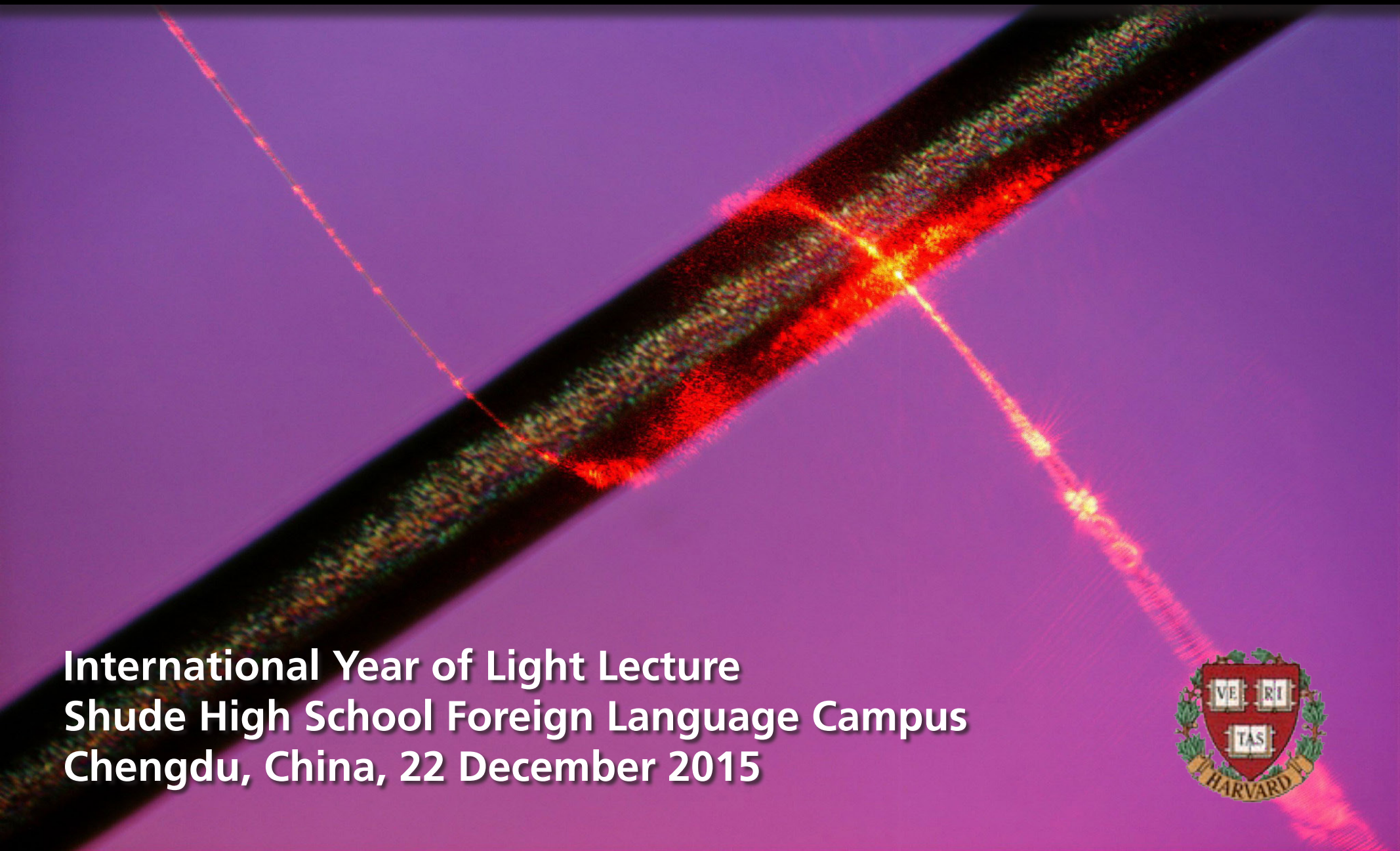
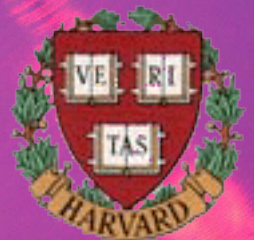


Wrapping light around a hair



International Year of Light Lecture
Shude High School Foreign Language Campus
Chengdu, China, 22 December 2015



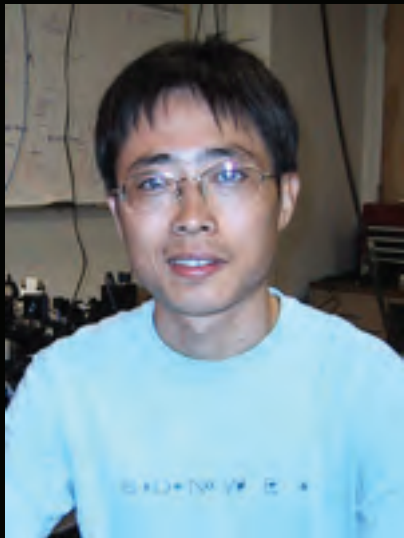
Wrapping light around a hair



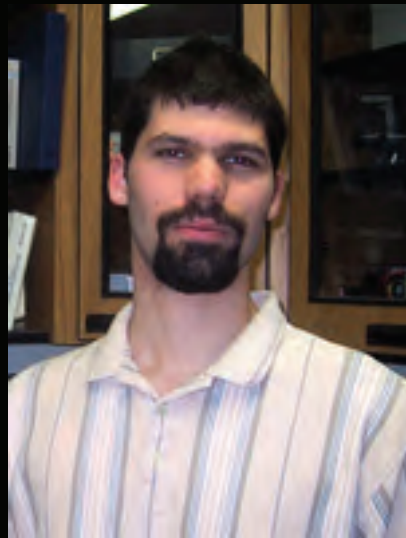
ericmazur

International Year of Light Lecture
Shude High School Foreign Language Campus
Chengdu, China, 22 December 2015





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

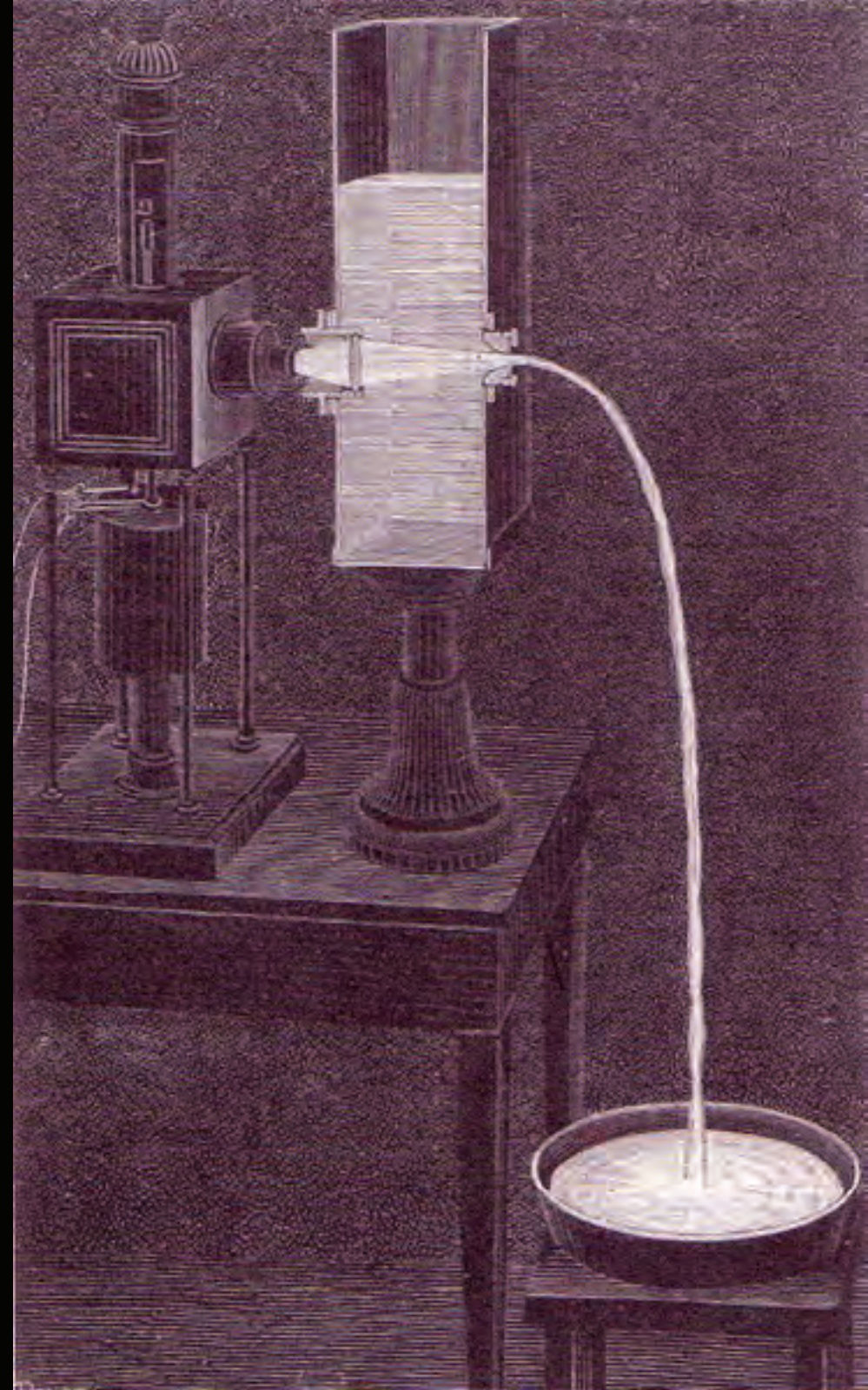
Zhanghua Han

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)



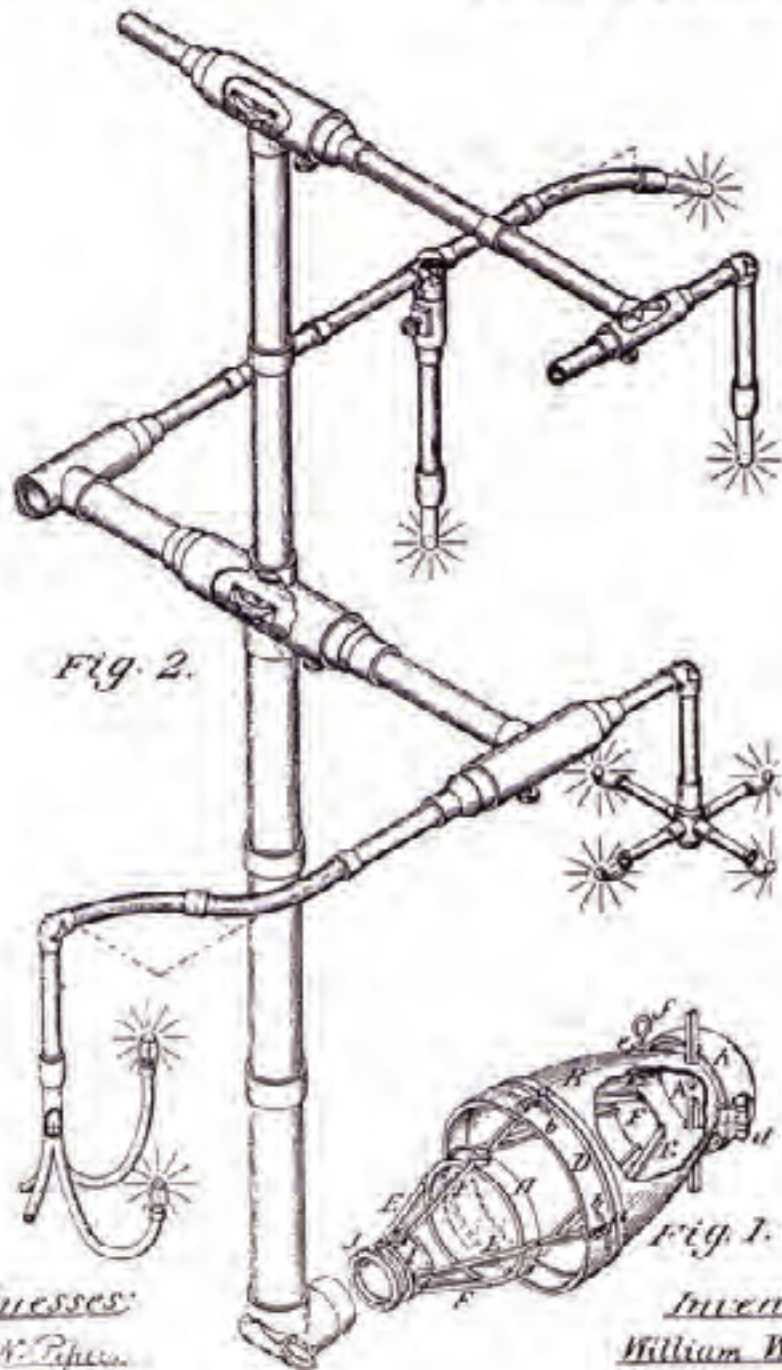


W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.



US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

Waveguiding

how does water surface look from bottom?

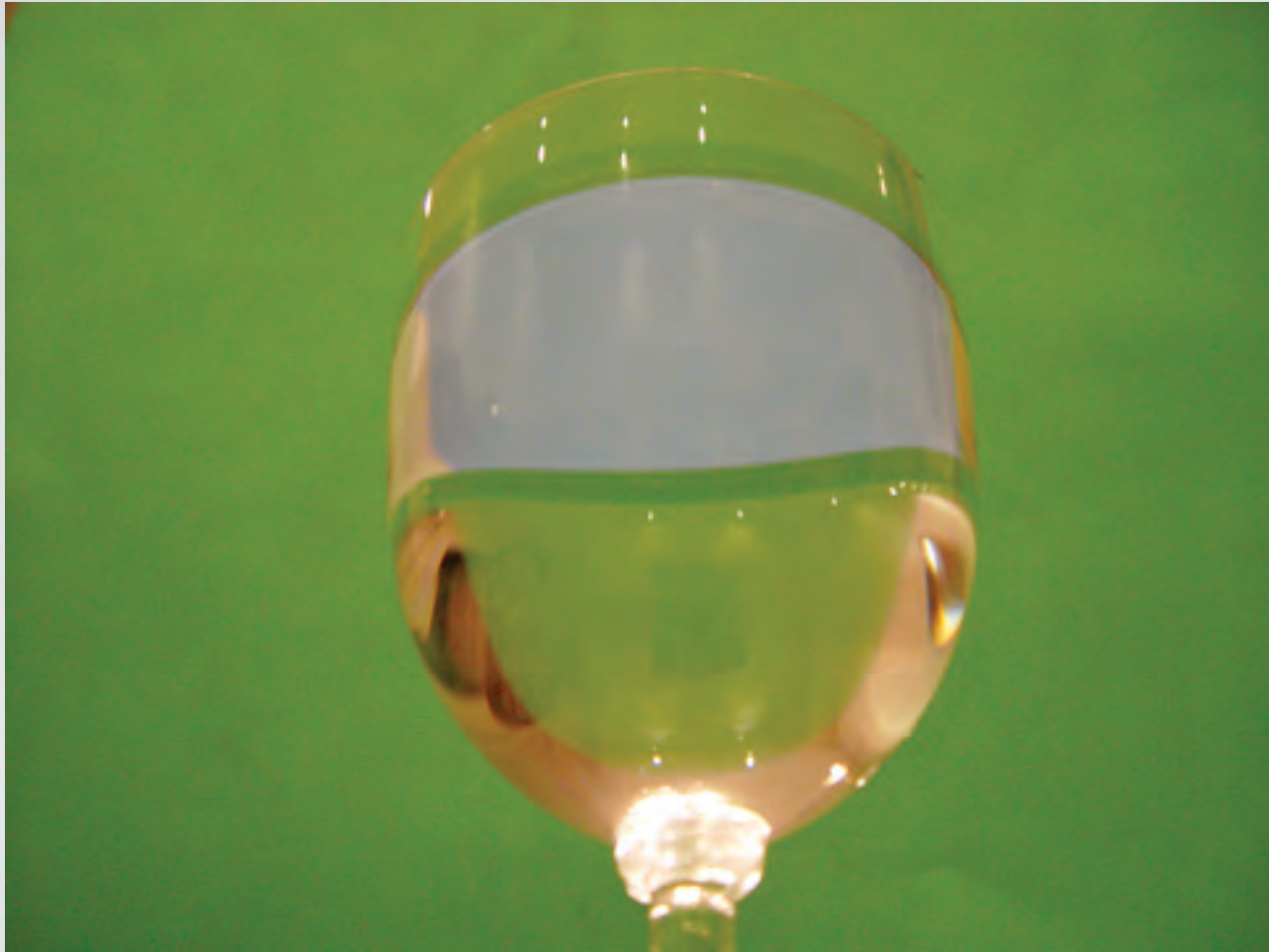


Waveguiding

from top partially transmitting!



Waveguiding

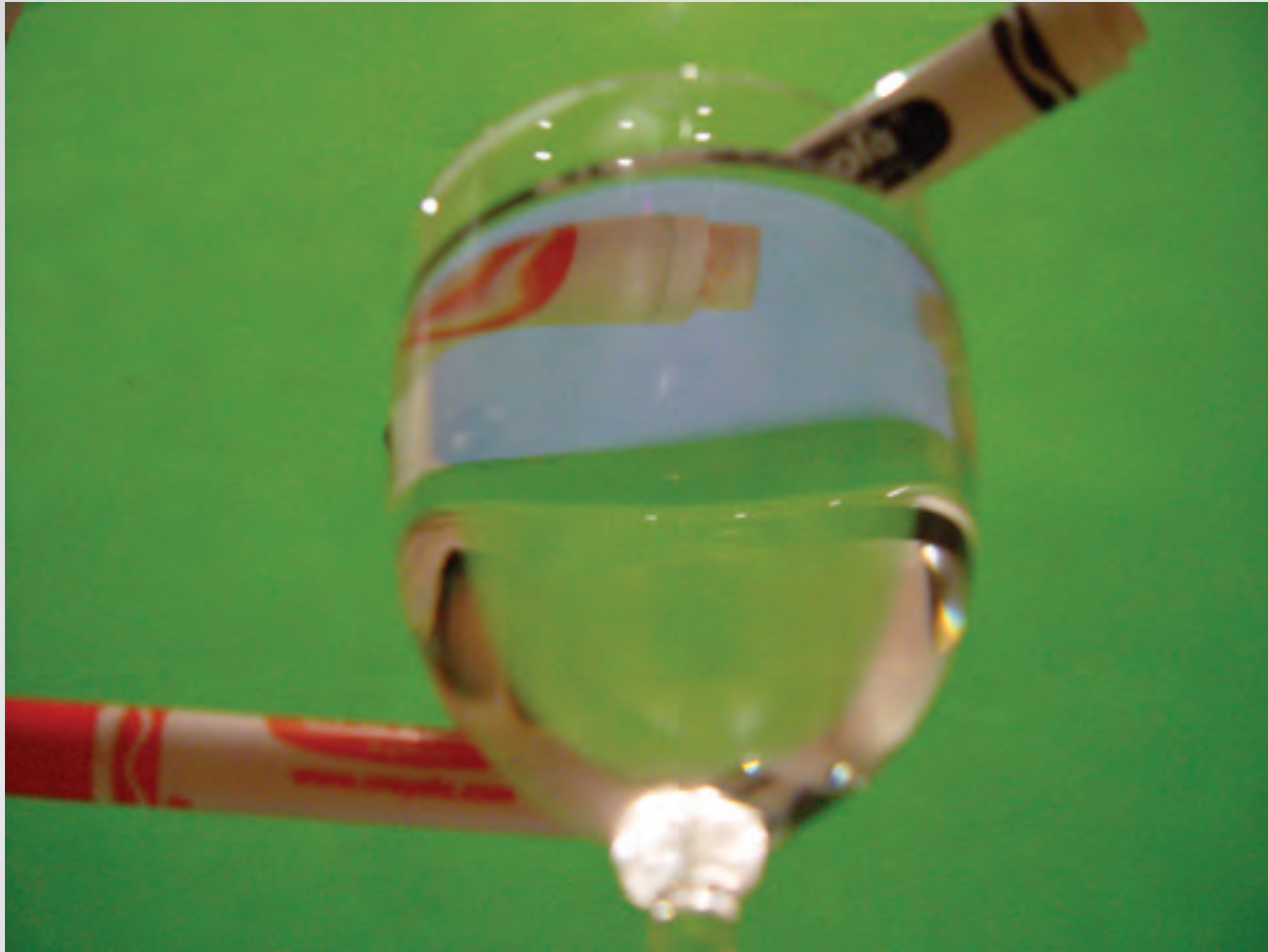


Waveguiding



Waveguiding

water surface is perfect one-way mirror!



