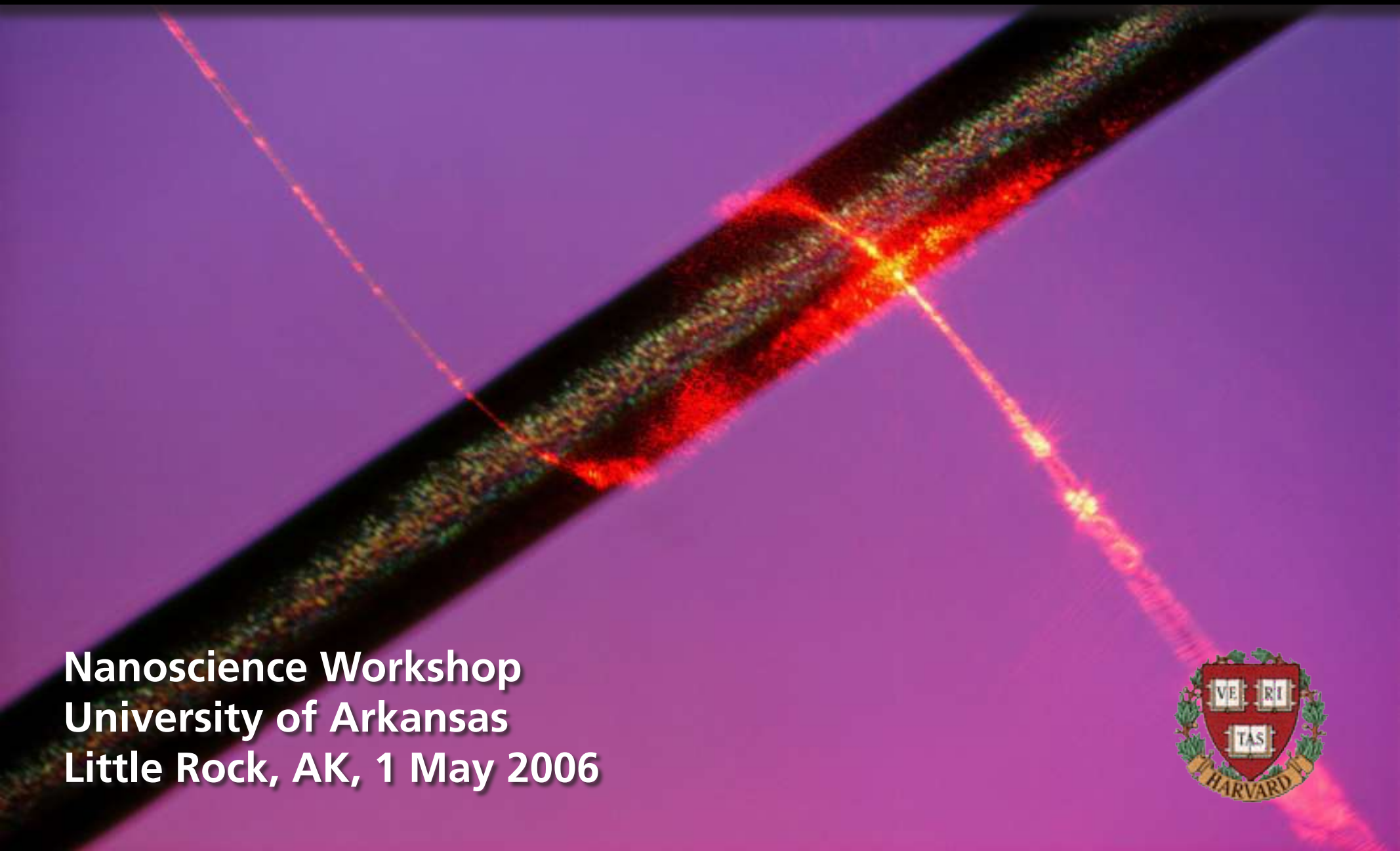
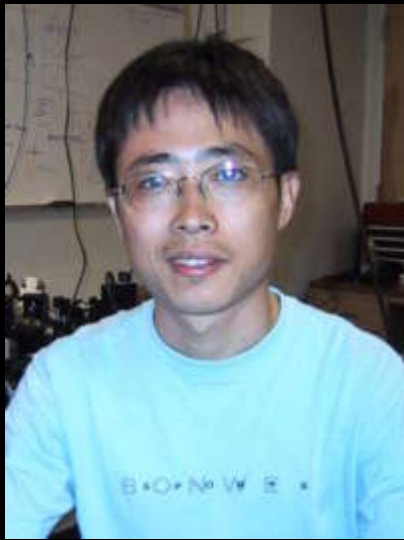


# Wrapping light around a hair: manipulating light at the nanoscale



Nanoscience Workshop  
University of Arkansas  
Little Rock, AK, 1 May 2006





**Limin Tong**



**Rafael Gattass**



**Geoff Svacha**



**Tommaso Baldacchini**

**and also....**

**at Harvard:**

**Jonathan Aschom**

**Mengyan Shen**

**Iva Maxwell**

**James Carey**

**Brian Tull**

**Dr. Yuan Lu**

**Dr. Richard Schalek**

**Prof. Federico Capasso**

**Prof. Cynthia Friend**

**and elsewhere:**

**Xuwen Chen (Zhejiang University)**

**Zhanghua Han (Zhejiang University)**

**Dr. Sailing He (Zhejiang University)**

**Prof. Igor Khruschev (Aston University)**

**Dr. Jingyi Lou (Zhejiang University)**

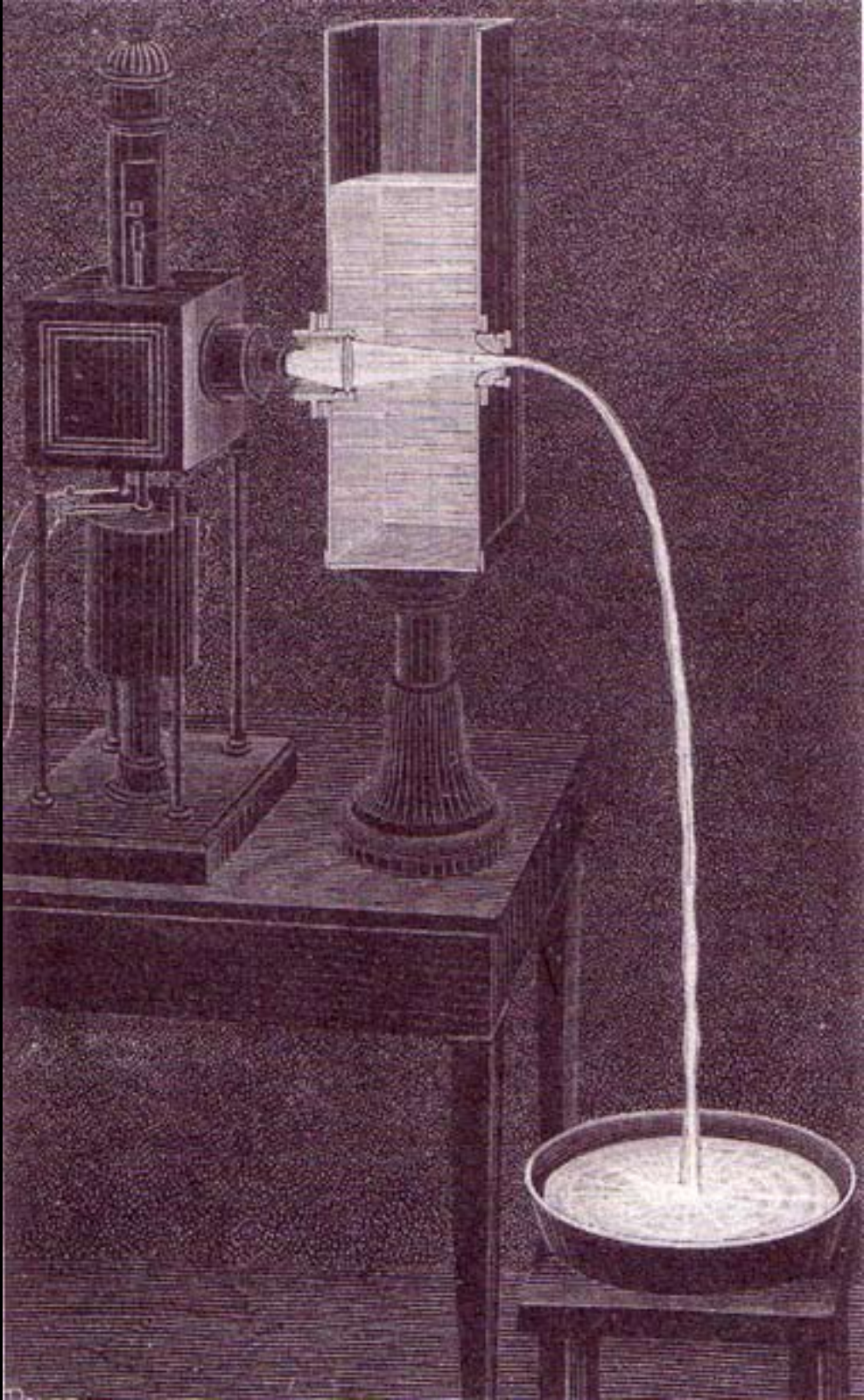
**Dr. Ray Mariella (LLNL)**

**Liu Liu (Zhejiang University)**

***“I managed to illuminate the interior of a stream in a dark space. I have discovered that this strange arrangement offers one of the most beautiful, and most curious experiments that one can perform in a course on Optics.”***

**Daniel Colladon, *Comptes Rendus*, 15, 800–802 (1842)**





D. Colladon, *La Nature*, 325 (1884)

W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.

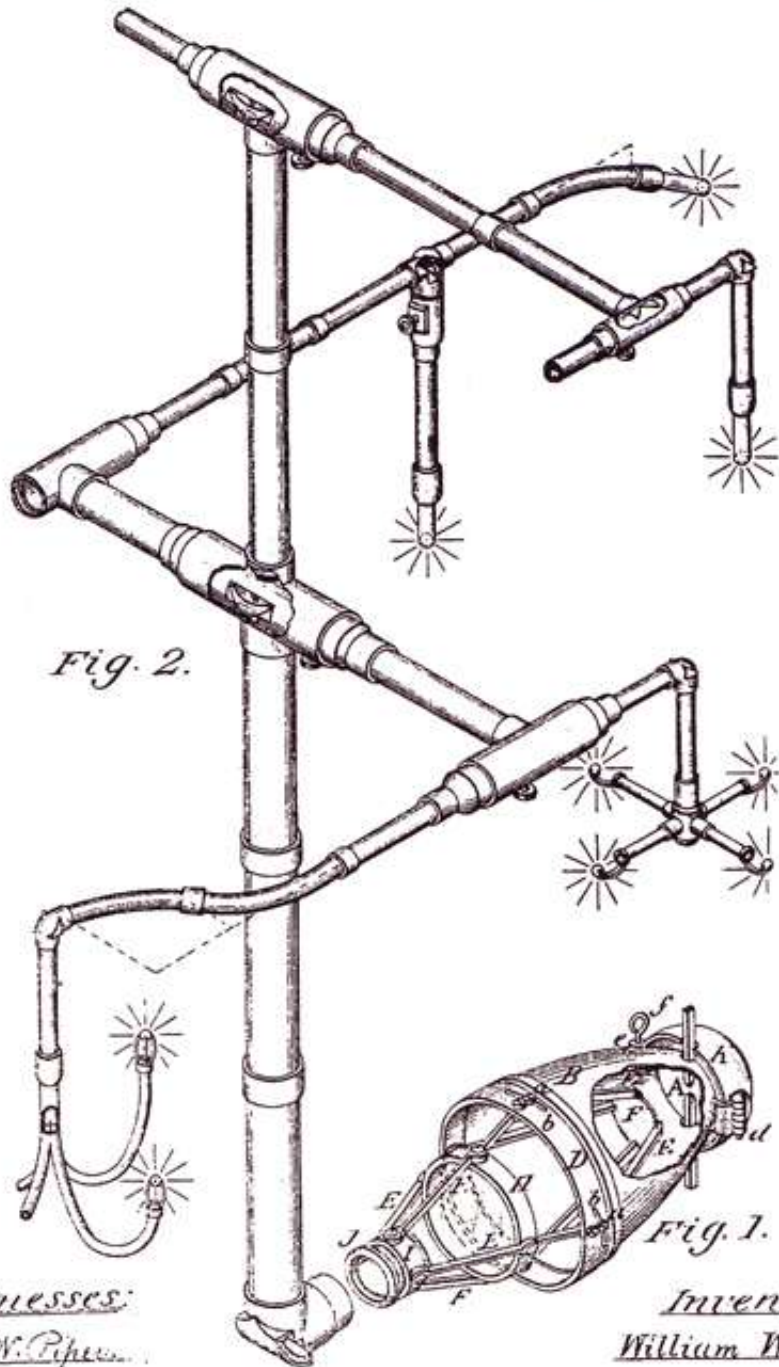


Fig. 2.

Fig. 1.

Witnesses:  
*J. W. Piper*  
*Ed. [unclear]*

Inventor:  
*William Wheeler*  
 by attorney  
*[unclear]*

US Patent 247, 229 (1881)





# Waveguiding

single mode condition for 600-nm light:

$$M \doteq 2 \frac{d}{\lambda} (n_1^2 - n_2^2)^{1/2}$$

without cladding:  $d < 268 \text{ nm}$

Add cladding with 0.4% index difference:

$$d < 5 \text{ } \mu\text{m}$$

# Waveguiding

commercial single-mode fiber (Corning Titan<sup>®</sup>)



	core	cladding
index	$n_1 = 1.468$	$n_2 = 1.462$
diameter:	$8.3 \mu\text{m}$	$125.0 \pm 1.0 \mu\text{m}$

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

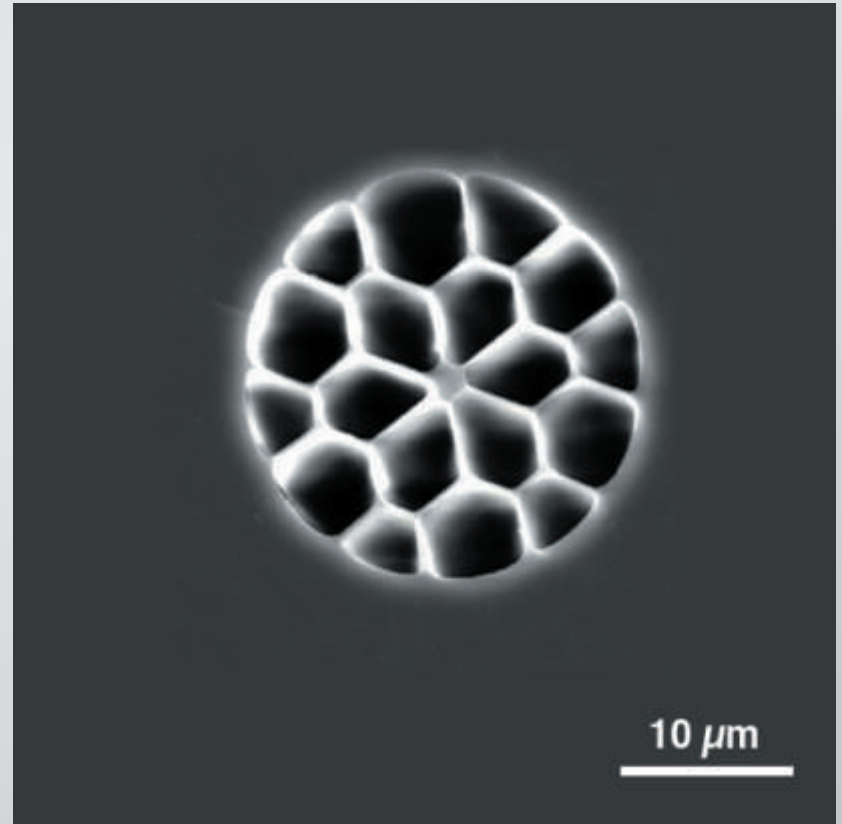
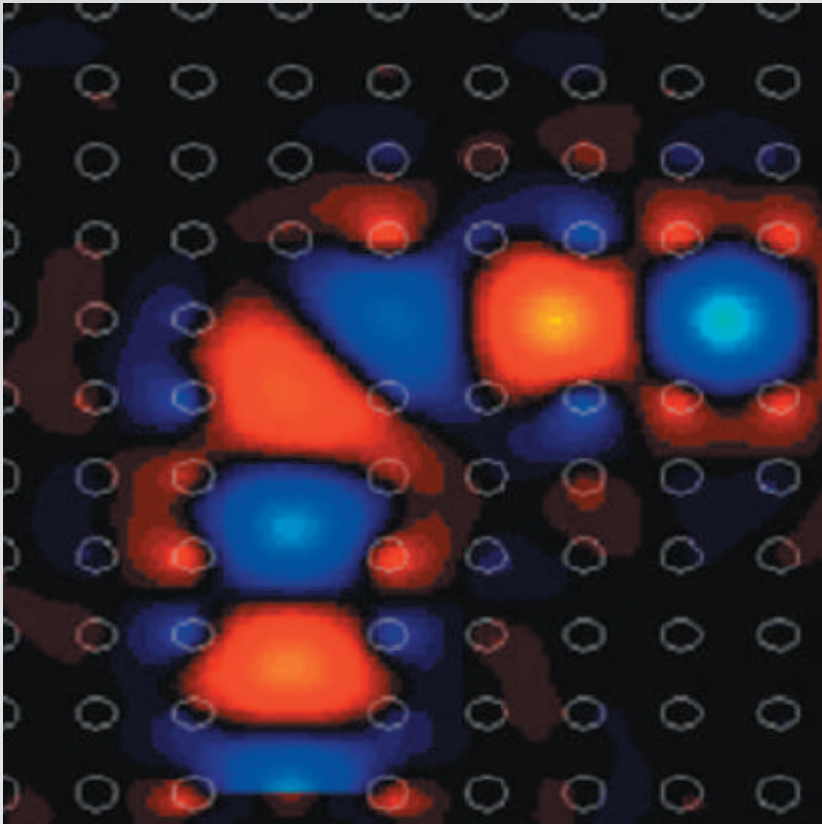
# Waveguiding

