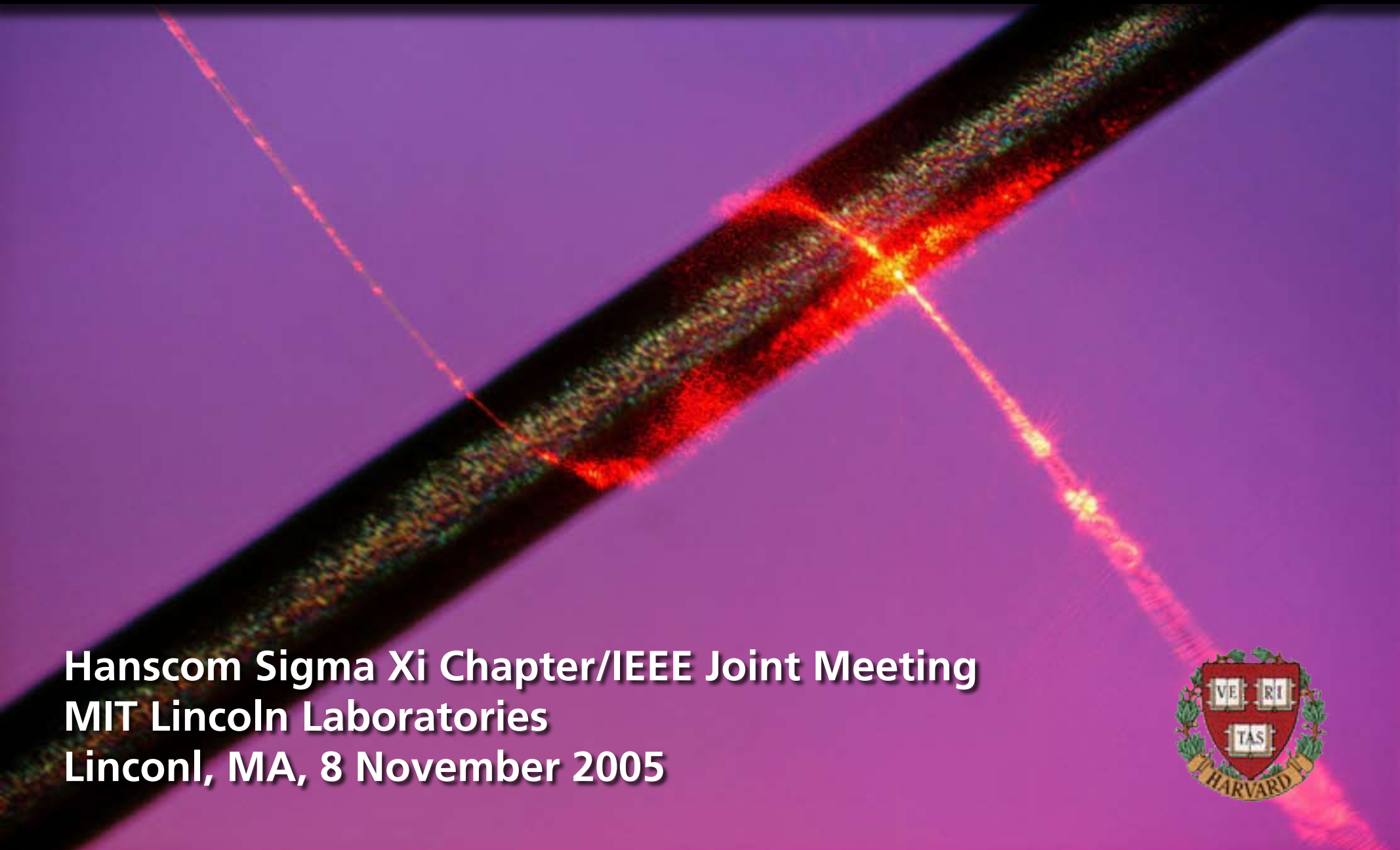
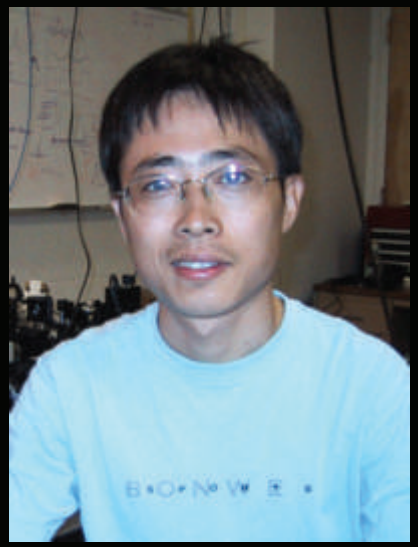
Wrapping light around a hair: silica nanowires for optical components



Hanscom Sigma Xi Chapter/IEEE Joint Meeting
MIT Lincoln Laboratories
Linconl, MA, 8 November 2005



Limin Tong

Rafael Gattass

Geoff Svacha

Eric Mazur

and also....

at Harvard:

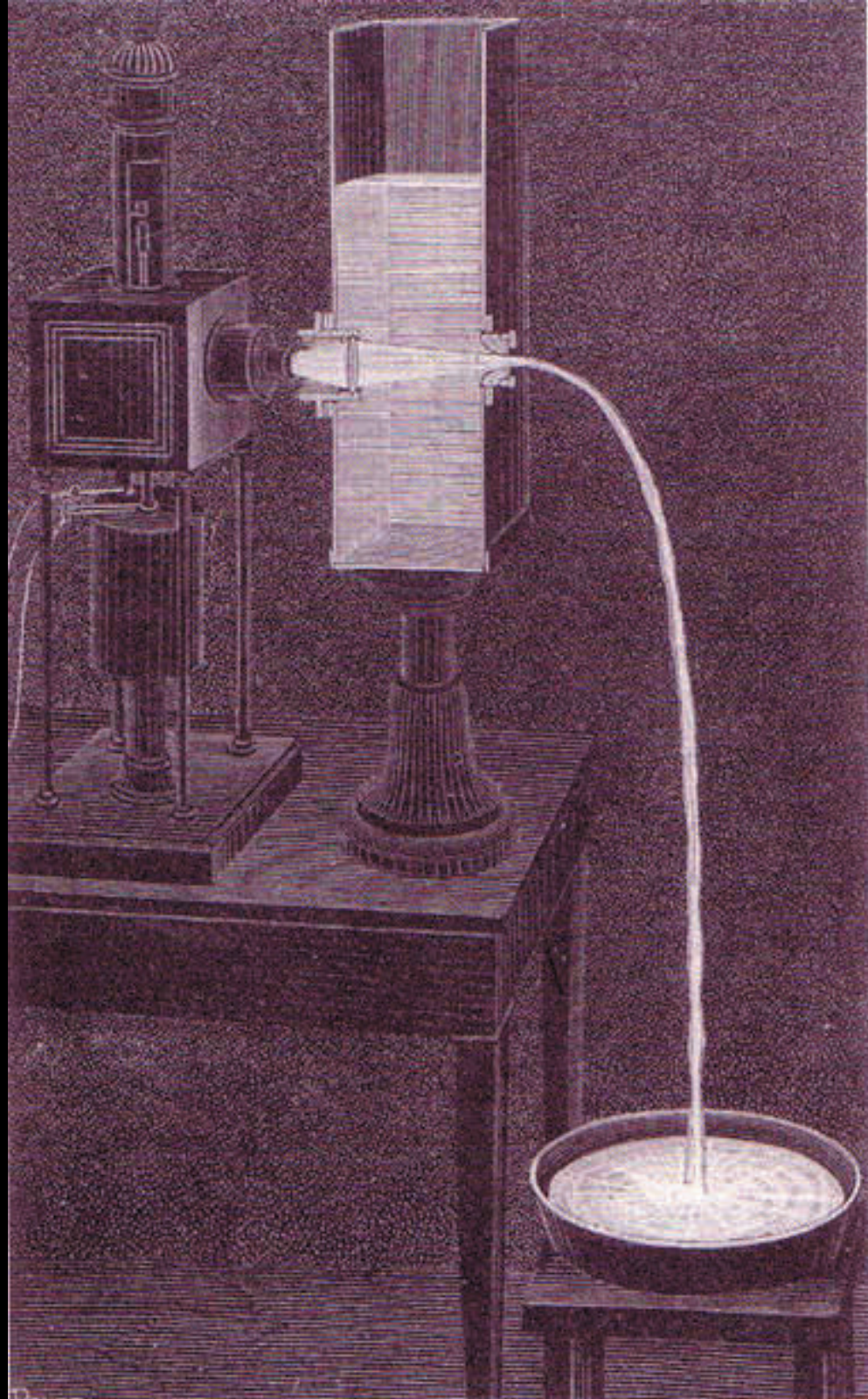
Jonathan Aschom
Mengyan Shen
Iva Maxwell
James Carey
Brian Tull
Dr. Yuan Lu
Dr. Richard Schalek
Prof. Federico Capasso
Prof. Cynthia Friend

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)

"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.

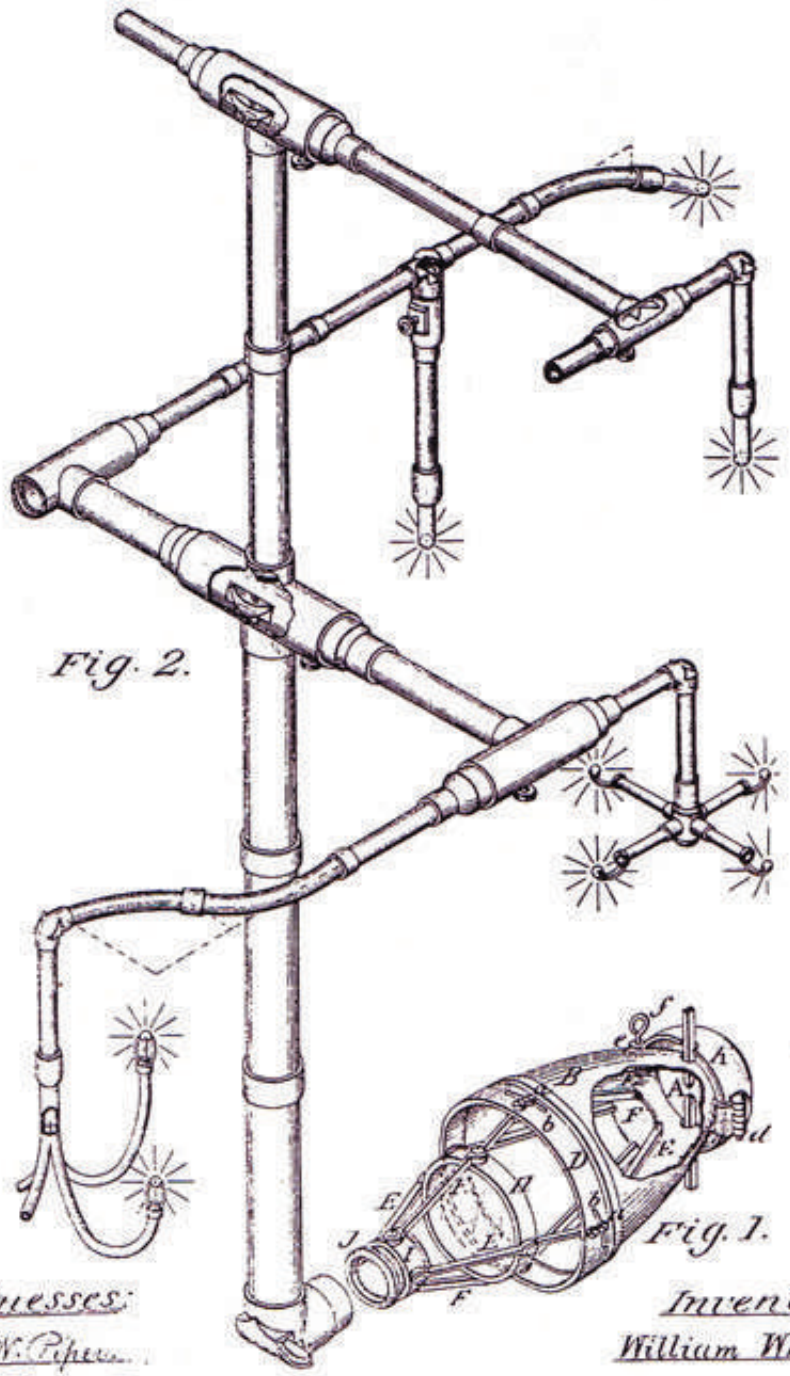


Fig. 2.

Fig. 1.

Witnesses:
A. W. Pipes.

Inventor:
William Wheeler
by attorney

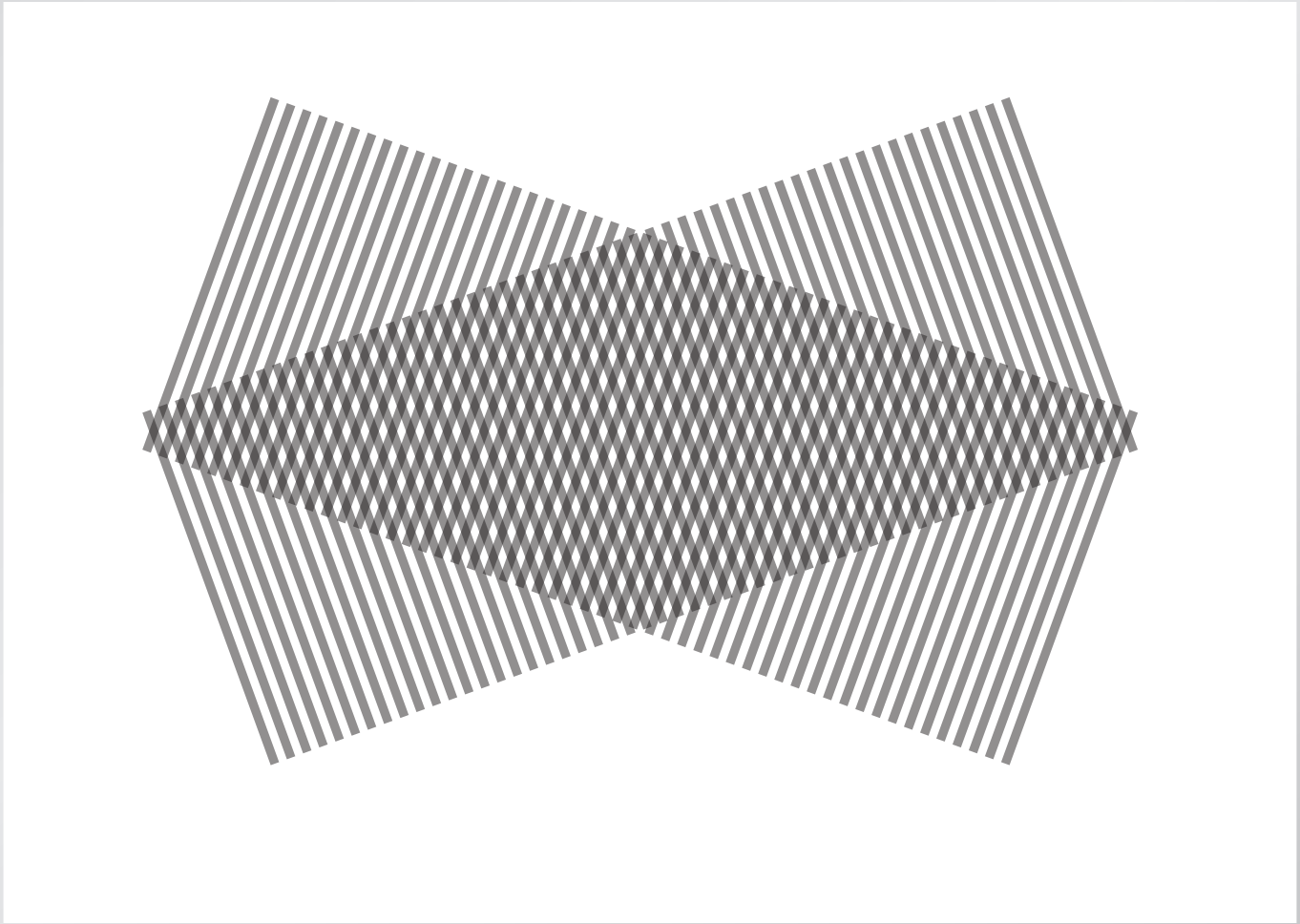
US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

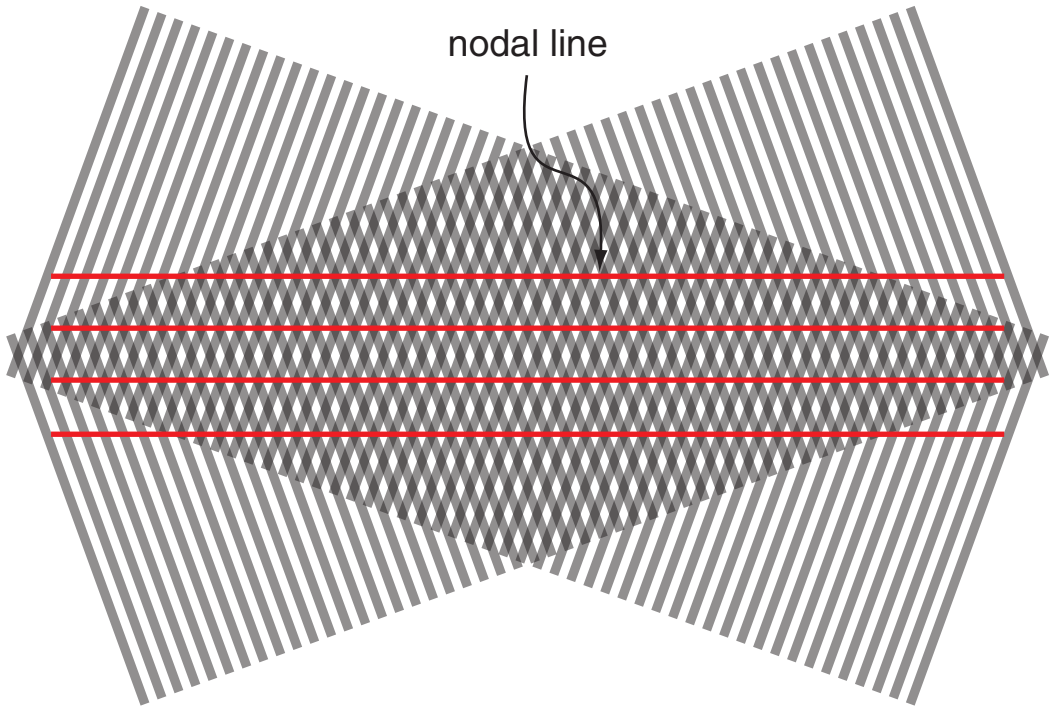
Waveguiding

two crossed planar waves…



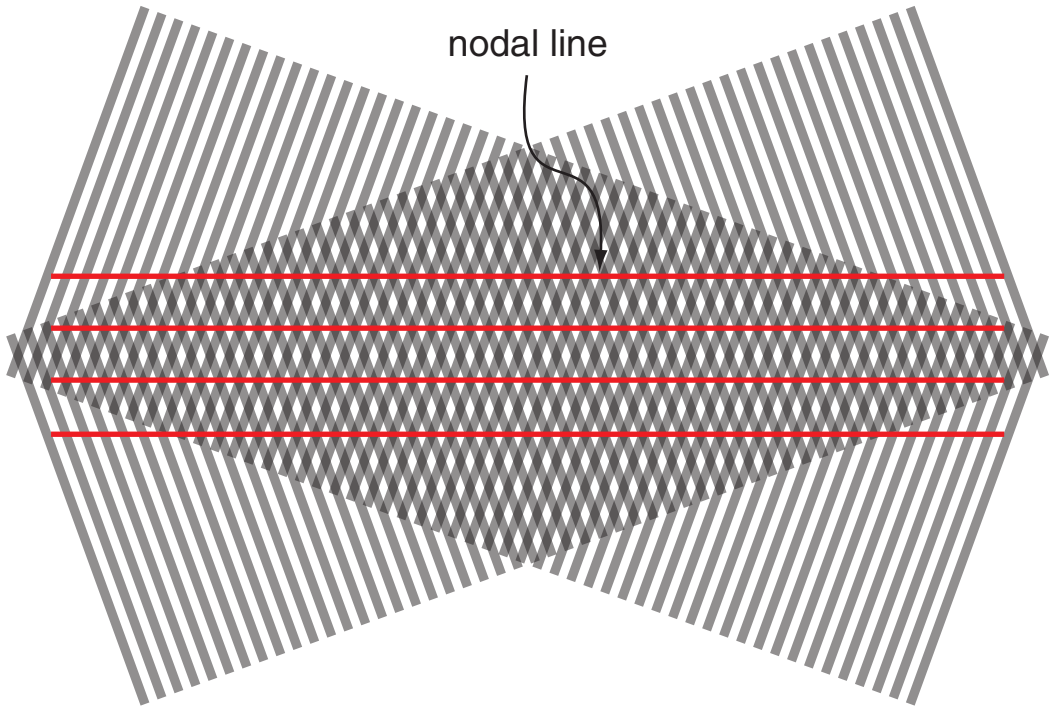
Waveguiding

…cause an interference pattern



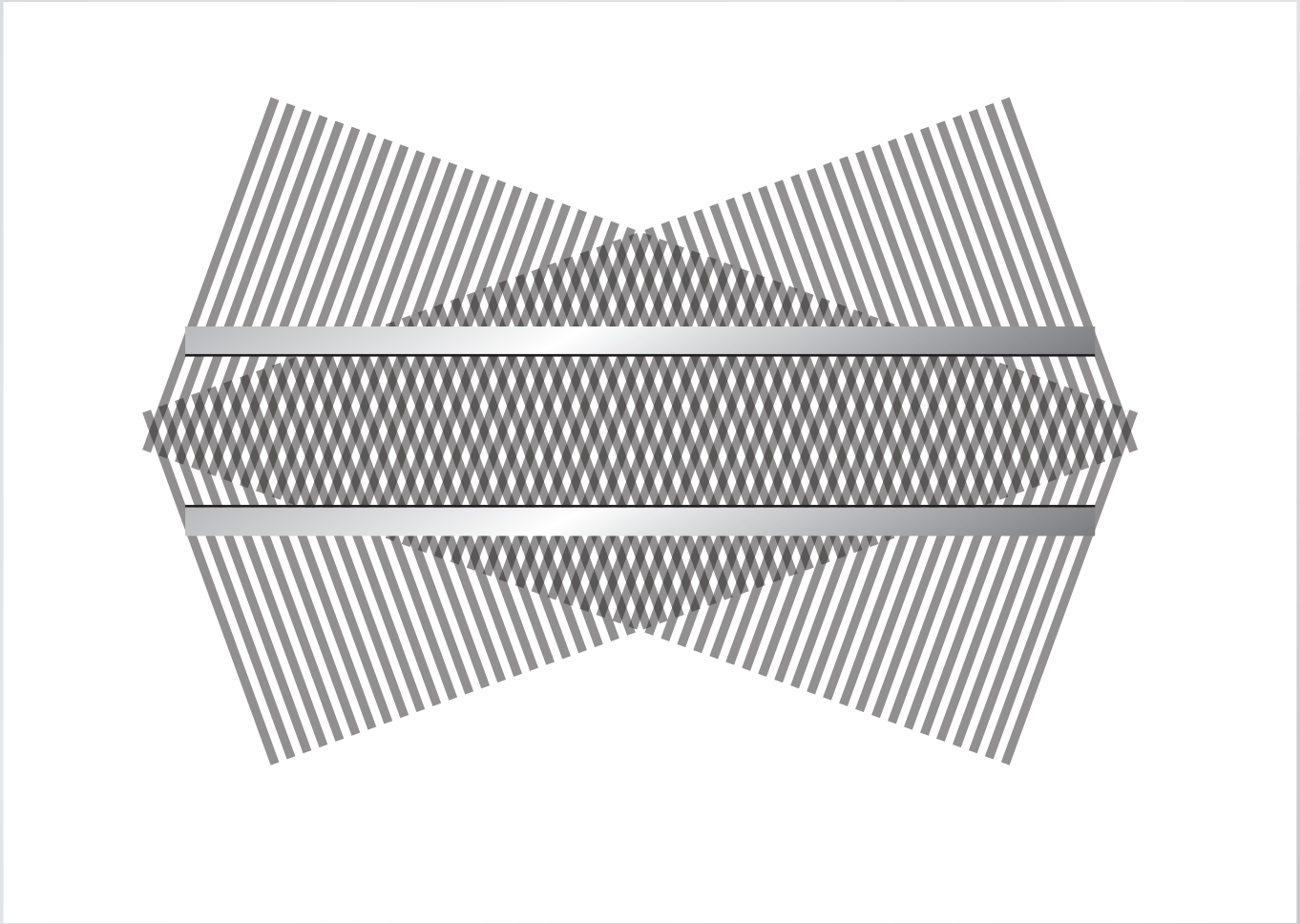
Waveguiding

$E = 0$ **on the nodal lines**



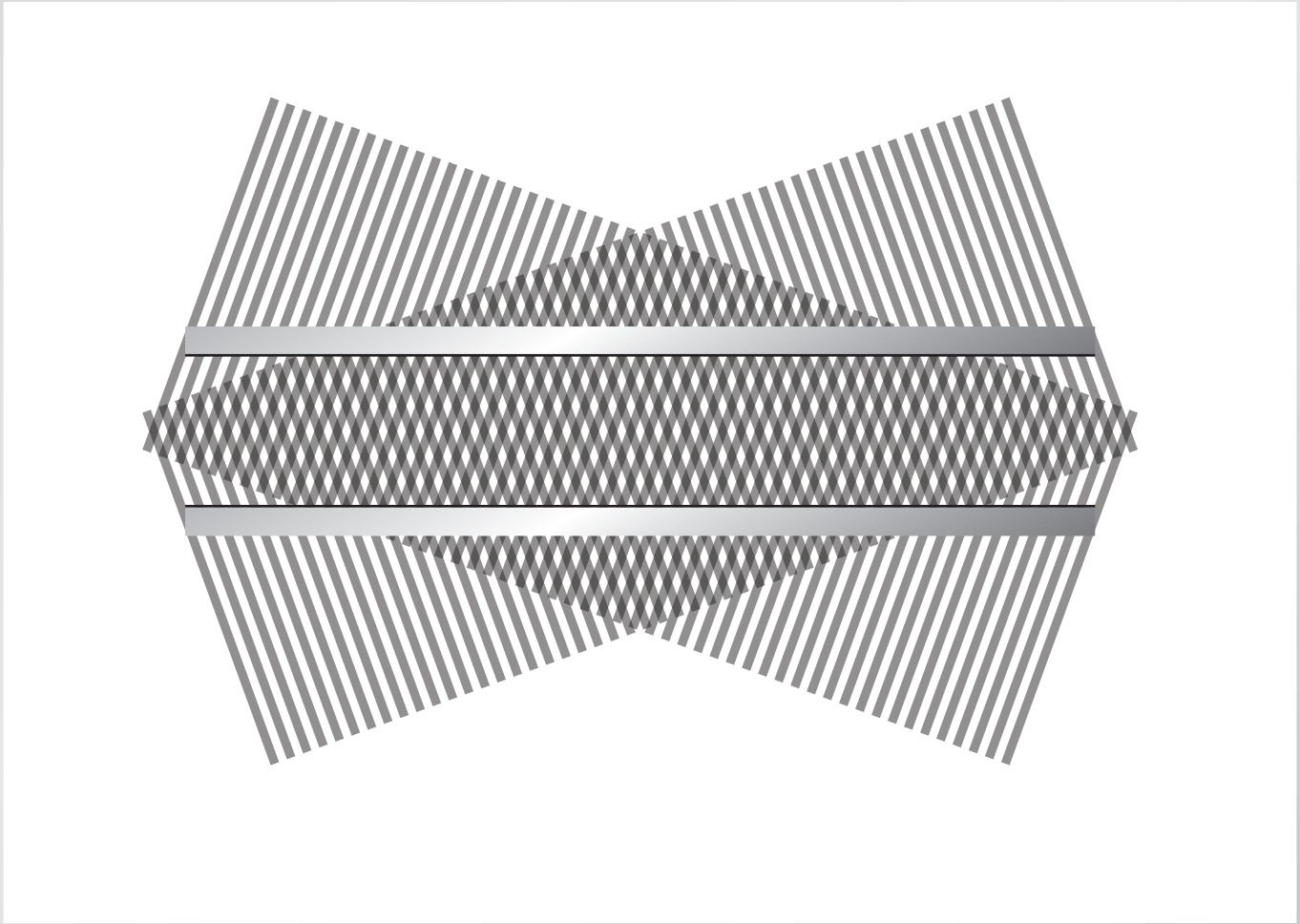
Waveguiding

…satisfying boundary conditions for planar-mirror waveguide



Waveguiding

transverse standing wave, traveling along axis



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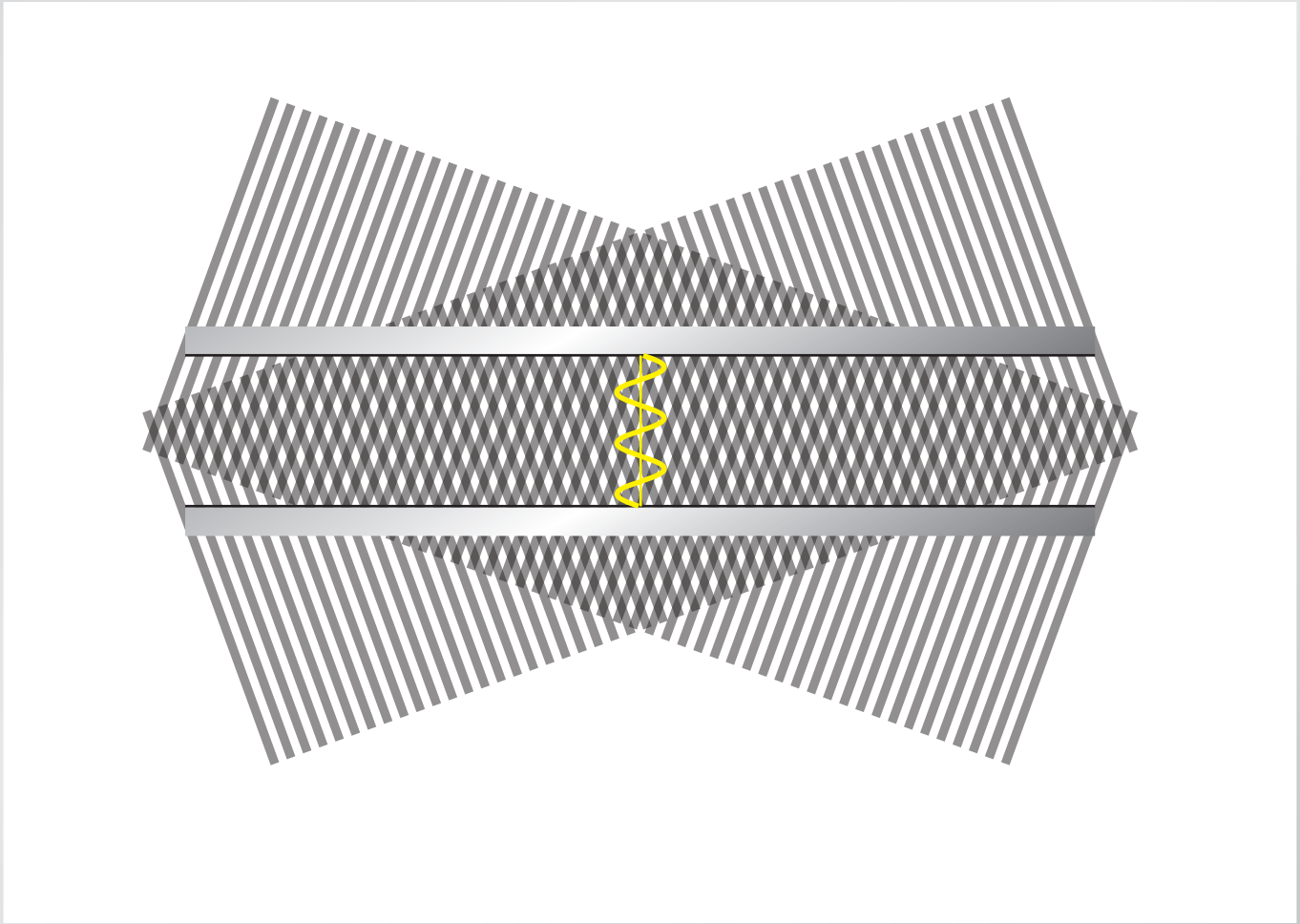
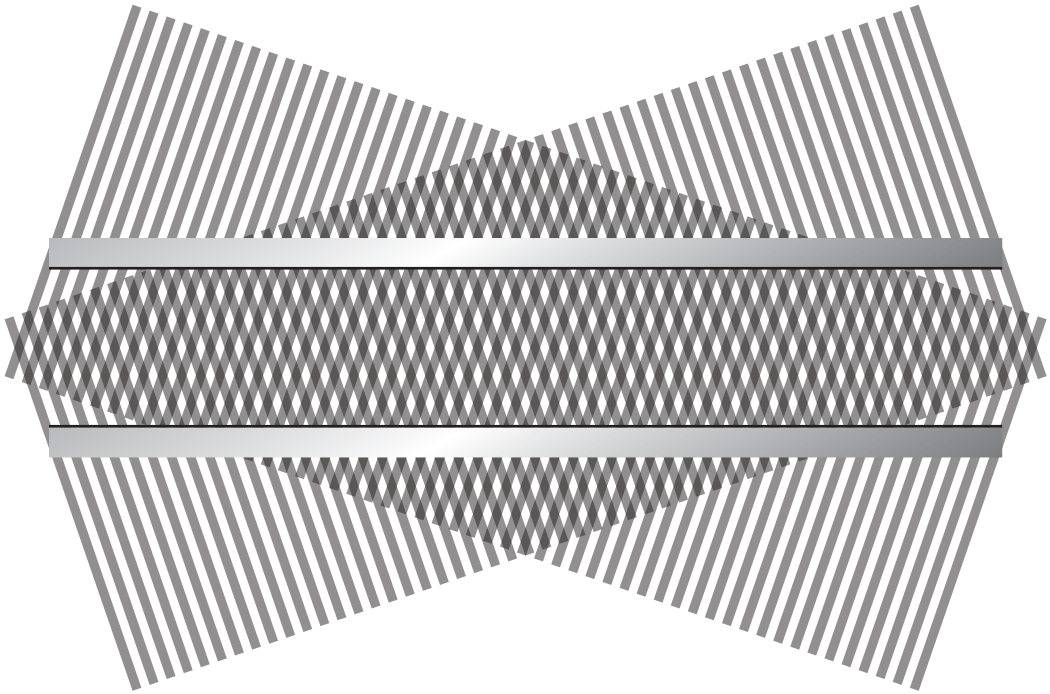


Waveguiding

change angle of incident waves…



Waveguiding

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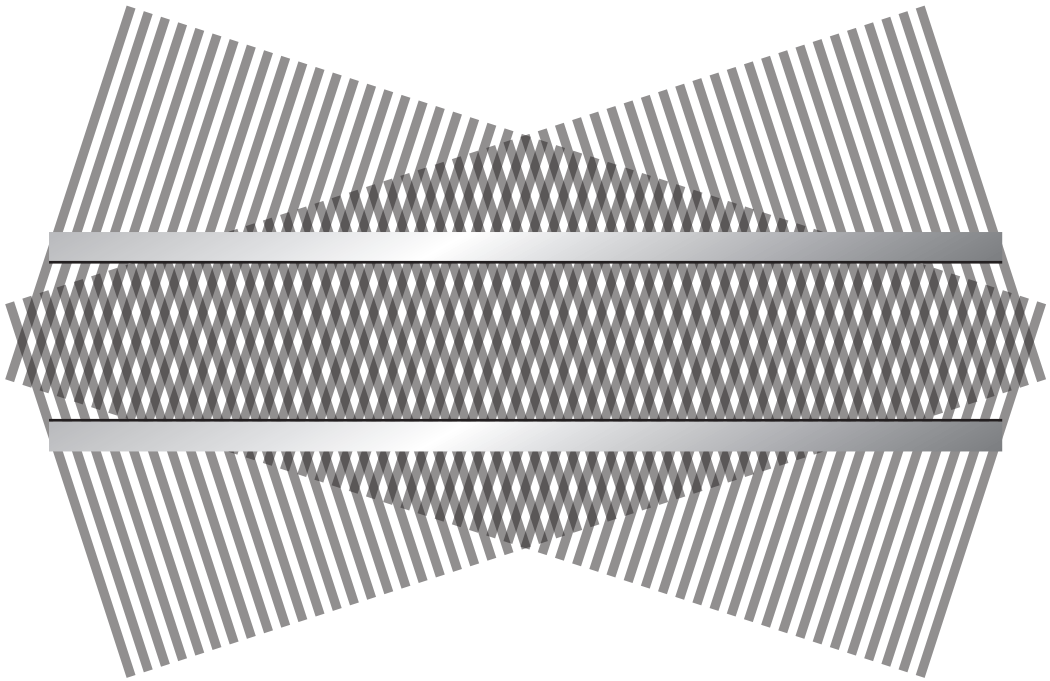

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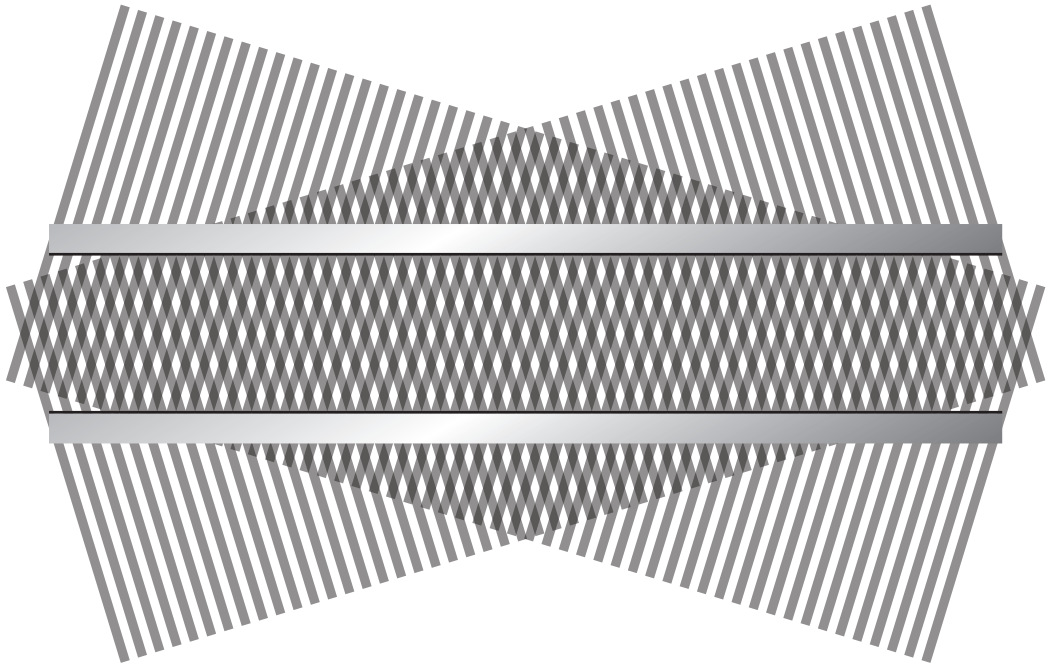

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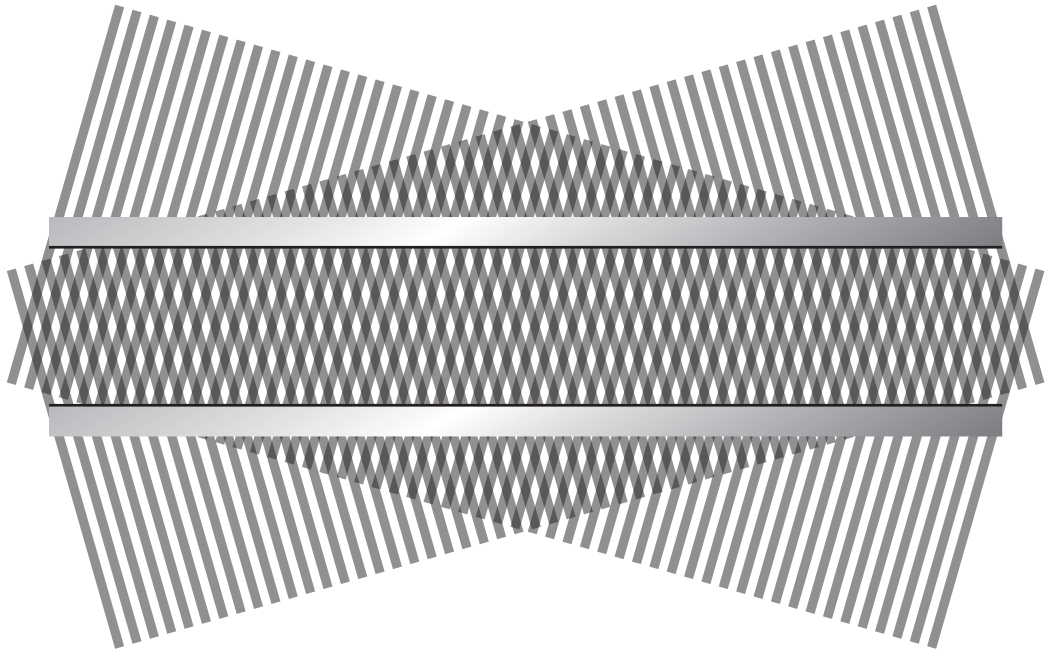

Waveguiding

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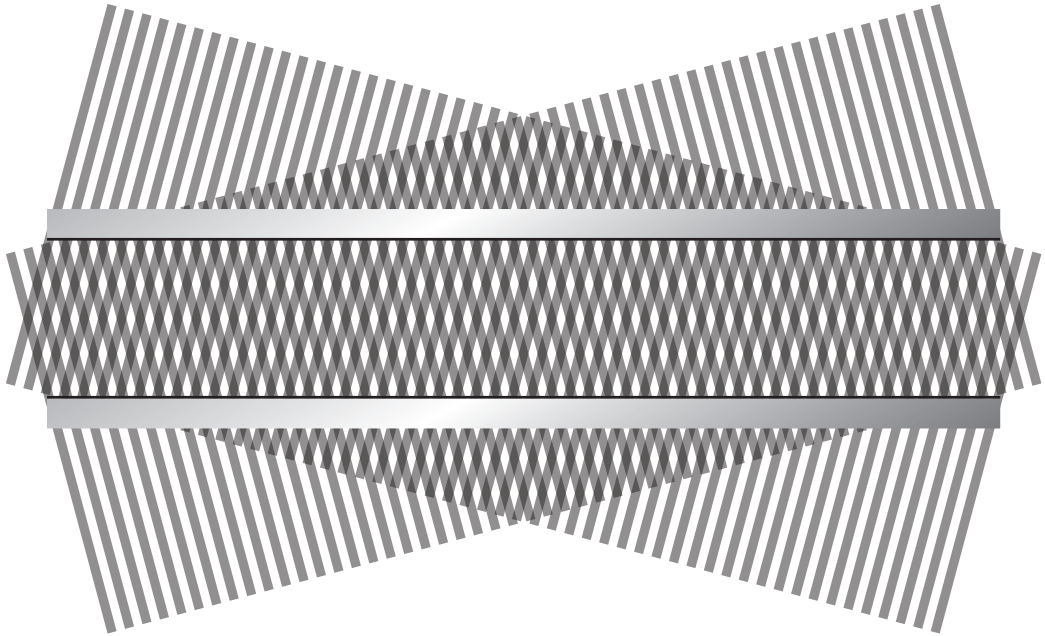

Waveguiding

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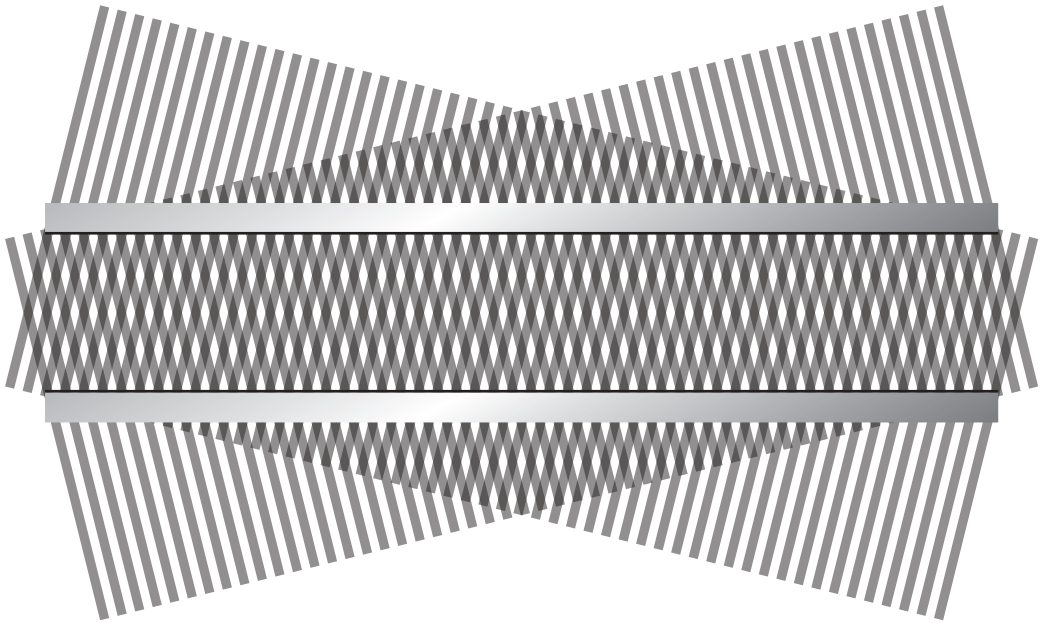

Waveguiding

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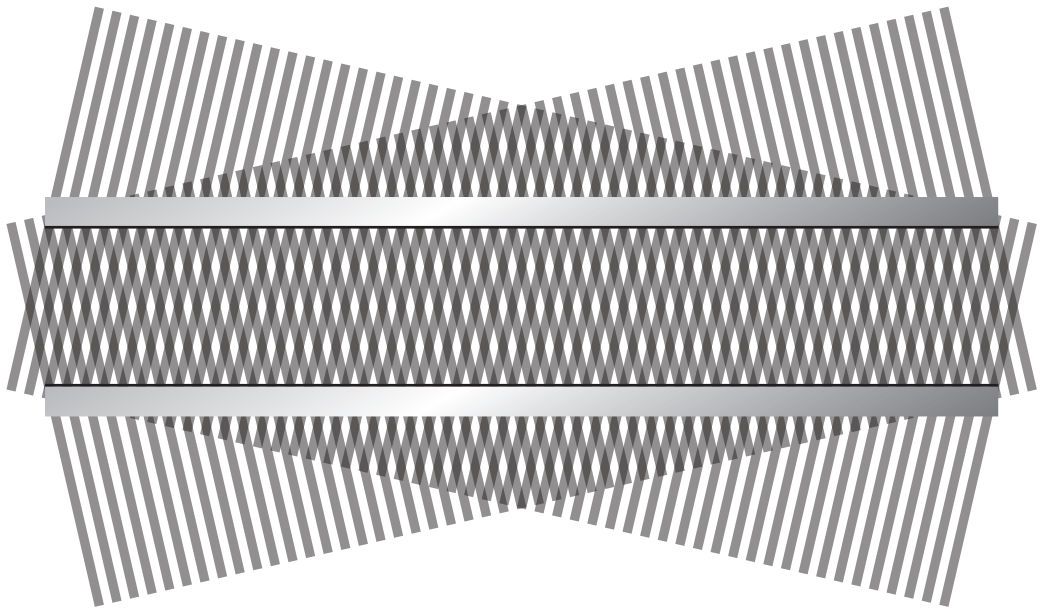

Waveguiding

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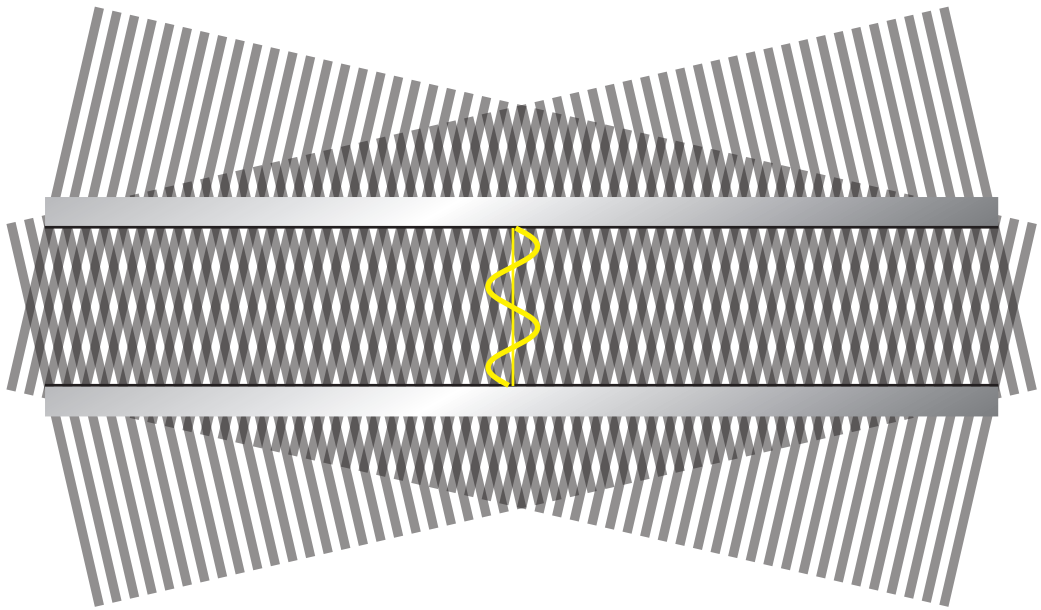

Waveguiding

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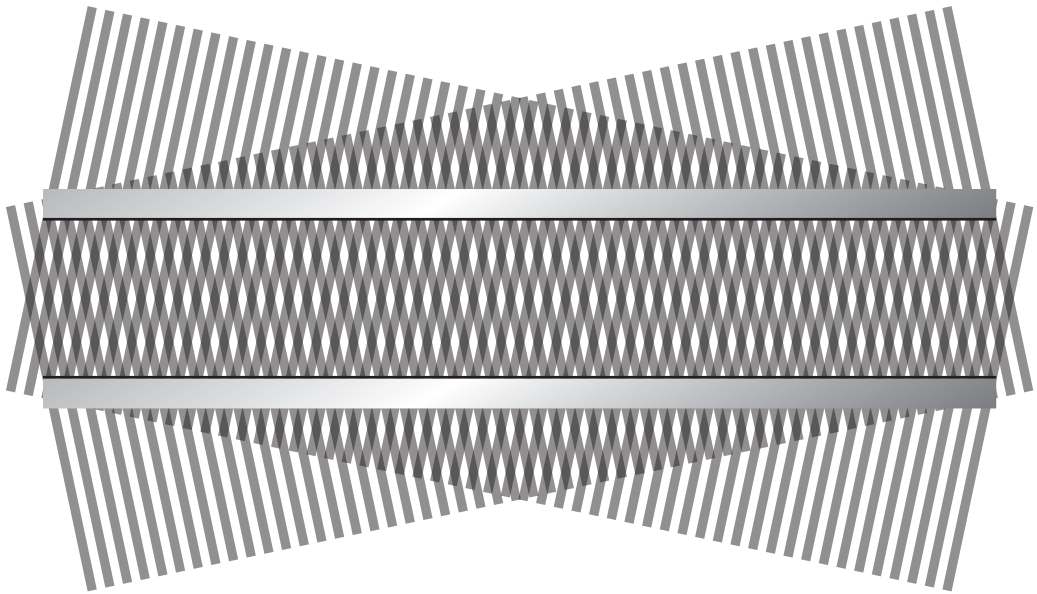

Waveguiding

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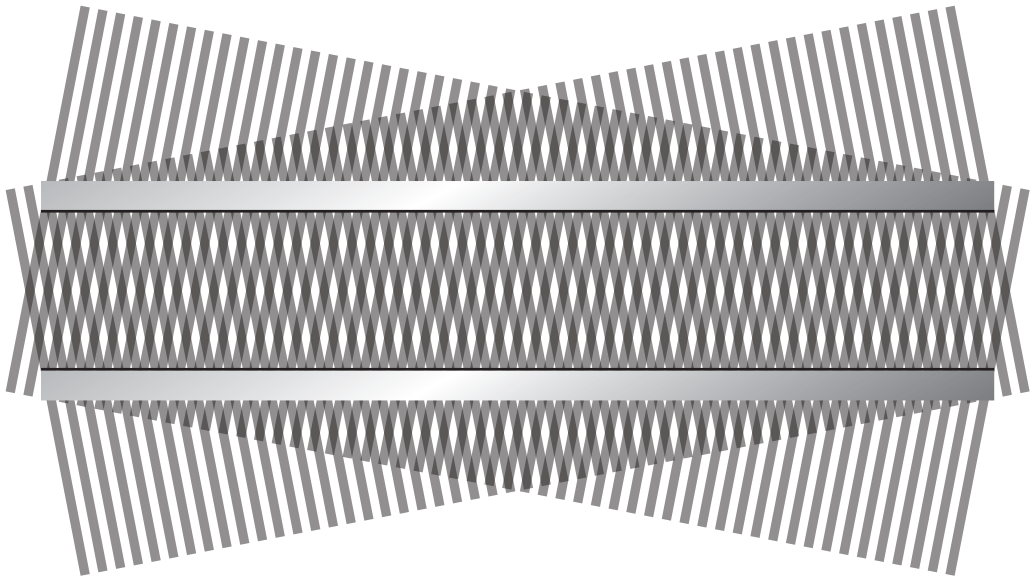
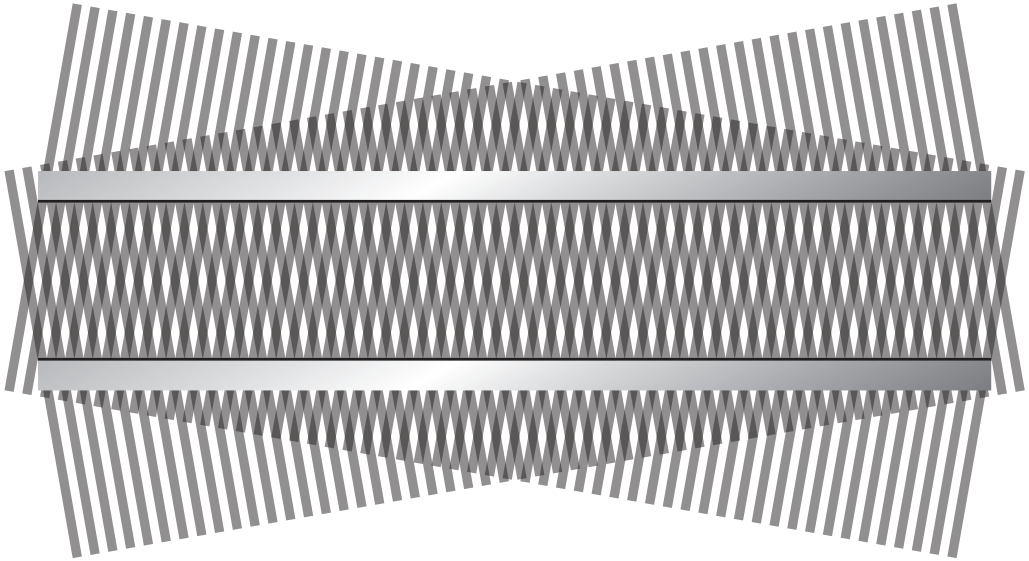


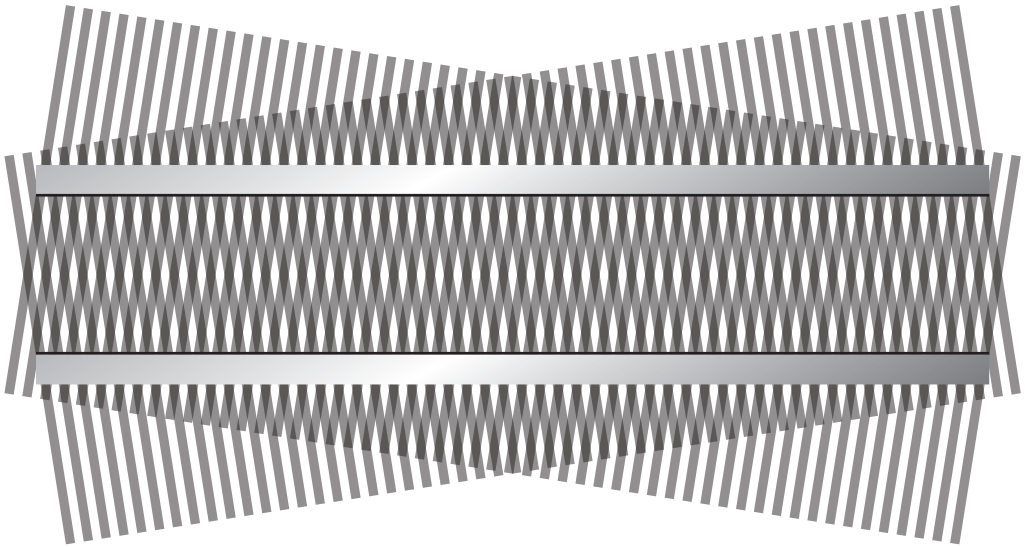
Waveguiding

change angle of incident waves…



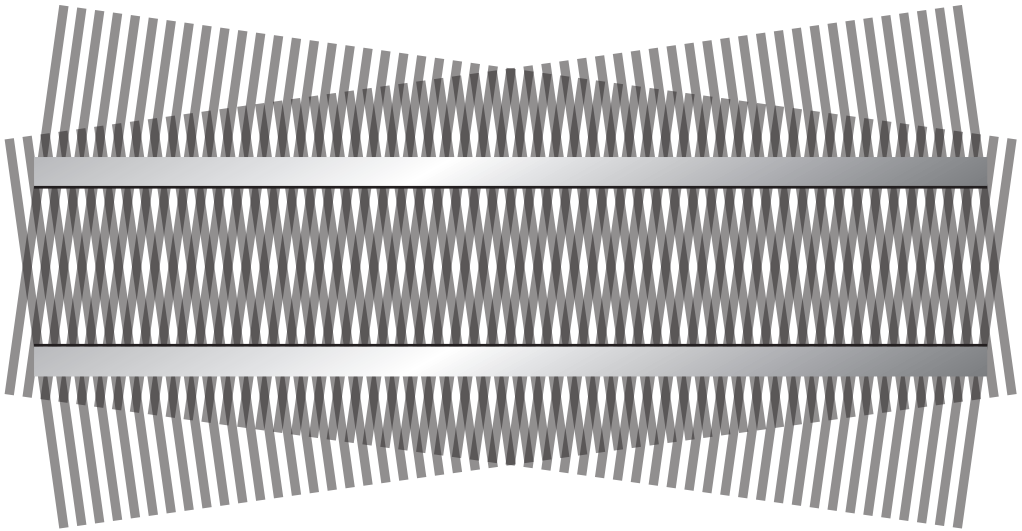
Waveguiding

change angle of incident waves…



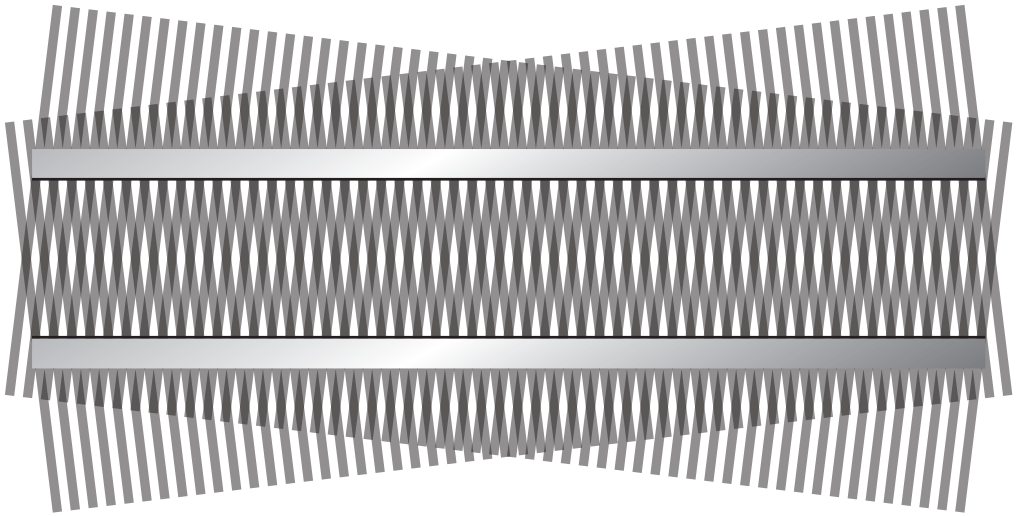
Waveguiding

change angle of incident waves…



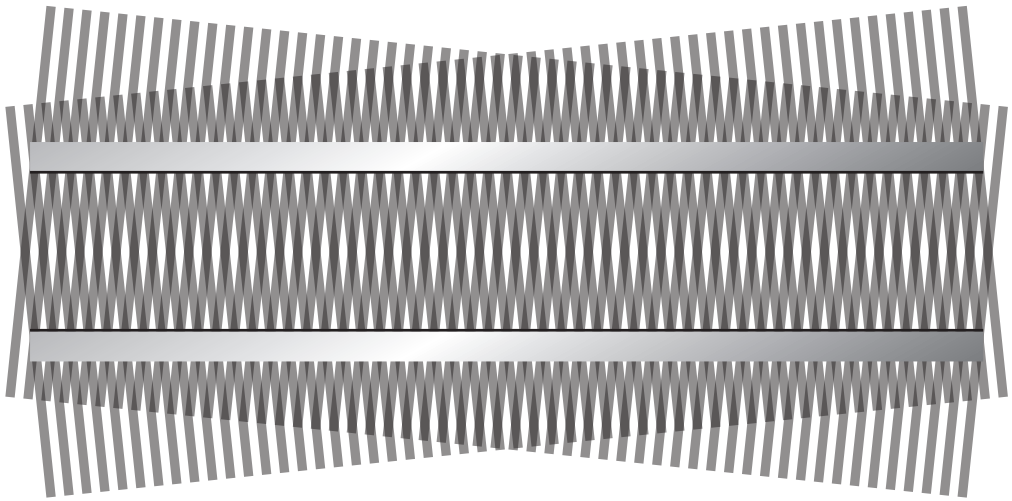
Waveguiding

change angle of incident waves…



Waveguiding

change angle of incident waves…



Waveguiding

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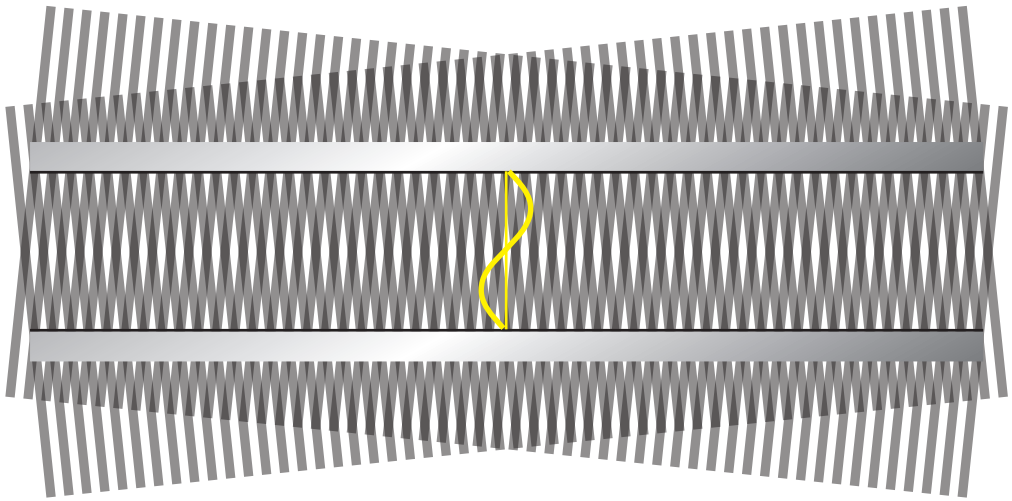
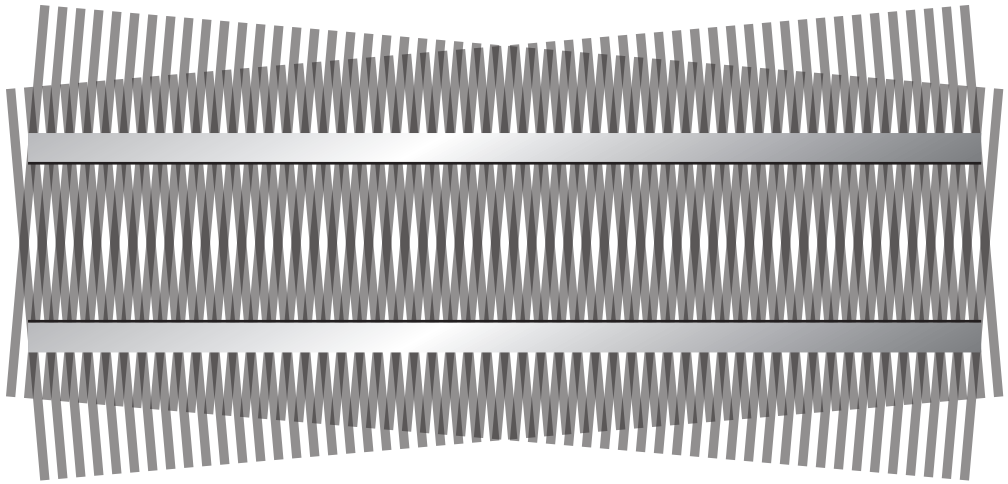


