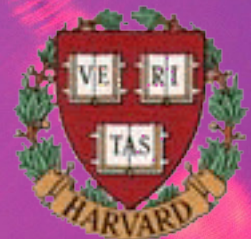


Wrapping light around a hair



@eric_mazur

ISTA Annual Conference 2016
Limerick, Ireland, 9 April 2016

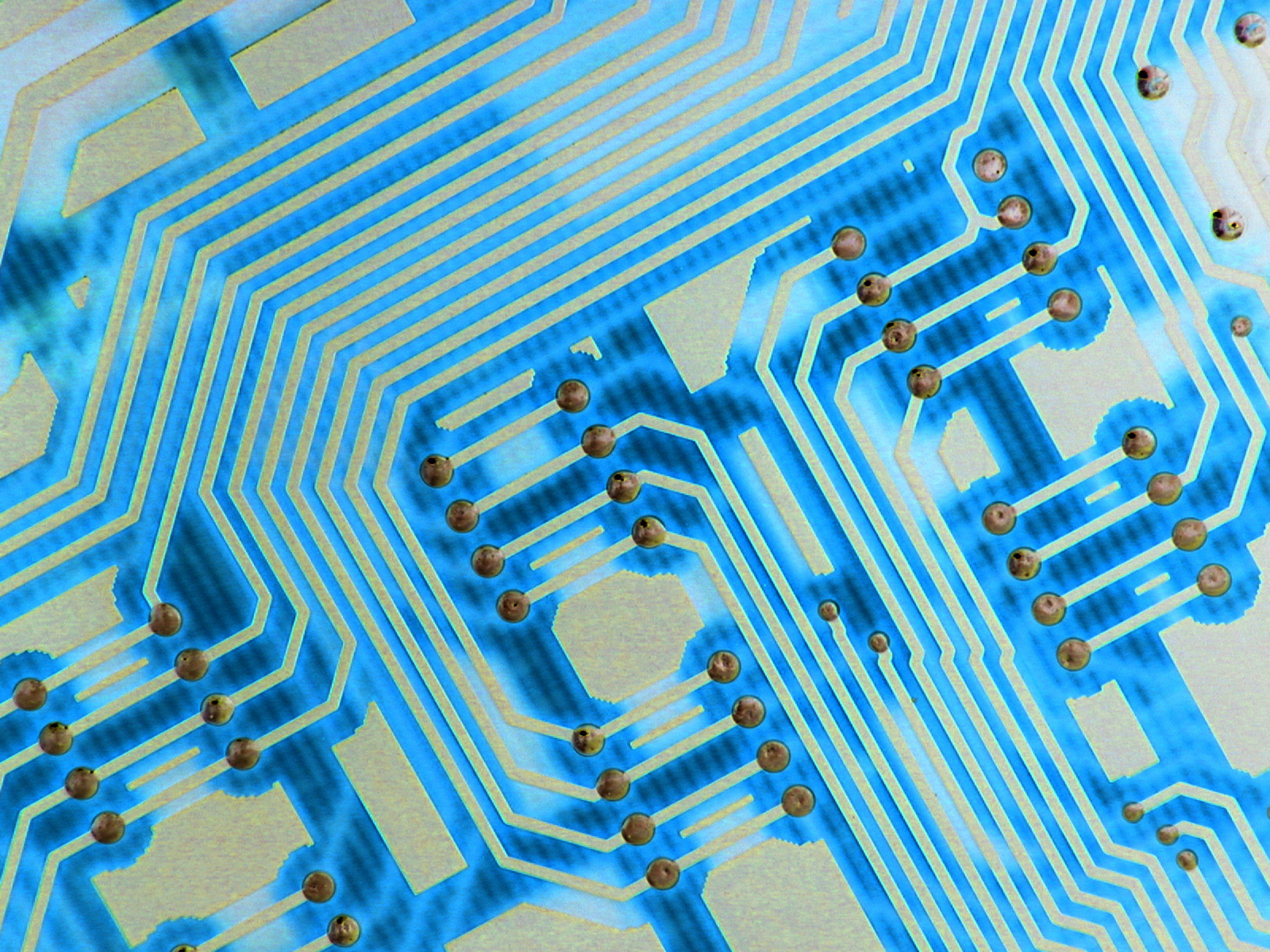


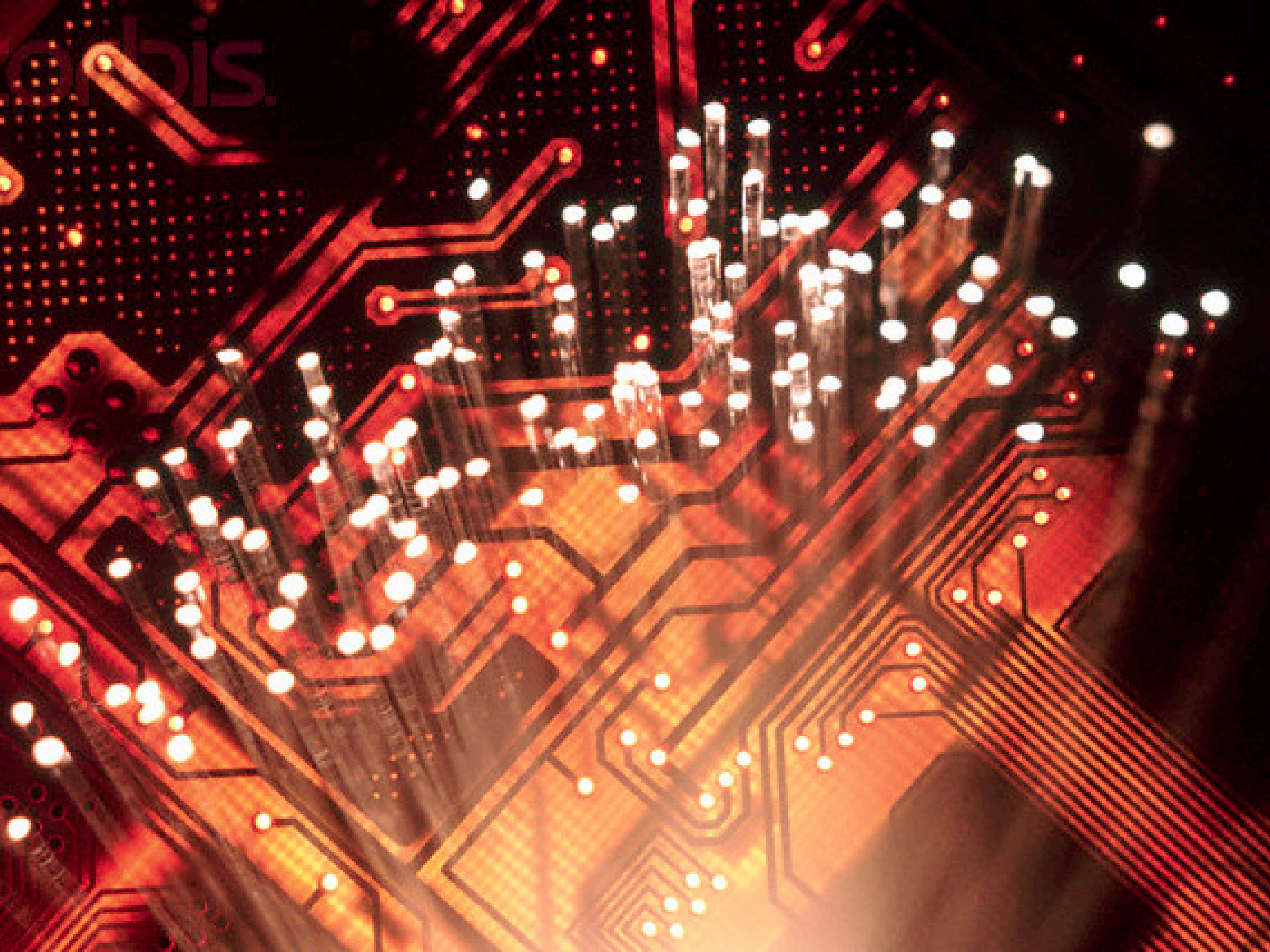
Wrapping light around a hair



ISTA Annual Conference 2016
Limerick, Ireland, 9 April 2016



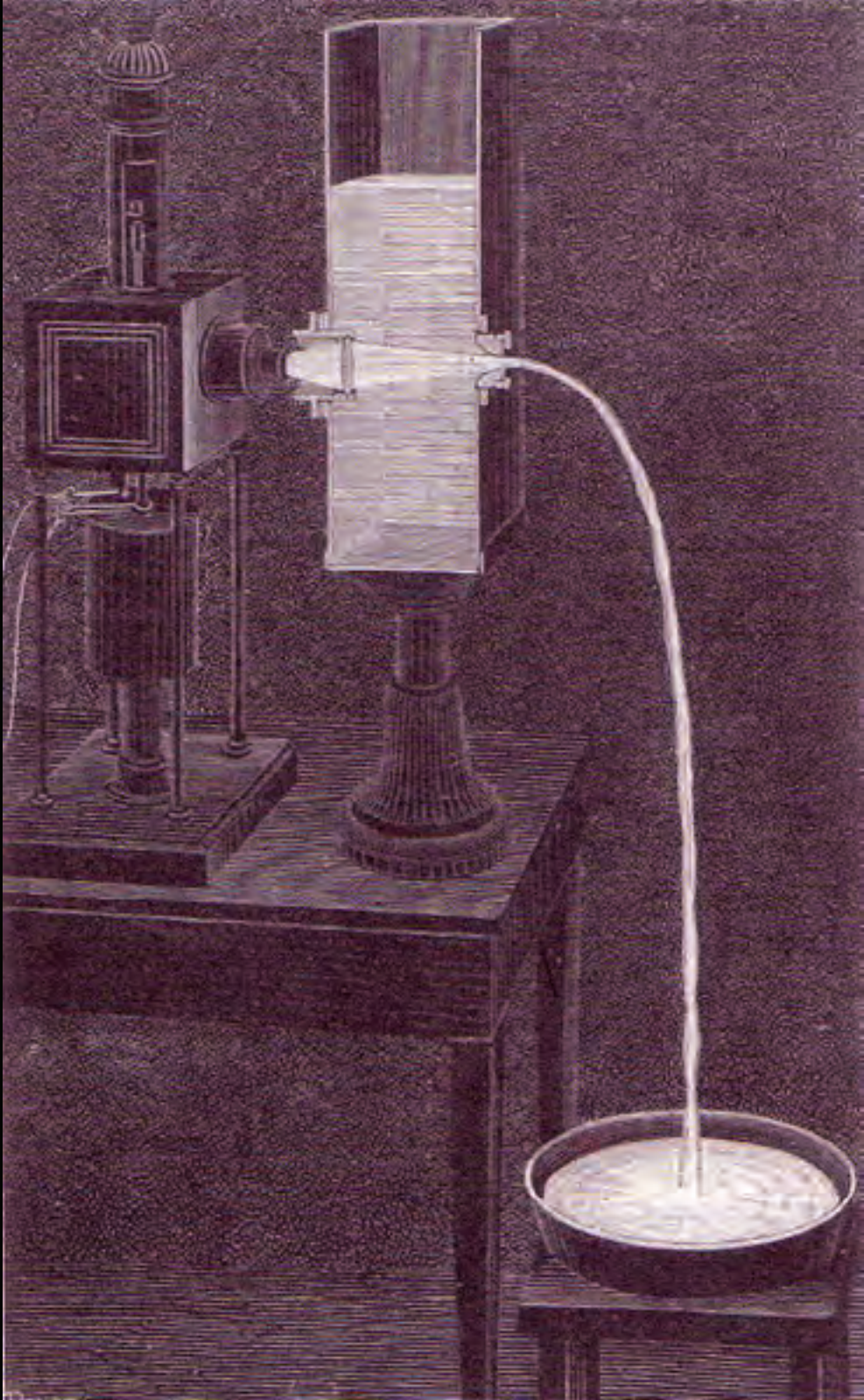




obis.

“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.

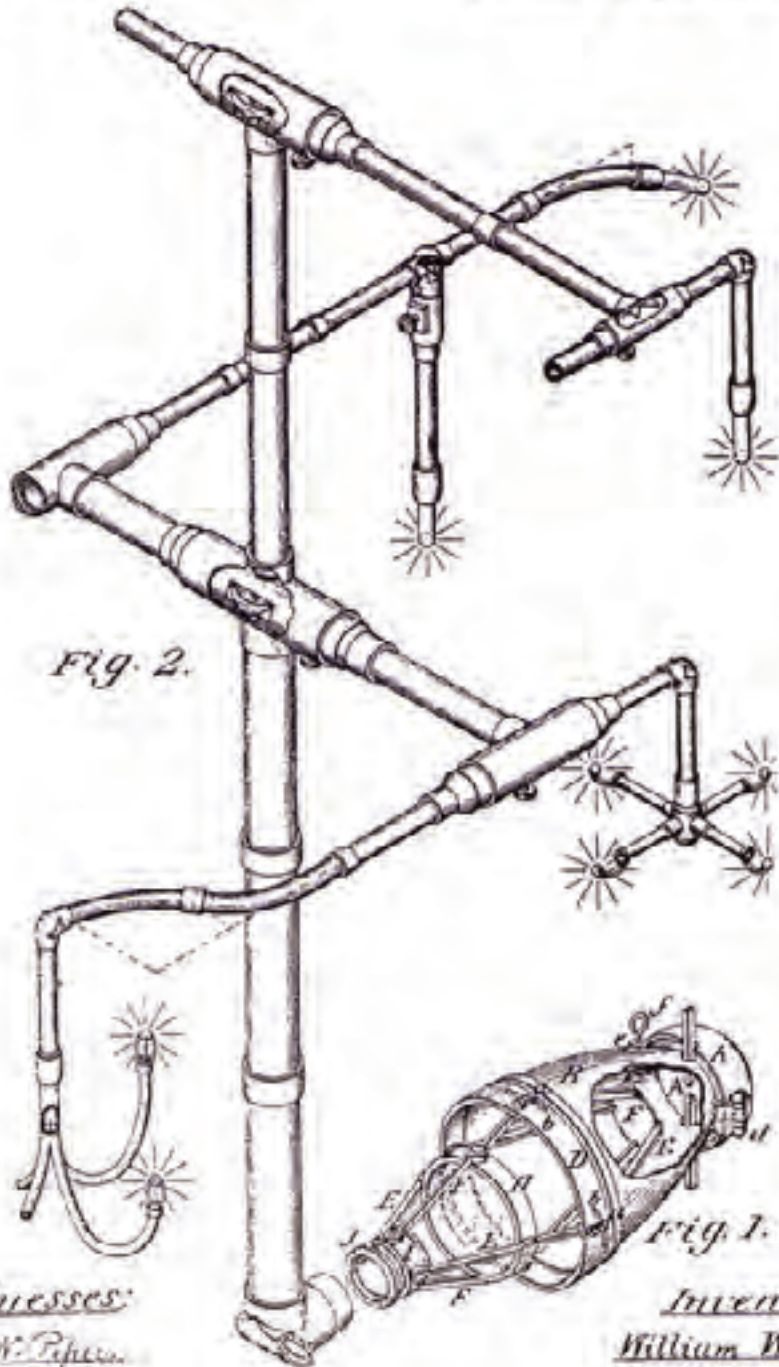


Fig. 2.

Fig. 1.

Witnesses:
J. A. Piper
Ed. H. [unclear]

Inventor:
William Wheeler
 by attorney
[unclear]

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



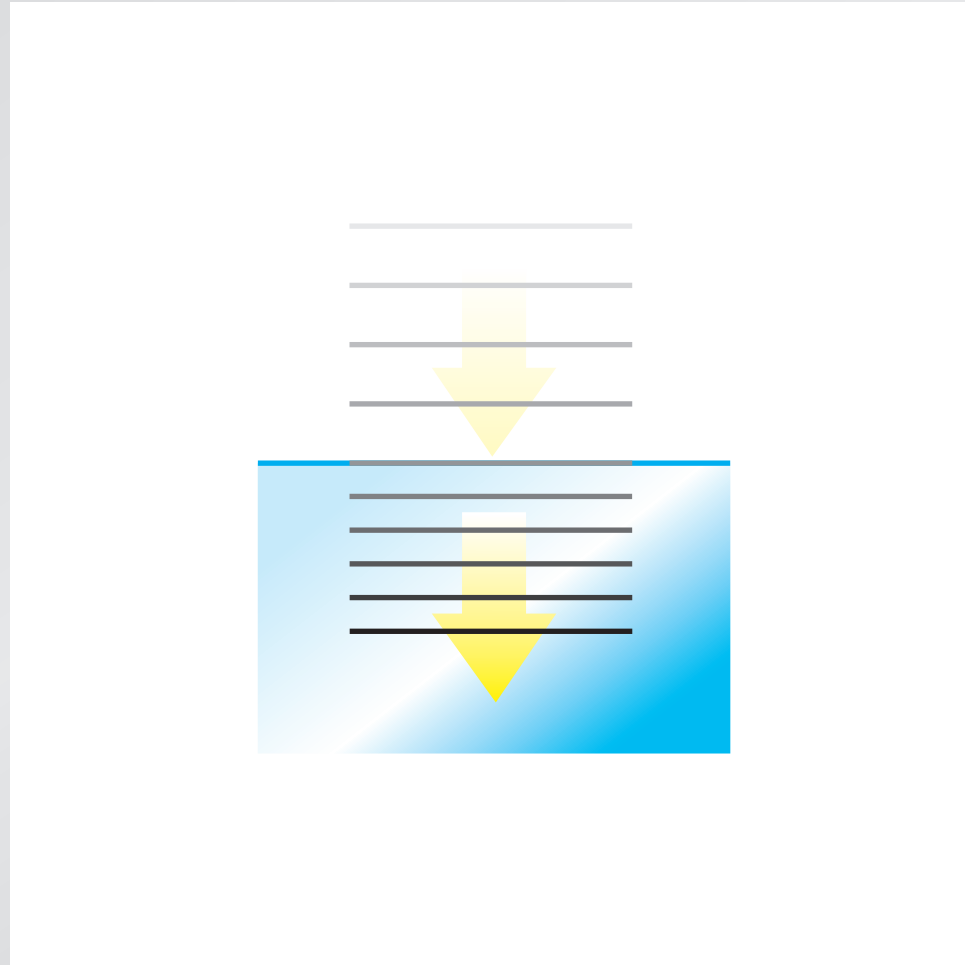
Waveguiding

water surface is perfect one-way mirror!