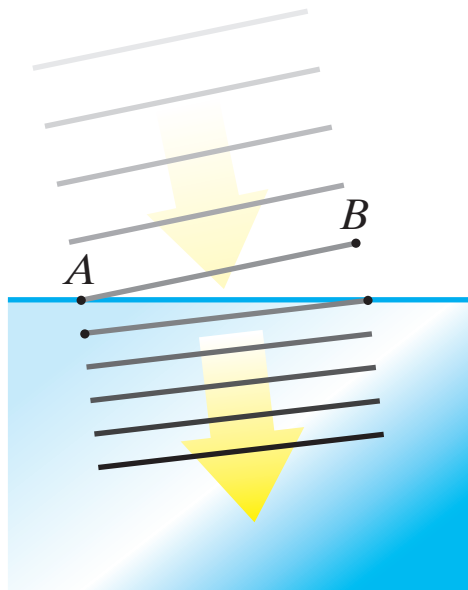
Waveguiding

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



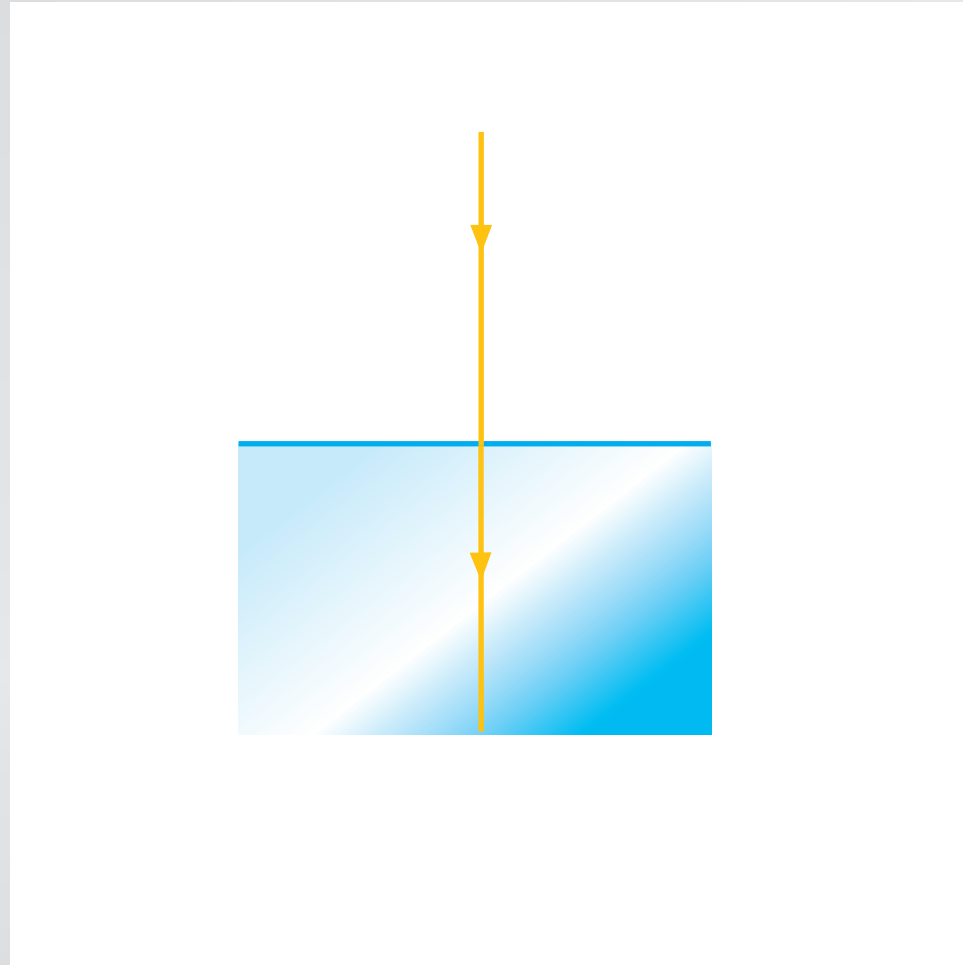
Waveguiding

...making it bend as it crosses surface



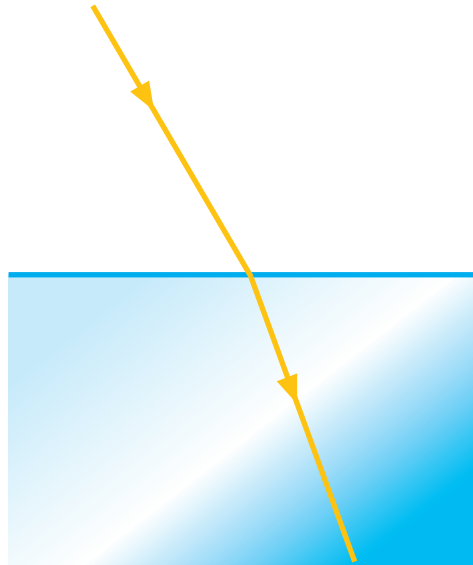
Waveguiding

The more angled the incident ray, the stronger the bending



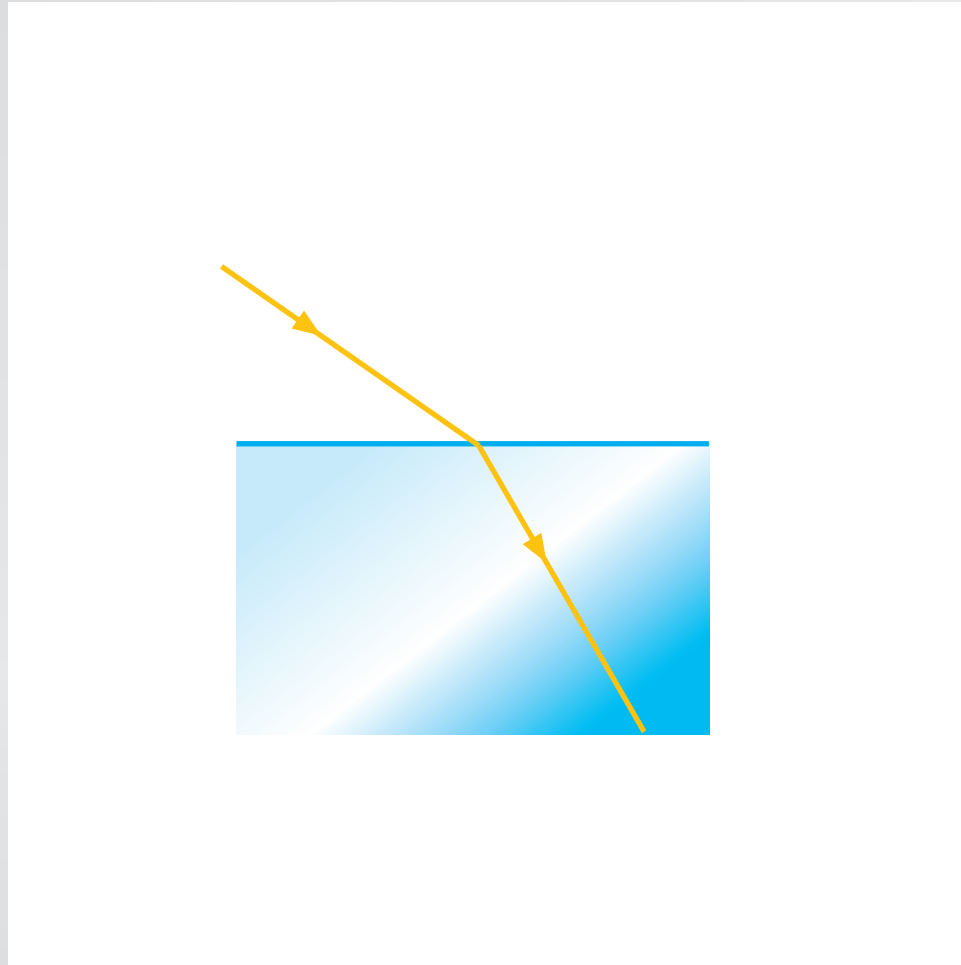
Waveguiding

The more angled the incident ray, the stronger the bending



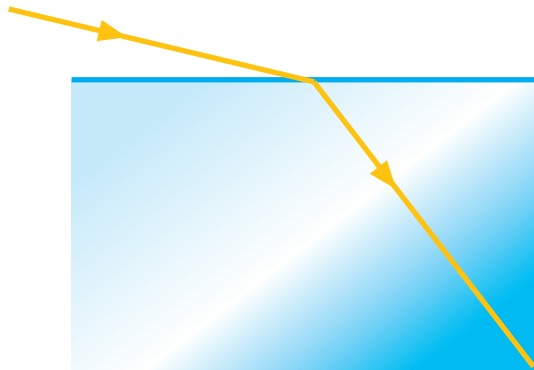
Waveguiding

The more angled the incident ray, the stronger the bending



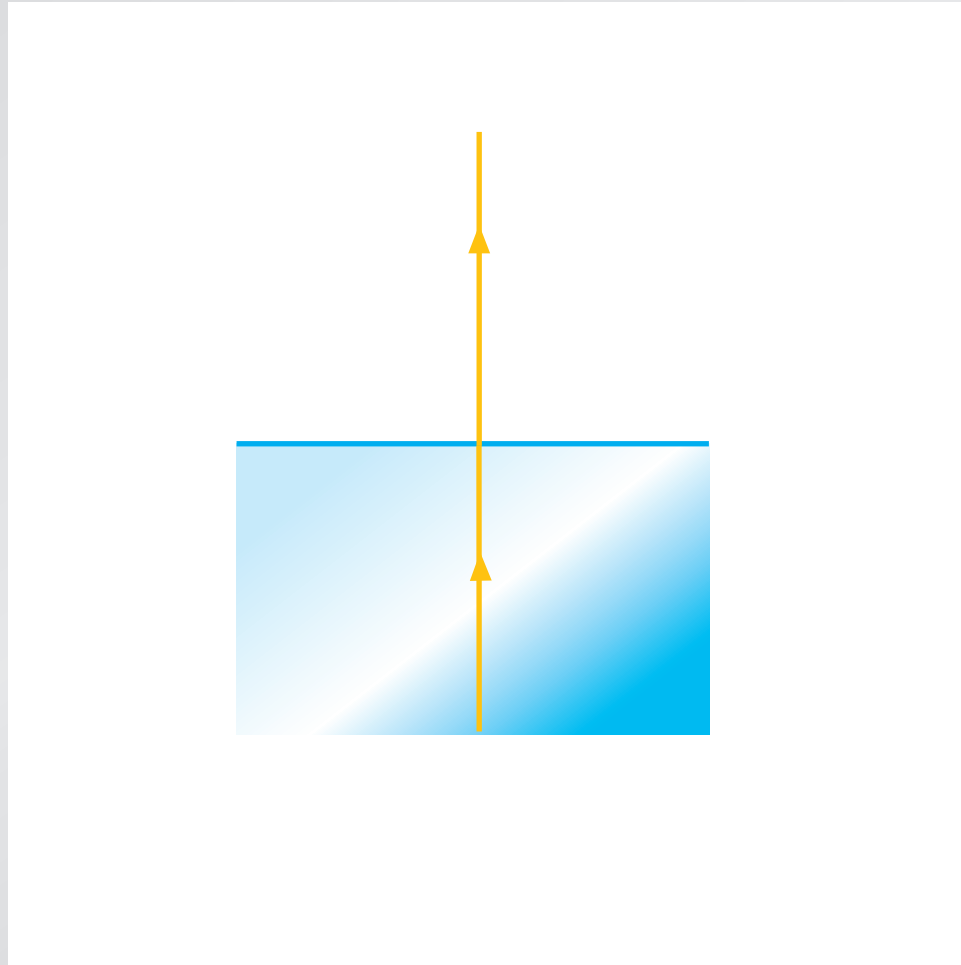
Waveguiding

The more angled the incident ray, the stronger the bending



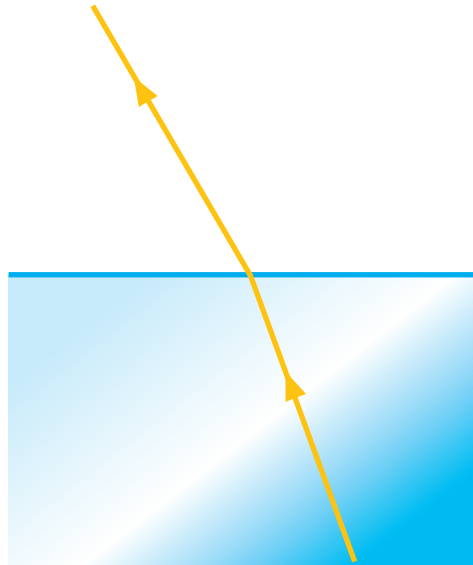
Waveguiding

The amount of bending is the same in reverse



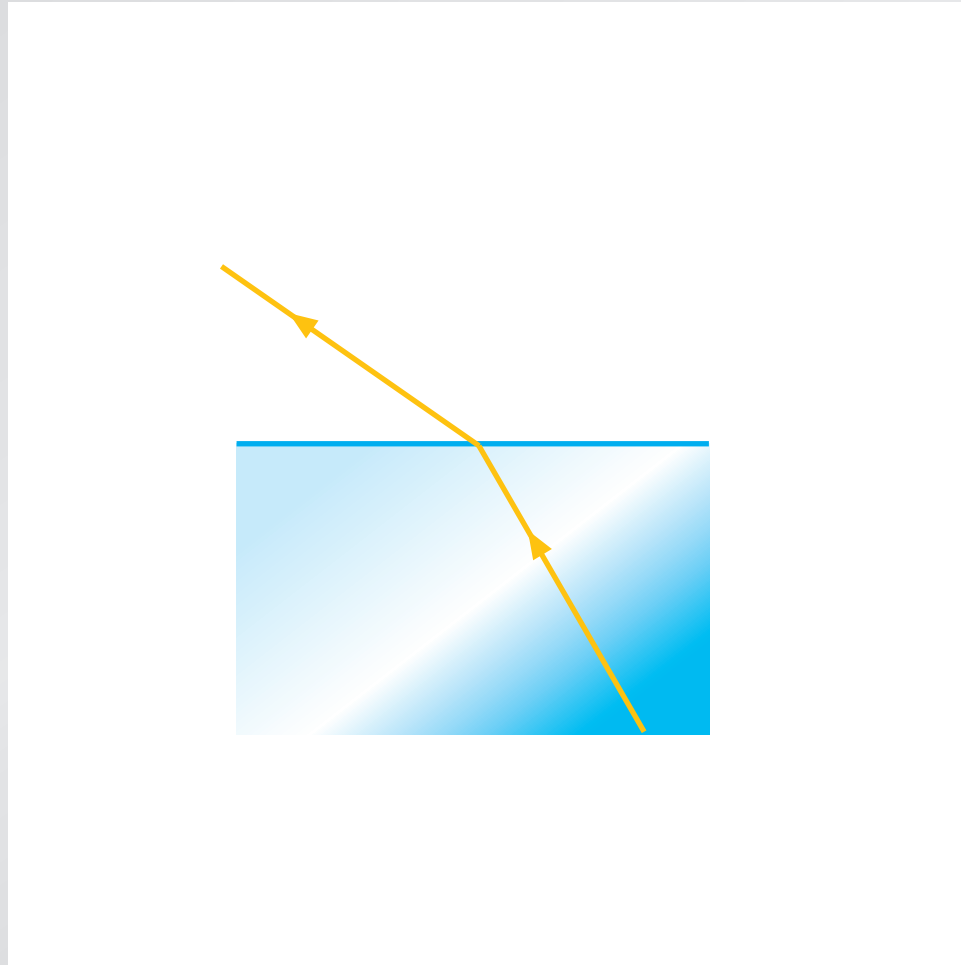
Waveguiding

The amount of bending is the same in reverse



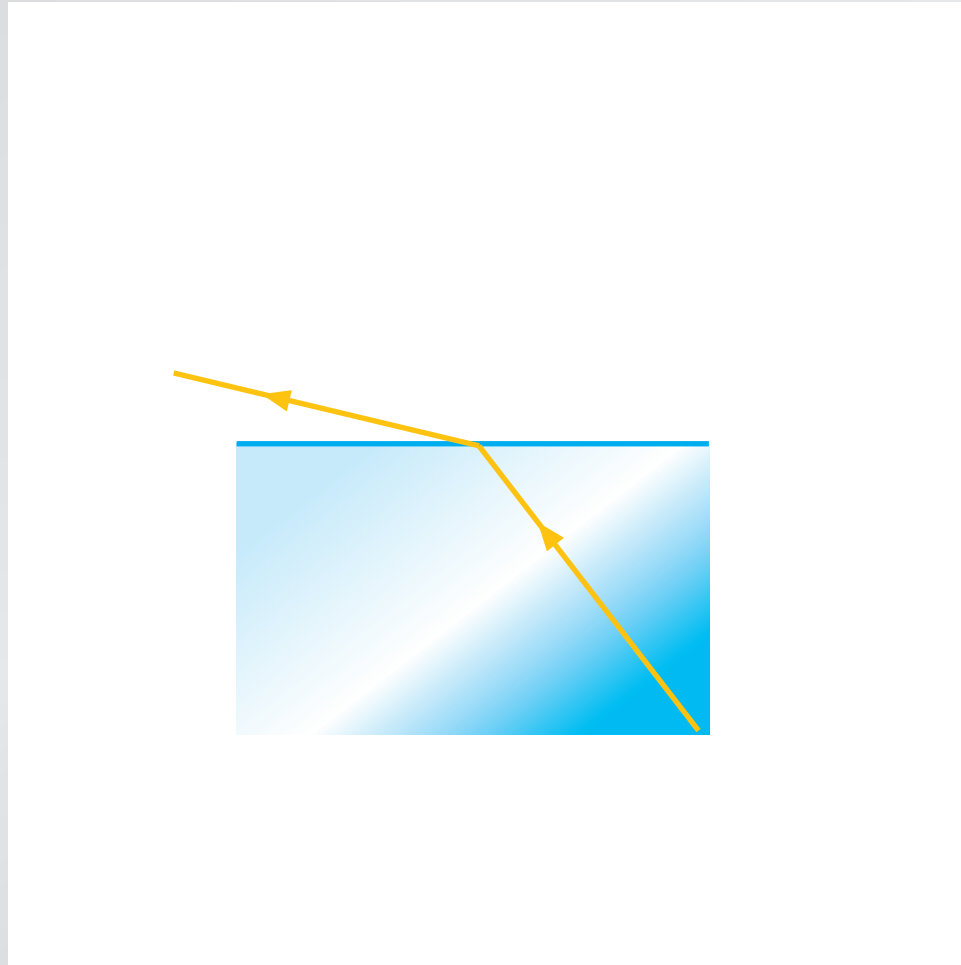
Waveguiding

The amount of bending is the same in reverse



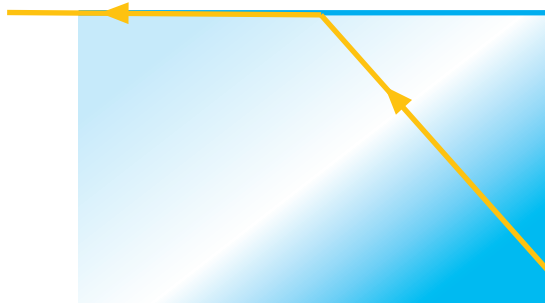
Waveguiding

The amount of bending is the same in reverse



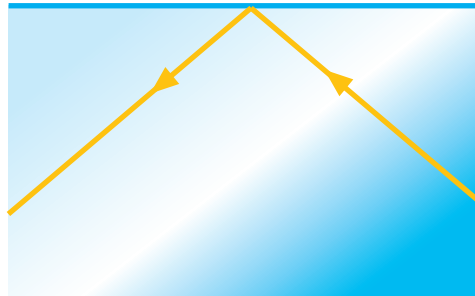
Waveguiding

At 'critical angle' bent ray travels along surface



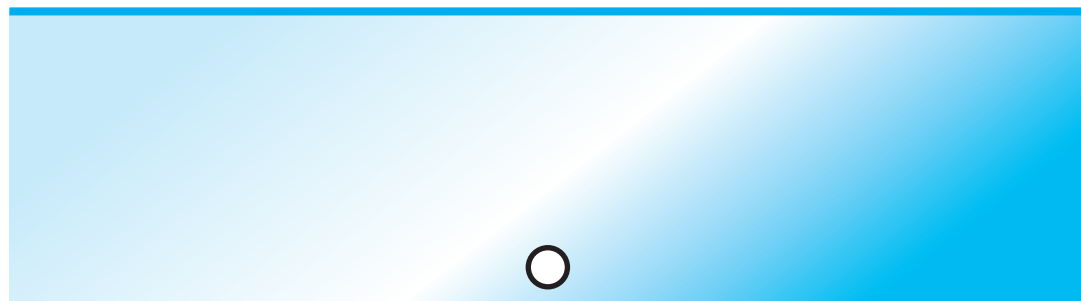
Waveguiding

Beyond 'critical angle': total internal reflection



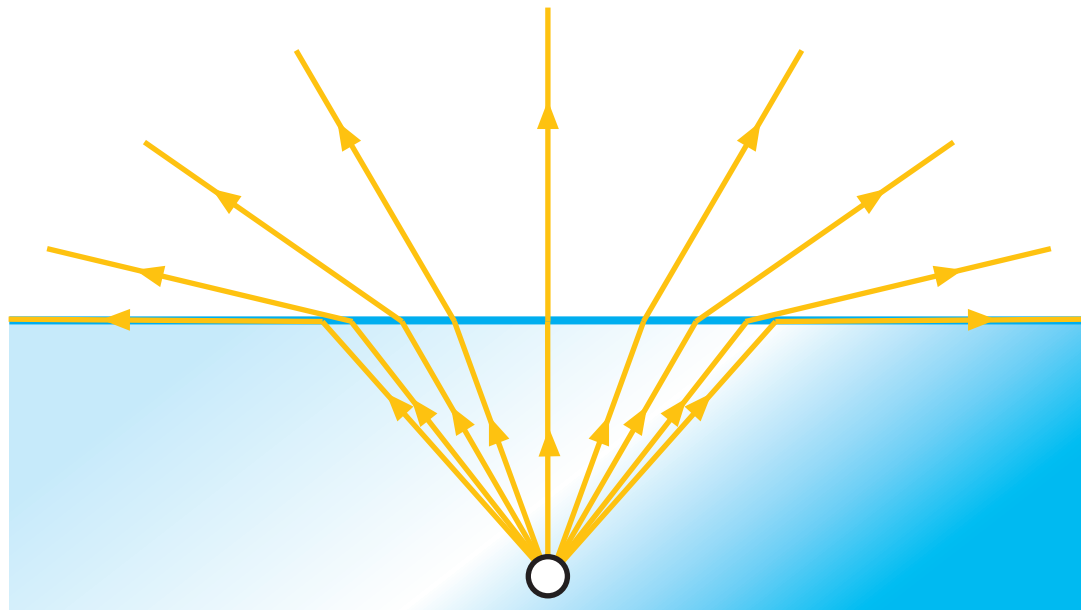
Waveguiding

seeing underwater



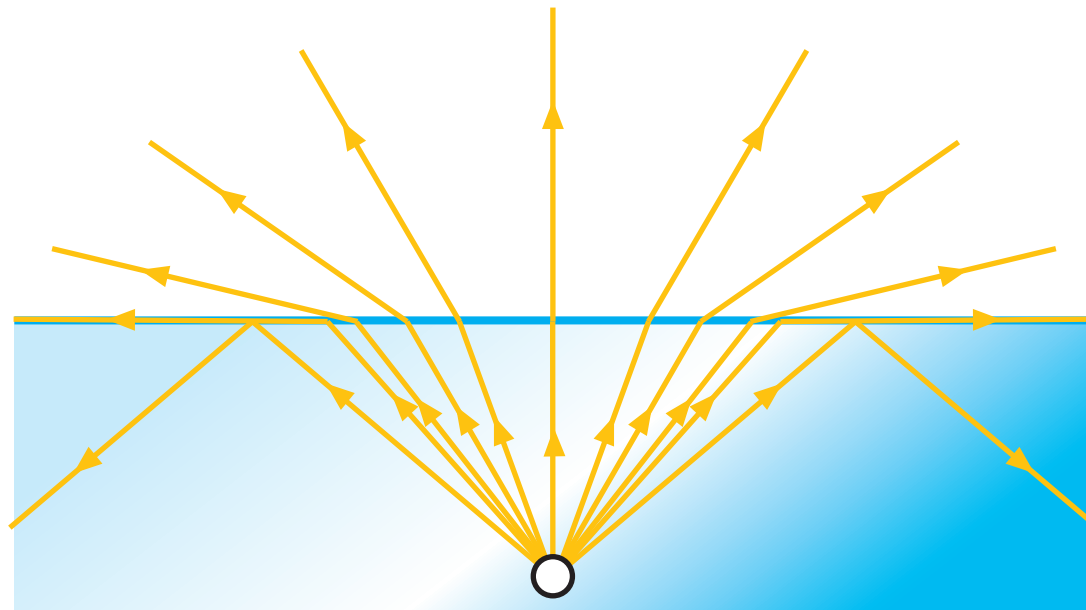
Waveguiding

seeing underwater



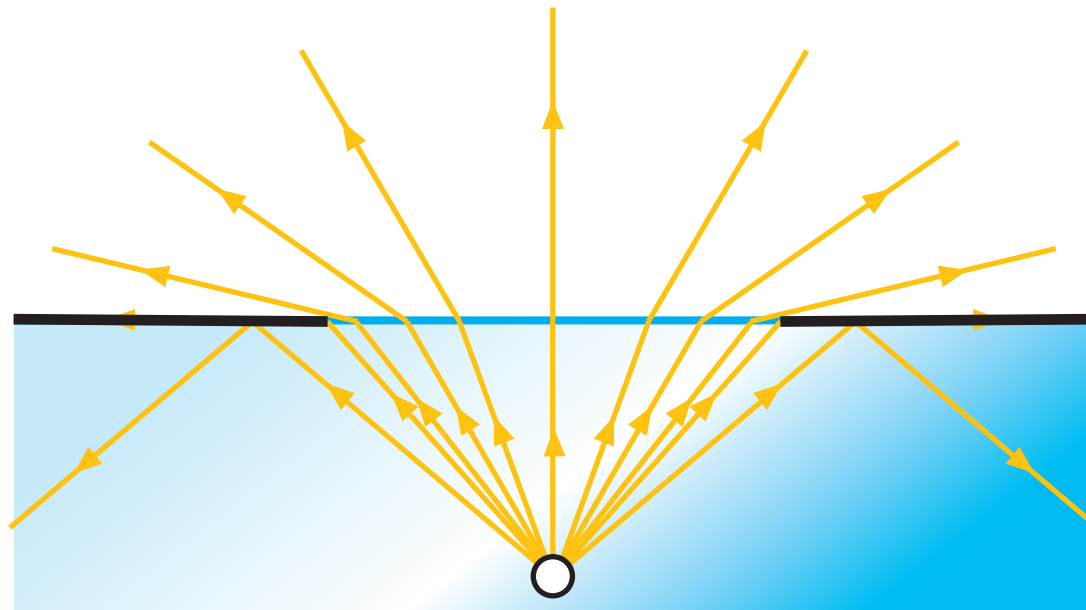
Waveguiding

seeing underwater



Waveguiding

surface looks like mirror with a circular hole



Waveguiding



Waveguiding



Waveguiding



Waveguiding

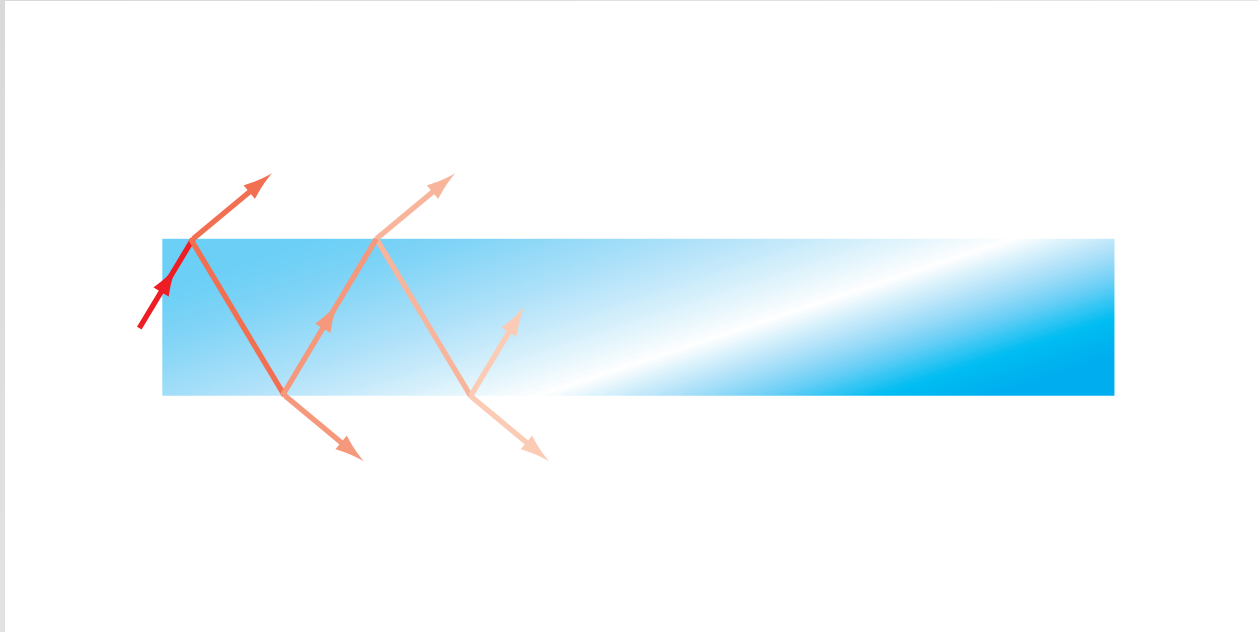


Waveguiding



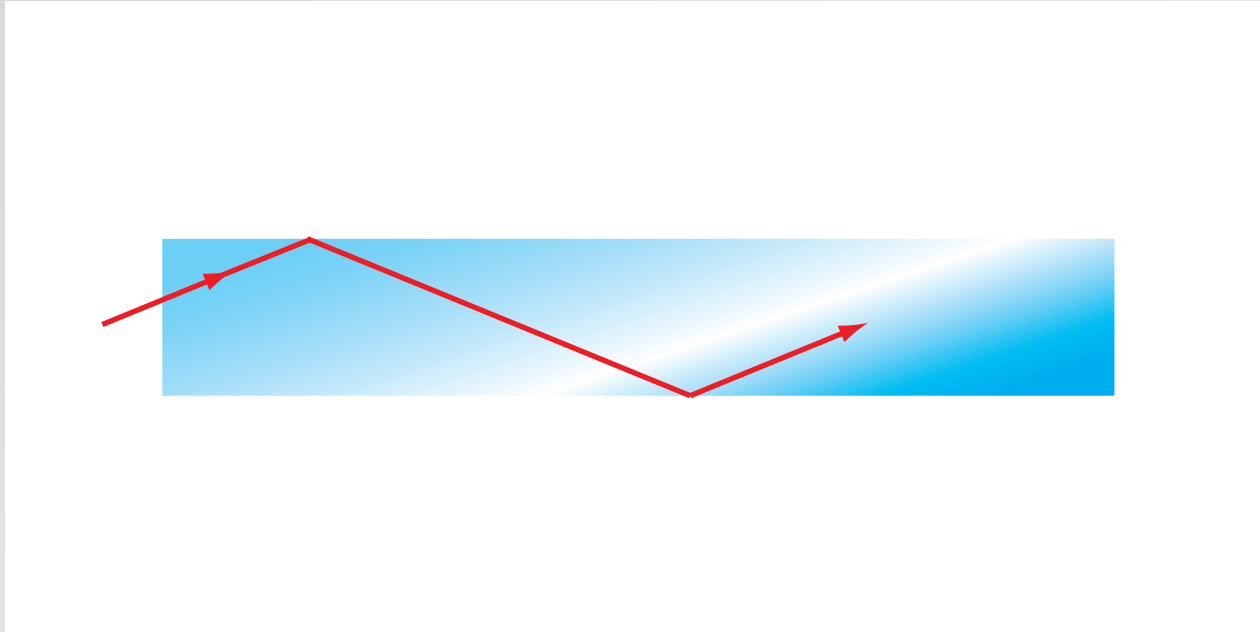
now consider a planar dielectric waveguide