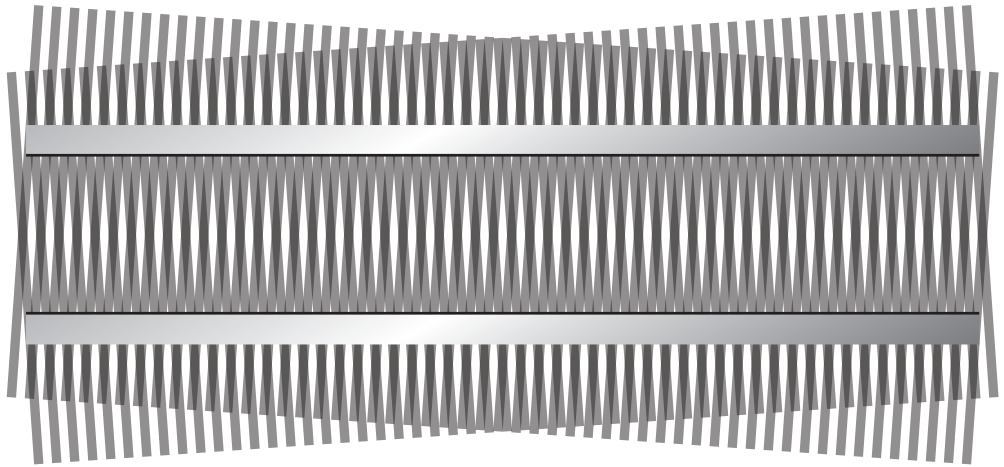
Waveguiding

change angle of incident waves…



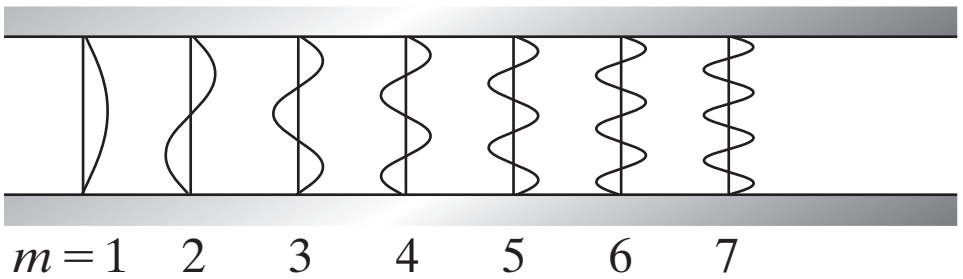
Waveguiding

change angle of incident waves…



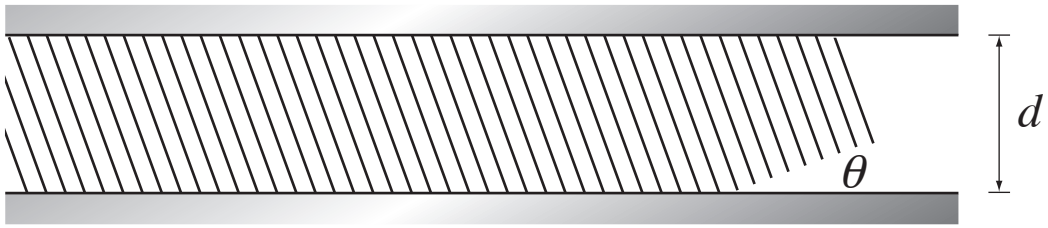
Waveguiding

boundary conditions only satisfied for certain θ



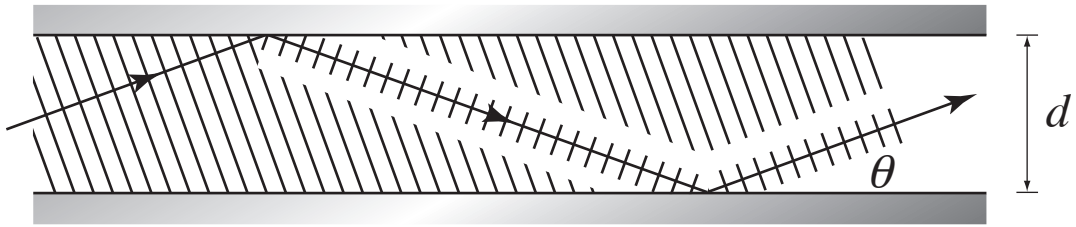
standing wave in *y*-direction, traveling in *z*-direction

Waveguiding



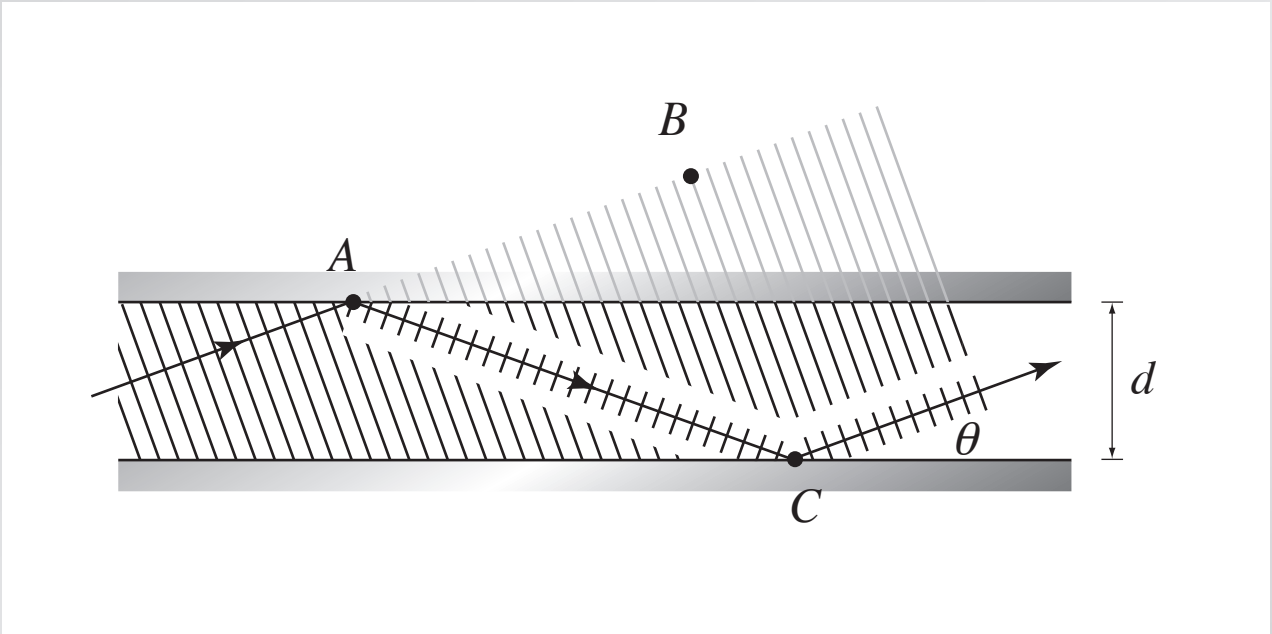
consider wave incident at angle θ

Waveguiding



twice-reflected wave

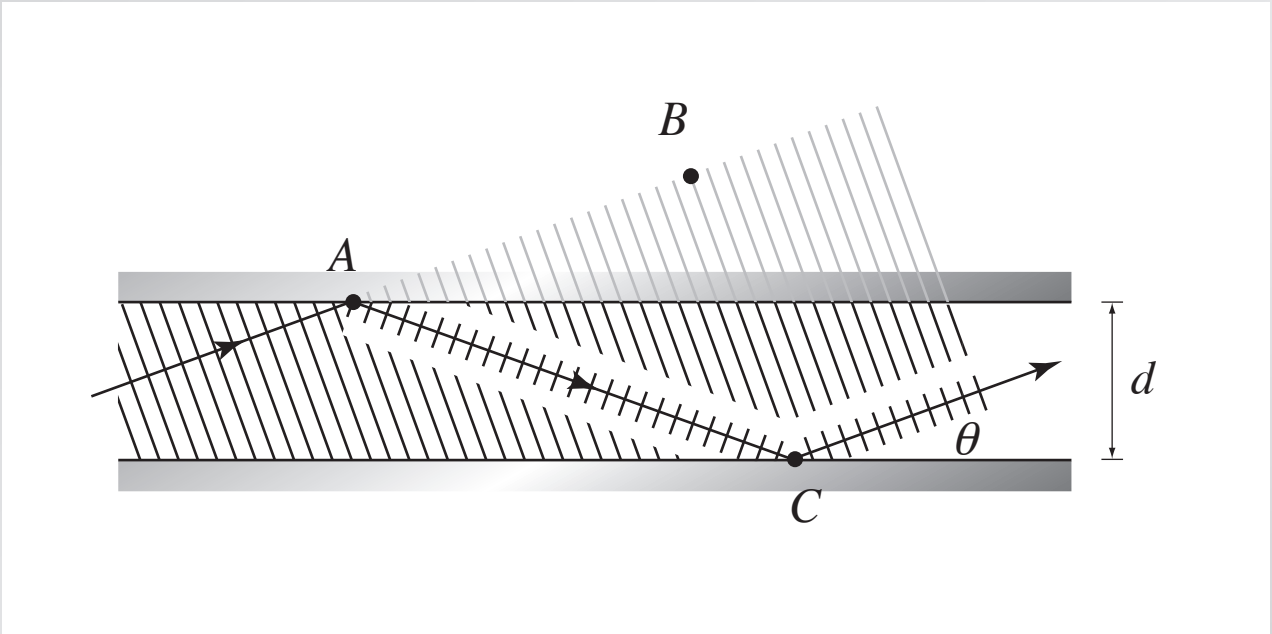
Waveguiding



self consistency:

$$AC - AB = 2d\sin\theta = m\lambda \quad (m = 1, 2, ...)$$

Waveguiding



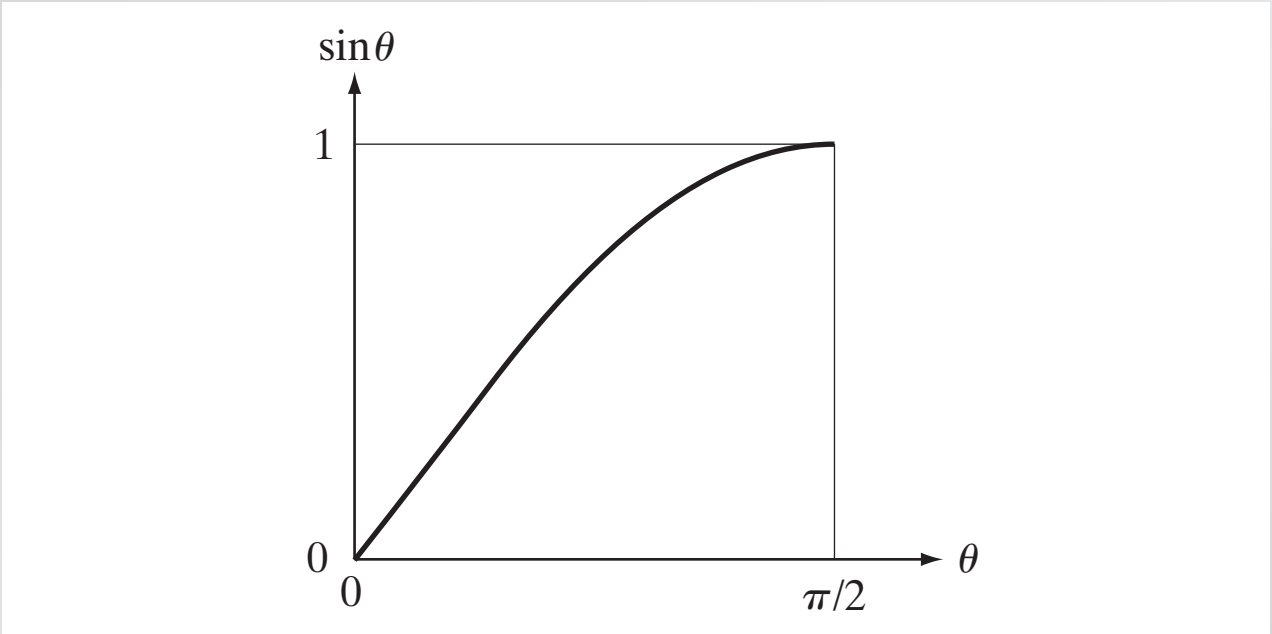
self consistency:

$$AC - AB = 2d\sin\theta = m\lambda \quad (m = 1, 2, ...)$$

so:

$$\sin\theta_m = m\frac{\lambda}{2d}$$

Waveguiding



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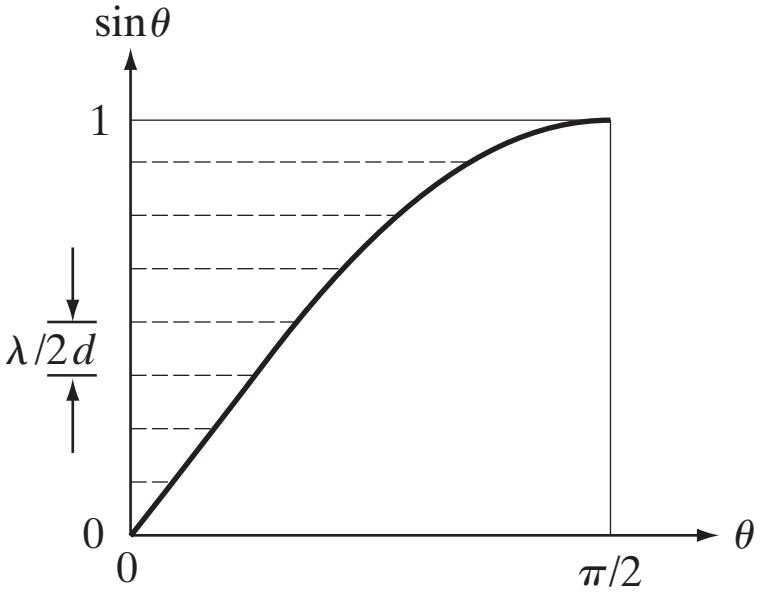
Waveguiding



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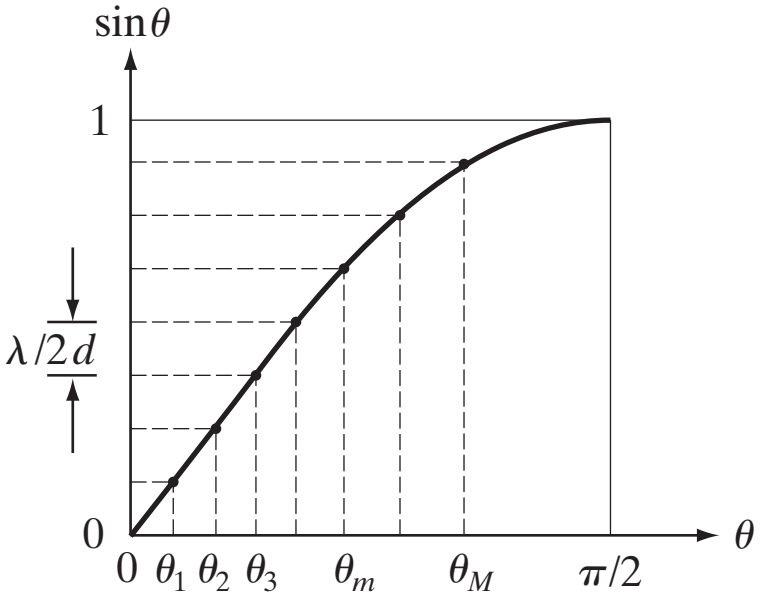

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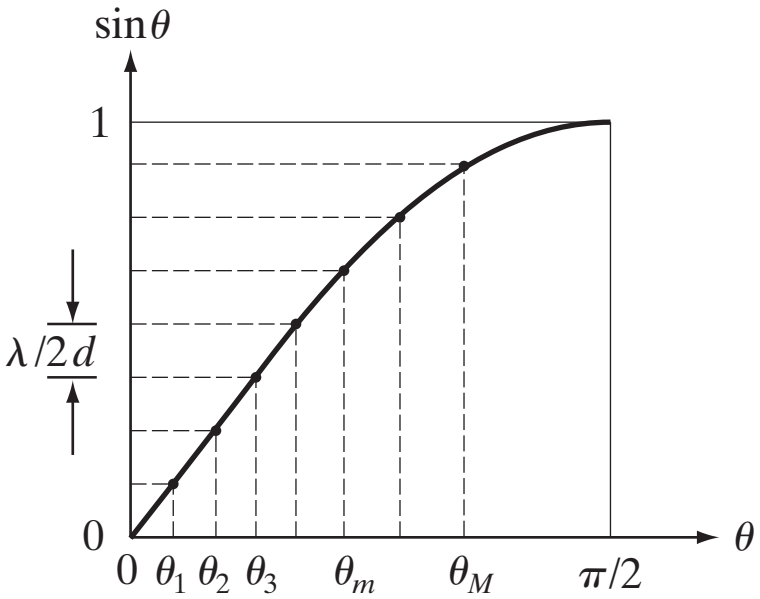
Waveguiding



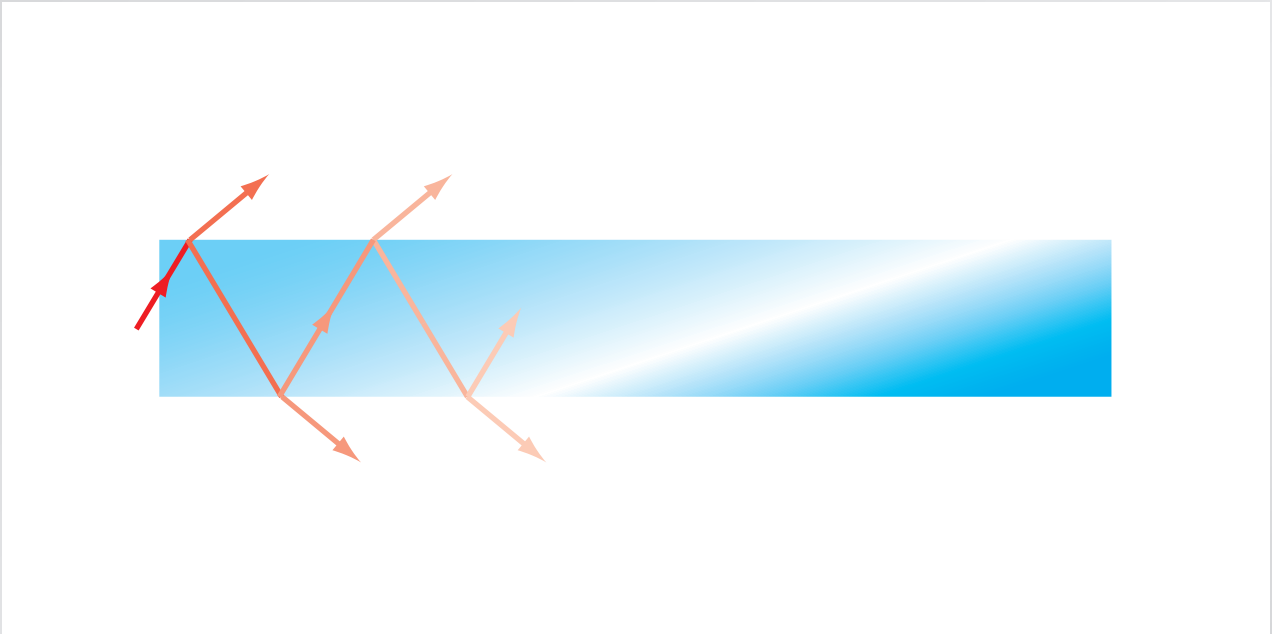
number of modes:

$$M \doteq \frac{2d}{\lambda}$$

Waveguiding

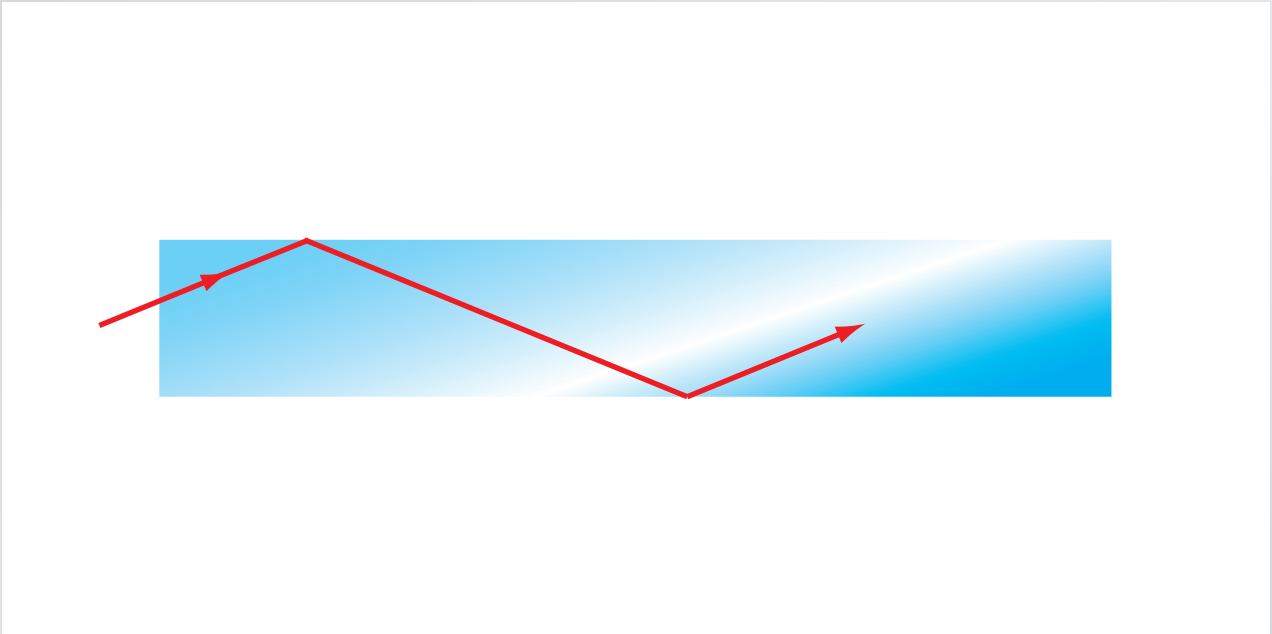
now consider a planar dielectric waveguide

Waveguiding



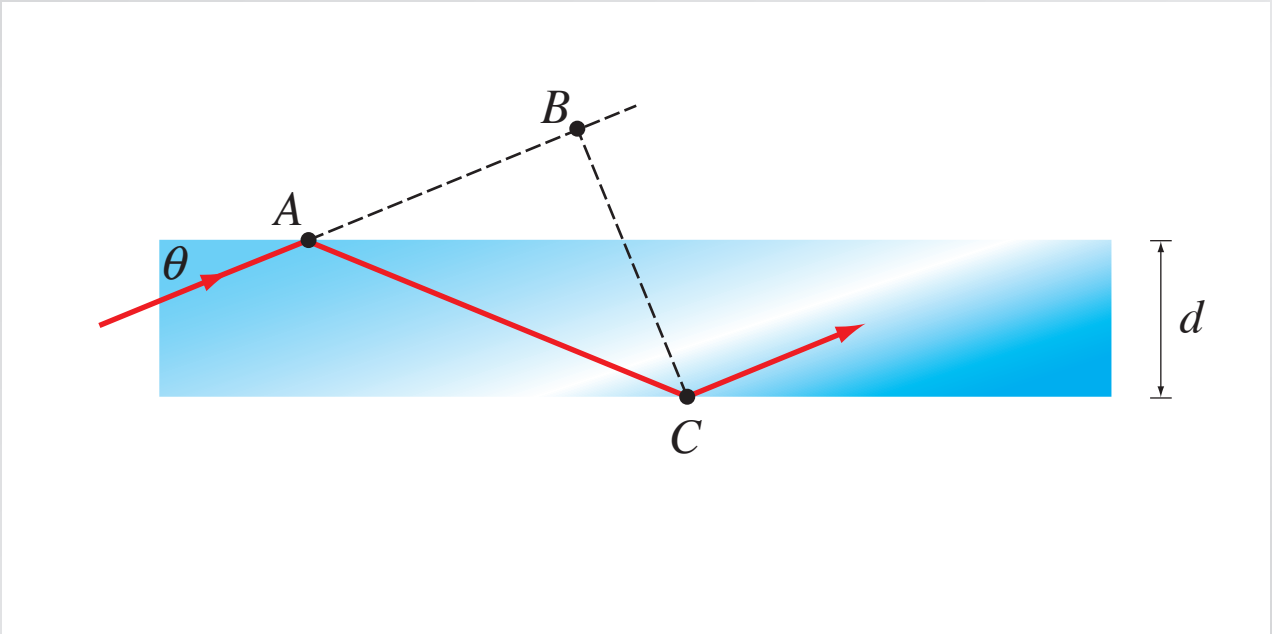
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



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

Waveguiding



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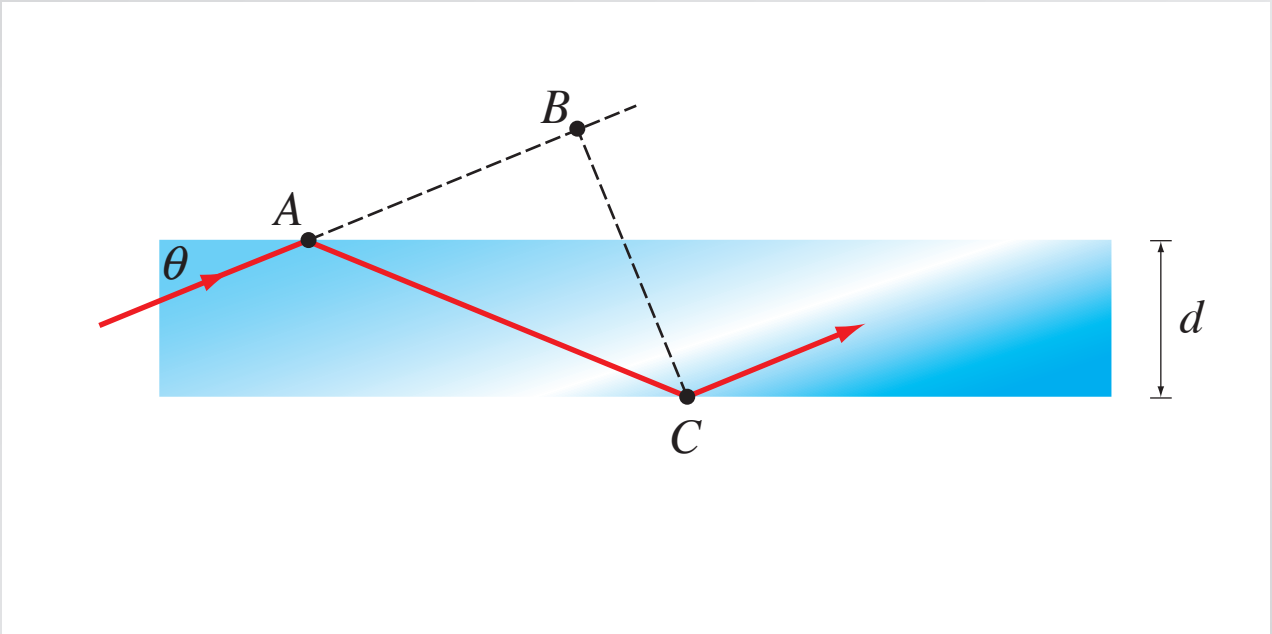
Waveguiding



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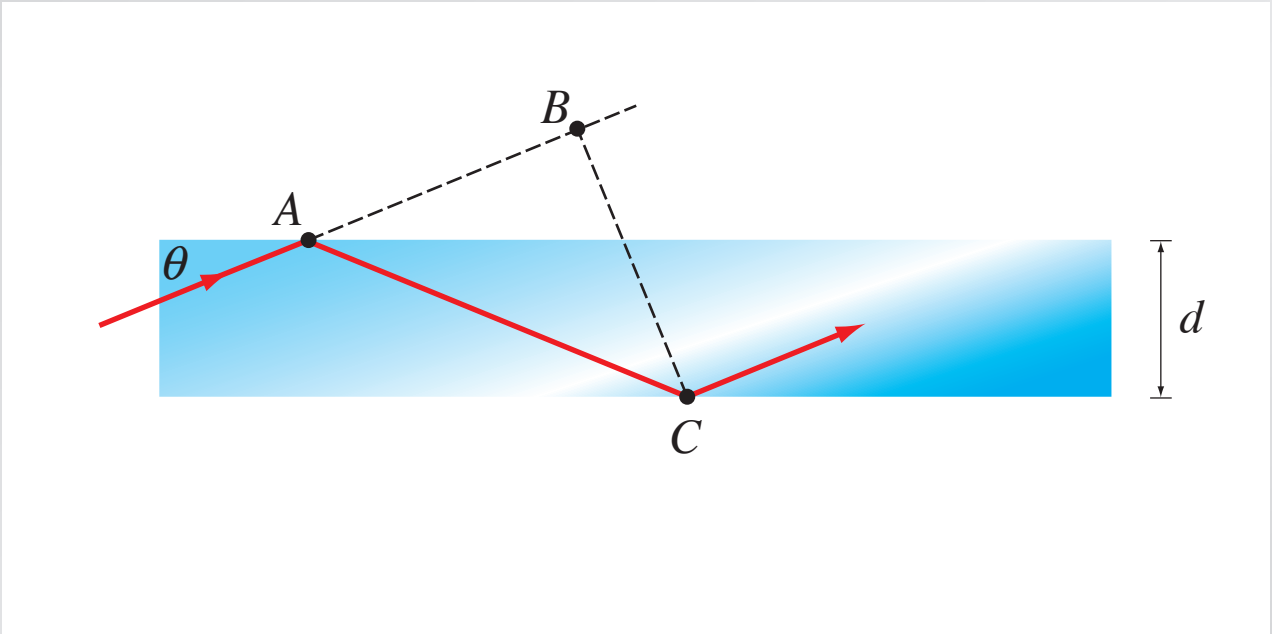
Waveguiding



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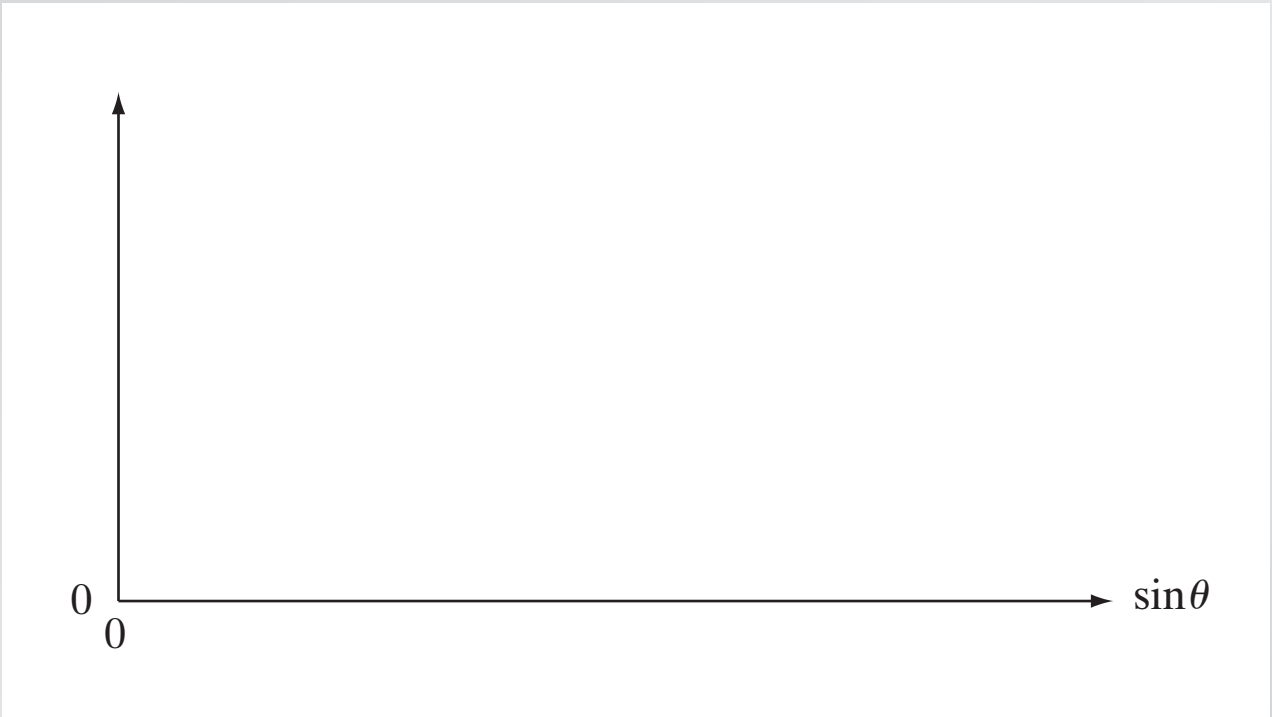
so:

$$\tan\left(\frac{\pi d}{\lambda}\sin\theta - m\frac{\pi}{2}\right) = \left(\frac{\sin^2(\pi/2 - \theta_c)}{\sin^2\theta} - 1\right)^{1/2}$$

Waveguiding



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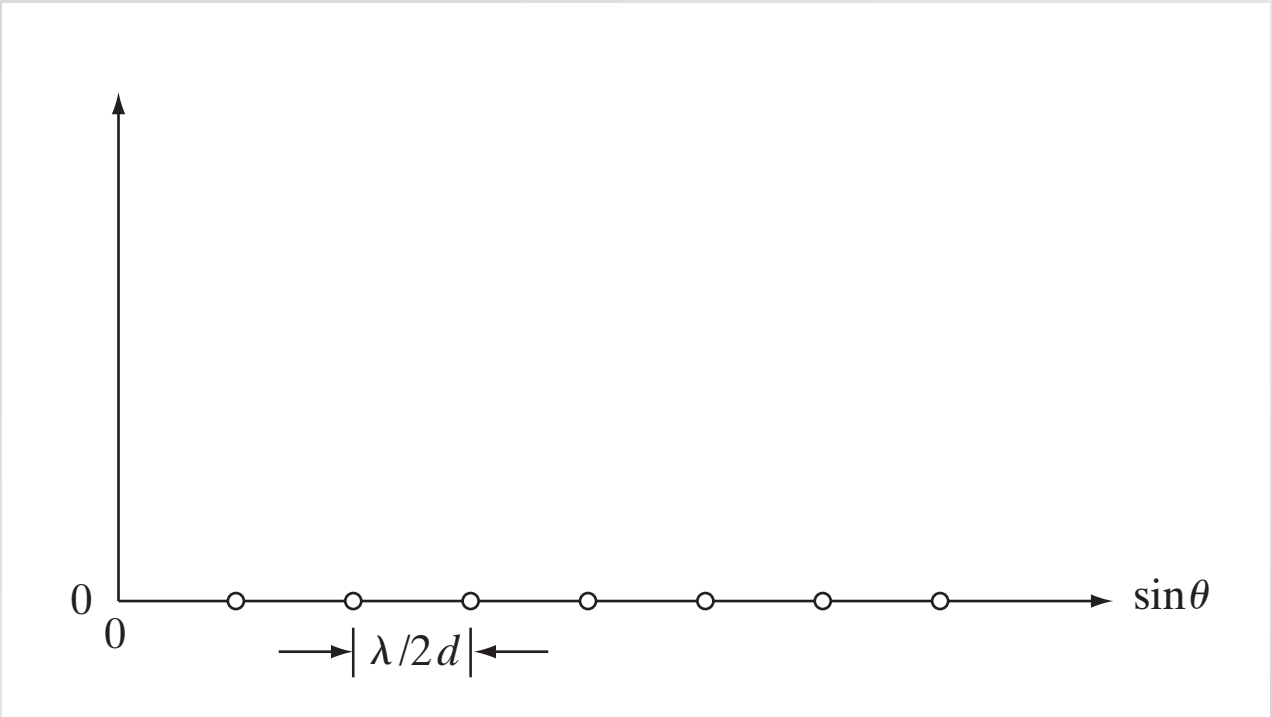

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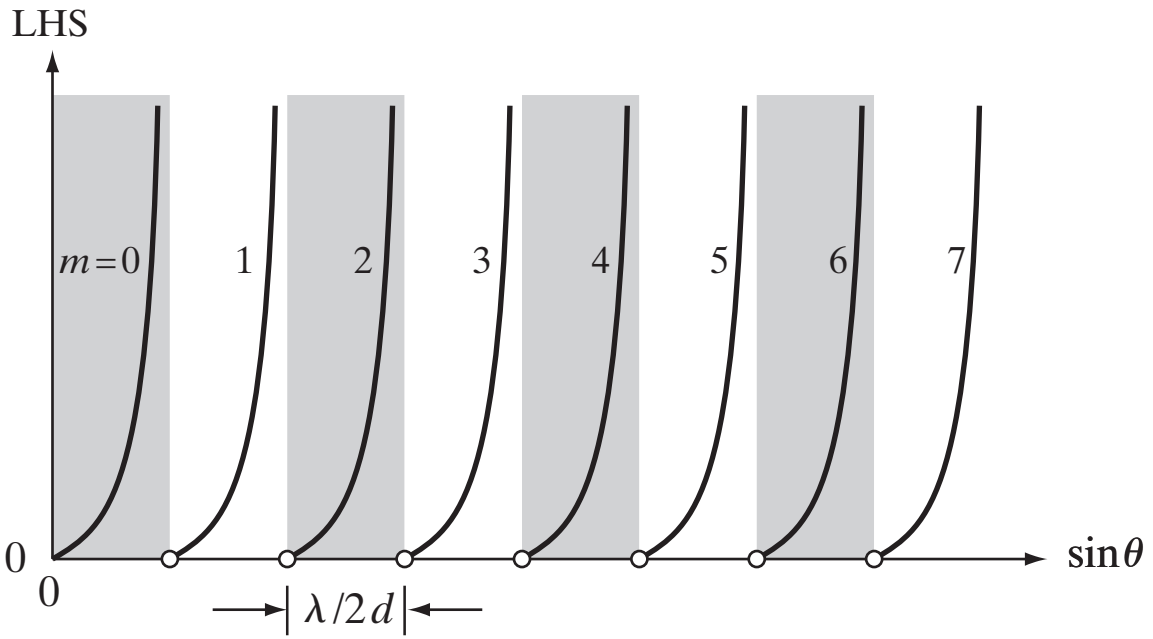

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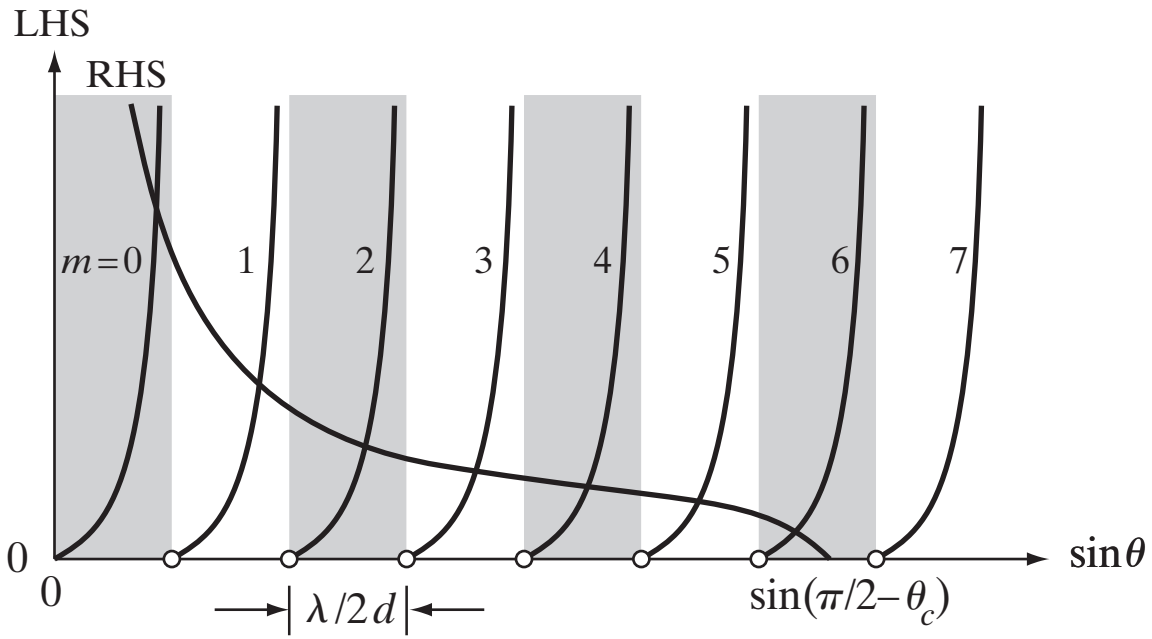
Waveguiding



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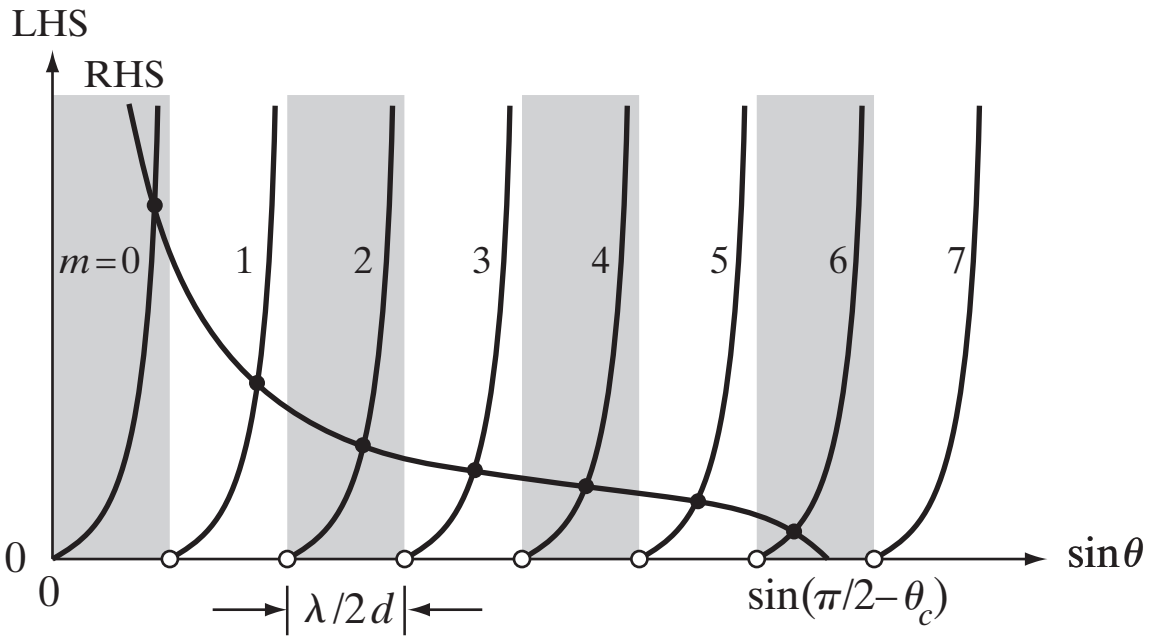
Waveguiding



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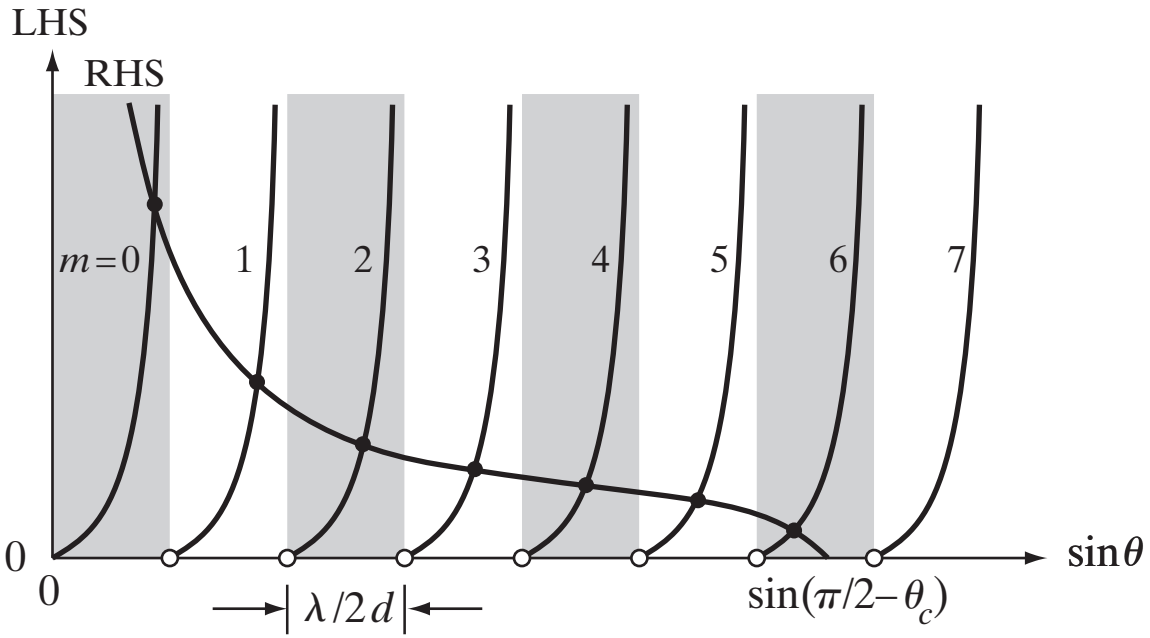
$$AC - AB = 2d\sin\theta - \frac{\varphi_r}{\pi}\lambda = m\lambda \quad (m = 0, 1, 2\ldots)$$

so:

$$\tan\left(\frac{\pi d}{\lambda}\sin\theta - m\frac{\pi}{2}\right) = \left(\frac{\sin^2(\pi/2-\theta_c)}{\sin^2\theta} - 1\right)^{1/2}$$

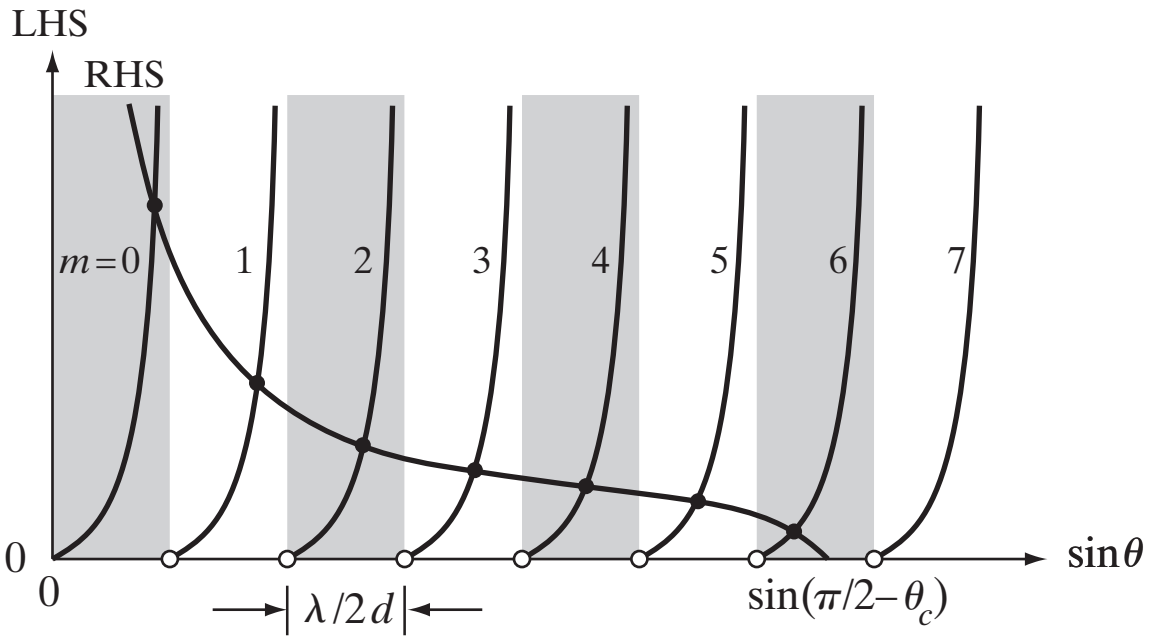
Waveguiding



number of modes:

$$M \doteq \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d}$$

Waveguiding



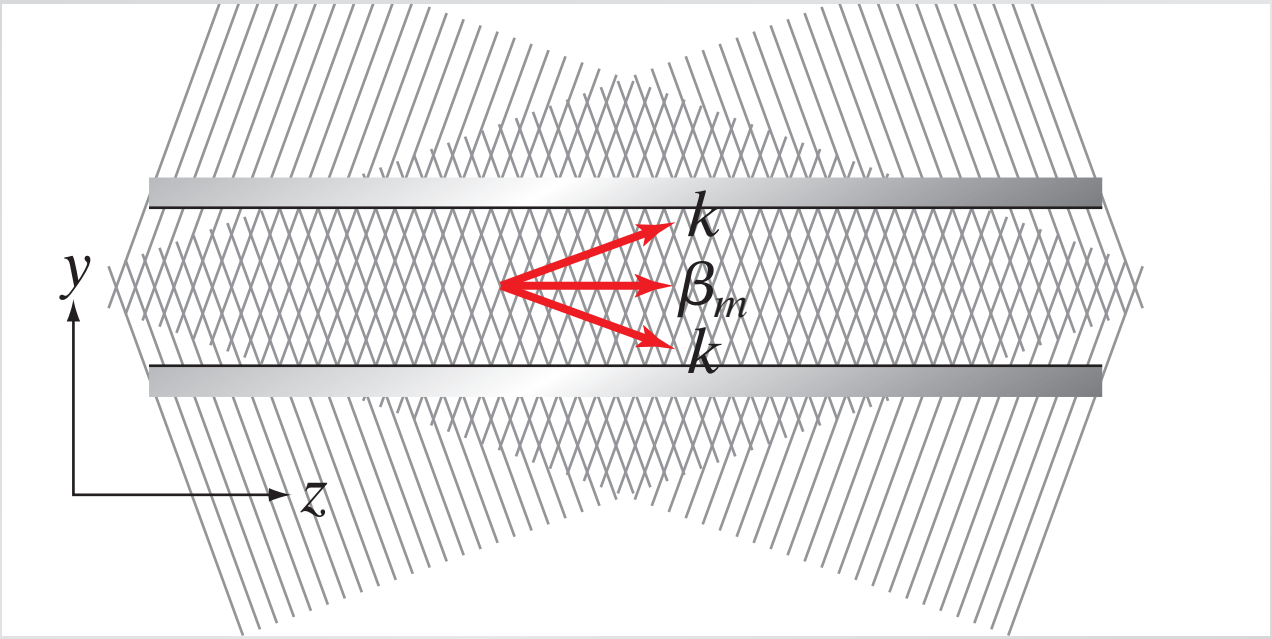
number of modes:

$$M \doteq \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d}$$

or:

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

Waveguiding



propagation constant of guided wave:

$$\beta_m^2 = k^2 - k_y^2 = k^2 - \frac{m^2\pi^2}{d^2}$$

group velocity:

$$v_m = c\cos\theta_m$$

Waveguiding

single mode condition for 600-nm light:

planar mirror $M \doteq \frac{2d}{\lambda}$ $300 < d < 600$ nm

dielectric $M \doteq 2\frac{d}{\lambda}(n_1^2 - n_2^2)^{1/2}$ $d < 268$ nm

Waveguiding

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can make d larger by making $n_1 - n_2$ smaller!

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = -i\omega\mu_o \nabla \epsilon \Phi$$

Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_o \epsilon \vec{A} = 0$$

Waveguiding

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Substituting $\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$

Waveguiding

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yields:

$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0$$

Waveguiding

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Substituting $\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$

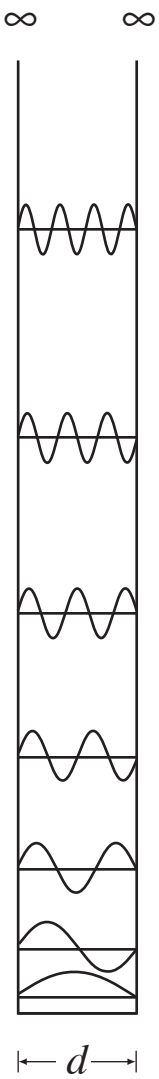
yields:

$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0$$

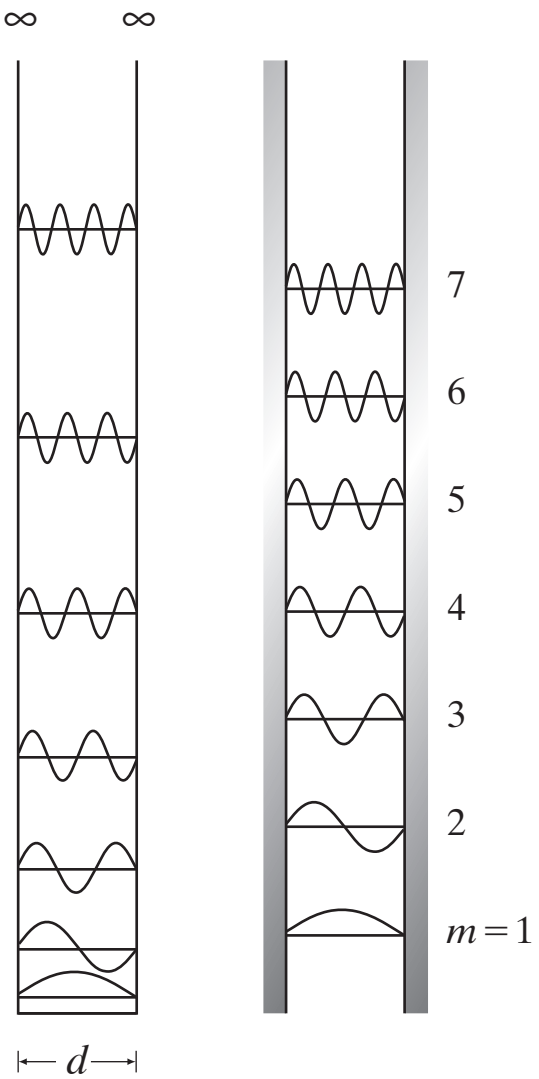
Compare to time-independent Schrödinger equation:

$$\nabla^2 \psi + \frac{2m}{\hbar^2}[E - V(r)]\psi = 0$$

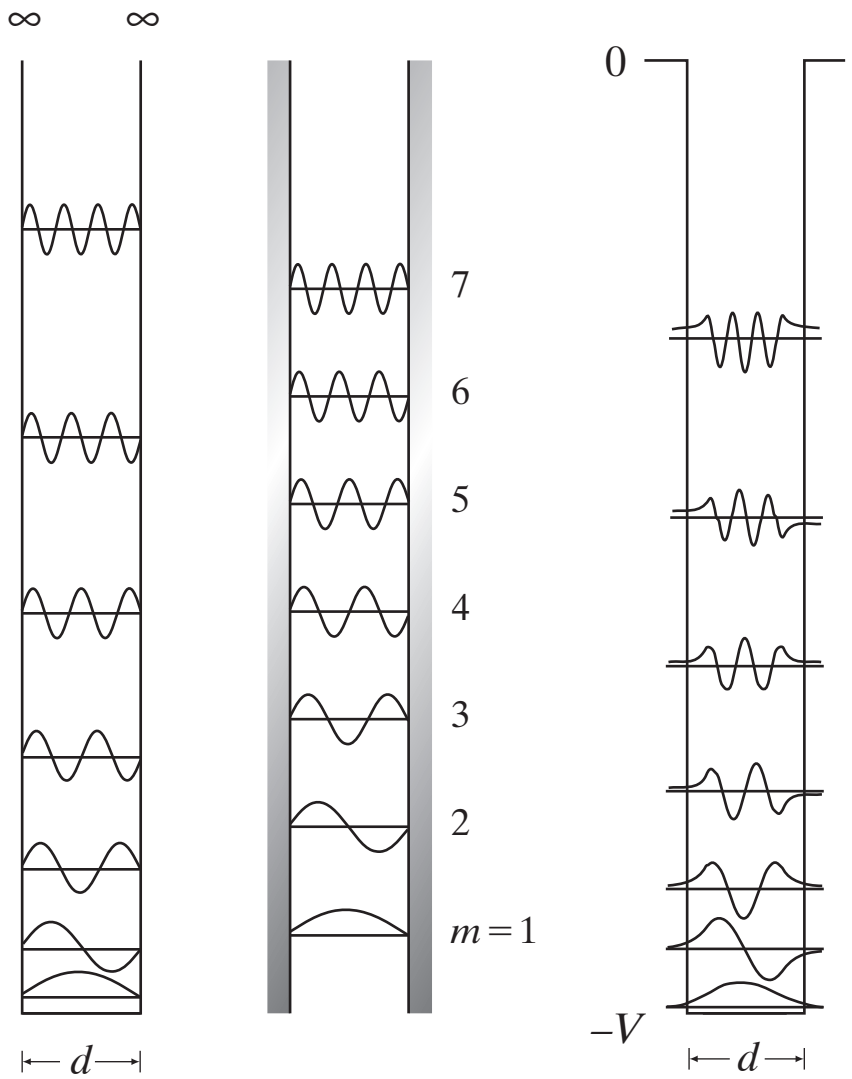
Waveguiding



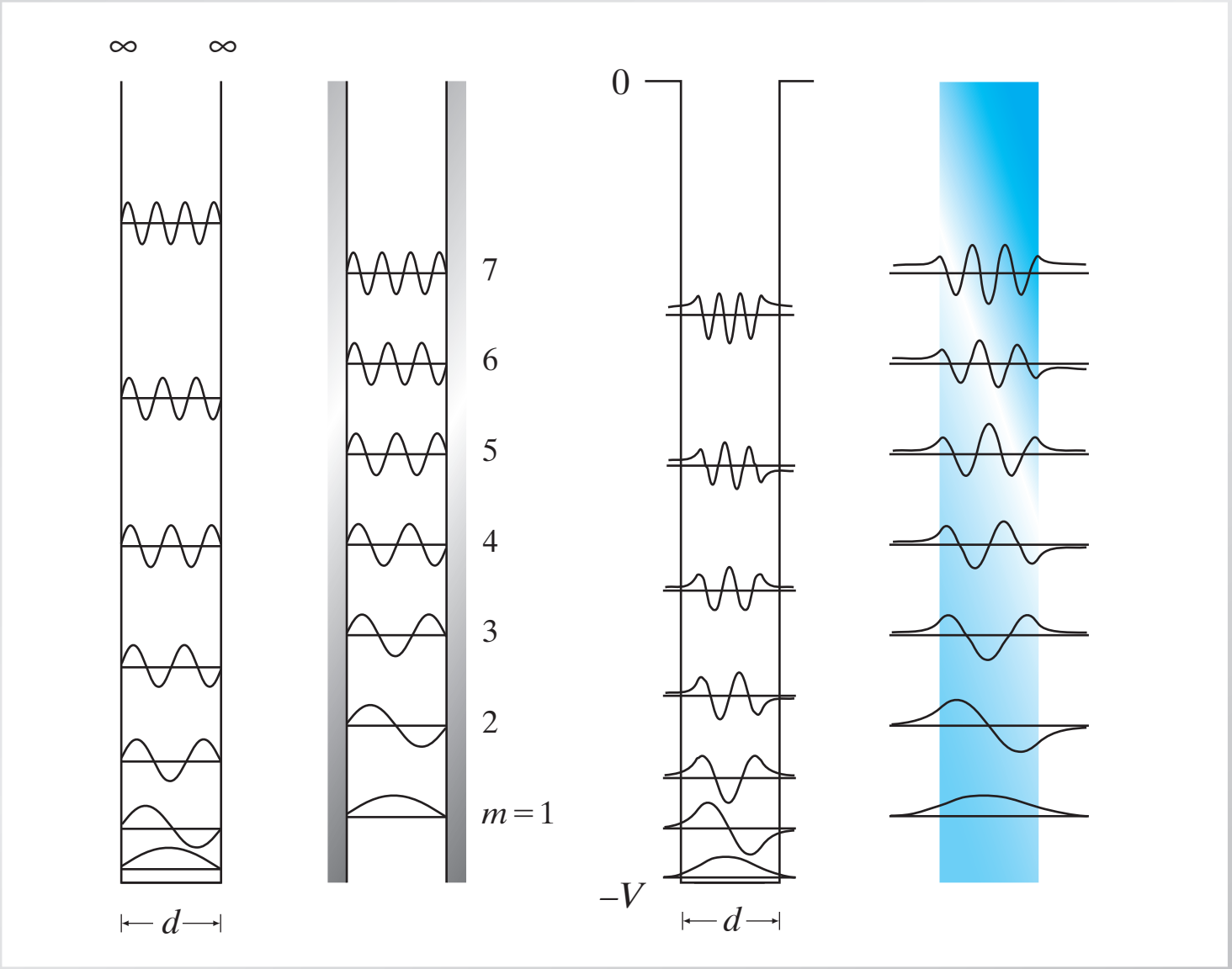
Waveguiding



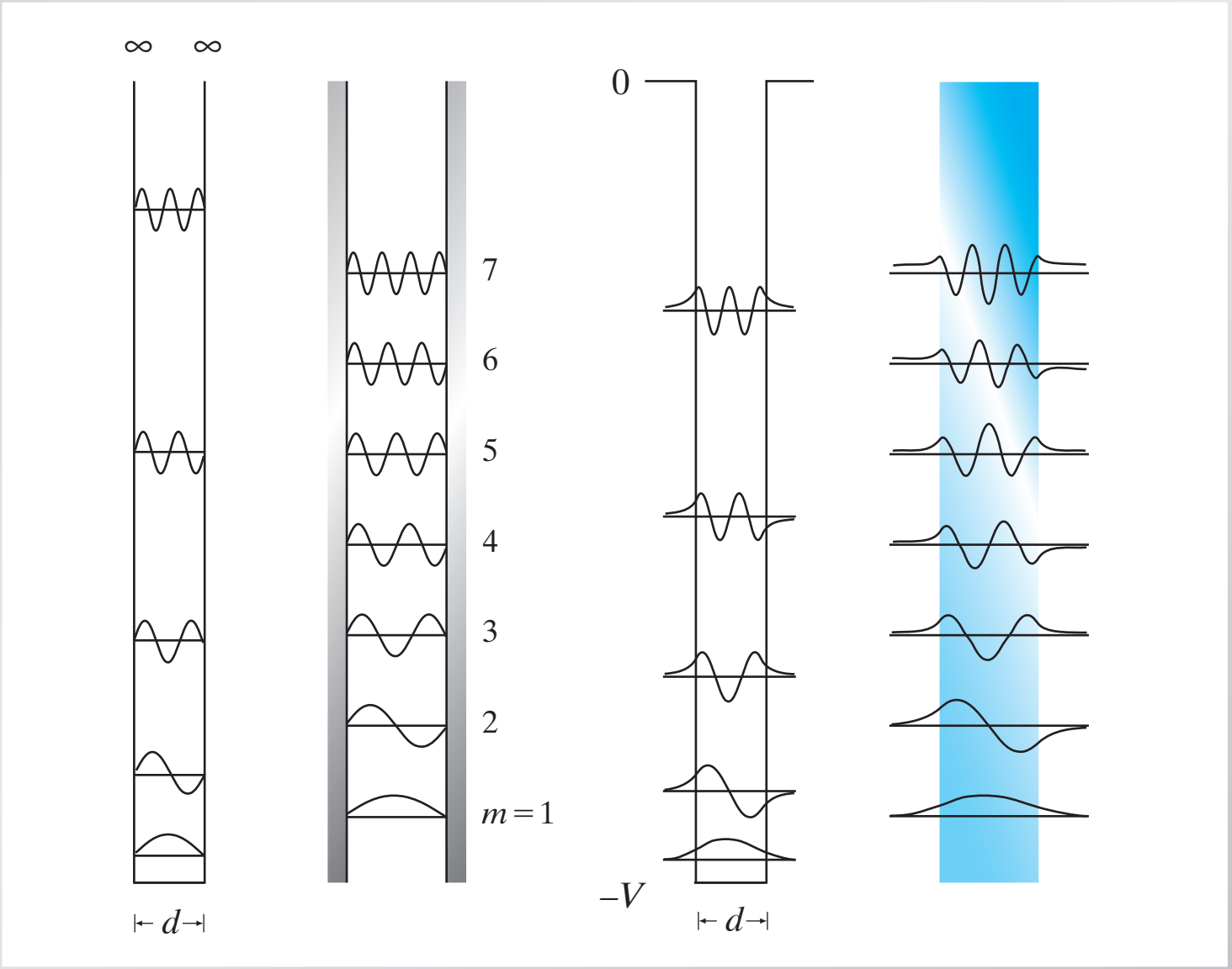
Waveguiding



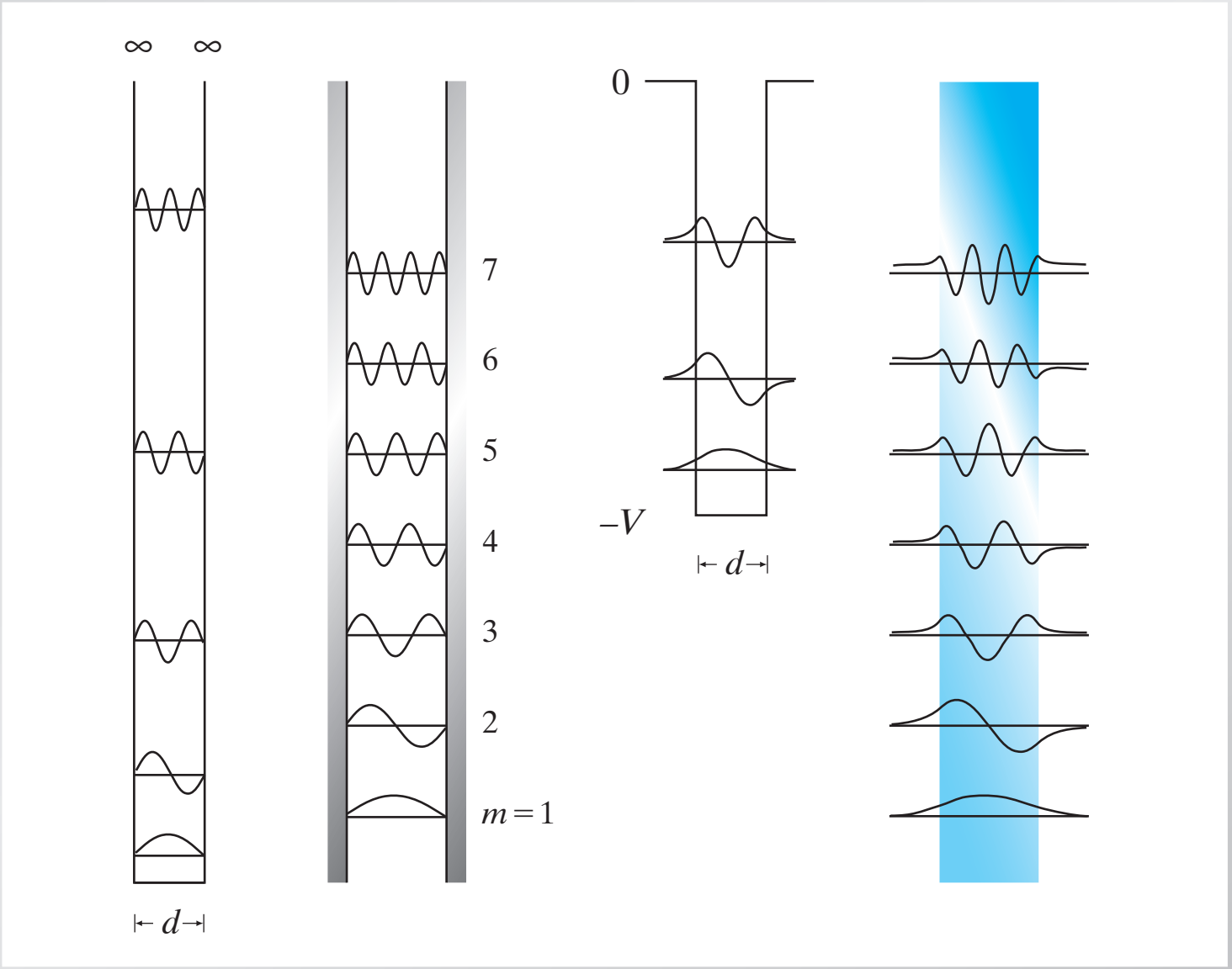
Waveguiding



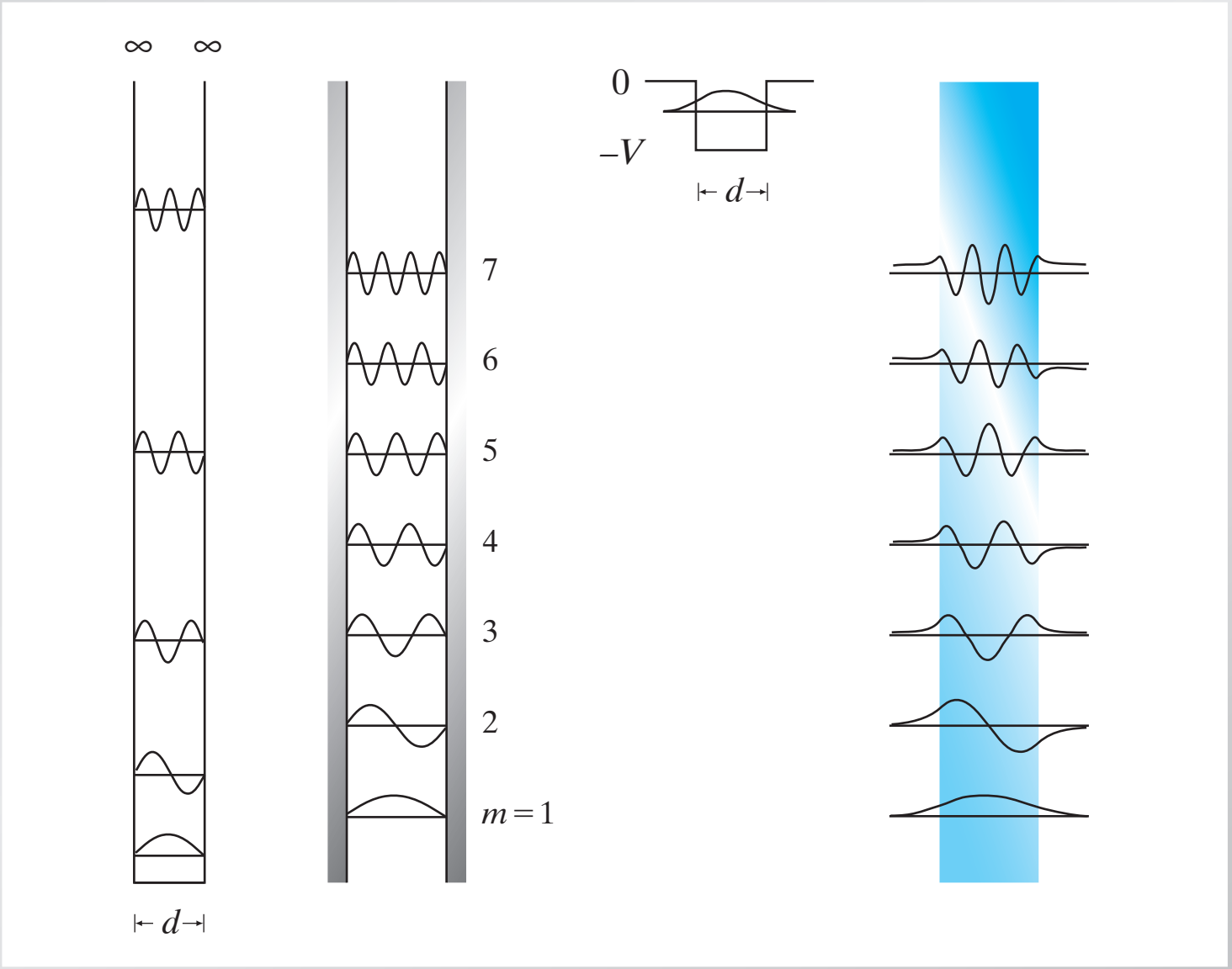
Waveguiding



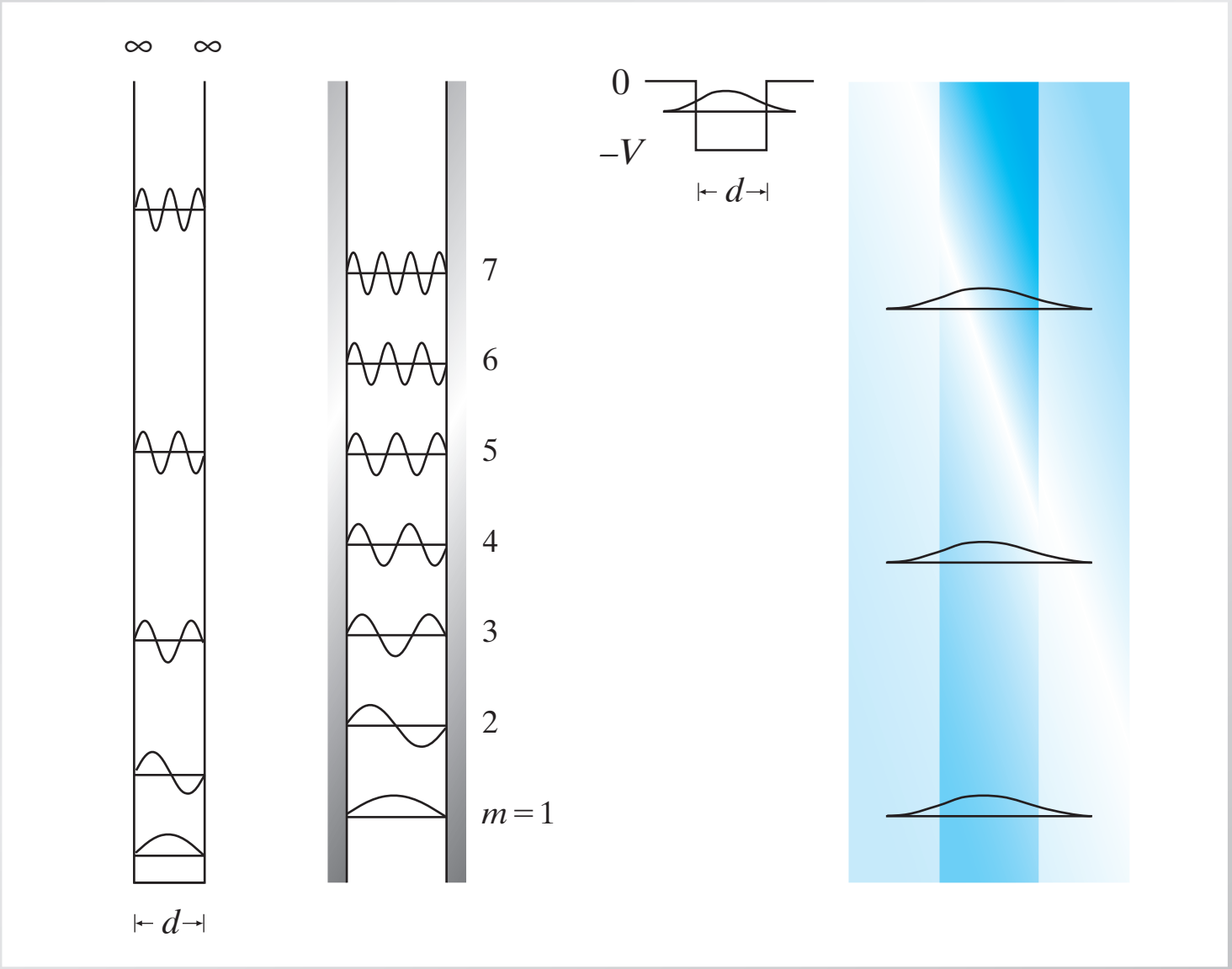
Waveguiding



Waveguiding



Waveguiding



Waveguiding

single mode condition for 600-nm light:

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

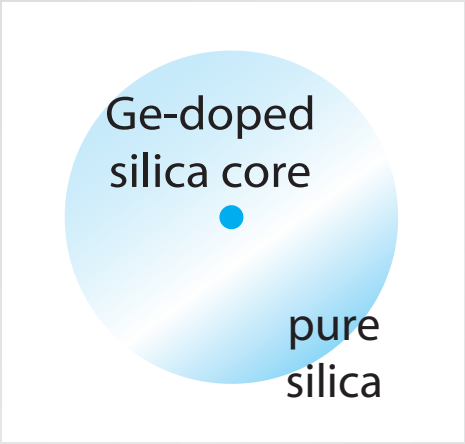
without cladding: $d < 268\ \text{nm}$

Add cladding with 0.4% index difference:

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

Waveguiding

commercial single-mode fiber (Corning Titan®)



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

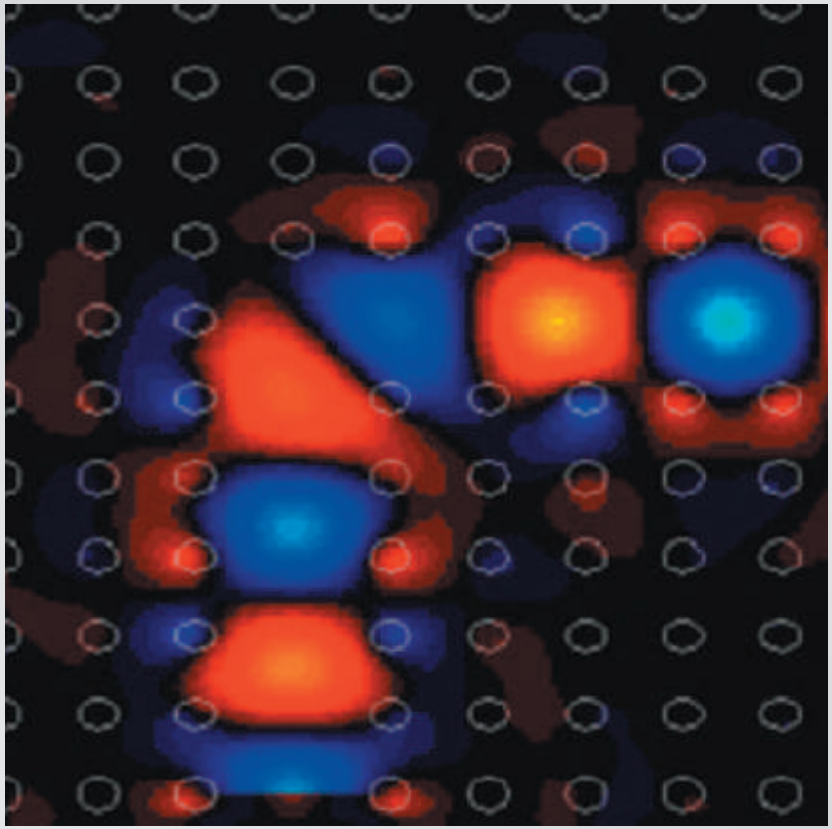
operating wavelength: $\lambda = 1310\ \text{nm}/1550\ \text{nm}$

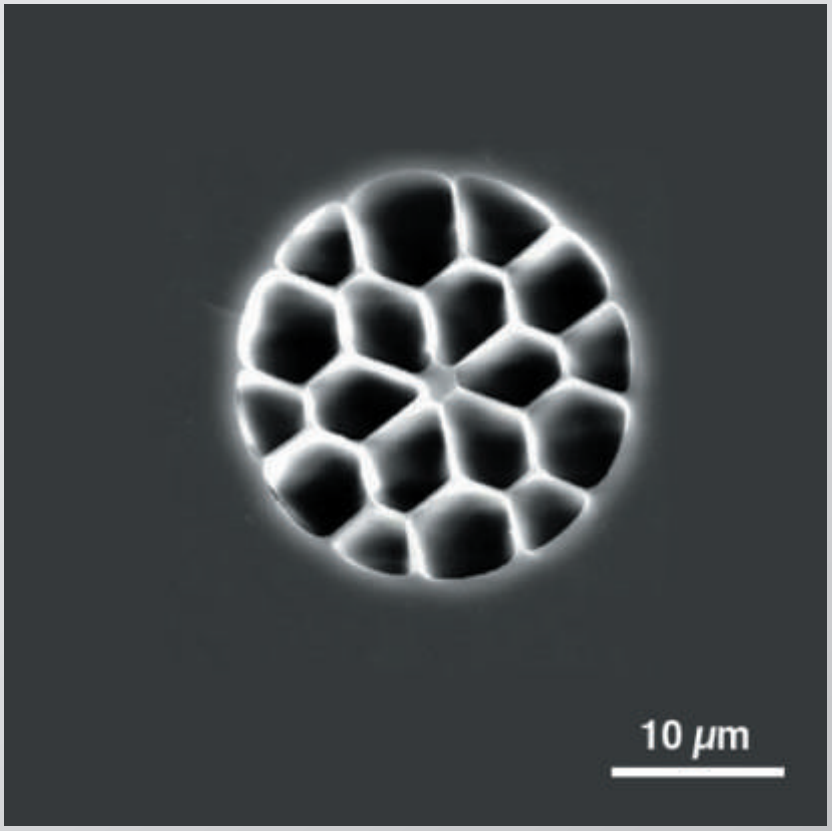
Waveguiding

drawbacks of clad fibers:

- weak confinement
- no tight bending
- coupling requires splicing

Waveguiding



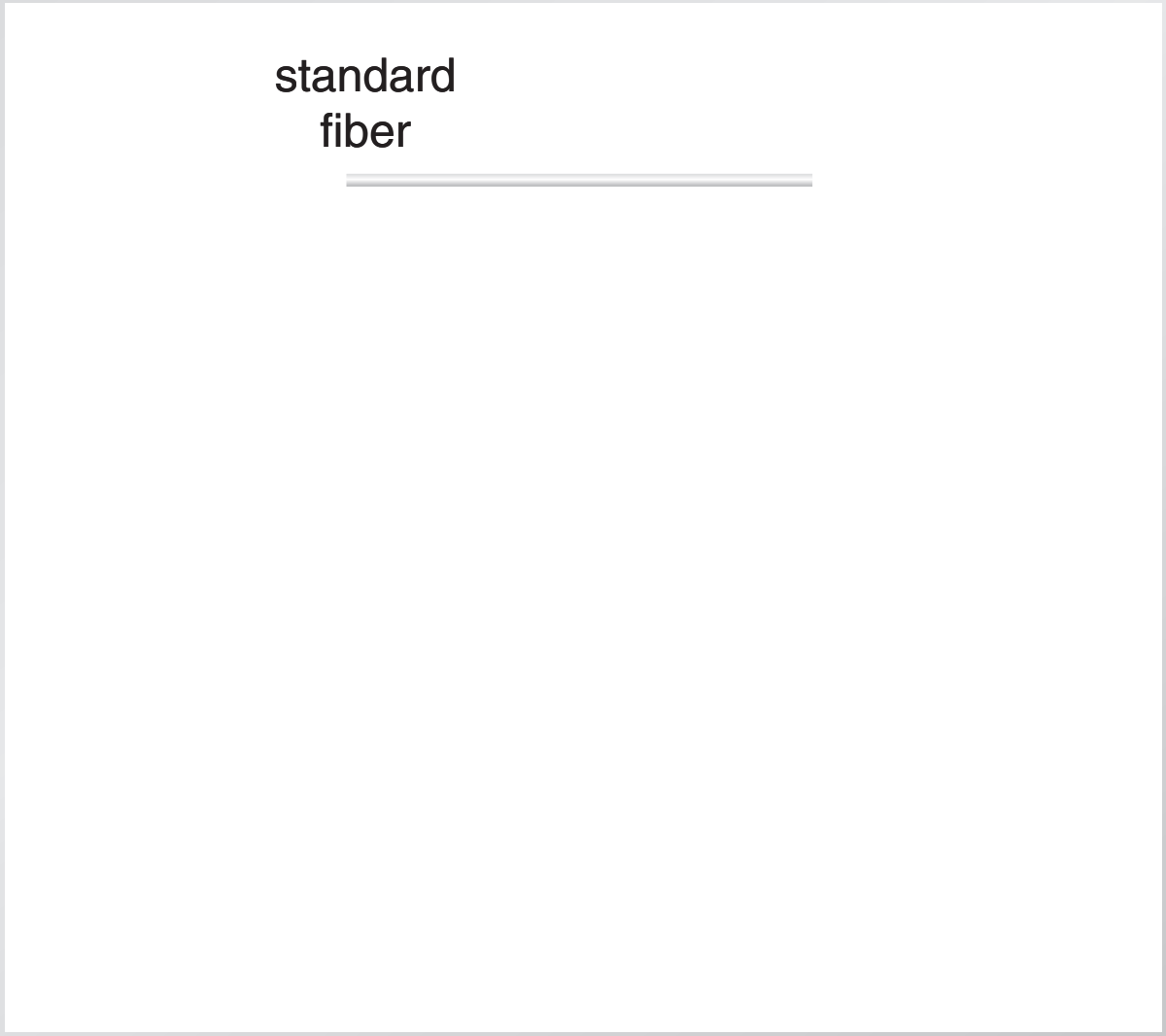


Outline

- waveguiding
- **nanowire fabrication**
- optical properties

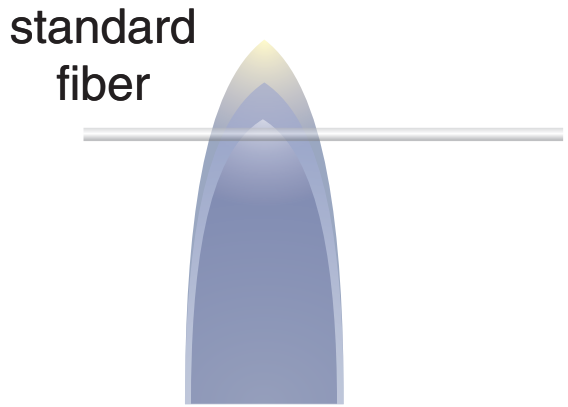
Nanowire fabrication

two-step drawing process



Nanowire fabrication

two-step drawing process



Nanowire fabrication

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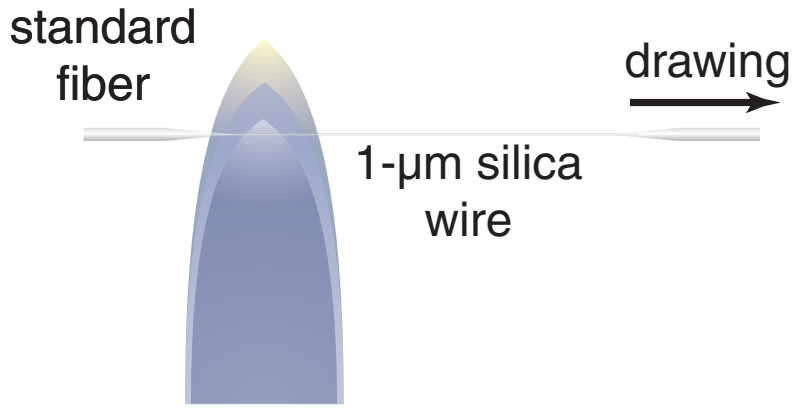

Nanowire fabrication

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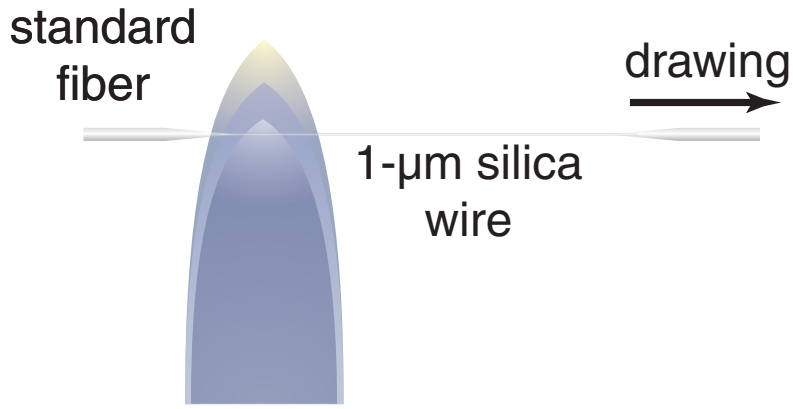

Nanowire fabrication

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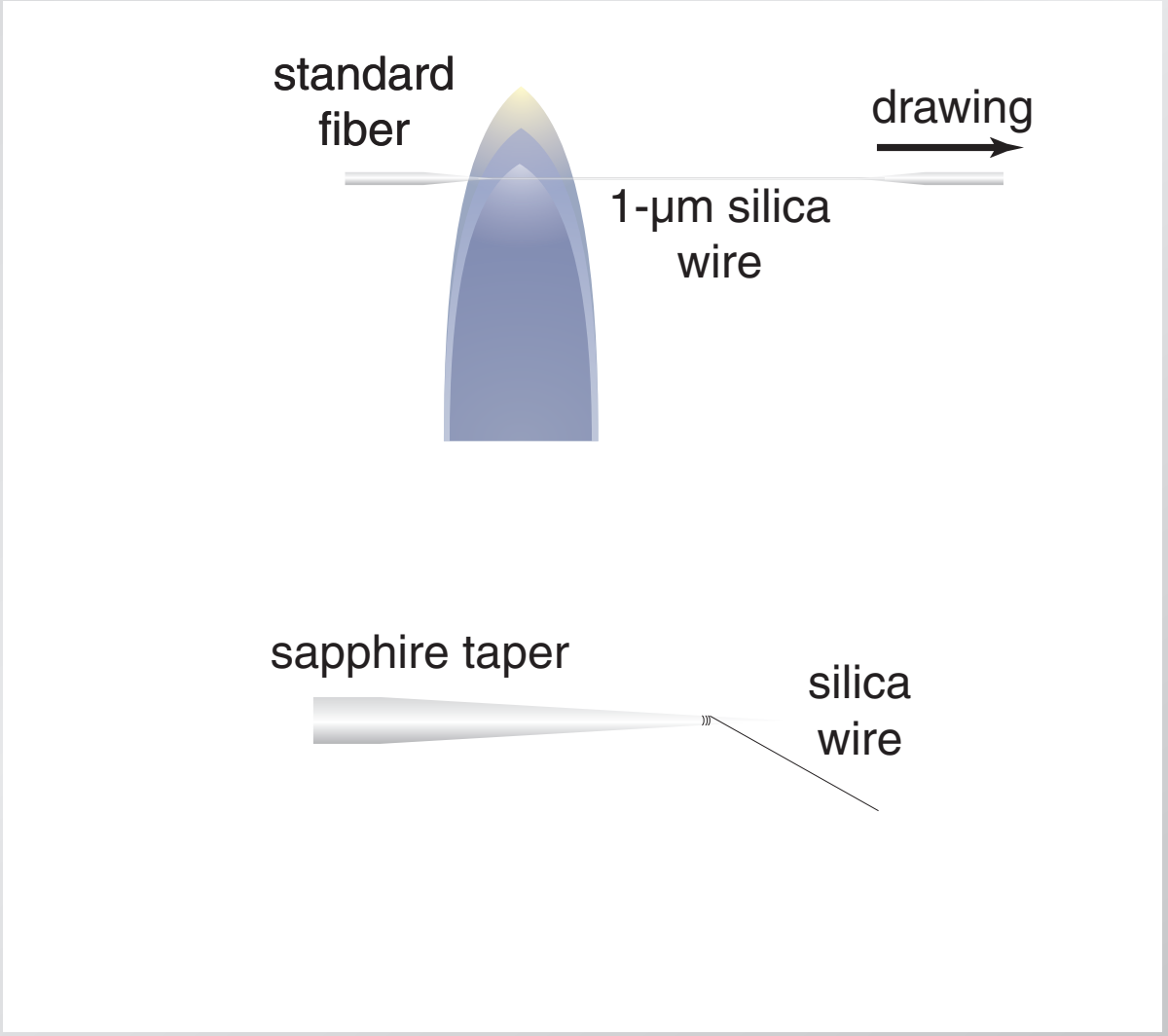

Nanowire fabrication

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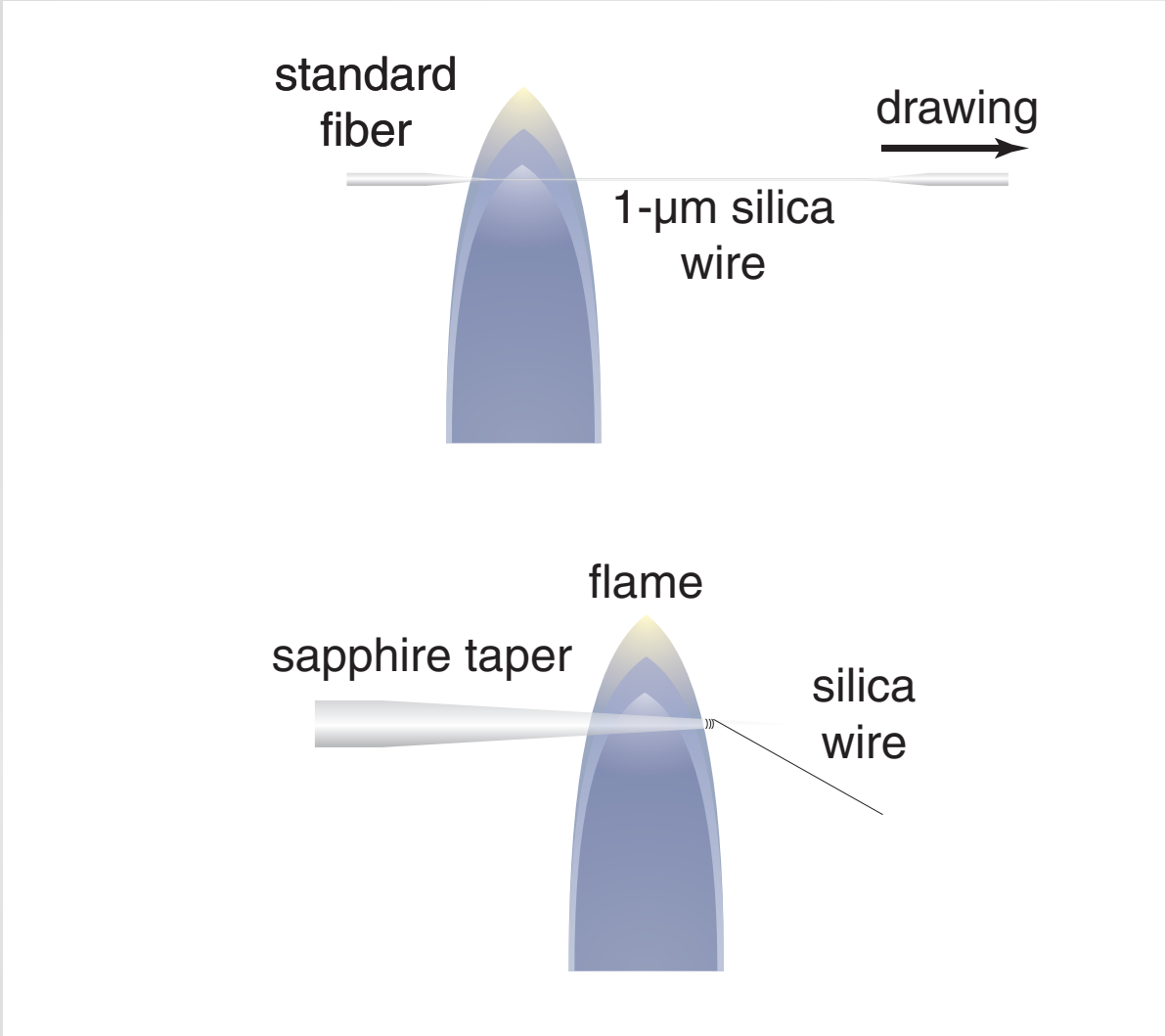

Nanowire fabrication

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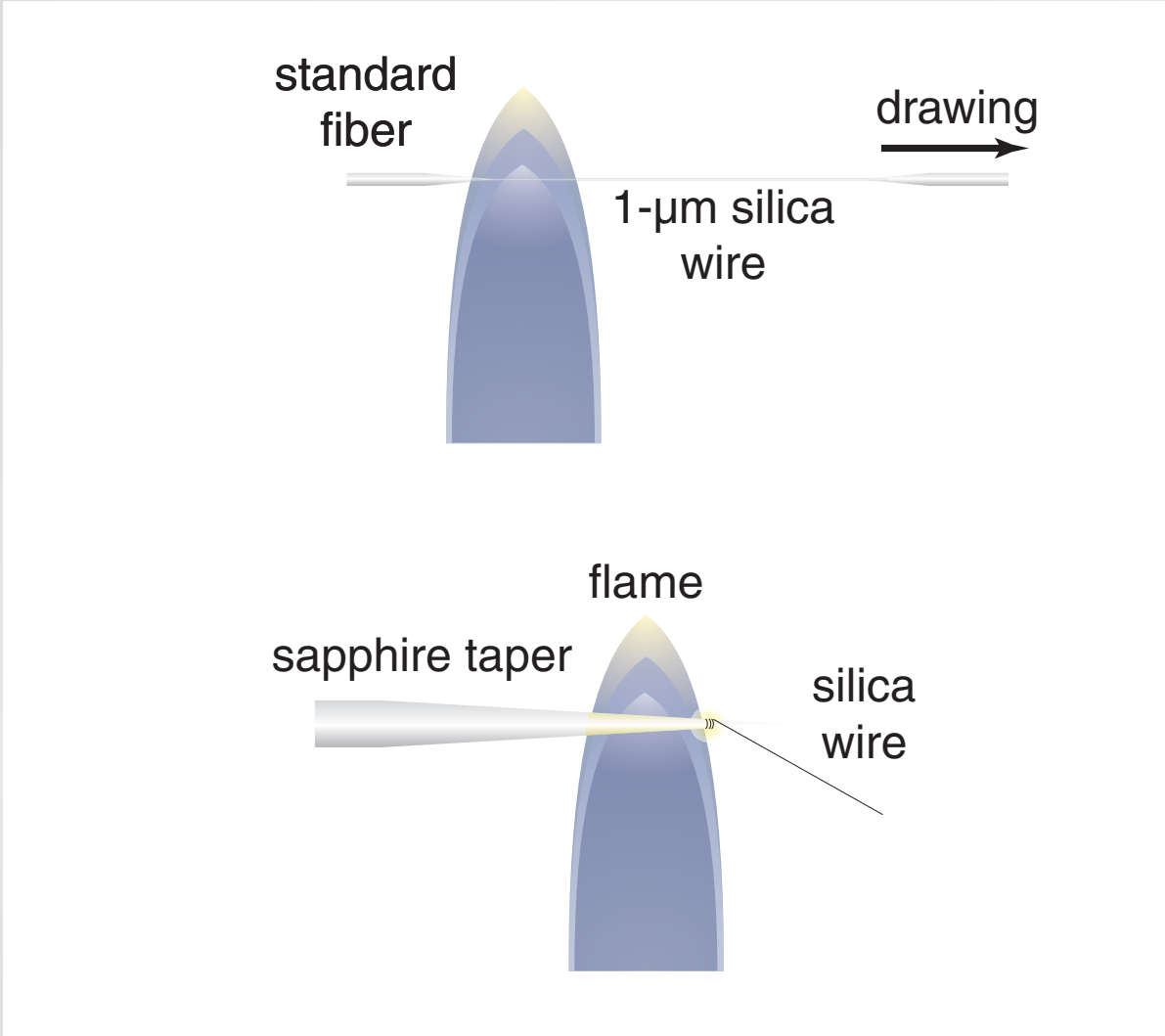

Nanowire fabrication

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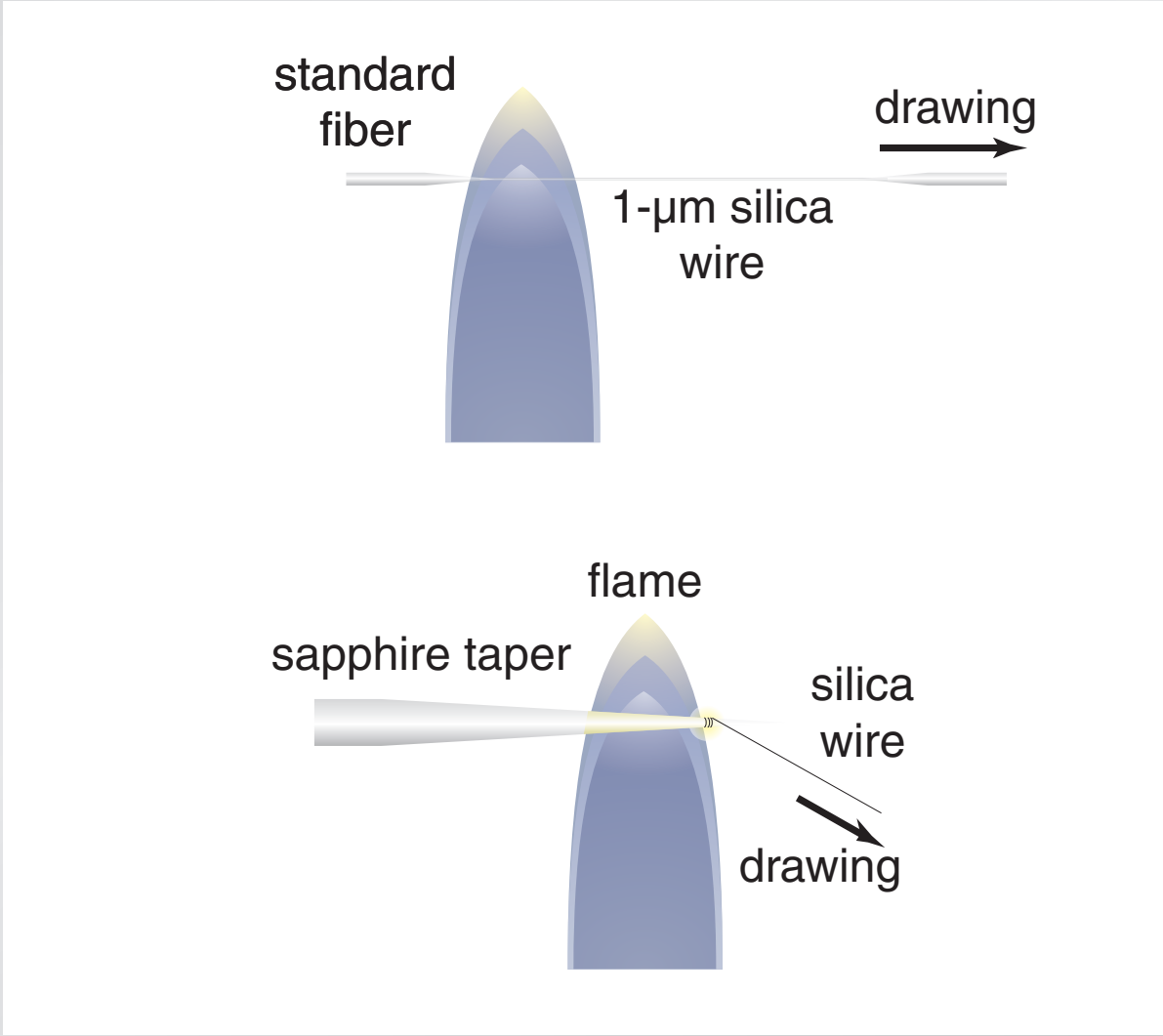
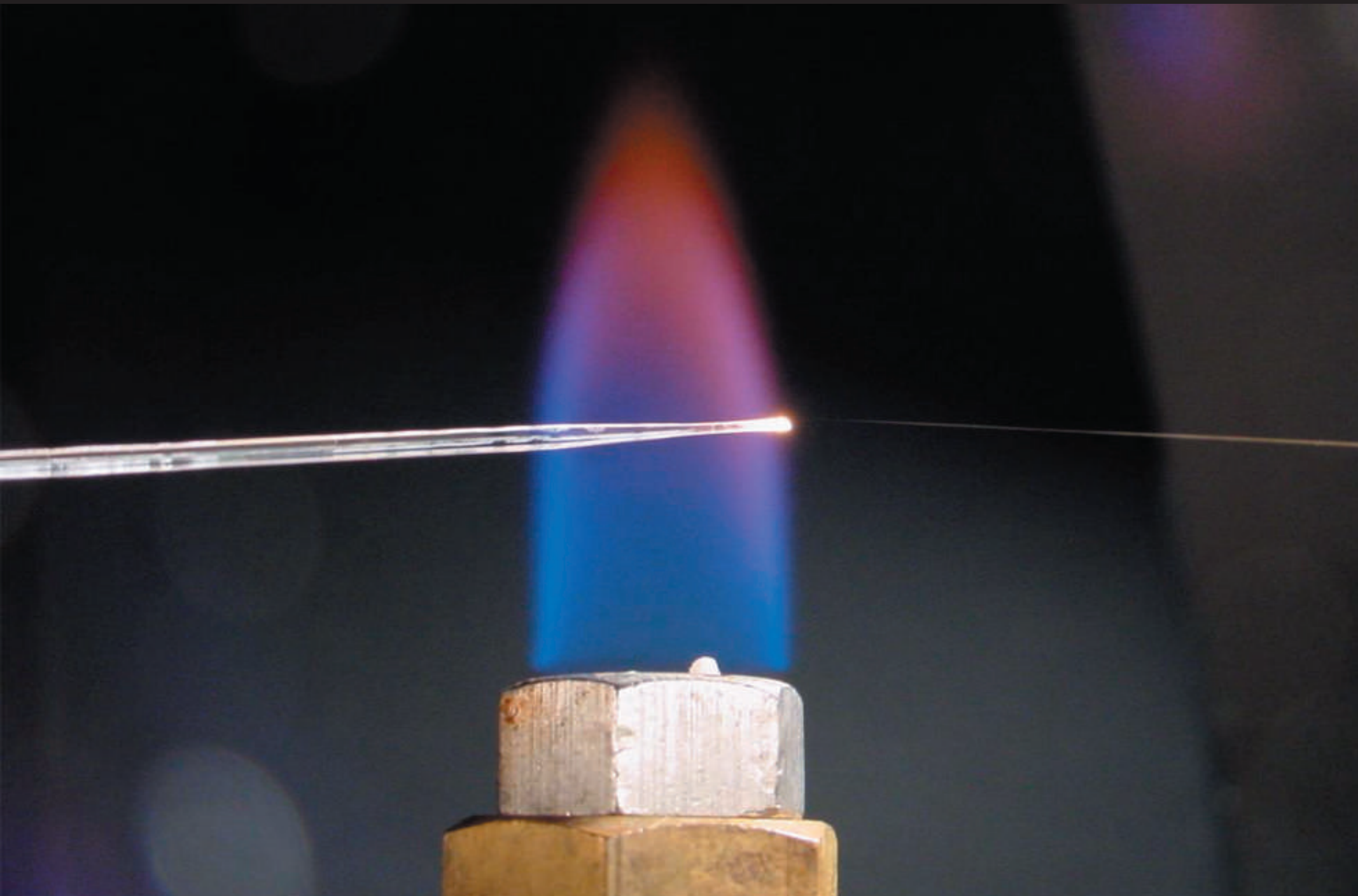


Nanowire fabrication

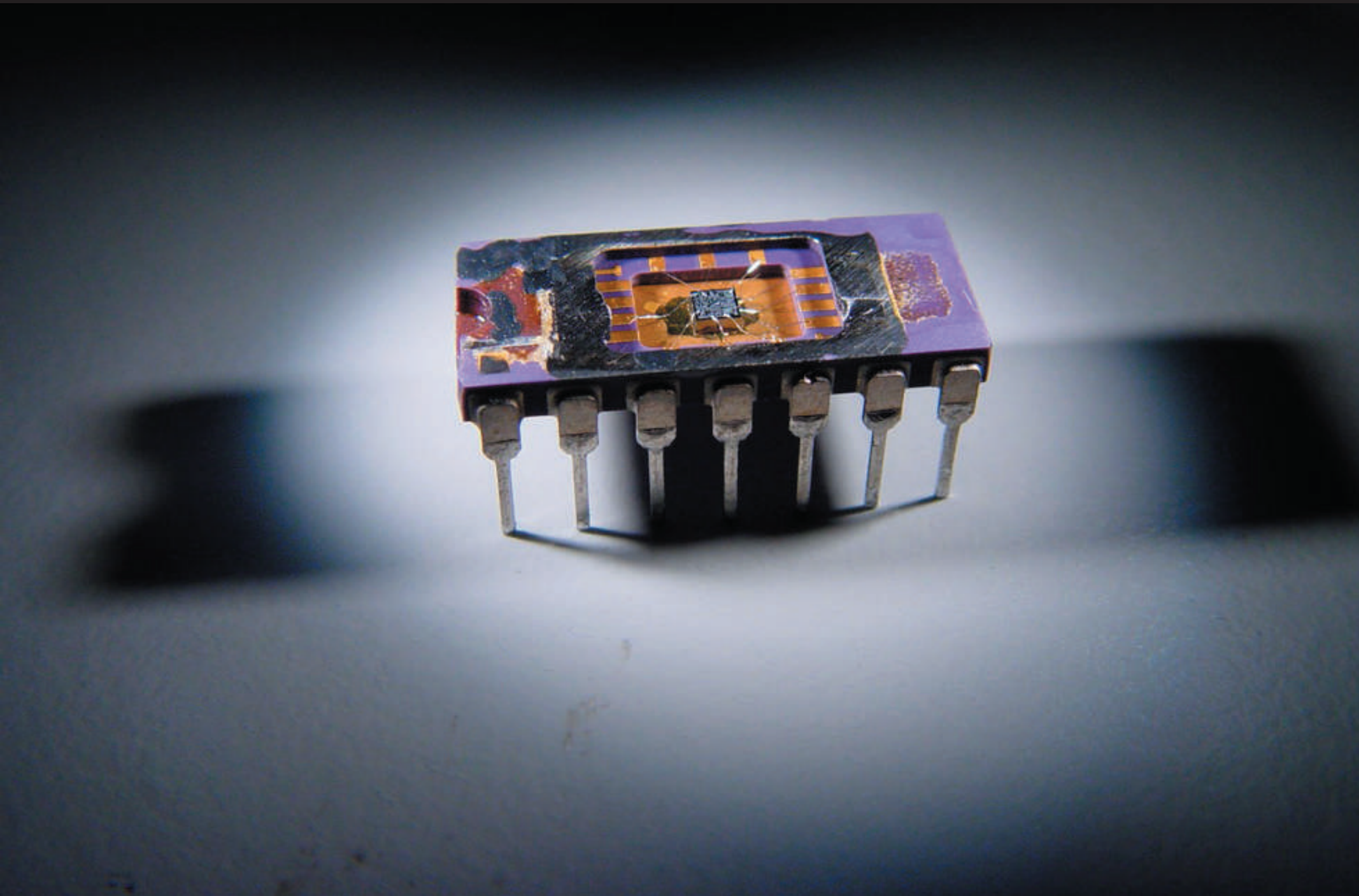


Nanowire fabrication

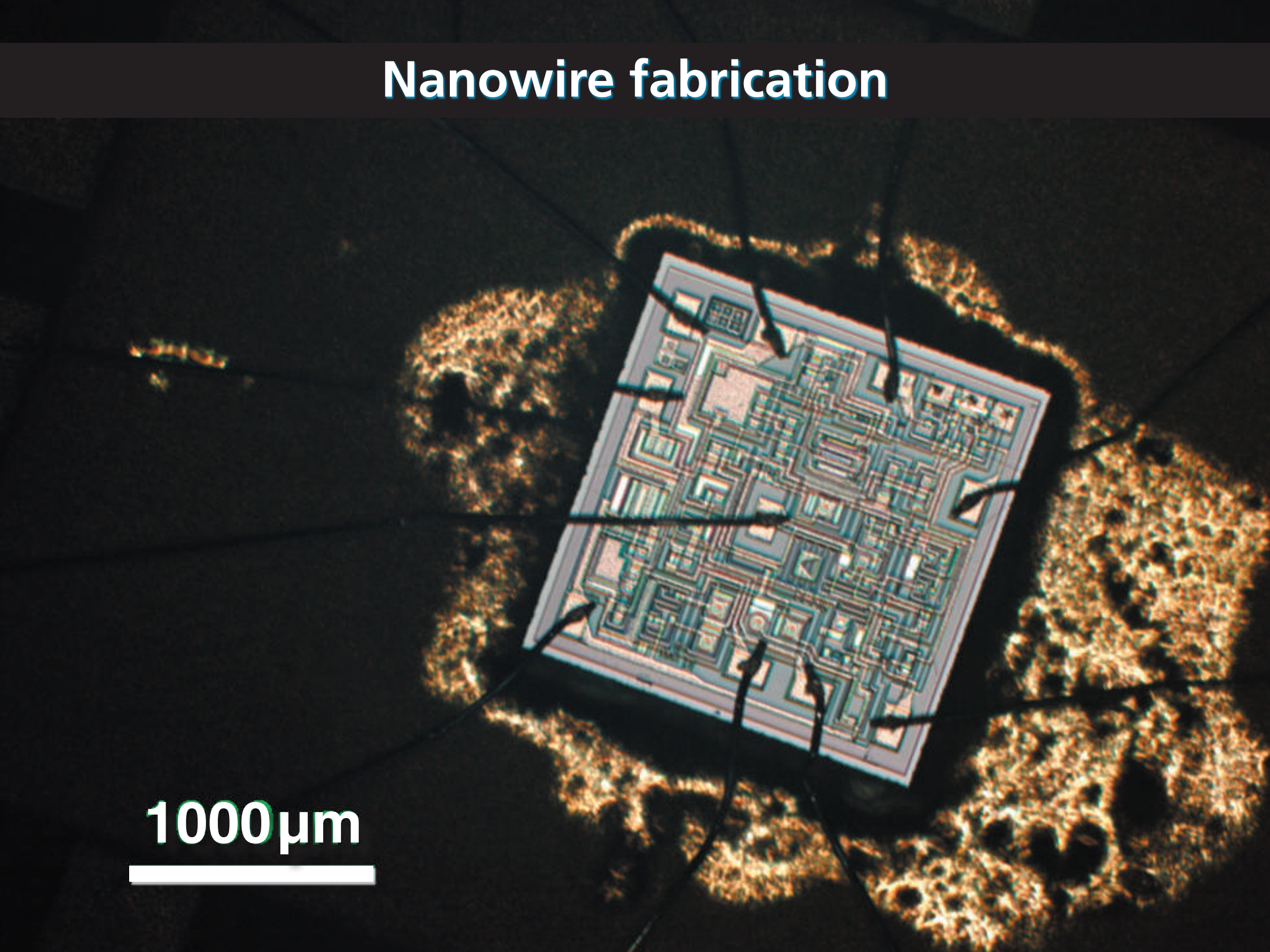
1 μm

Nature, 426, 816 (2003)

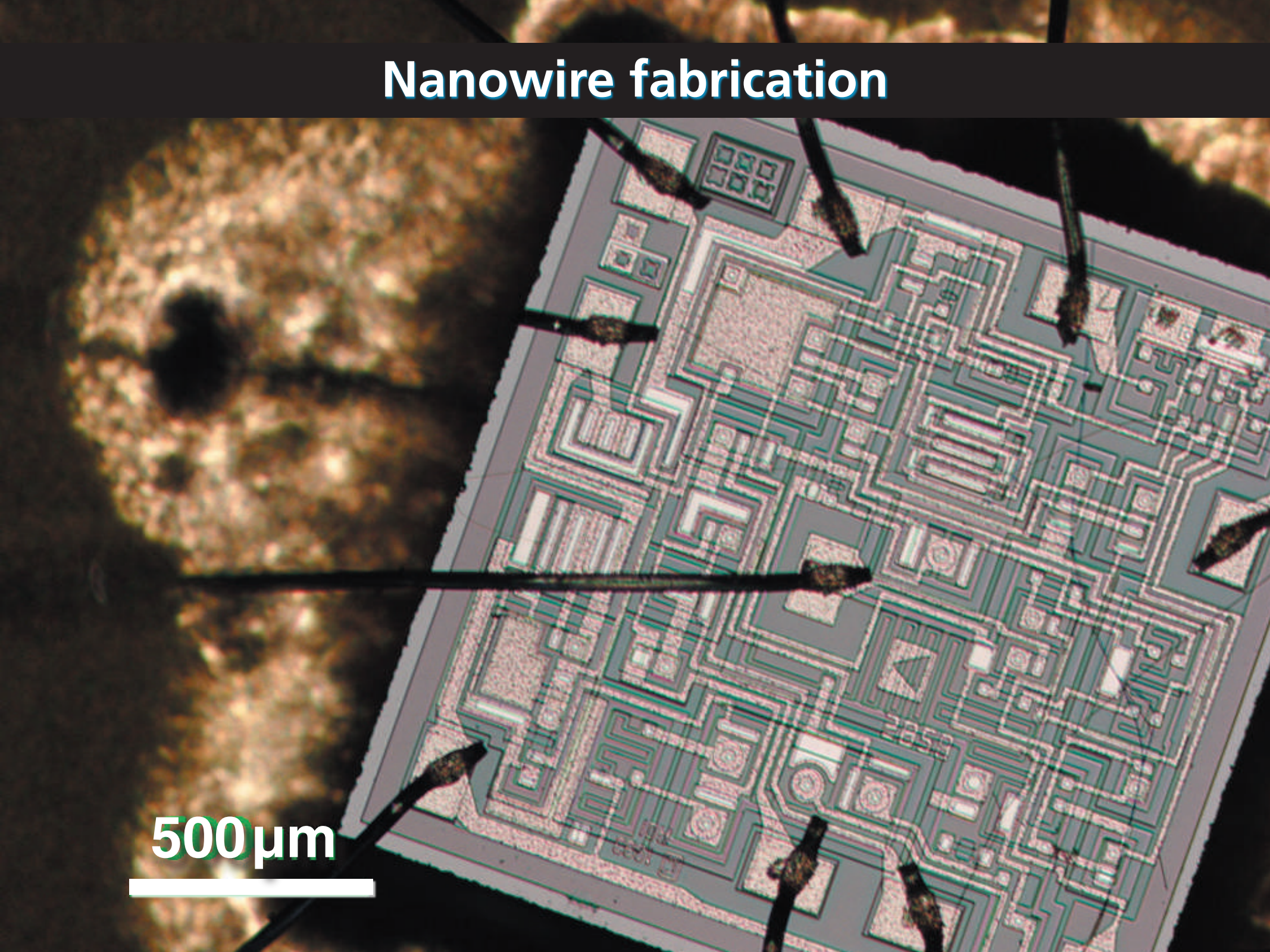
Nanowire fabrication



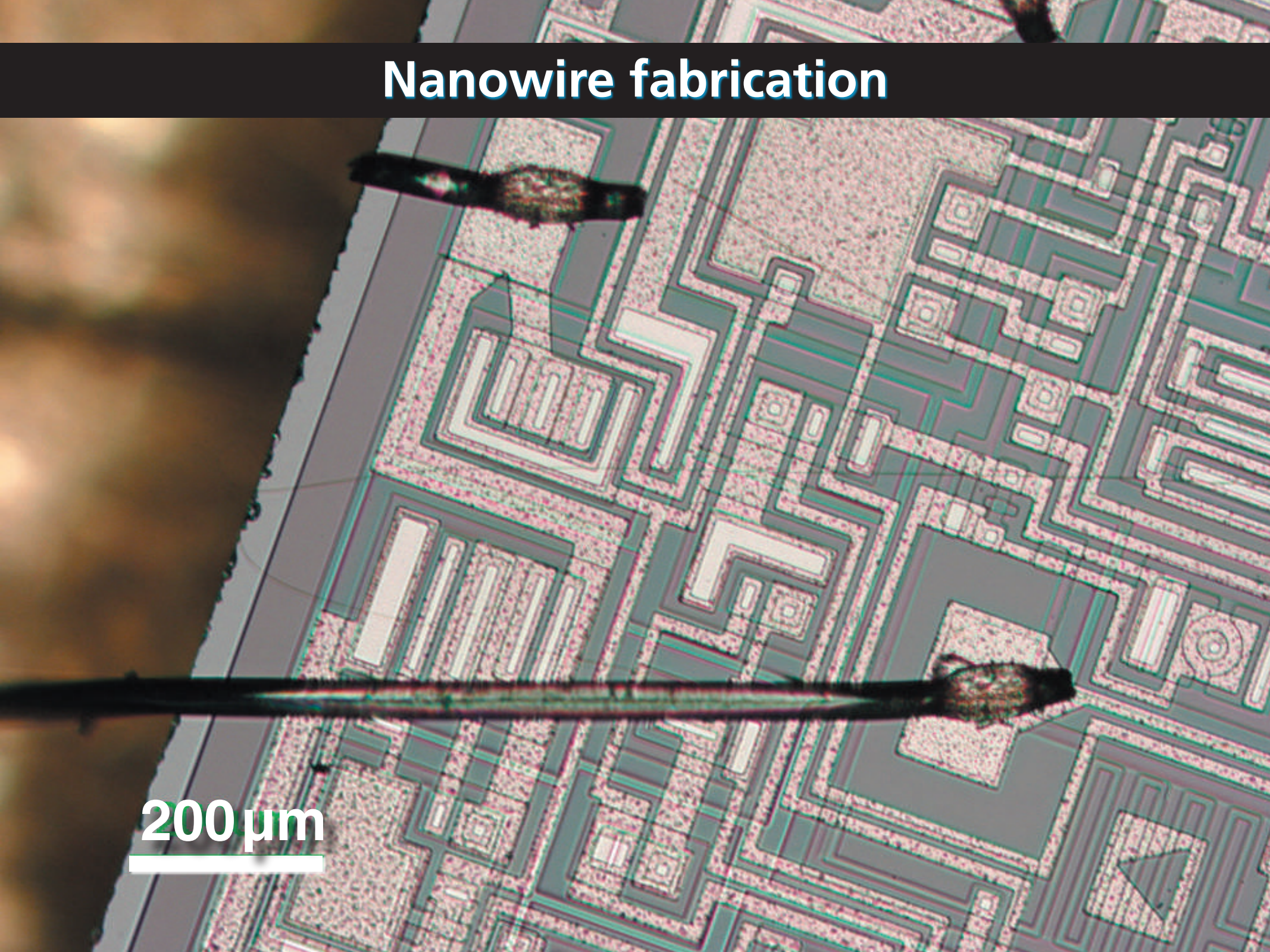
Nanowire fabrication



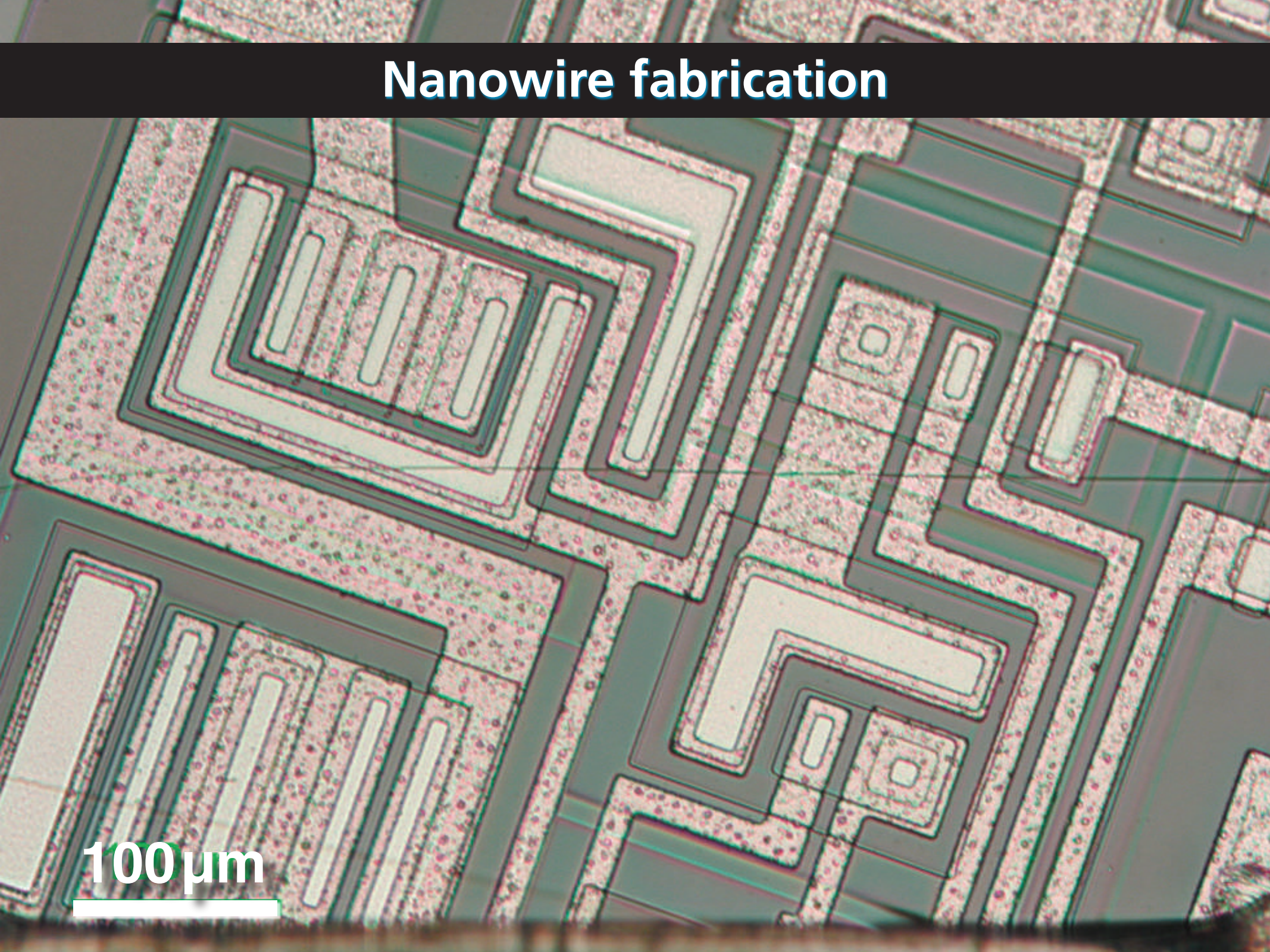
Nanowire fabrication



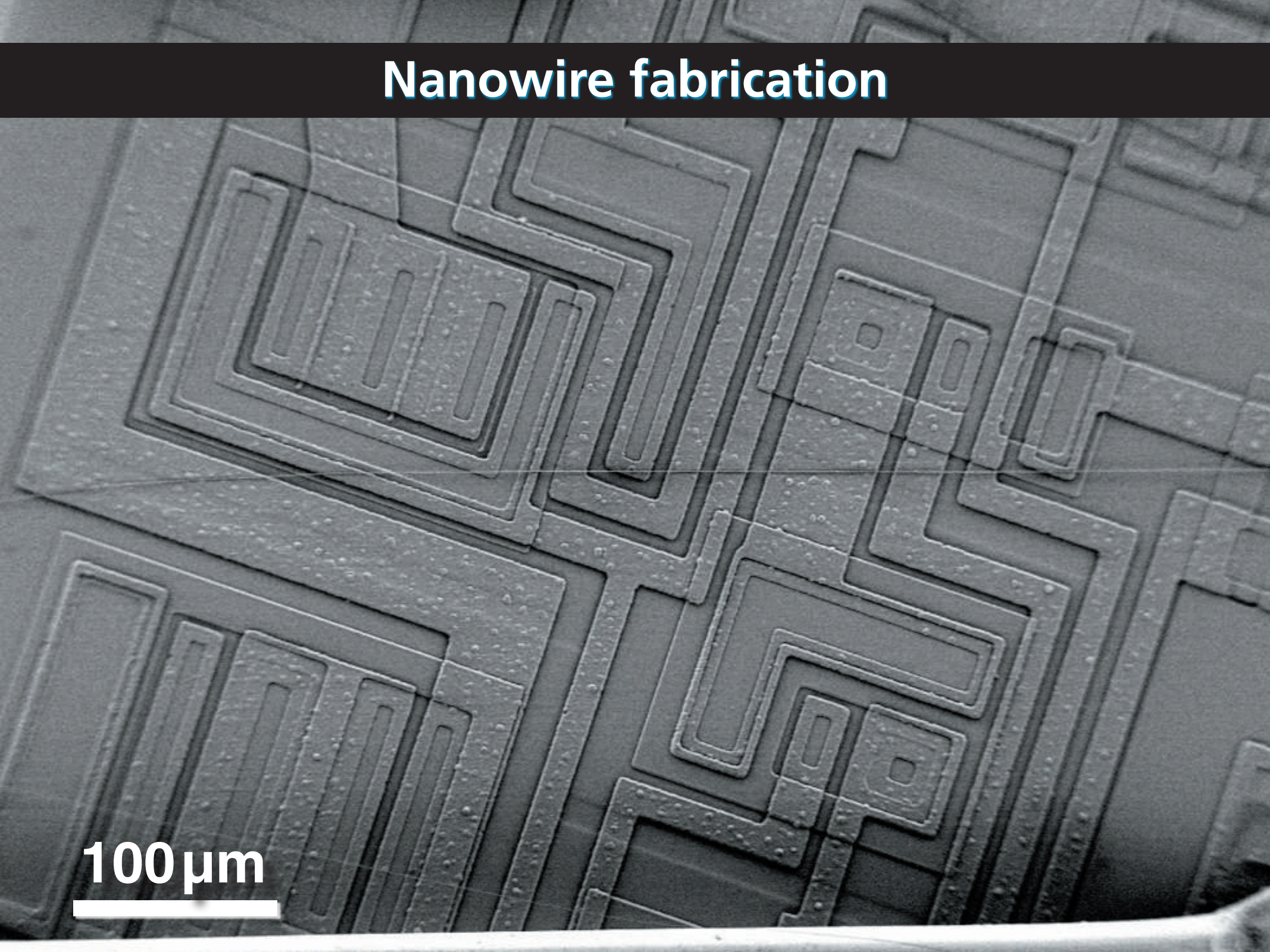
Nanowire fabrication



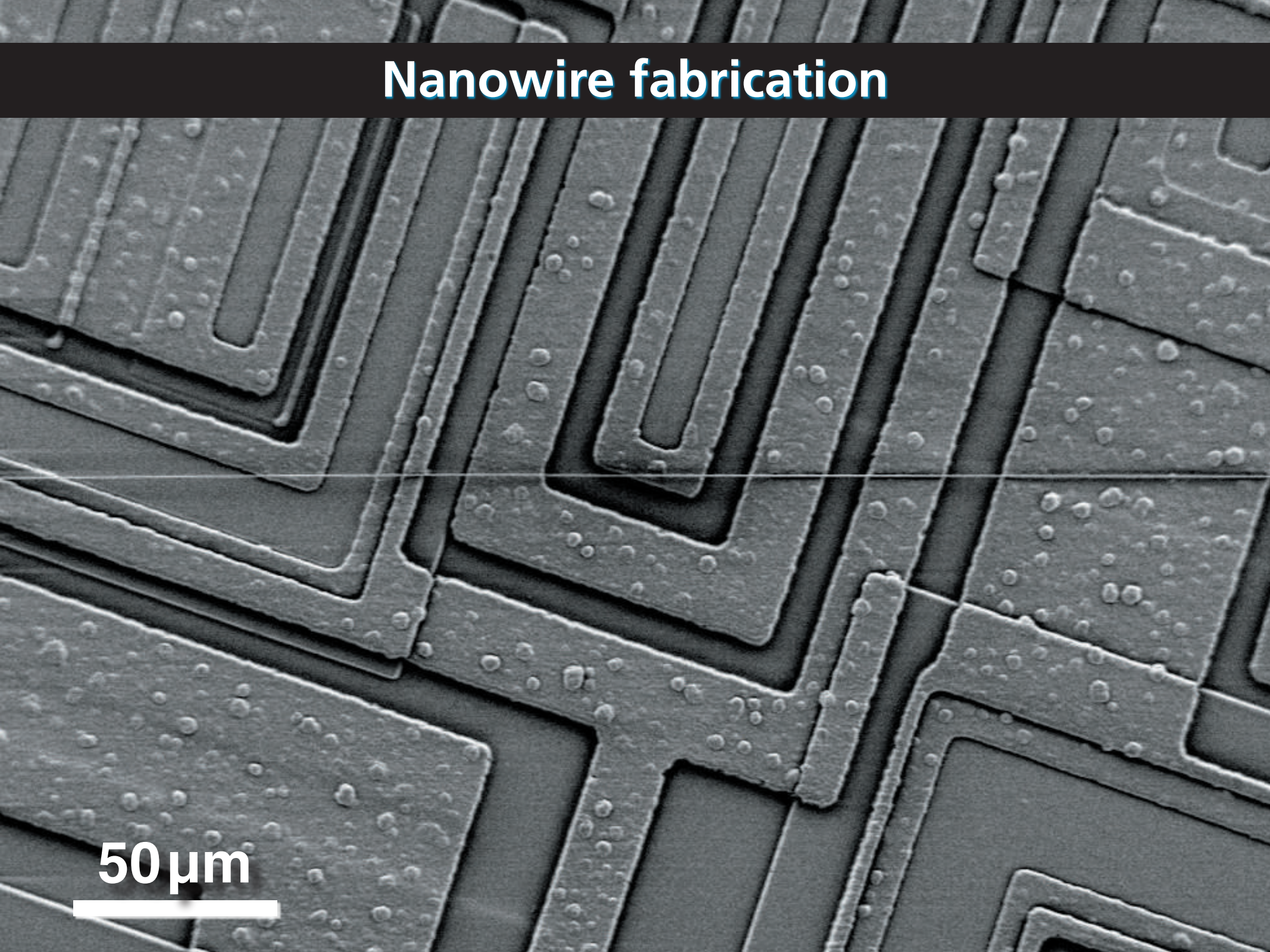
Nanowire fabrication



Nanowire fabrication



Nanowire fabrication



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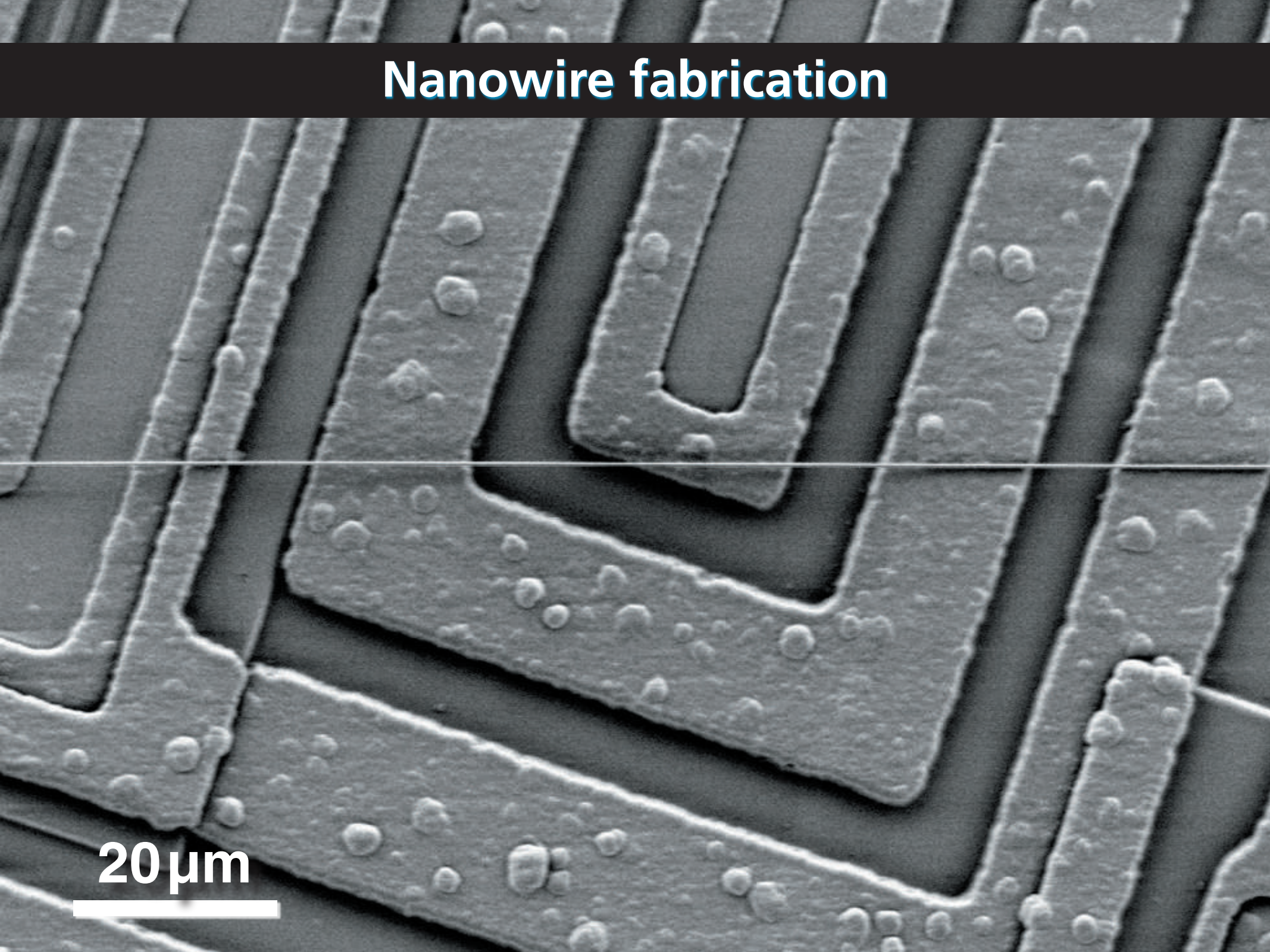

