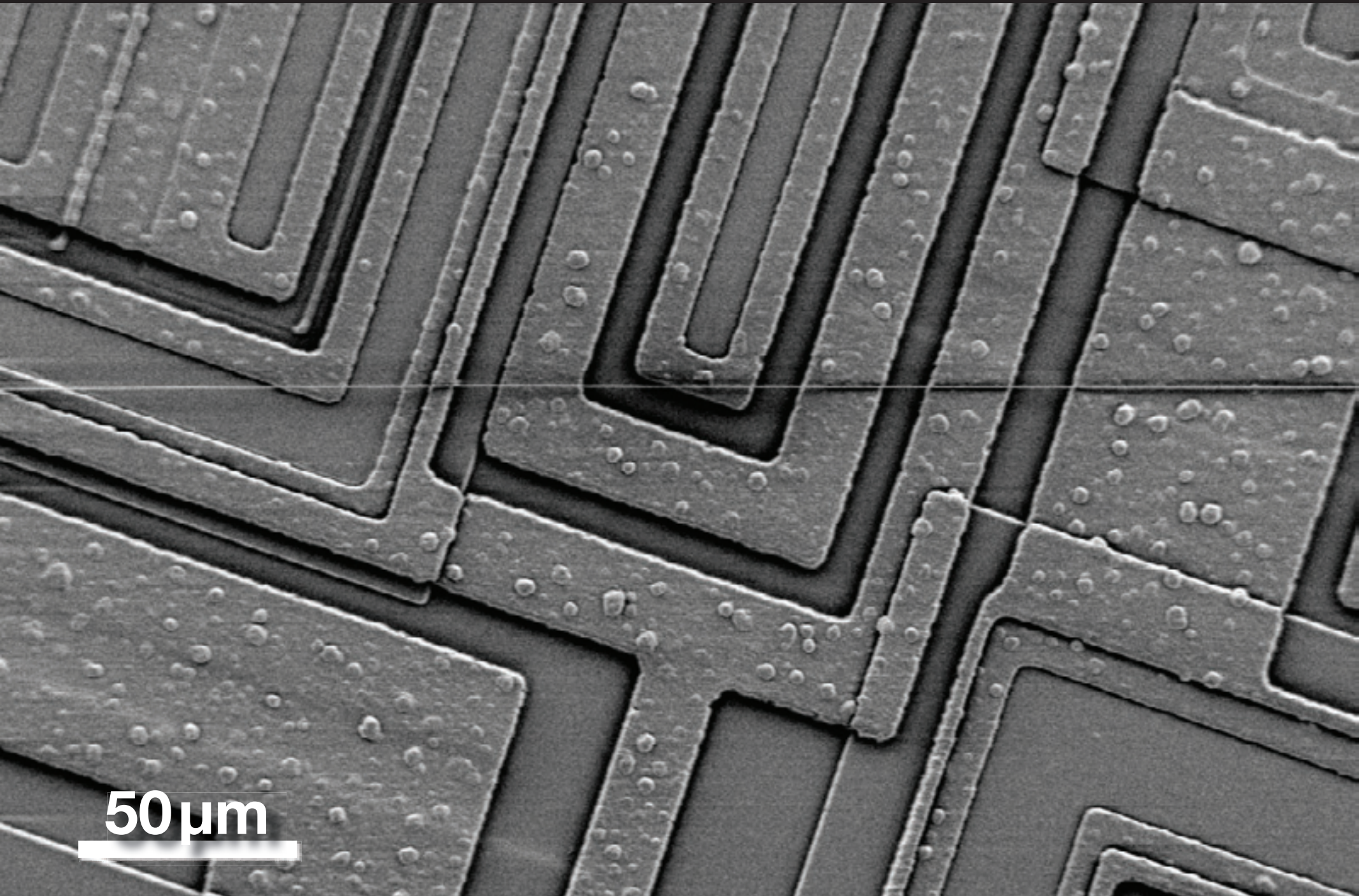
Nanowire fabrication



Nanowire fabrication

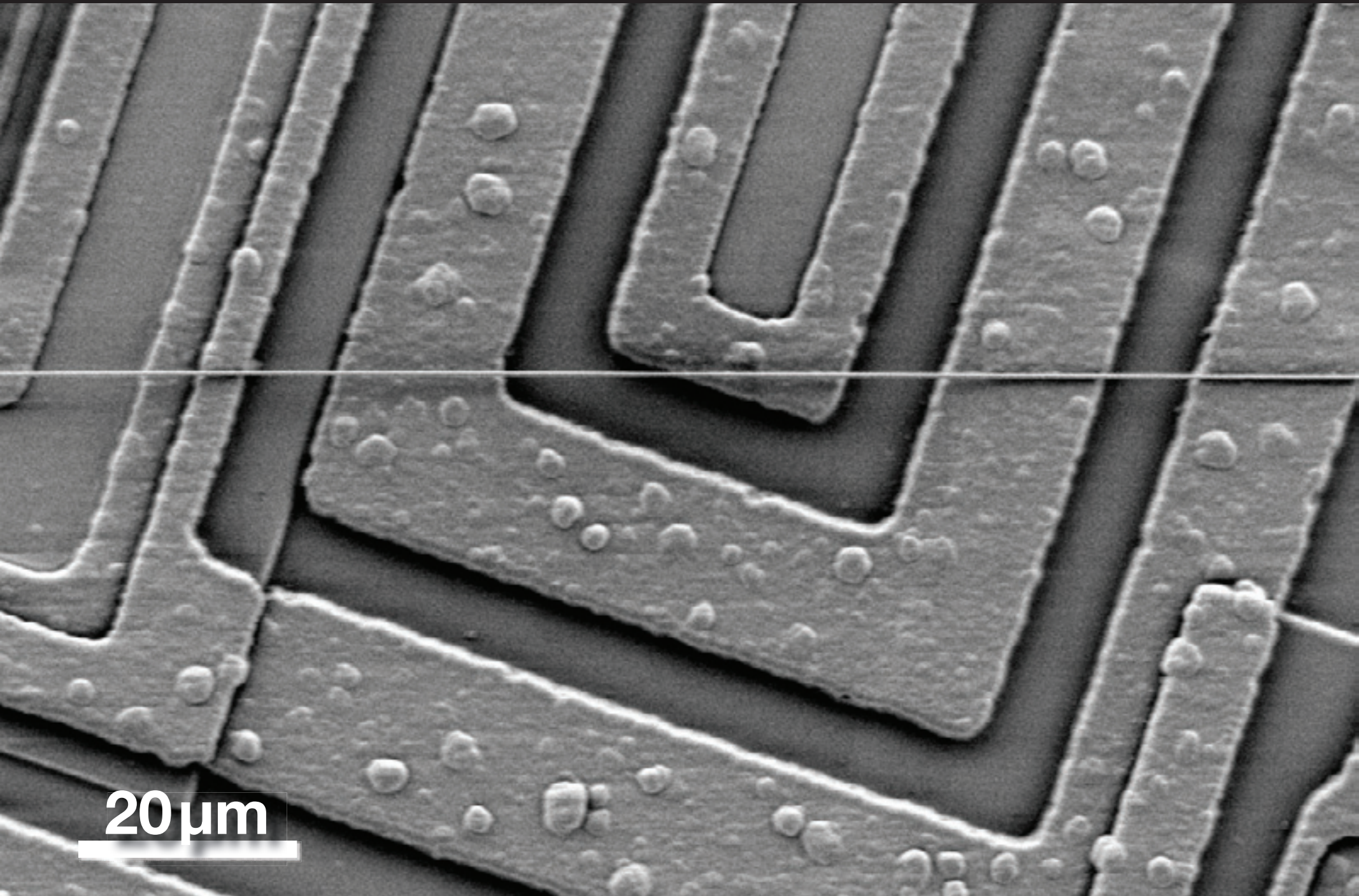


Nanowire fabrication



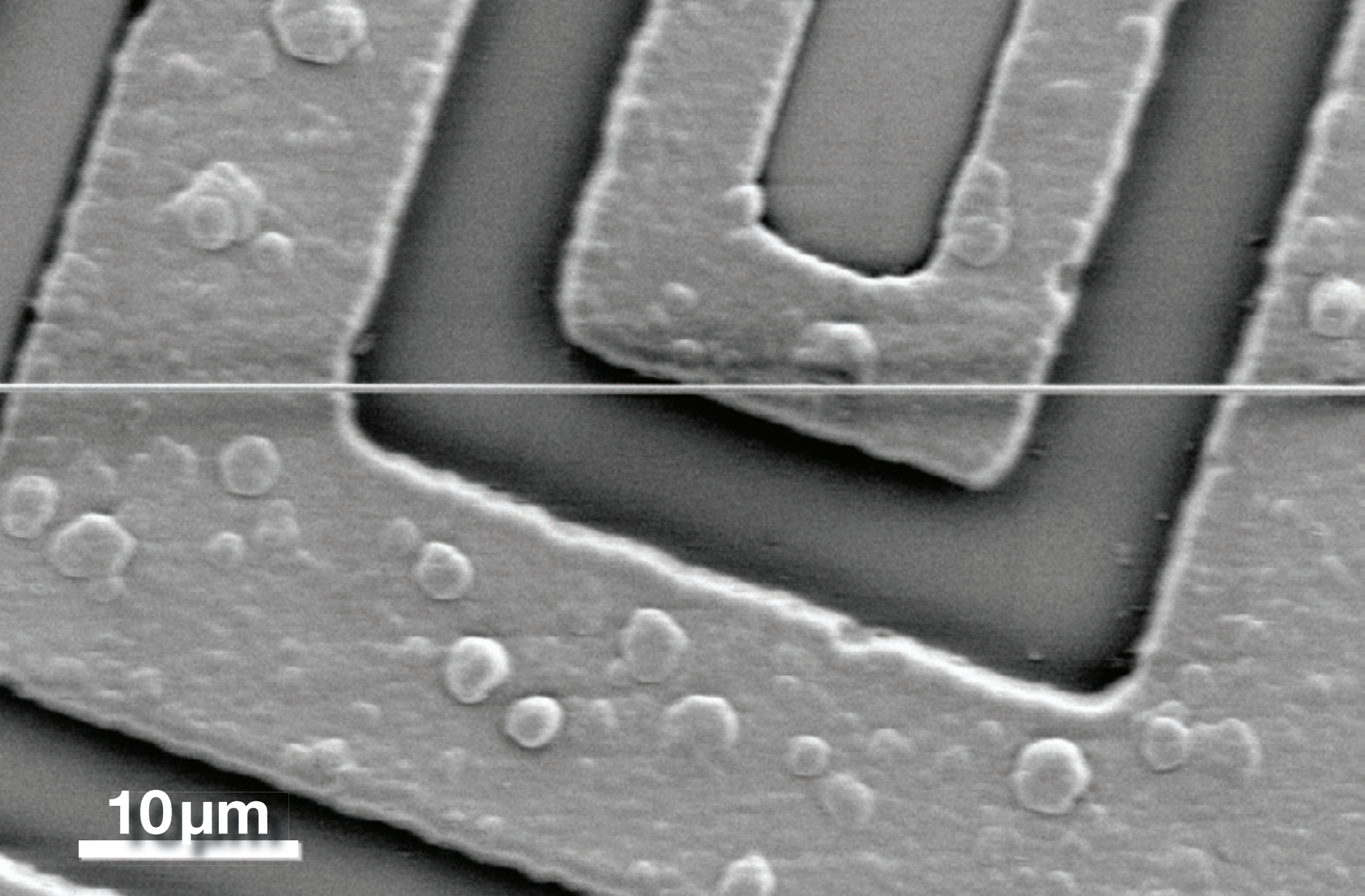
50 μm

Nanowire fabrication



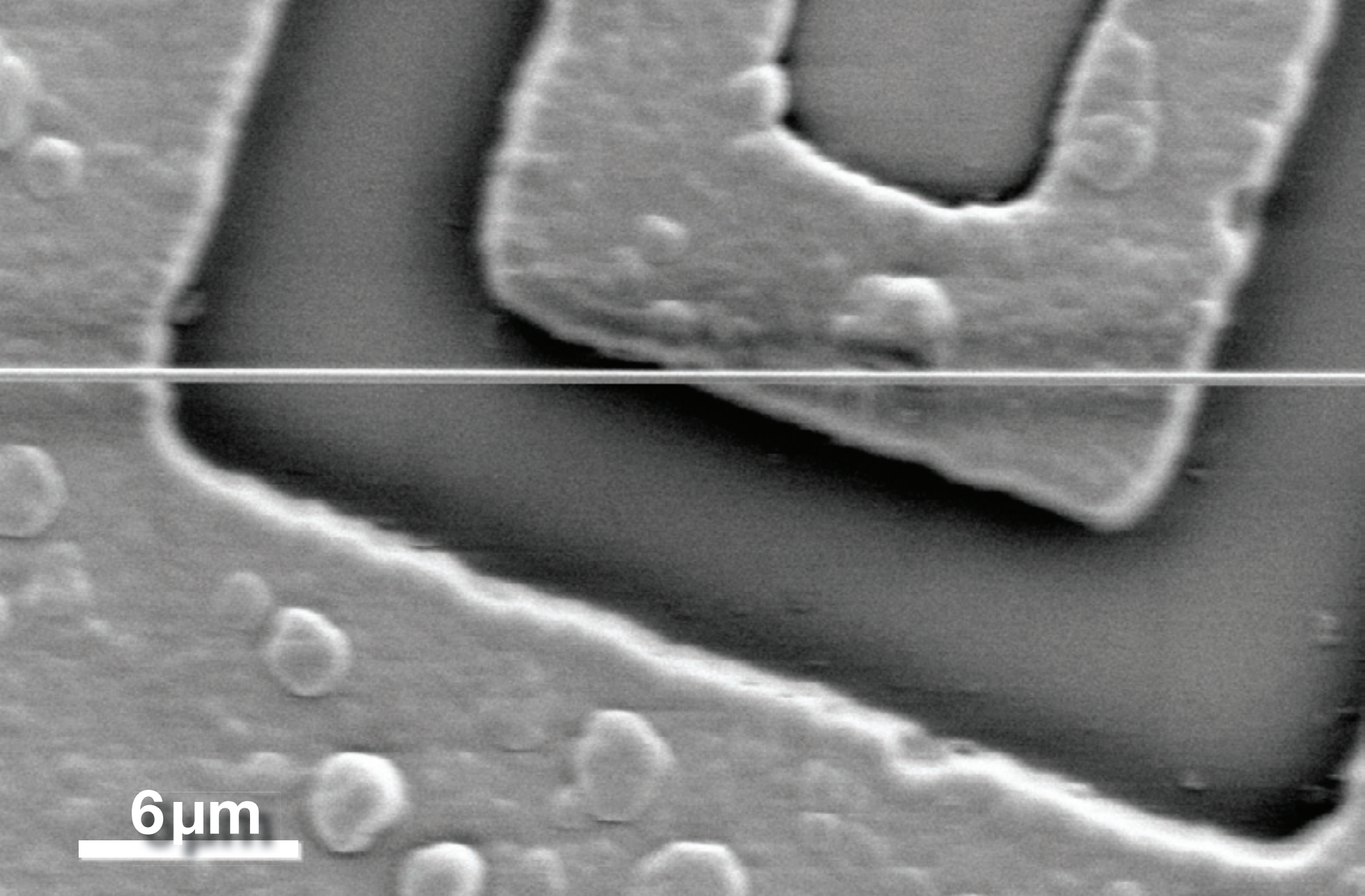
20 μm

Nanowire fabrication



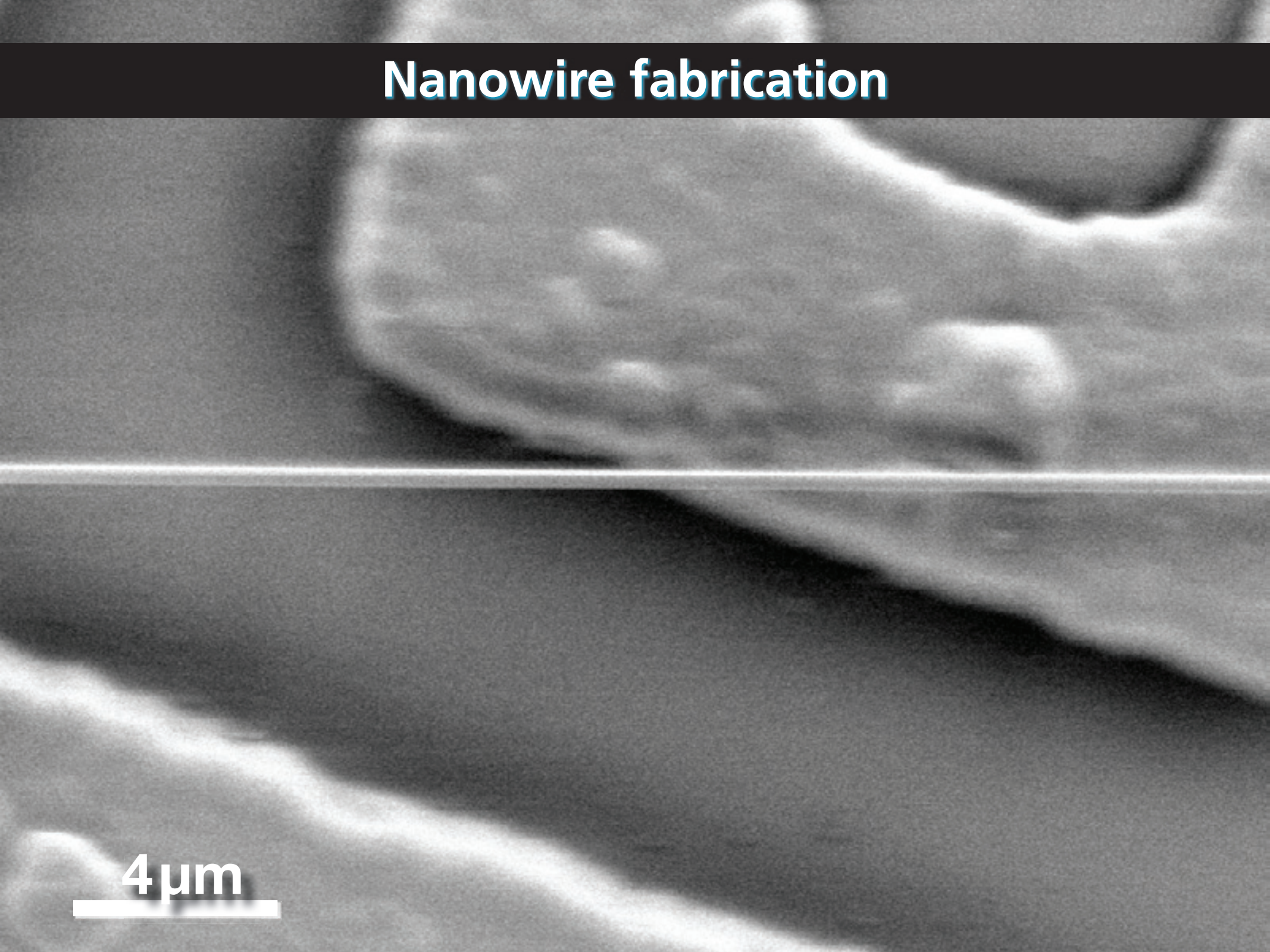
10 μm

Nanowire fabrication



6 μm

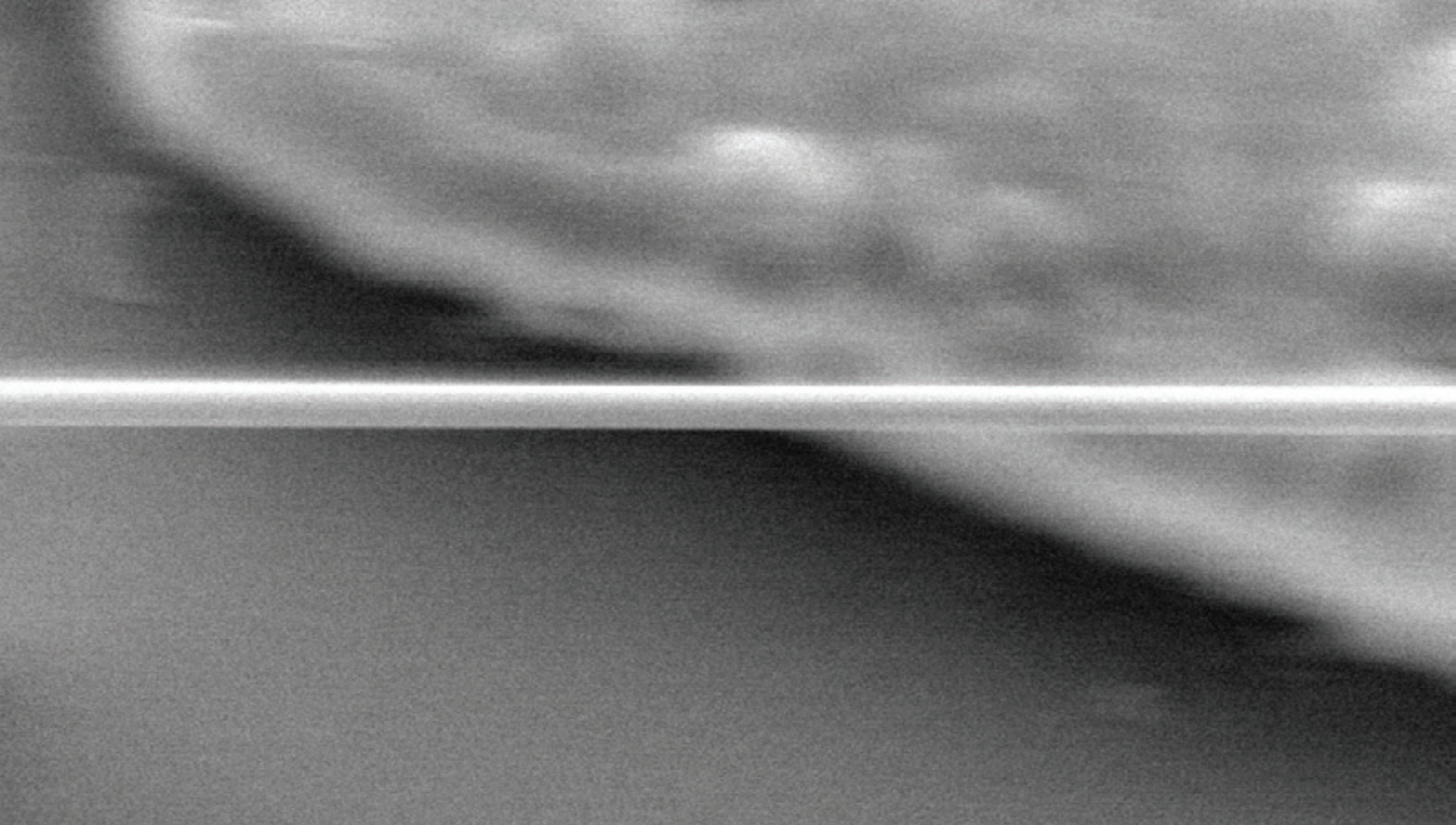
Nanowire fabrication



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 background is a dark, textured gray.