**drawbacks of clad fibers:**

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



# Waveguiding



# Outline

- **silica nanowires**
- **optical properties**
- **nonlinear properties**

# Silica nanowires

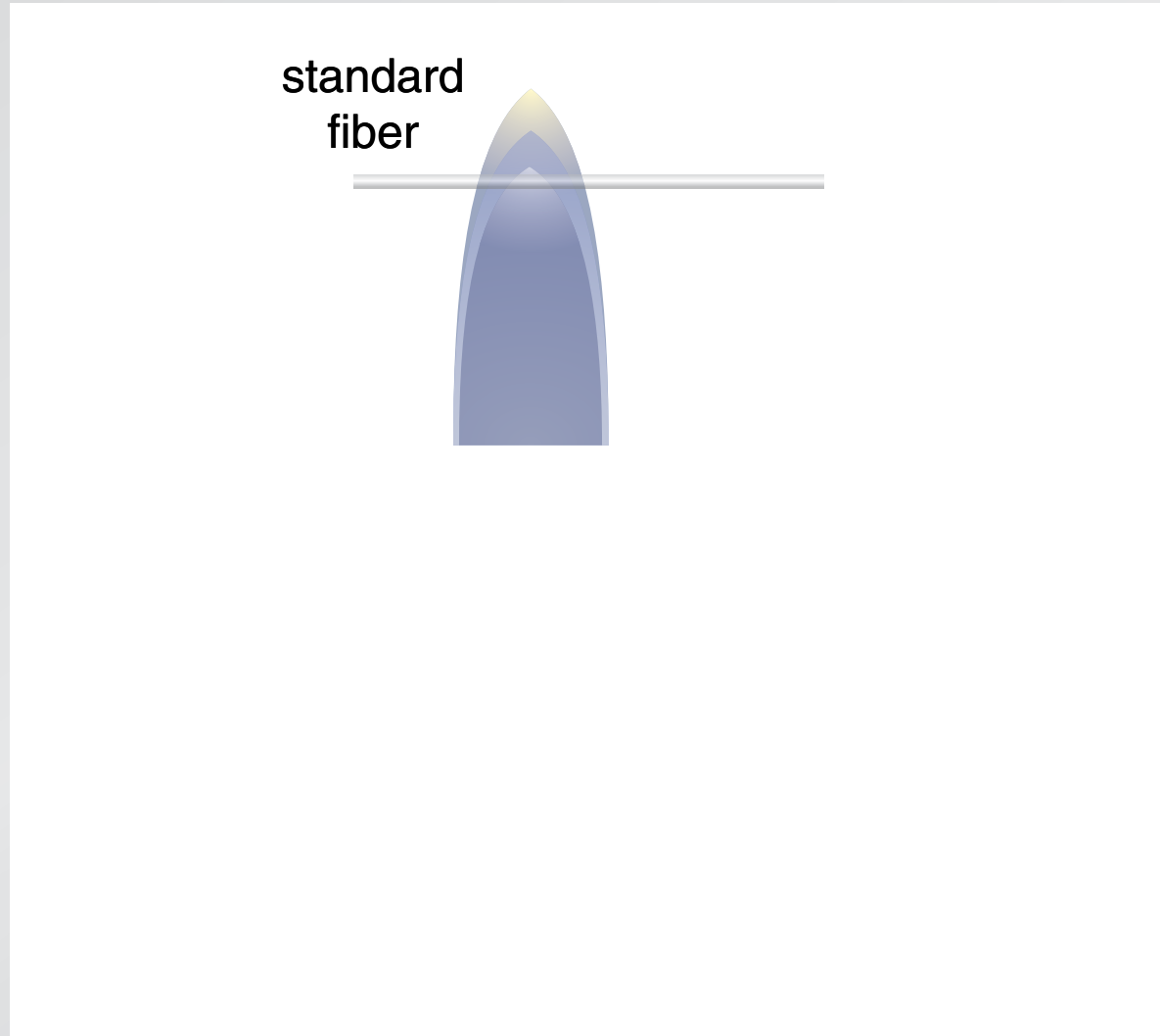
two-step drawing process

standard  
fiber



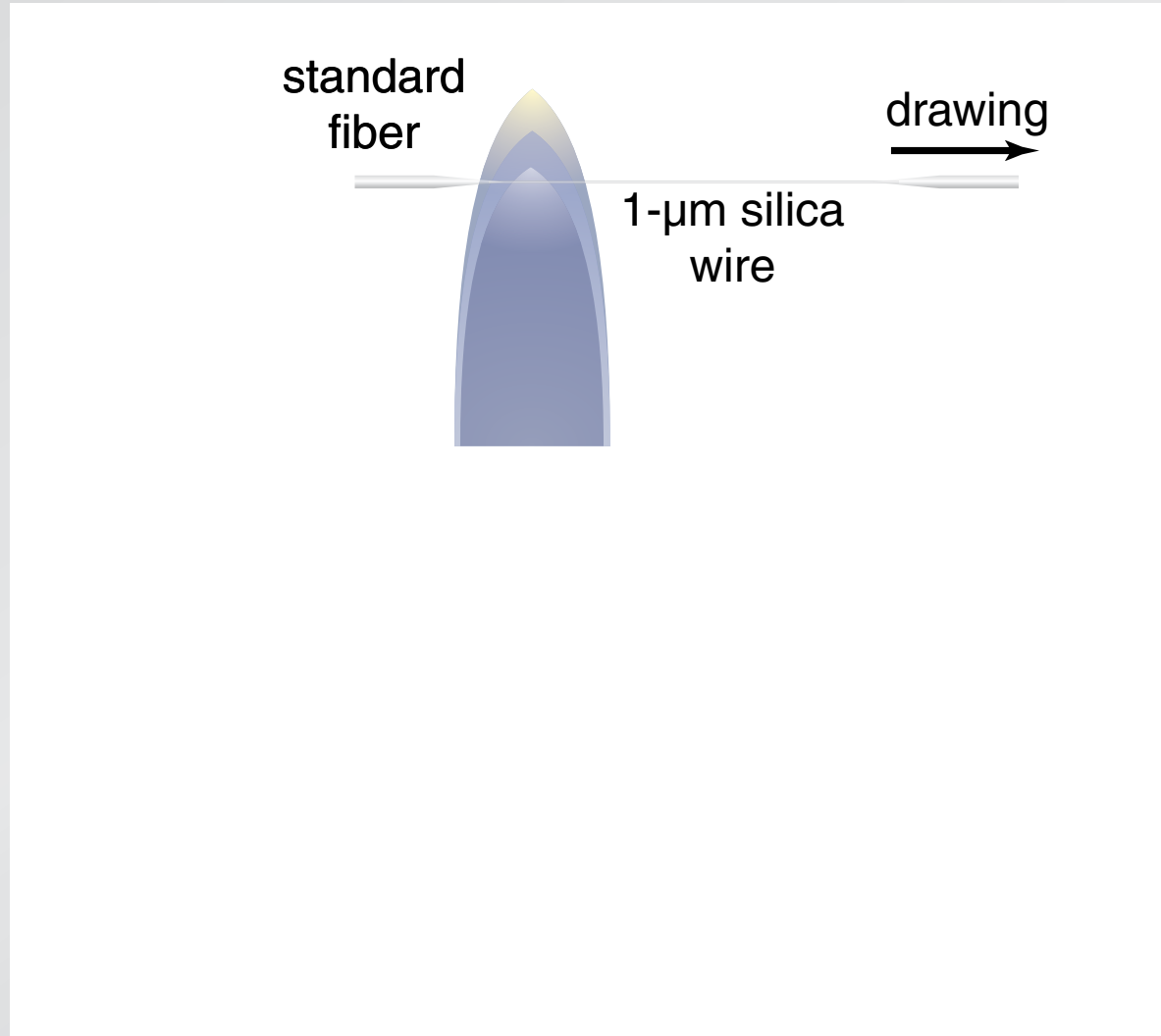
# Silica nanowires

two-step drawing process



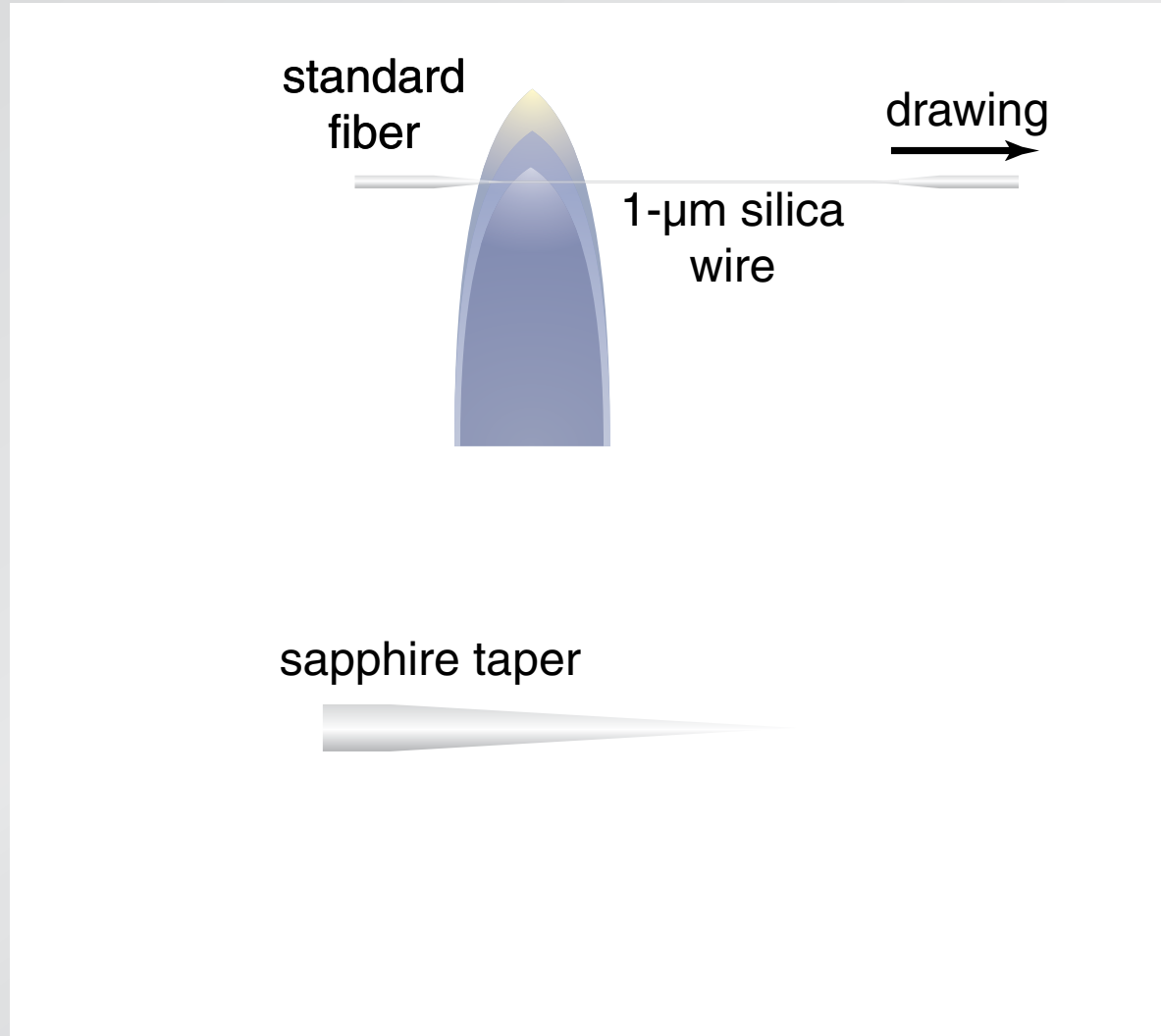
# Silica nanowires

two-step drawing process



# Silica nanowires

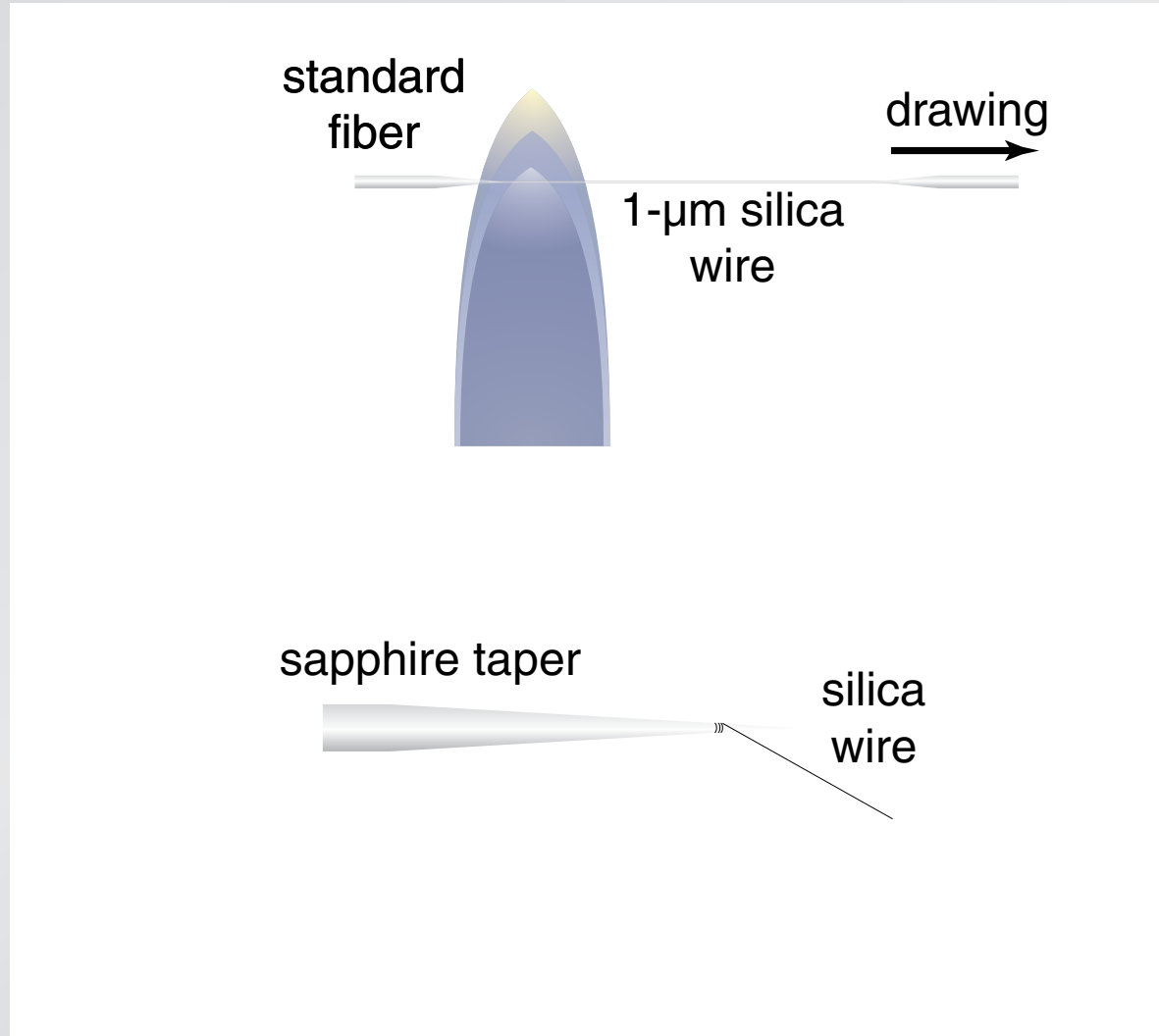
two-step drawing process





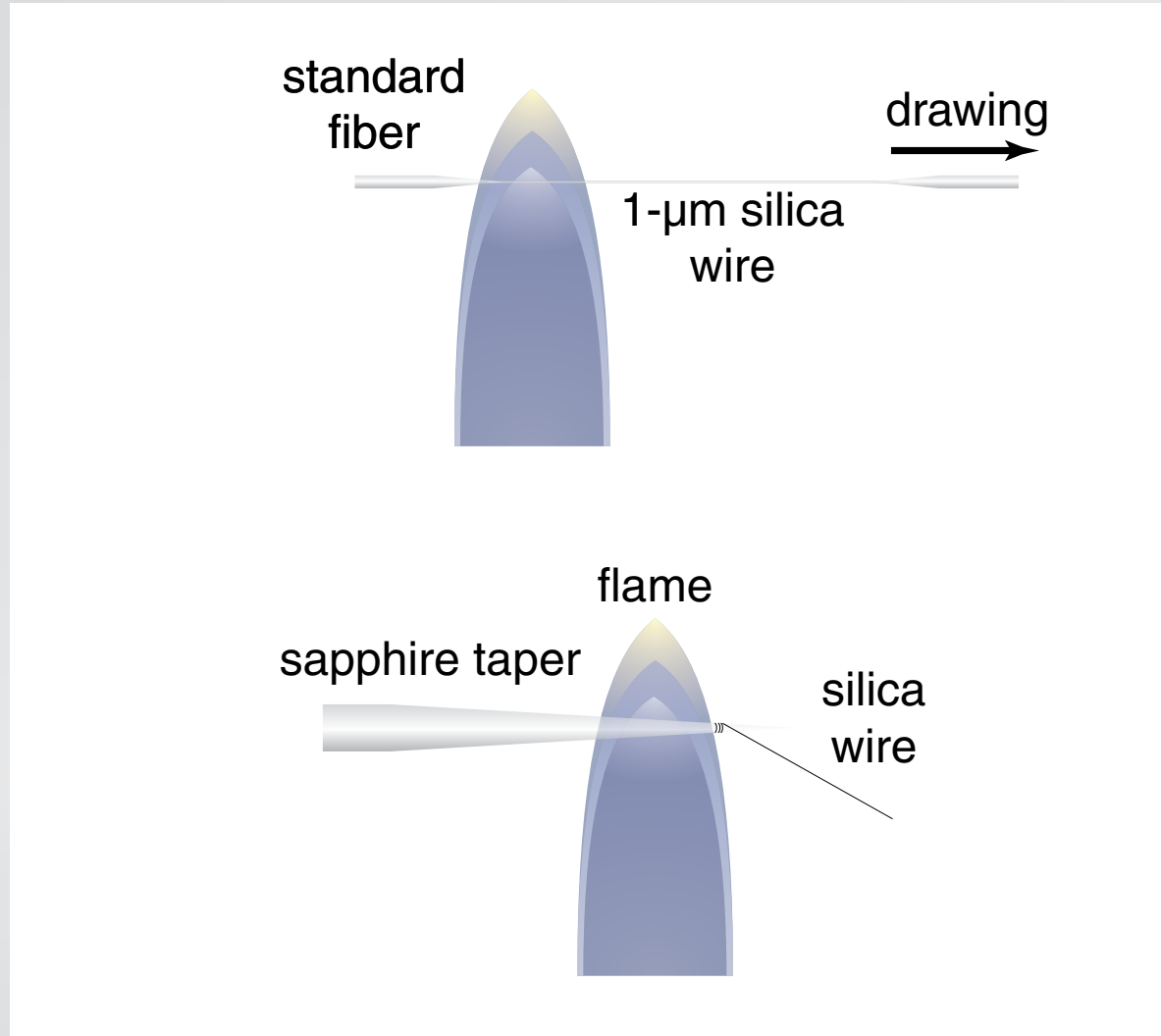
# Silica nanowires

## two-step drawing process



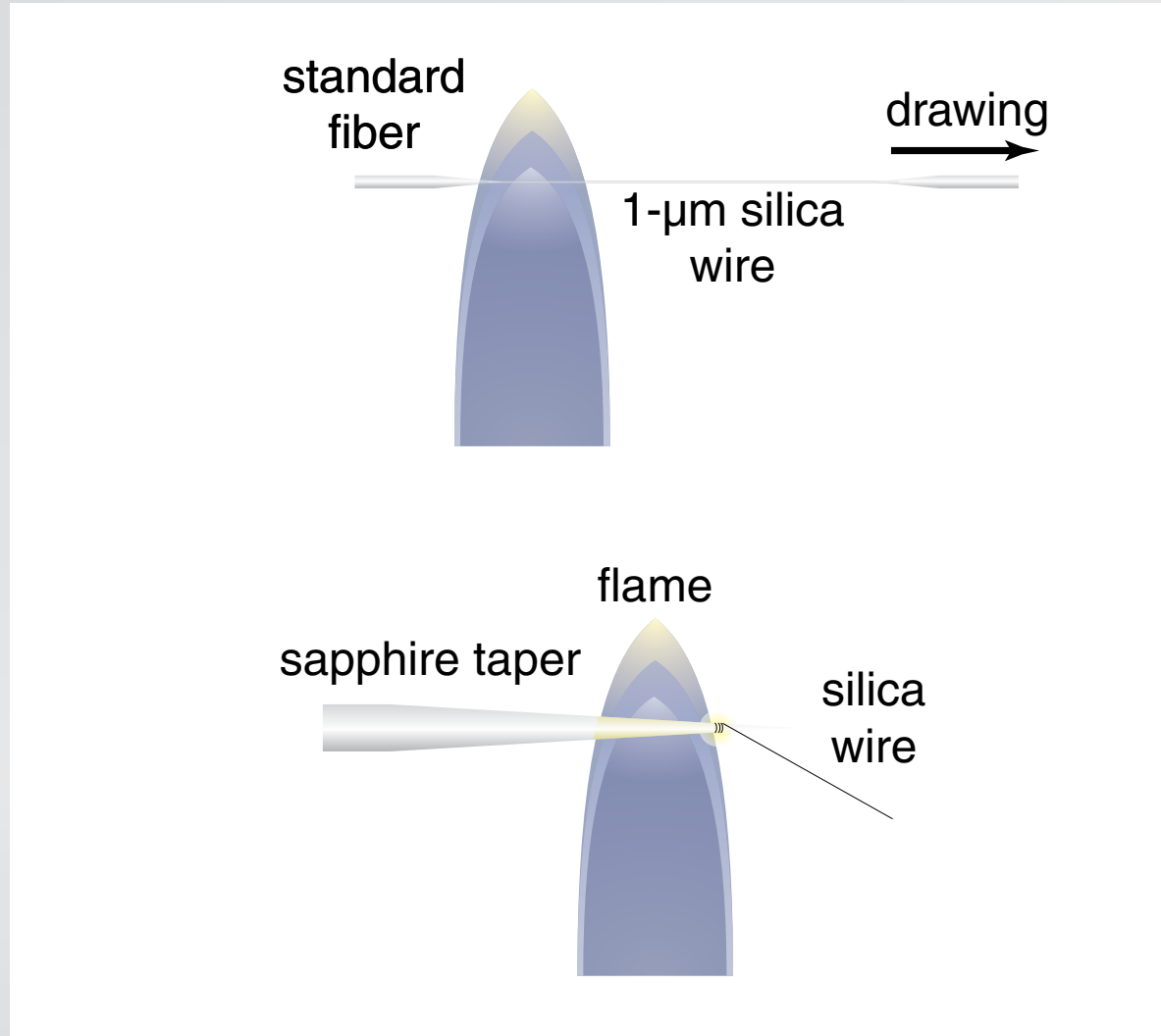
# Silica nanowires

## two-step drawing process



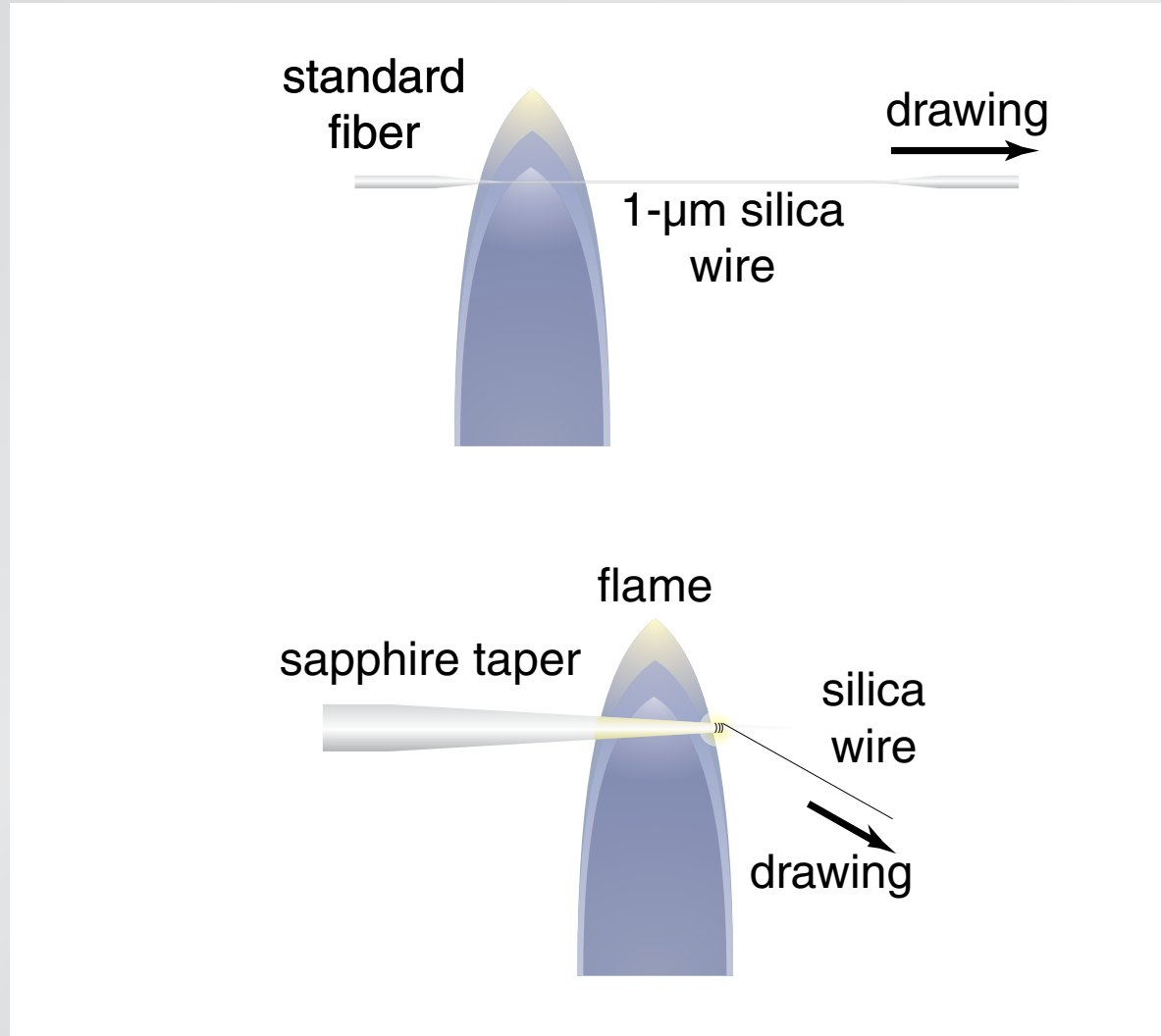
# Silica nanowires

## two-step drawing process



# Silica nanowires

## two-step drawing process



# Silica nanowires





# Silica nanowires

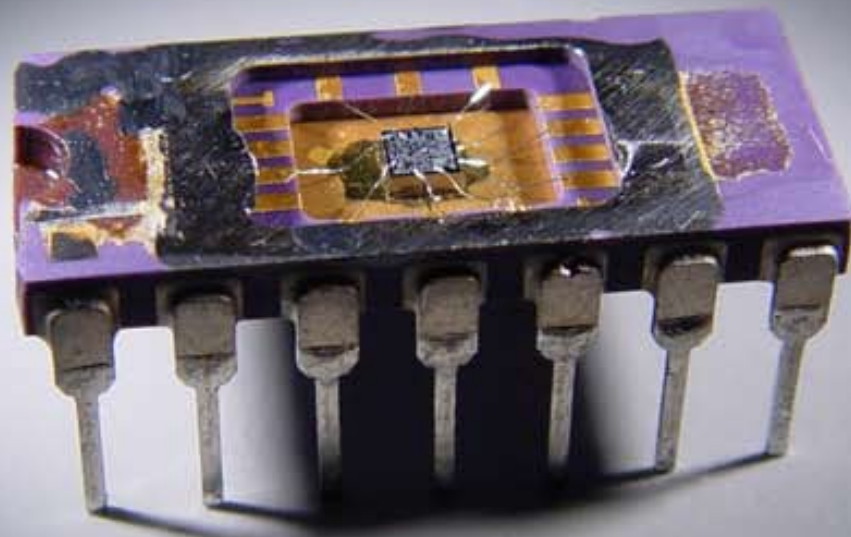
1  $\mu\text{m}$



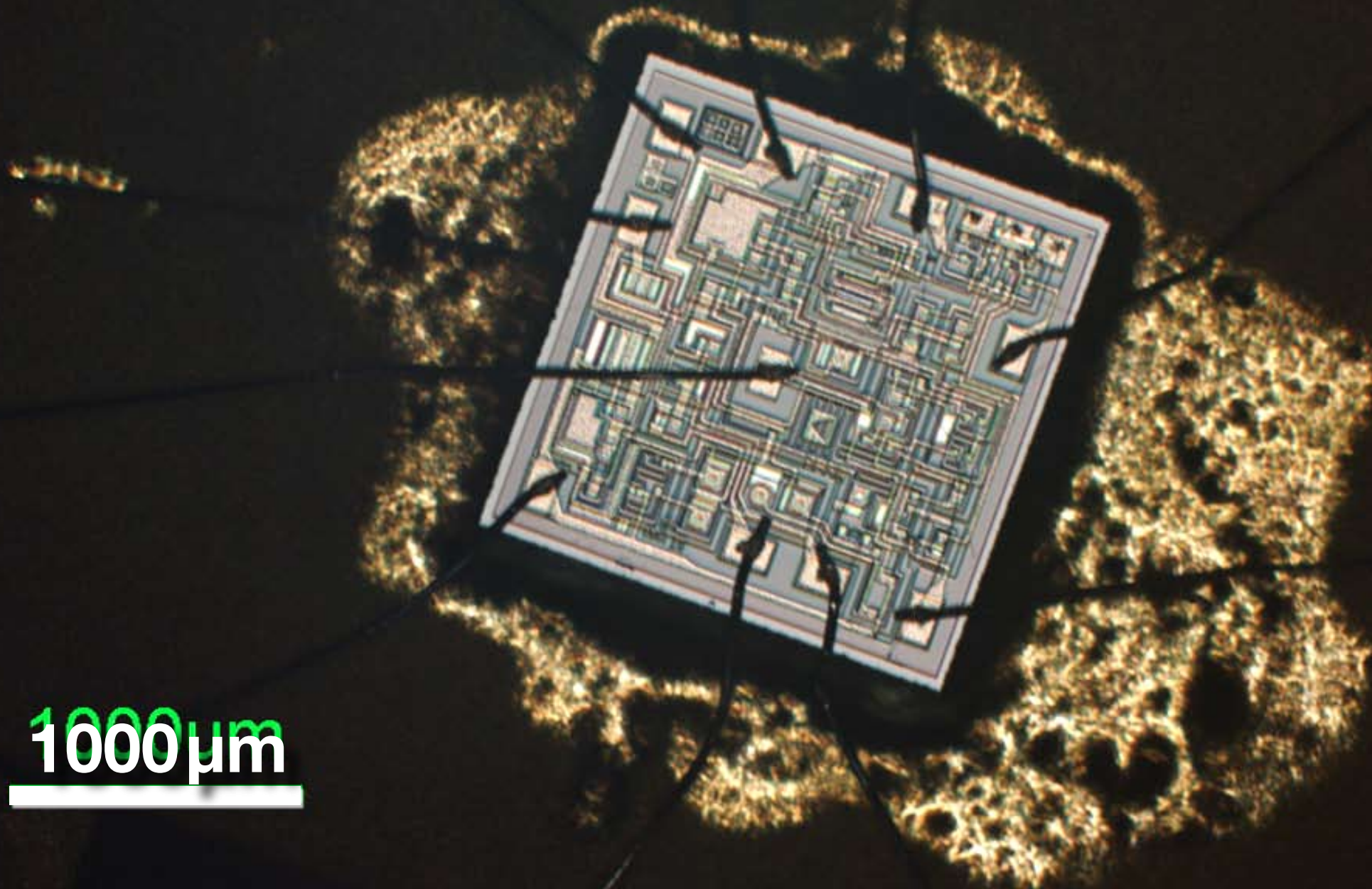
*Nature*, 426, 816 (2003)



# Silica nanowires



# Silica nanowires

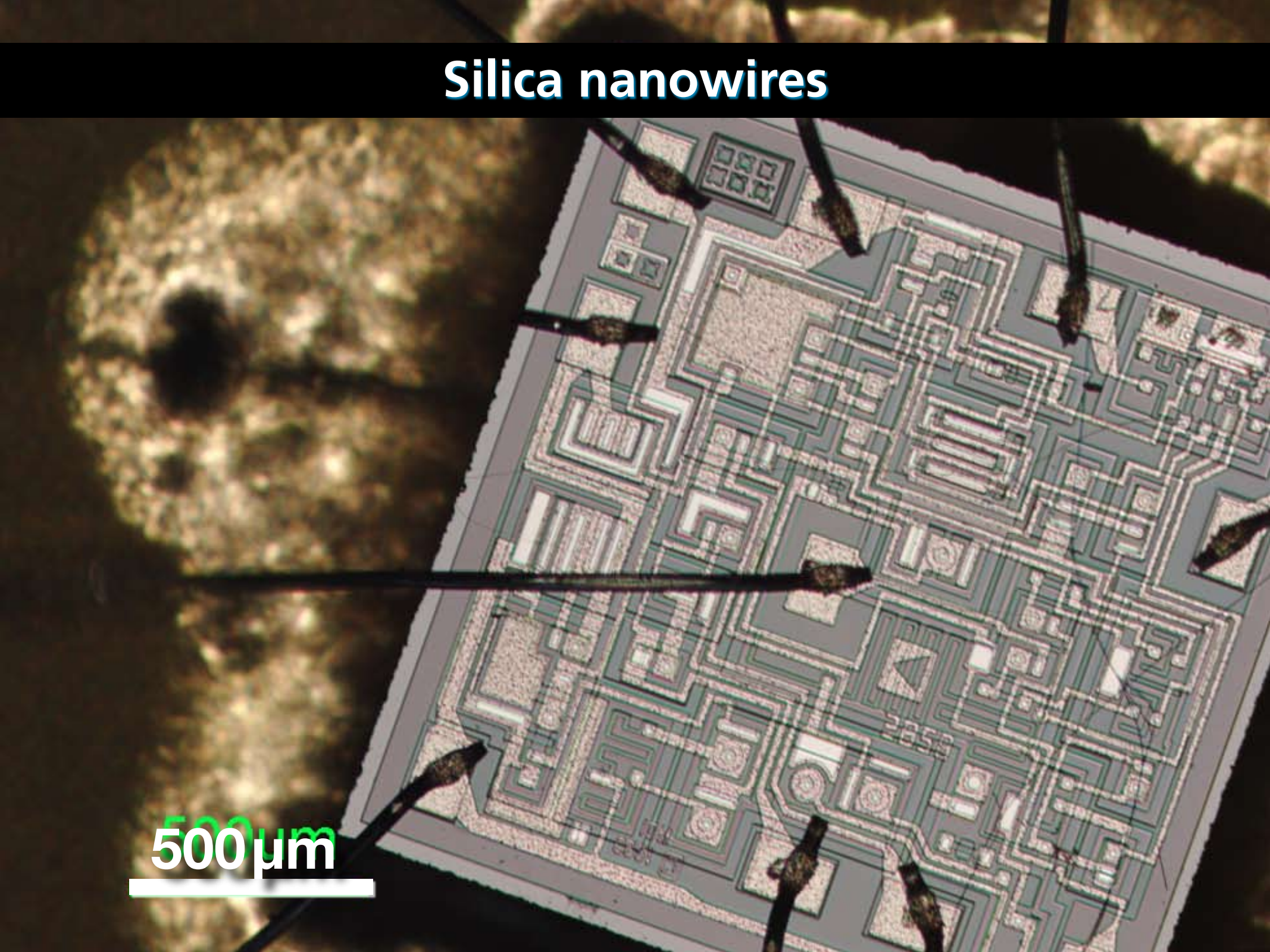


1000 μm



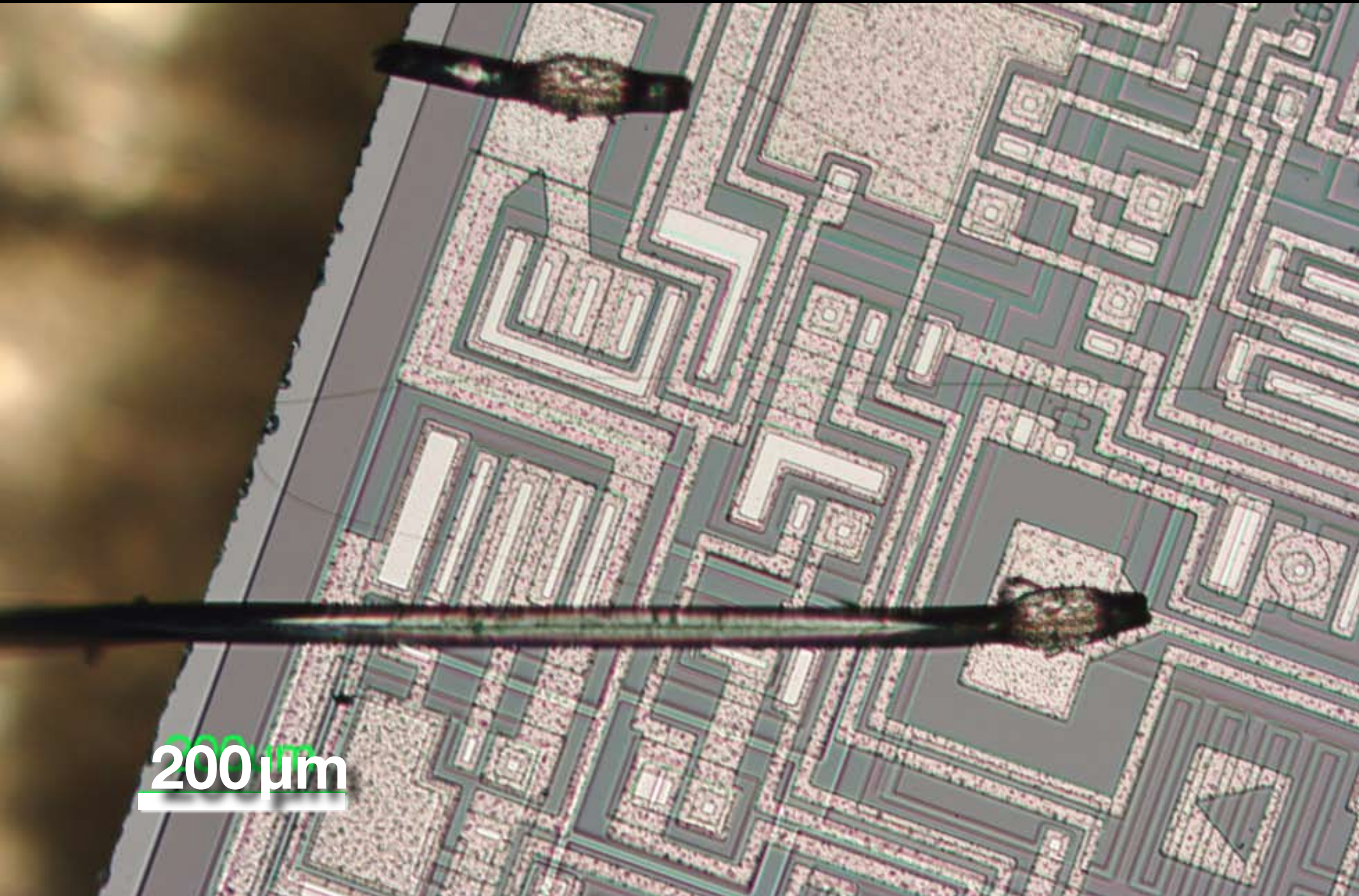
# Silica nanowires

500  $\mu\text{m}$





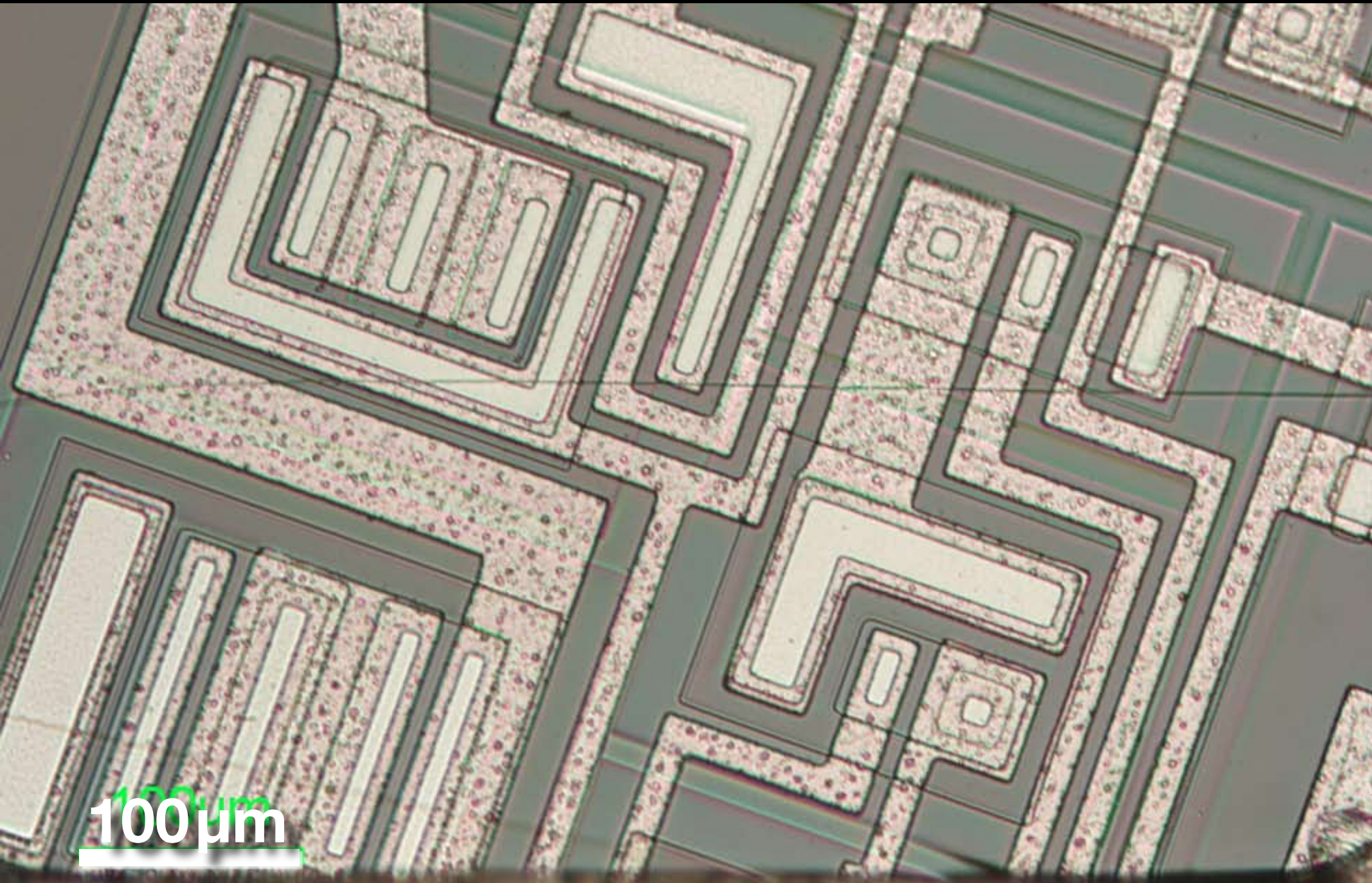
# Silica nanowires



200  $\mu\text{m}$

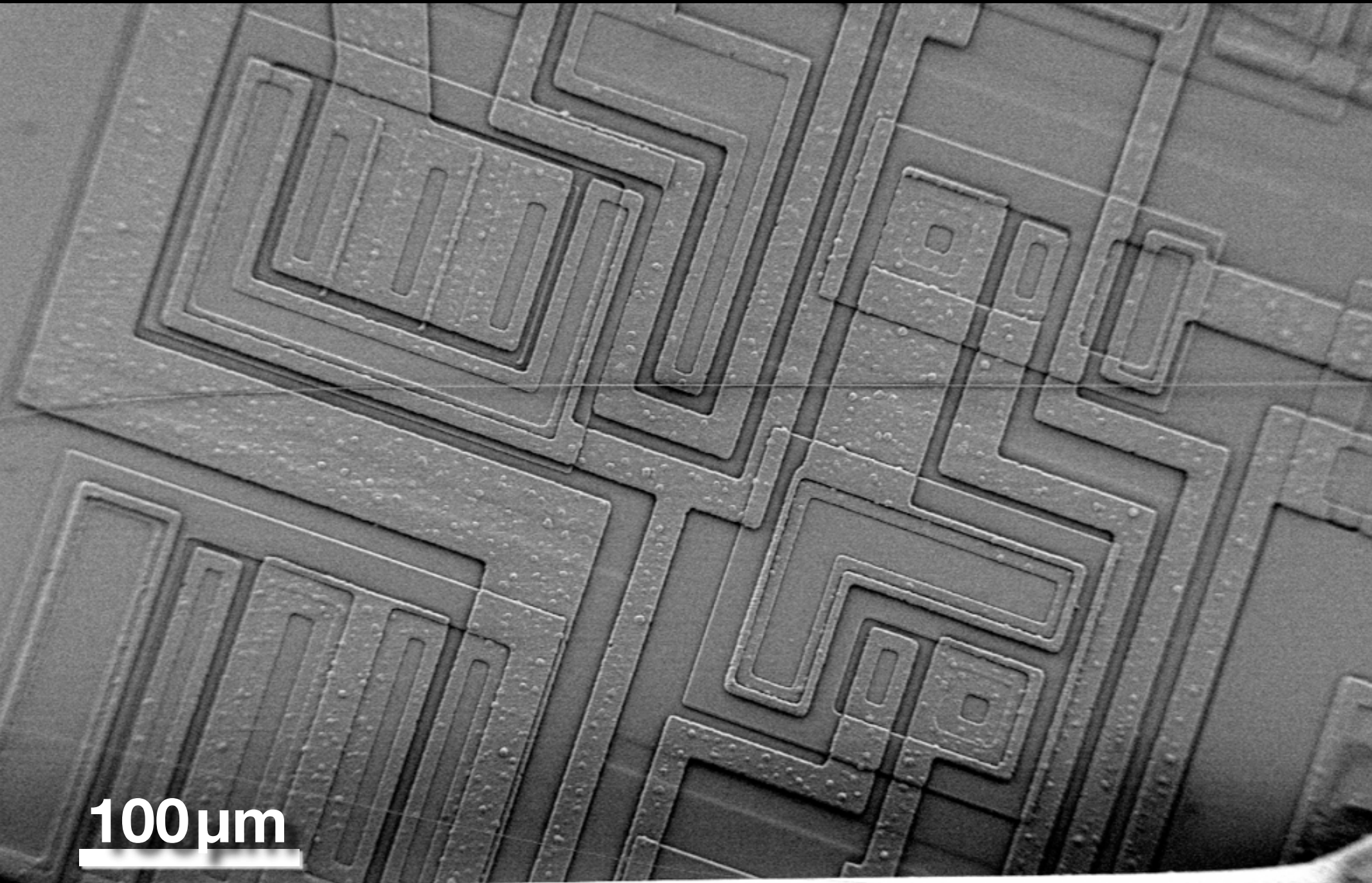


# Silica nanowires





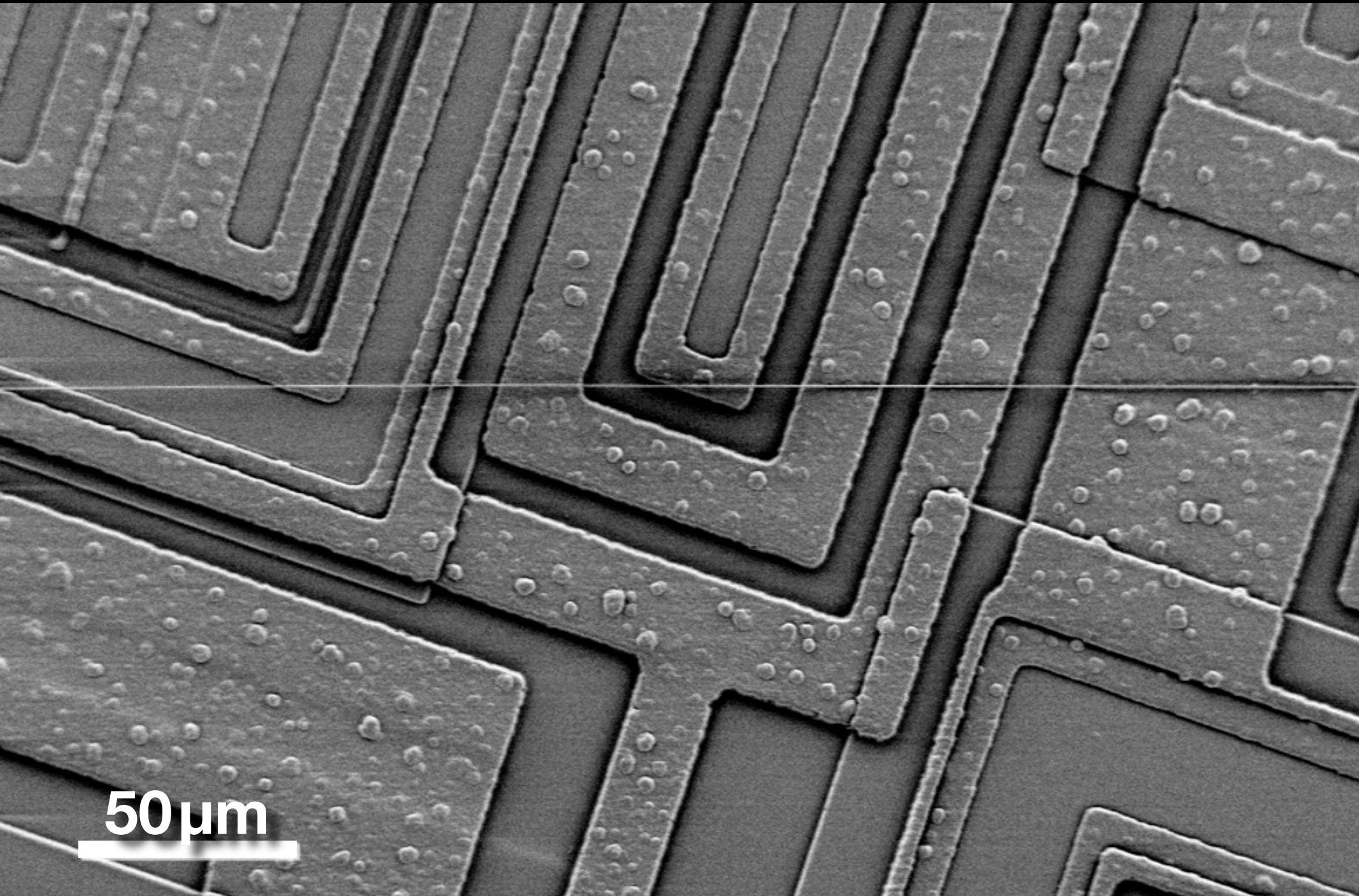
# Silica nanowires



100  $\mu\text{m}$



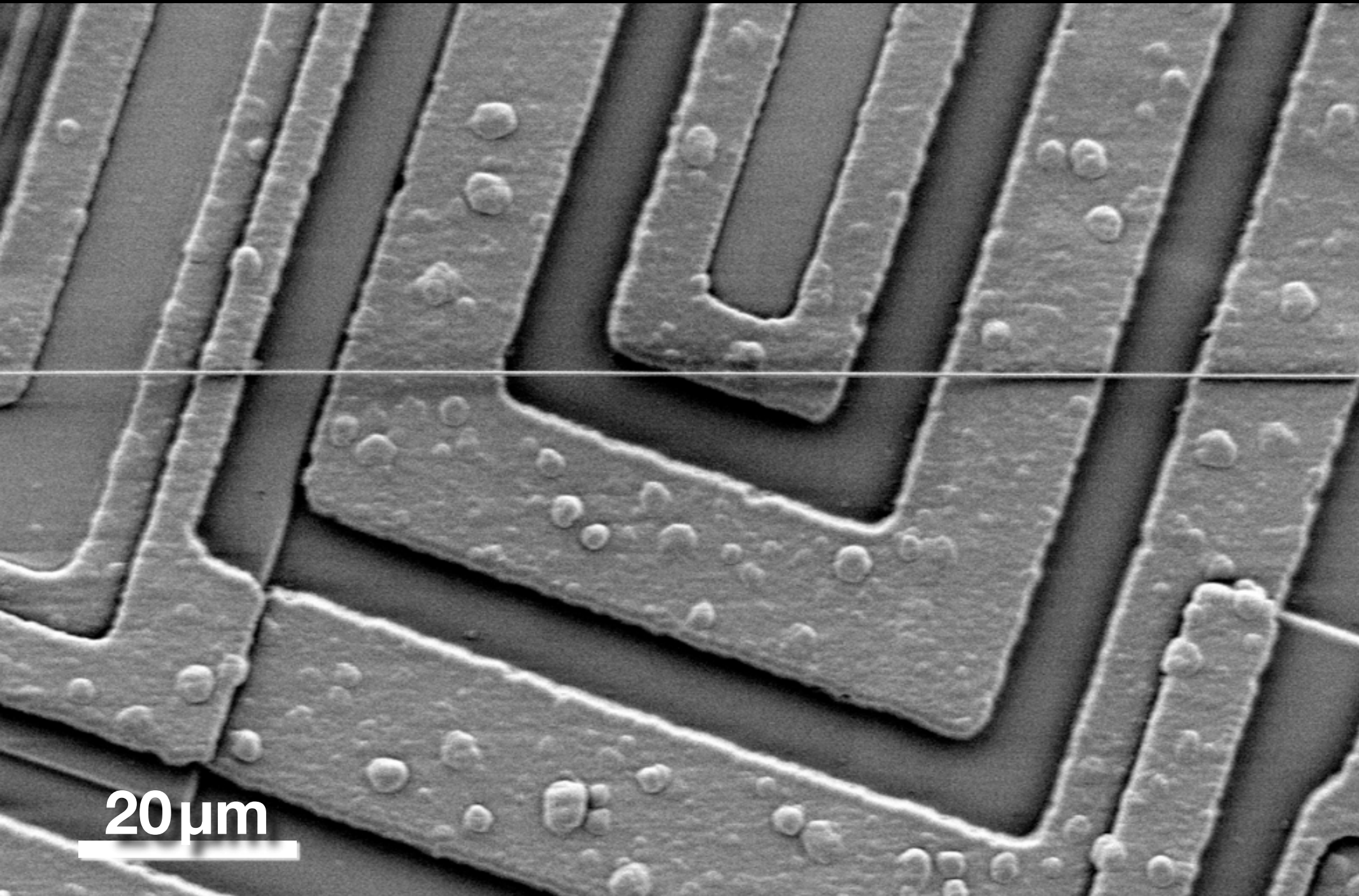
# Silica nanowires



50  $\mu\text{m}$



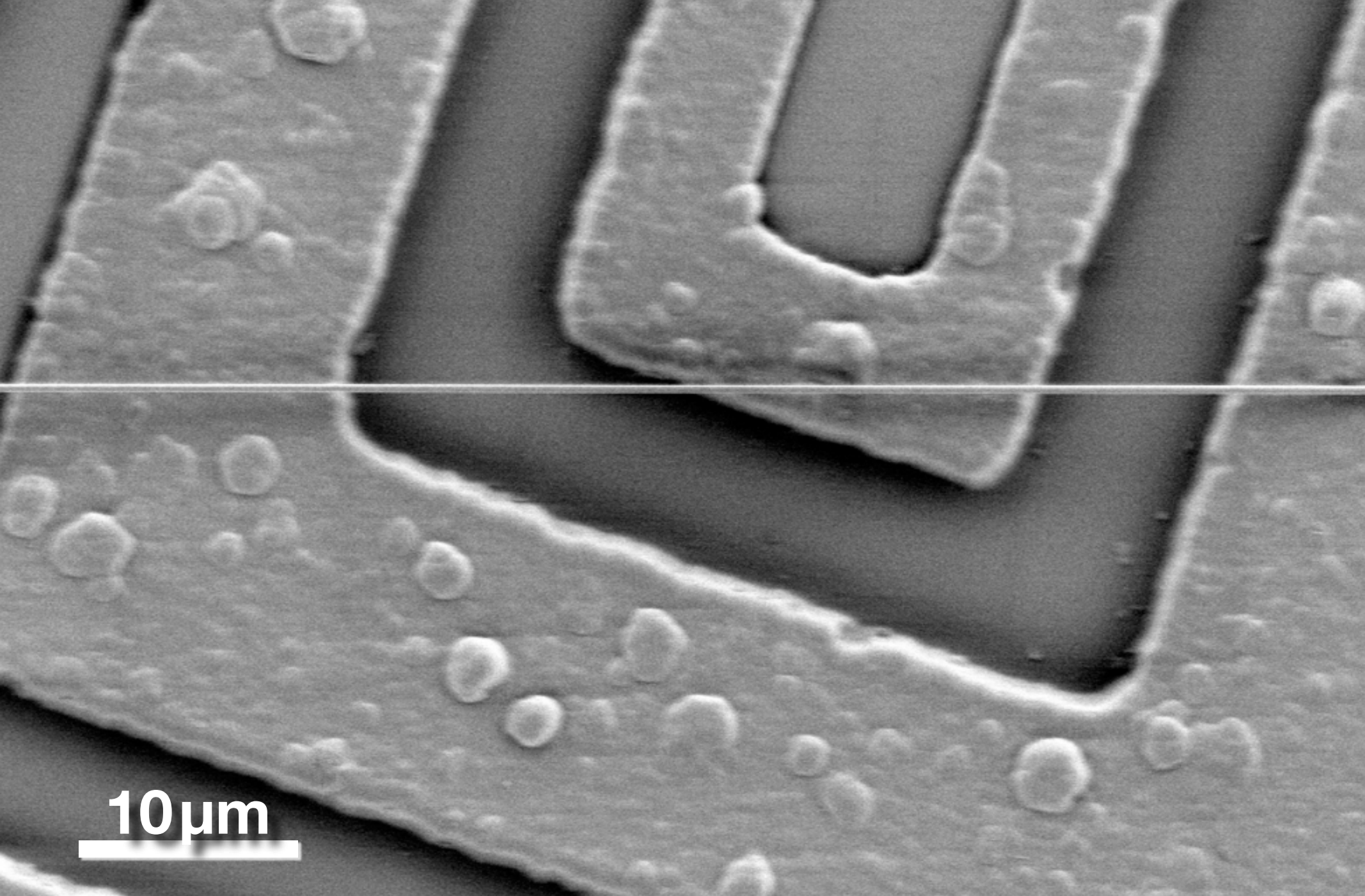
# Silica nanowires



20  $\mu\text{m}$

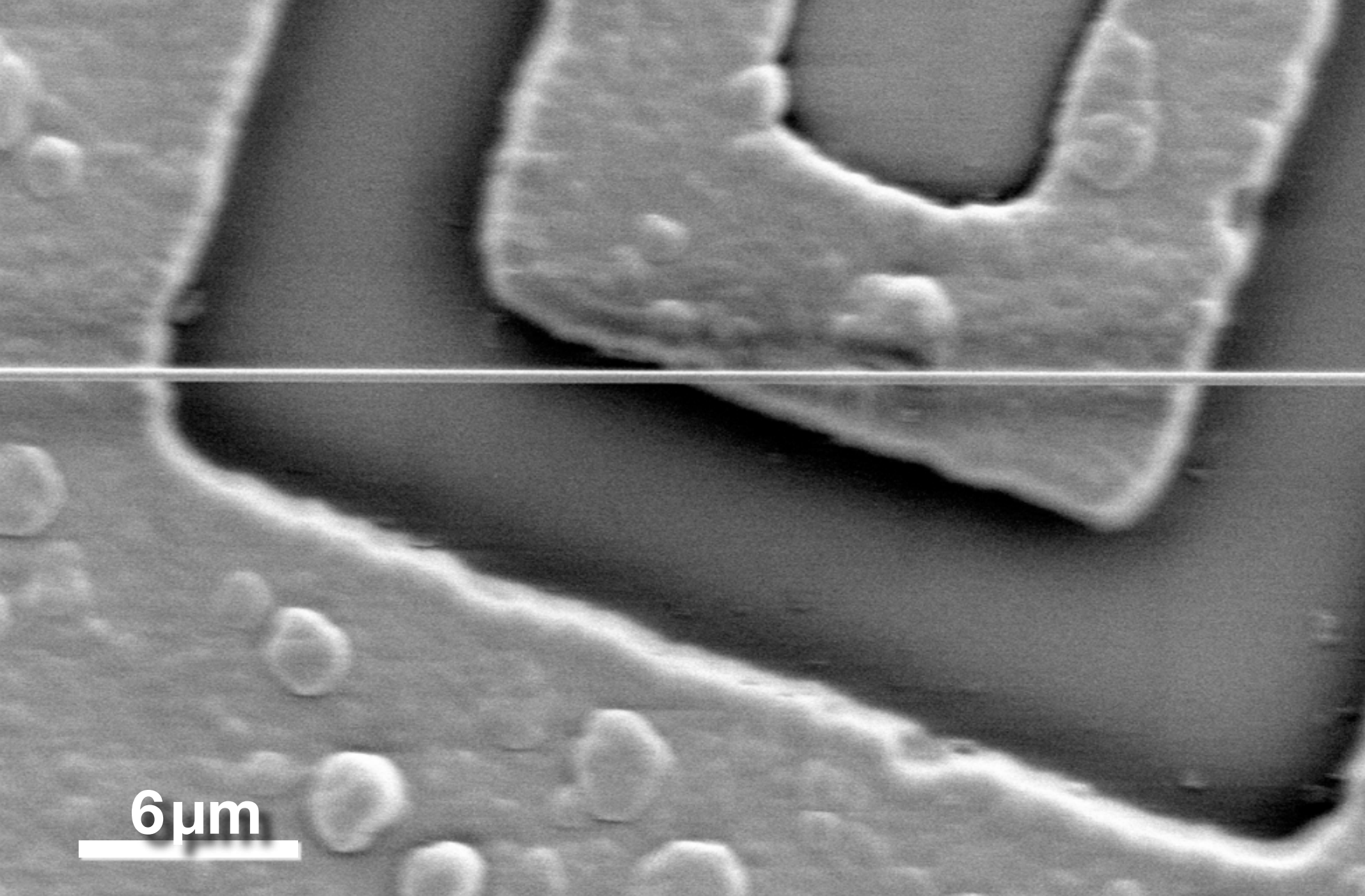


# Silica nanowires



10  $\mu\text{m}$

# Silica nanowires



6  $\mu\text{m}$



# Silica nanowires

4  $\mu\text{m}$

This scanning electron microscope (SEM) image displays silica nanowires. A single, thin nanowire is clearly visible, extending horizontally across the middle of the frame. The background shows larger, more irregular silica structures. A scale bar in the bottom left corner indicates a length of 4 micrometers.