Waveguiding



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

Waveguiding



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

Waveguiding



Outline

- waveguiding
- nanowire fabrication
- optical properties

Nanowire fabrication

two-step drawing process

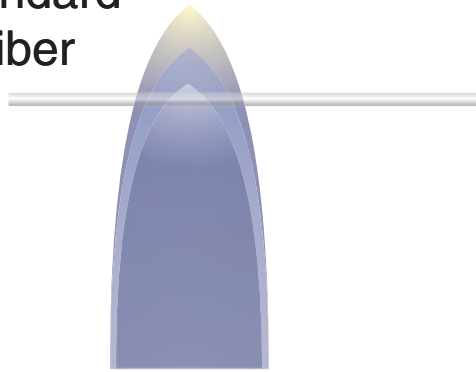
standard
fiber



Nanowire fabrication

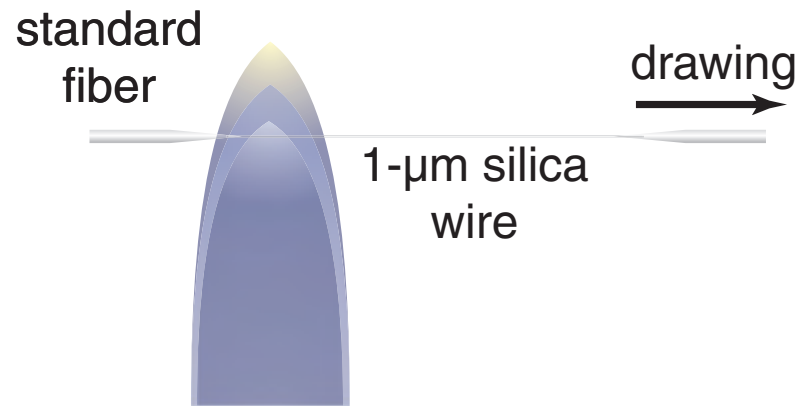
two-step drawing process

standard
fiber



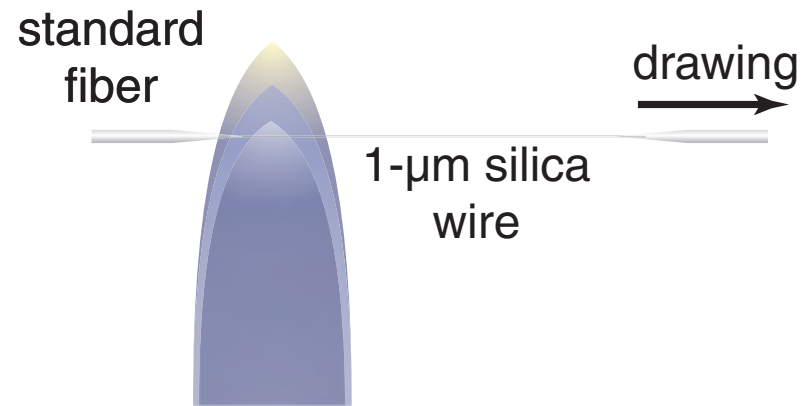
Nanowire fabrication

two-step drawing process



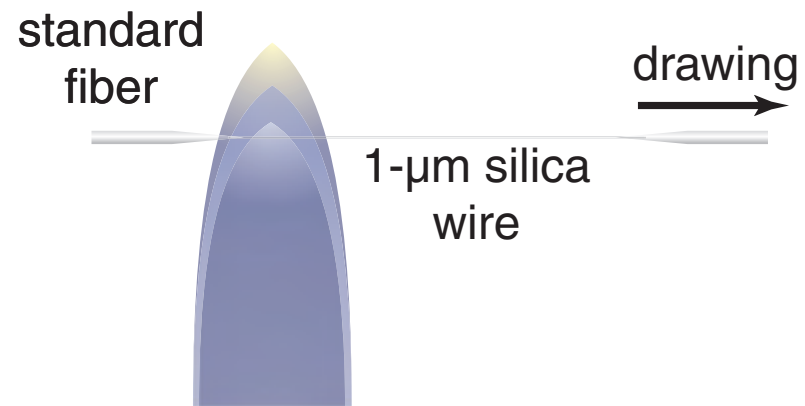
Nanowire fabrication

two-step drawing process



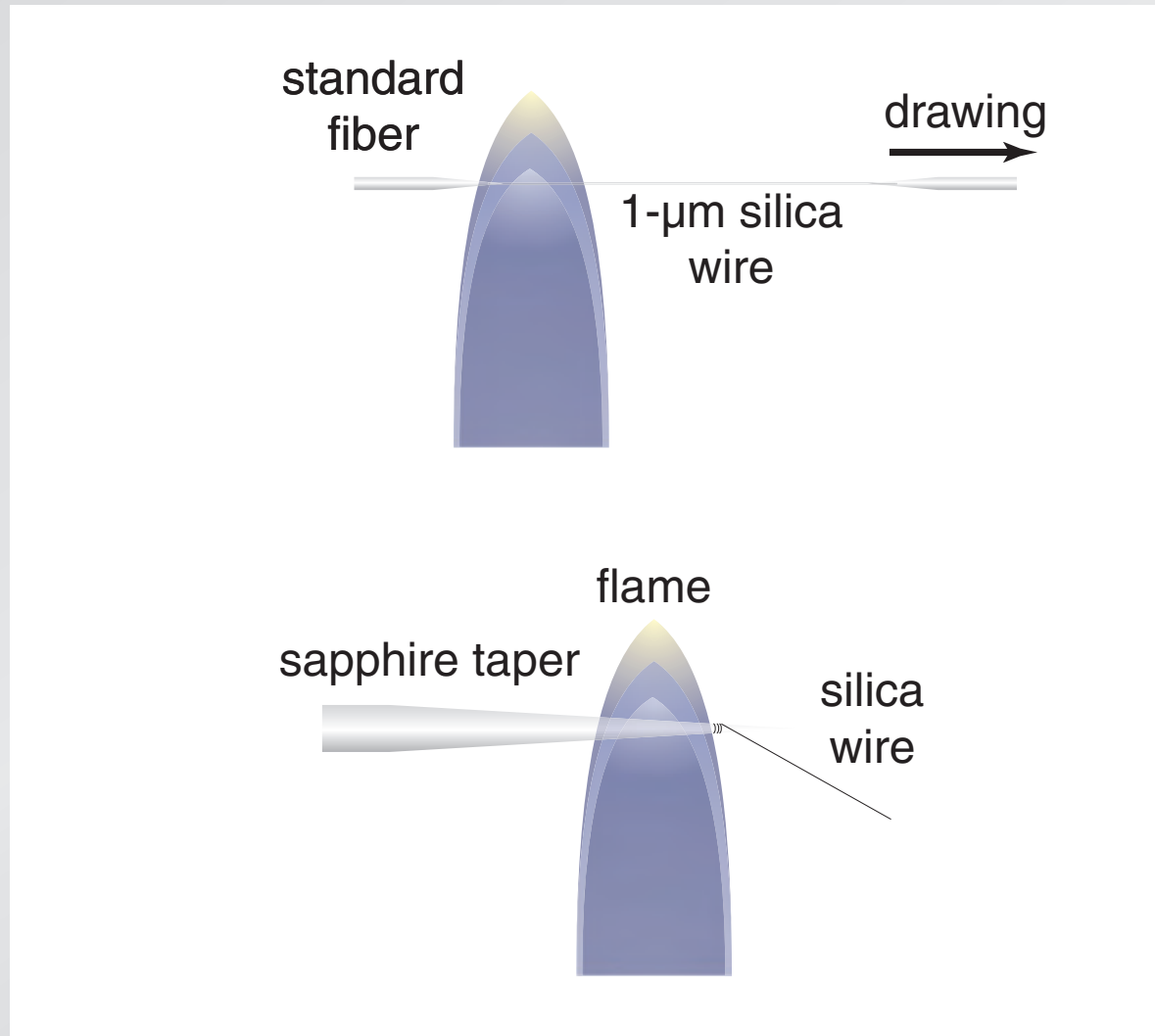
Nanowire fabrication

two-step drawing process



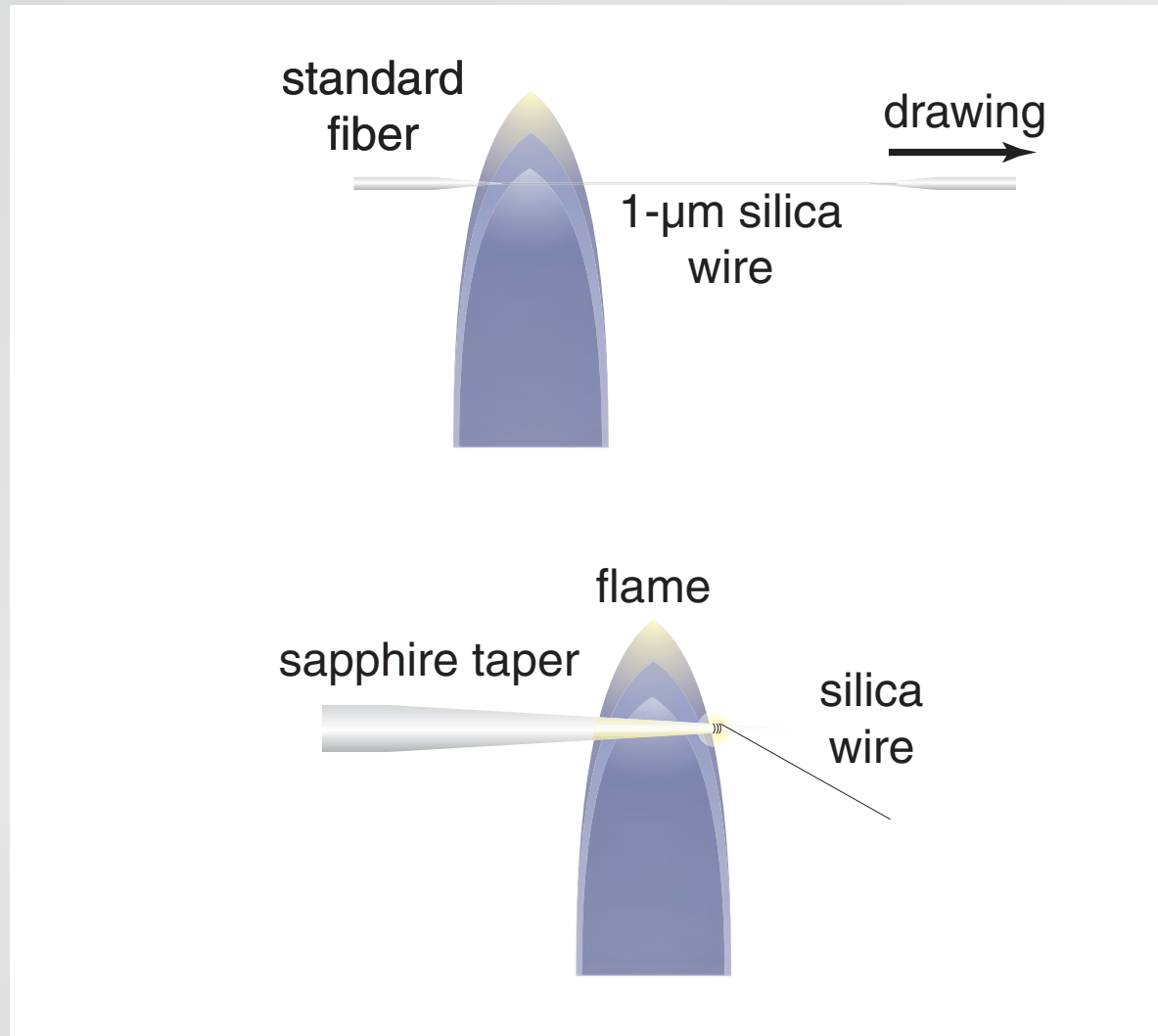
Nanowire fabrication

two-step drawing process



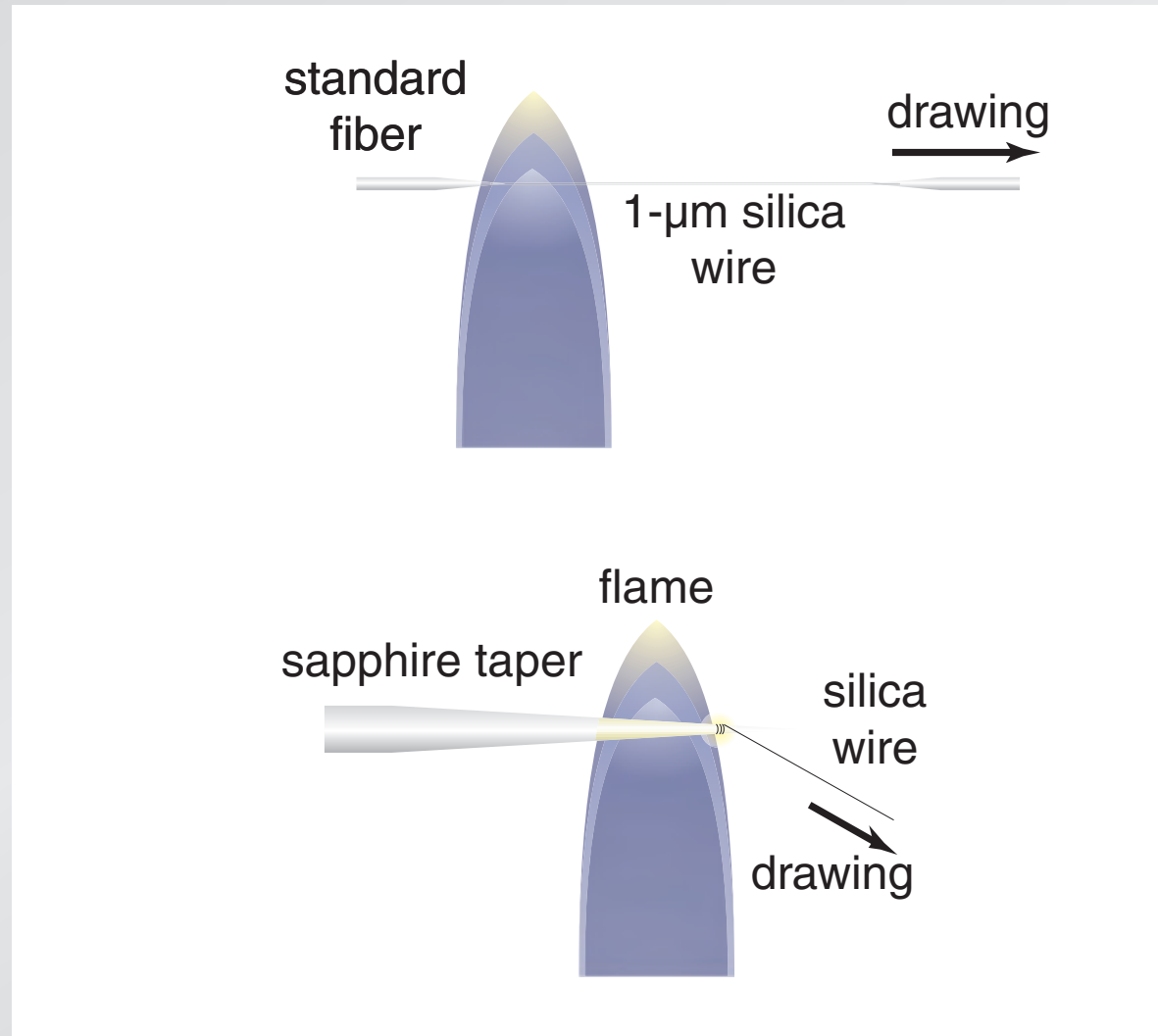
Nanowire fabrication

two-step drawing process



Nanowire fabrication

two-step drawing process



Nanowire fabrication



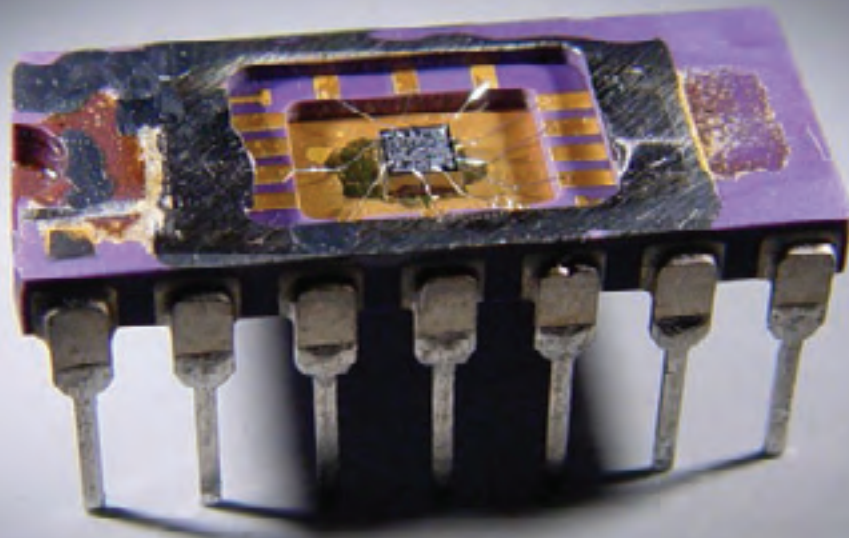
Nanowire fabrication

1 μm

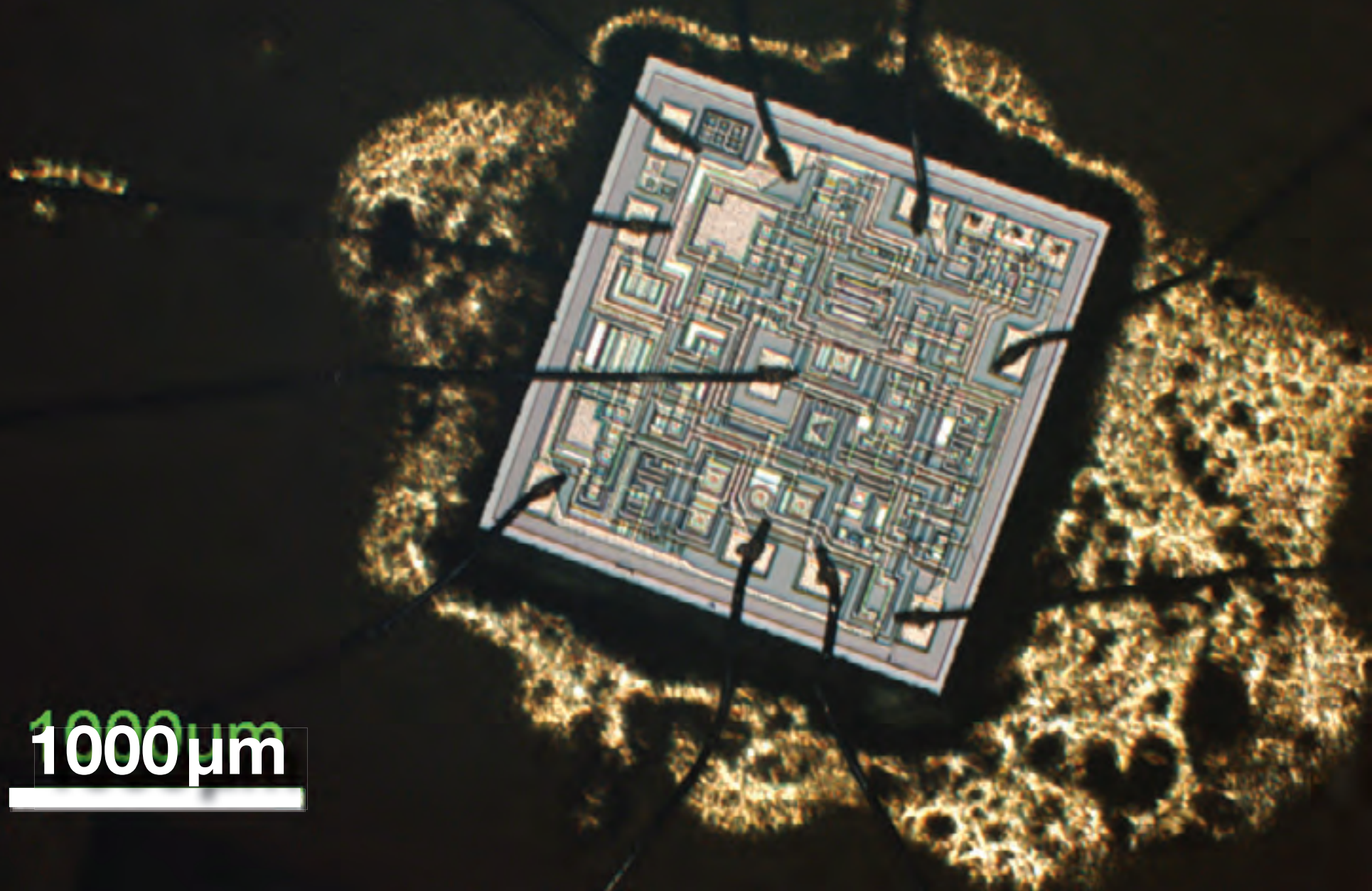


Nature, 426, 816 (2003)

Nanowire fabrication



Nanowire fabrication

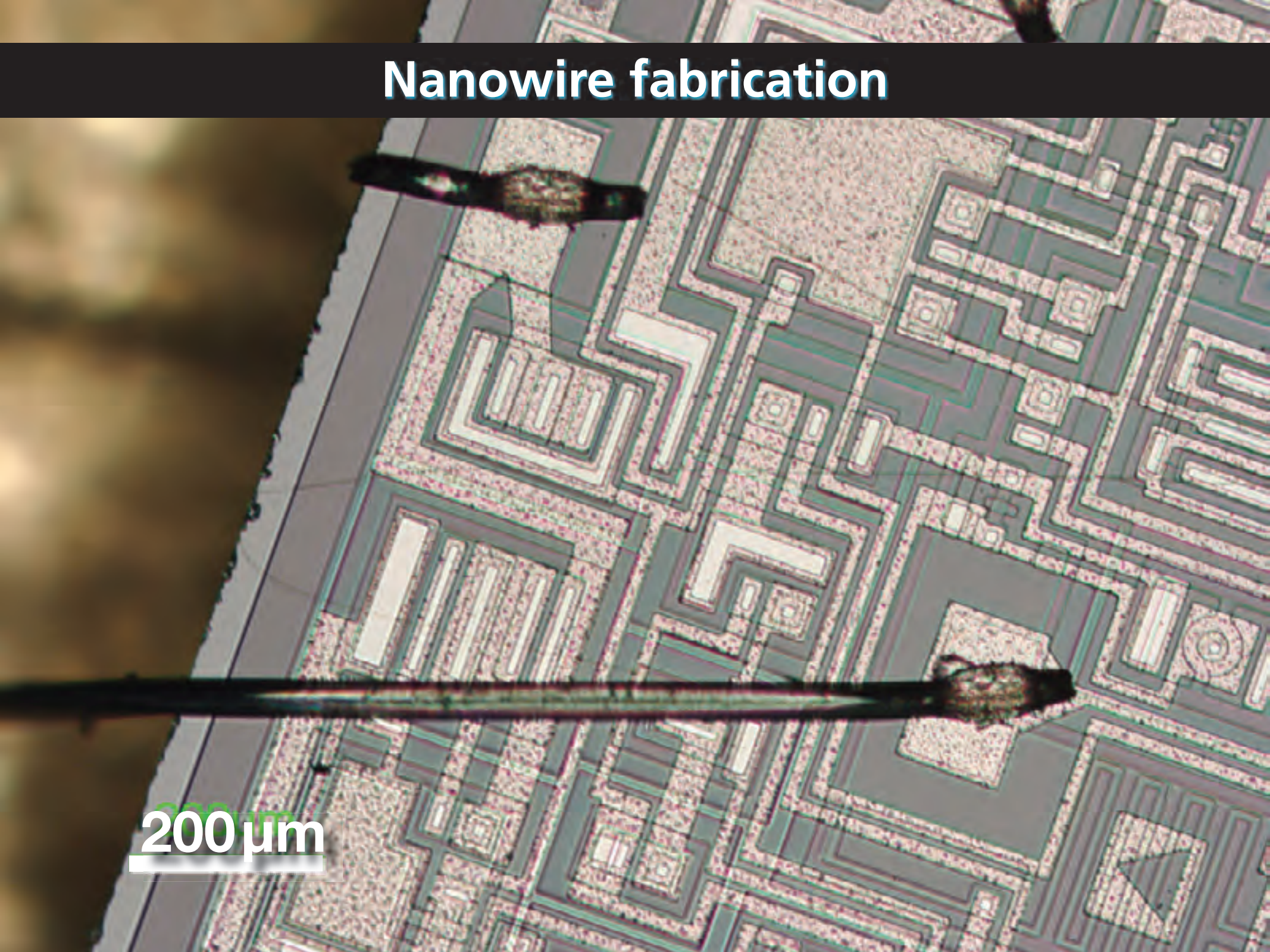


Nanowire fabrication

500 μm

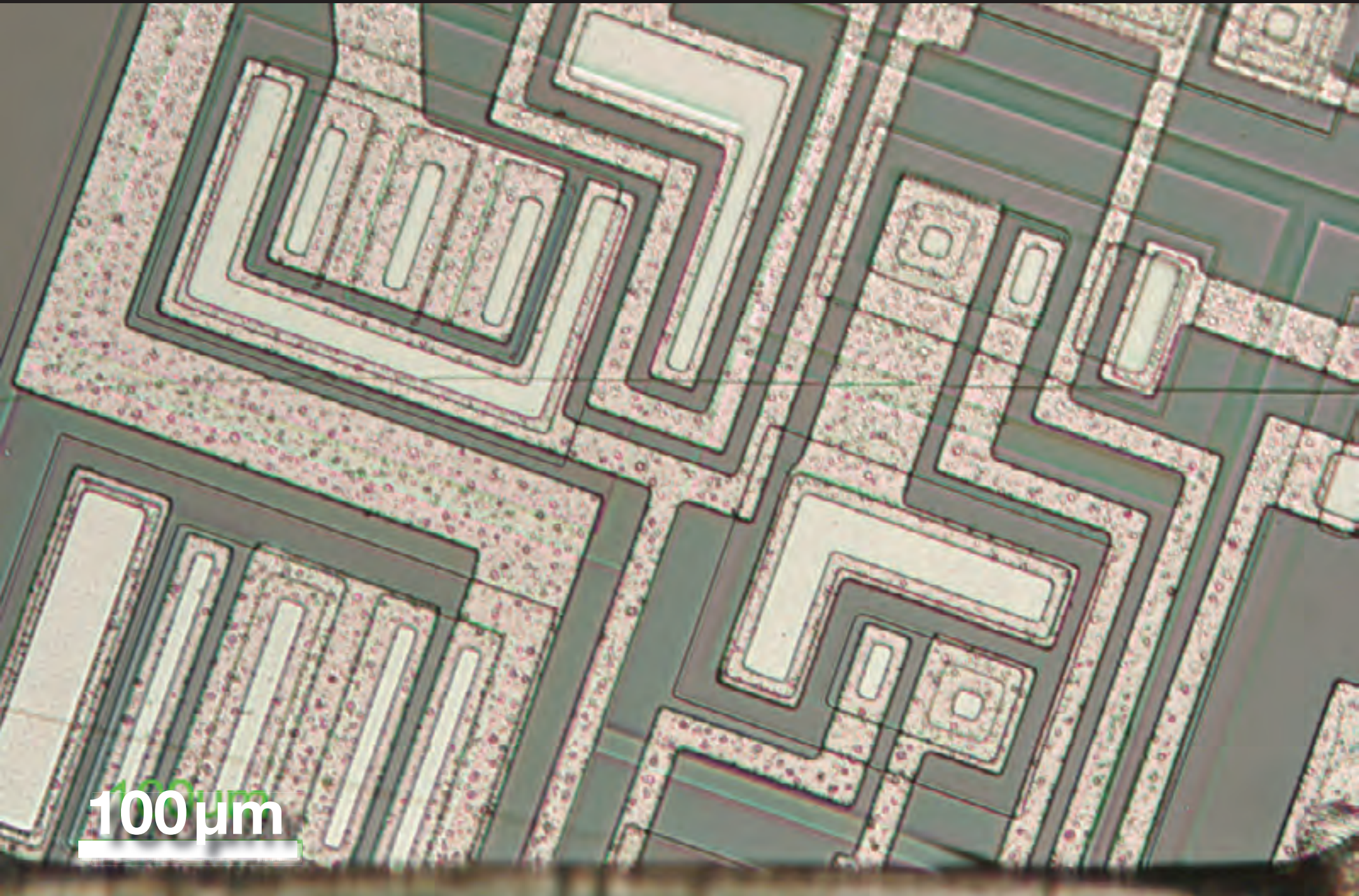
A scanning electron micrograph (SEM) of a nanowire device. The device is a rectangular chip with a complex pattern of nanowires and gates, appearing as a dense network of light-colored lines on a darker background. Several black probes are in contact with the device. A scale bar in the bottom left corner indicates 500 micrometers.