1 μm

A white horizontal scale bar located in the bottom left corner of the image. It is used to provide a reference length for the nanowire.

Waveguiding

Specifications

diameter D : down to 20 nm

length L : up to 90 mm

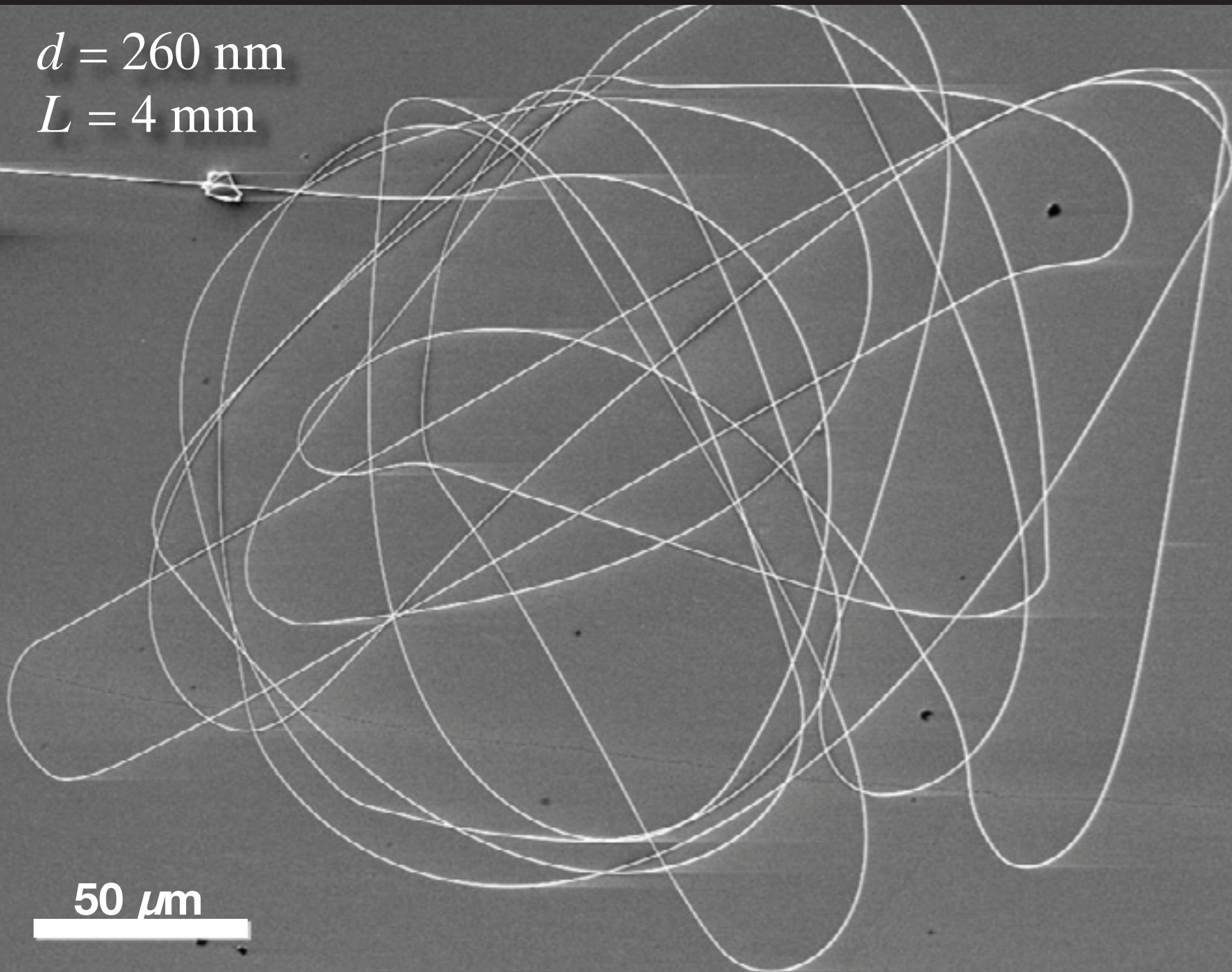
aspect ratio D/L : up to 10^6

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

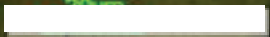
RMS roughness < 0.5 nm

20 nm



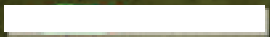
Nanowire fabrication

bend to
breaking point



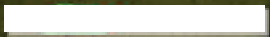
Nanowire fabrication

bend to
breaking point

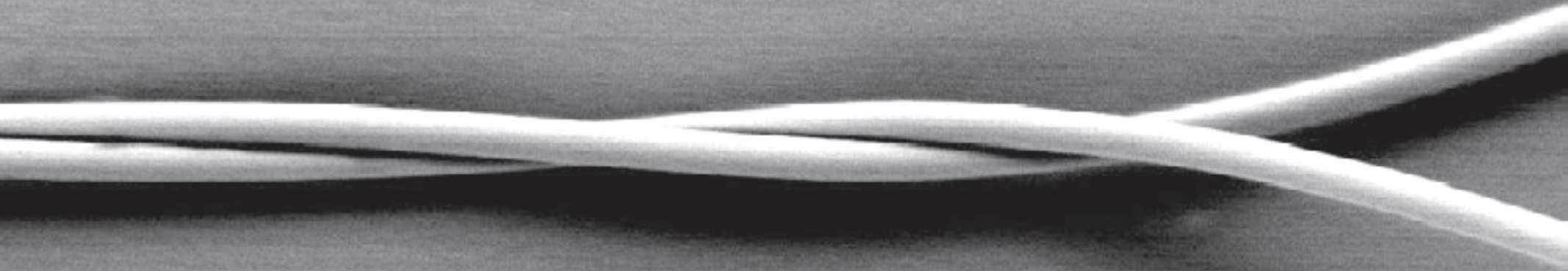


Nanowire fabrication

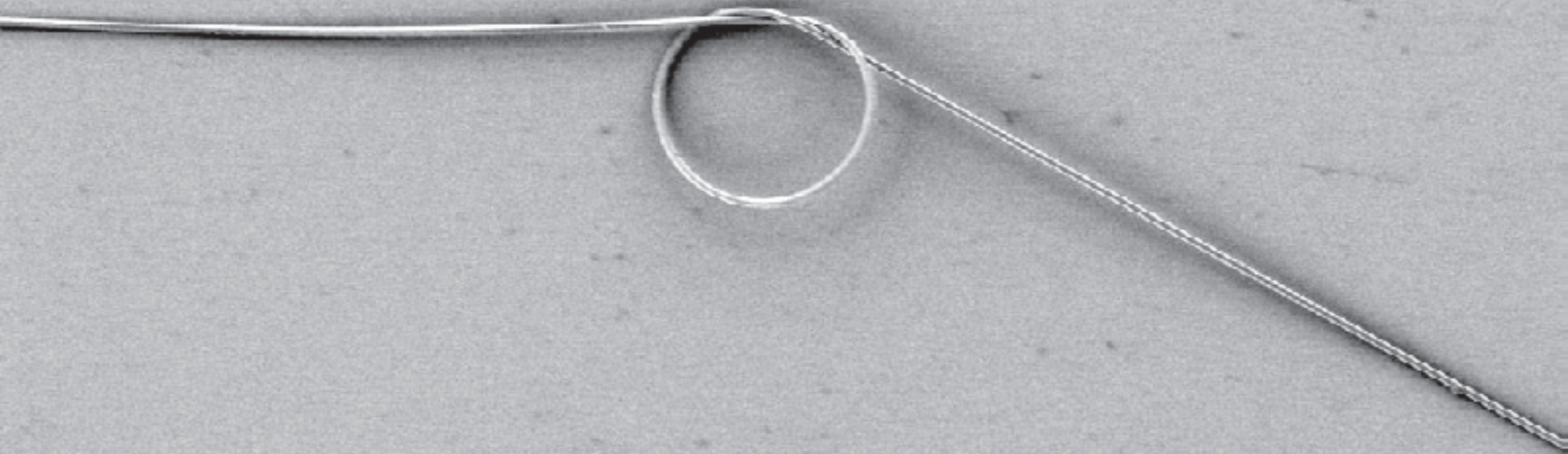
bend to
breaking point



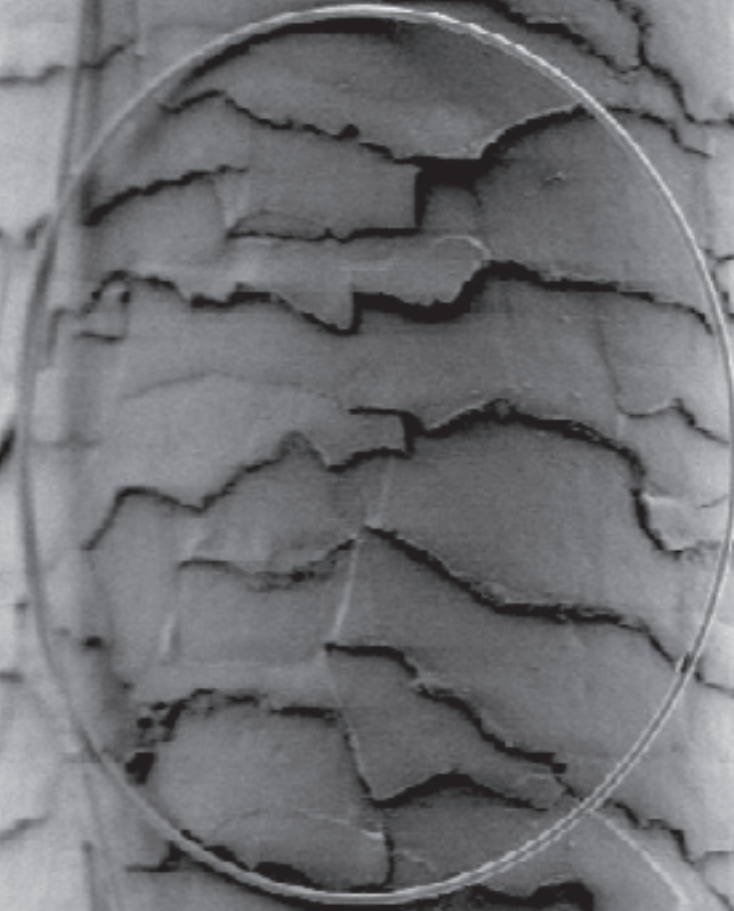
Nanowire fabrication



Nanowire fabrication