# Silica nanowires

2  $\mu\text{m}$

A grayscale micrograph showing a single, long, thin silica nanowire oriented horizontally across the center of the frame. The nanowire is very uniform in thickness and extends across most of the width of the image. In the bottom-left corner, there is a white horizontal scale bar with the text "2 μm" positioned above it.



# Silica nanowires

312 nm

A transmission electron micrograph (TEM) showing a single silica nanowire. The nanowire is a bright, horizontal 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 nanowire has a smooth surface and a uniform diameter.

1  $\mu\text{m}$

A white horizontal scale bar located in the bottom left corner of the image, representing a length of 1 micrometer.

# Silica nanowires

## Specifications

diameter  $D$ : down to 20 nm

length  $L$ : up to 90 mm

aspect ratio  $D/L$ : up to  $10^6$

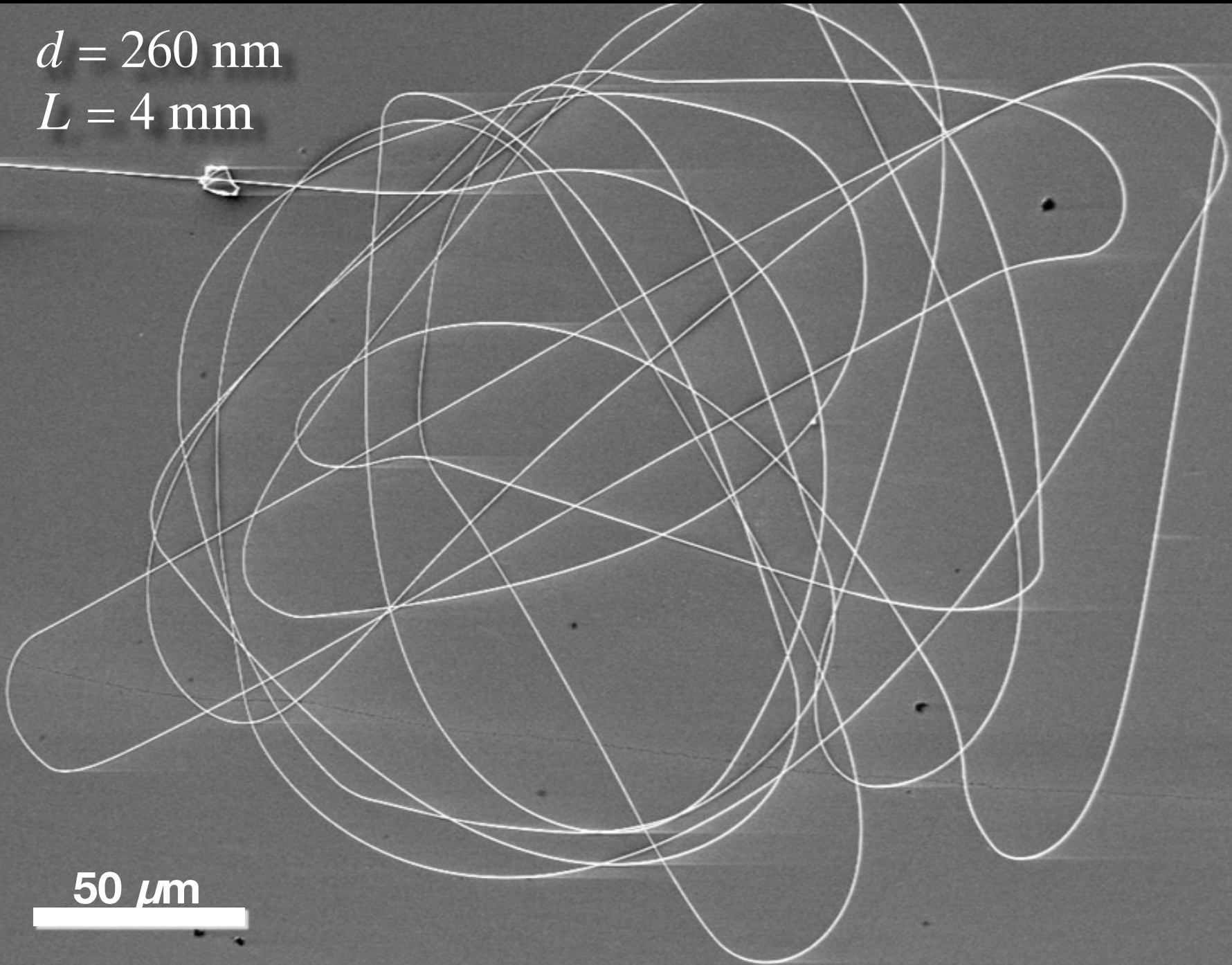
diameter uniformity  $\Delta D/L$ :  $2 \times 10^{-6}$



# Silica nanowires

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



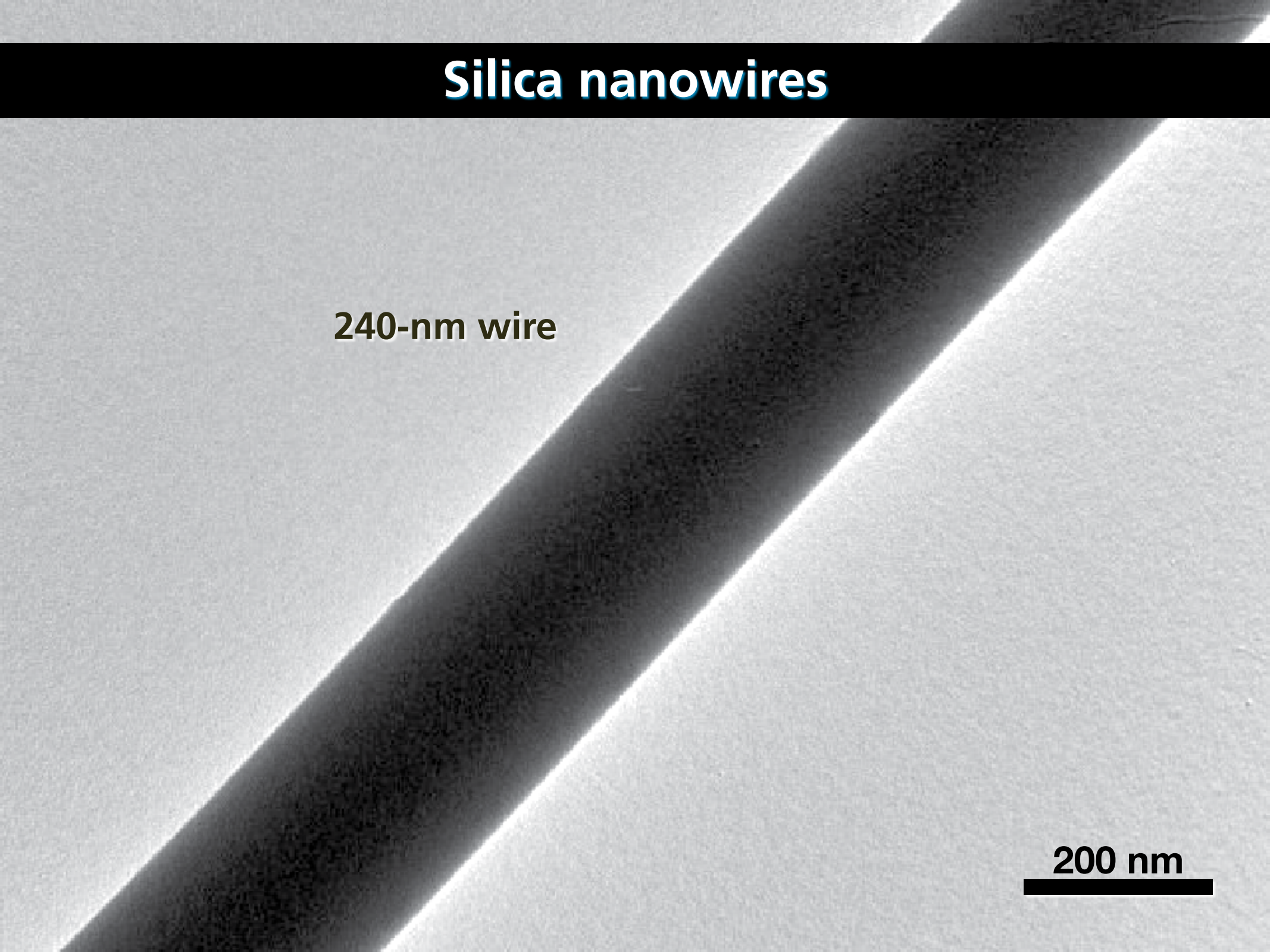
50  $\mu\text{m}$



# Silica nanowires

240-nm wire

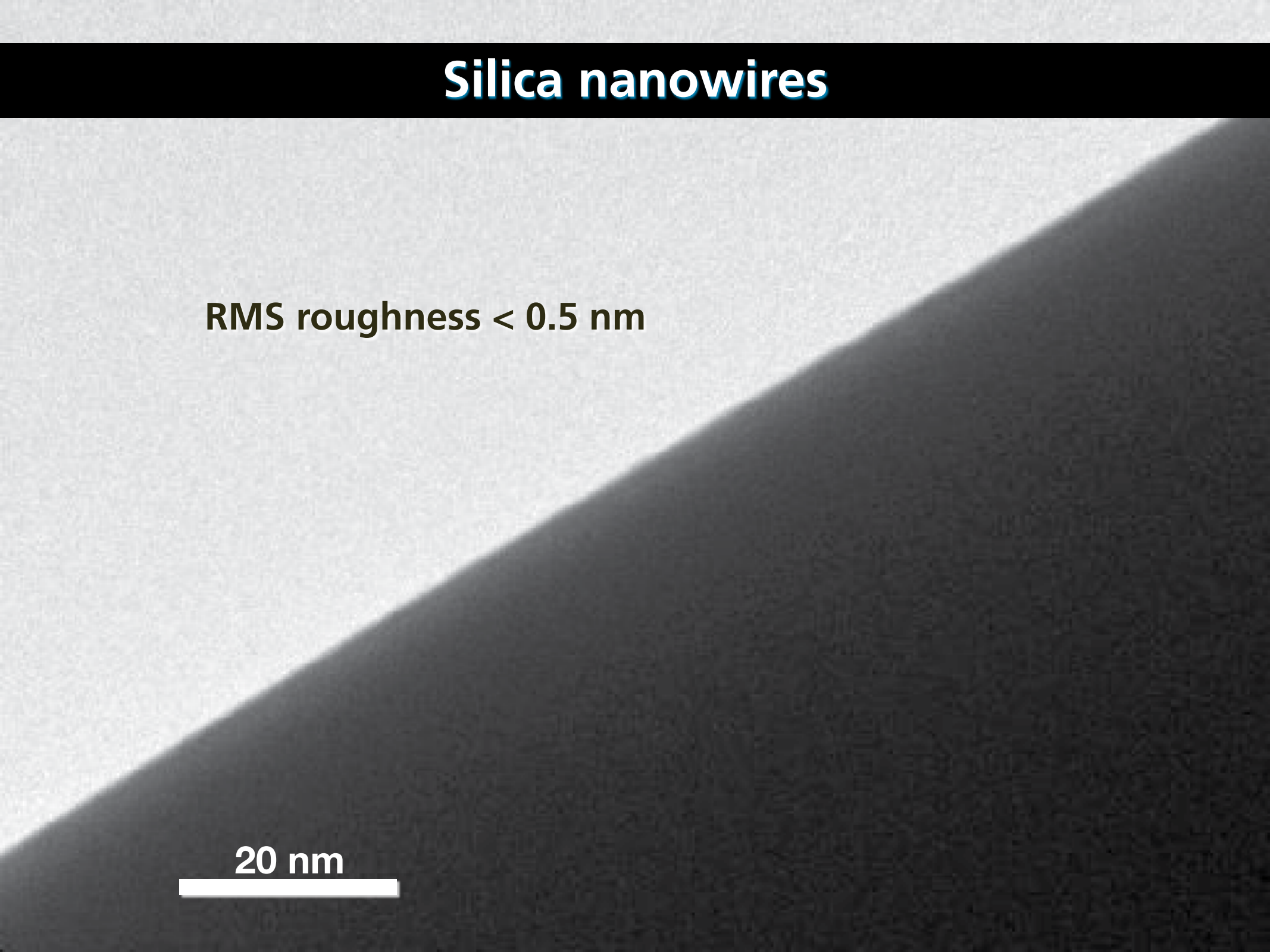
200 nm

A transmission electron micrograph (TEM) showing a single, dark, cylindrical silica nanowire oriented diagonally across the frame. The wire has a uniform diameter and a smooth surface. The background is a light gray, textured surface. A scale bar in the bottom right corner indicates a length of 200 nm. The text '240-nm wire' is positioned to the left of the wire, and the title 'Silica nanowires' is at the top.