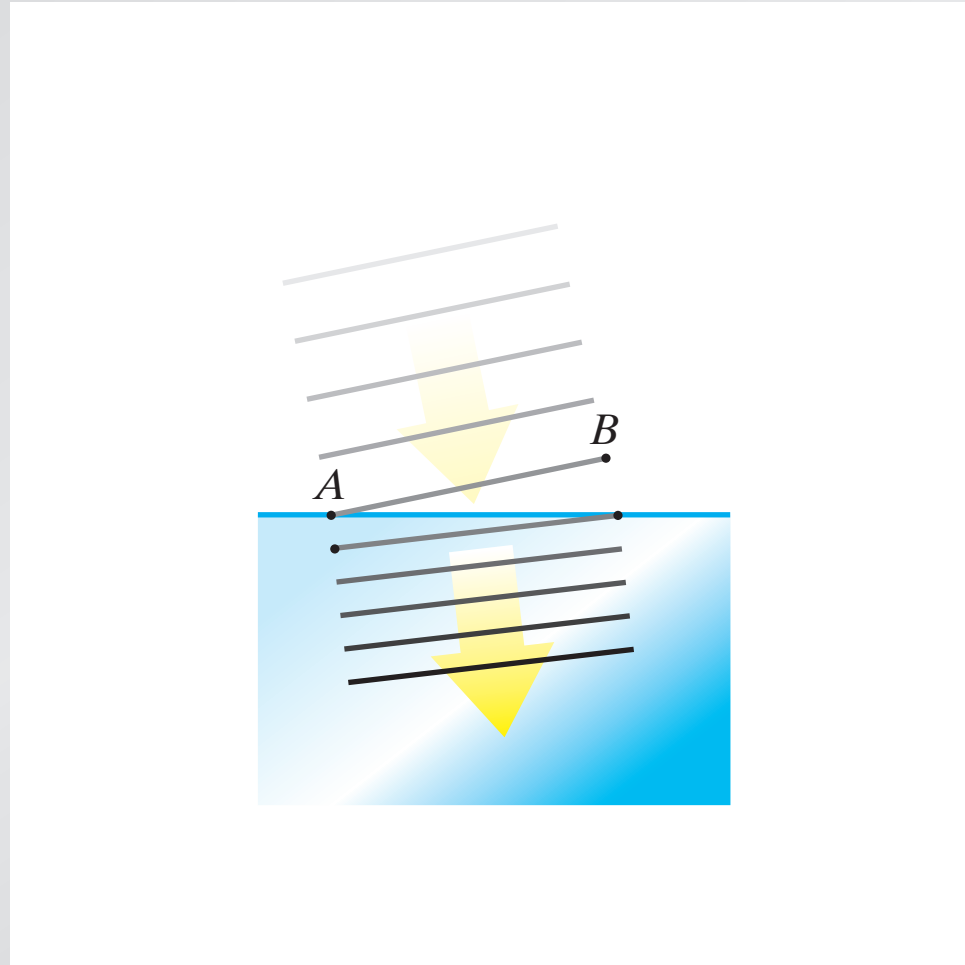
Waveguiding

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



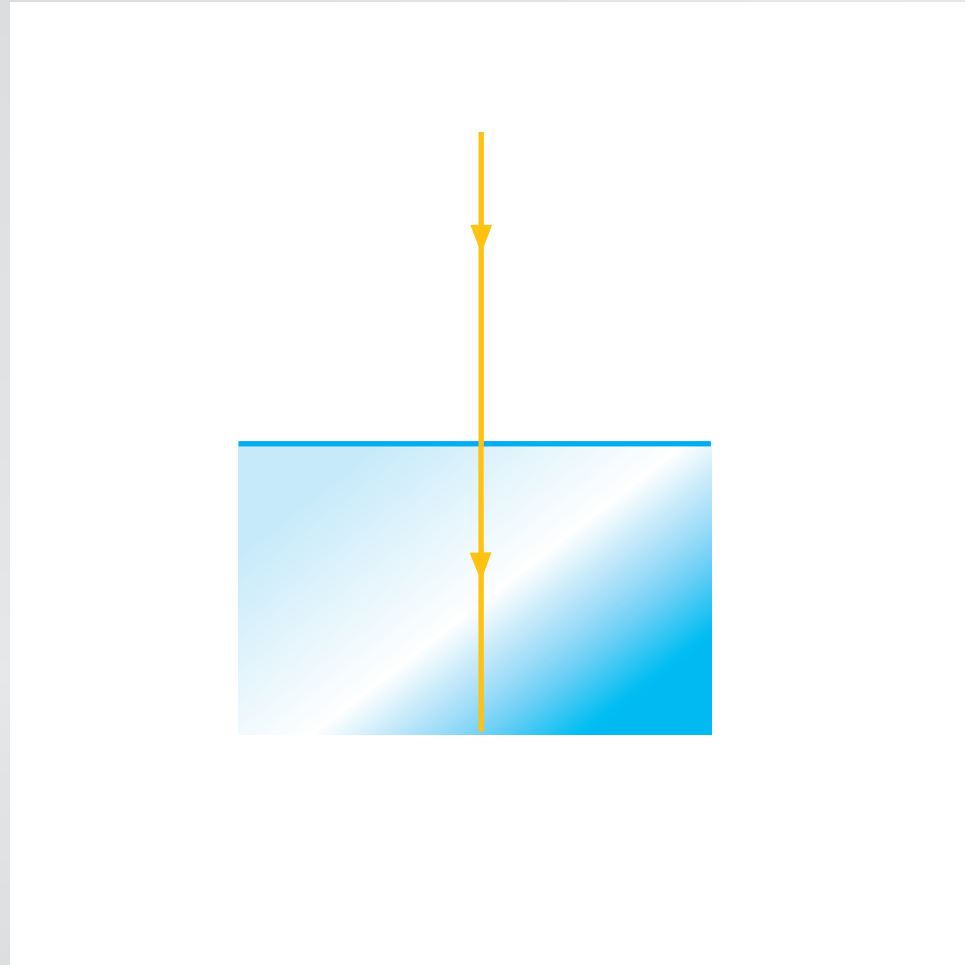
Waveguiding

...making it bend as it crosses surface



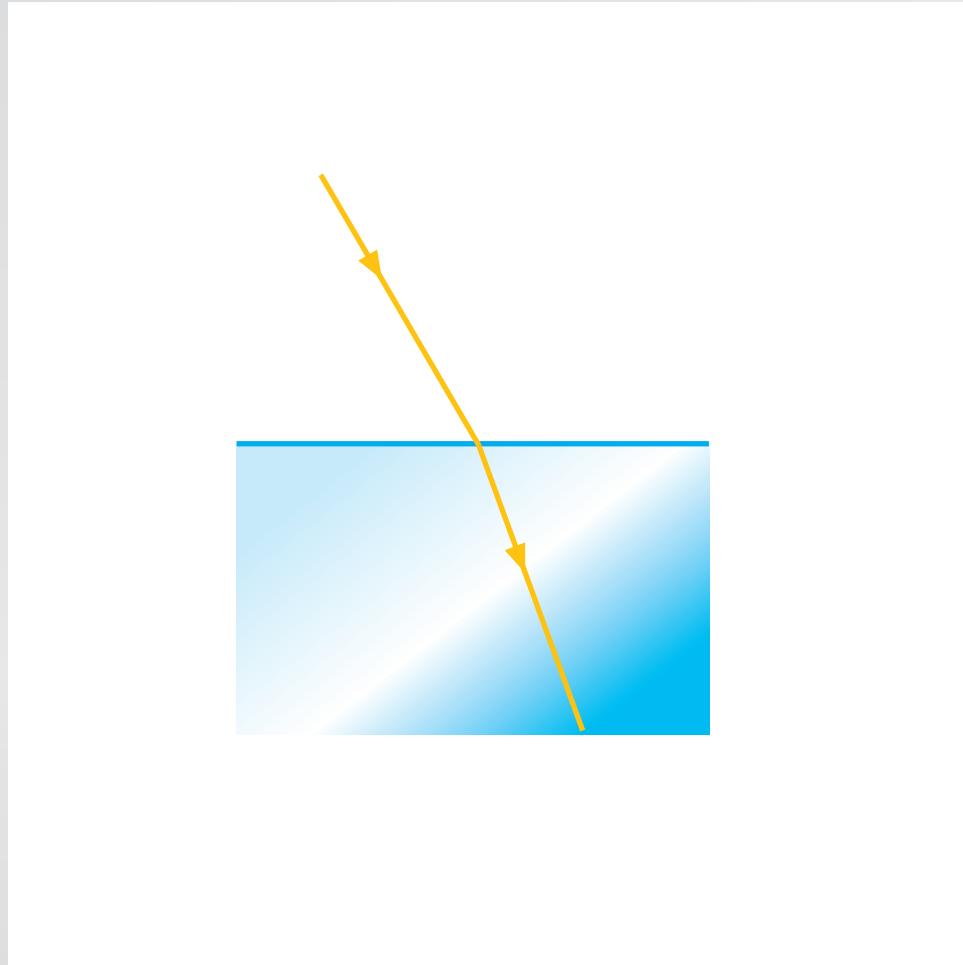
Waveguiding

The more angled the incident ray, the stronger the bending



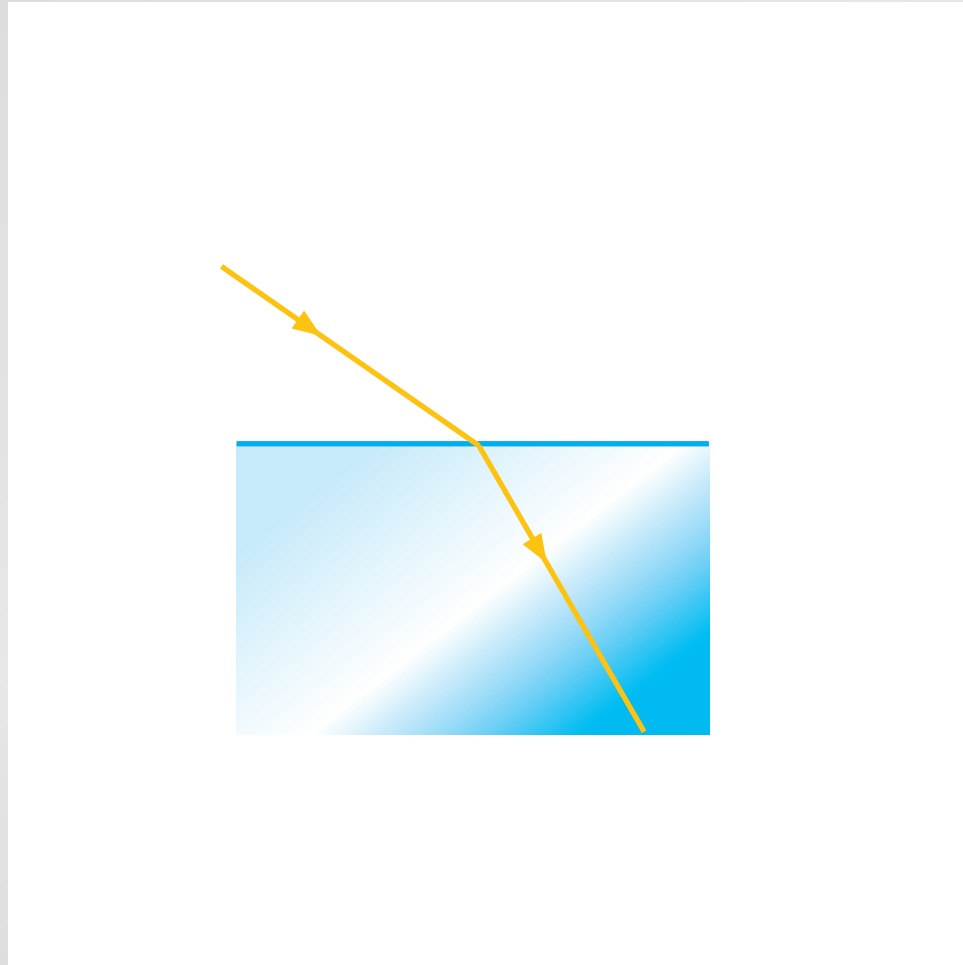
Waveguiding

The more angled the incident ray, the stronger the bending



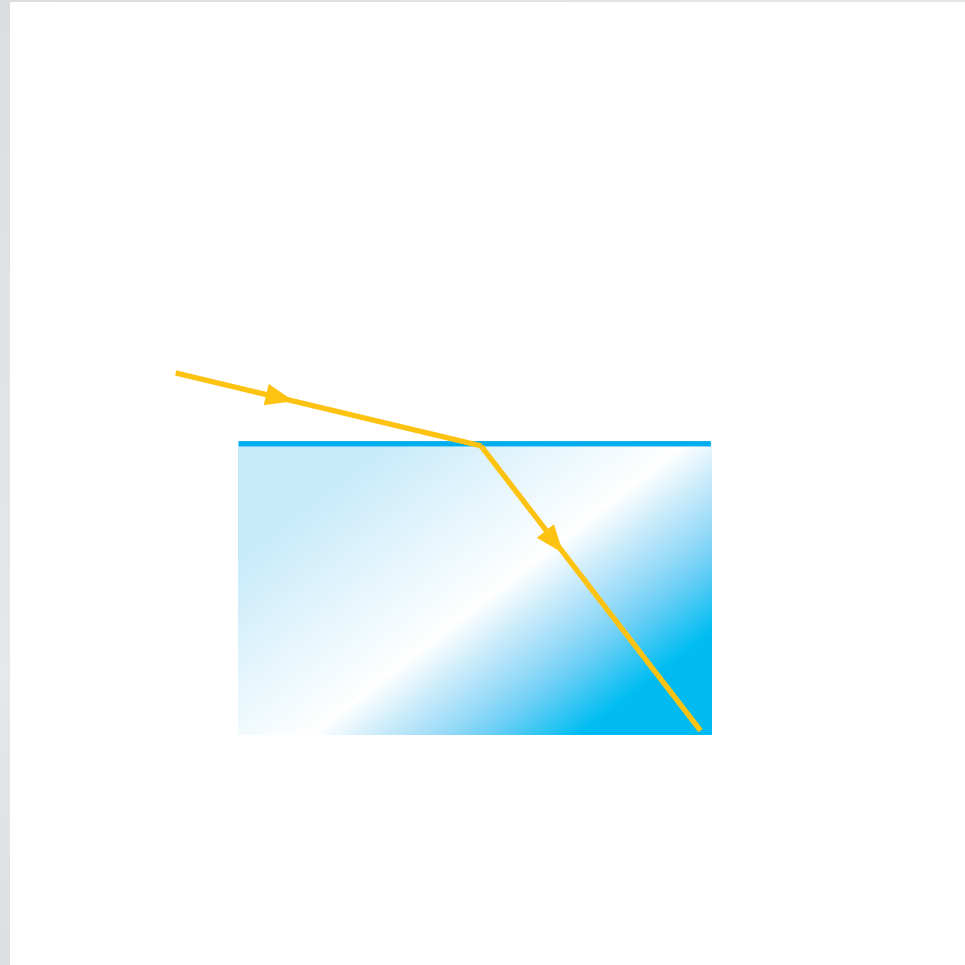
Waveguiding

The more angled the incident ray, the stronger the bending



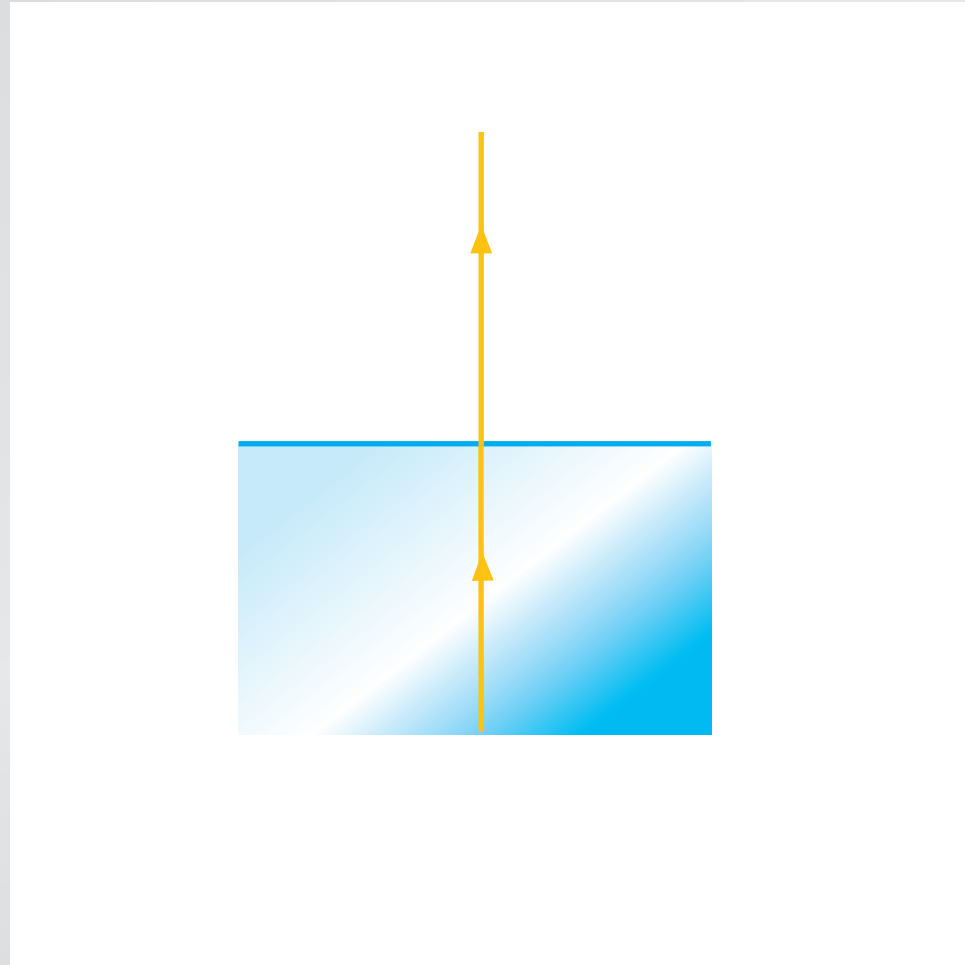
Waveguiding

The more angled the incident ray, the stronger the bending



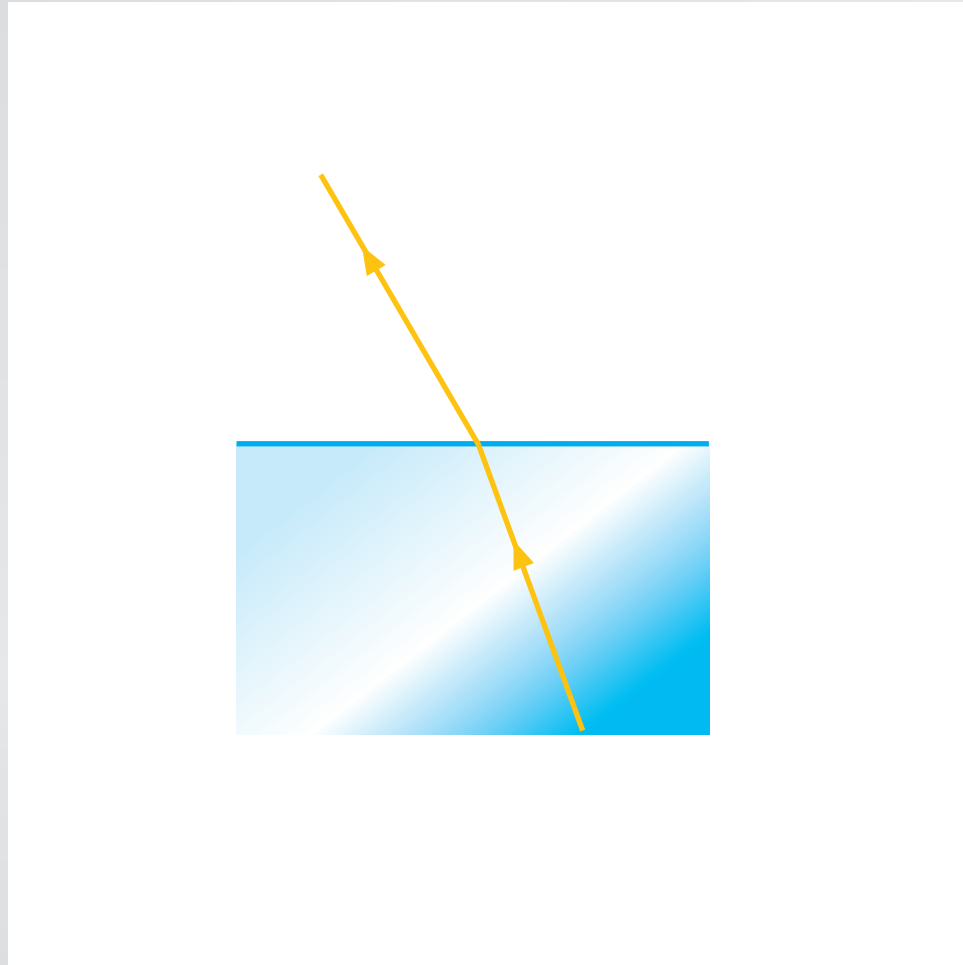
Waveguiding

The amount of bending is the same in reverse



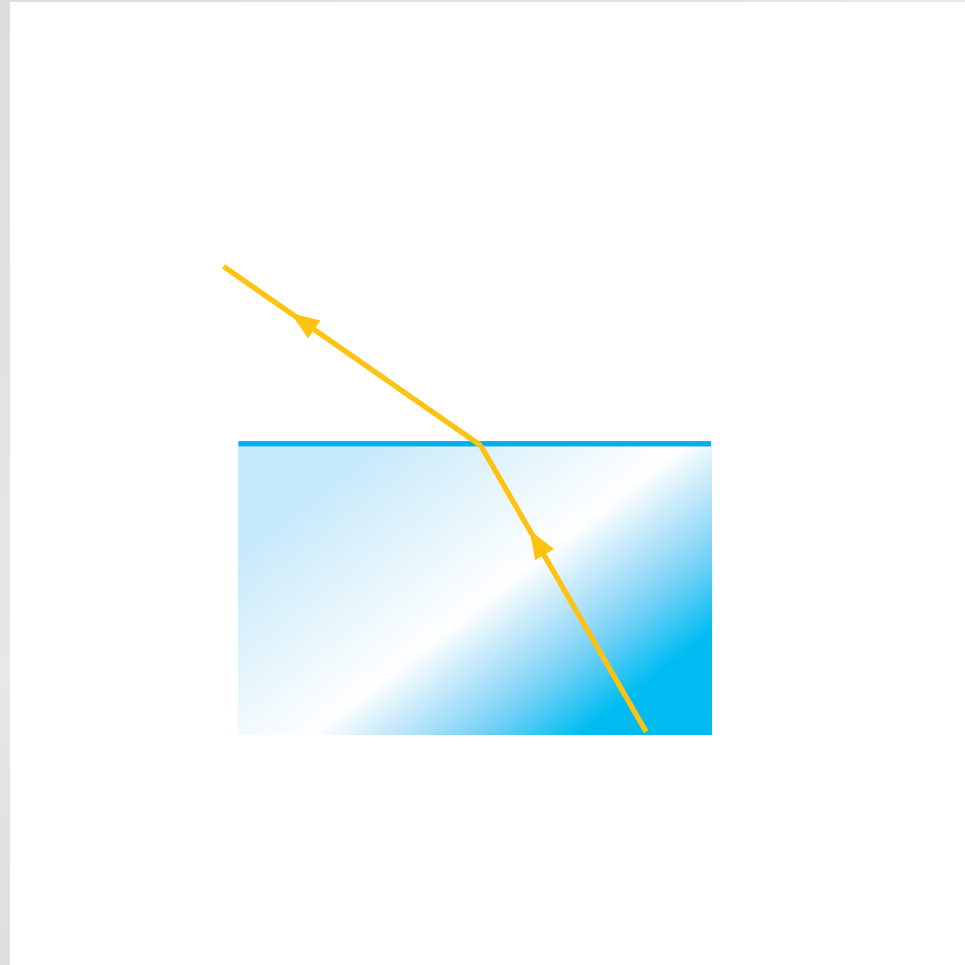
Waveguiding

The amount of bending is the same in reverse



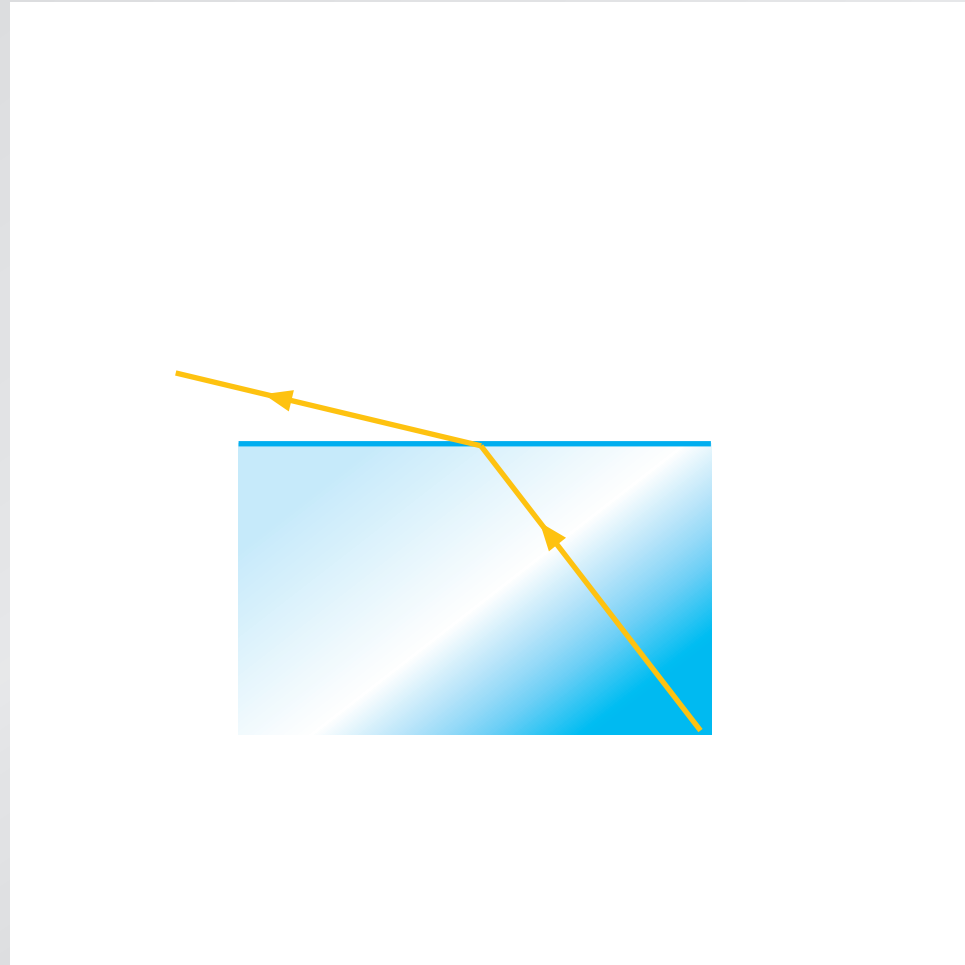
Waveguiding

The amount of bending is the same in reverse



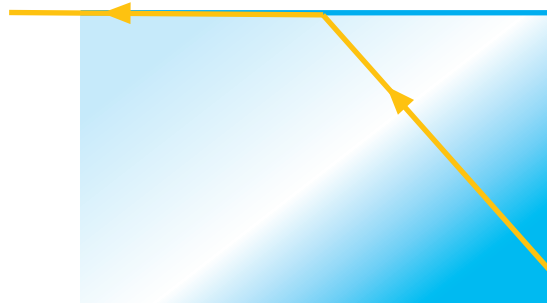
Waveguiding

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



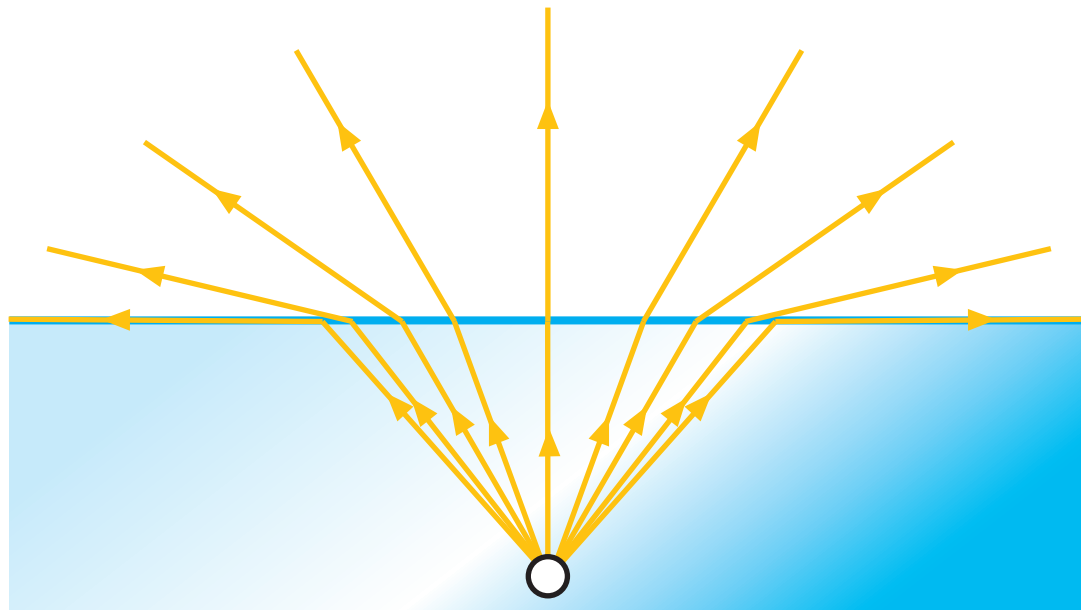
Waveguiding

seeing underwater



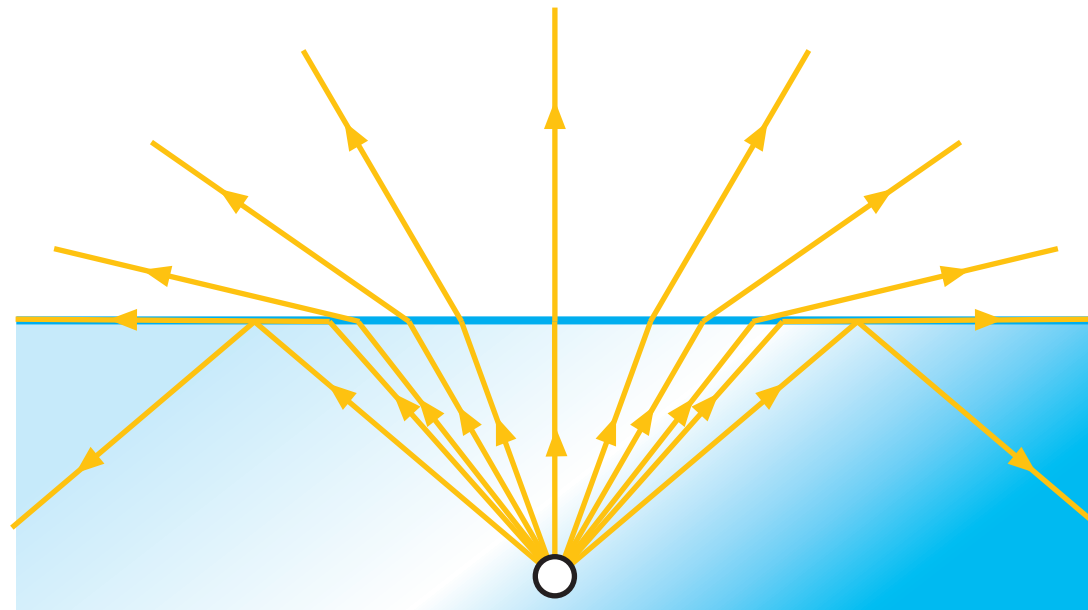
Waveguiding

seeing underwater



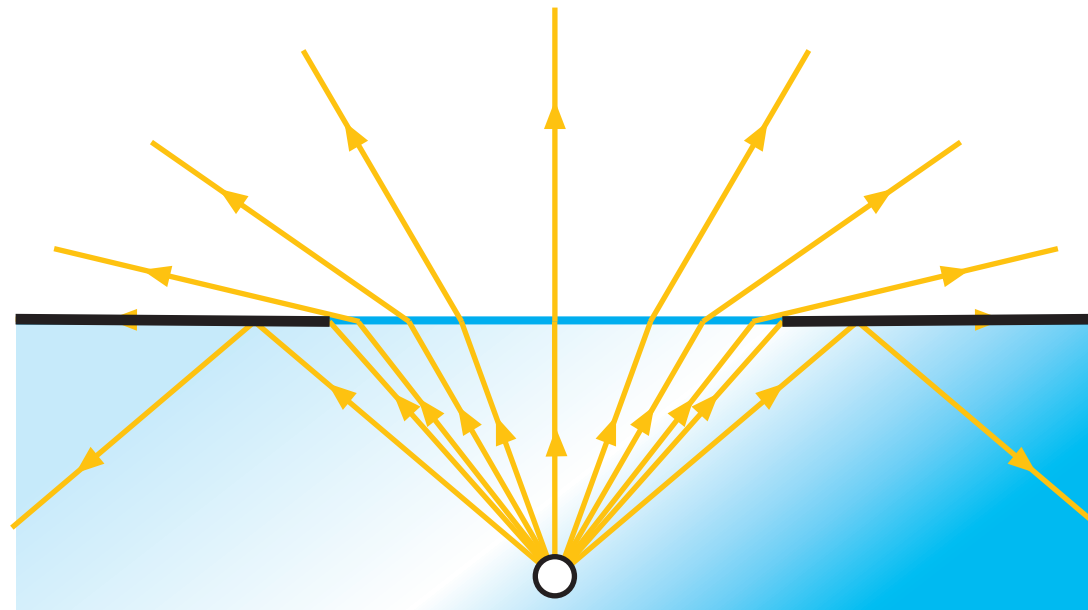
Waveguiding

seeing underwater



Waveguiding

surface looks like mirror with a circular hole



Waveguiding



Waveguiding



Waveguiding



Waveguiding

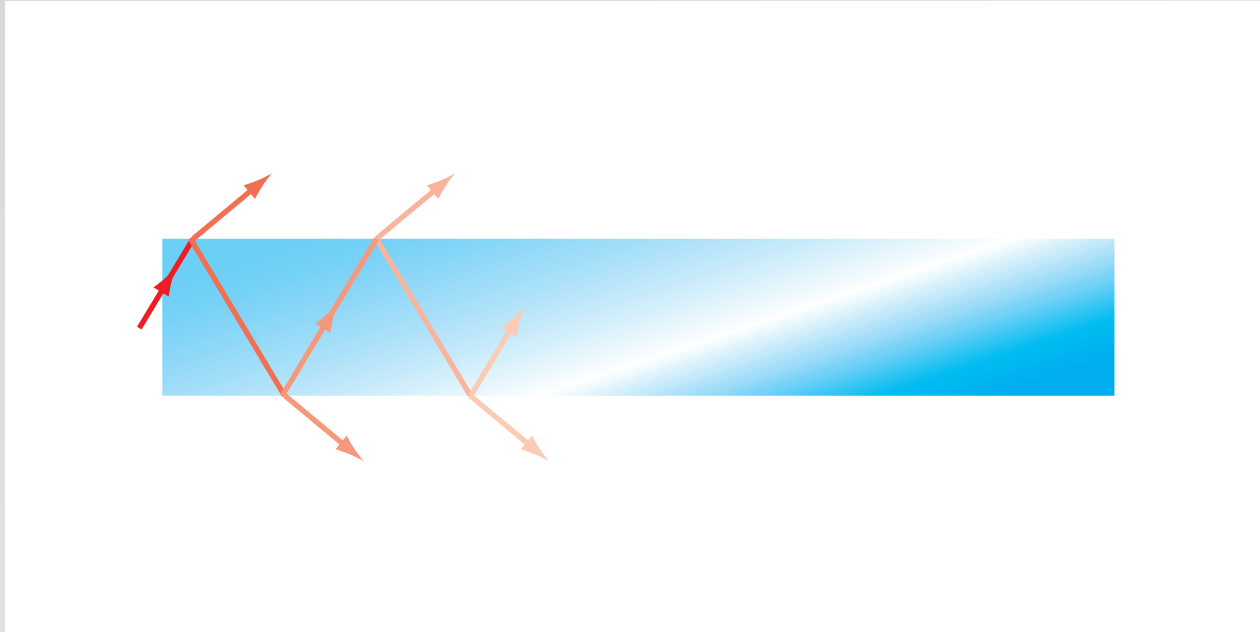


Waveguiding



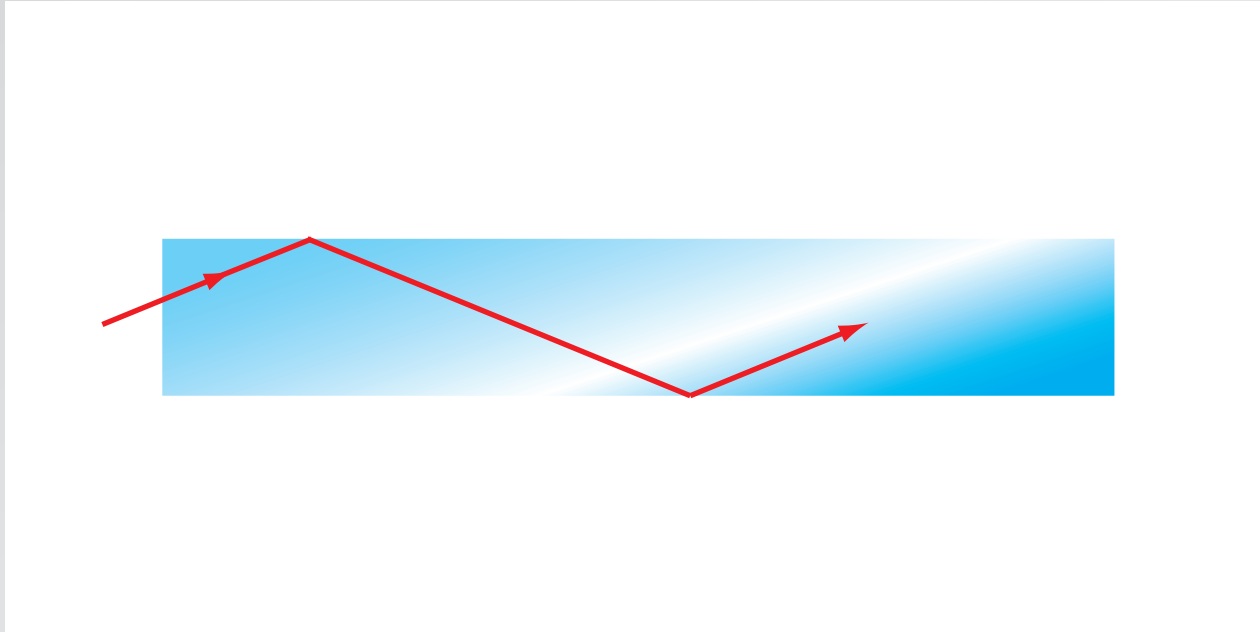
now consider a planar dielectric waveguide