Nanowire fabrication

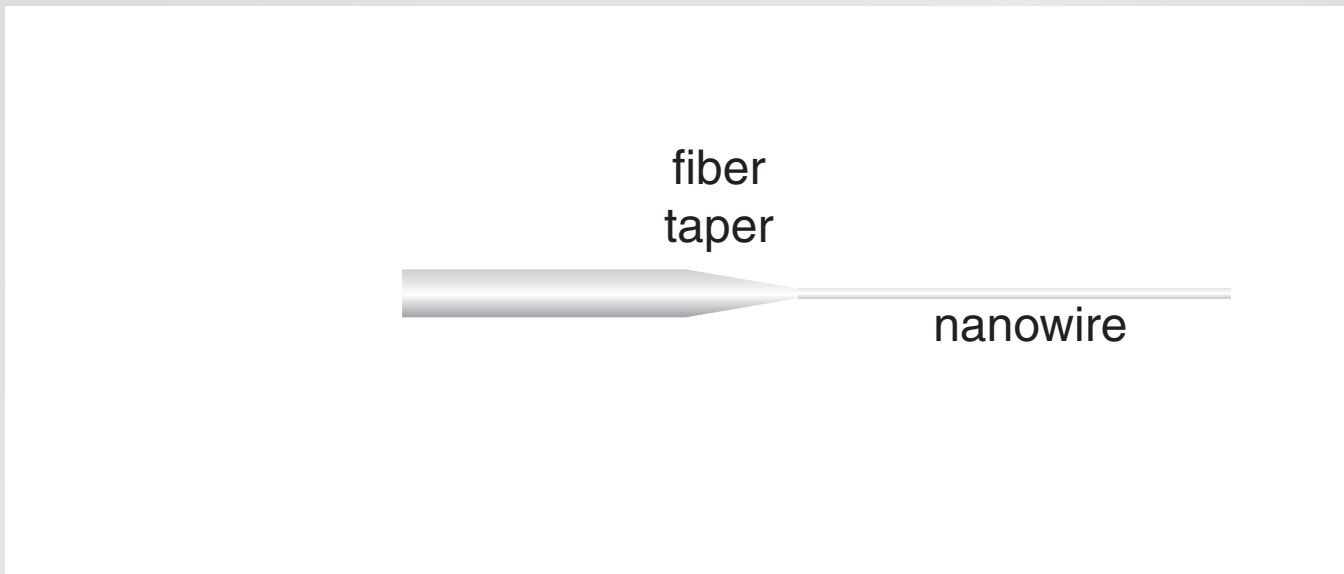


Outline

- waveguiding
- nanowire fabrication
- optical properties

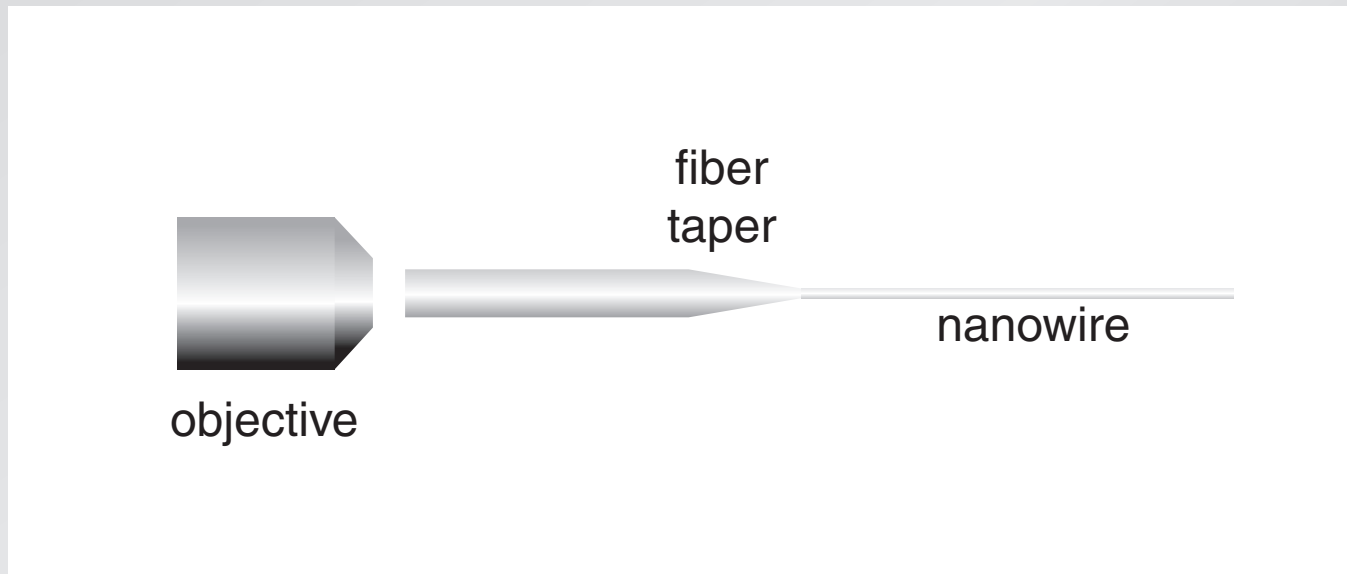
Optical properties

coupling light into nanowires



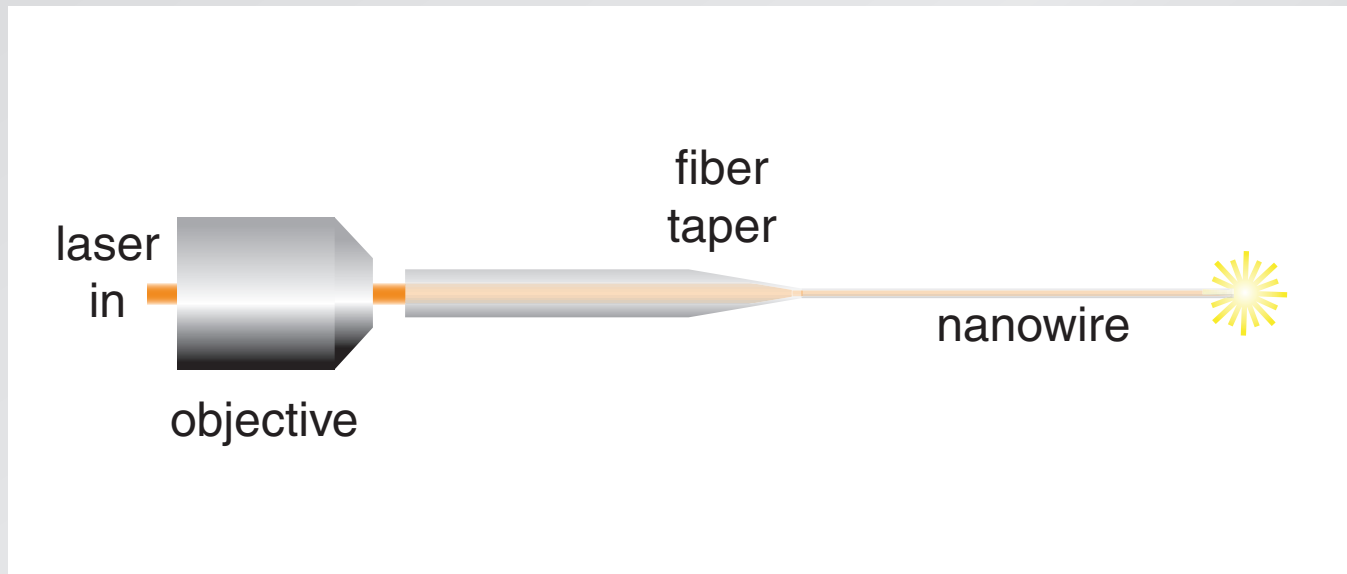
Optical properties

coupling light into nanowires

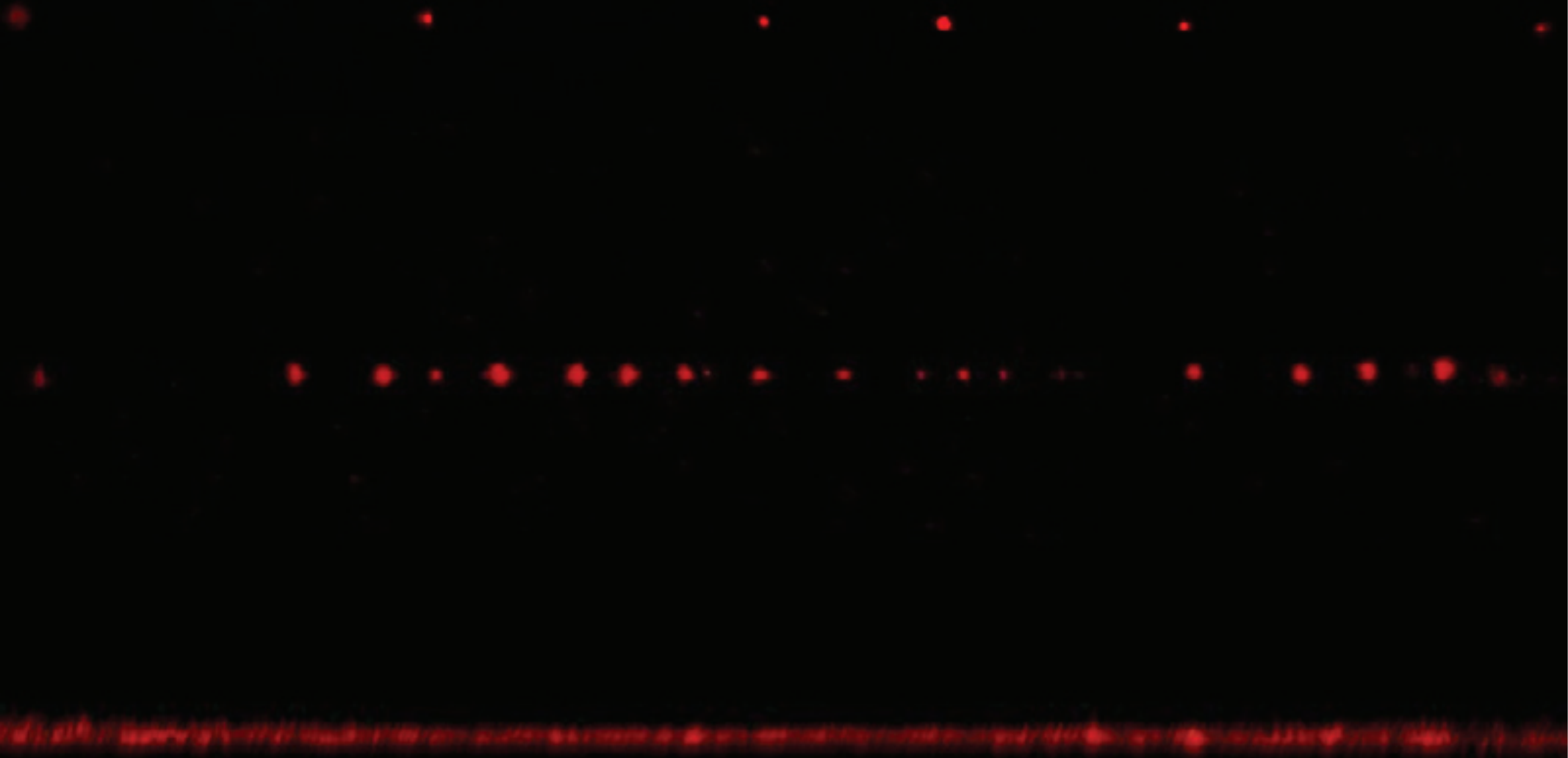


Optical properties

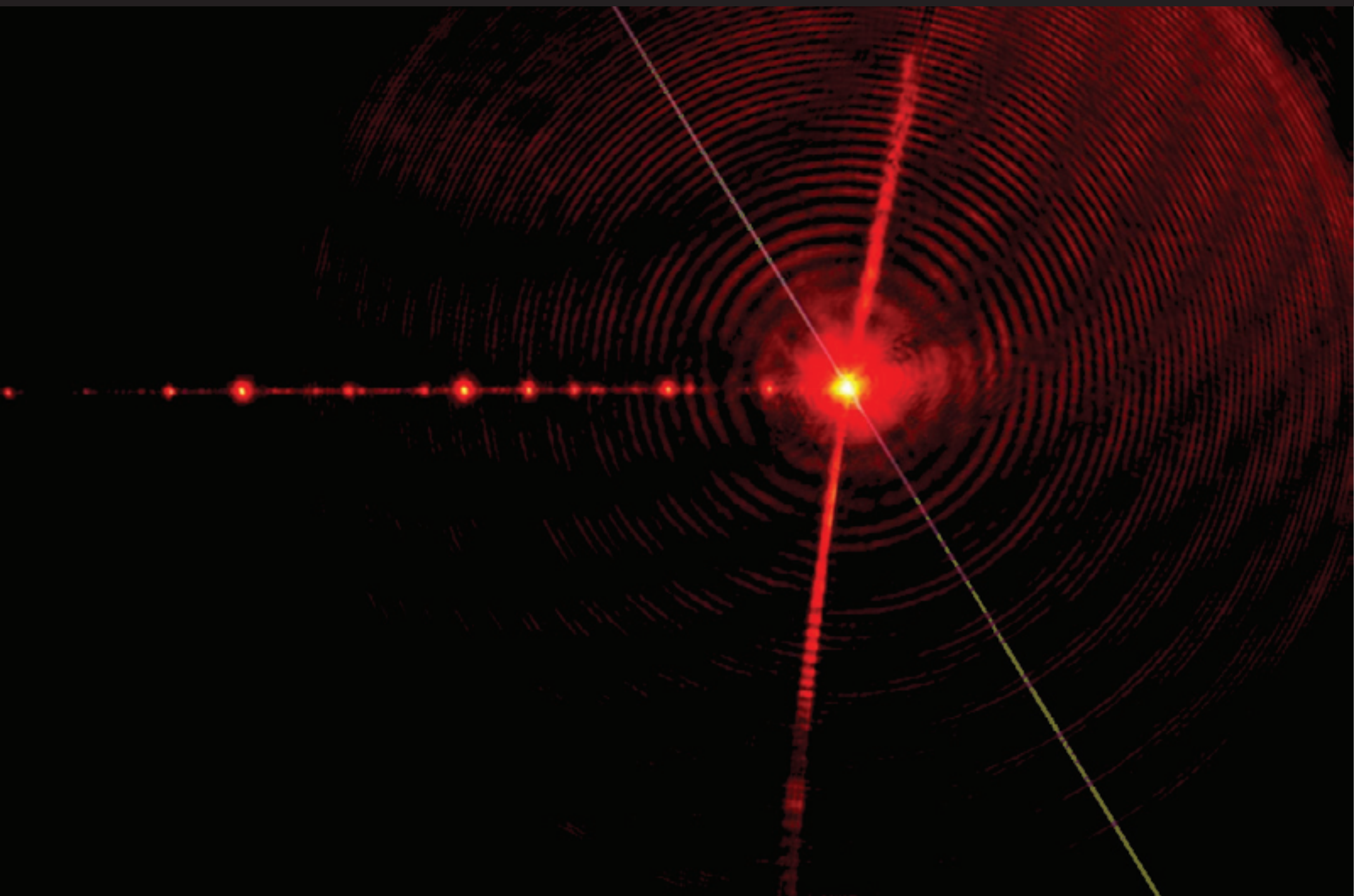
coupling light into nanowires



Optical properties



Optical properties

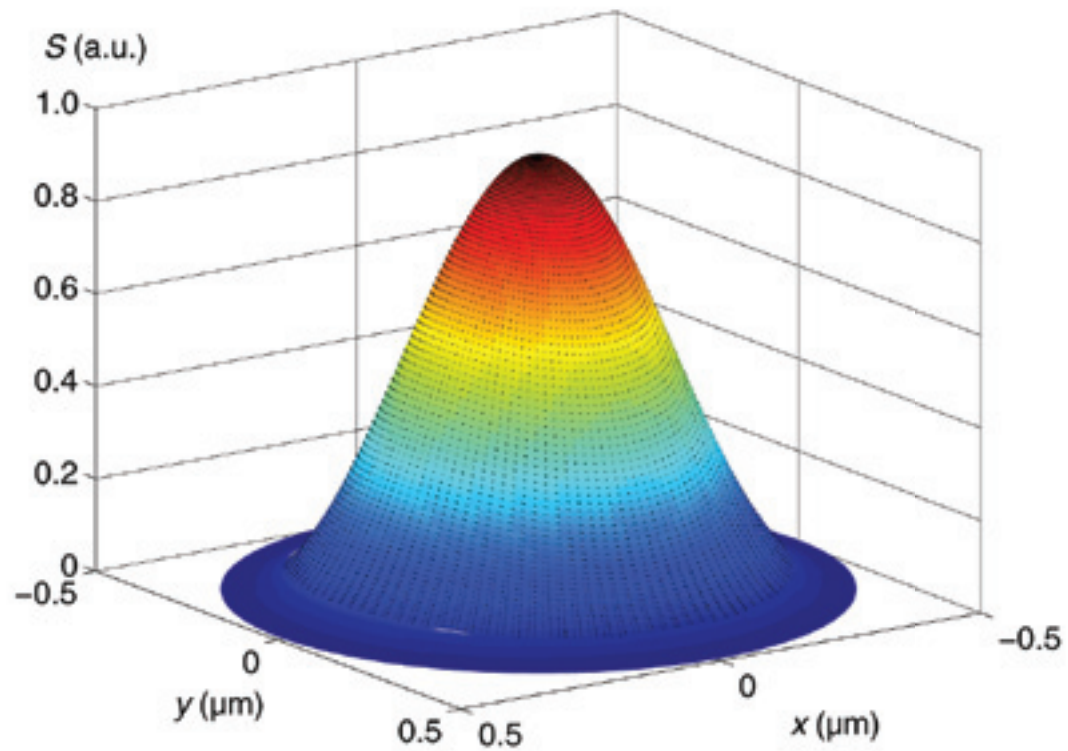


Optical properties



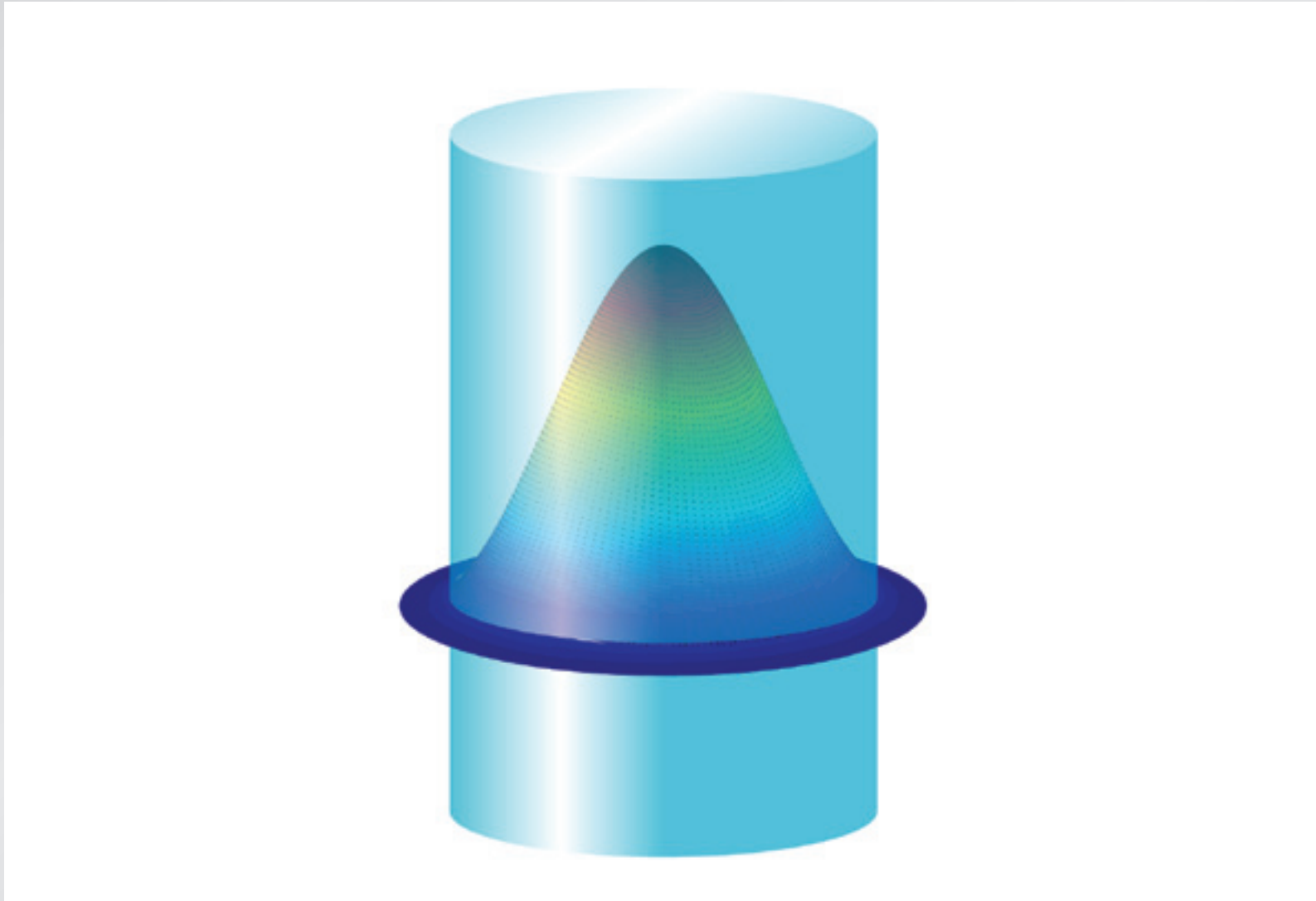
Optical properties

Poynting vector profile for 800-nm nanowire



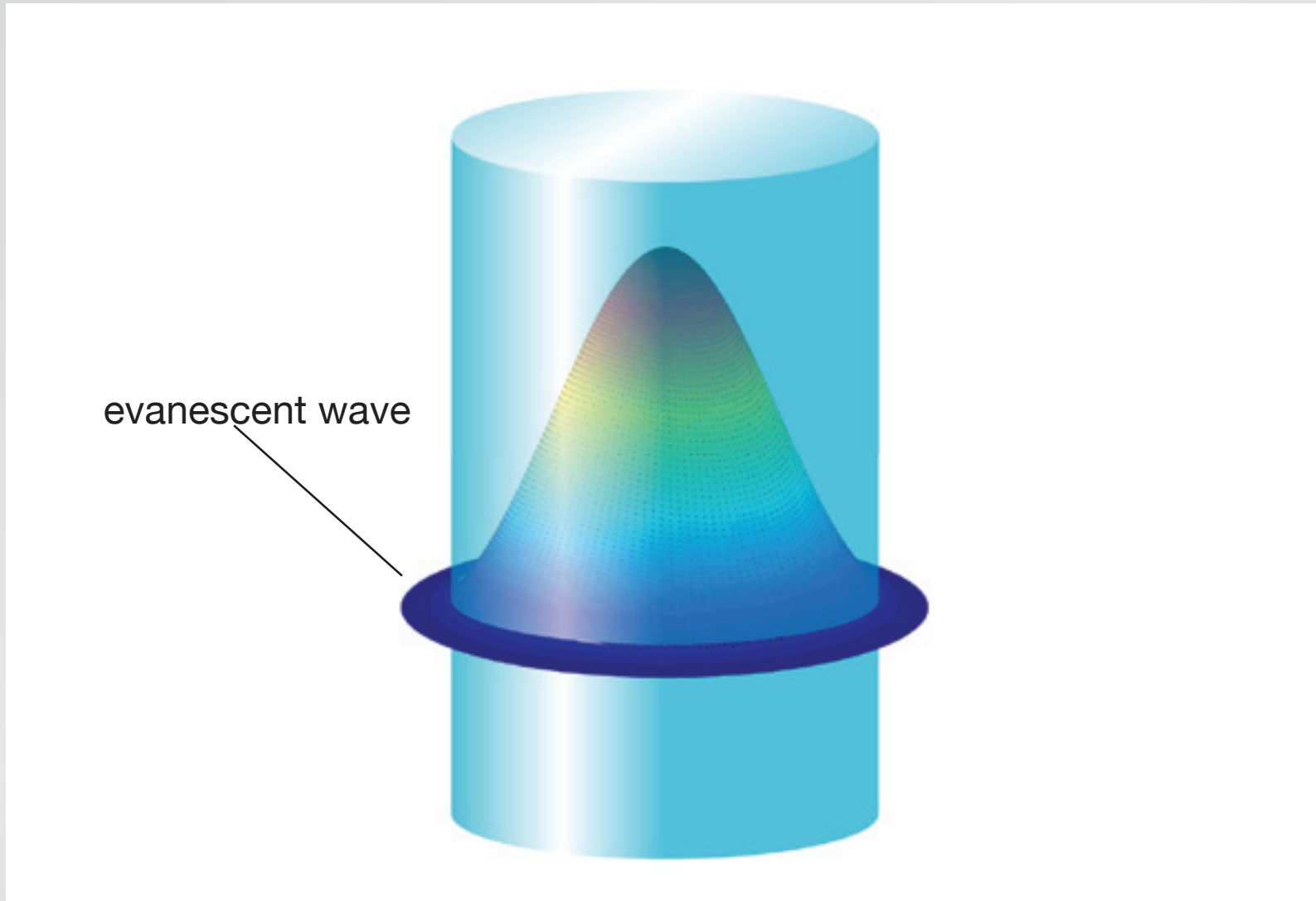
Optical properties

Poynting vector profile for 800-nm nanowire



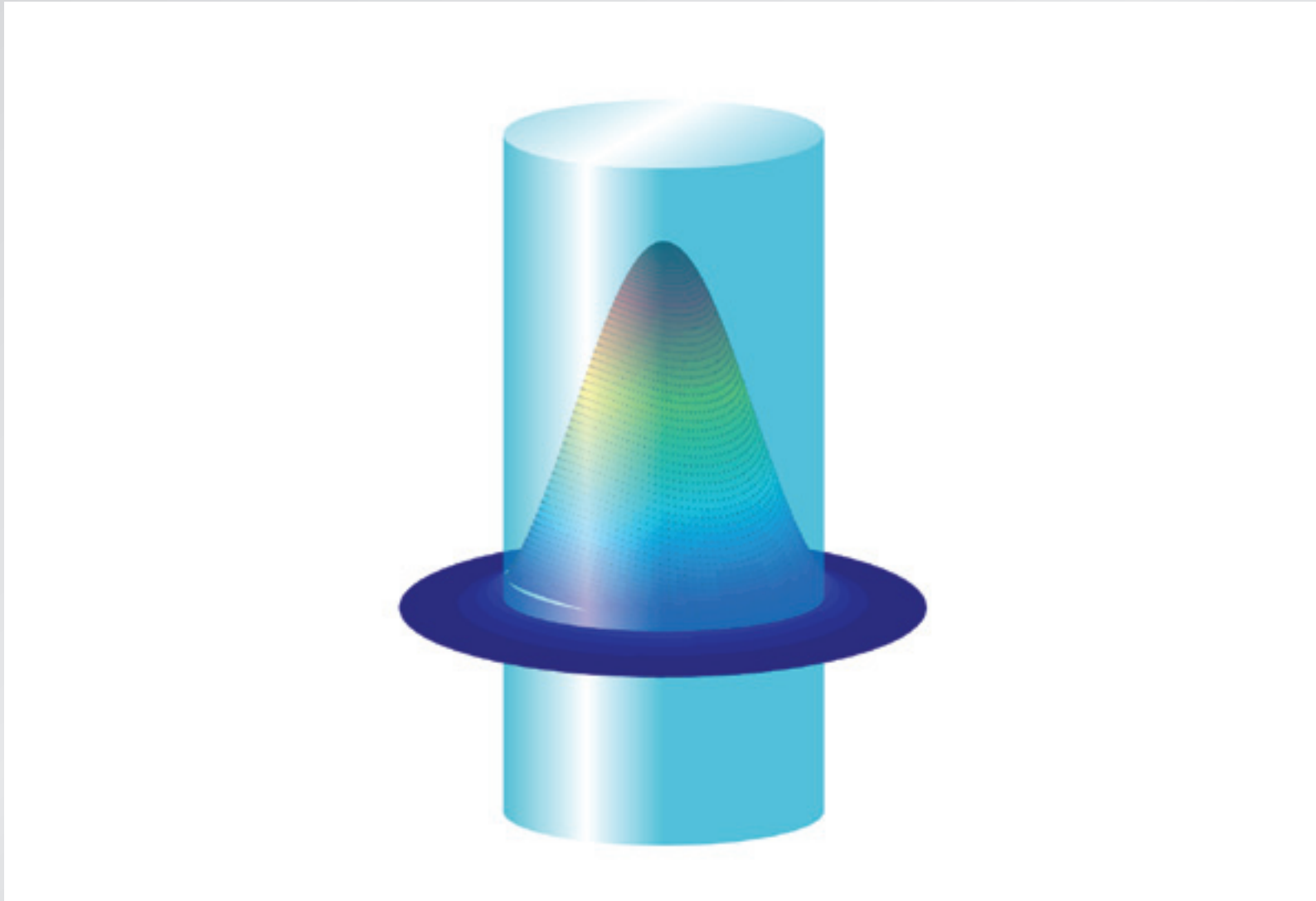