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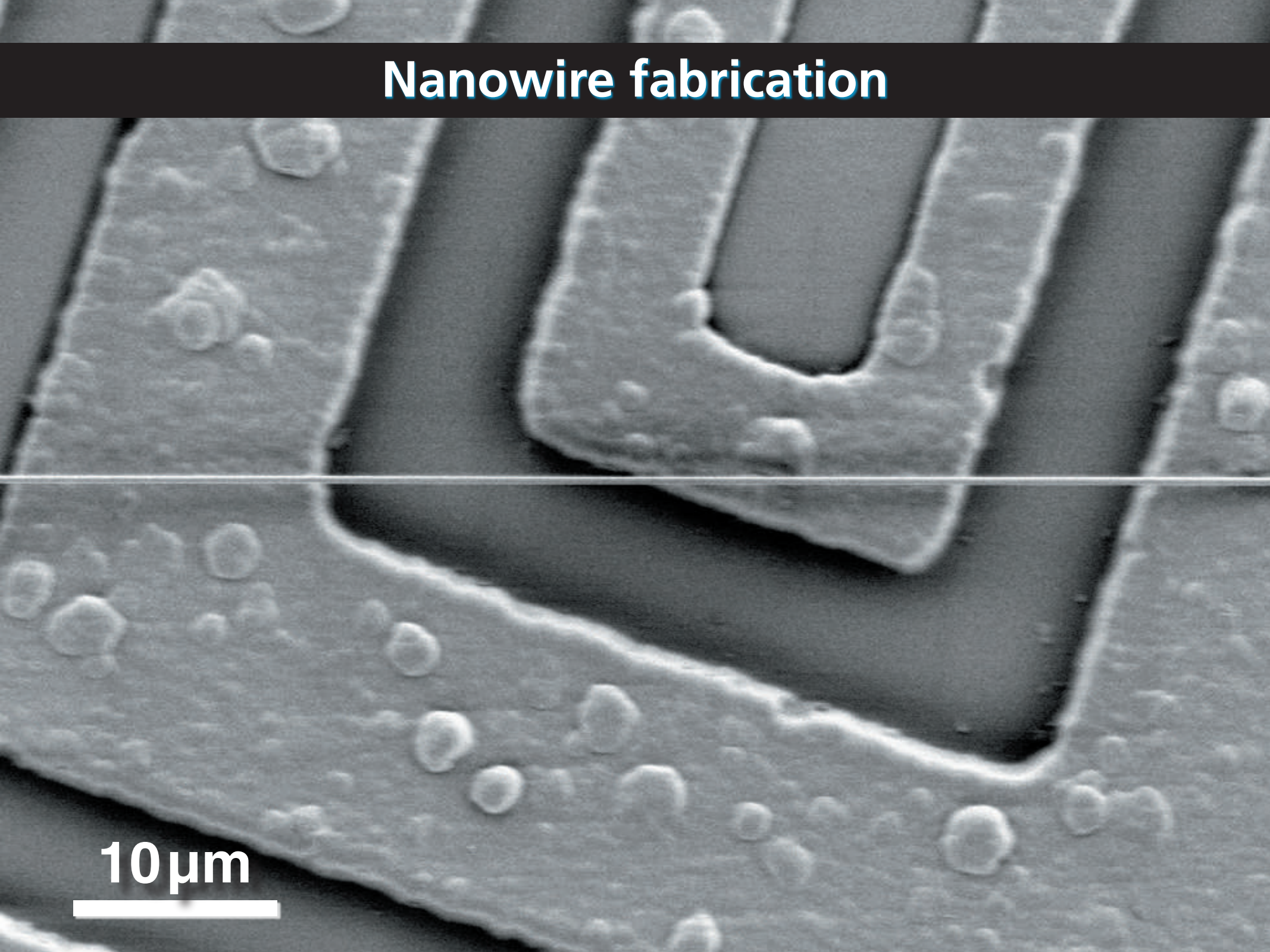

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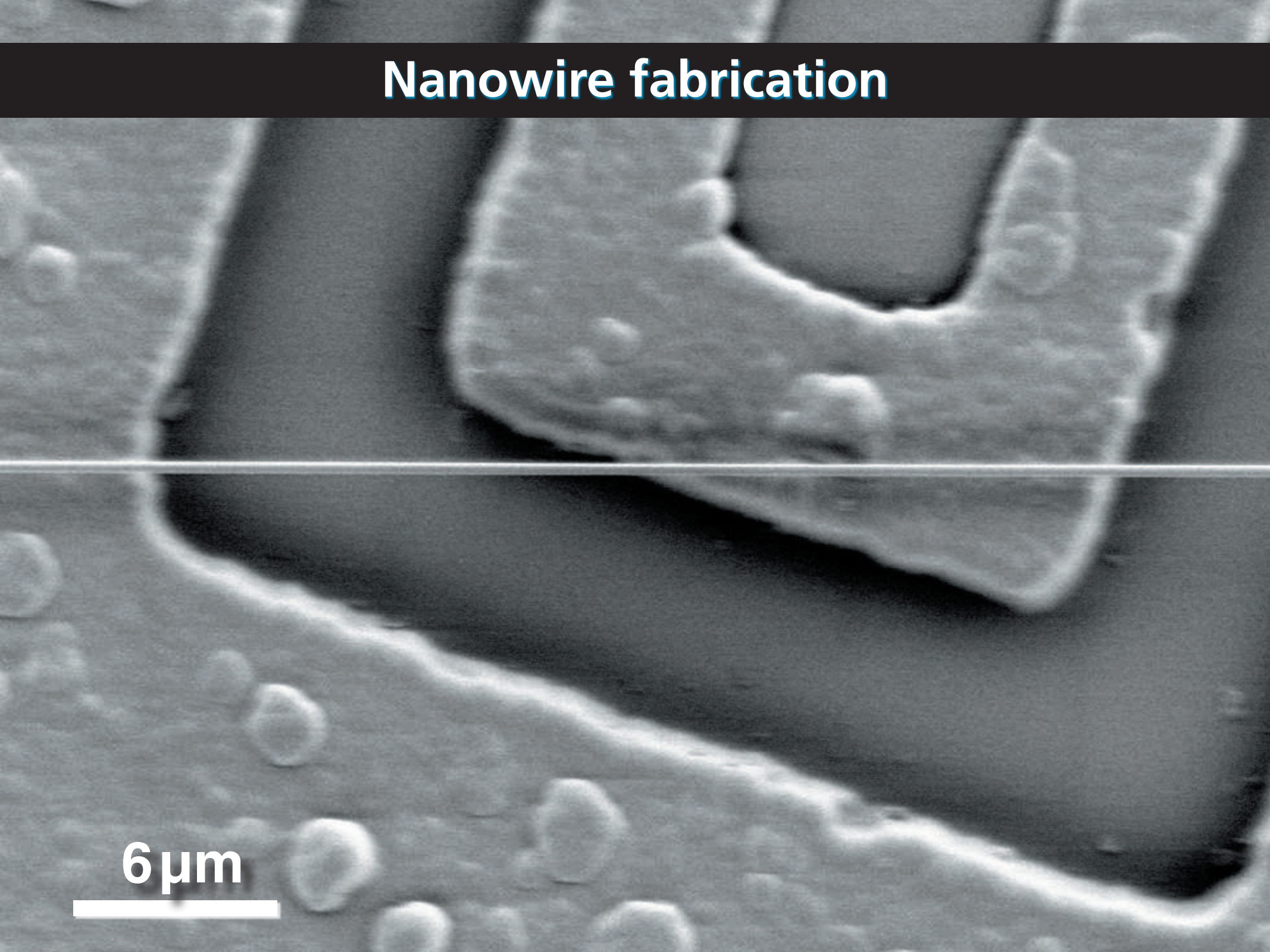
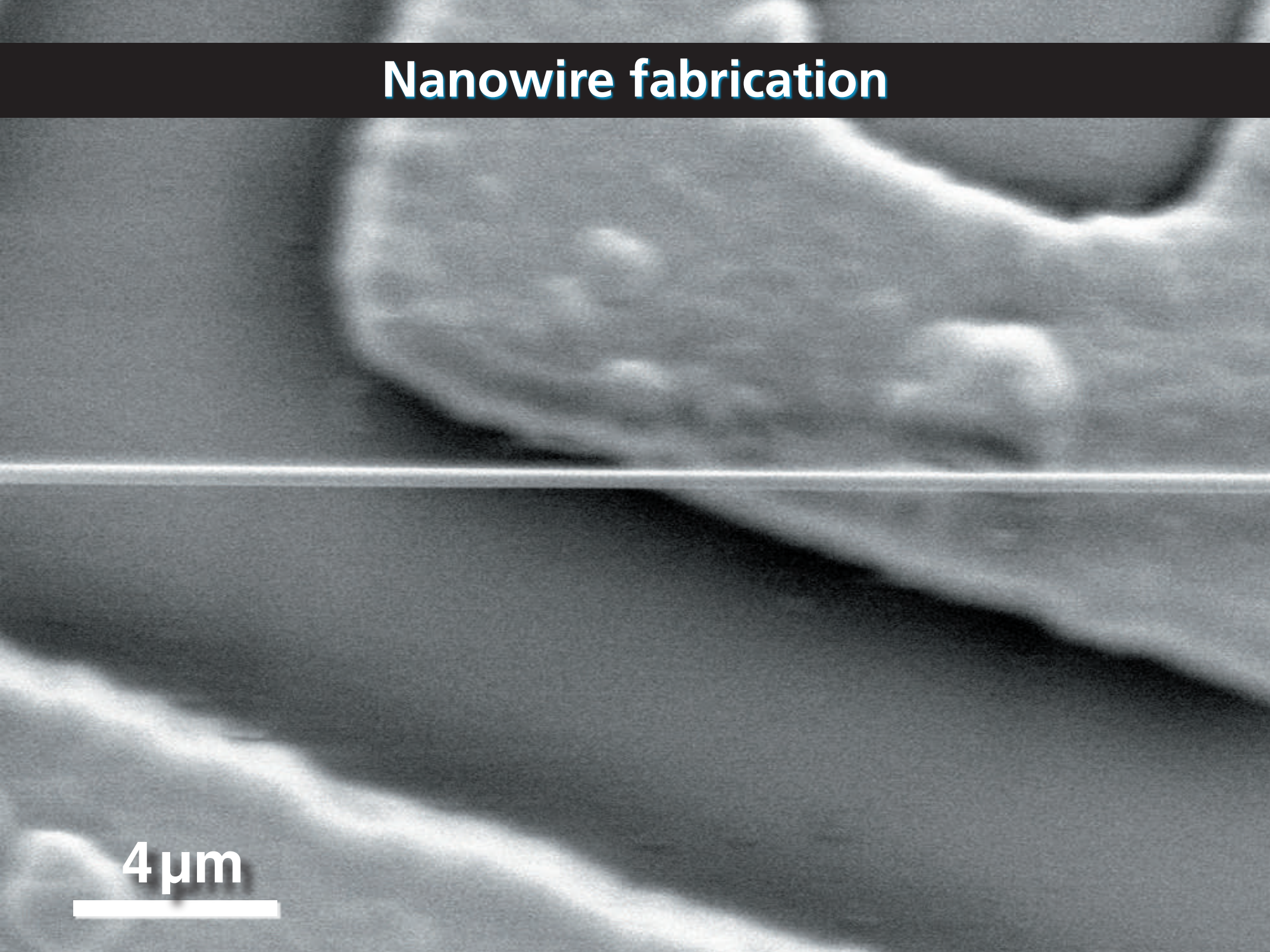
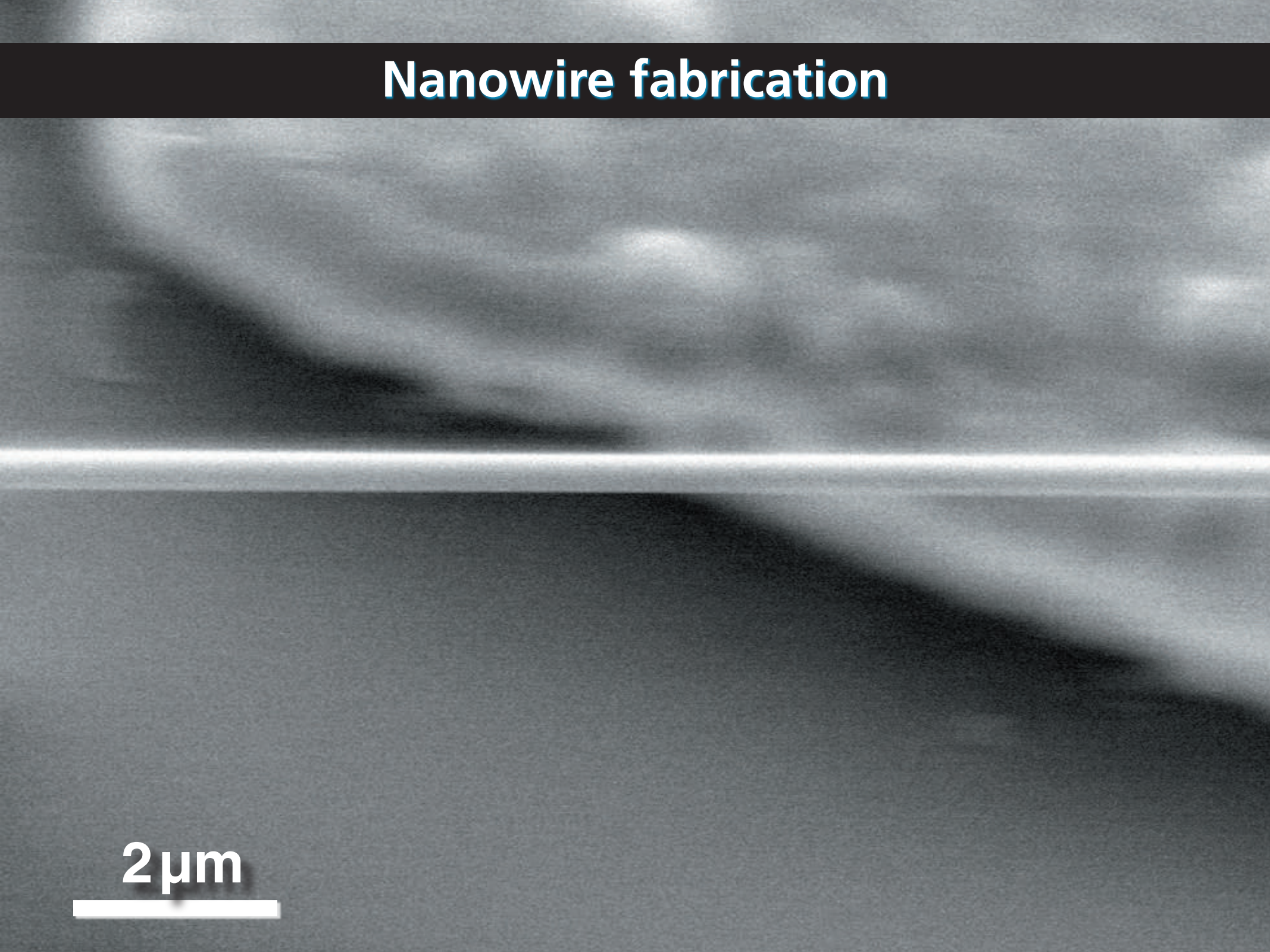


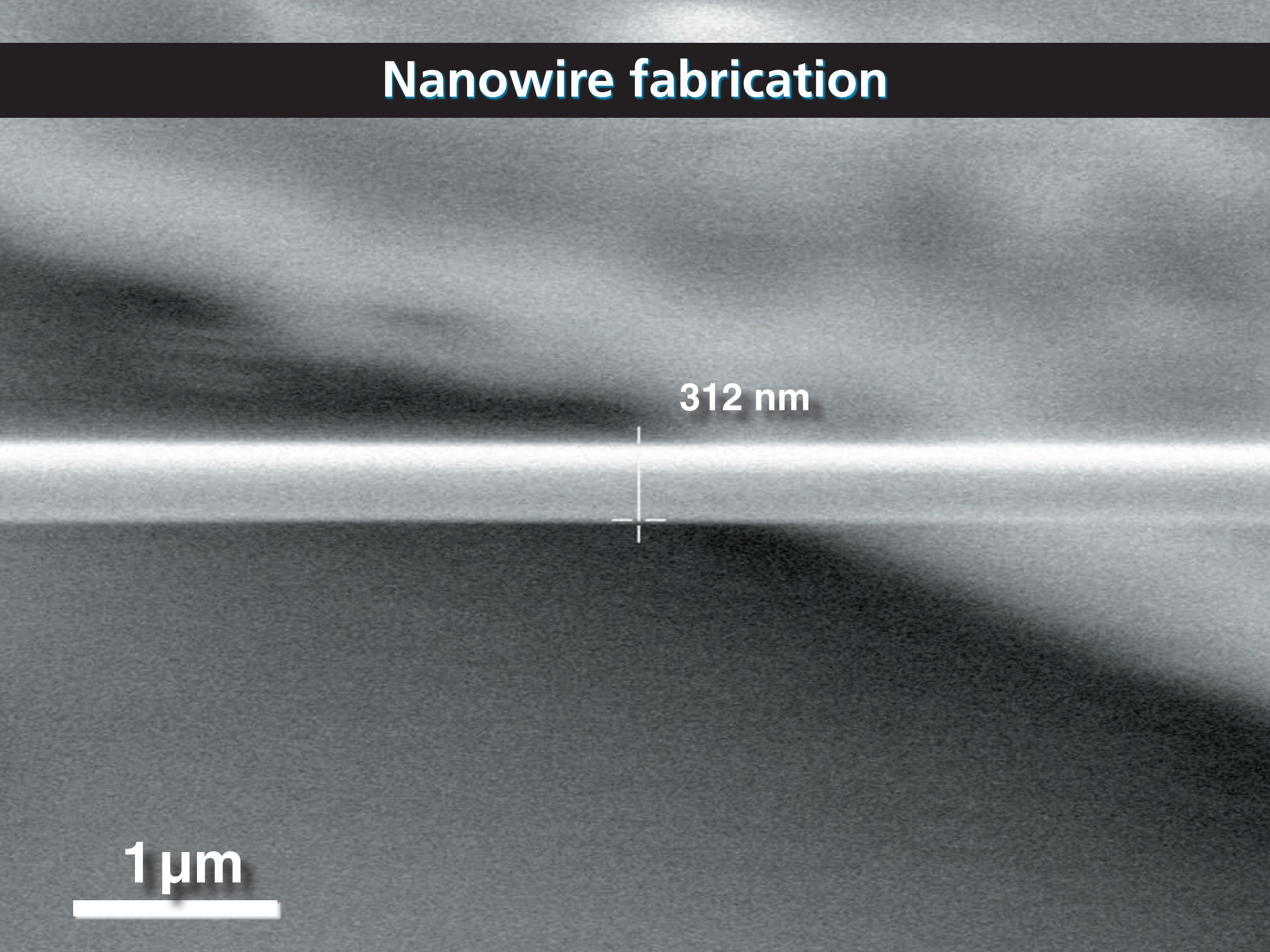
Nanowire fabrication



Nanowire fabrication



Nanowire fabrication

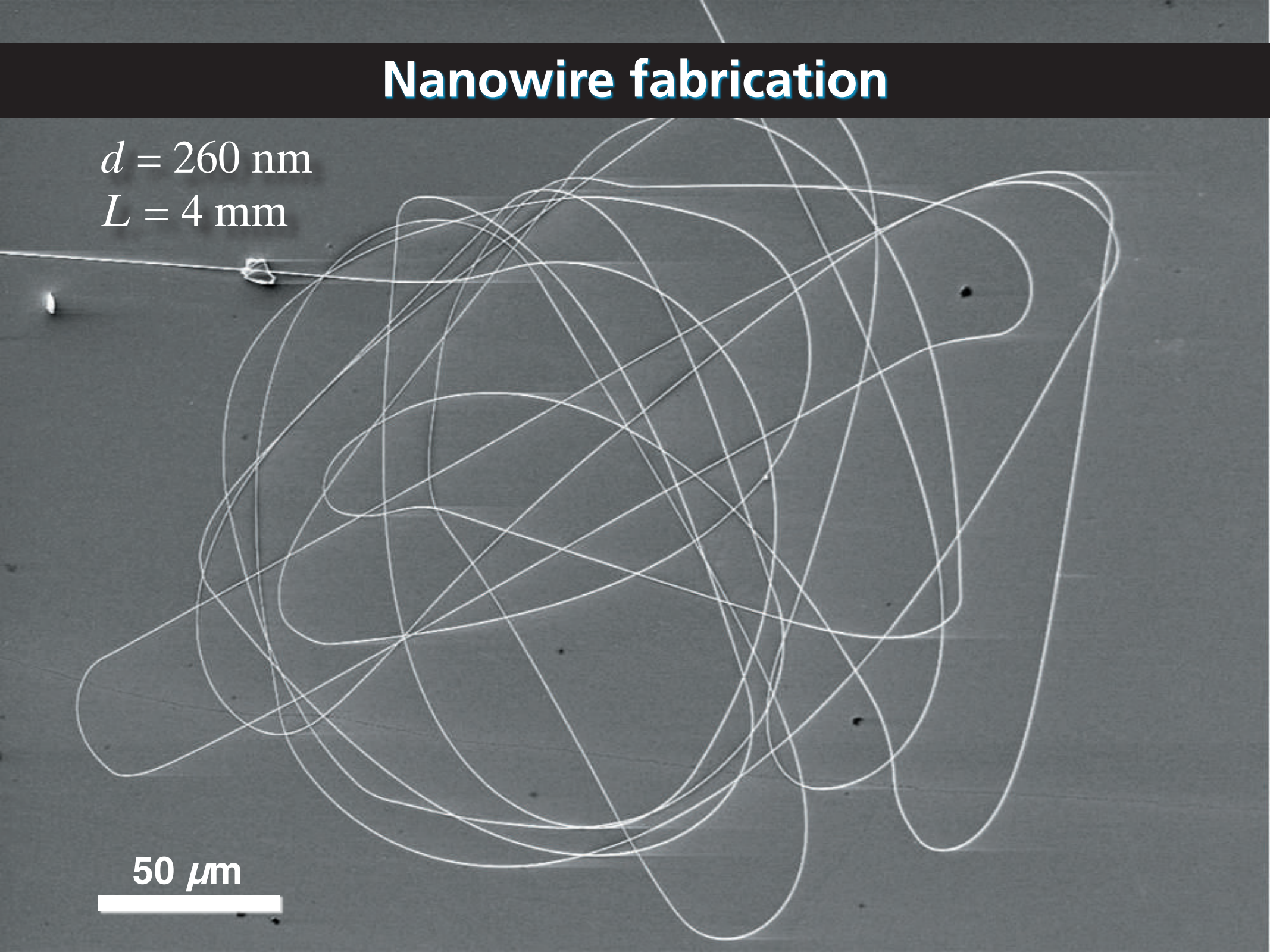


Waveguiding

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 x 10^{-6}

Nanowire fabrication



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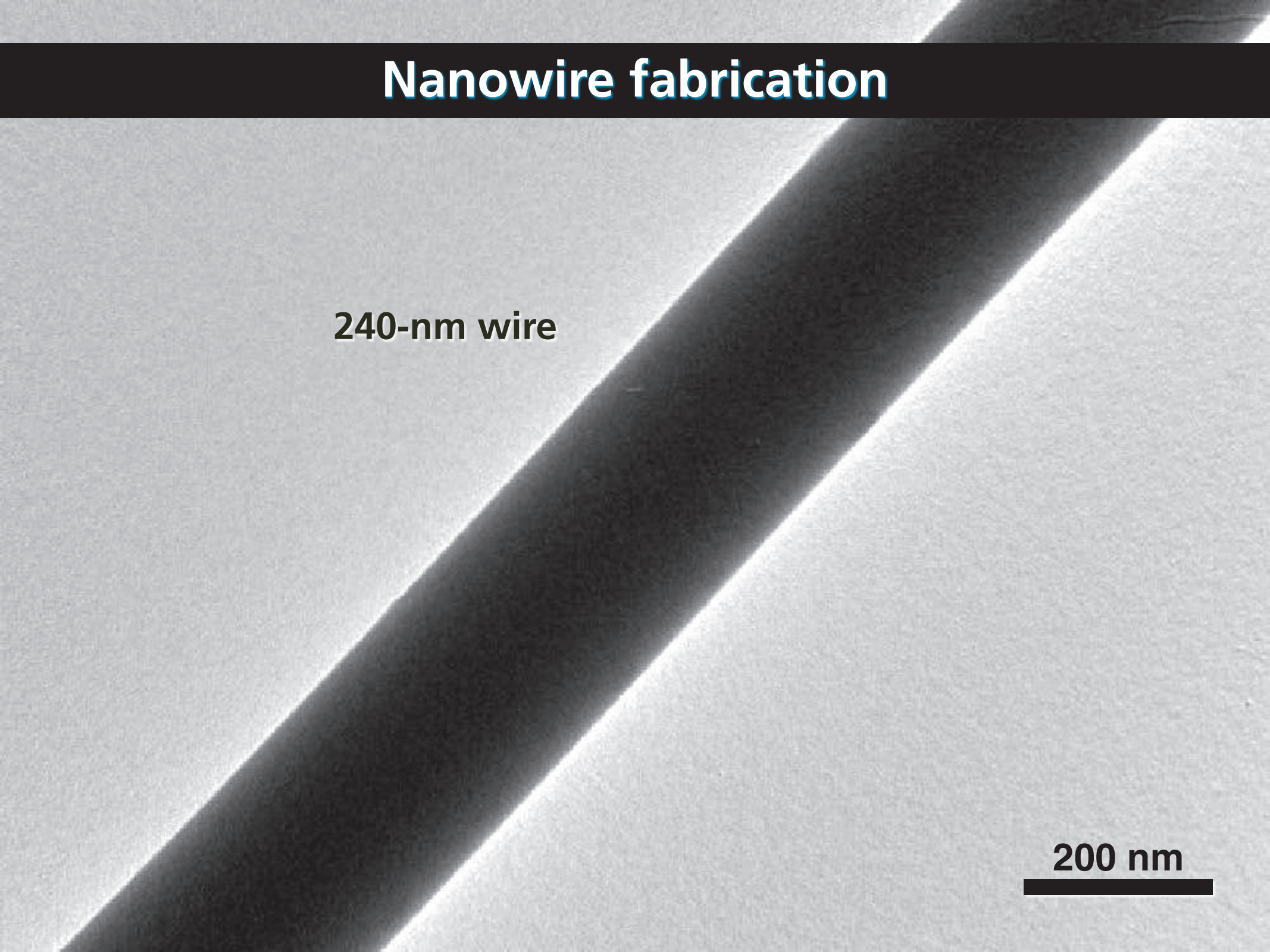

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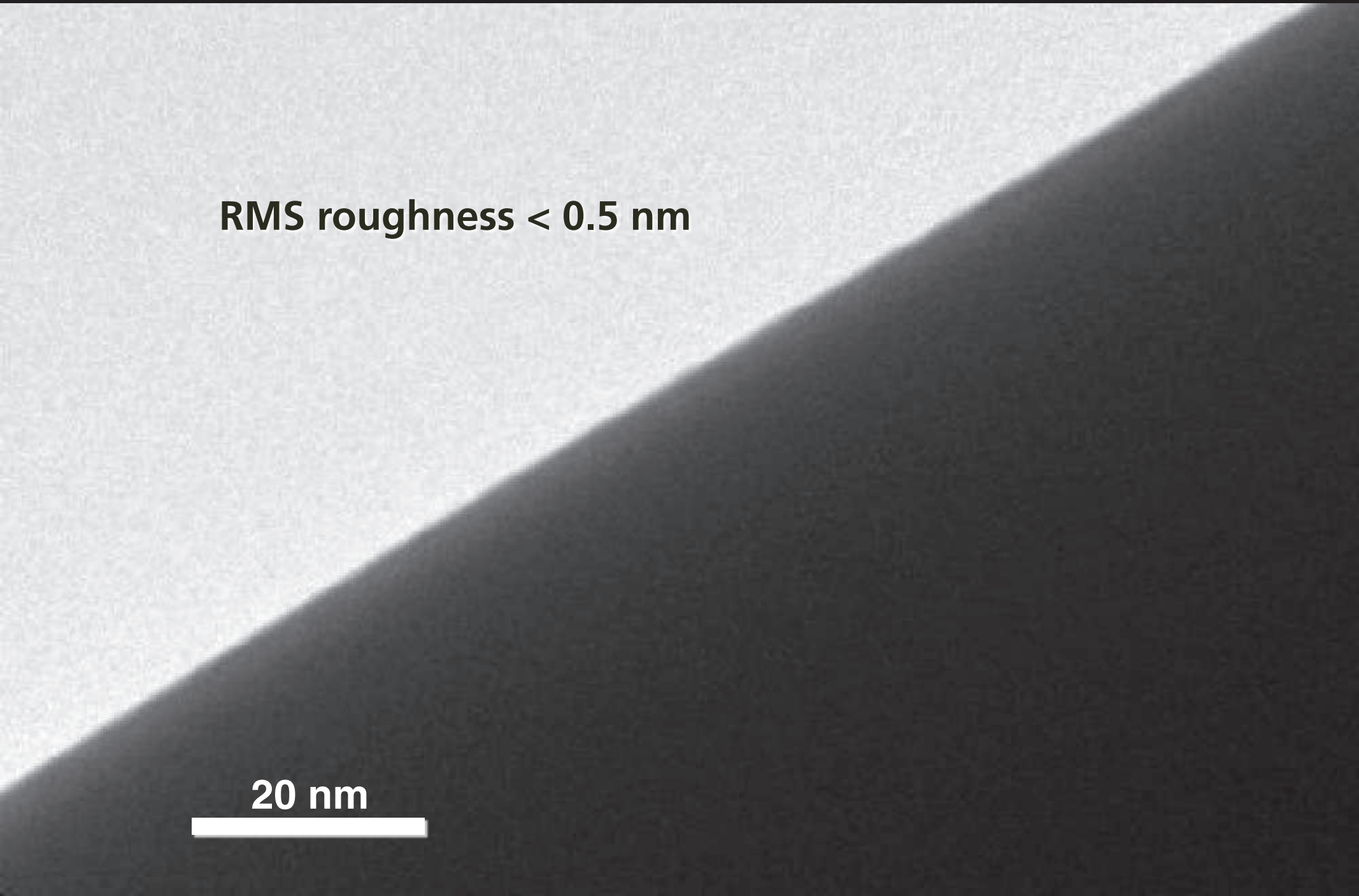

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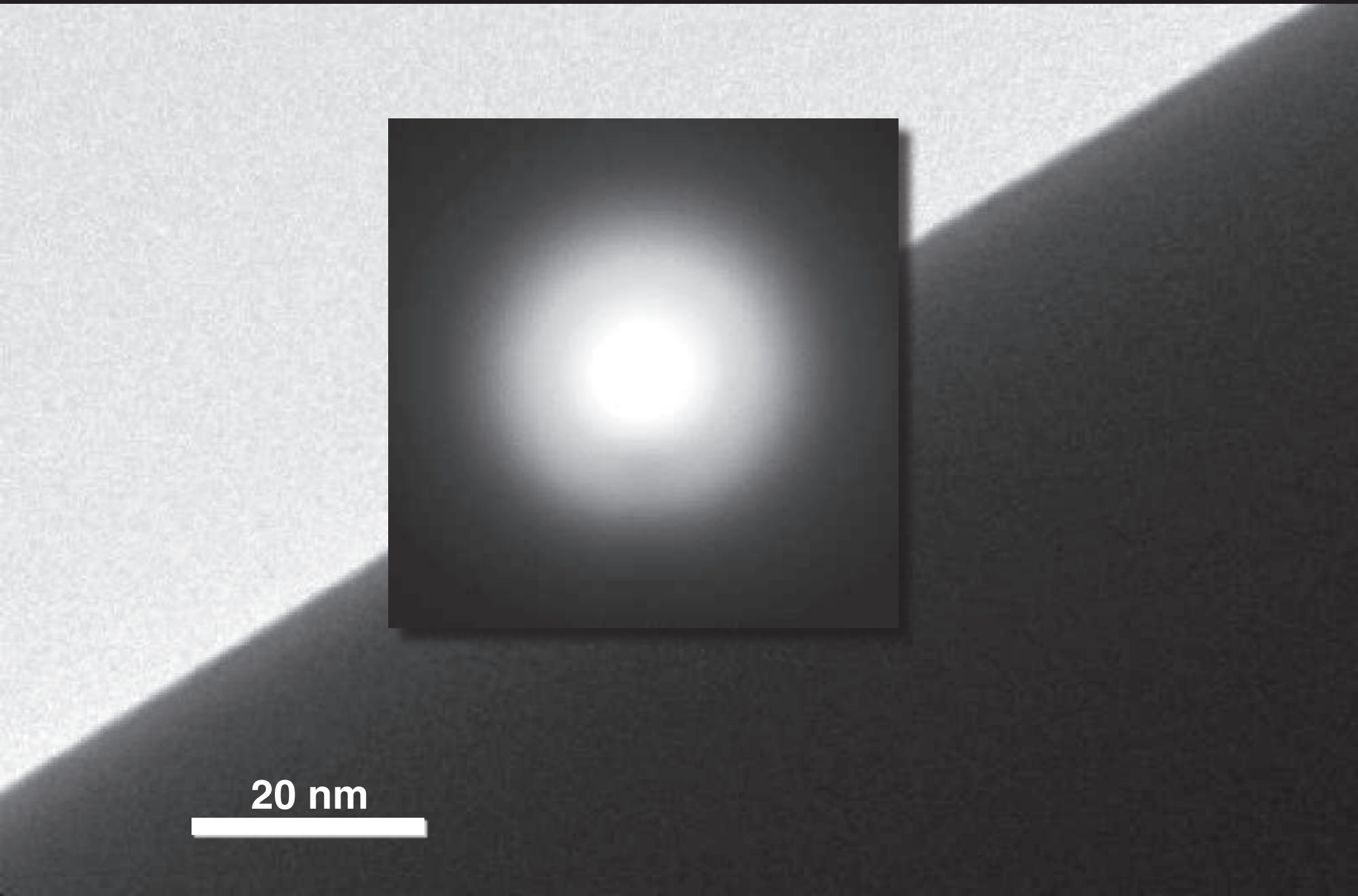

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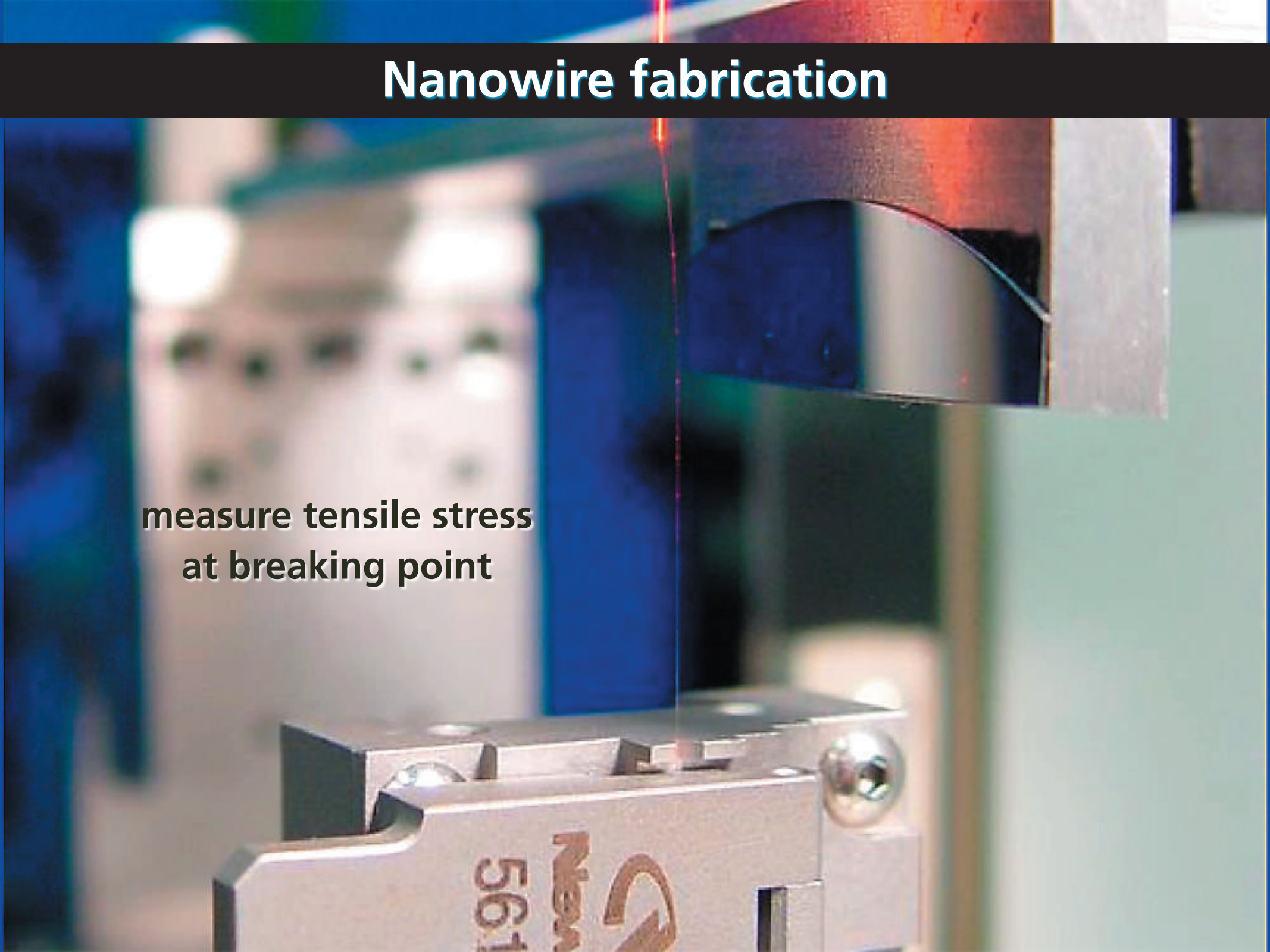

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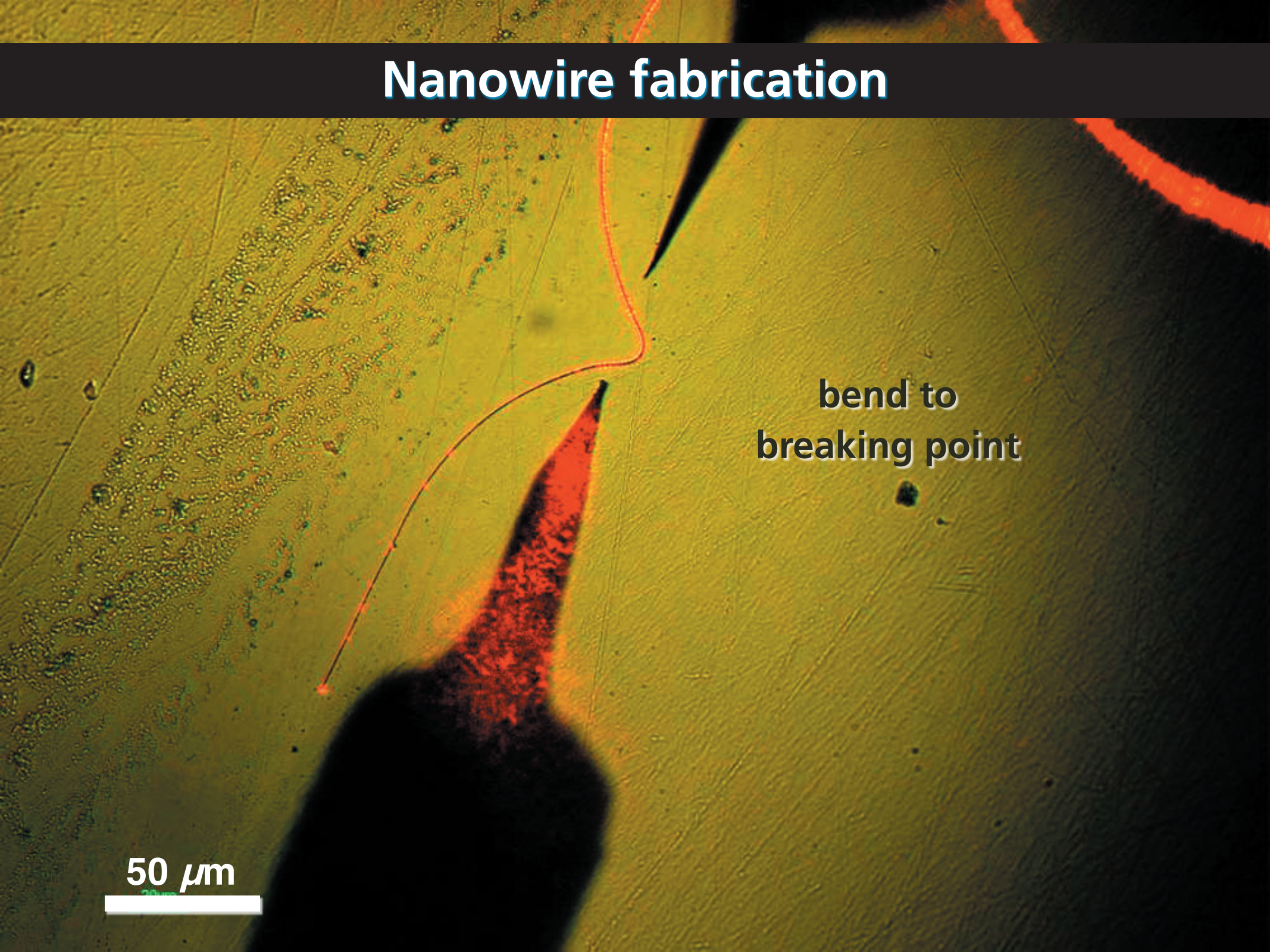
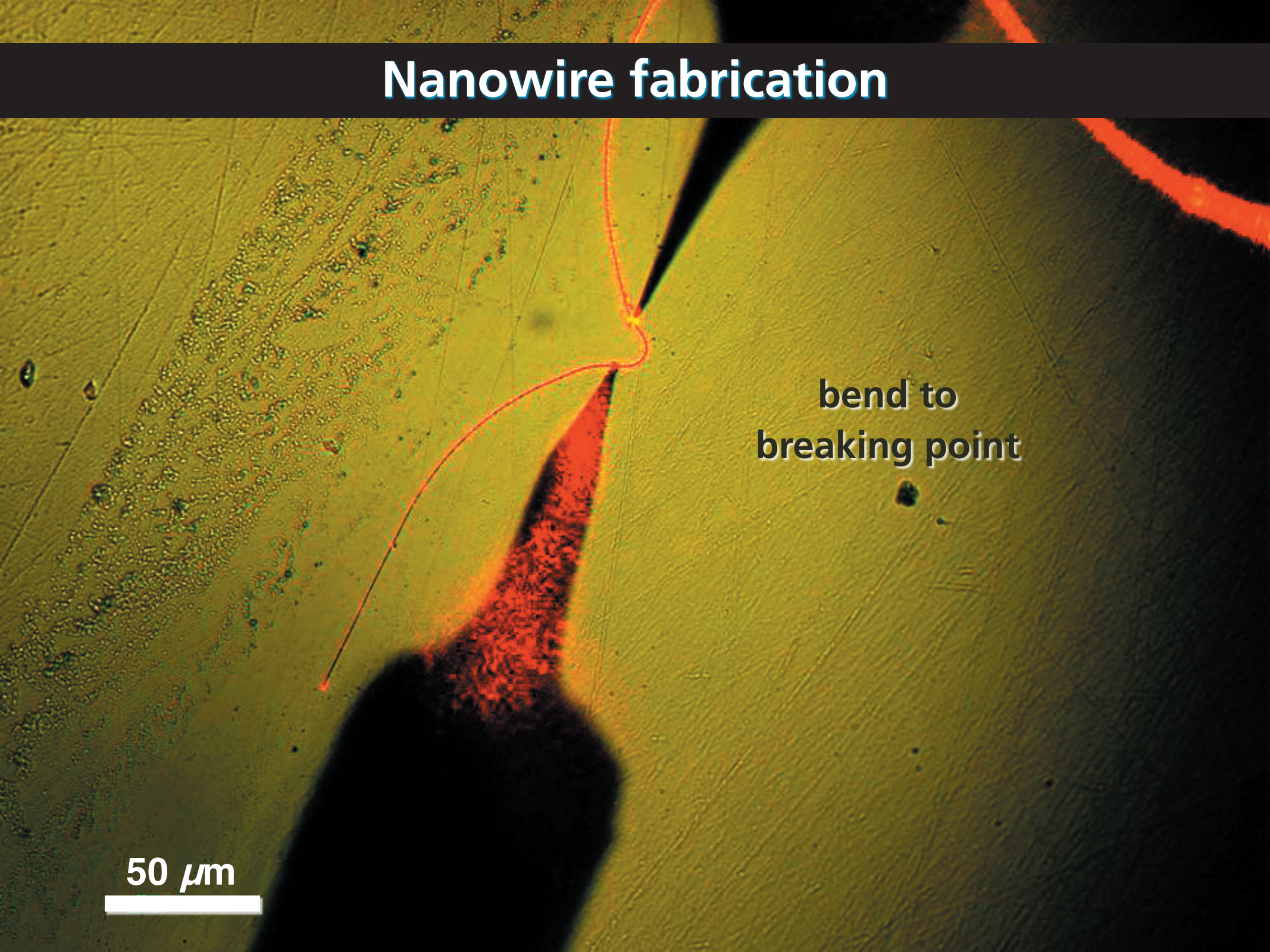


Nanowire fabrication



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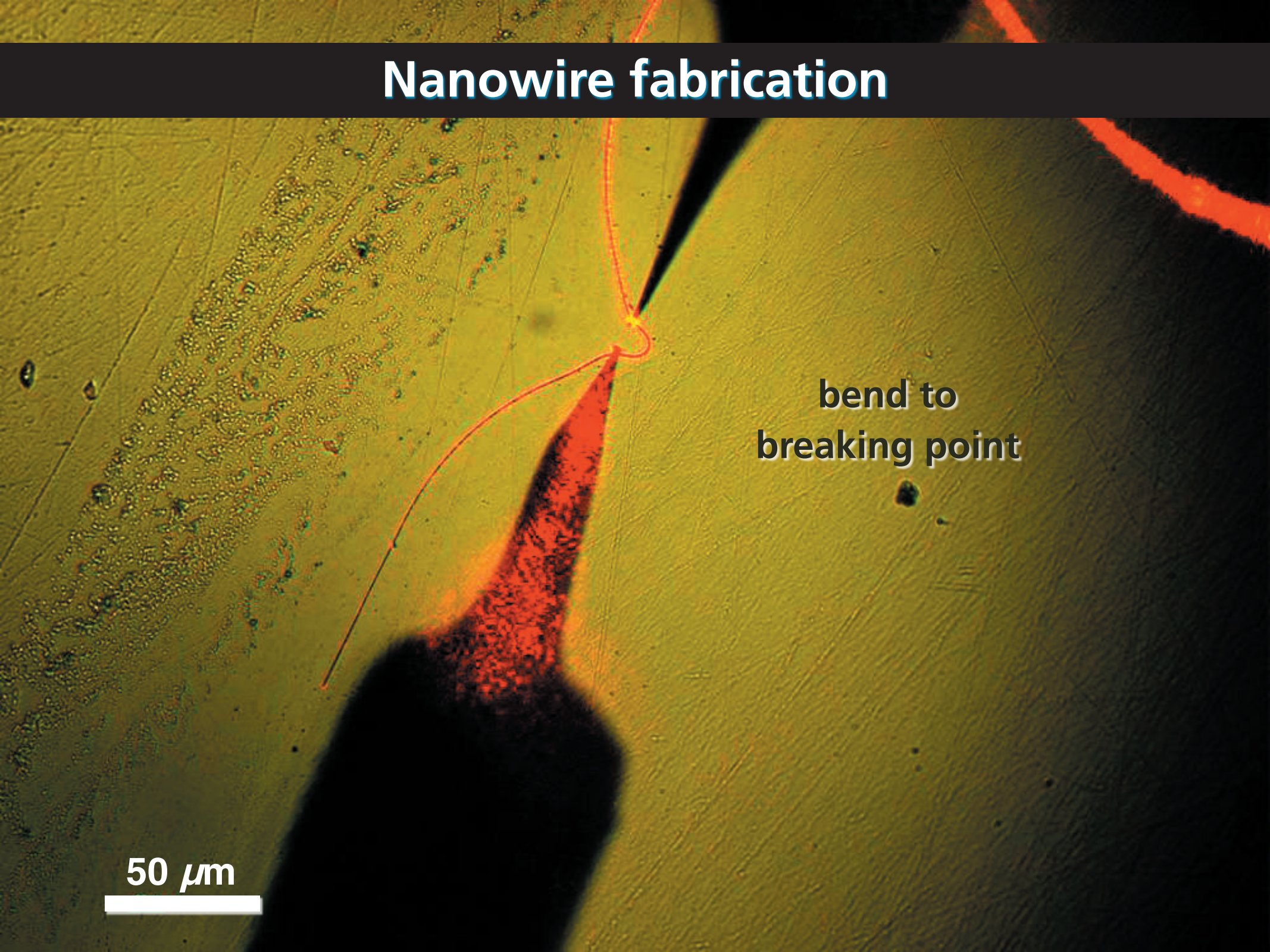
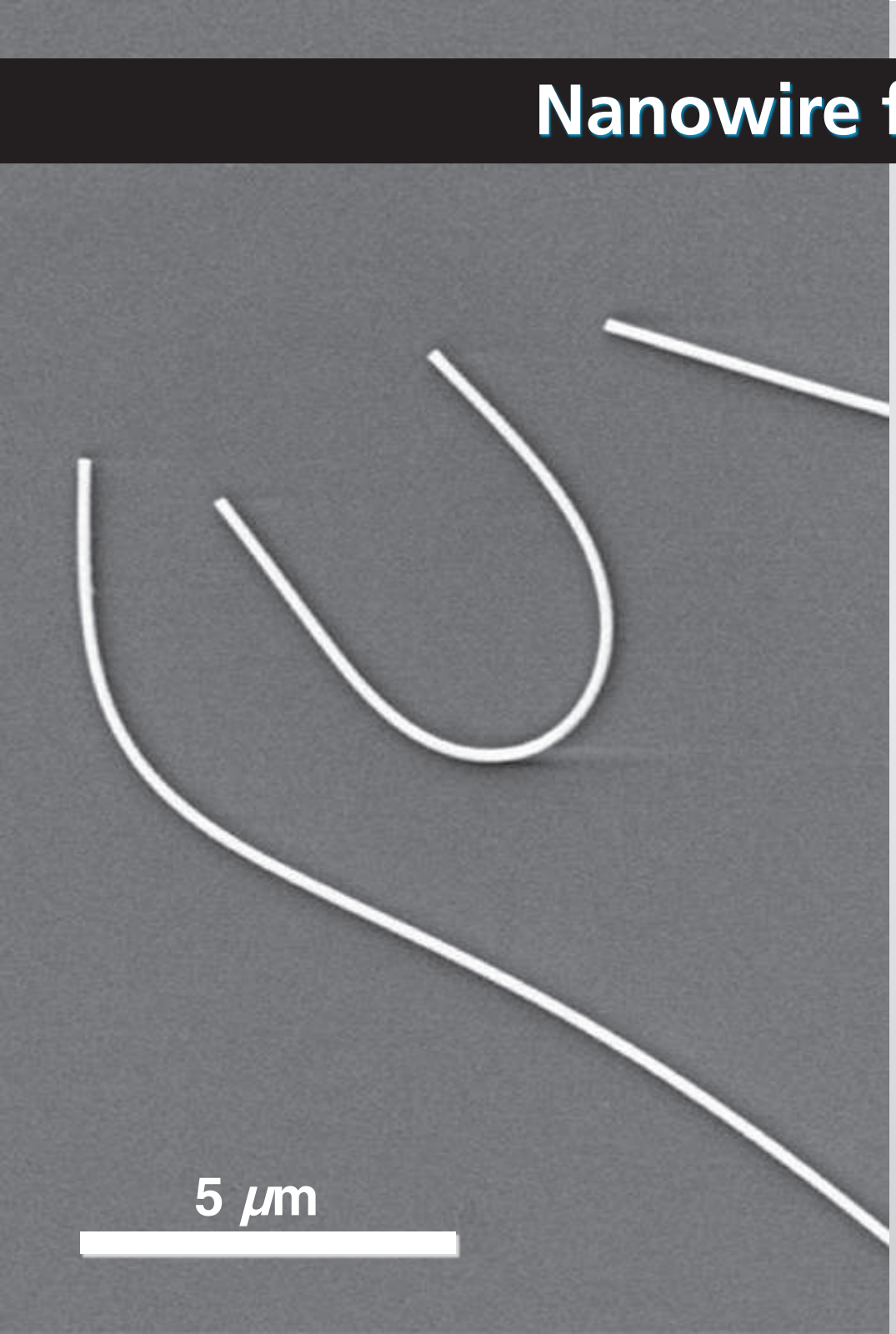


Nanowire fabrication



minimum bending radius R_{EB} gives tensile stress:

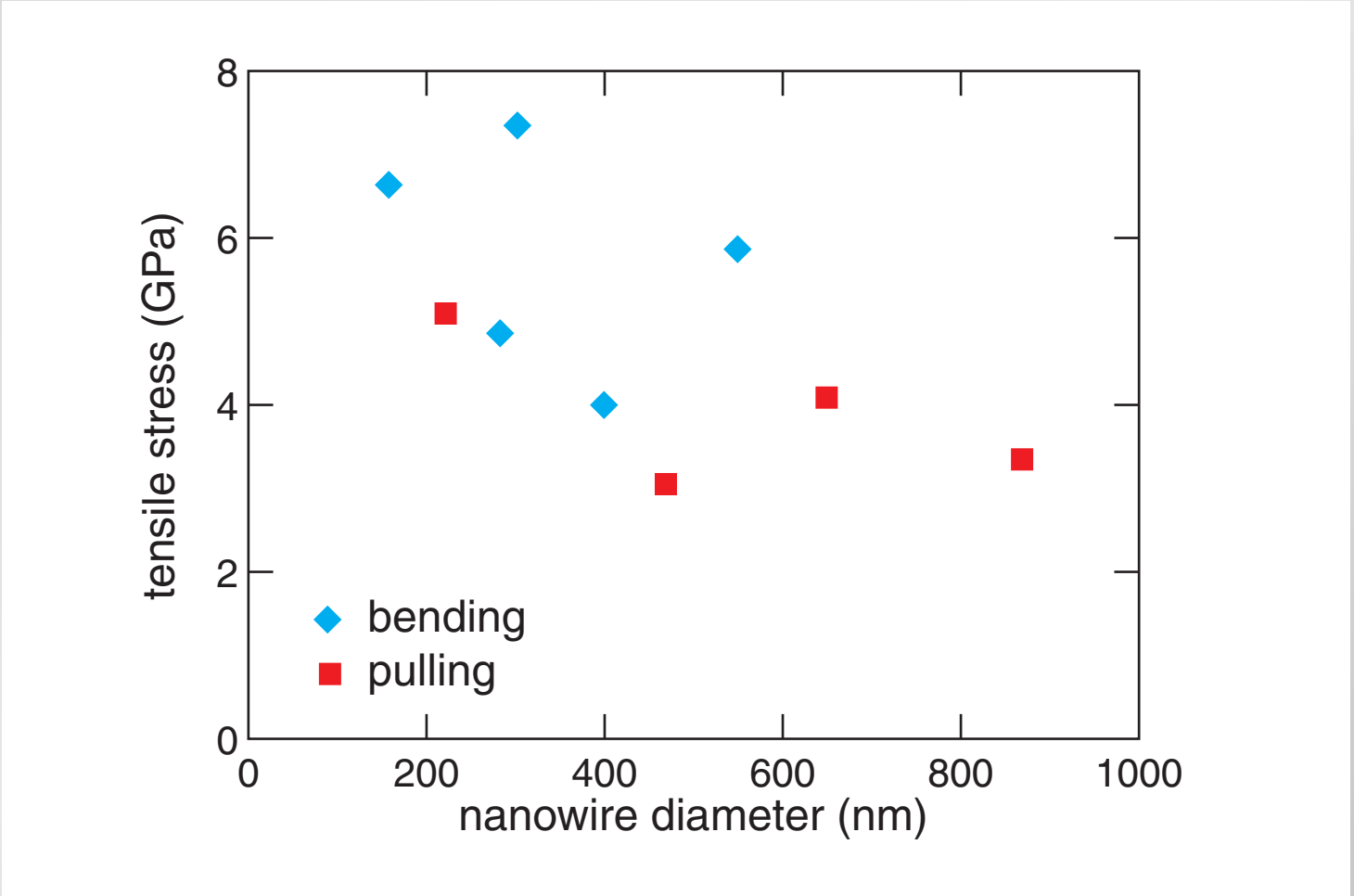
$$\sigma = \frac{ED}{2R_{EB}}$$

E = Young's modulus

D = wire diameter

Waveguiding

tensile strength



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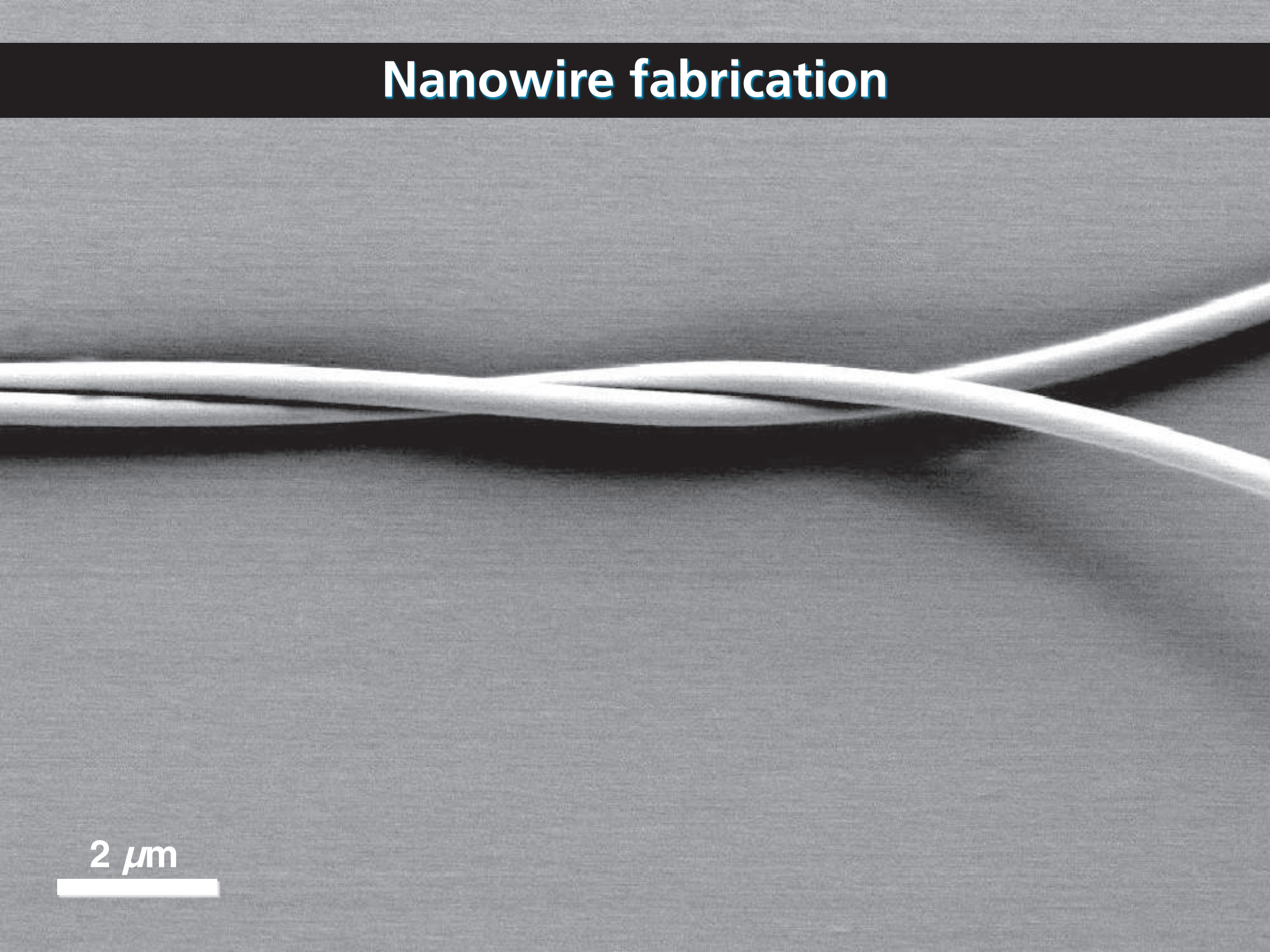
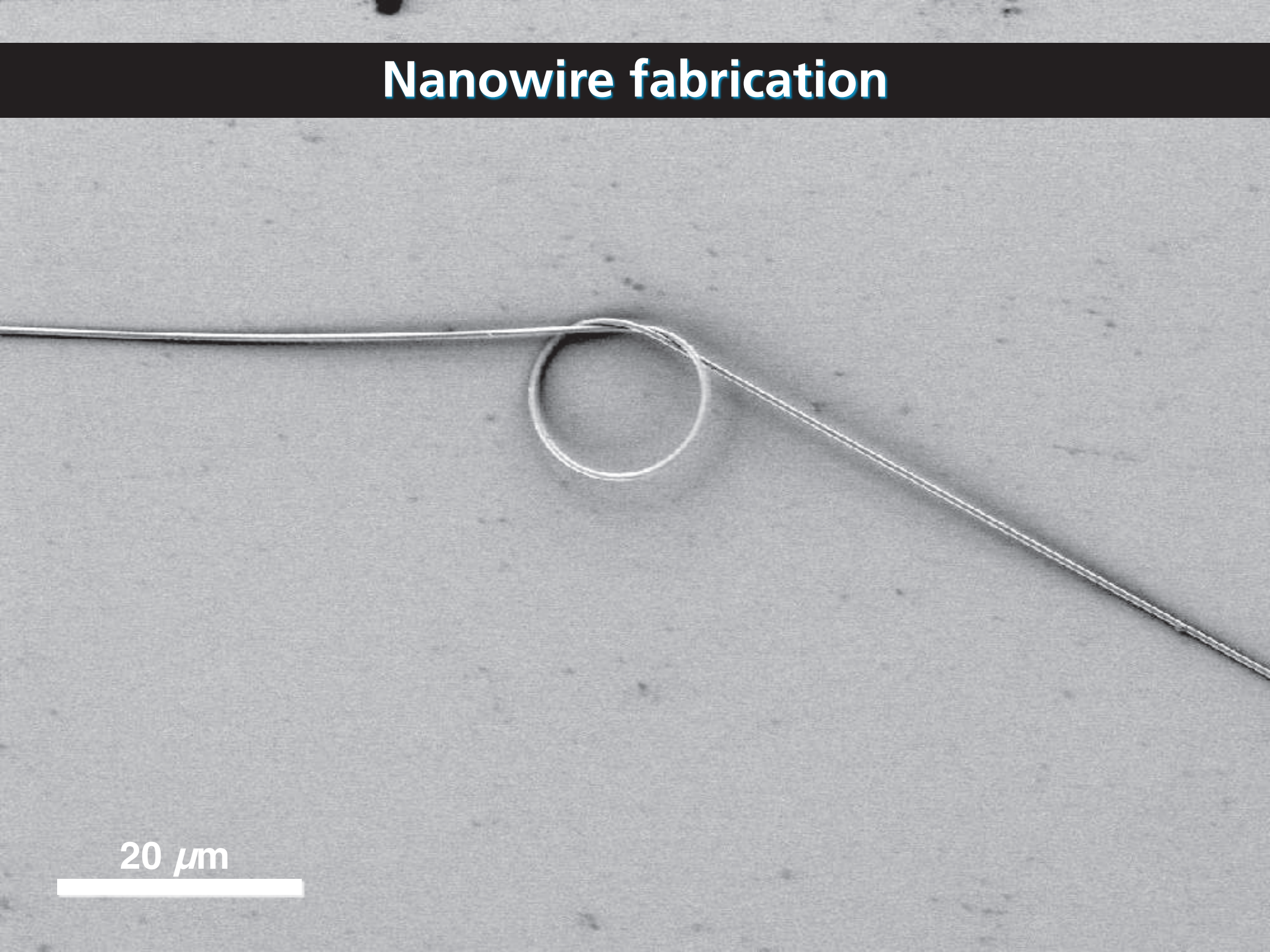
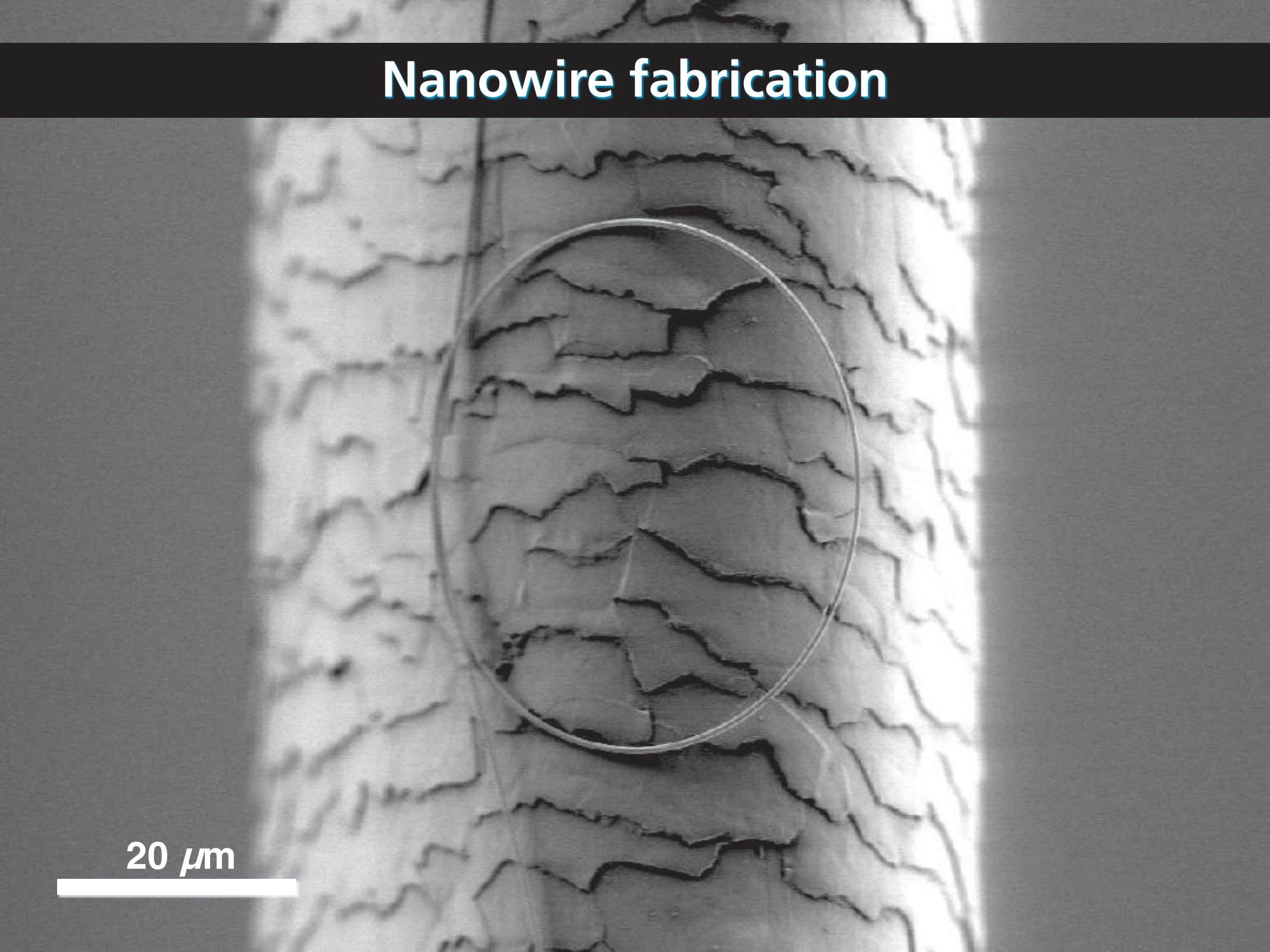


