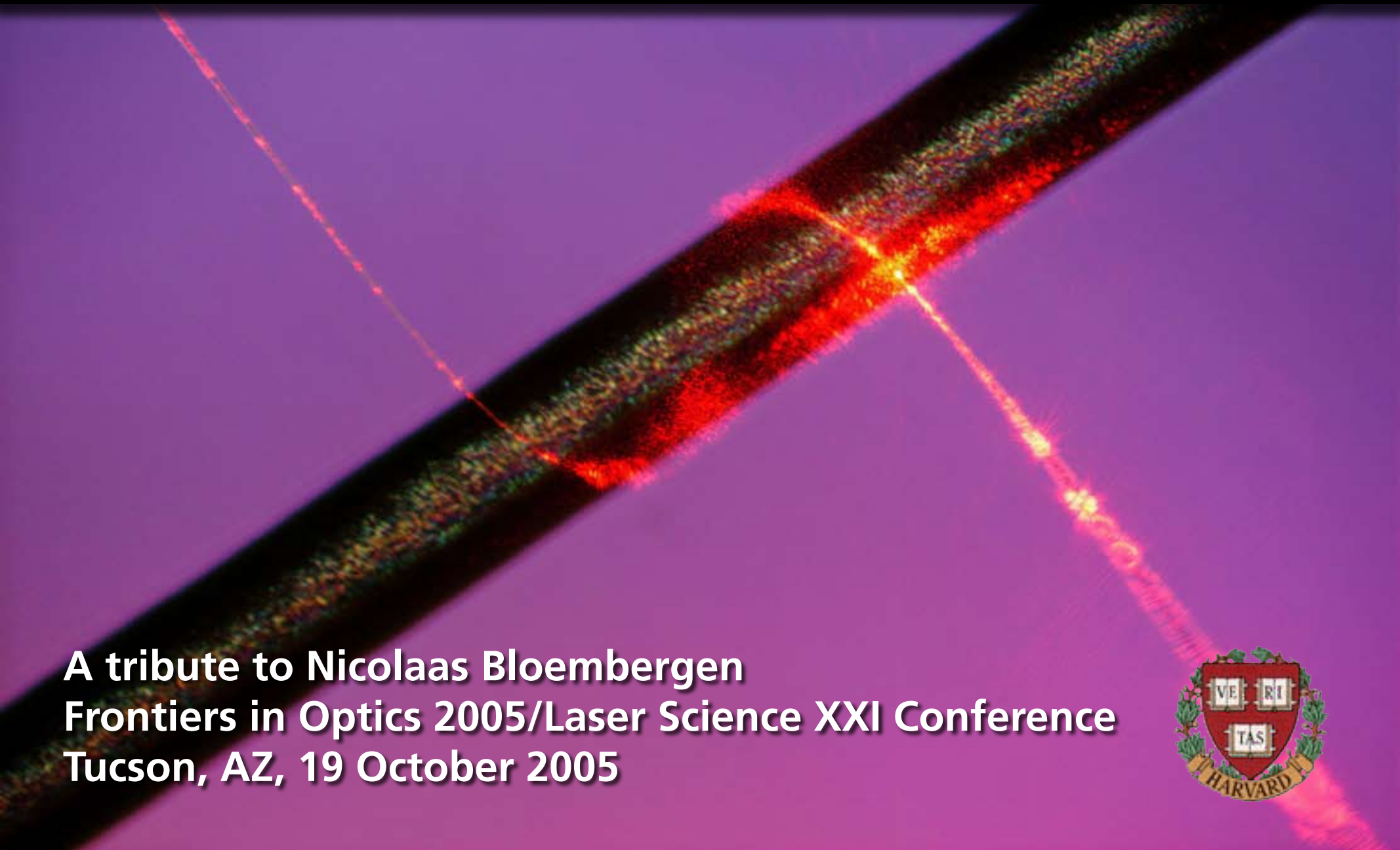
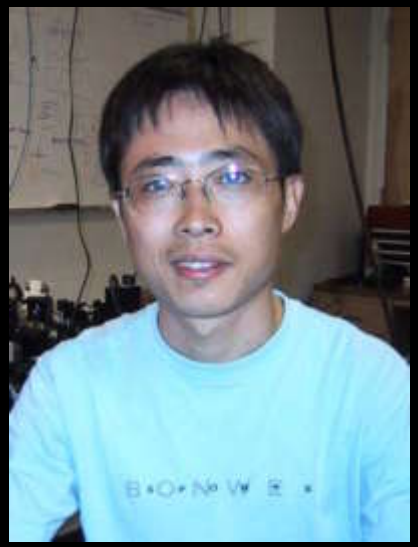
Nonlinear optics at the nanoscale



A tribute to Nicolaas Bloembergen
Frontiers in Optics 2005/Laser Science XXI Conference
Tucson, AZ, 19 October 2005



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:

Xuewen 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)

NONLINEAR OPTICS

NICOLAAS BLOEMBERGEN

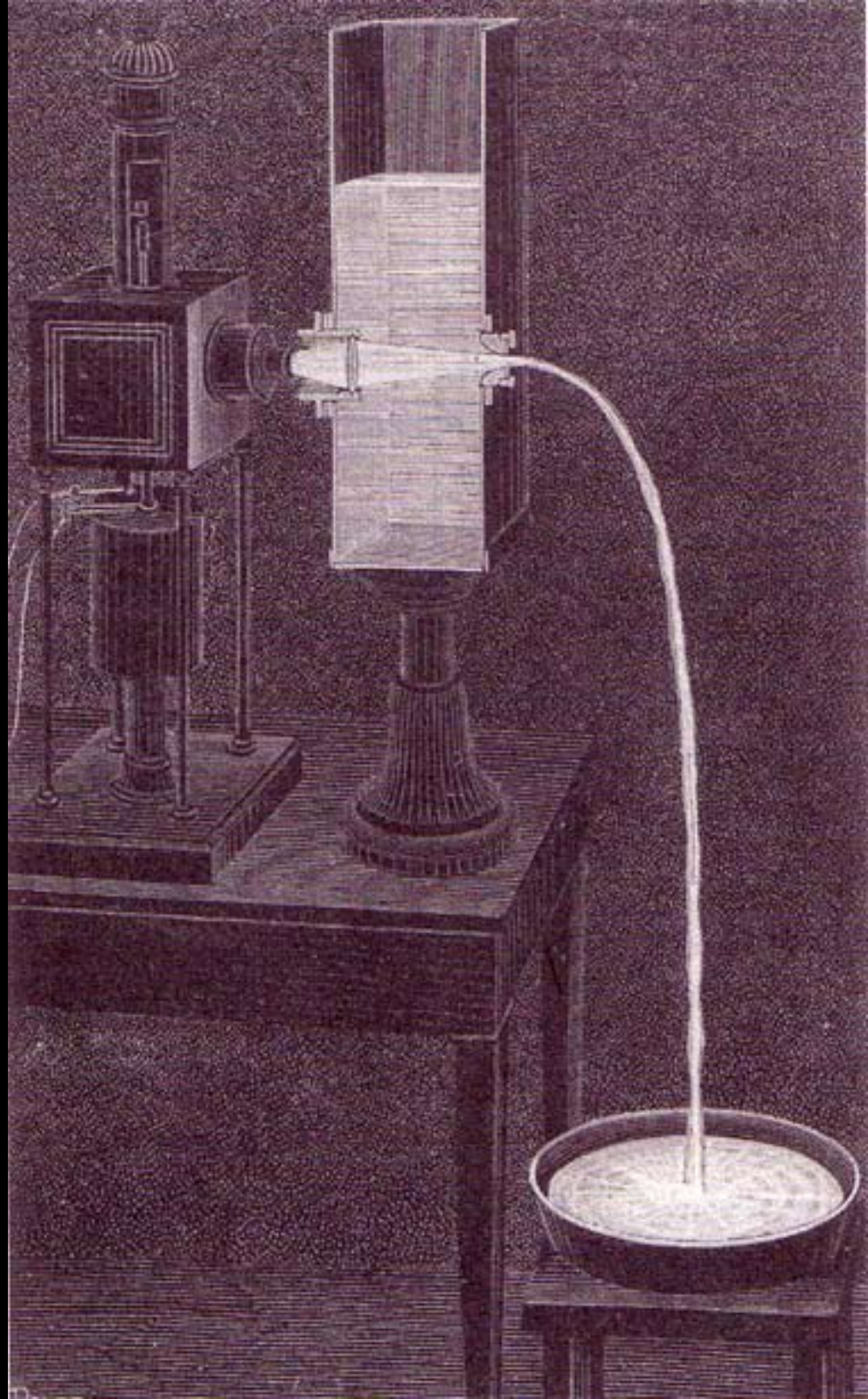
- create lots of photons (lasers)

- create lots of photons (lasers)
- squeeze photons together in time (short pulses)

- create lots of photons (lasers)
- squeeze photons together in time (short pulses)
- squeeze photons together in space

"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)

(No model.) 4 Sheets—Sheet

W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229. Patented Sept. 20, 1881.

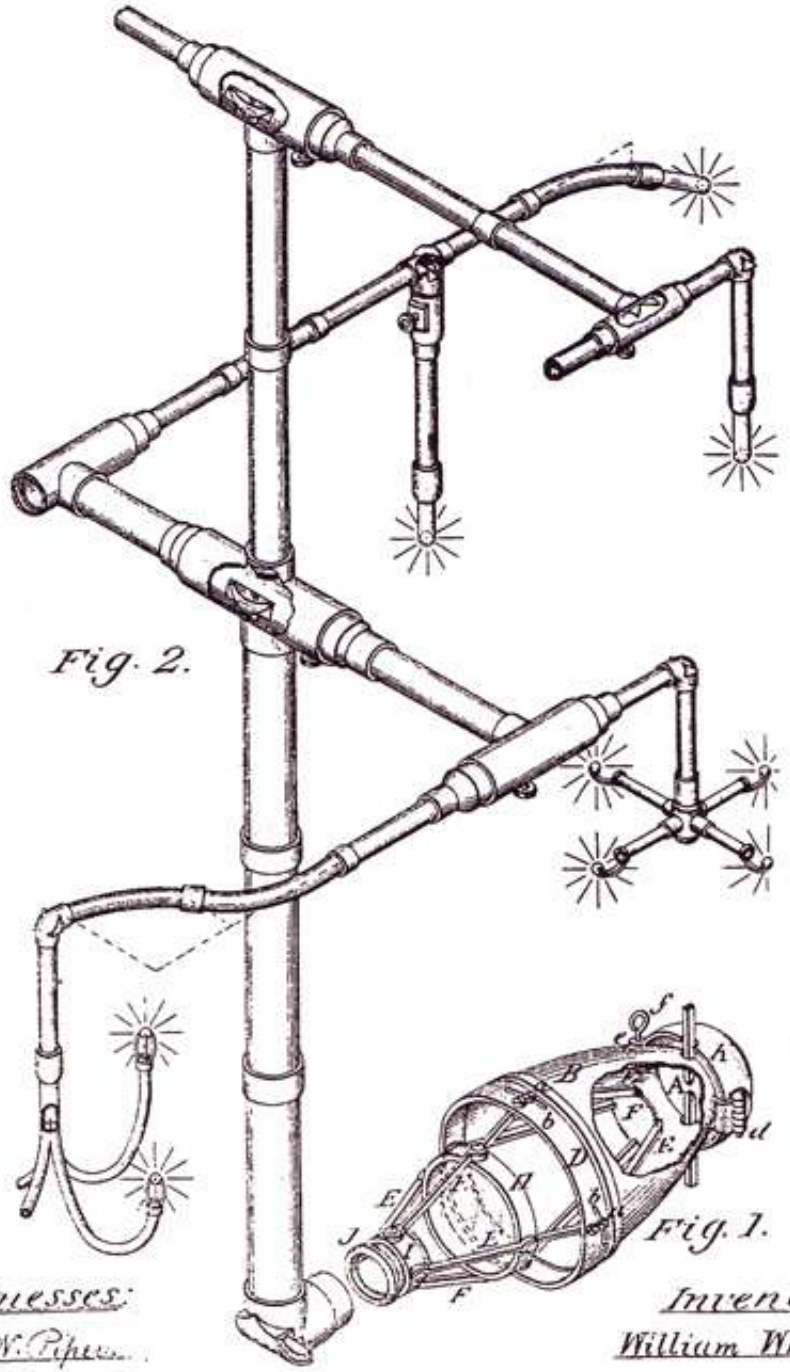


Fig. 2.

Fig. 1.

Witnesses:
S. N. Piper
[illegible]

Inventor:
William Wheeler
by attorney
[illegible]

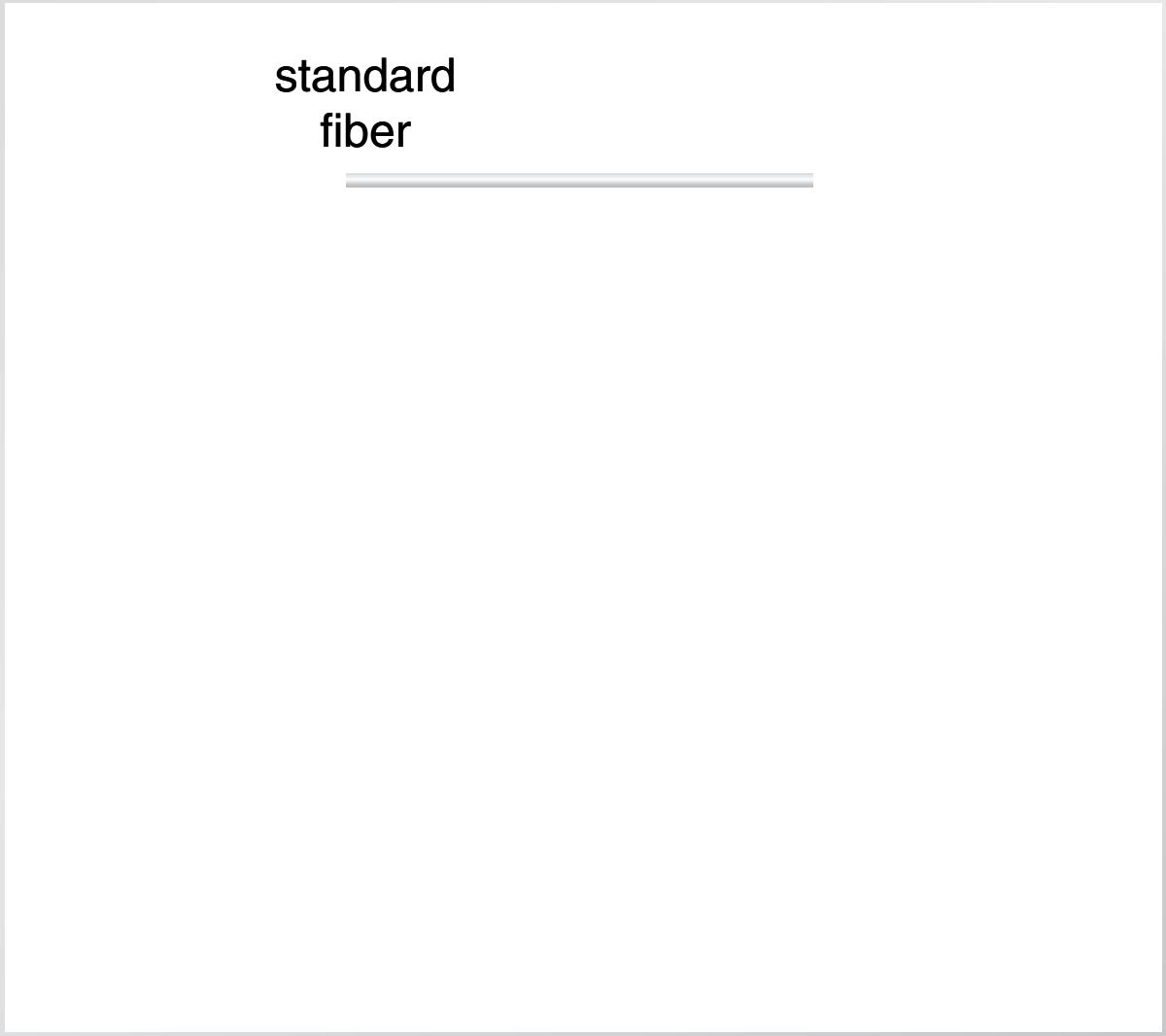
US Patent 247, 229 (1881)

Outline

- silica nanowires
- optical properties
- nonlinear properties

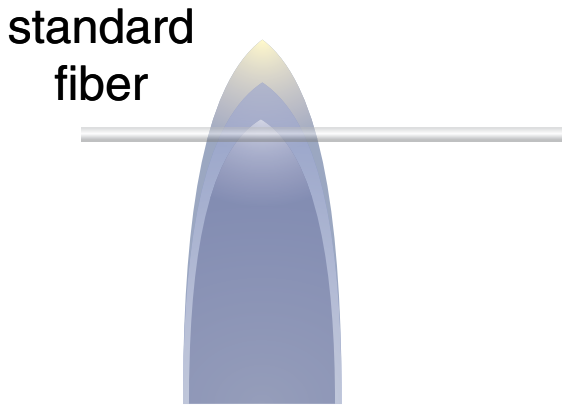
Silica nanowires

two-step drawing process



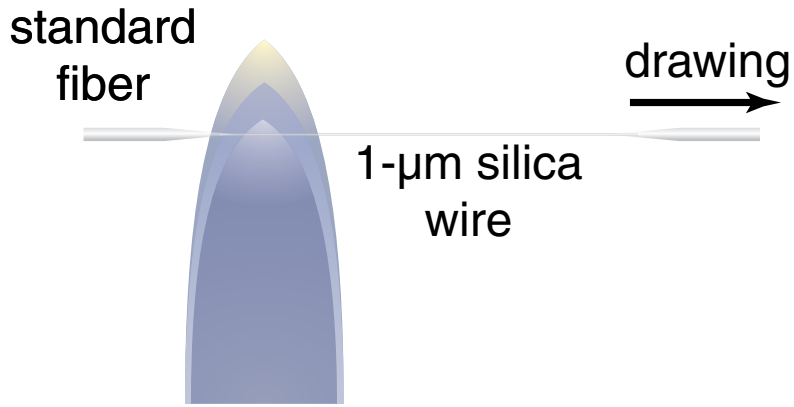
Silica nanowires

two-step drawing process



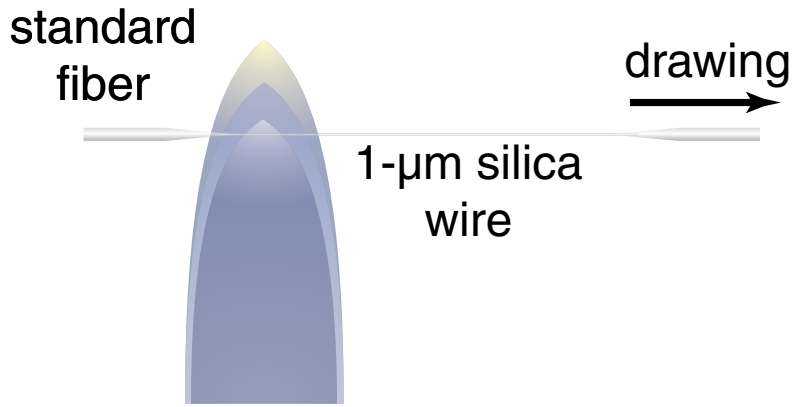
Silica nanowires

two-step drawing process



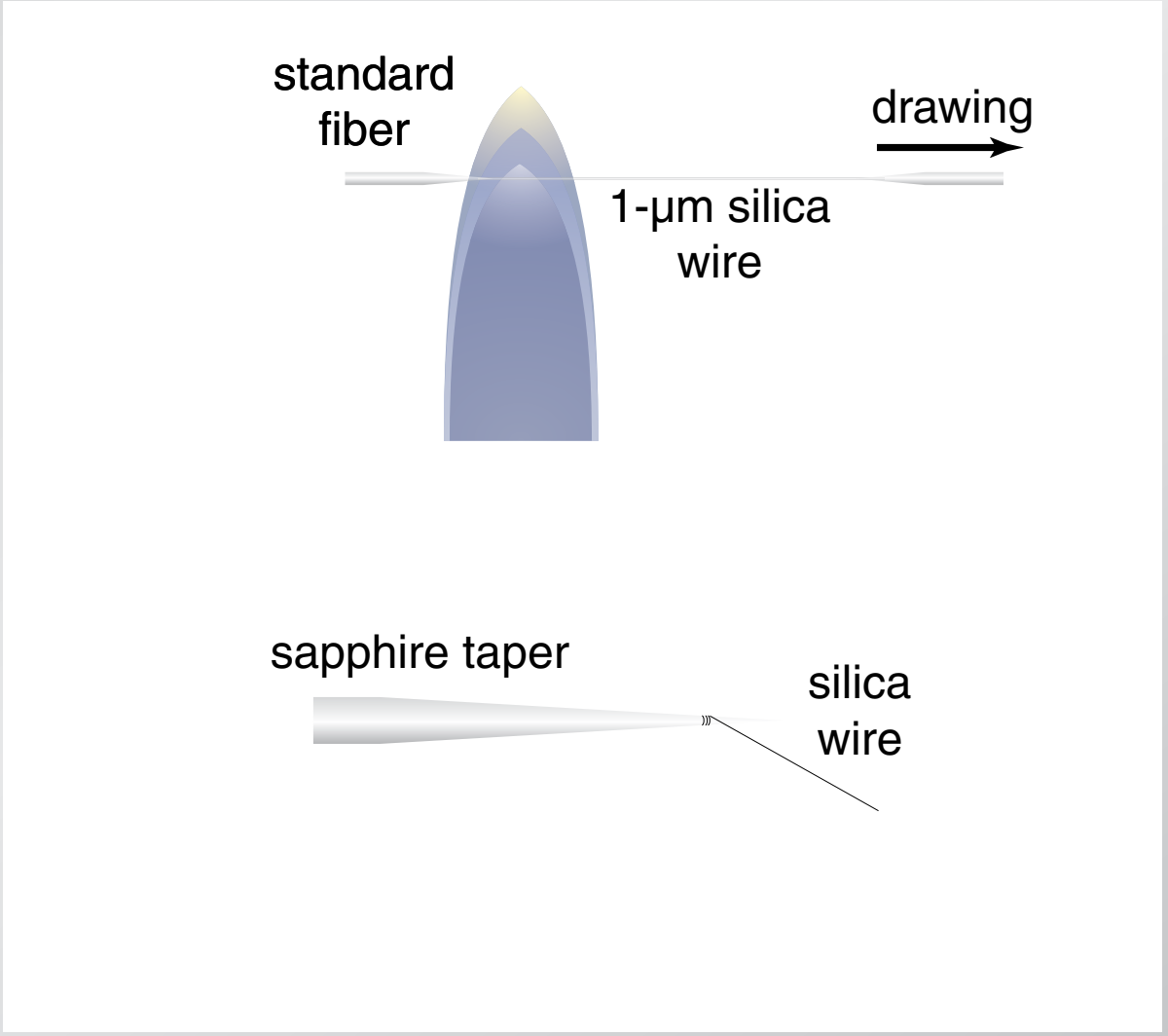
Silica nanowires

two-step drawing process



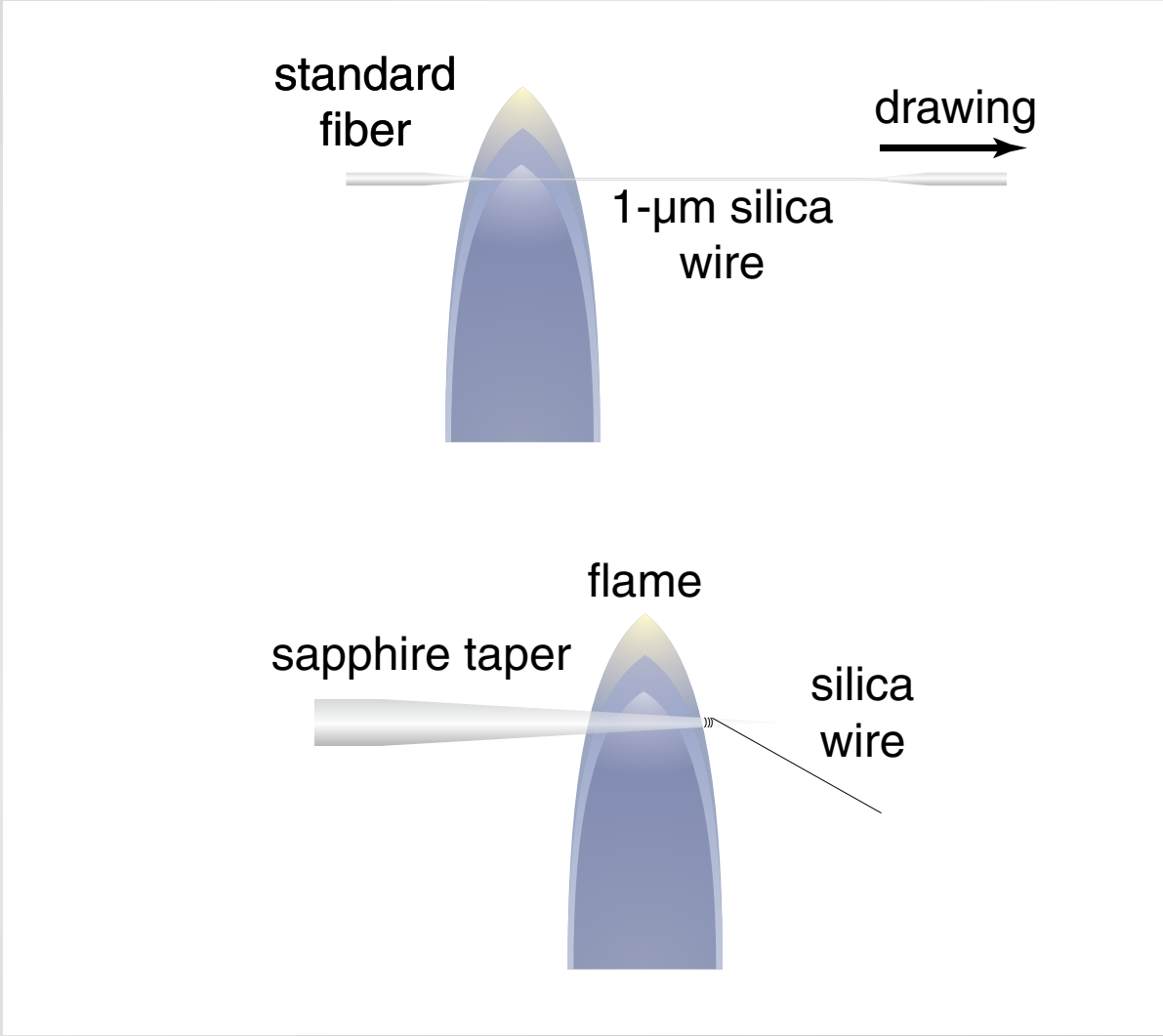
Silica nanowires

two-step drawing process



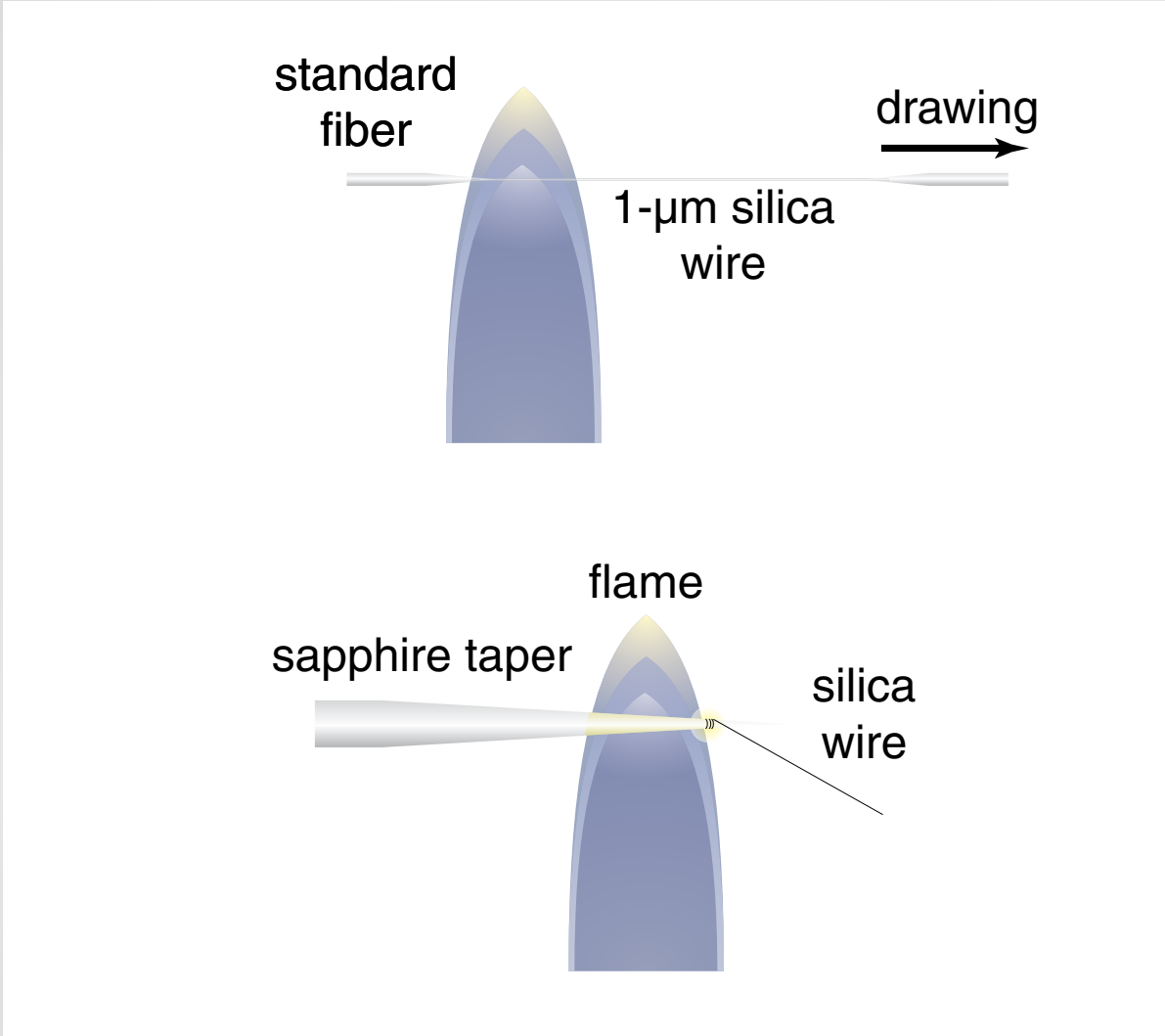
Silica nanowires

two-step drawing process



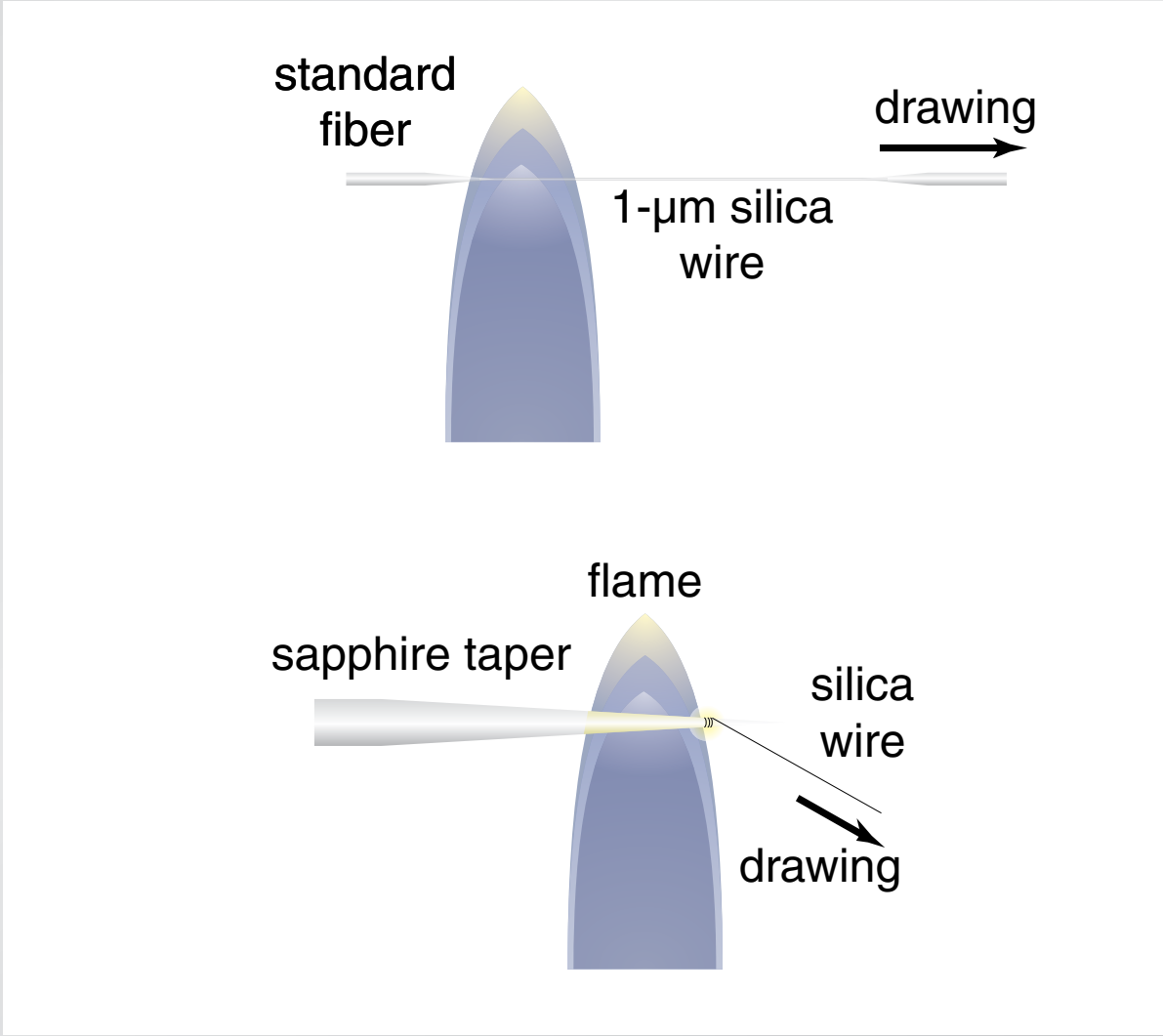
Silica nanowires

two-step drawing process



Silica nanowires

two-step drawing process



Silica nanowires

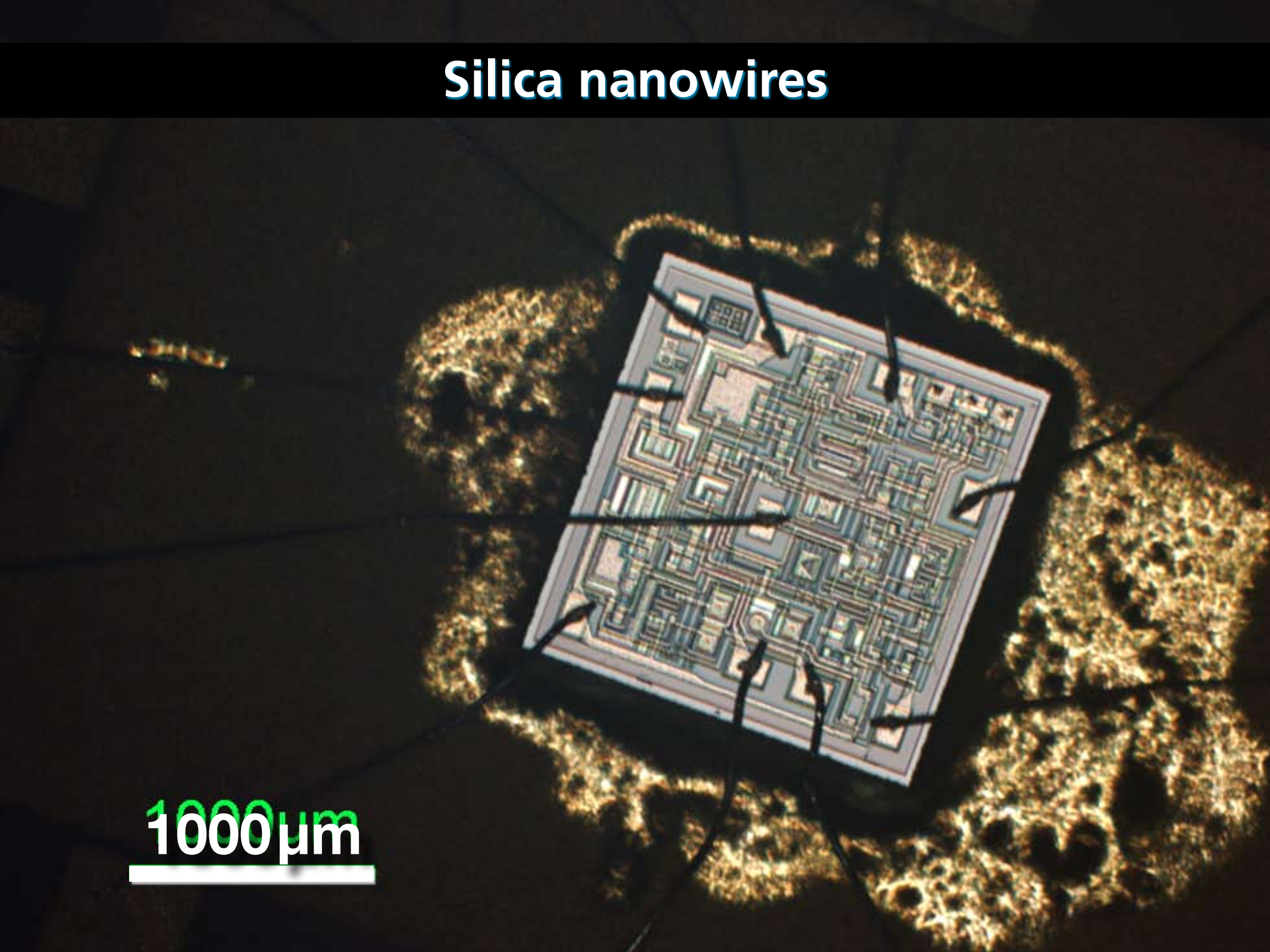
Silica nanowires

1 μm

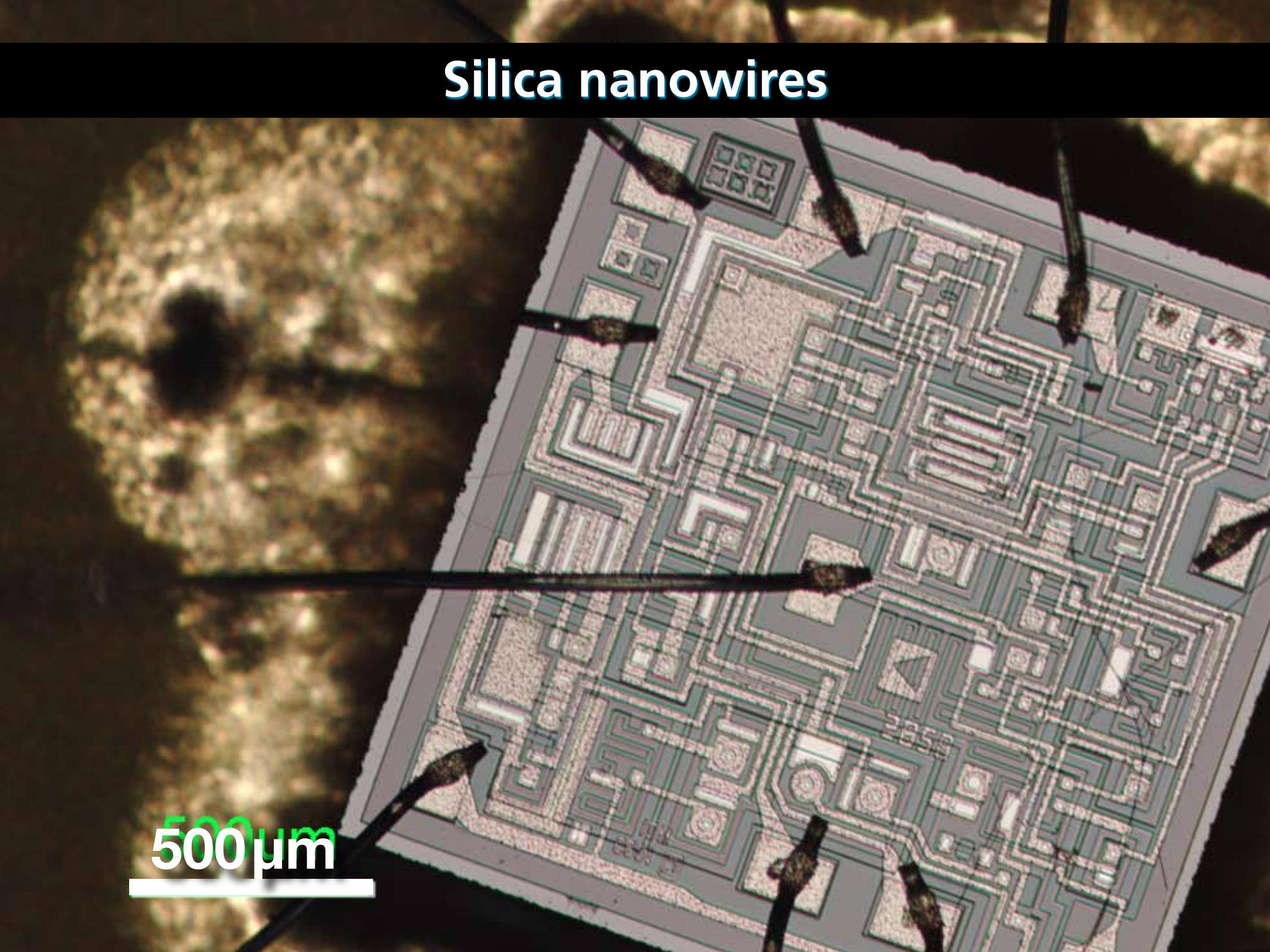
Nature, 426, 816 (2003)