Optical properties

Poynting vector profile for 800-nm nanowire



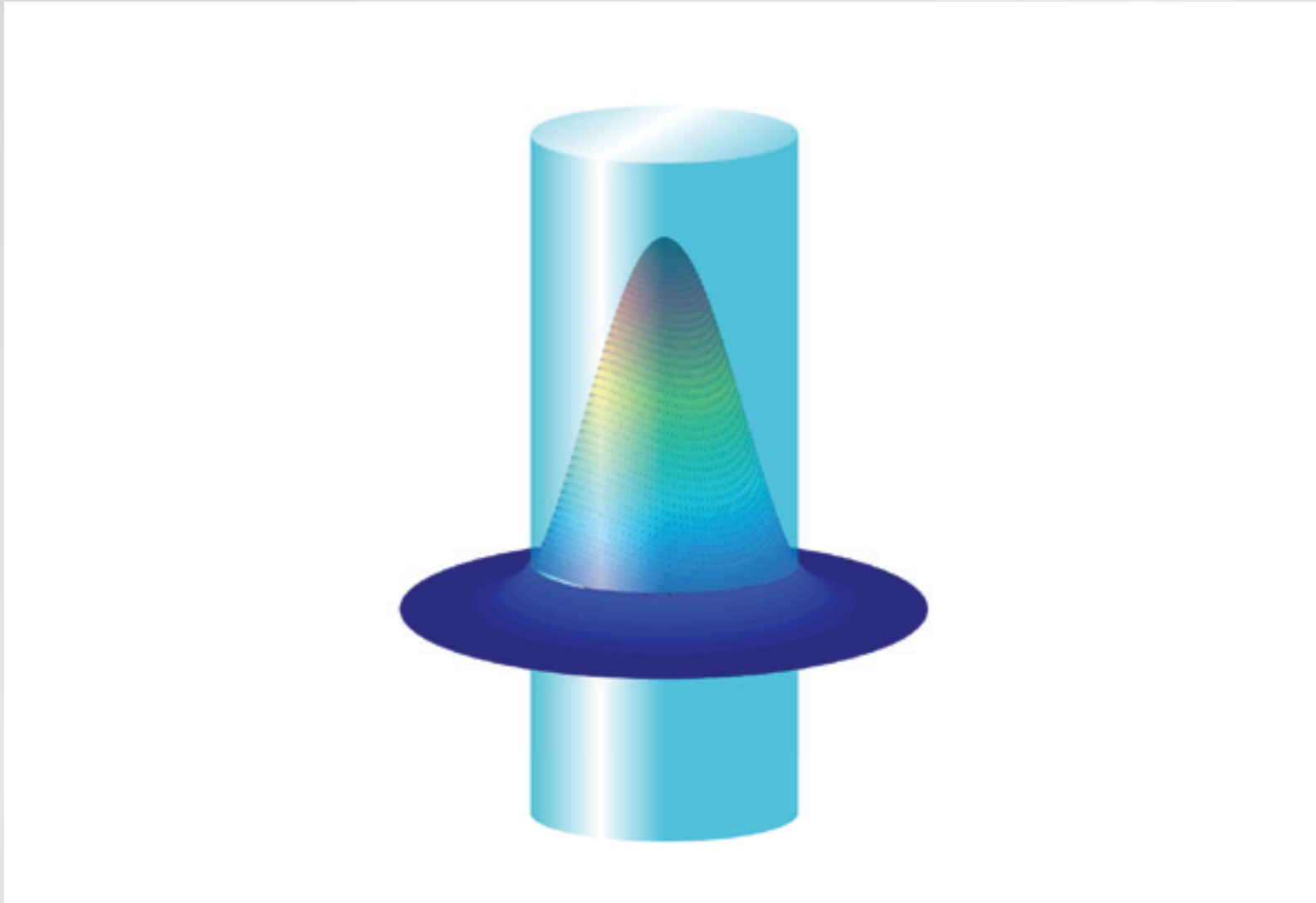
Optical properties

Poynting vector profile for 600-nm nanowire



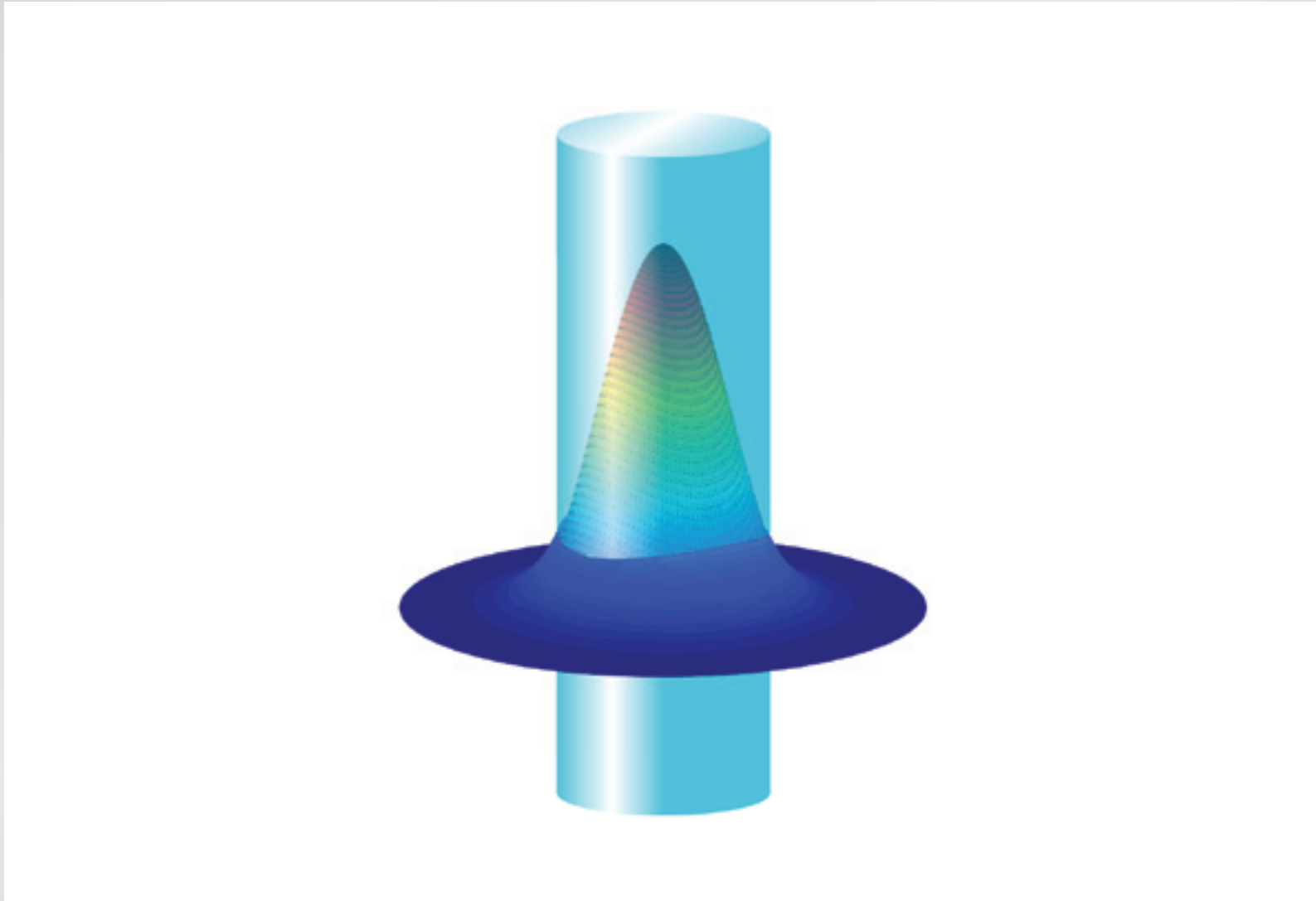
Optical properties

Poynting vector profile for 500-nm nanowire



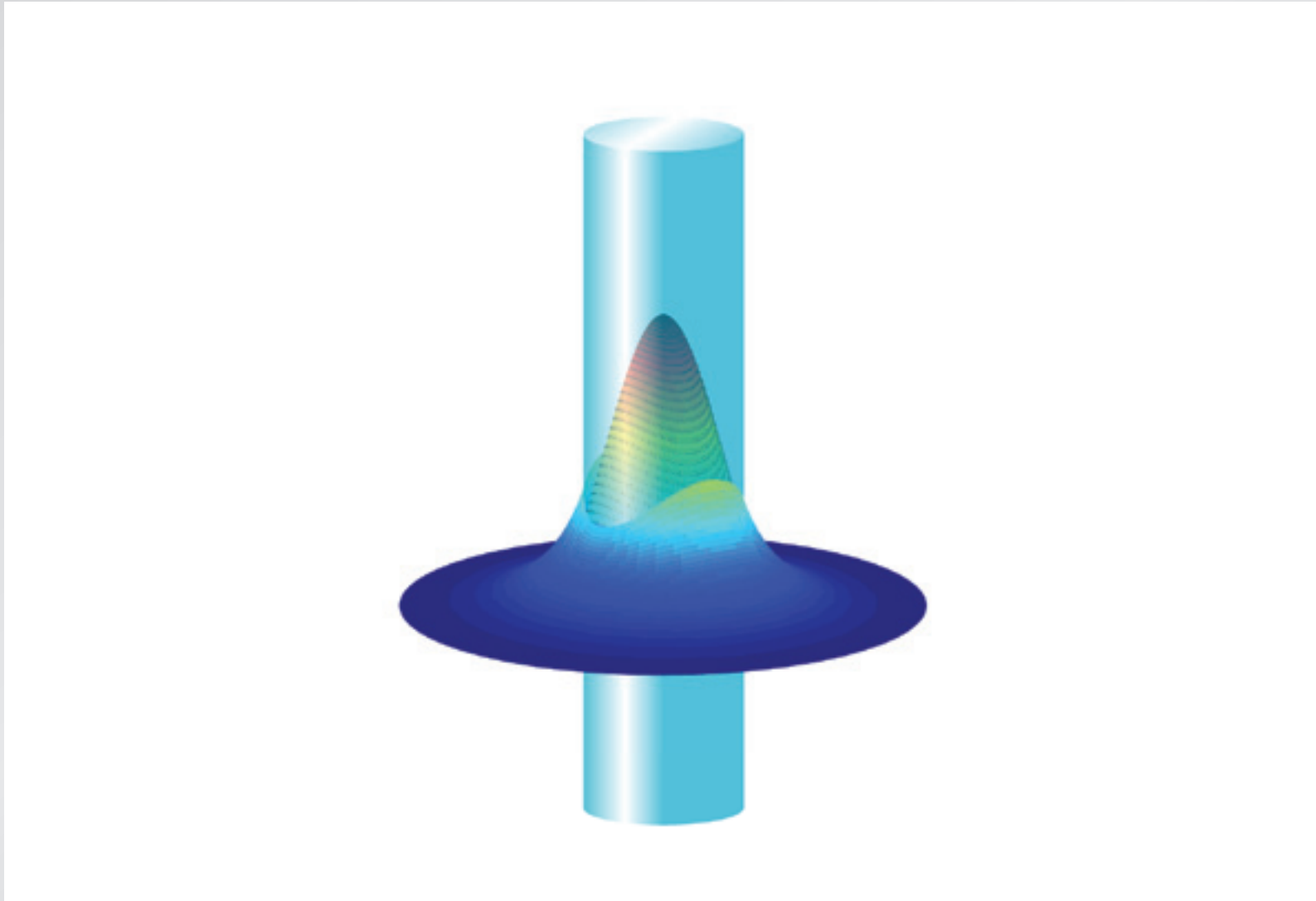
Optical properties

Poynting vector profile for 400-nm nanowire



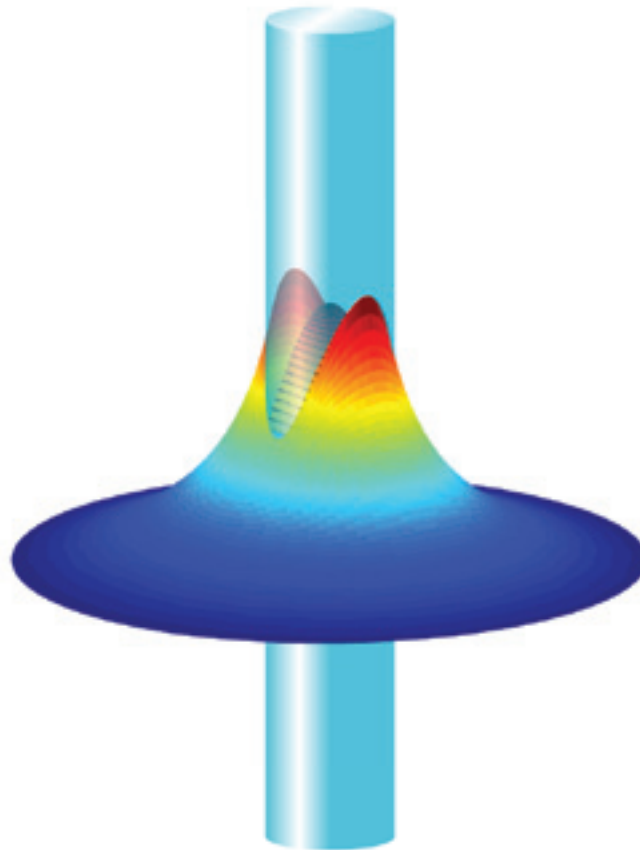
Optical properties

Poynting vector profile for 300-nm nanowire



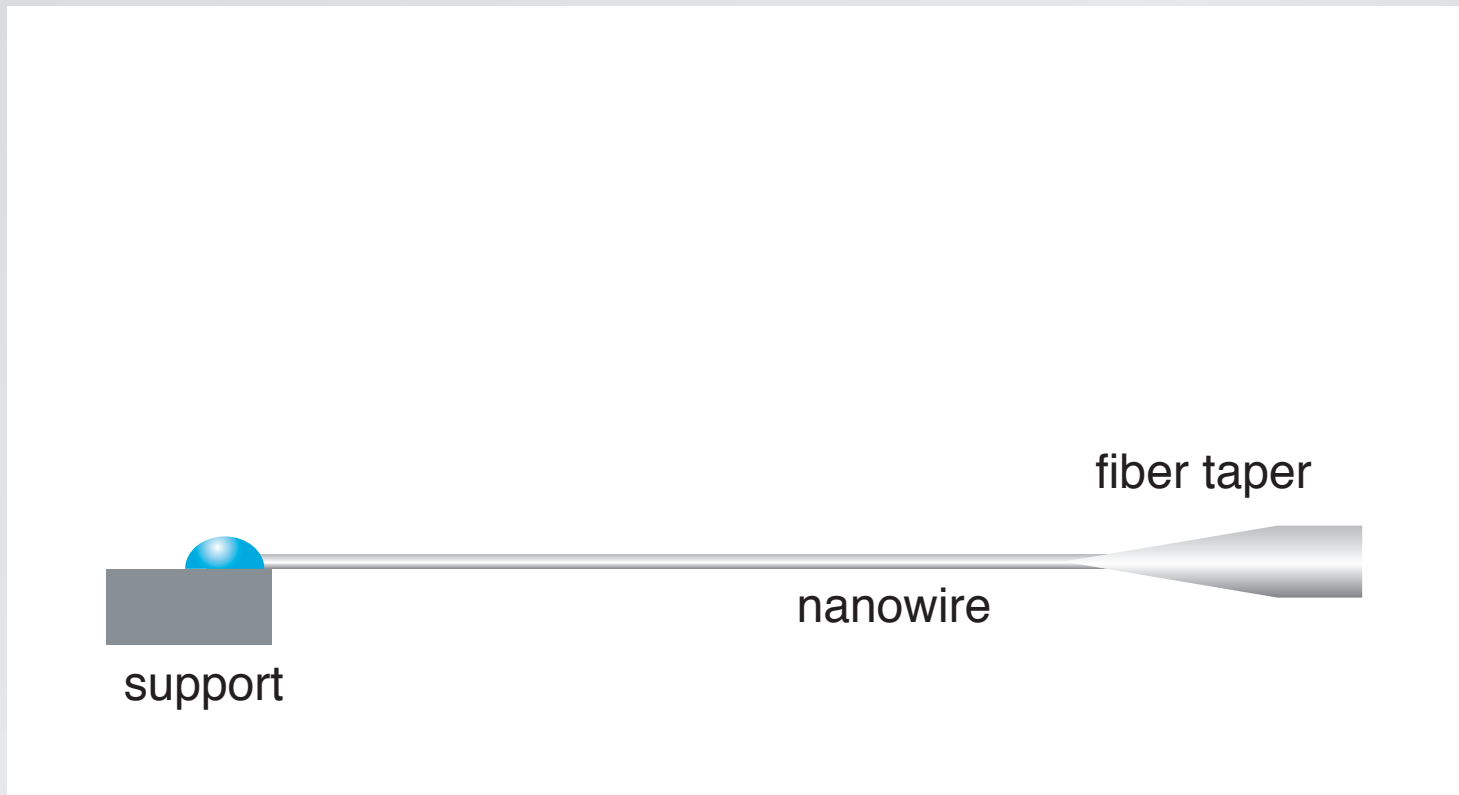
Optical properties

Poynting vector profile for 200-nm nanowire



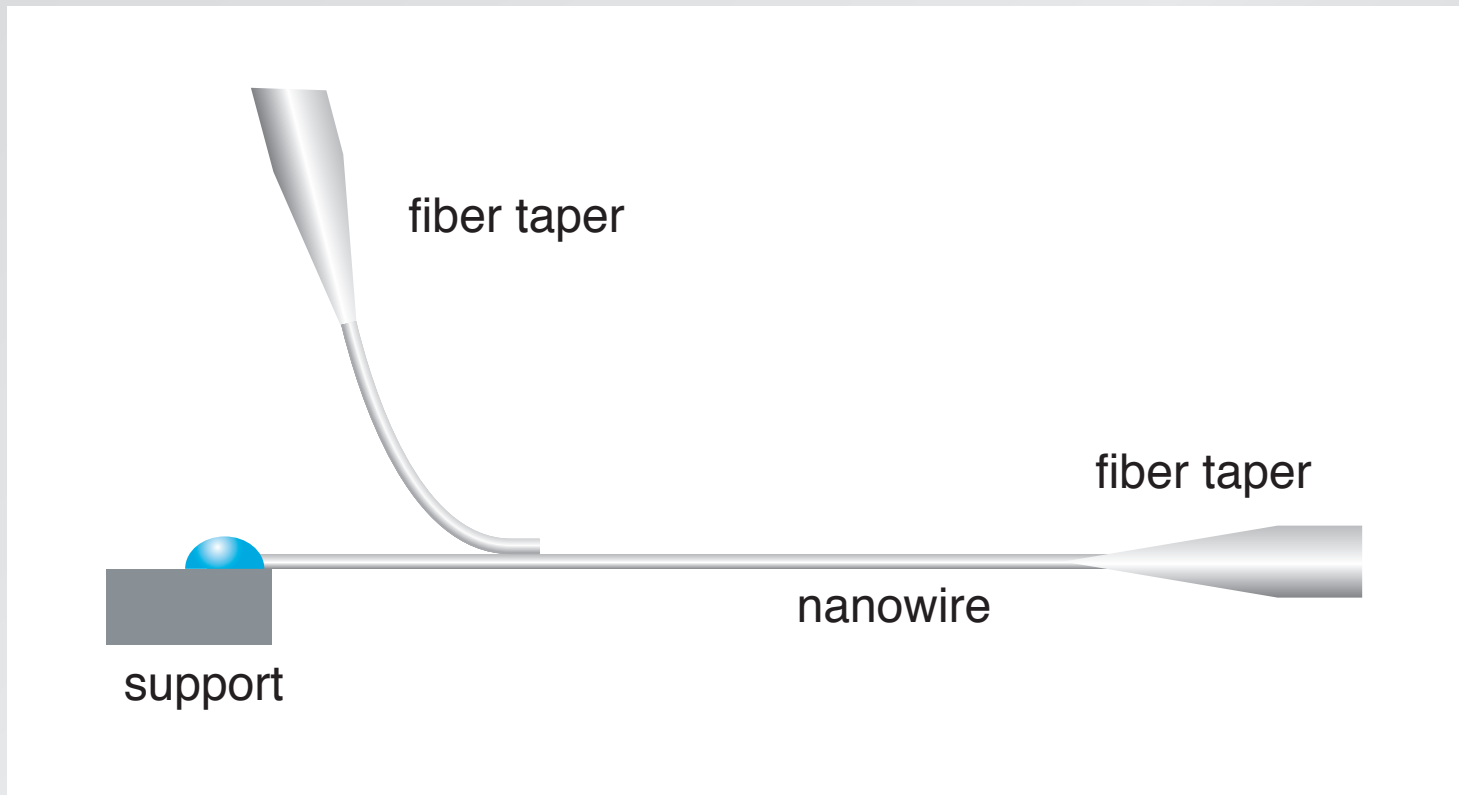
Optical properties

coupling light between nanowires



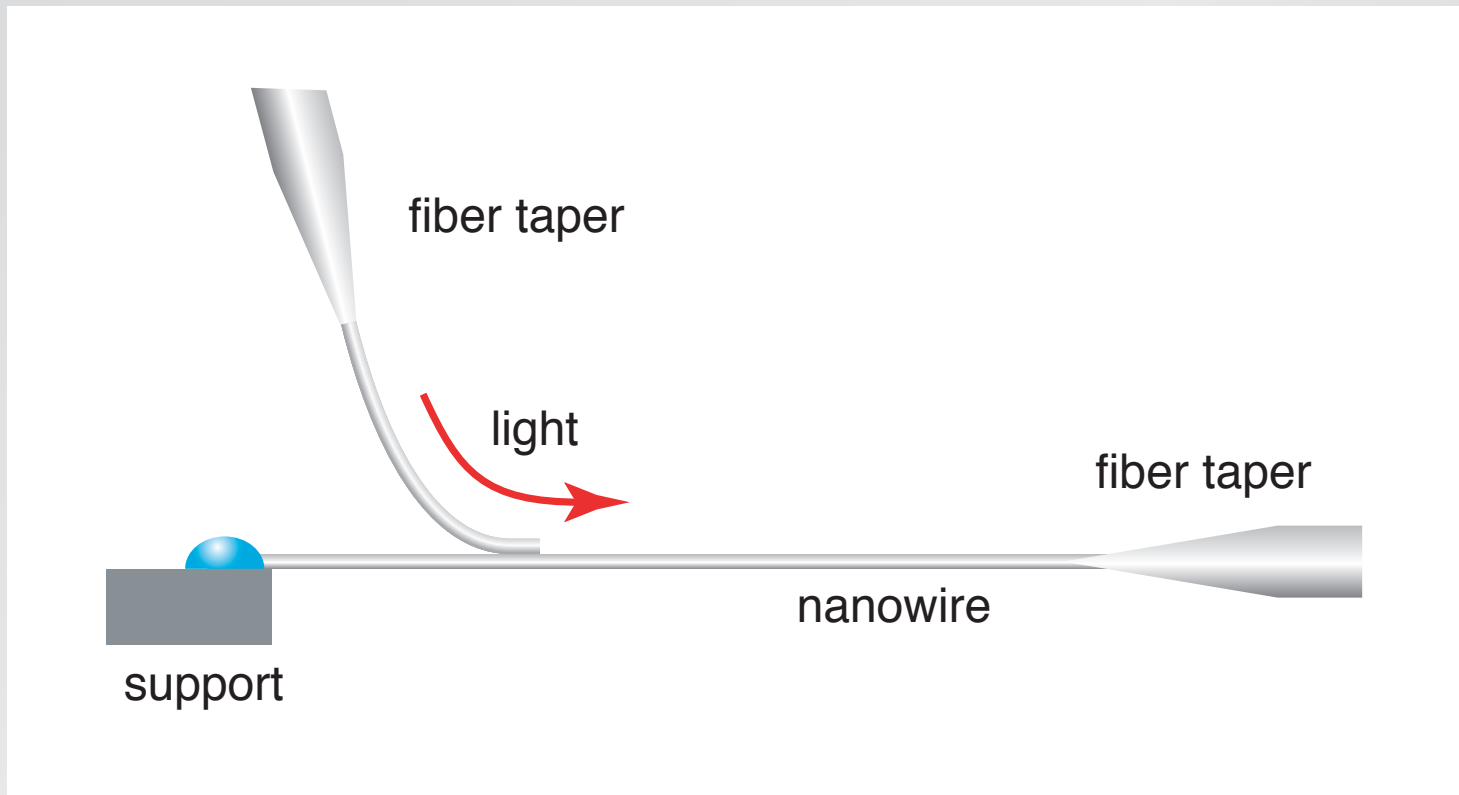
Optical properties

coupling light between nanowires

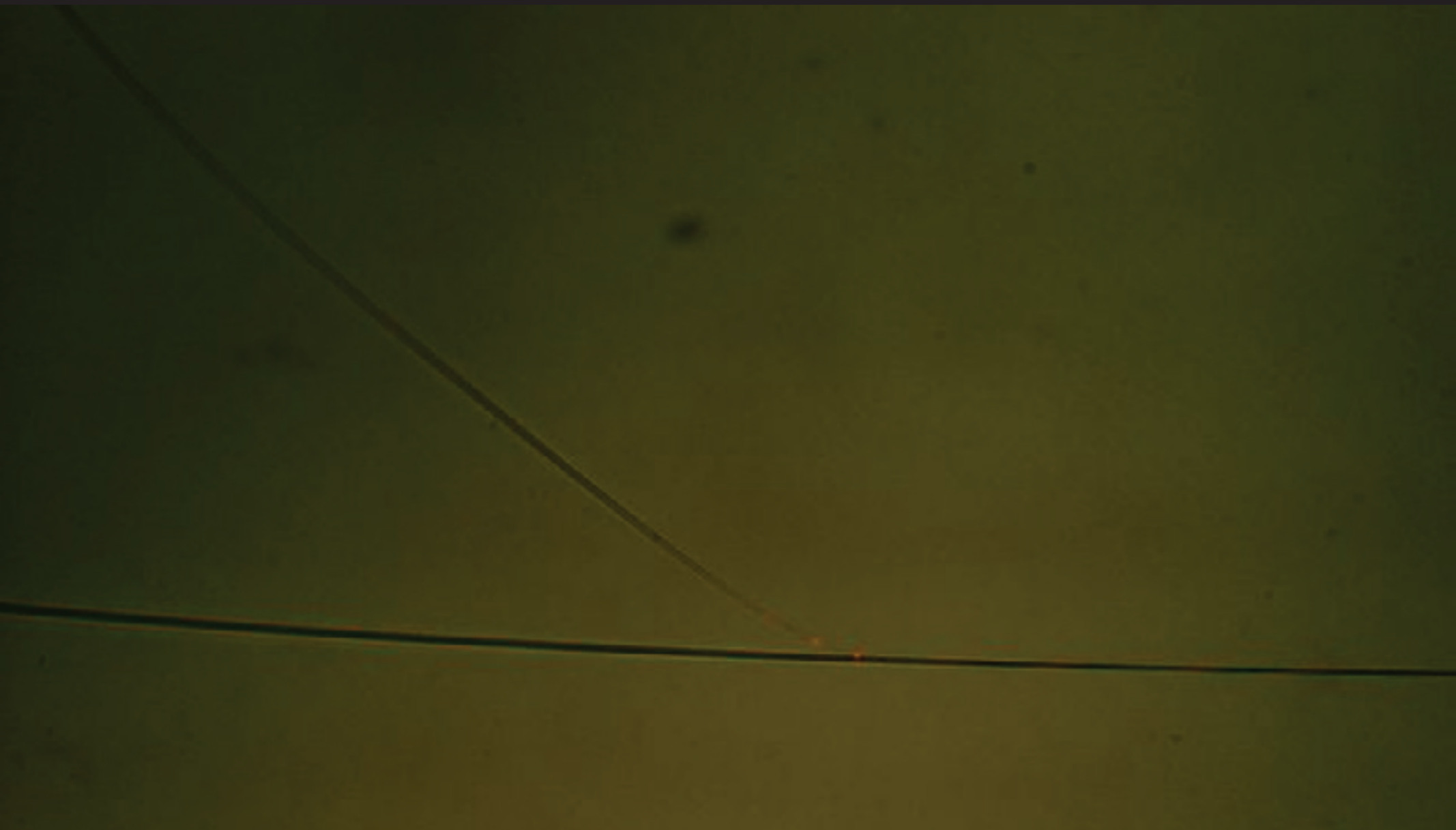