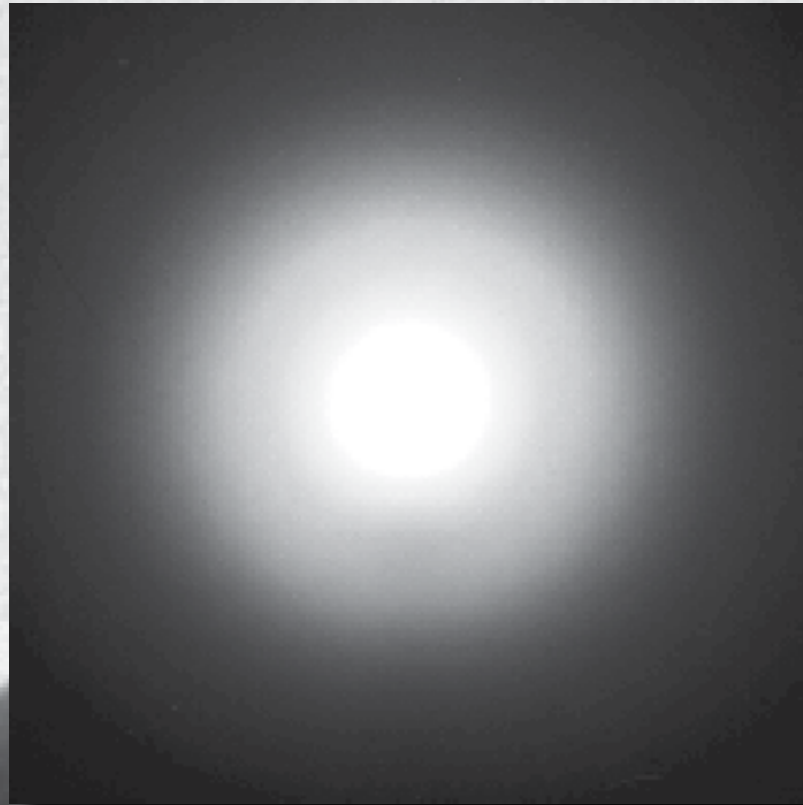
# Silica nanowires

RMS roughness < 0.5 nm

20 nm



# Silica nanowires

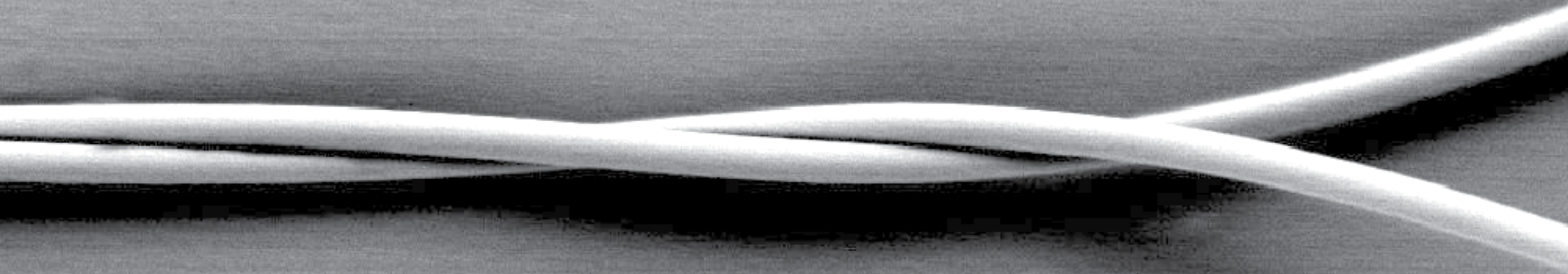


20 nm





# Silica nanowires

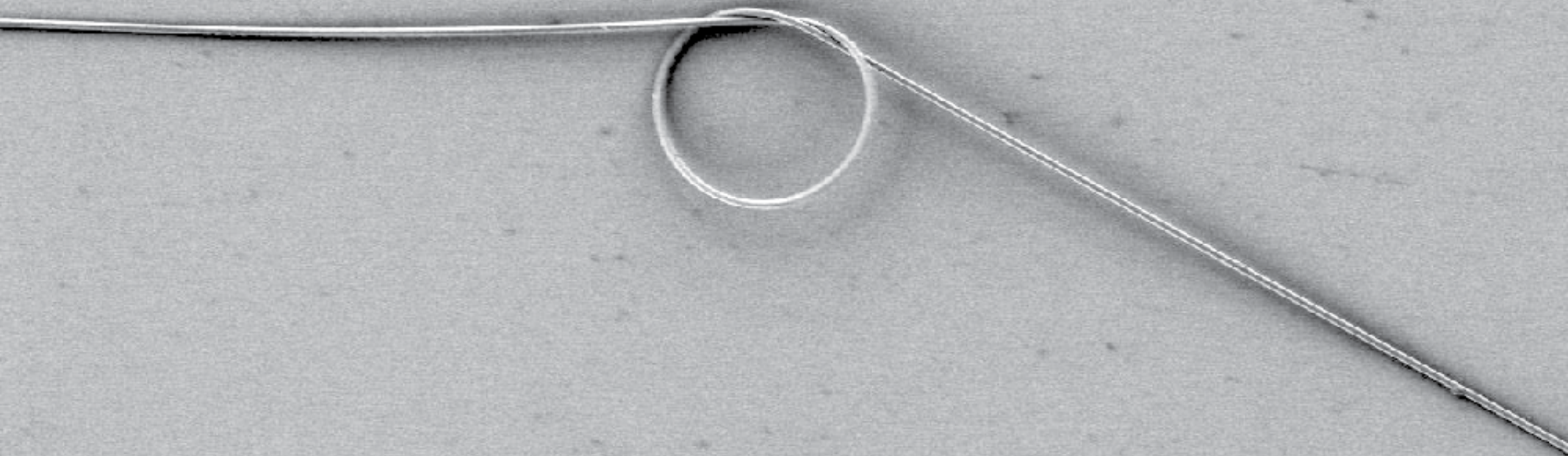


2  $\mu\text{m}$

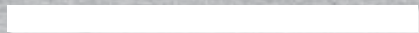




# Silica nanowires



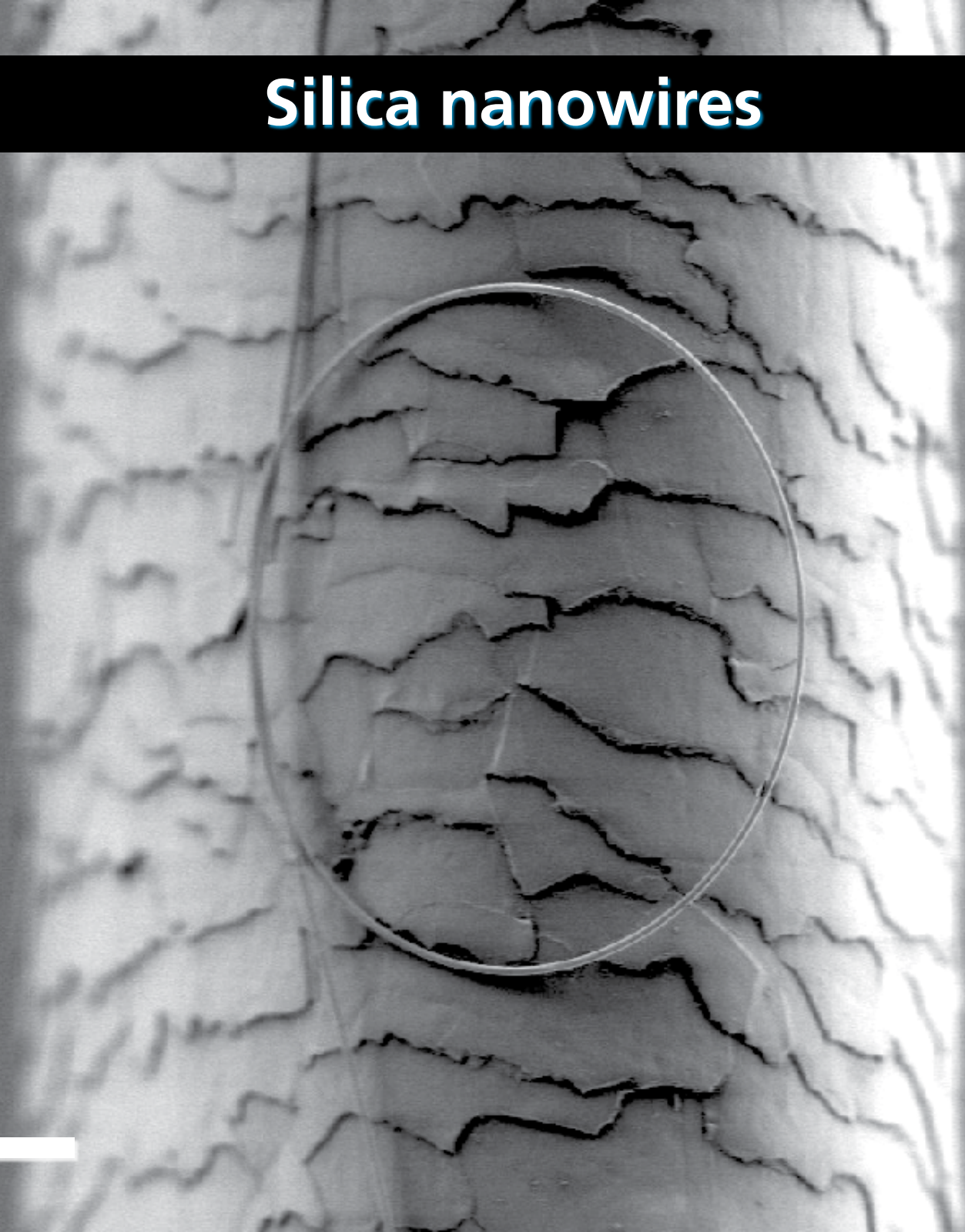
20  $\mu\text{m}$





# Silica nanowires

20  $\mu\text{m}$



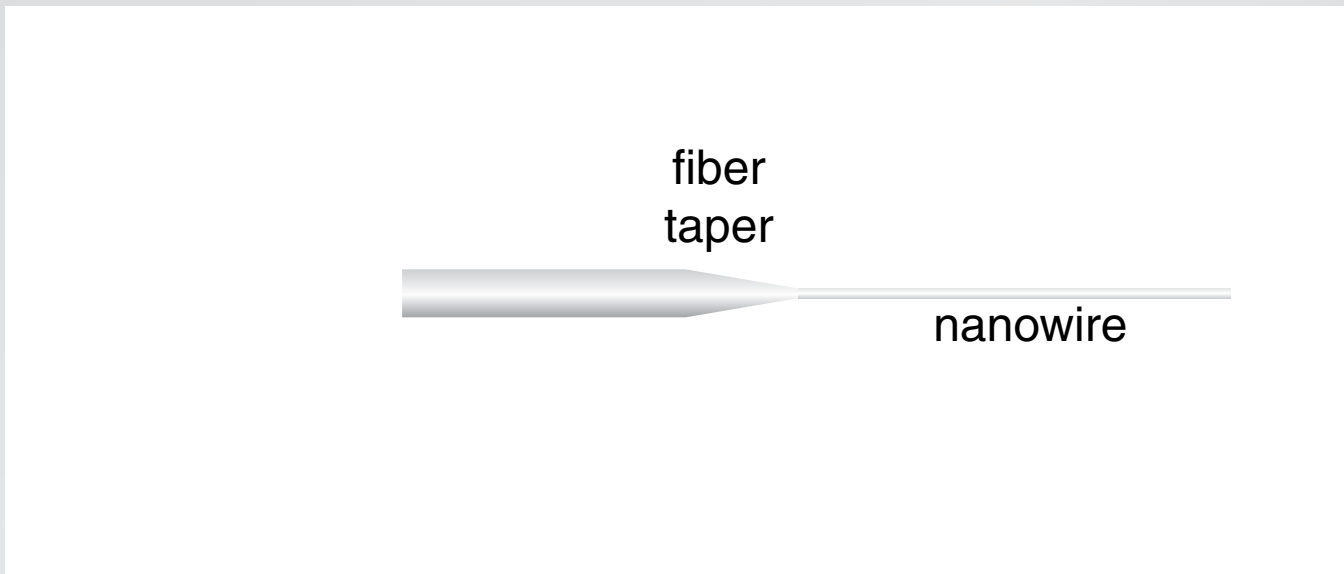


# Outline

- silica nanowires
- optical properties
- nonlinear properties

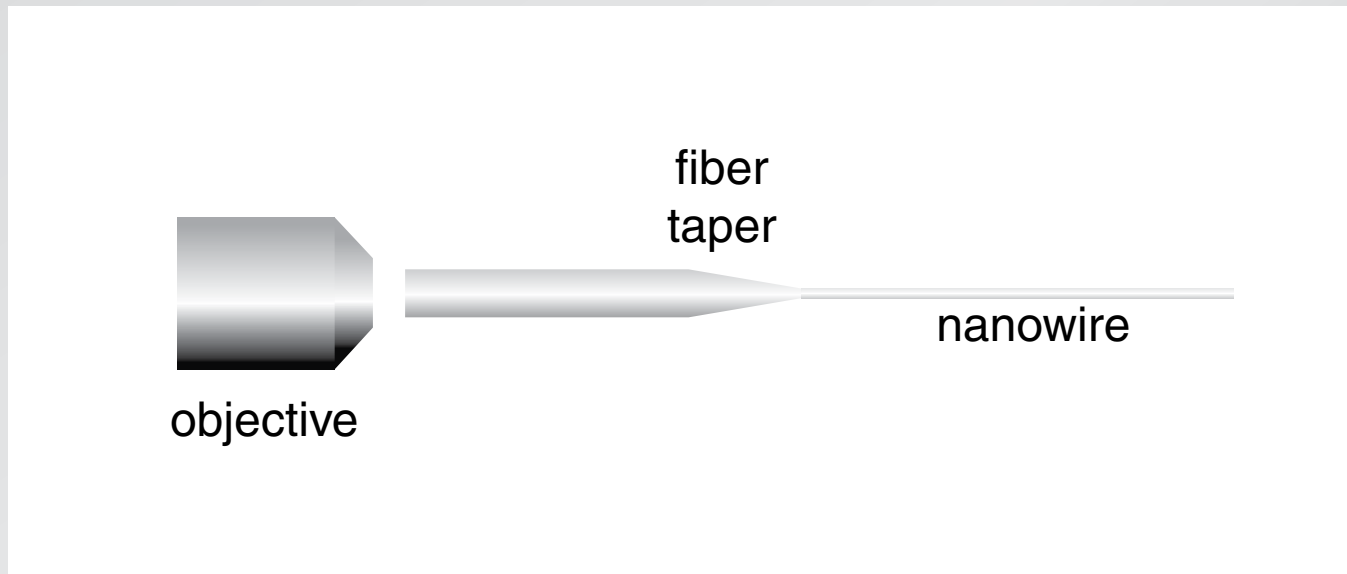
# Optical properties

coupling light into nanowires



# Optical properties

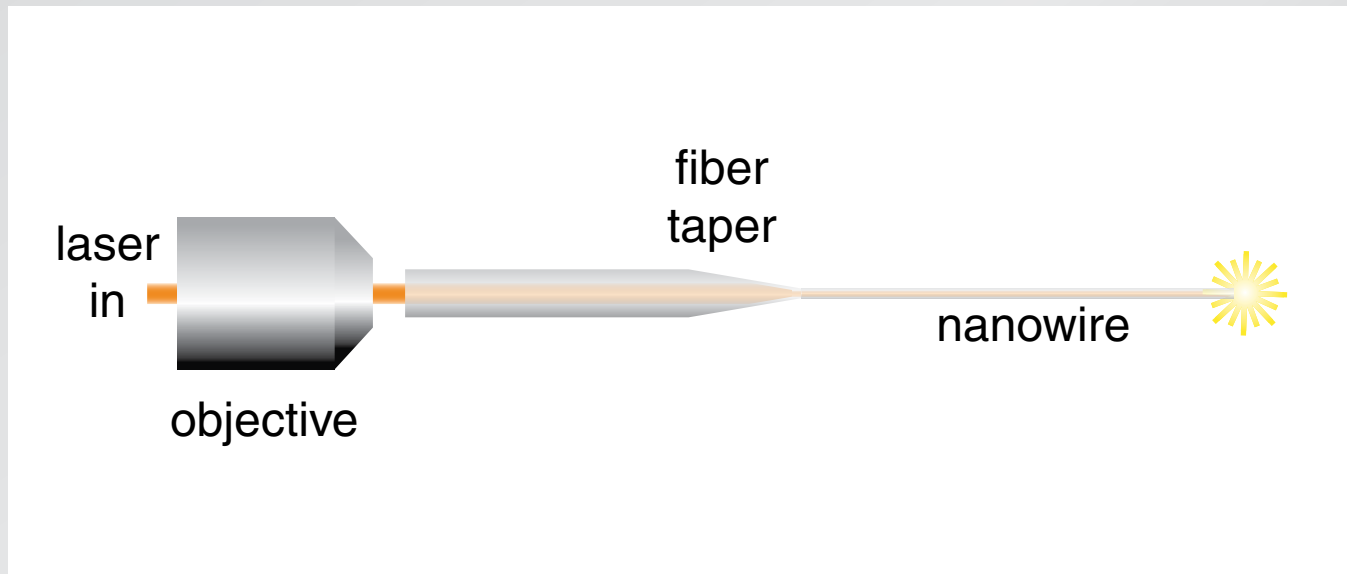
coupling light into nanowires





# Optical properties

coupling light into nanowires



# Optical properties

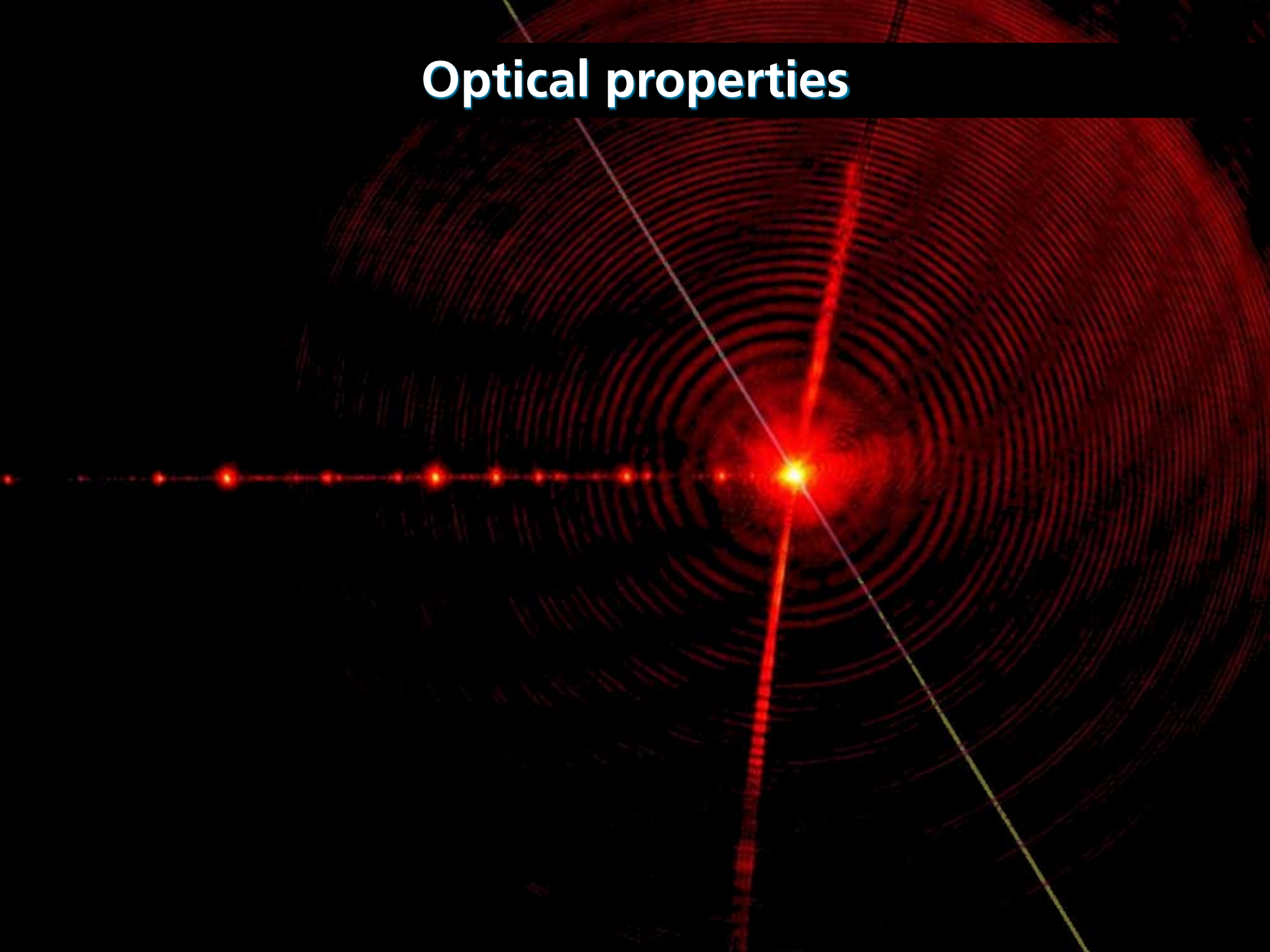
280-nm nanowire



360 nm

450 nm

# Optical properties



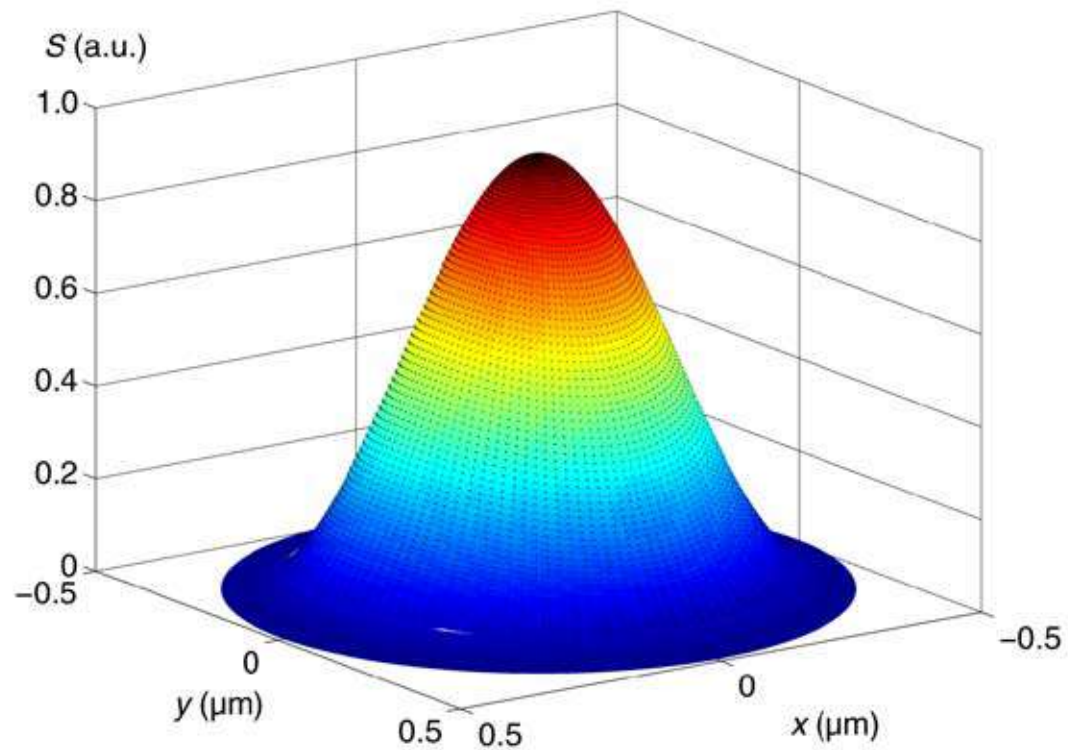


# Optical properties



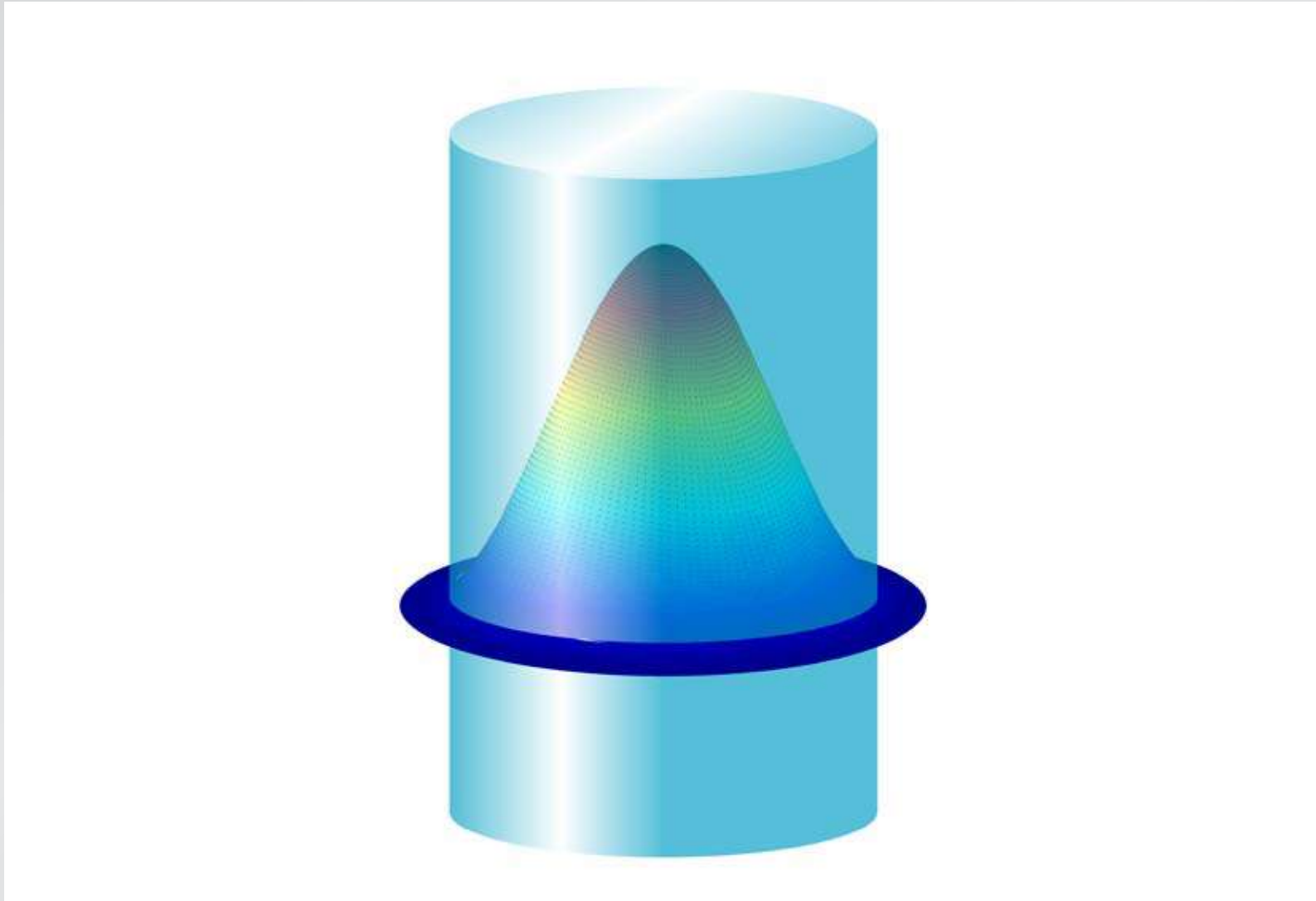
# Optical properties

Poynting vector profile for 800-nm nanowire



# Optical properties

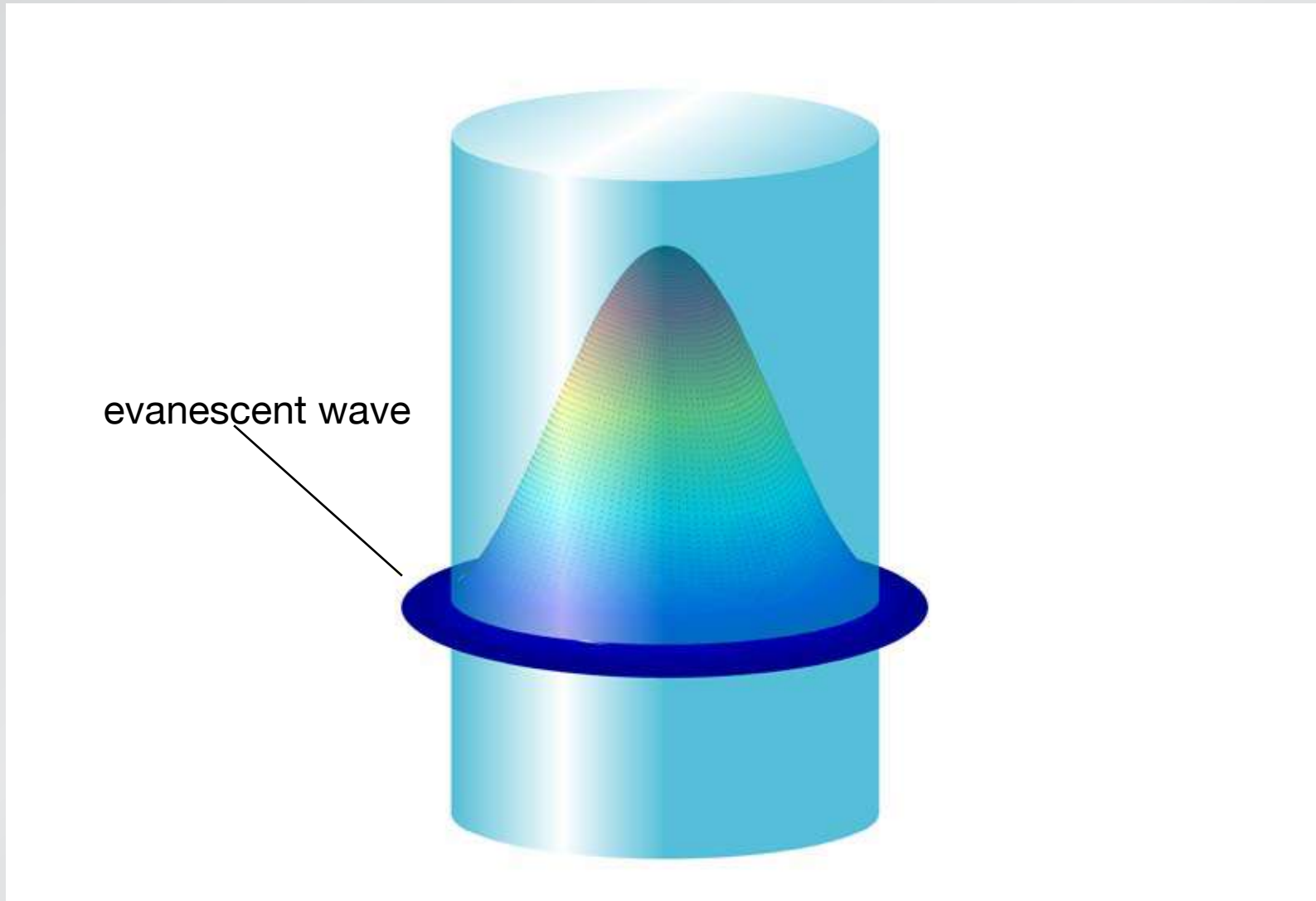
Poynting vector profile for 800-nm nanowire





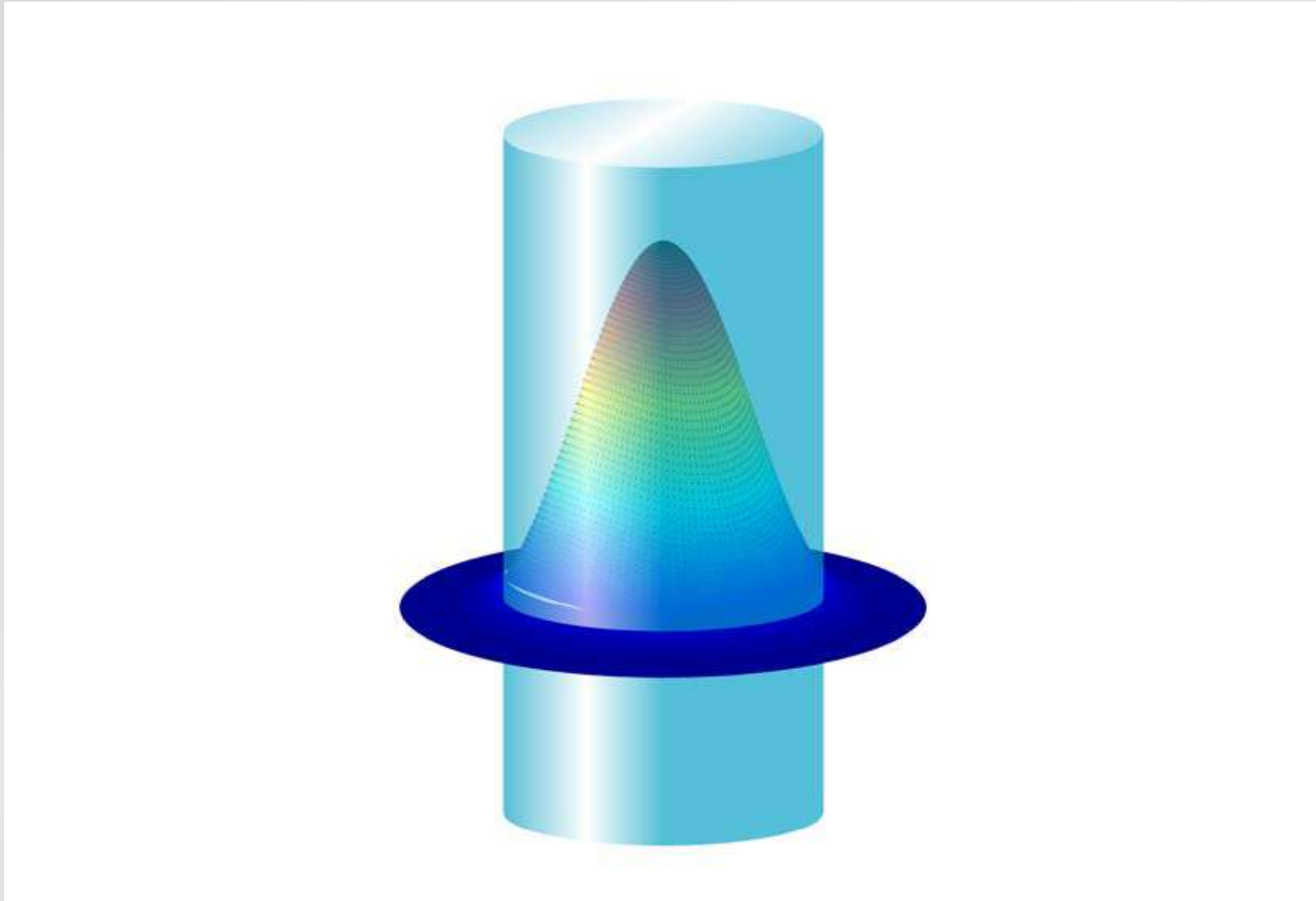
# Optical properties

Poynting vector profile for 800-nm nanowire



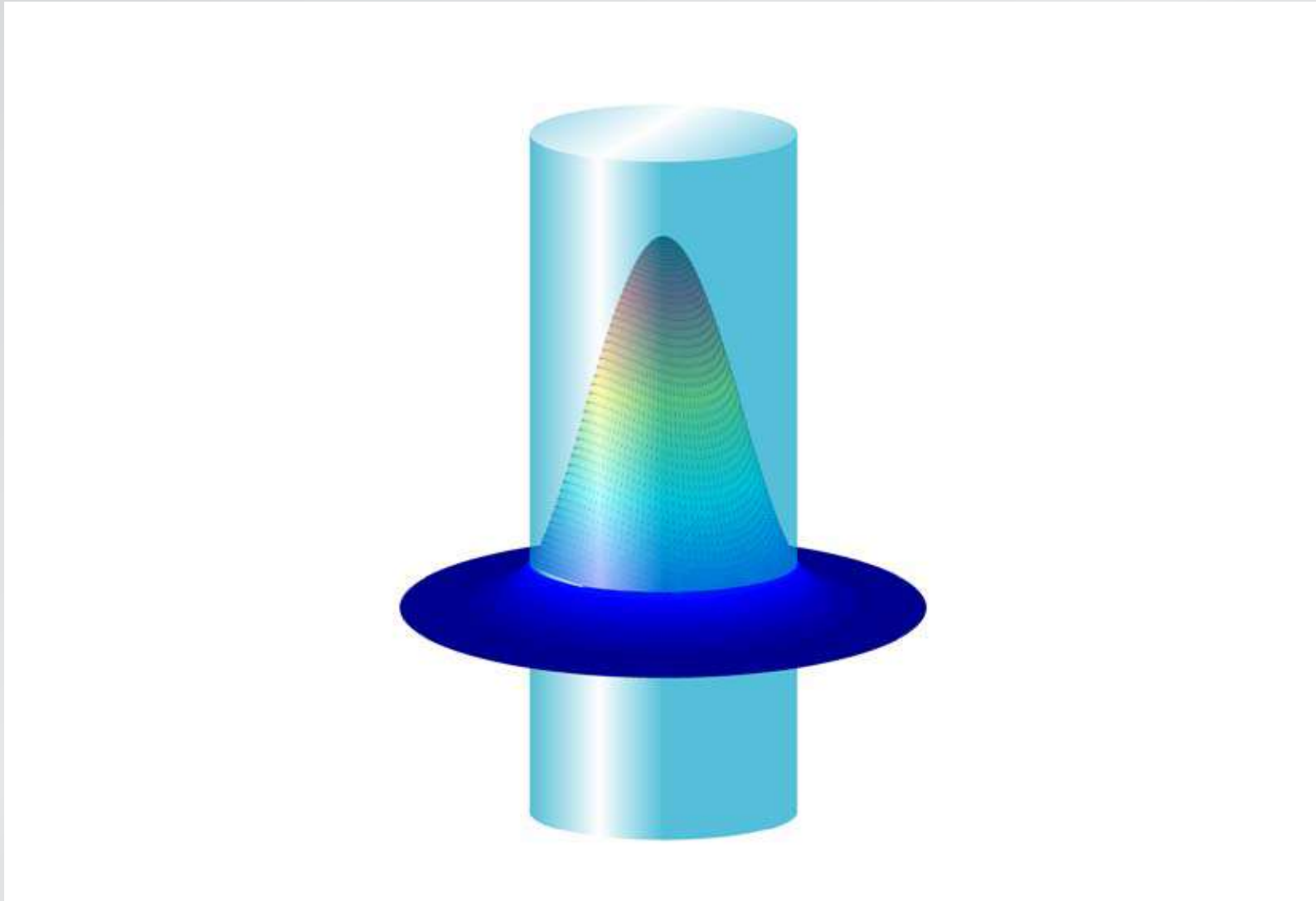
# Optical properties

Poynting vector profile for 600-nm nanowire



# Optical properties

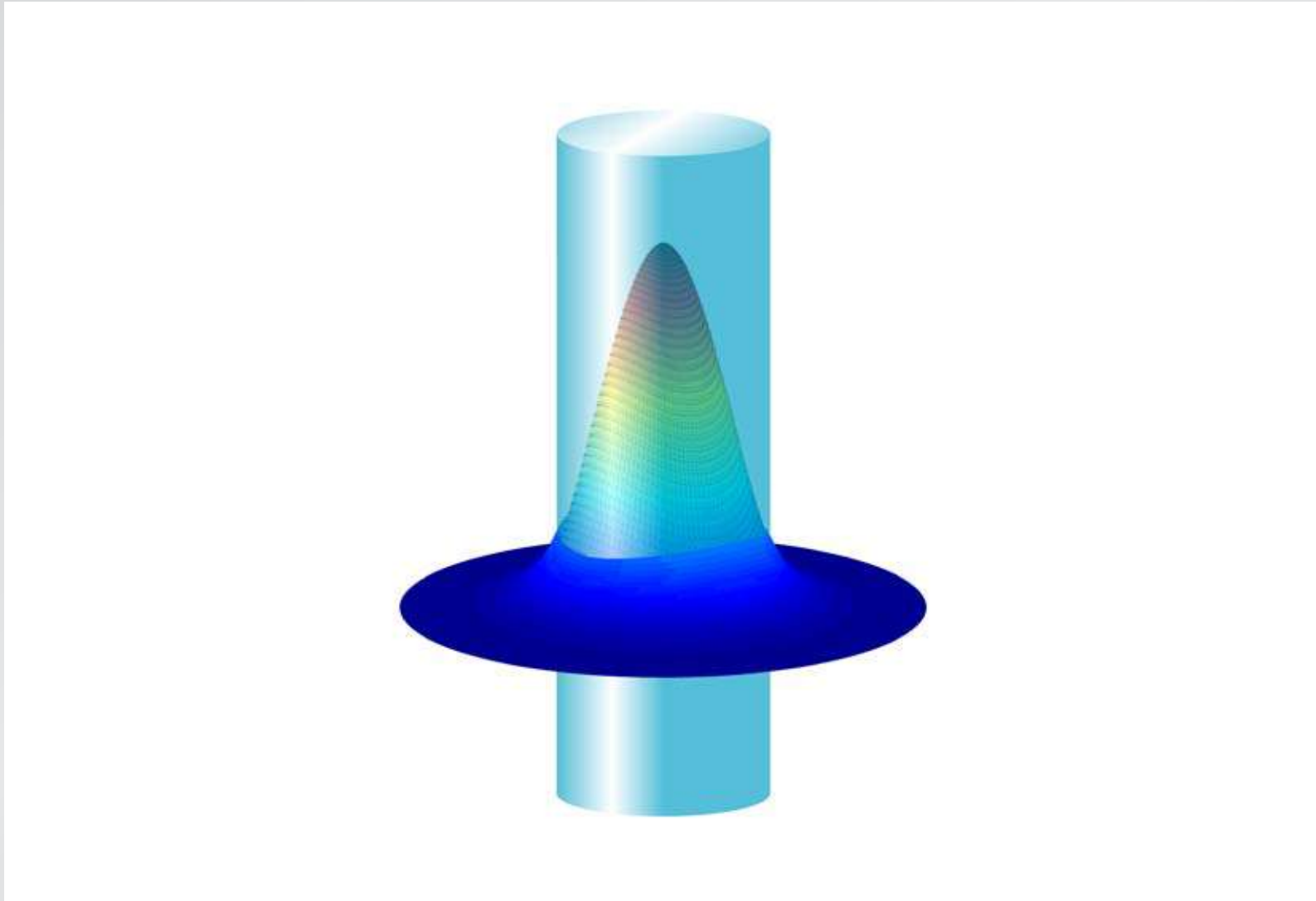
Poynting vector profile for 500-nm nanowire





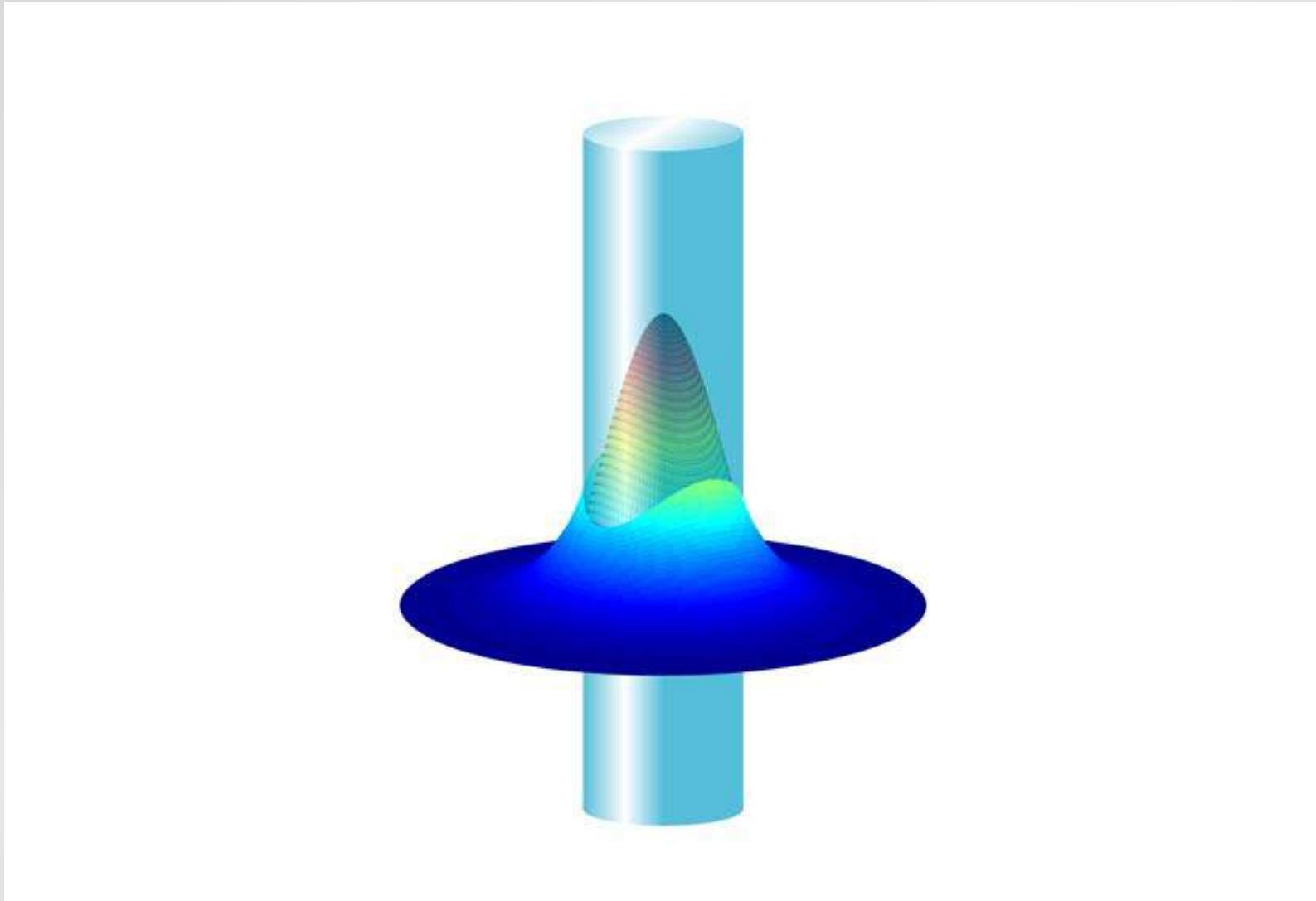
# Optical properties

Poynting vector profile for 400-nm nanowire



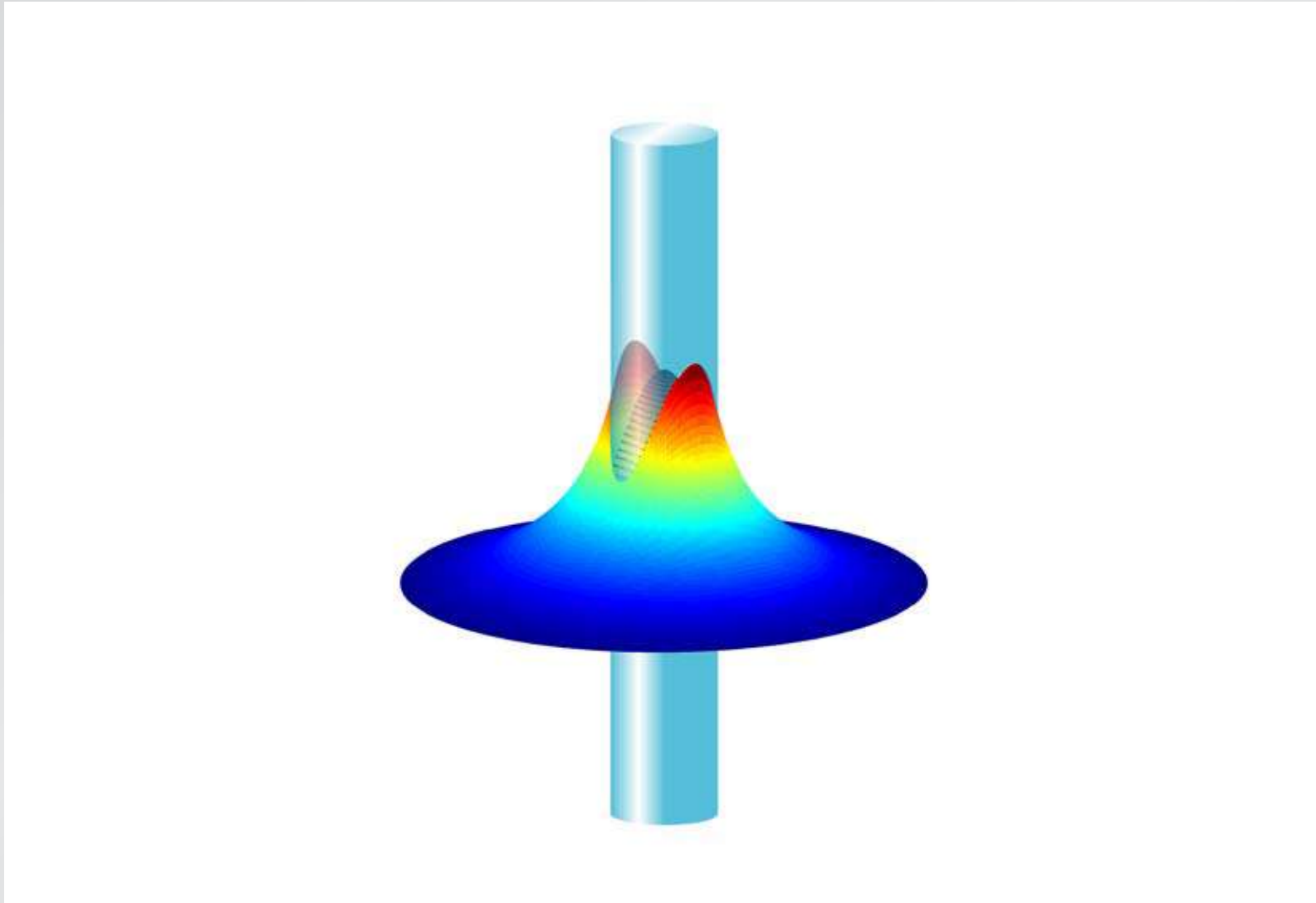
# Optical properties

Poynting vector profile for 300-nm nanowire



# Optical properties

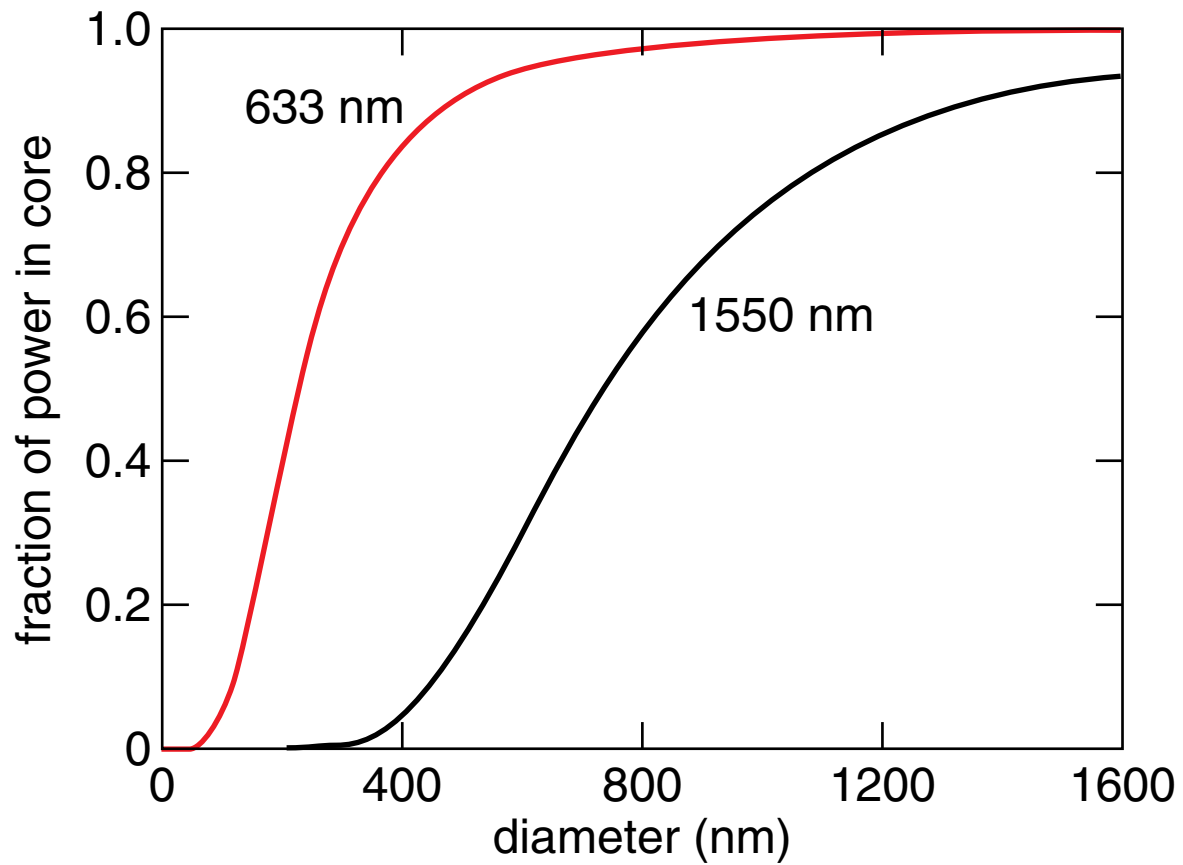
Poynting vector profile for 200-nm nanowire