Nanowire fabrication



Nanowire fabrication

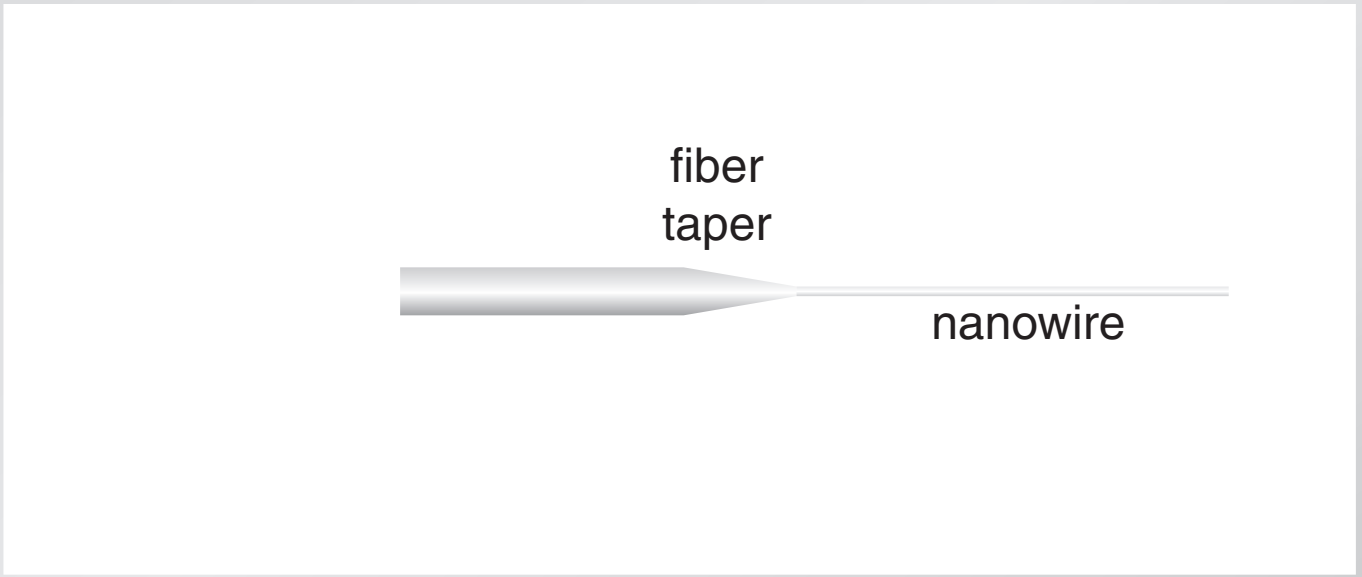


Outline

- waveguiding
- nanowire fabrication
- optical properties

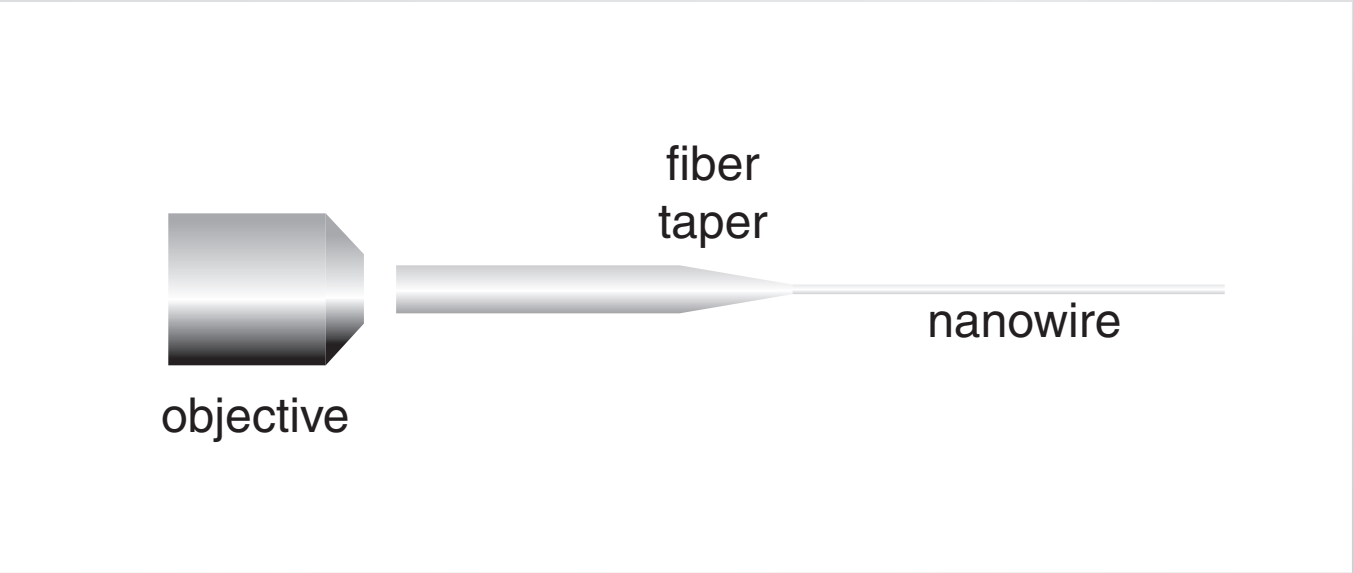
Optical properties

coupling light into nanowires



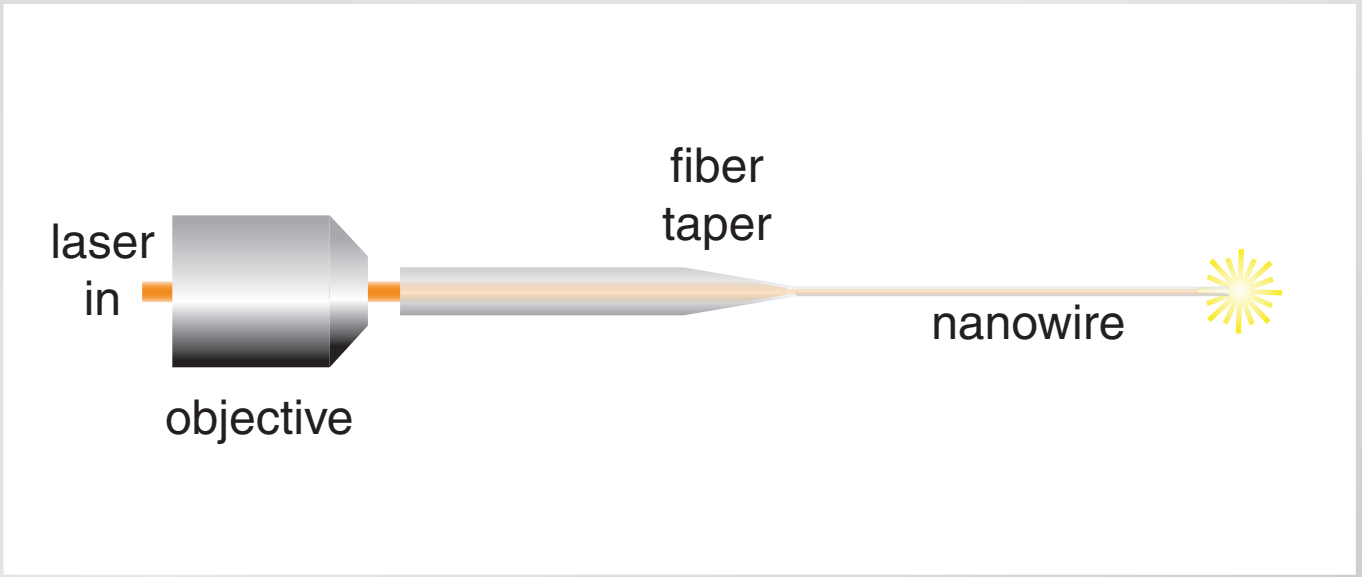
Optical properties

coupling light into nanowires

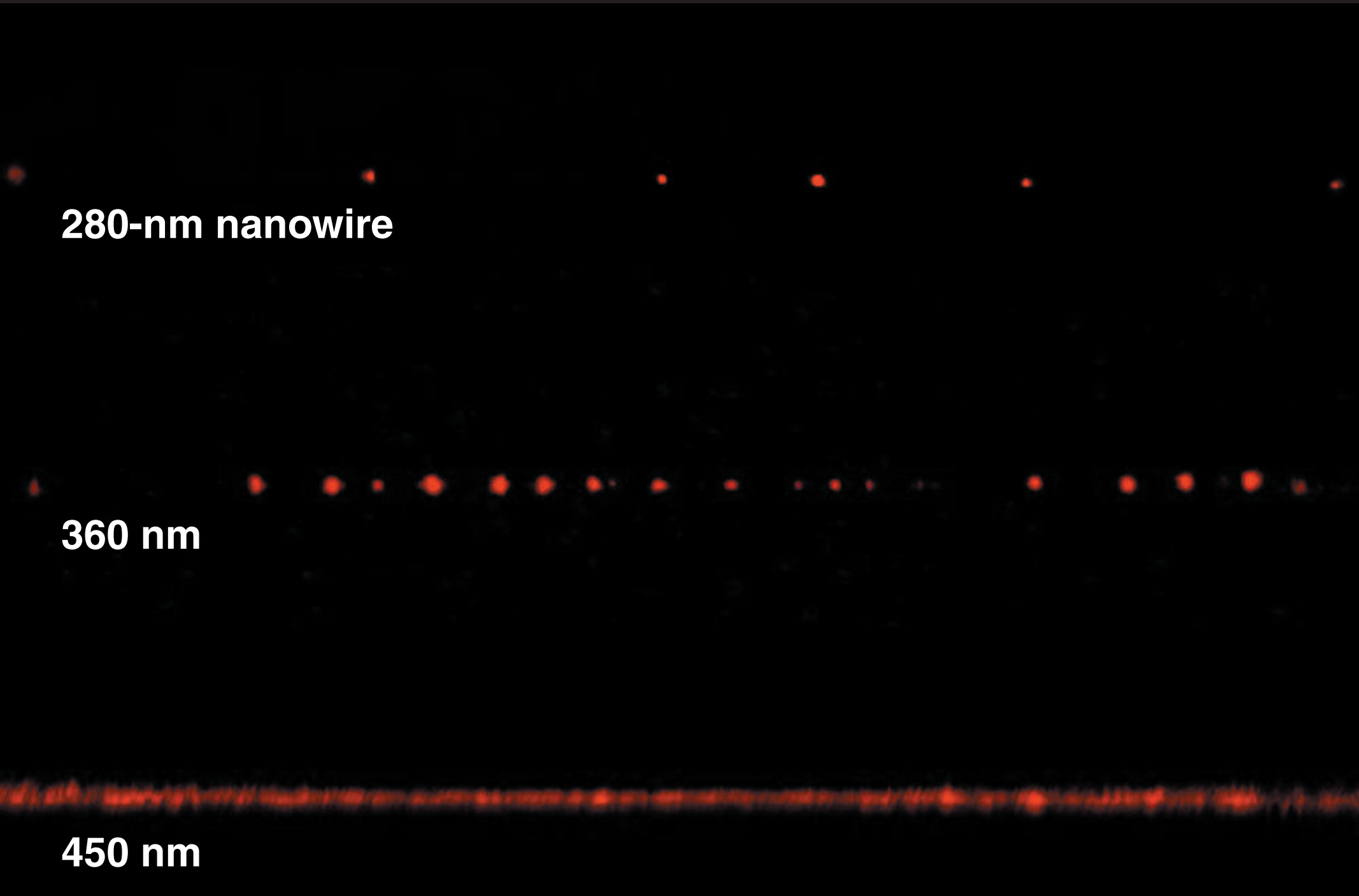


Optical properties

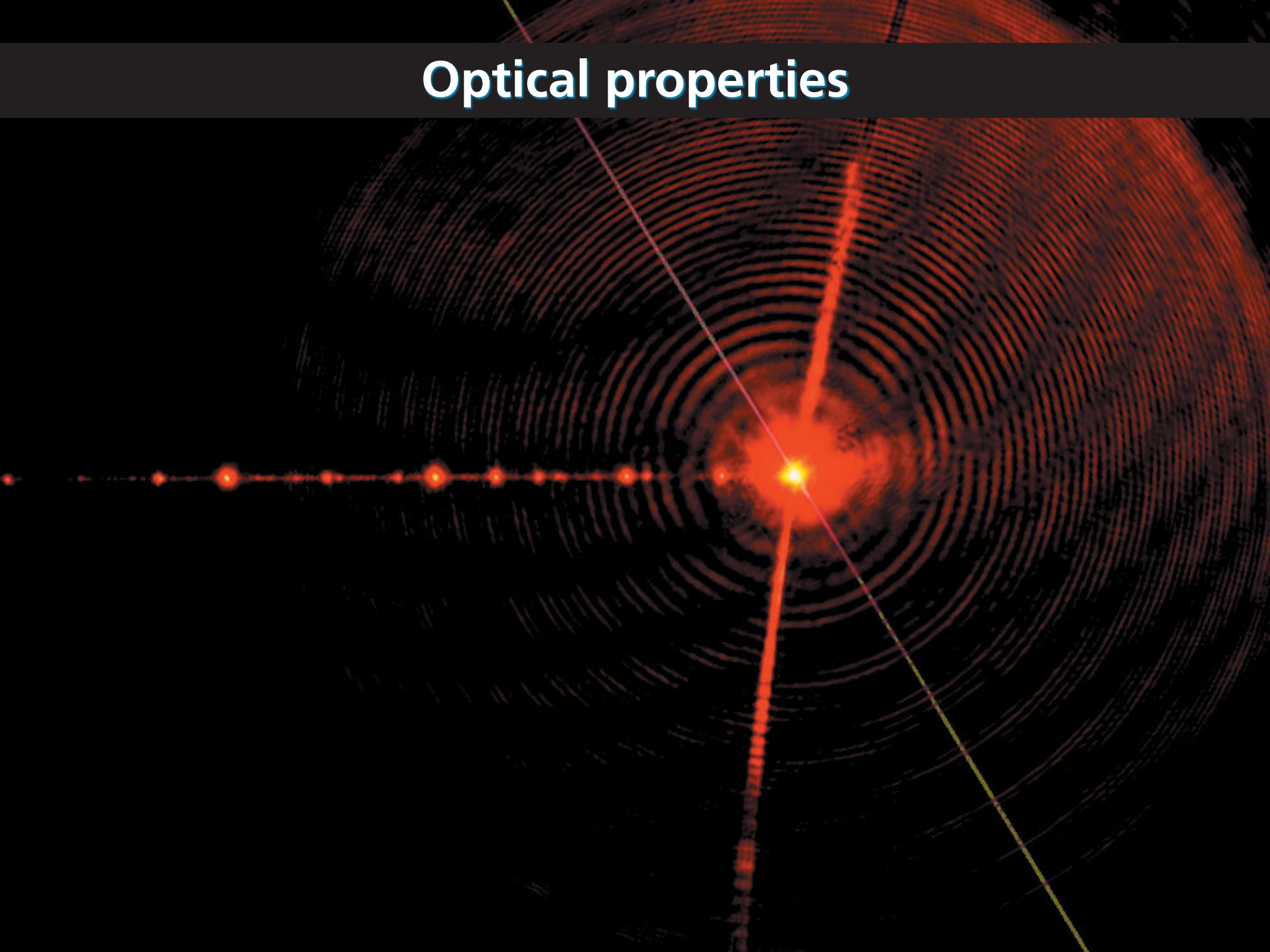
coupling light into nanowires



Optical properties



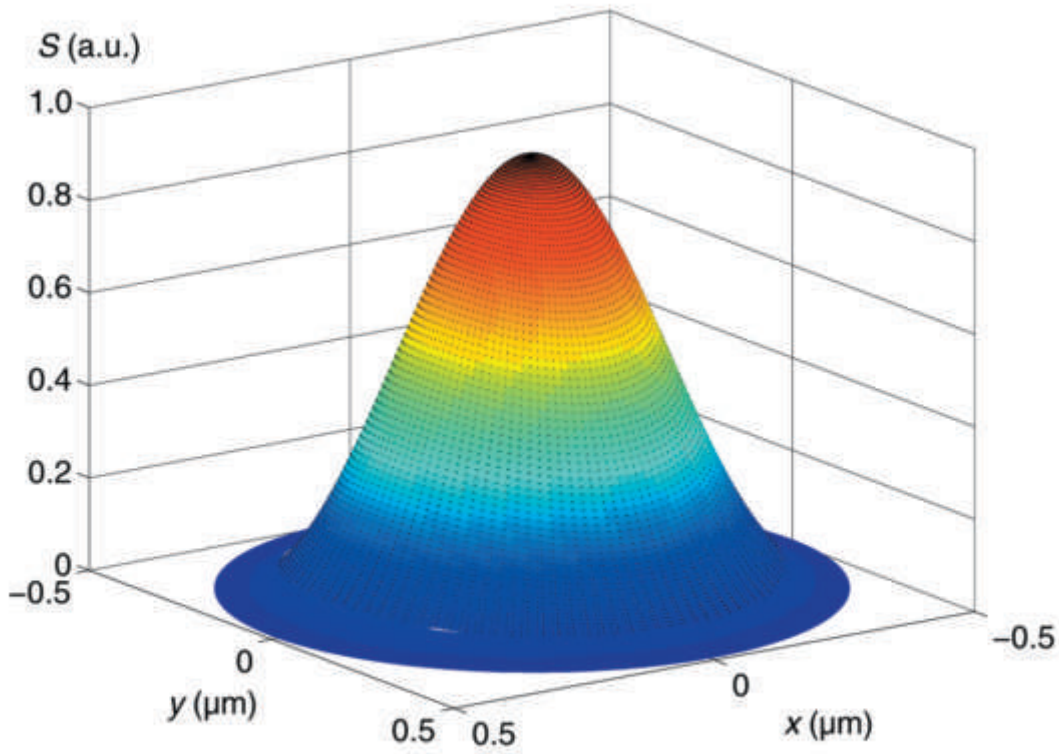
Optical properties



Optical properties

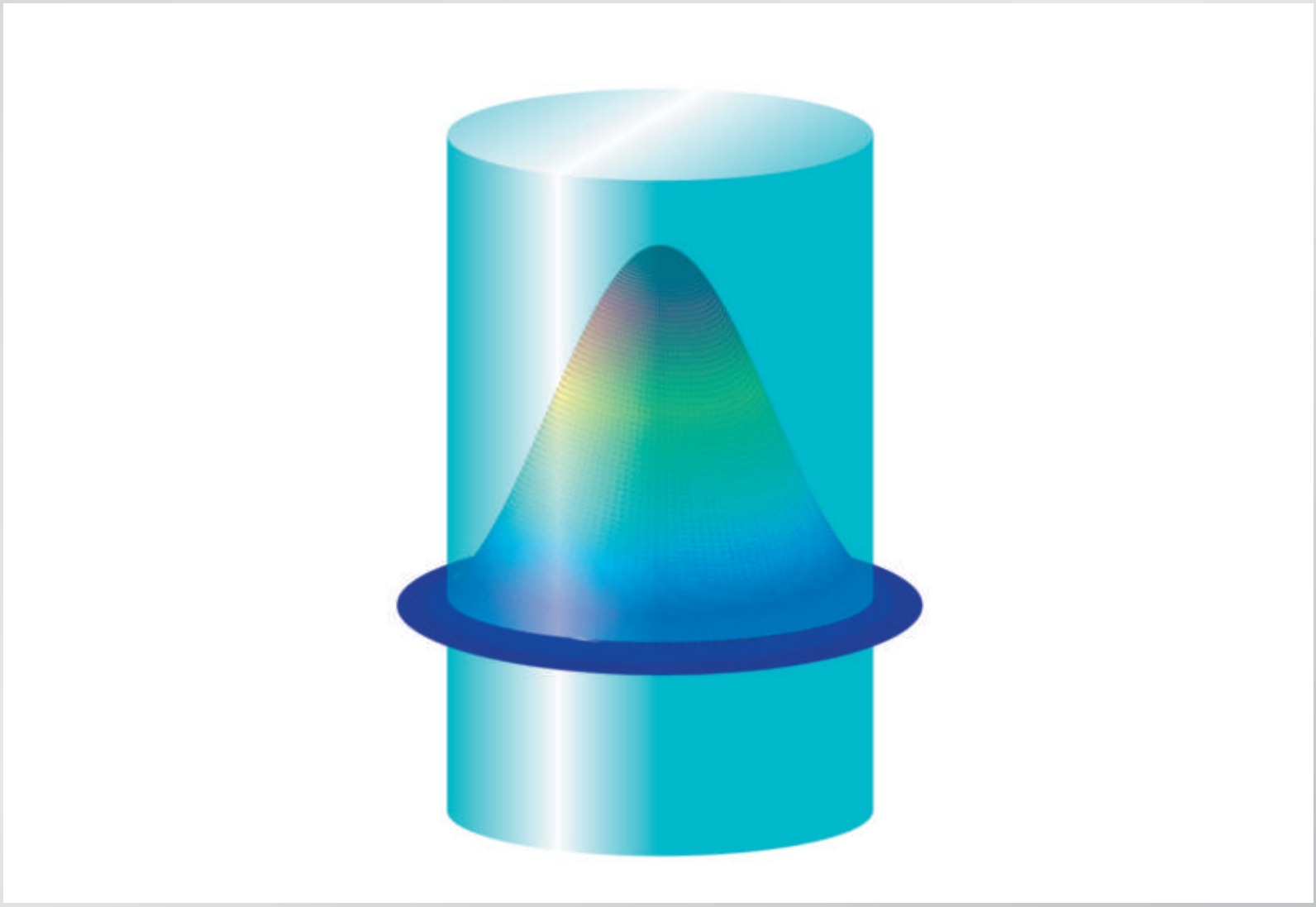
Optical properties

Poynting vector profile for 800-nm nanowire



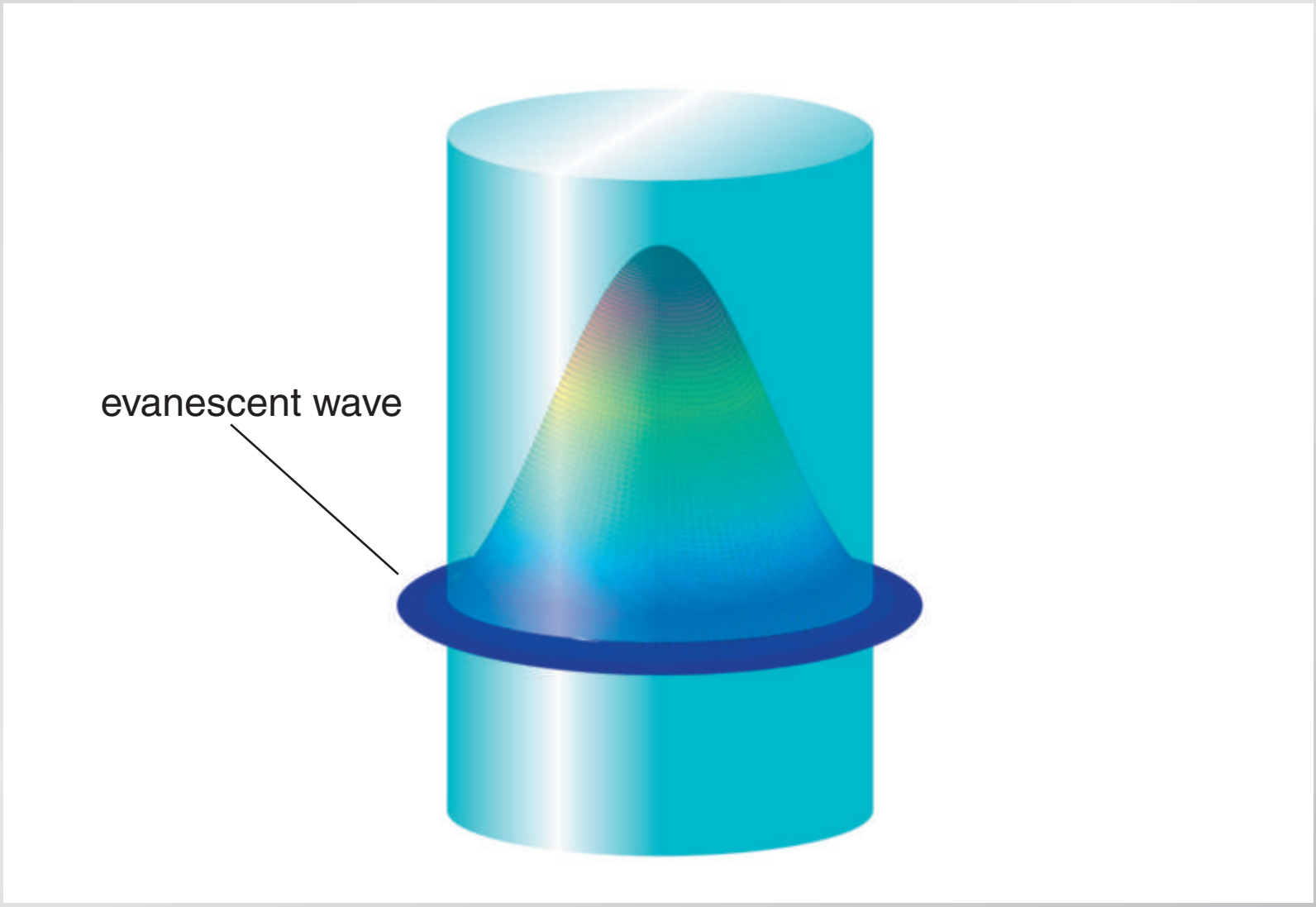
Optical properties

Poynting vector profile for 800-nm nanowire



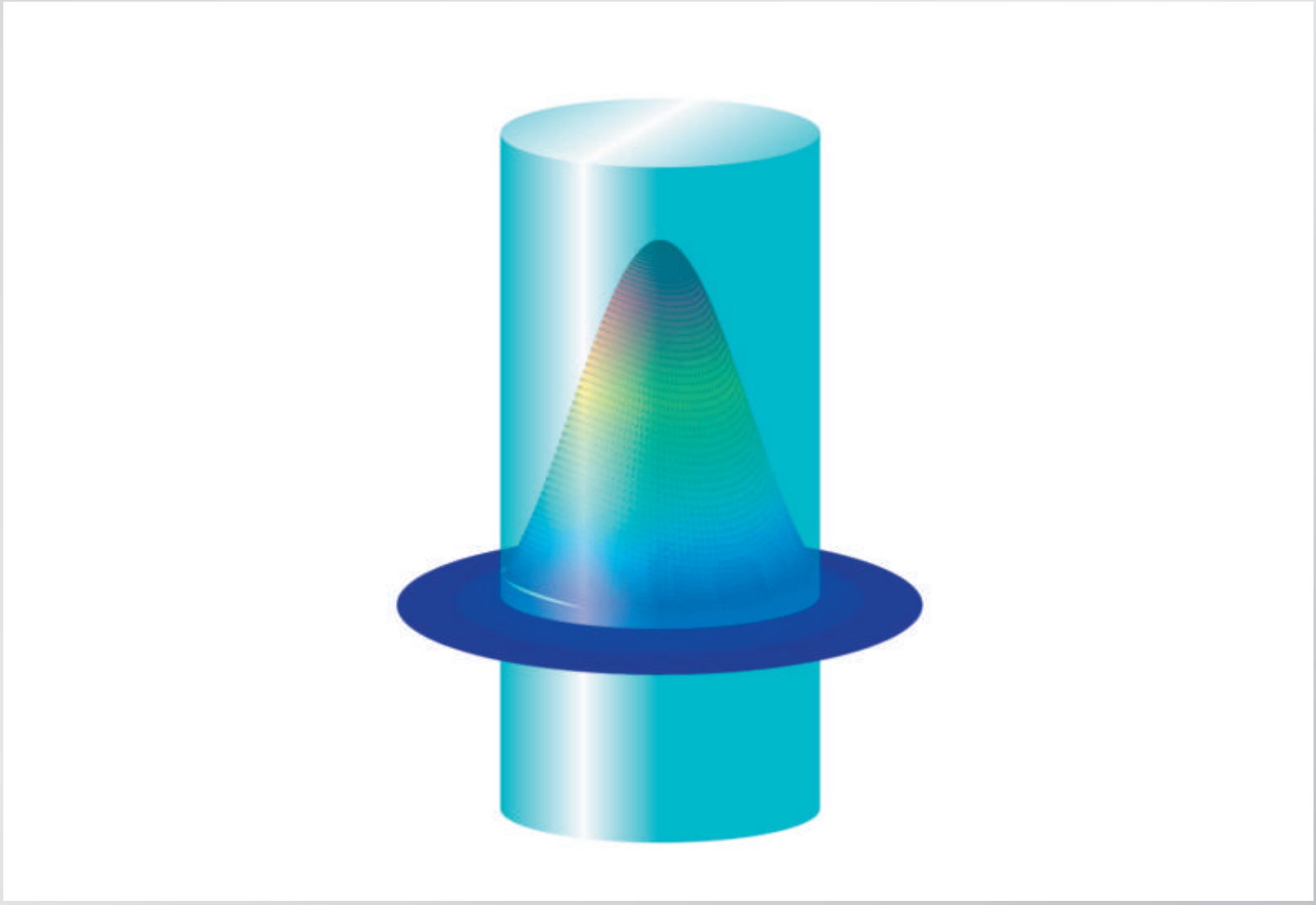
Optical properties

Poynting vector profile for 800-nm nanowire



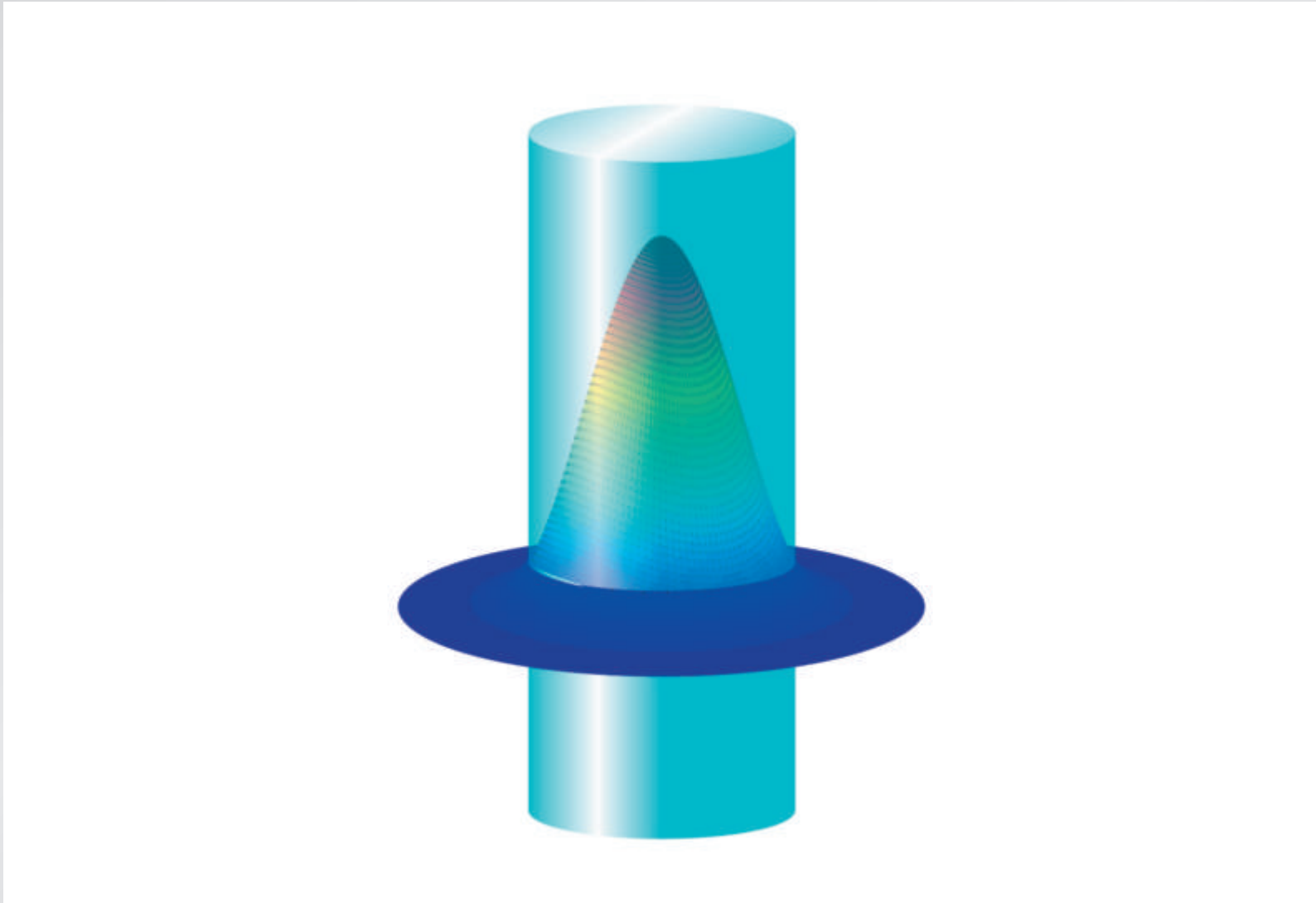
Optical properties

Poynting vector profile for 600-nm nanowire



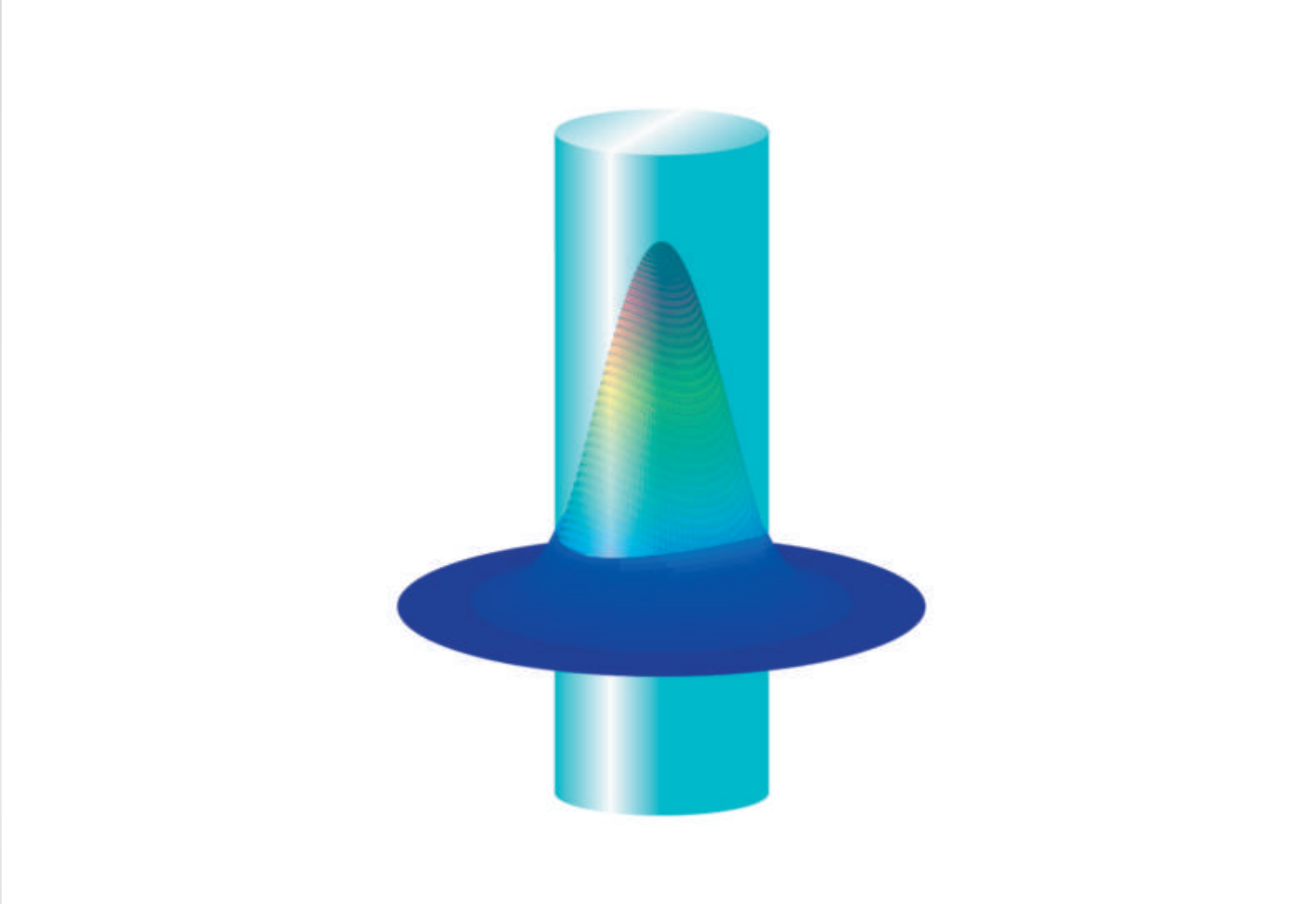
Optical properties

Poynting vector profile for 500-nm nanowire



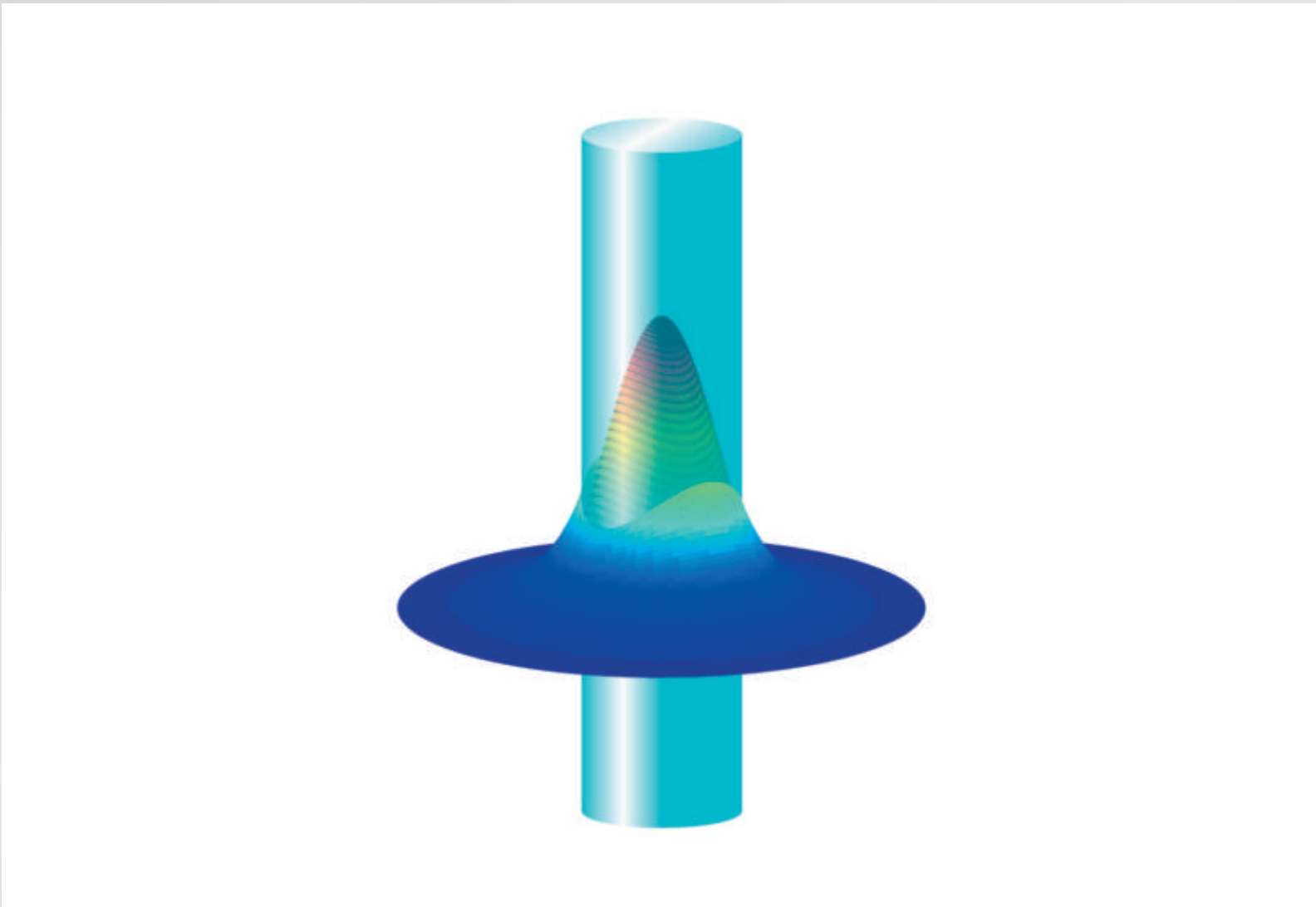
Optical properties

Poynting vector profile for 400-nm nanowire



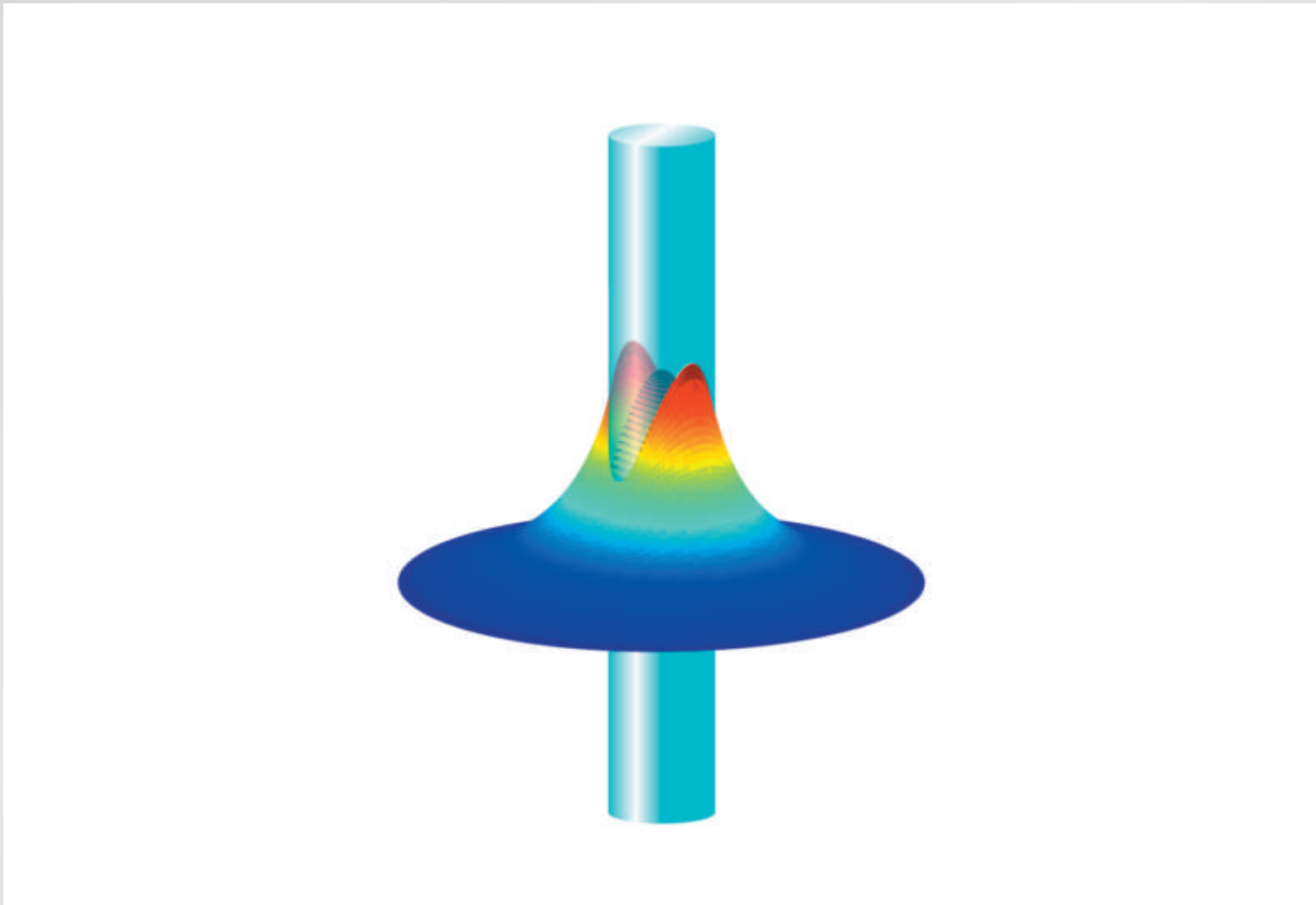
Optical properties

Poynting vector profile for 300-nm nanowire



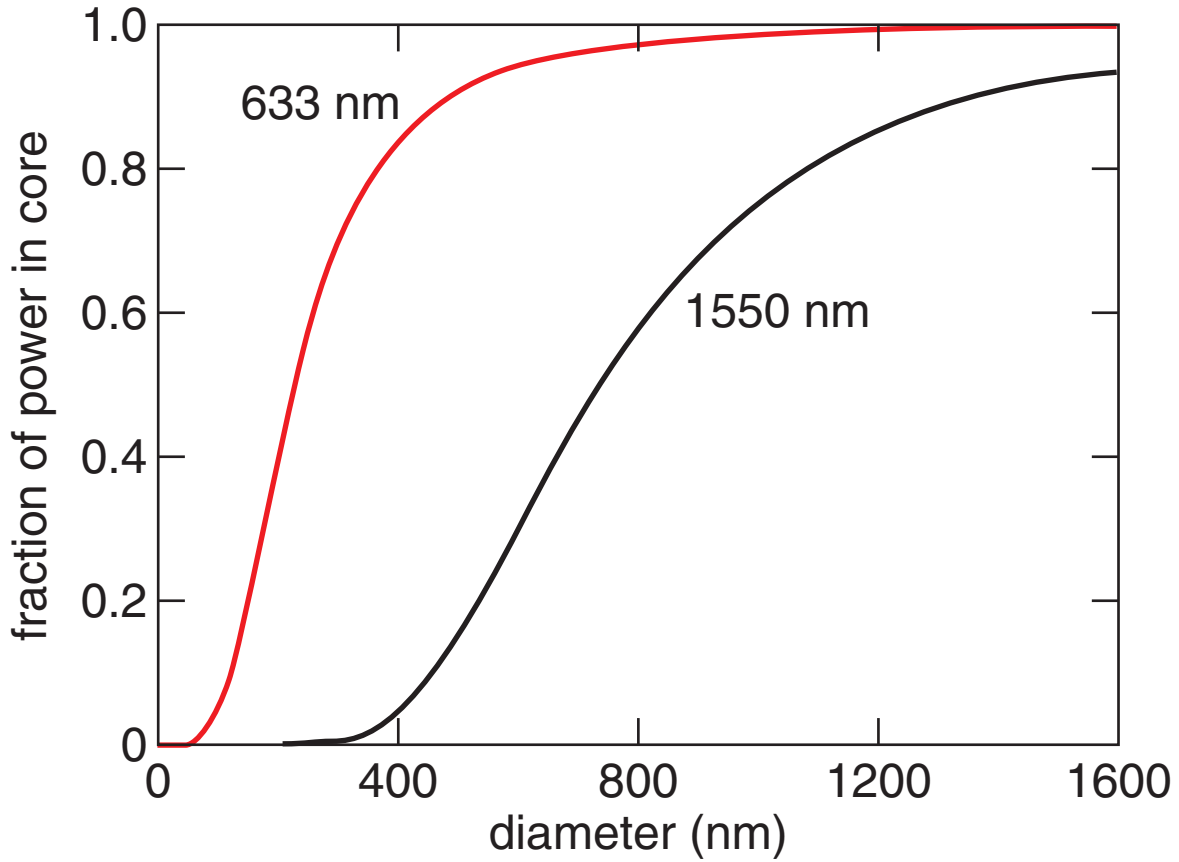
Optical properties

Poynting vector profile for 200-nm nanowire



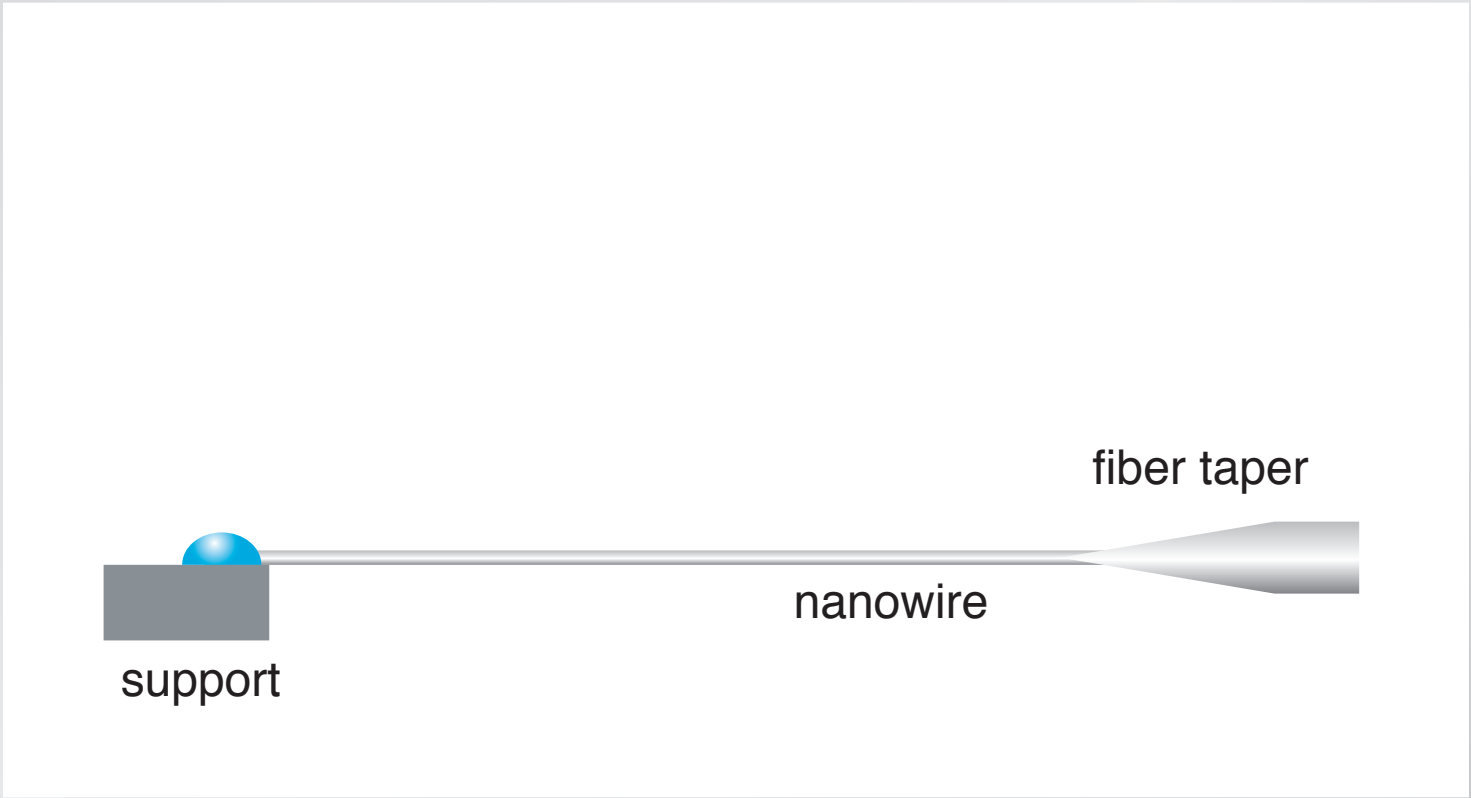
Waveguiding

fraction of power carried in core



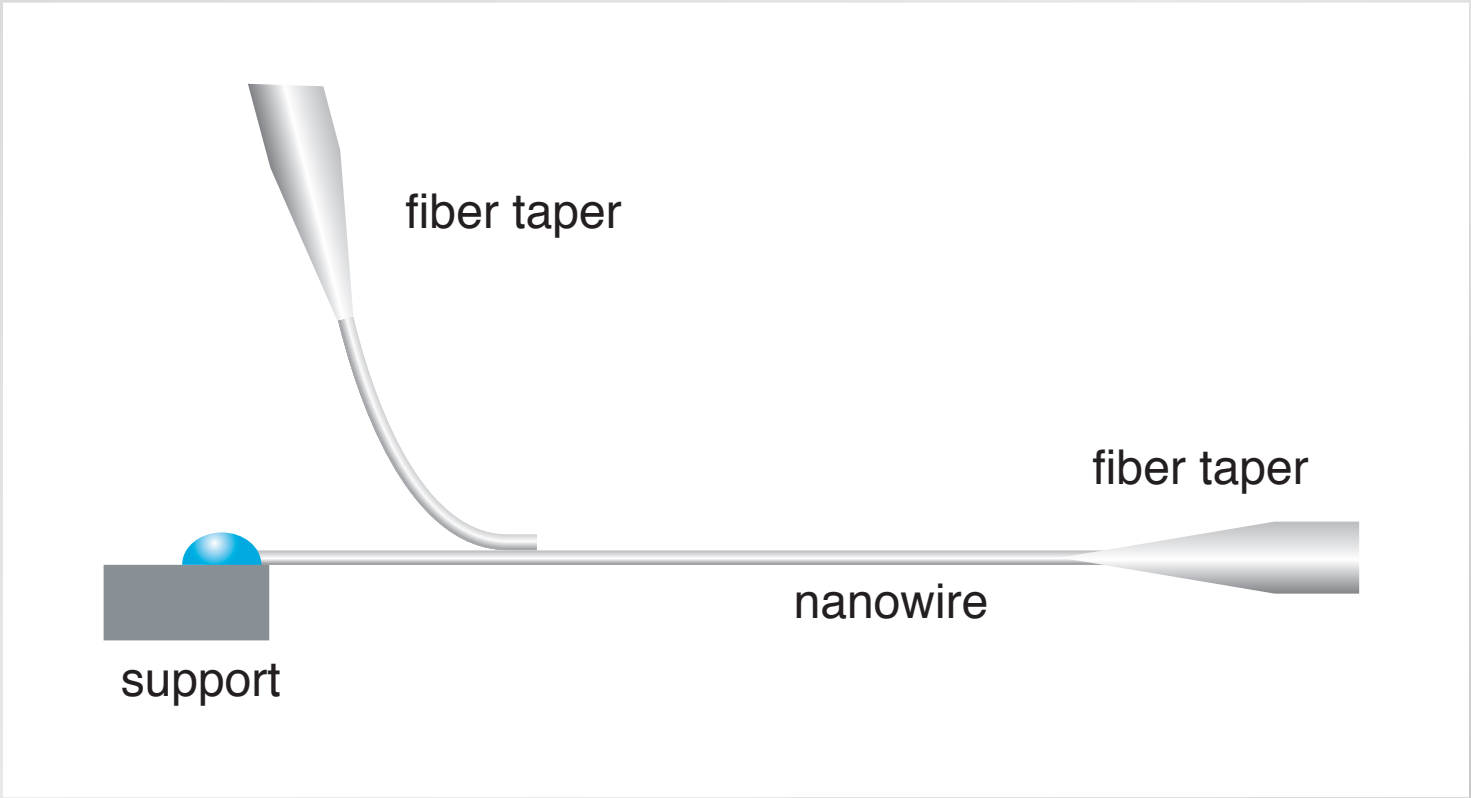