Silica nanowires

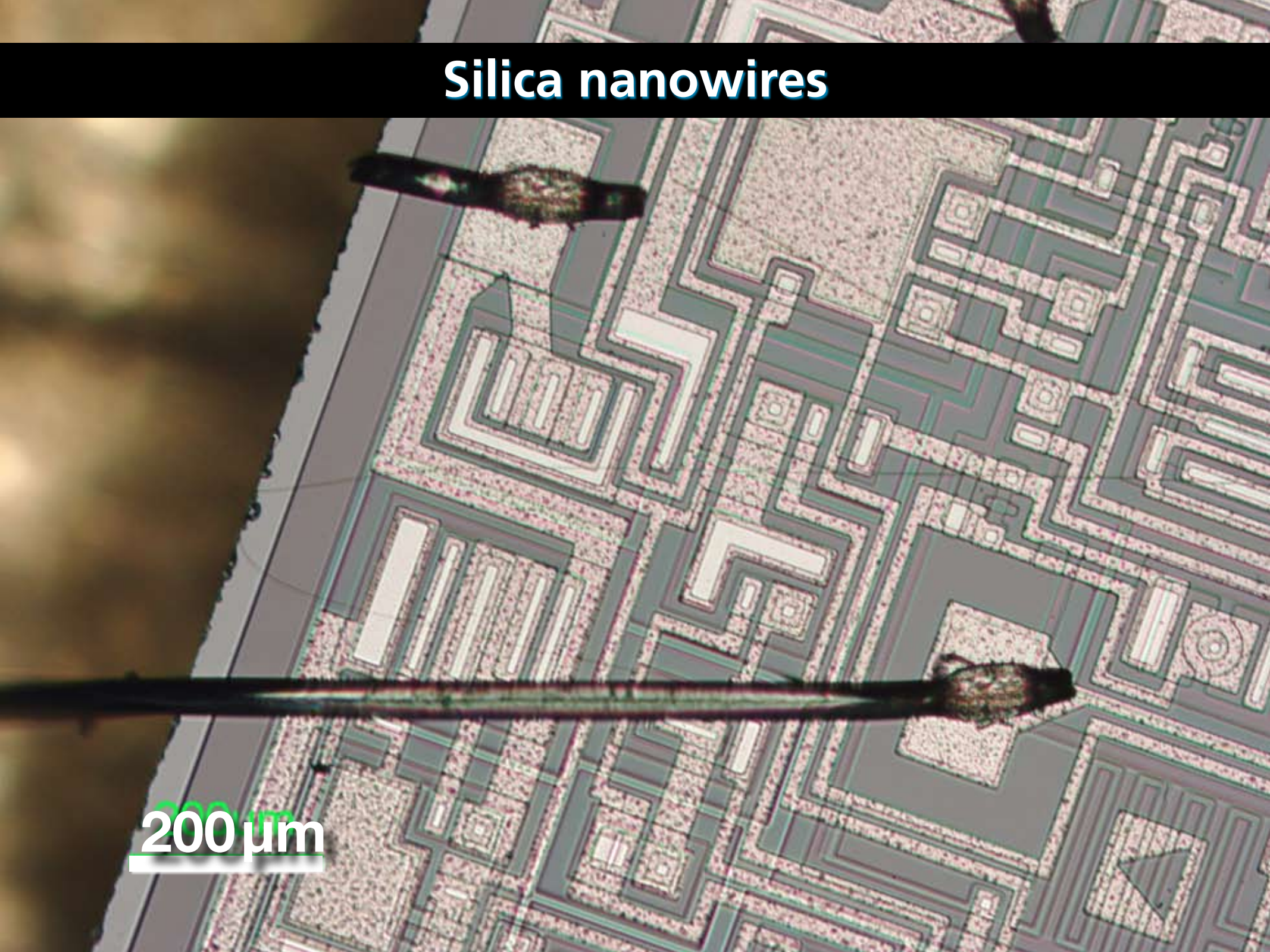
Silica nanowires



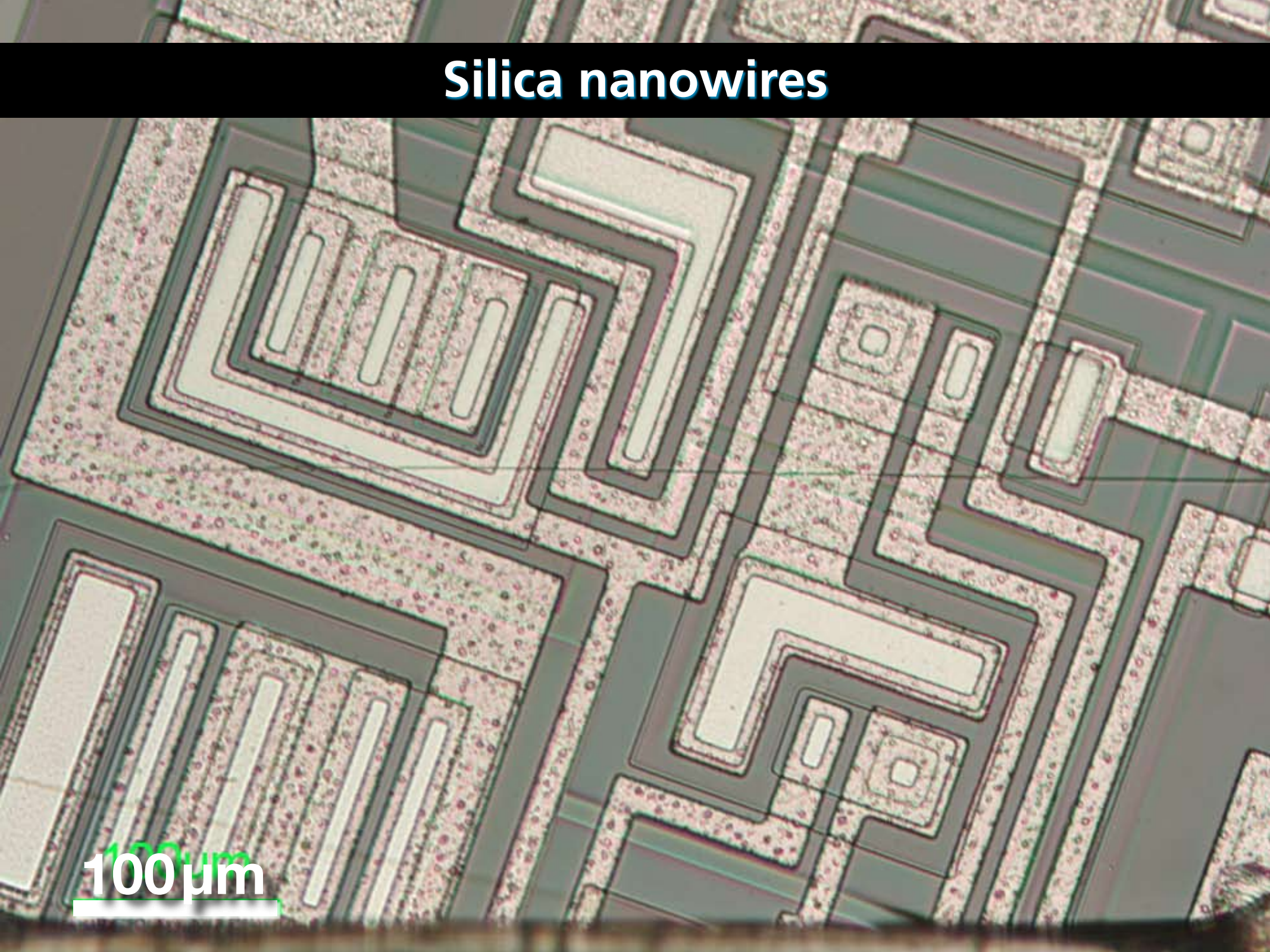
Silica nanowires

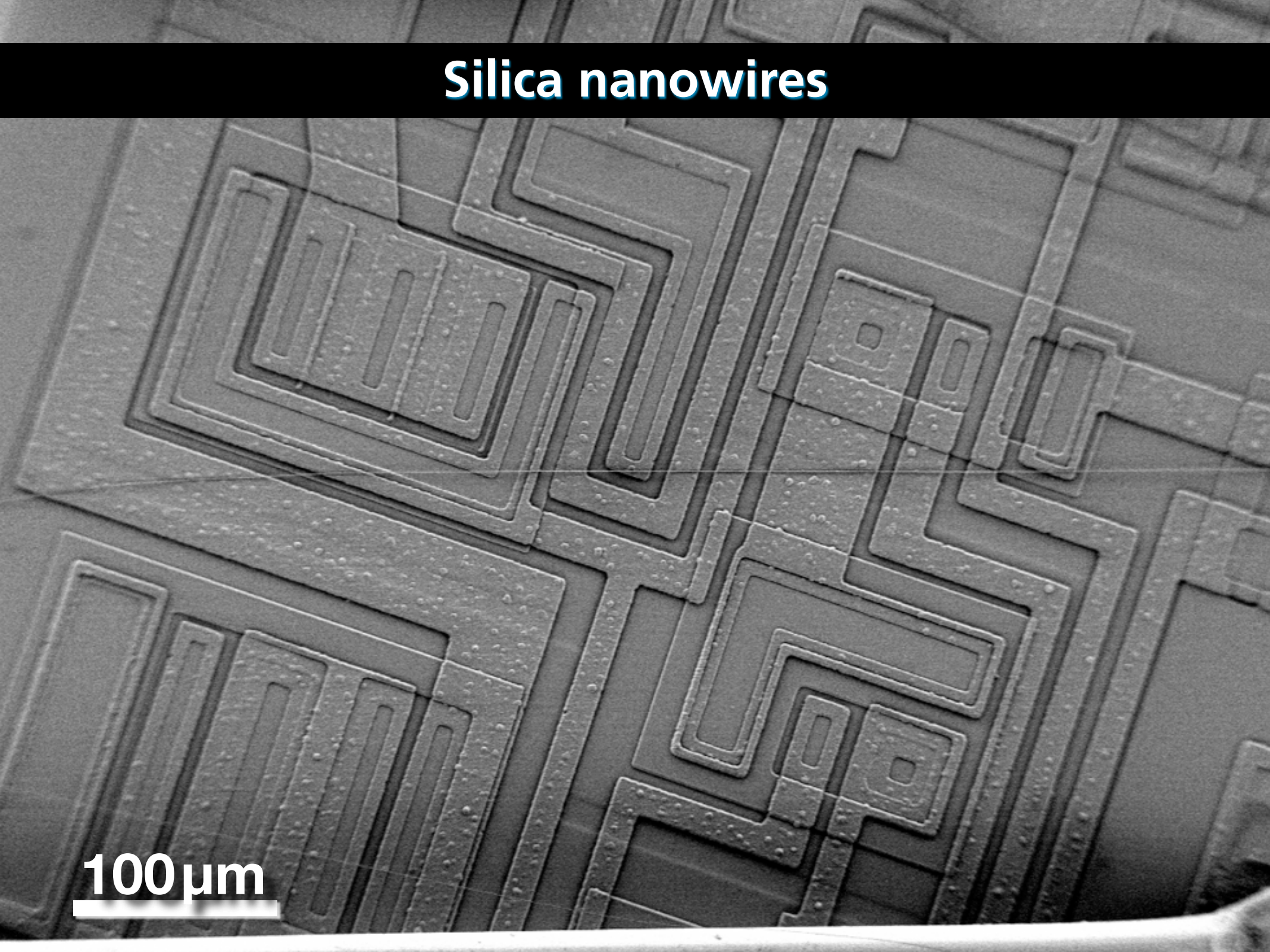


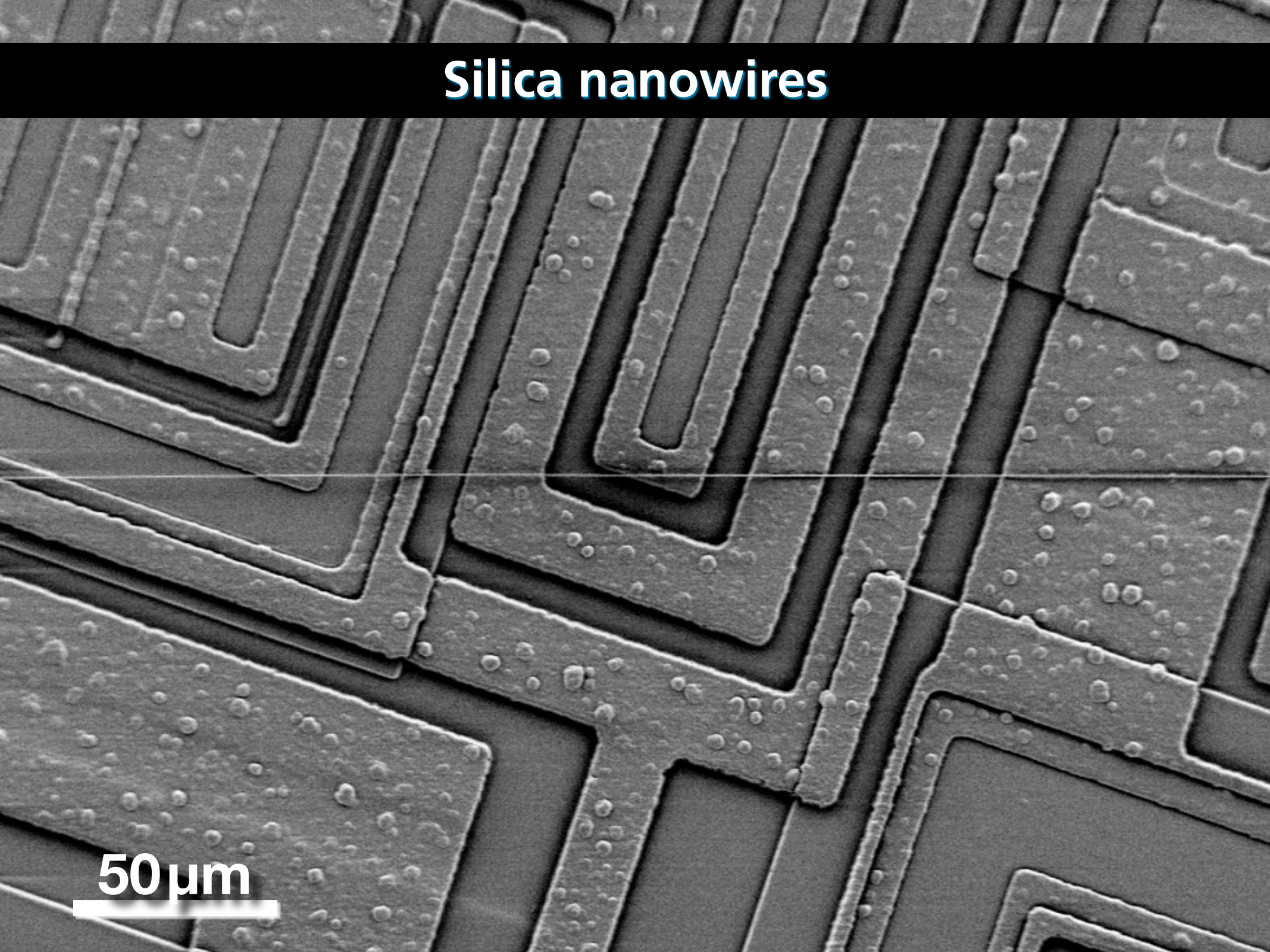
Silica nanowires

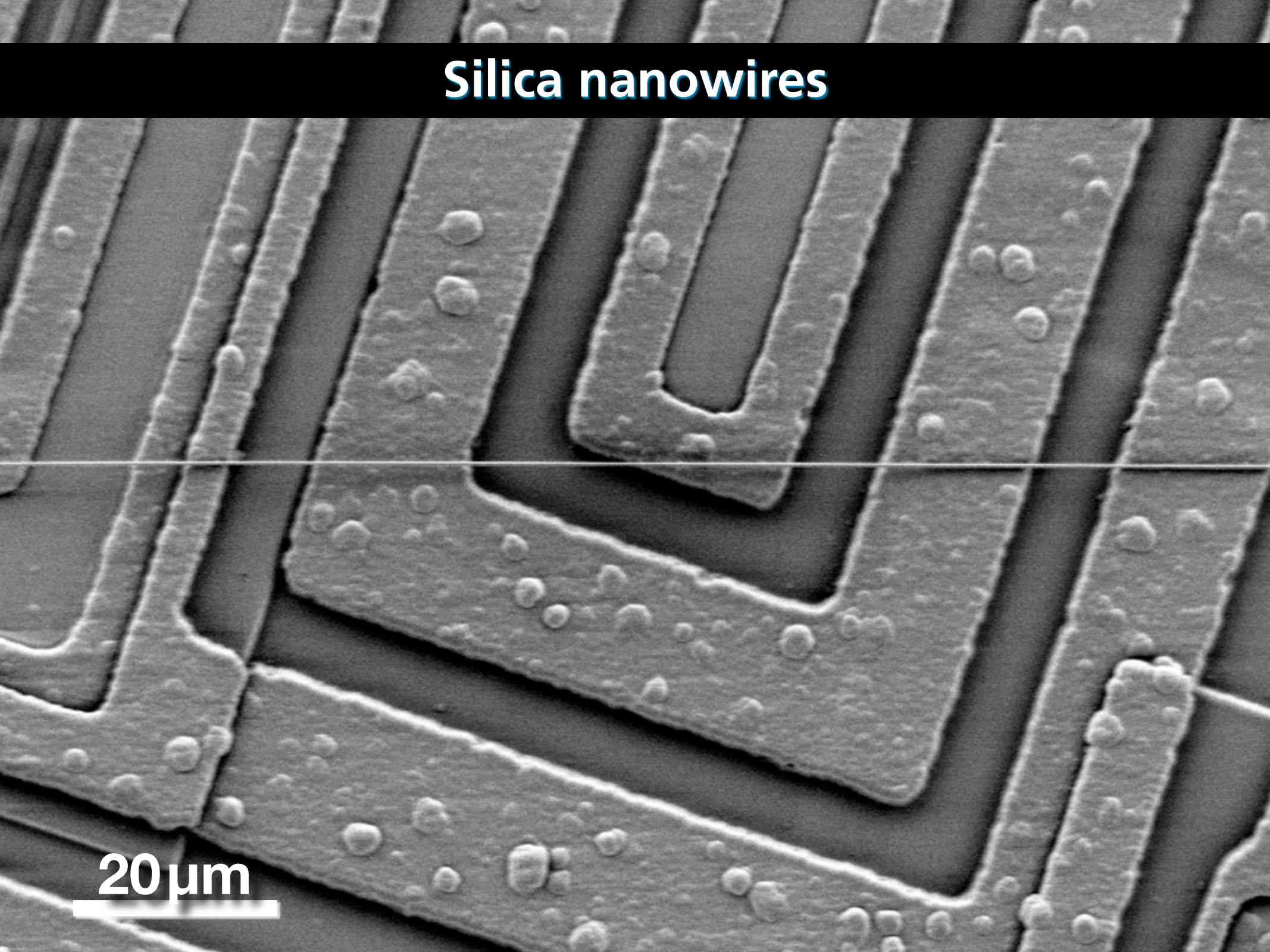


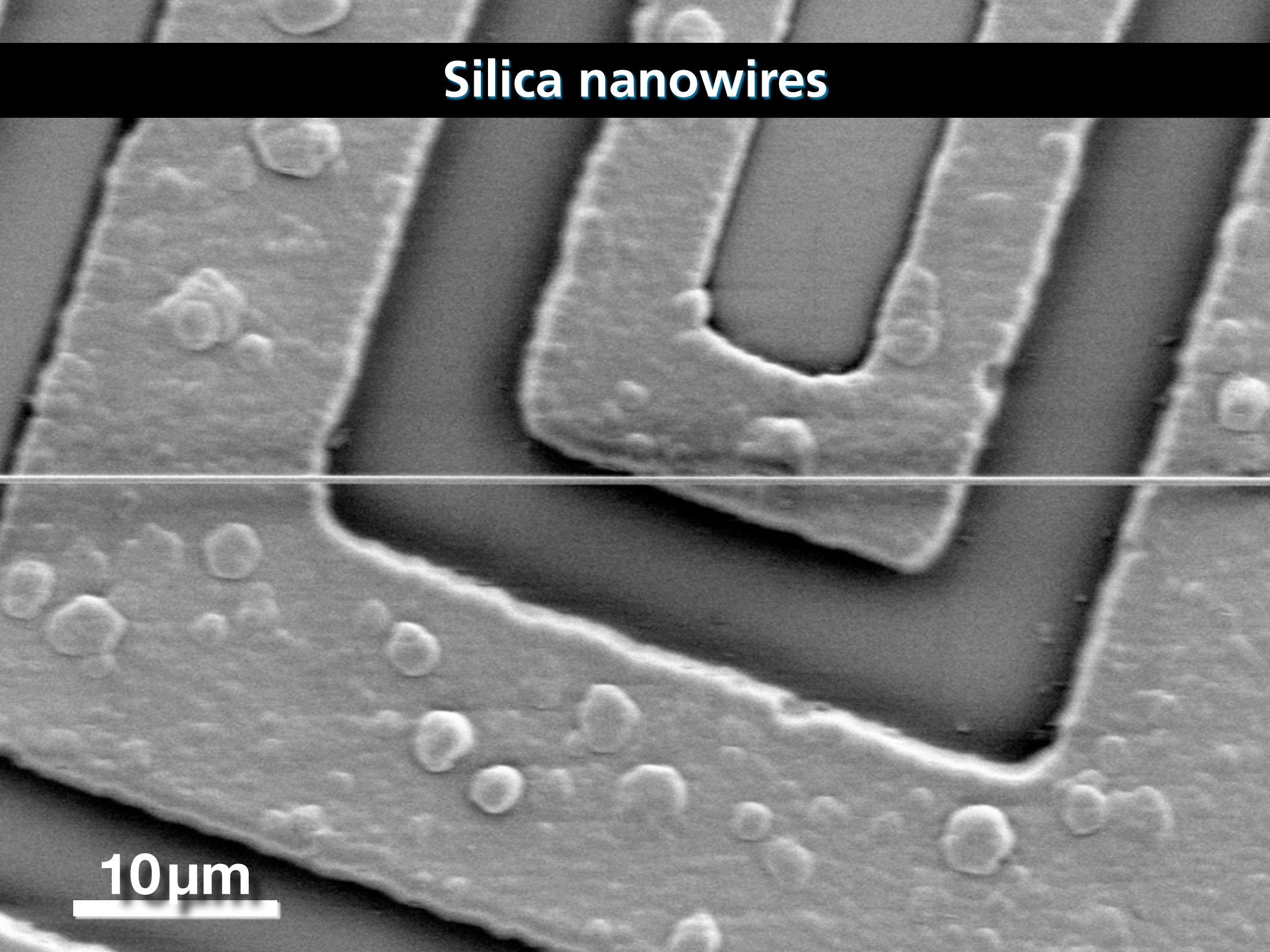
Silica nanowires

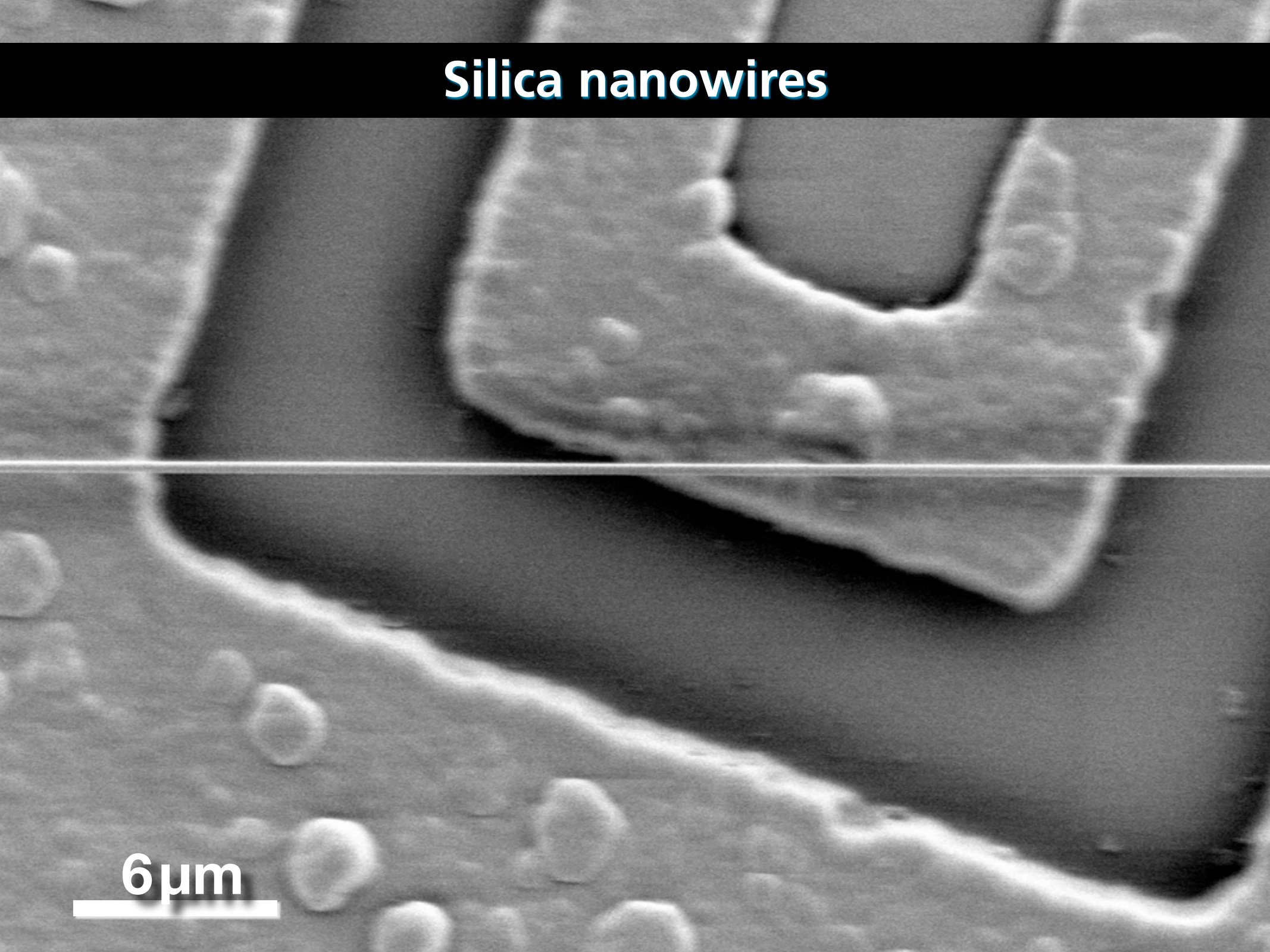


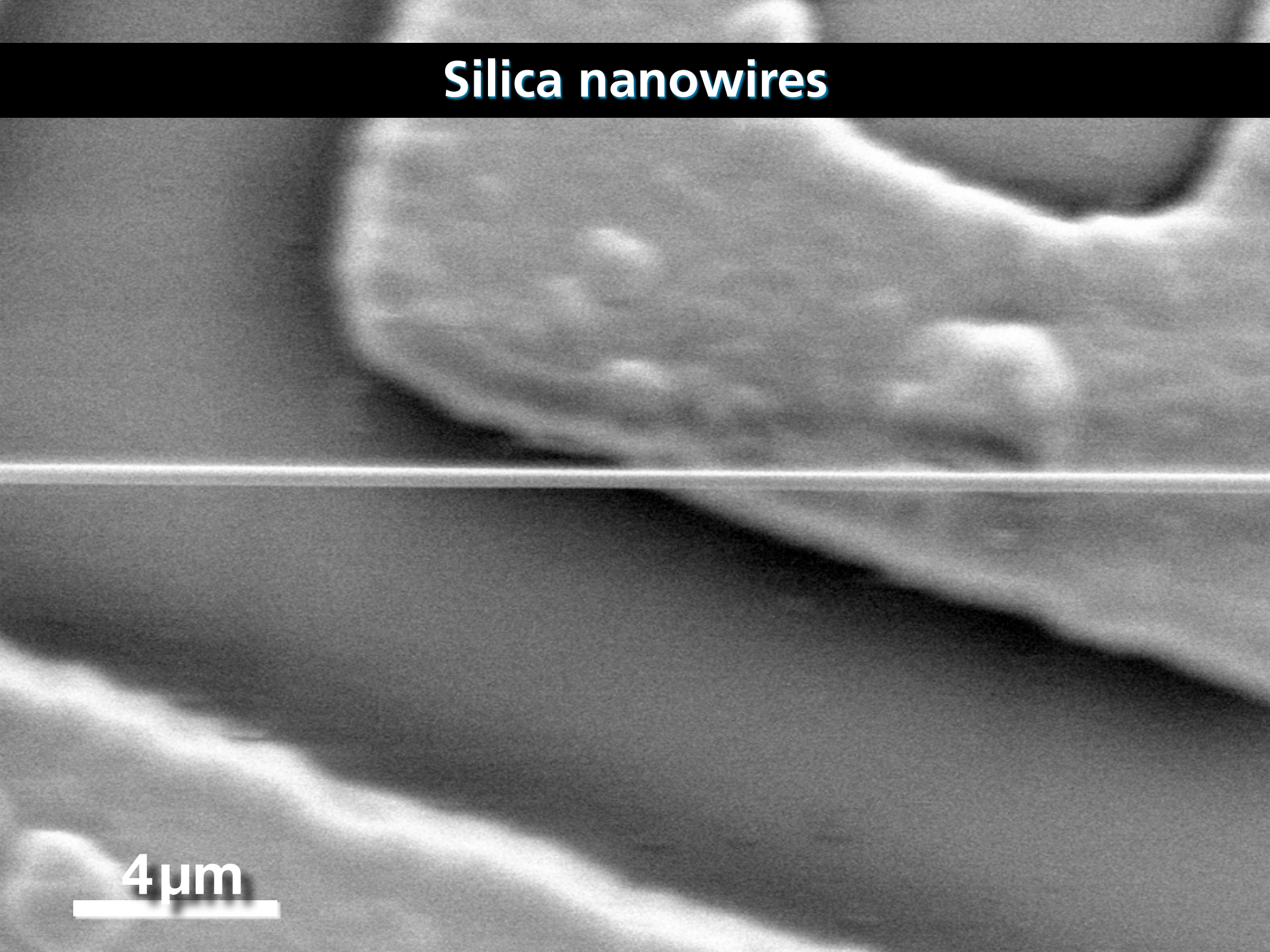

Silica nanowires
100 µm

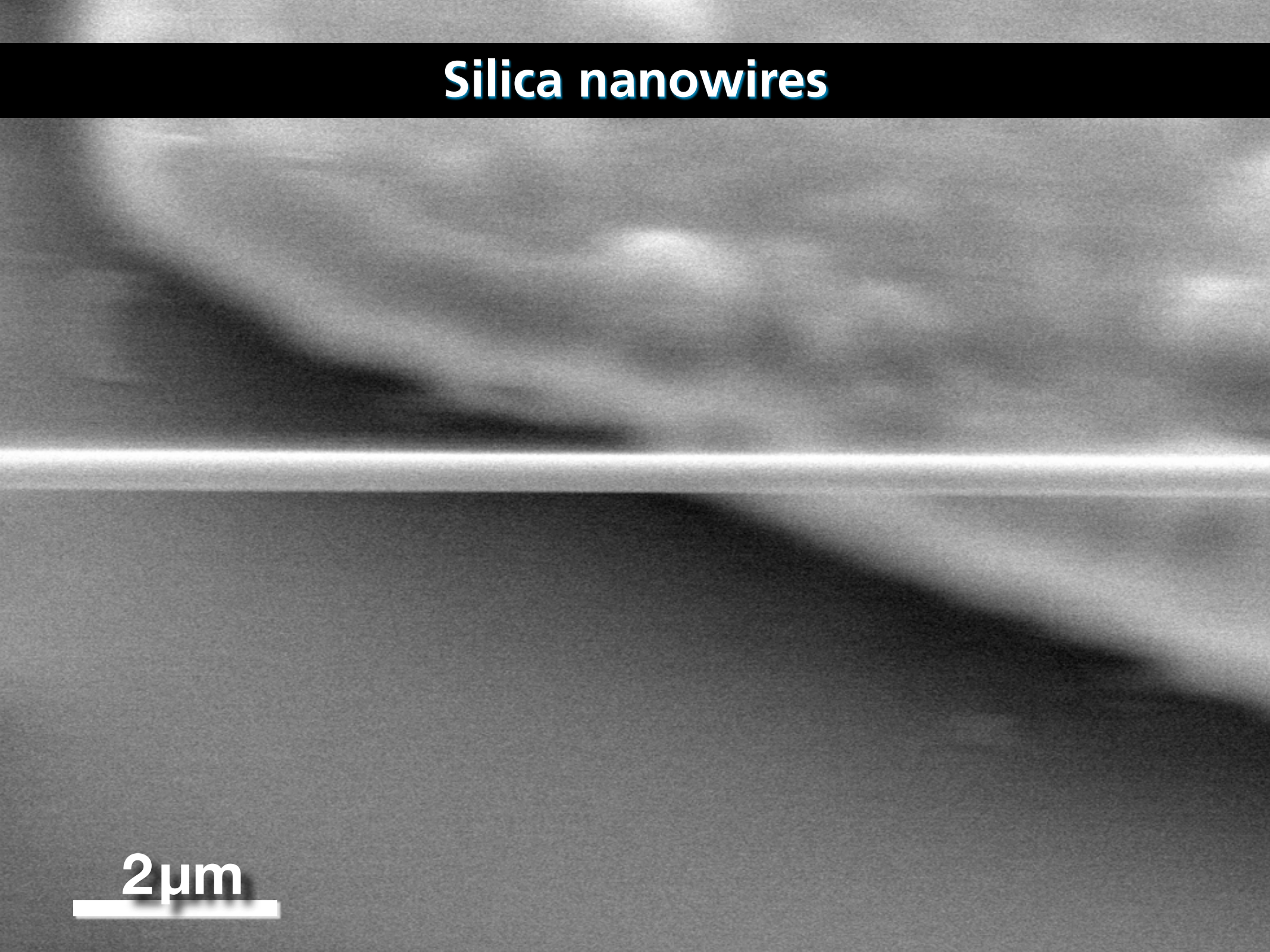

Silica nanowires
50 µm

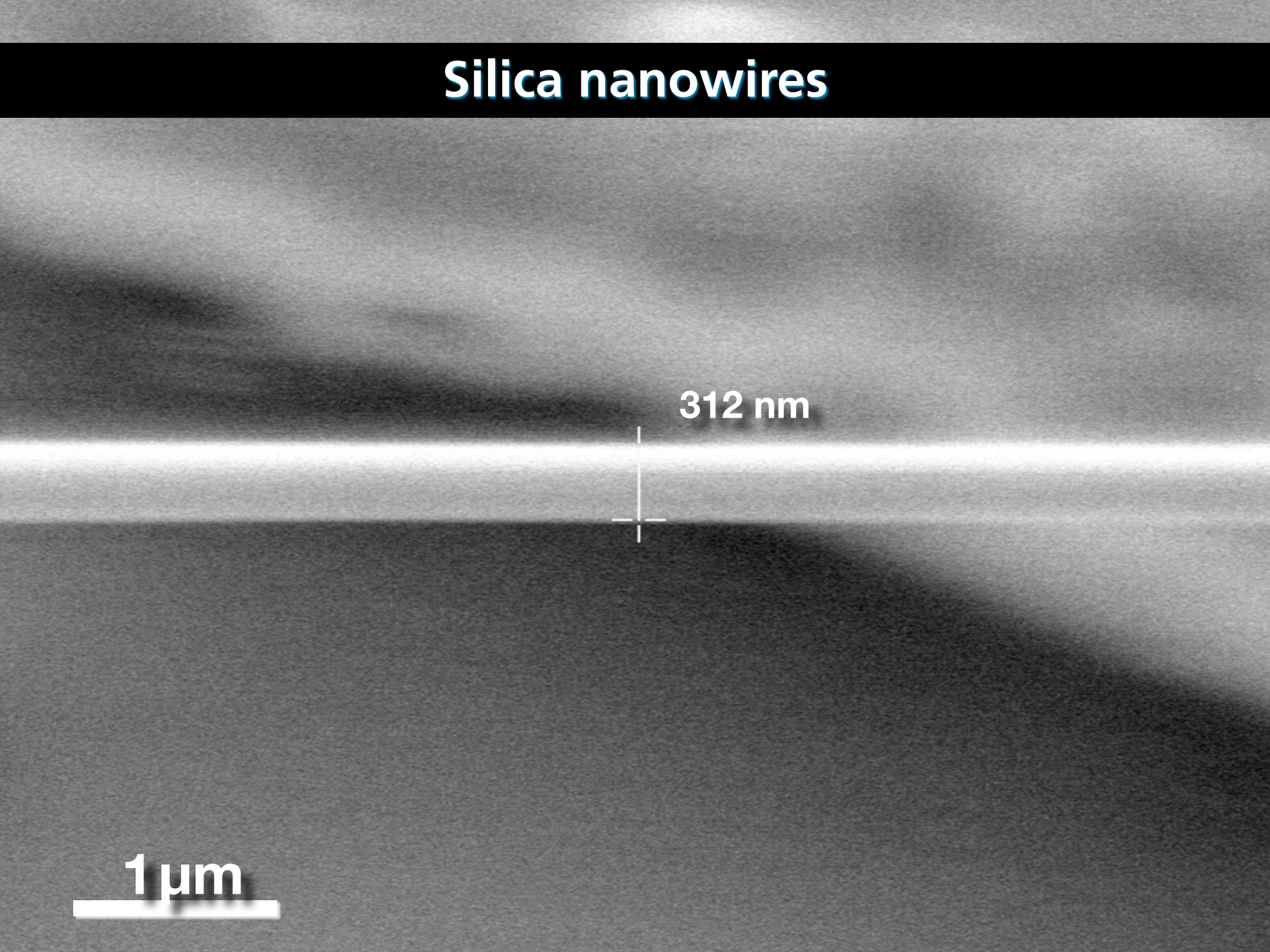

Silica nanowires
20 µm


Silica nanowires
10µm


Silica nanowires
6 µm


Silica nanowires
4 µm


Silica nanowires
2µm

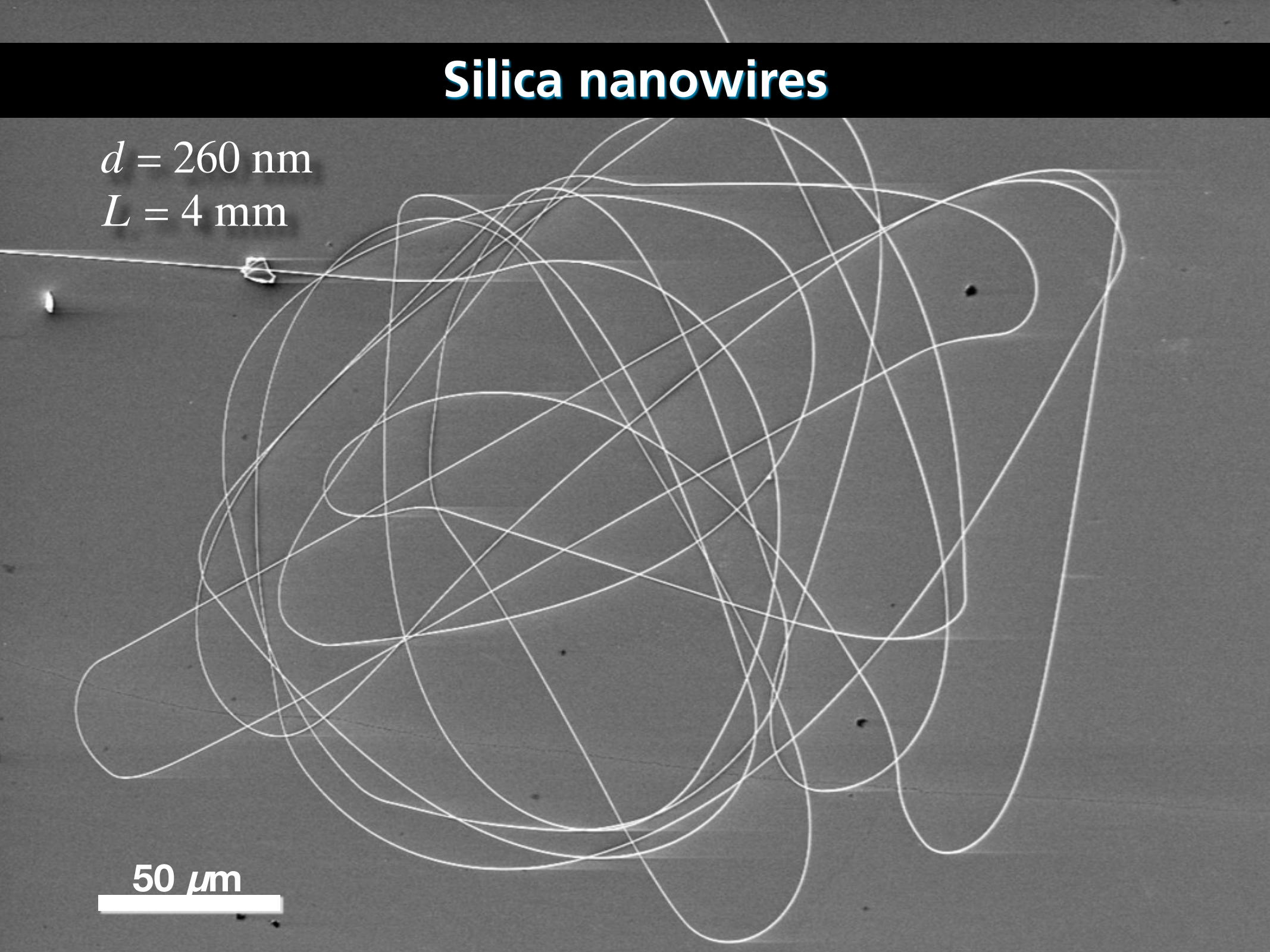

Silica nanowires
312 nm
1 µm

Silica nanowires

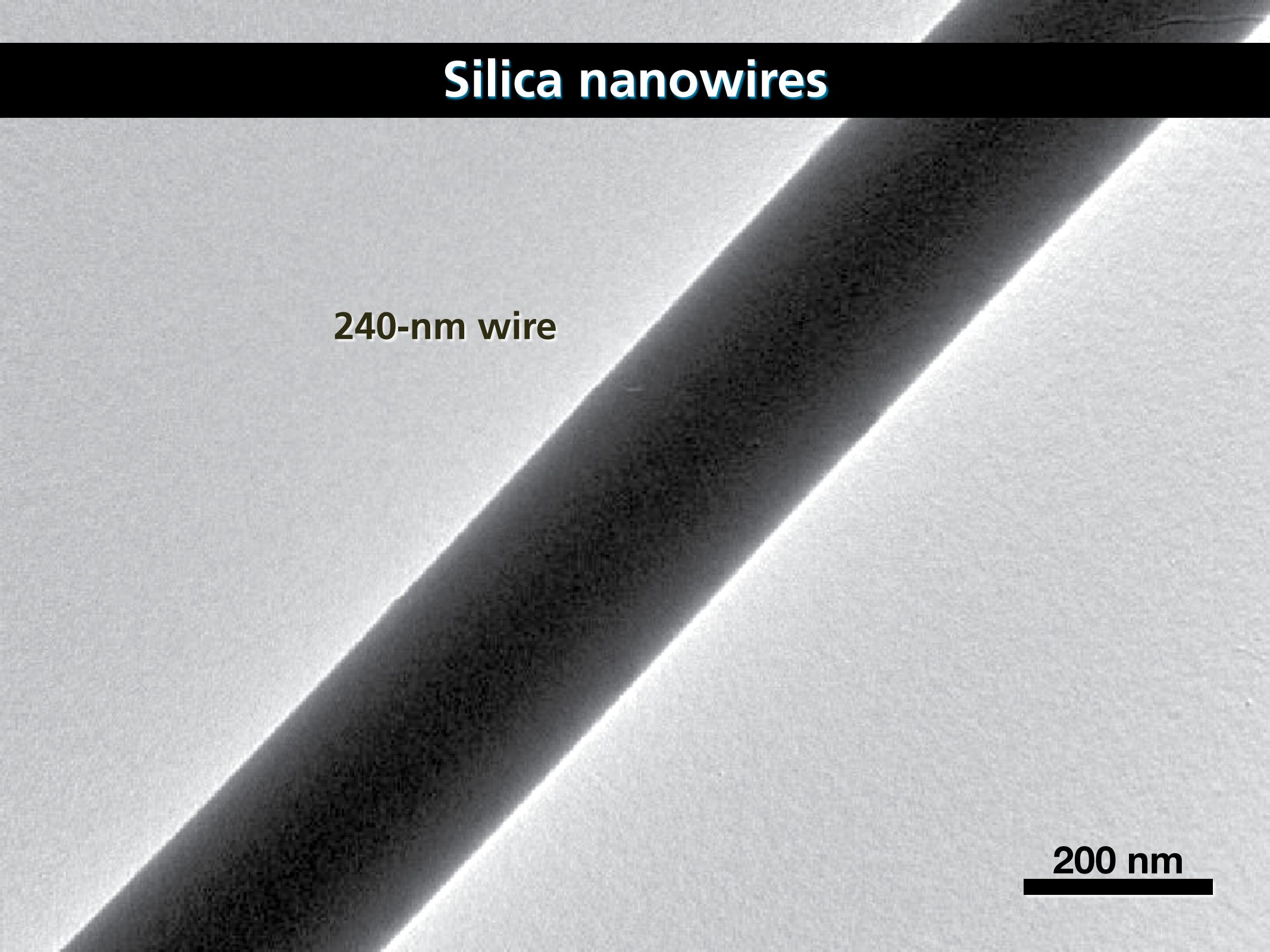
Specifications

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 x 10^{-6}

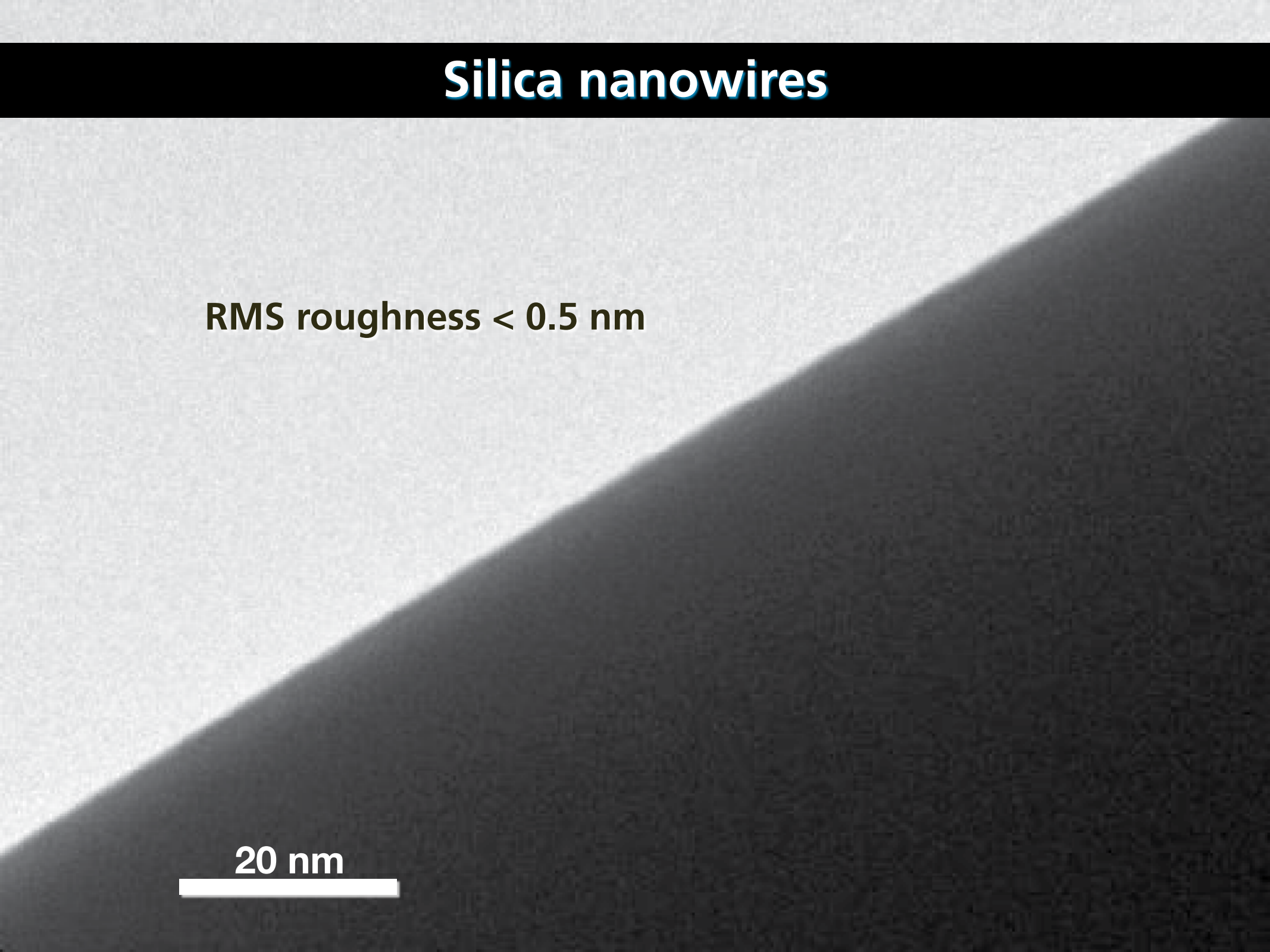
Nature, 426, 816 (2003)