# Optical properties

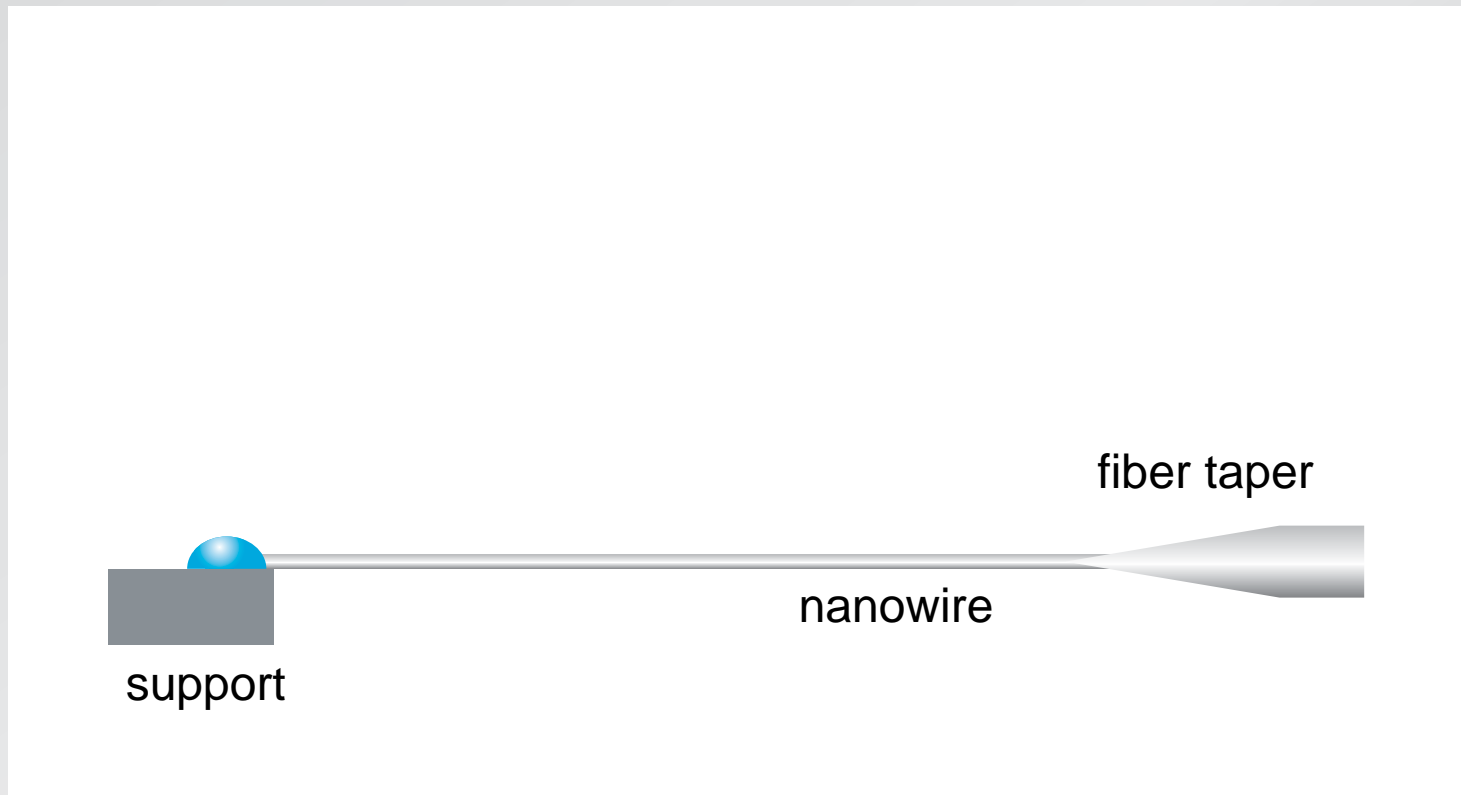
fraction of power carried in core





# Optical properties

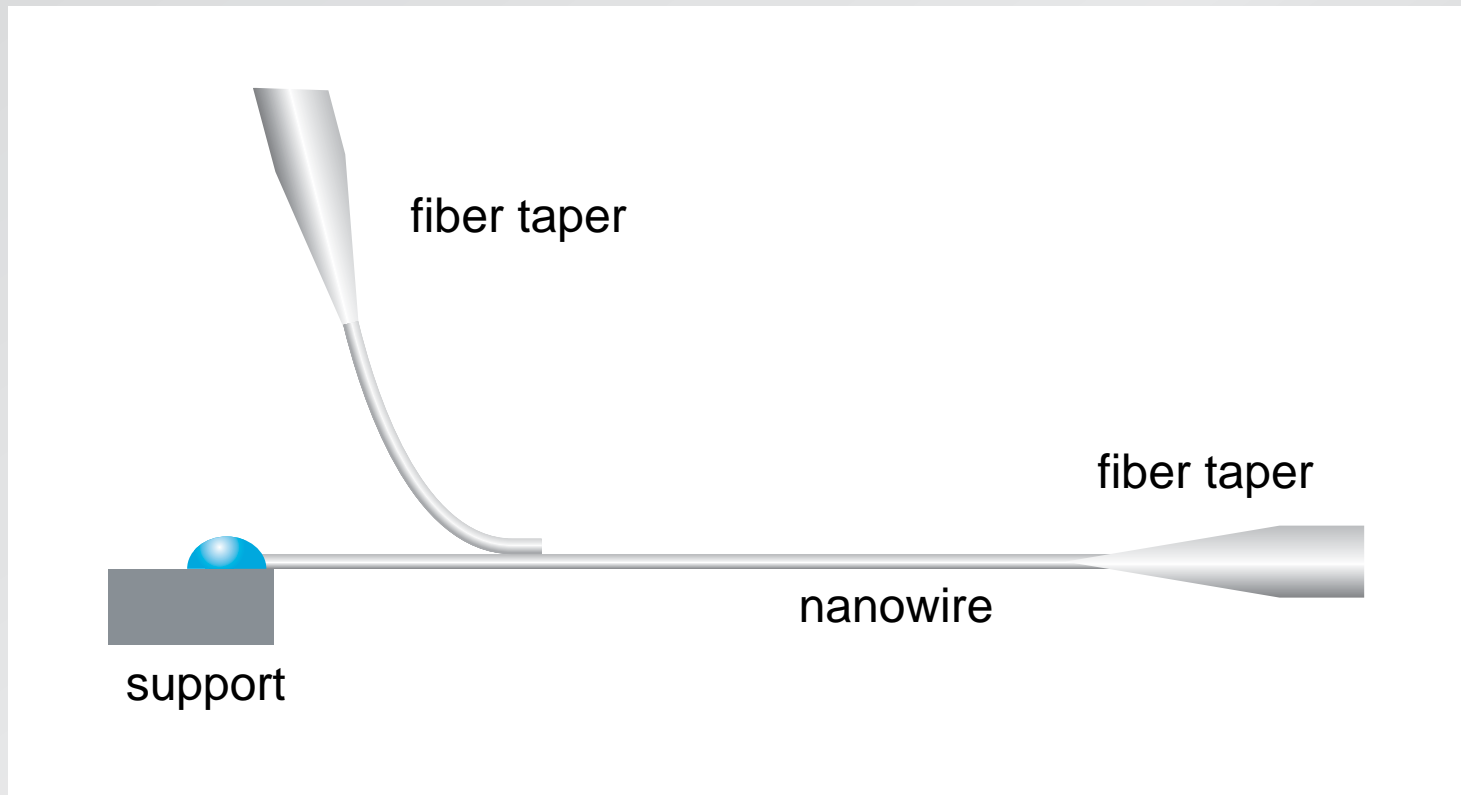
coupling light between nanowires





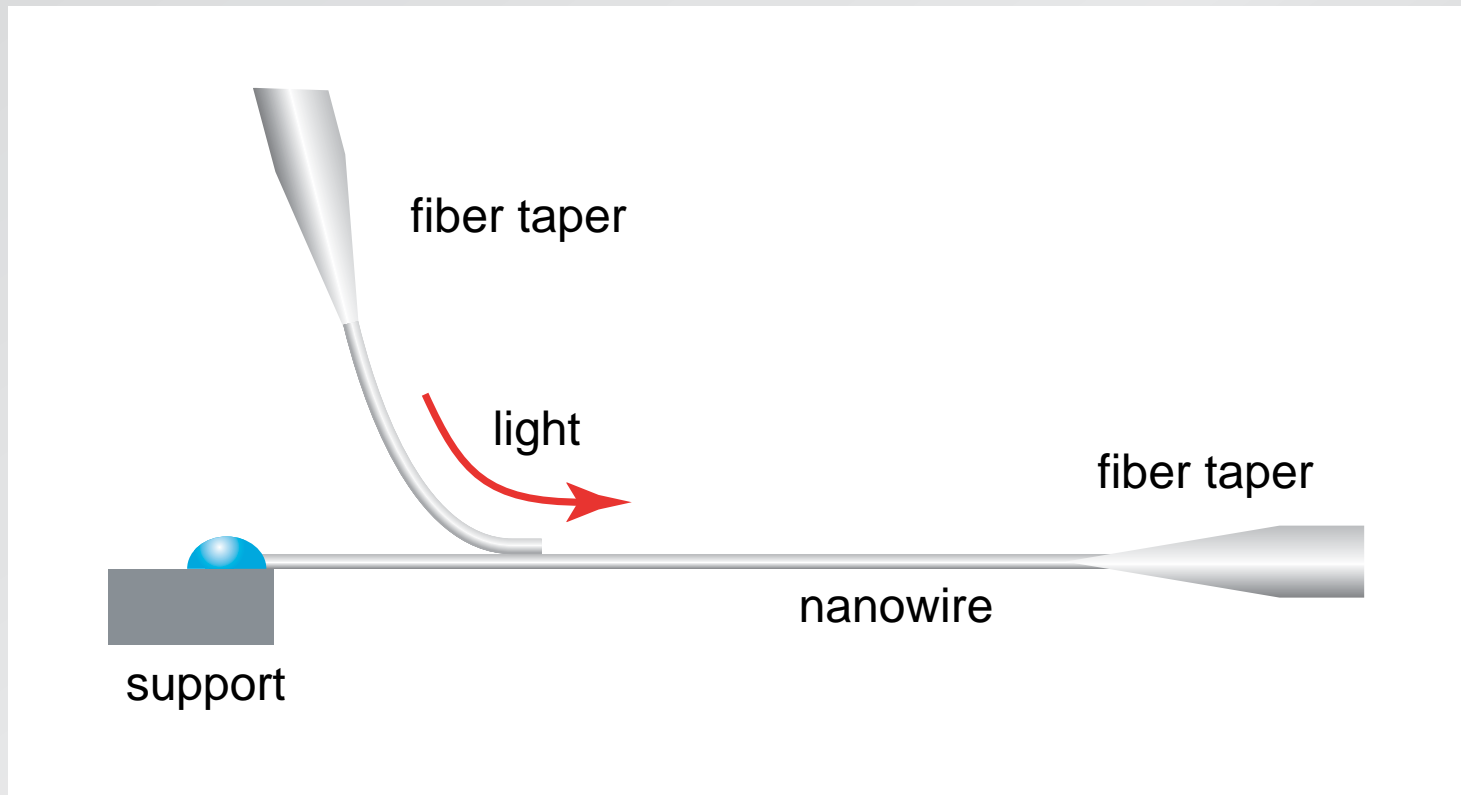
# Optical properties

coupling light between nanowires



# Optical properties

coupling light between nanowires



# Optical properties



**50  $\mu\text{m}$**



# Optical properties



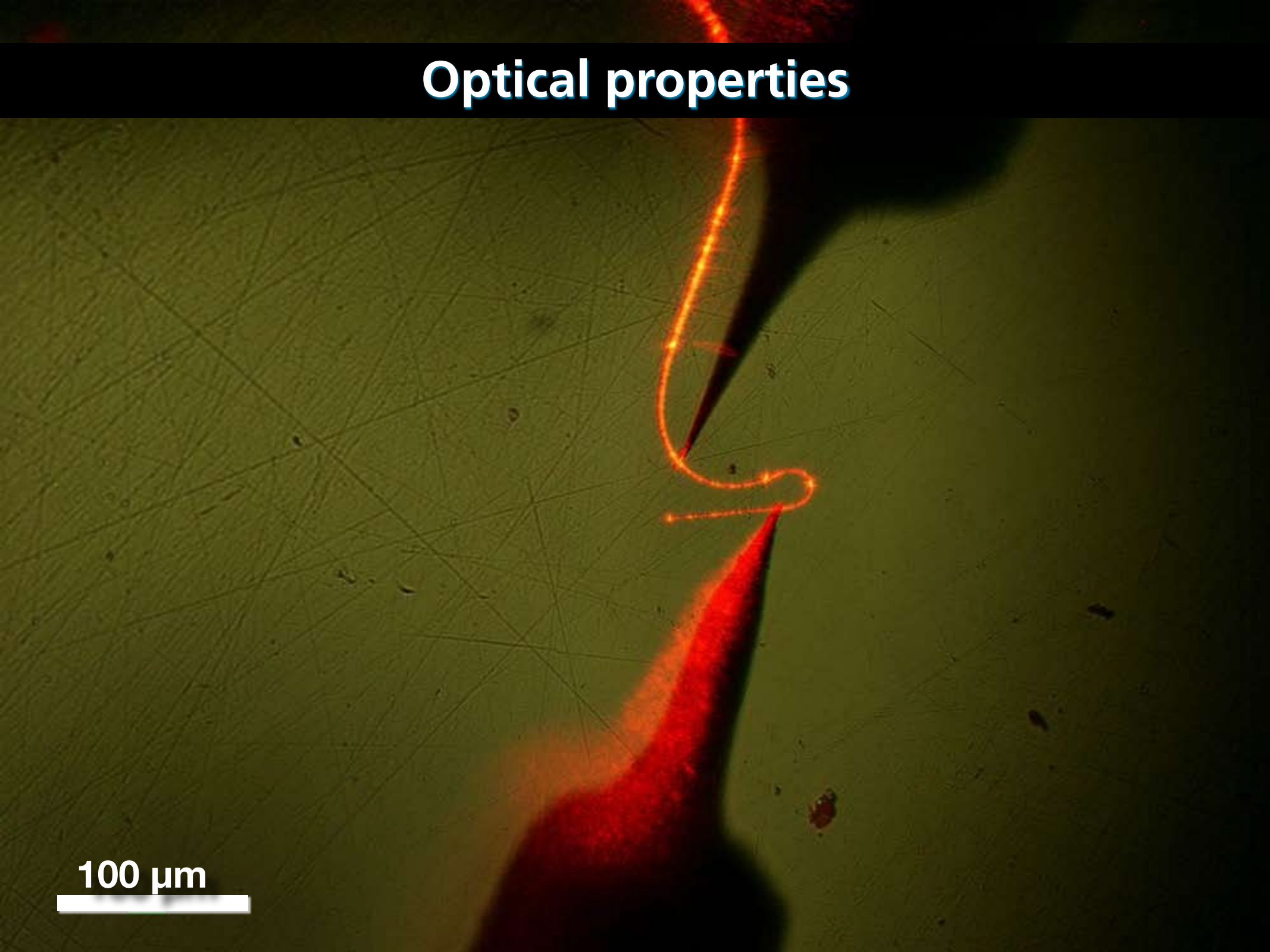
**50  $\mu\text{m}$**

# Optical properties



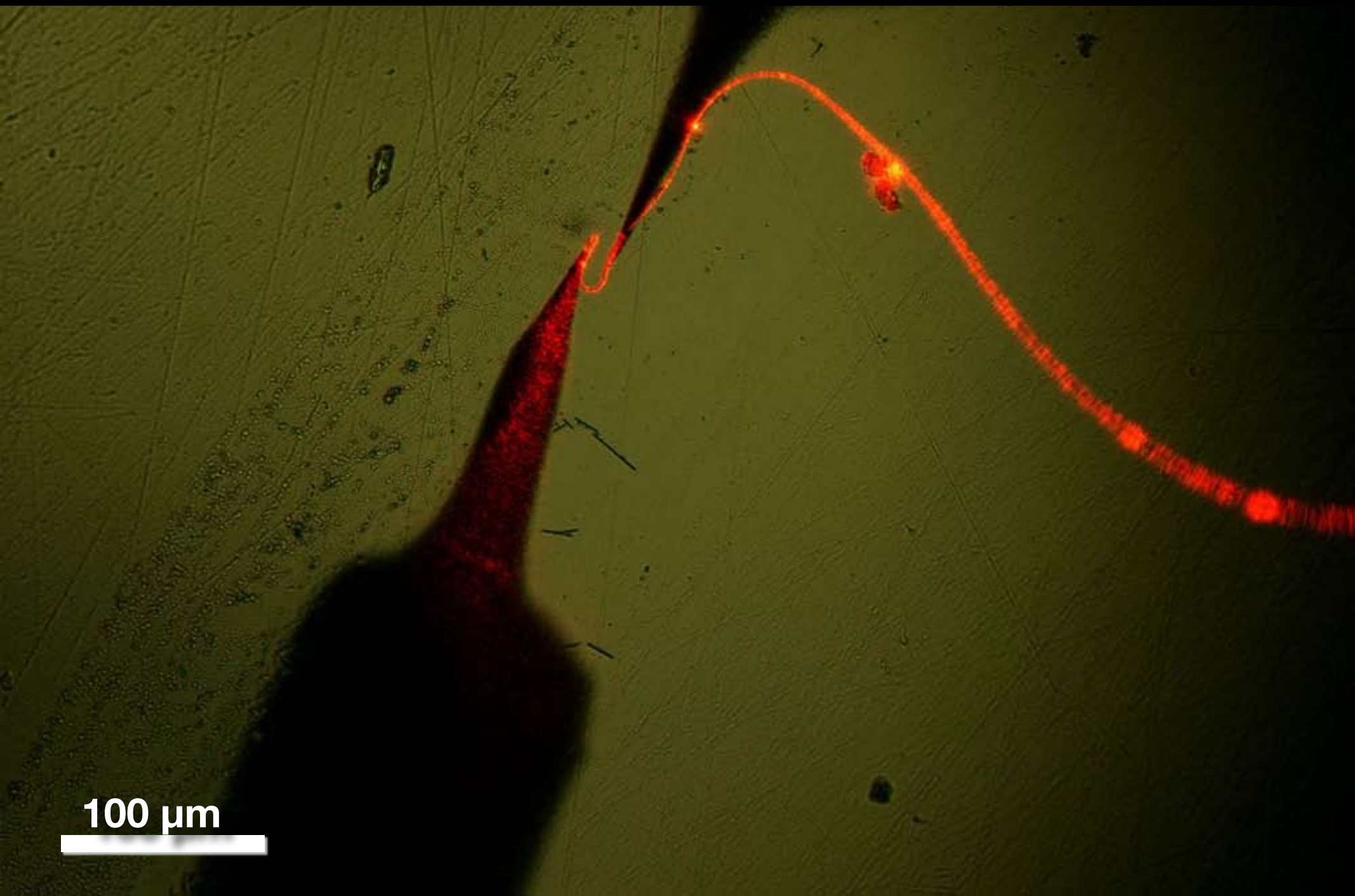
# Optical properties

100  $\mu\text{m}$

An optical micrograph showing a fiber optic tip on the right side, emitting a bright red laser beam. The beam is focused into a curved path, forming a loop. The background is a dark, textured surface with fine scratches. A white scale bar is located in the bottom left corner, labeled '100 μm'.



# Optical properties

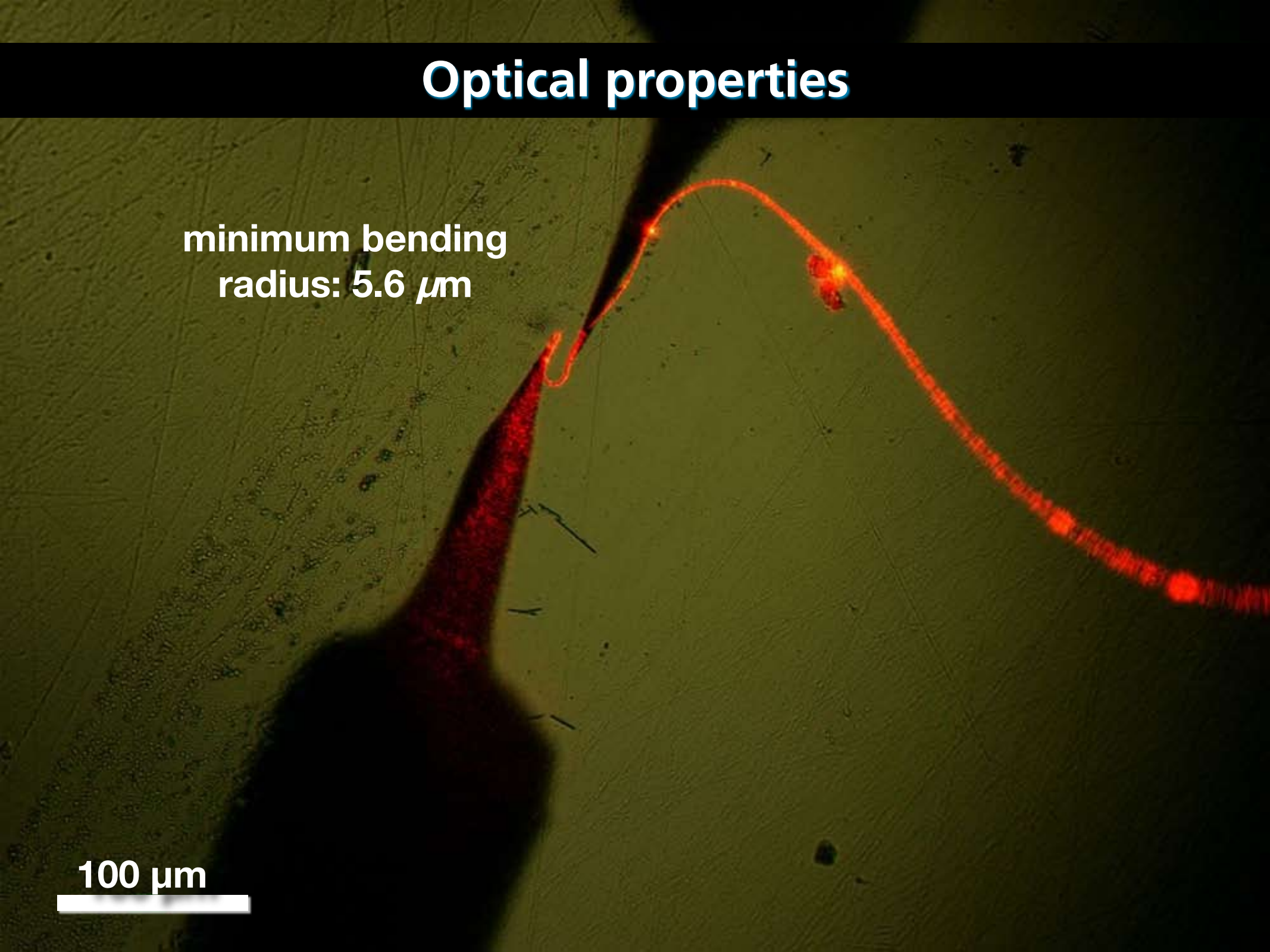


100  $\mu\text{m}$

# Optical properties

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

100  $\mu\text{m}$

An optical micrograph showing a fiber structure. A red laser light path is visible, starting from a thick section on the left and curving upwards and to the right. The fiber has a minimum bending radius of 5.6 micrometers. A scale bar in the bottom left corner indicates 100 micrometers.

# Optical properties

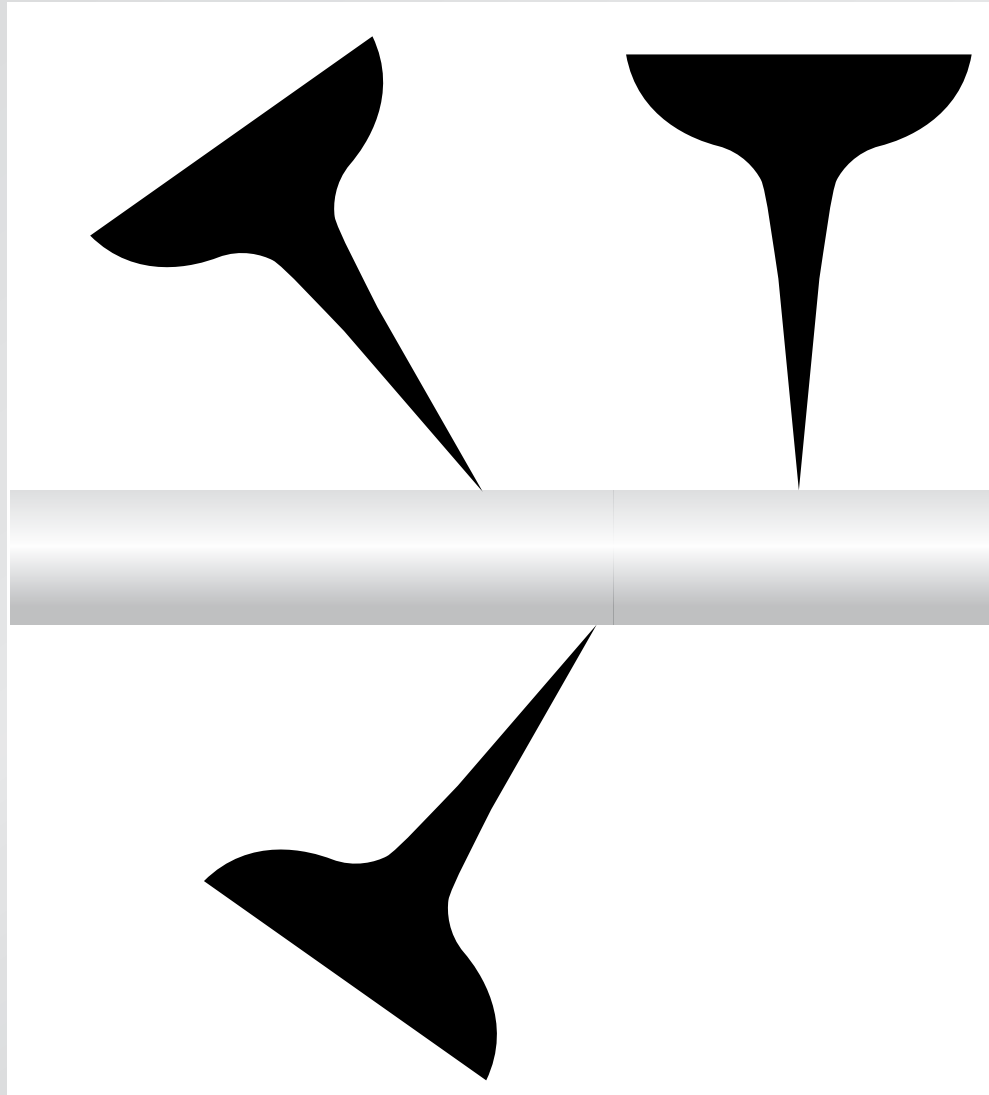
microphotonic components





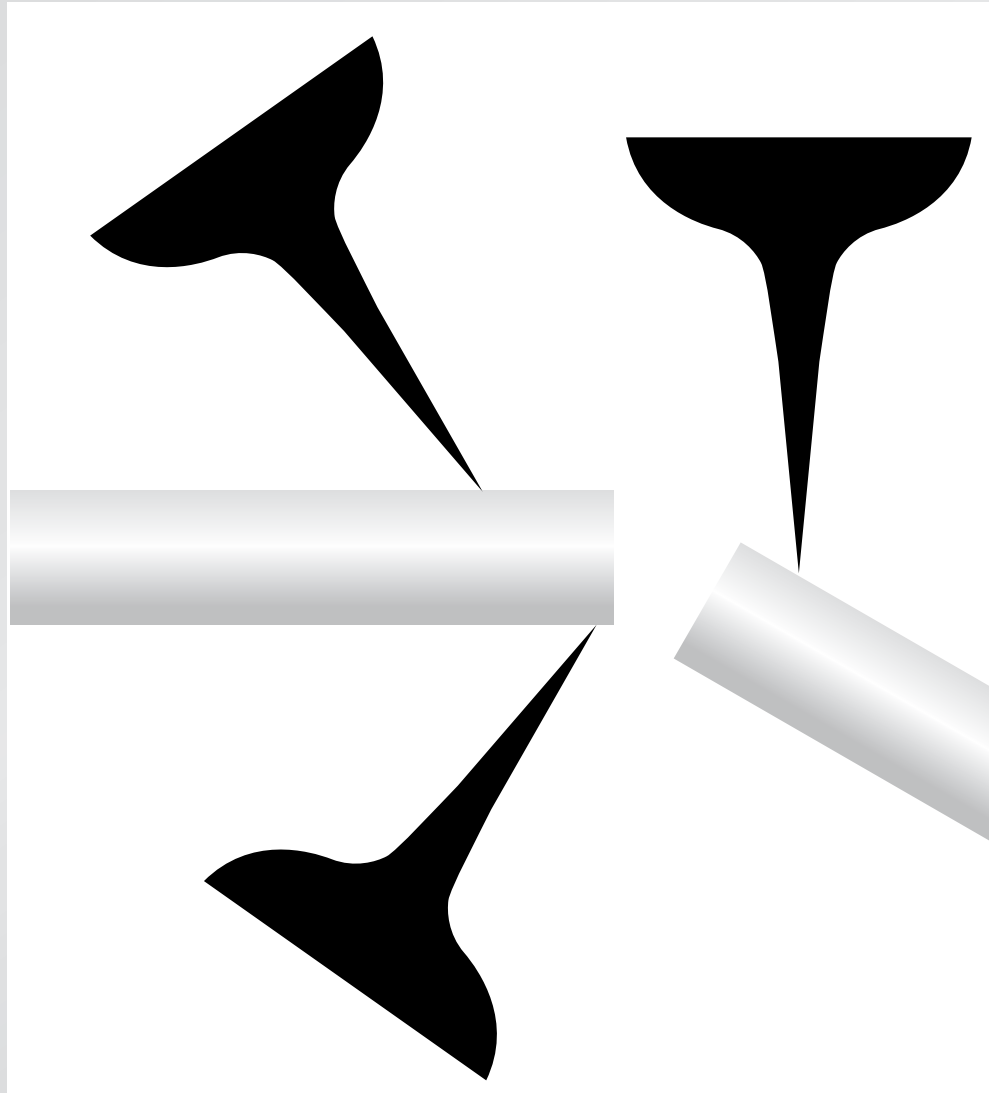
# Optical properties

microphotonic components



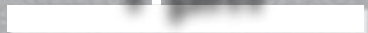
# Optical properties

microphotonic components



# Optical properties

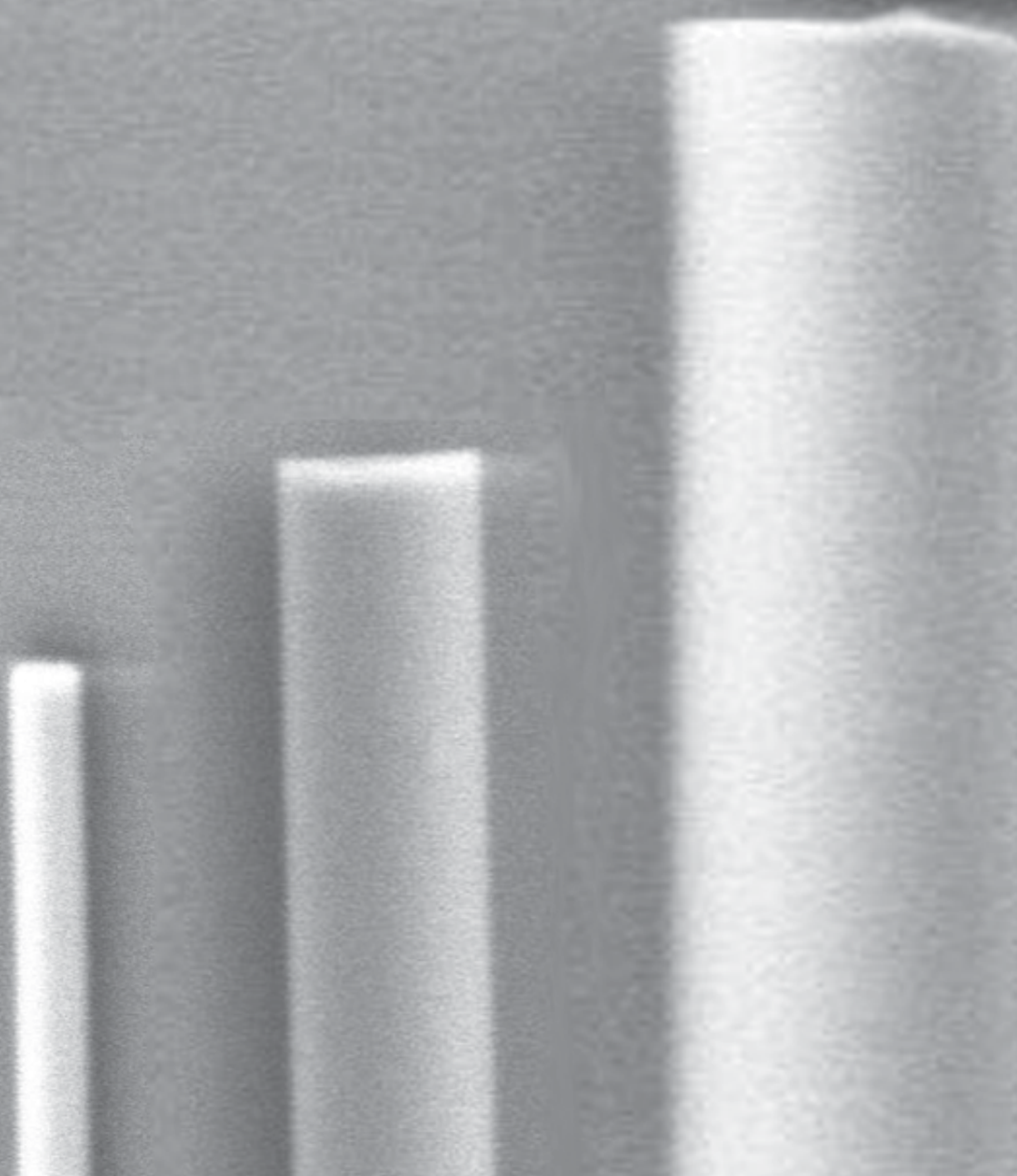
1  $\mu\text{m}$





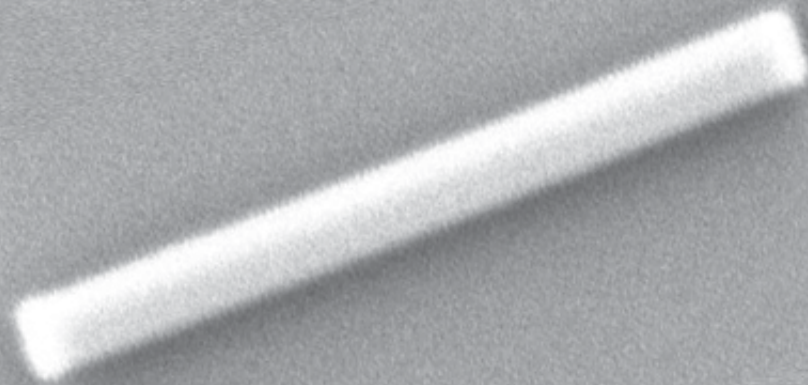
# Optical properties

500 nm





# Optical properties



500 nm



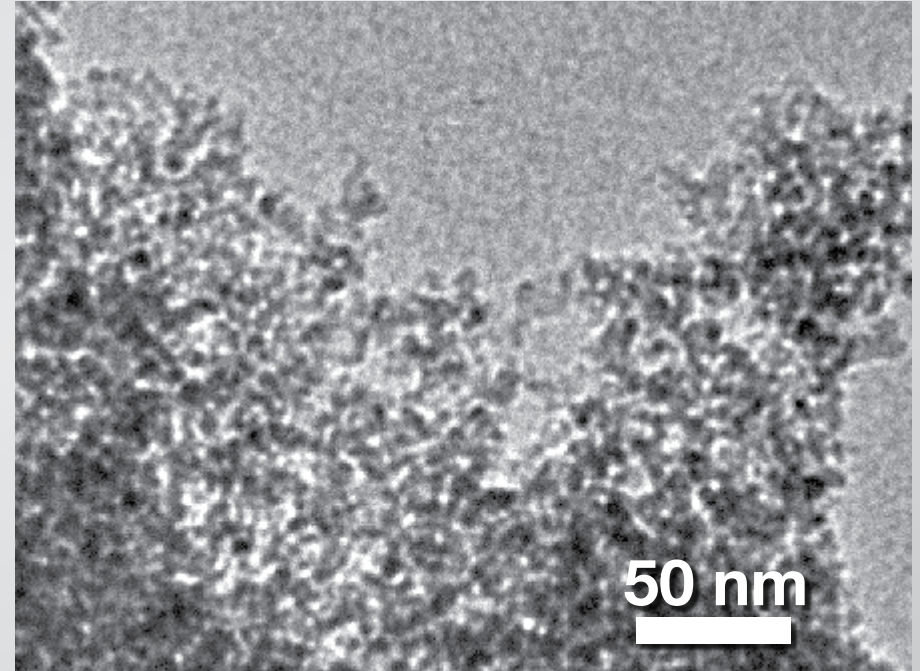
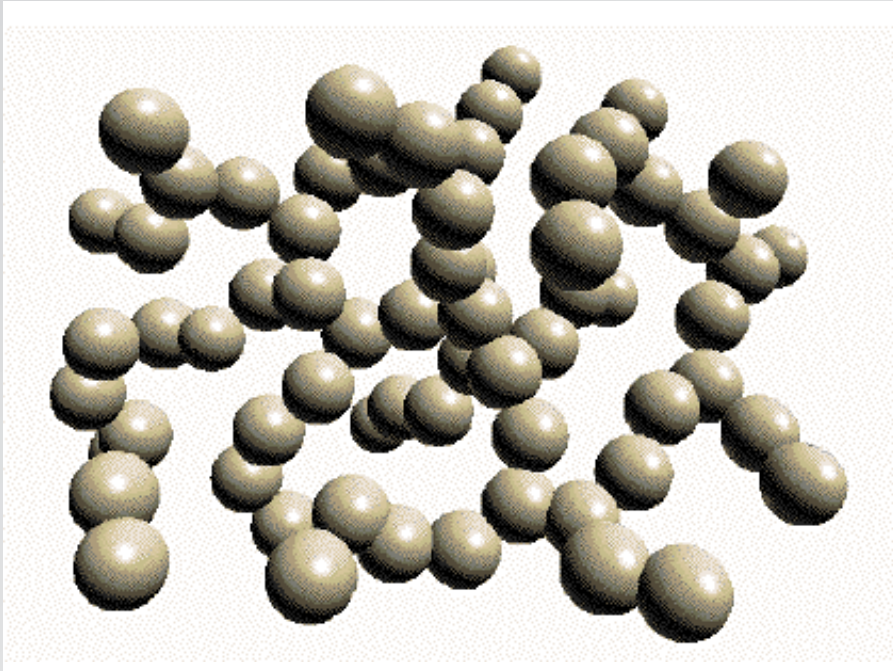
# Optical properties





# Optical properties

## Aerogel



density:  $1.9 \text{ kg/m}^3$

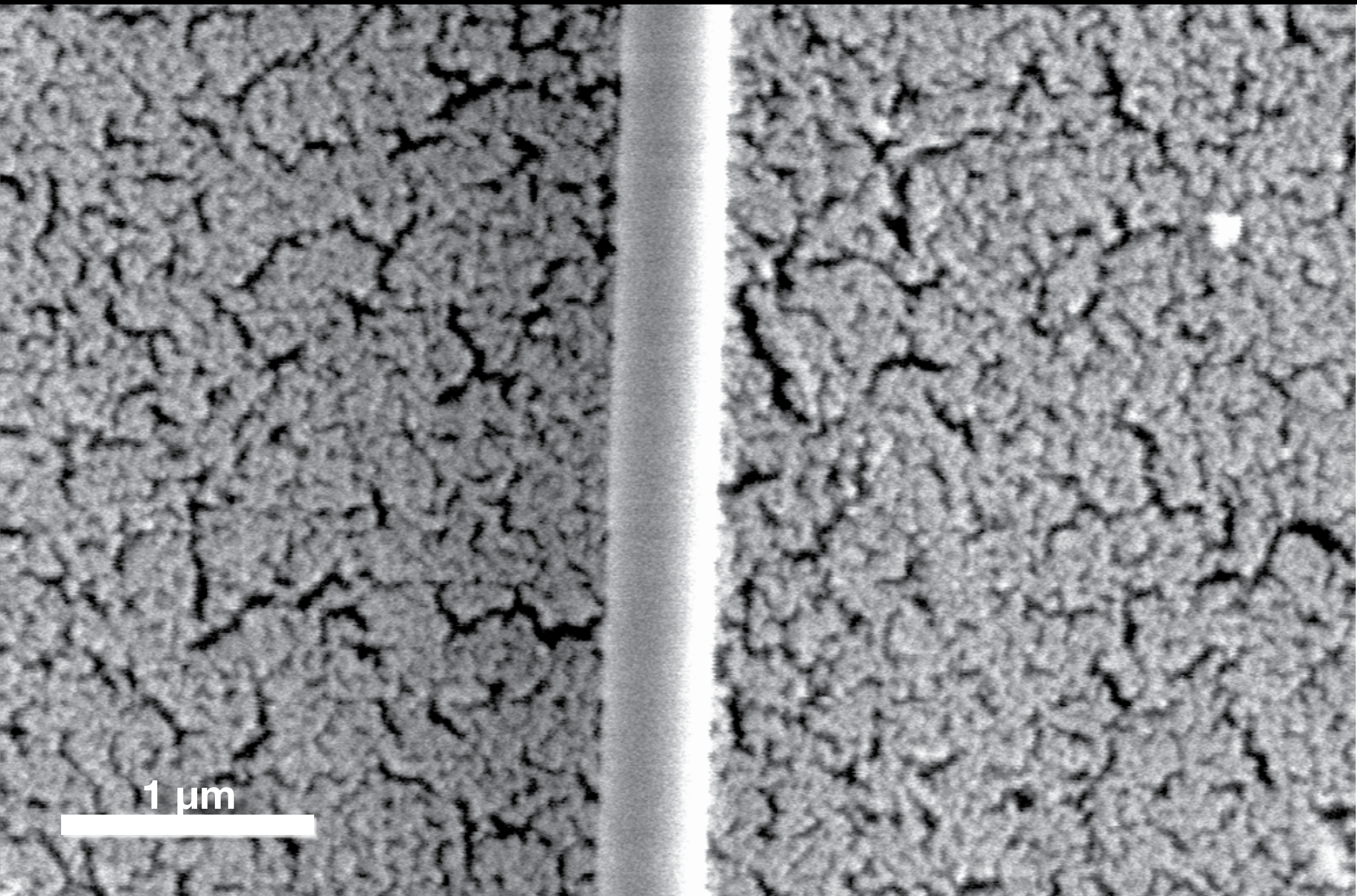
index of refraction: 1.03–1.08

# Optical properties





# Optical properties



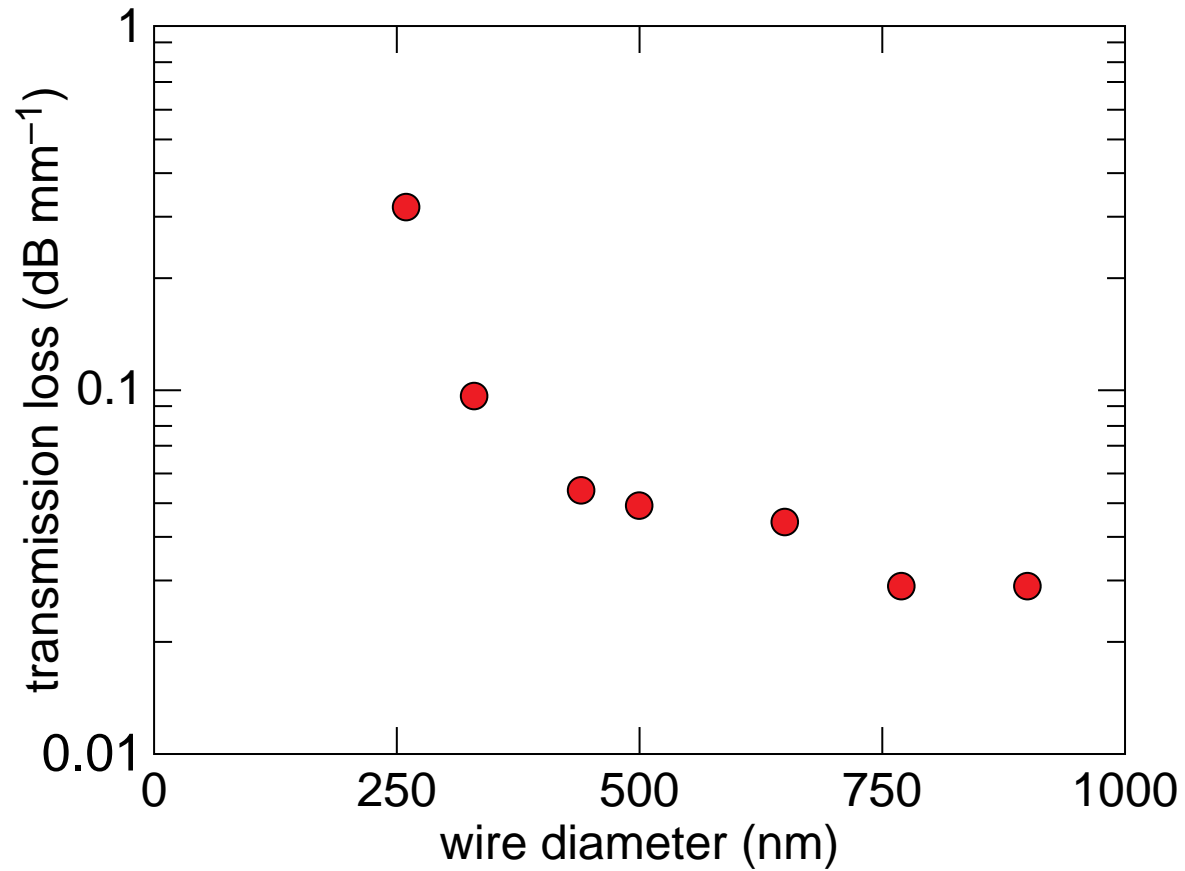
1  $\mu\text{m}$





# Optical properties

loss measurement @ 633 nm



*Nano Lett.*, 5, 259–262 (2005)