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

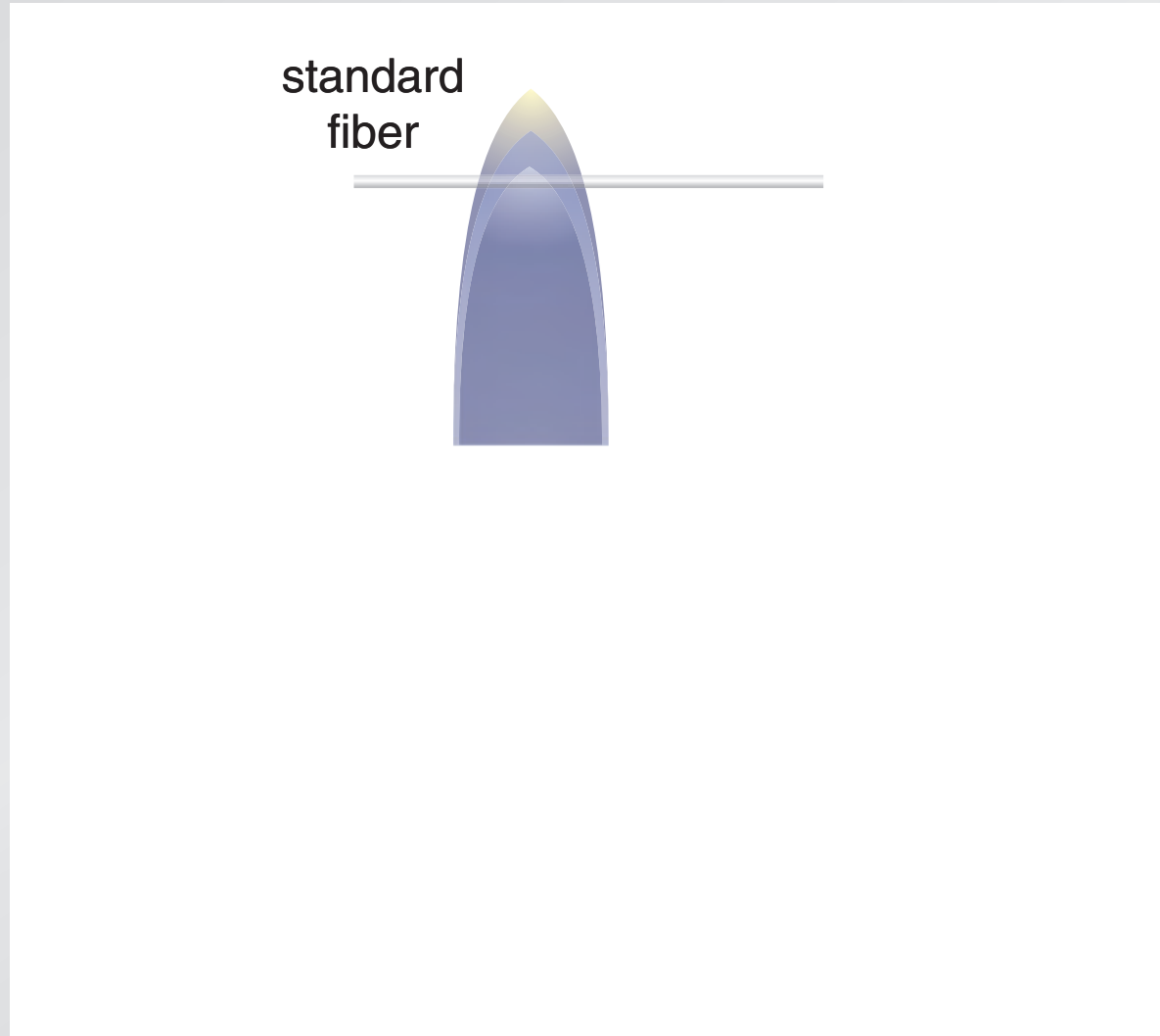
two-step drawing process

standard
fiber



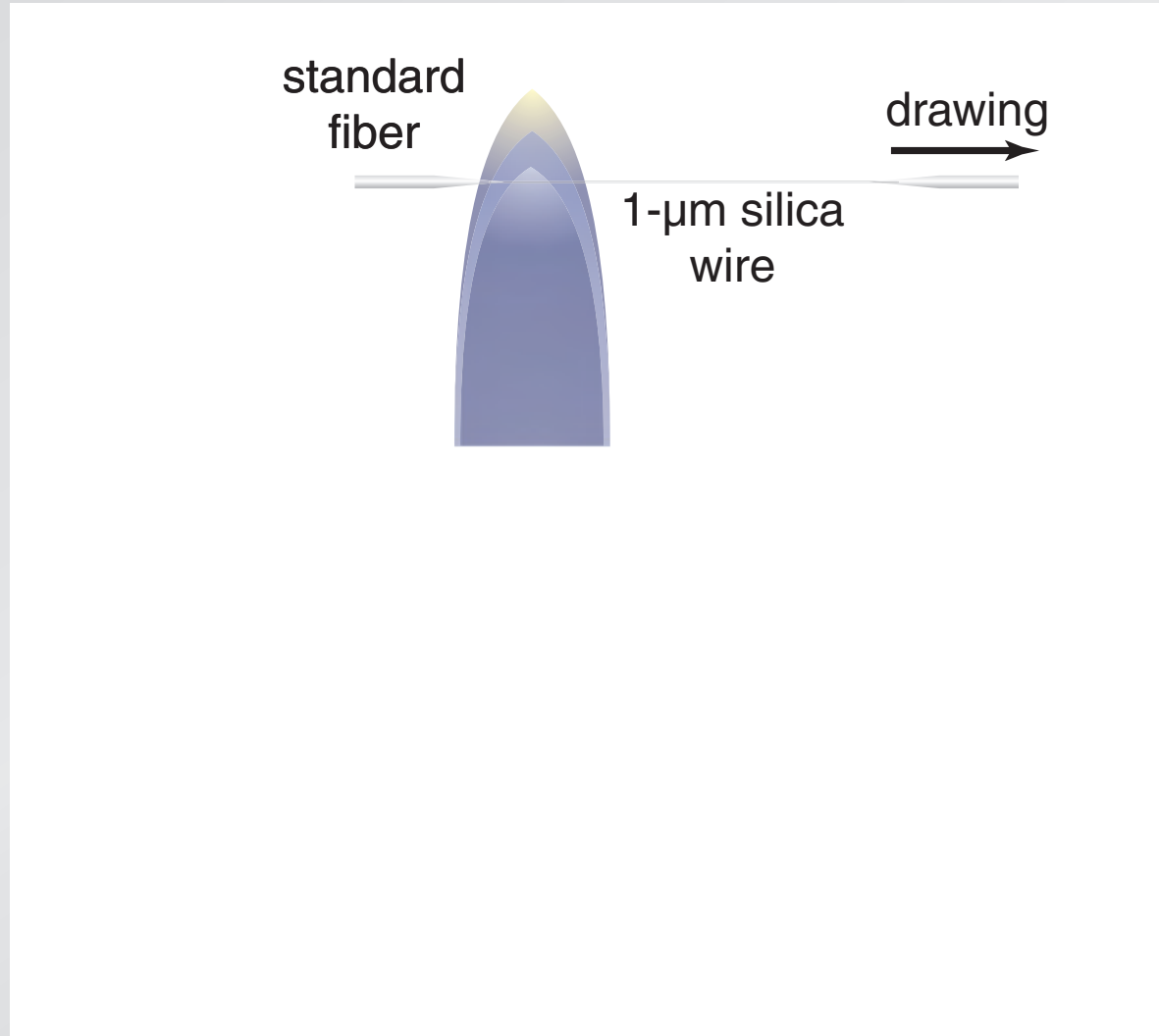
Nanowire fabrication

two-step drawing process



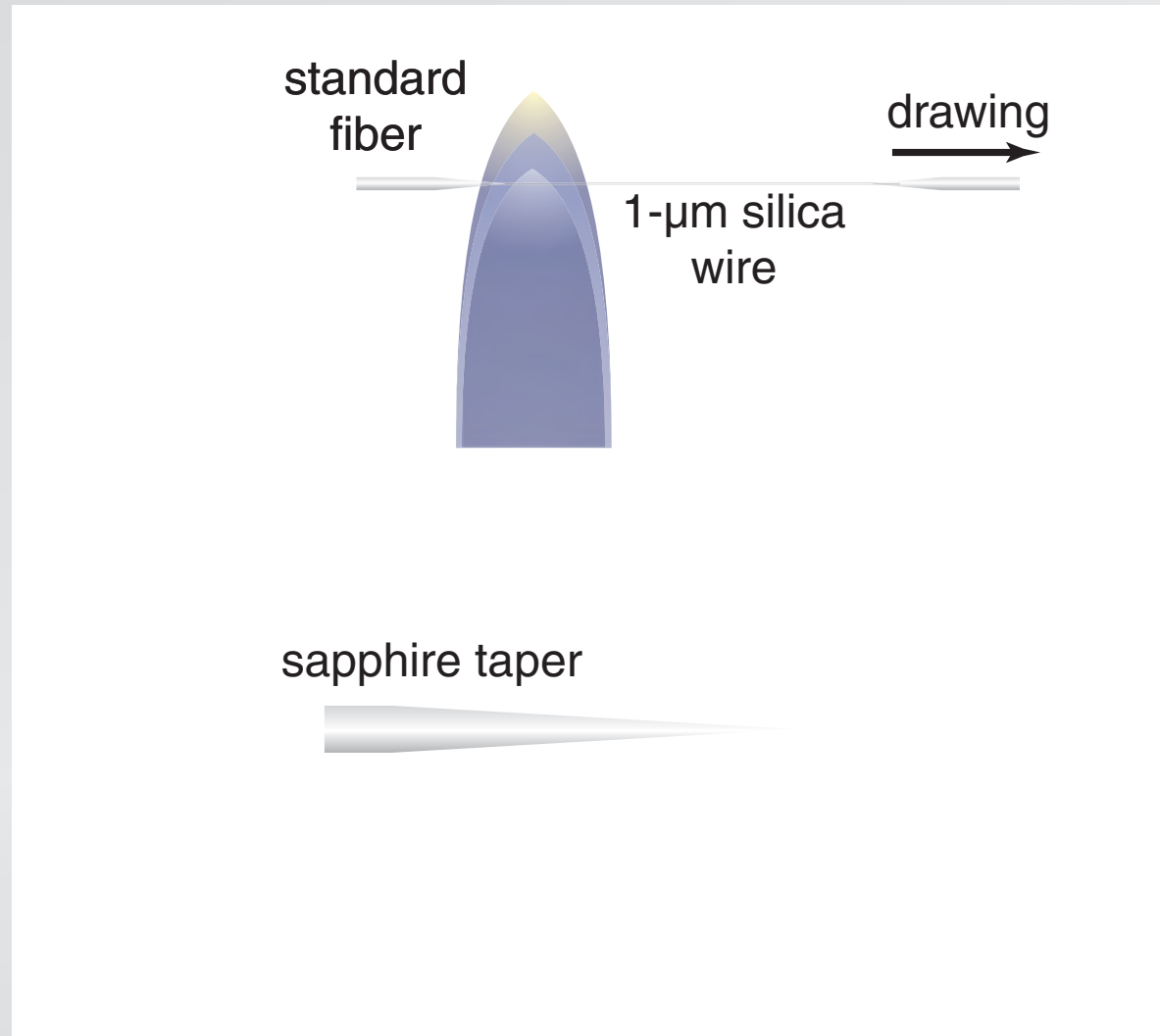
Nanowire fabrication

two-step drawing process



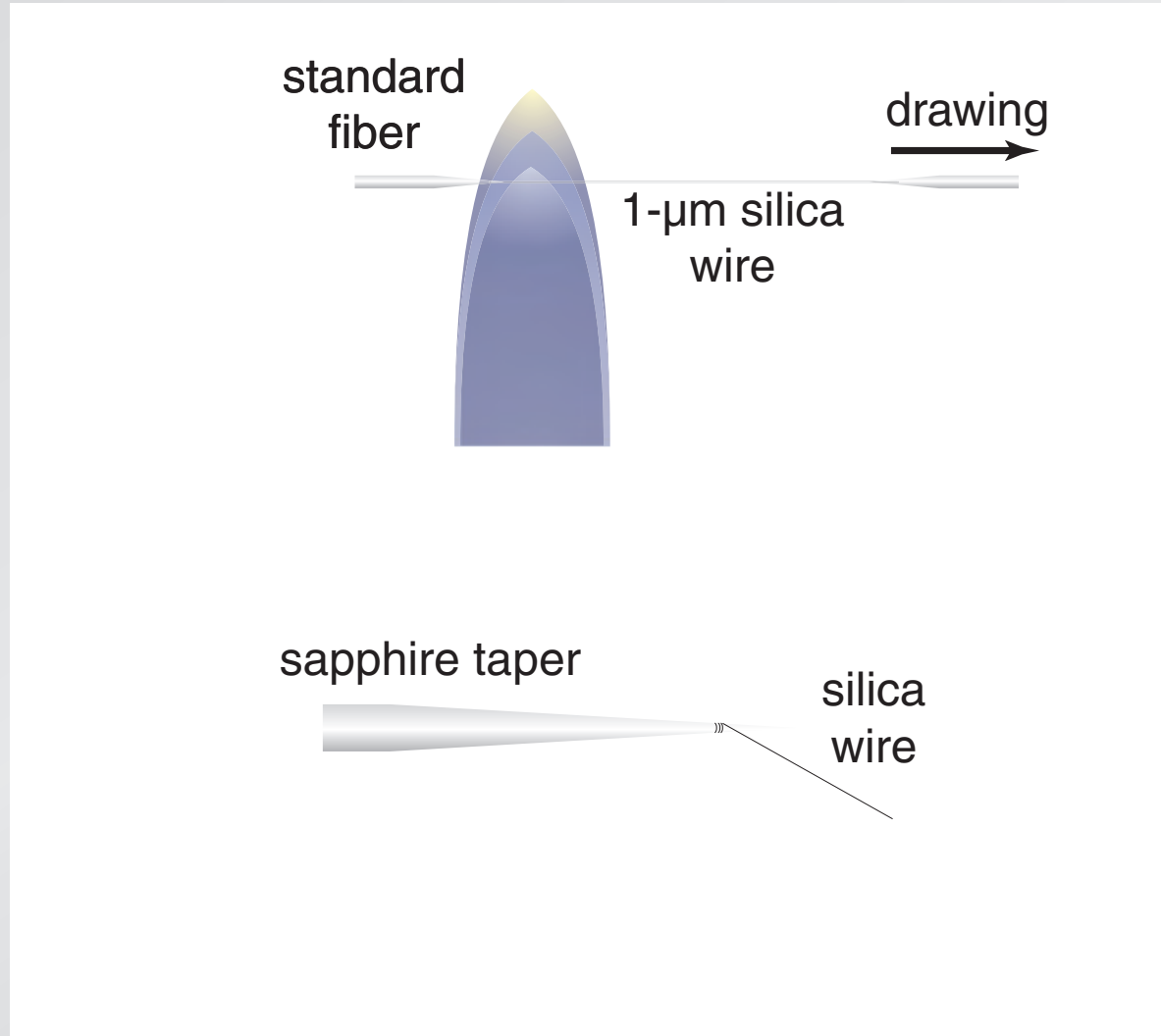
Nanowire fabrication

two-step drawing process



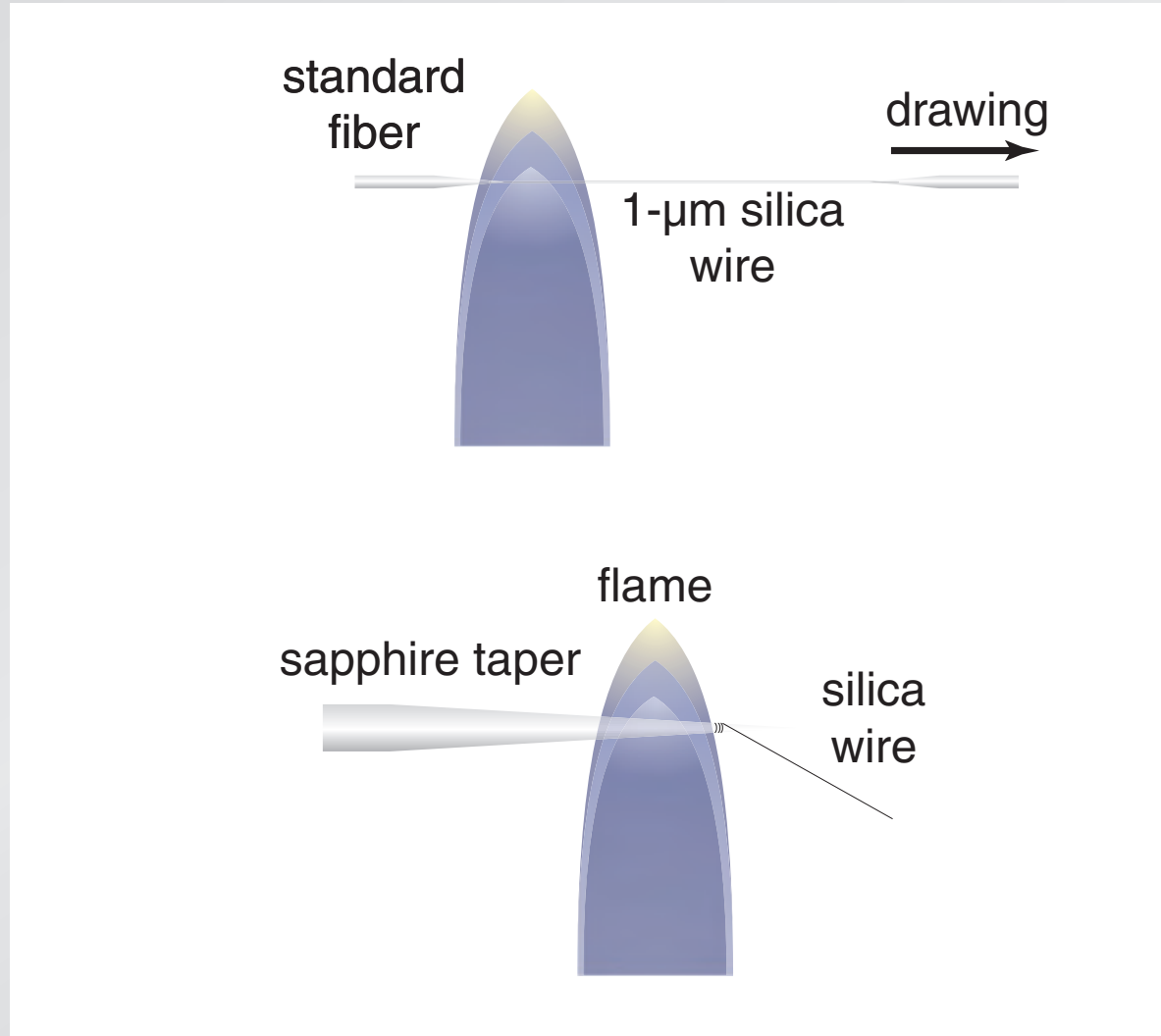
Nanowire fabrication

two-step drawing process



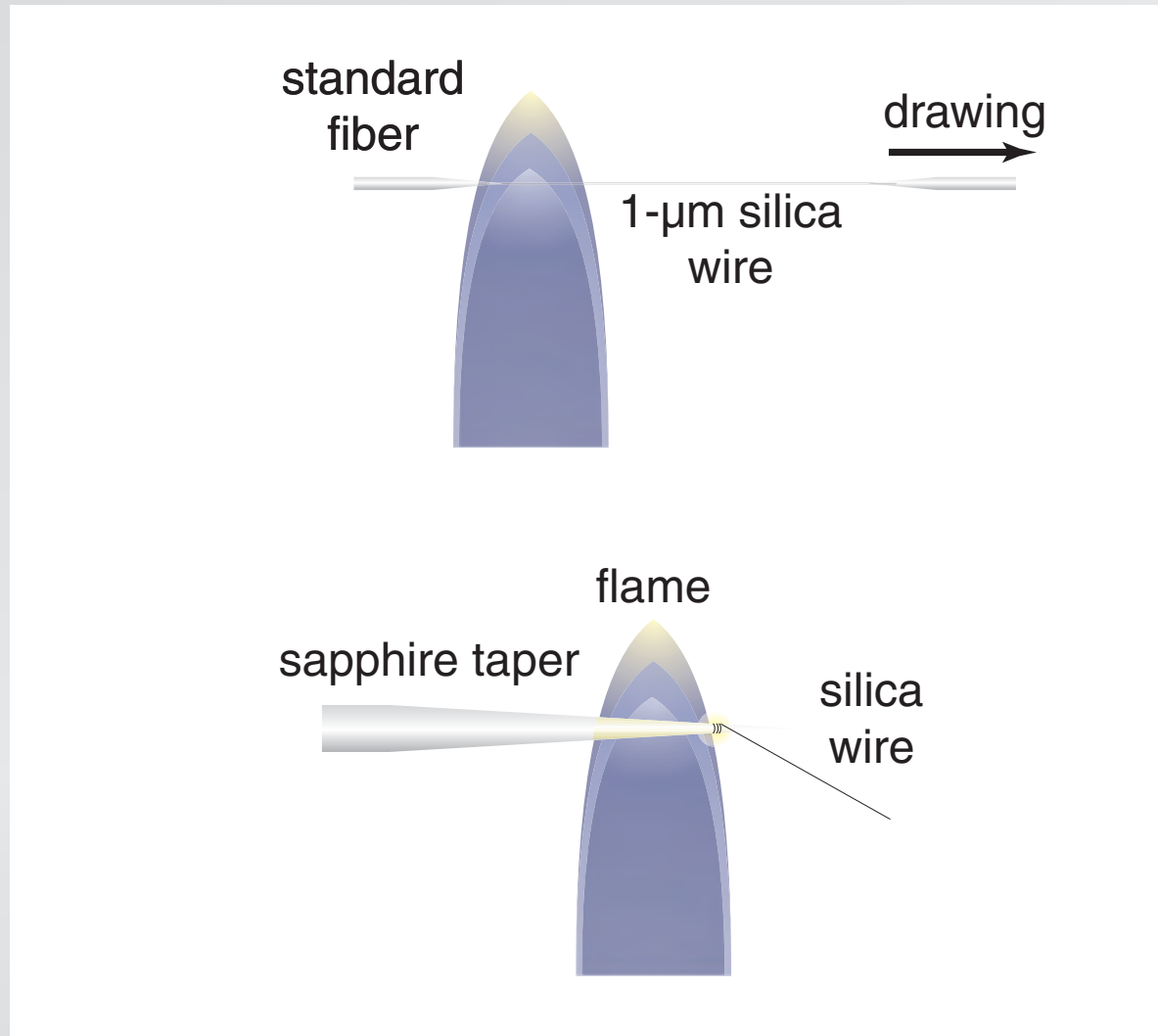
Nanowire fabrication

two-step drawing process



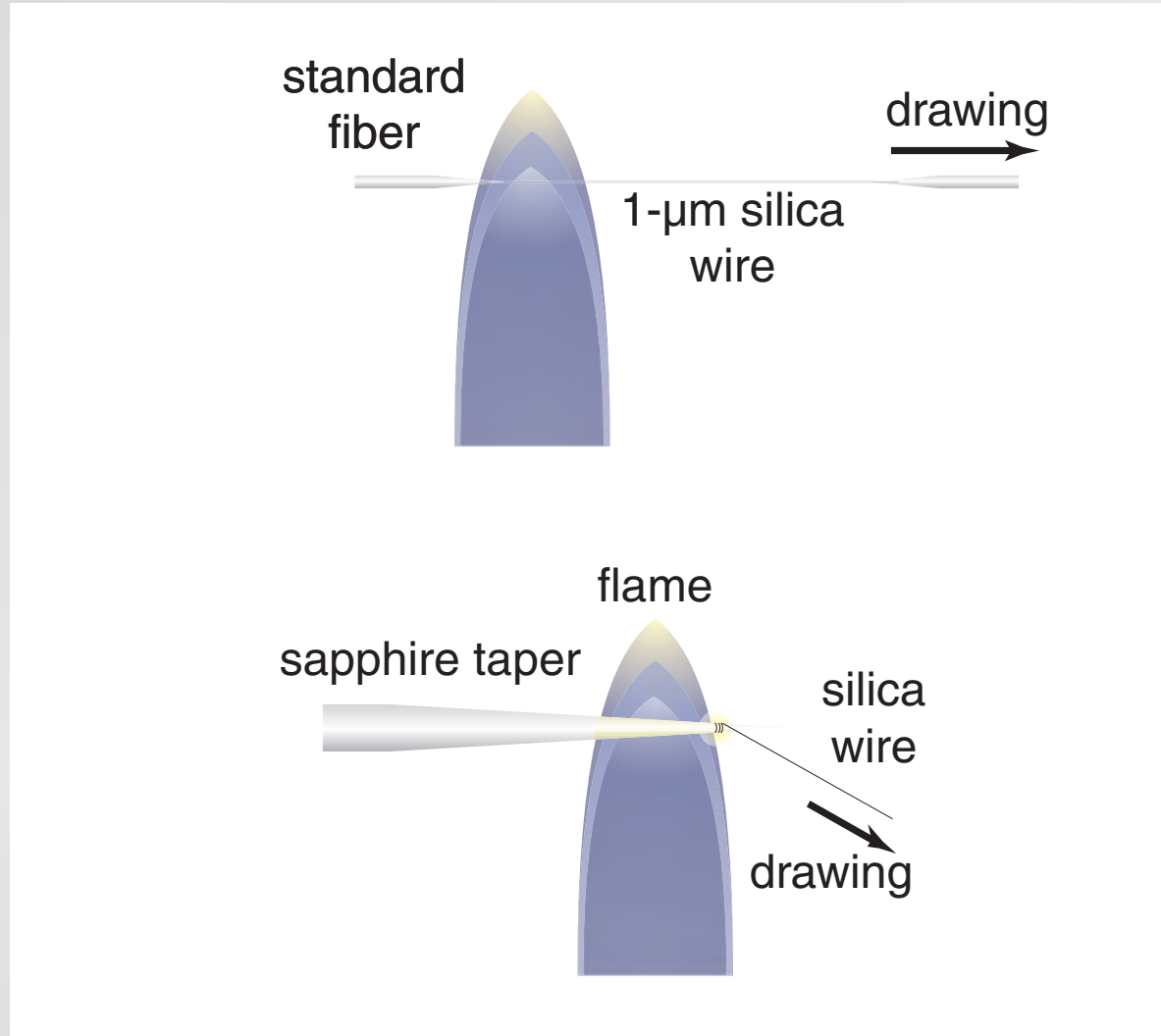
Nanowire fabrication

two-step drawing process



Nanowire fabrication

two-step drawing process



Nanowire fabrication



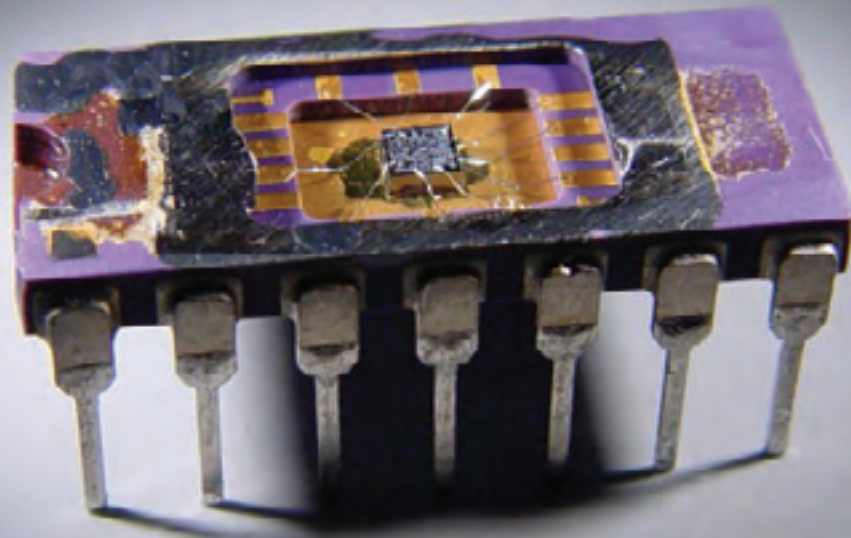
Nanowire fabrication

1 μm

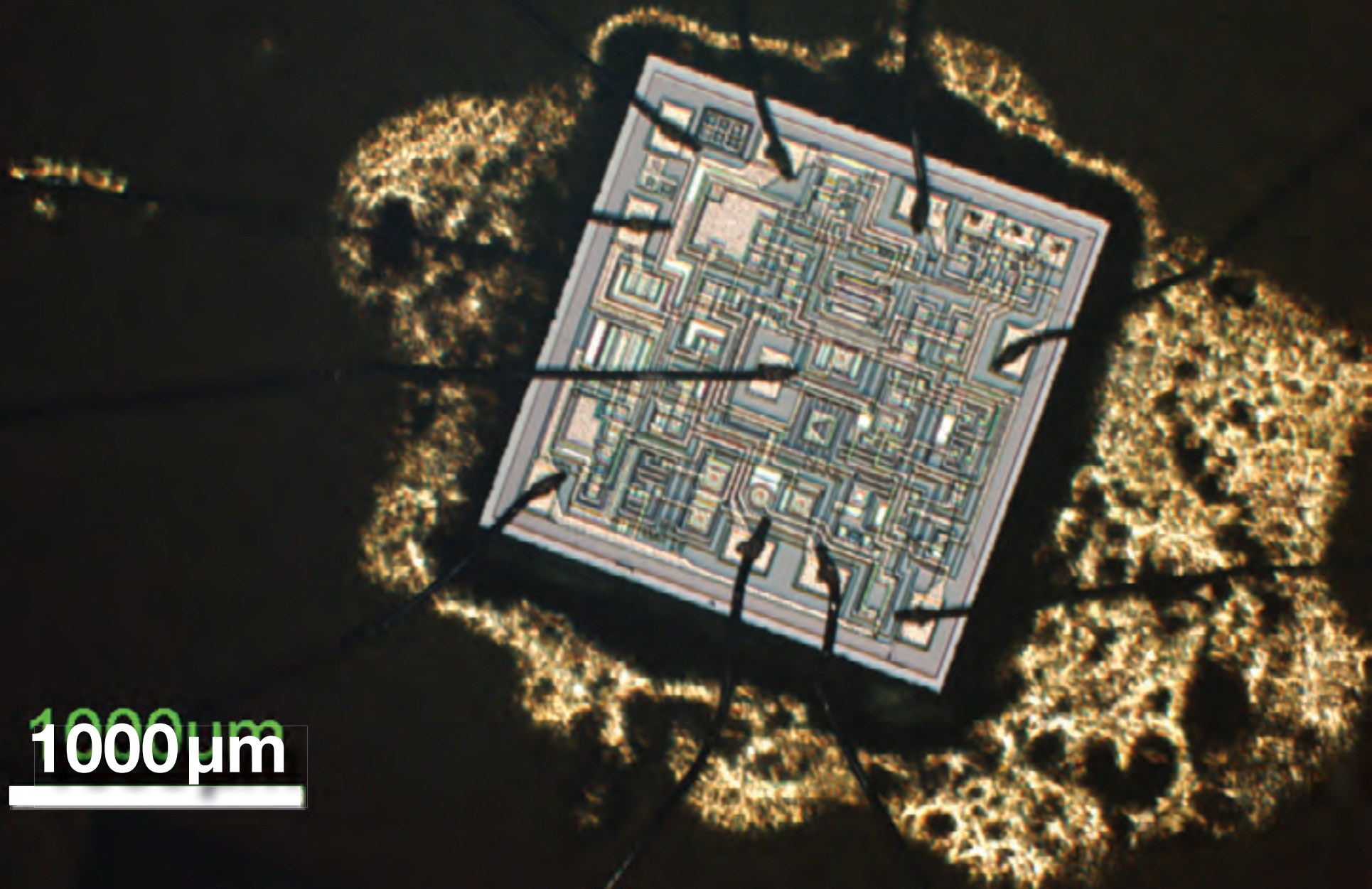


Nature, 426, 816 (2003)