Silica nanowires
$d = 260$ nm
$L = 4$ mm
50 μm

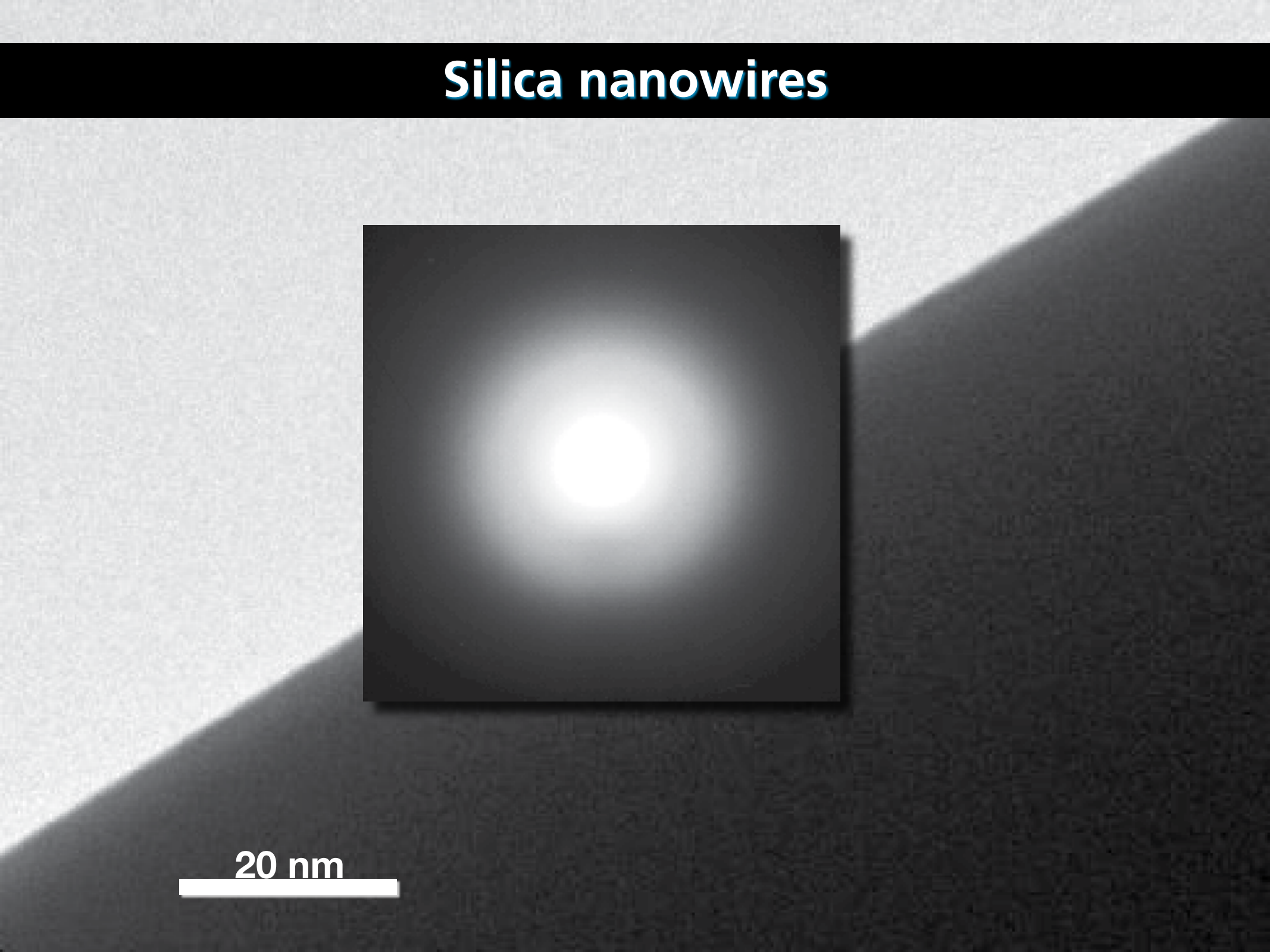
Silica nanowires



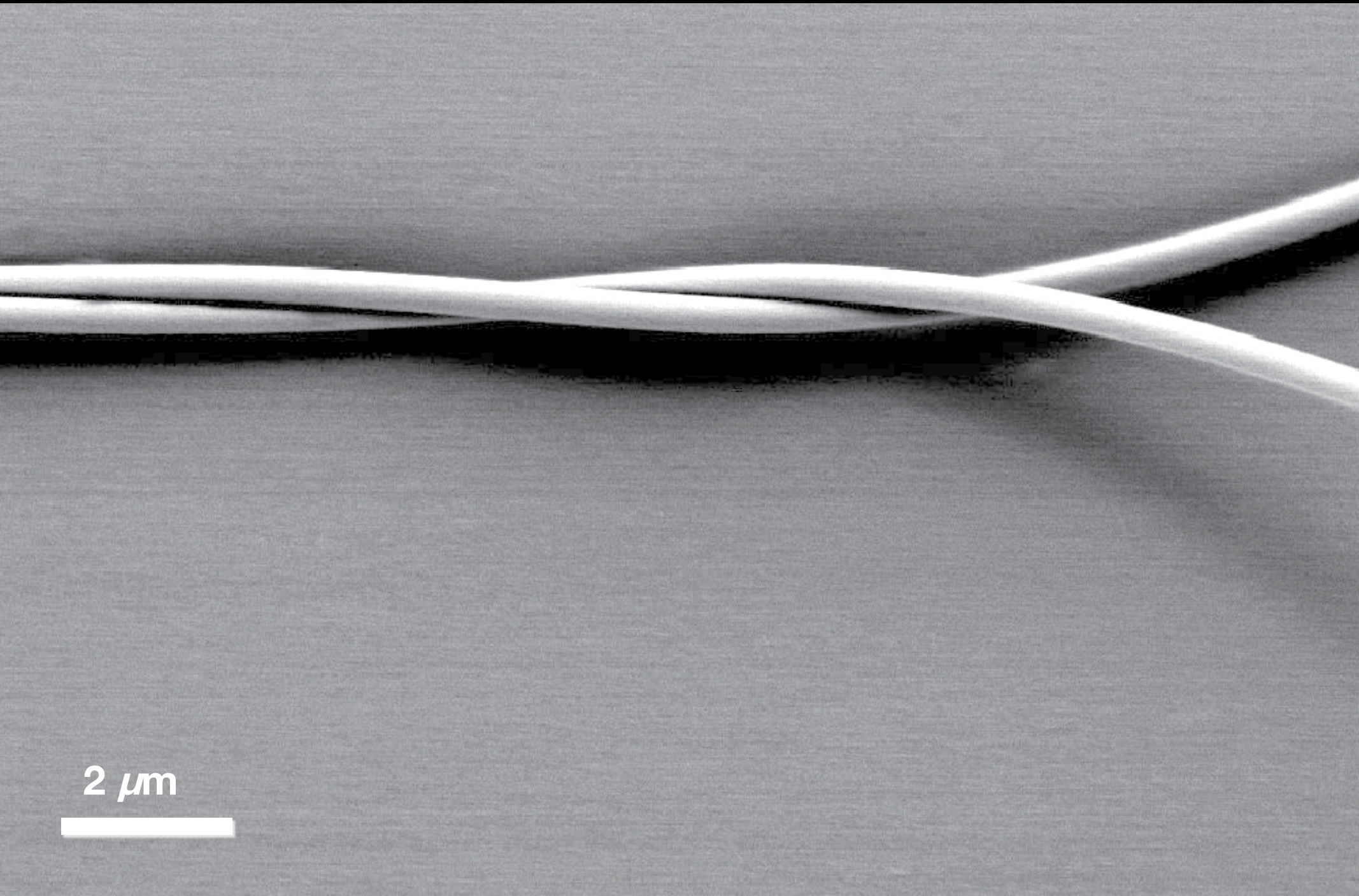
Silica nanowires



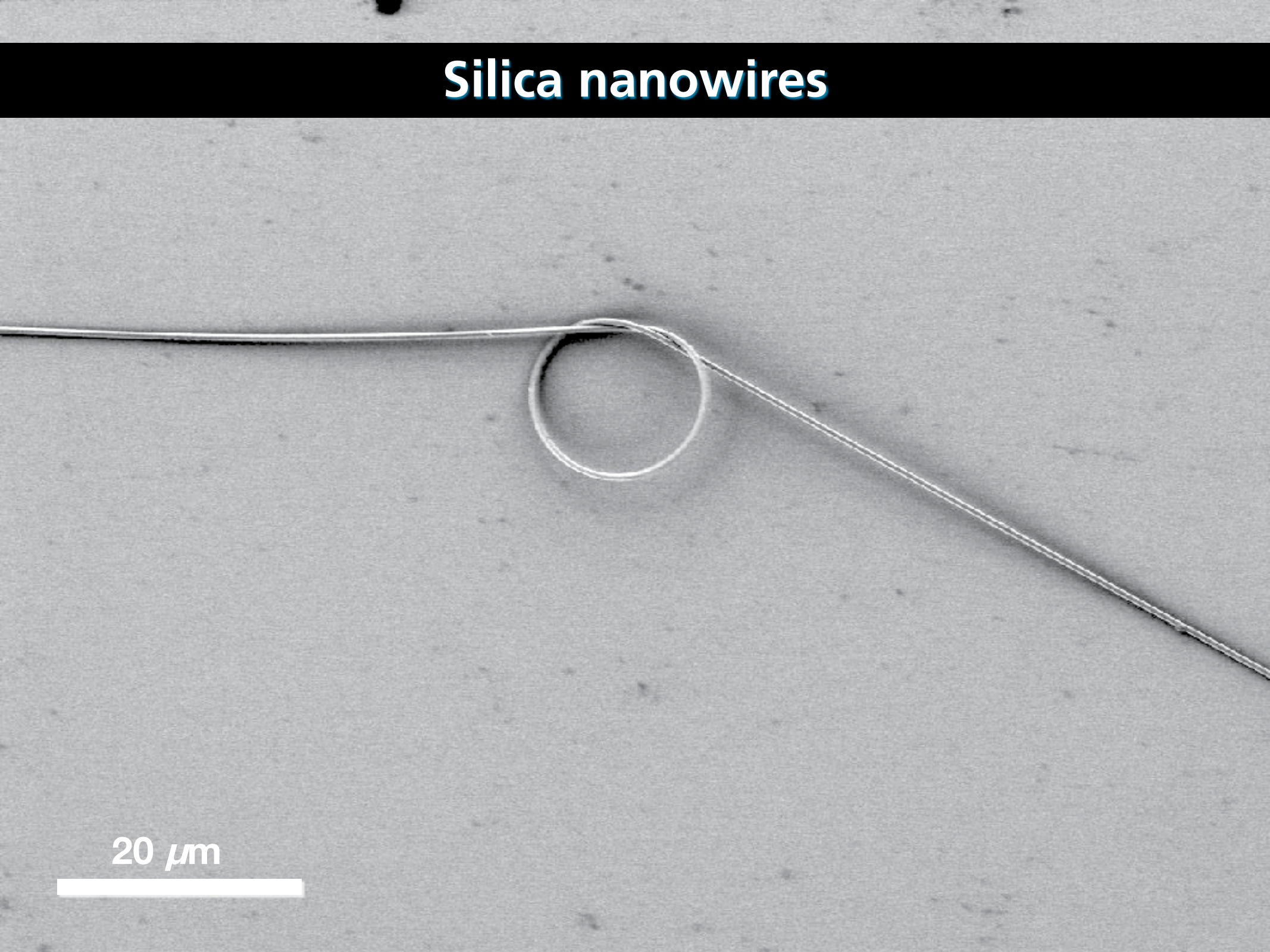
Silica nanowires

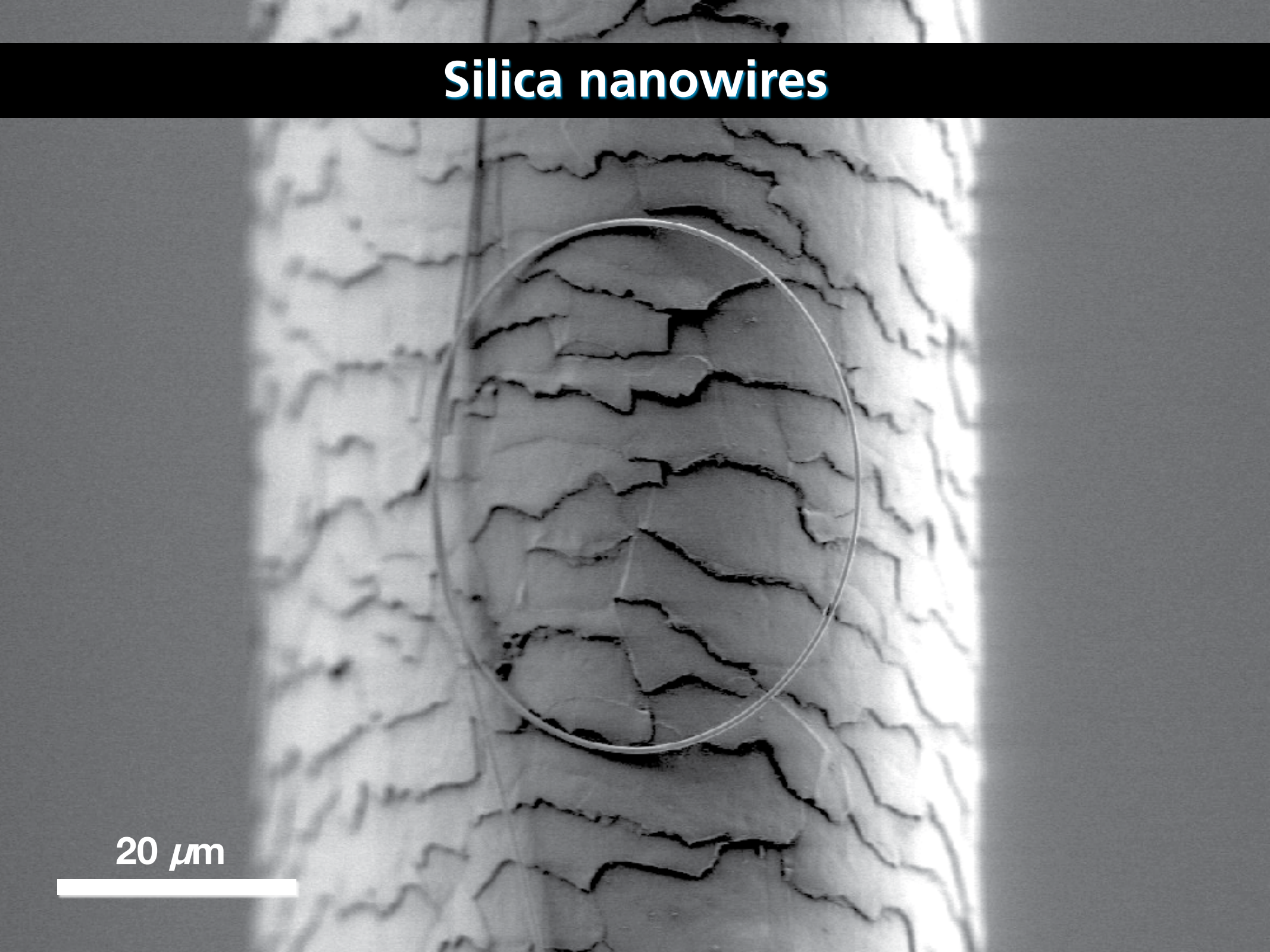


Silica nanowires



Silica nanowires



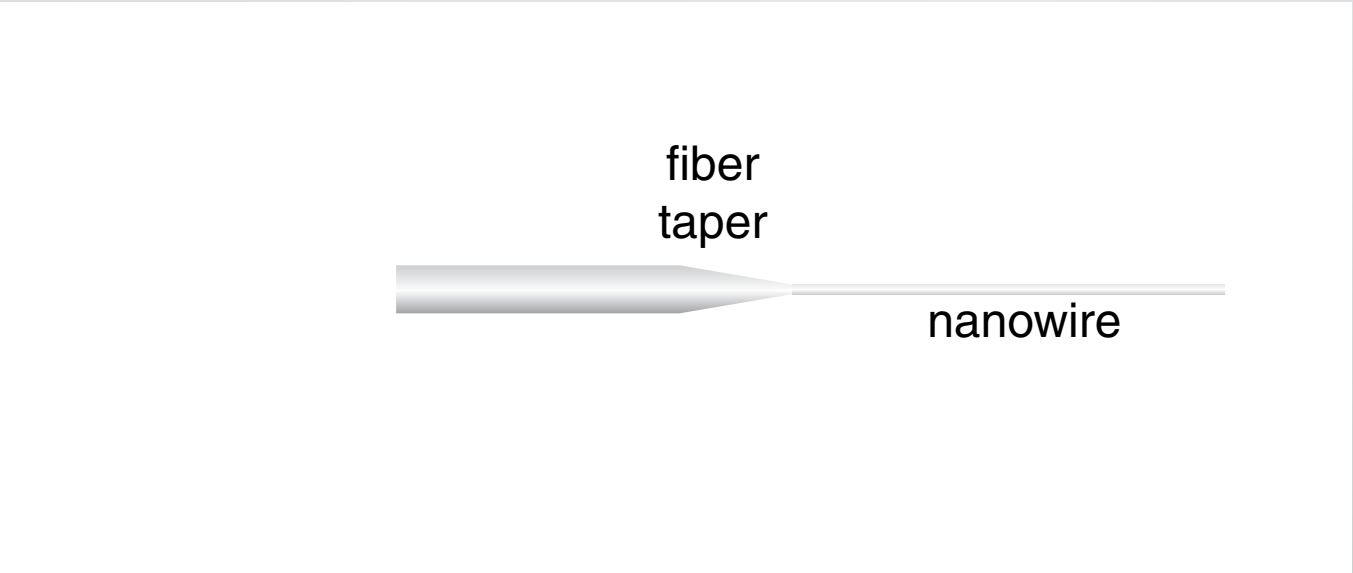

Silica nanowires
20 μm

Outline

- silica nanowires
- optical properties
- nonlinear properties

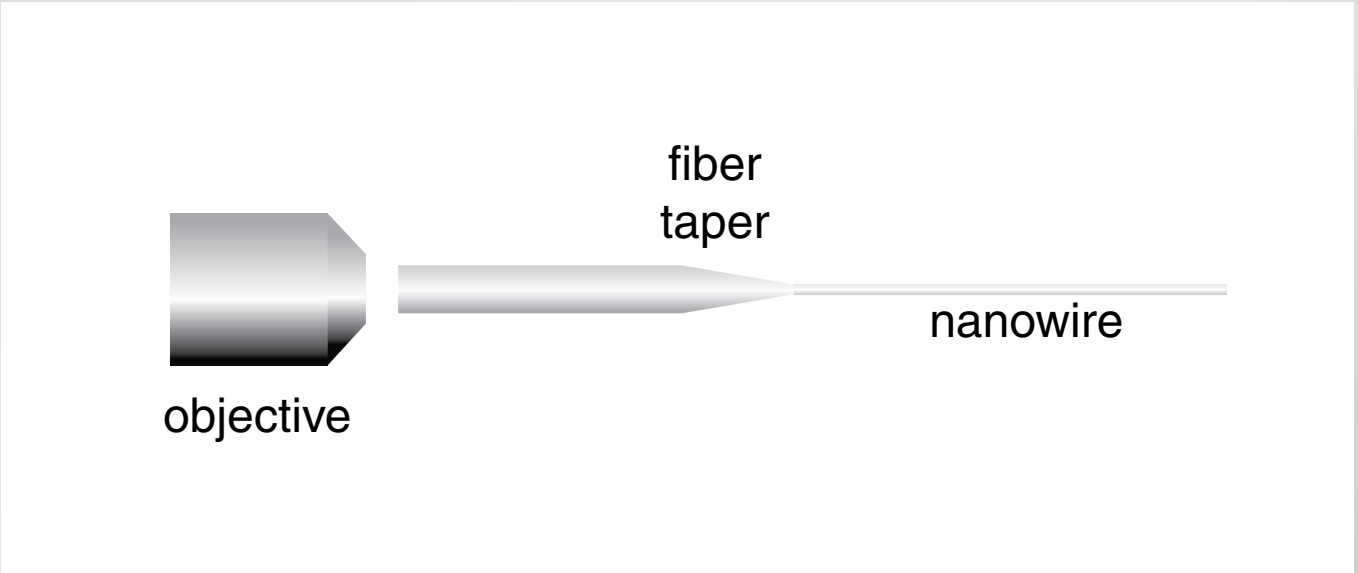
Optical properties

coupling light into nanowires



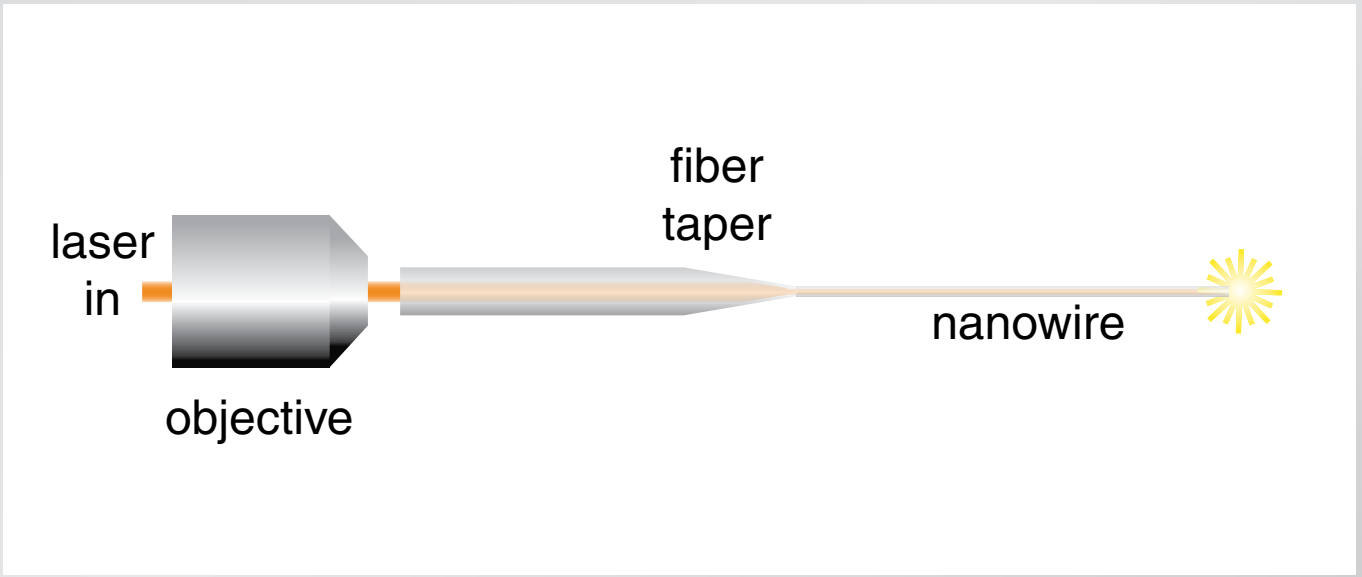
Optical properties

coupling light into nanowires

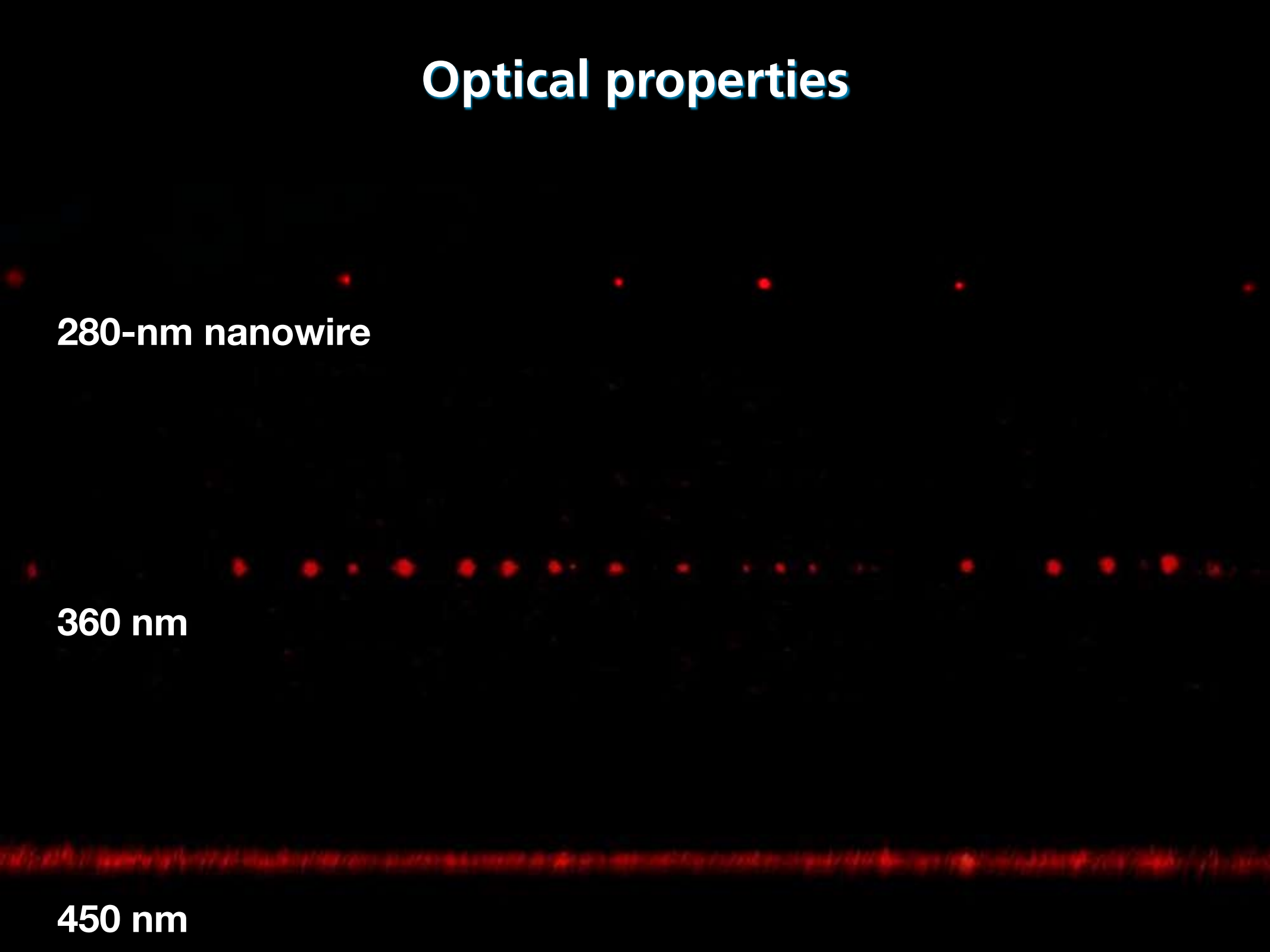


Optical properties

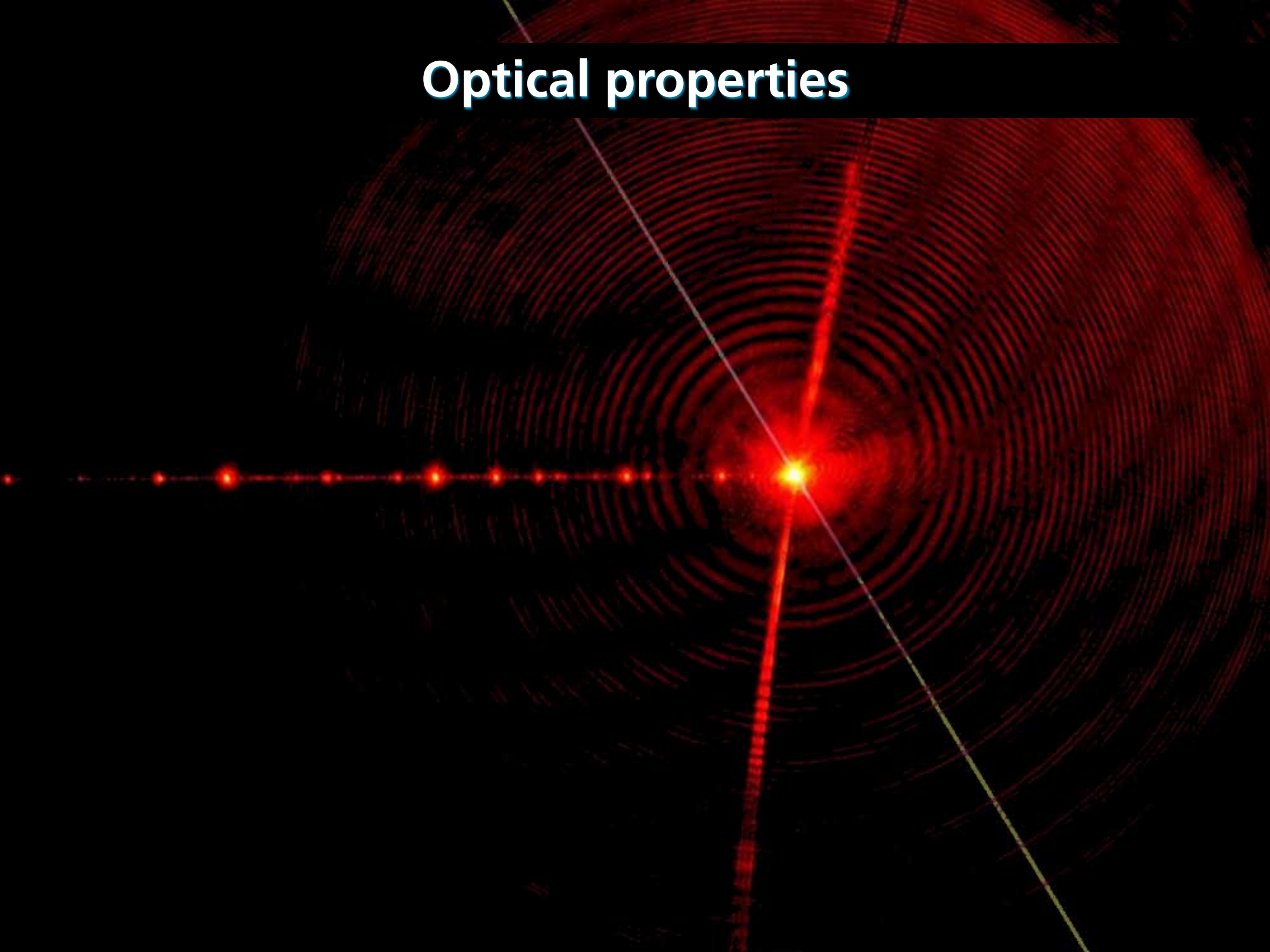
coupling light into nanowires



Optical properties



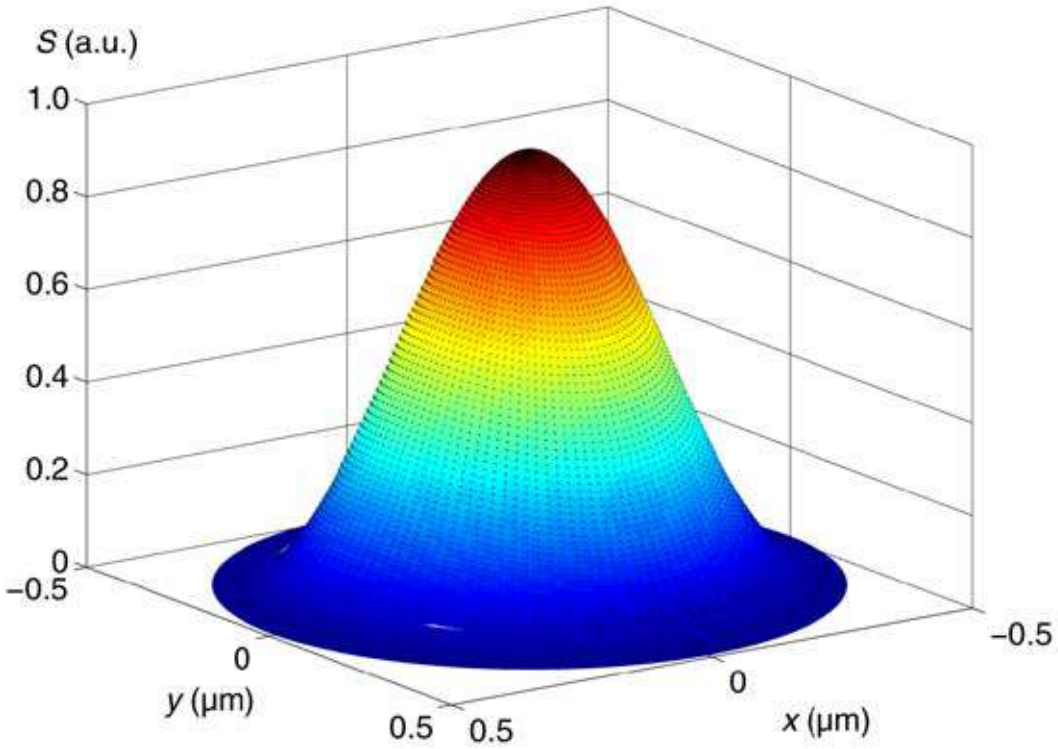
Optical properties



Optical properties

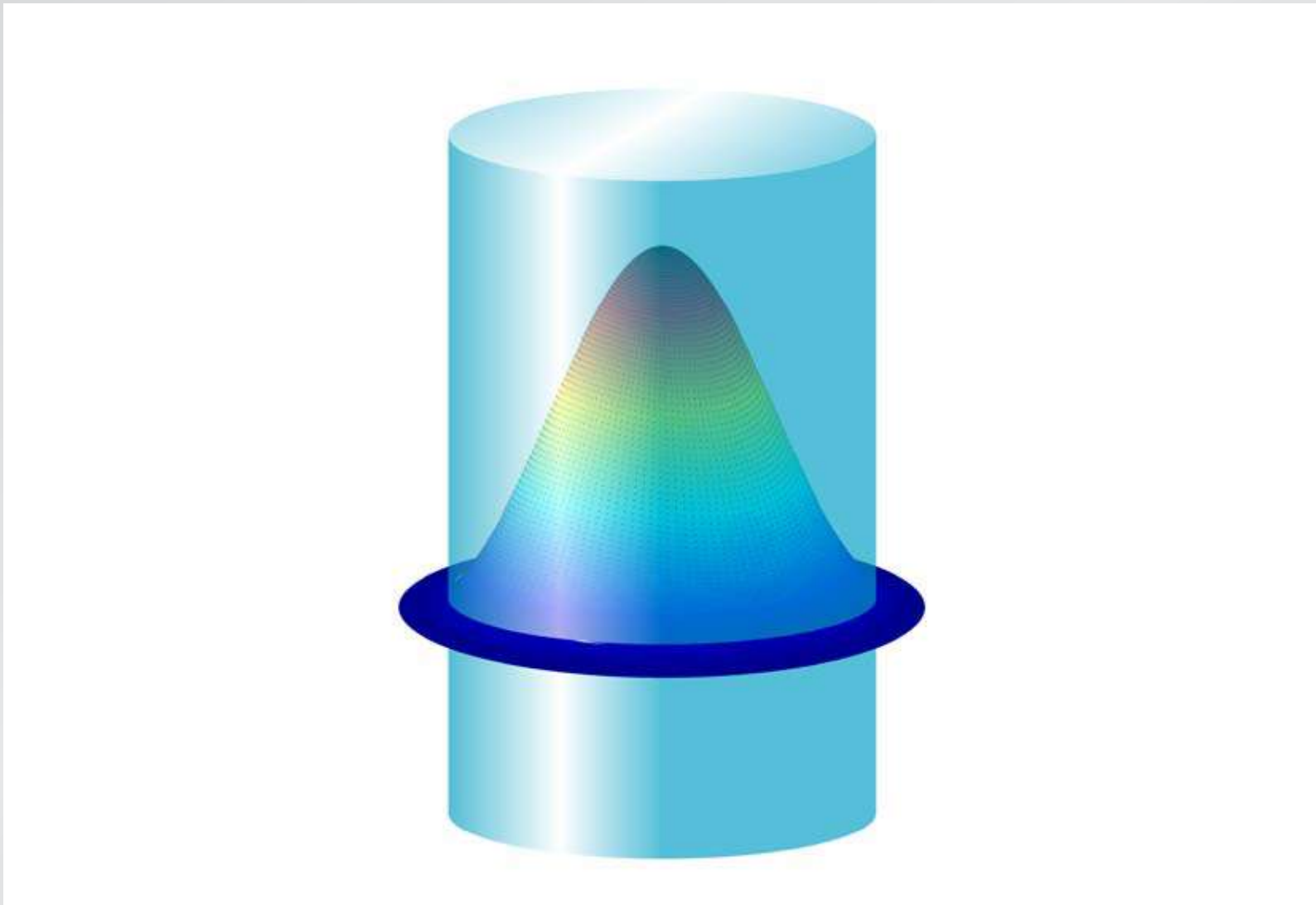
Optical properties

Poynting vector profile for 800-nm nanowire