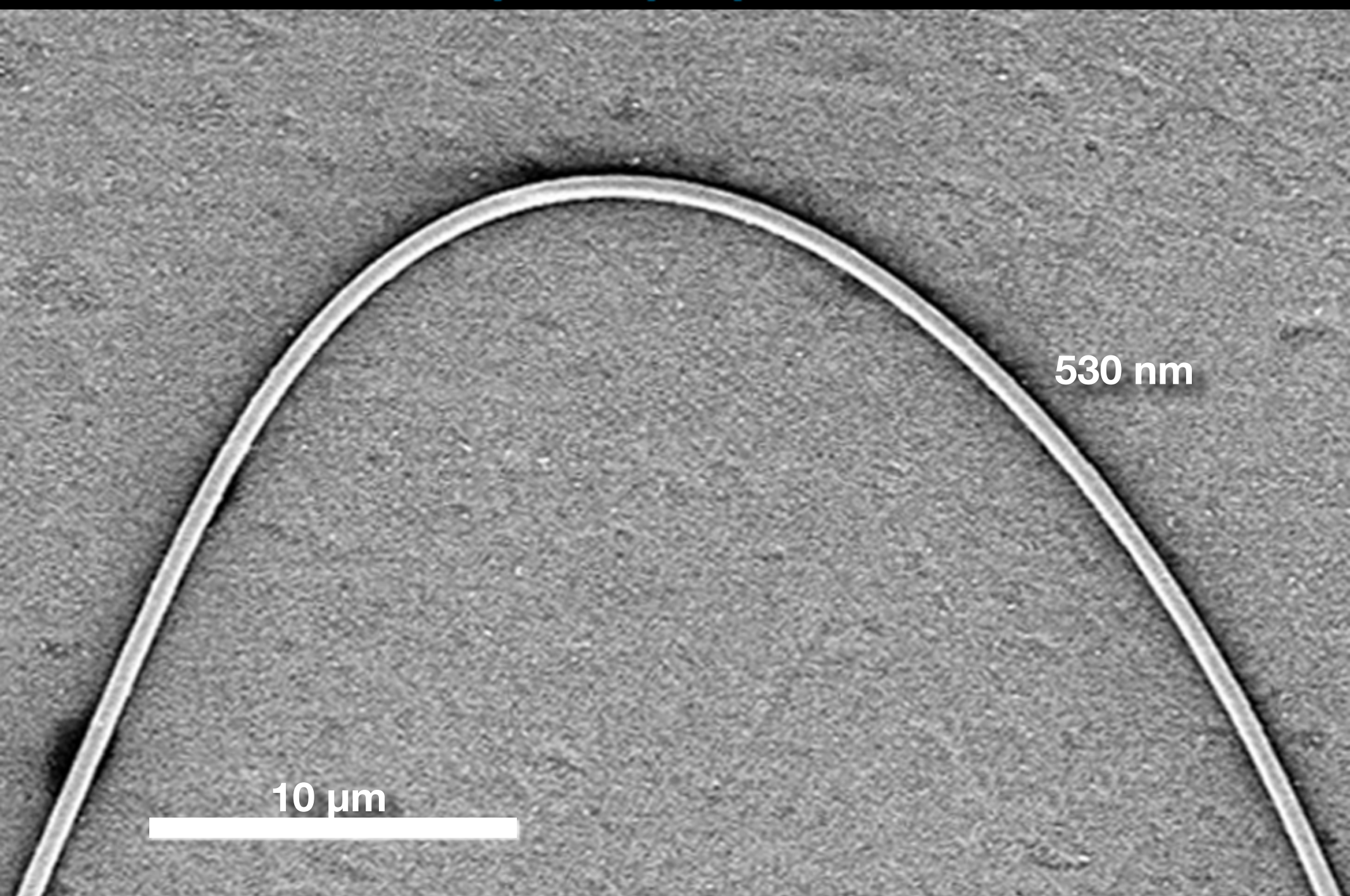
# Optical properties

530 nm



50  $\mu\text{m}$

# Optical properties

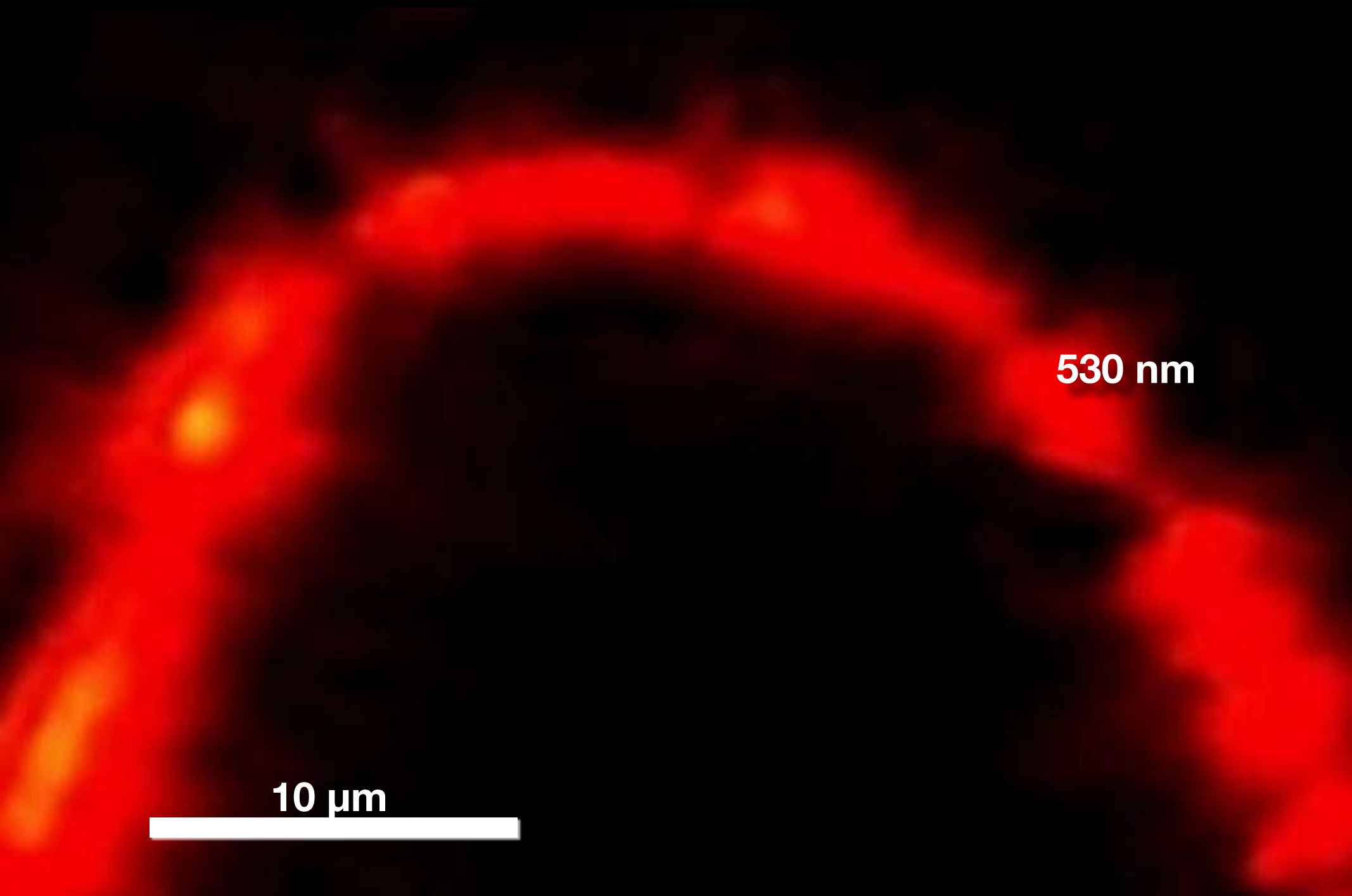


10  $\mu\text{m}$

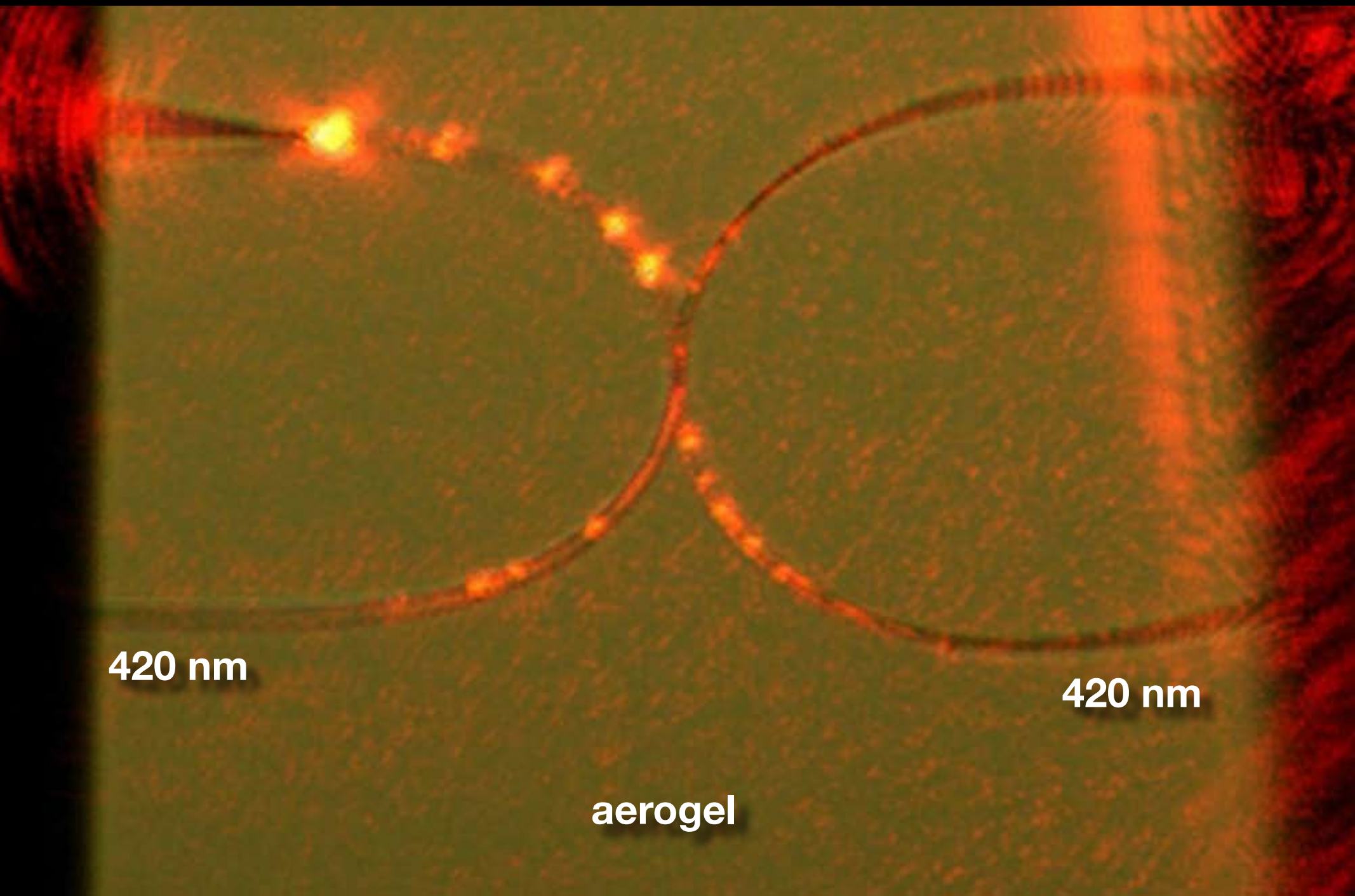
530 nm



# Optical properties



# Optical properties

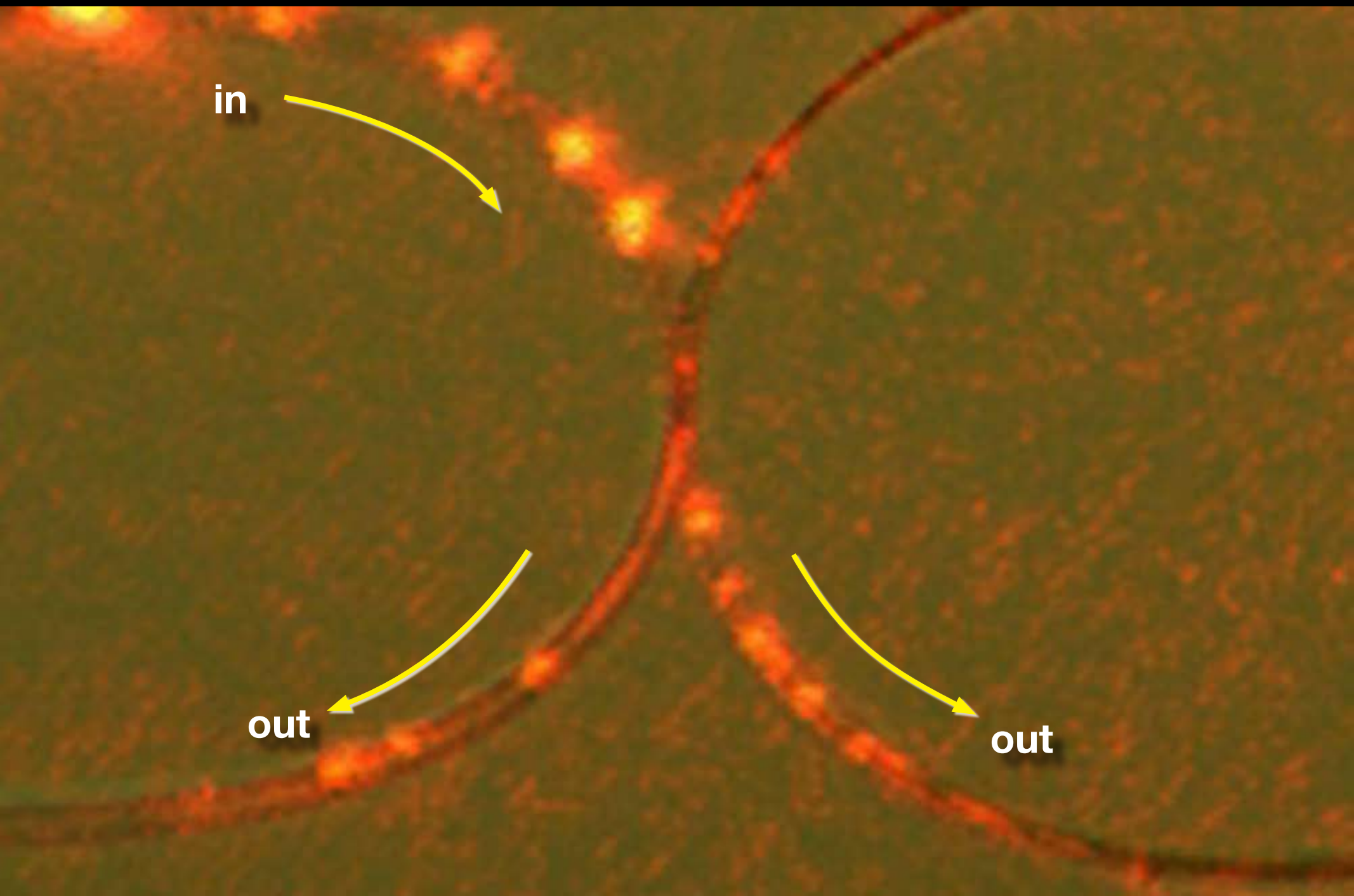


420 nm

420 nm

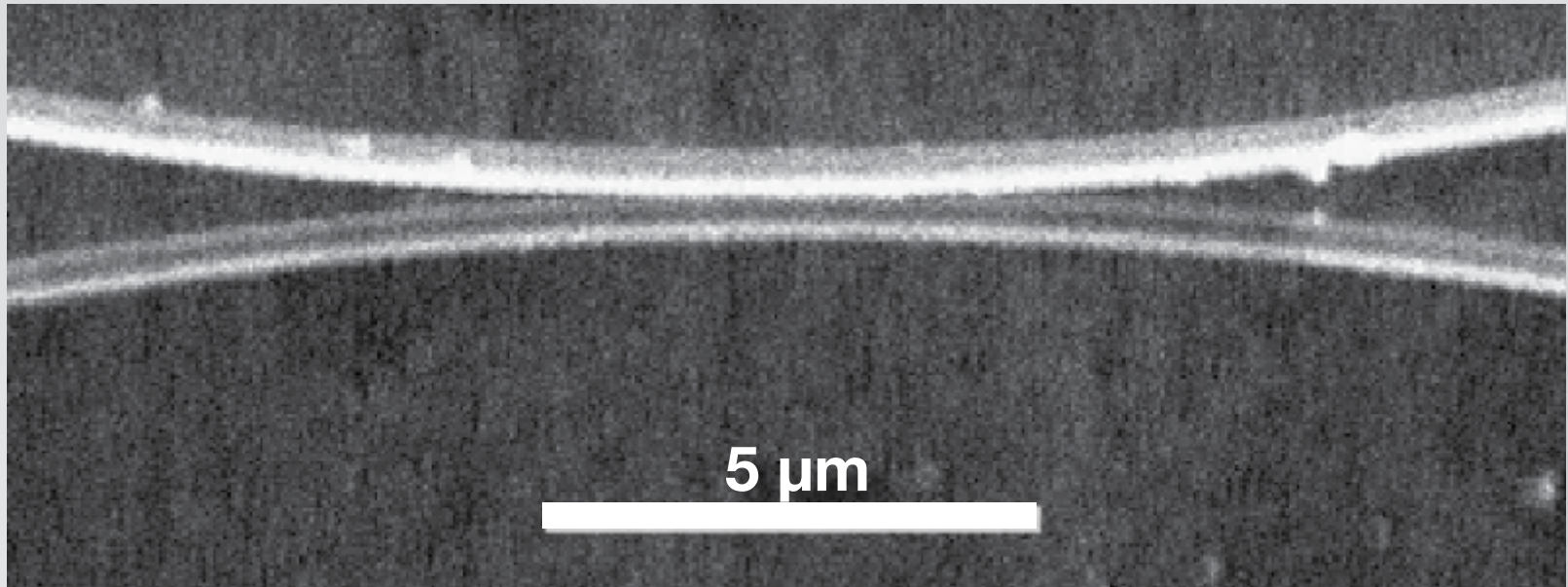
aerogel

# Optical properties





# Optical properties

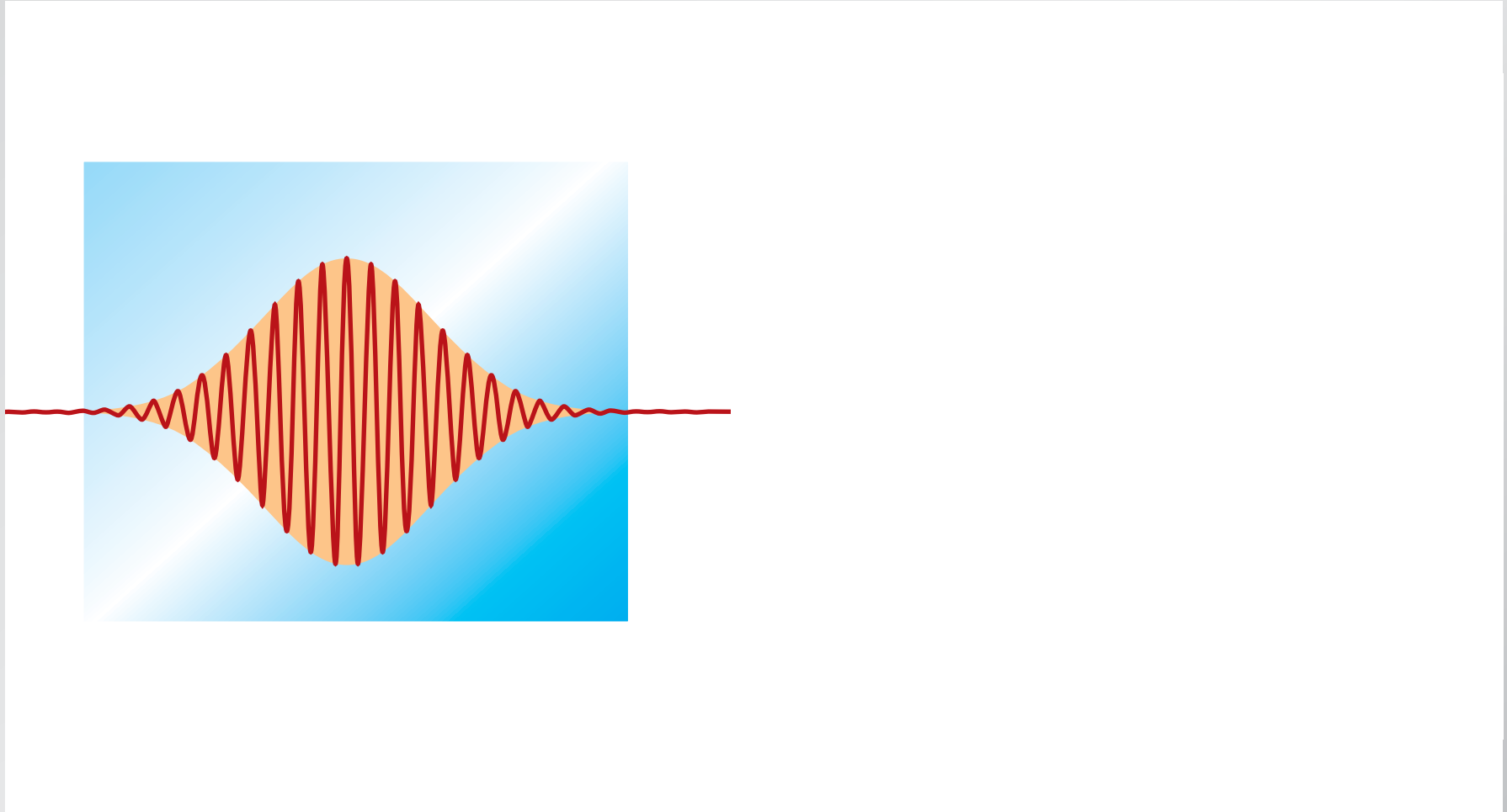


# Outline

- silica nanowires
- optical properties
- nonlinear properties

# Nonlinear properties

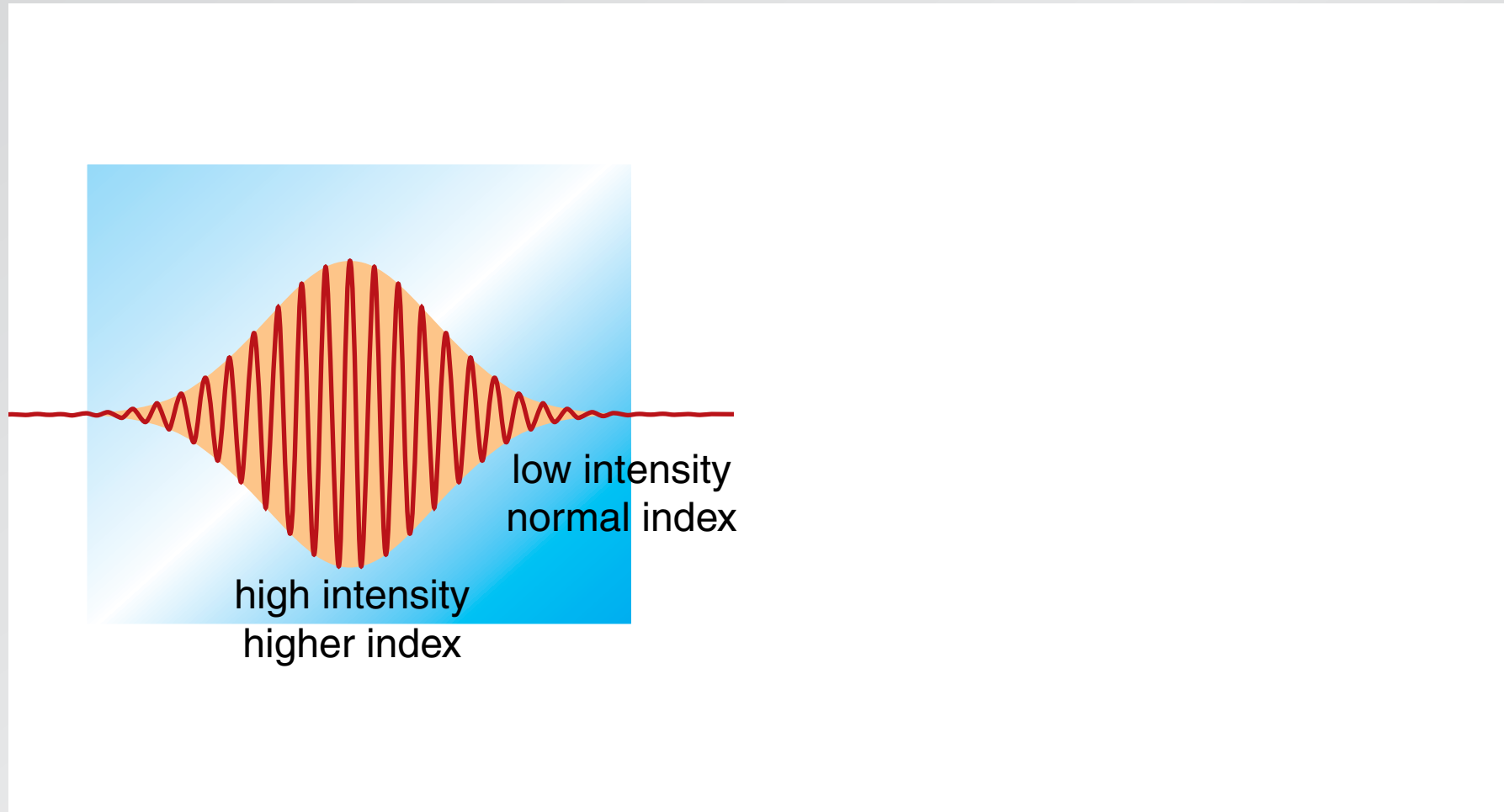
nonlinear dispersion:  $n = n_0 + n_2 I$





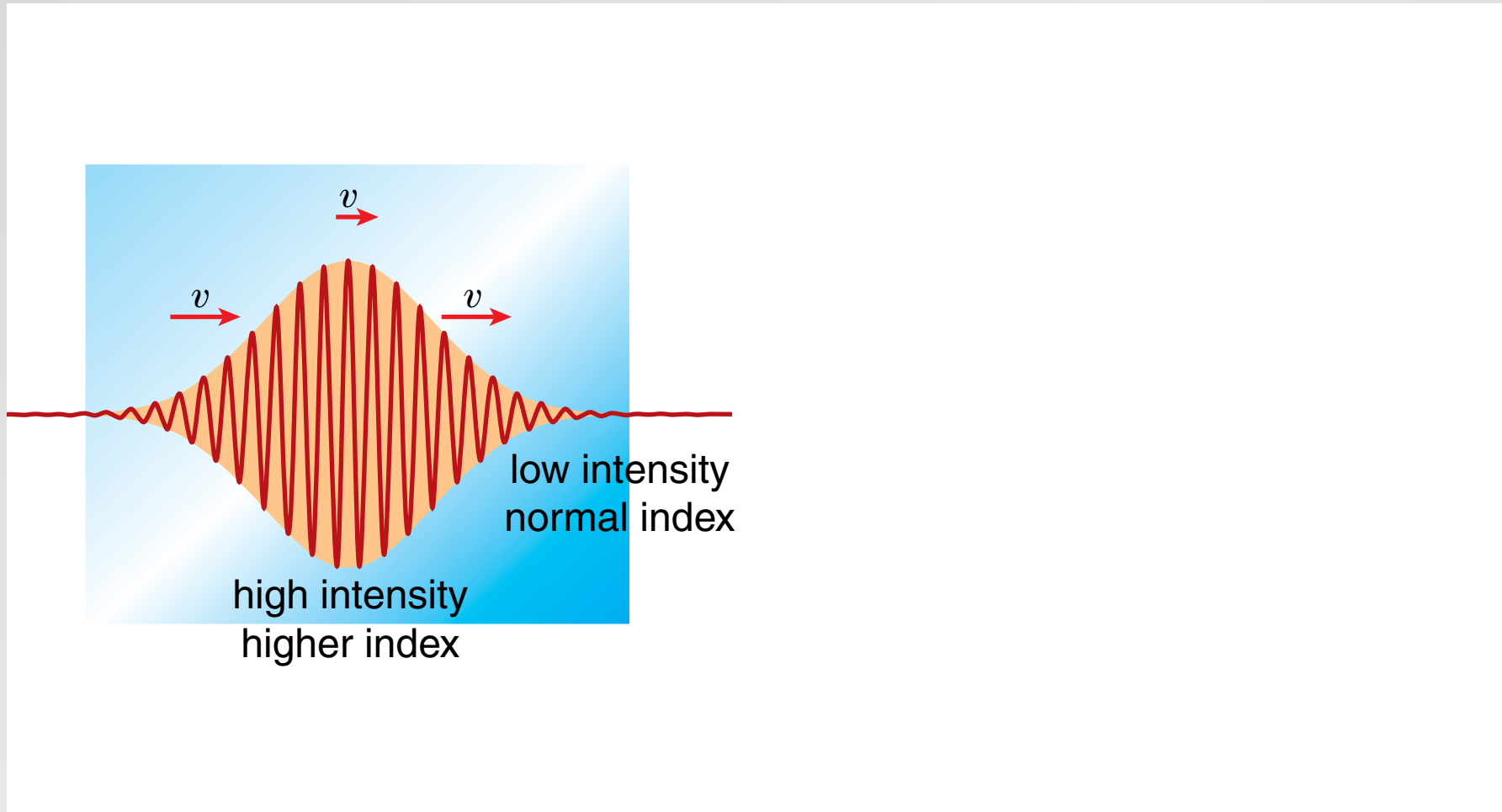
# Nonlinear properties

nonlinear dispersion:  $n = n_0 + n_2 I$



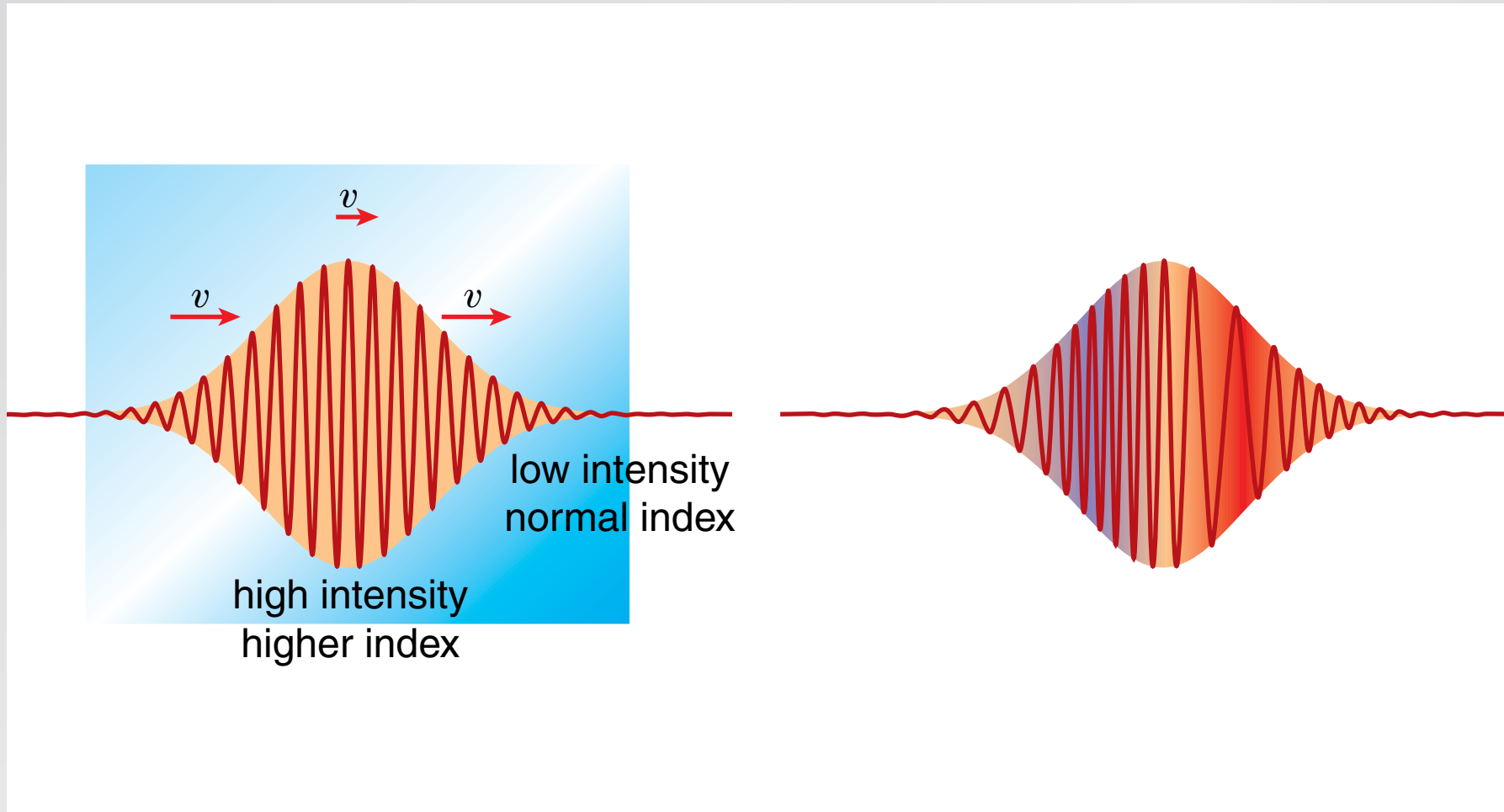
# Nonlinear properties

nonlinear dispersion:  $n = n_0 + n_2 I$



# Nonlinear properties

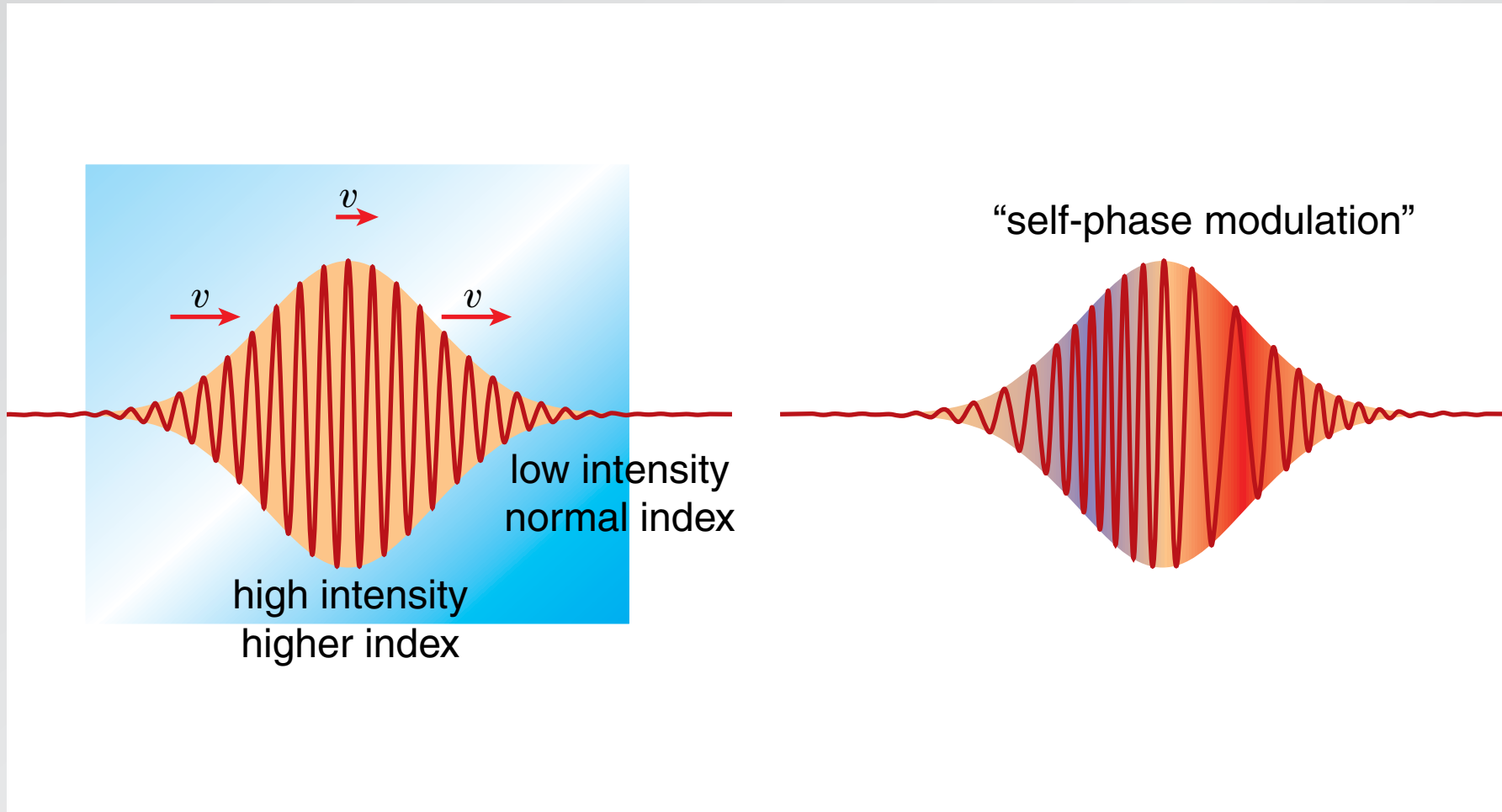
nonlinear dispersion:  $n = n_0 + n_2 I$