Nanowire fabrication



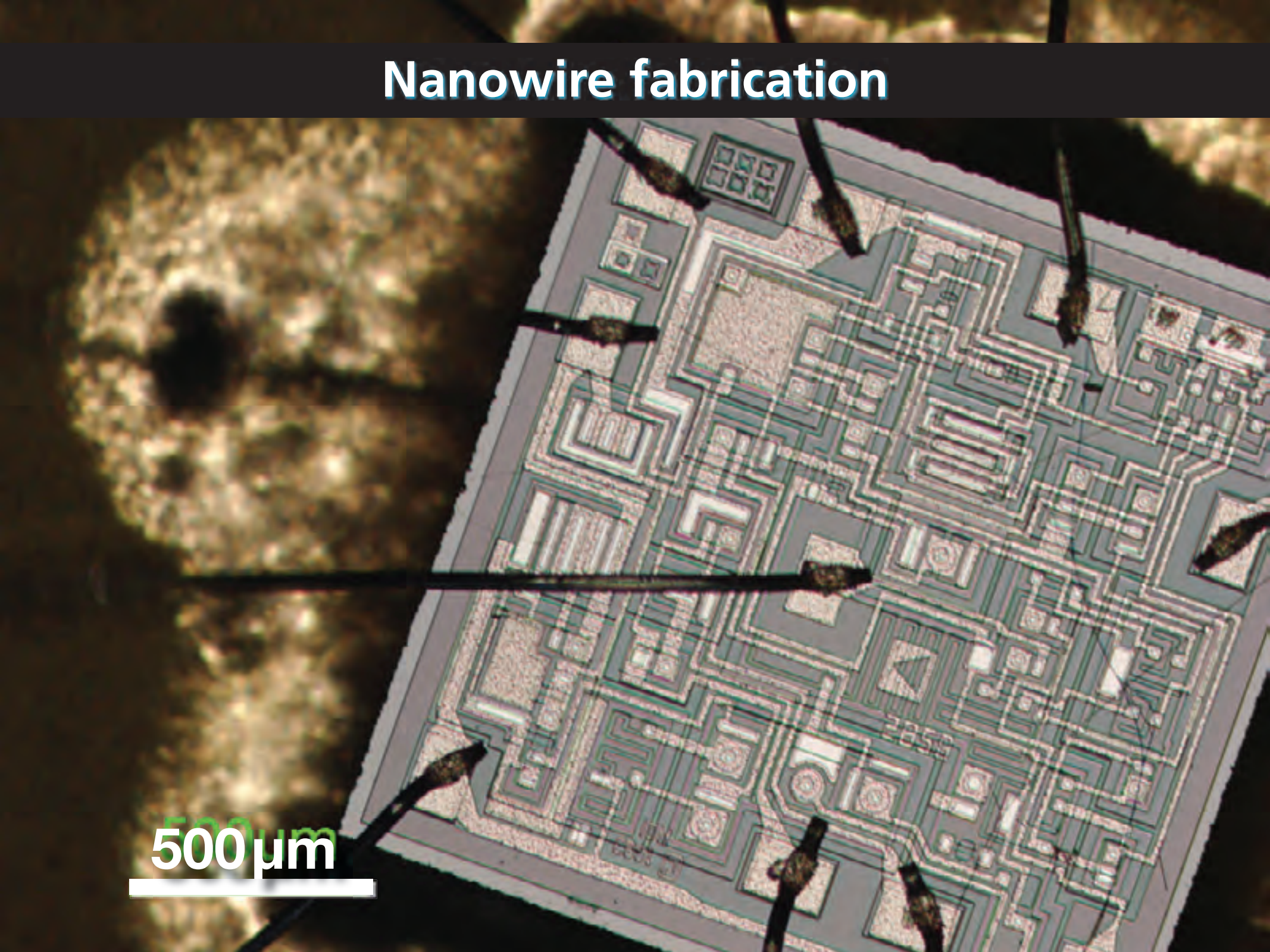
Nanowire fabrication



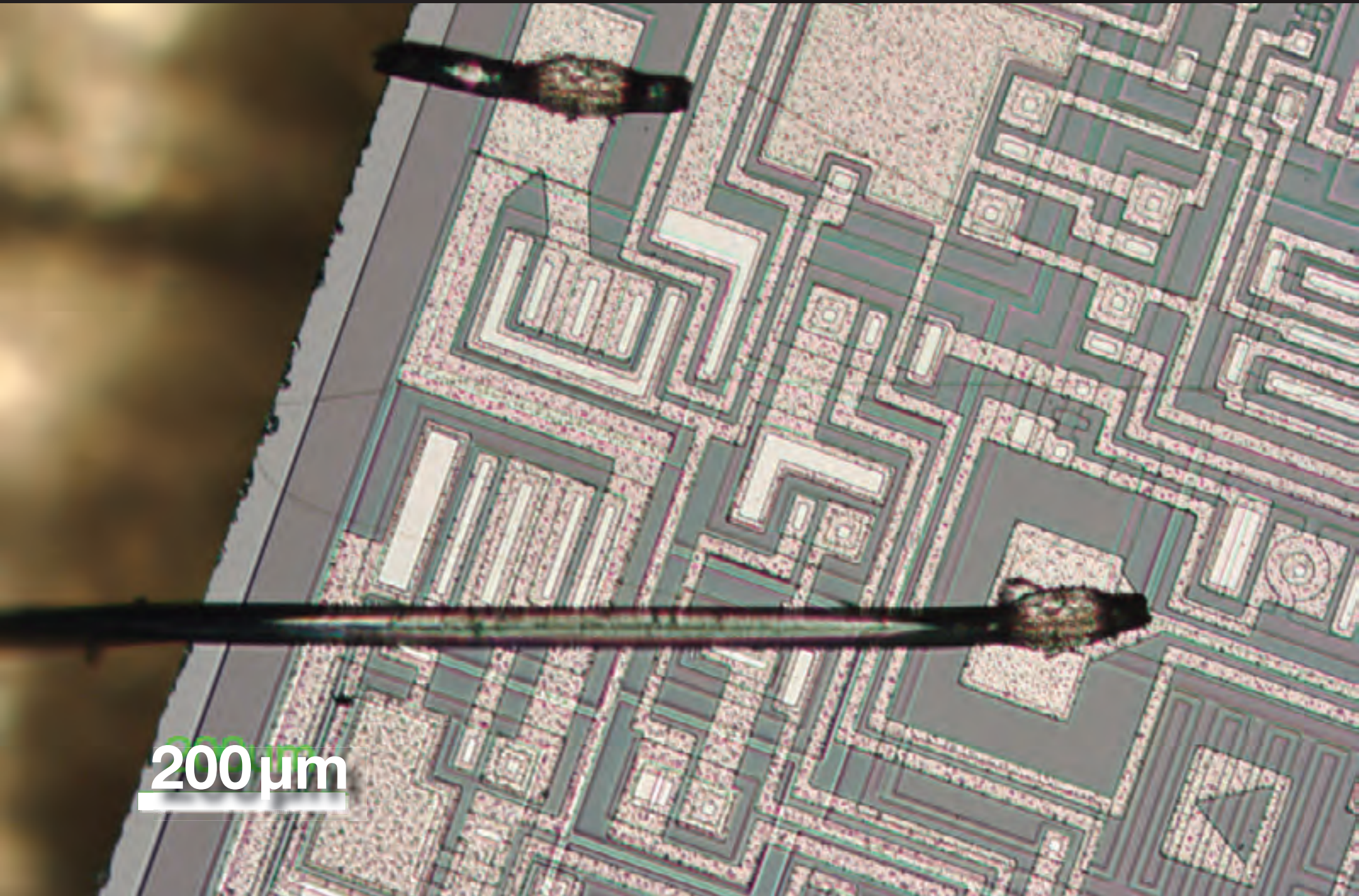
1000 μm

Nanowire fabrication

500 μm

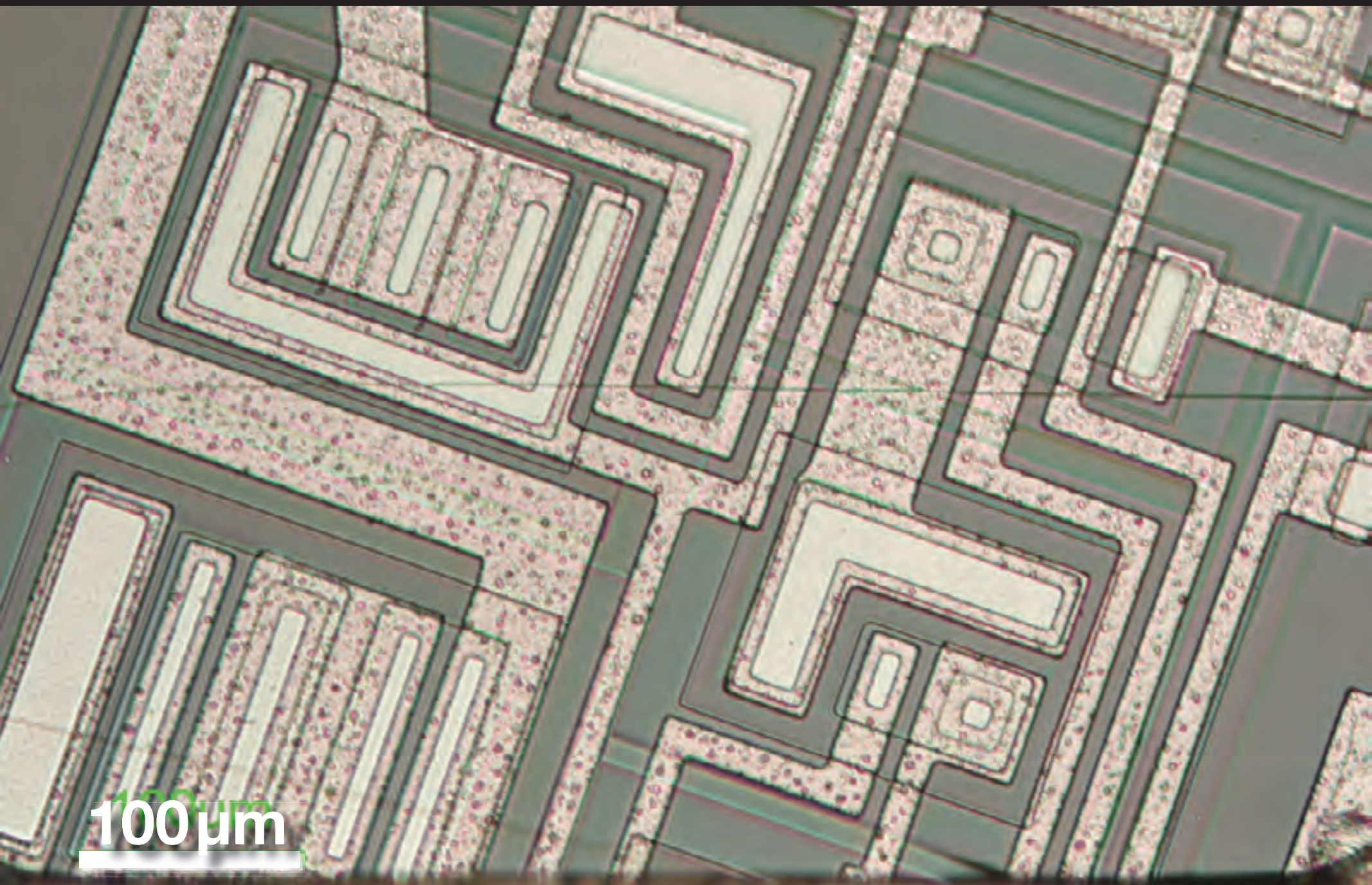


Nanowire fabrication

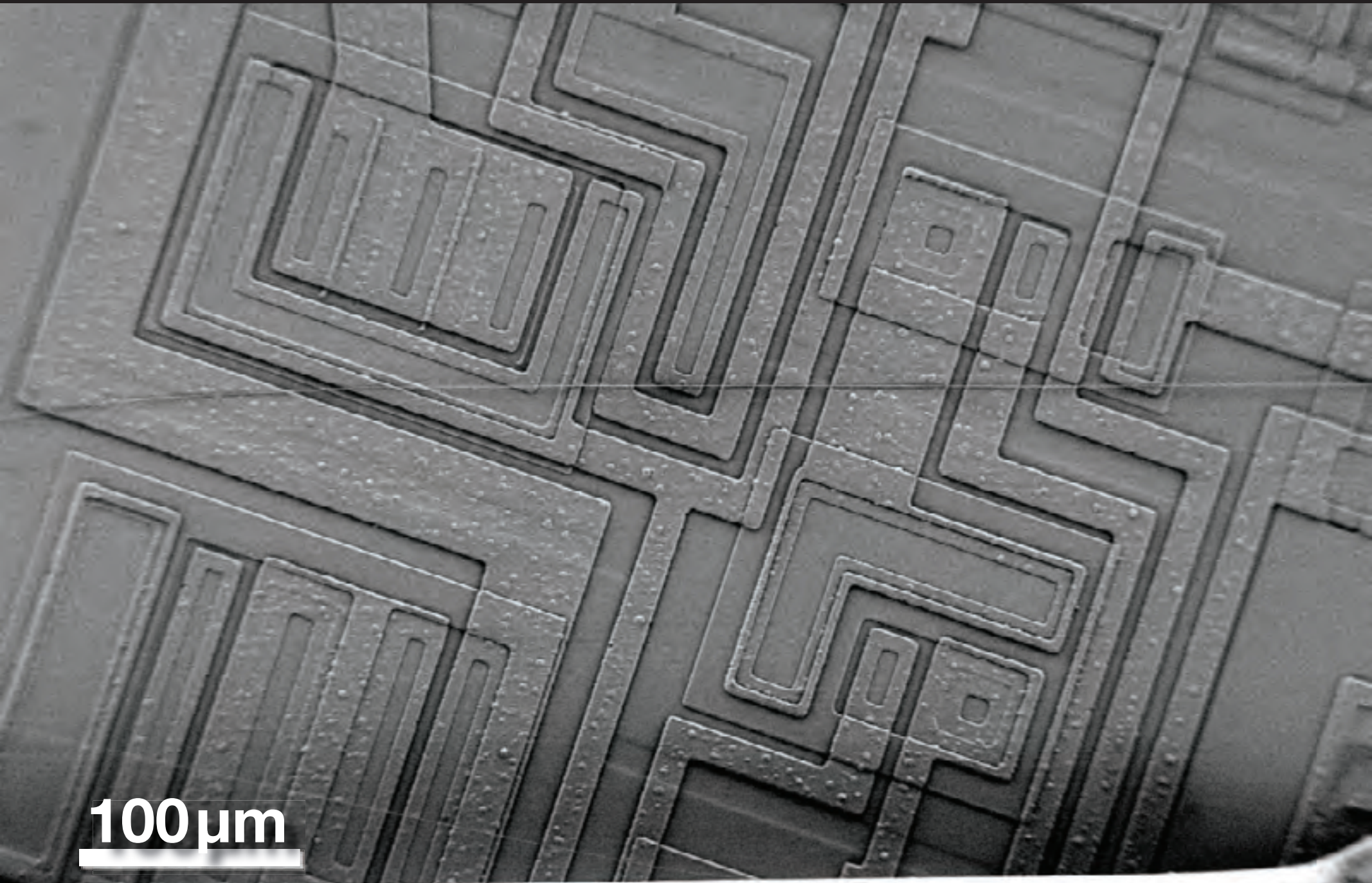


200 μm

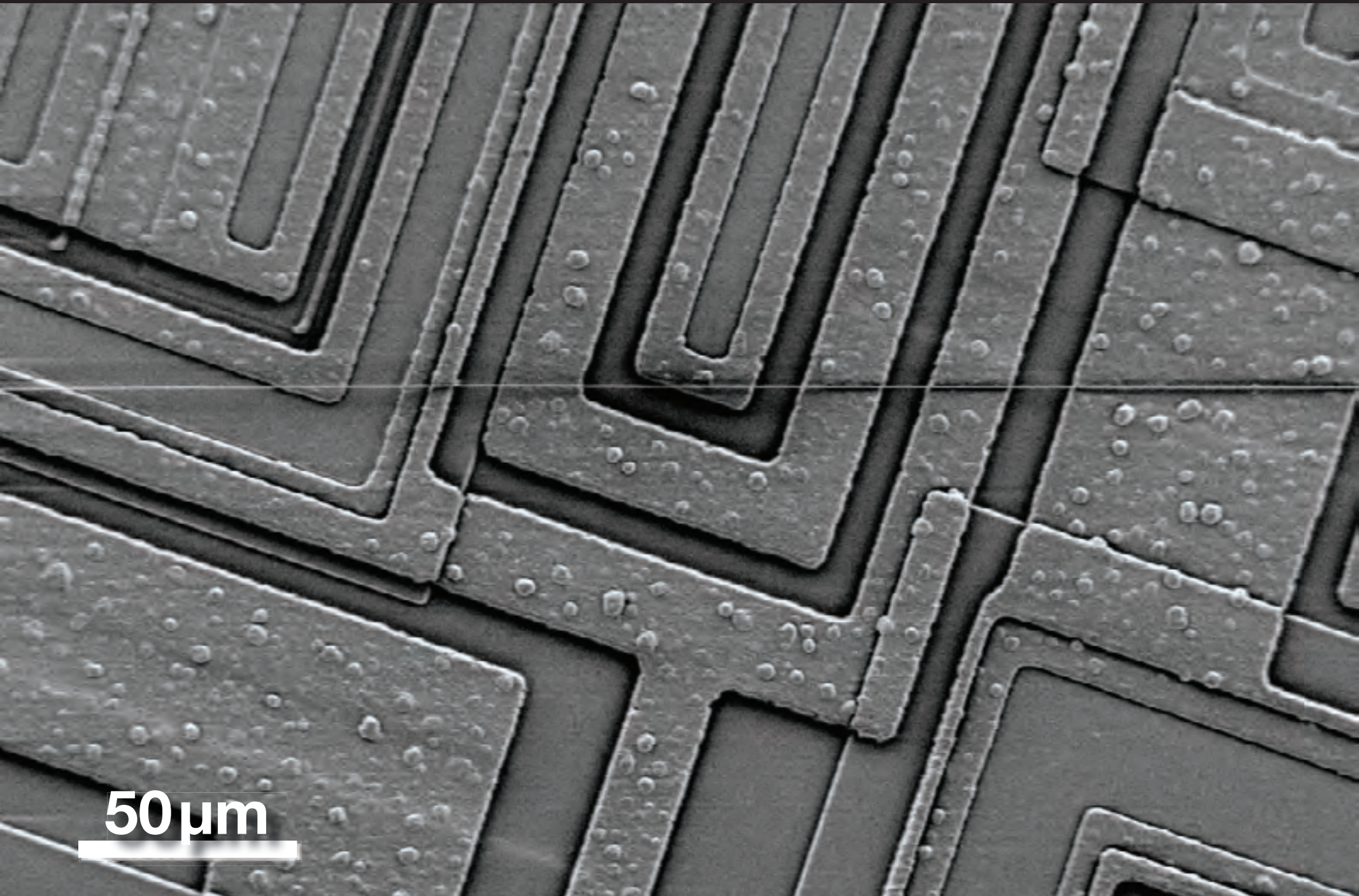
Nanowire fabrication



Nanowire fabrication

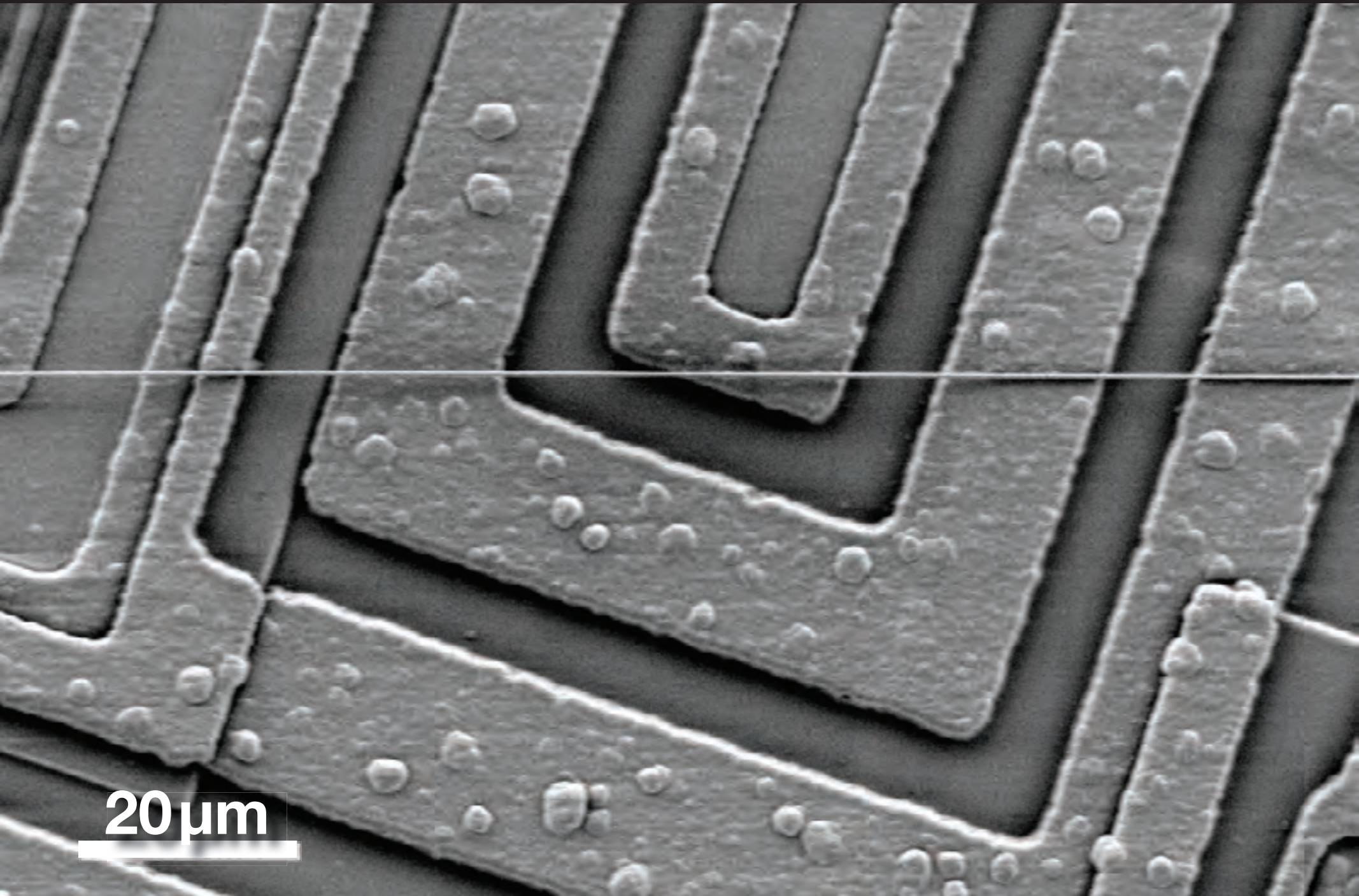


Nanowire fabrication



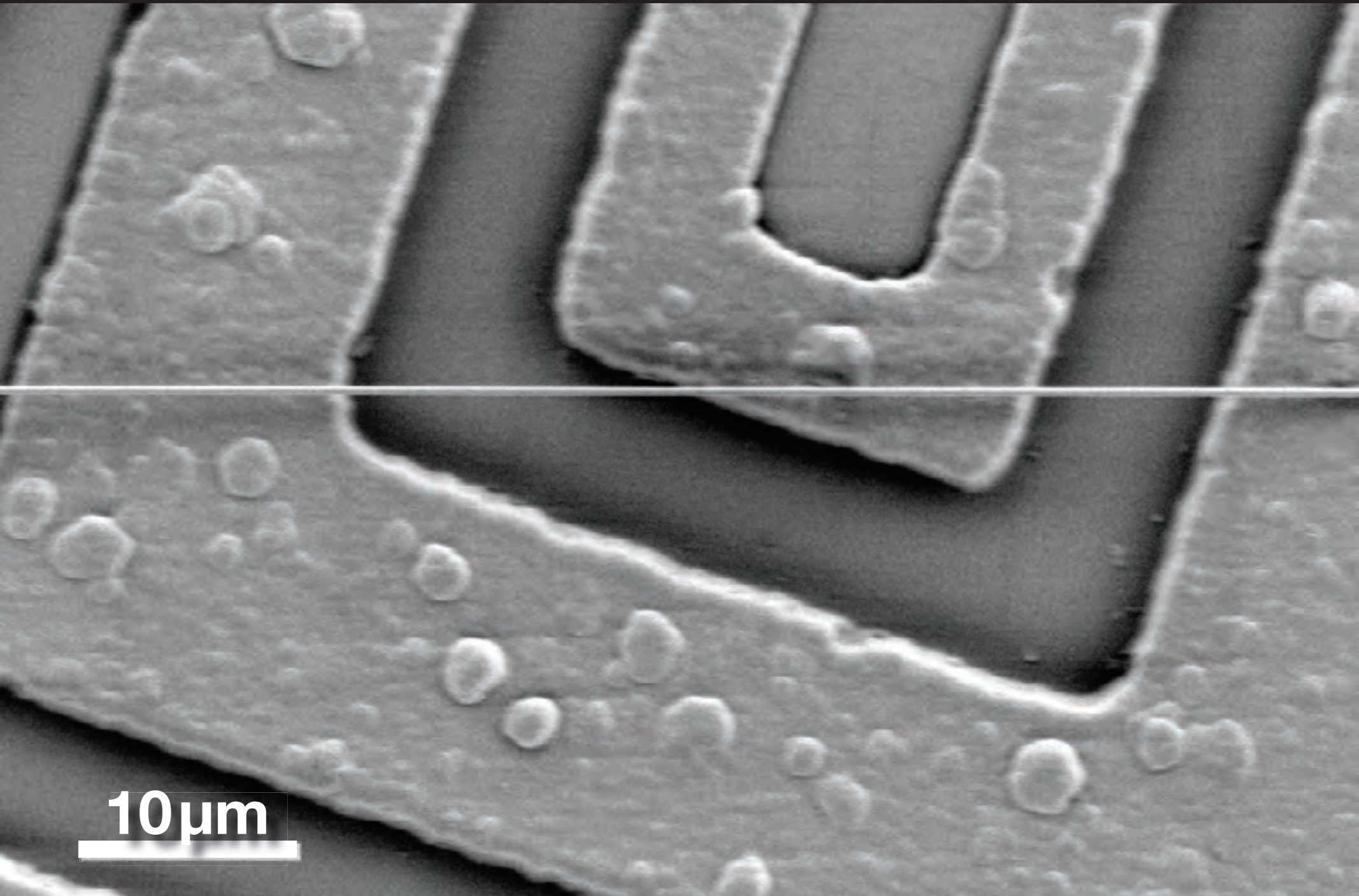
50 μm

Nanowire fabrication



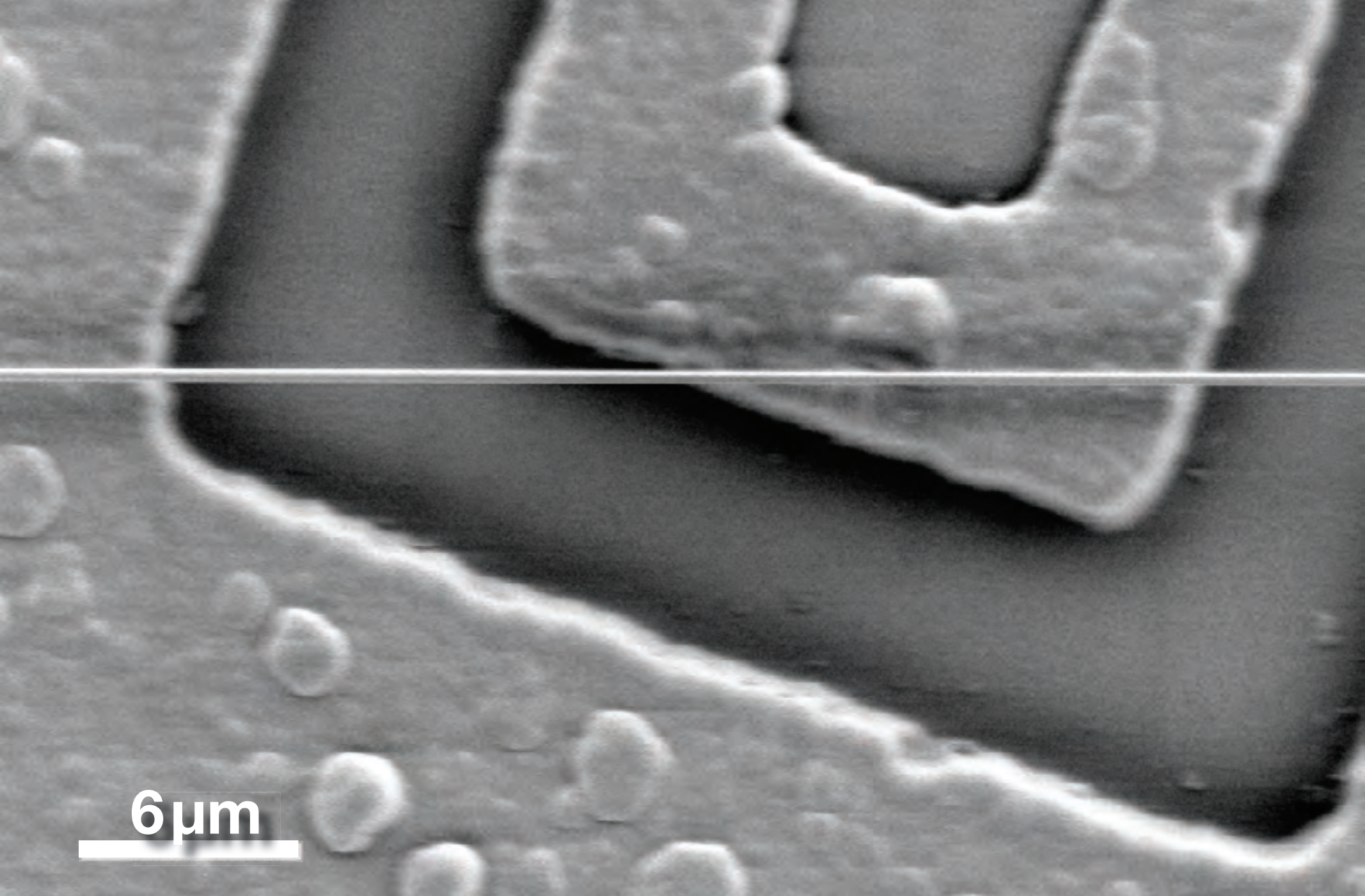
20 μm

Nanowire fabrication



10 μm

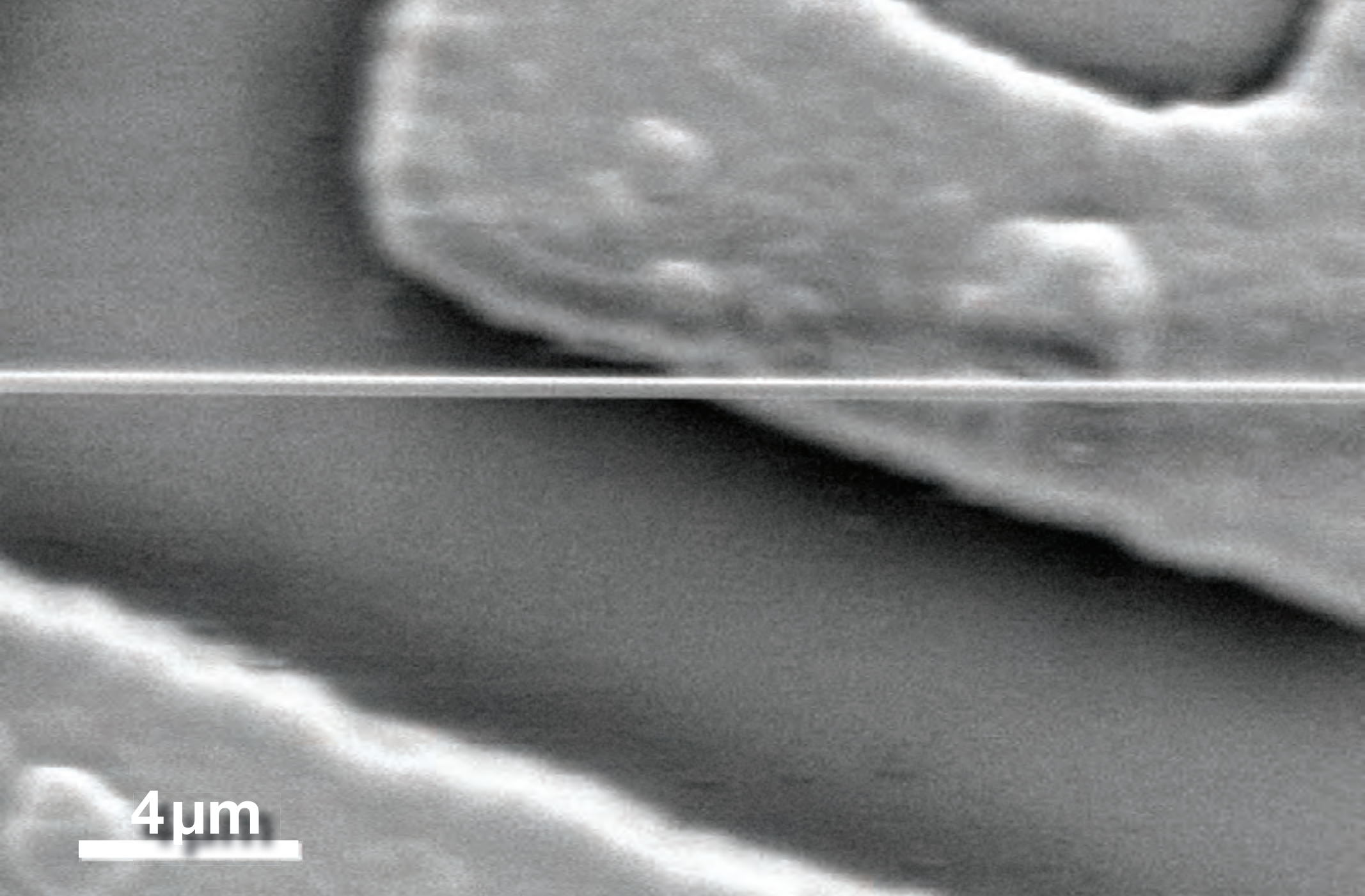
Nanowire fabrication



6 μm



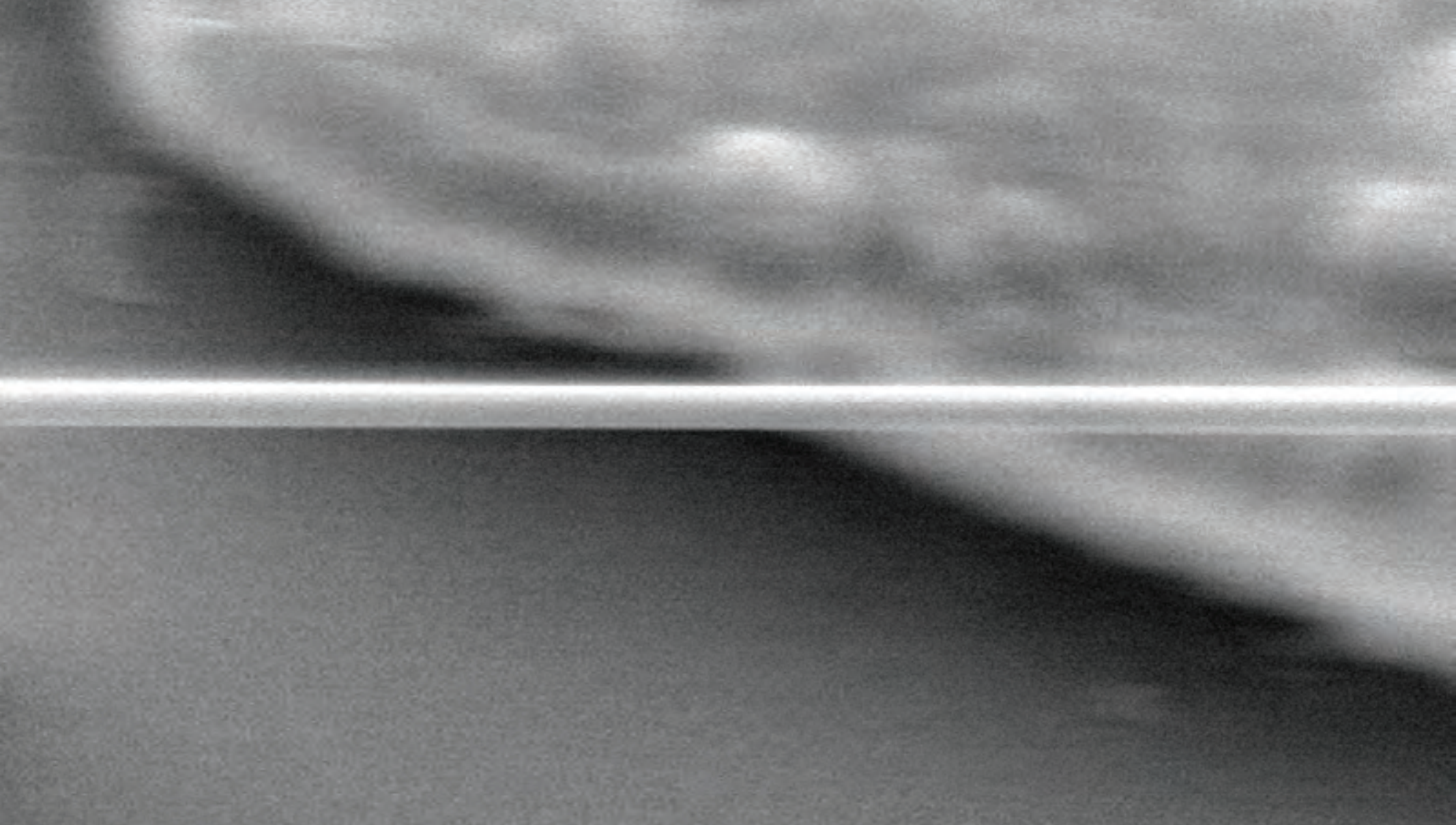
Nanowire fabrication



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 line with a horizontal crossbar at its base is drawn across the center of the nanowire to indicate its diameter. The background is a dark, grainy texture.