Optical properties

coupling light between nanowires

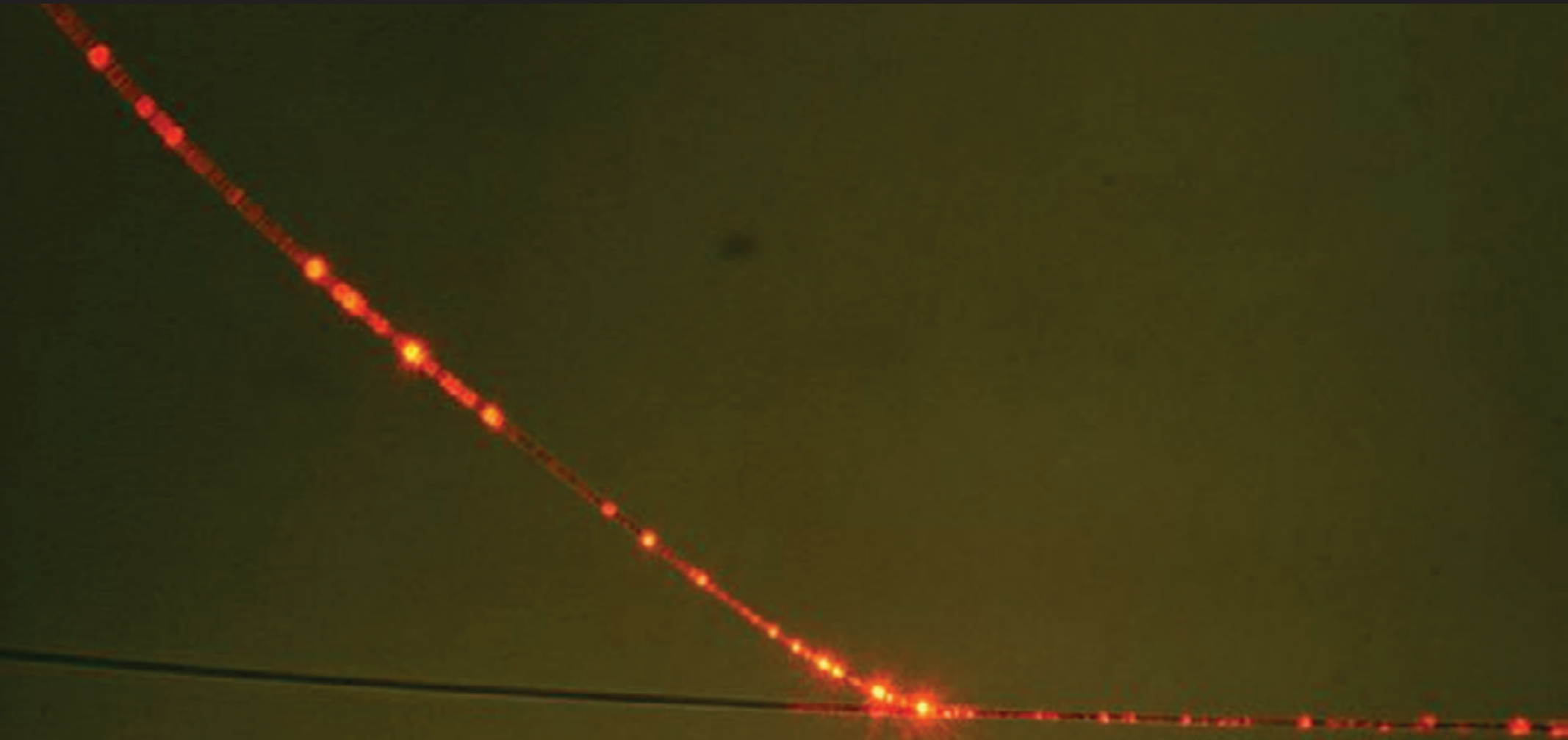


Optical properties



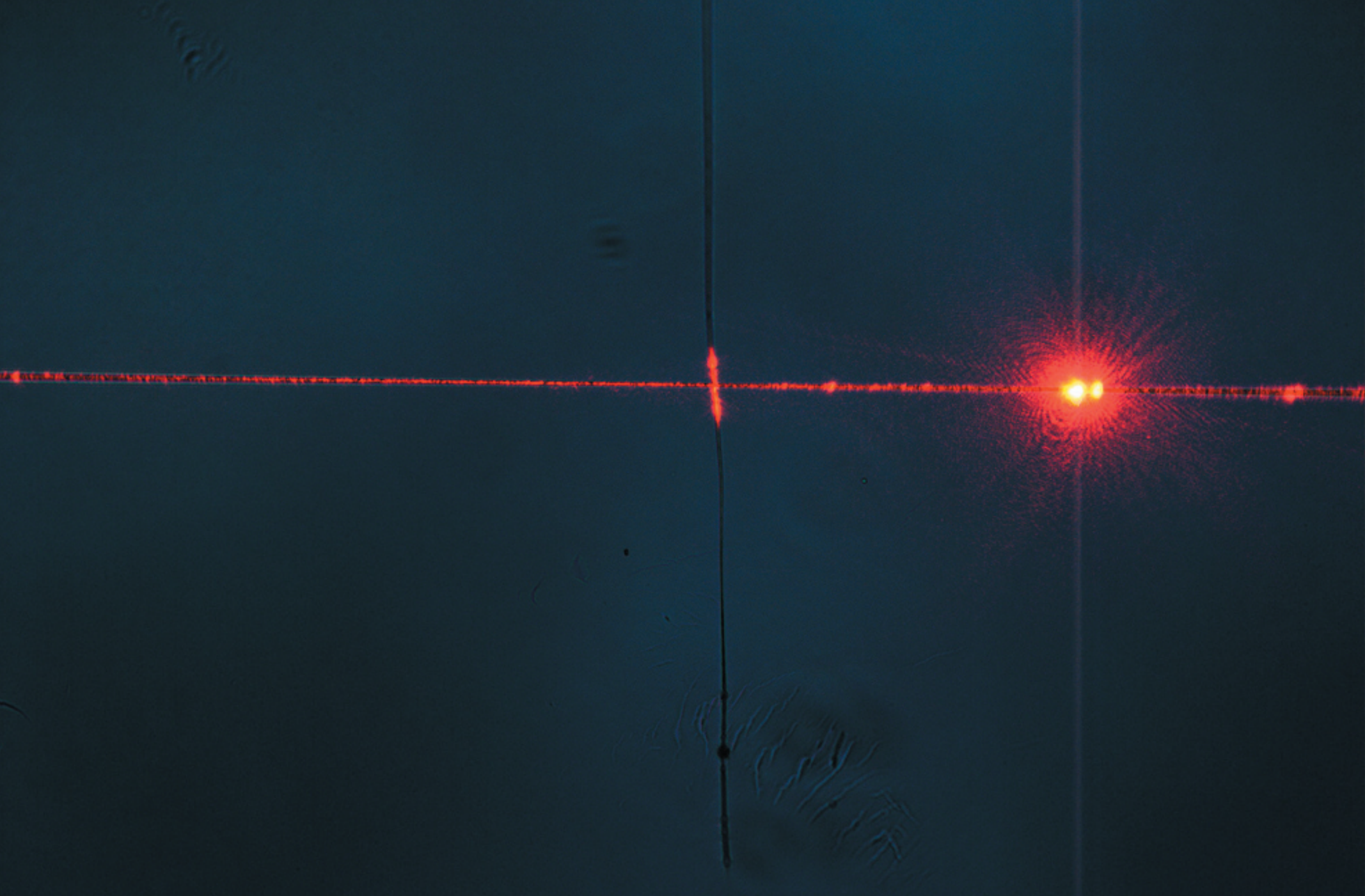
50 μm

Optical properties

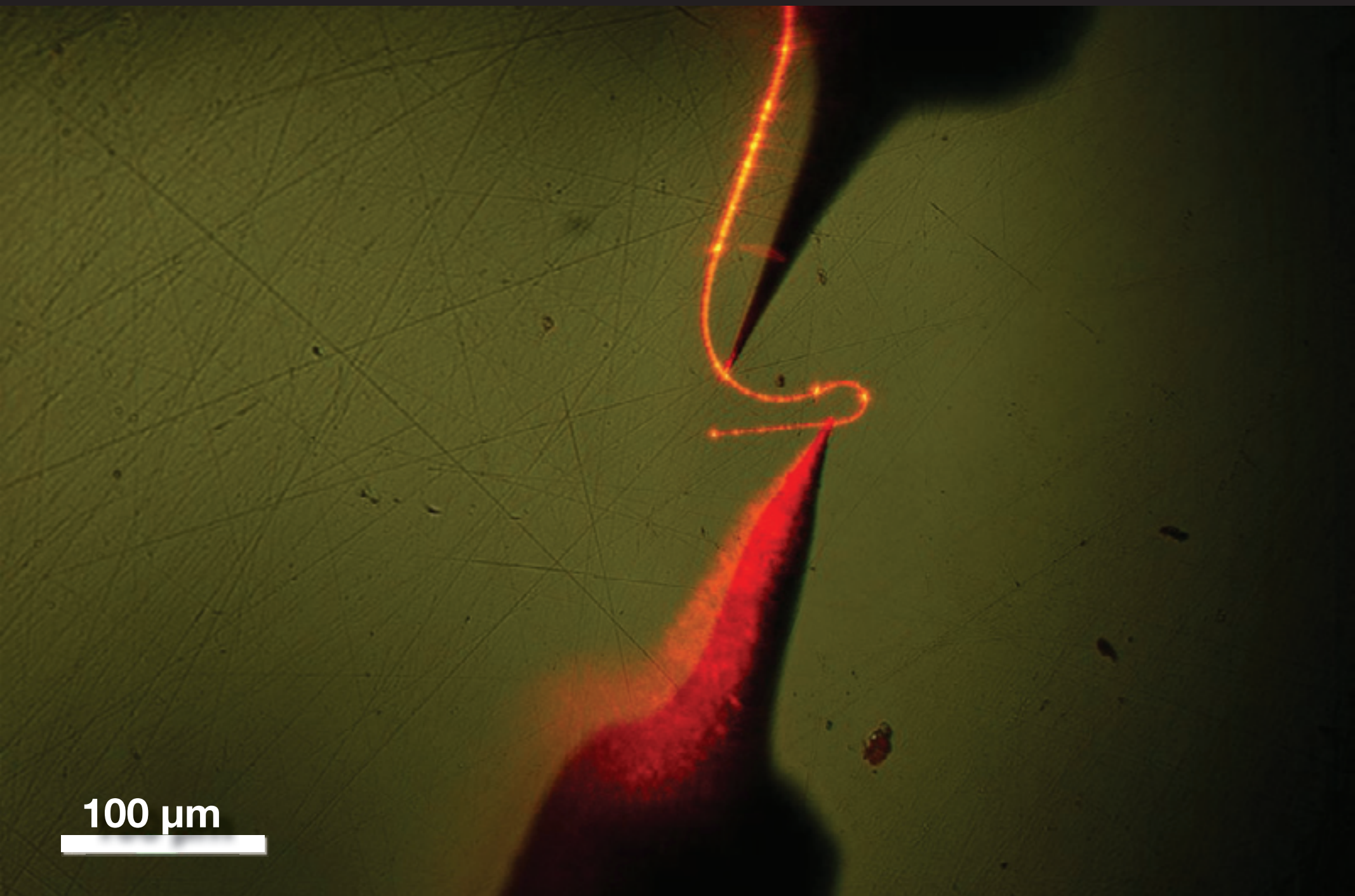


50 μm

Optical properties

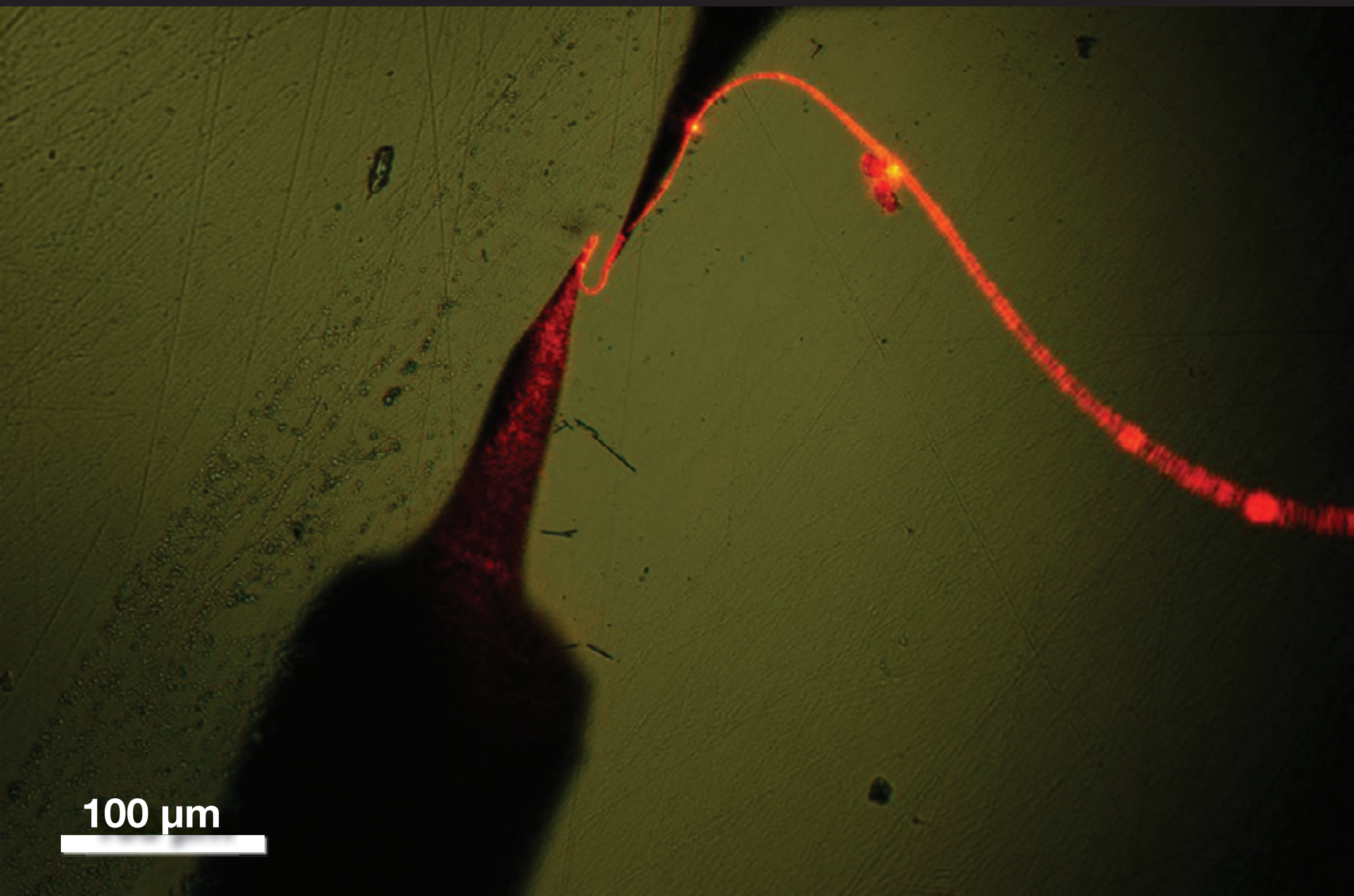


Optical properties



100 μm

Optical properties

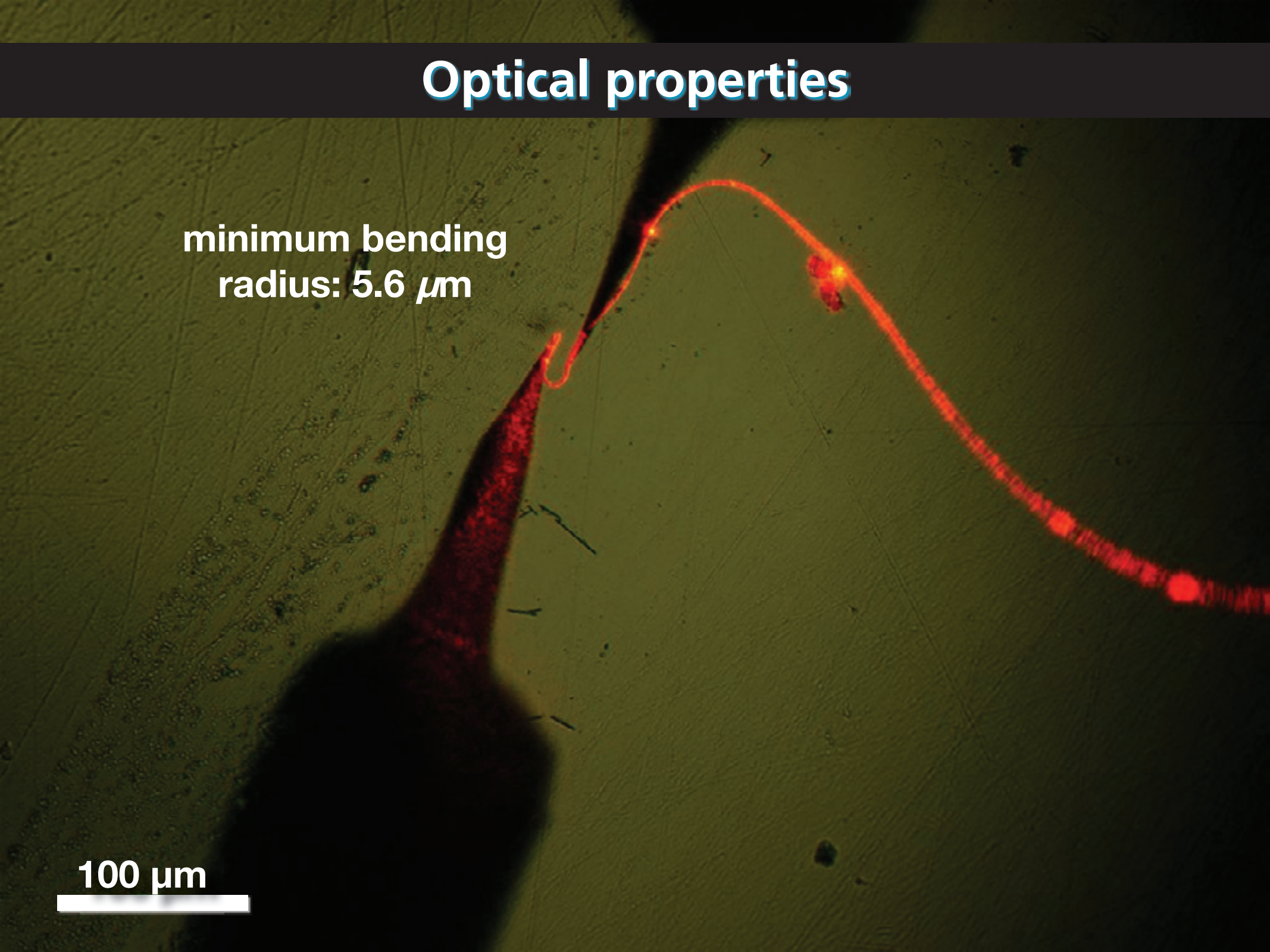


100 μm

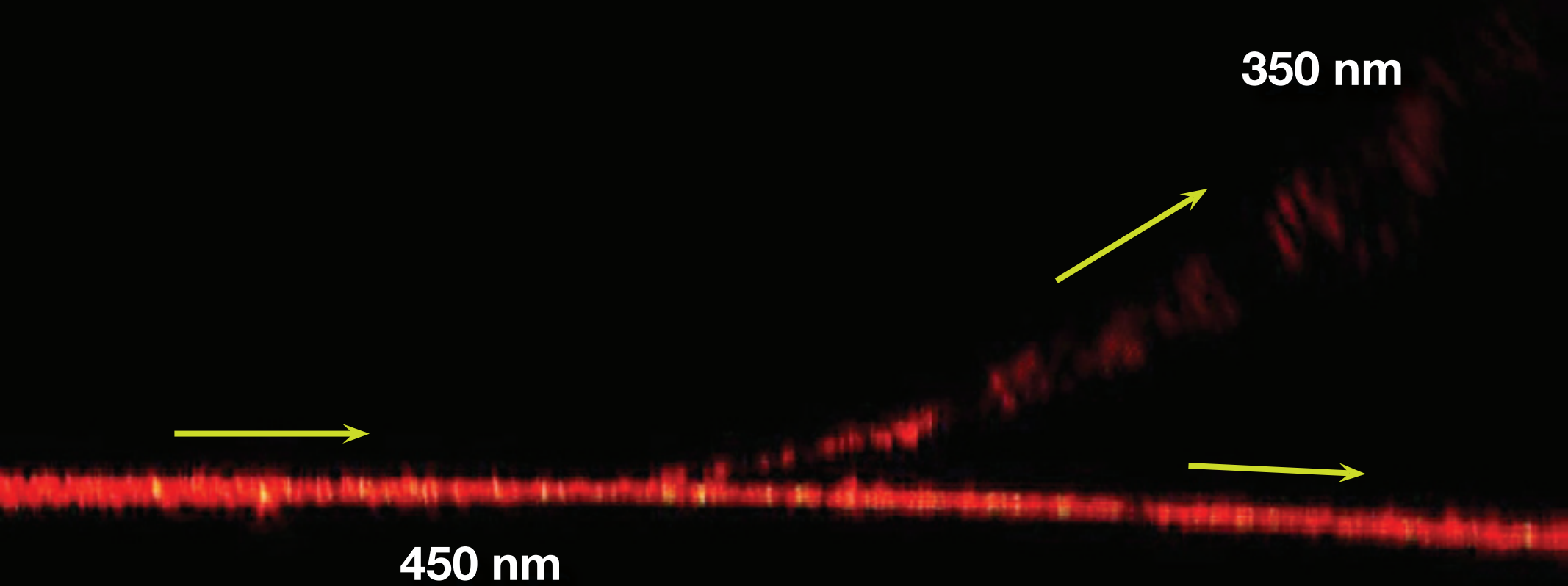
Optical properties

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

100 μm

An optical micrograph showing a fiber optic cable. A red laser light path is visible, starting from a point on the left and curving upwards and then downwards to the right. The fiber is illuminated with a green light, showing its texture and some surface imperfections. A scale bar at the bottom left indicates 100 micrometers. Text in the upper left corner states the minimum bending radius is 5.6 micrometers.