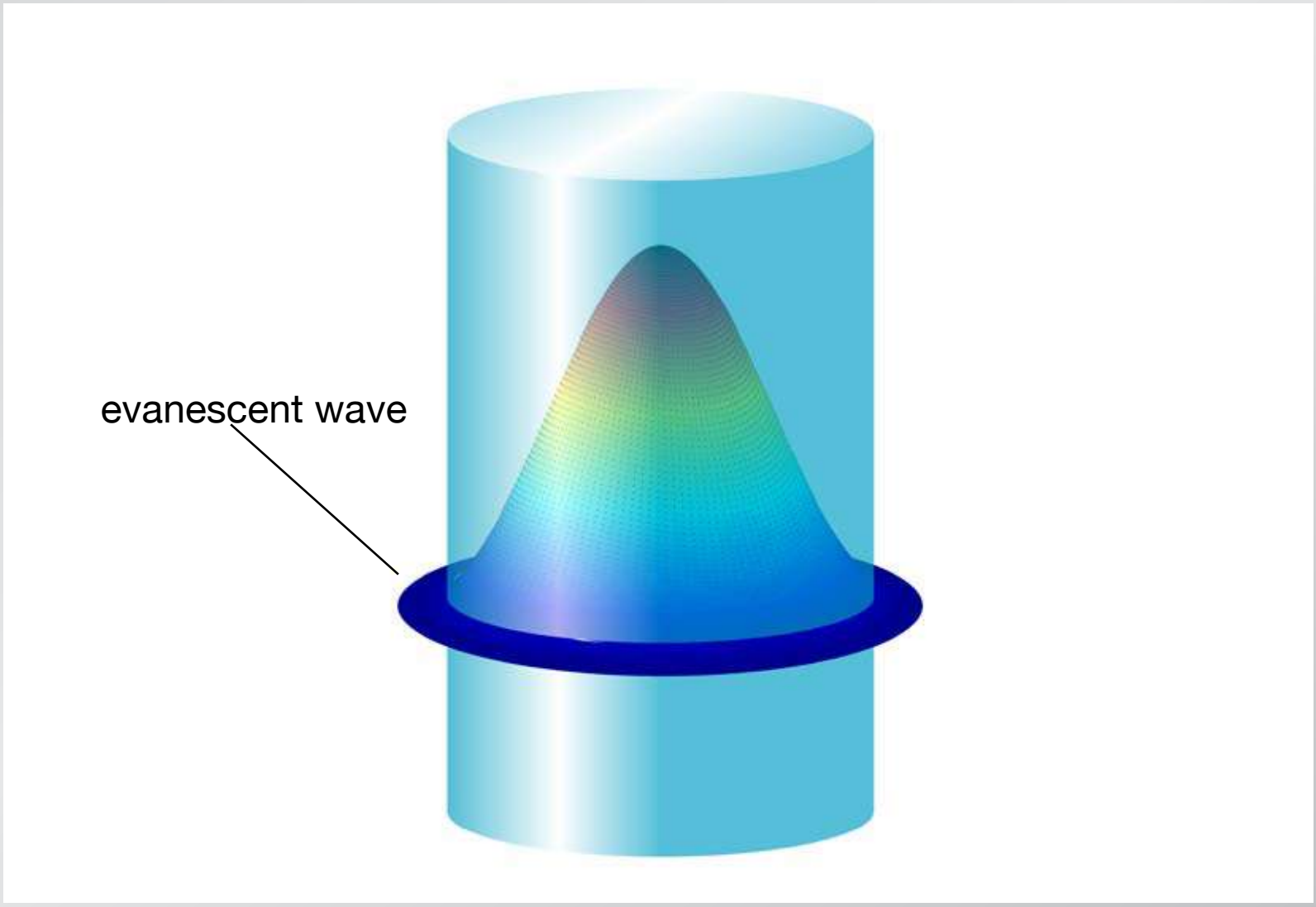
Optical properties

Poynting vector profile for 800-nm nanowire



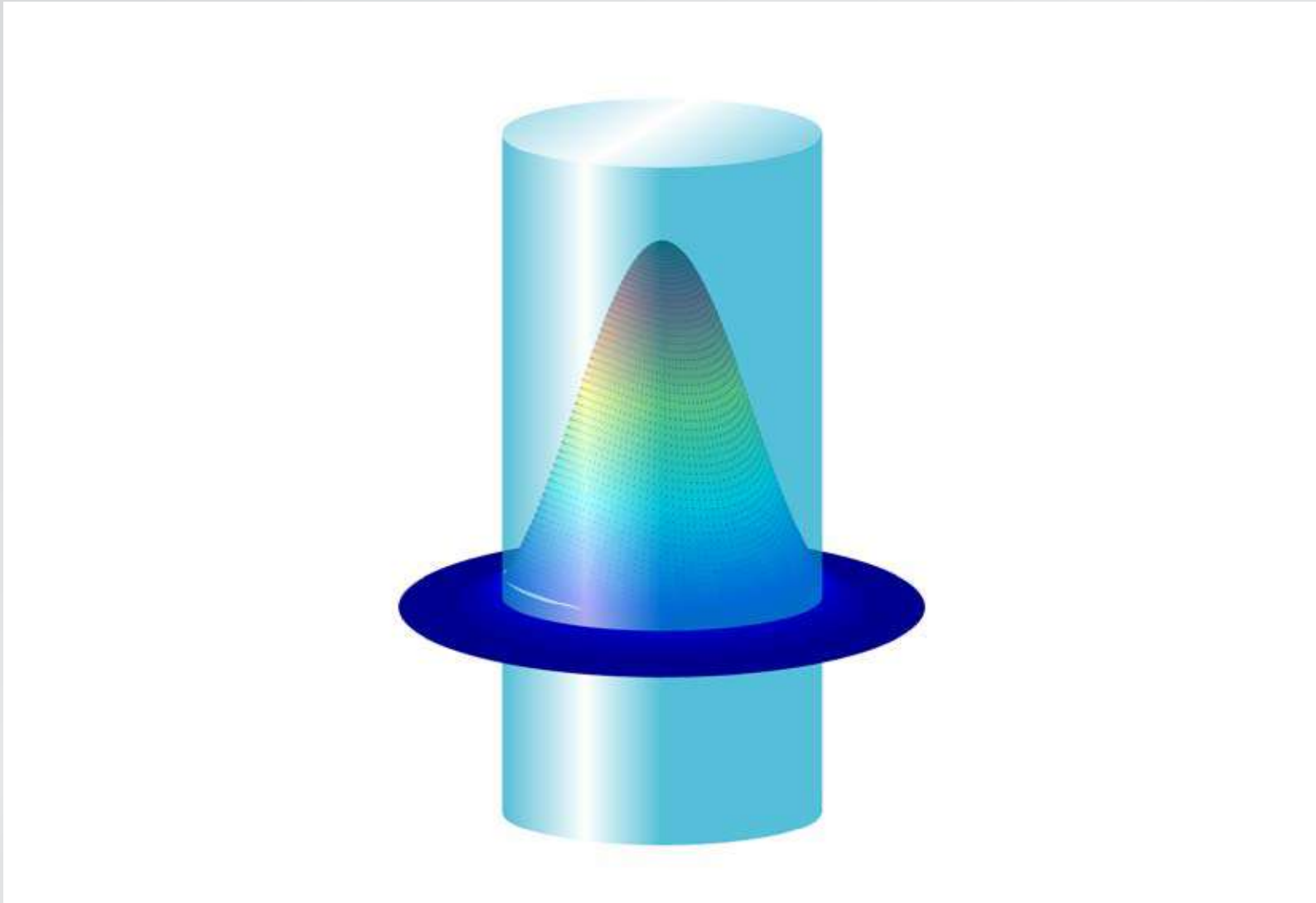
Optical properties

Poynting vector profile for 800-nm nanowire



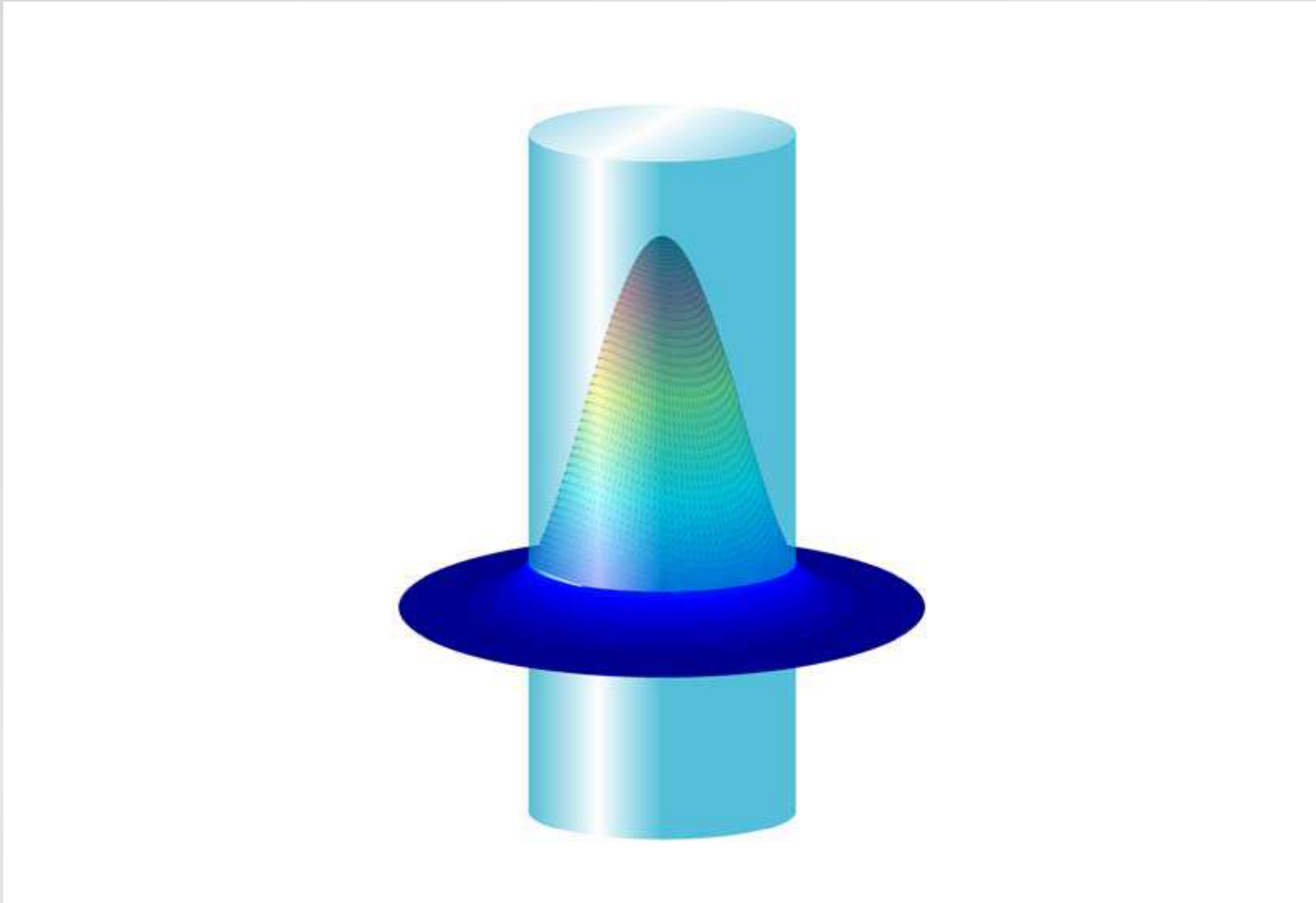
Optical properties

Poynting vector profile for 600-nm nanowire



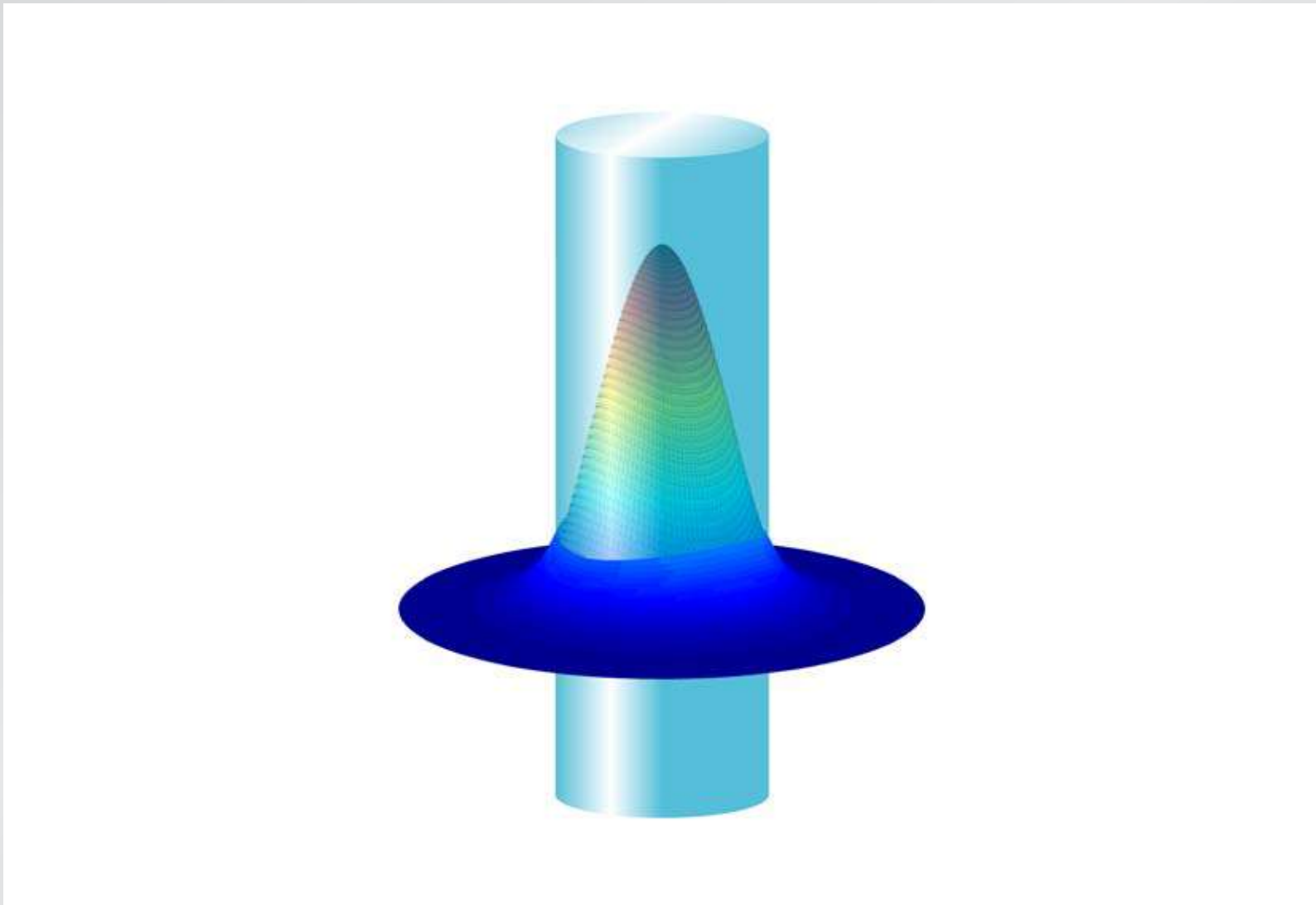
Optical properties

Poynting vector profile for 500-nm nanowire



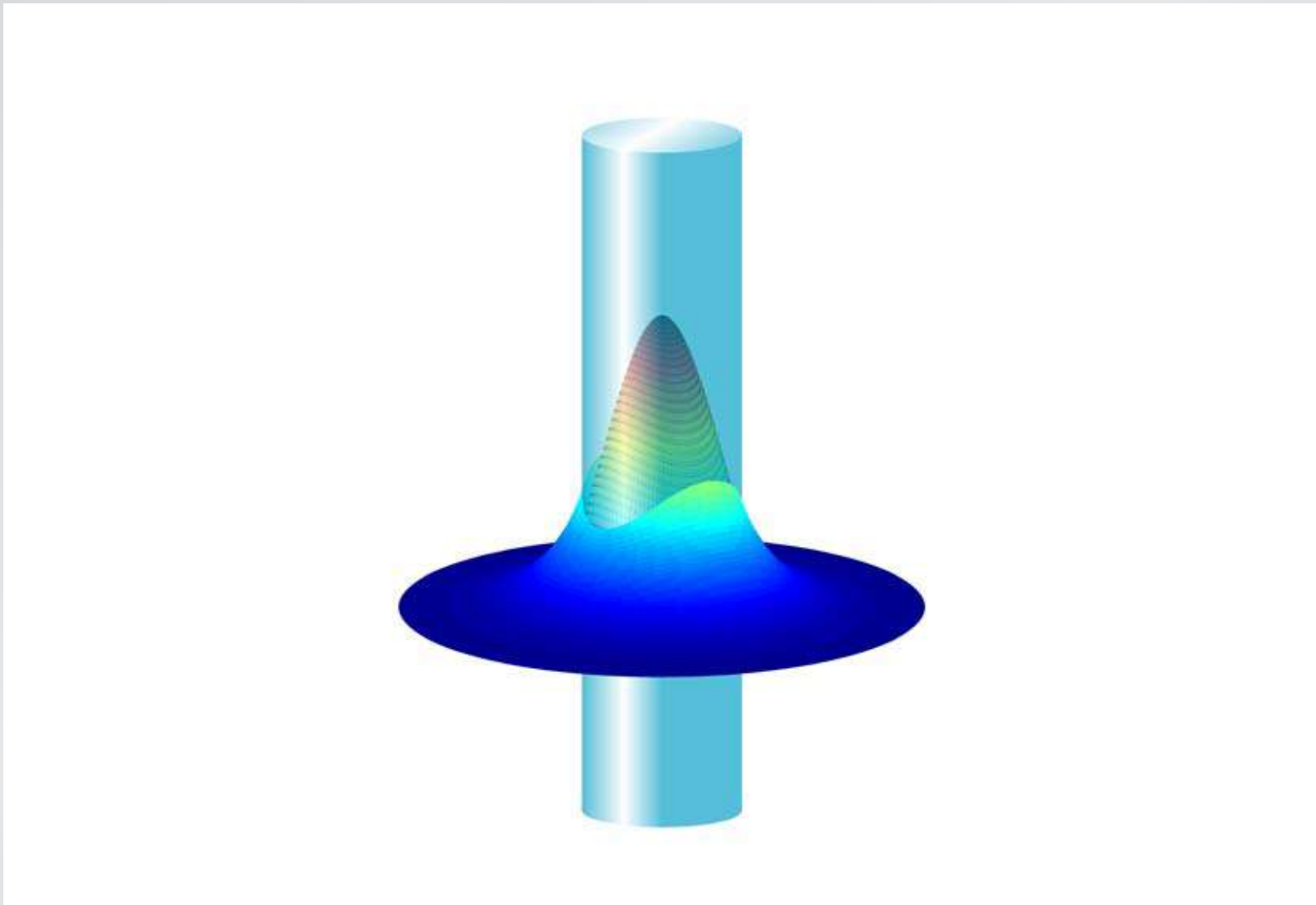
Optical properties

Poynting vector profile for 400-nm nanowire



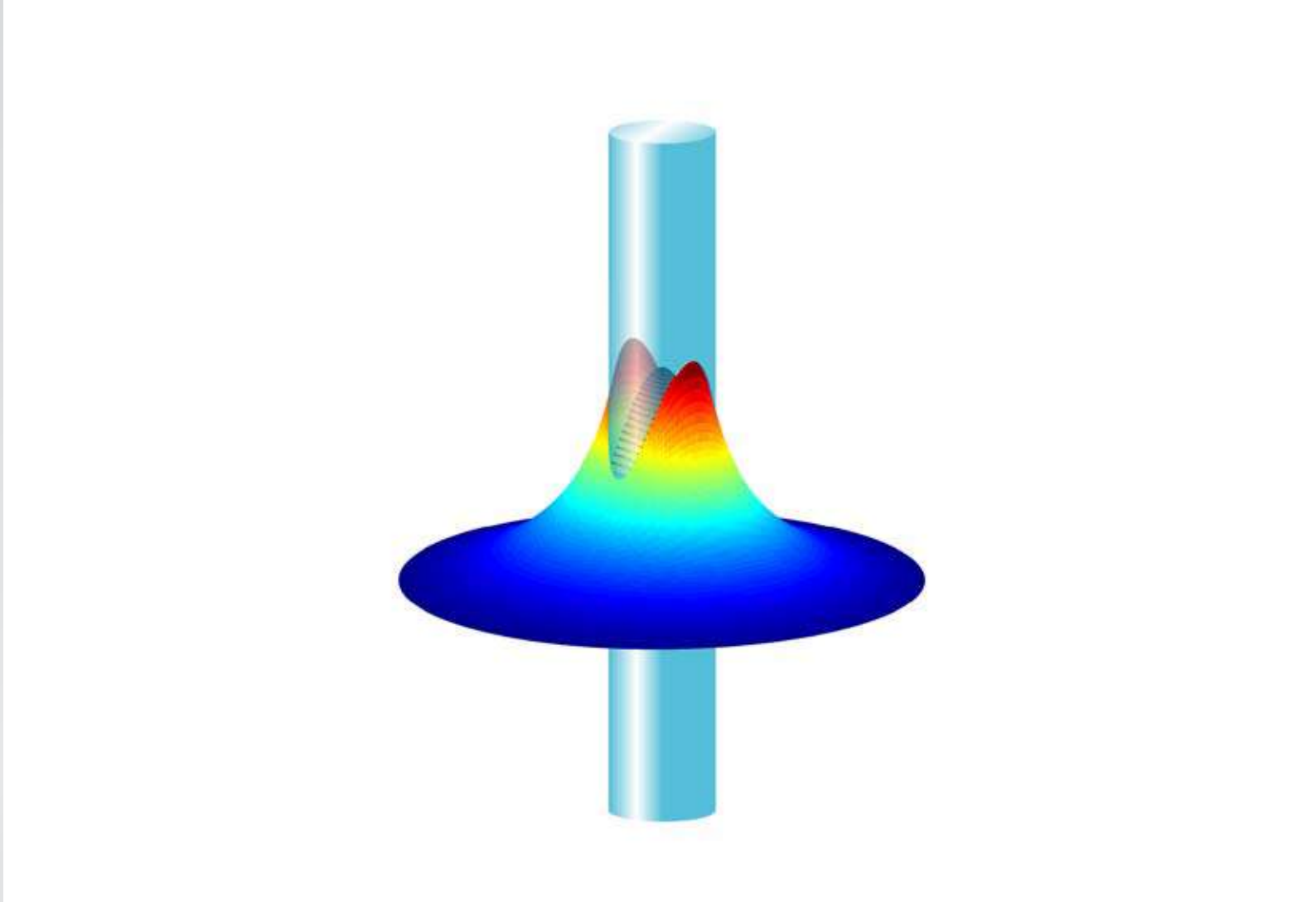
Optical properties

Poynting vector profile for 300-nm nanowire



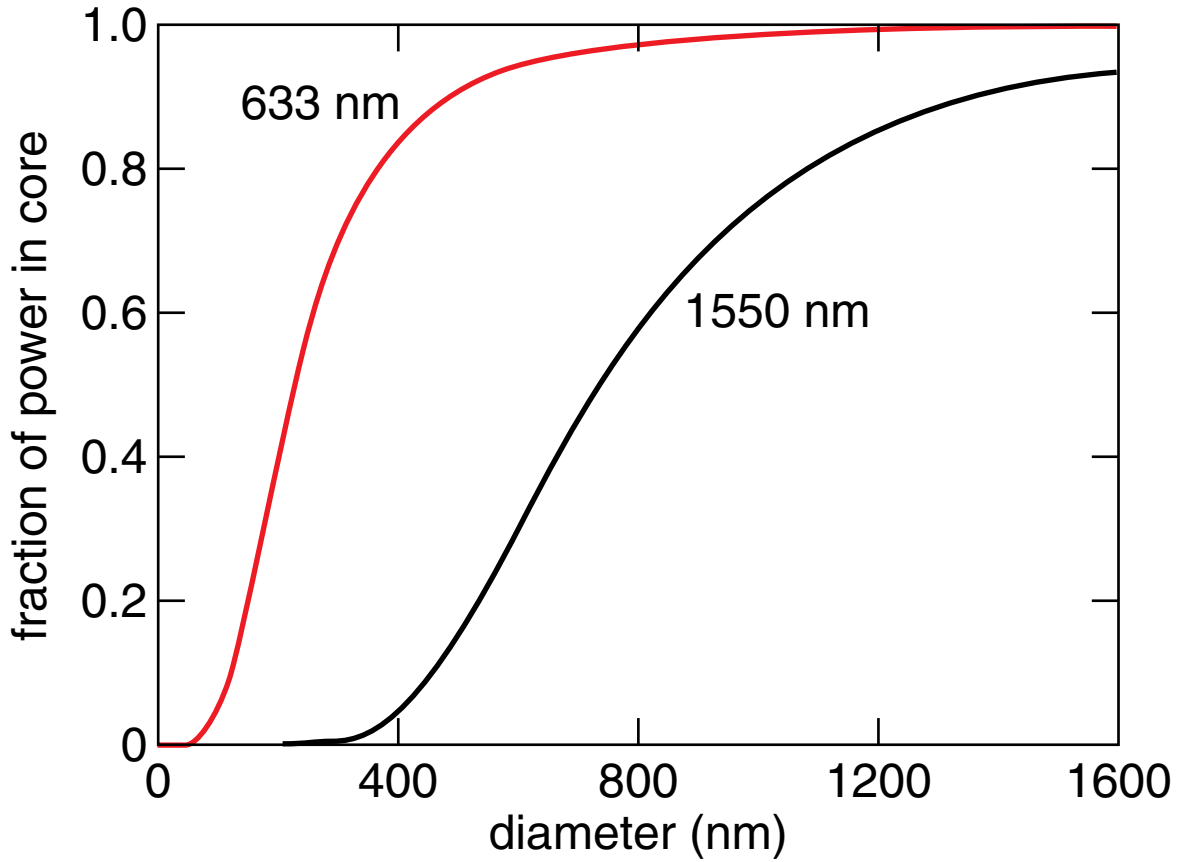
Optical properties

Poynting vector profile for 200-nm nanowire



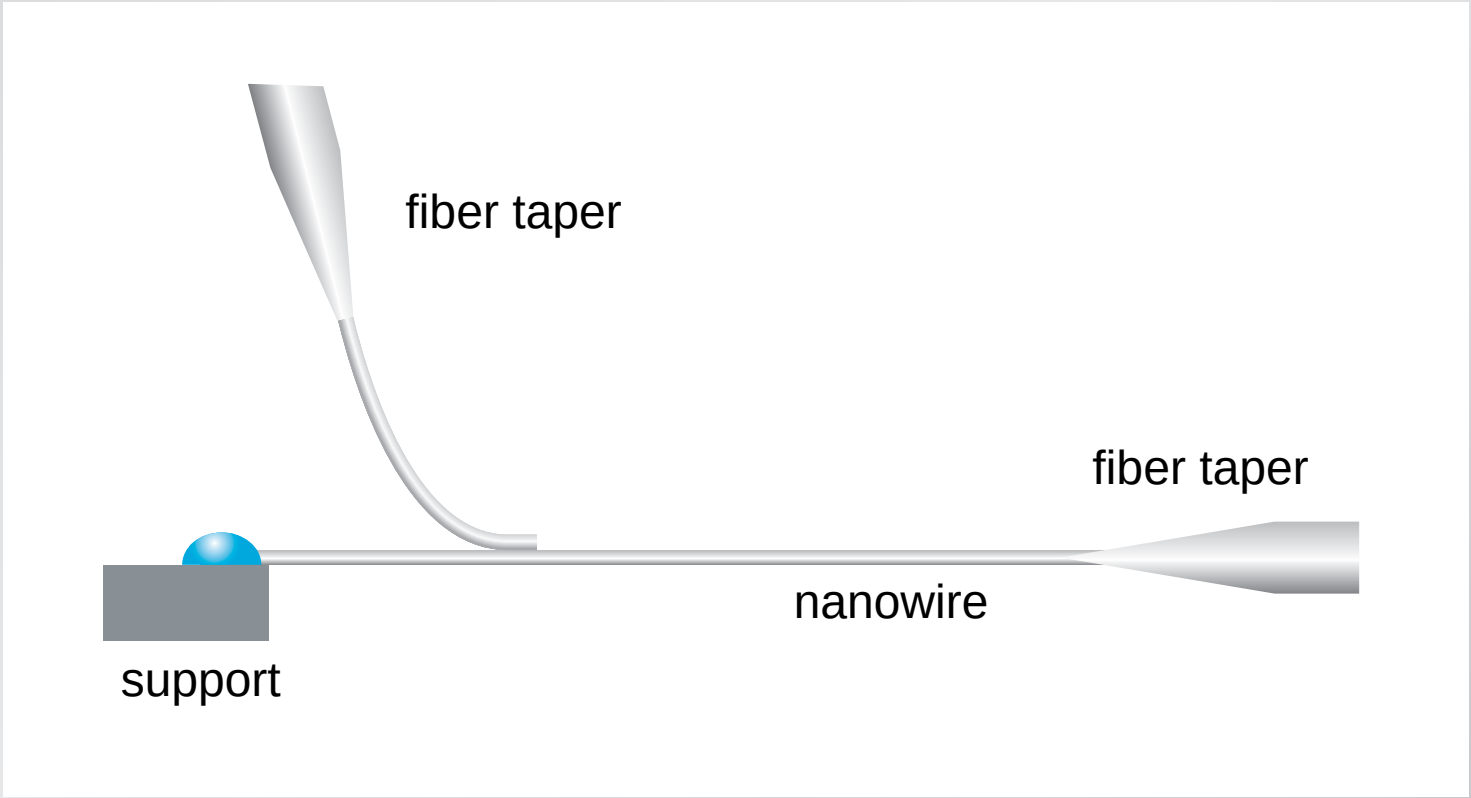
Optical properties

fraction of power carried in core



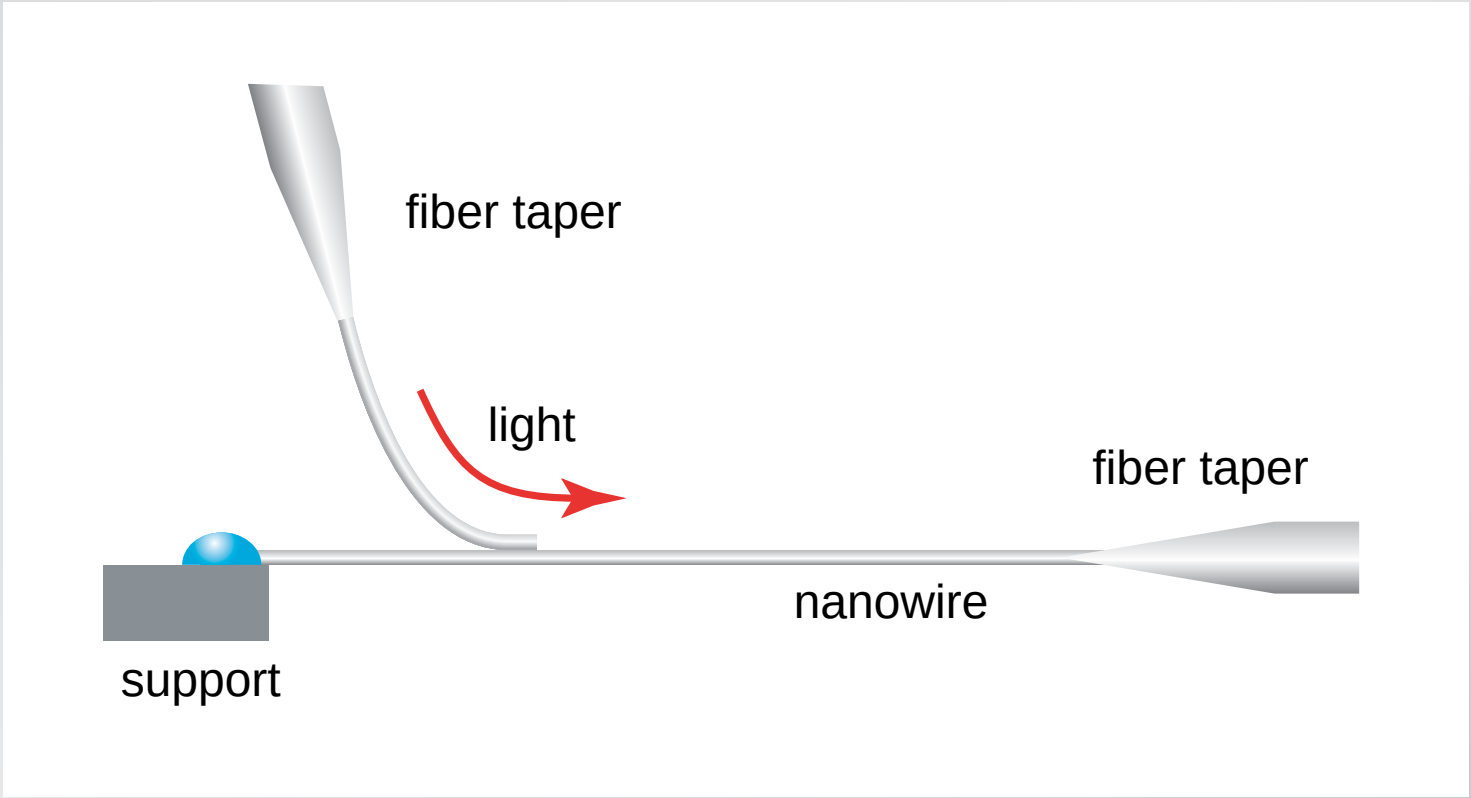
Optical properties

coupling light between nanowires



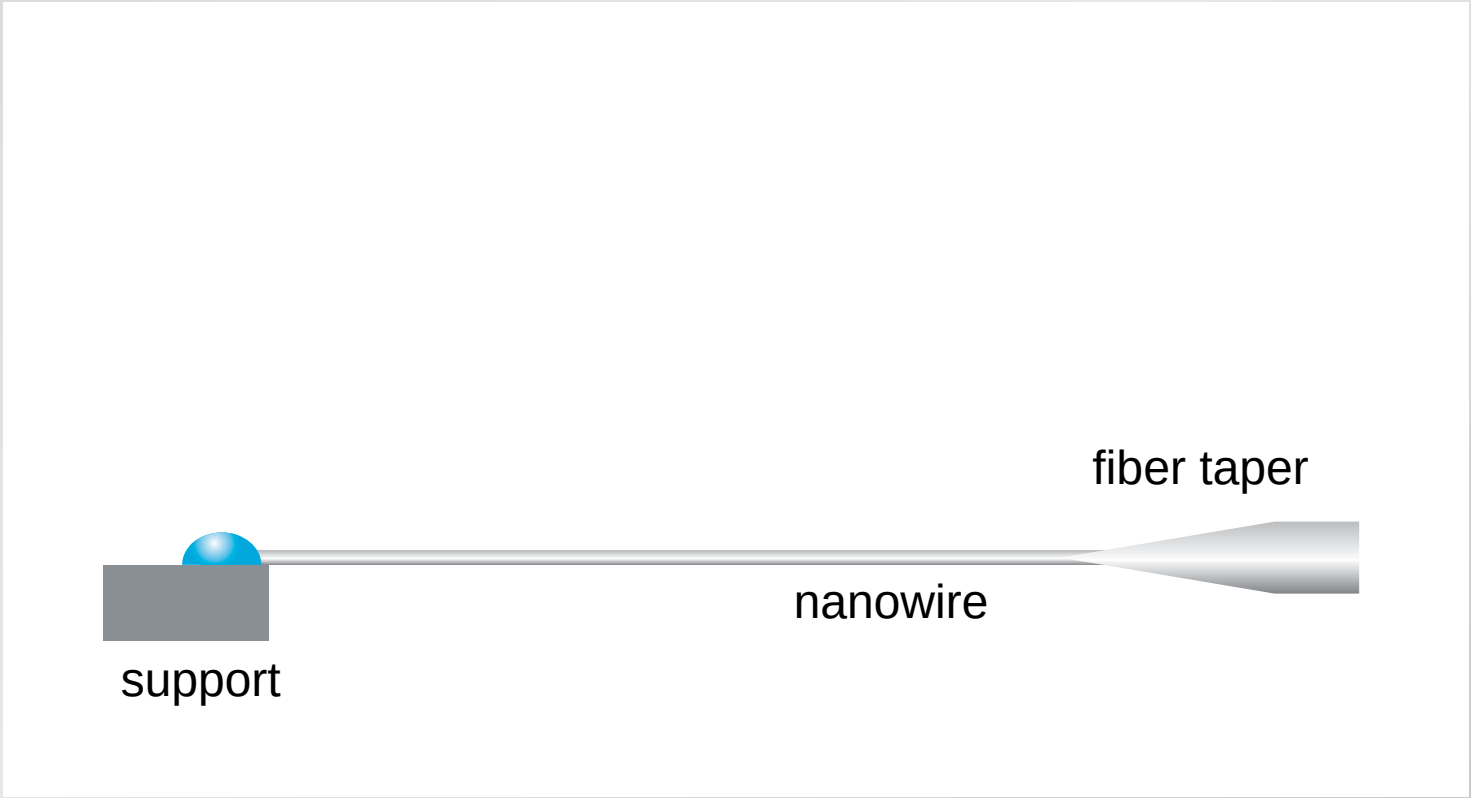
Optical properties