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

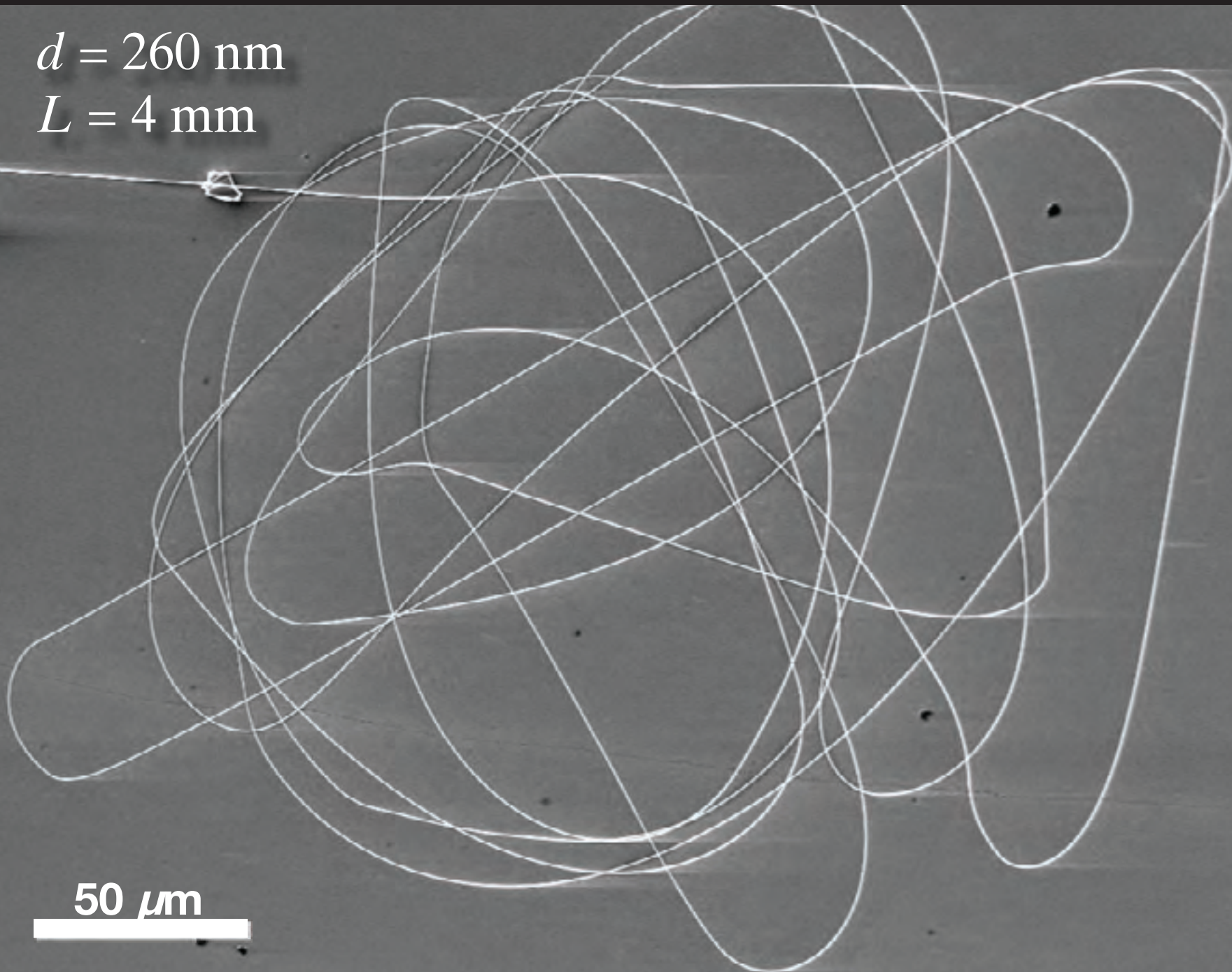
aspect ratio D/L : up to 10^6

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



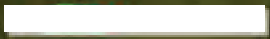
Nanowire fabrication

bend to
breaking point



Nanowire fabrication

bend to
breaking point

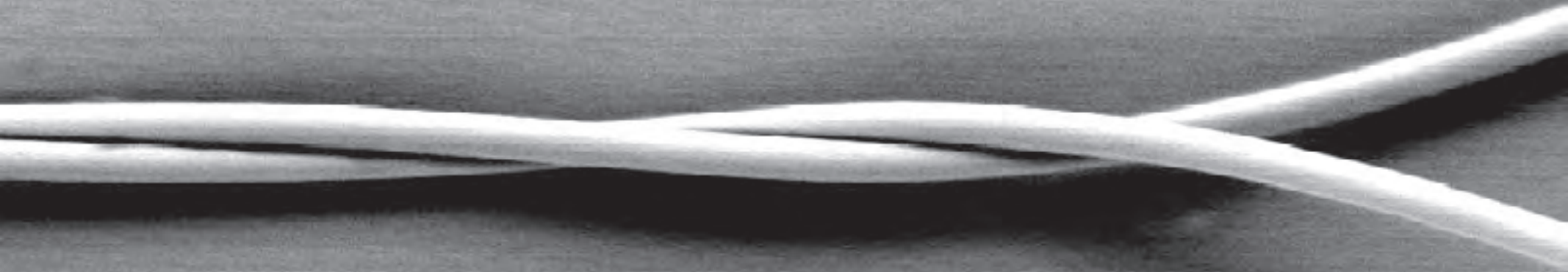


Nanowire fabrication

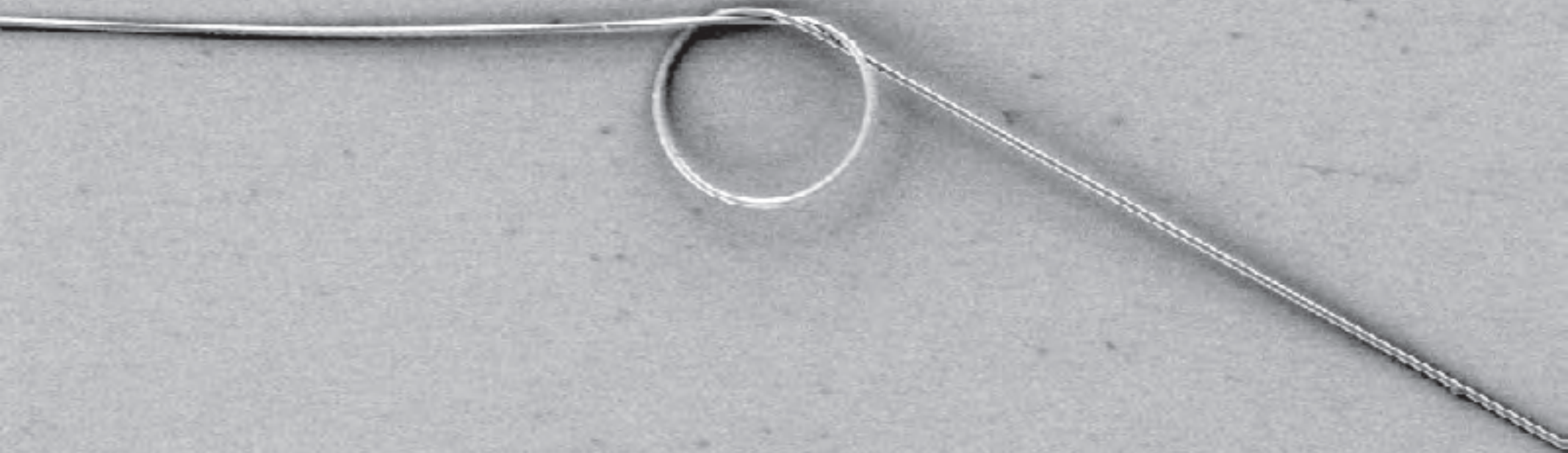
bend to
breaking point



Nanowire fabrication



Nanowire fabrication



Nanowire fabrication

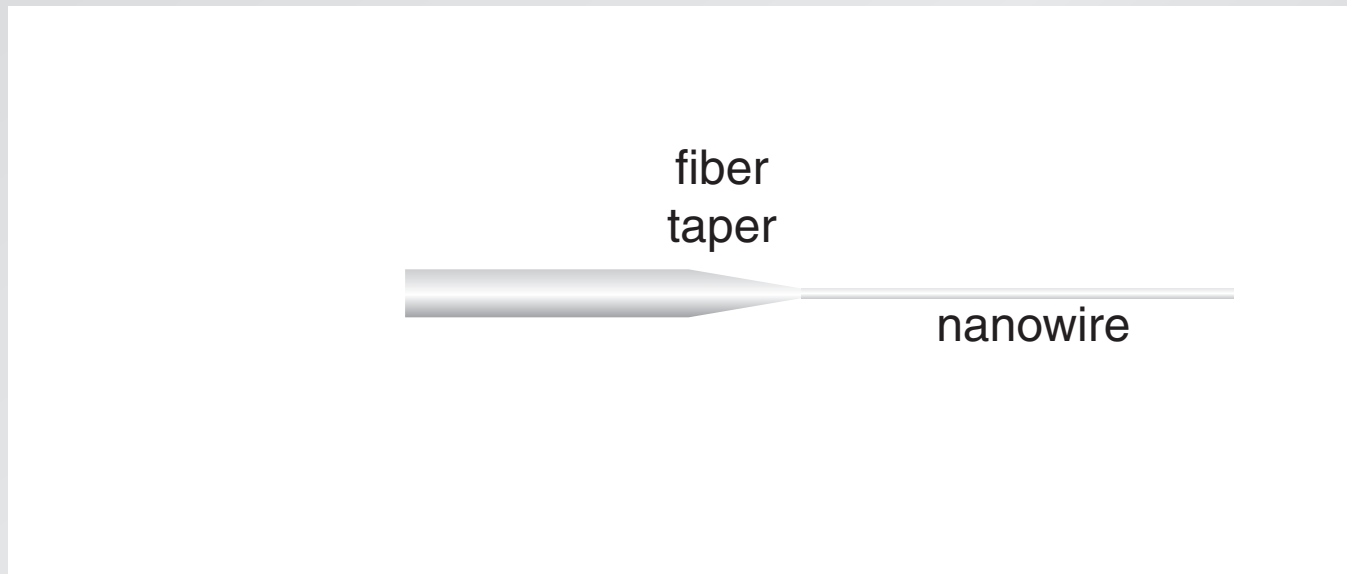


Outline

- waveguiding
- nanowire fabrication
- optical properties

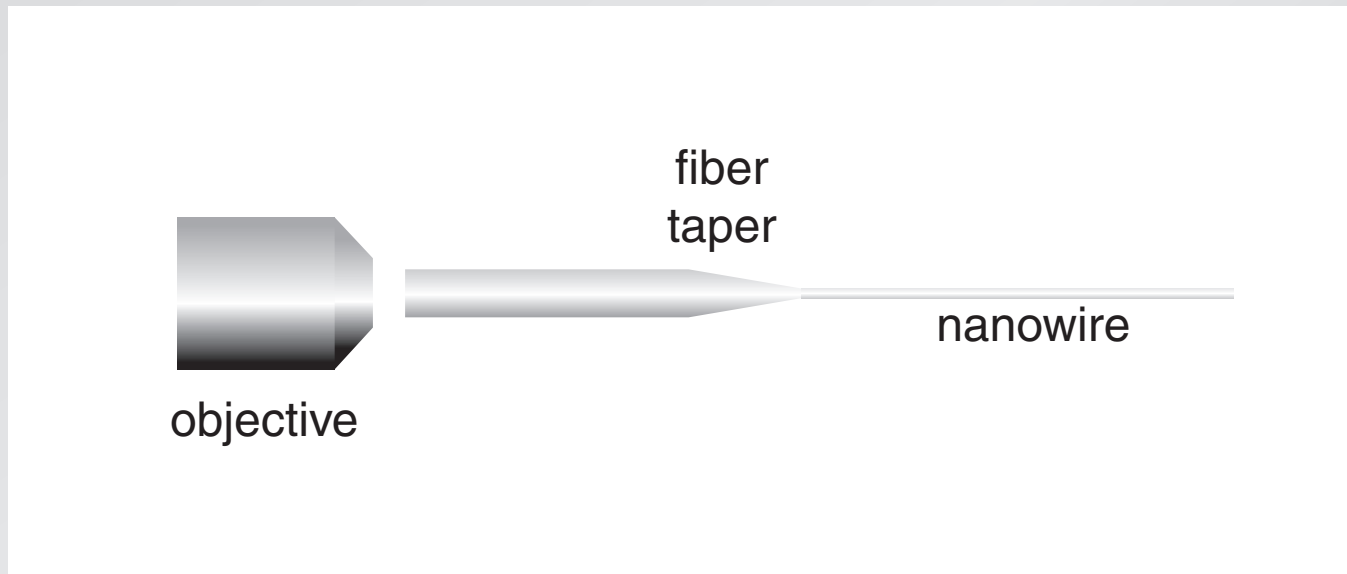
Optical properties

coupling light into nanowires



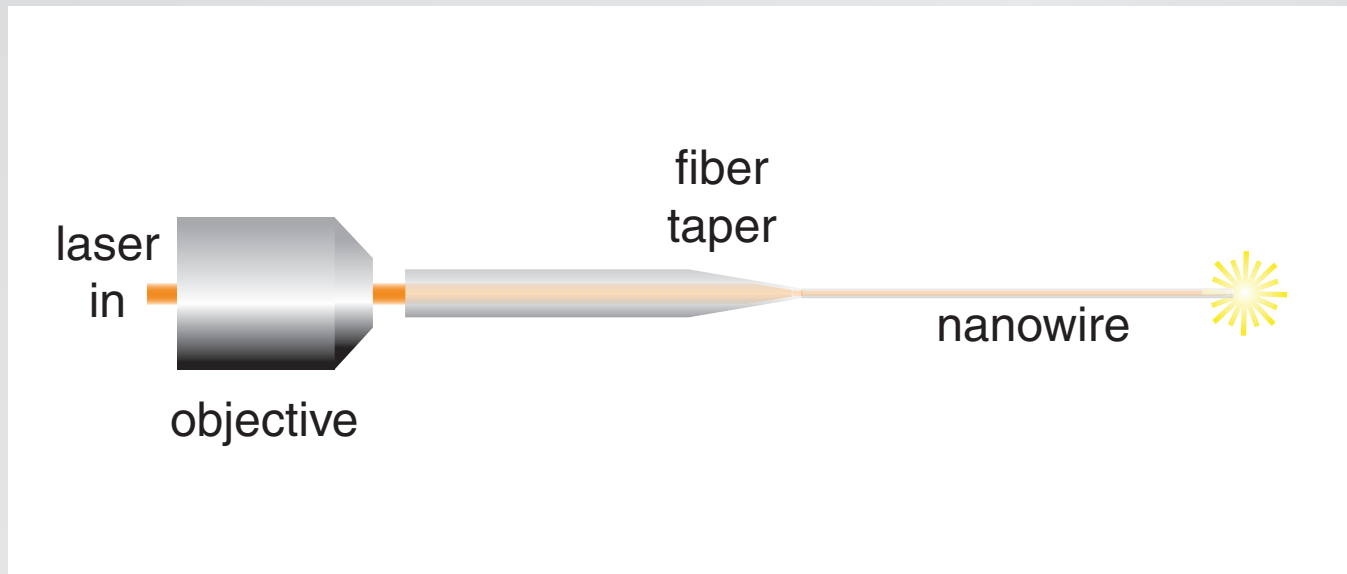
Optical properties

coupling light into nanowires

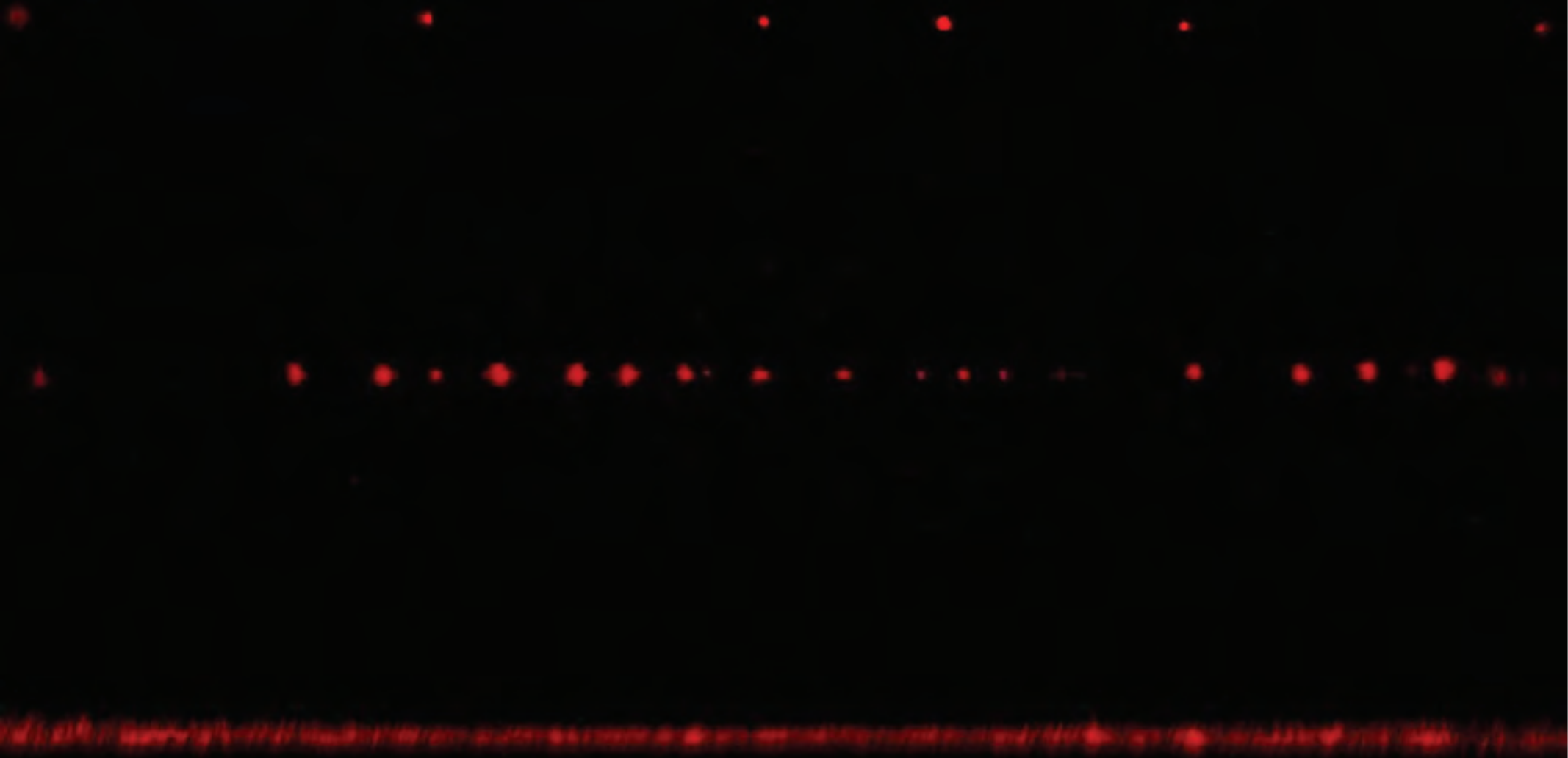


Optical properties

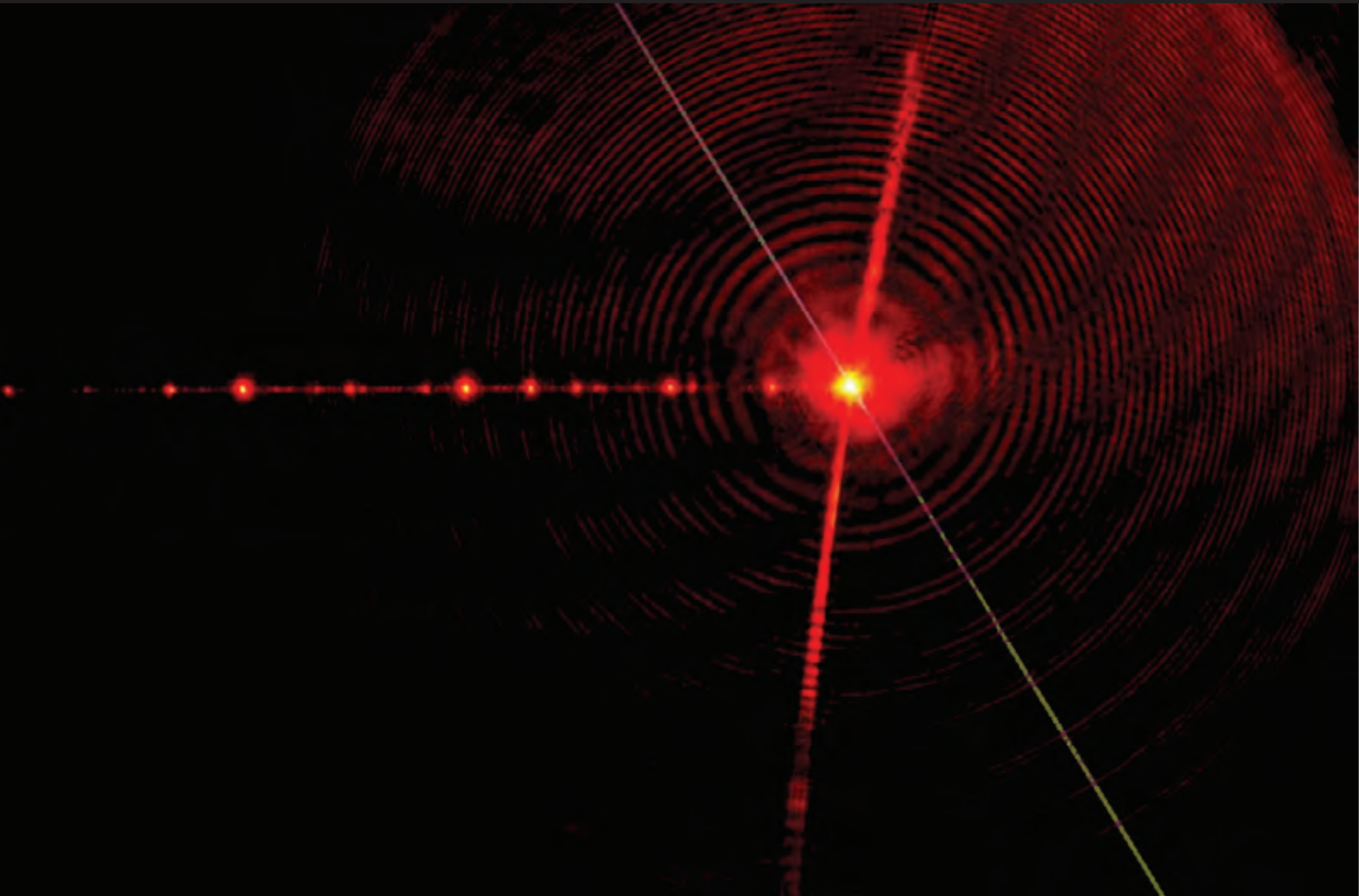
coupling light into nanowires



Optical properties



Optical properties