Outlook



10 μm

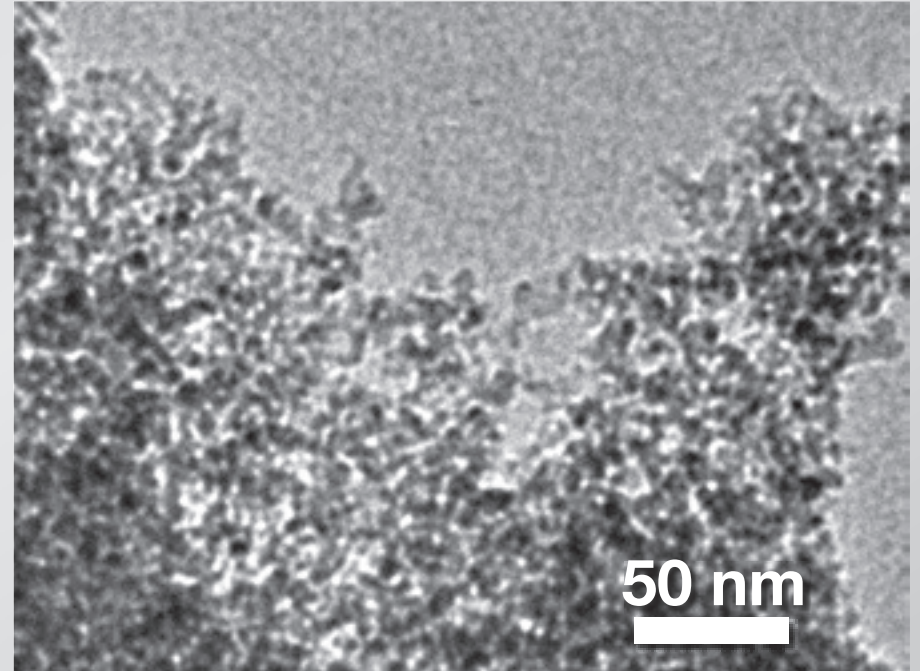
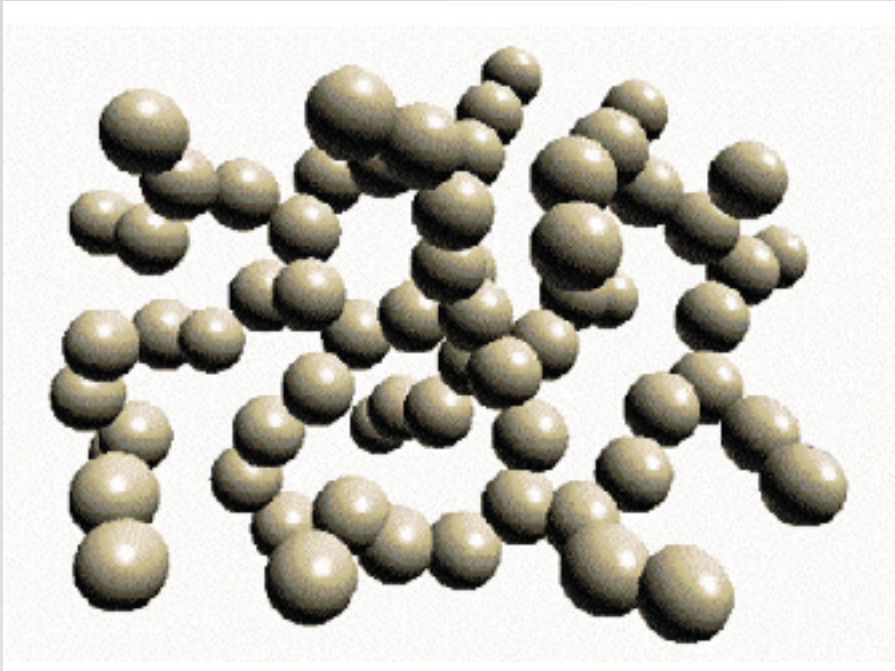


Outlook



Outlook

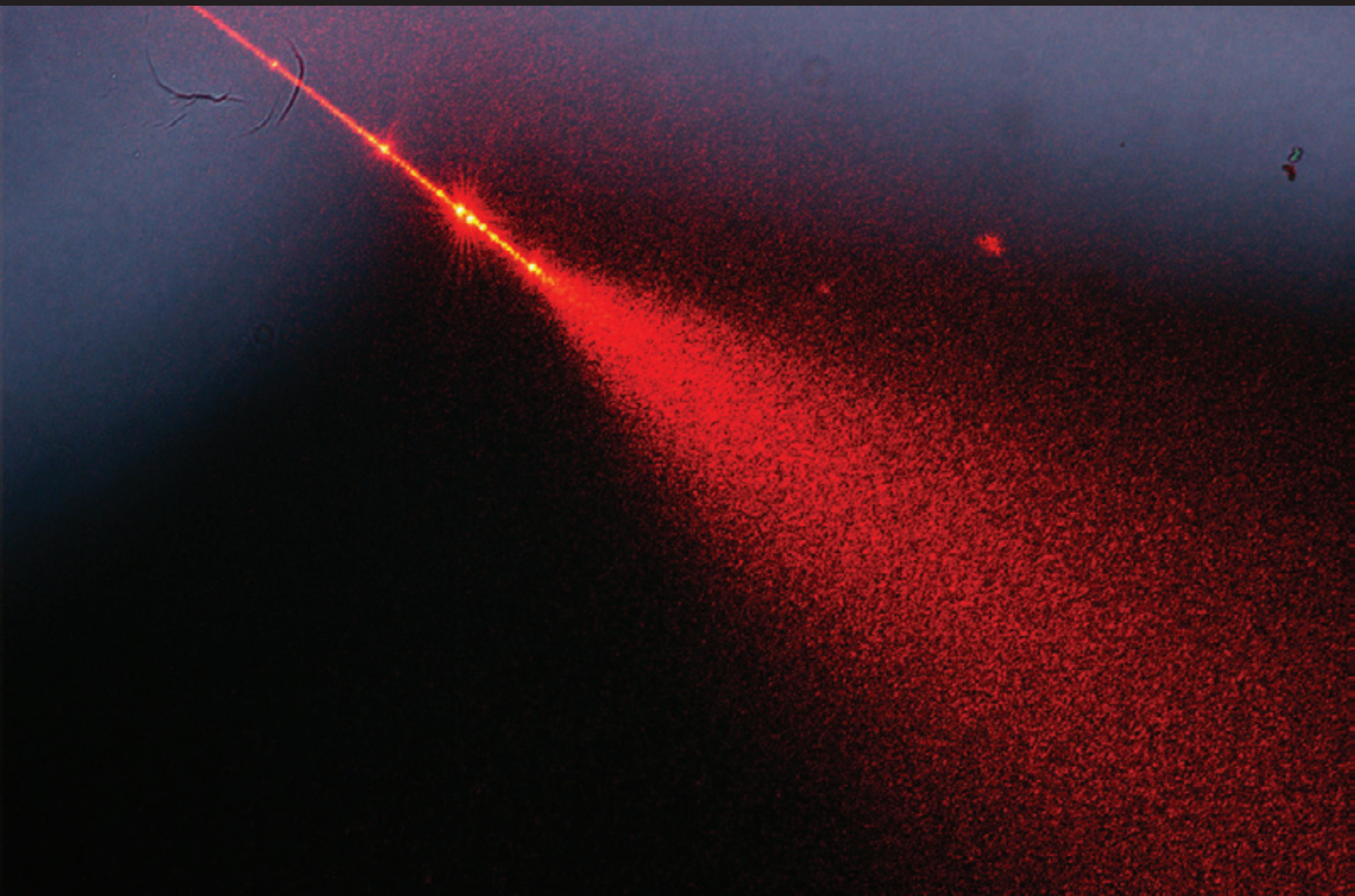
Aerogel



density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Outlook



Outlook

1 μm



Outlook

530 nm

50 μm

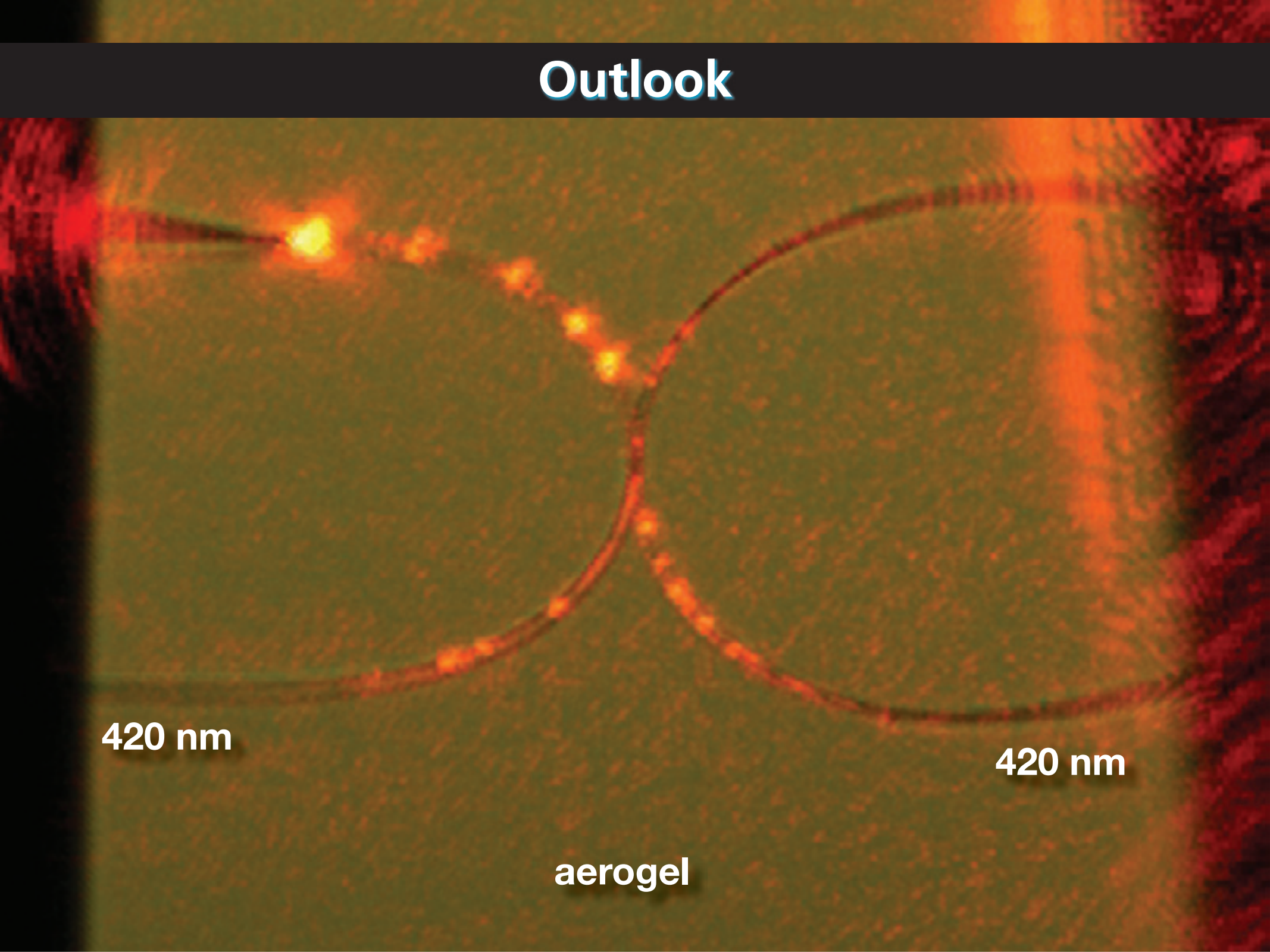
A fluorescence microscopy image showing a red fluorescent structure on a dark background. The structure is elongated and has a rounded, bulbous end. A white scale bar is located in the bottom left corner. The text '530 nm' is positioned above the structure, and '50 μm' is positioned above the scale bar. A thin, curved line is visible in the upper right quadrant of the image.