Nanowire fabrication



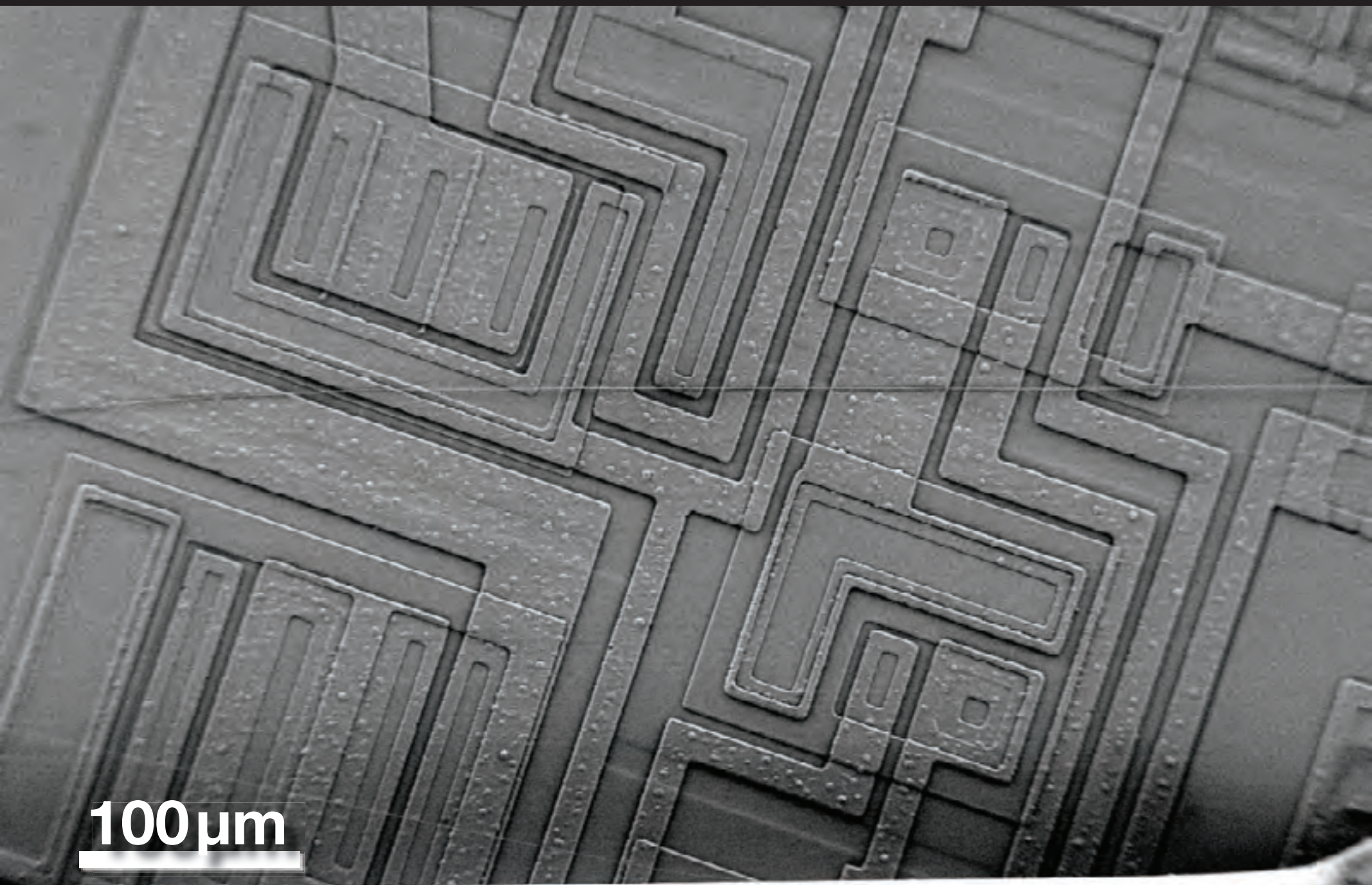
200 μm

Nanowire fabrication

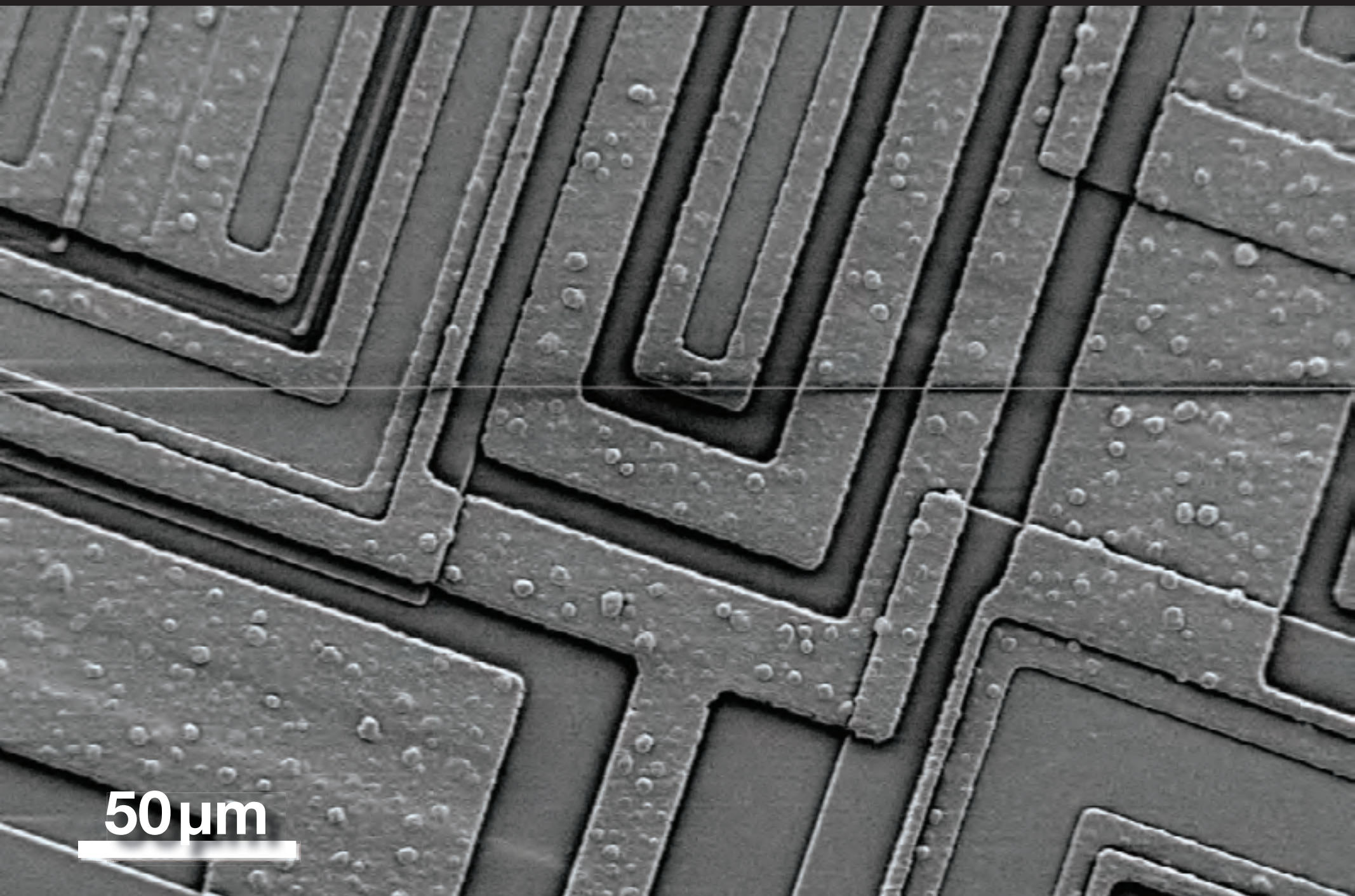


100 μm

Nanowire fabrication

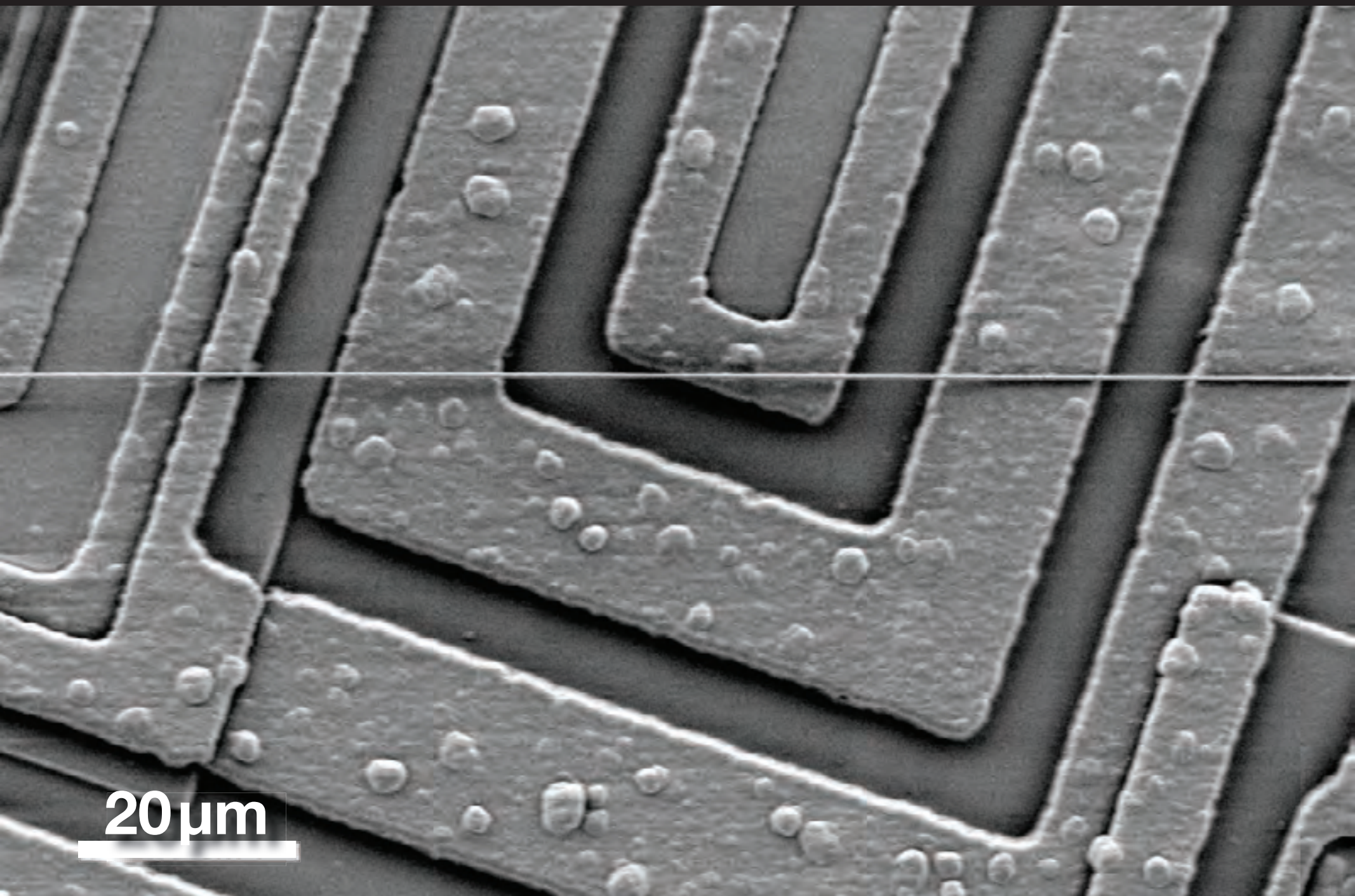


Nanowire fabrication



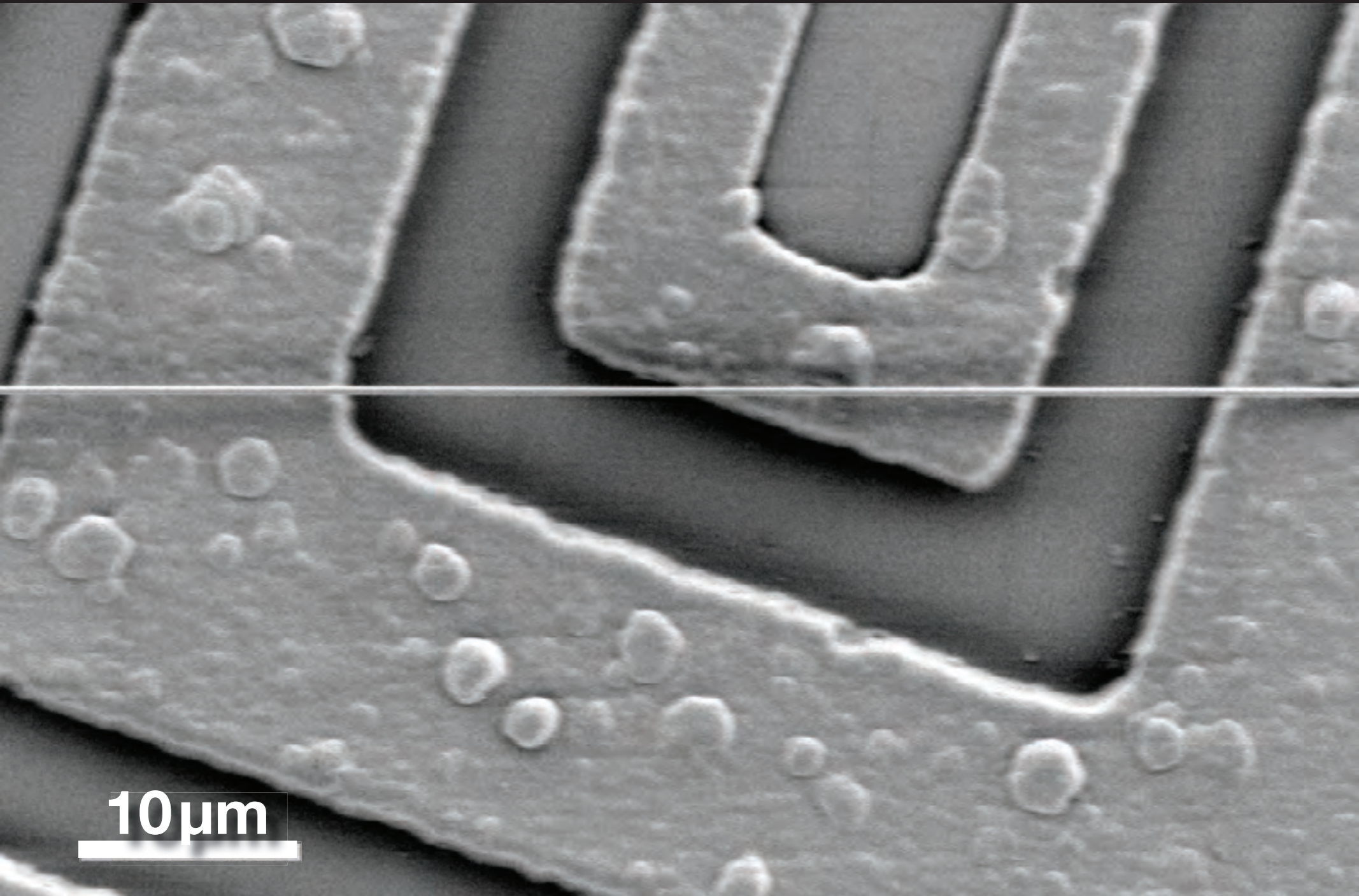
50 μm

Nanowire fabrication



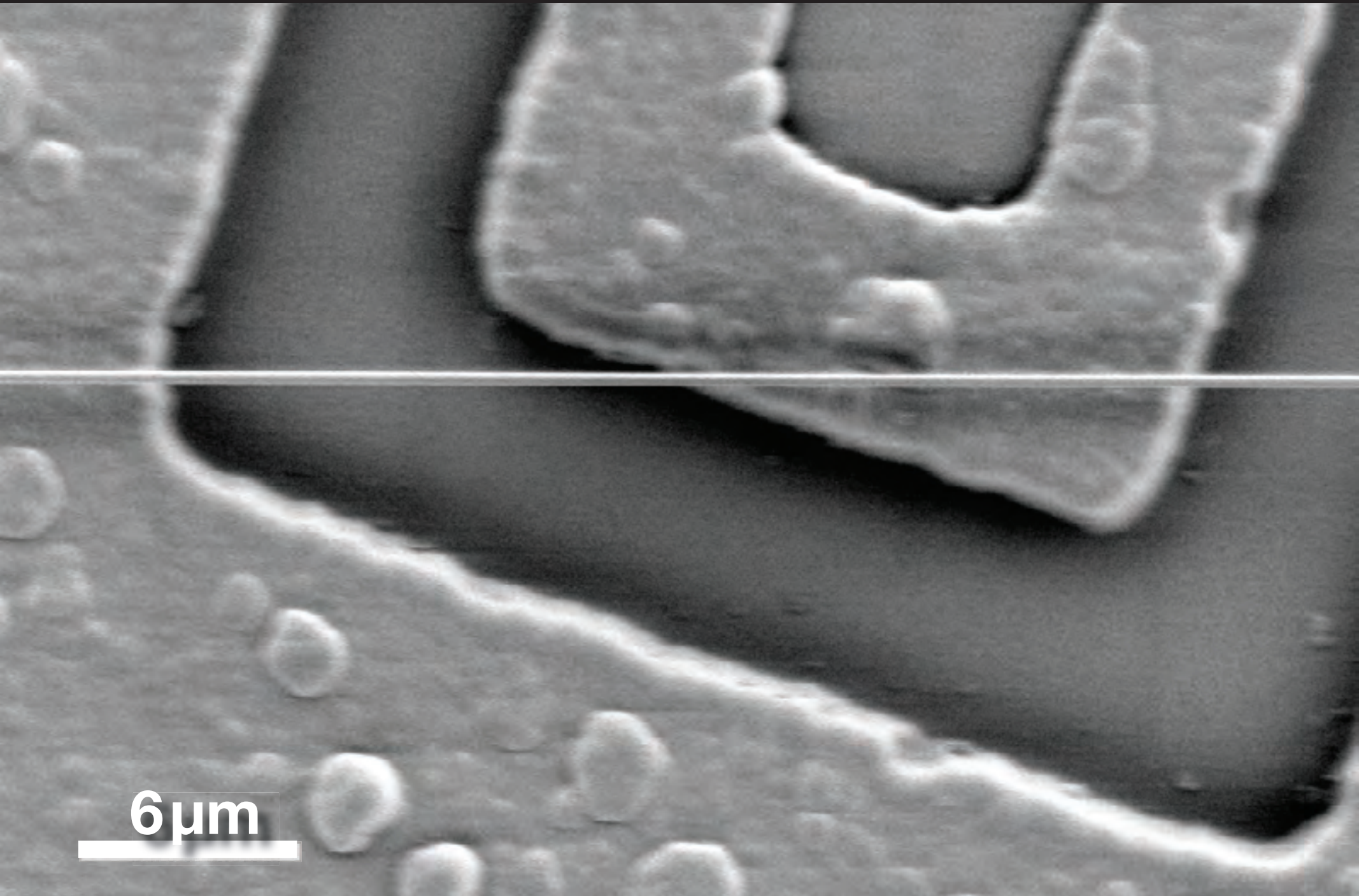
20 μm

Nanowire fabrication



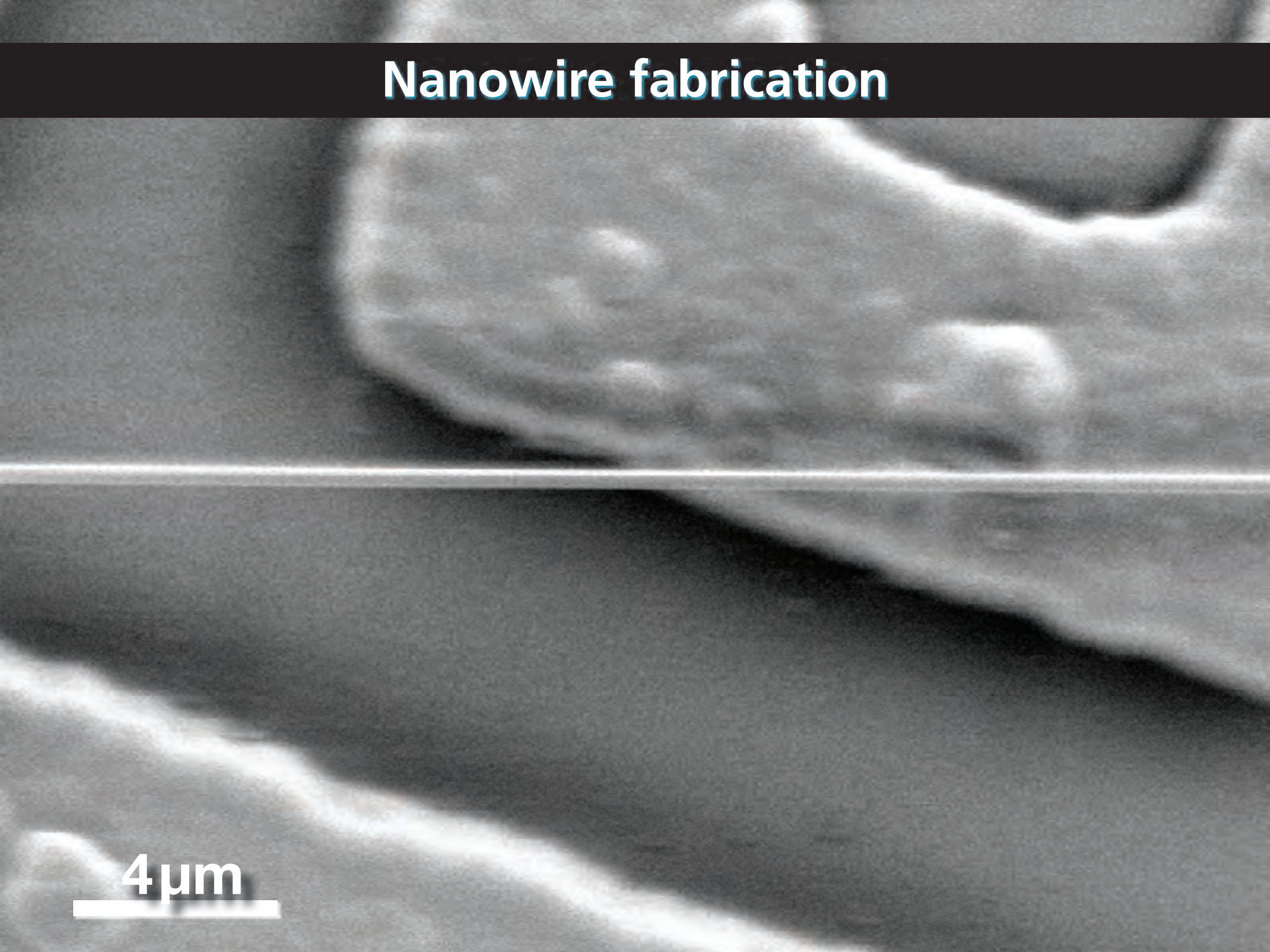
10 μm

Nanowire fabrication



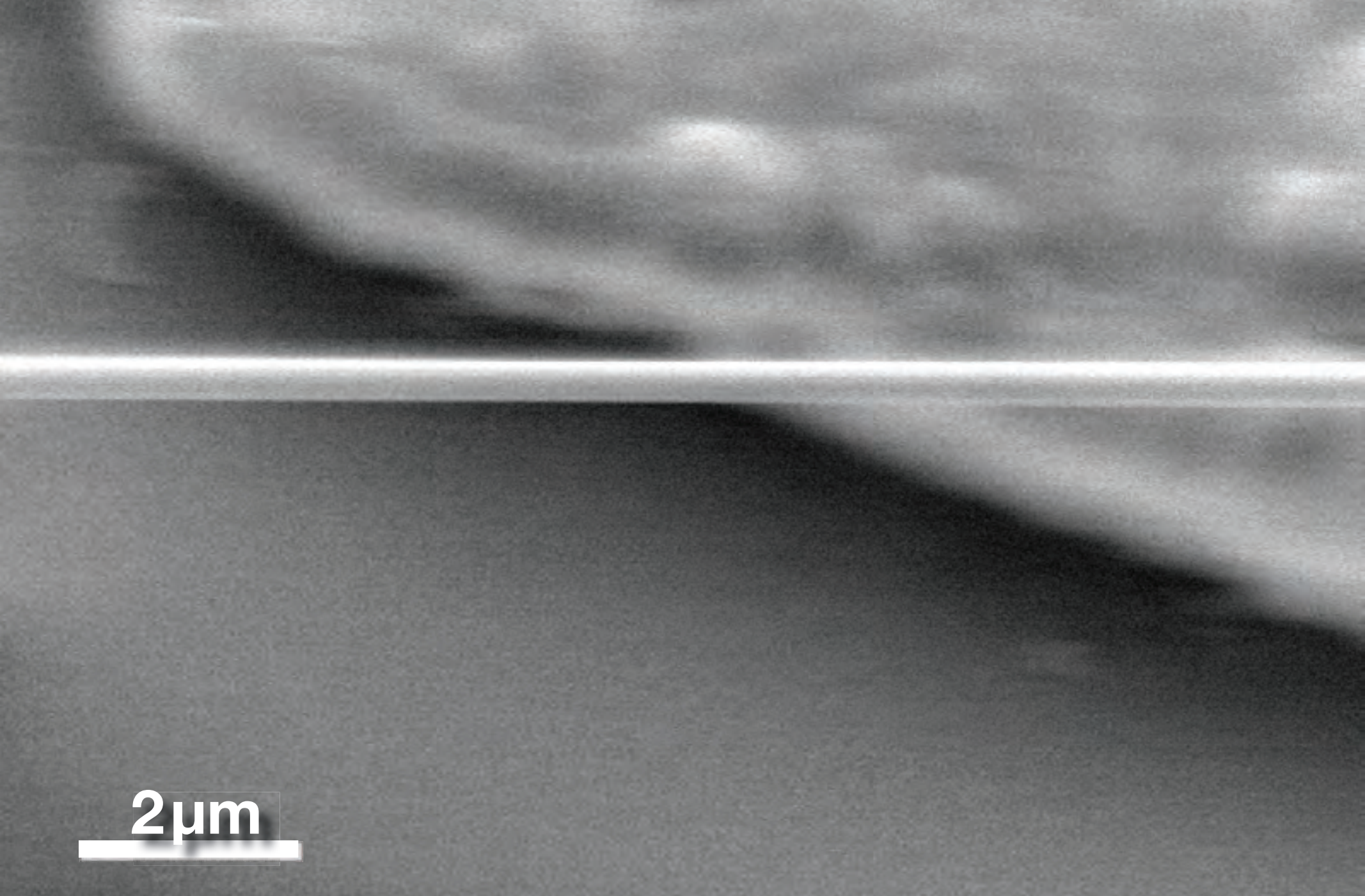
6 μm

Nanowire fabrication



4 μm

Nanowire fabrication



2 μm

Nanowire fabrication

312 nm

A scanning electron micrograph (SEM) showing a single, long, thin nanowire. A vertical line with horizontal end-caps is drawn across the nanowire to indicate its diameter. The background is a dark, textured surface.

1 μm

A horizontal white scale bar located in the bottom left corner of the image.

Waveguiding

Specifications

diameter D : down to 20 nm

length L : up to 90 mm

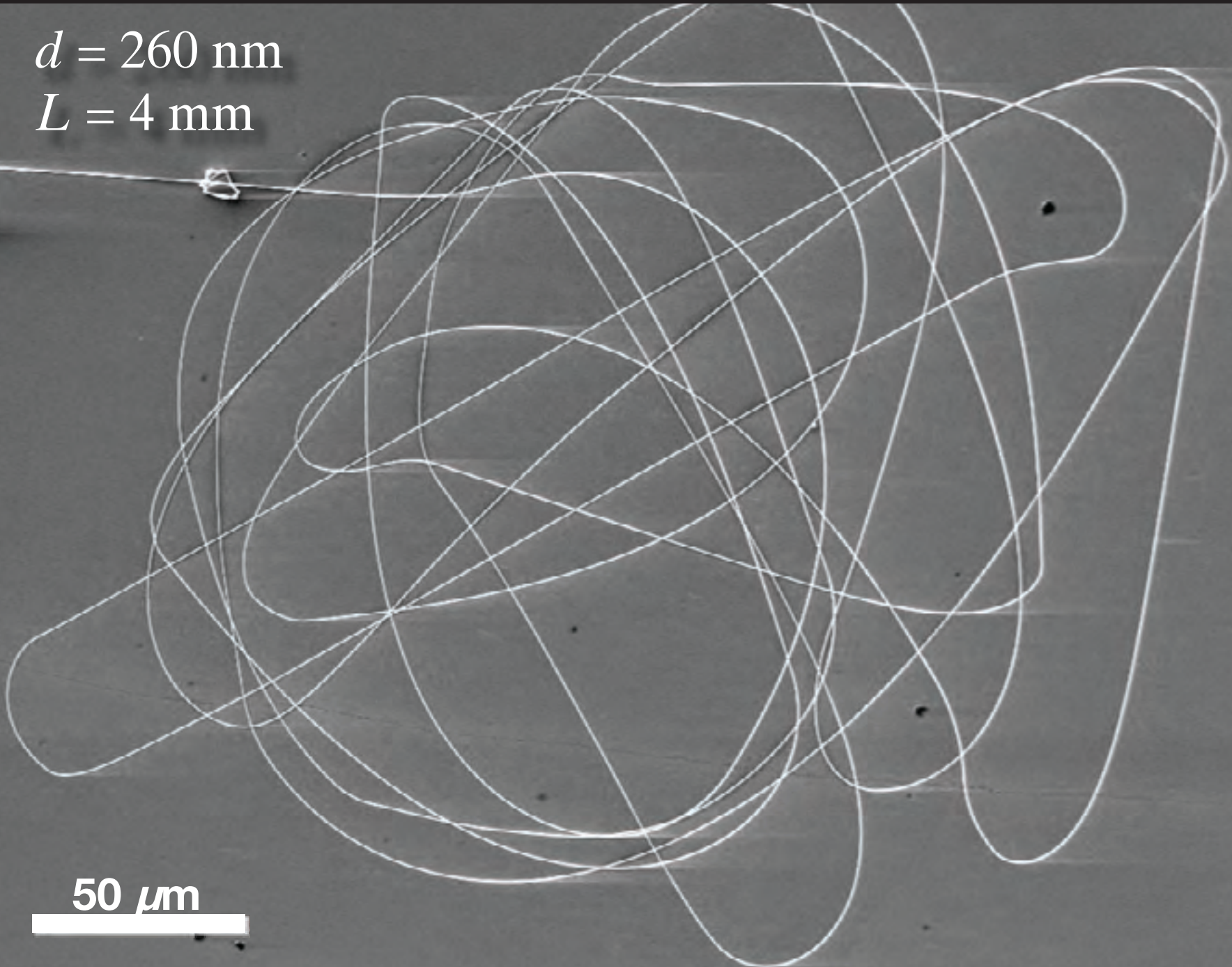
aspect ratio D/L : up to 10^6

diameter uniformity $\Delta D/L$: 2×10^{-6}

Nanowire fabrication

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



Nanowire fabrication

240-nm wire

200 nm

A scanning electron micrograph (SEM) showing a single, dark, cylindrical nanowire oriented diagonally from the bottom-left to the top-right. 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



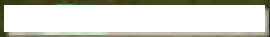
Nanowire fabrication

bend to
breaking point

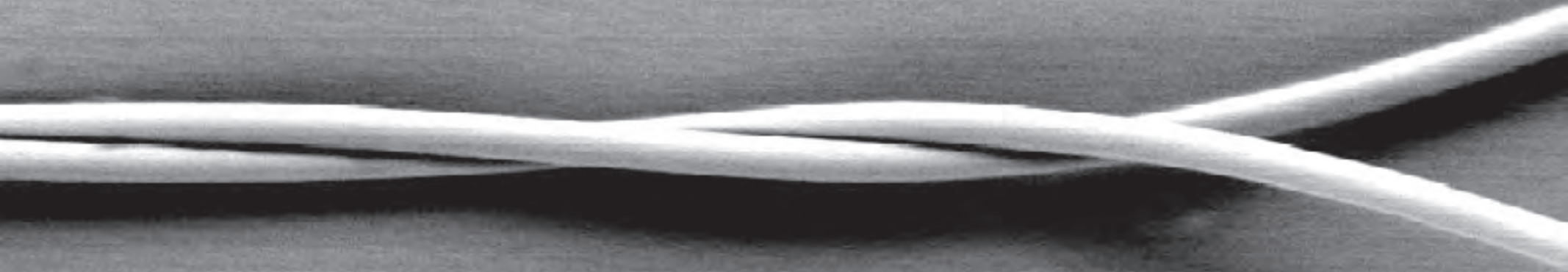


Nanowire fabrication

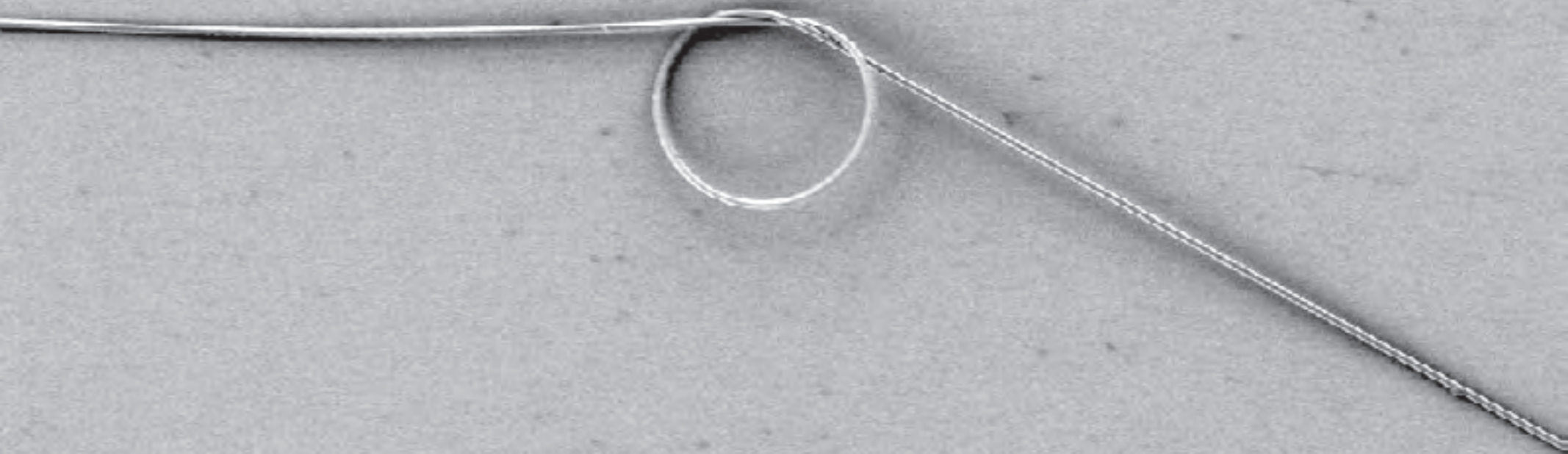
bend to
breaking point



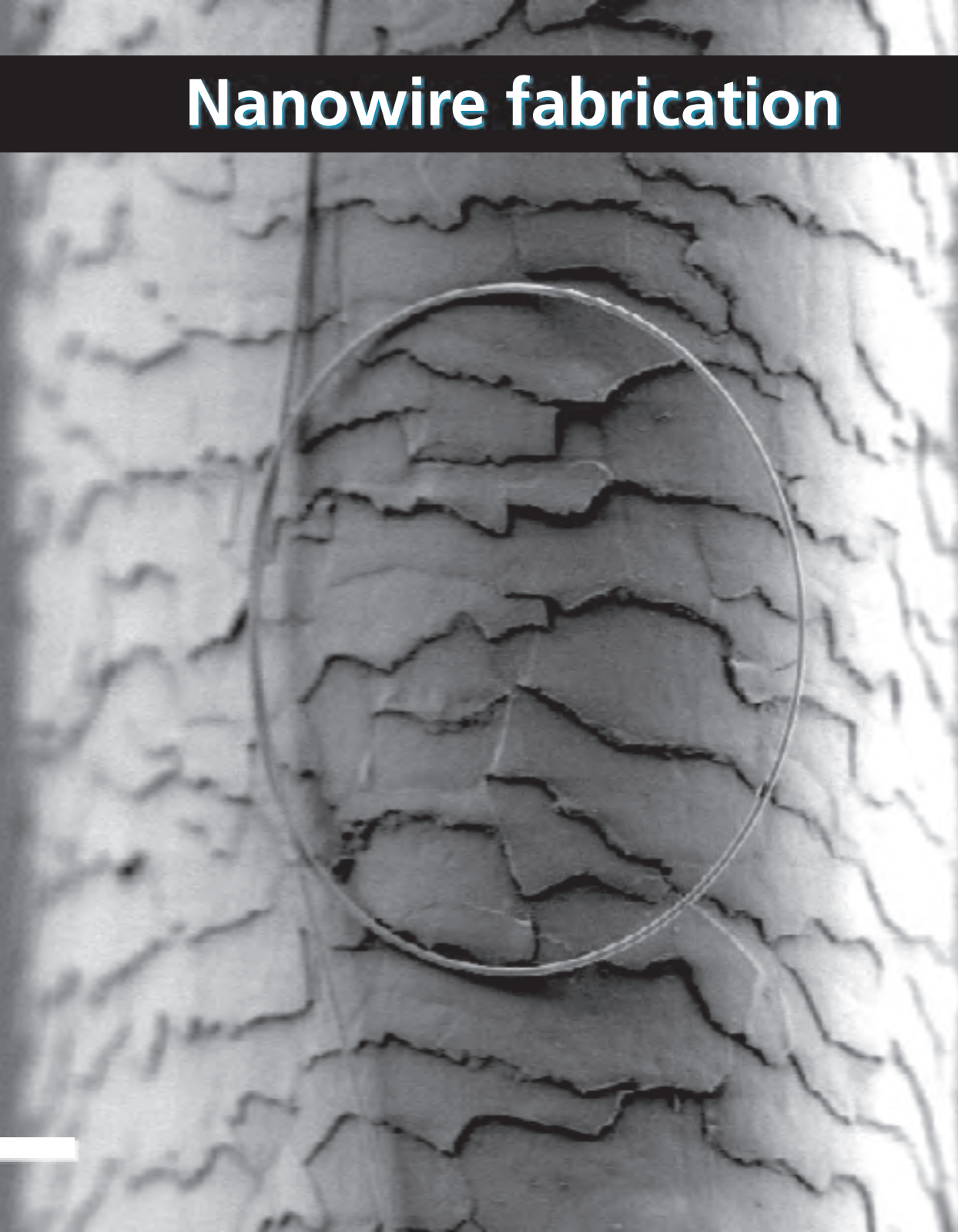
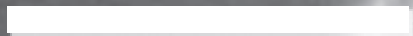
Nanowire fabrication