coupling light between nanowires

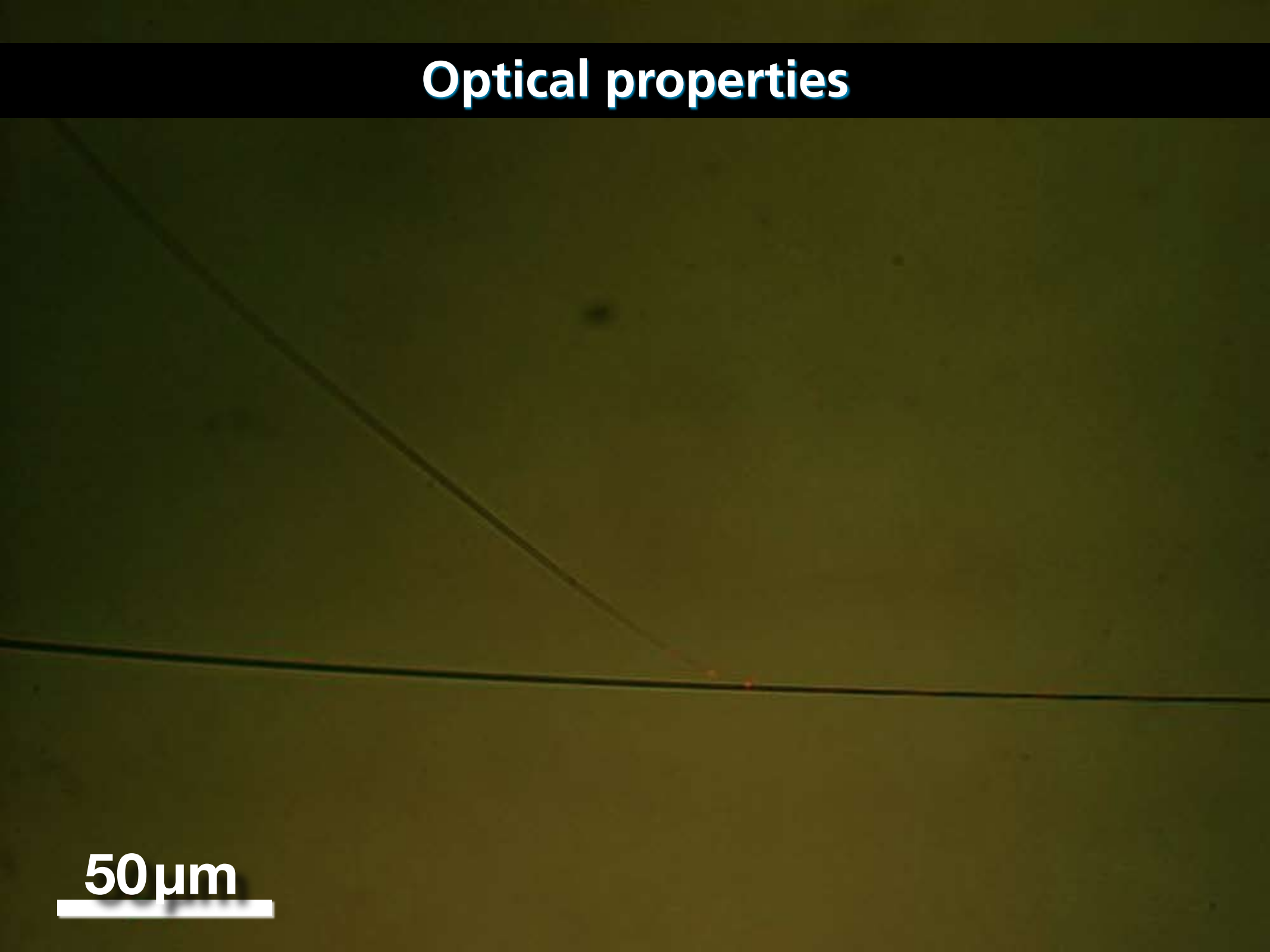


Optical properties

coupling light between nanowires

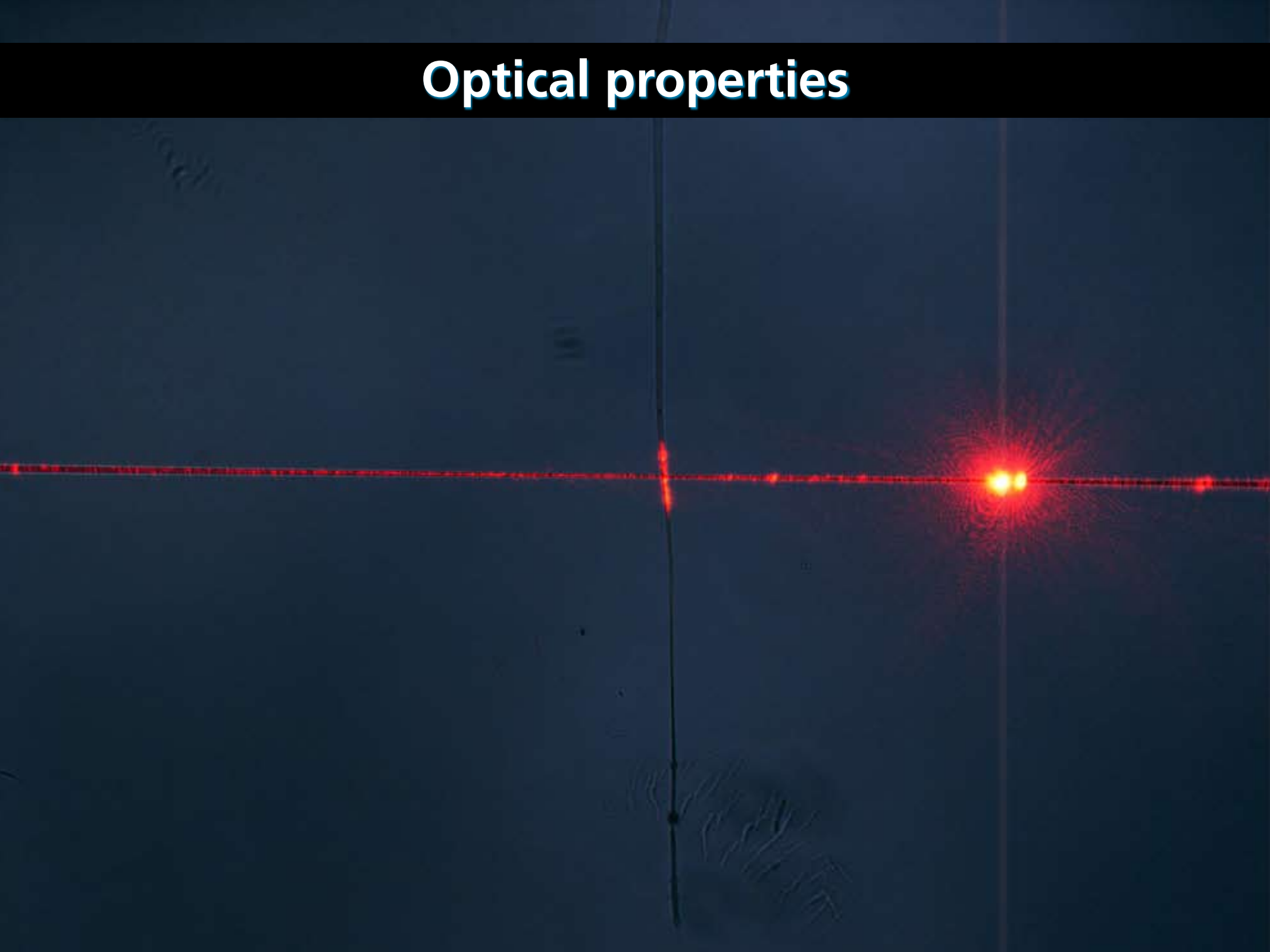


Optical properties

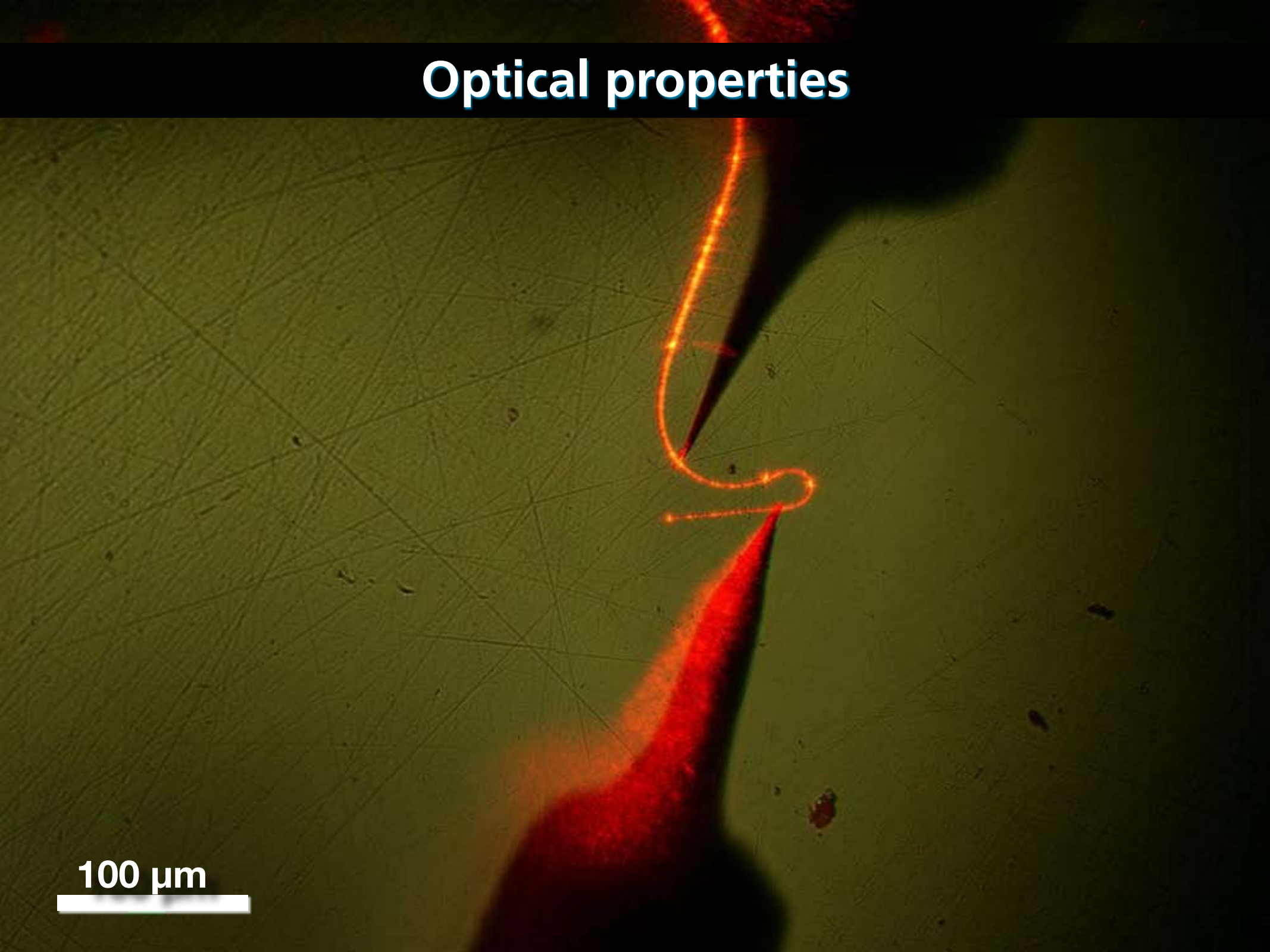


Optical properties

Optical properties



Optical properties



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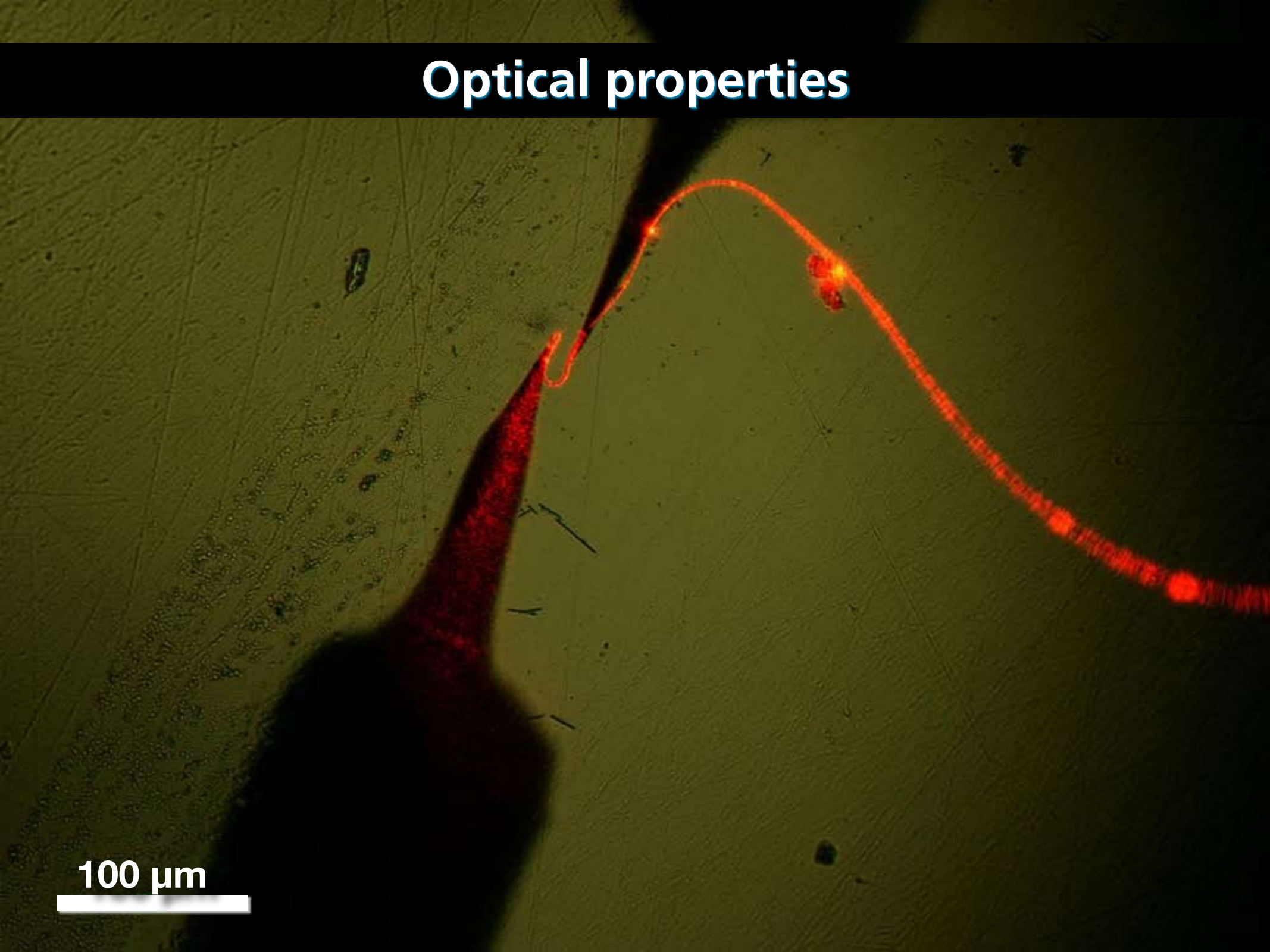

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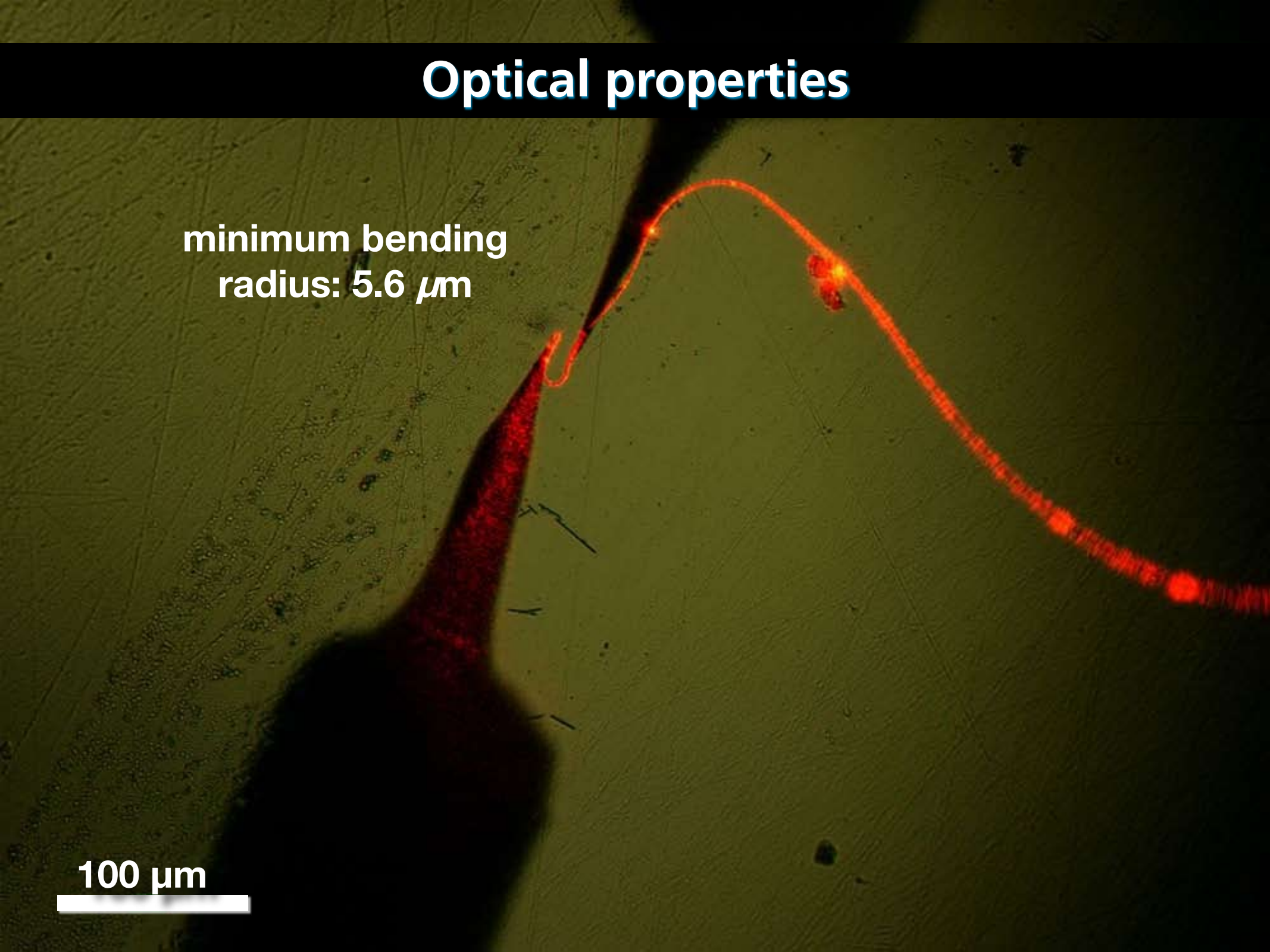
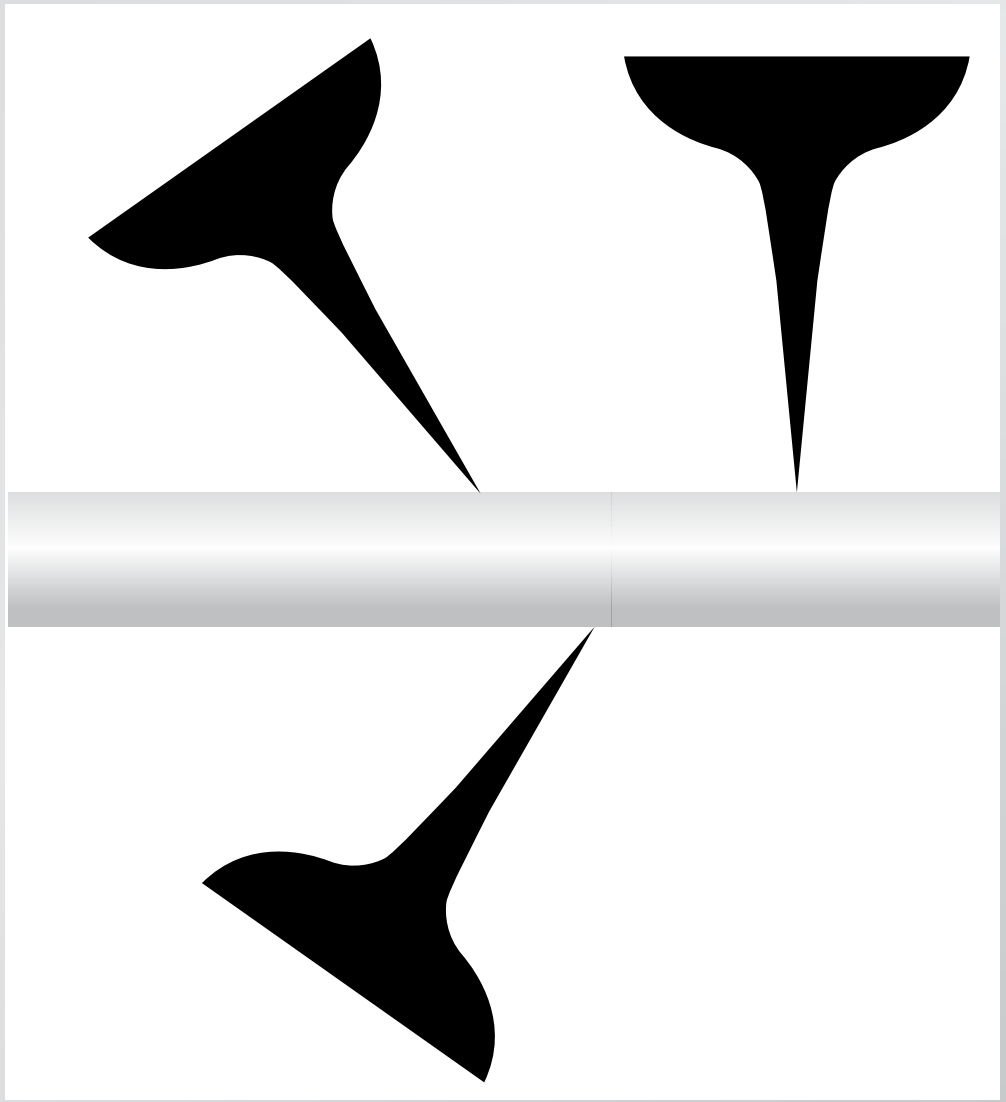


Optical properties

microphotonic components

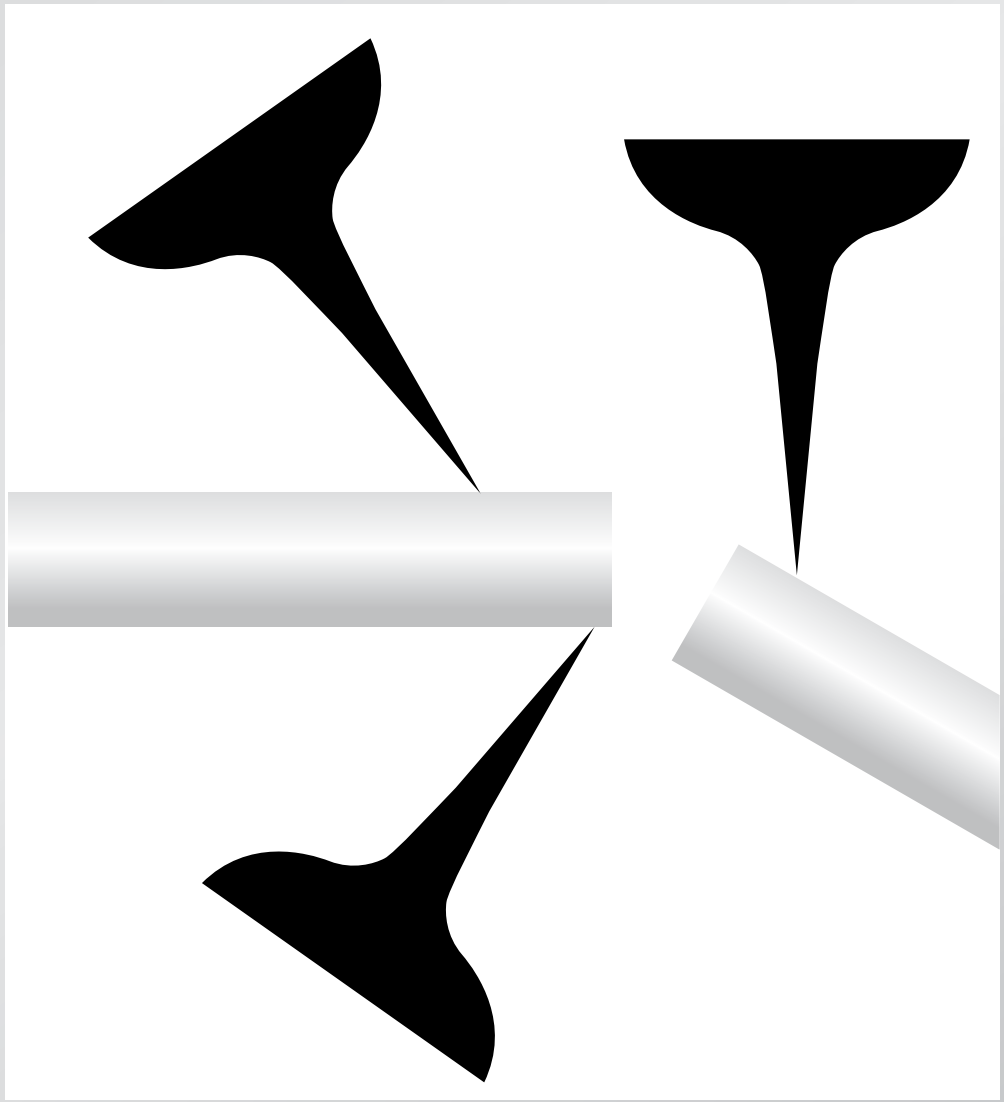
Optical properties

microphotonic components



Optical properties

microphotonic components



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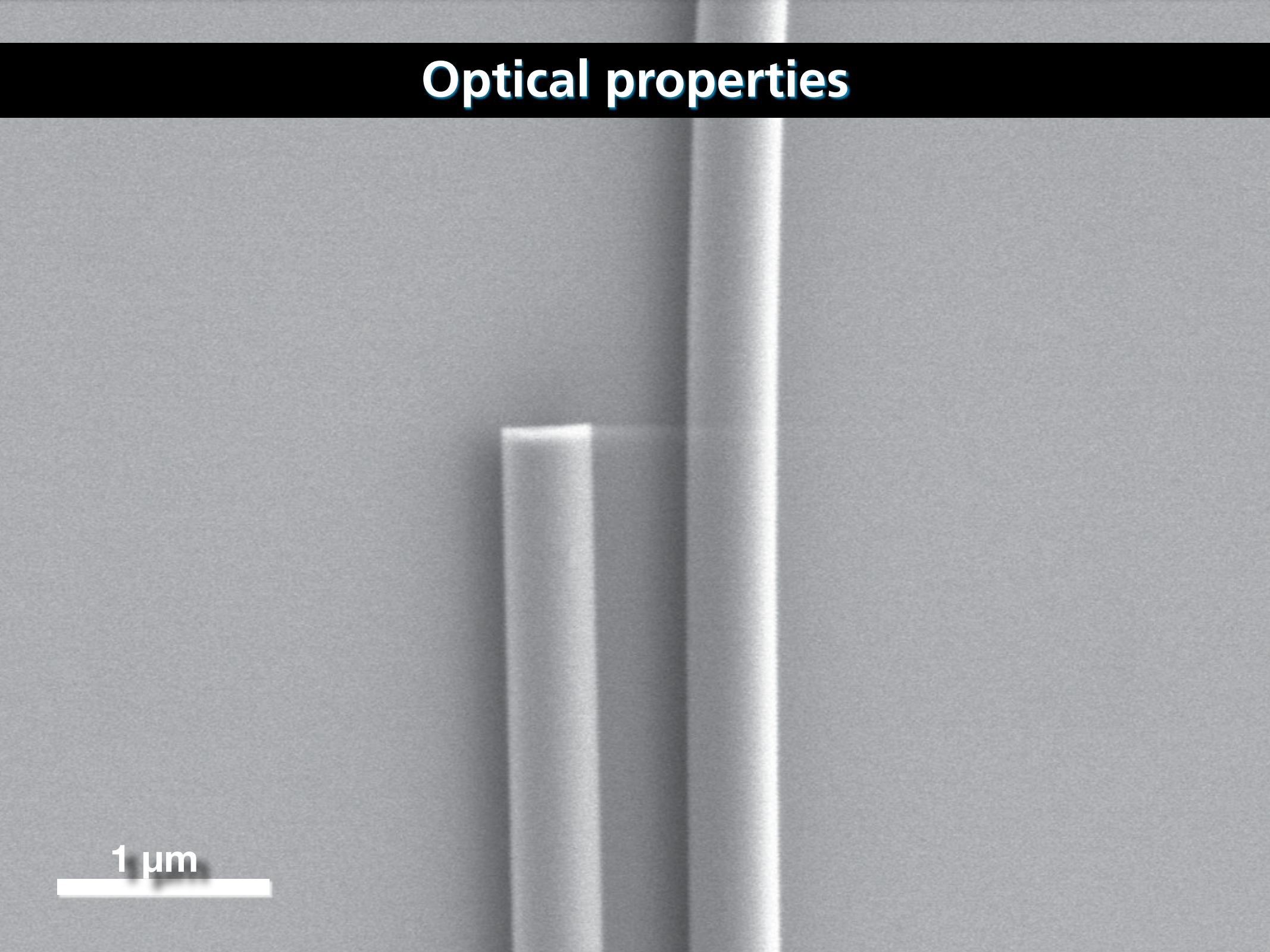

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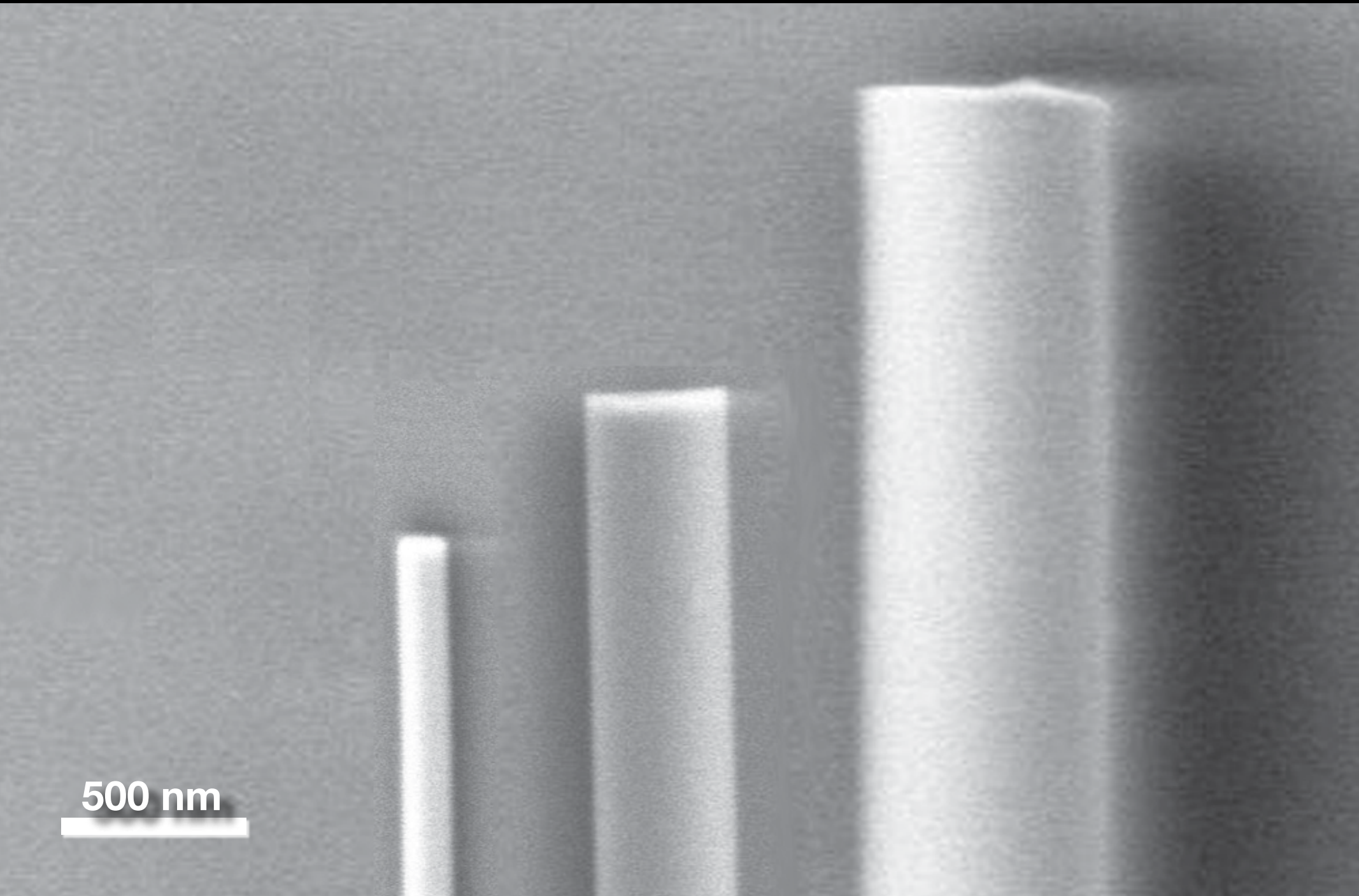

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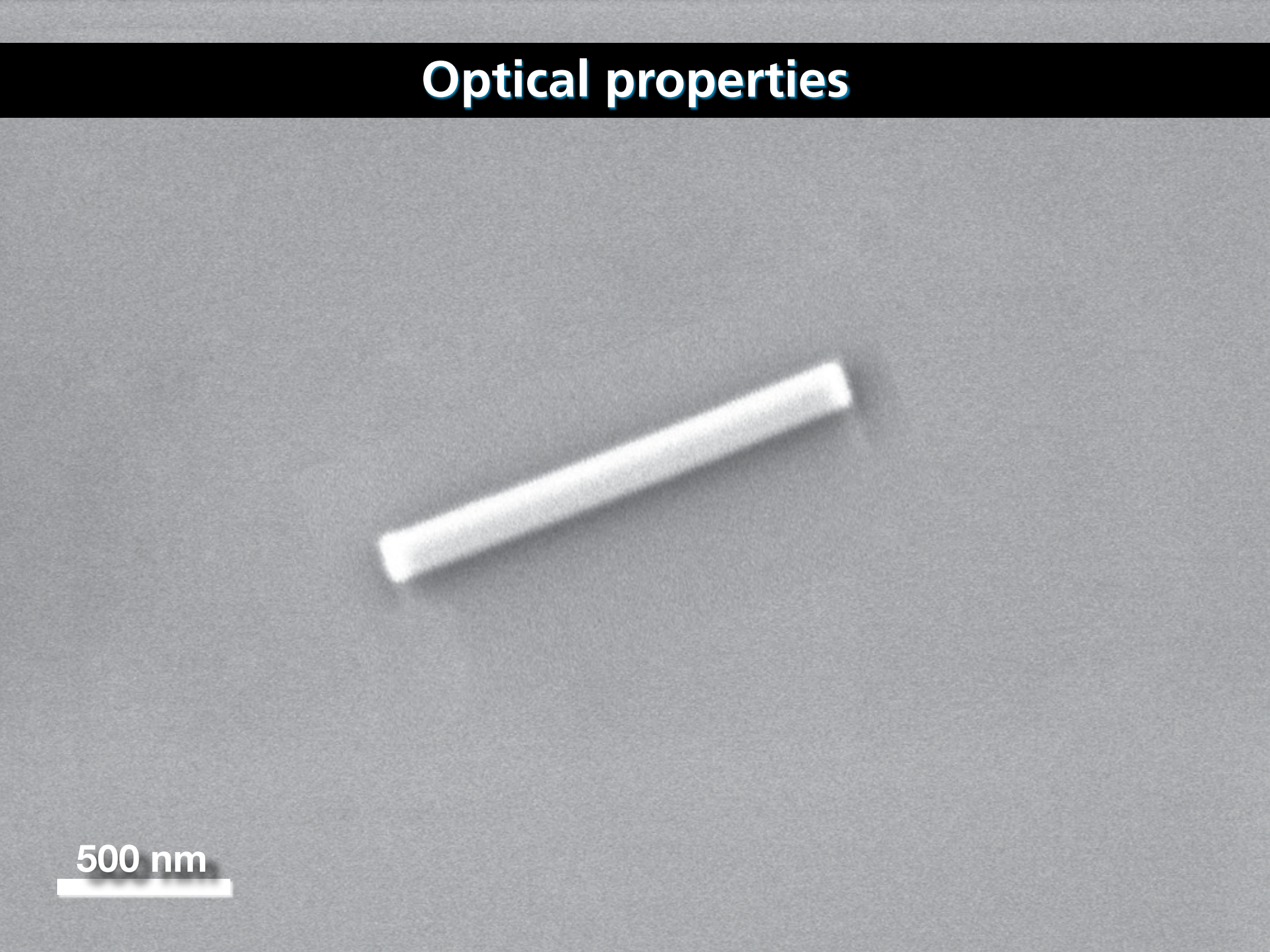