Optical properties

coupling light between nanowires



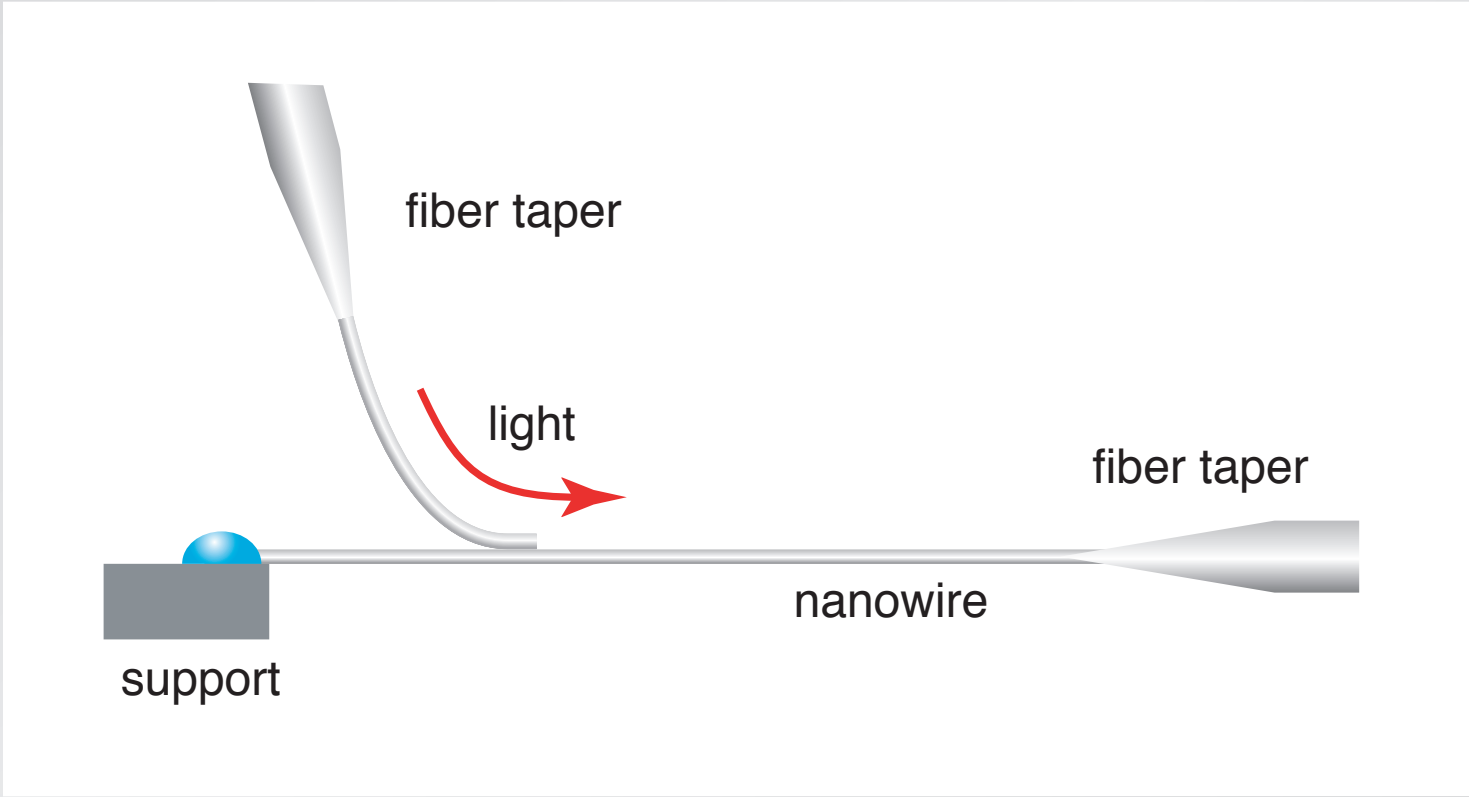
Optical properties

coupling light between nanowires

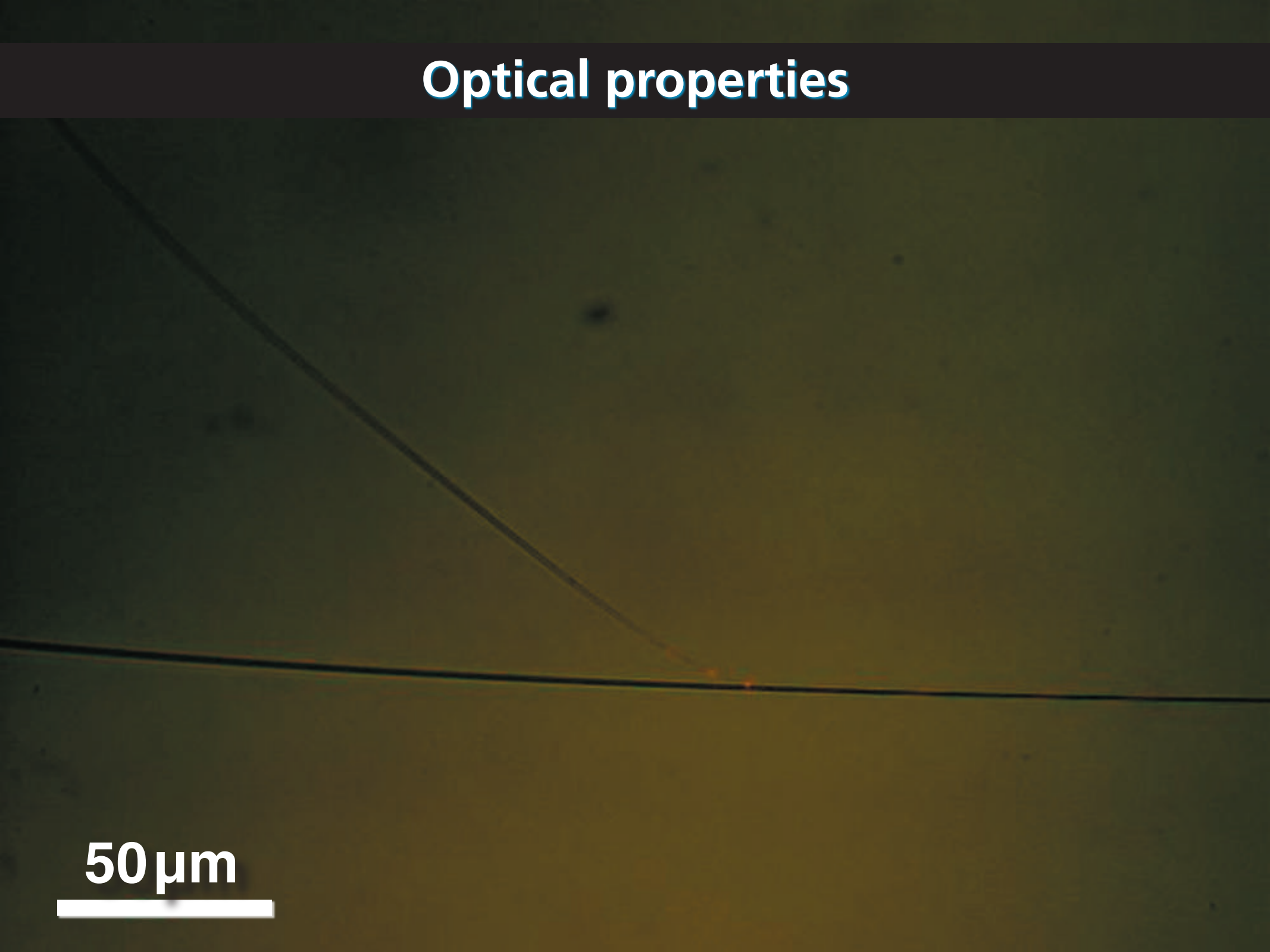


Optical properties

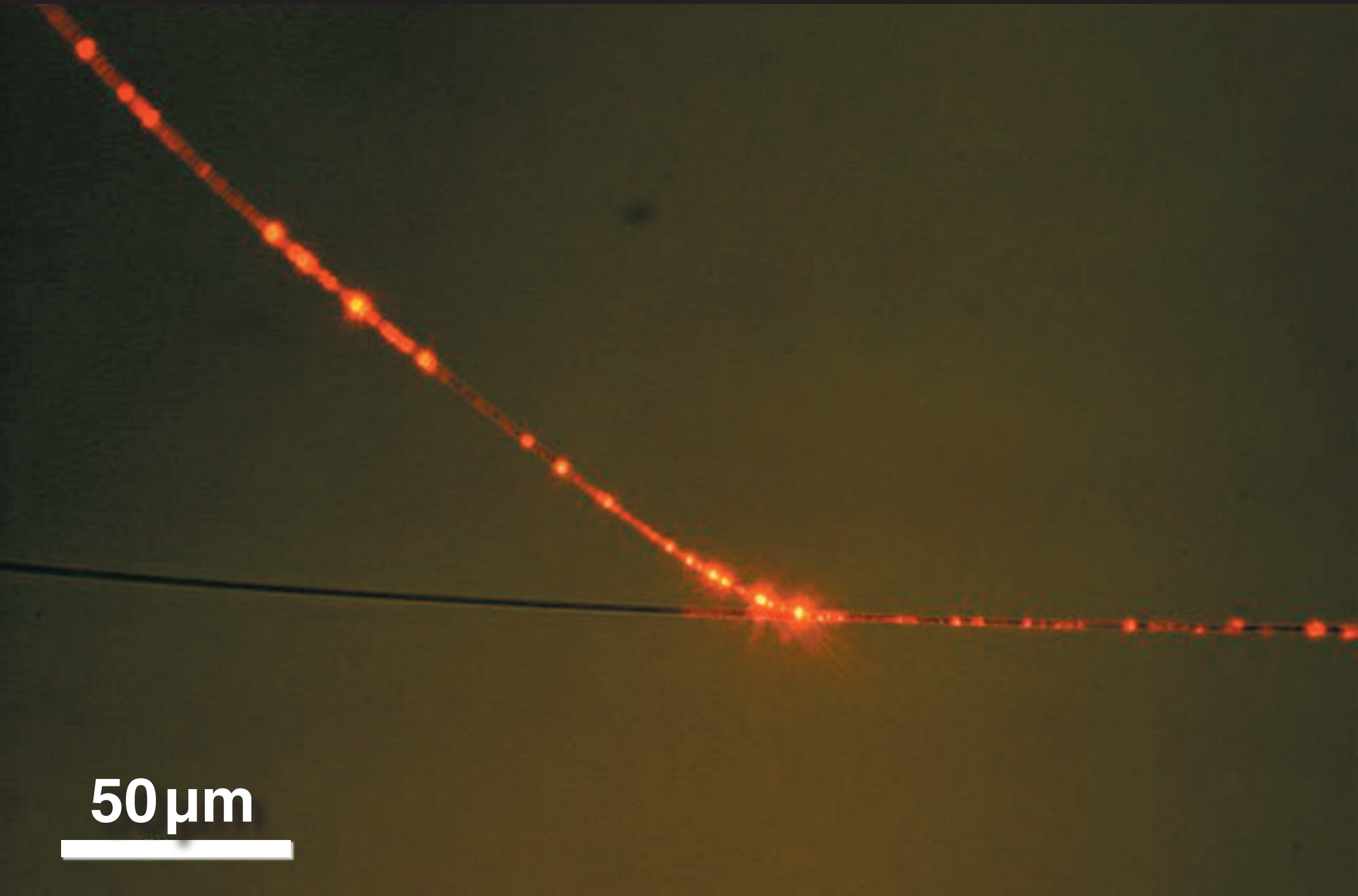
coupling light between nanowires



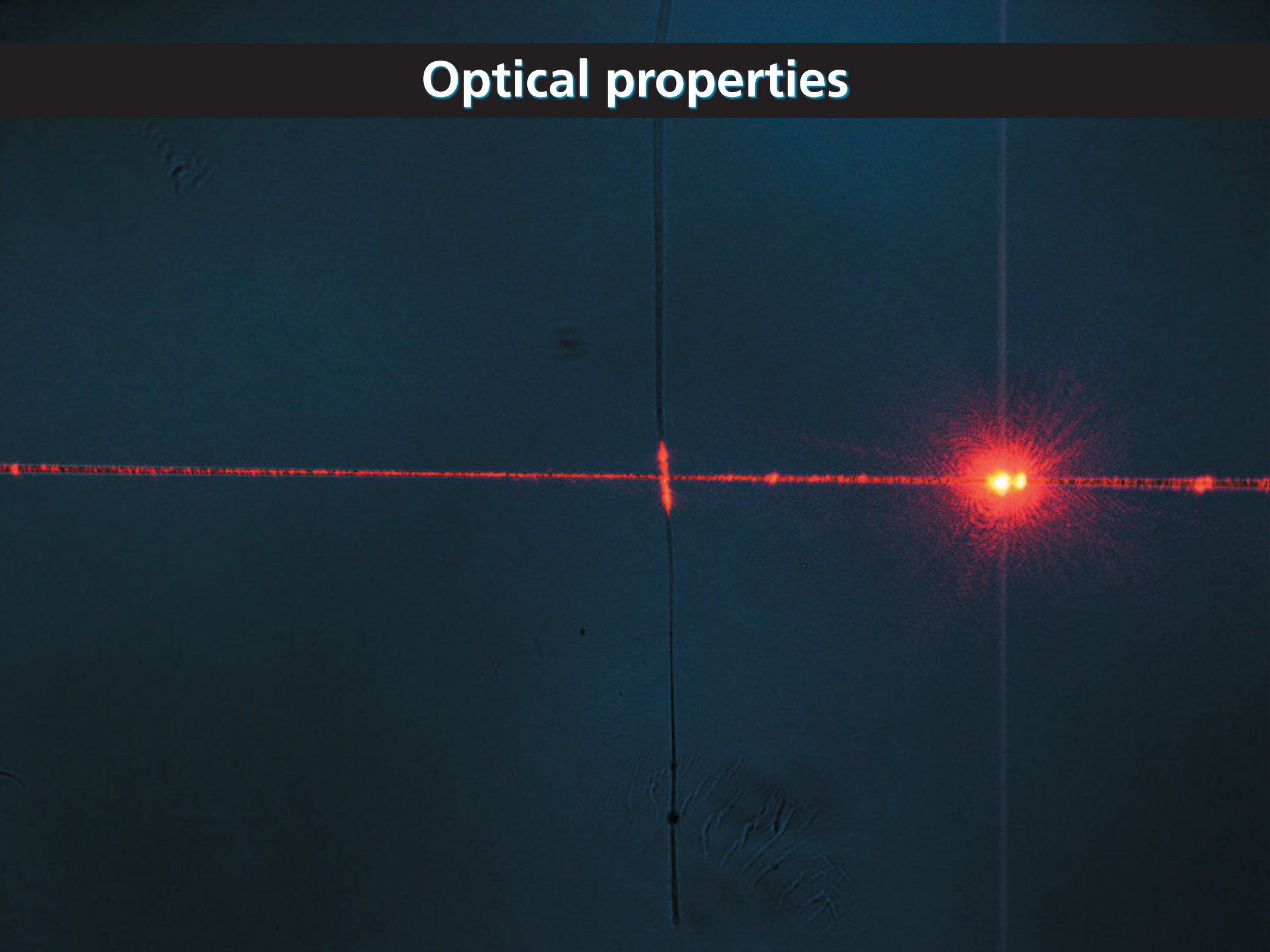
Optical properties



Optical properties

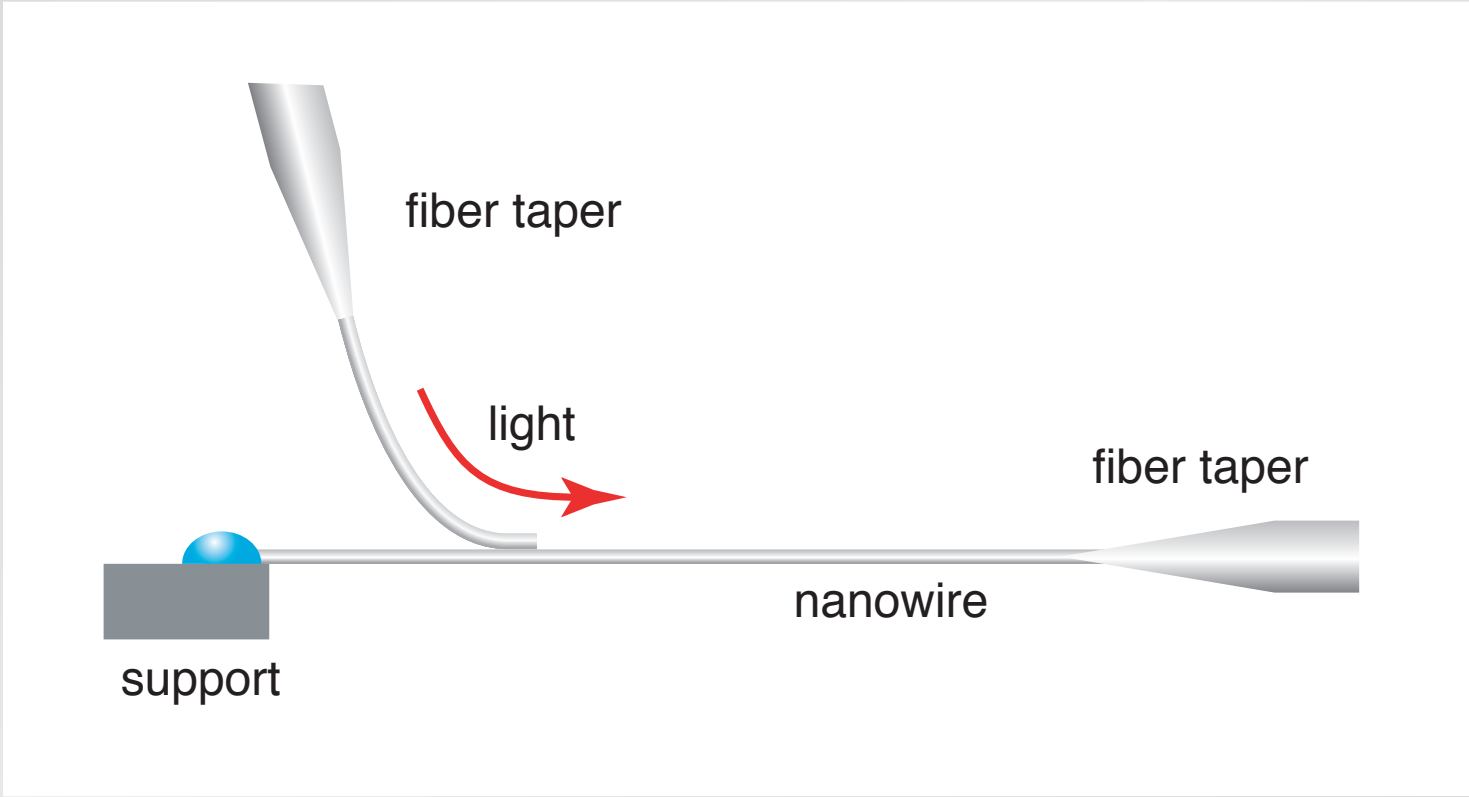


Optical properties



Optical properties

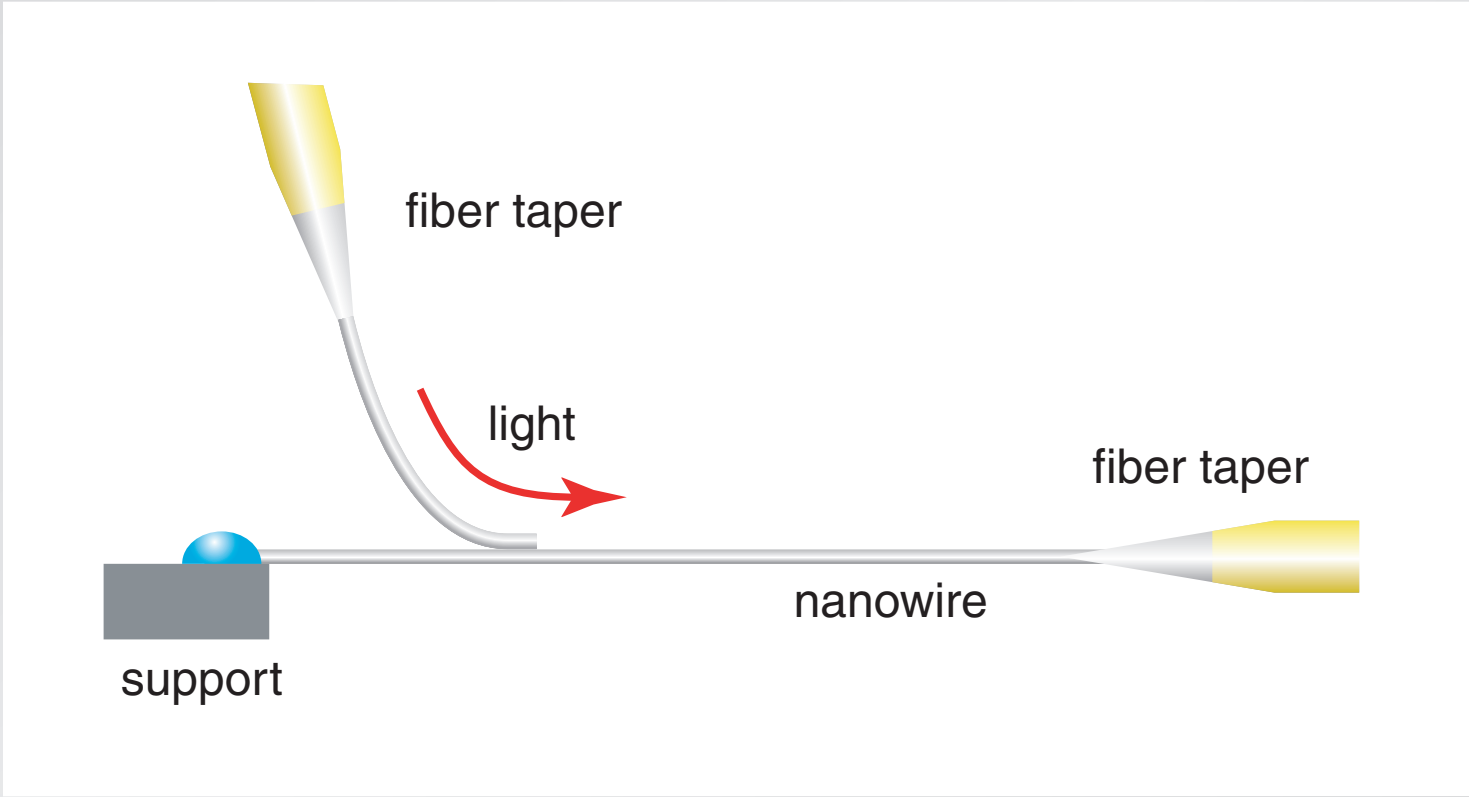
loss measurement



Nature, 426, 816 (2003)

Optical properties

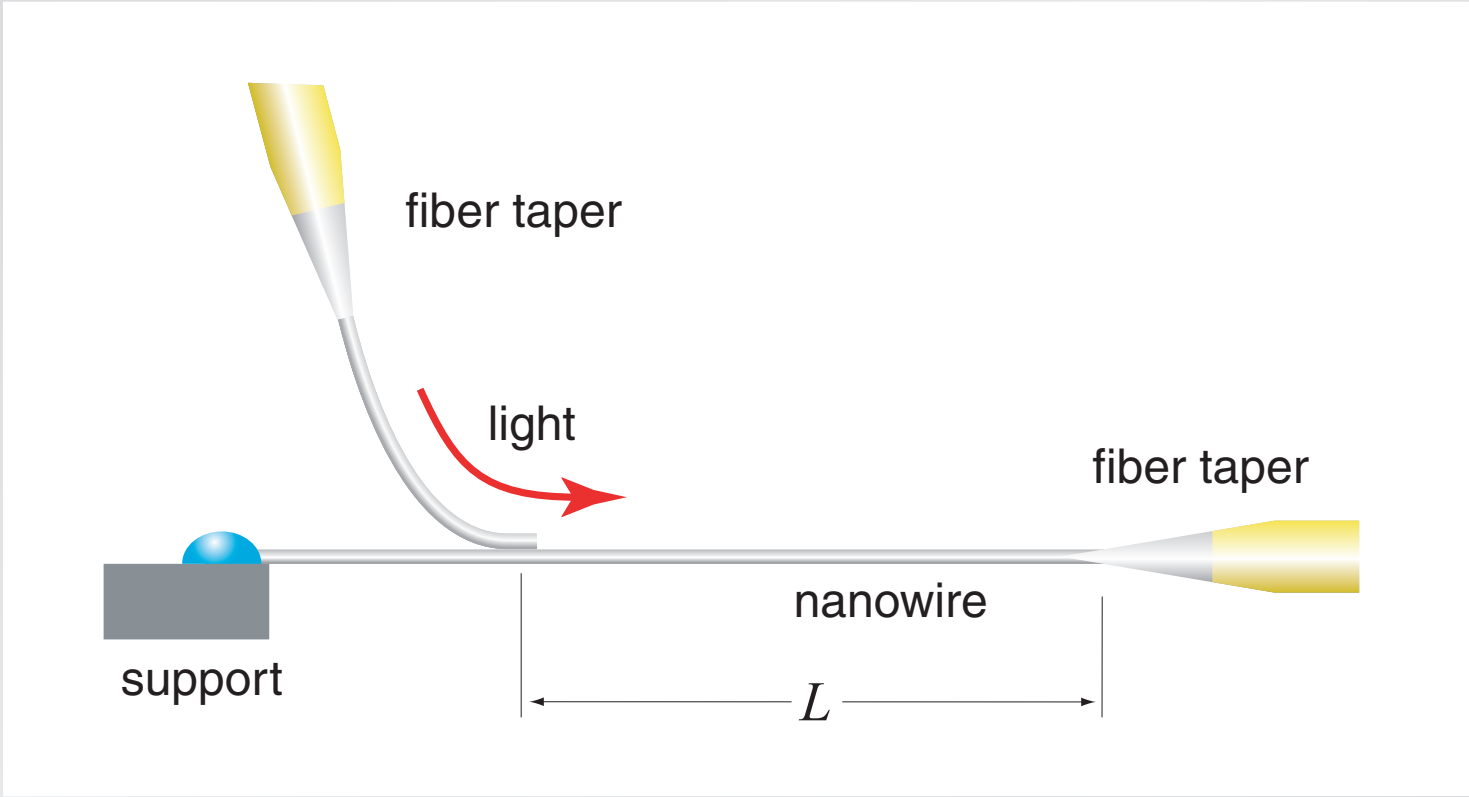
loss measurement



Nature, 426, 816 (2003)

Optical properties

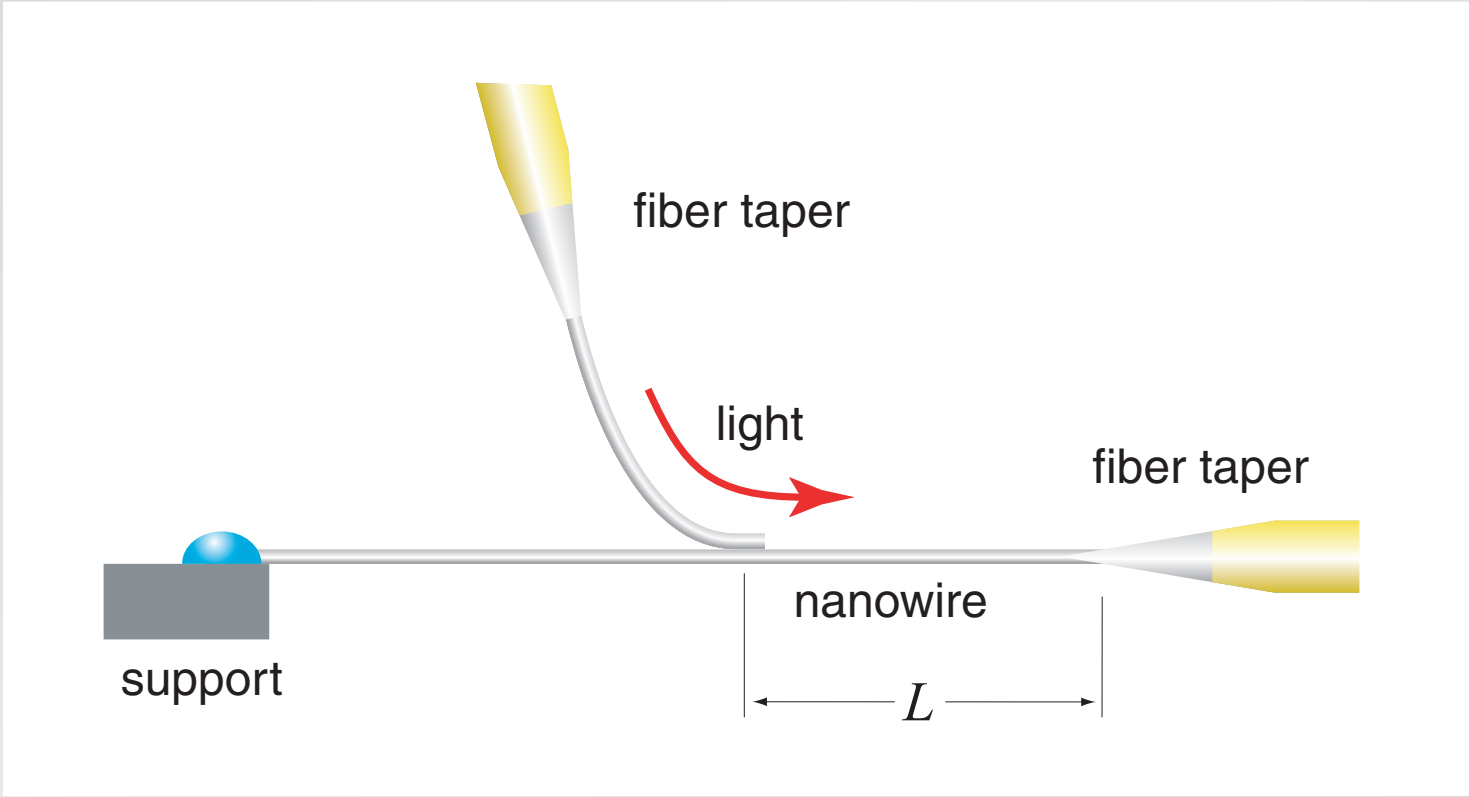
loss measurement



Nature, 426, 816 (2003)

Optical properties

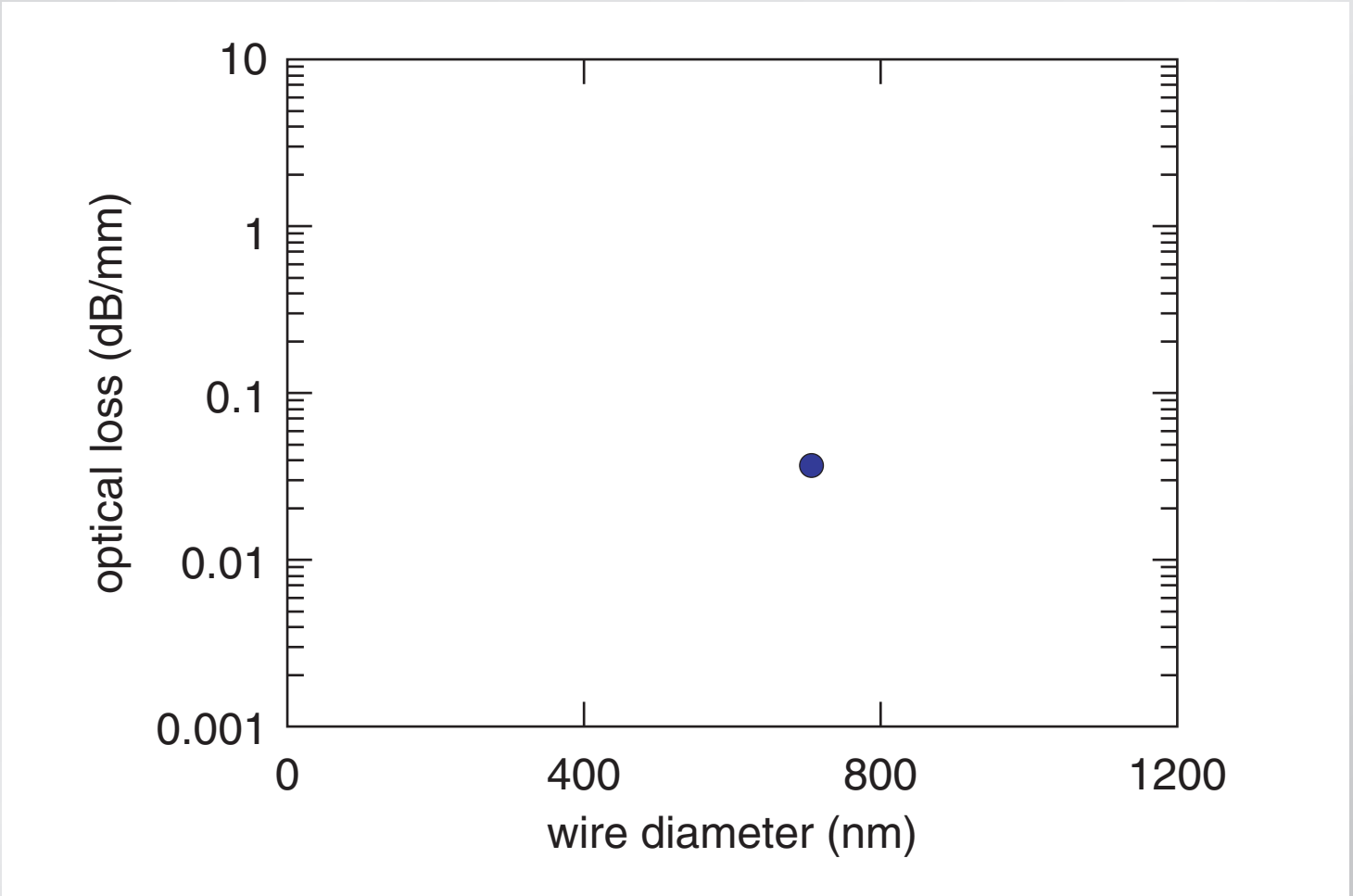
loss measurement



Nature, 426, 816 (2003)

Optical properties

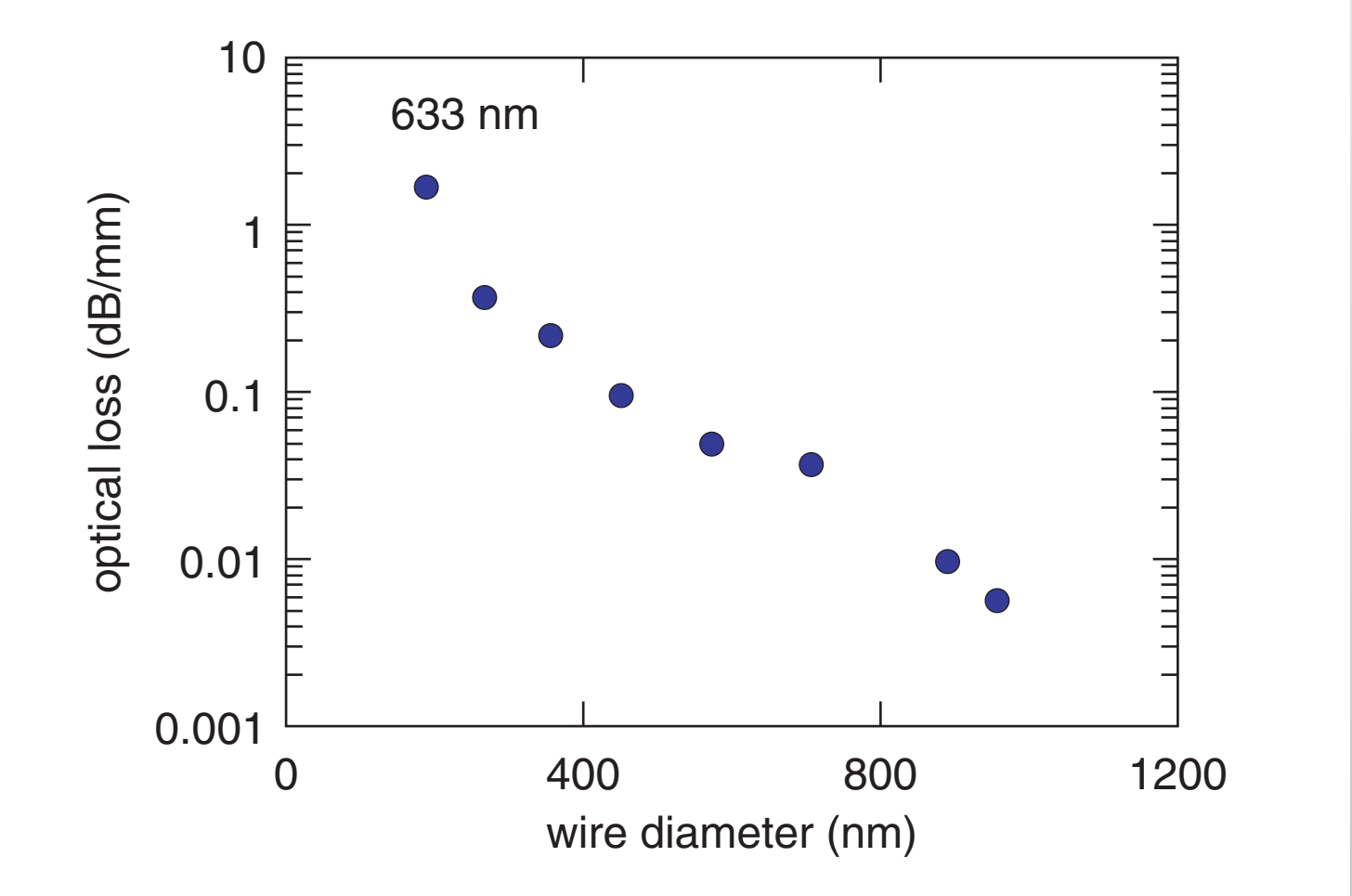
loss measurement



Nature, 426, 816 (2003)

Optical properties

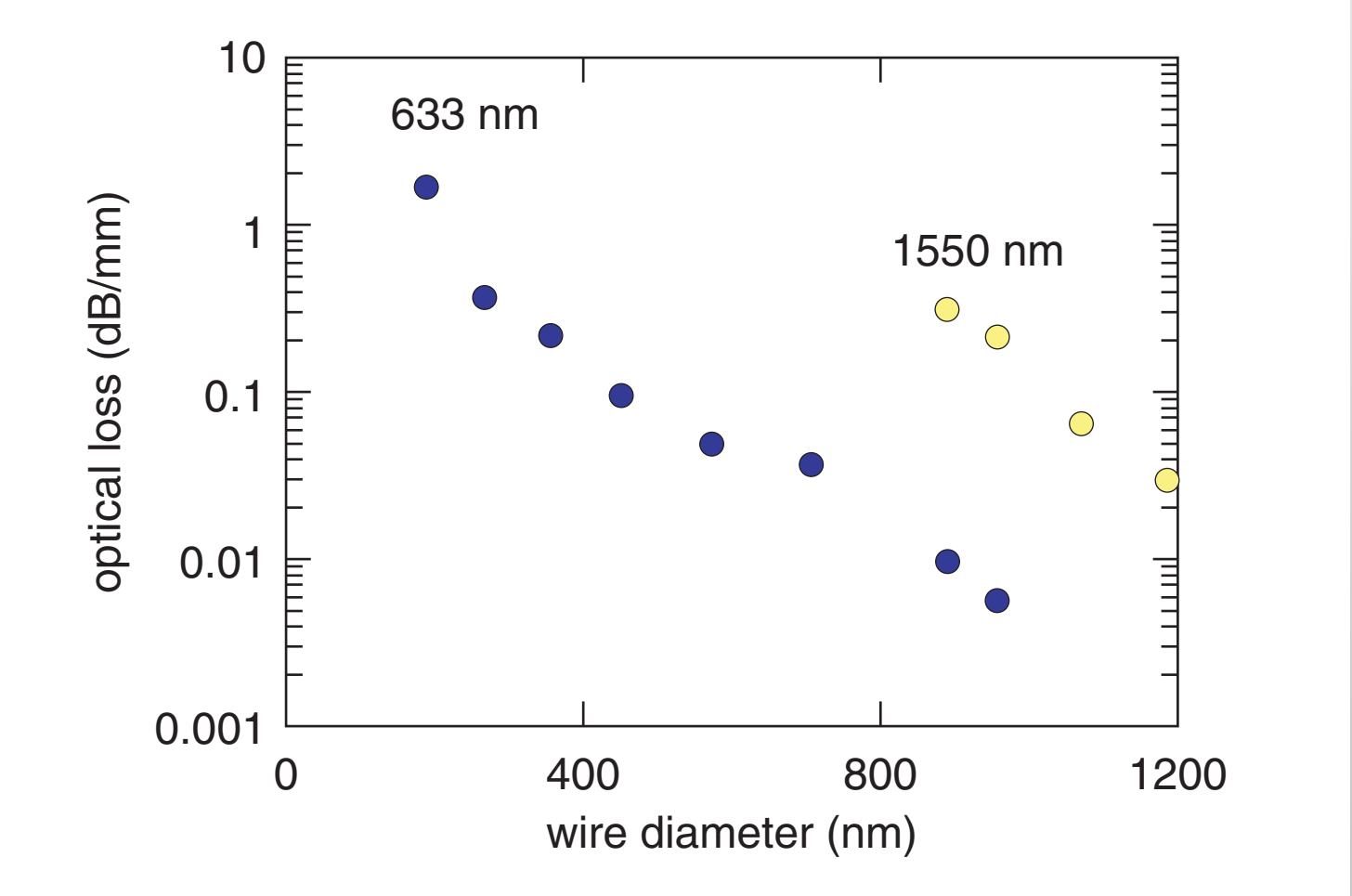
loss measurement



Nature, 426, 816 (2003)

Optical properties

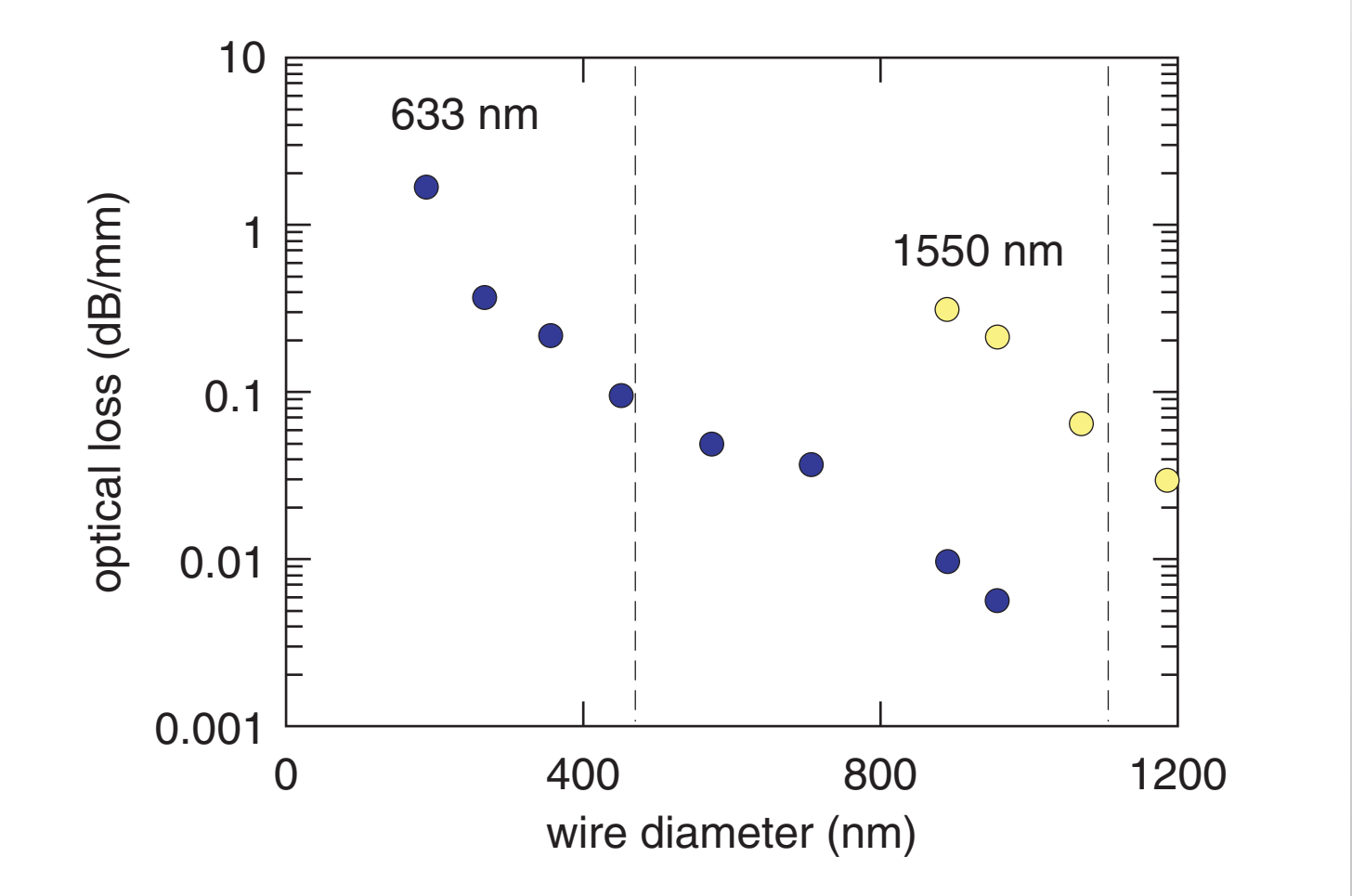
loss measurement



Nature, 426, 816 (2003)

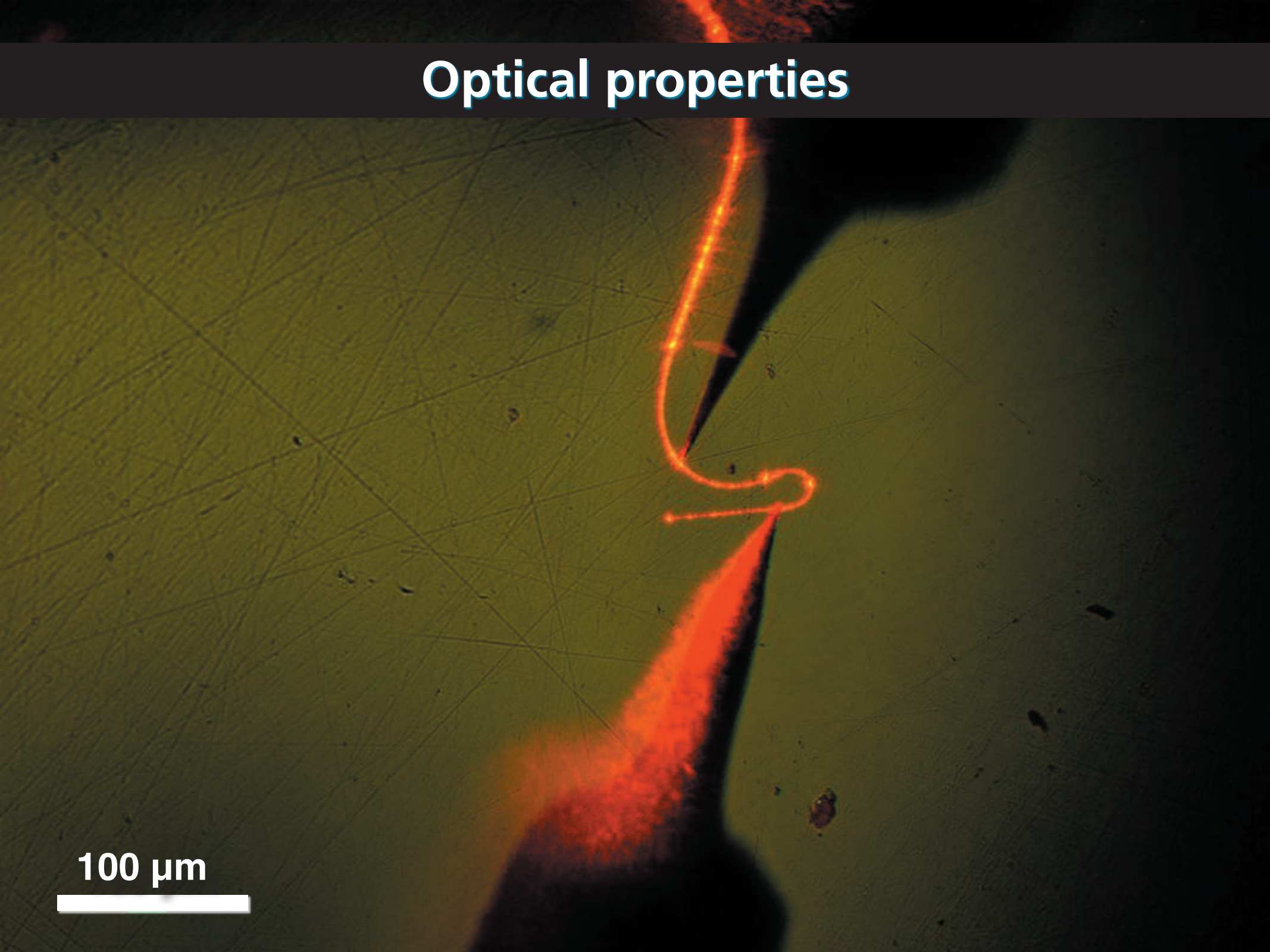
Optical properties

loss a single-mode diameter < 0.1 dB/mm

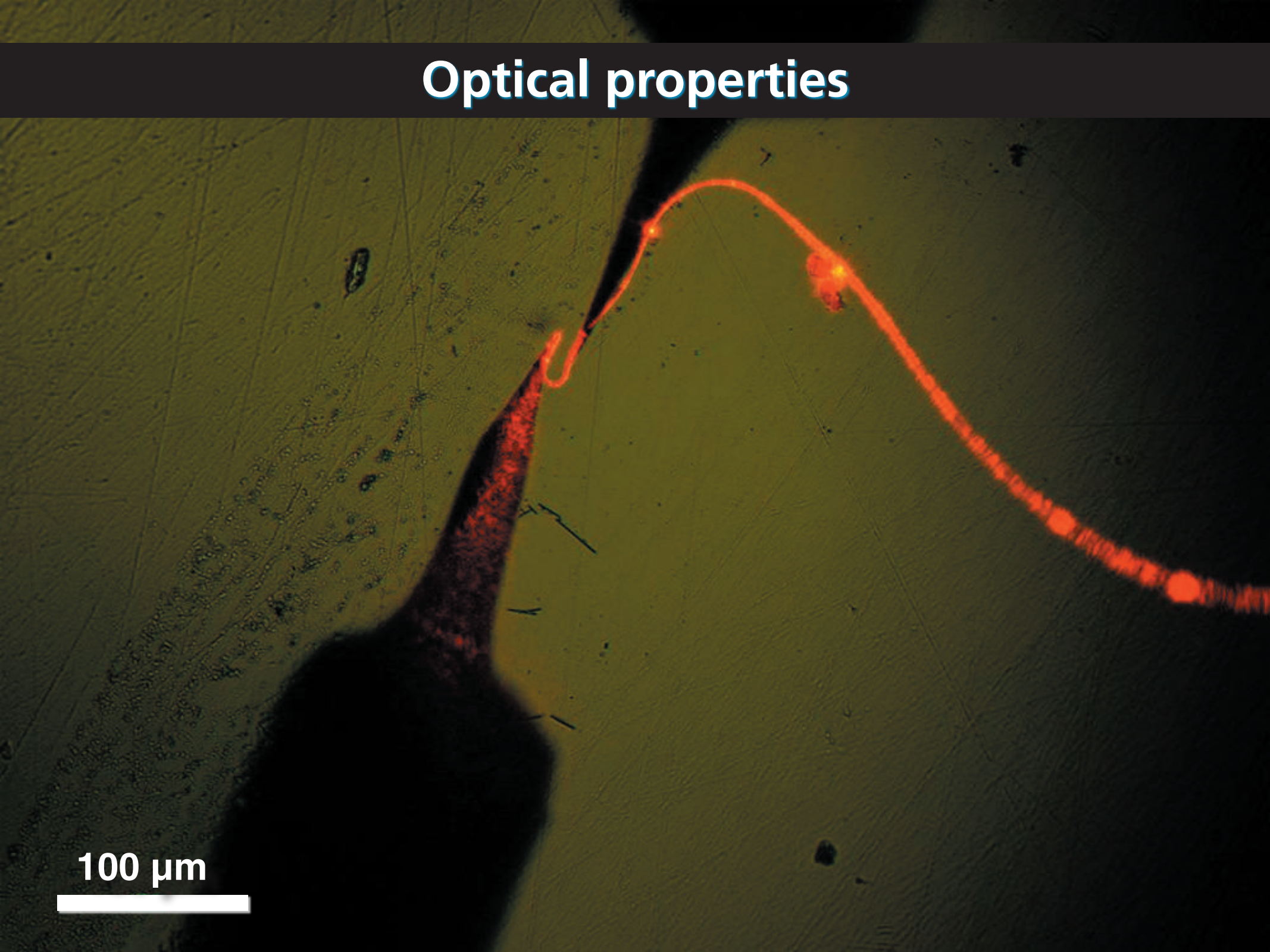


Nature, 426, 816 (2003)

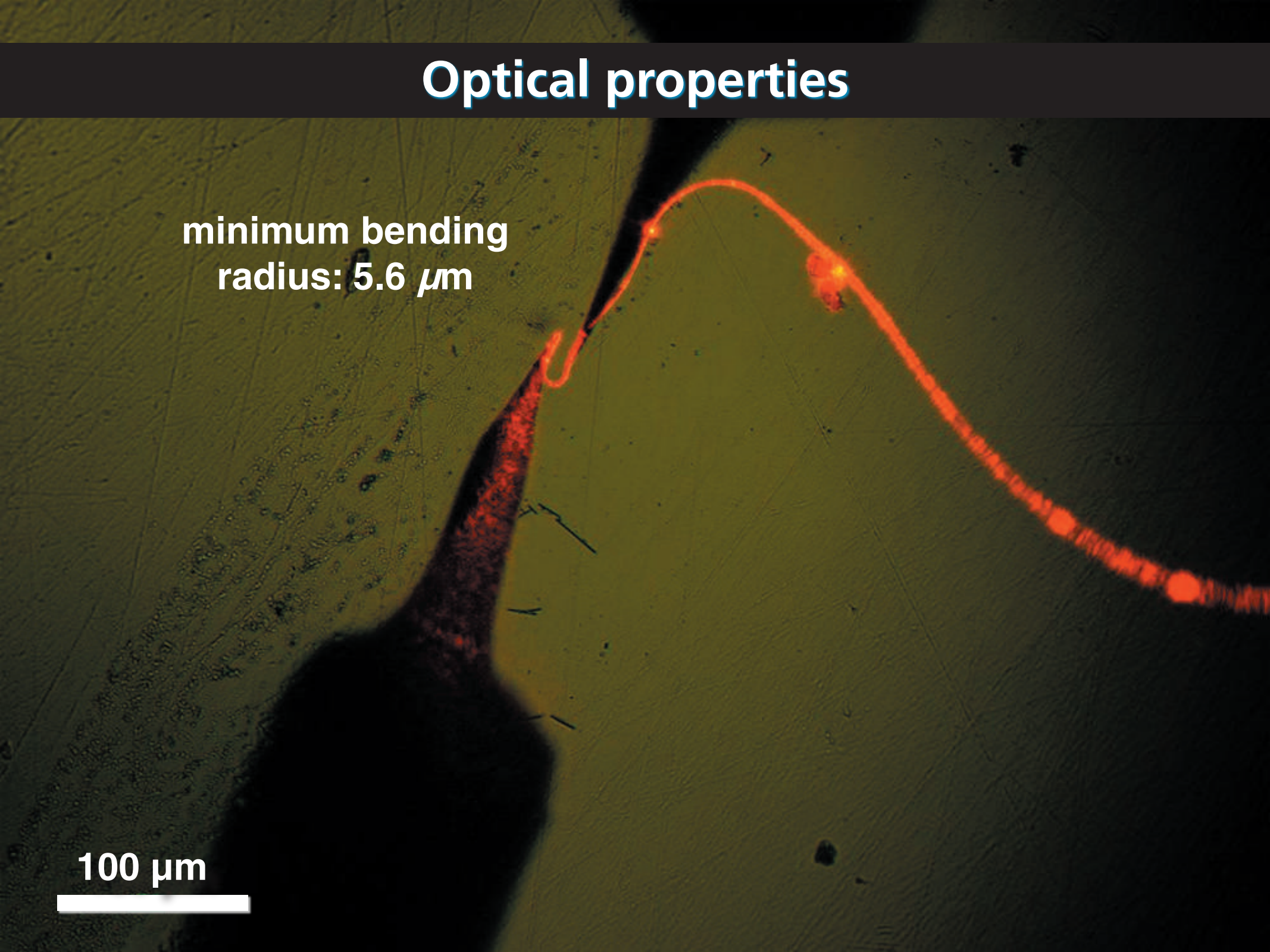
Optical properties



Optical properties

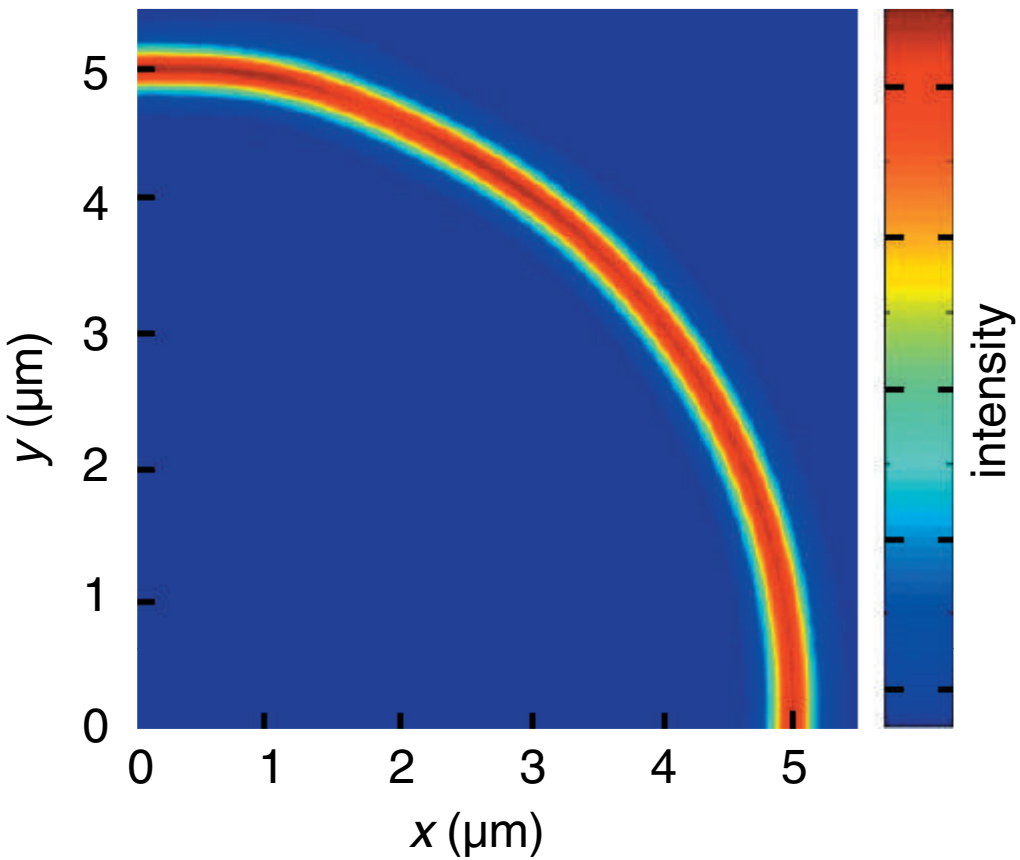


Optical properties



Optical properties

virtually no loss through 5 μm corner!