Nanowire fabrication



Nanowire fabrication

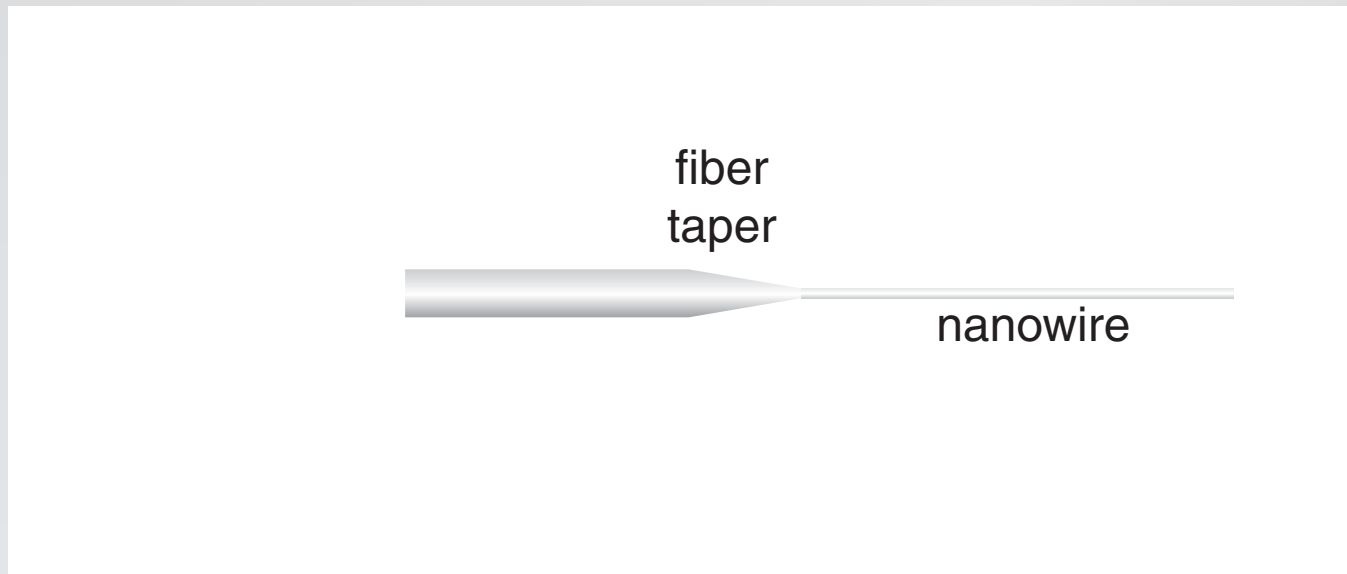


Outline

- waveguiding
- nanowire fabrication
- optical properties

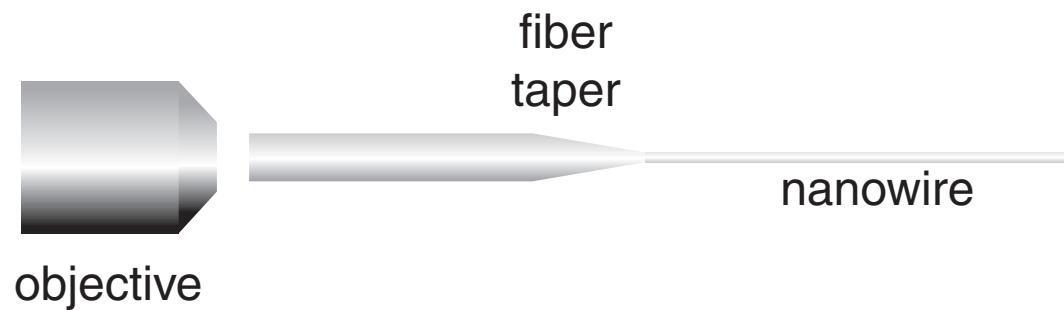
Optical properties

coupling light into nanowires



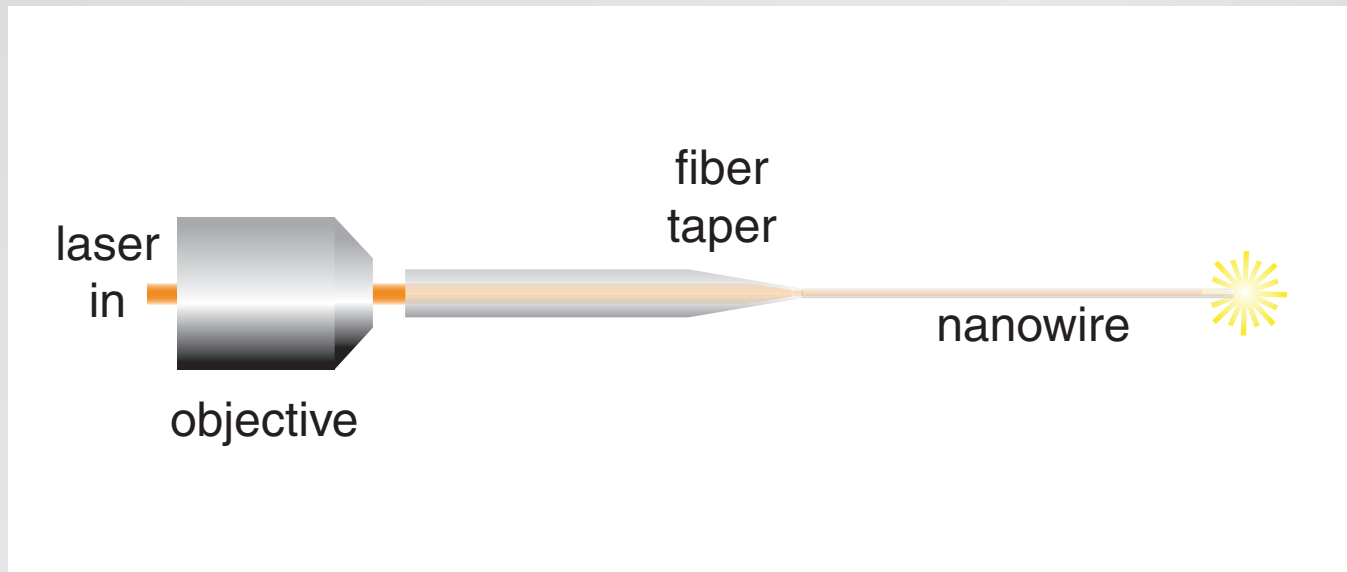
Optical properties

coupling light into nanowires

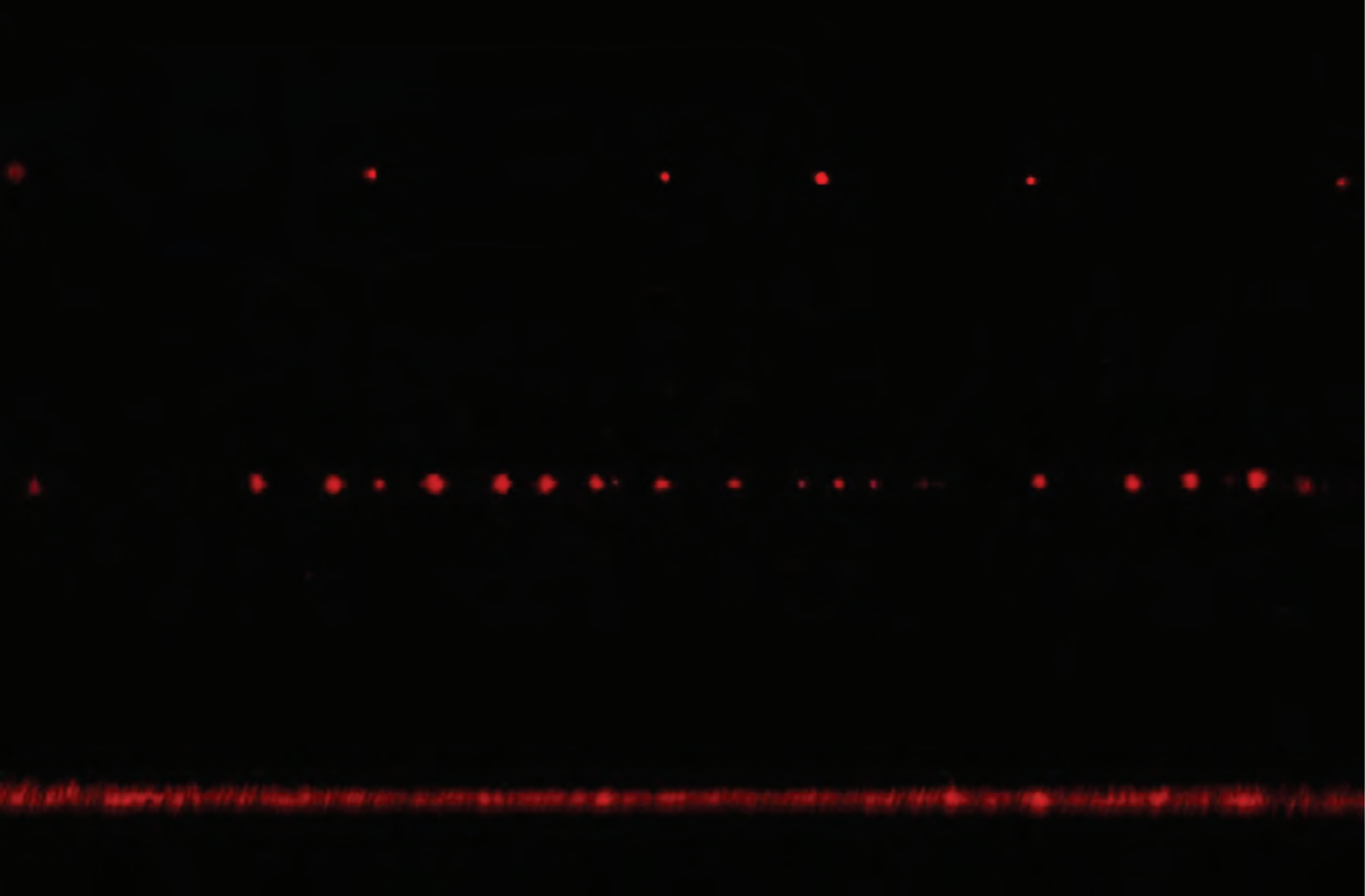


Optical properties

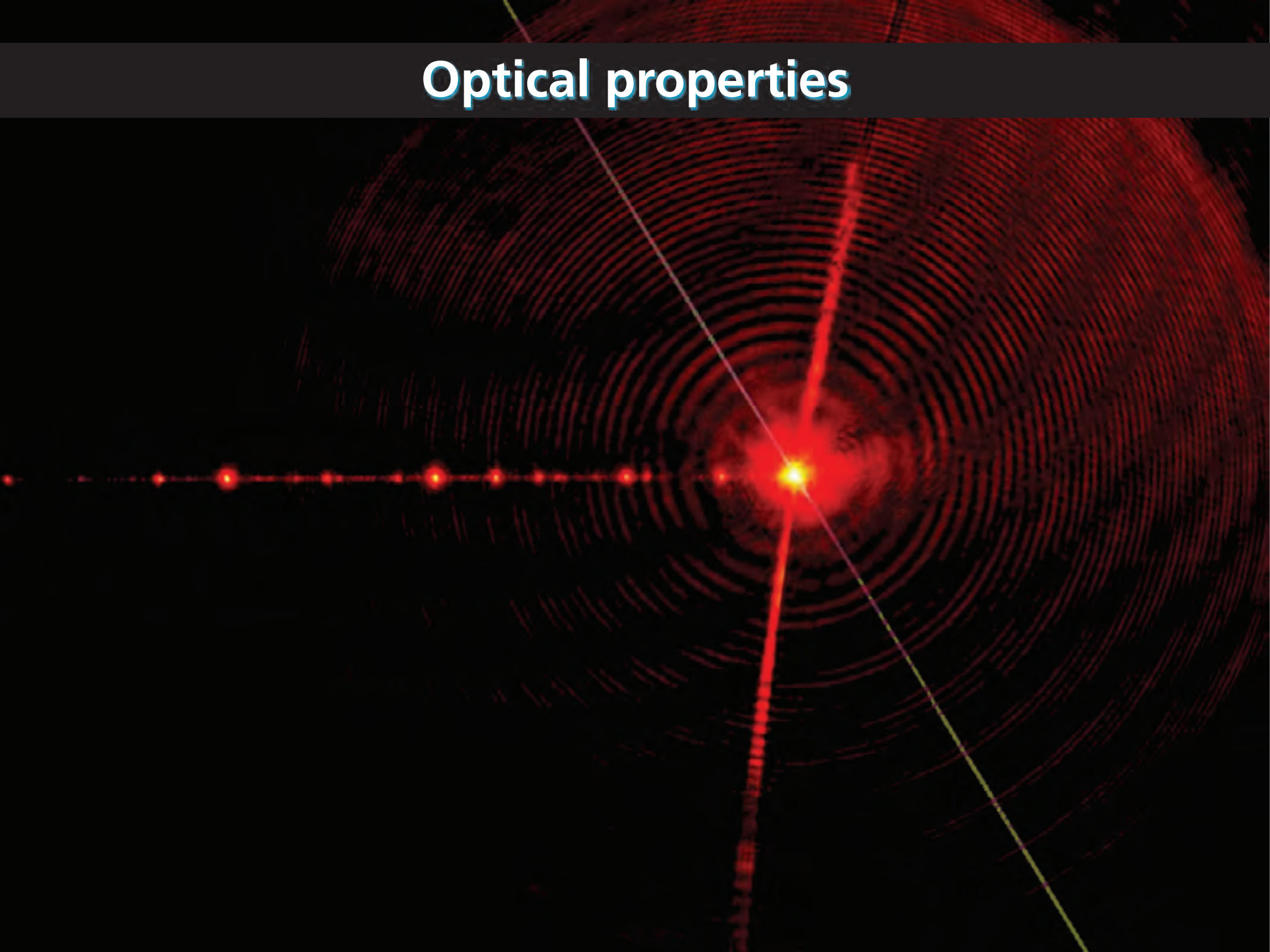
coupling light into nanowires



Optical properties



Optical properties

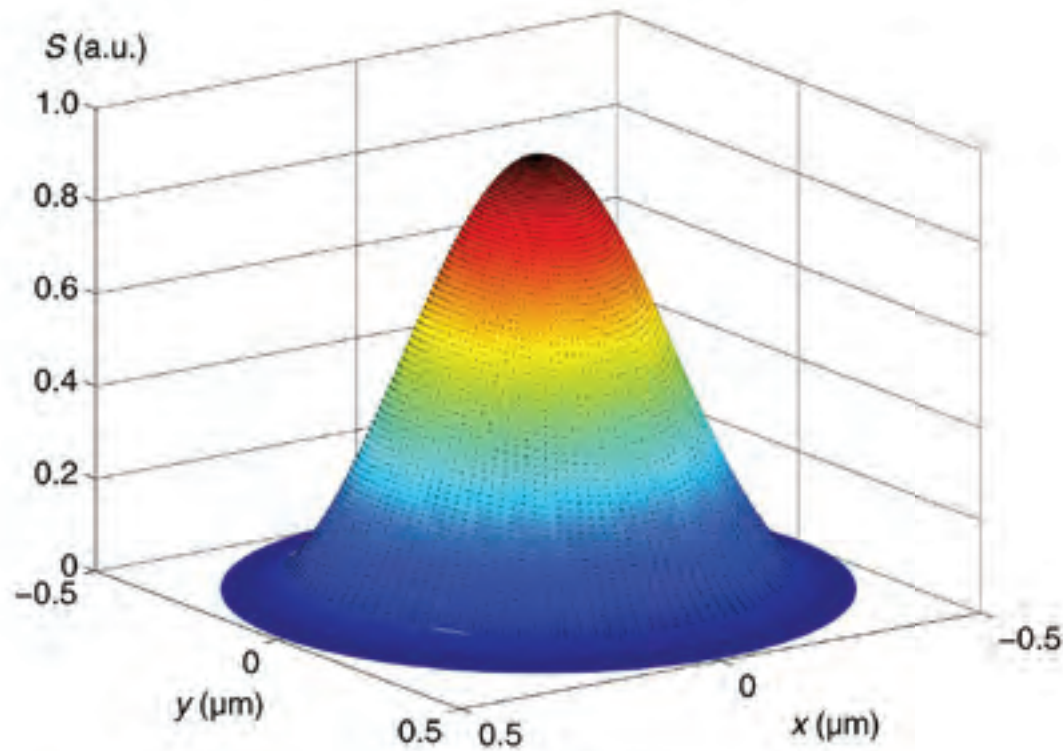


Optical properties



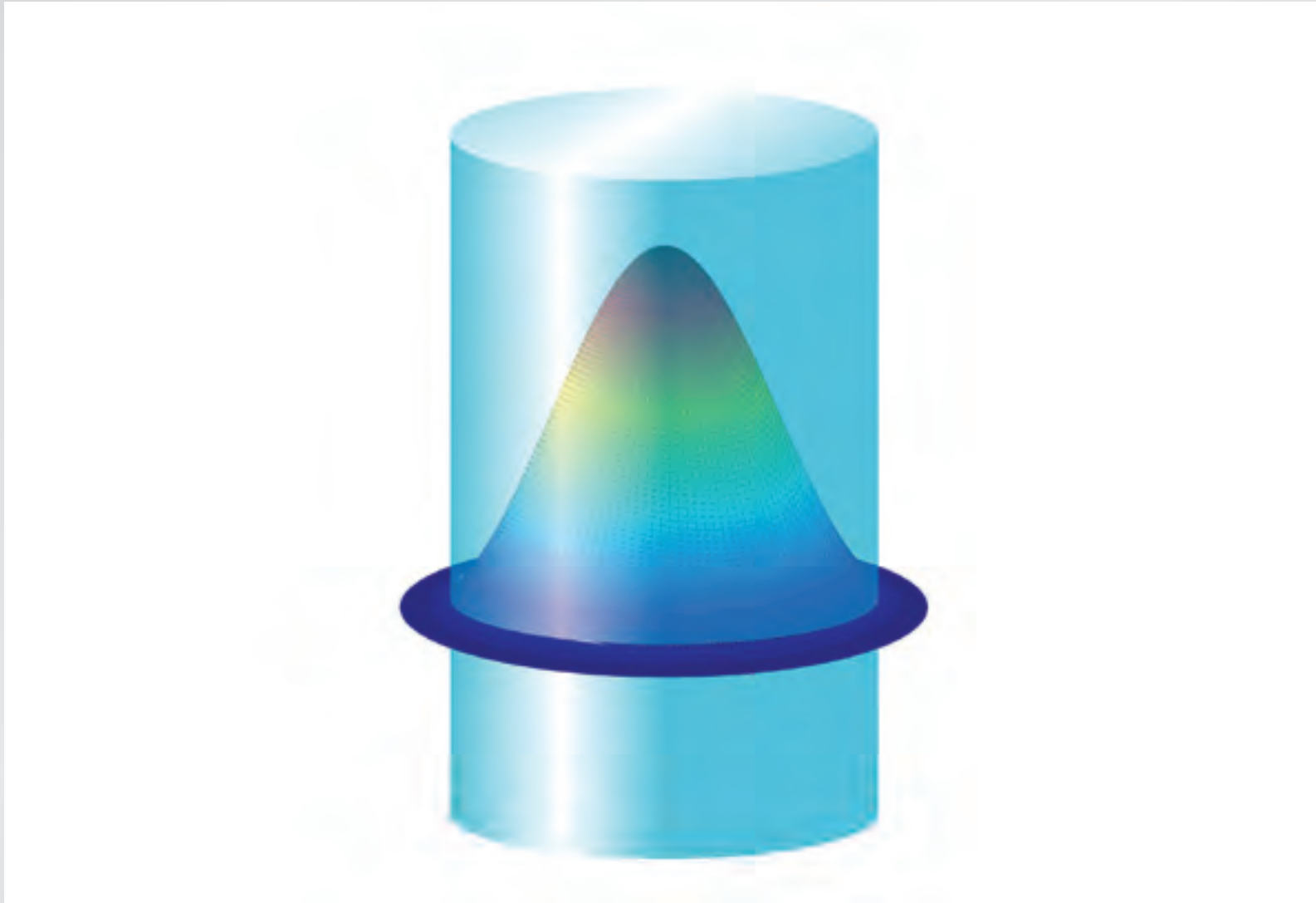
Optical properties

Poynting vector profile for 800-nm nanowire



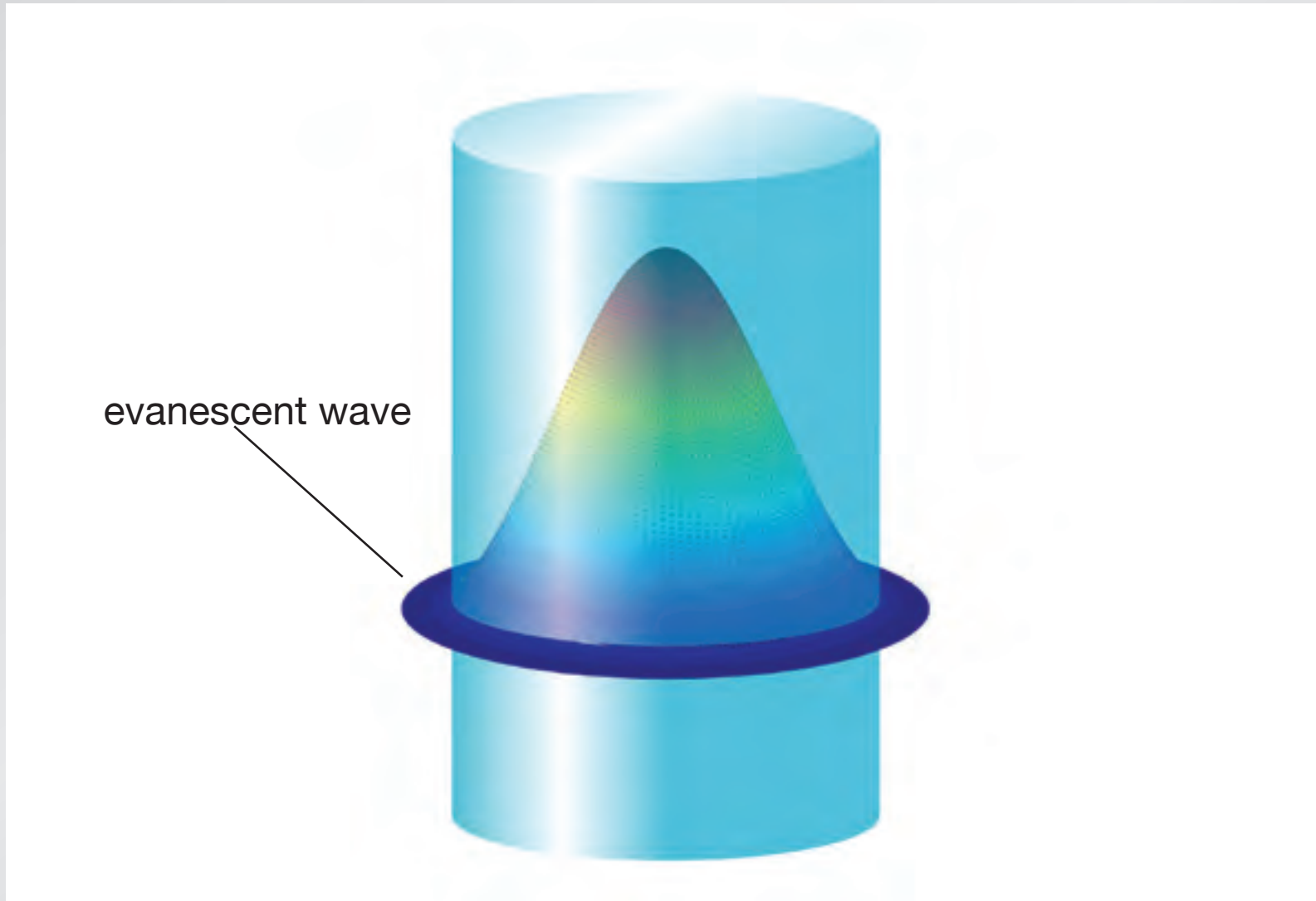
Optical properties

Poynting vector profile for 800-nm nanowire



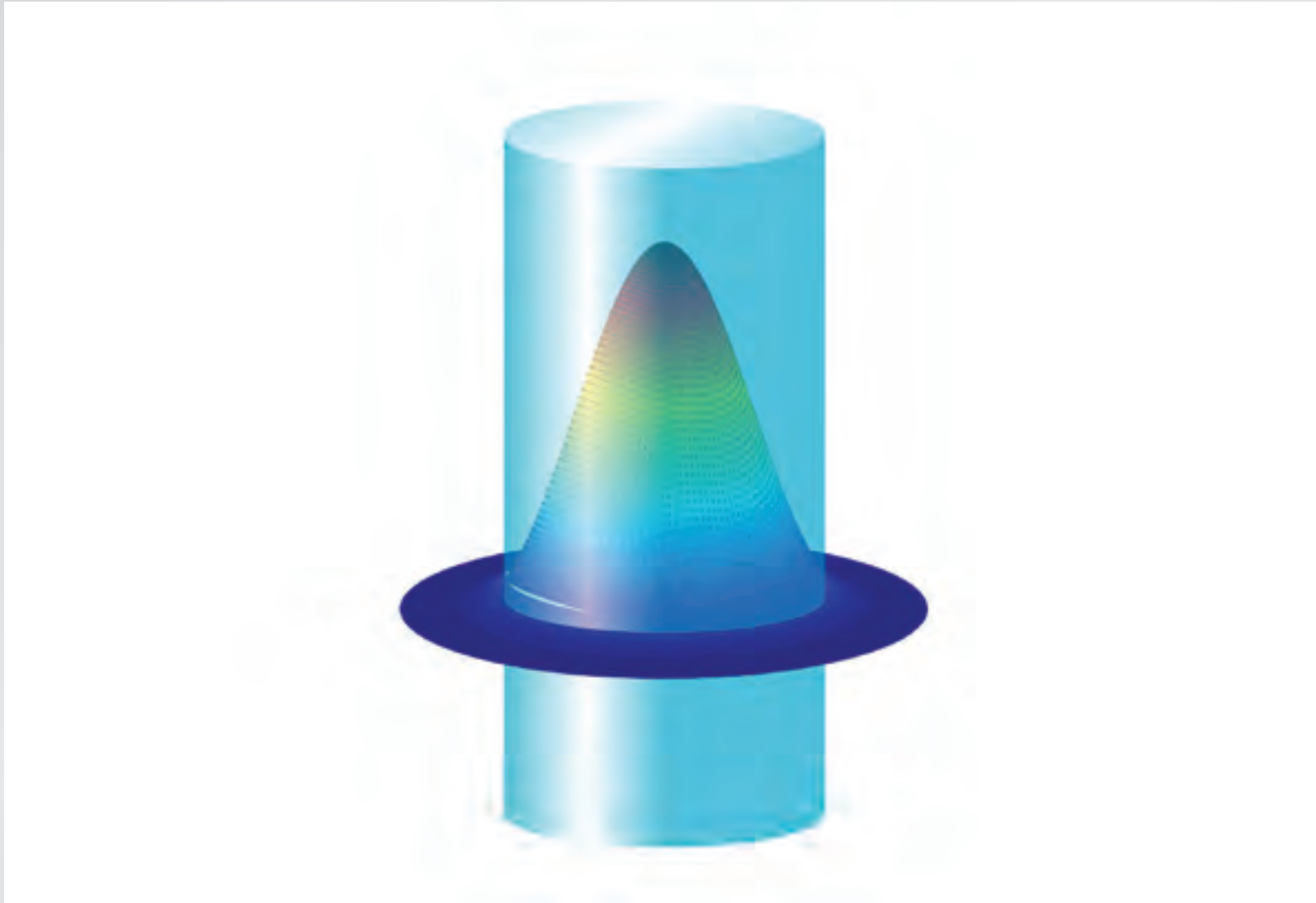
Optical properties

Poynting vector profile for 800-nm nanowire



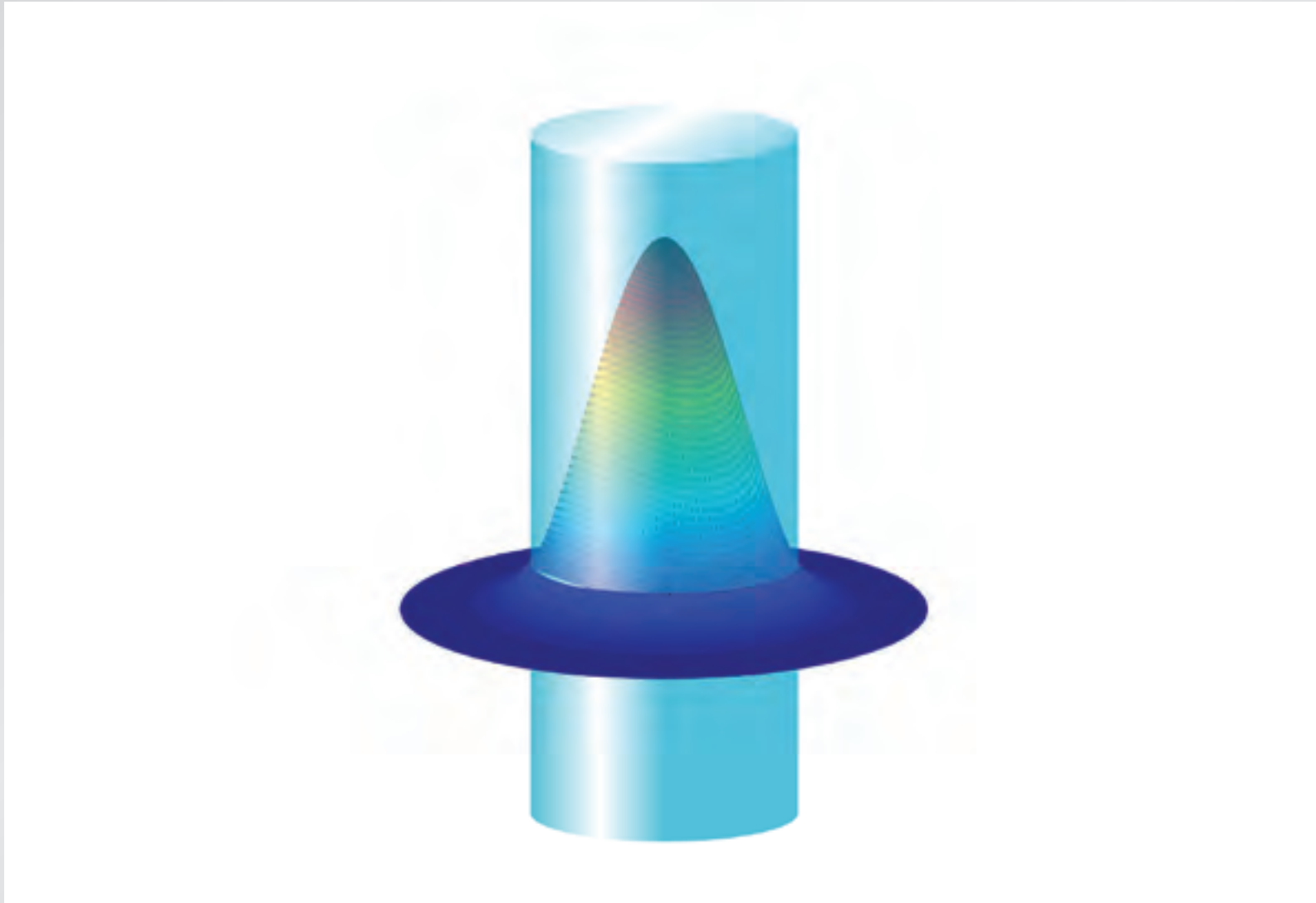
Optical properties

Poynting vector profile for 600-nm nanowire



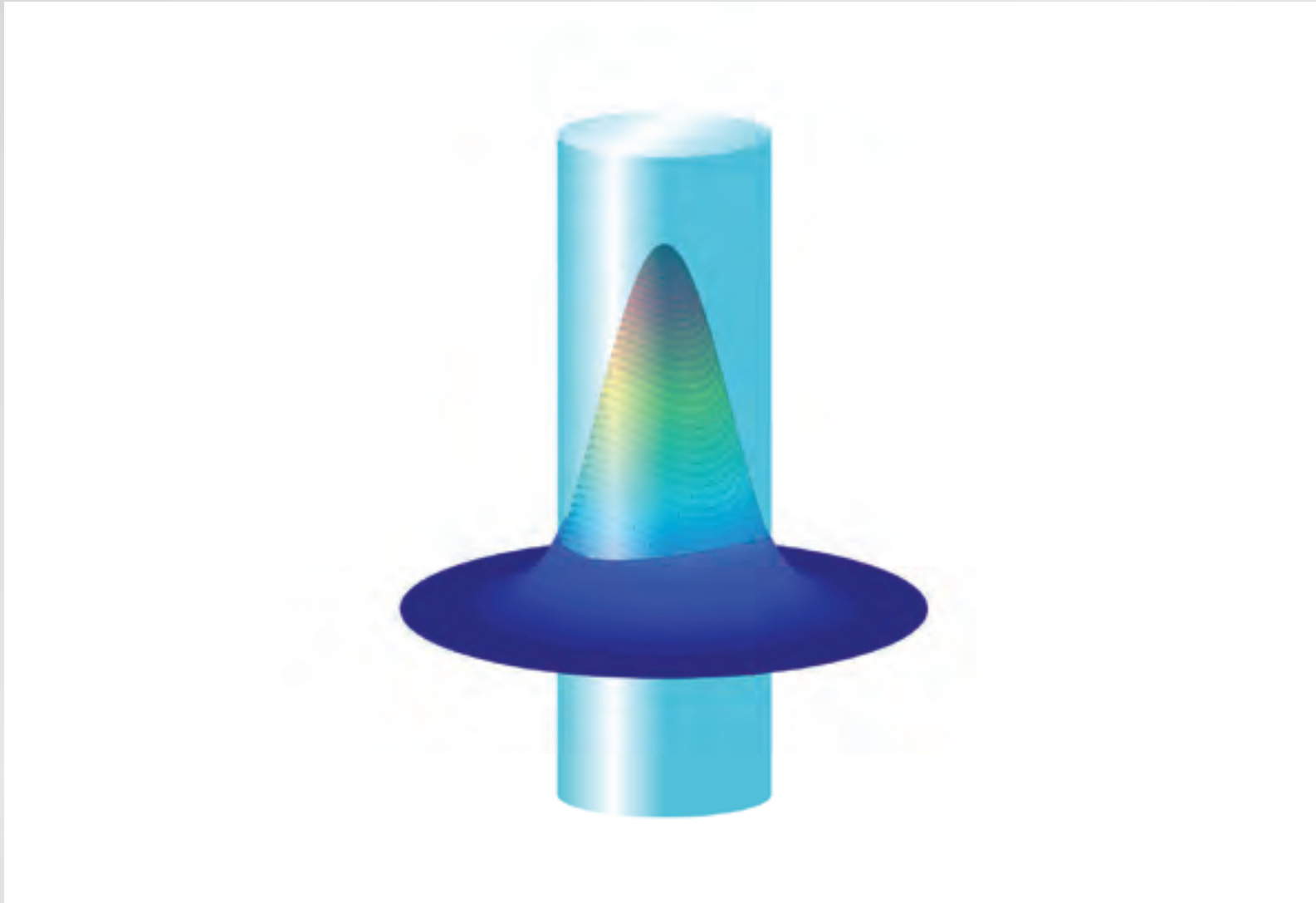
Optical properties

Poynting vector profile for 500-nm nanowire



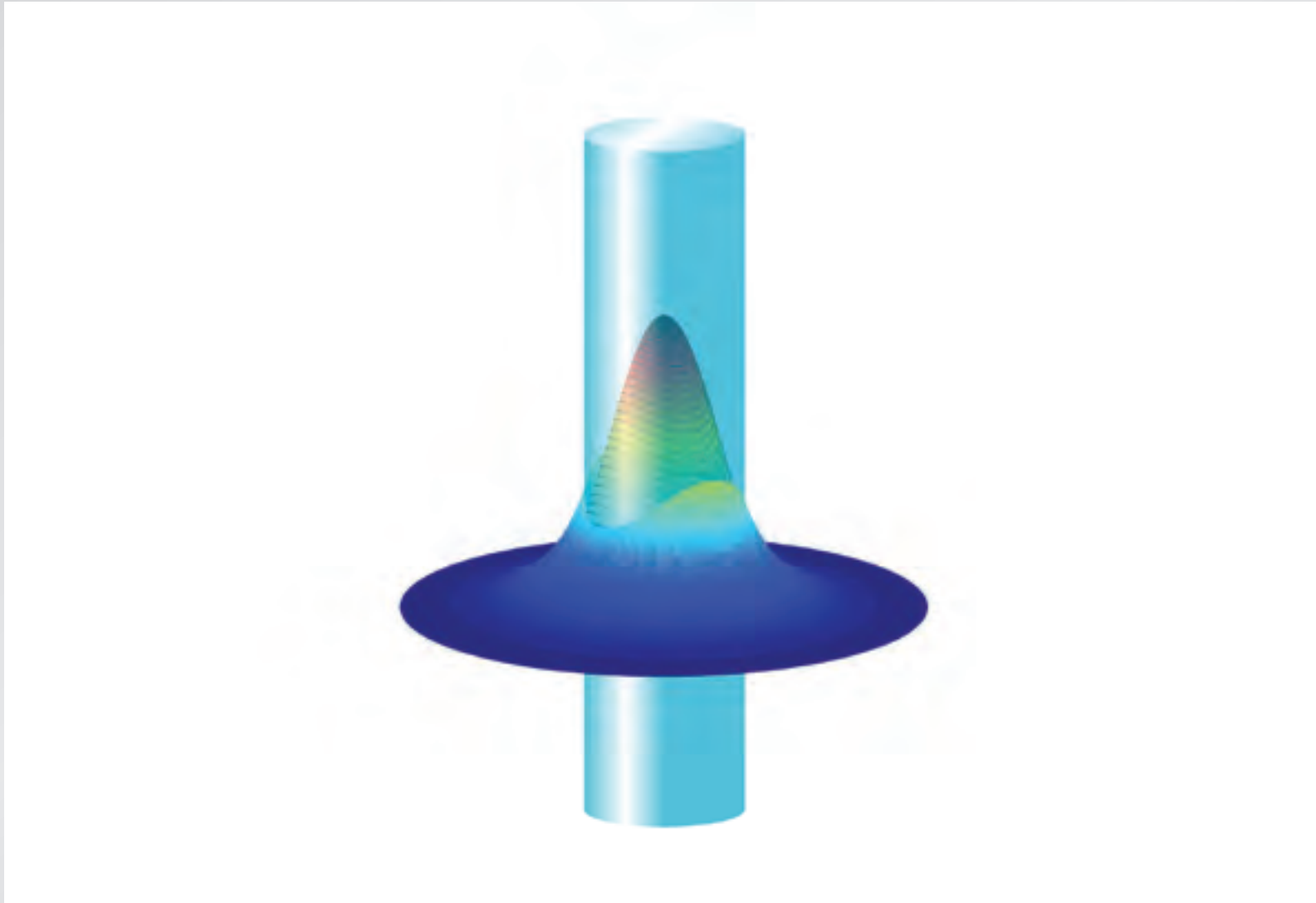
Optical properties

Poynting vector profile for 400-nm nanowire