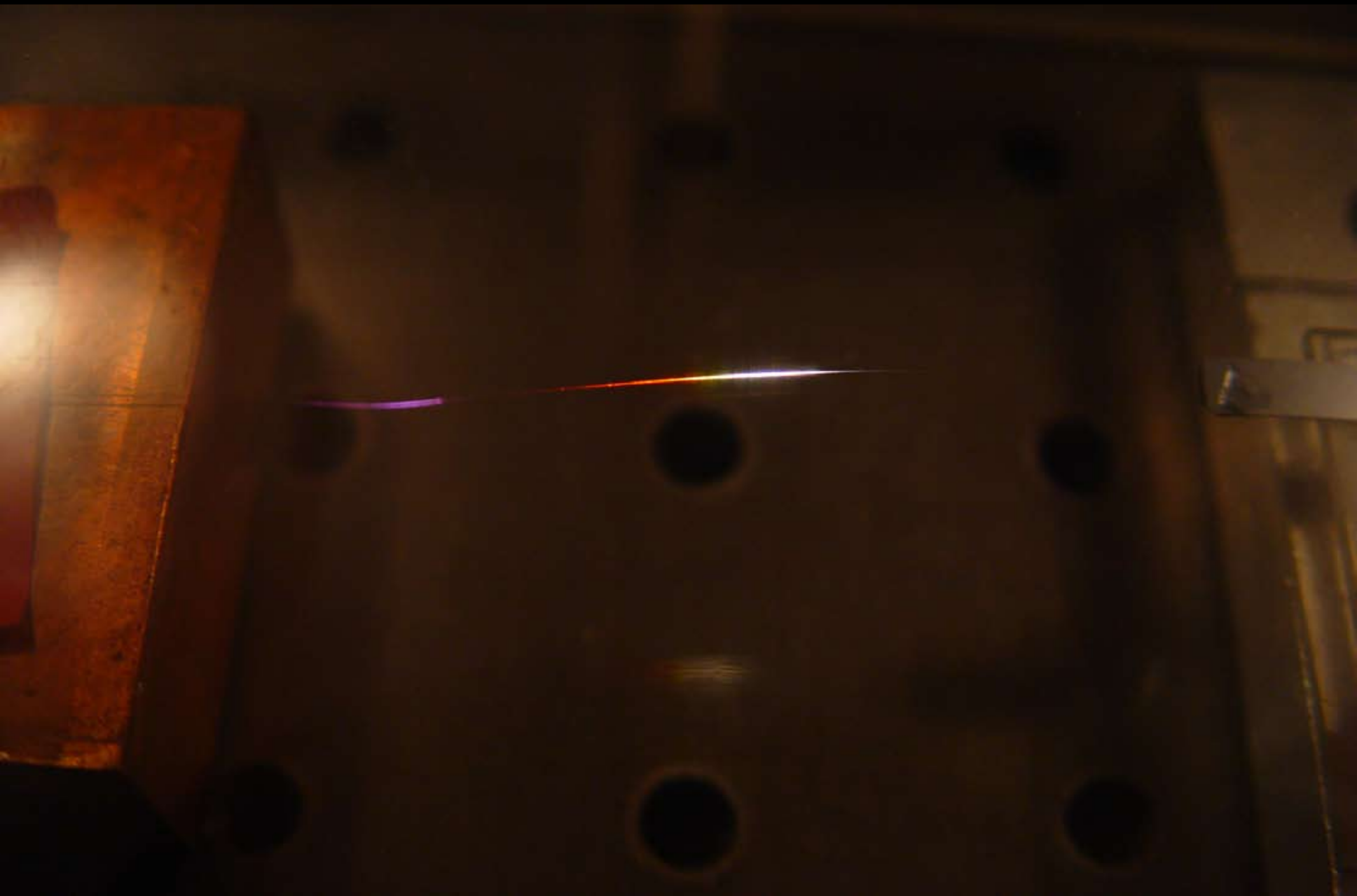


# Nonlinear properties

nonlinear dispersion:  $n = n_0 + n_2 I$



# Nonlinear properties



# Nonlinear properties



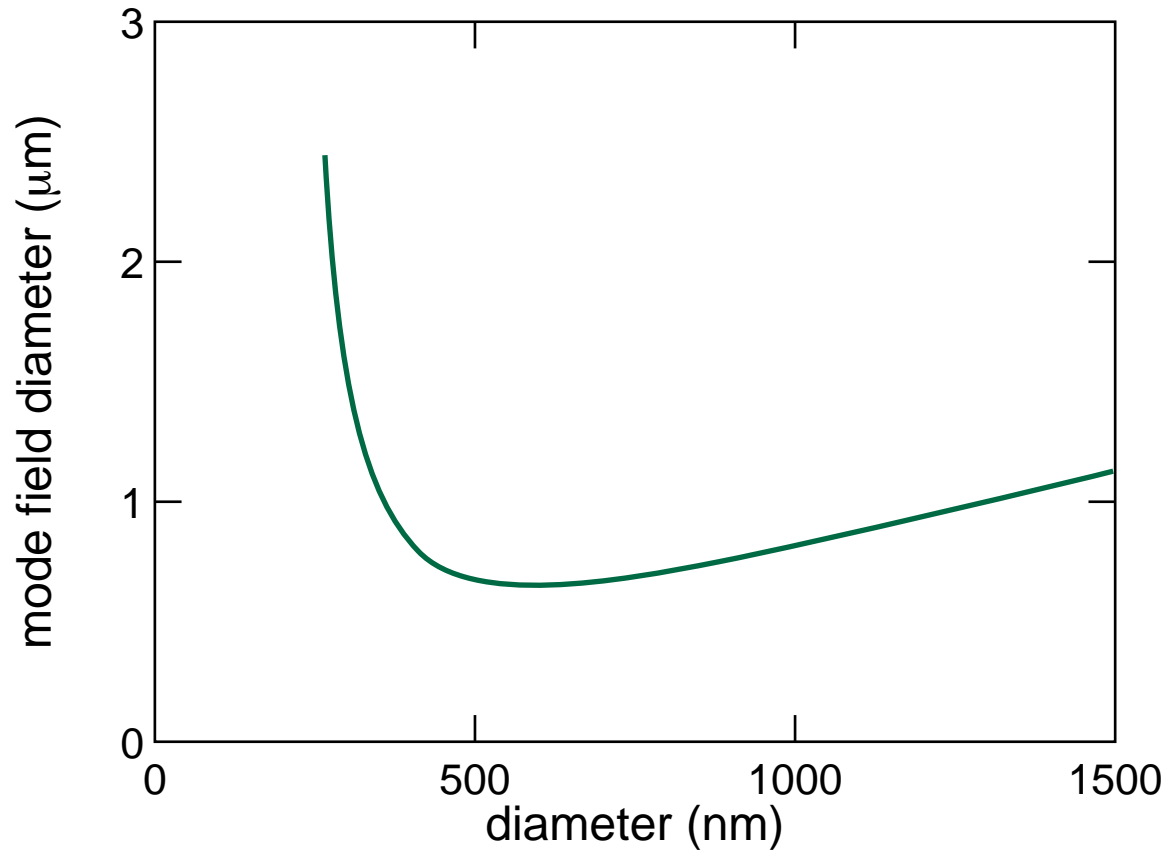


# Nonlinear properties

**strong confinement**  $\longrightarrow$  **high intensity**

# Nonlinear properties

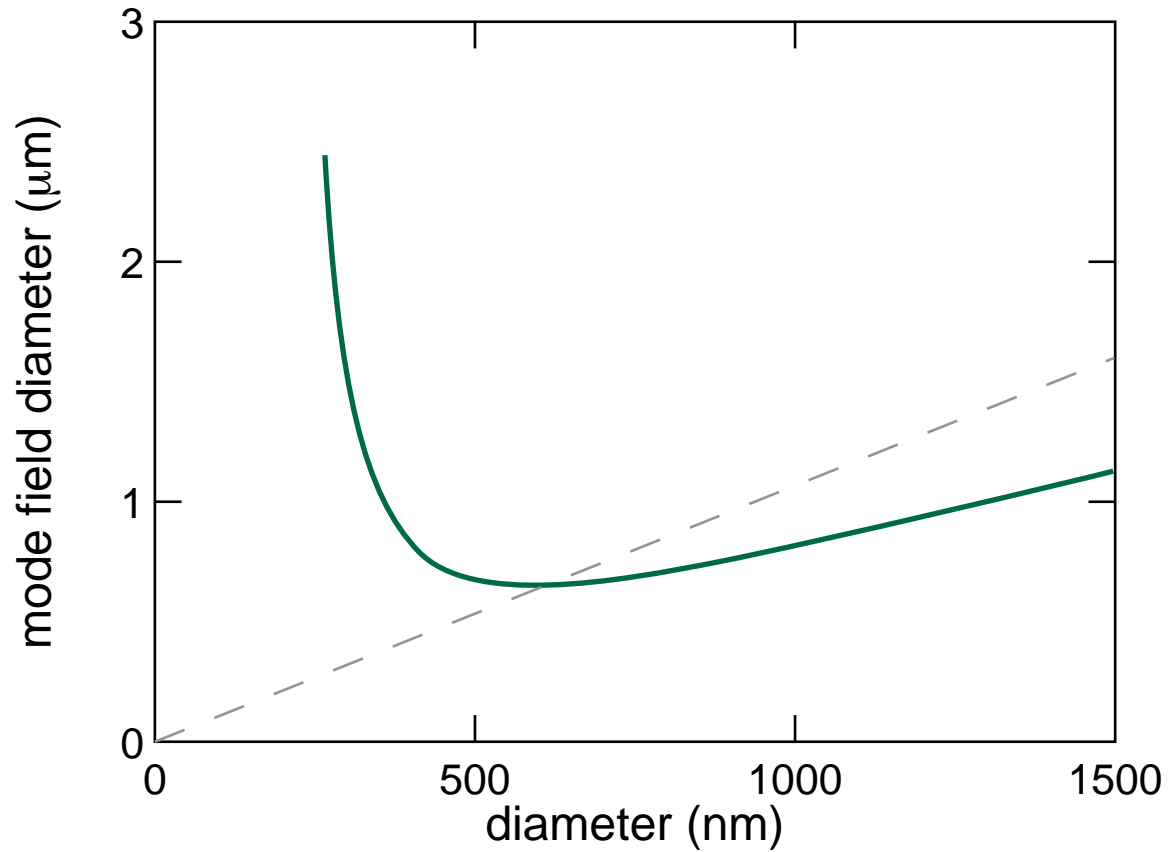
mode field diameter ( $\lambda = 800$  nm)



M.A. Foster, et al., *Optics Express*, 12, 2880 (2004)

# Nonlinear properties

mode field diameter ( $\lambda = 800$  nm)

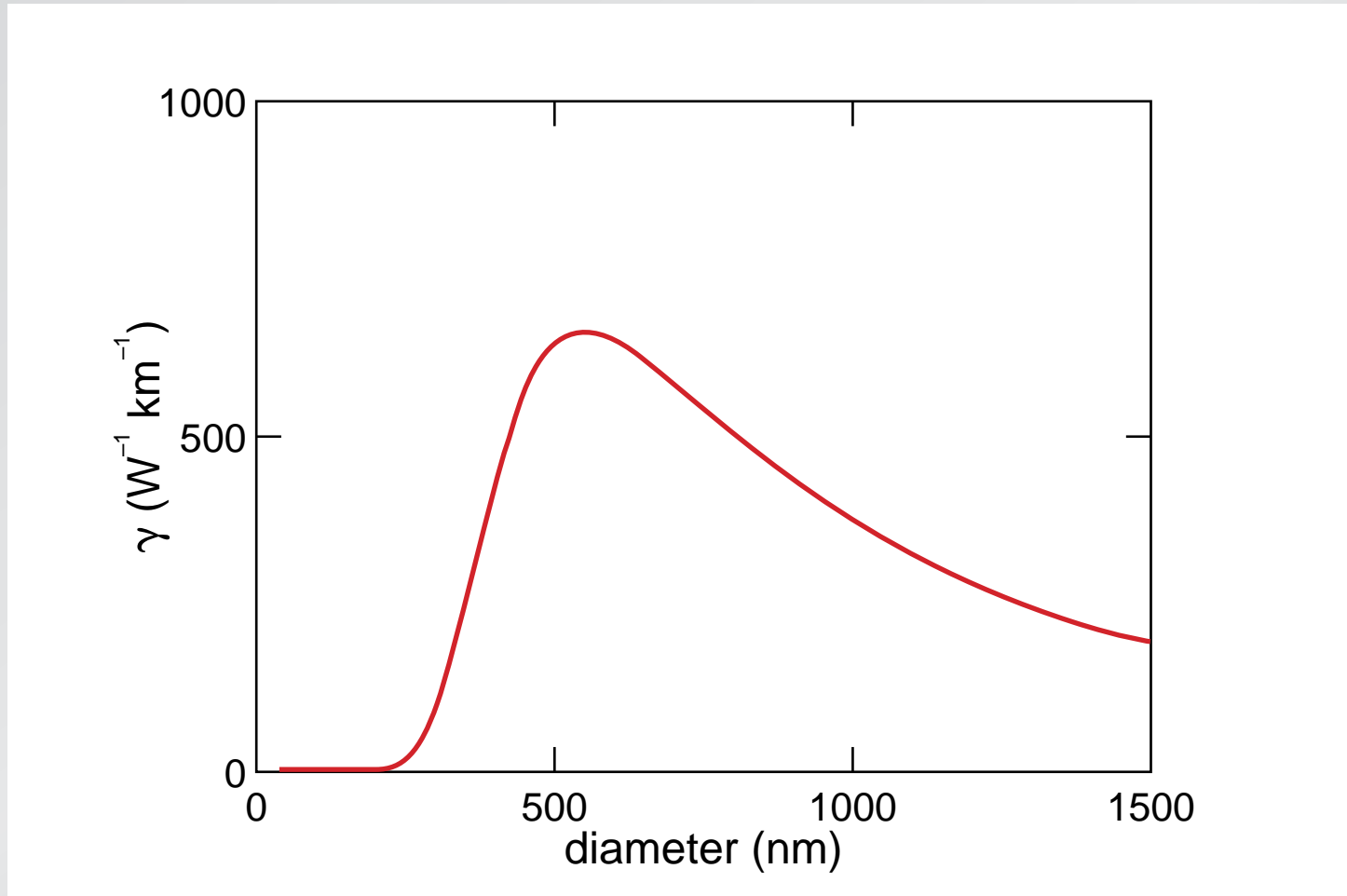


M.A. Foster, et al., *Optics Express*, 12, 2880 (2004)



# Nonlinear properties

nonlinear parameter



M.A. Foster, et al., *Optics Express*, 12, 2880 (2004)

# Nonlinear properties

**dispersion important!**

# Nonlinear properties

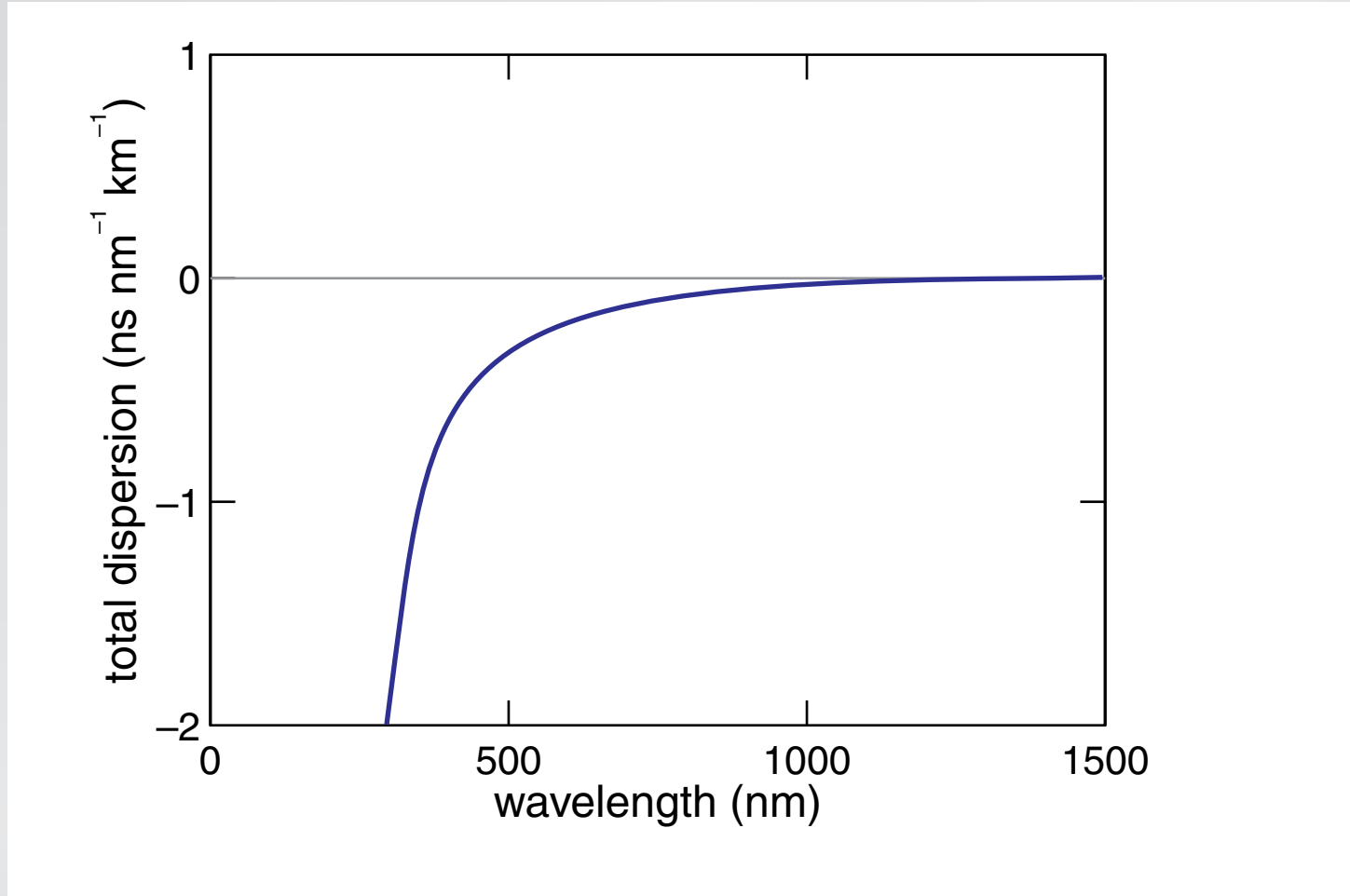
dispersion:

- modal dispersion
- material dispersion
- waveguide dispersion
- nonlinear dispersion



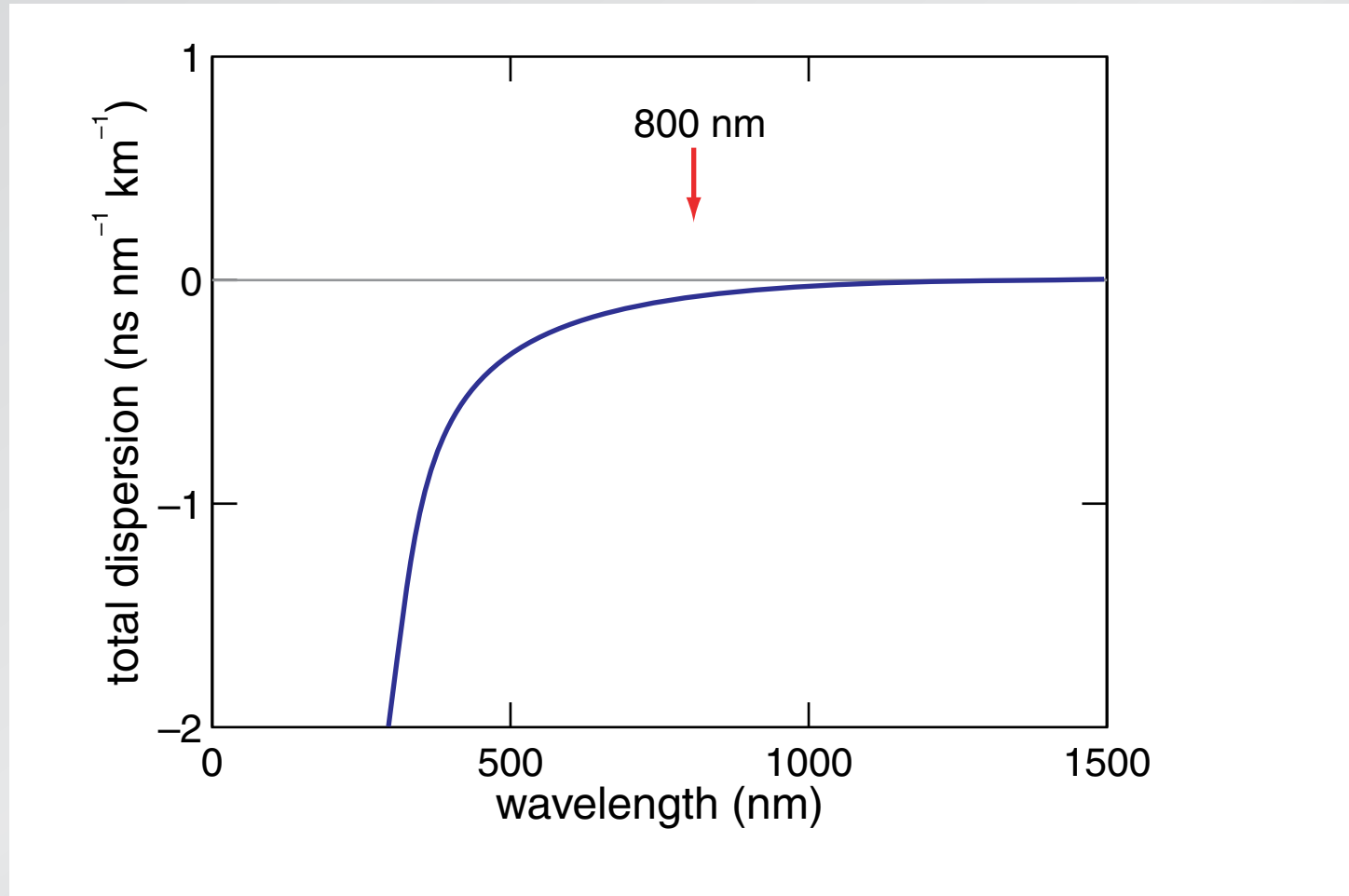
# Nonlinear properties

## waveguide dispersion



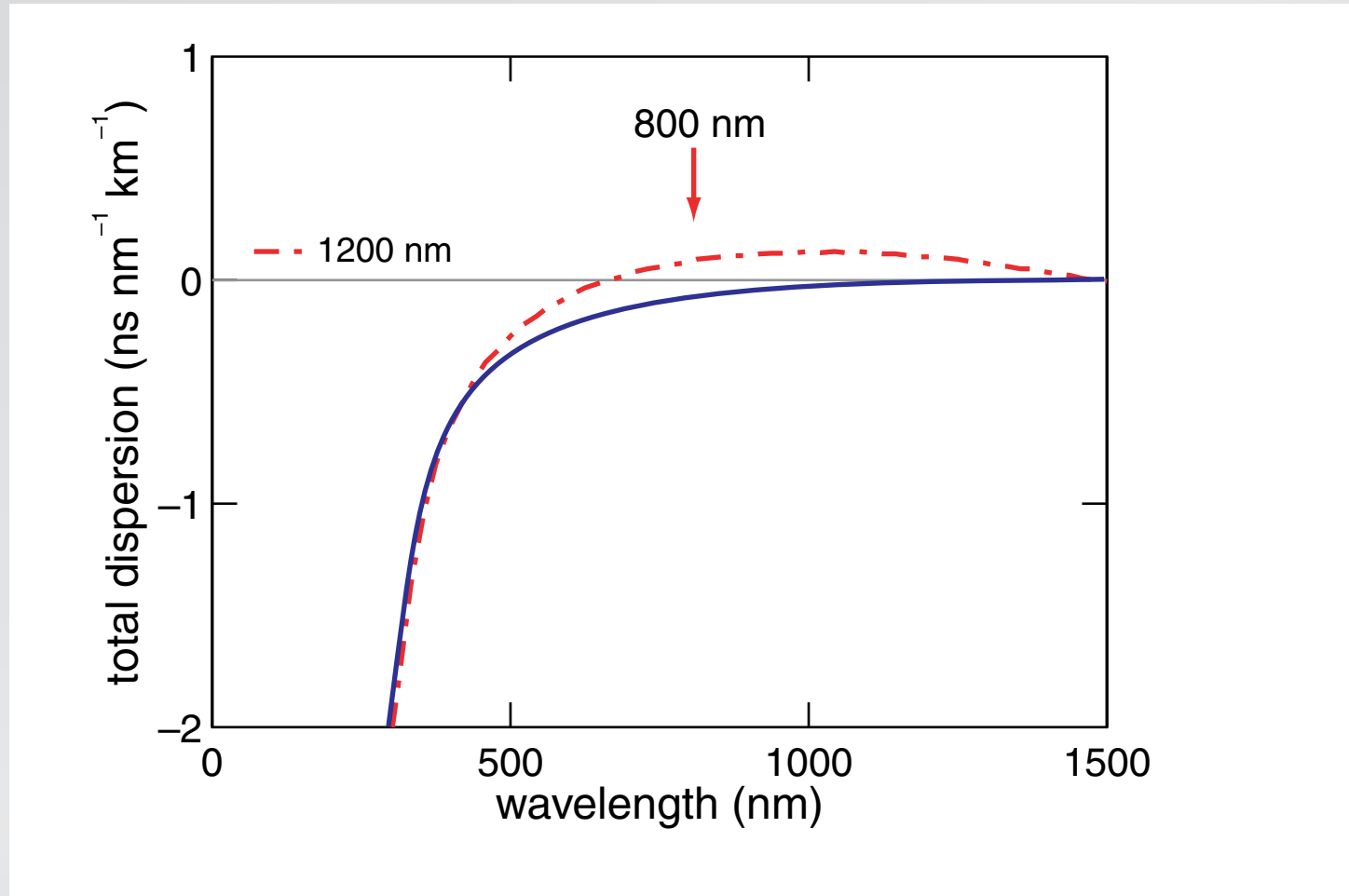
# Nonlinear properties

## waveguide dispersion



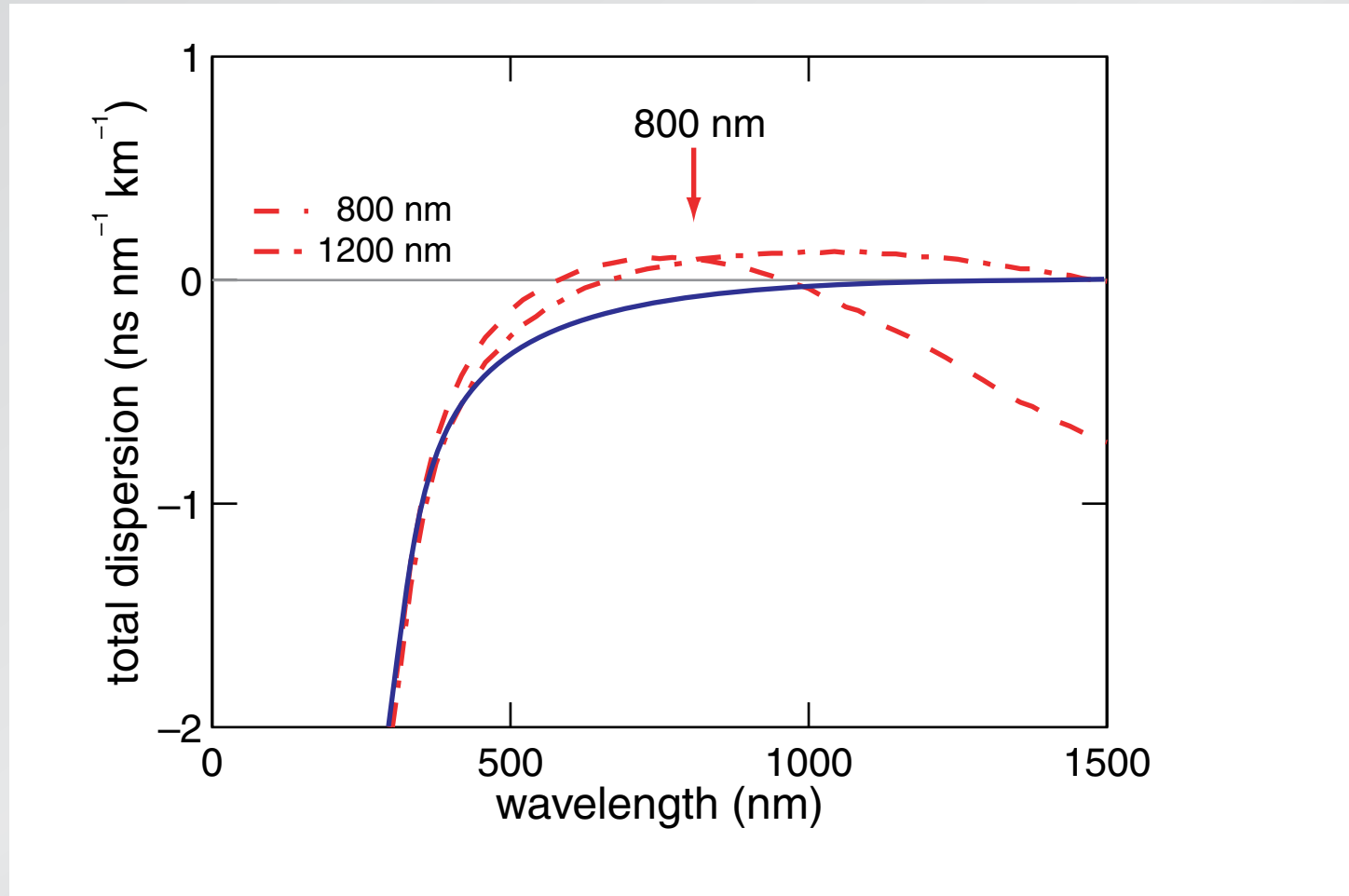
# Nonlinear properties

## waveguide dispersion



# Nonlinear properties

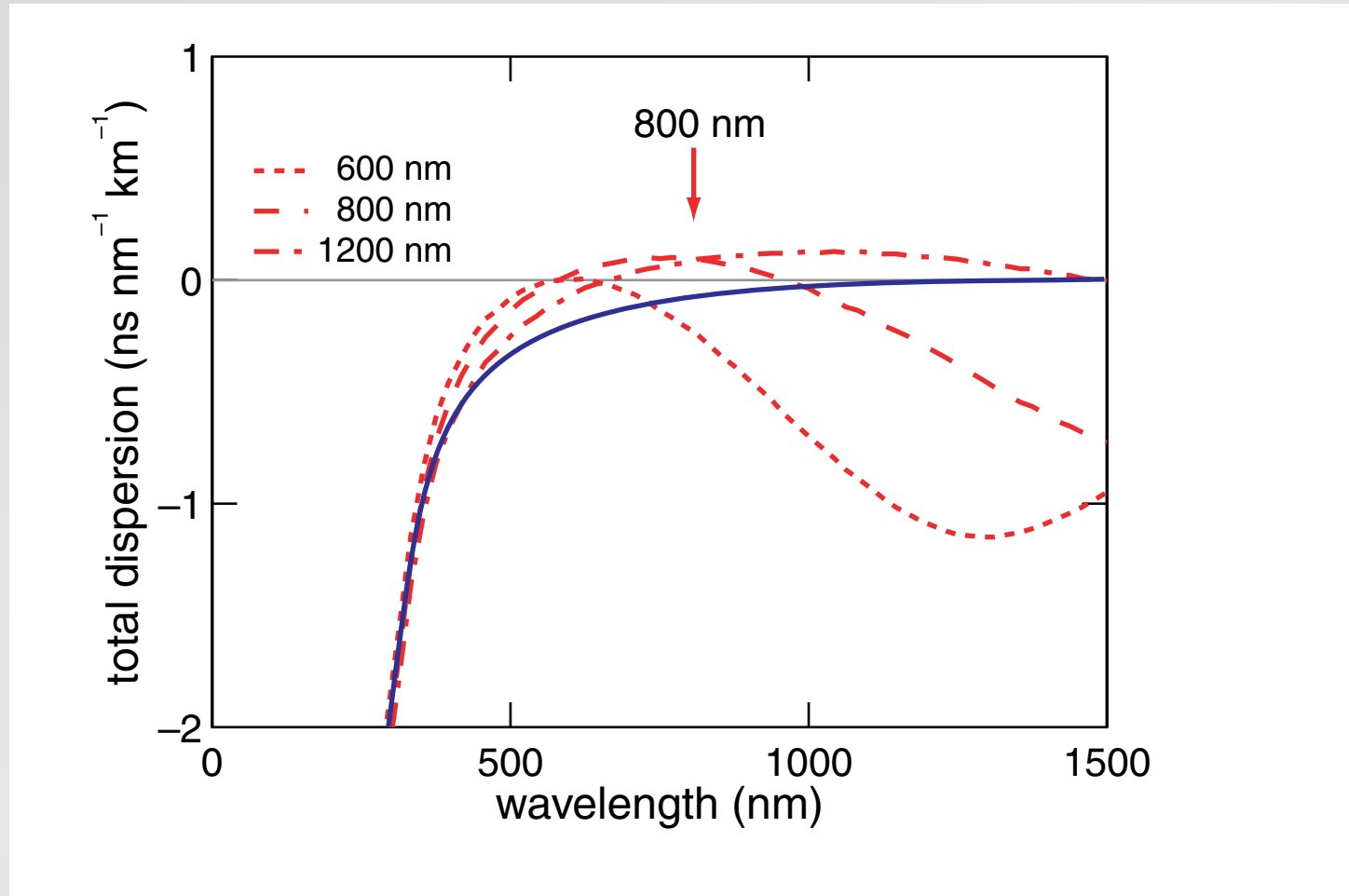
## waveguide dispersion





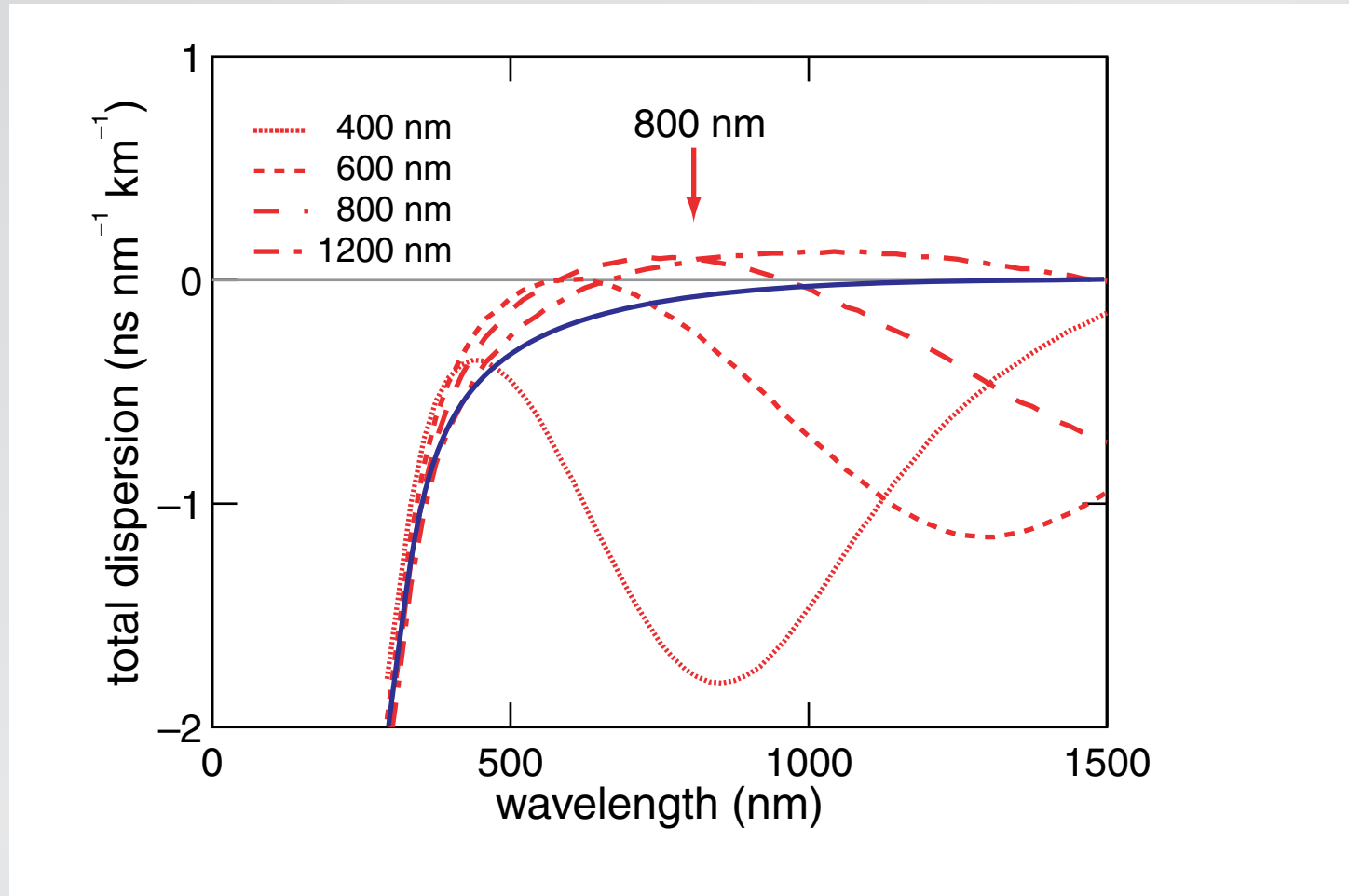
# Nonlinear properties

## waveguide dispersion



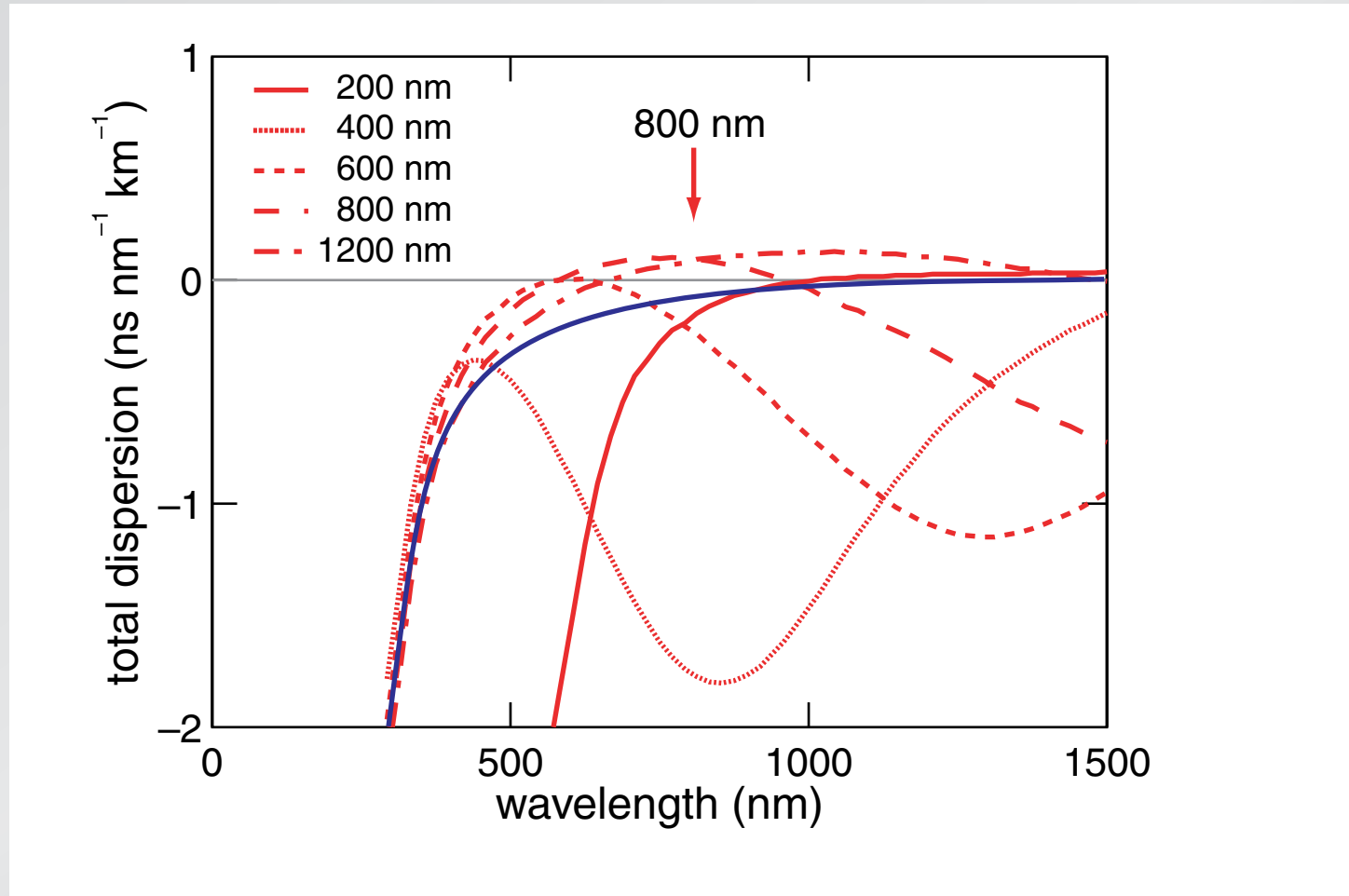
# Nonlinear properties

## waveguide dispersion



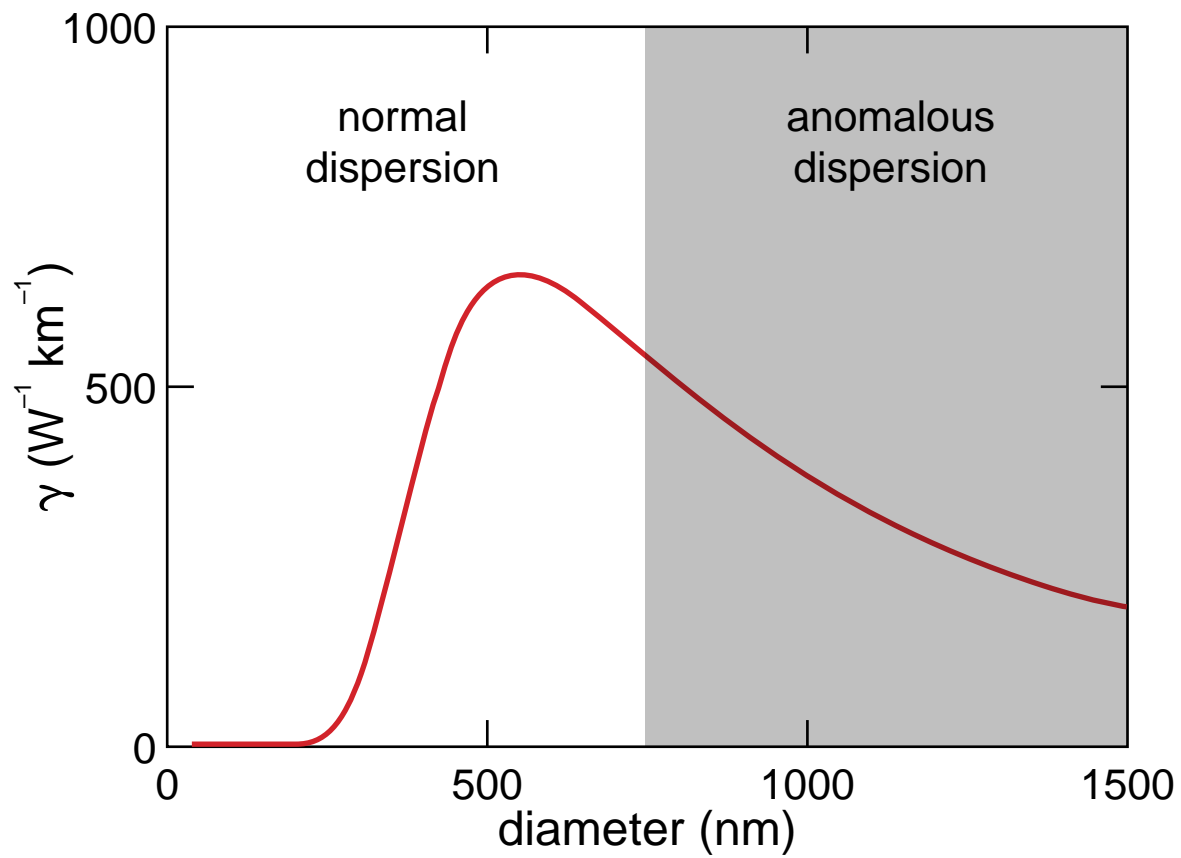
# Nonlinear properties

## waveguide dispersion



# Nonlinear properties

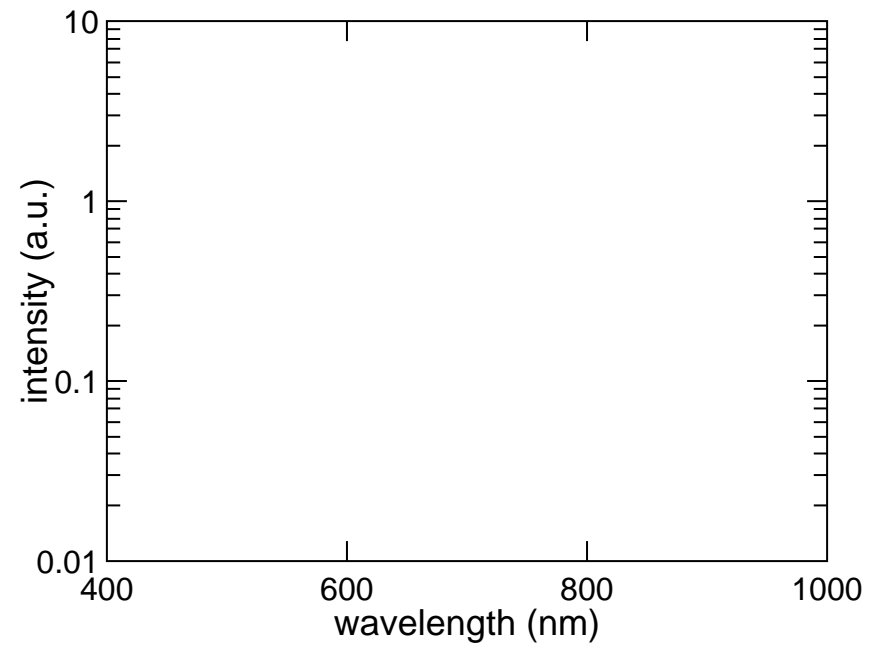
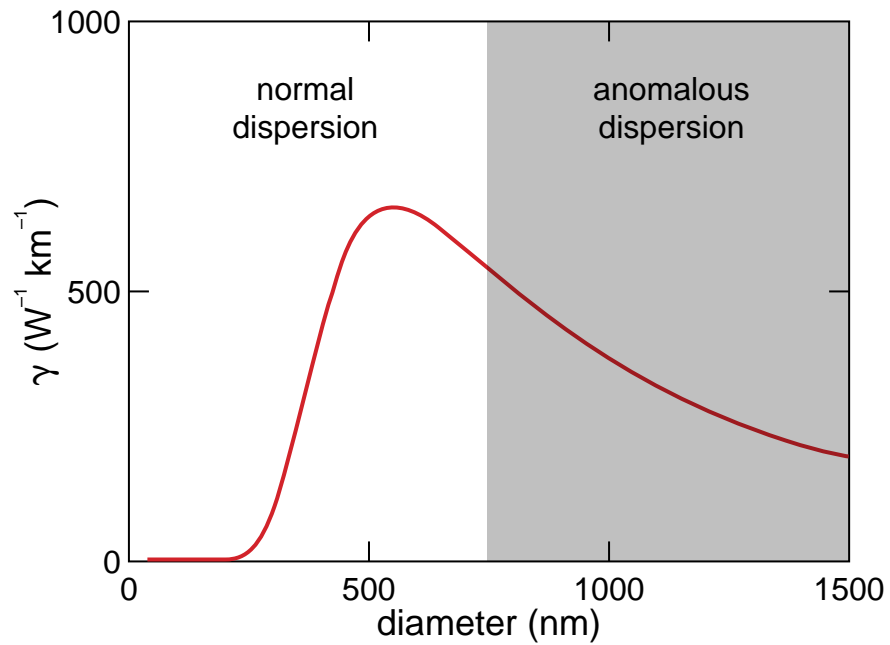
nonlinear parameter