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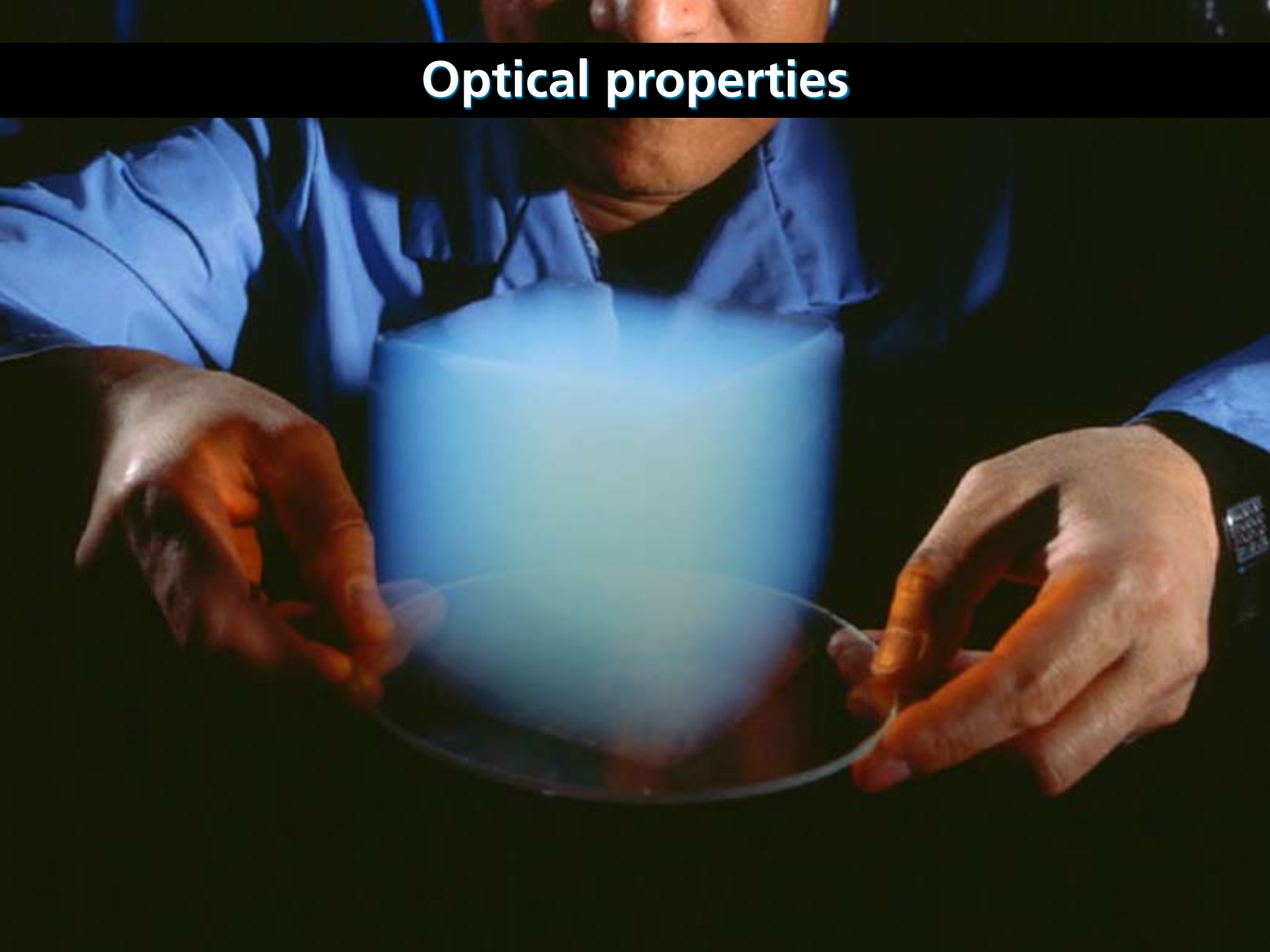
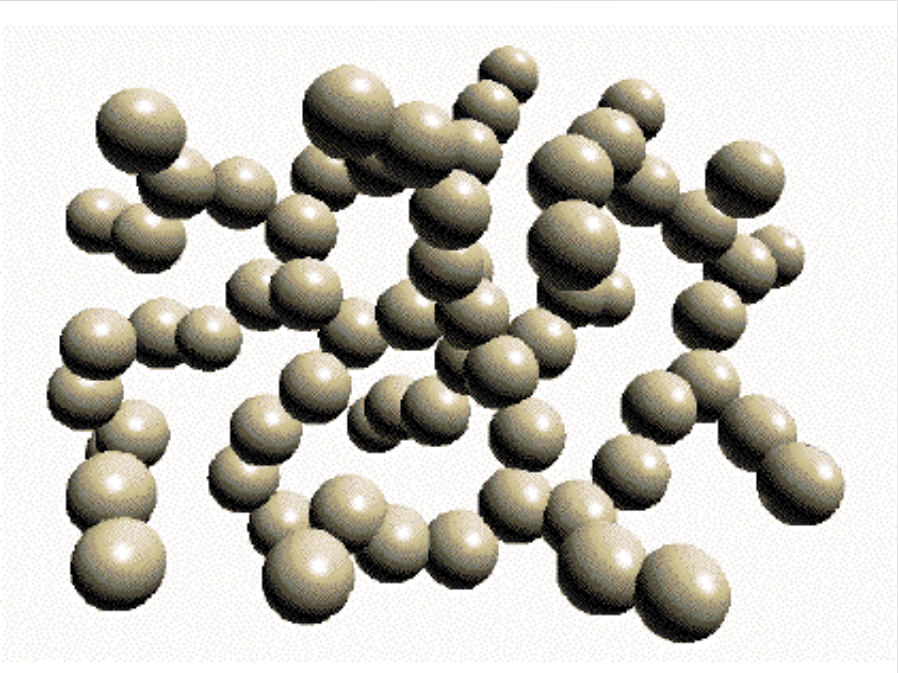
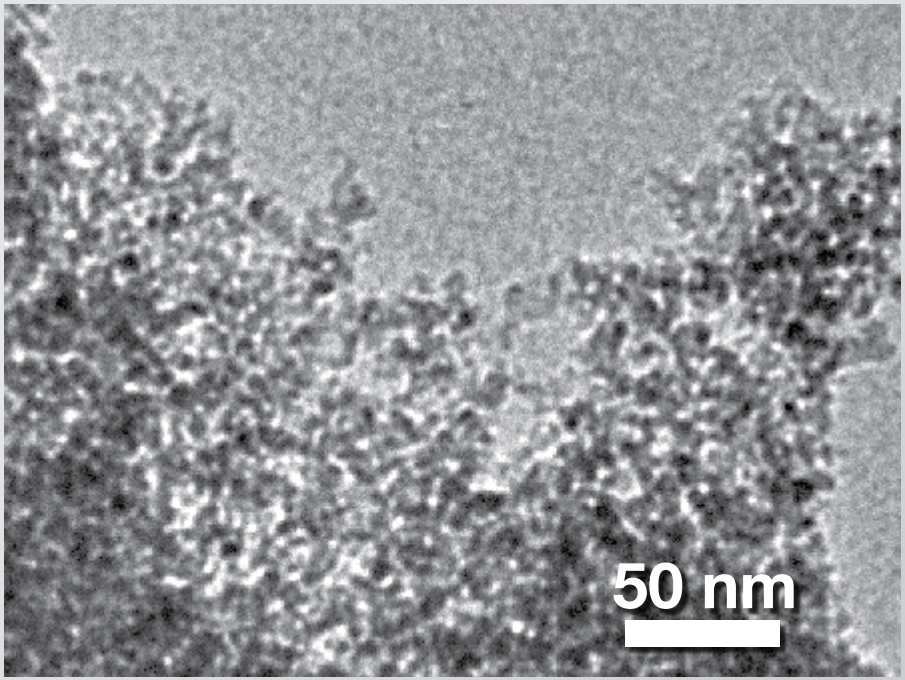


Optical properties

Aerogel

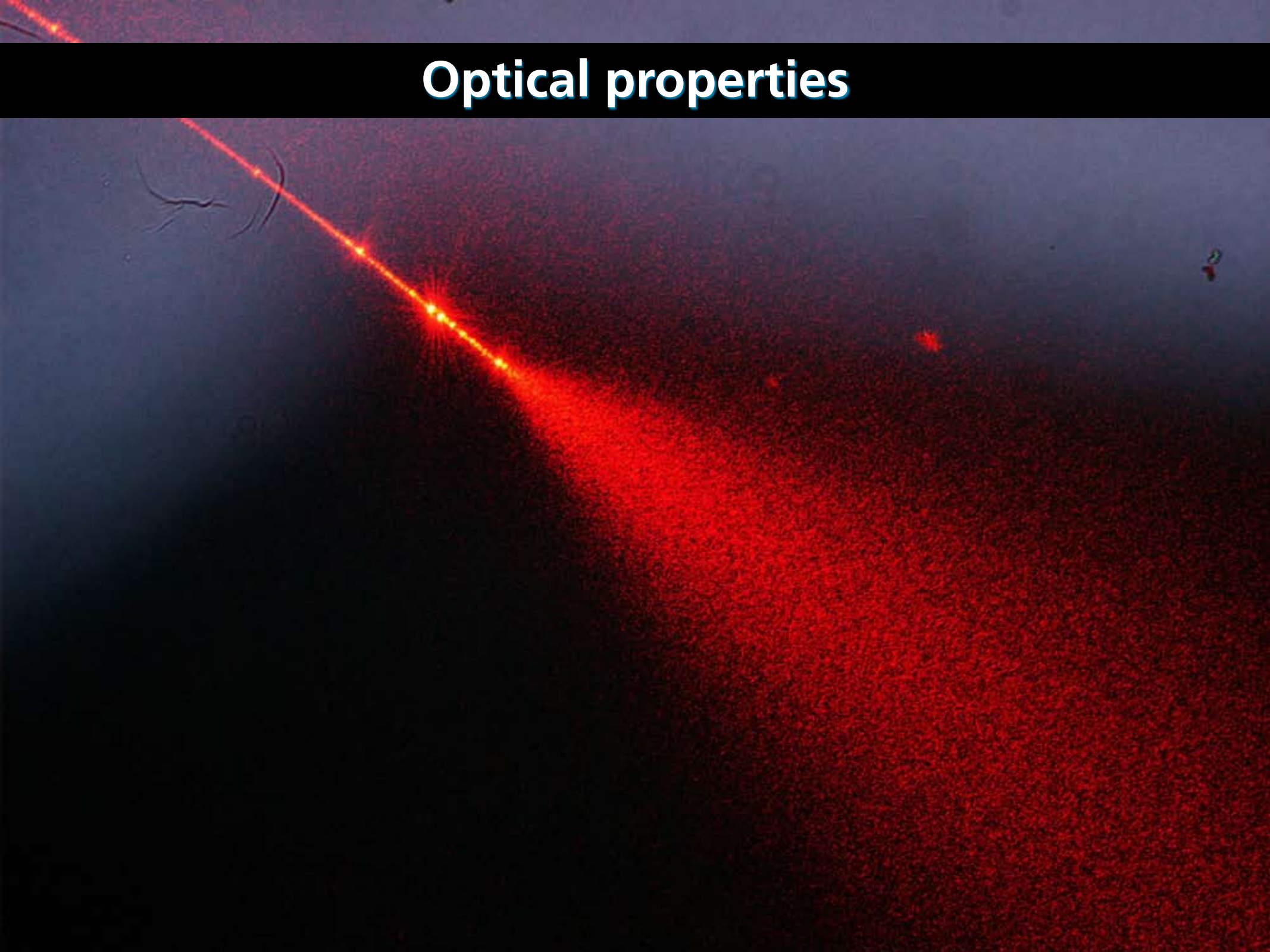




density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Optical properties



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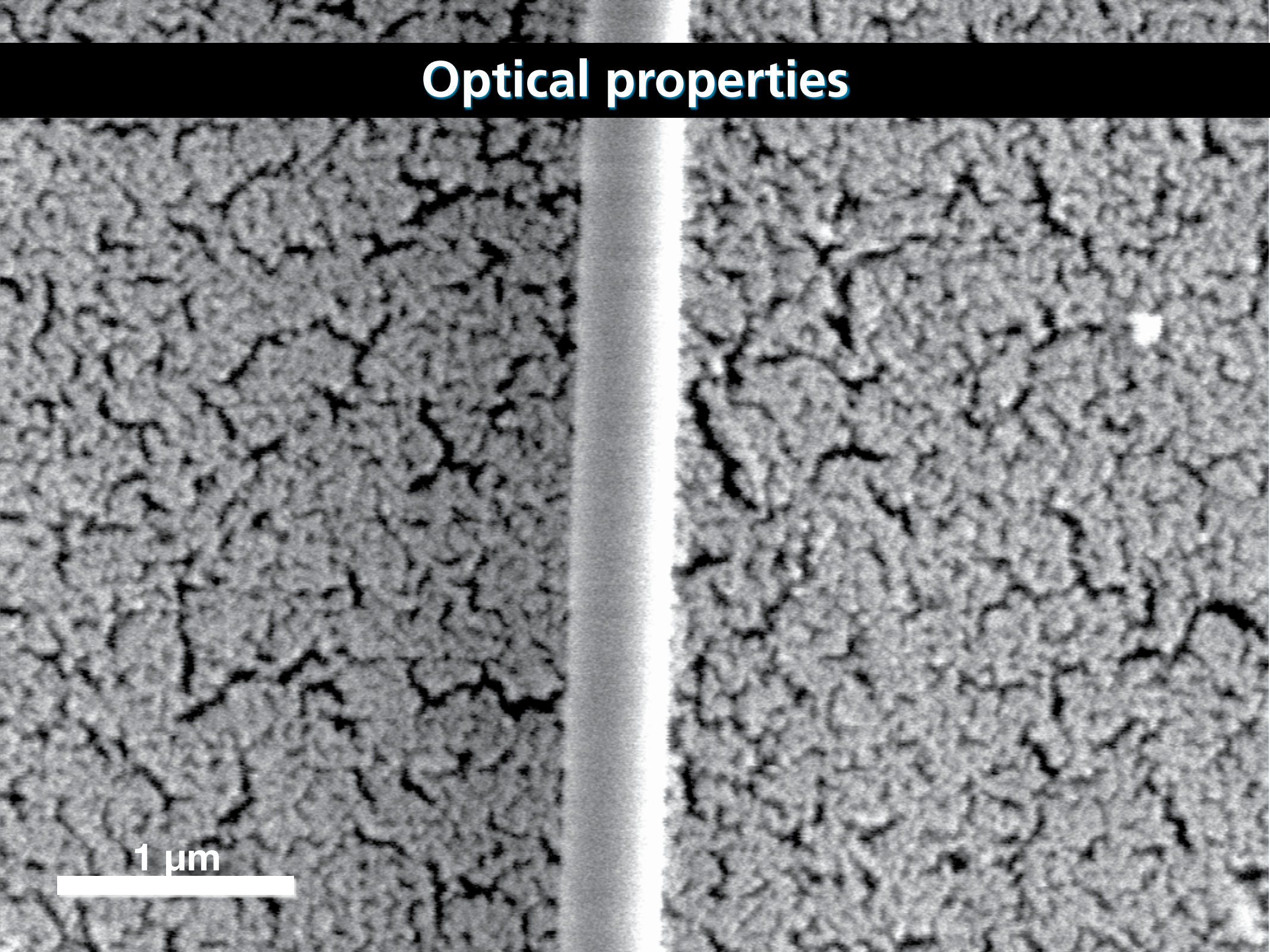
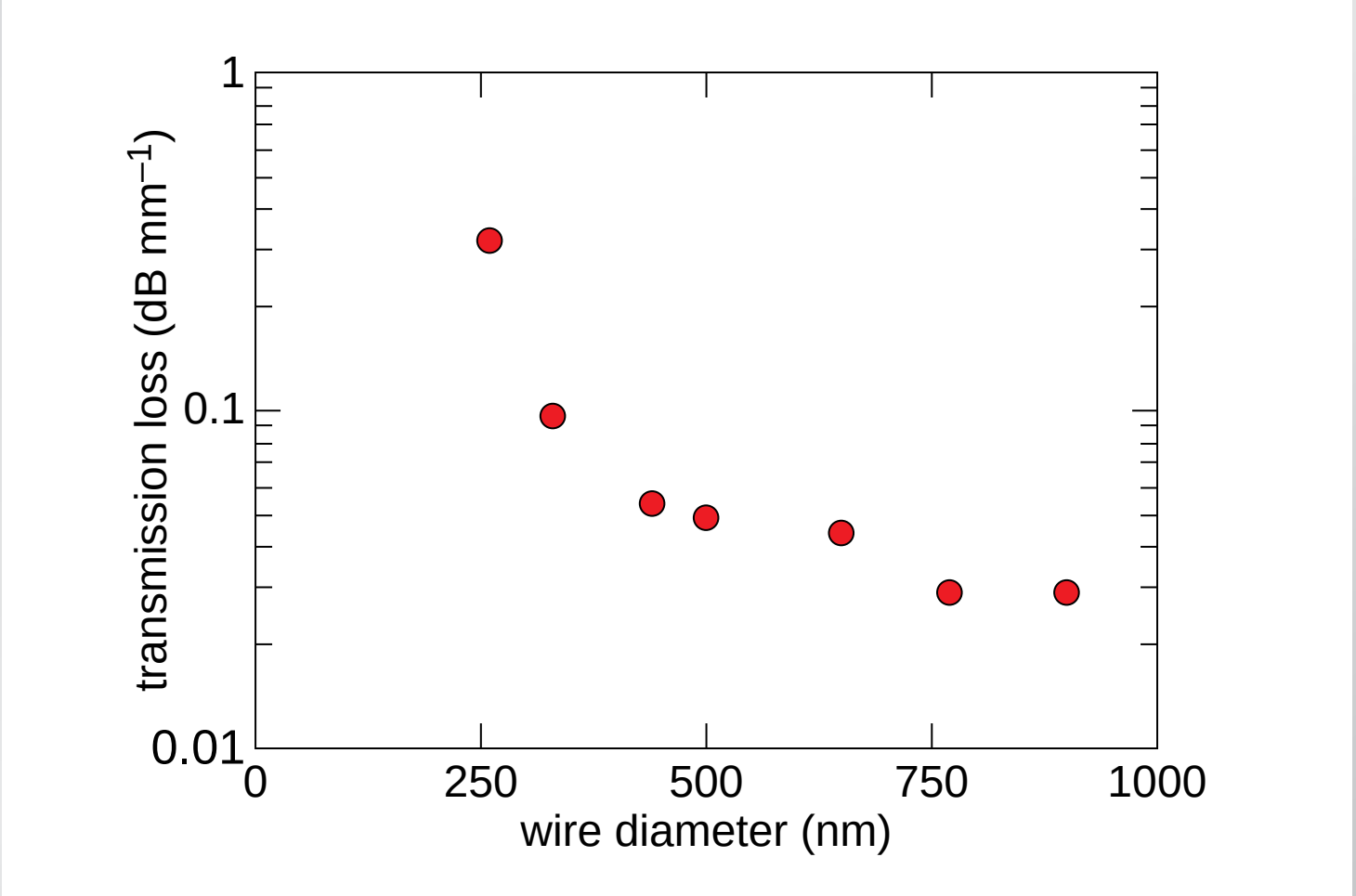


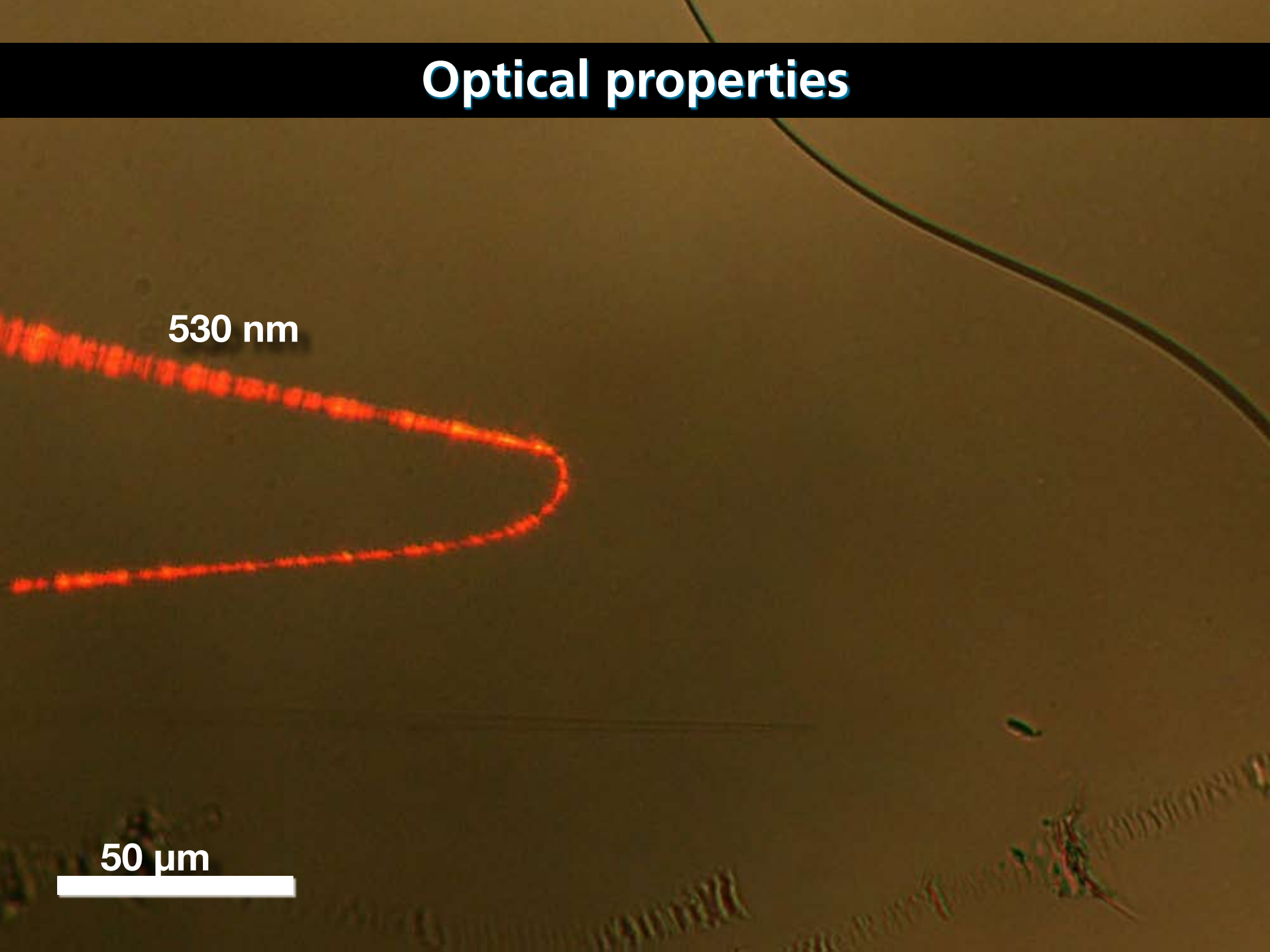
Optical properties

loss measurement @ 633 nm



Nano Lett., **5**, 259–262 (2005)

Optical properties



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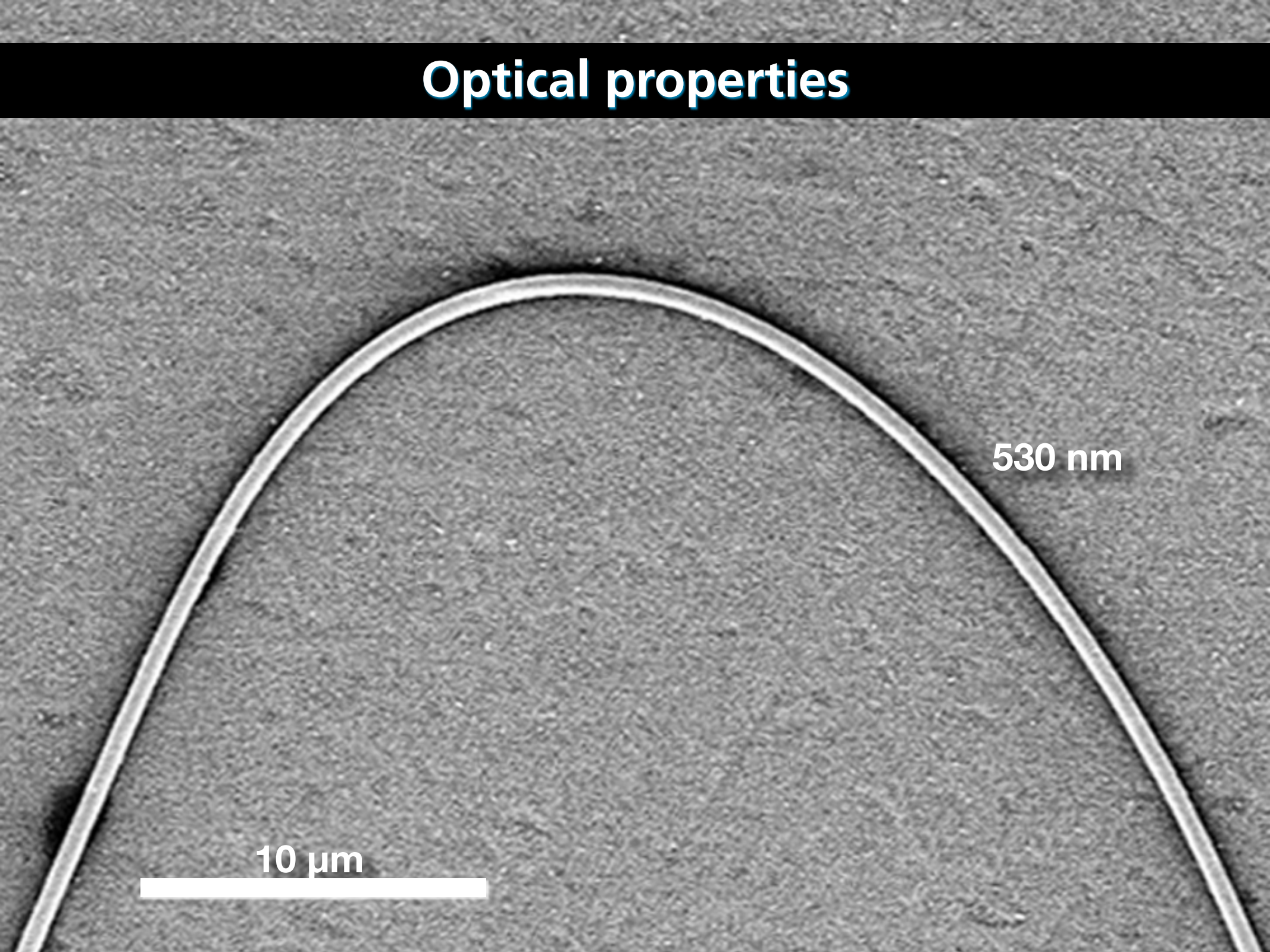

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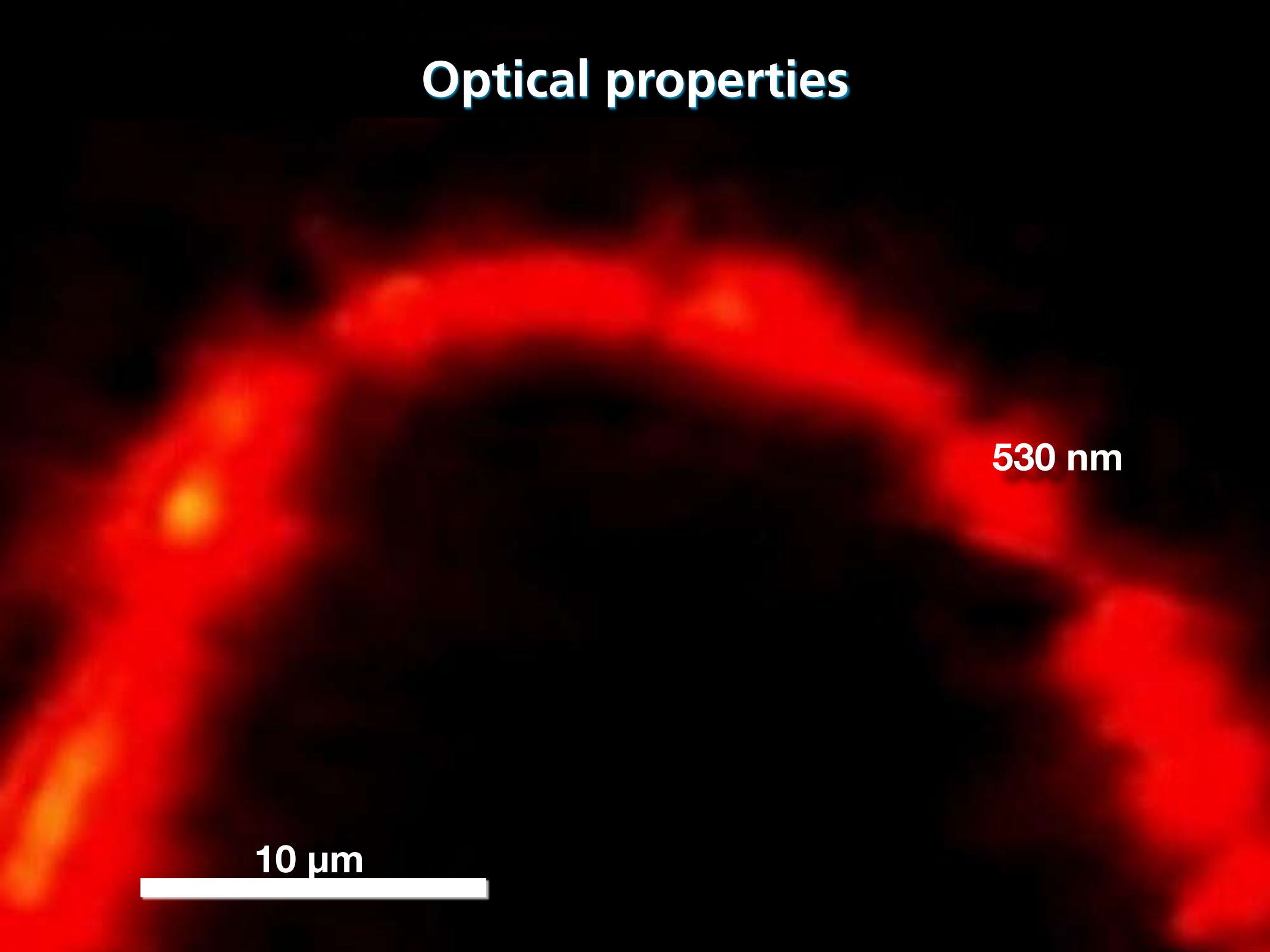

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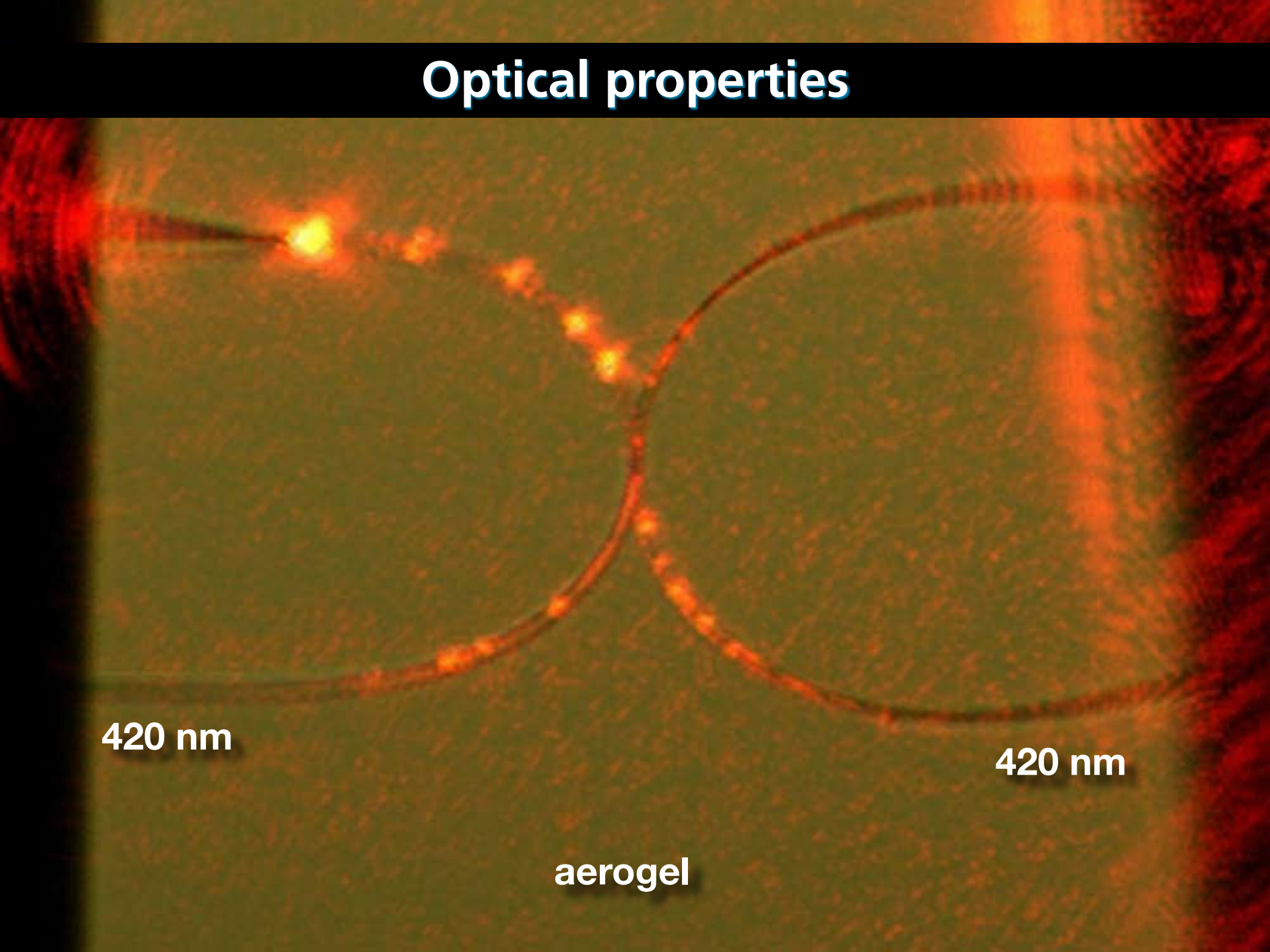
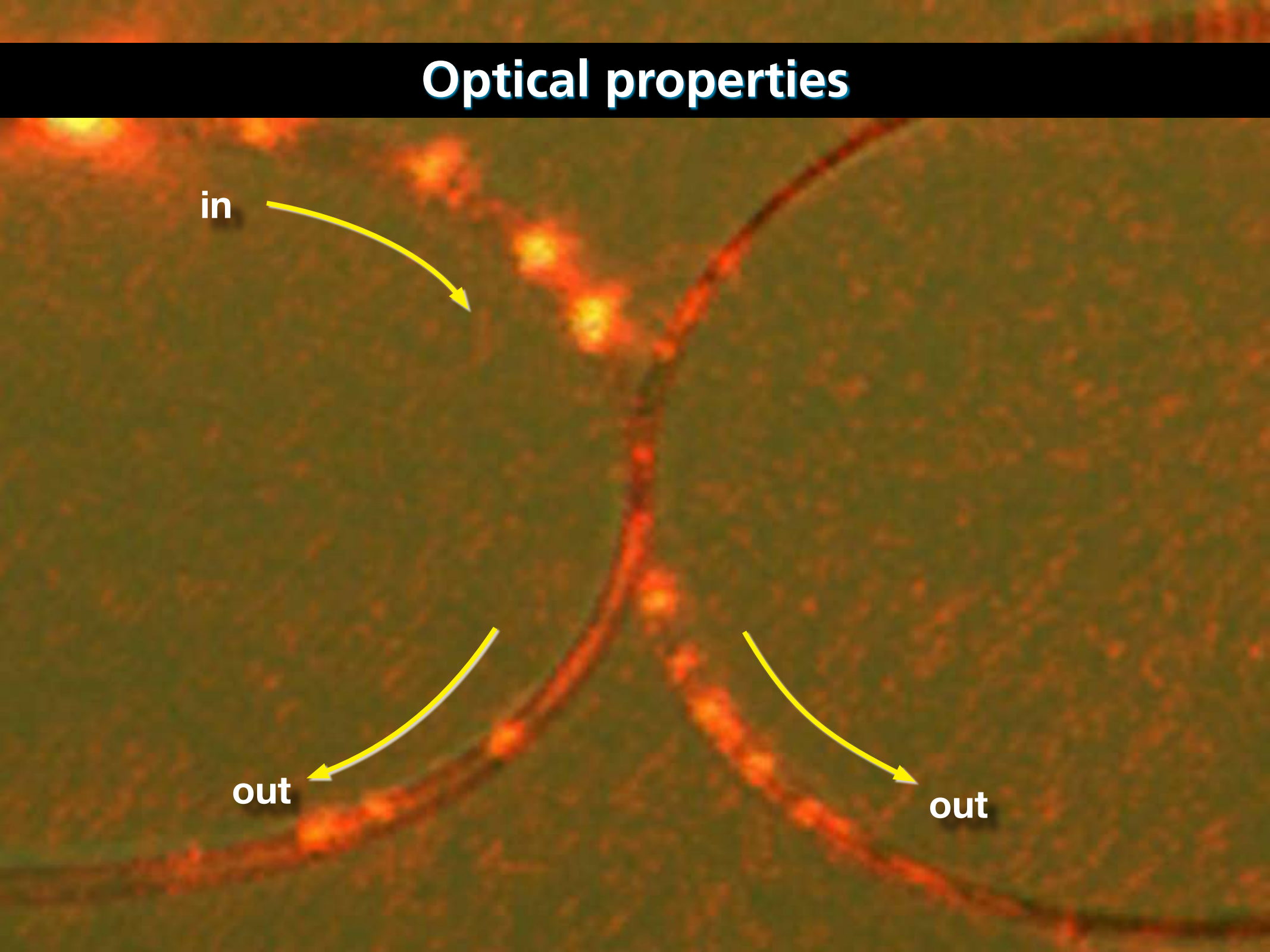
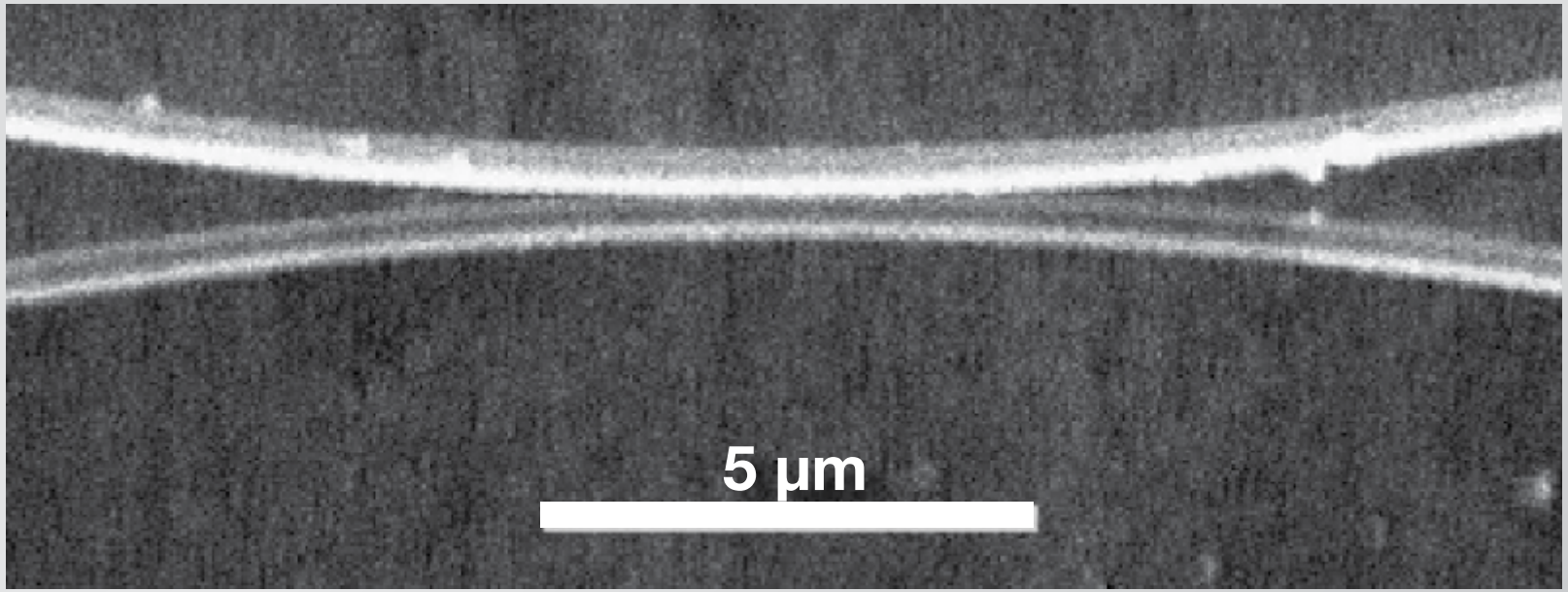


Optical properties



Optical properties

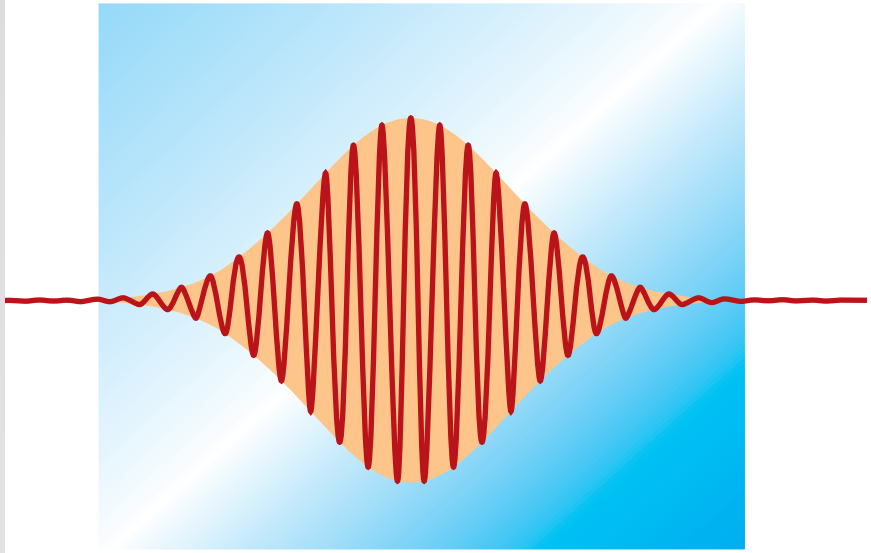


Outline

- silica nanowires
- optical properties
- nonlinear properties

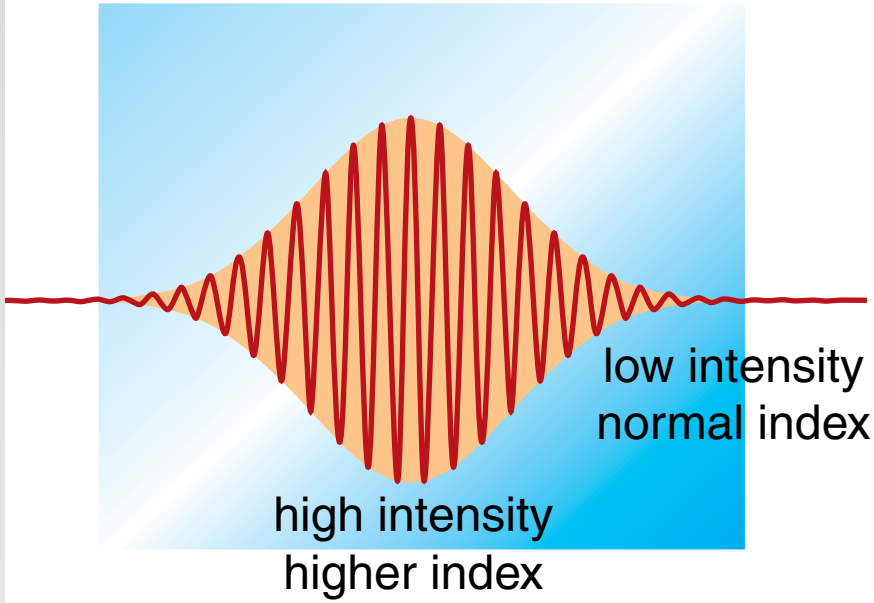
Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