Outlook

420 nm

420 nm

aerogel



Outlook

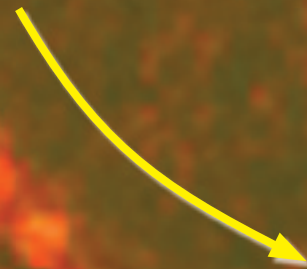
in



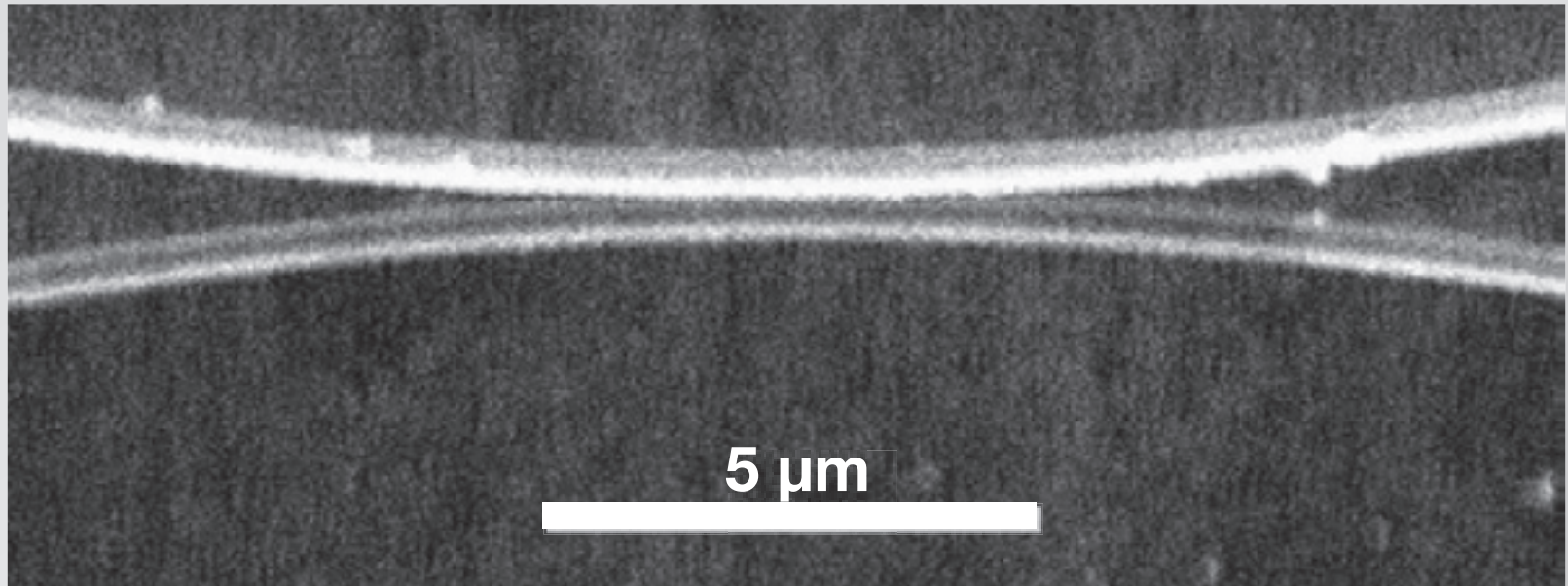
out



out

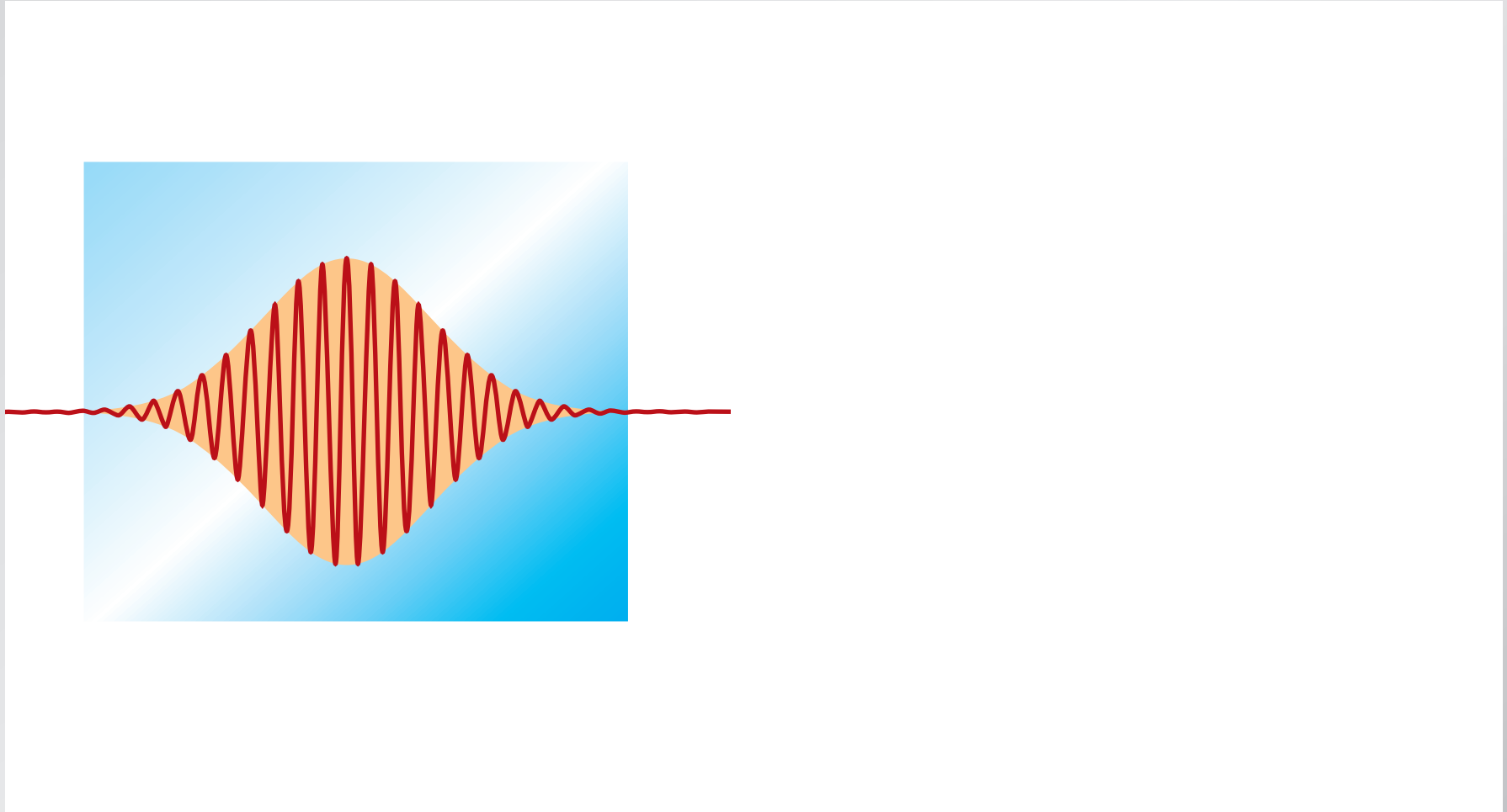


Outlook



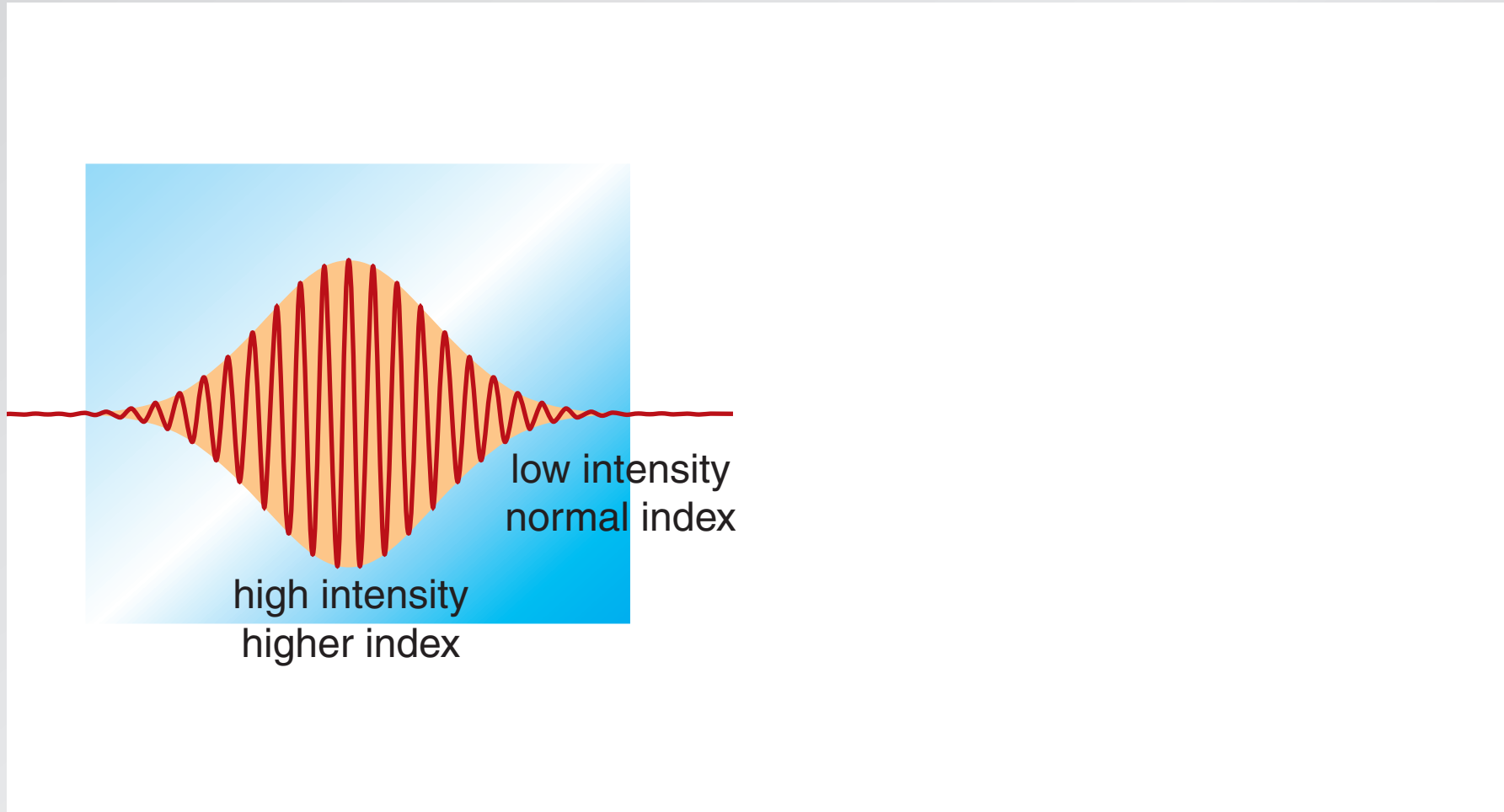
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



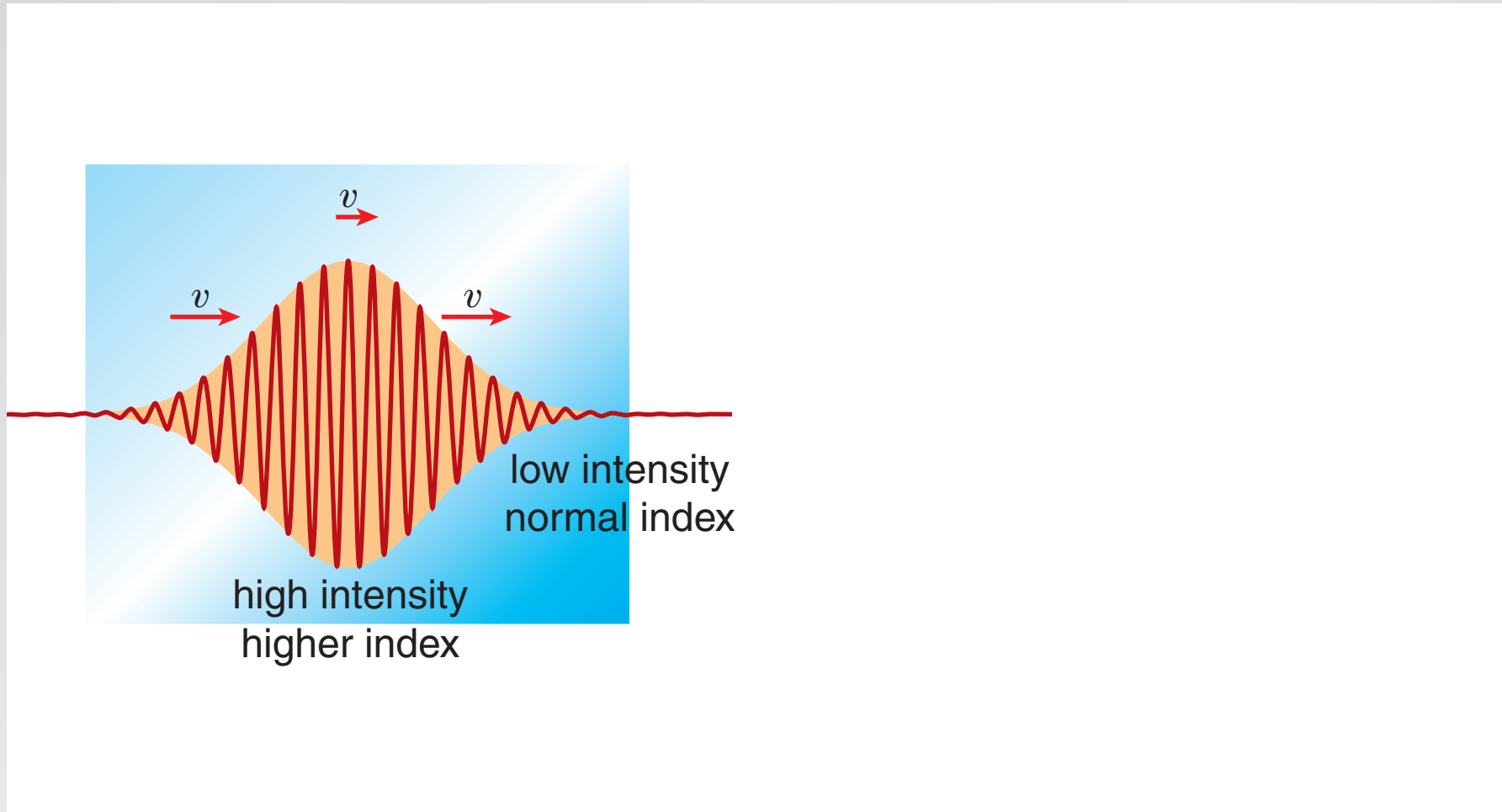
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



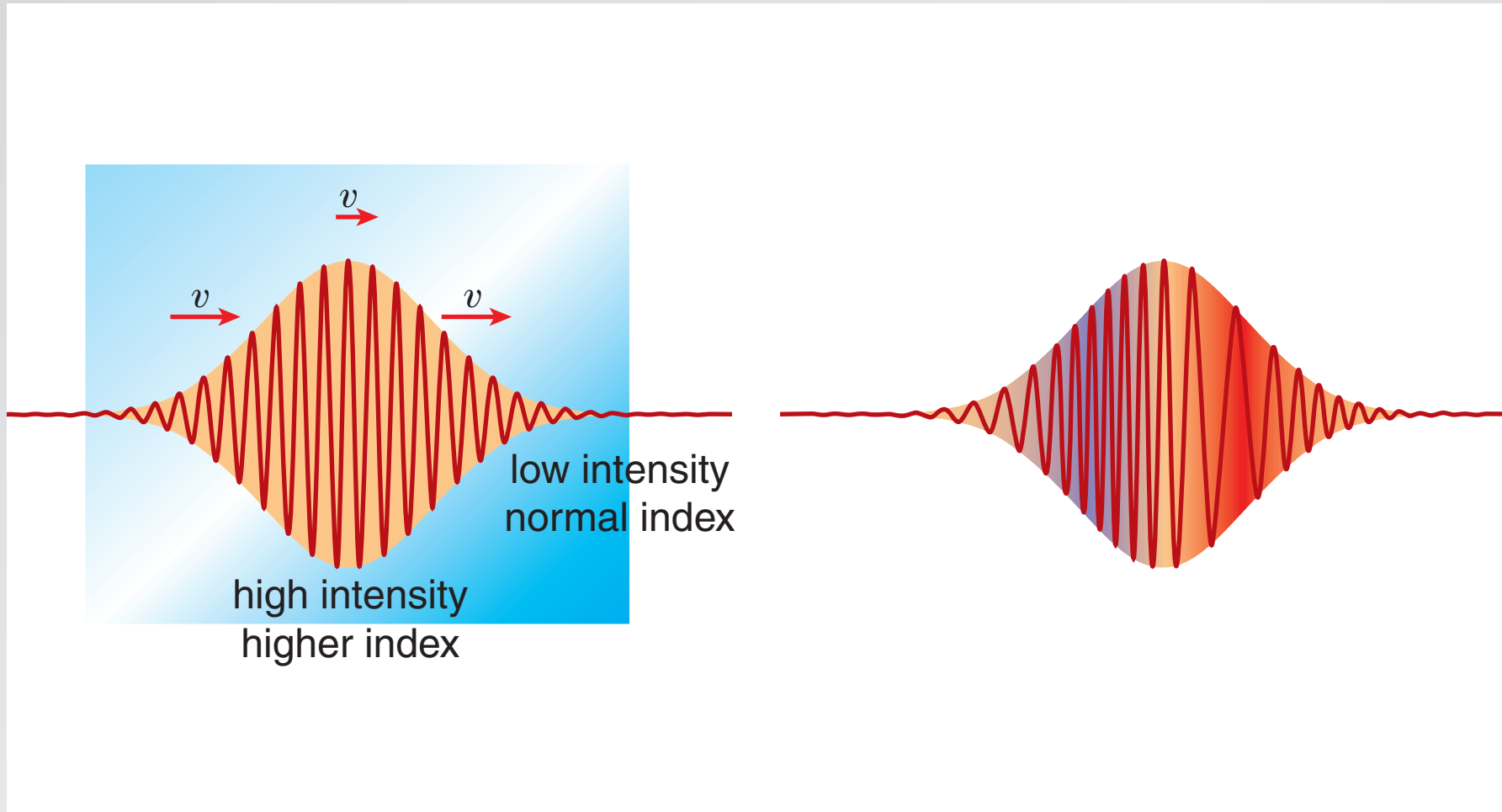
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