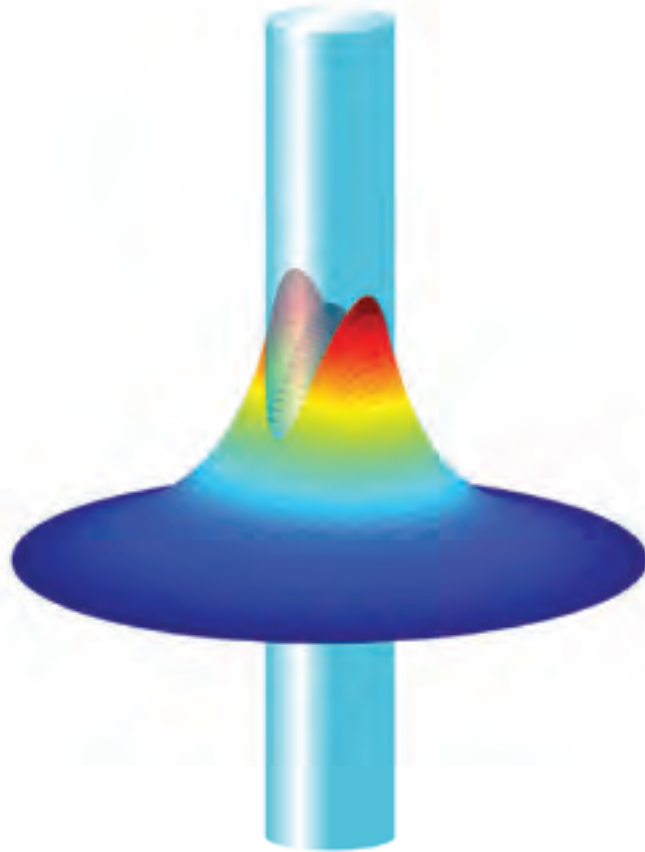
Optical properties

Poynting vector profile for 300-nm nanowire



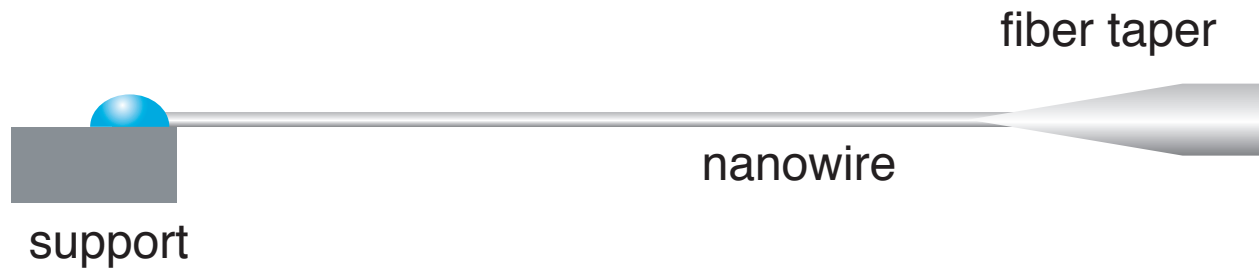
Optical properties

Poynting vector profile for 200-nm nanowire



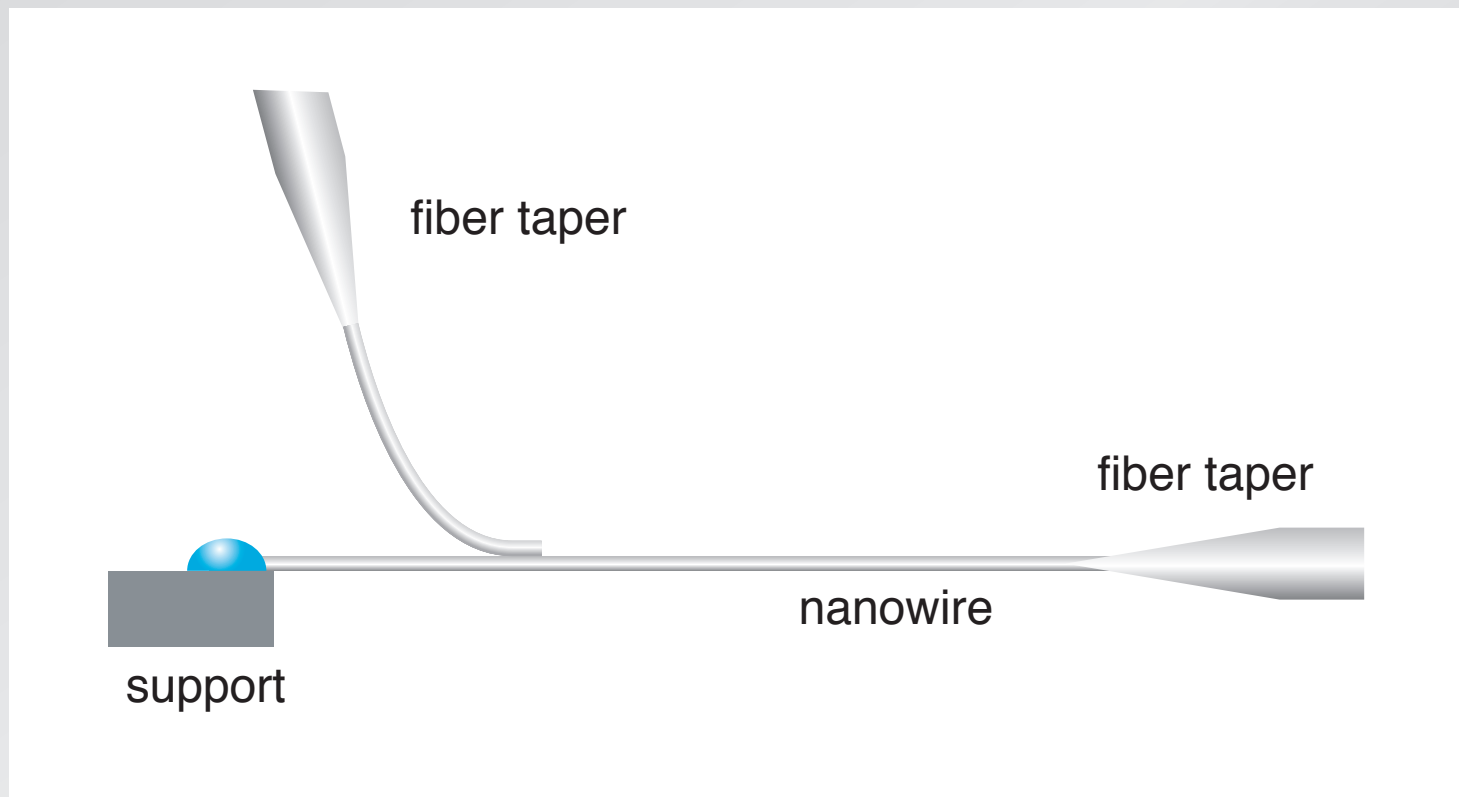
Optical properties

coupling light between nanowires



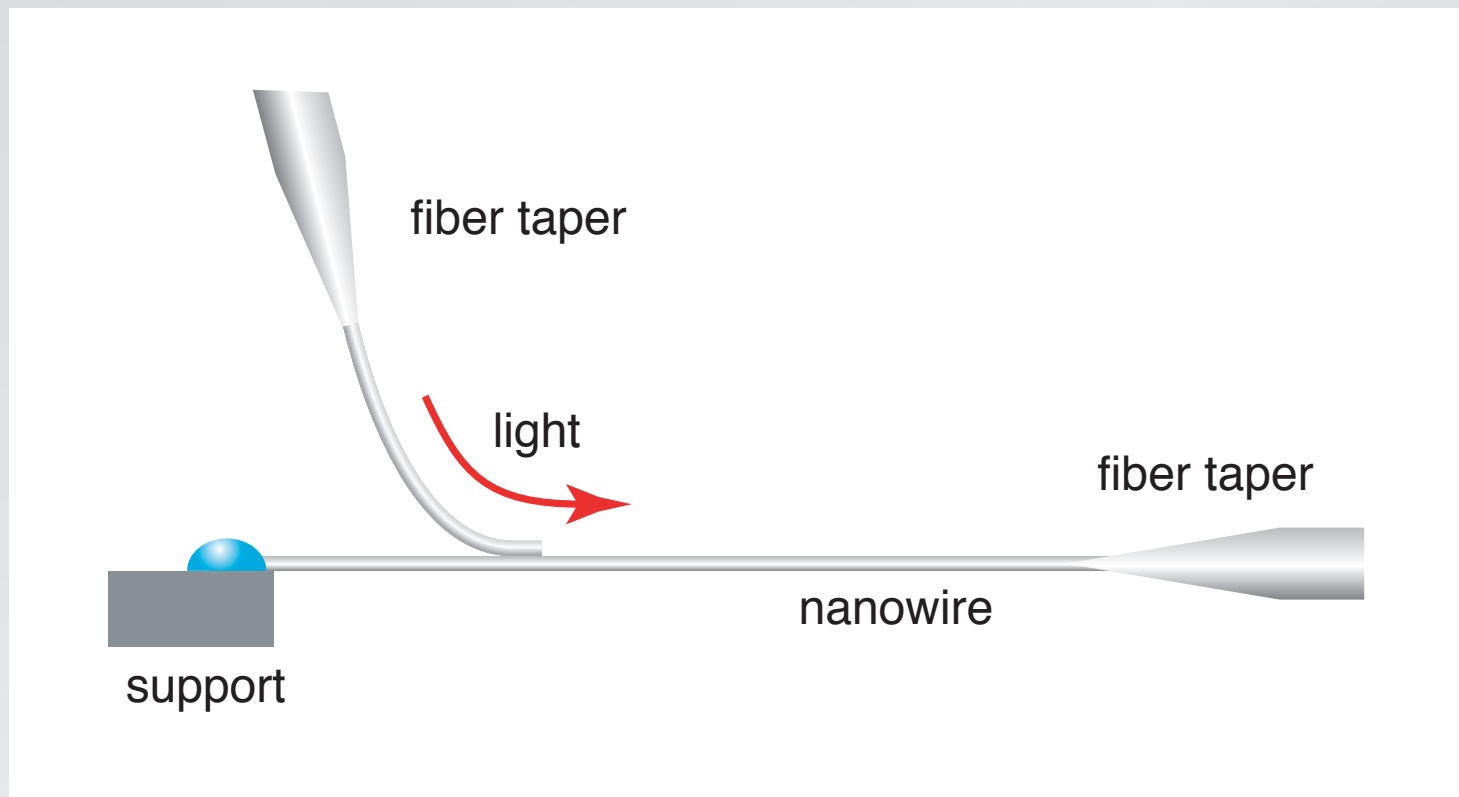
Optical properties

coupling light between nanowires



Optical properties

coupling light between nanowires



Optical properties

50 μm

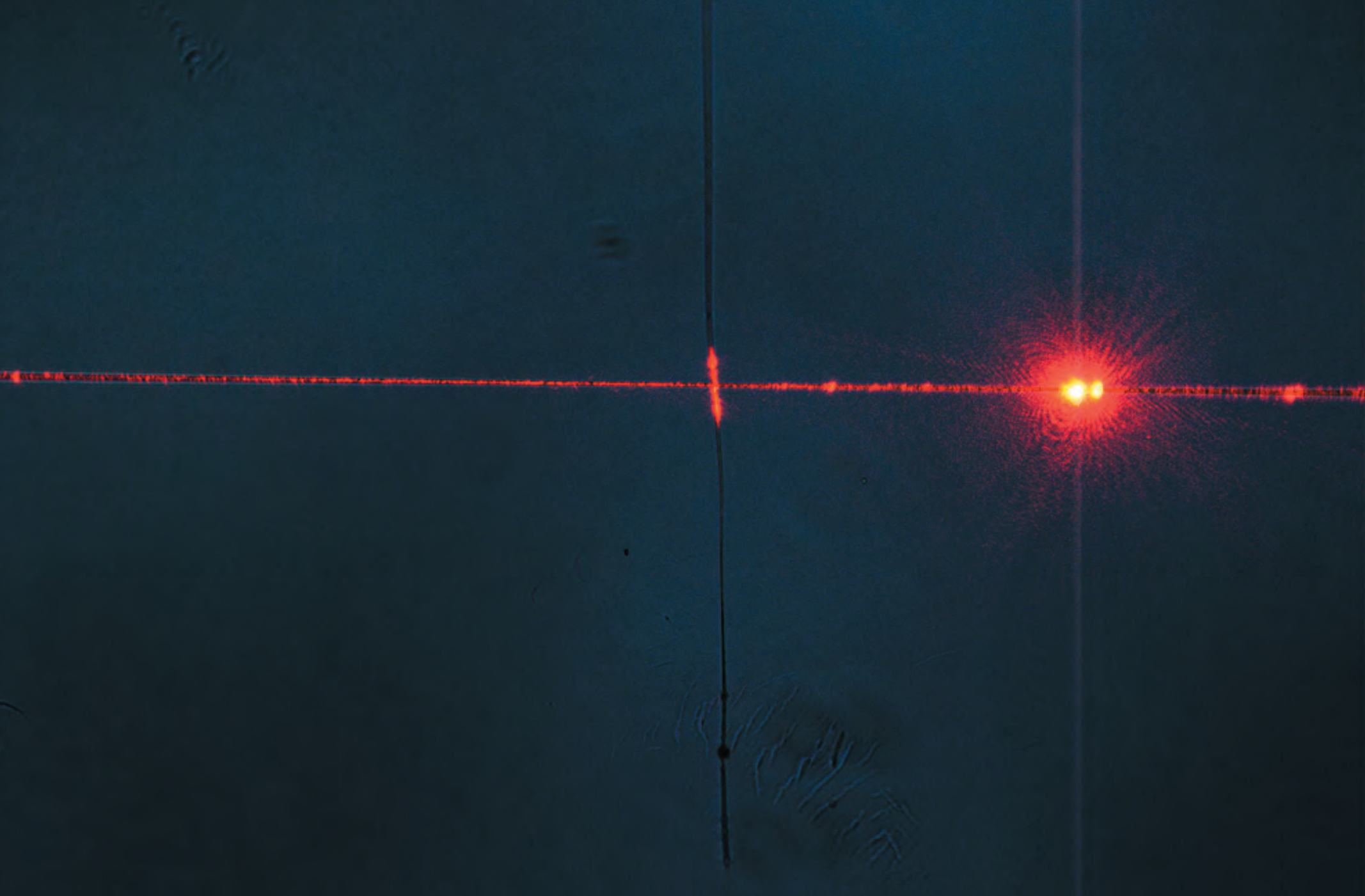
A micrograph showing a dark, textured surface with a prominent diagonal line and a horizontal line intersecting near the center. A scale bar in the bottom left corner indicates 50 μm.

Optical properties



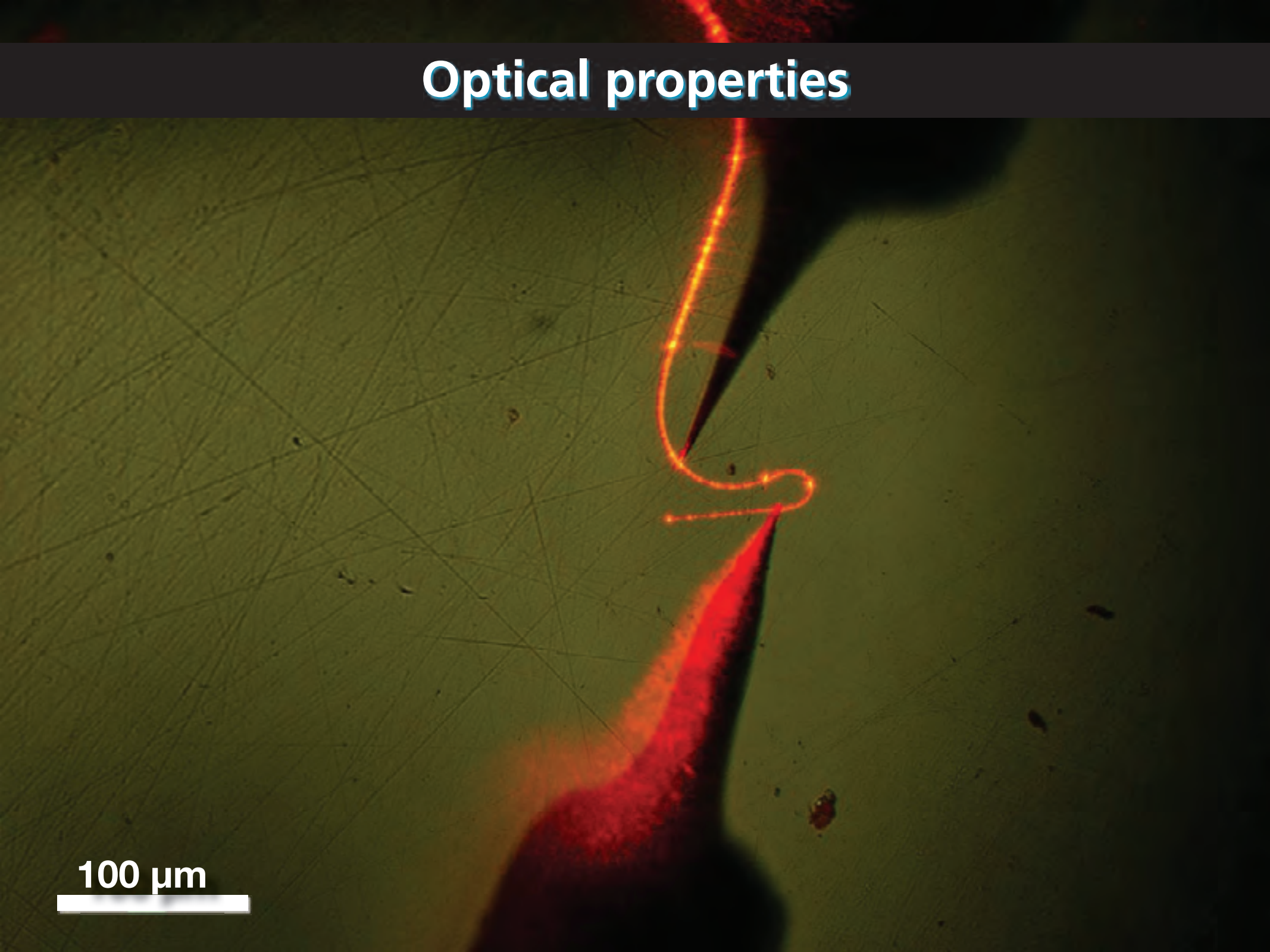
50 μm

Optical properties



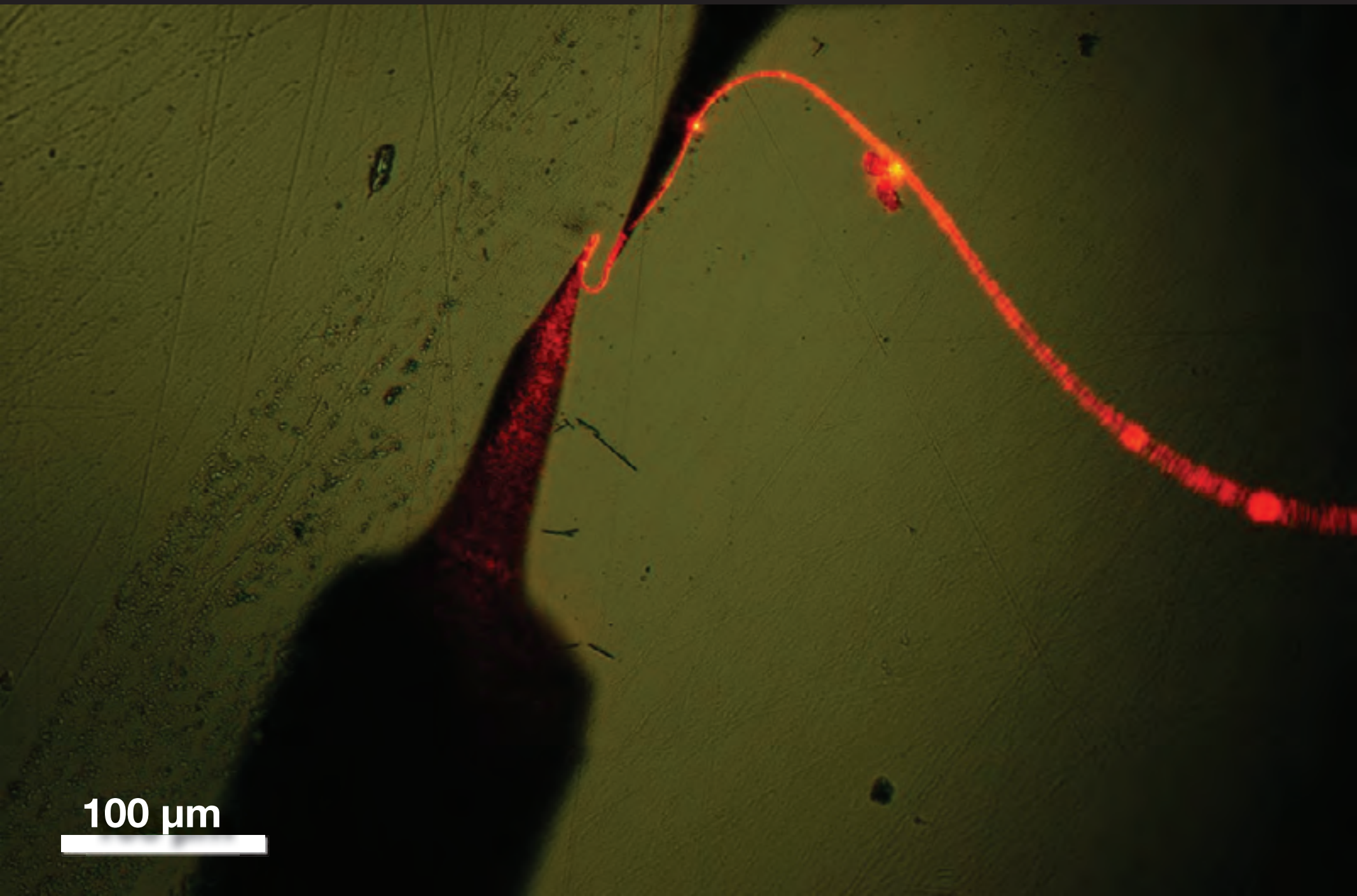
Optical properties

100 μm



An optical micrograph showing a fiber optic tip on the right side of the frame. A bright red laser beam is directed at the tip, creating a visible red glow and a small, curved, red, filamentary structure extending from the tip. The background is a dark, textured surface with many fine, light-colored scratches. A white scale bar in the bottom left corner indicates a length of 100 μm .