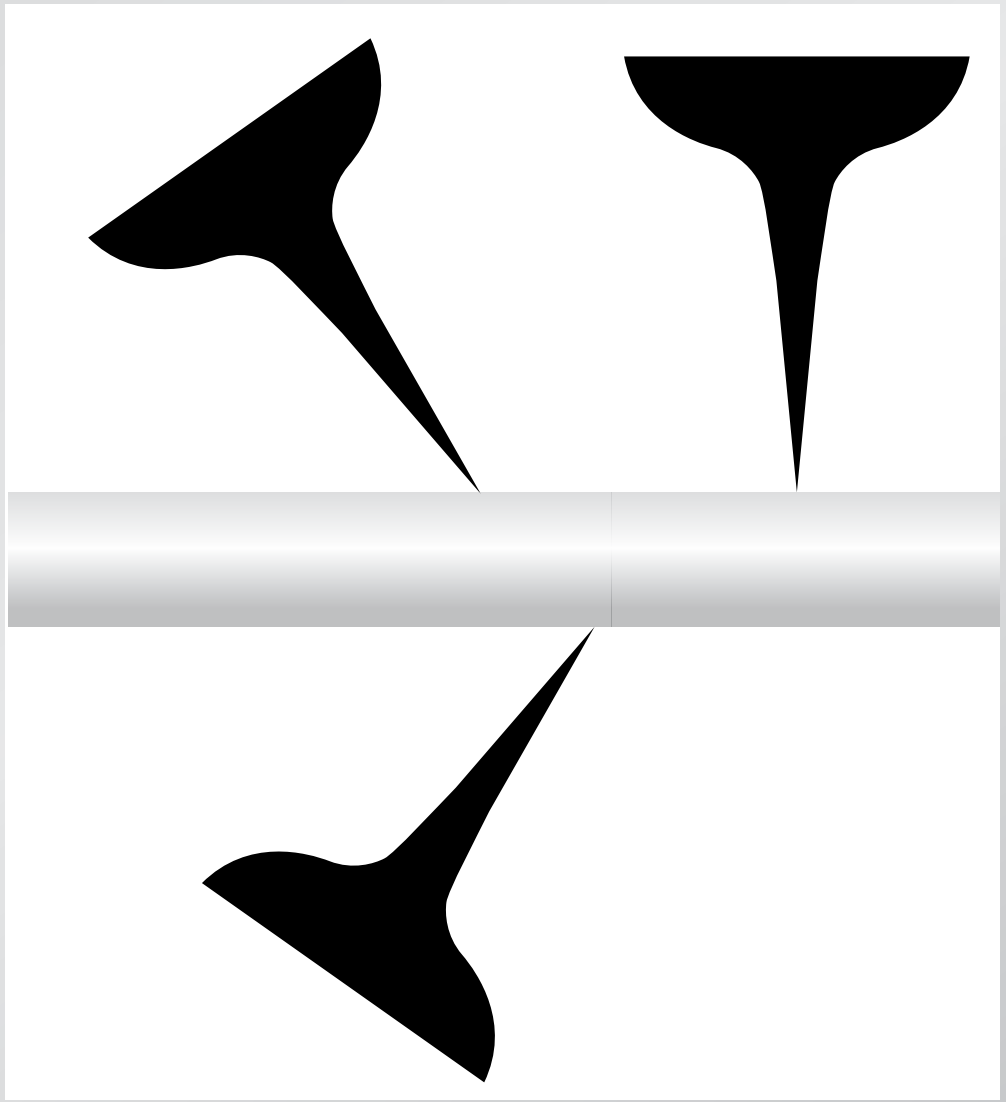


Optical properties

microphotonic components

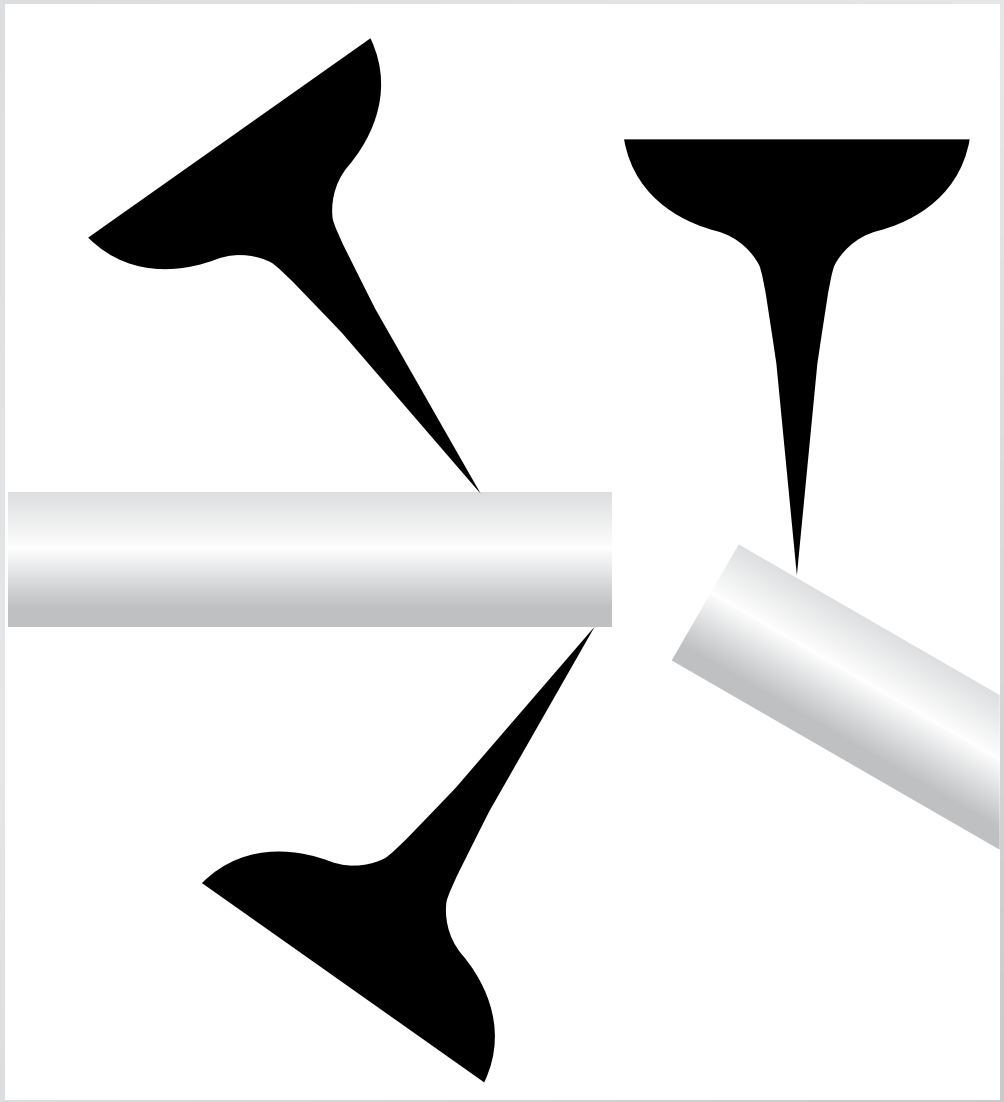
Optical properties

microphotonic components

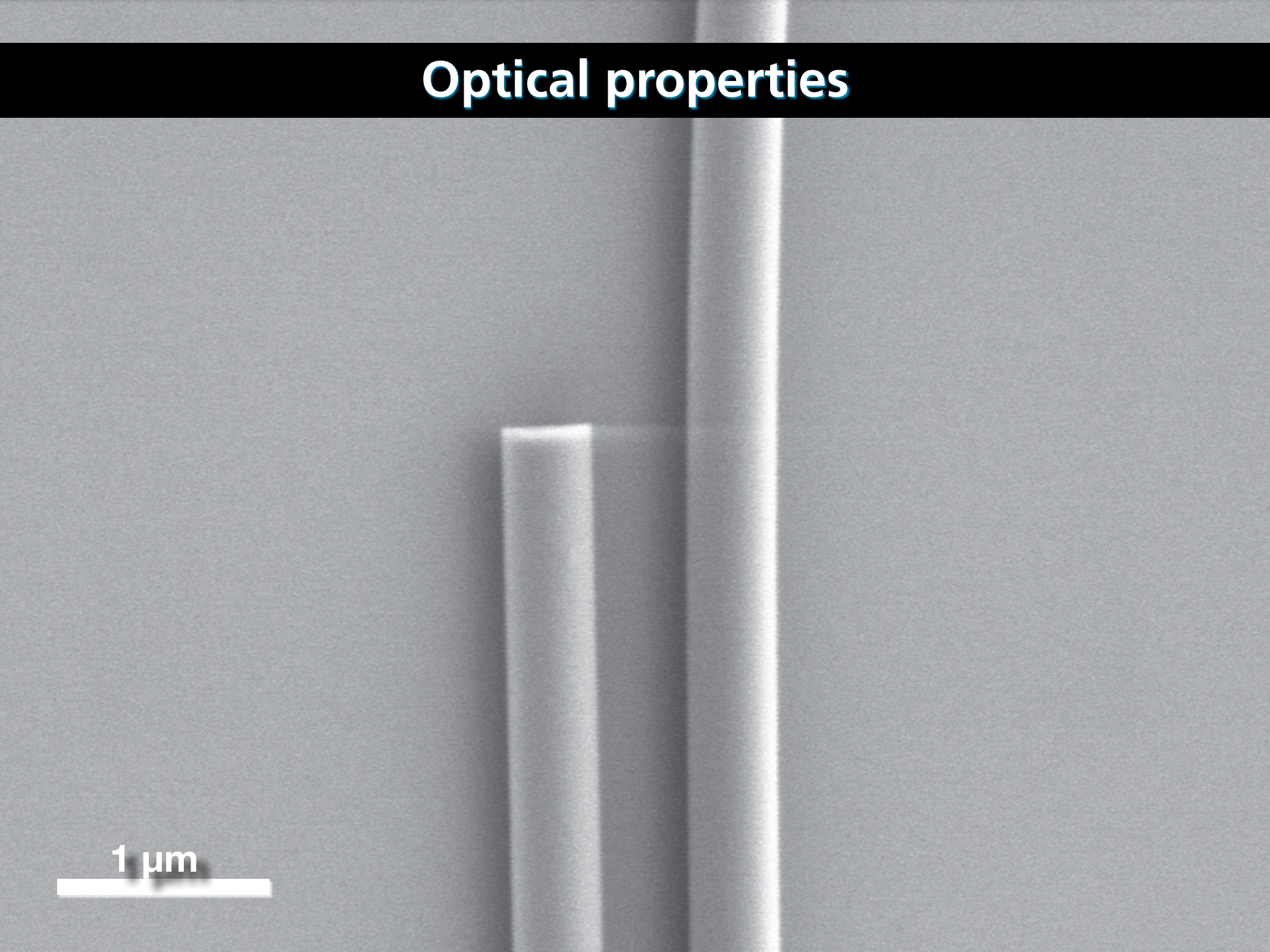


Optical properties

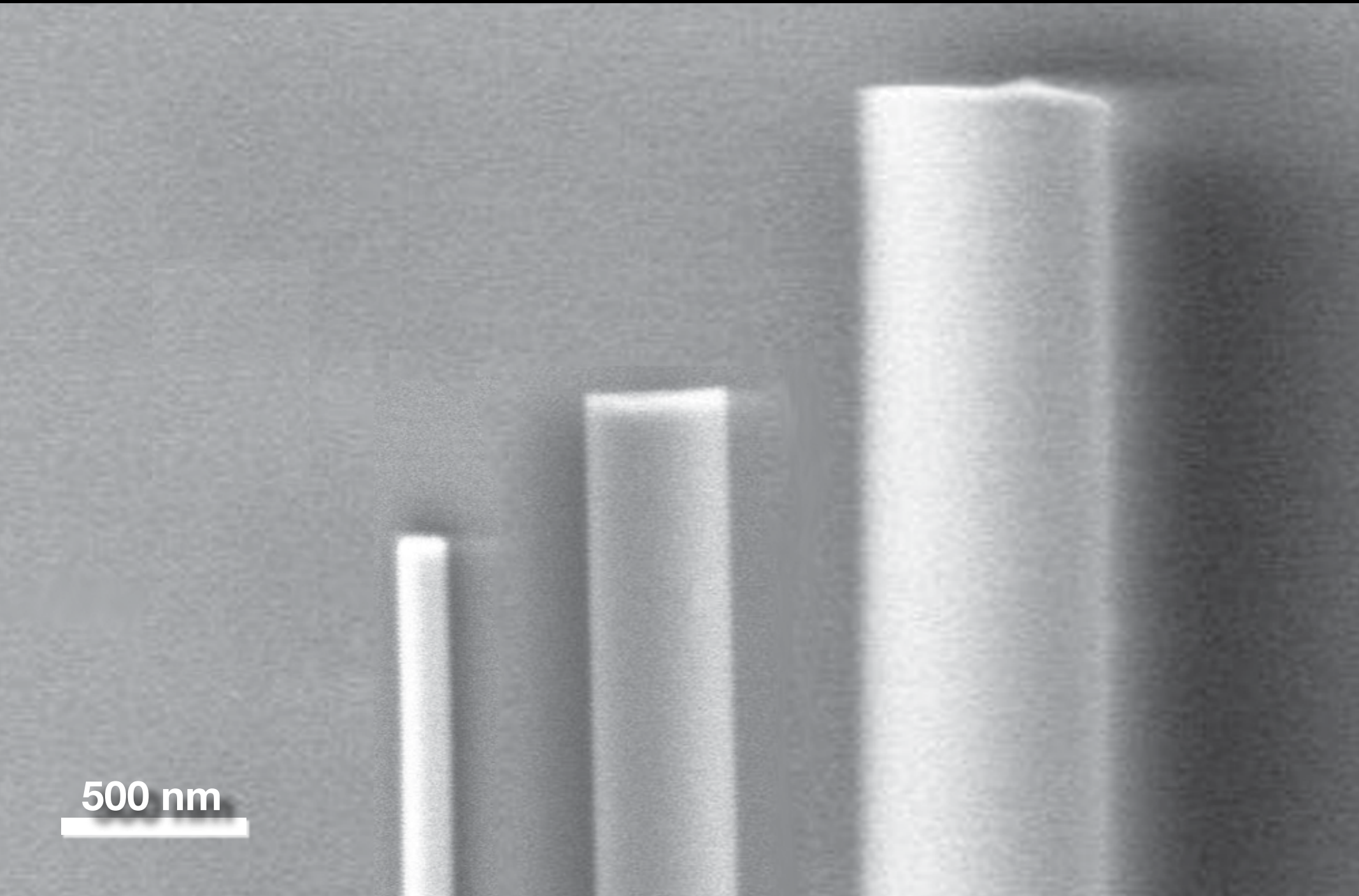
microphotonic components



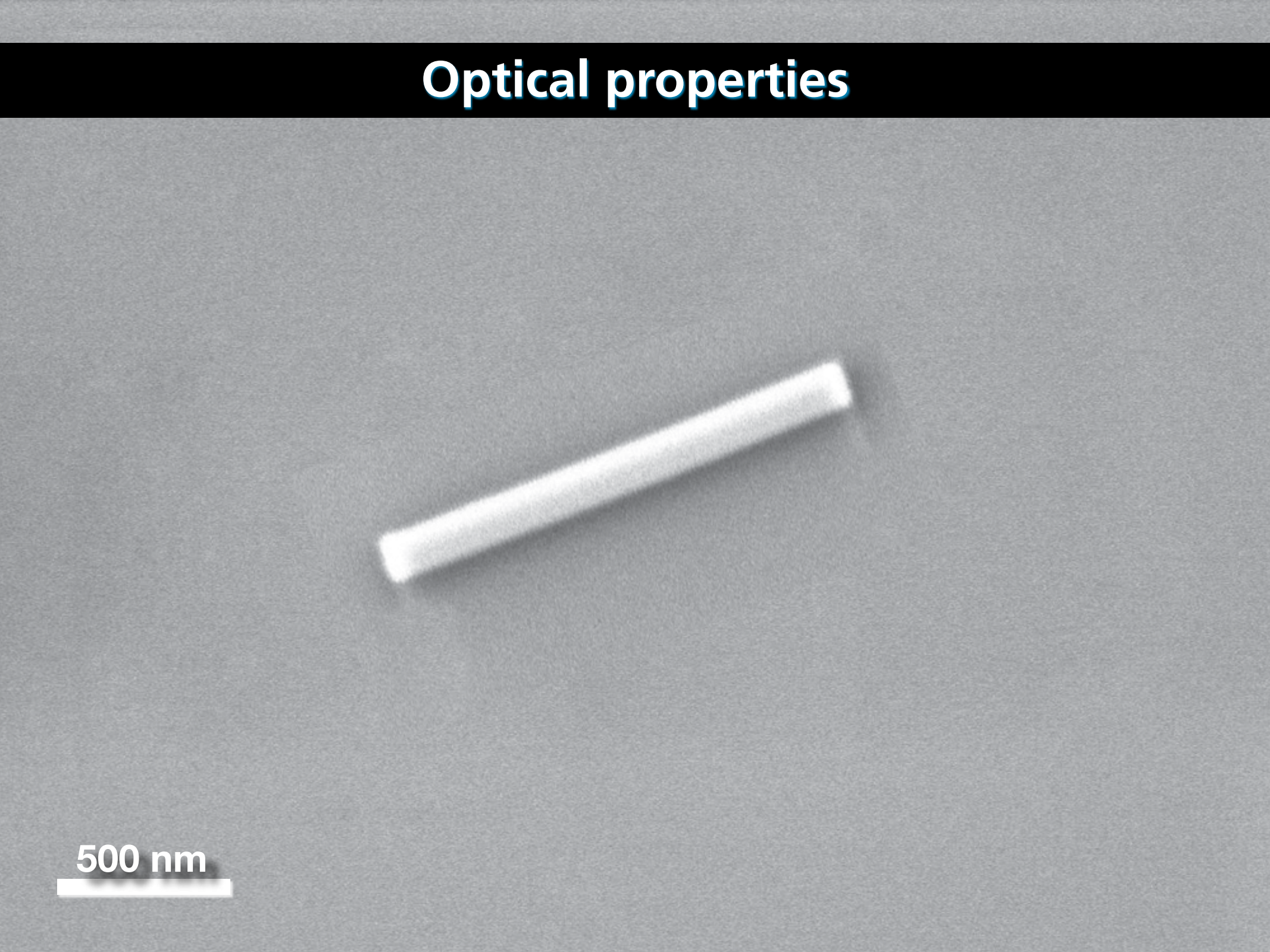
Optical properties



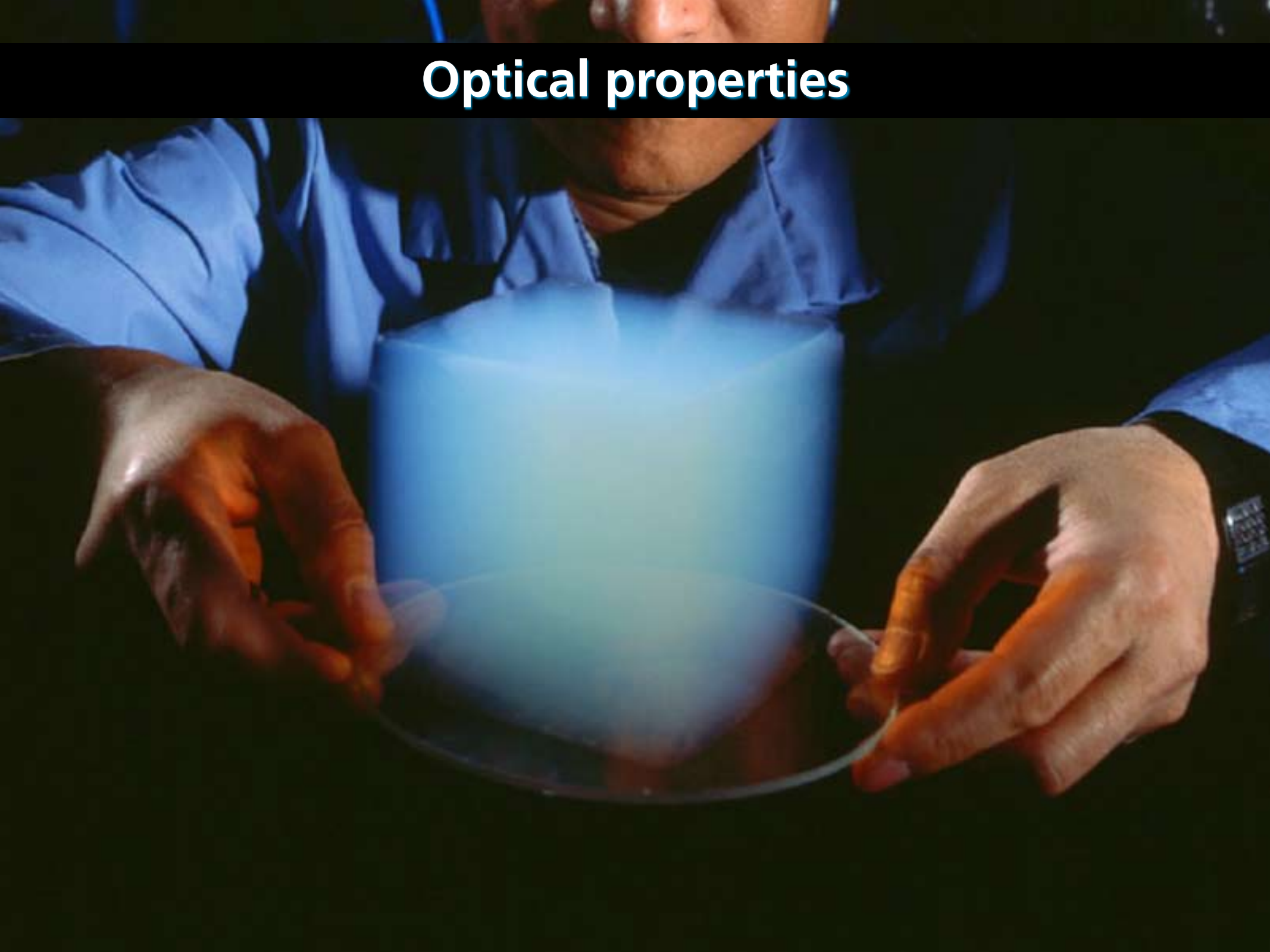
Optical properties



Optical properties

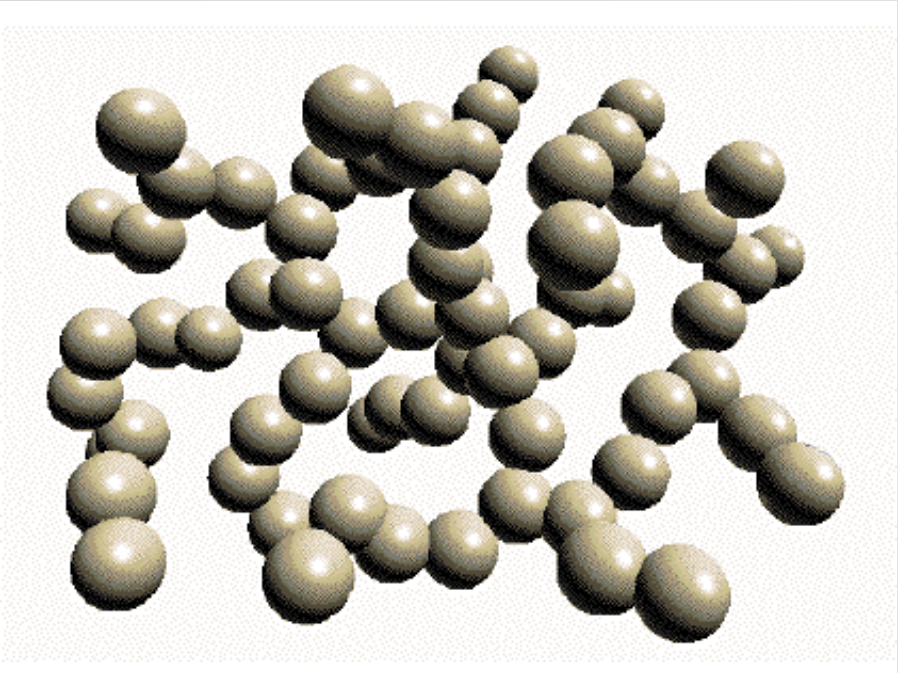


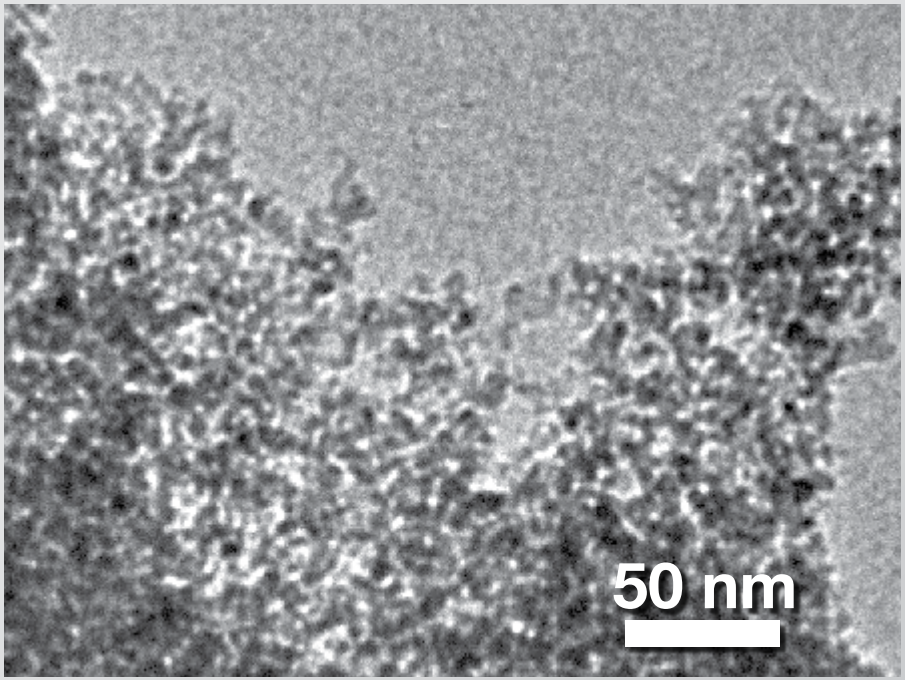
Optical properties



Optical properties

Aerogel

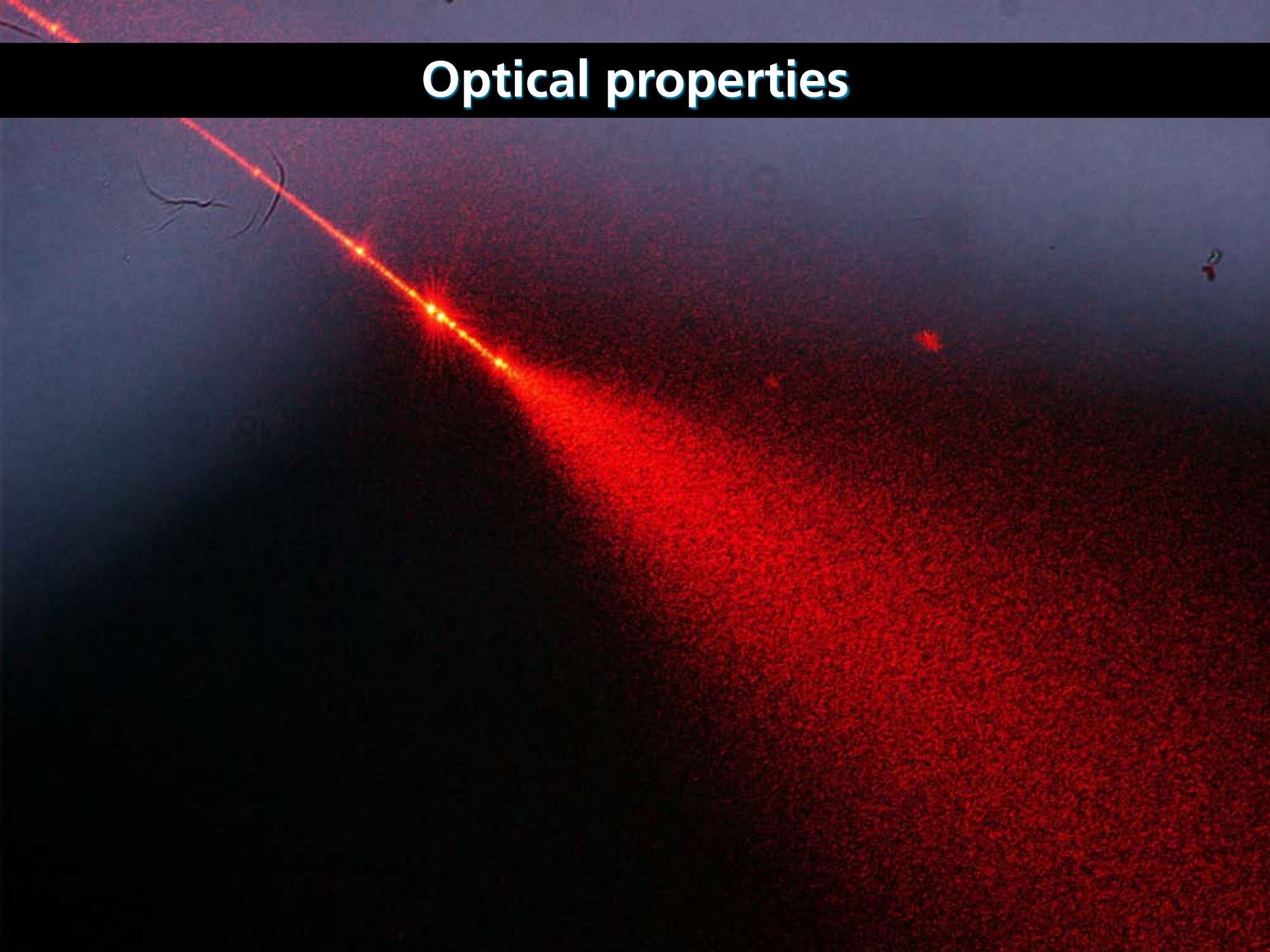




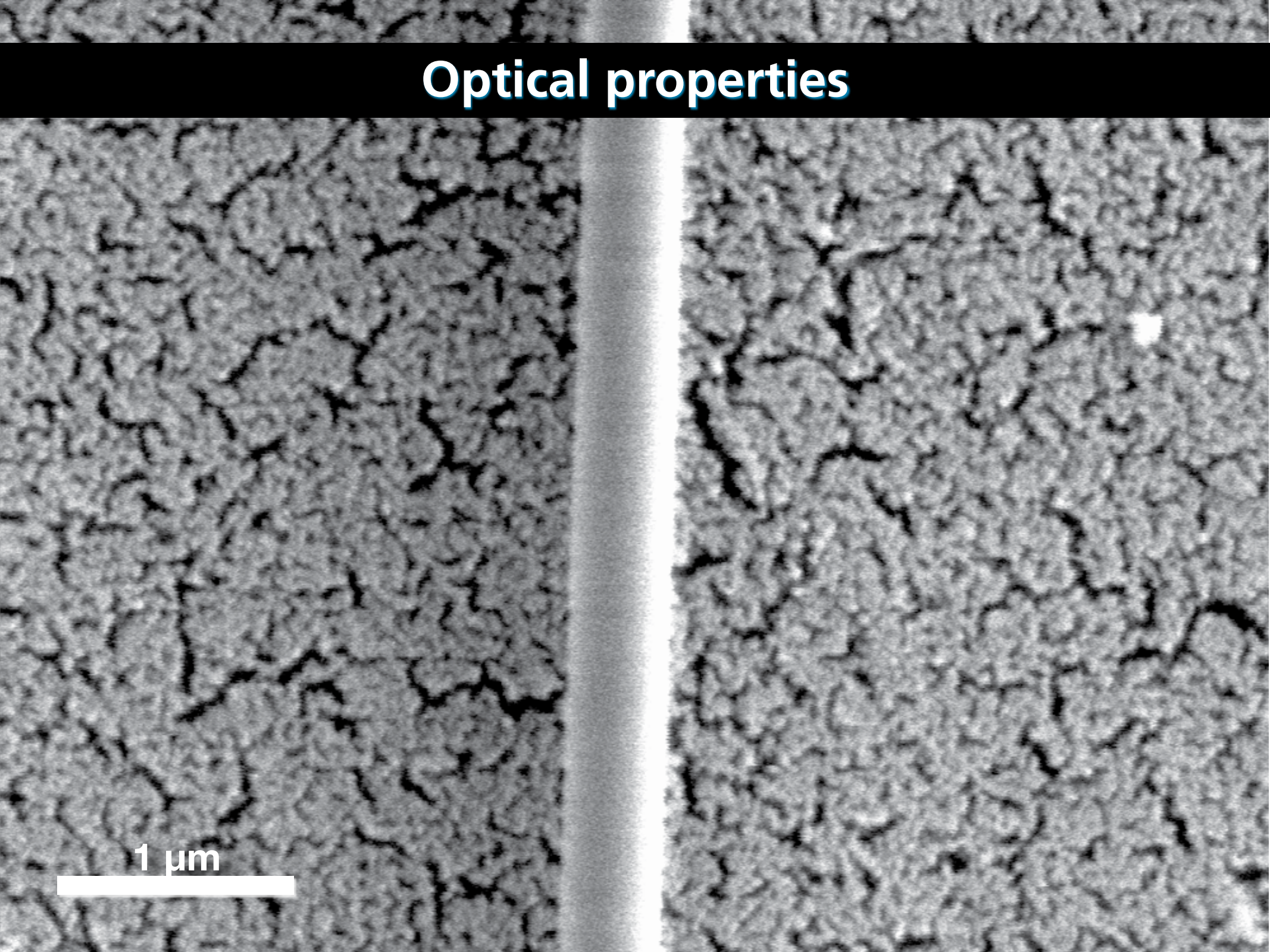
density: 1.9 kg/m^3

index of refraction: 1.03–1.08

Optical properties

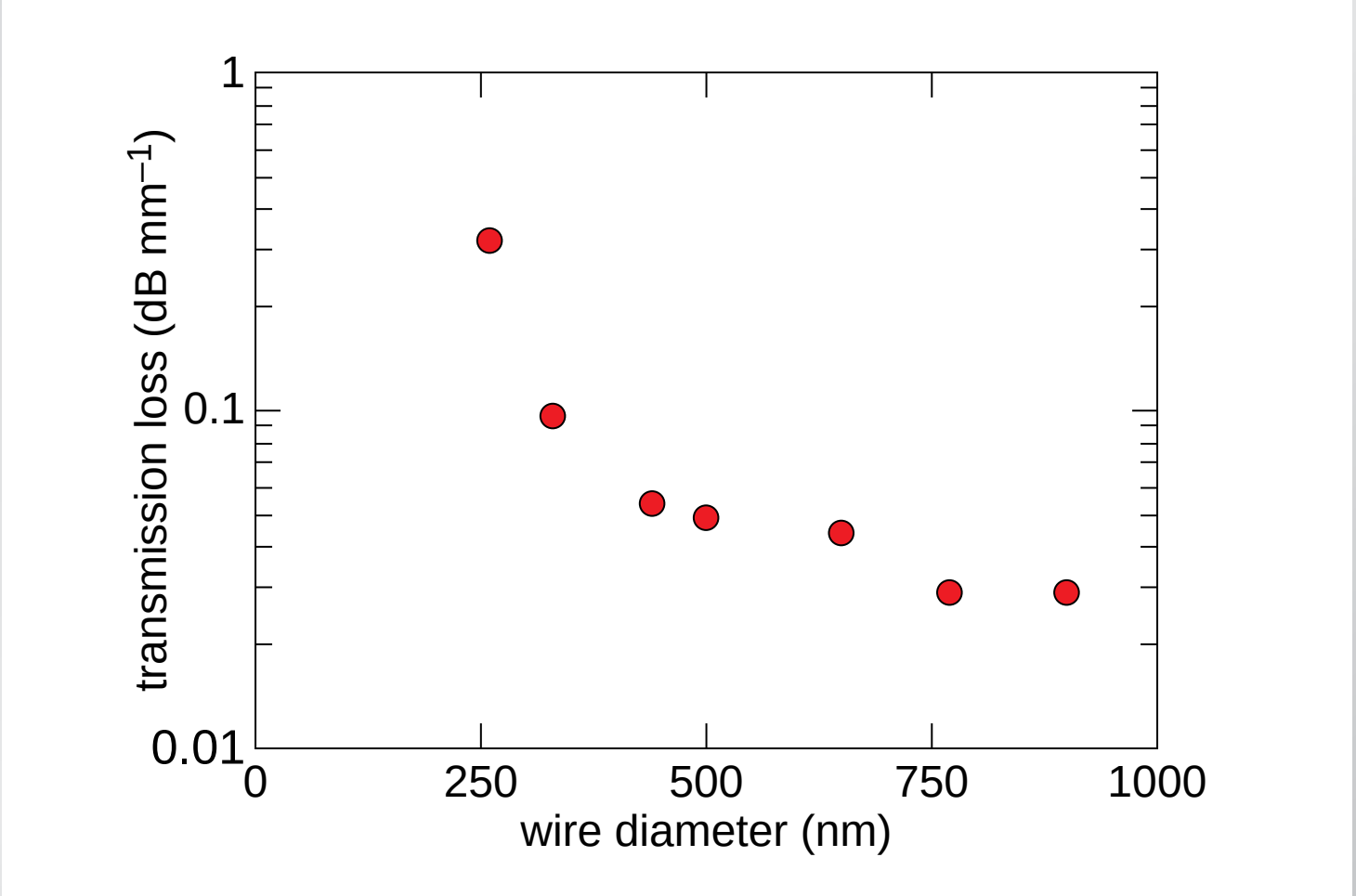


Optical properties



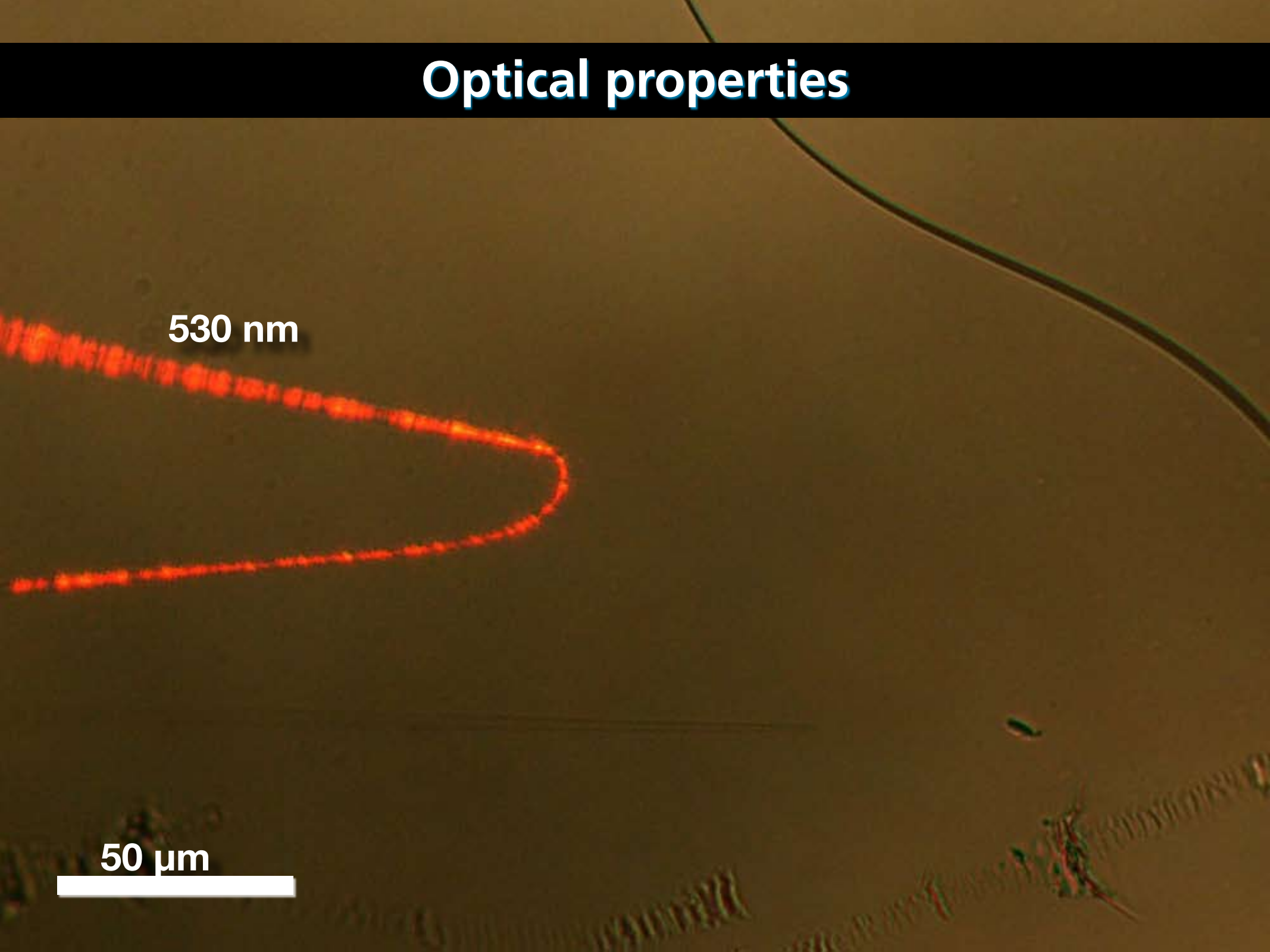
Optical properties

loss measurement @ 633 nm

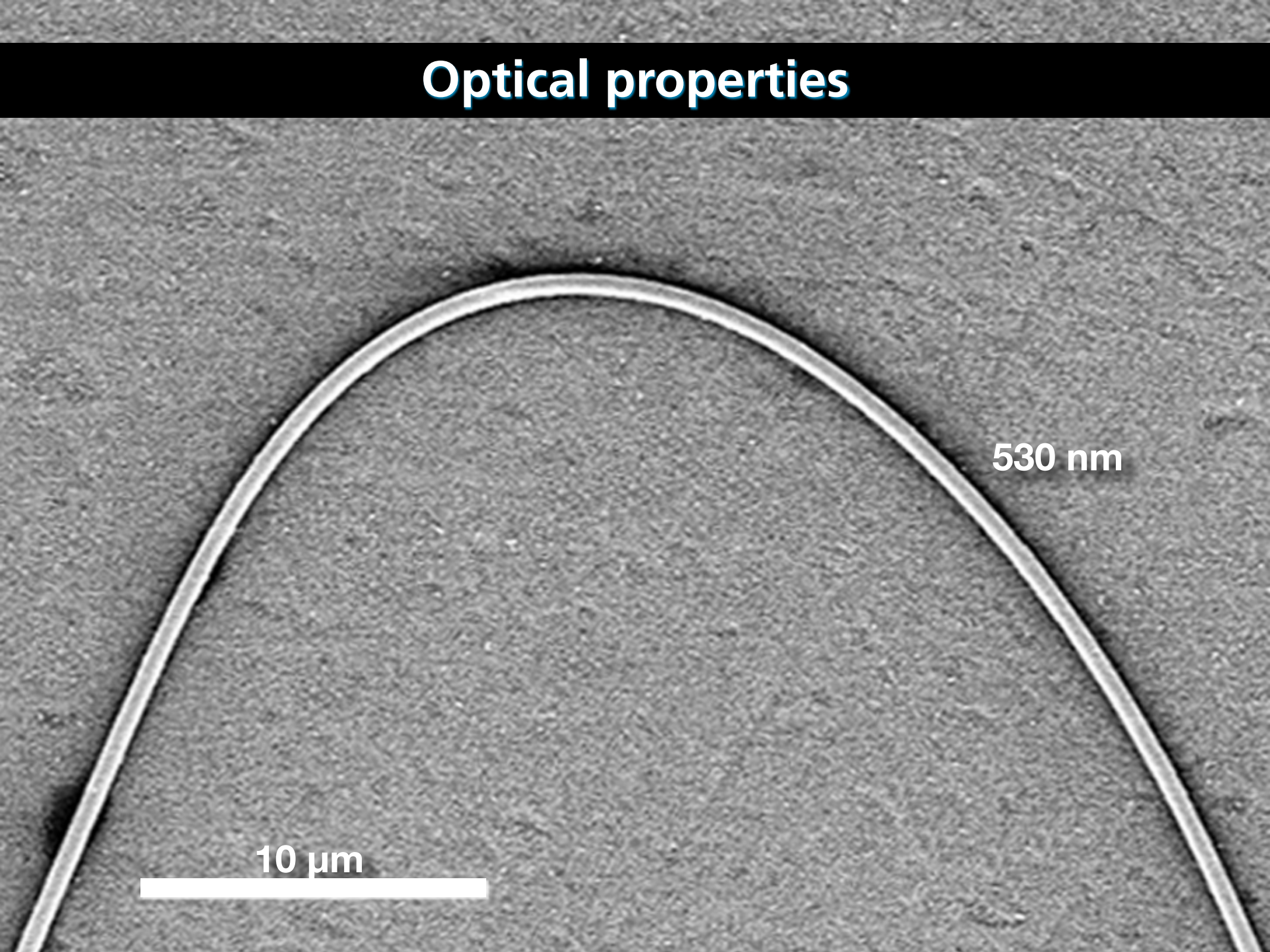


Nano Lett., **5**, 259–262 (2005)

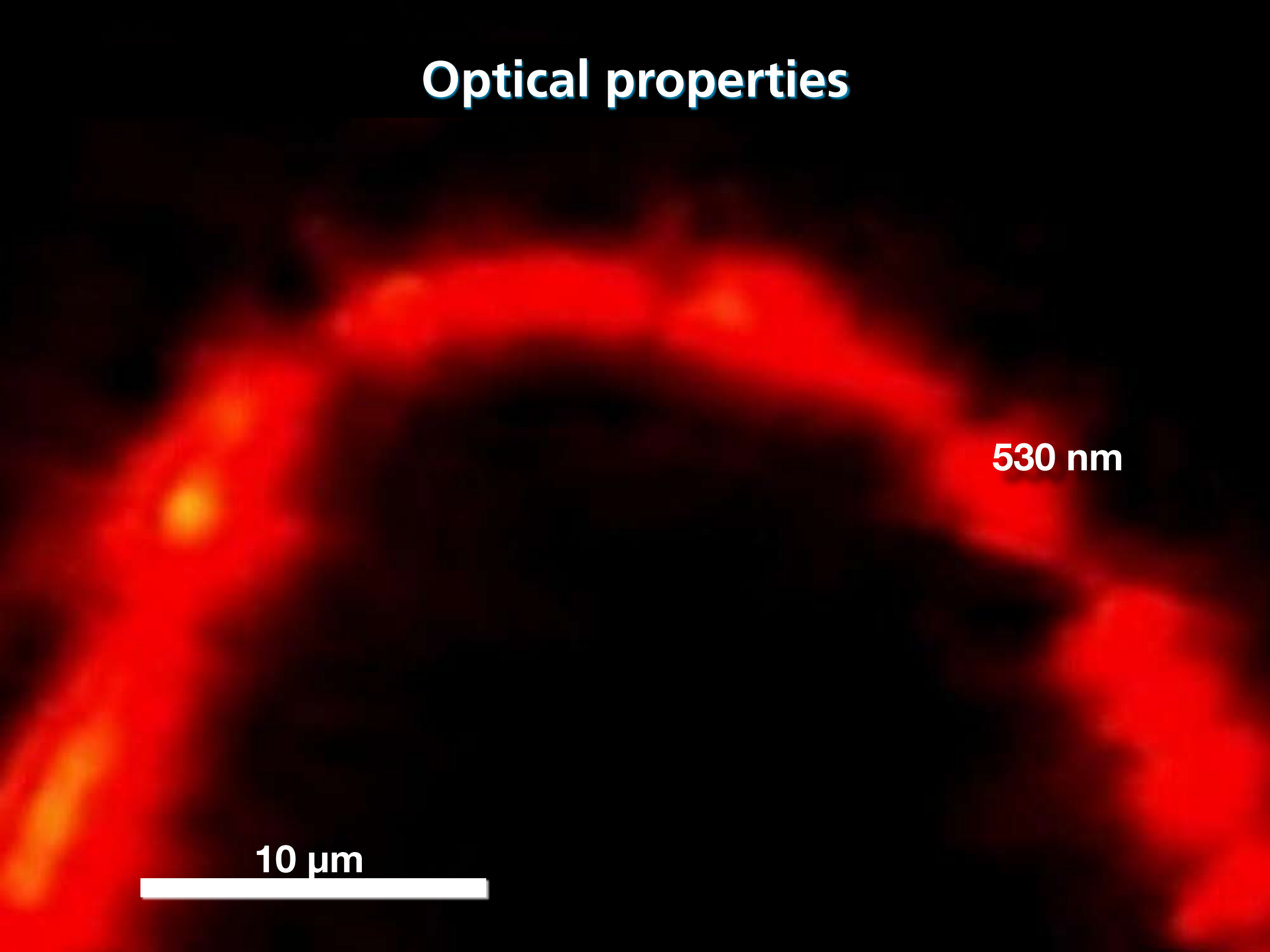
Optical properties



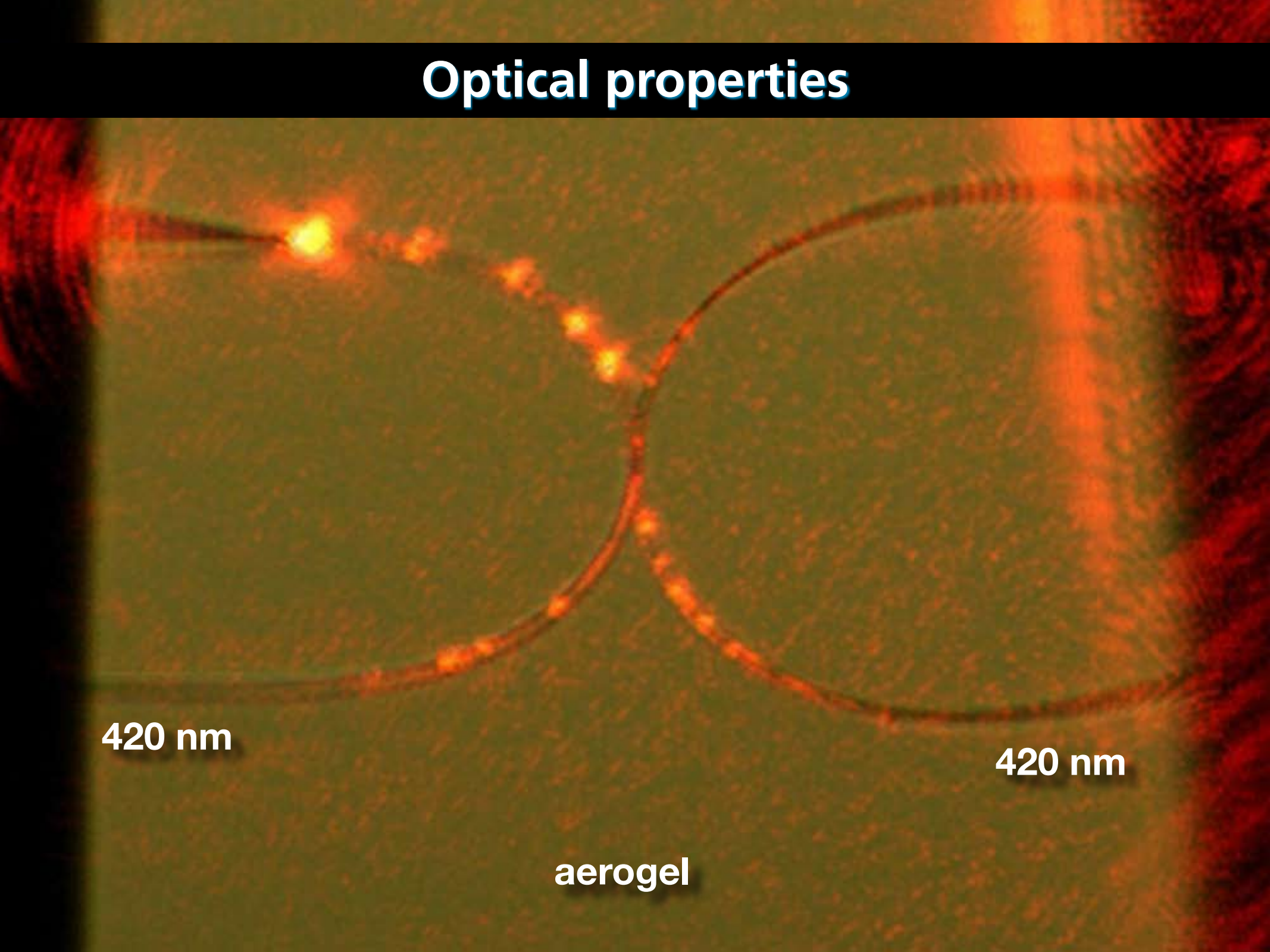
Optical properties



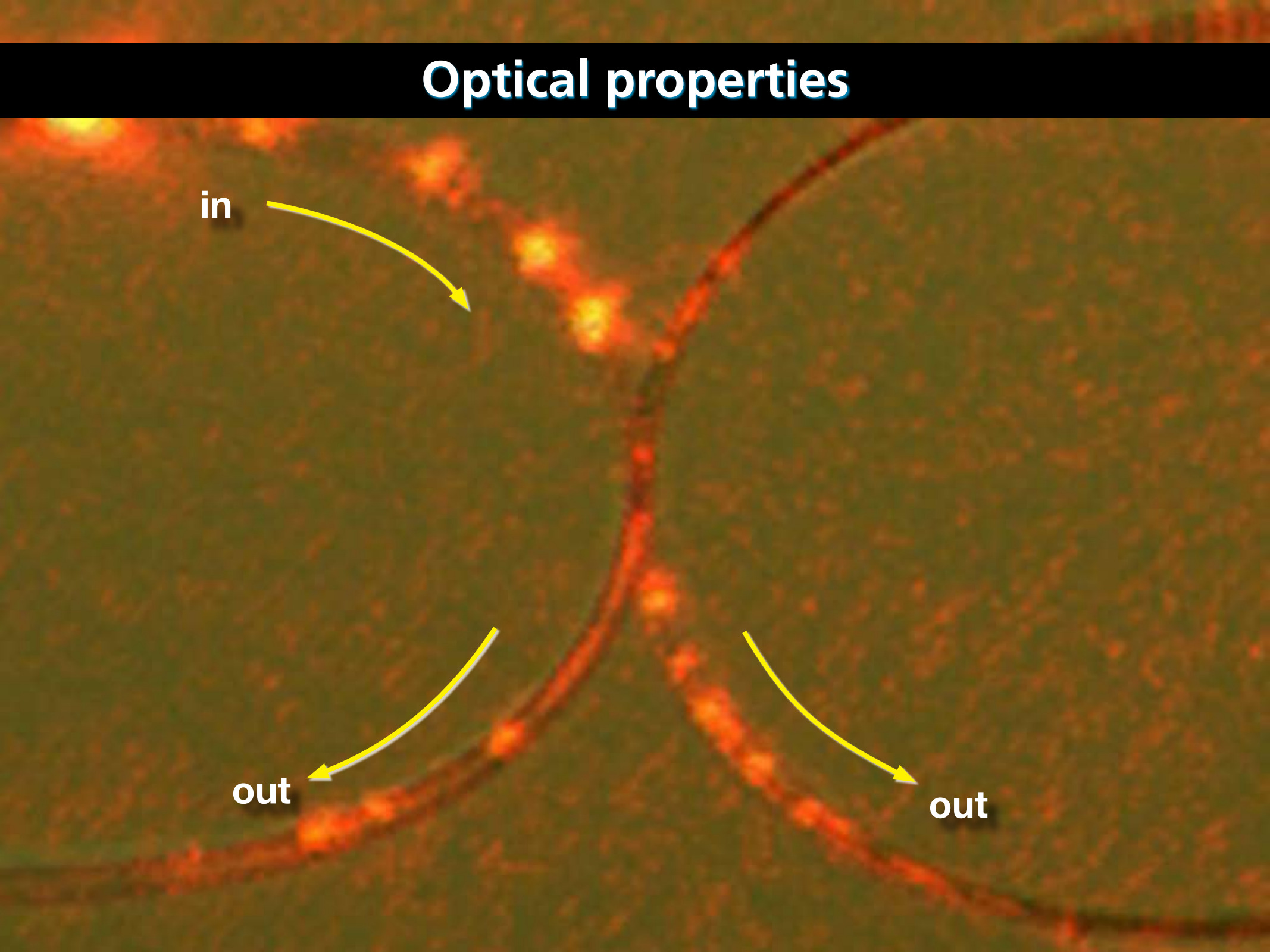
Optical properties



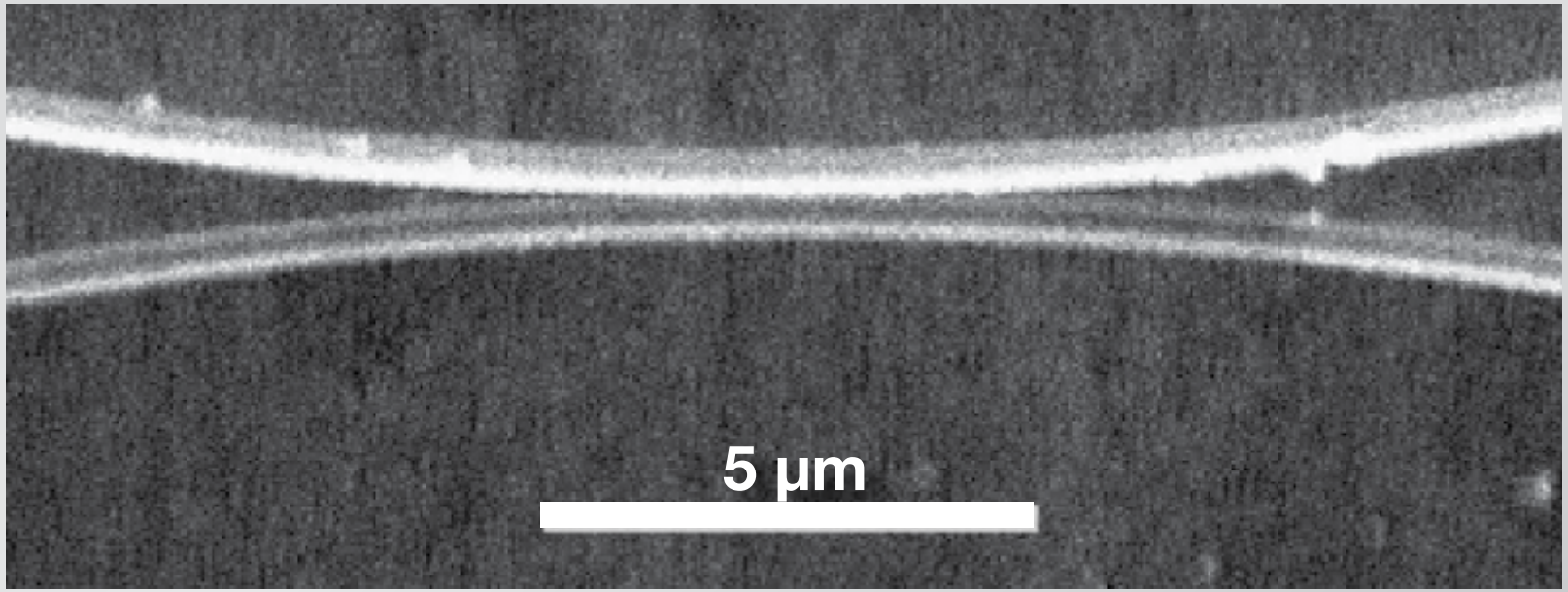
Optical properties



Optical properties

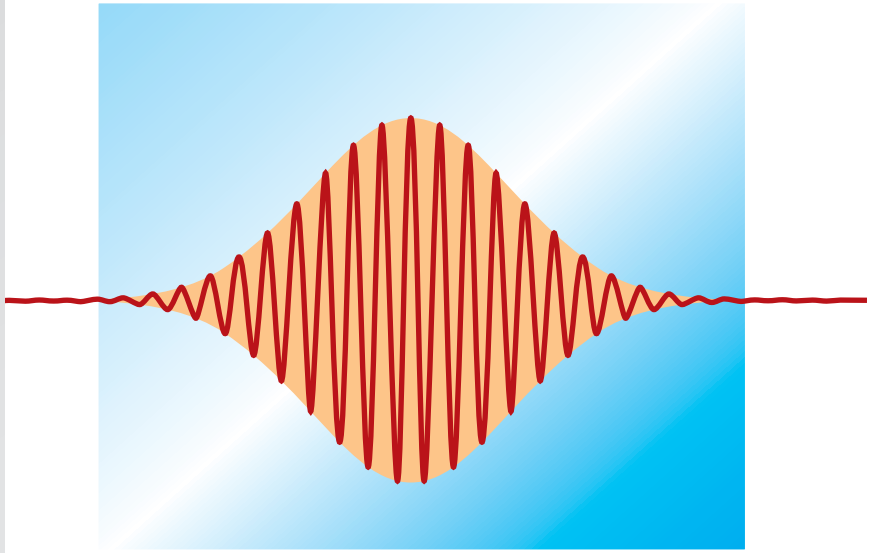


Optical properties



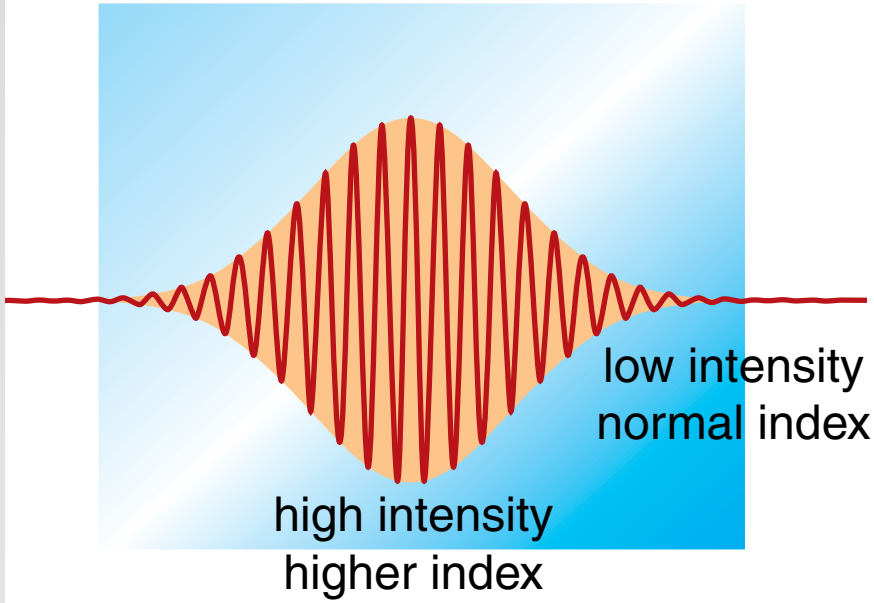
Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



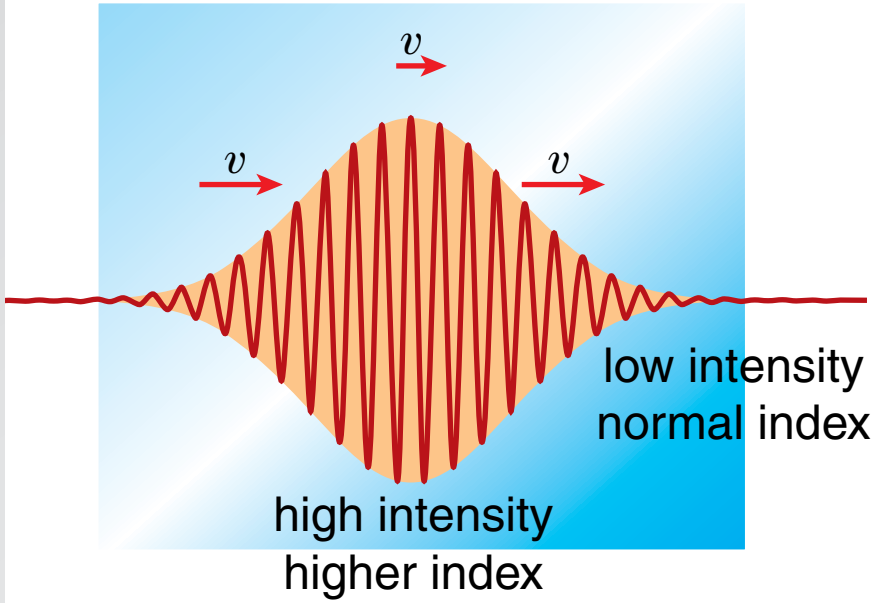
Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



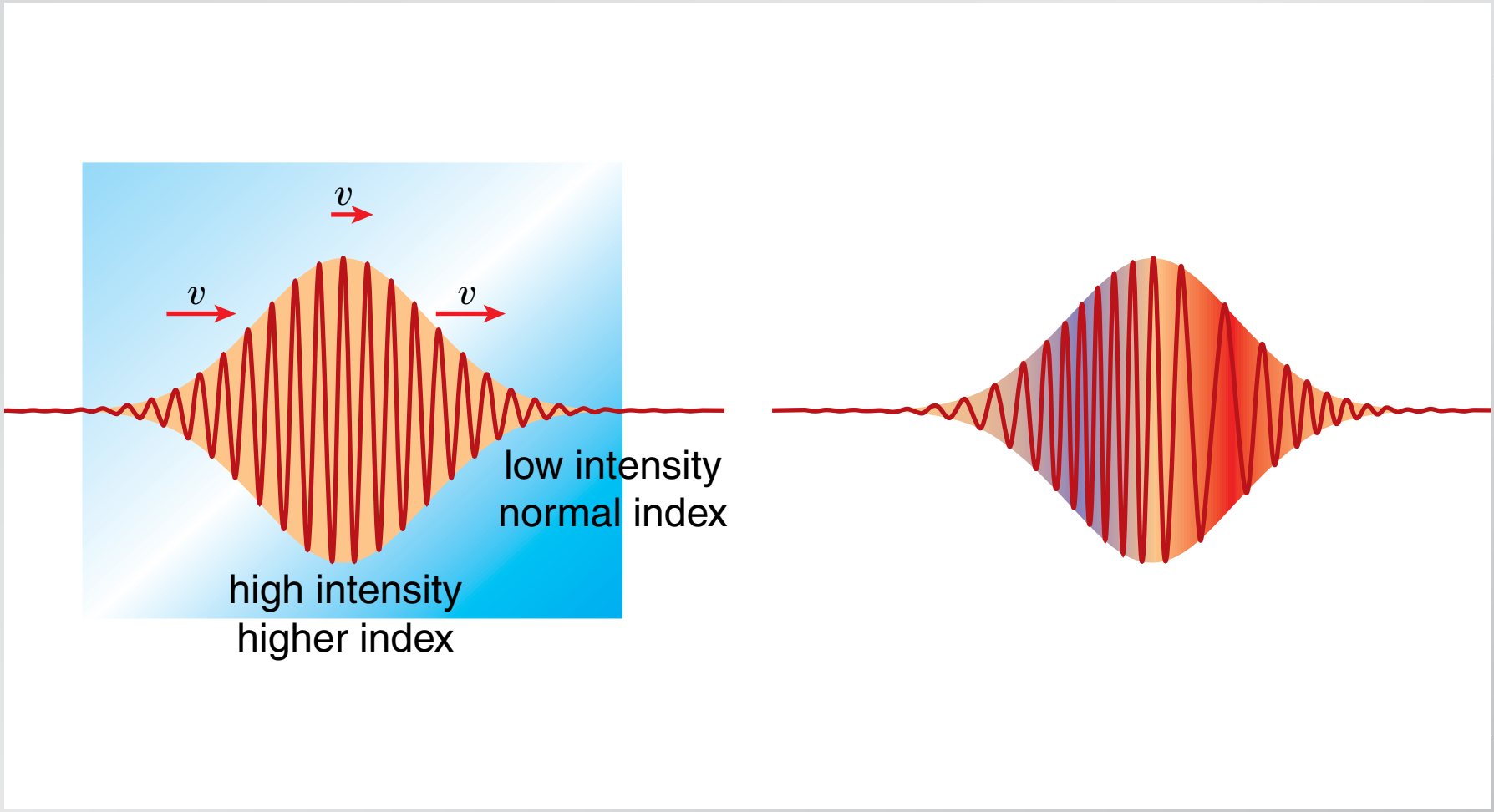
Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



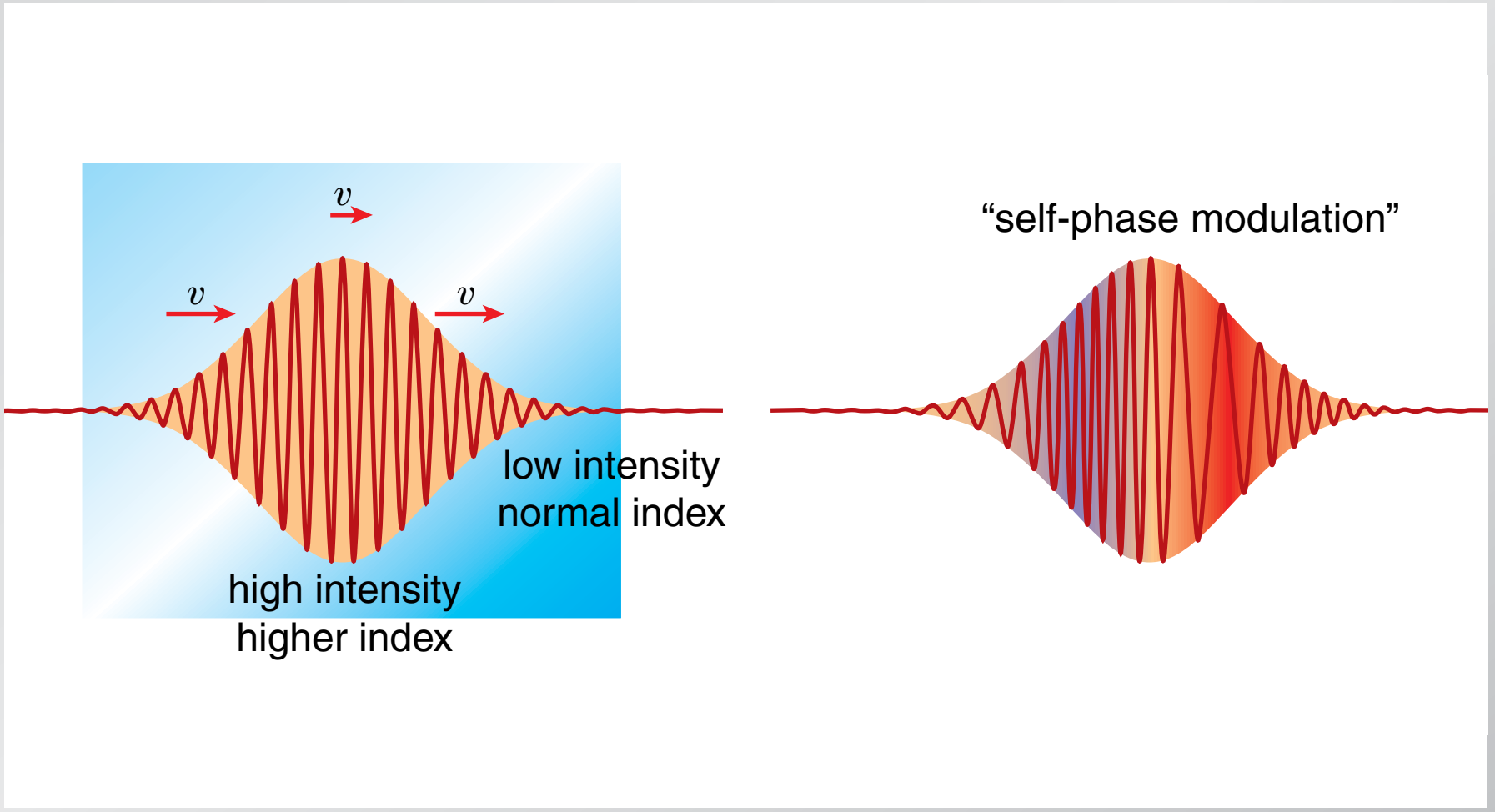
Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$

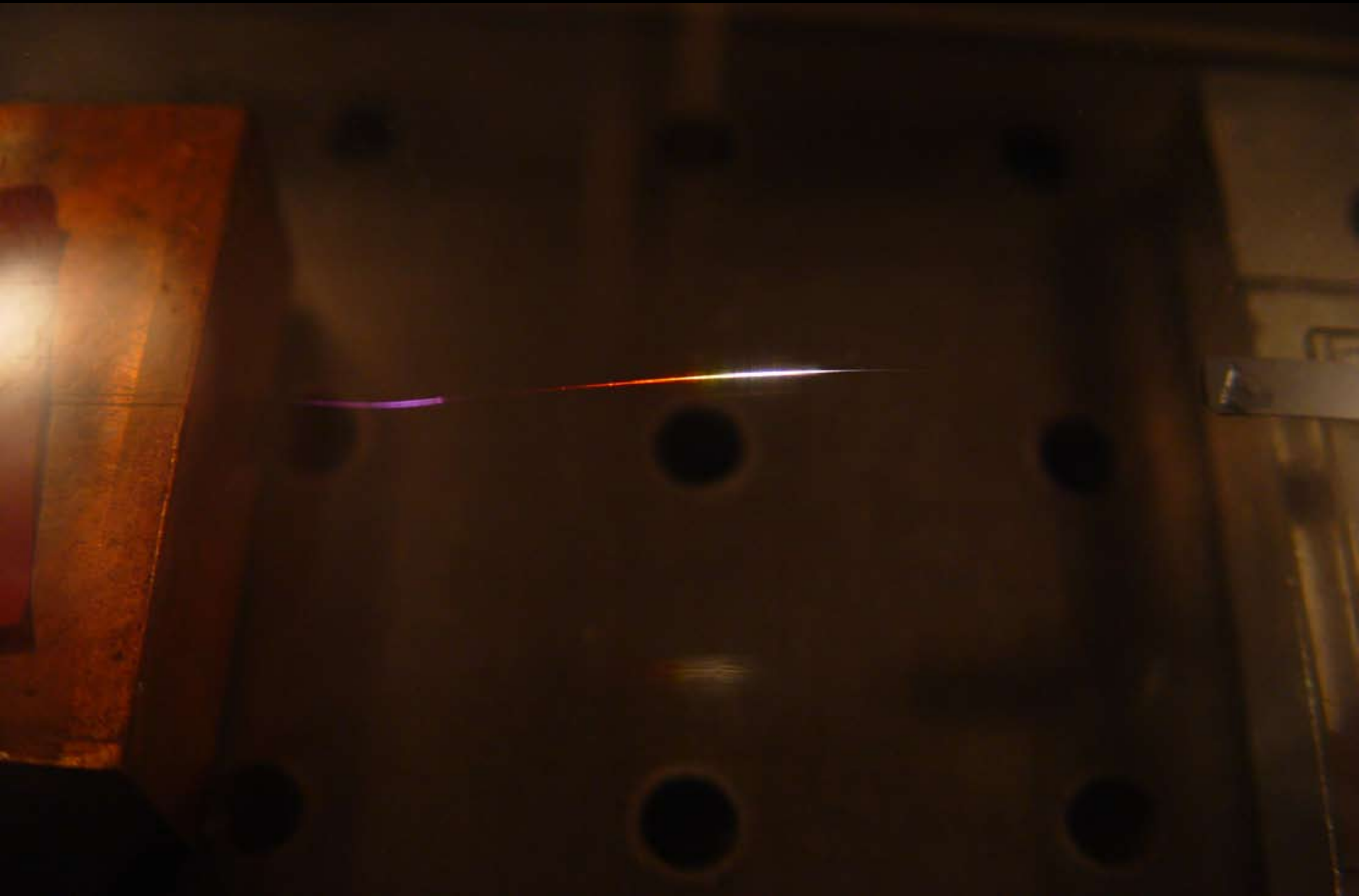


Nonlinear properties

nonlinear dispersion: $n = n_o + n_2 I$



Nonlinear properties



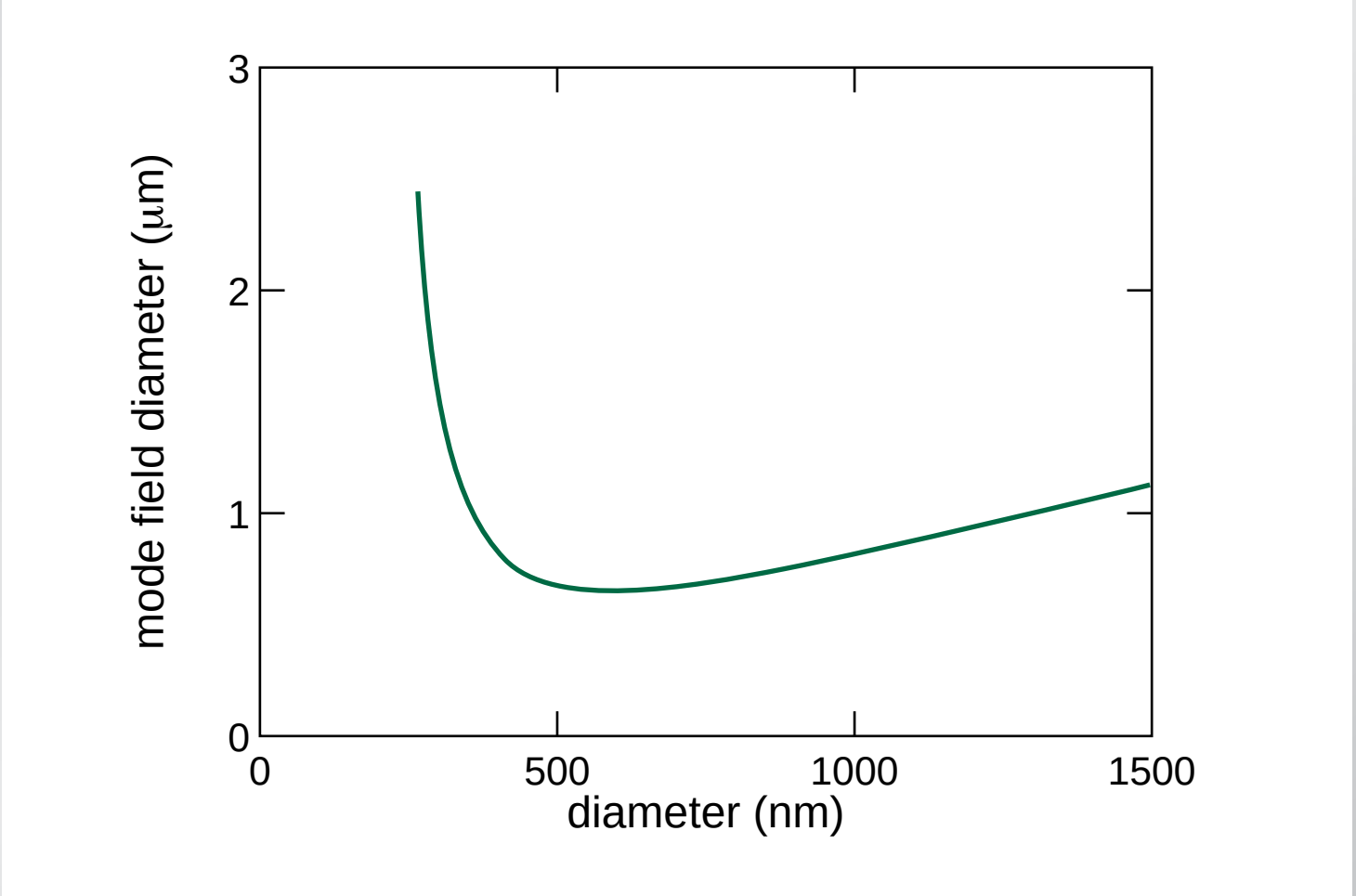
Nonlinear properties

Nonlinear properties

strong confinement $\longrightarrow$ high intensity

Nonlinear properties

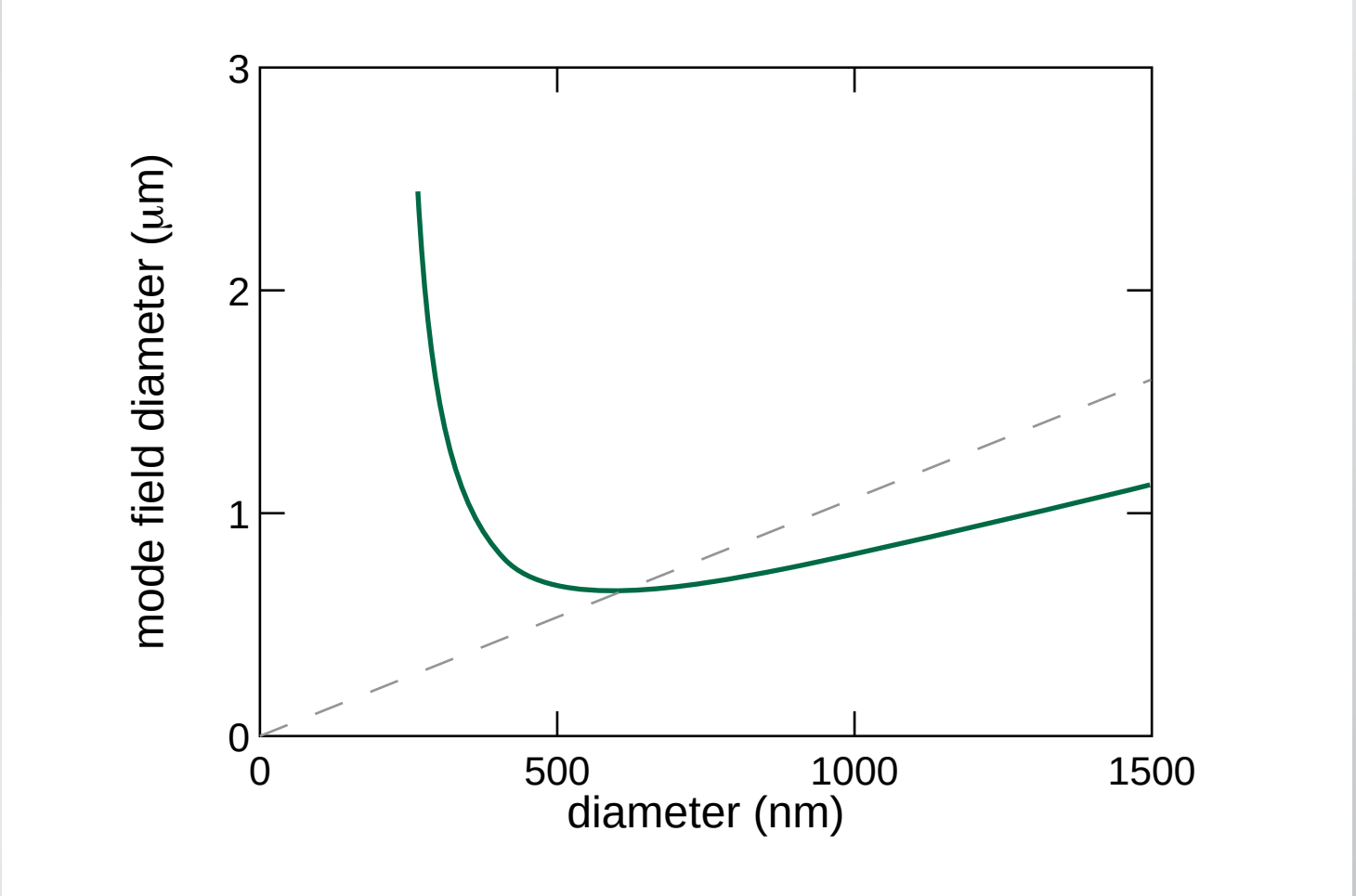
mode field diameter (λ = 800 nm)



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

Nonlinear properties

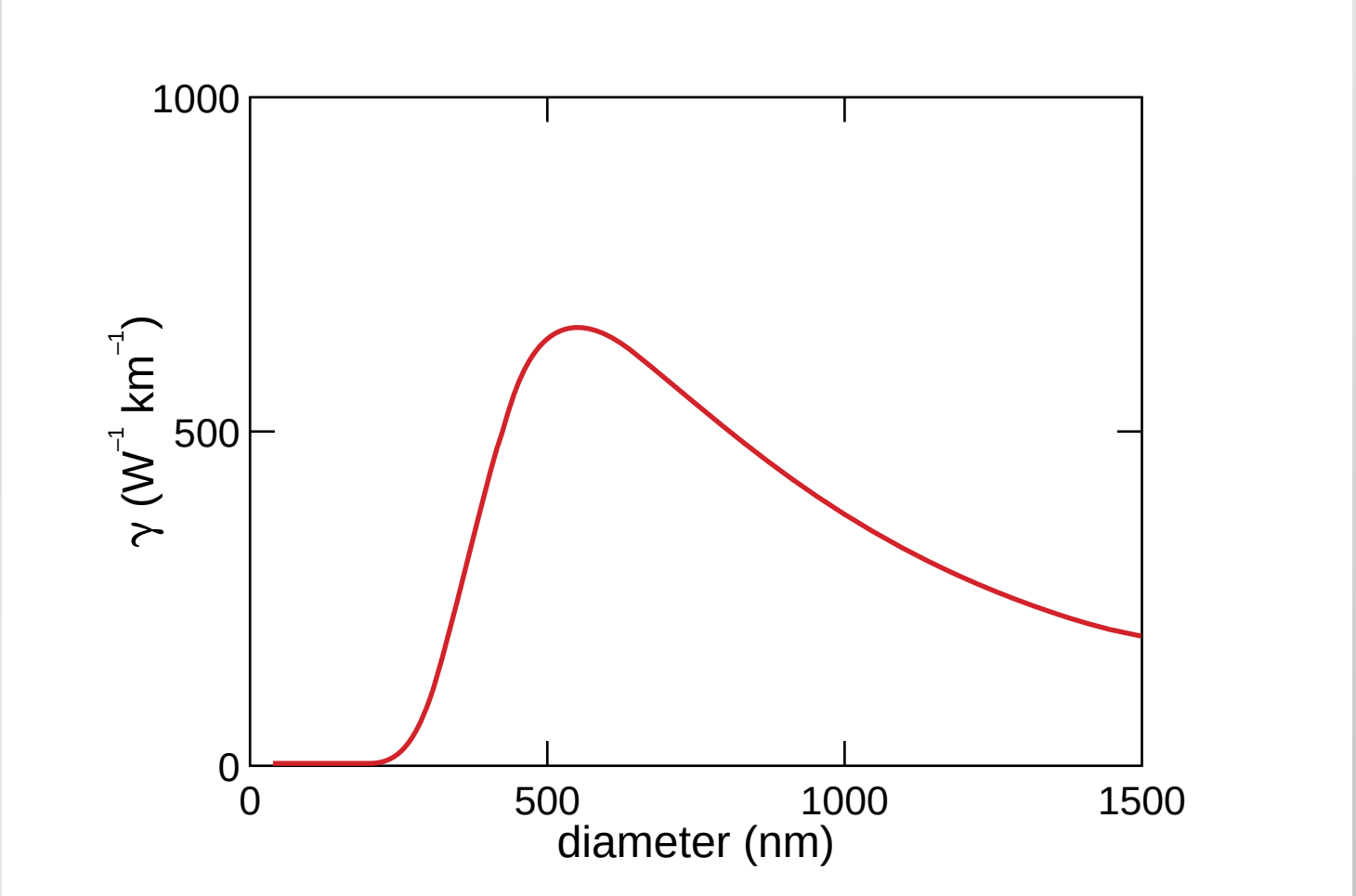
mode field diameter (λ = 800 nm)



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!