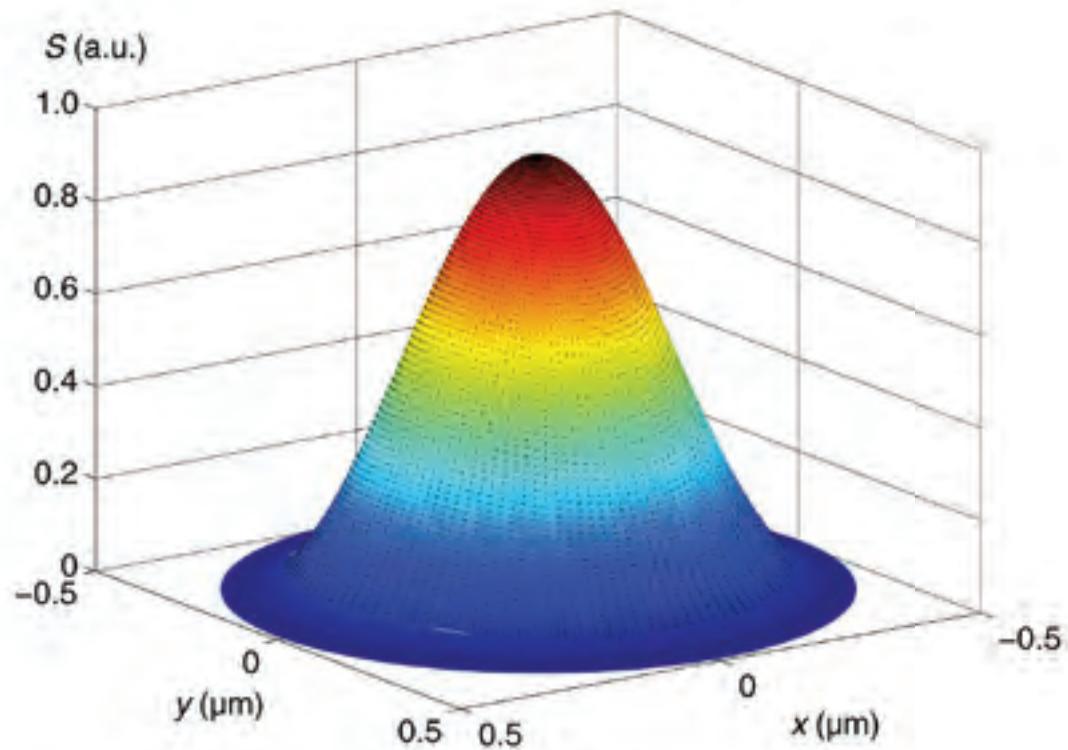


Optical properties



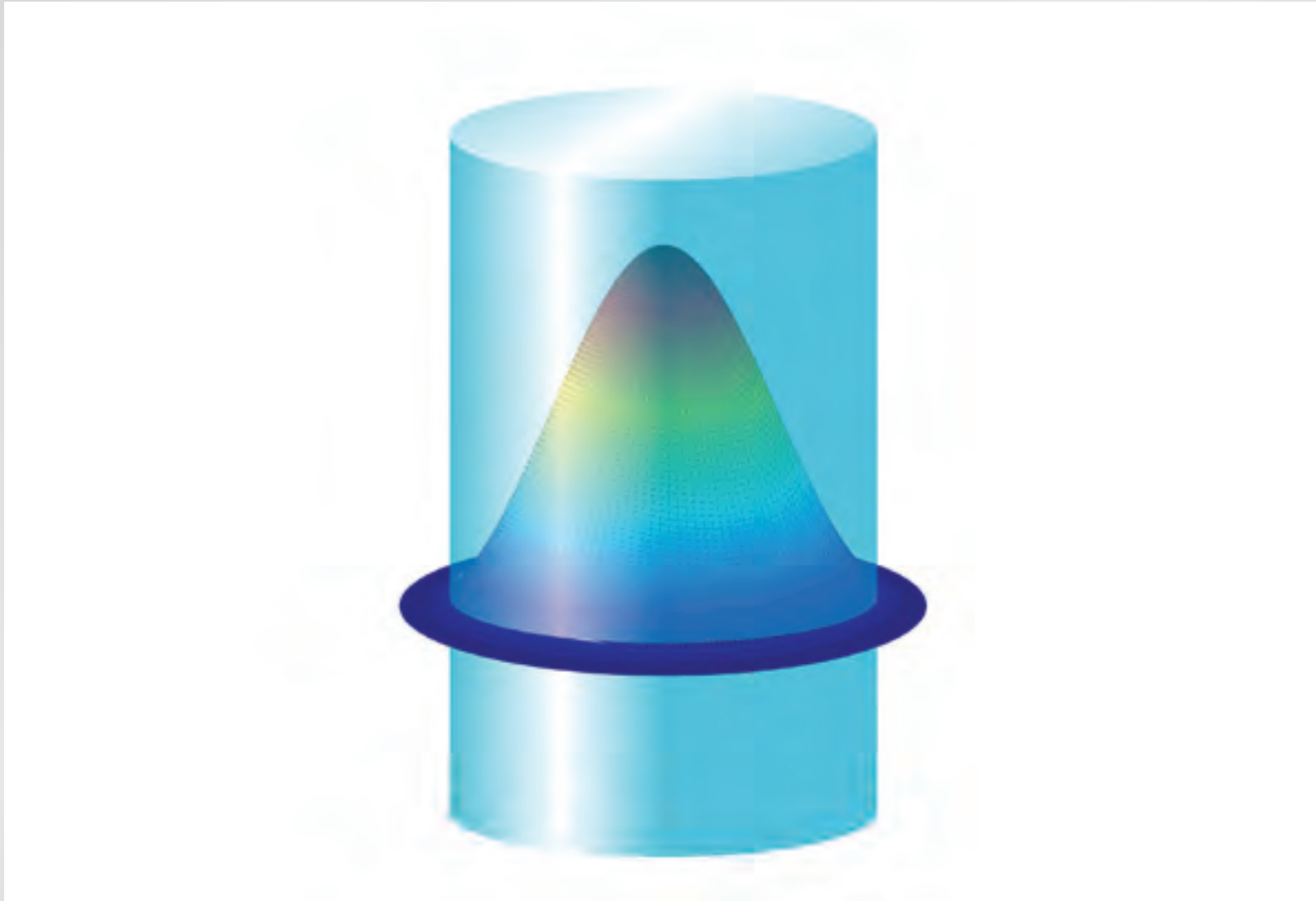
Optical properties

Poynting vector profile for 800-nm nanowire



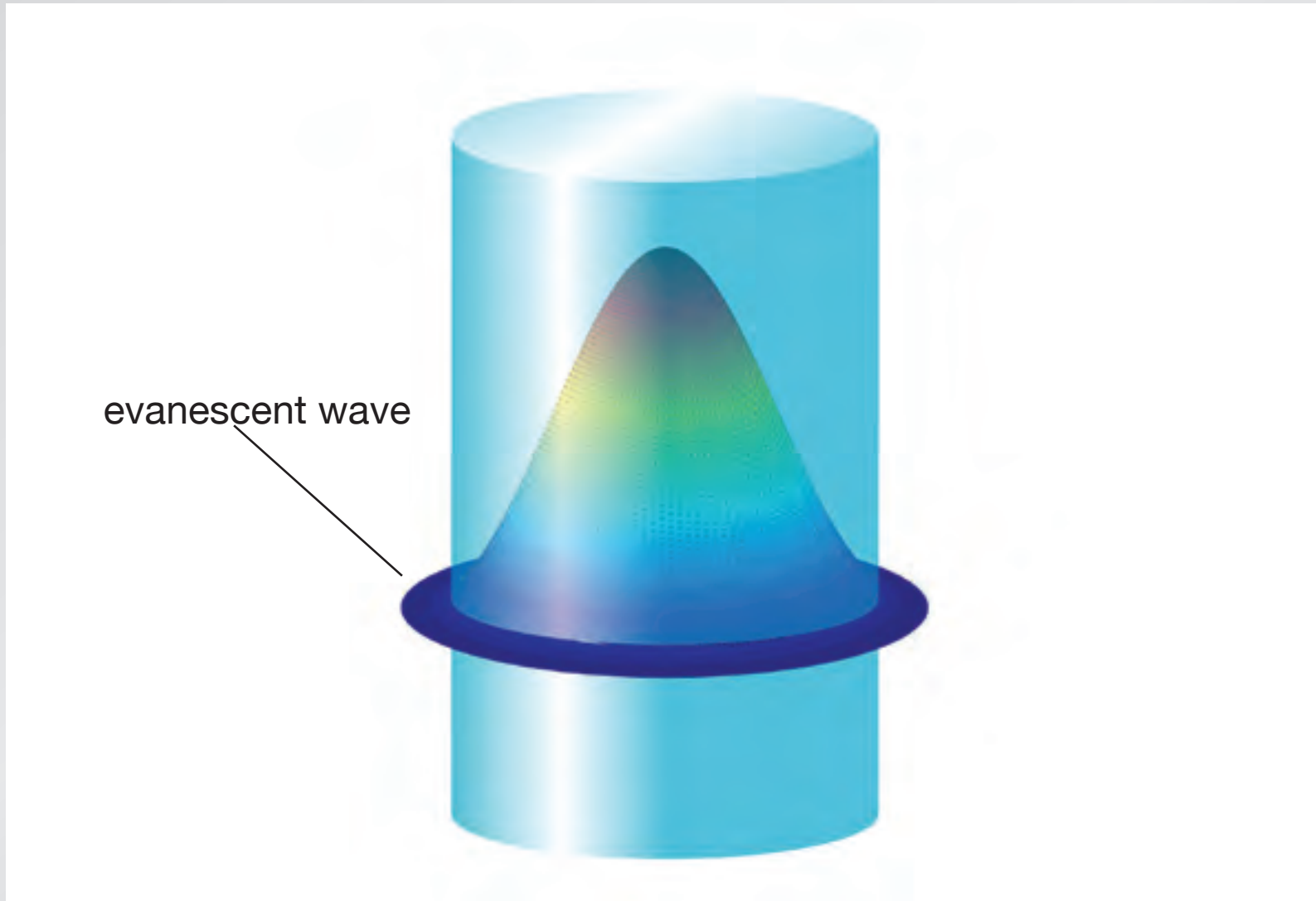
Optical properties

Poynting vector profile for 800-nm nanowire



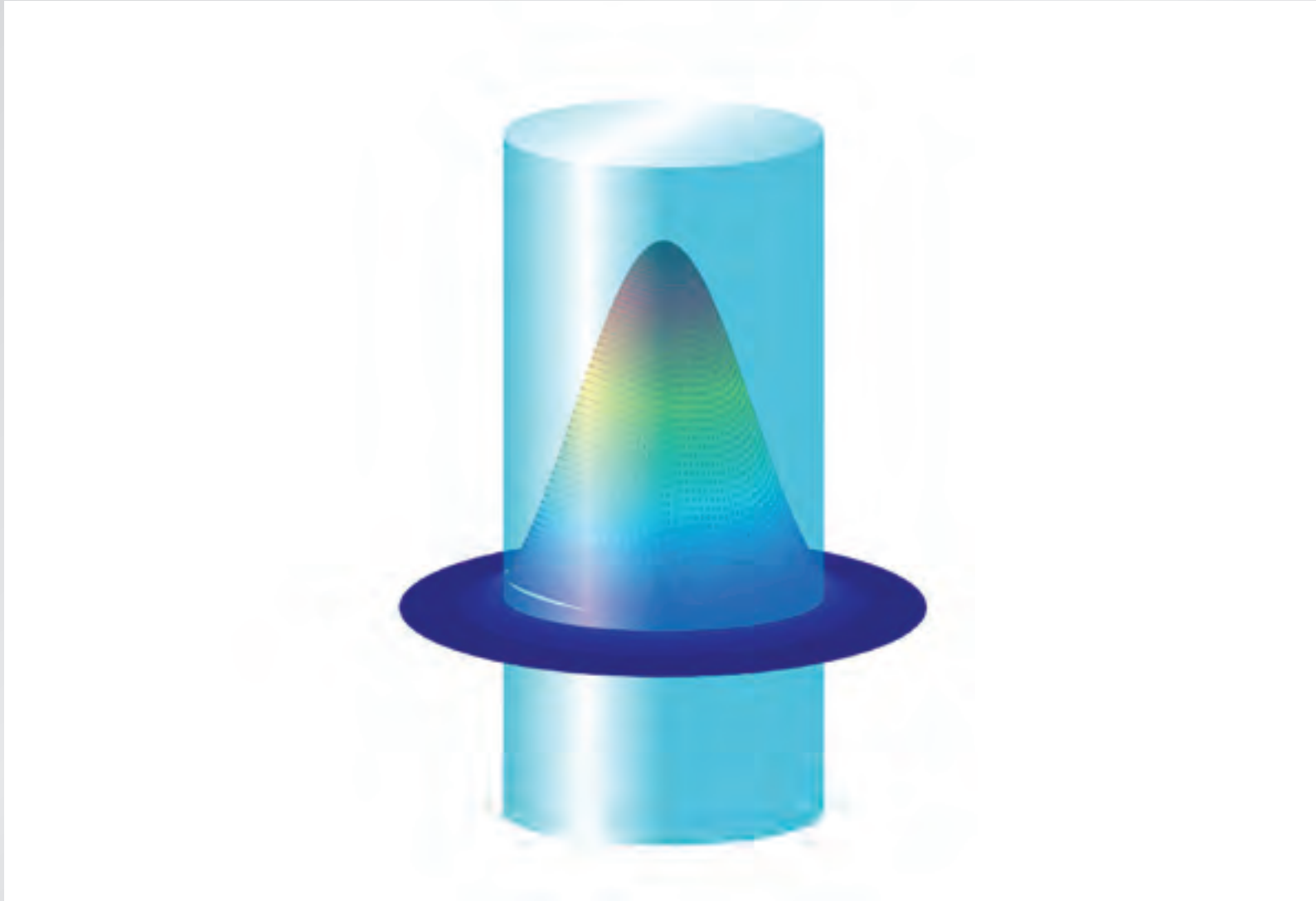
Optical properties

Poynting vector profile for 800-nm nanowire



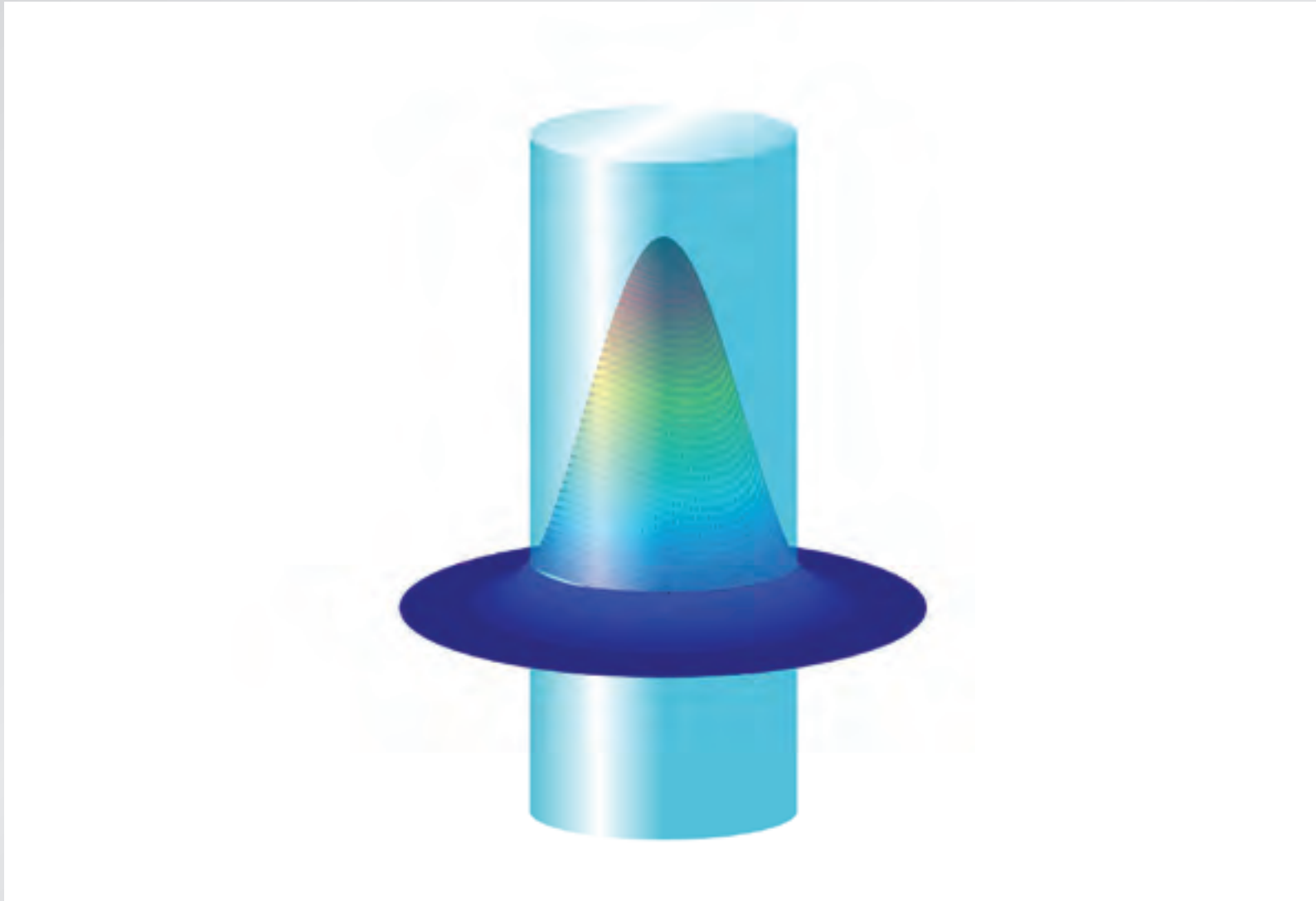
Optical properties

Poynting vector profile for 600-nm nanowire



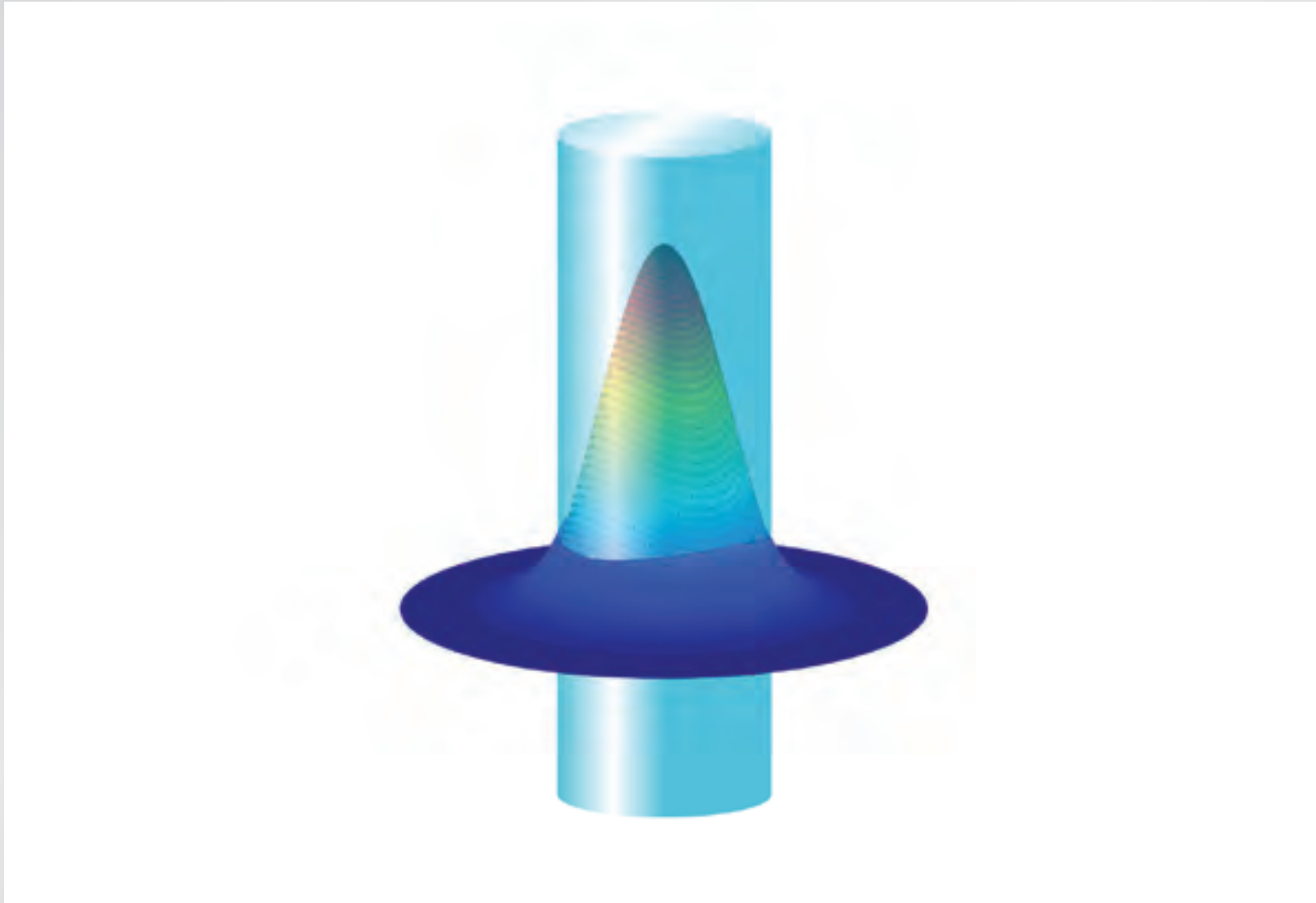
Optical properties

Poynting vector profile for 500-nm nanowire



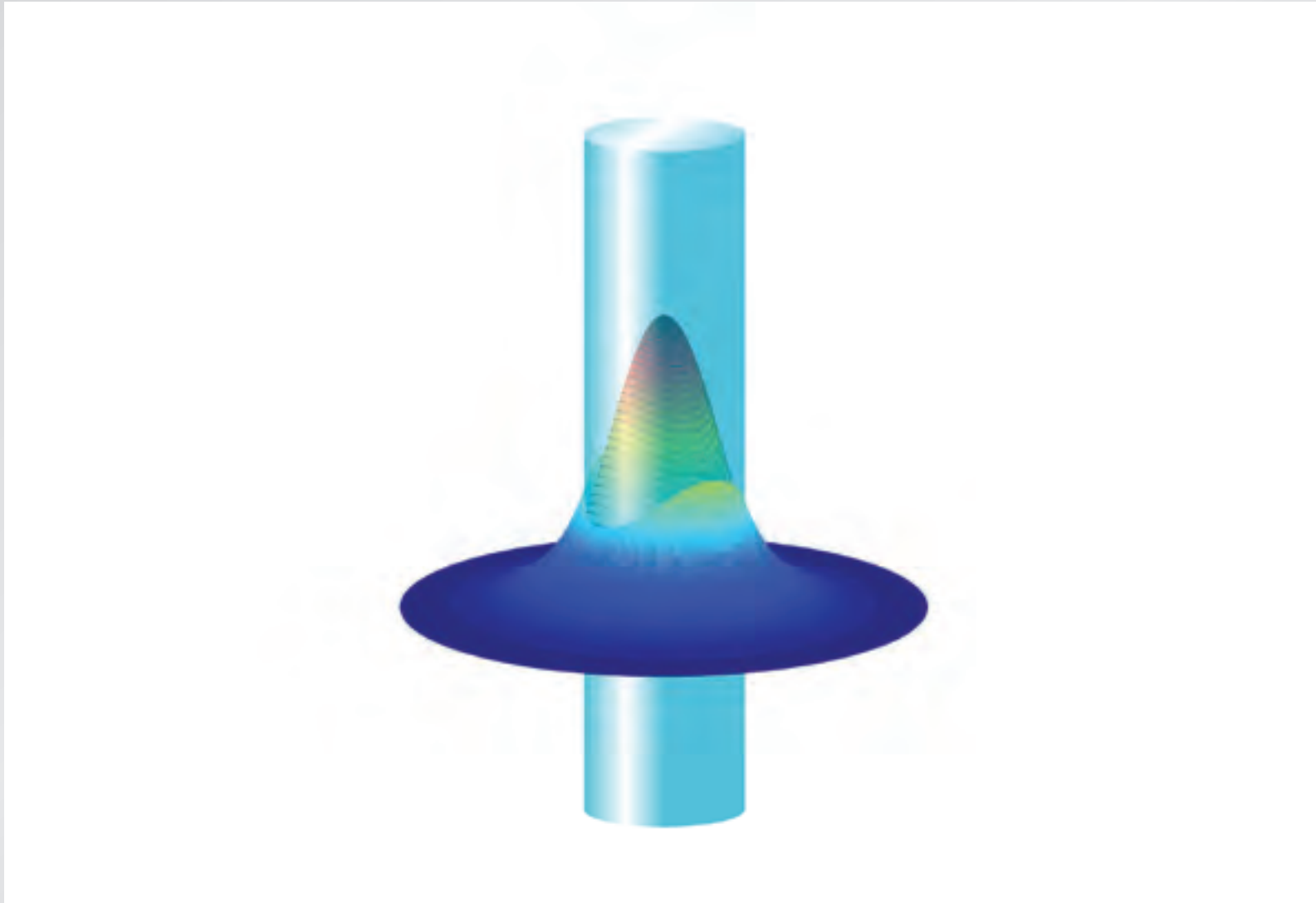
Optical properties

Poynting vector profile for 400-nm nanowire



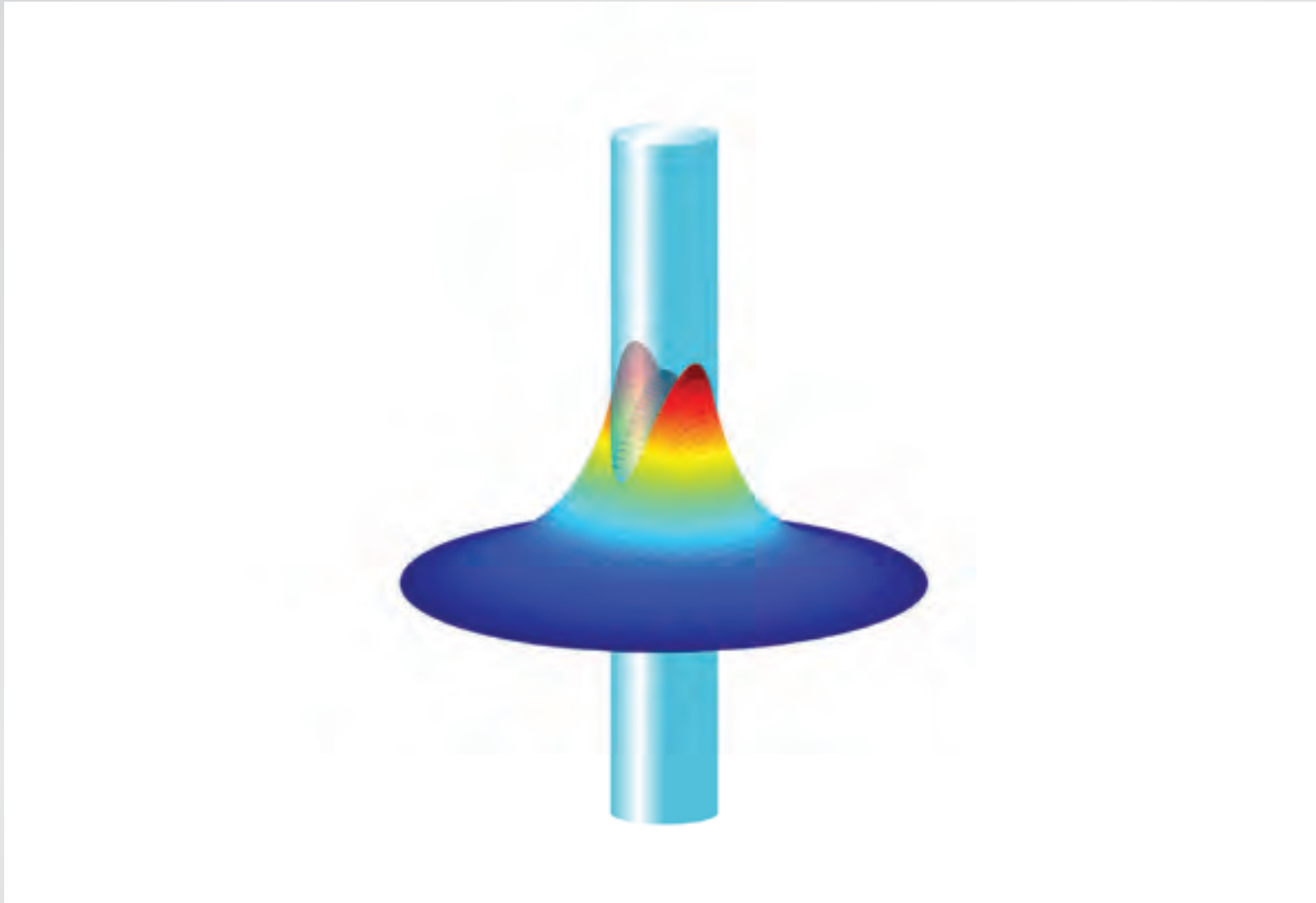
Optical properties

Poynting vector profile for 300-nm nanowire



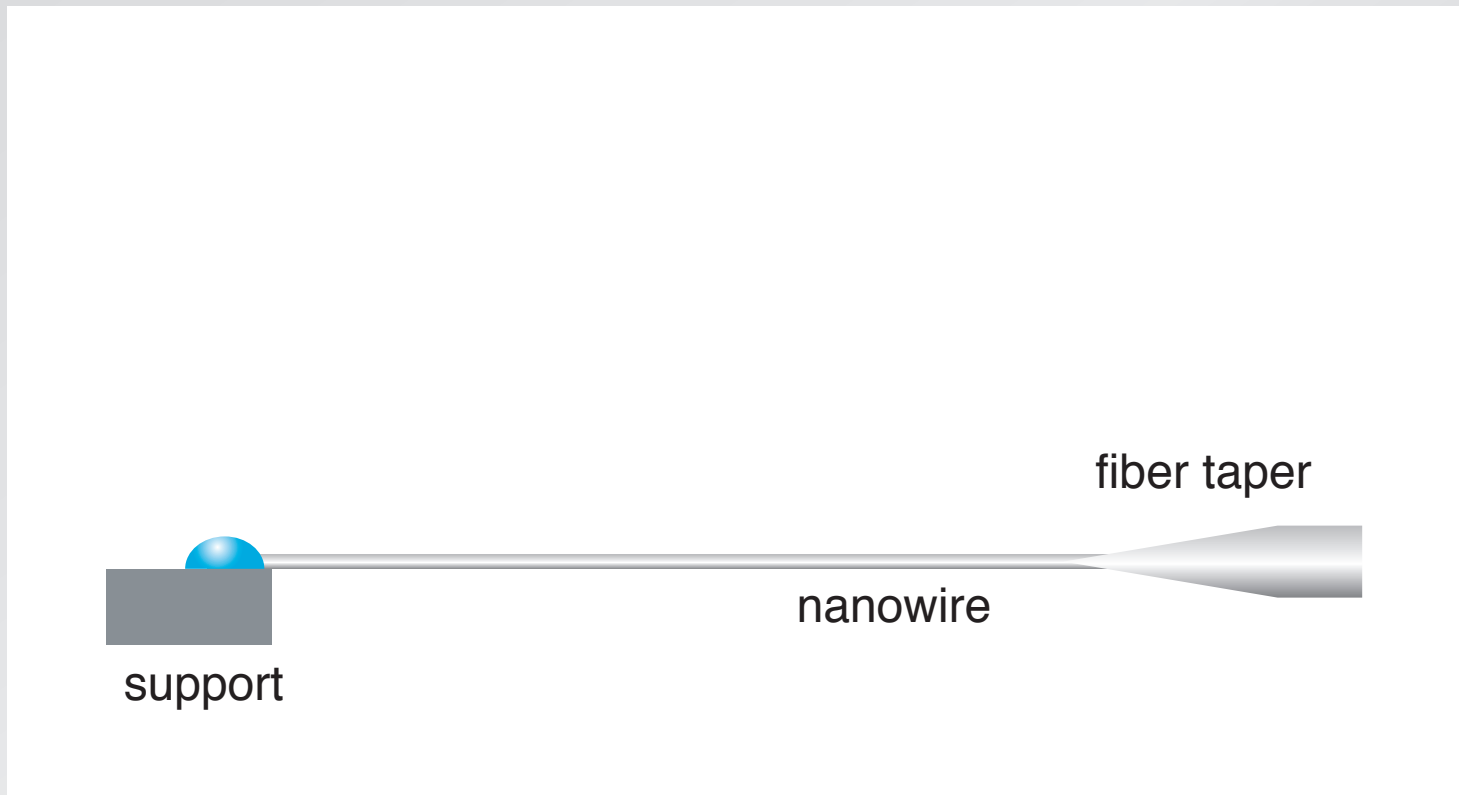
Optical properties

Poynting vector profile for 200-nm nanowire



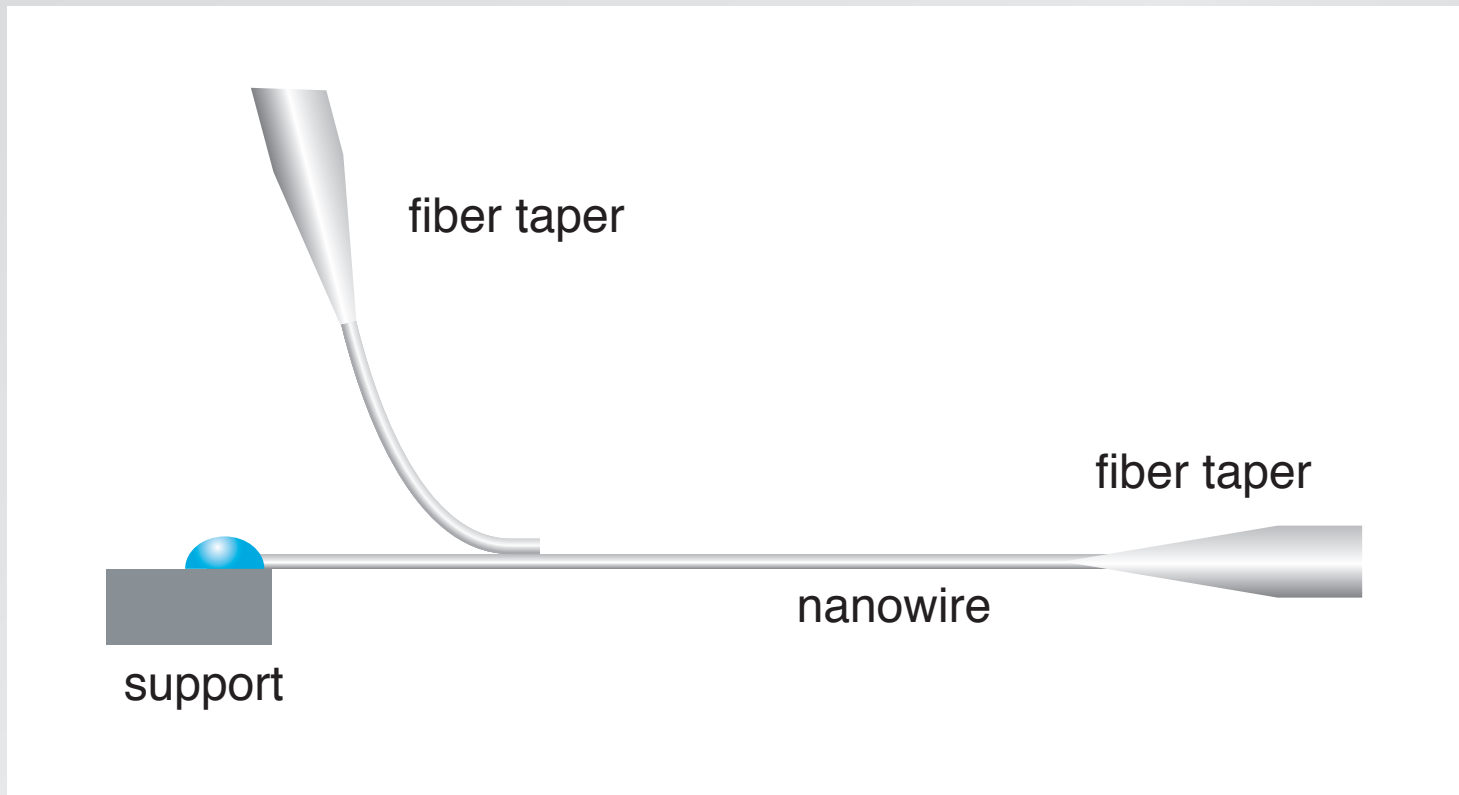
Optical properties

coupling light between nanowires