Optical properties

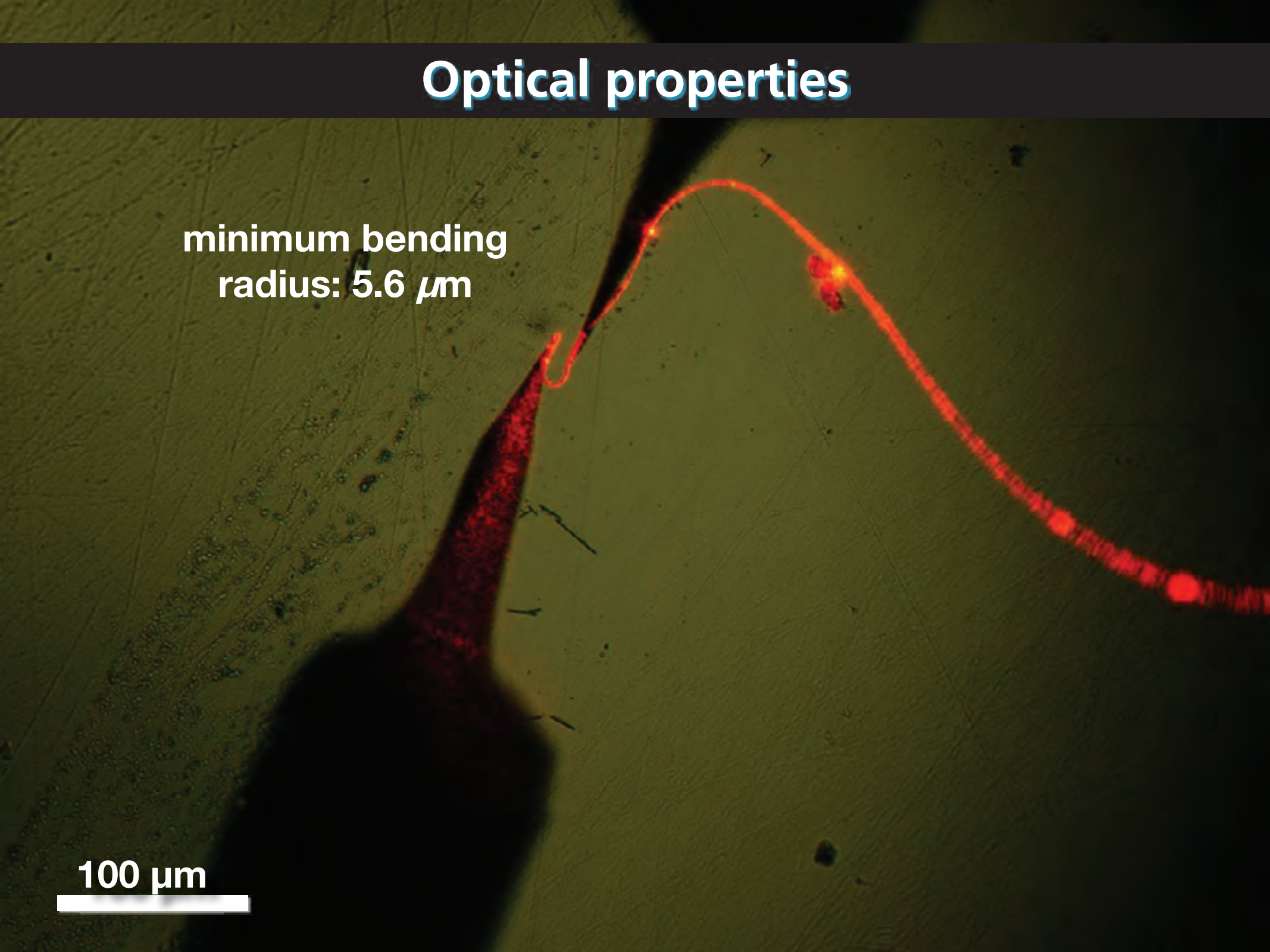


100 μm

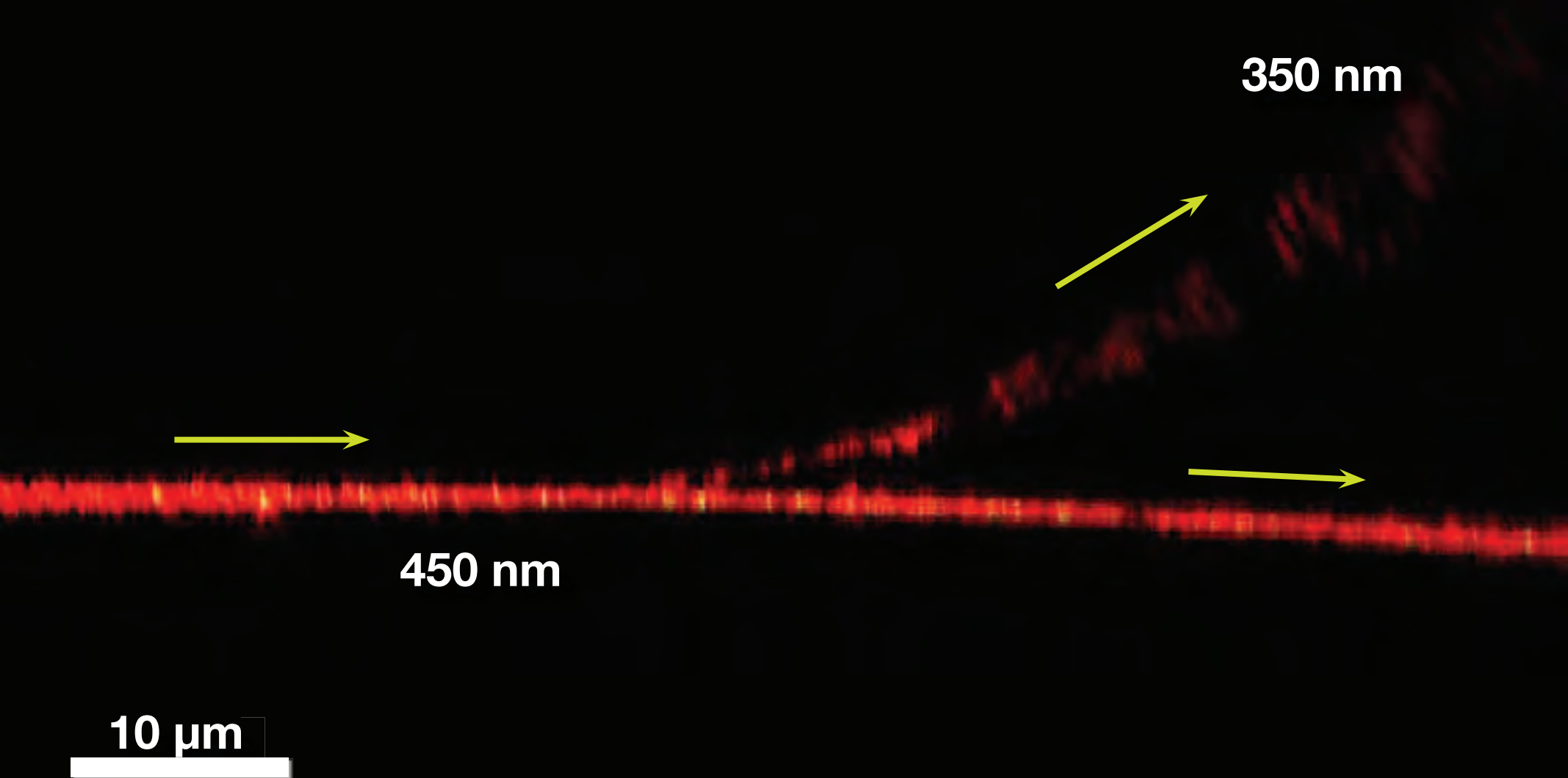
Optical properties

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

100 μm

An optical micrograph showing a fiber structure on a textured, olive-green substrate. A bright red laser line is projected along the length of the fiber, which exhibits a sharp bend. The background surface has fine, parallel scratches. A scale bar in the bottom left corner indicates 100 micrometers. Text in the upper left corner specifies a minimum bending radius of 5.6 micrometers.

Outlook

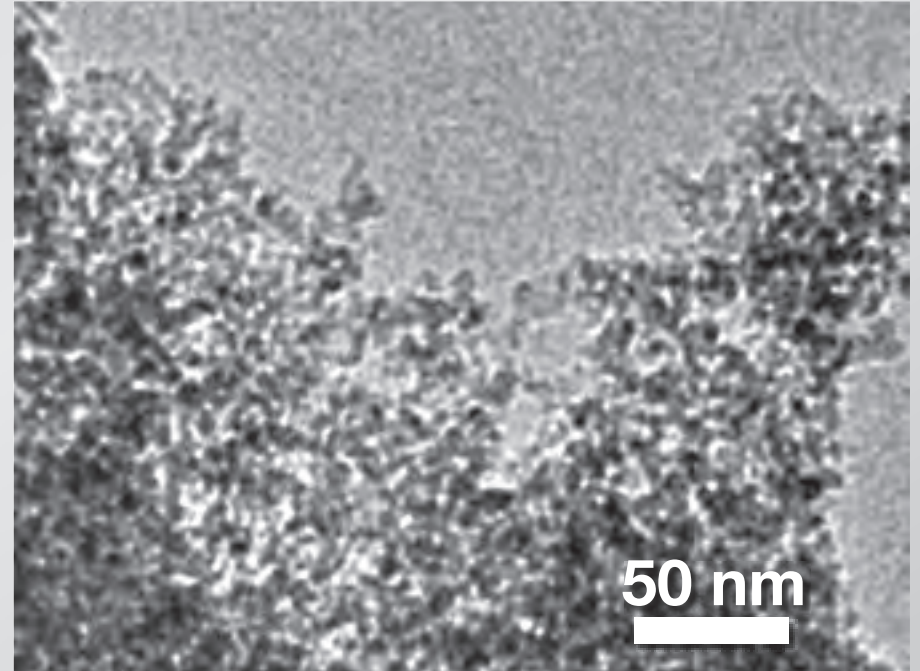
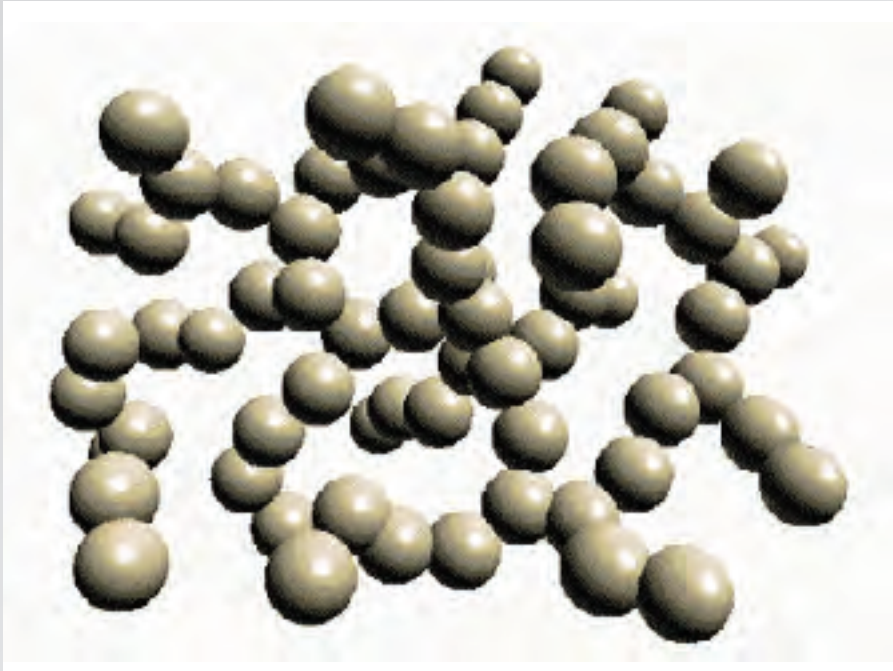


Outlook



Outlook

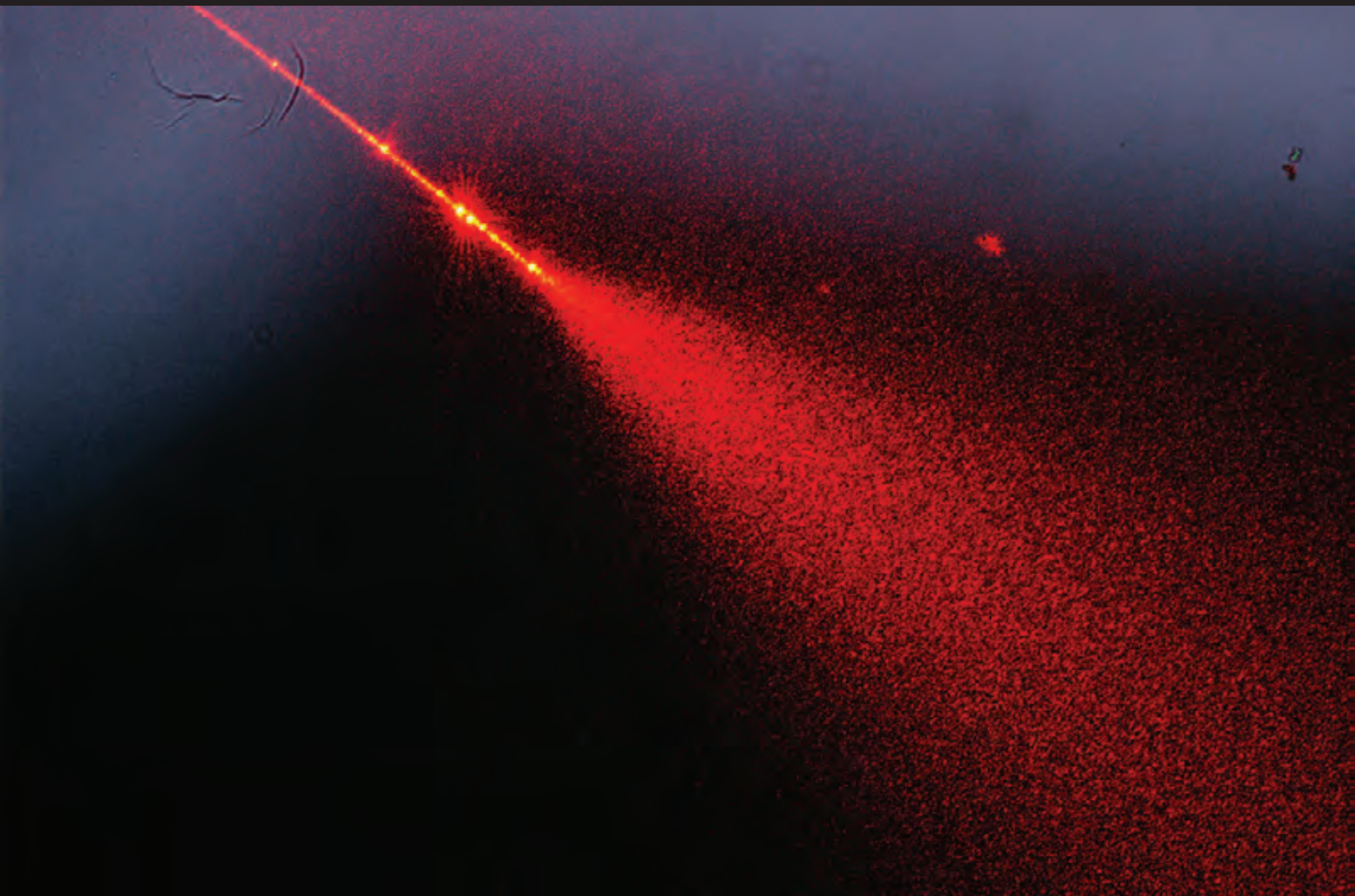
Aerogel



density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Outlook



Outlook

1 μm



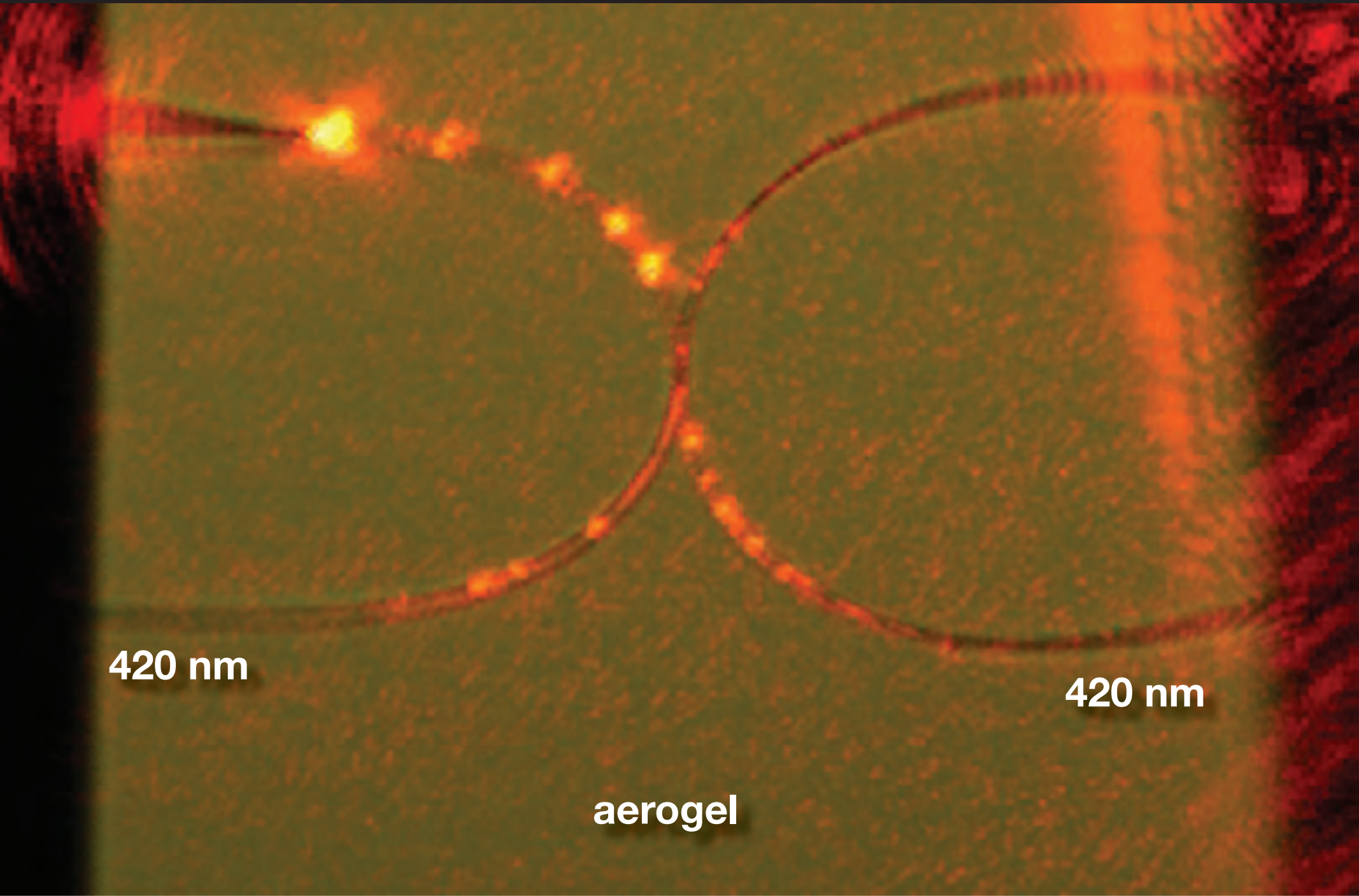
Outlook

530 nm

50 μm

A fluorescence microscopy image showing a red fluorescent structure, possibly a cell or a protein complex, against a dark background. The structure is elongated and has a distinct, rounded end. A scale bar in the bottom left corner indicates a length of 50 micrometers. The text "530 nm" is positioned above the structure, likely indicating the excitation wavelength used for imaging. The background is dark with some faint, out-of-focus structures visible in the lower right corner.

Outlook



420 nm

420 nm

aerogel

Outlook

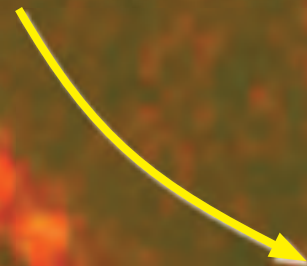
in



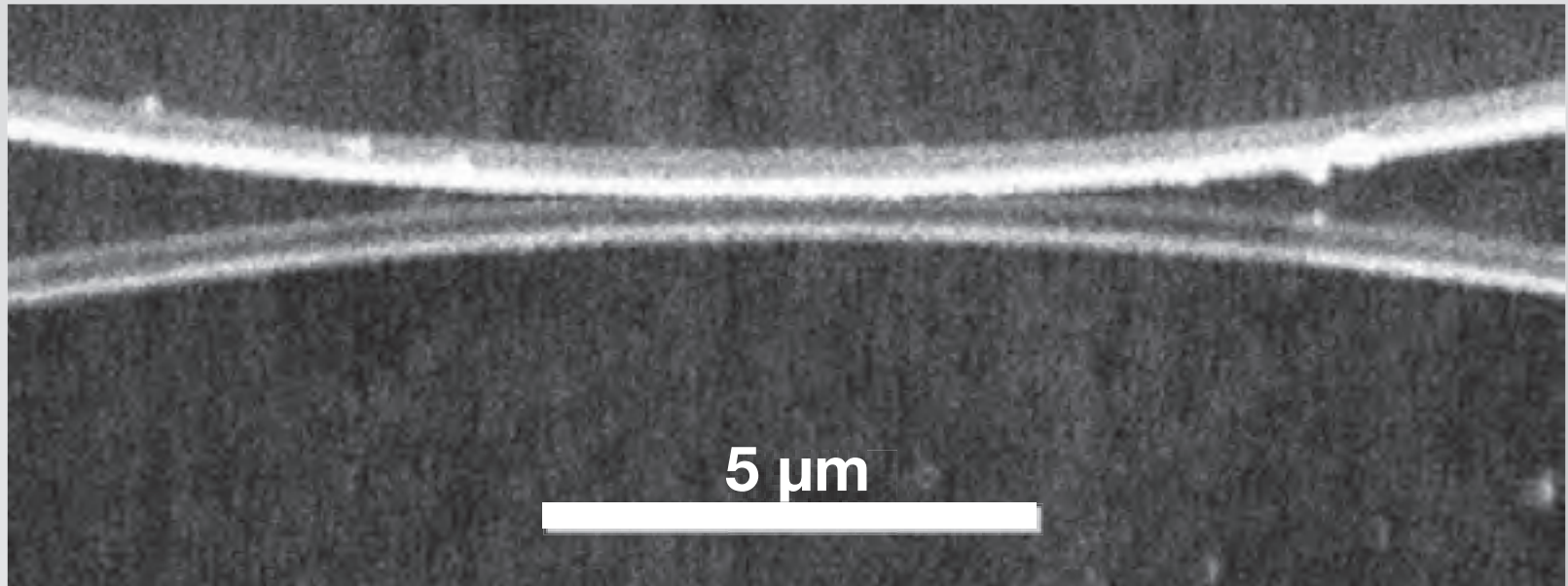
out



out

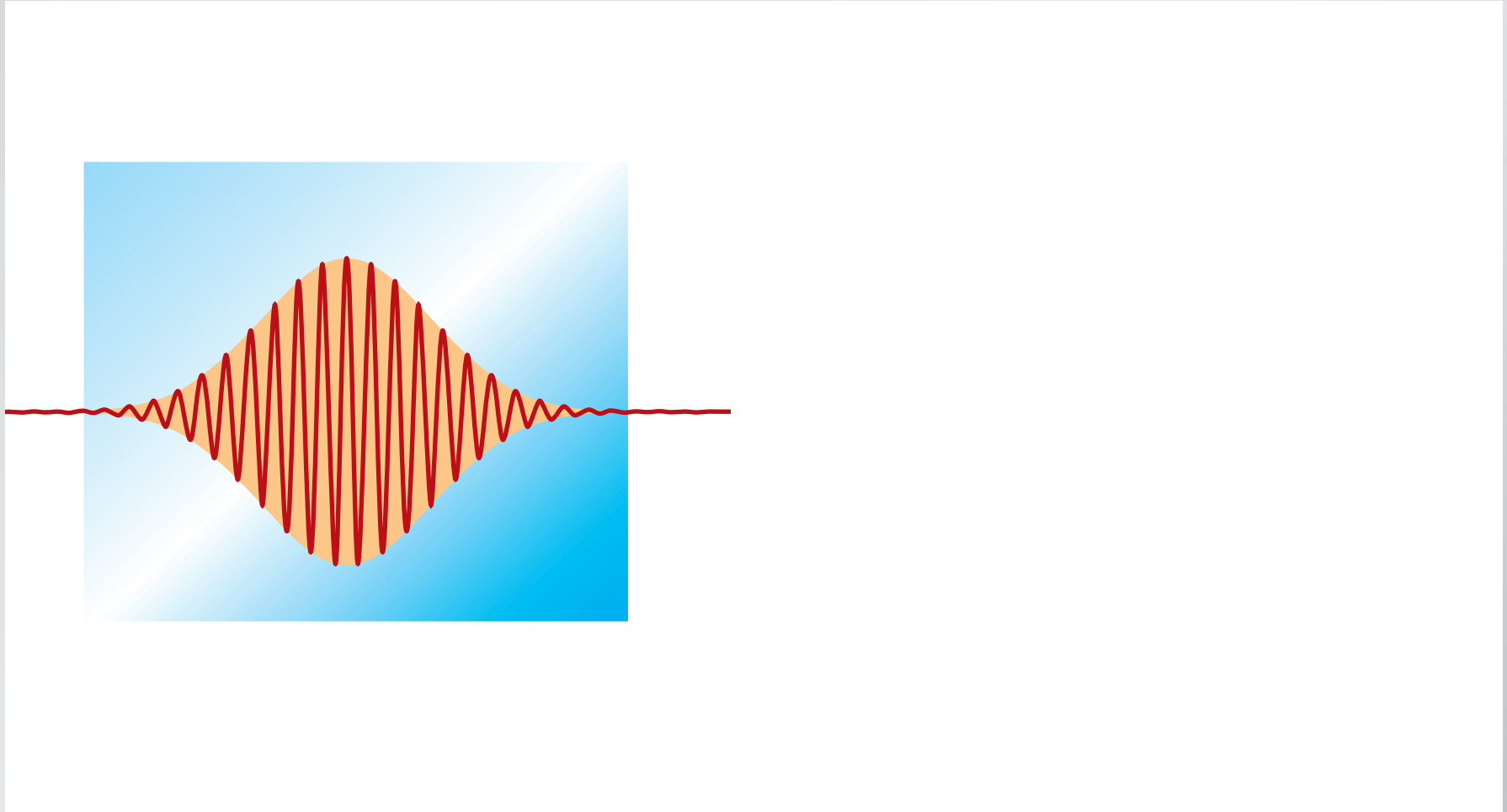


Outlook



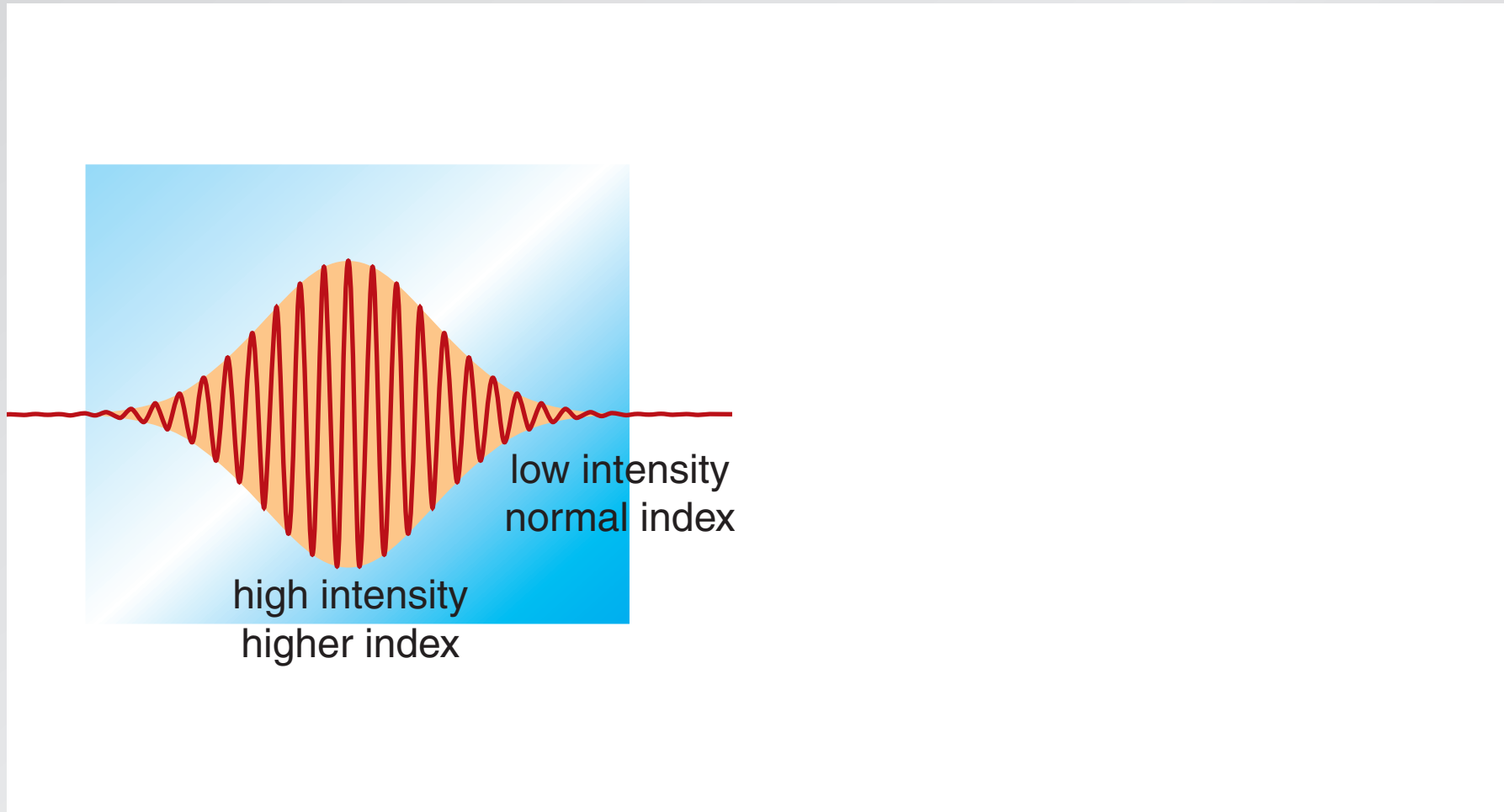
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