Nonlinear properties

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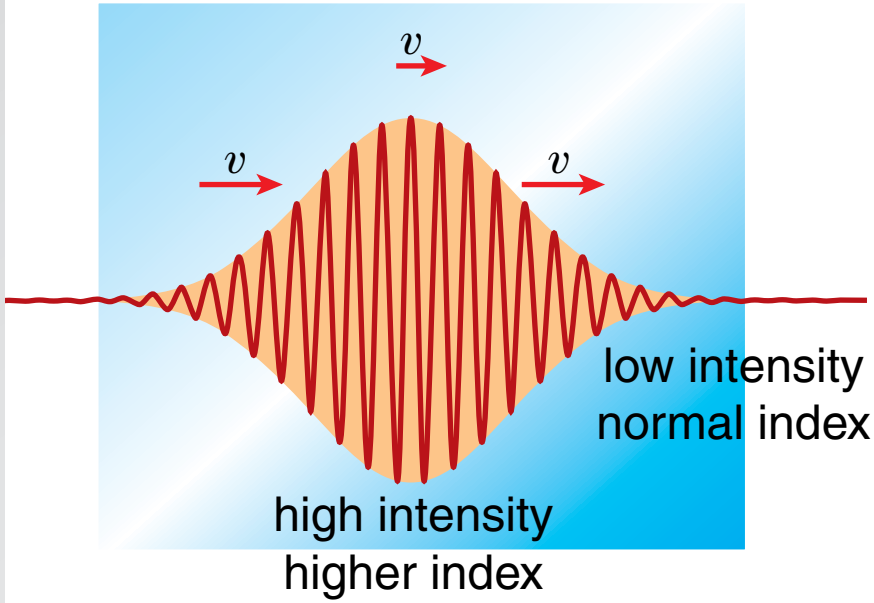

Nonlinear properties

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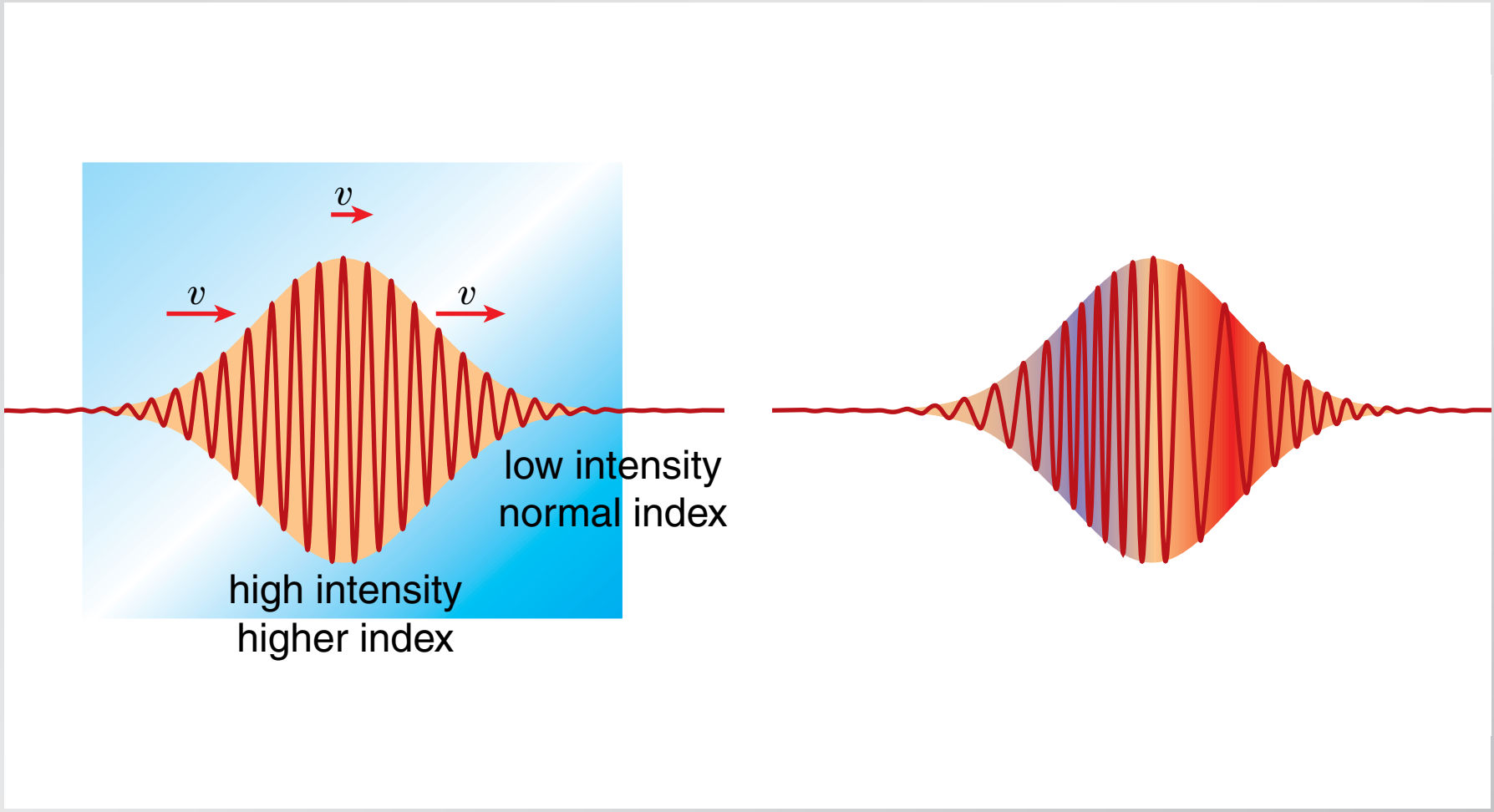
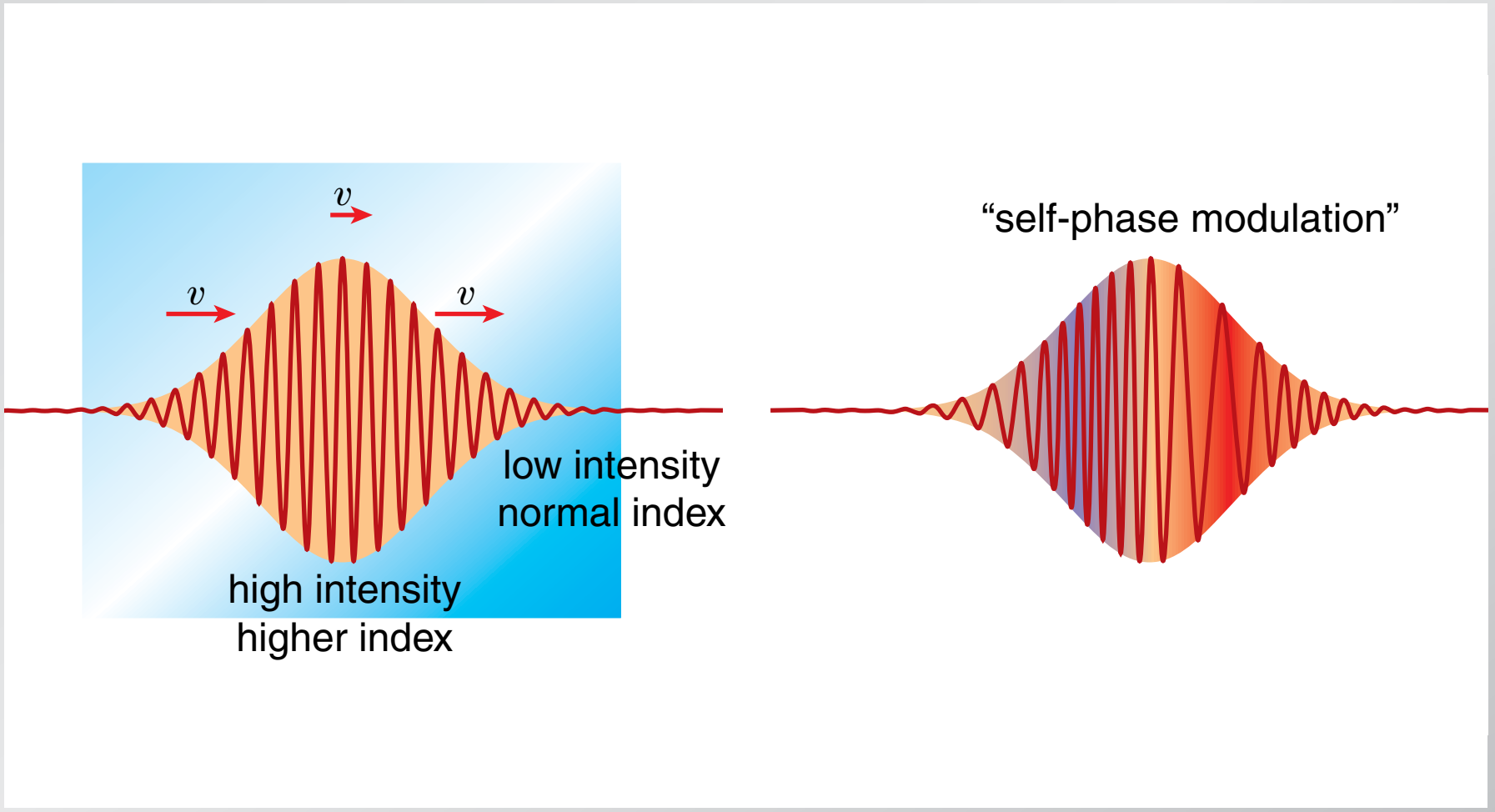
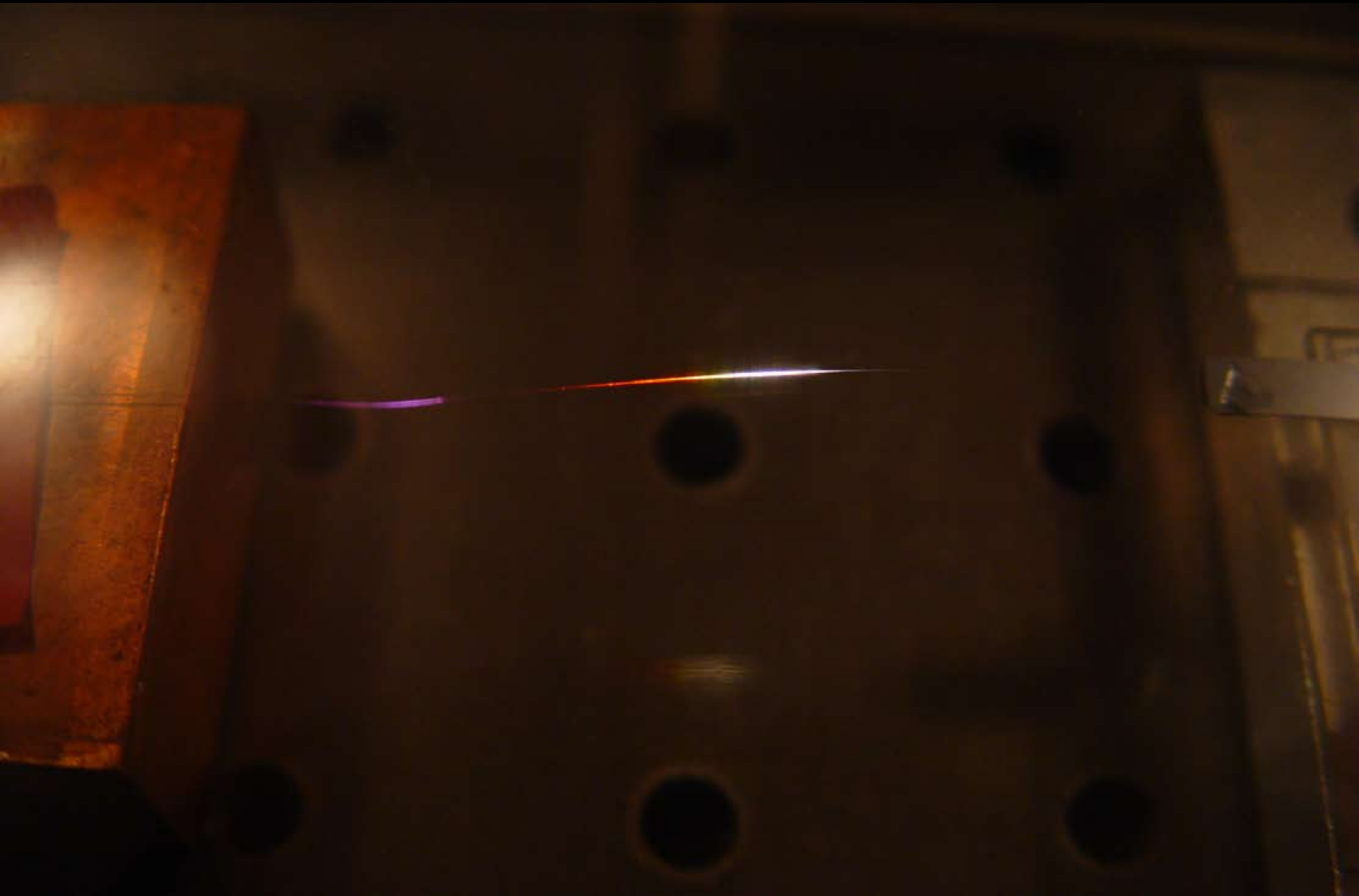


Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



Nonlinear properties



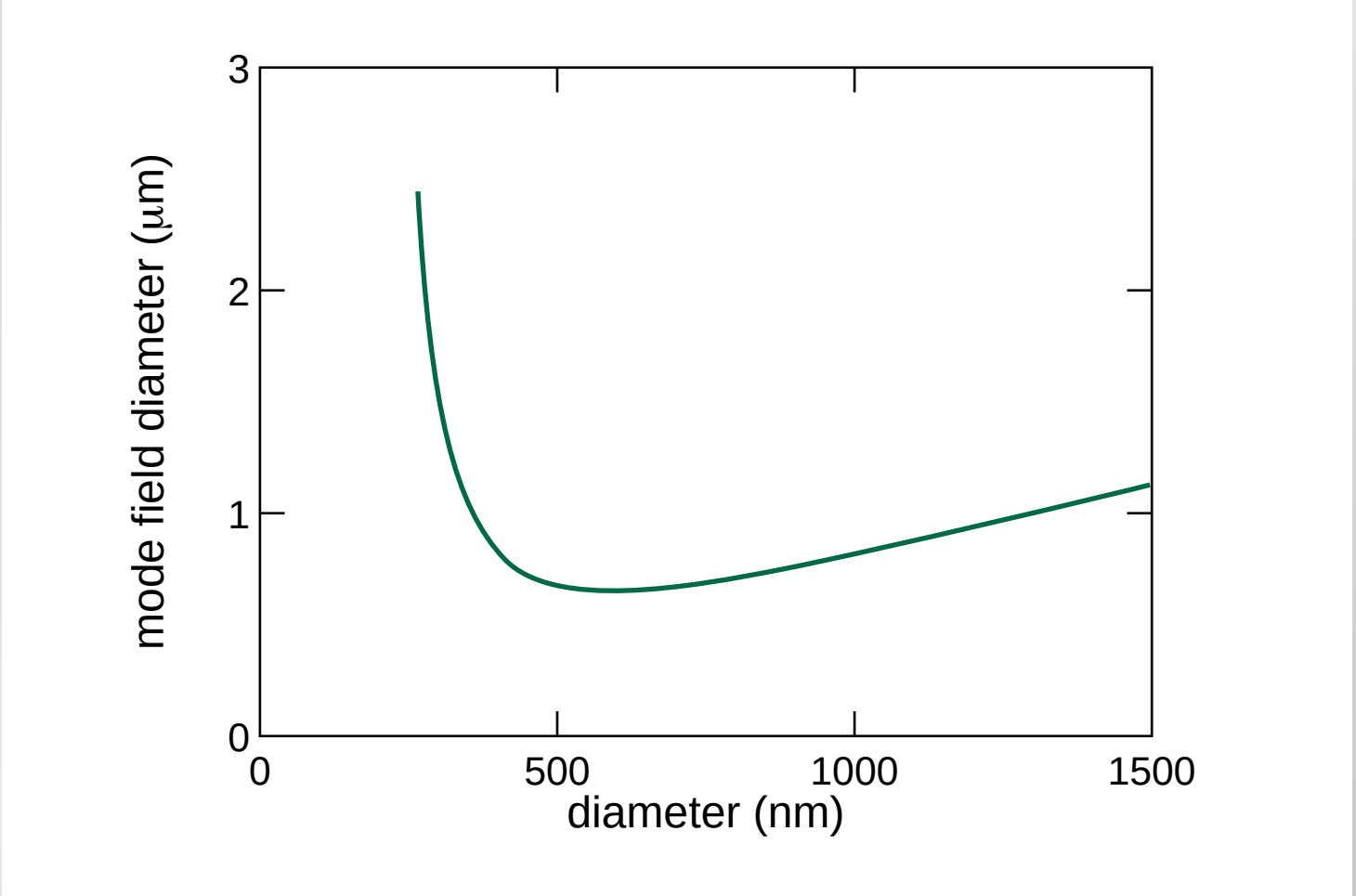
Nonlinear properties

Nonlinear properties

strong confinement $\longrightarrow$ high intensity

Nonlinear properties

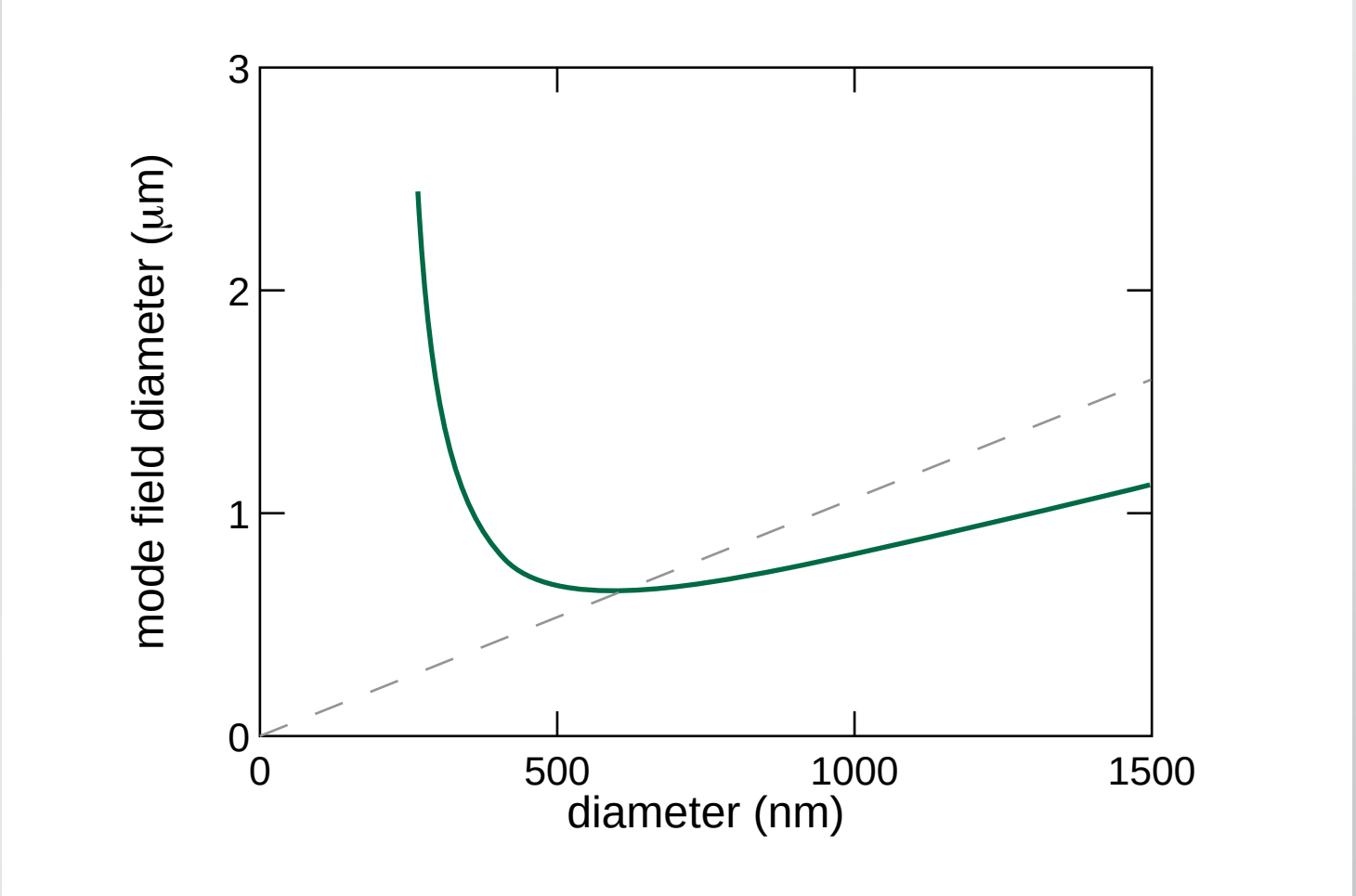
mode field diameter (λ = 800 nm)



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

Nonlinear properties

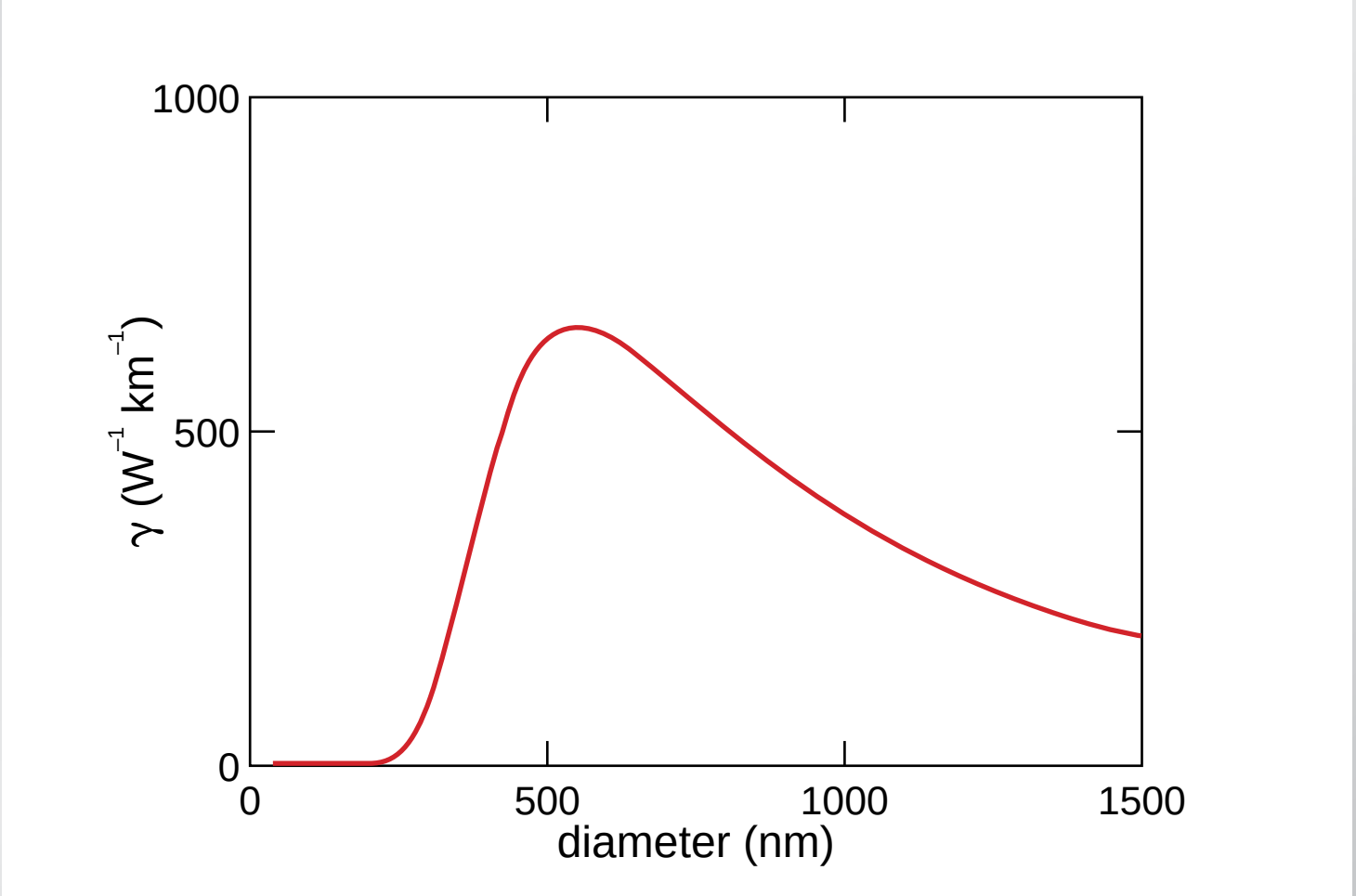
mode field diameter (λ = 800 nm)



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!

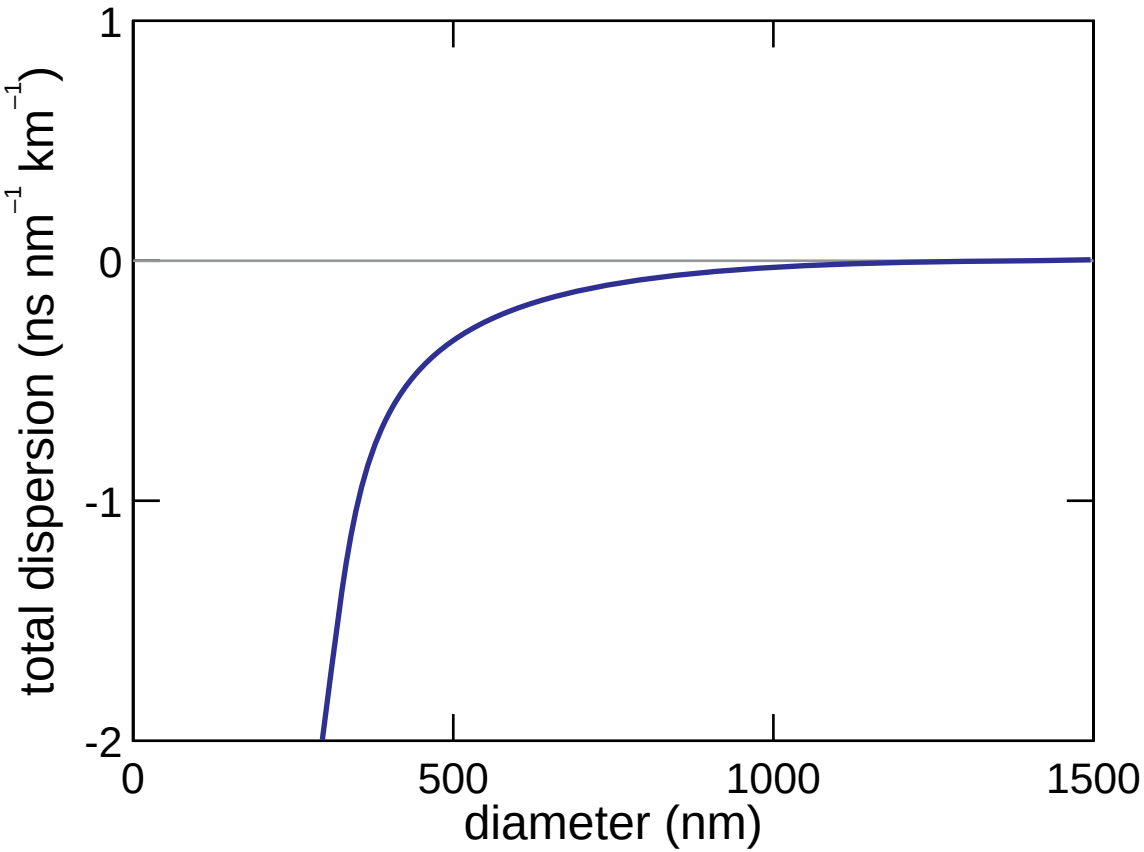
Nonlinear properties

dispersion:

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

Nonlinear properties

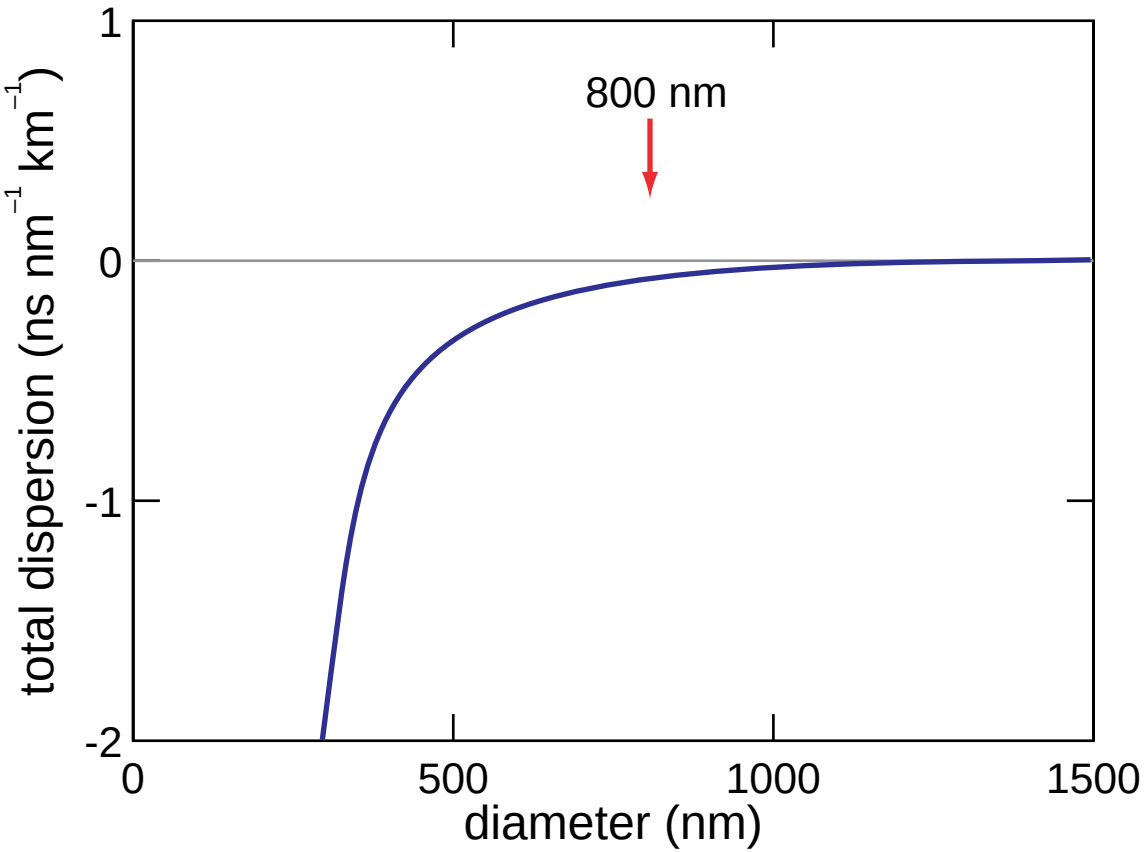
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

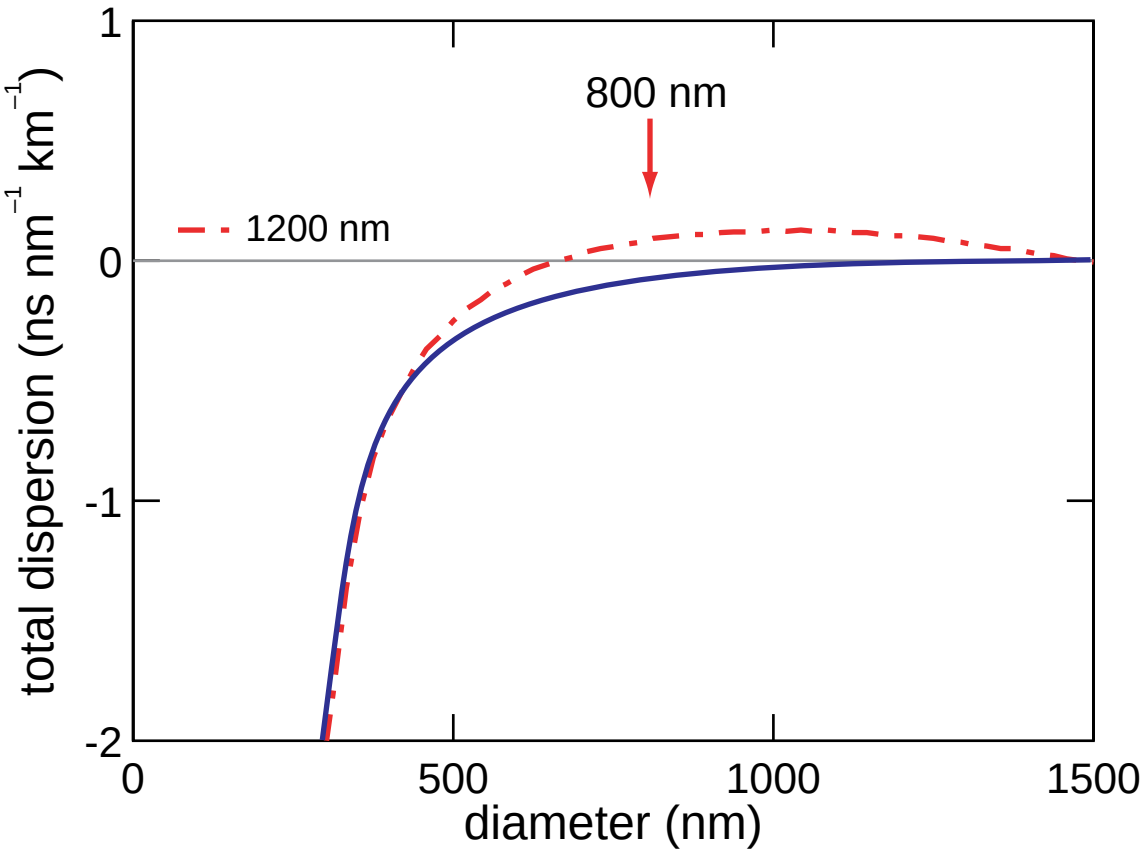
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

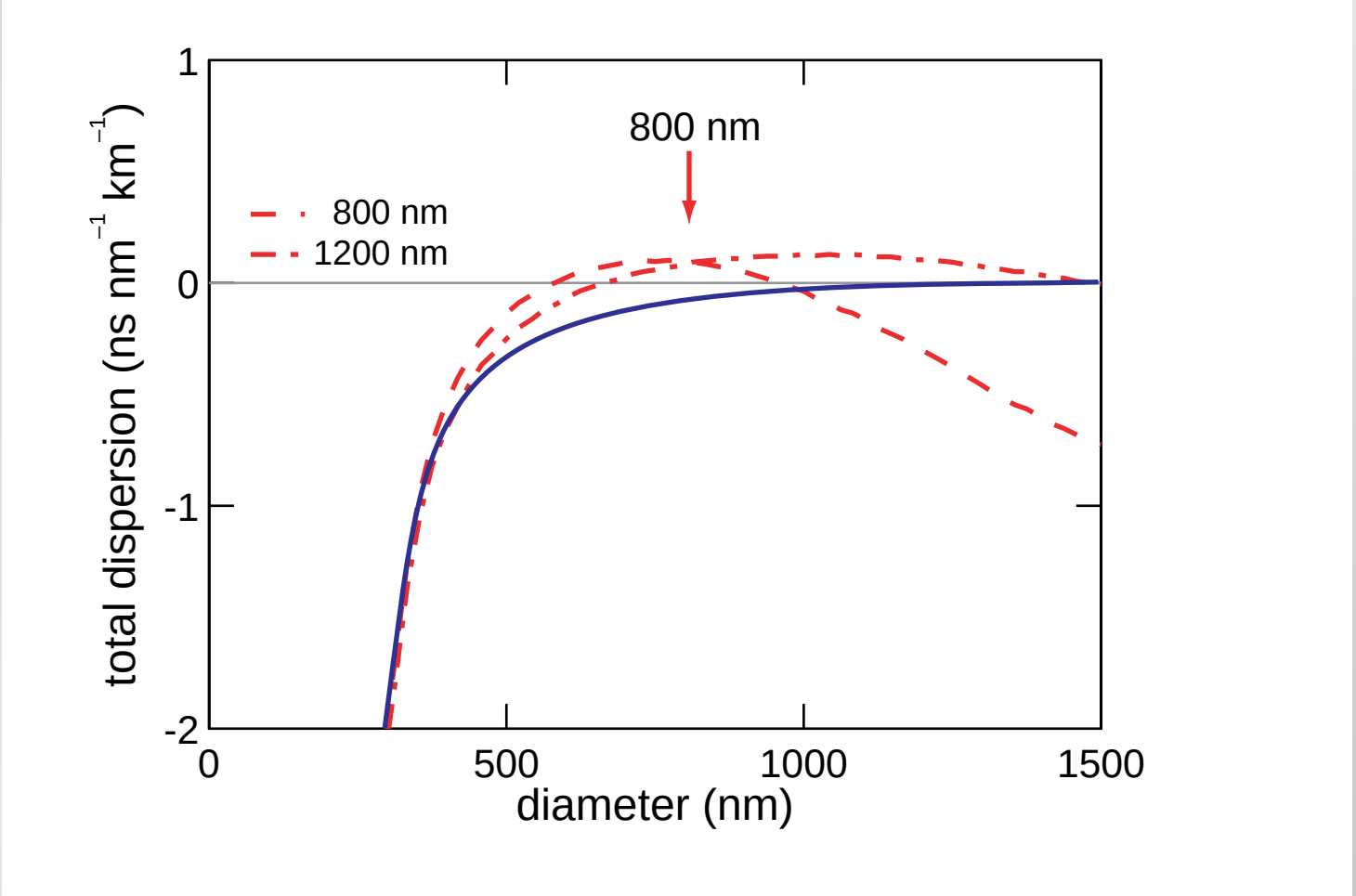
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

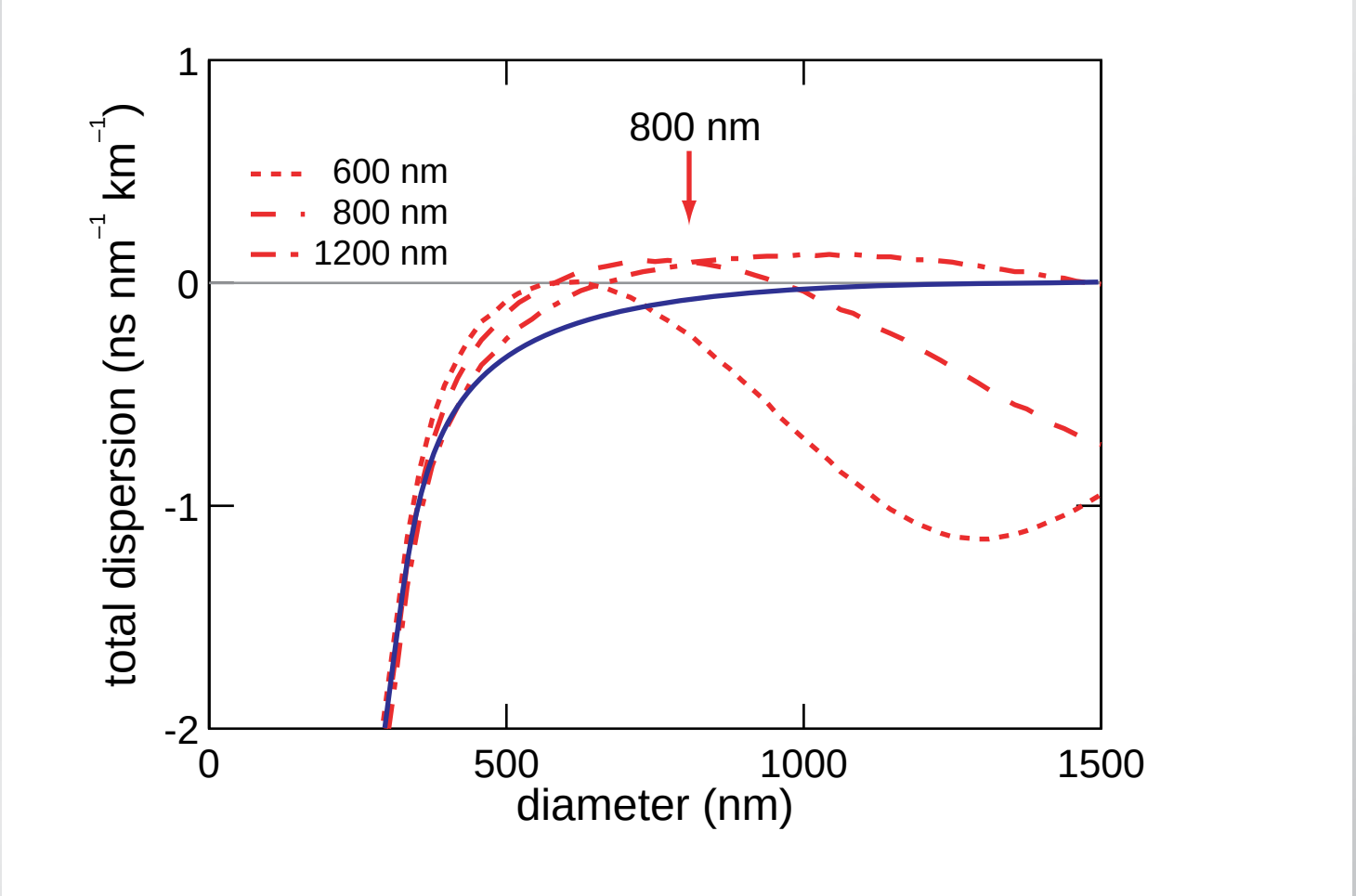
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