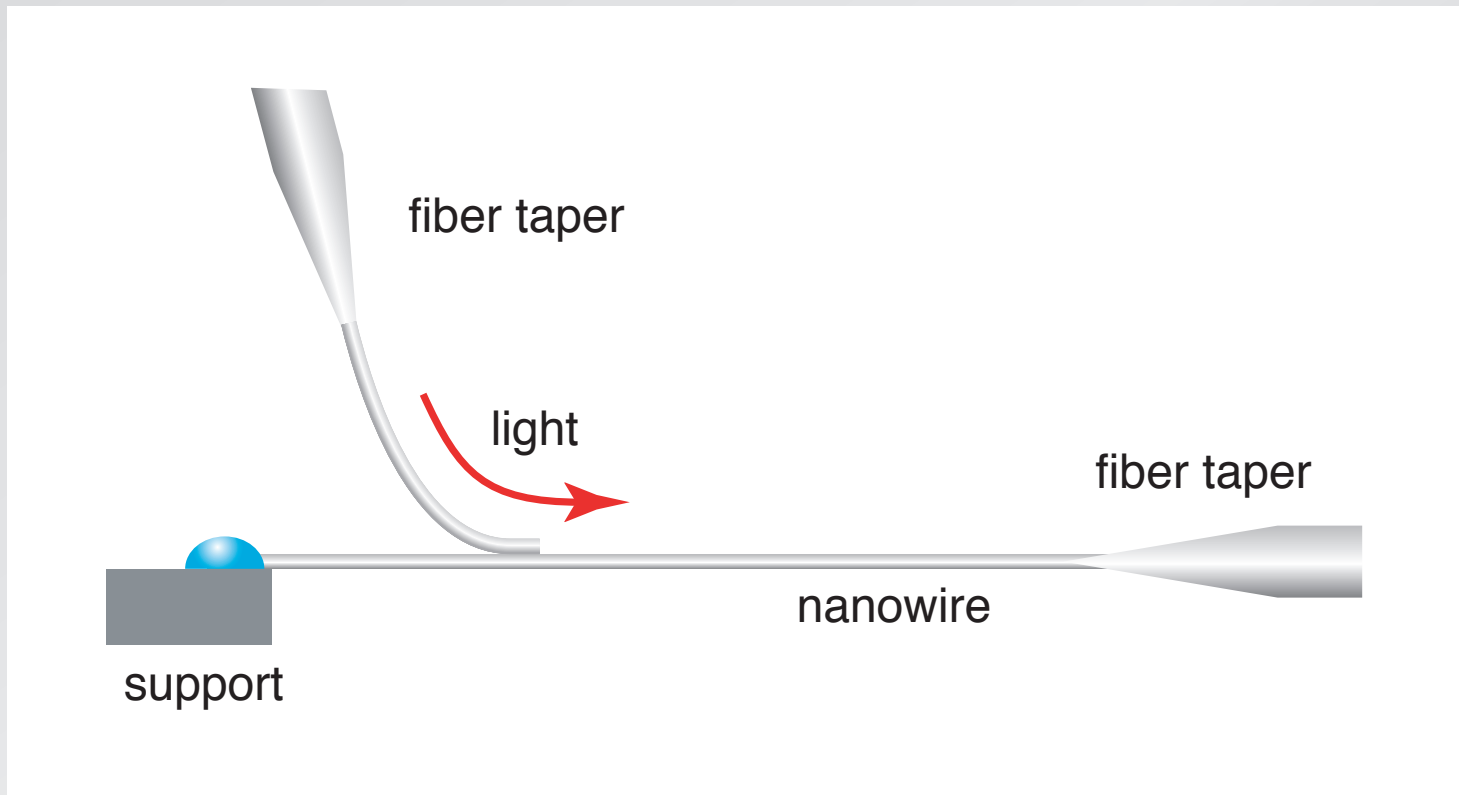
Optical properties

coupling light between nanowires



Optical properties

coupling light between nanowires

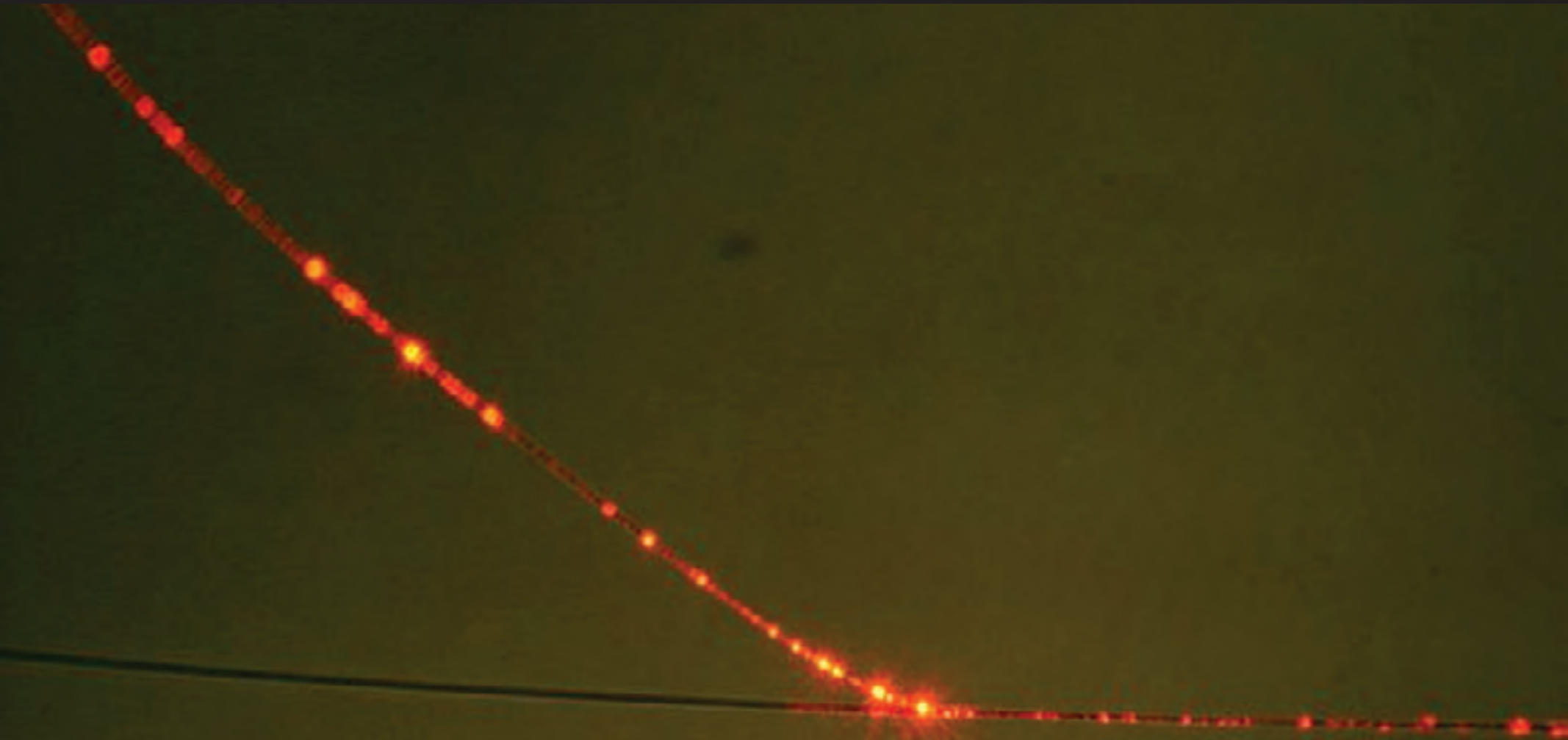


Optical properties



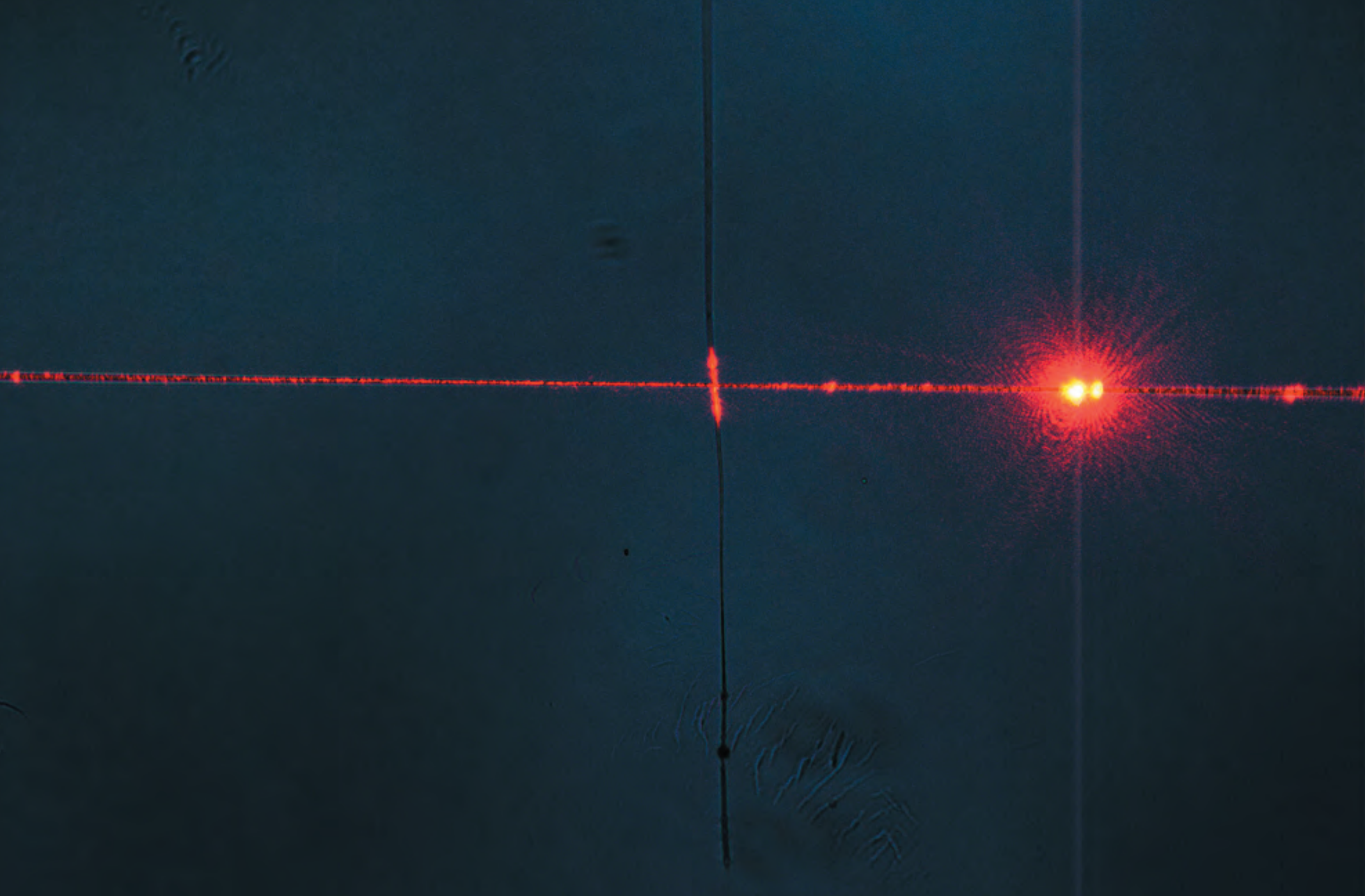
50 μm

Optical properties

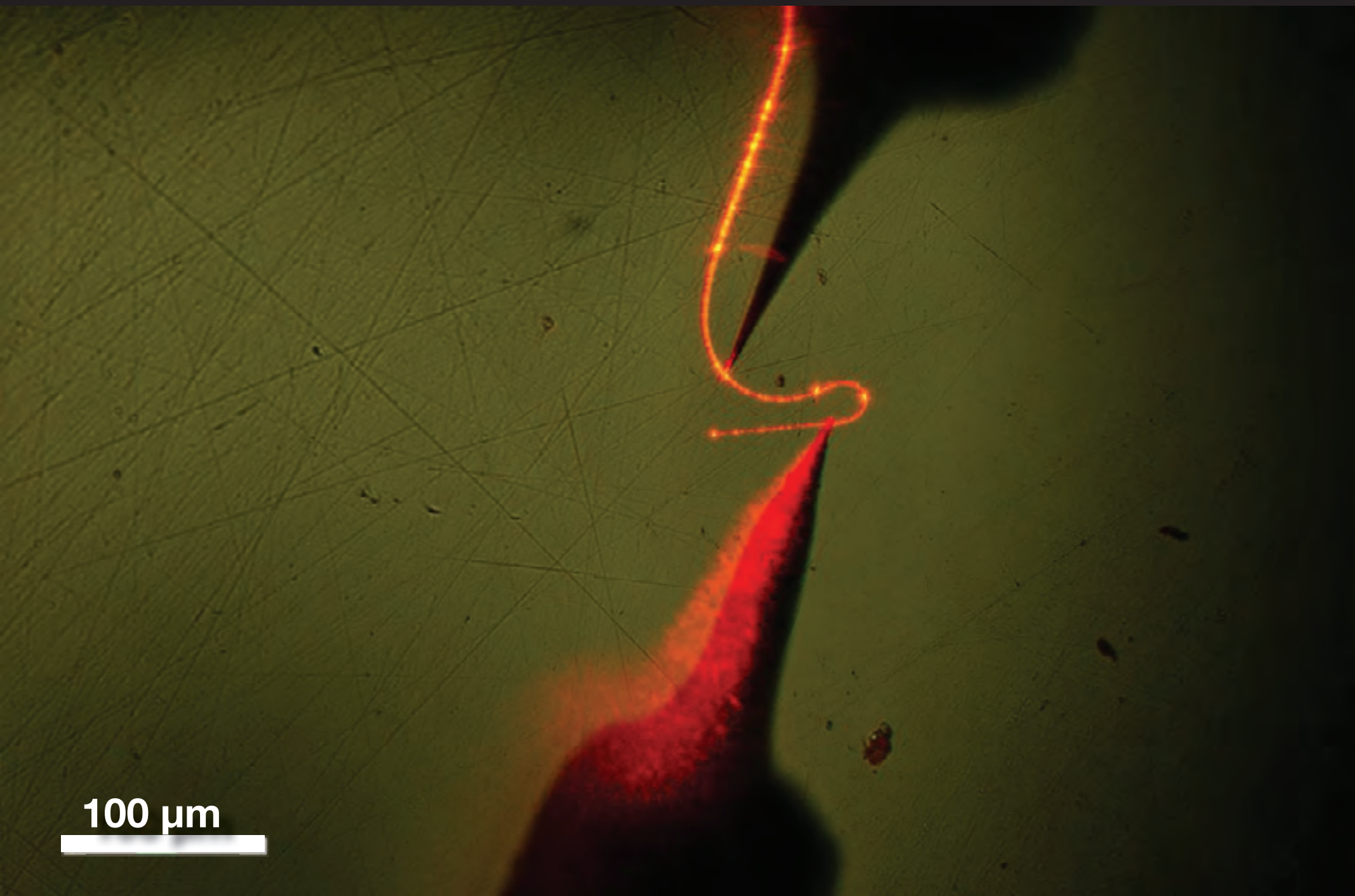


50 μm

Optical properties

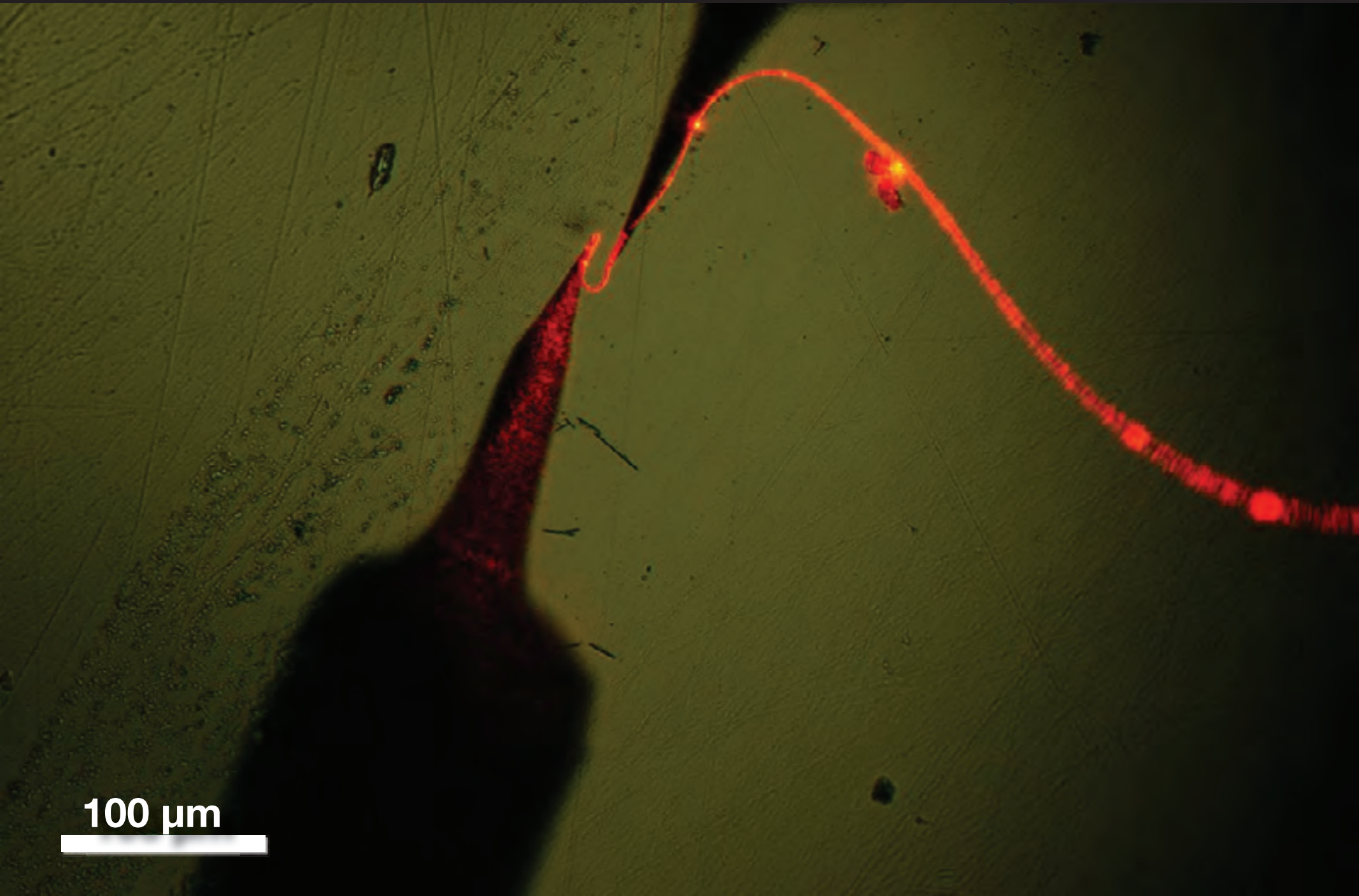


Optical properties



100 μm

Optical properties



100 μm



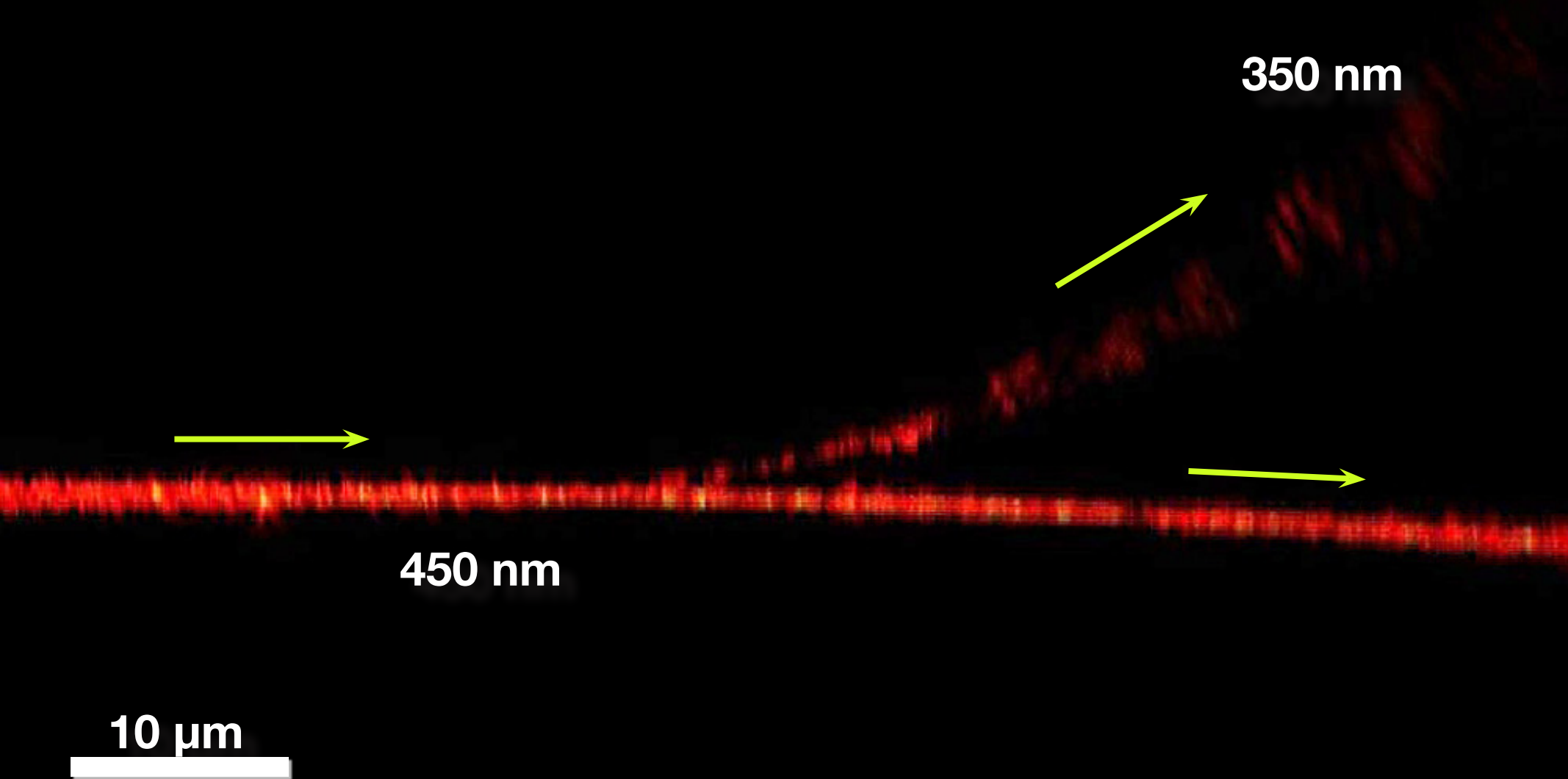
Optical properties

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

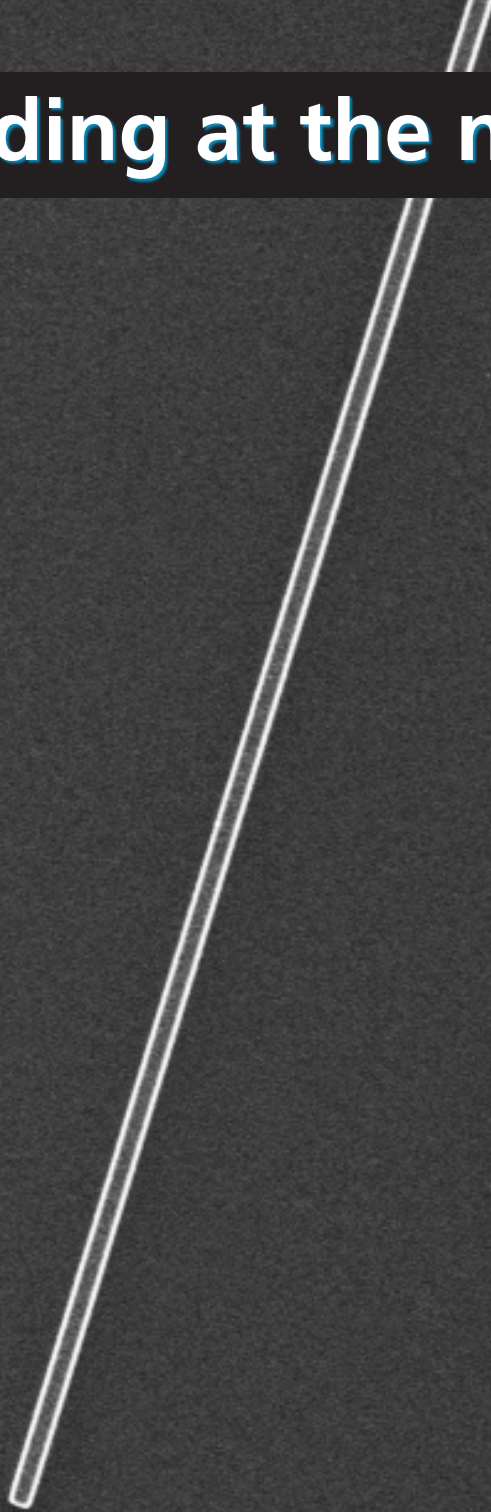
100 μm

An optical micrograph showing a fiber with a red laser spot. The fiber is dark and appears to be made of a material with a textured surface. The red laser spot is bright and elongated, following the curve of the fiber. The background is a dark, textured surface. A scale bar is located in the bottom left corner, and text indicating the minimum bending radius is in the upper left.