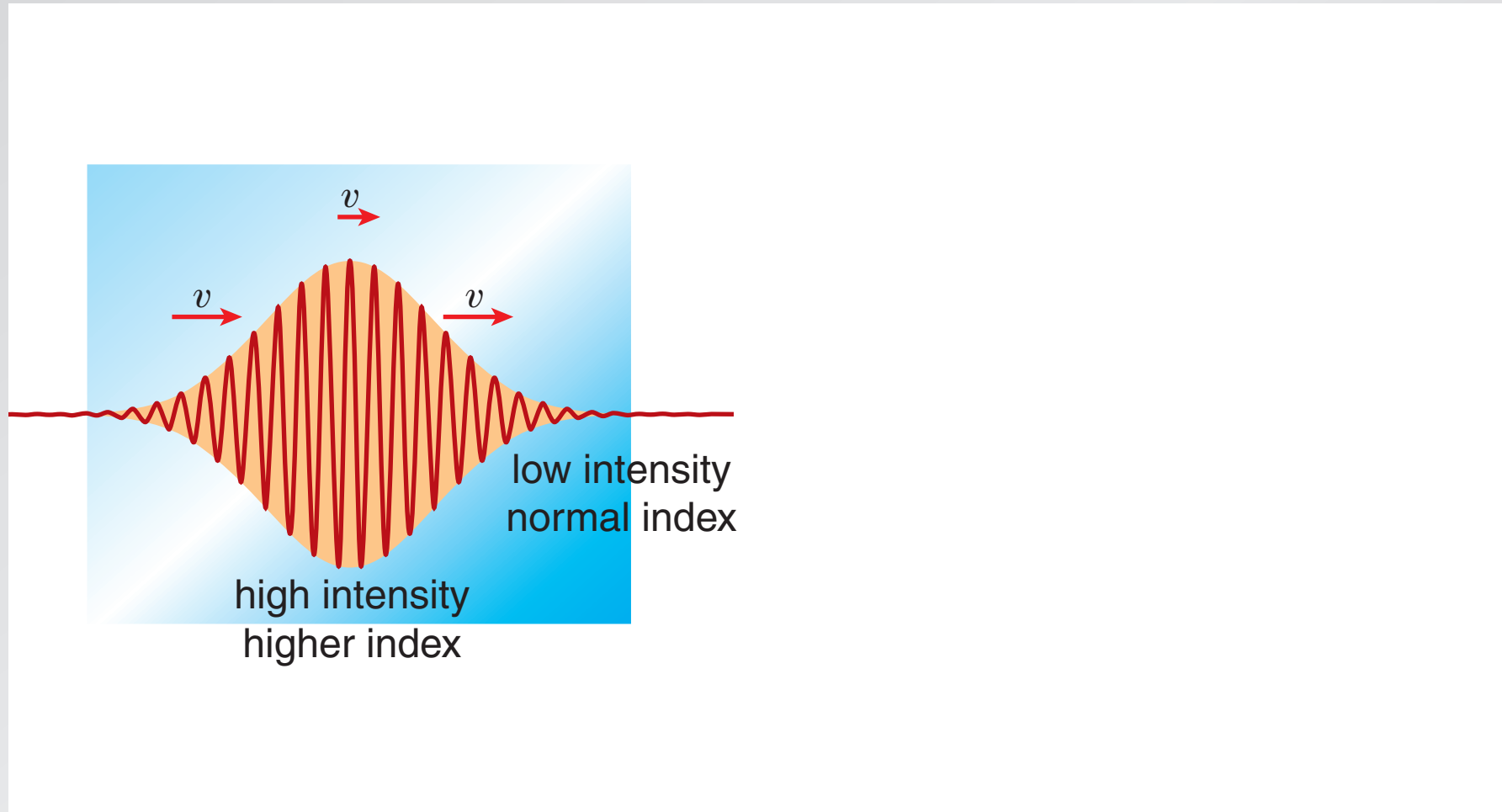
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



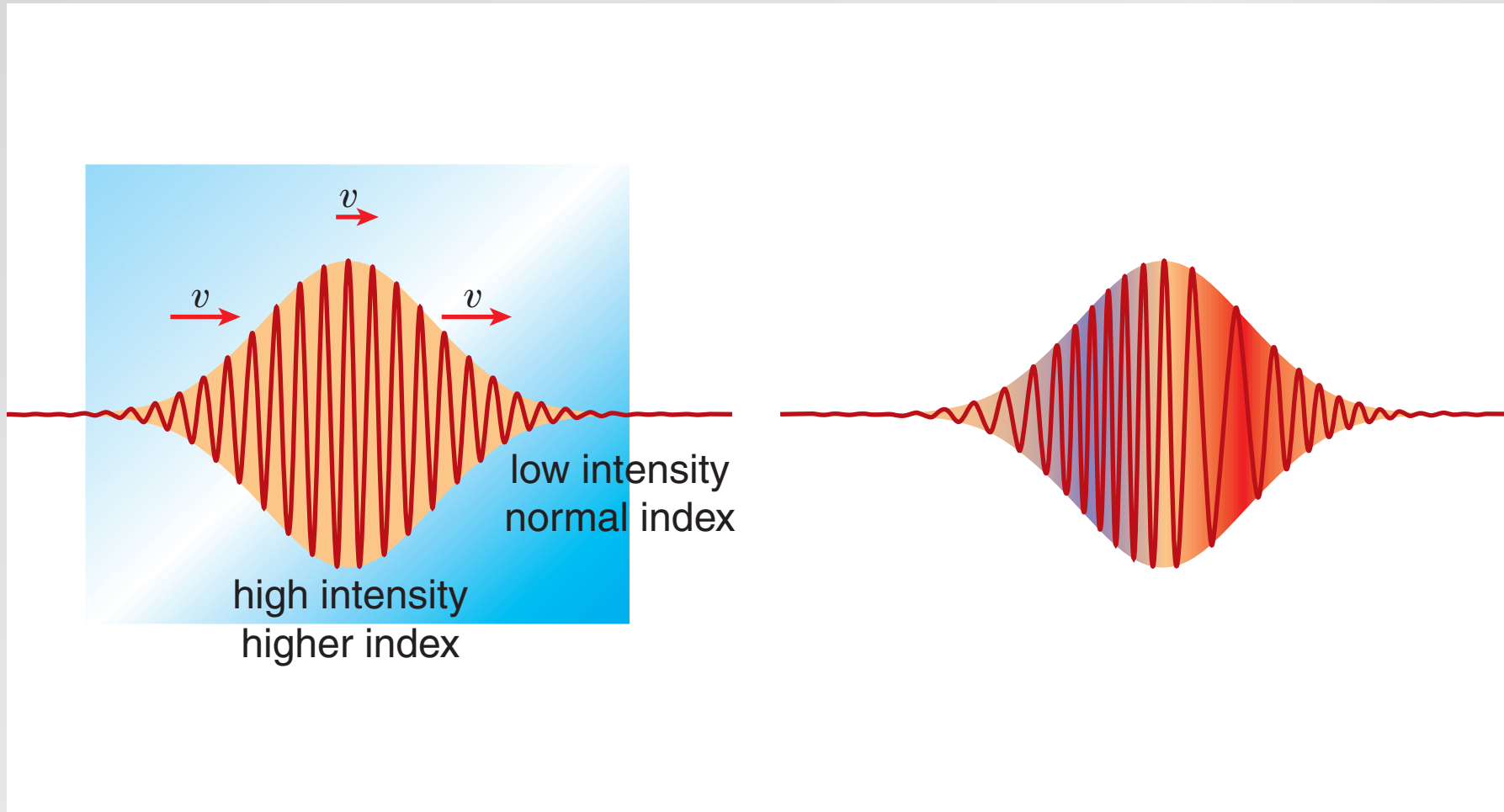
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



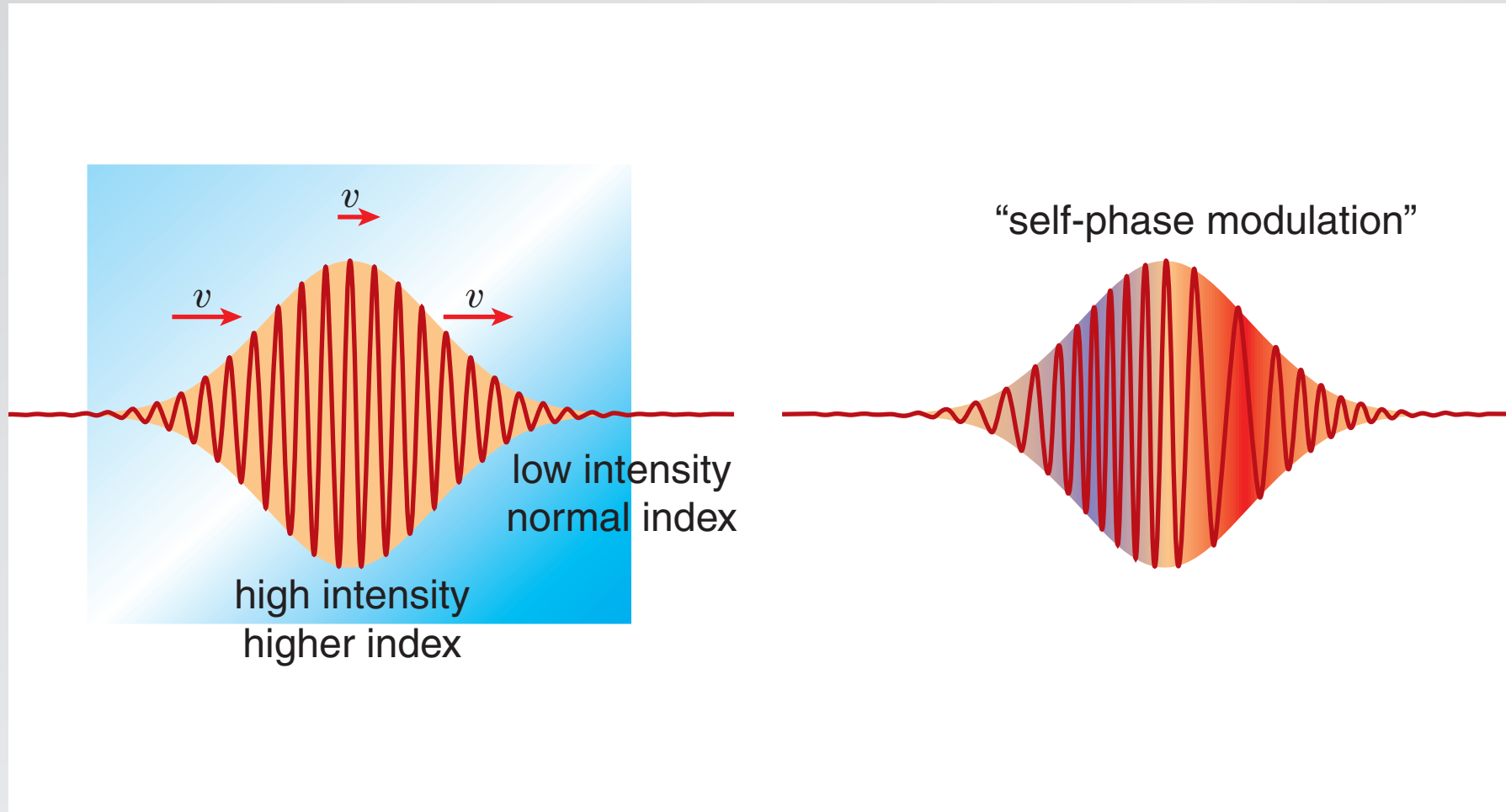
Nanoscale nonlinear optics

nonlinear dispersion: $n = n_o + n_2 I$



Nanoscale nonlinear optics

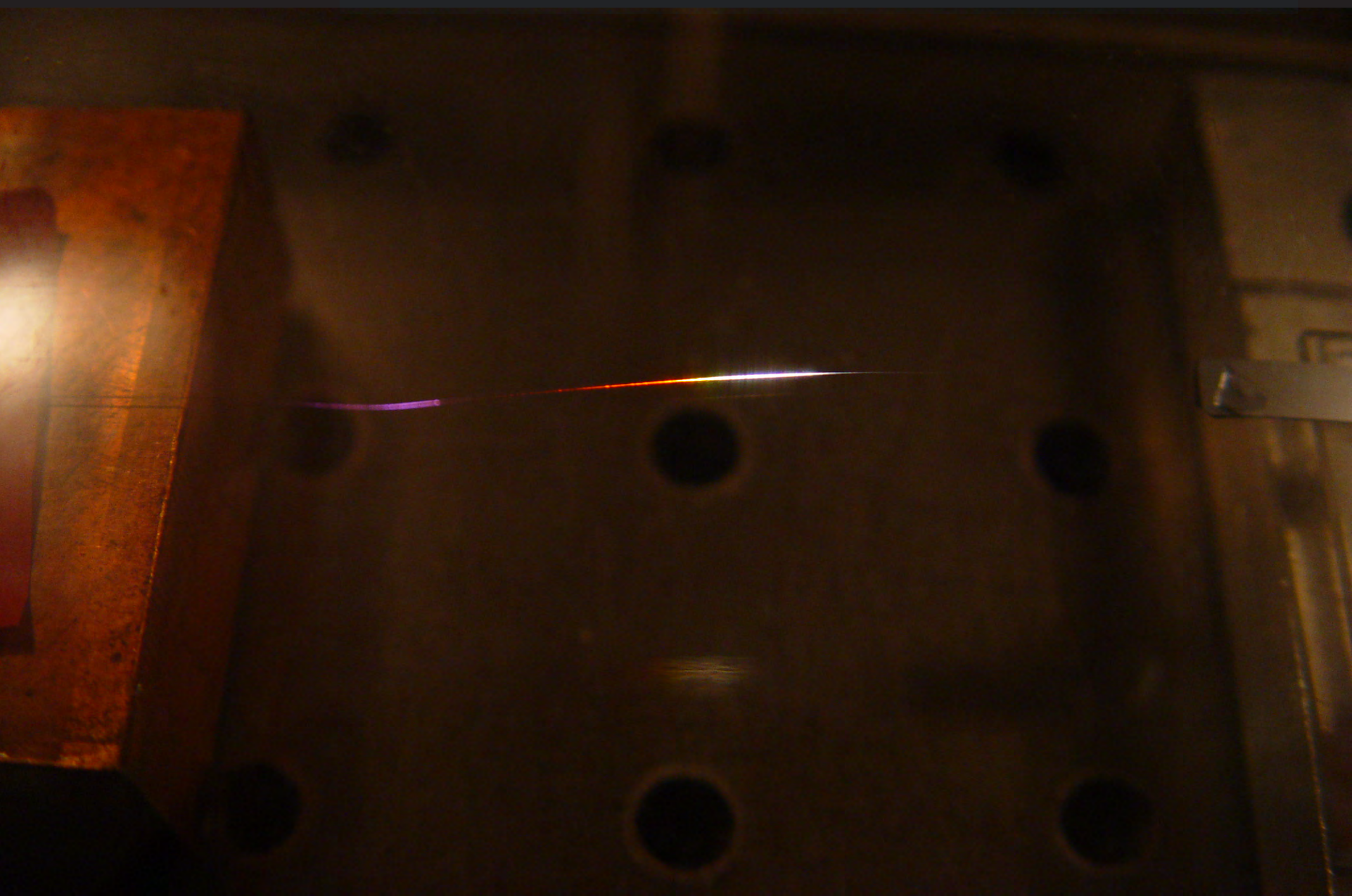
nonlinear dispersion: $n = n_o + n_2 I$



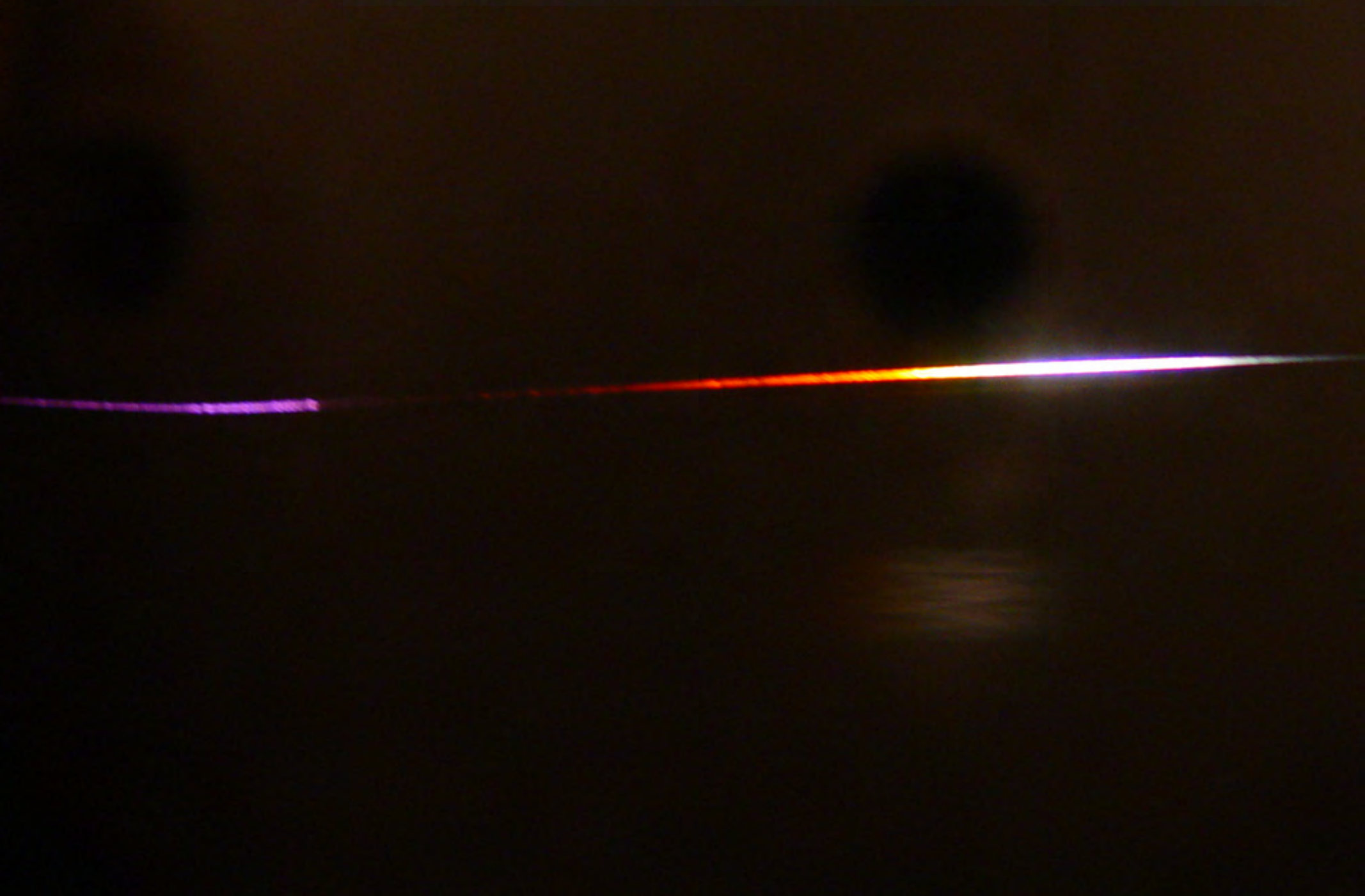
Nanoscale nonlinear optics

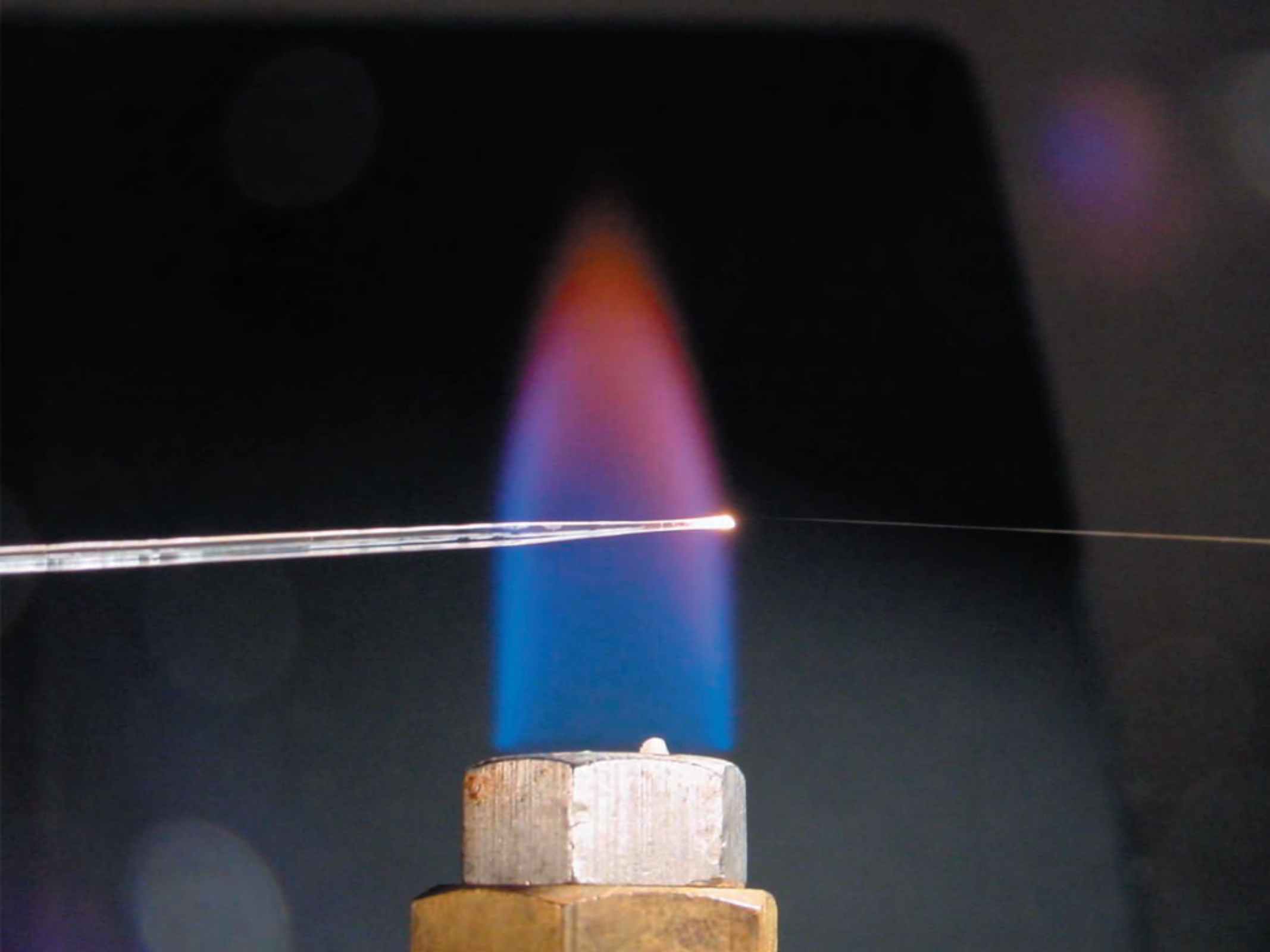
strong confinement \longrightarrow **high intensity**

Nanoscale nonlinear optics

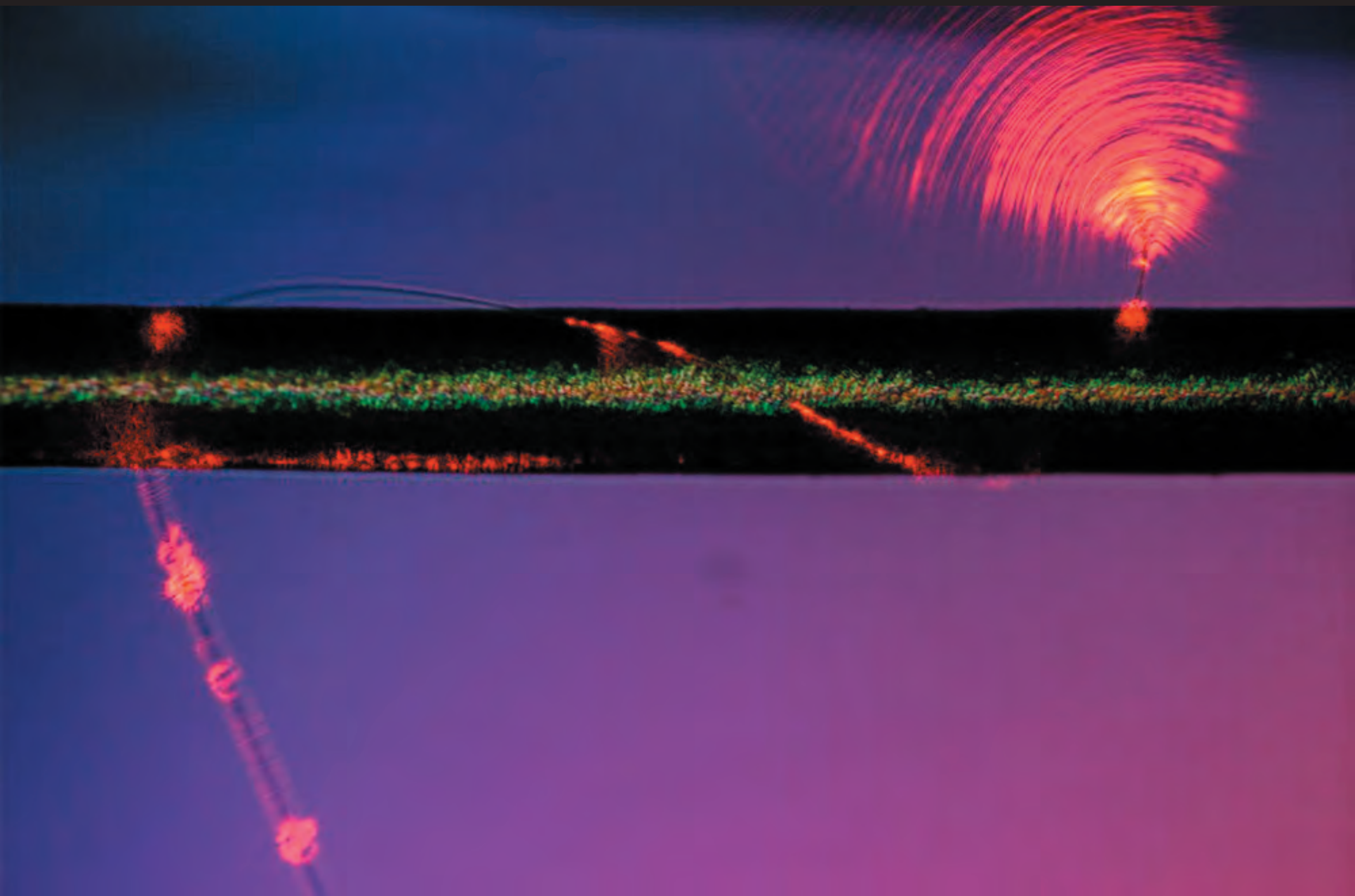


Nanoscale nonlinear optics





Summary



Summary

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





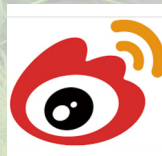
Funding:

**Harvard Center for Imaging and Mesoscopic Structures
National Science Foundation
National Natural Science Foundation of China**

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