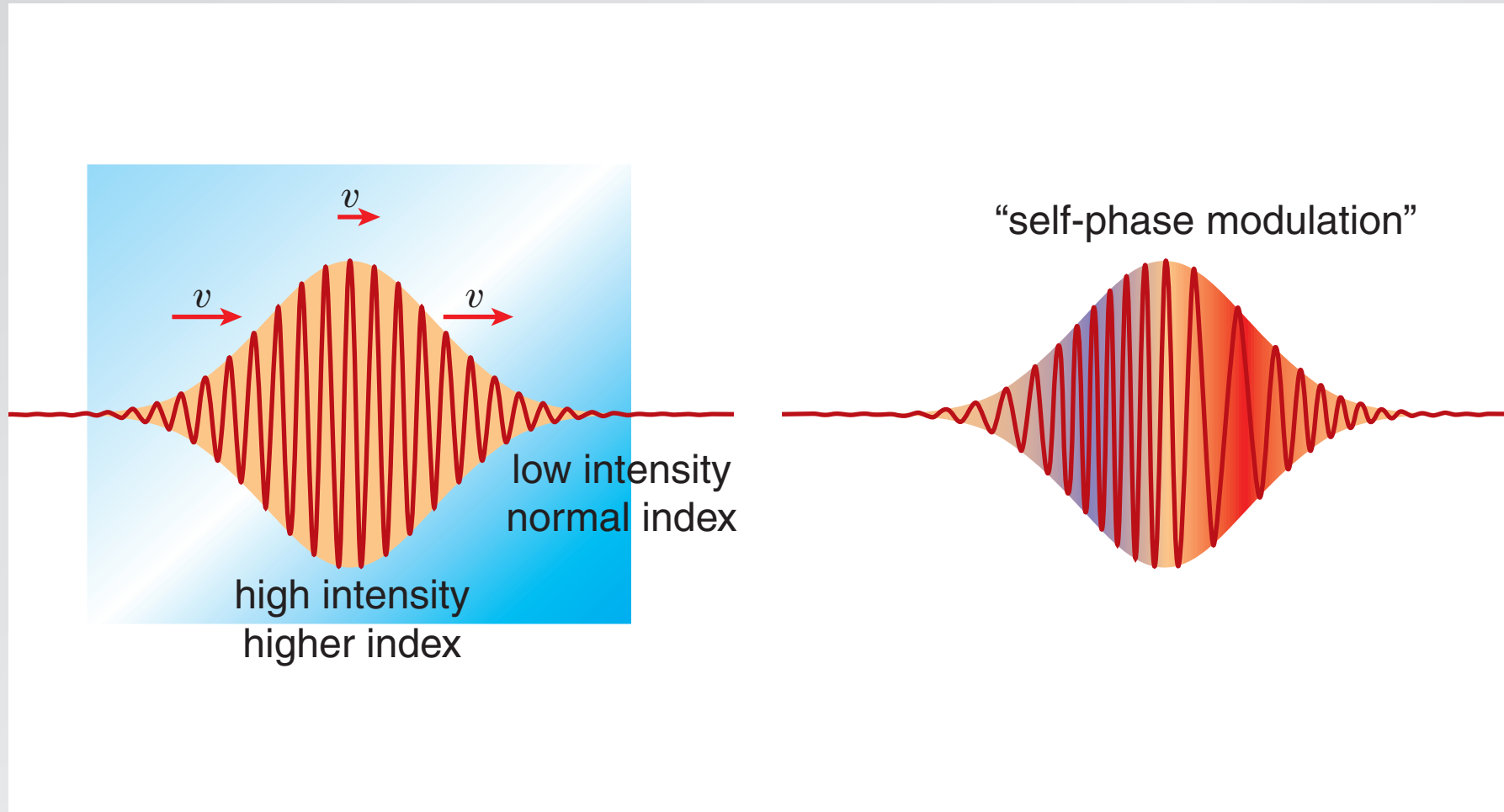
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_0 + n_2 I$



Nanoscale nonlinear optics

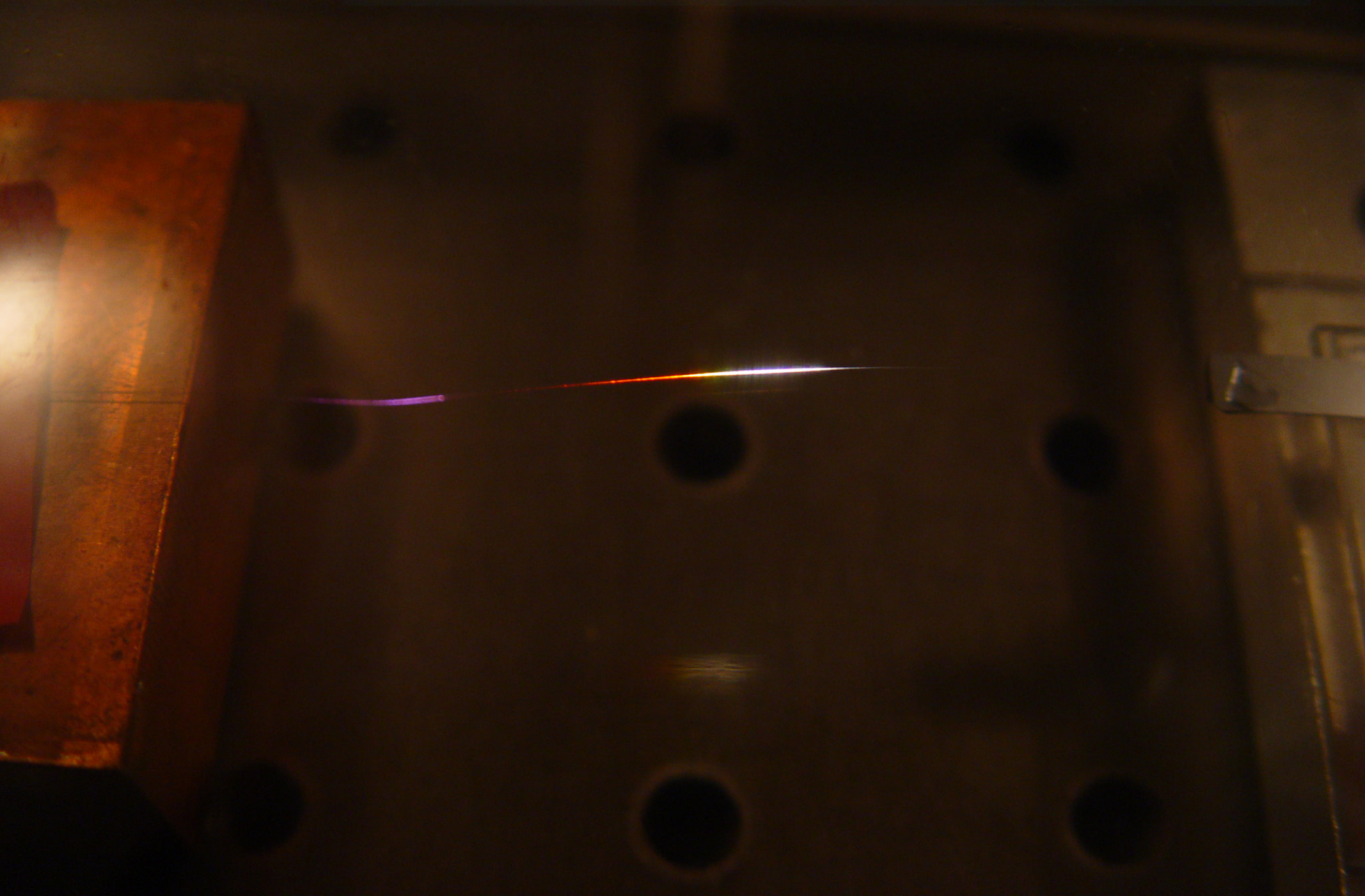
nonlinear dispersion: $n = n_0 + n_2 I$



Nanoscale nonlinear optics

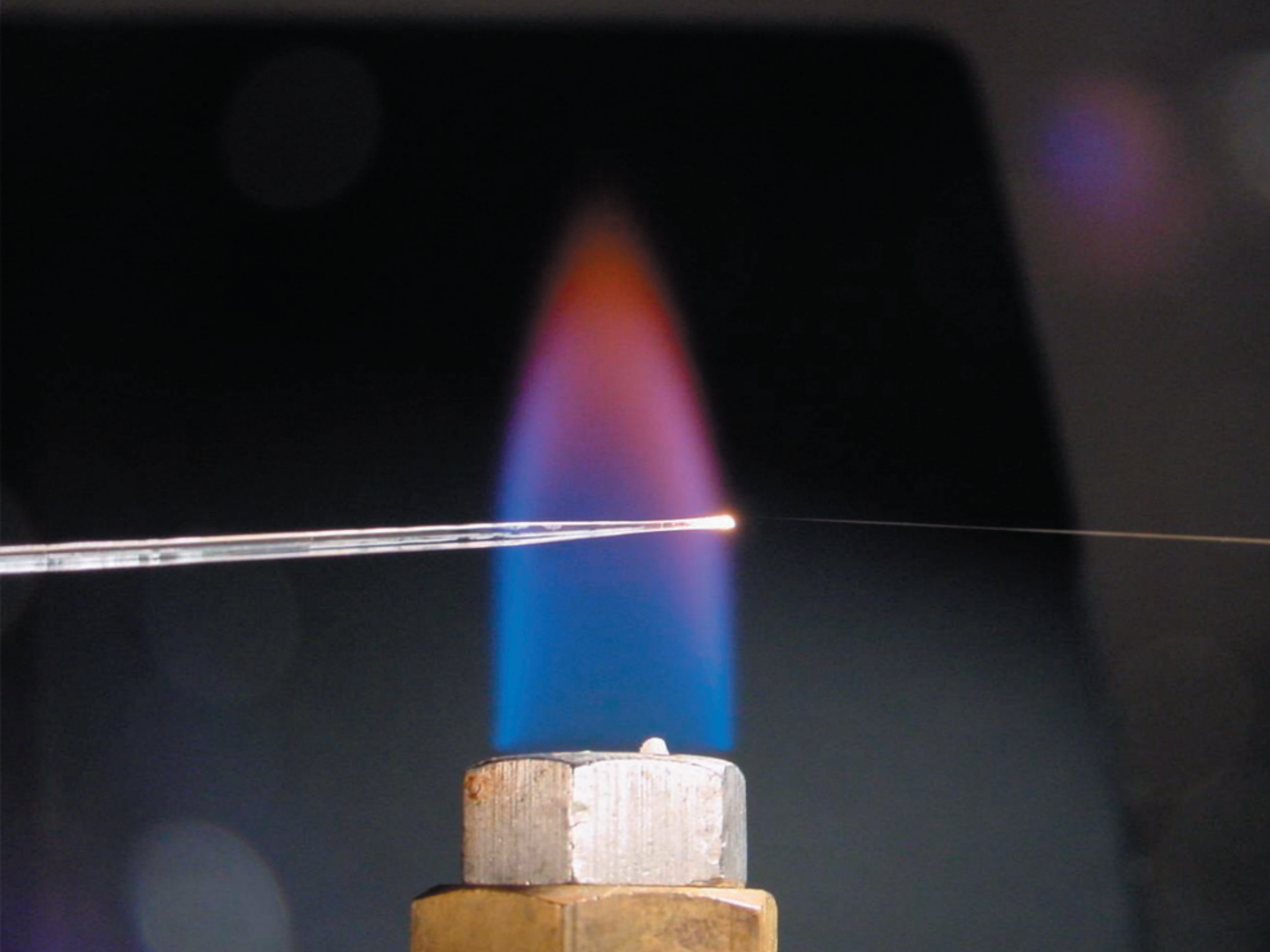
strong confinement \longrightarrow **high intensity**

Nanoscale nonlinear optics

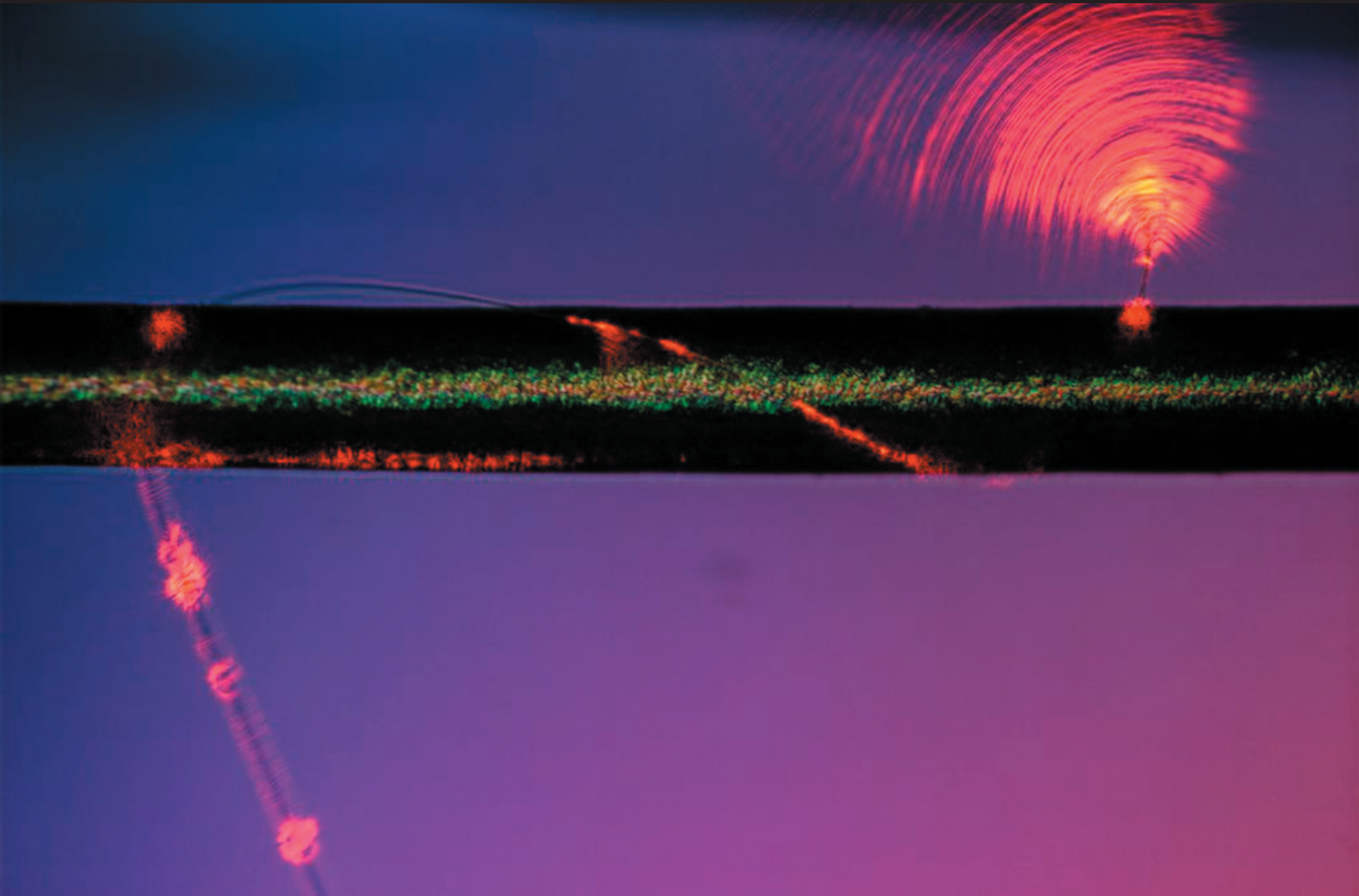


Nanoscale nonlinear optics

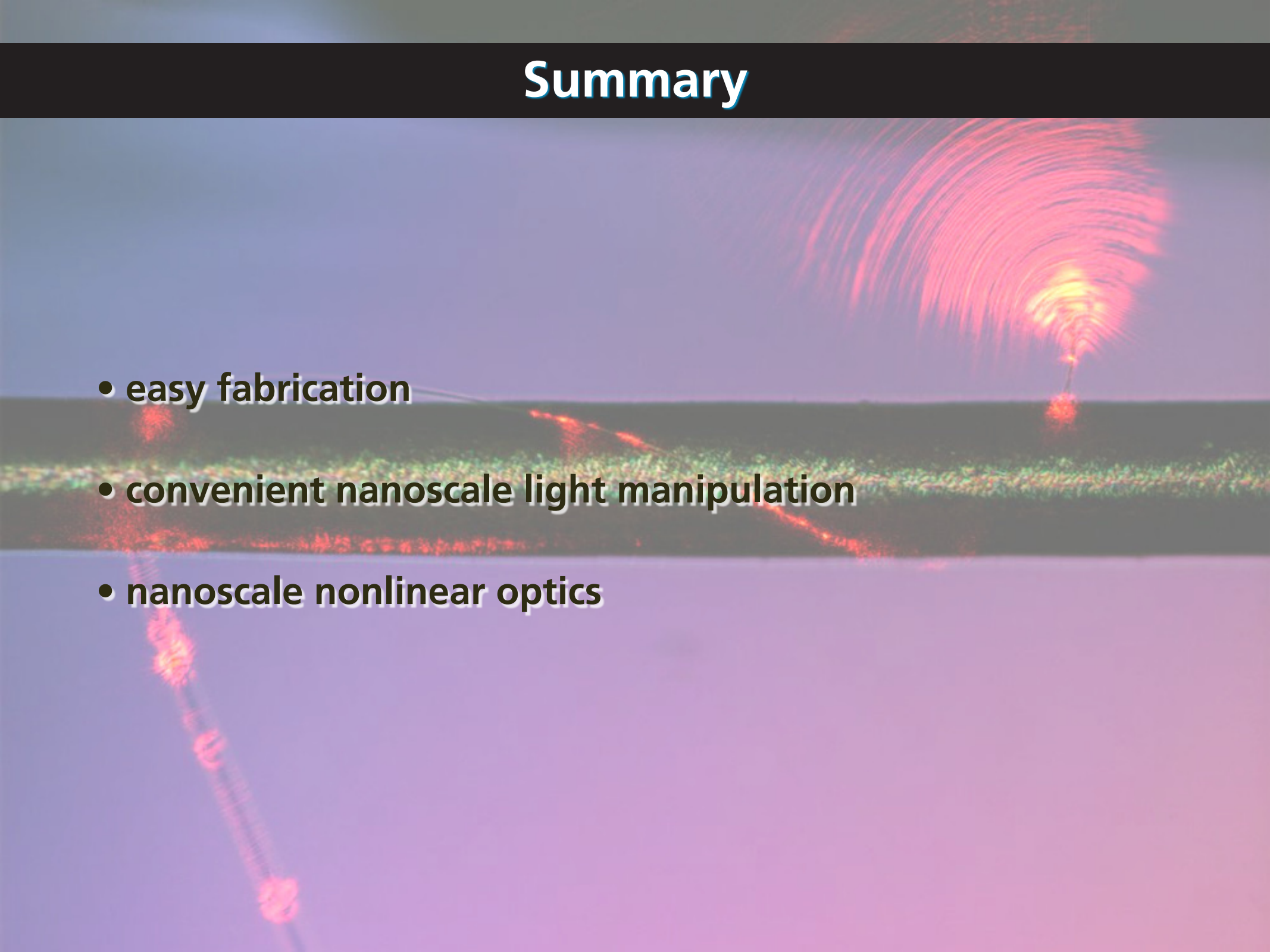




Summary



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



Funding:

Harvard Center for Imaging and Mesoscopic Structures

National Science Foundation

National Natural Science Foundation of China

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