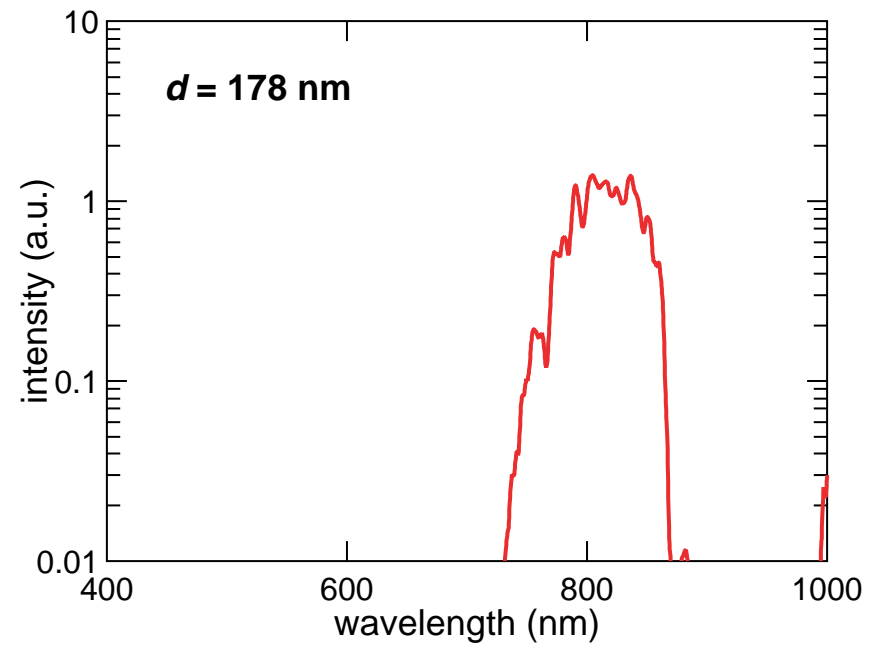
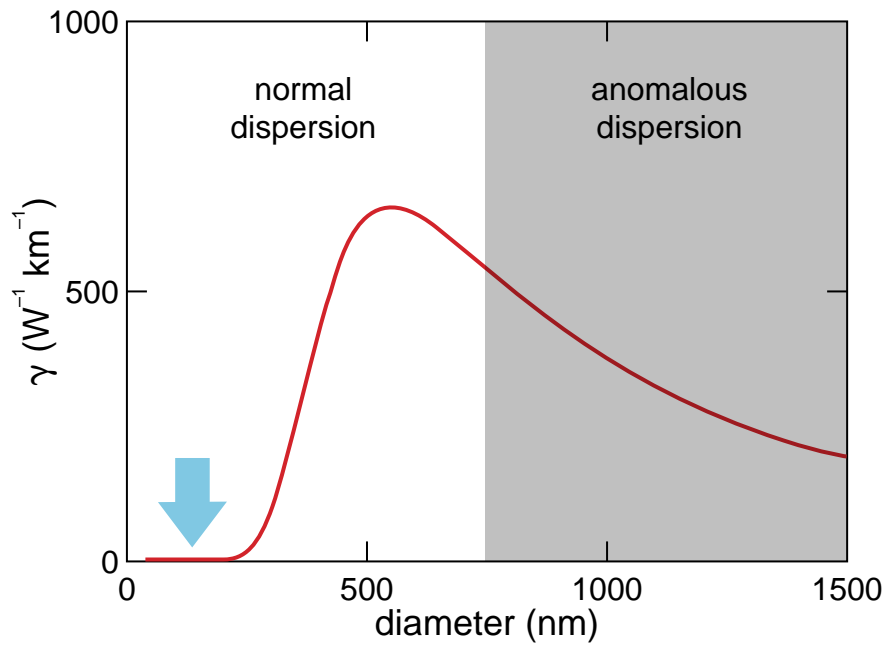
# Nonlinear properties

## nanowire continuum generation



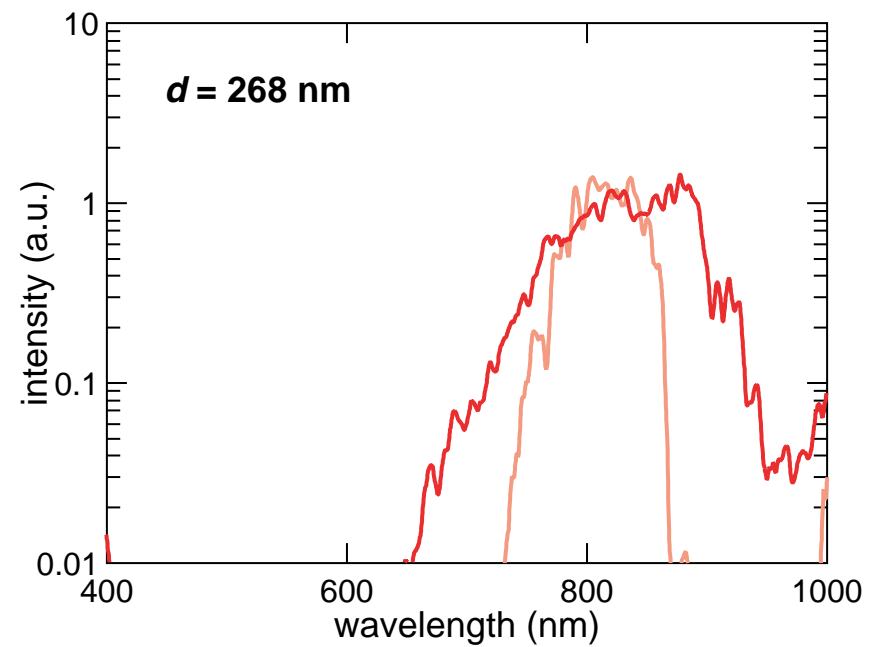
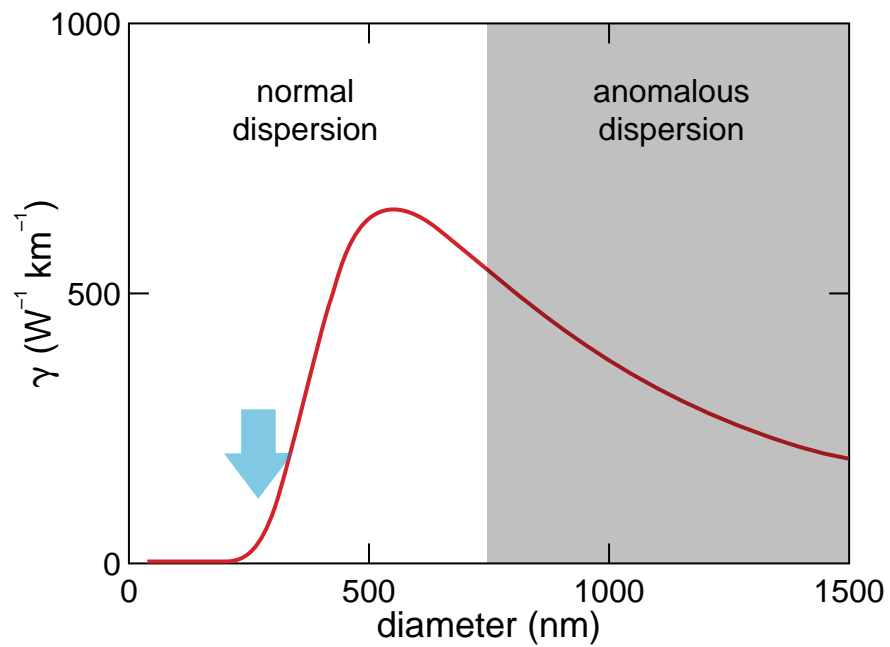
# Nonlinear properties

## nanowire continuum generation



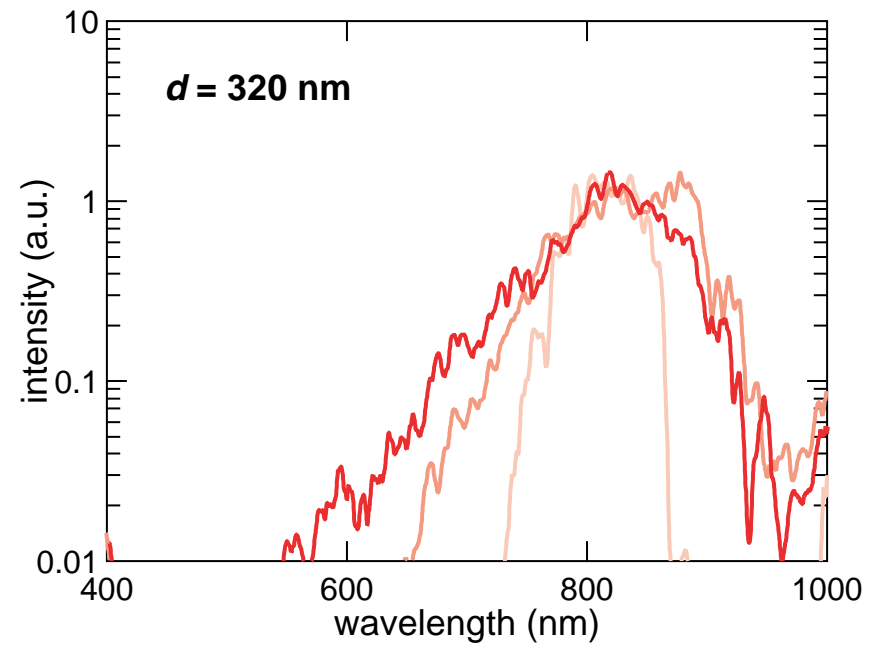
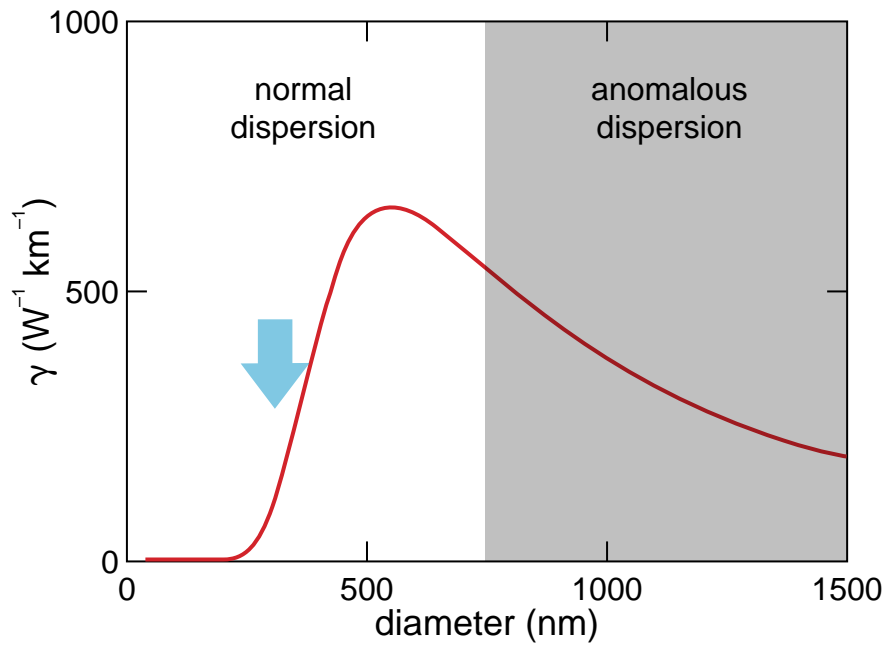
# Nonlinear properties

## nanowire continuum generation



# Nonlinear properties

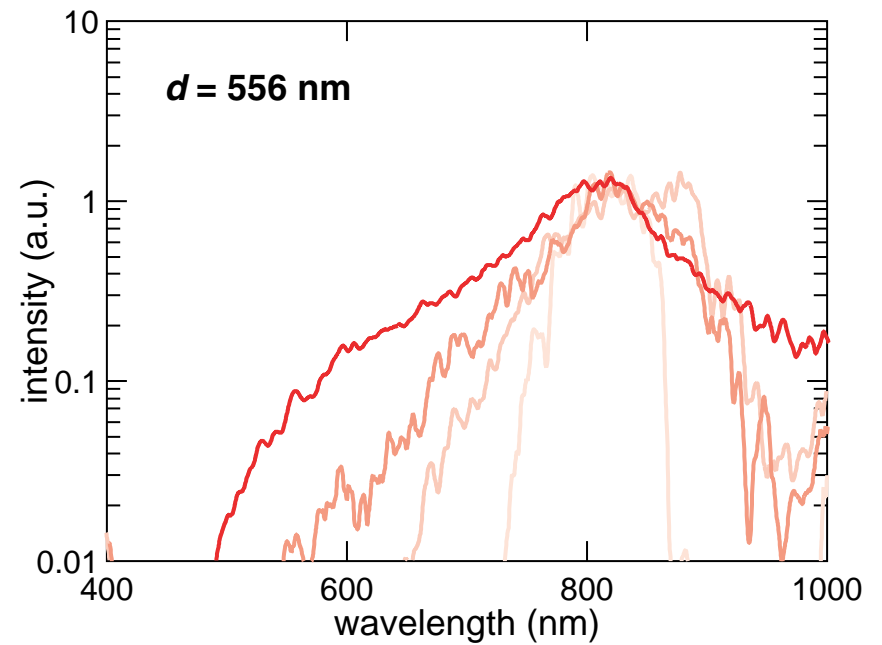
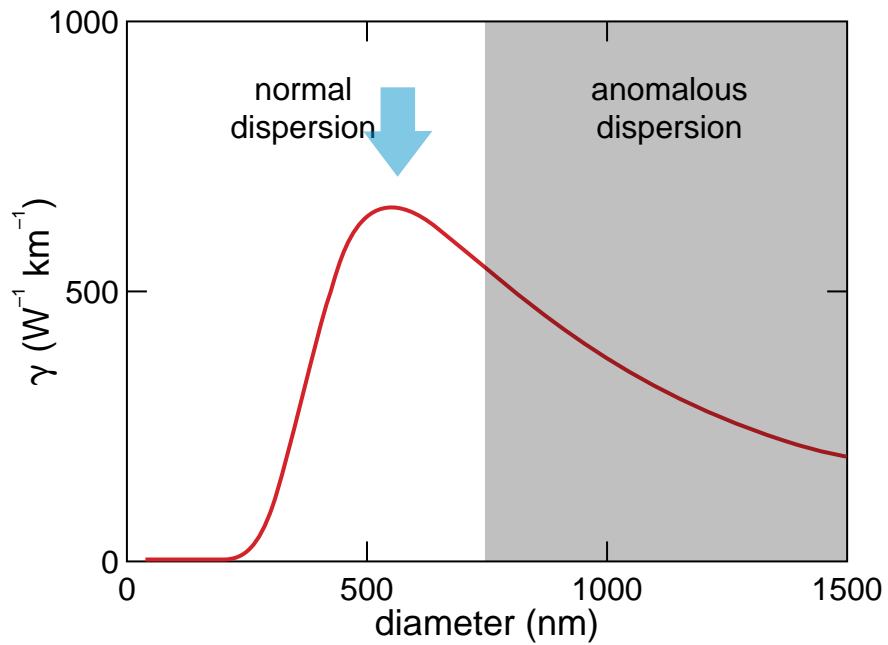
## nanowire continuum generation





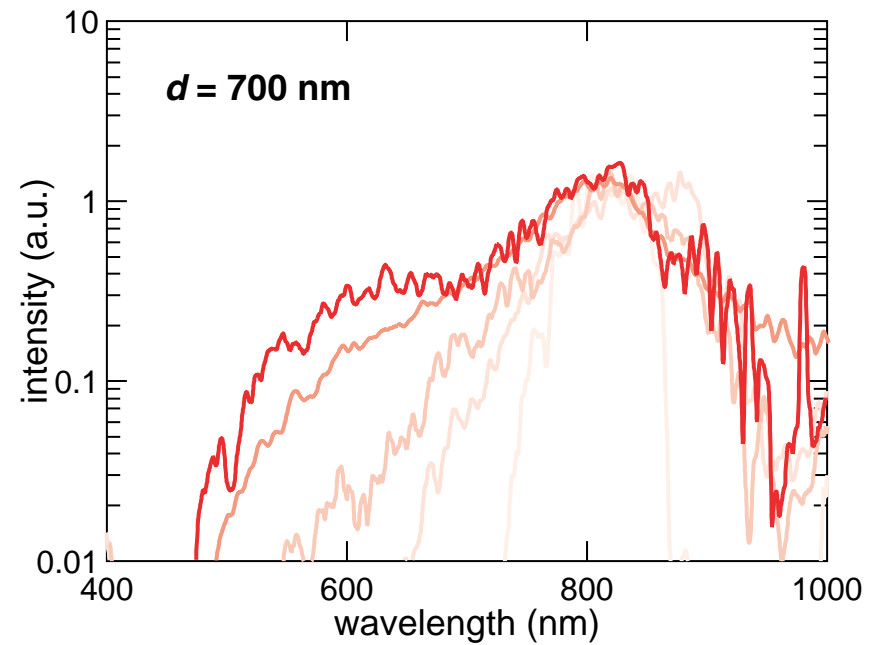
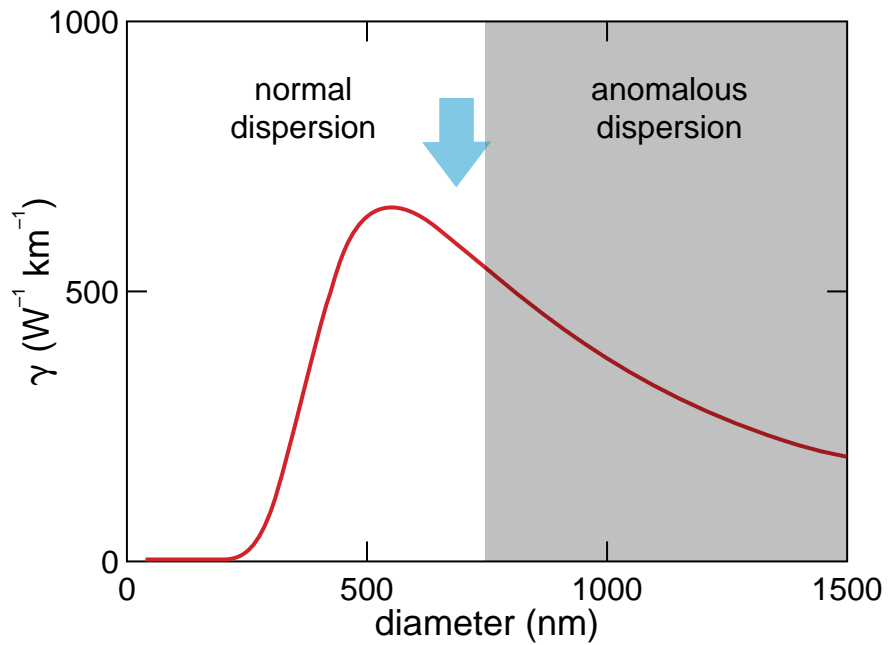
# Nonlinear properties

## nanowire continuum generation



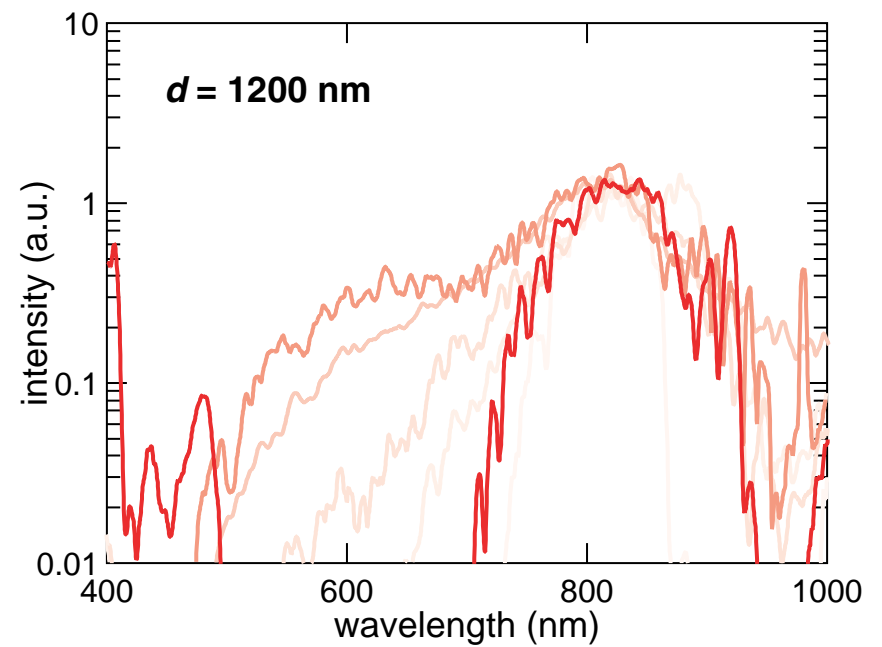
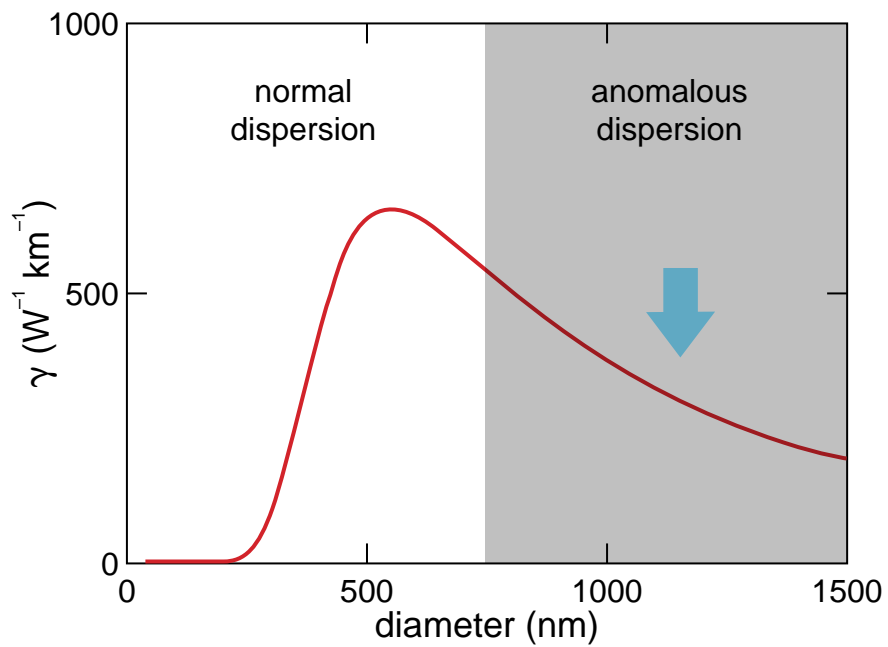
# Nonlinear properties

## nanowire continuum generation



# Nonlinear properties

## nanowire continuum generation



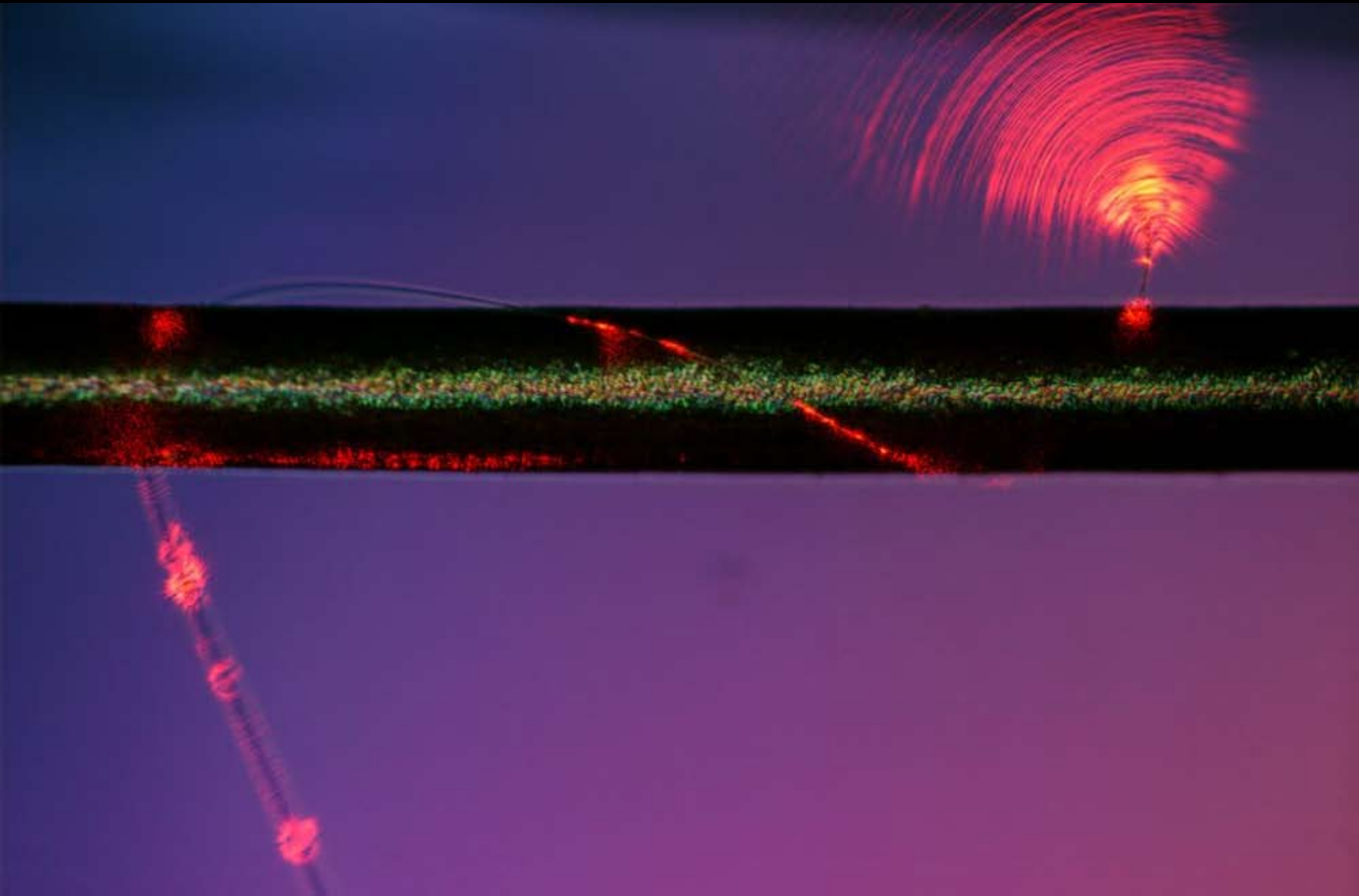
# Nonlinear properties

energy in nanowire  $< 100$  pJ!



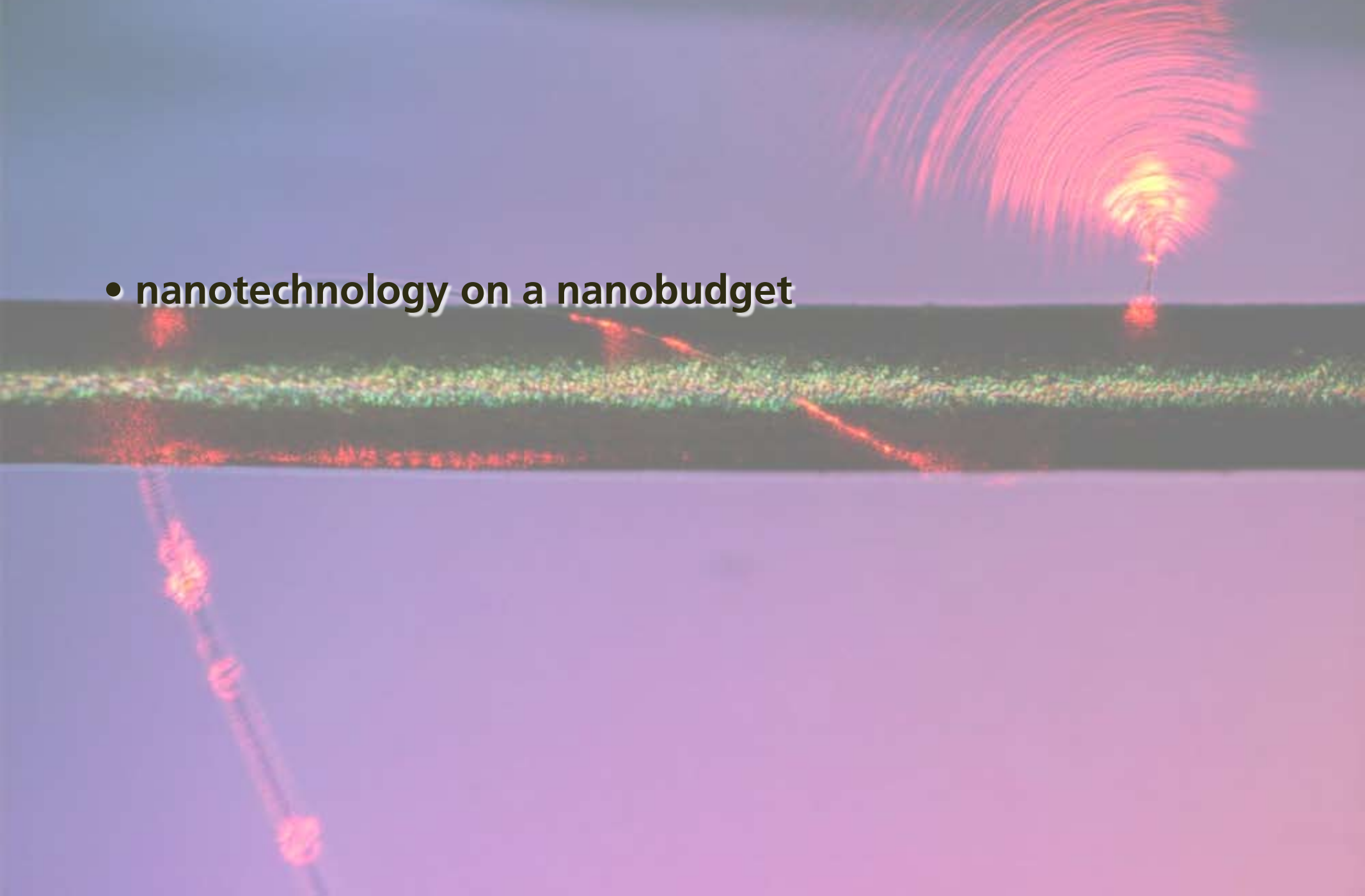


# Summary



# Summary

- nanotechnology on a nanobudget



# Summary

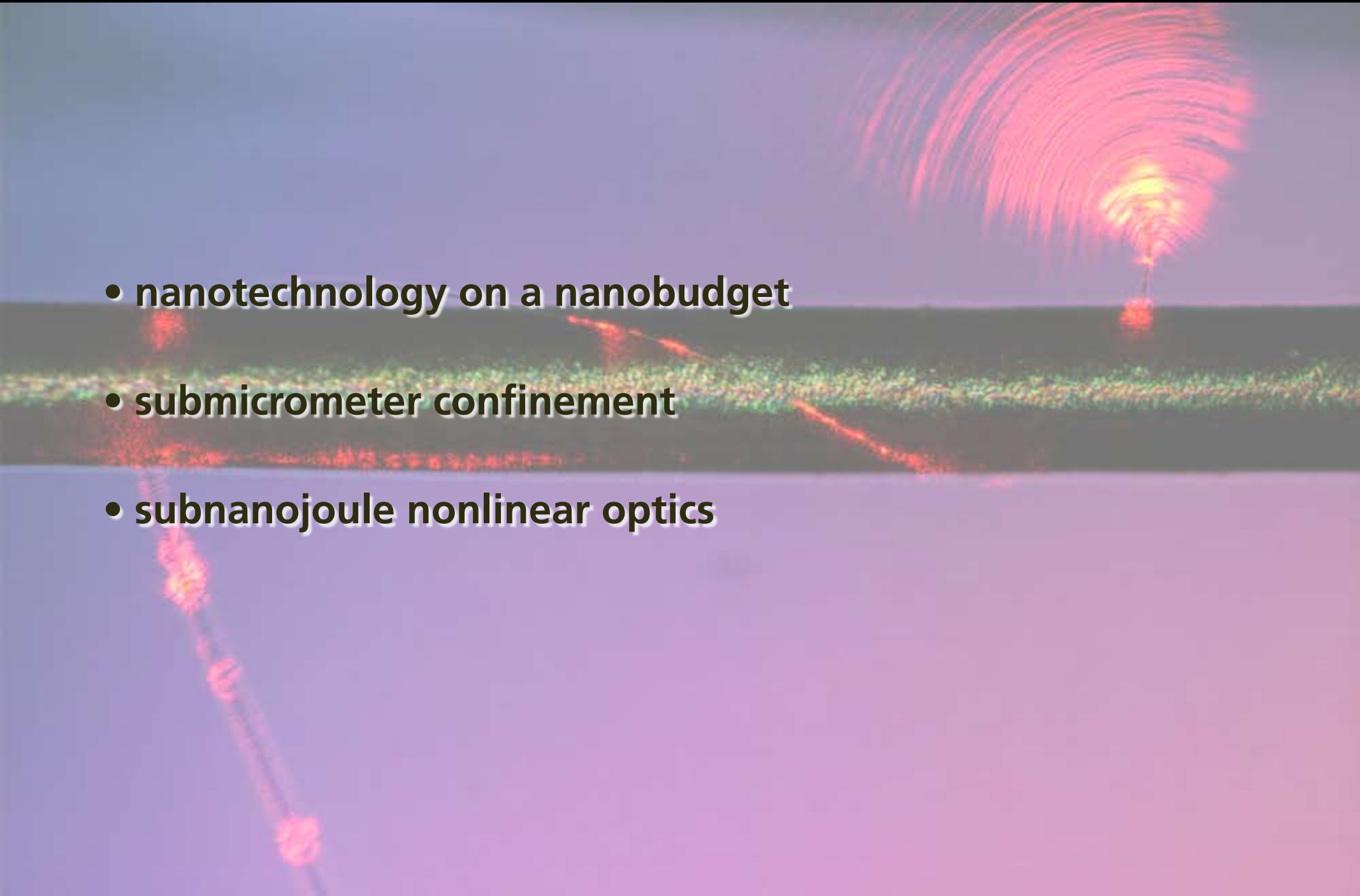
- nanotechnology on a nanobudget
- submicrometer confinement





# Summary

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









**Funding:**

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