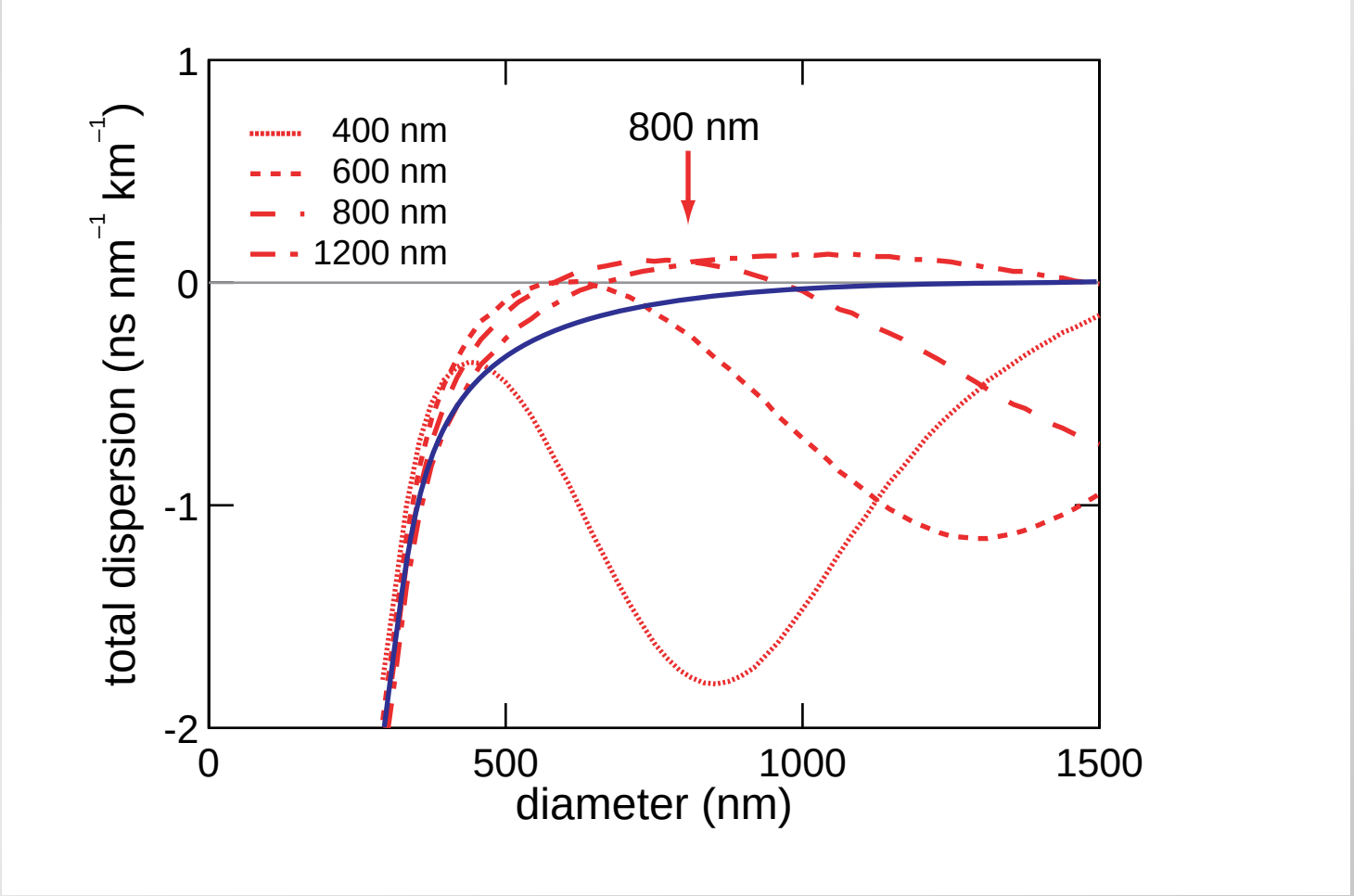
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

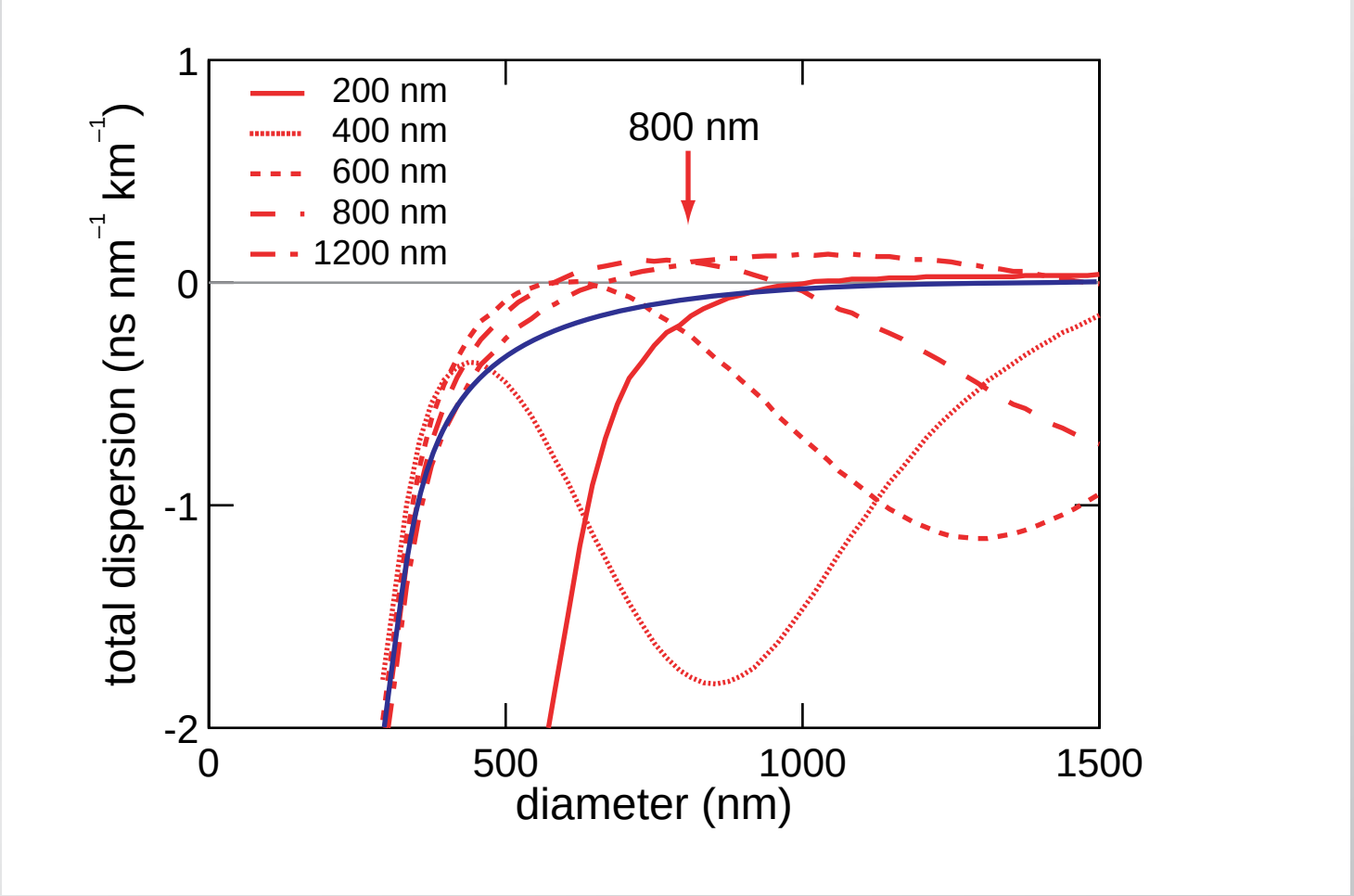
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

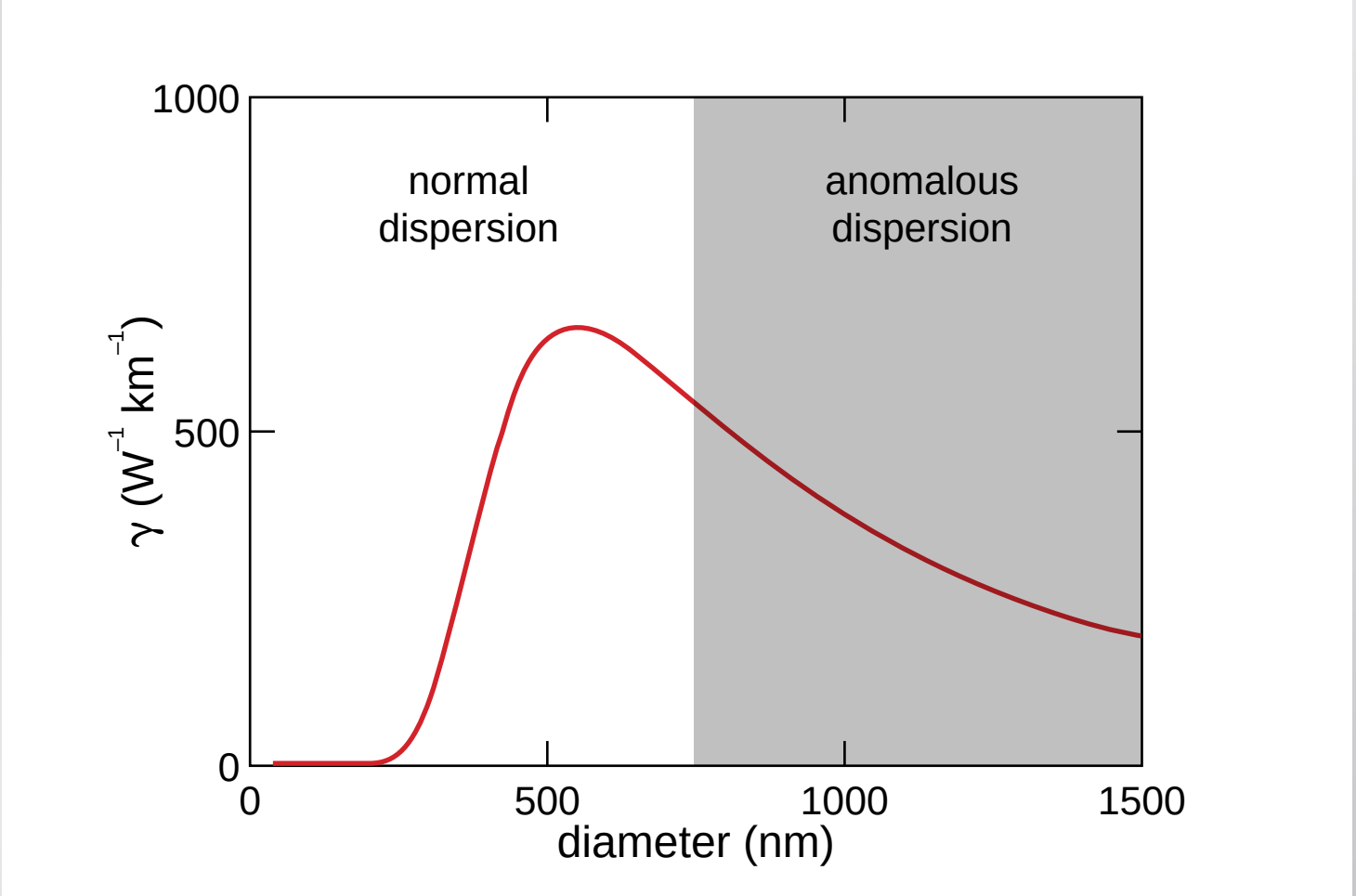
waveguide dispersion



Optics Express, 12, 1025 (2004)

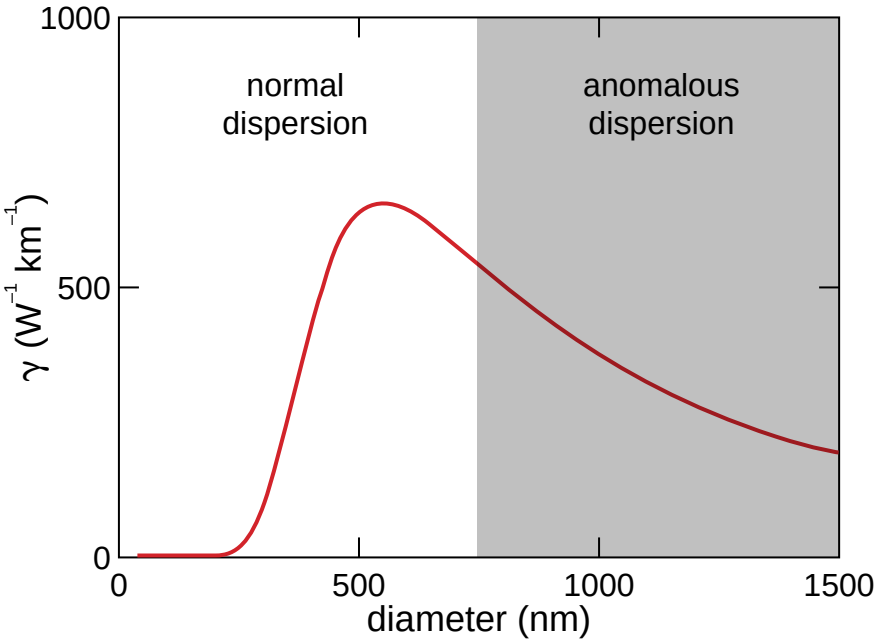
Nonlinear properties

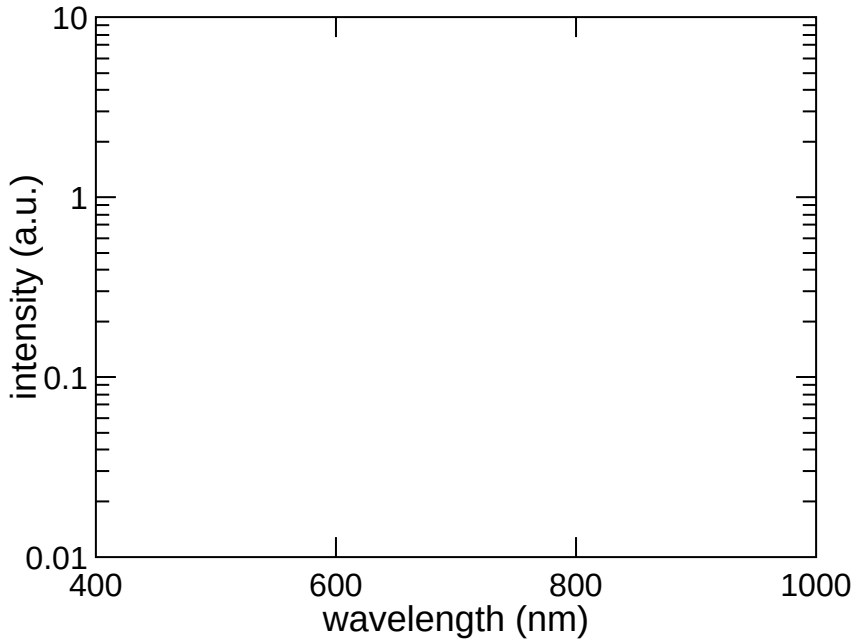
nonlinear parameter



Nonlinear properties

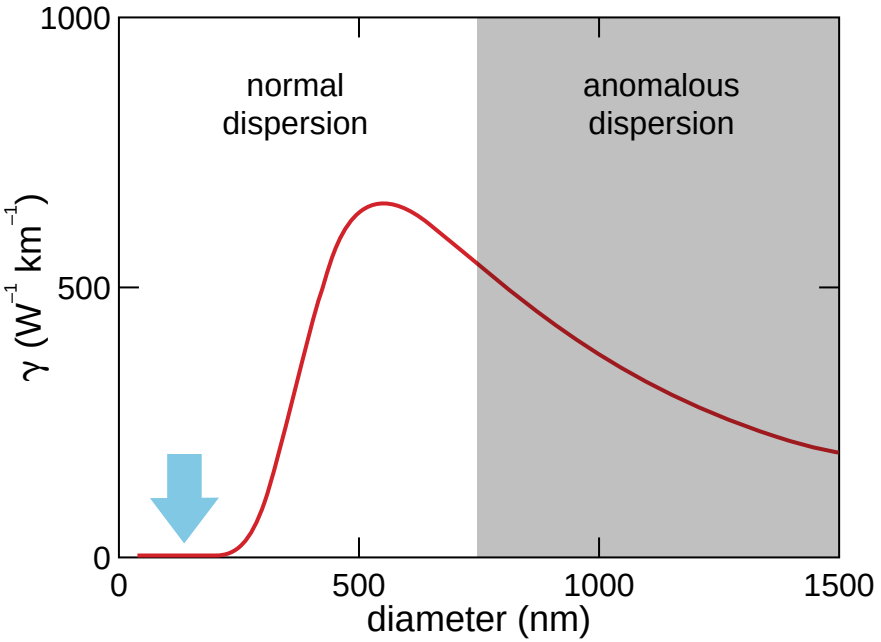
nanowire continuum generation

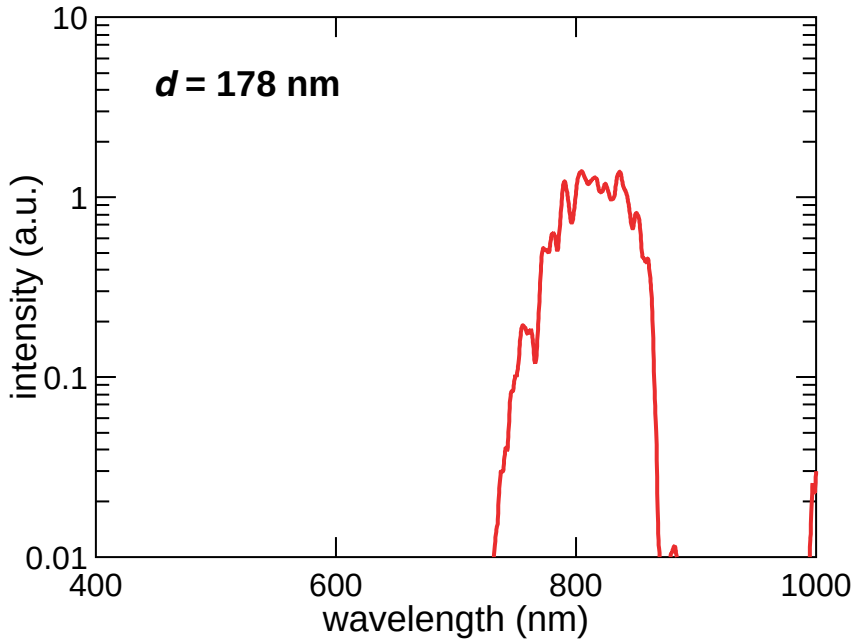




Nonlinear properties

nanowire continuum generation





Nonlinear properties

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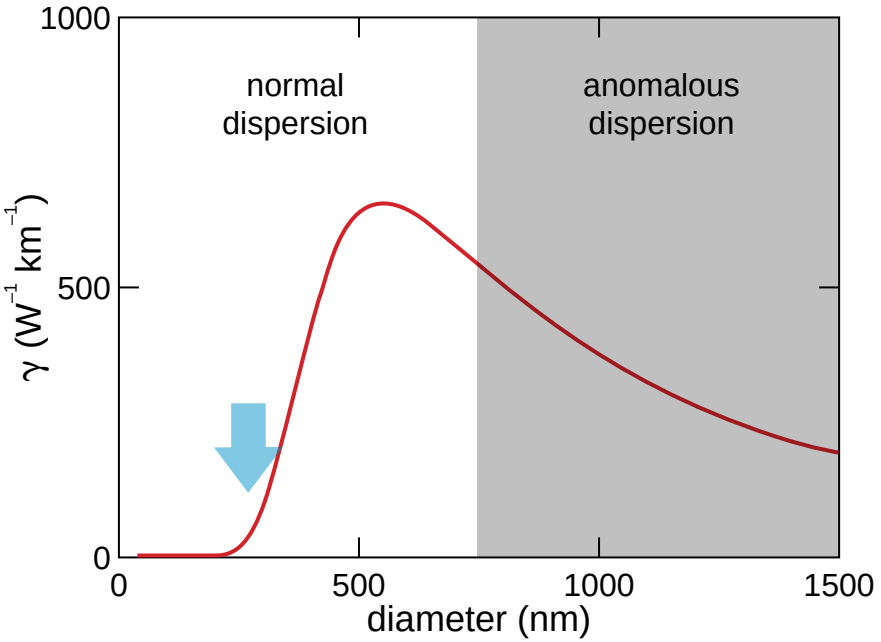
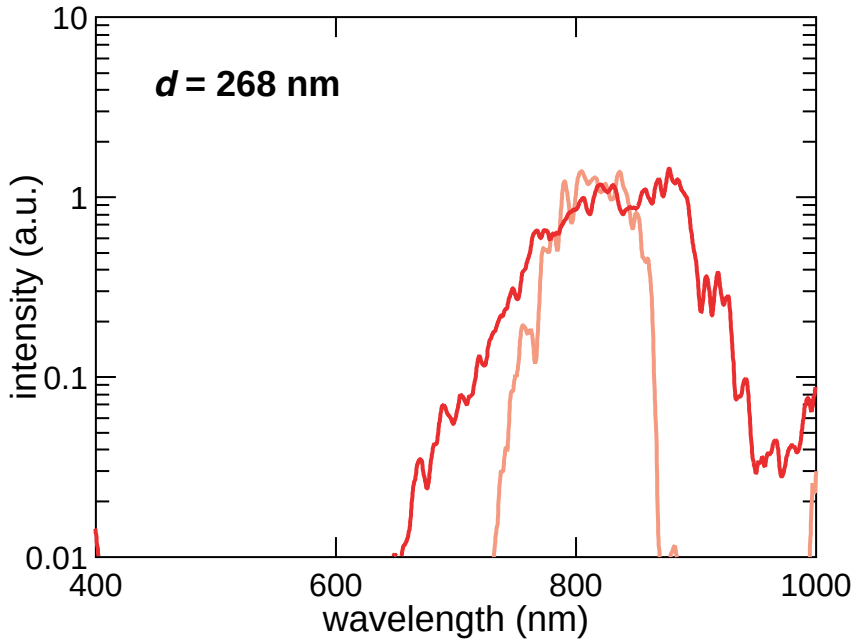
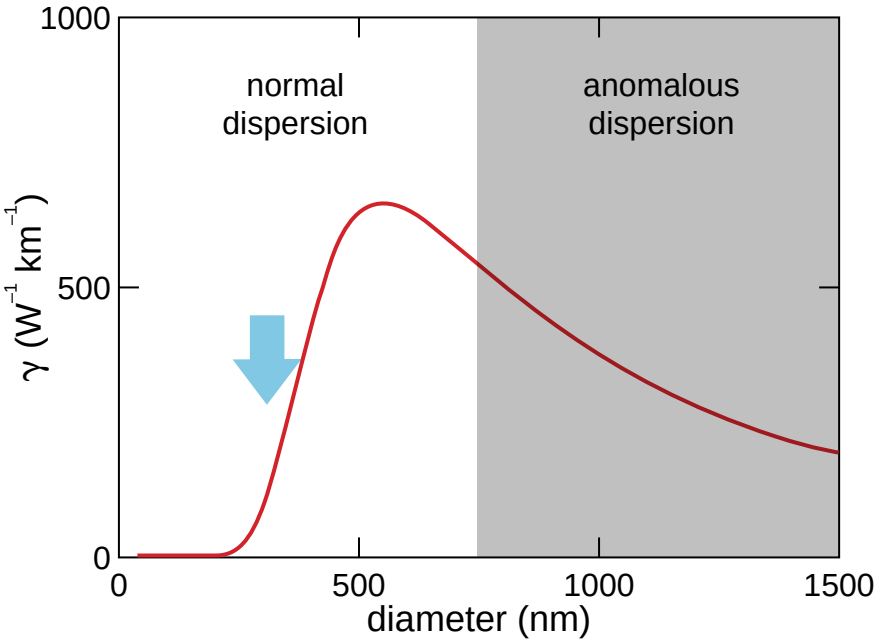
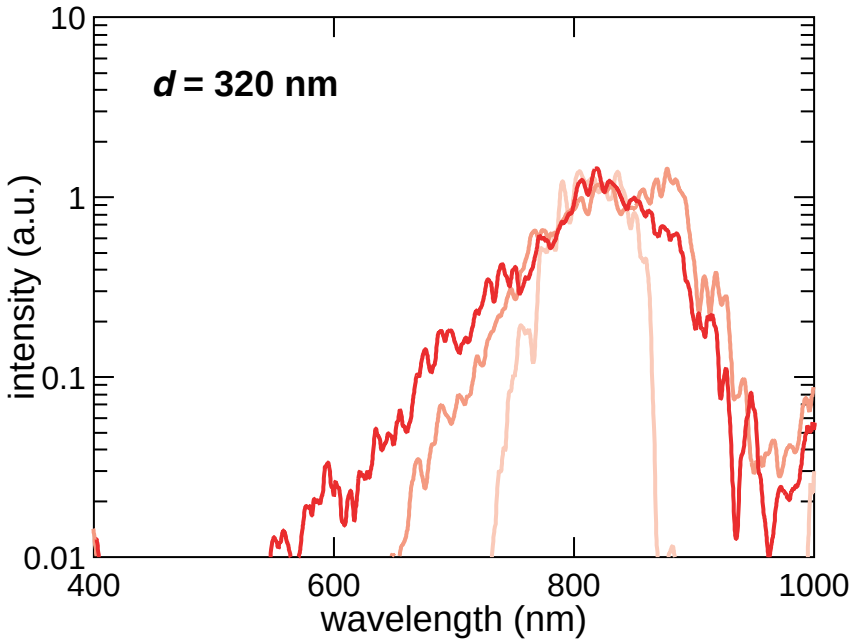




Nonlinear properties

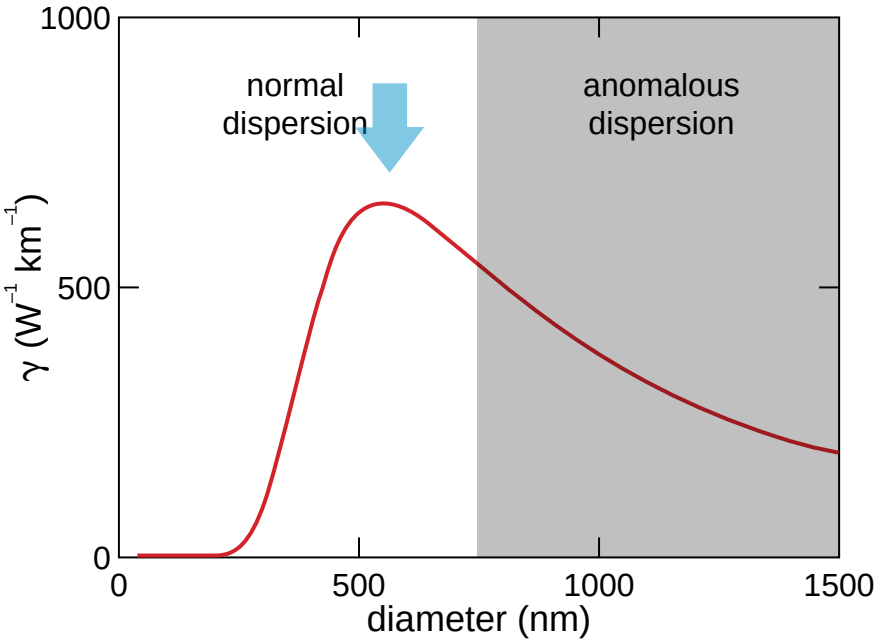
nanowire continuum generation

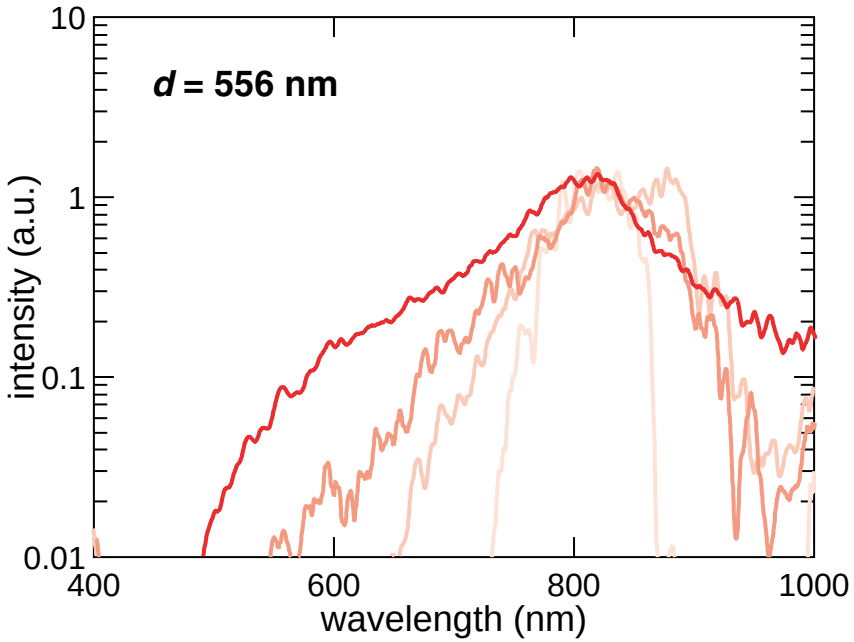




Nonlinear properties

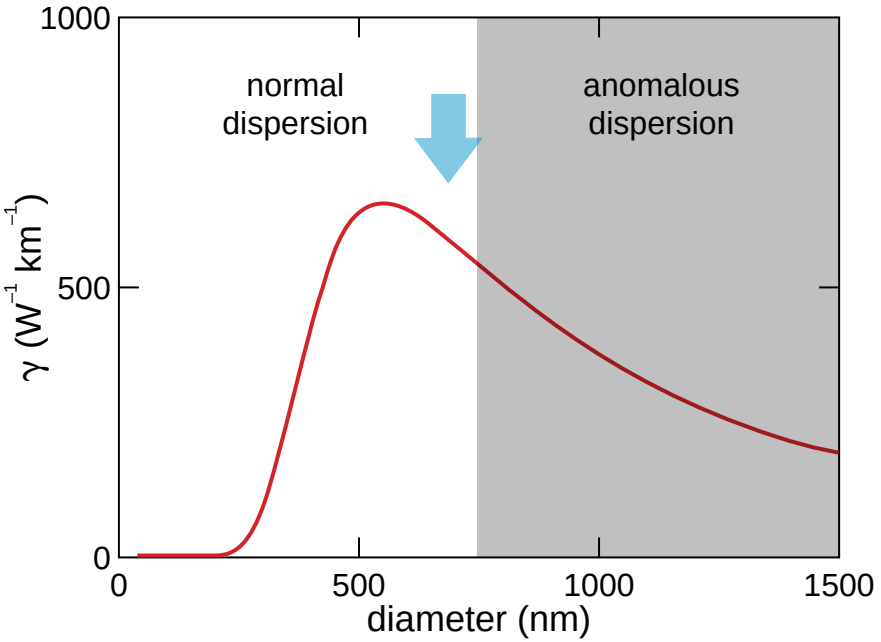
nanowire continuum generation

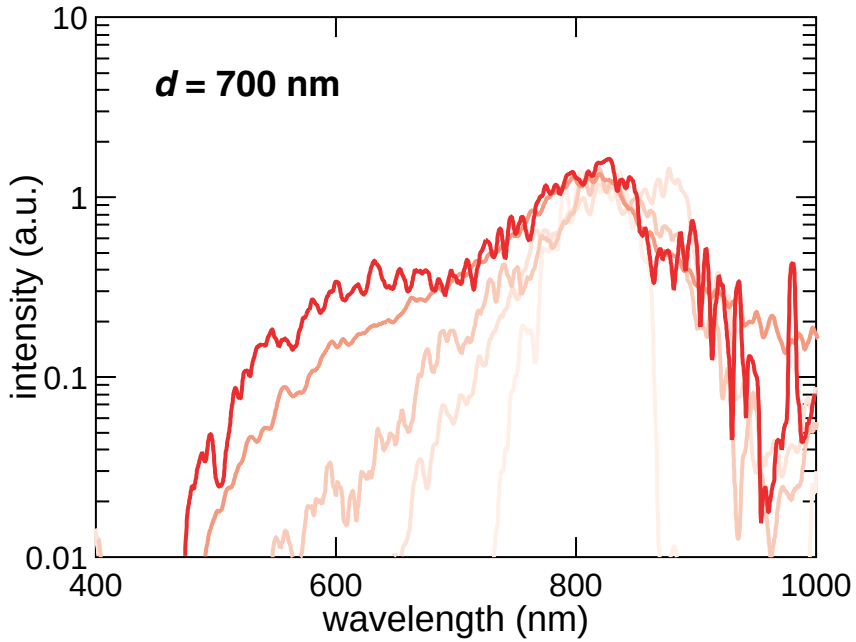




Nonlinear properties

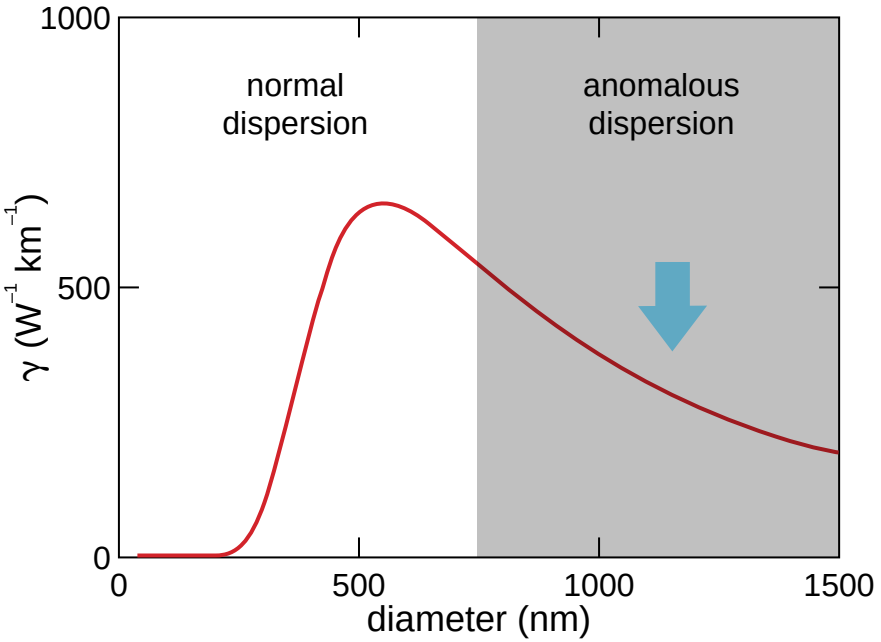
nanowire continuum generation

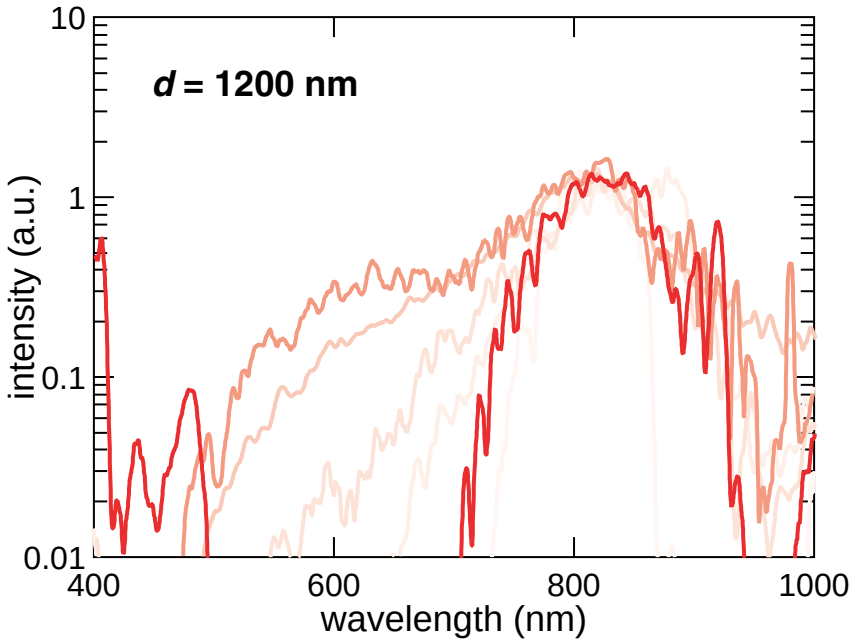




Nonlinear properties

nanowire continuum generation

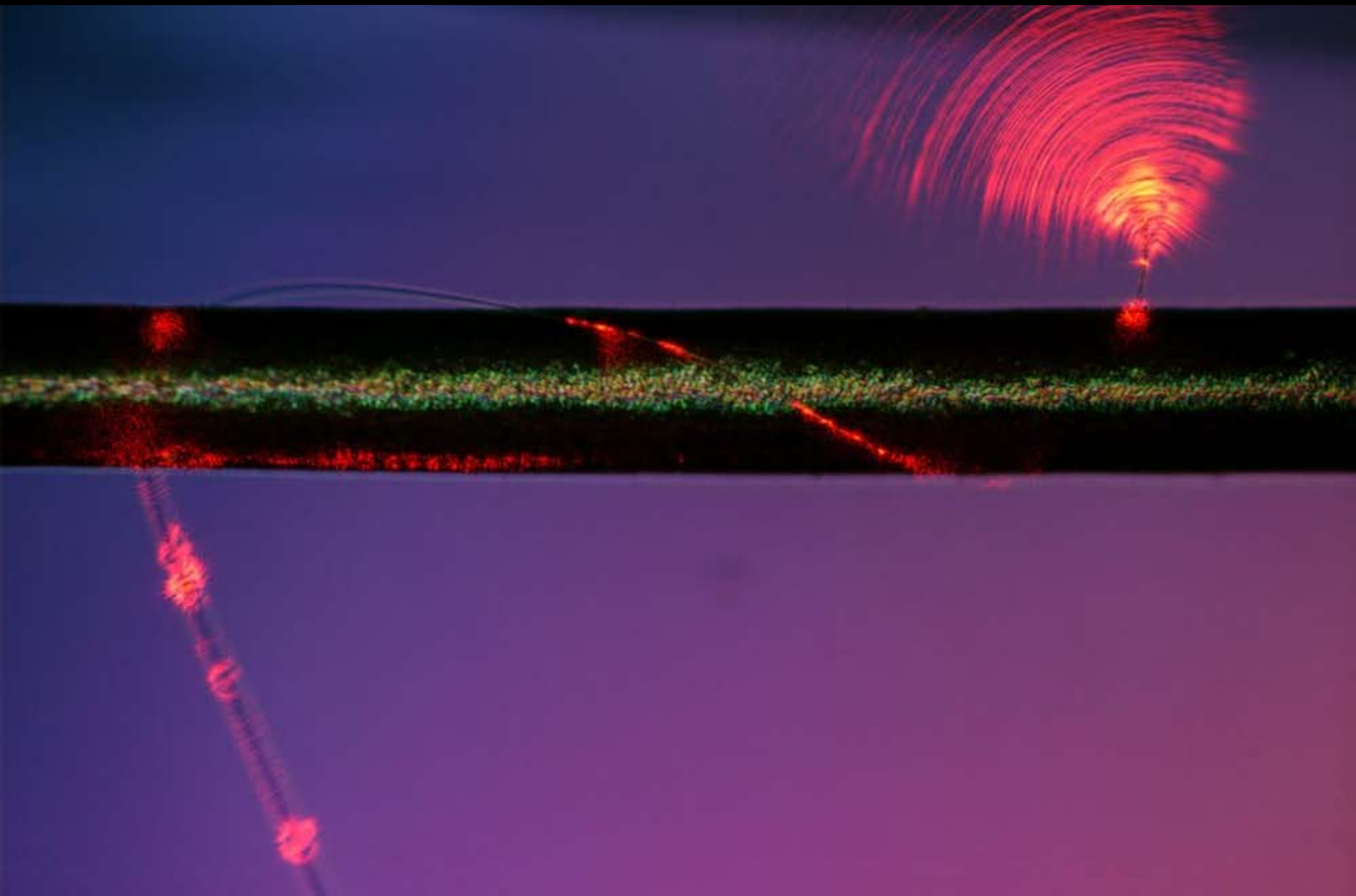




Nonlinear properties

energy in nanowire < 100 pJ!

Summary



Summary

- nanotechnology on a nanobudget

Summary

- nanotechnology on a nanobudget
- submicrometer confinement

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

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