Optical properties



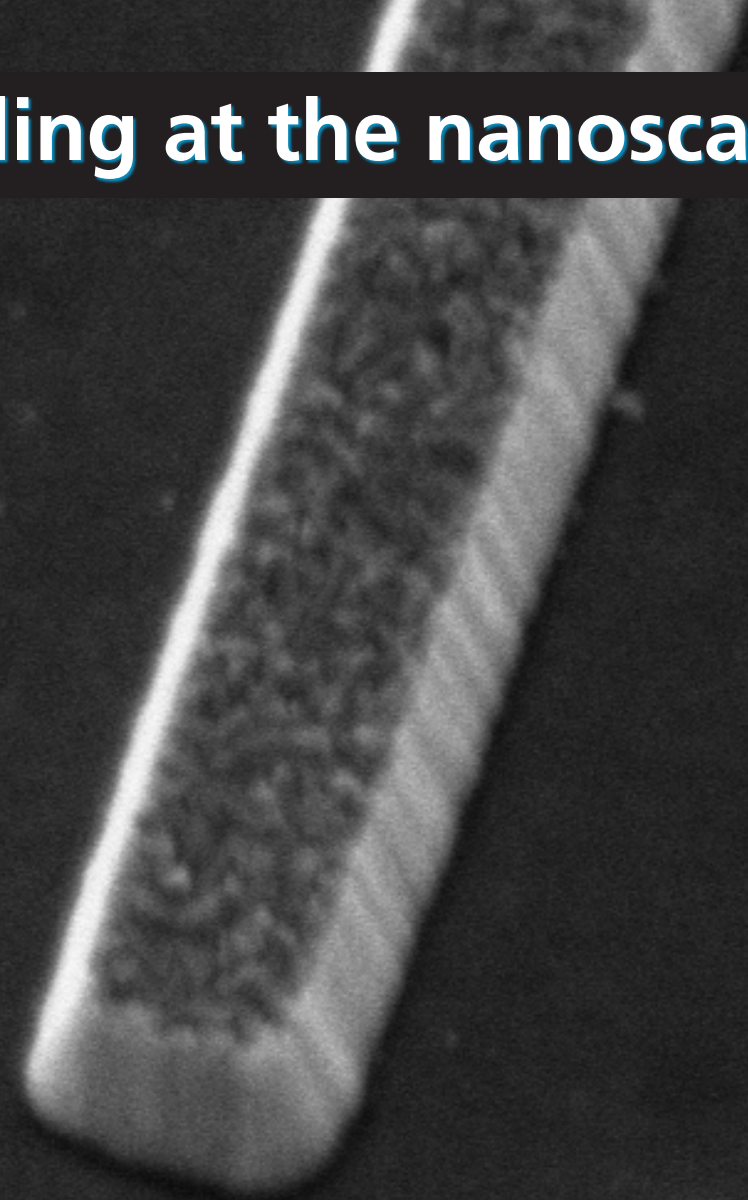
Waveguiding at the nanoscale



5 μm



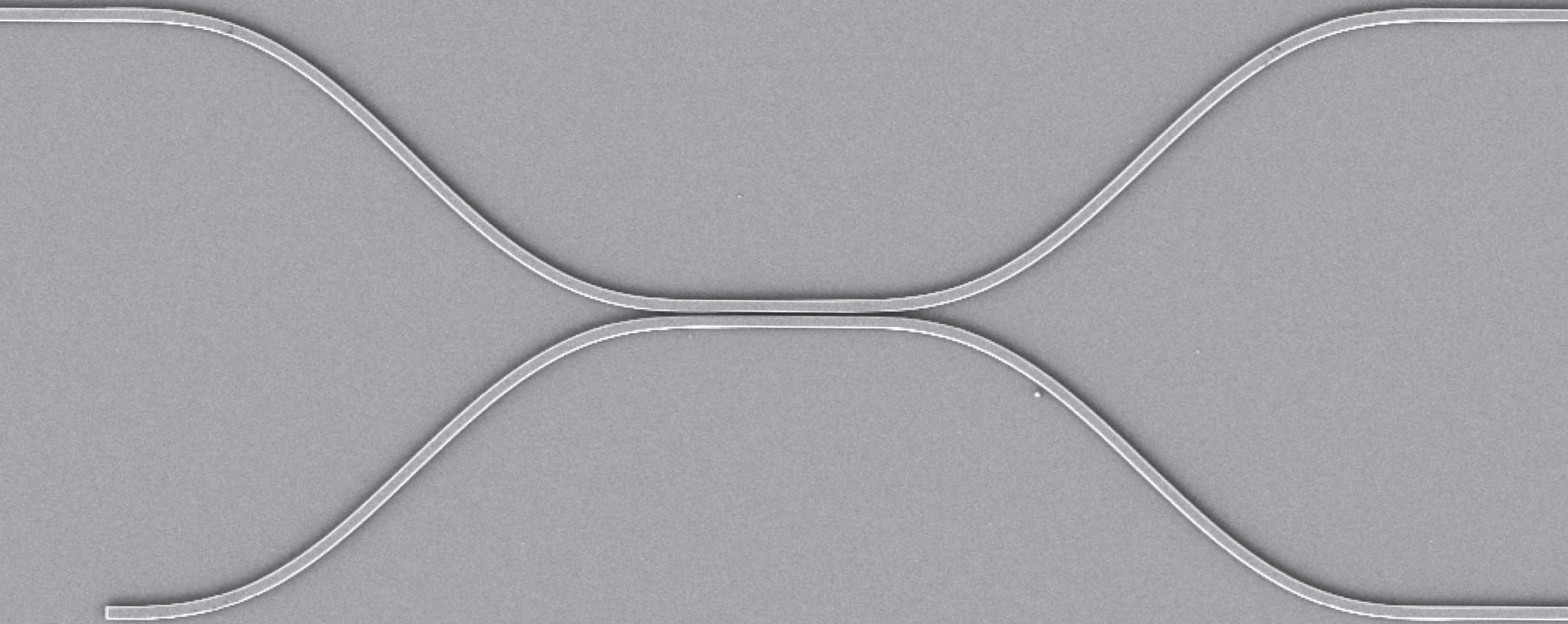
Waveguiding at the nanoscale



300 nm



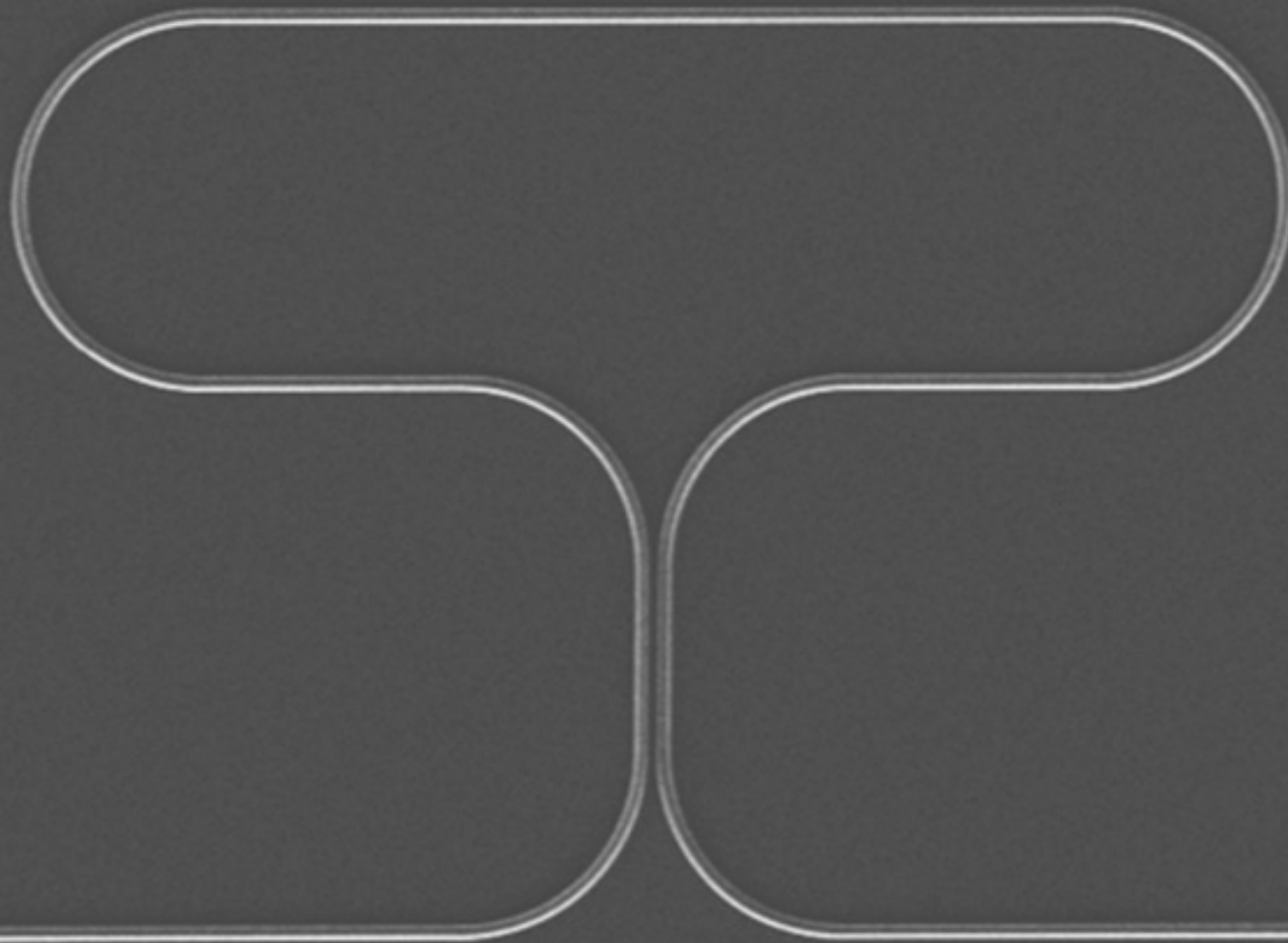
Waveguiding at the nanoscale



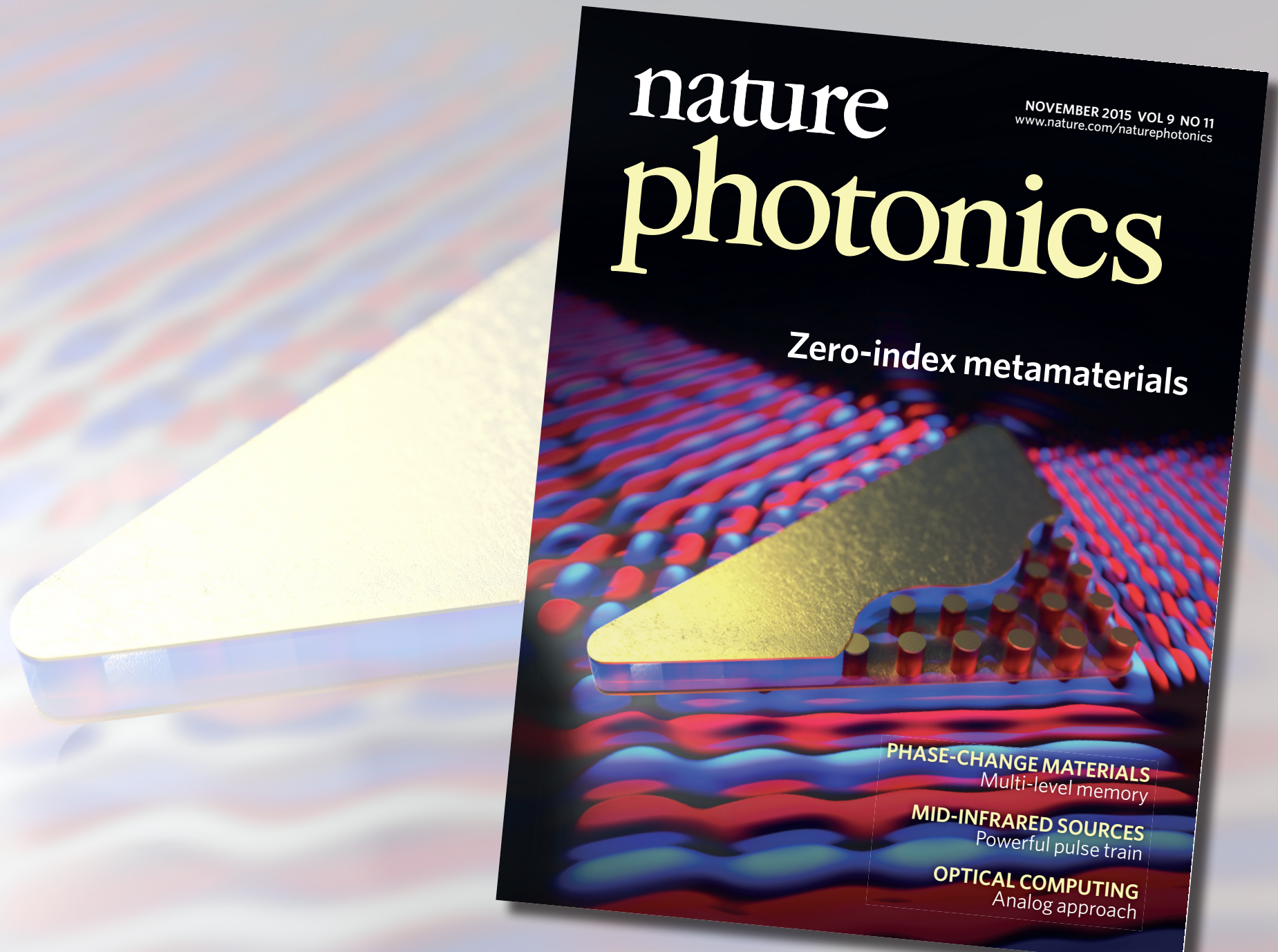
10 μm



Optical logic gates



Zero-index materials



nature photonics

NOVEMBER 2015 VOL 9 NO 11
www.nature.com/naturephotonics

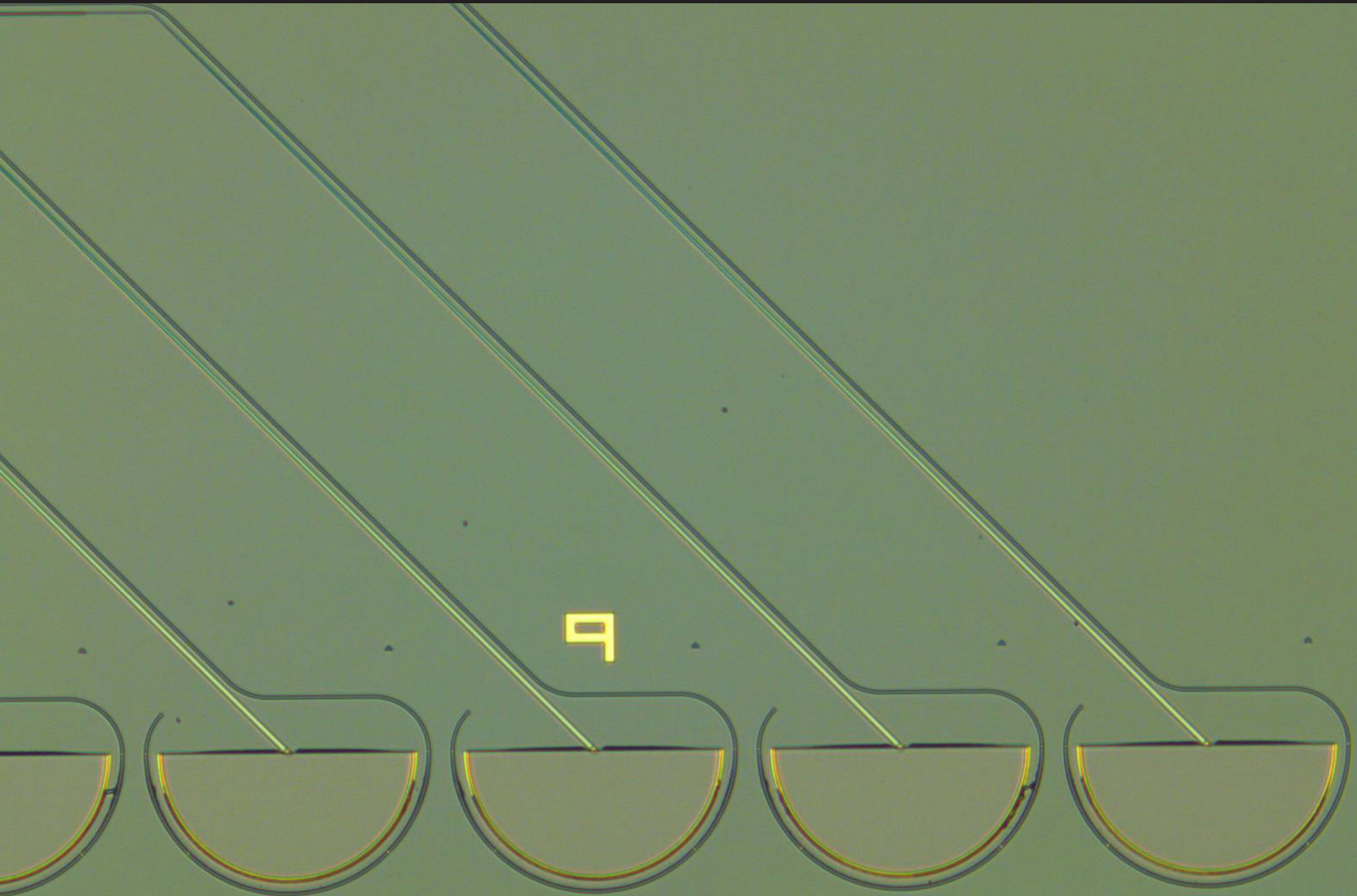
Zero-index metamaterials

PHASE-CHANGE MATERIALS
Multi-level memory

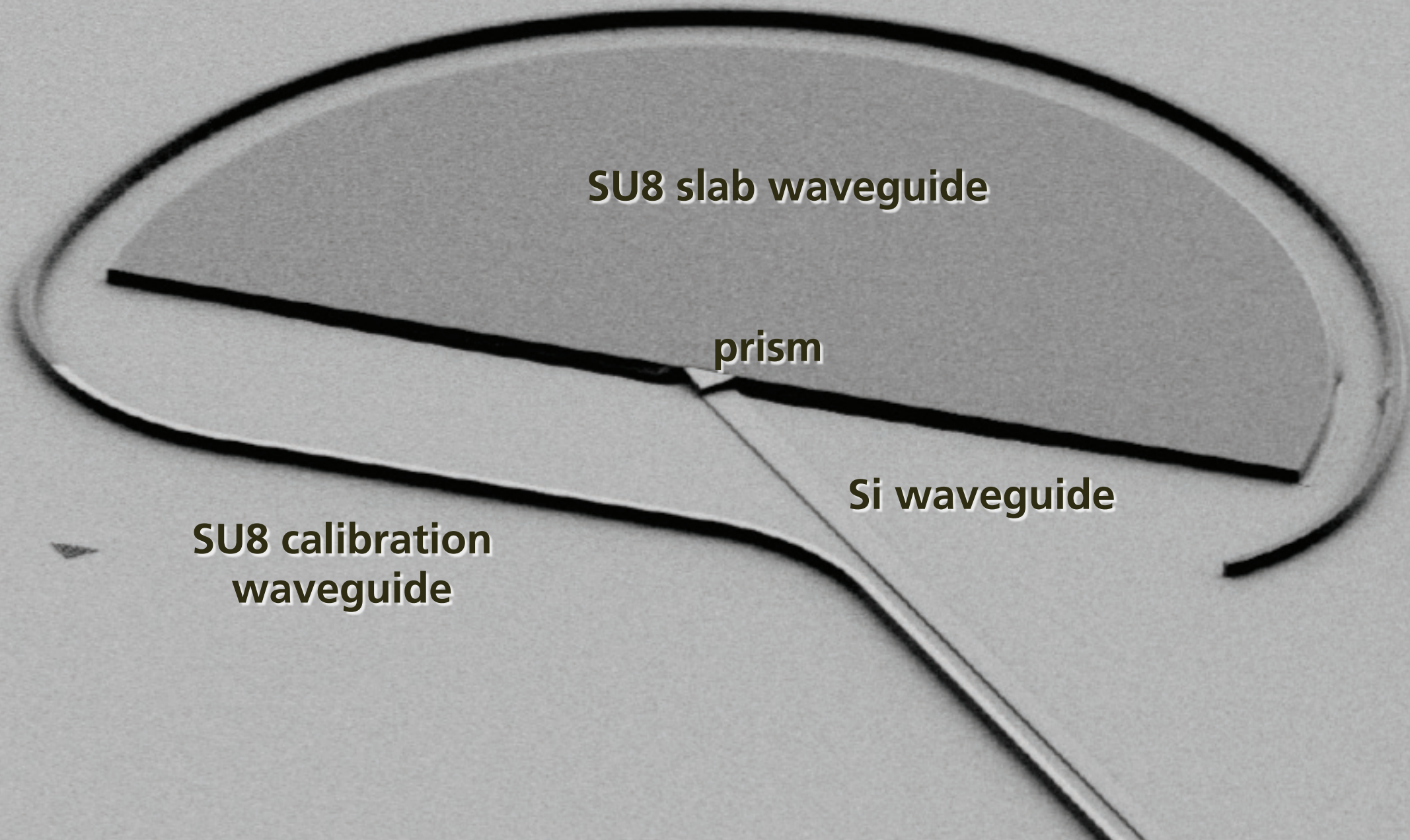
MID-INFRARED SOURCES
Powerful pulse train

OPTICAL COMPUTING
Analog approach

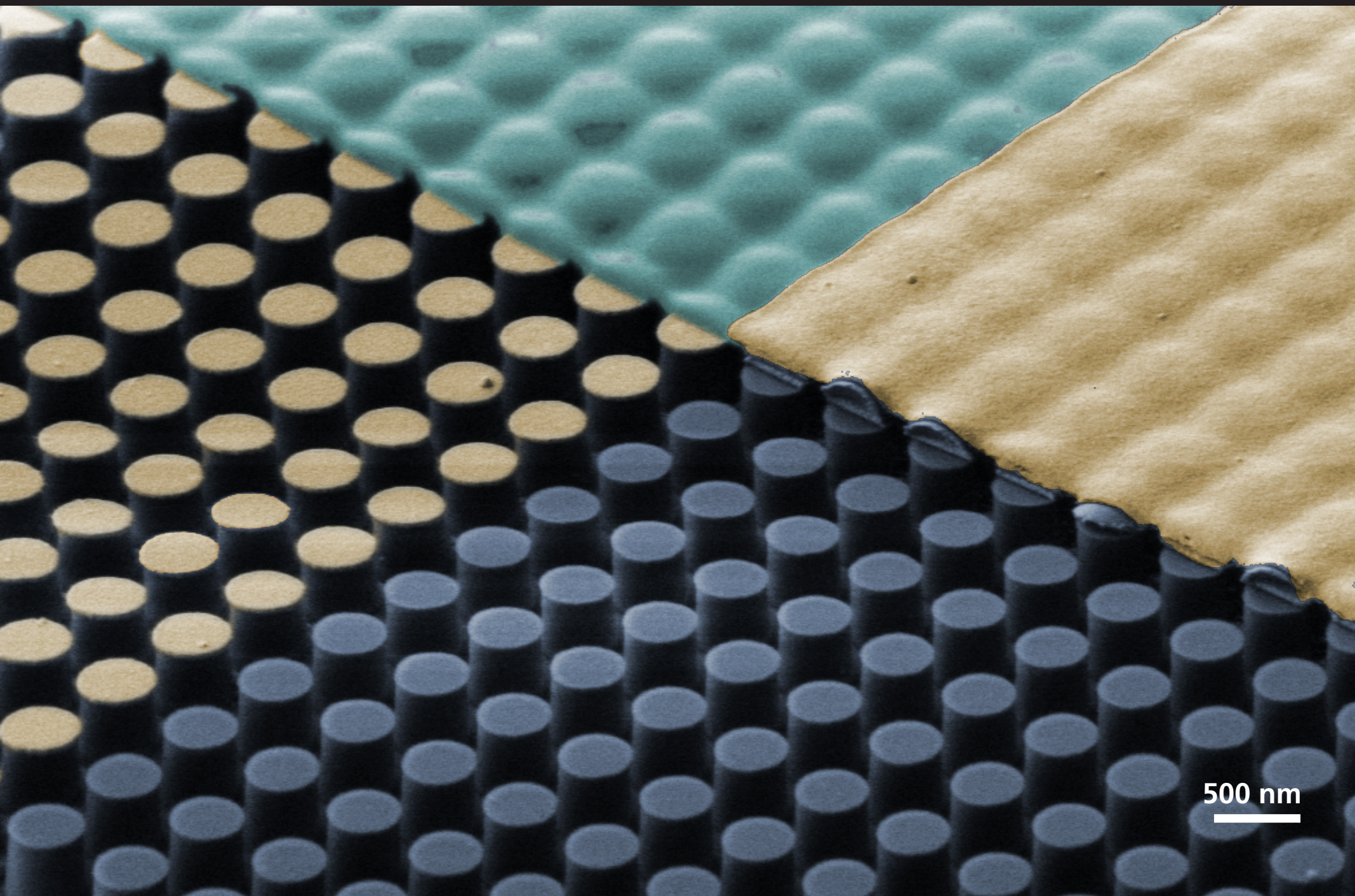
Zero-index materials



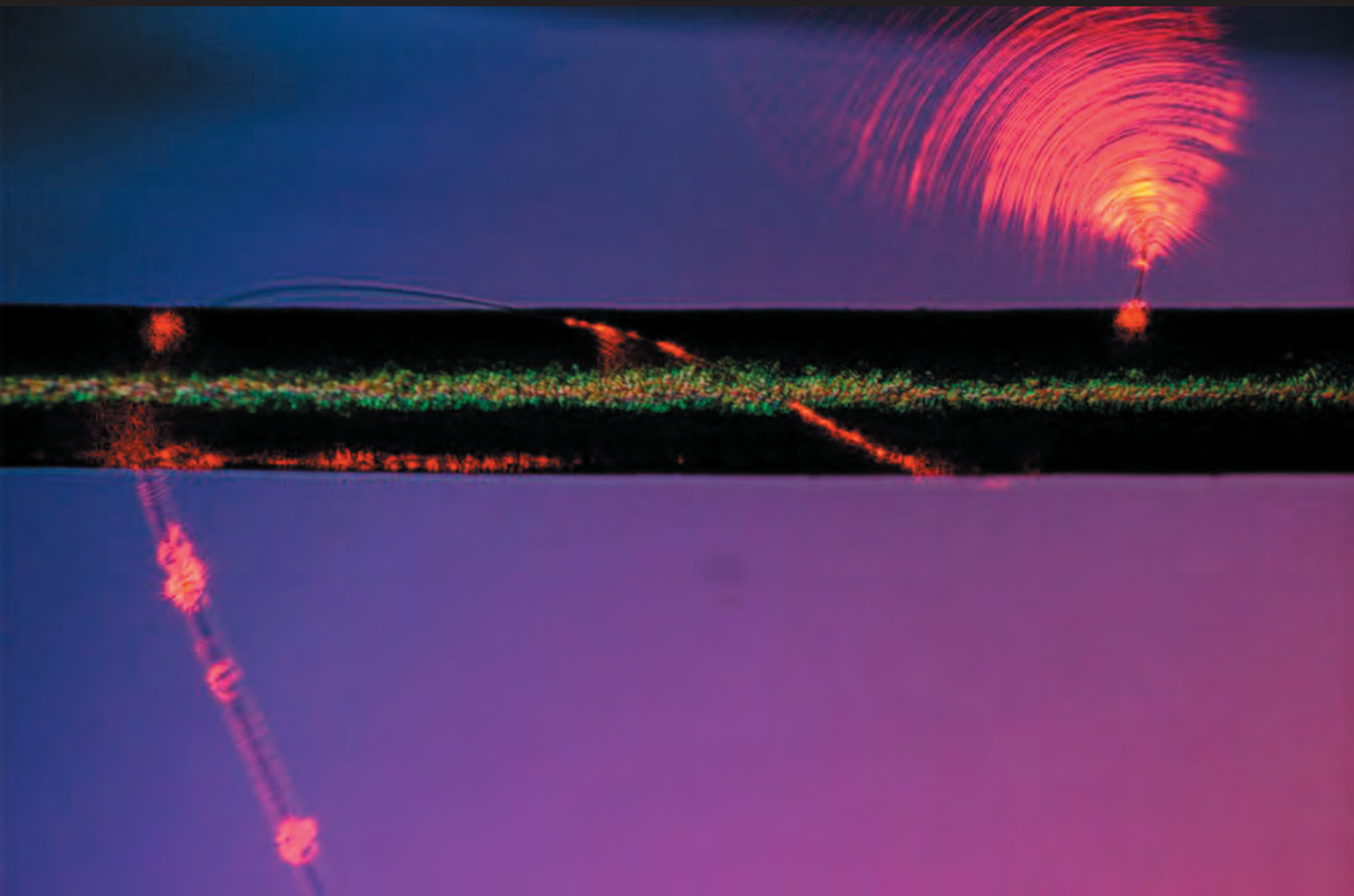
Zero-index materials




Zero-index materials



Summary



Summary

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



Funding:

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