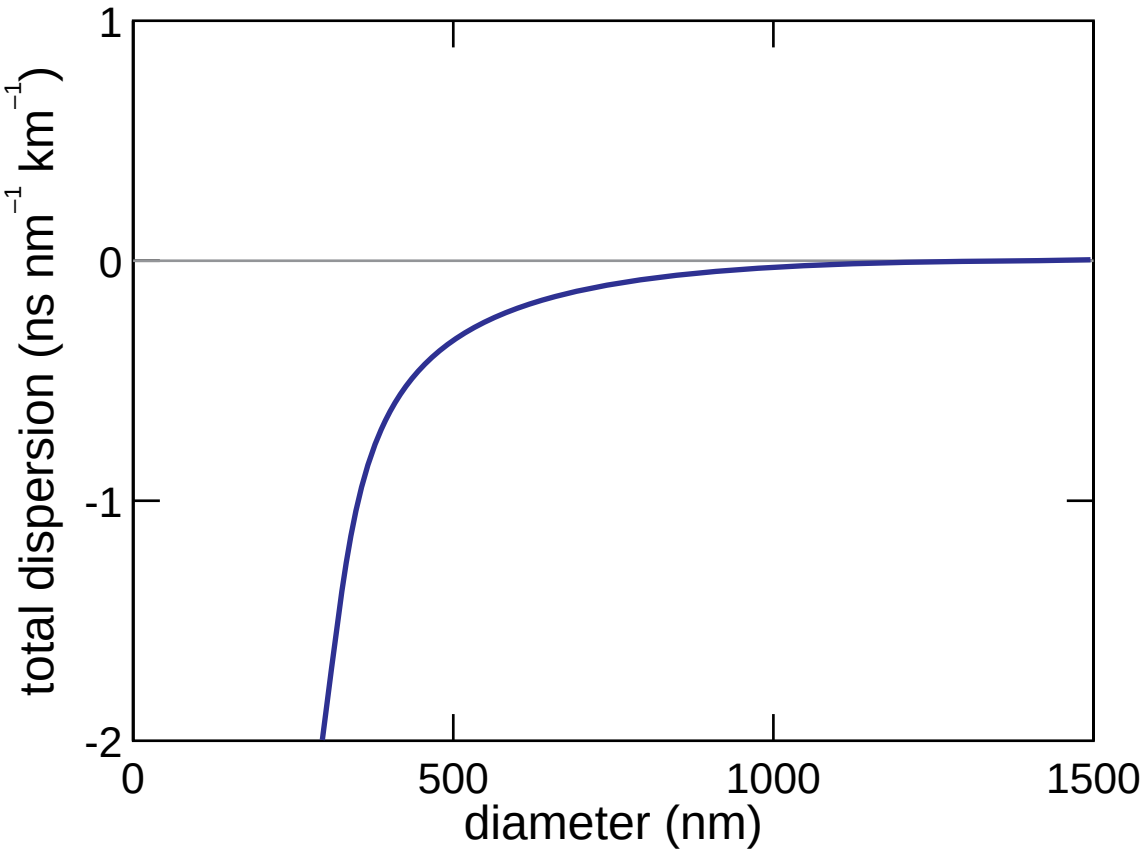
Nonlinear properties

dispersion:

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

Nonlinear properties

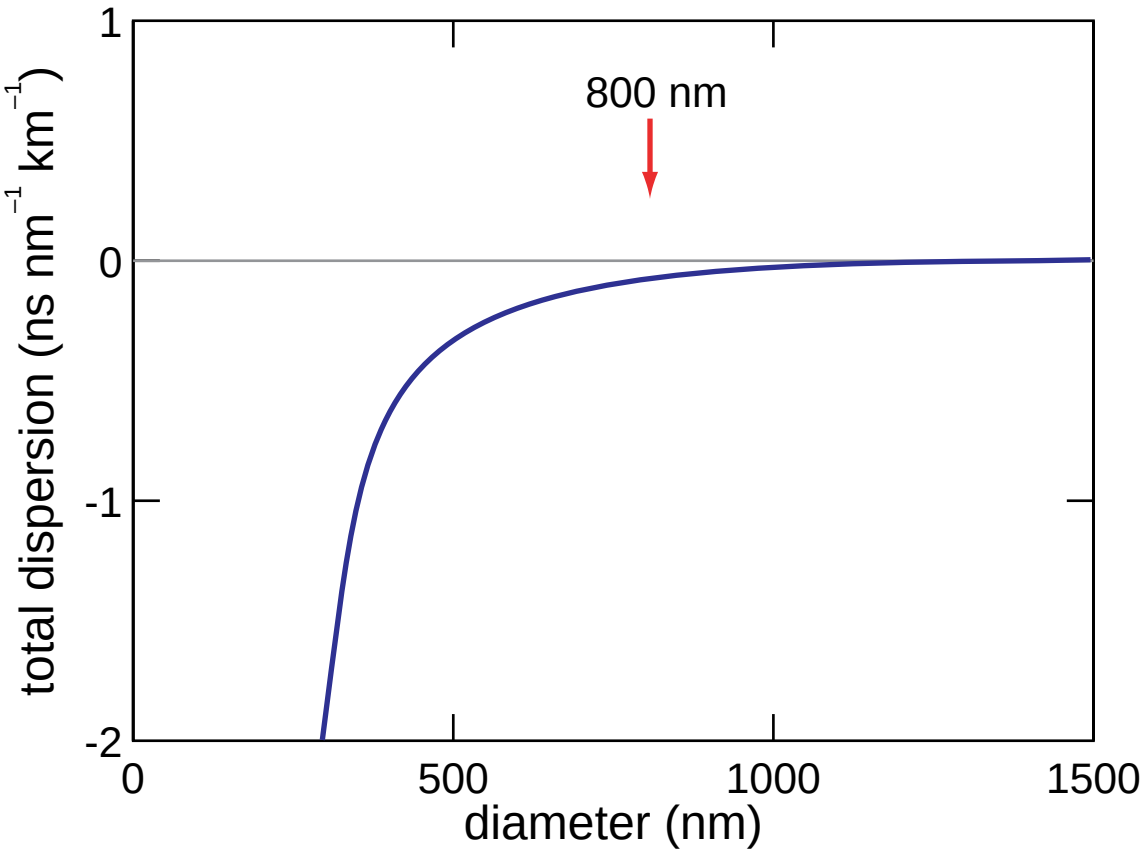
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

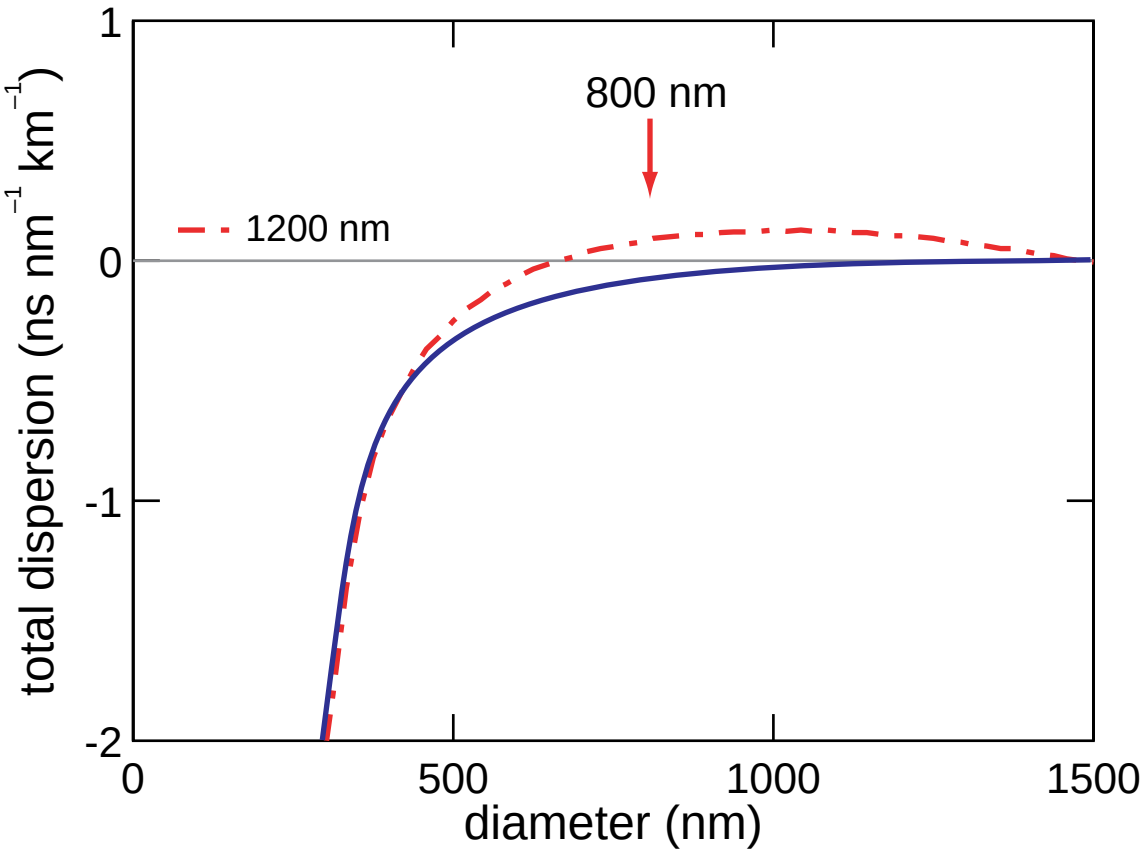
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

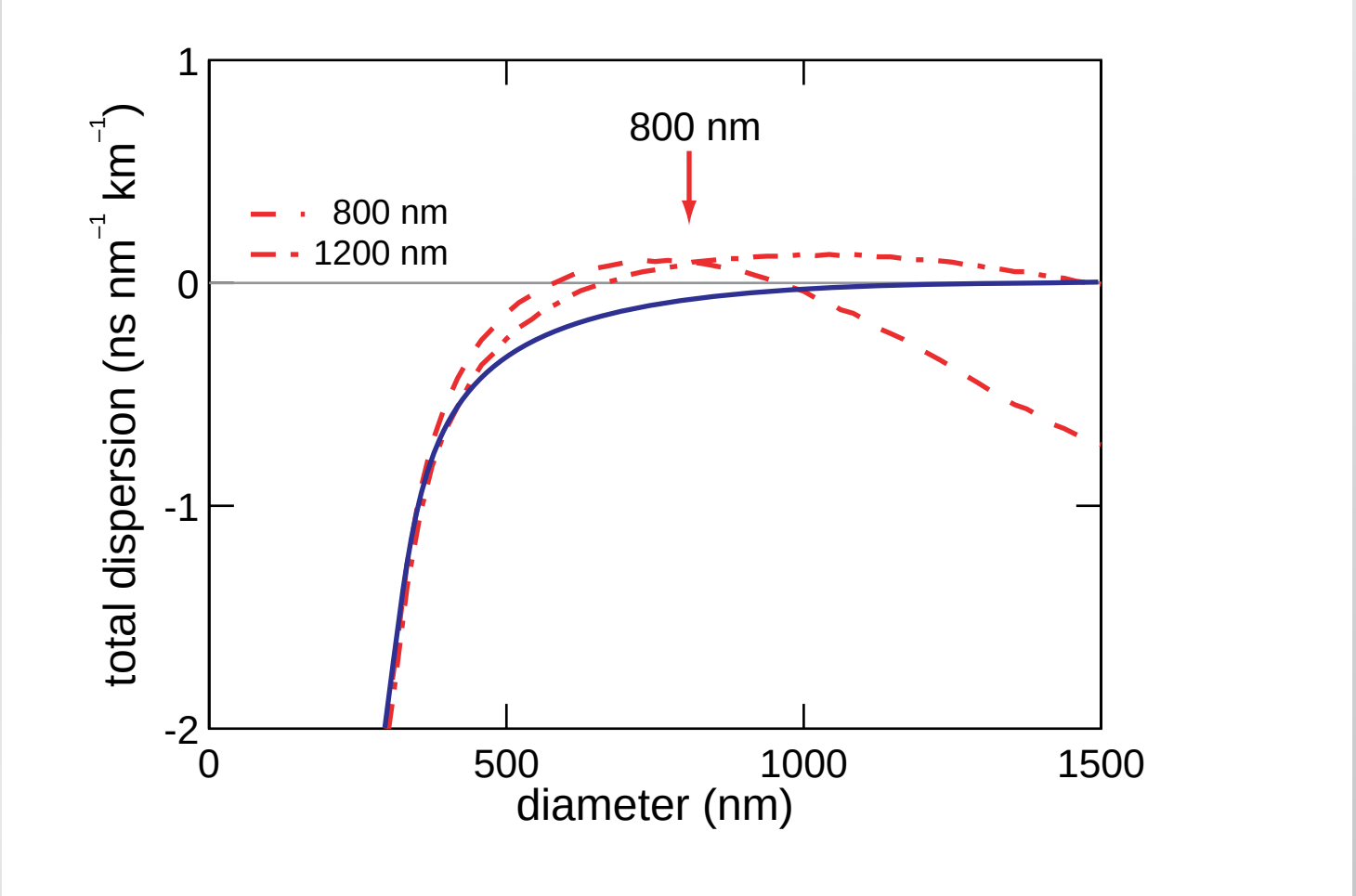
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

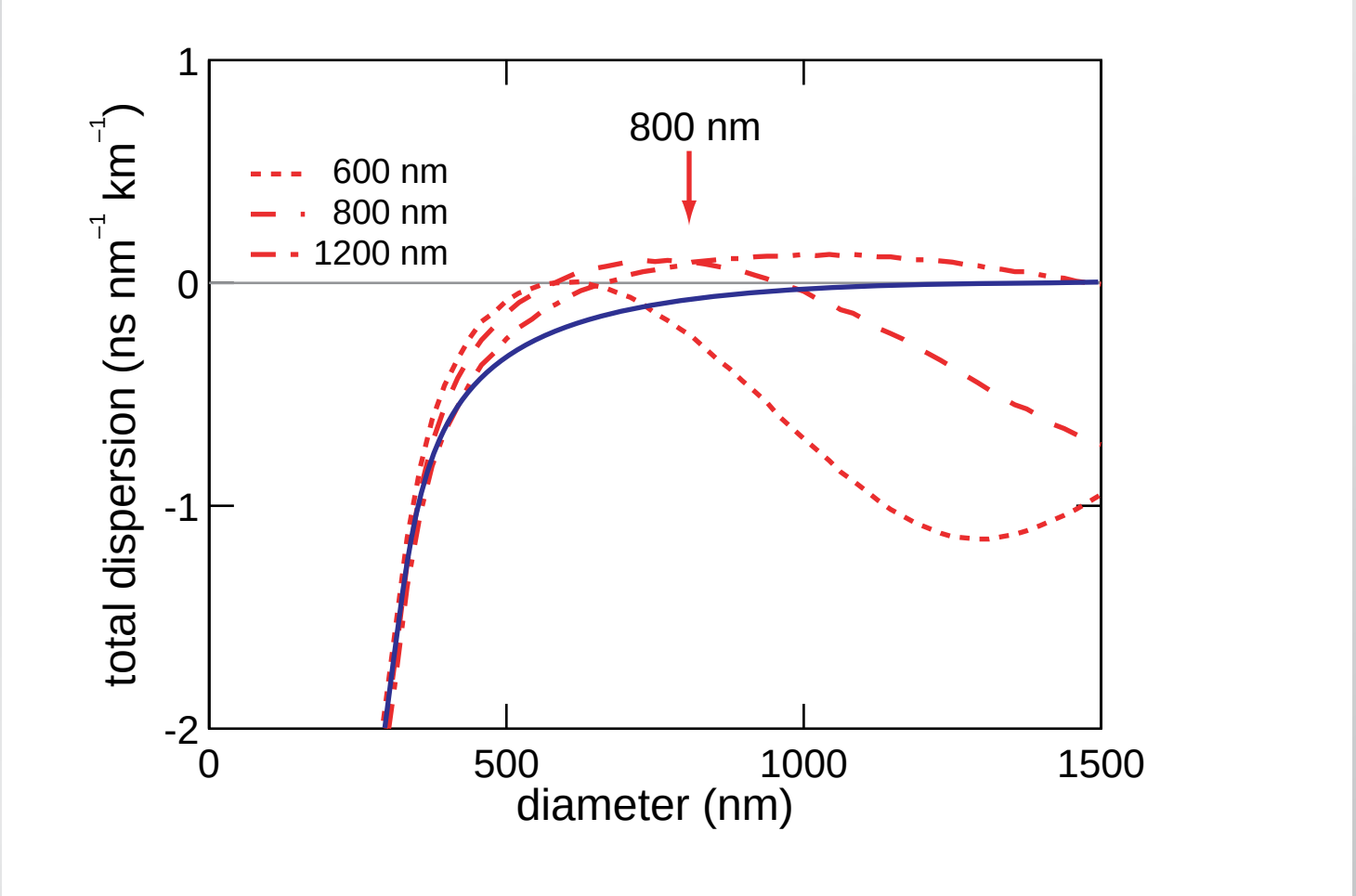
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

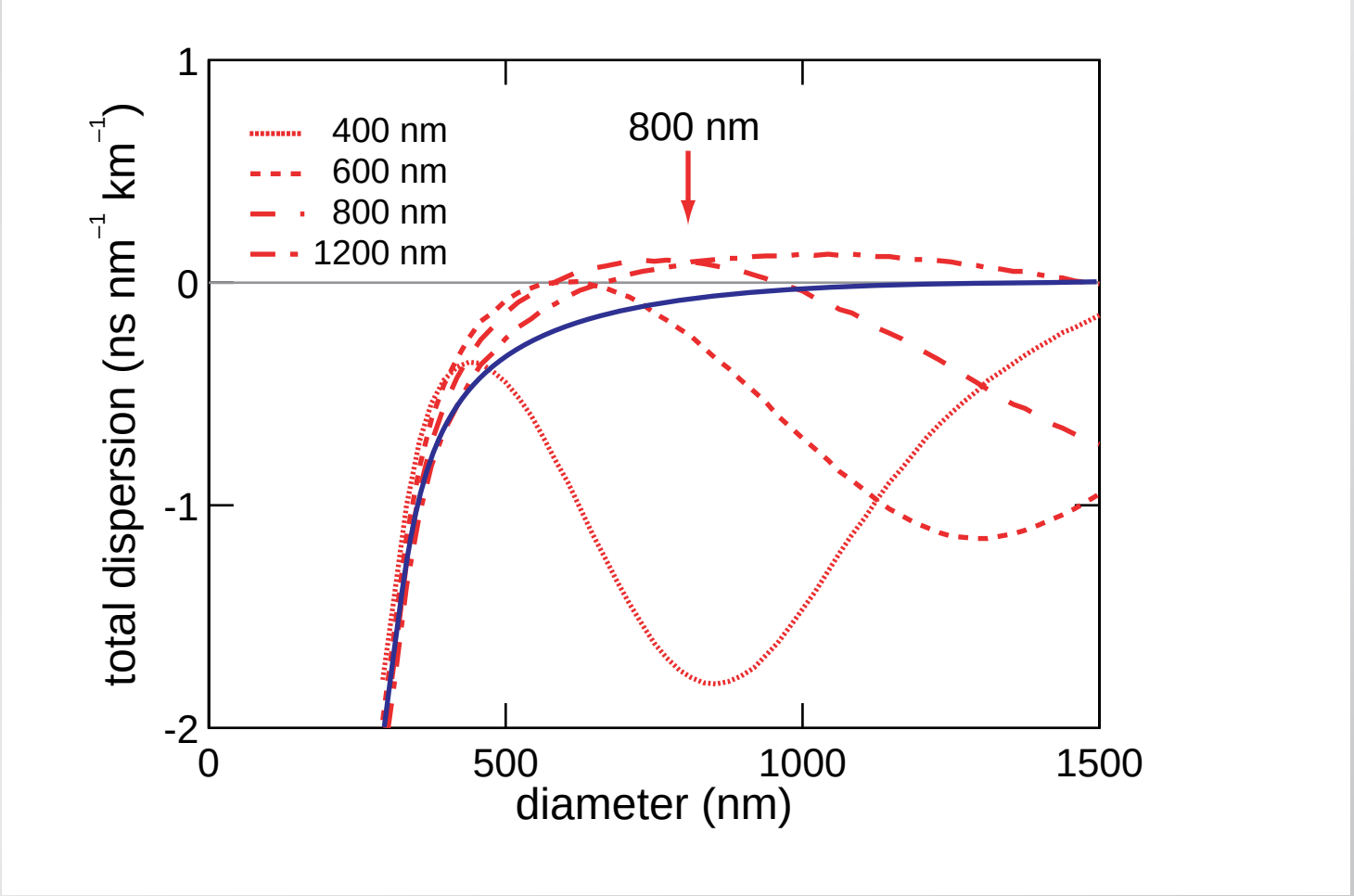
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

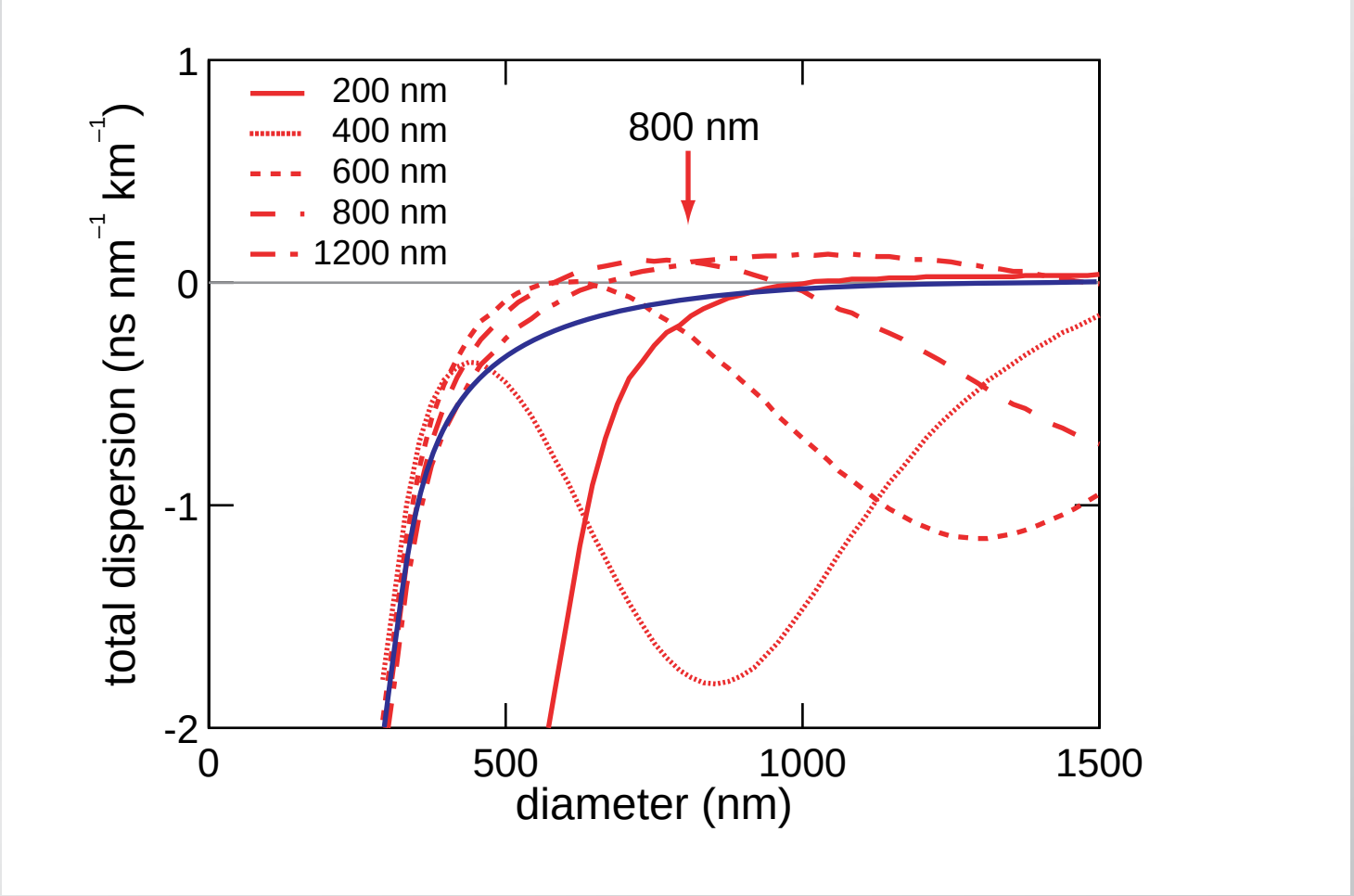
waveguide dispersion



Optics Express, 12, 1025 (2004)

Nonlinear properties

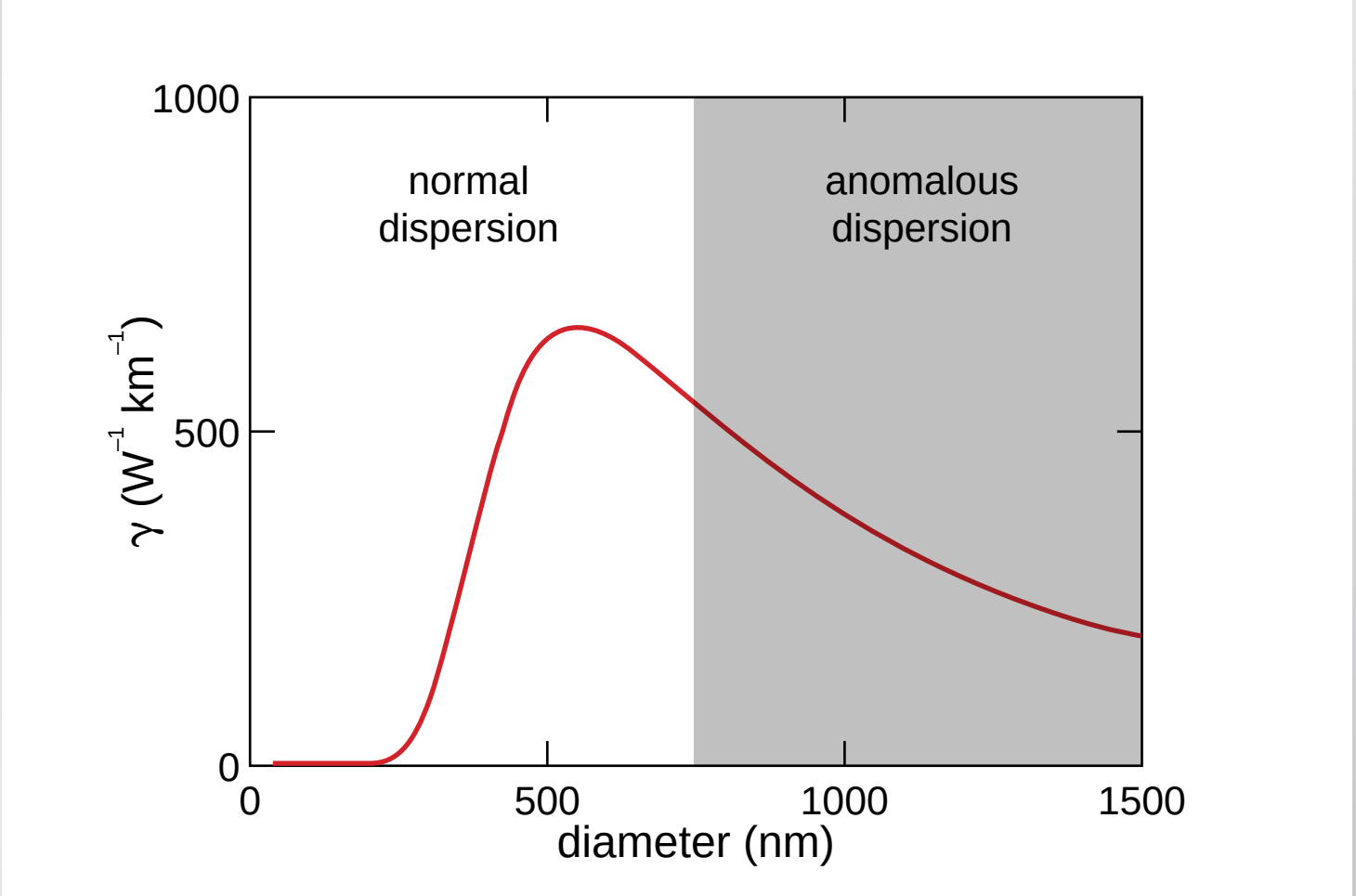
waveguide dispersion



Optics Express, 12, 1025 (2004)

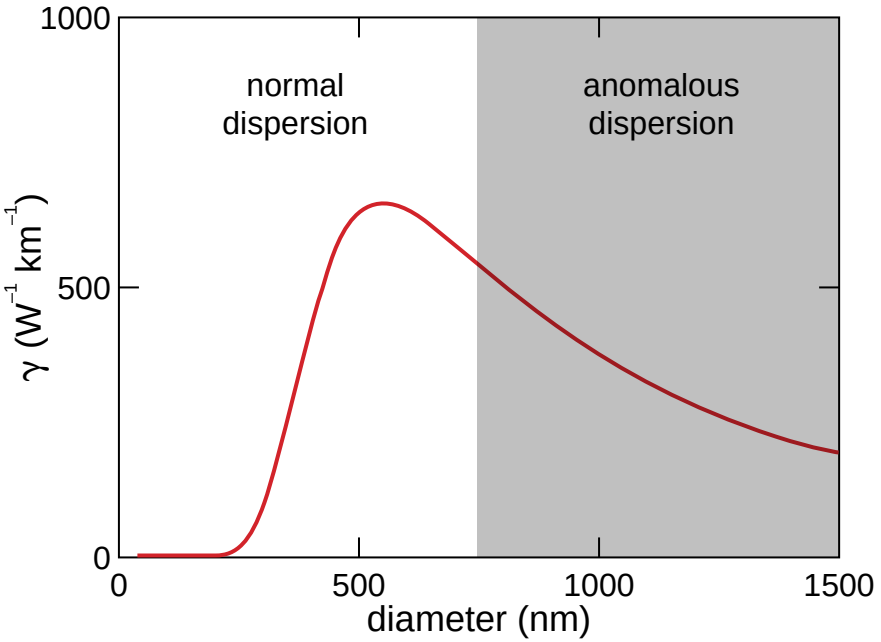
Nonlinear properties

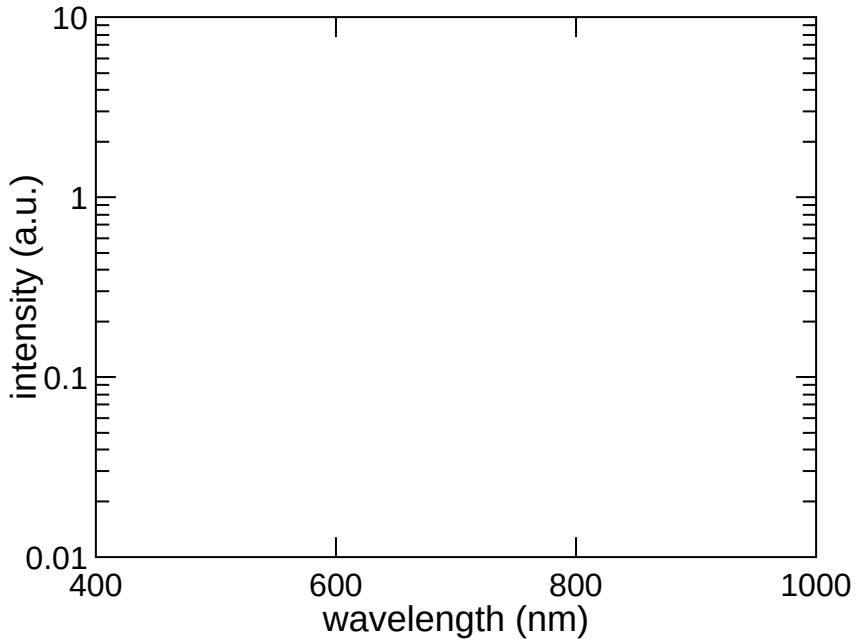
nonlinear parameter



Nonlinear properties

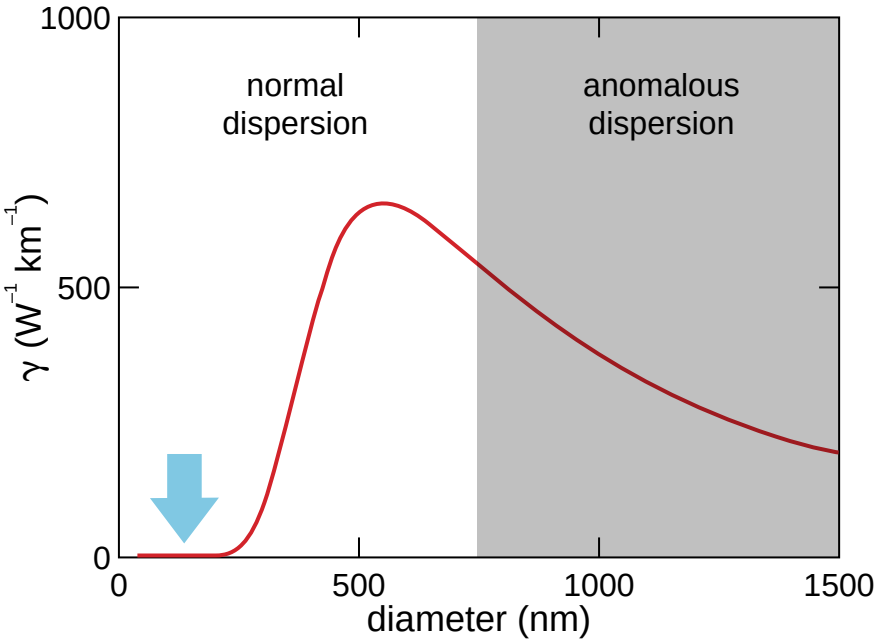
nanowire continuum generation

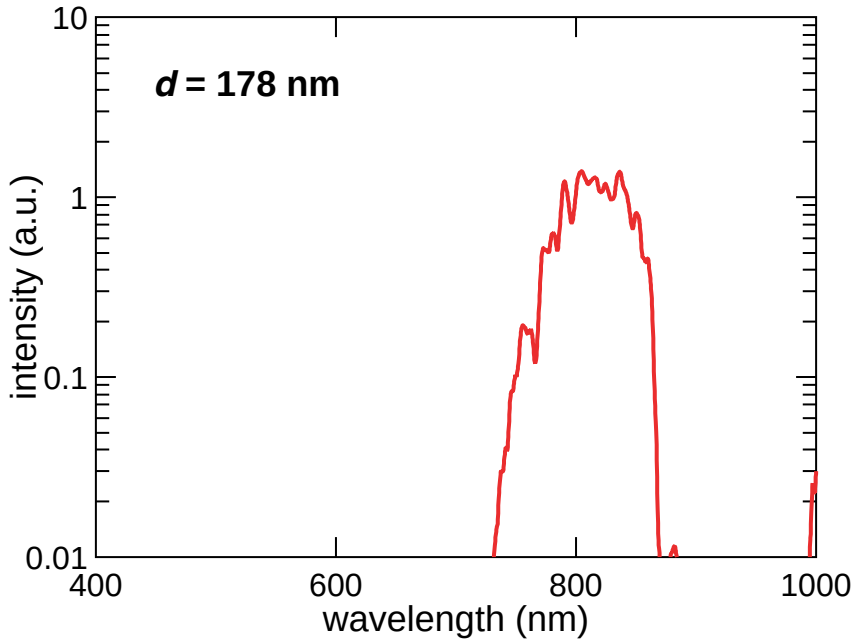




Nonlinear properties

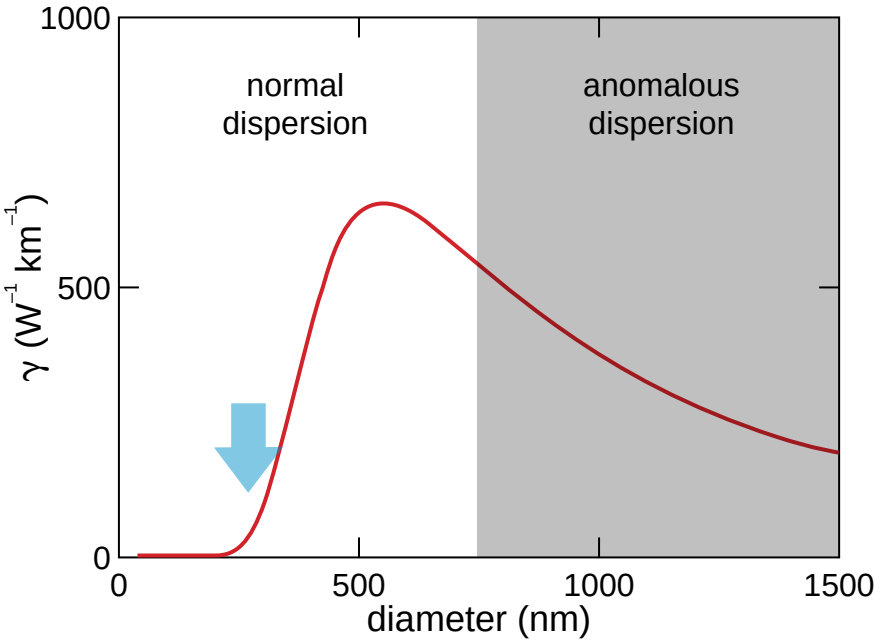
nanowire continuum generation

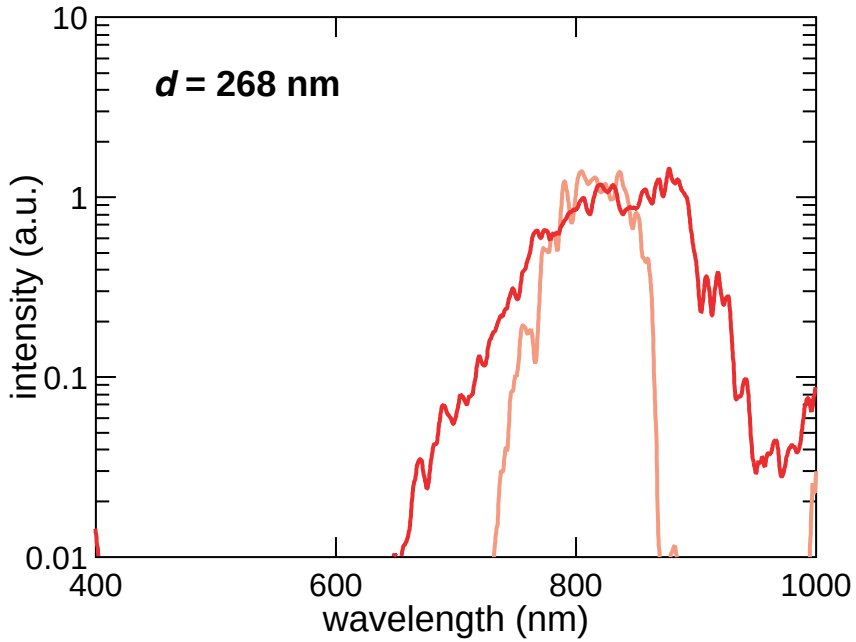




Nonlinear properties

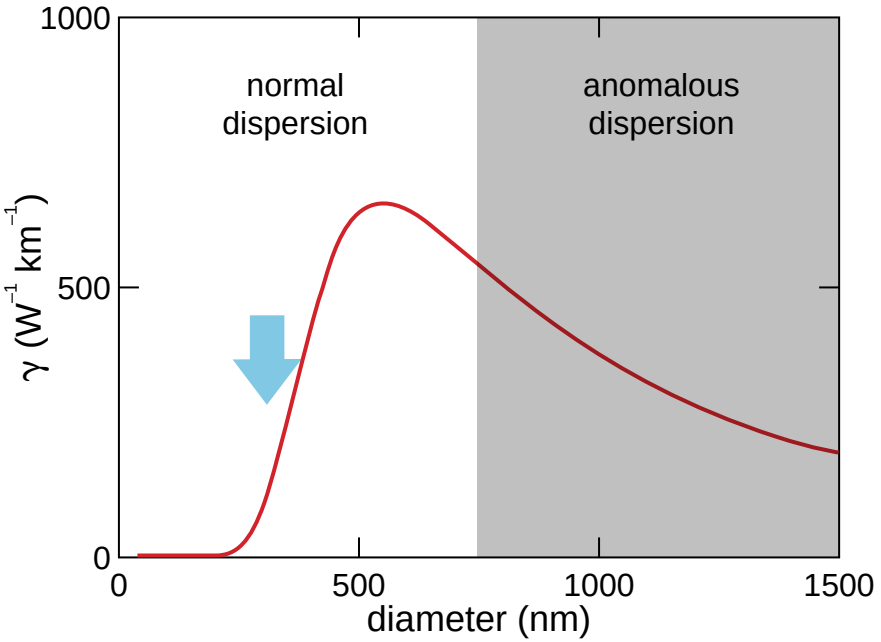
nanowire continuum generation

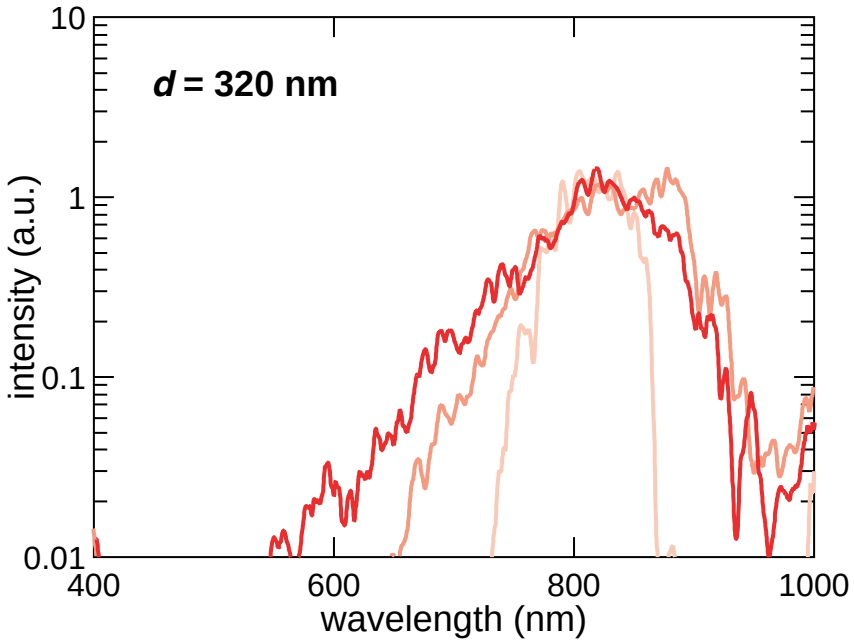




Nonlinear properties

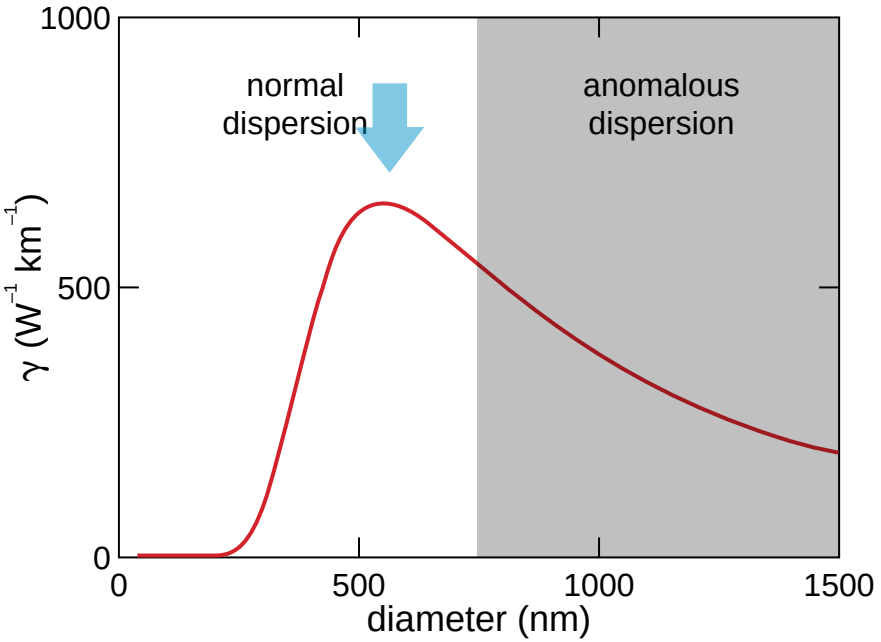
nanowire continuum generation

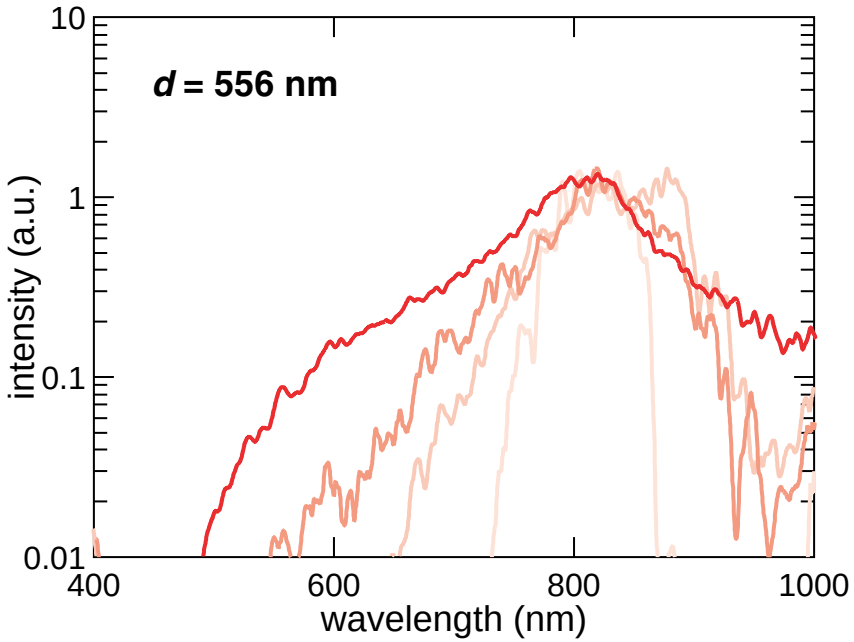




Nonlinear properties

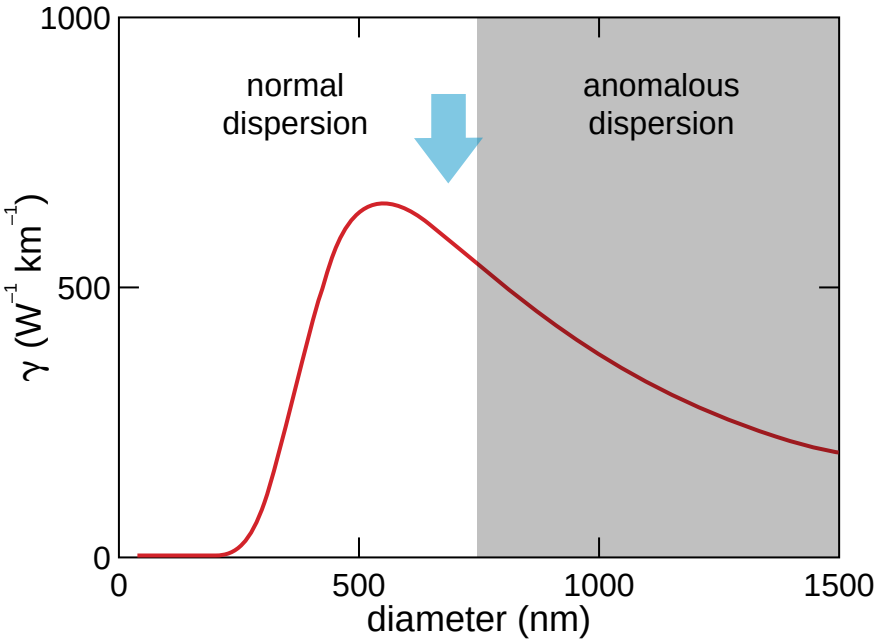
nanowire continuum generation

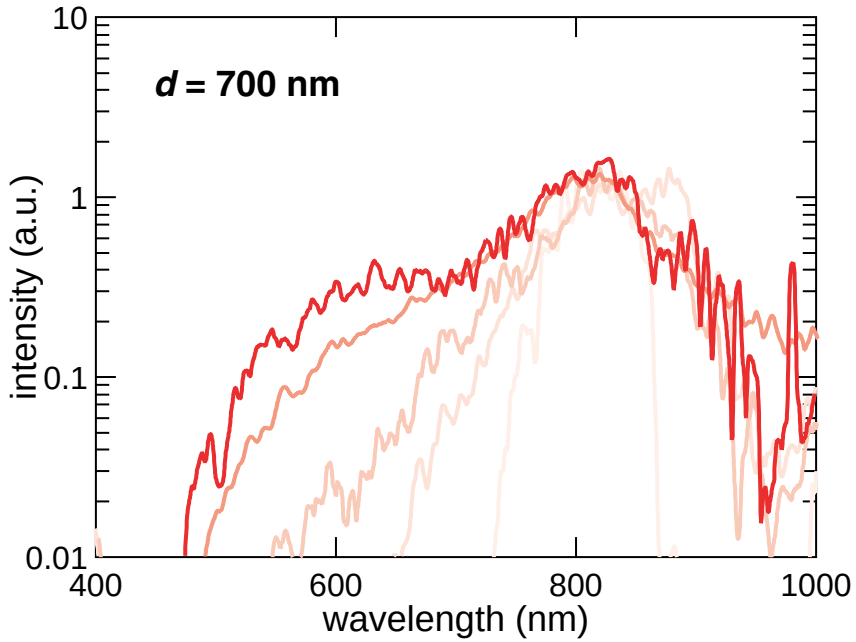




Nonlinear properties

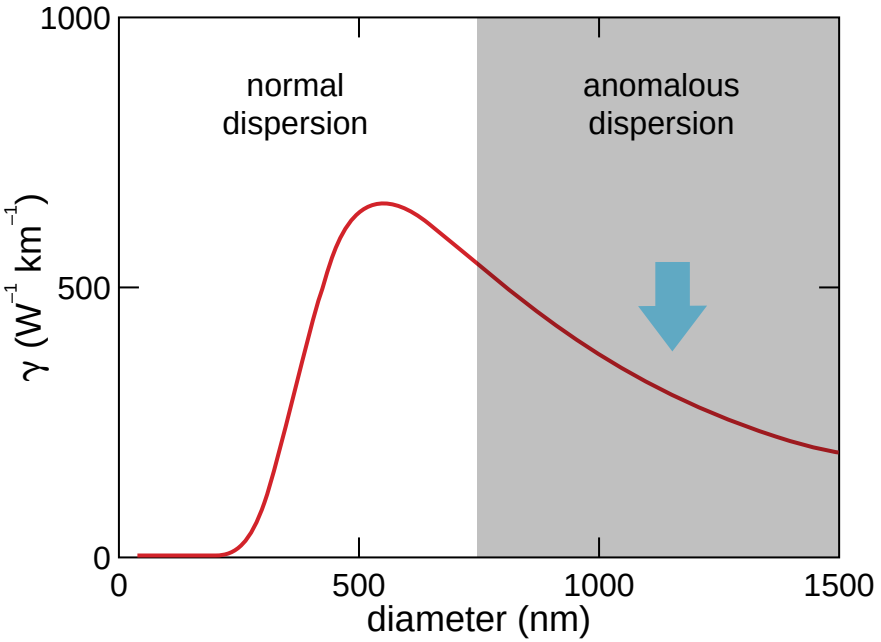
nanowire continuum generation

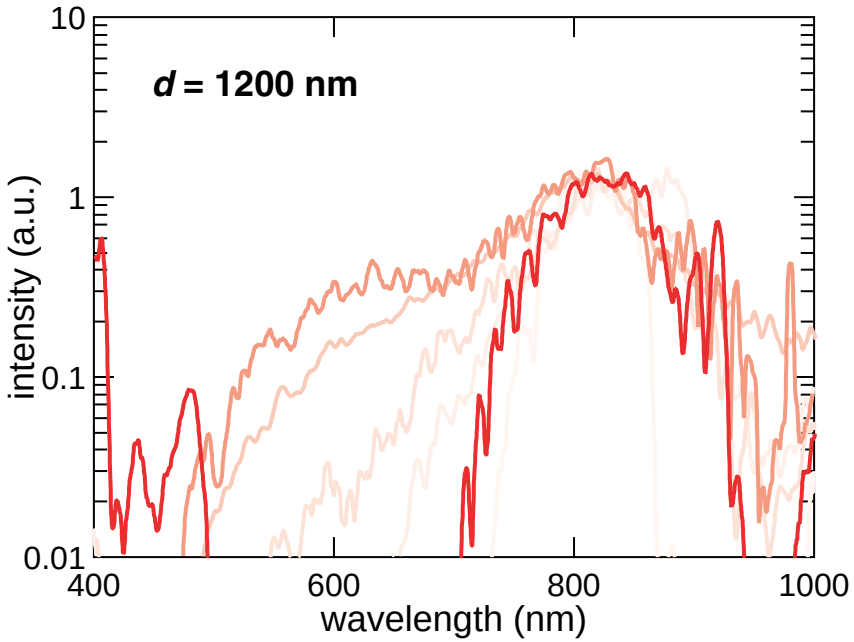




Nonlinear properties

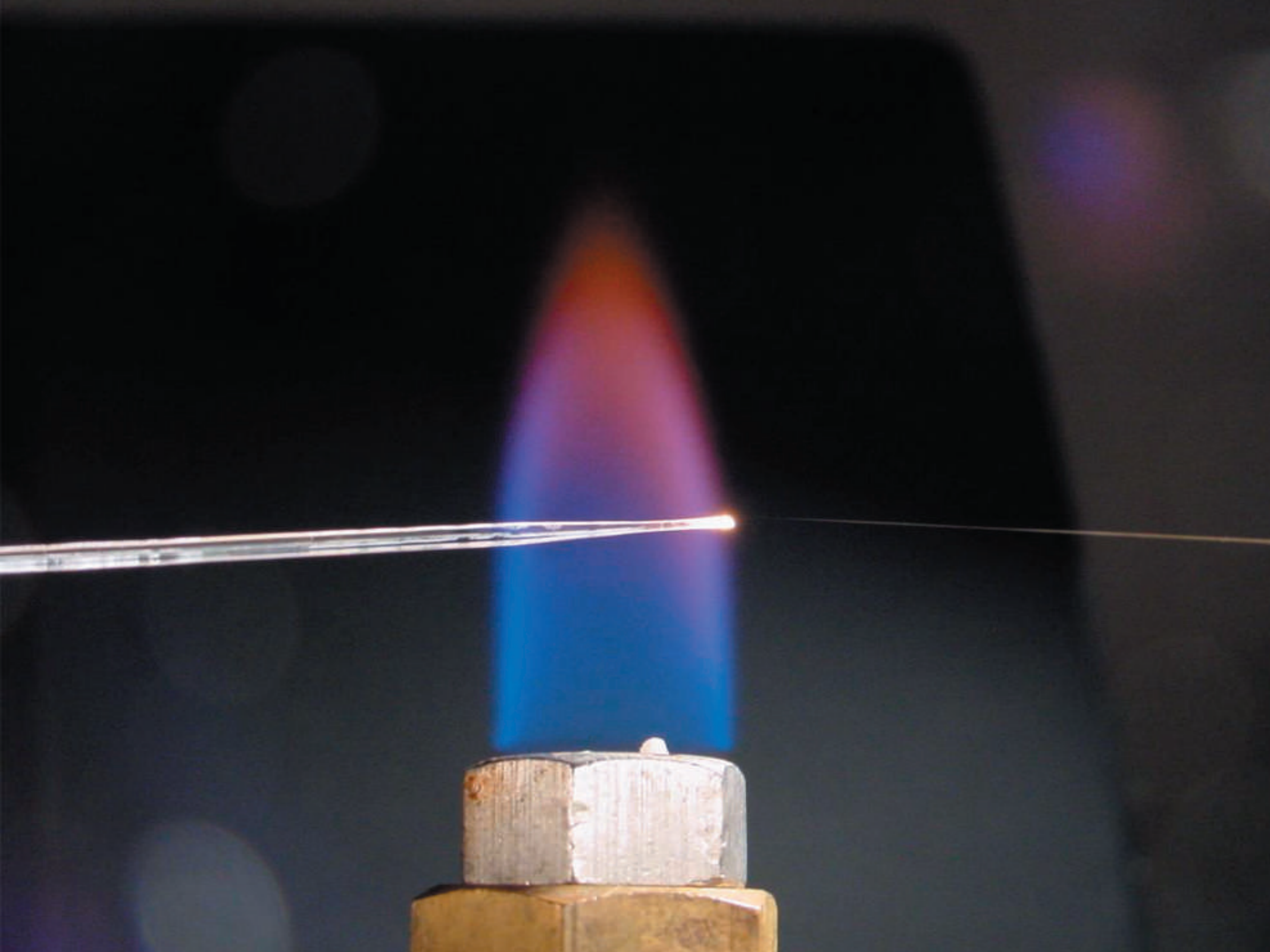
nanowire continuum generation



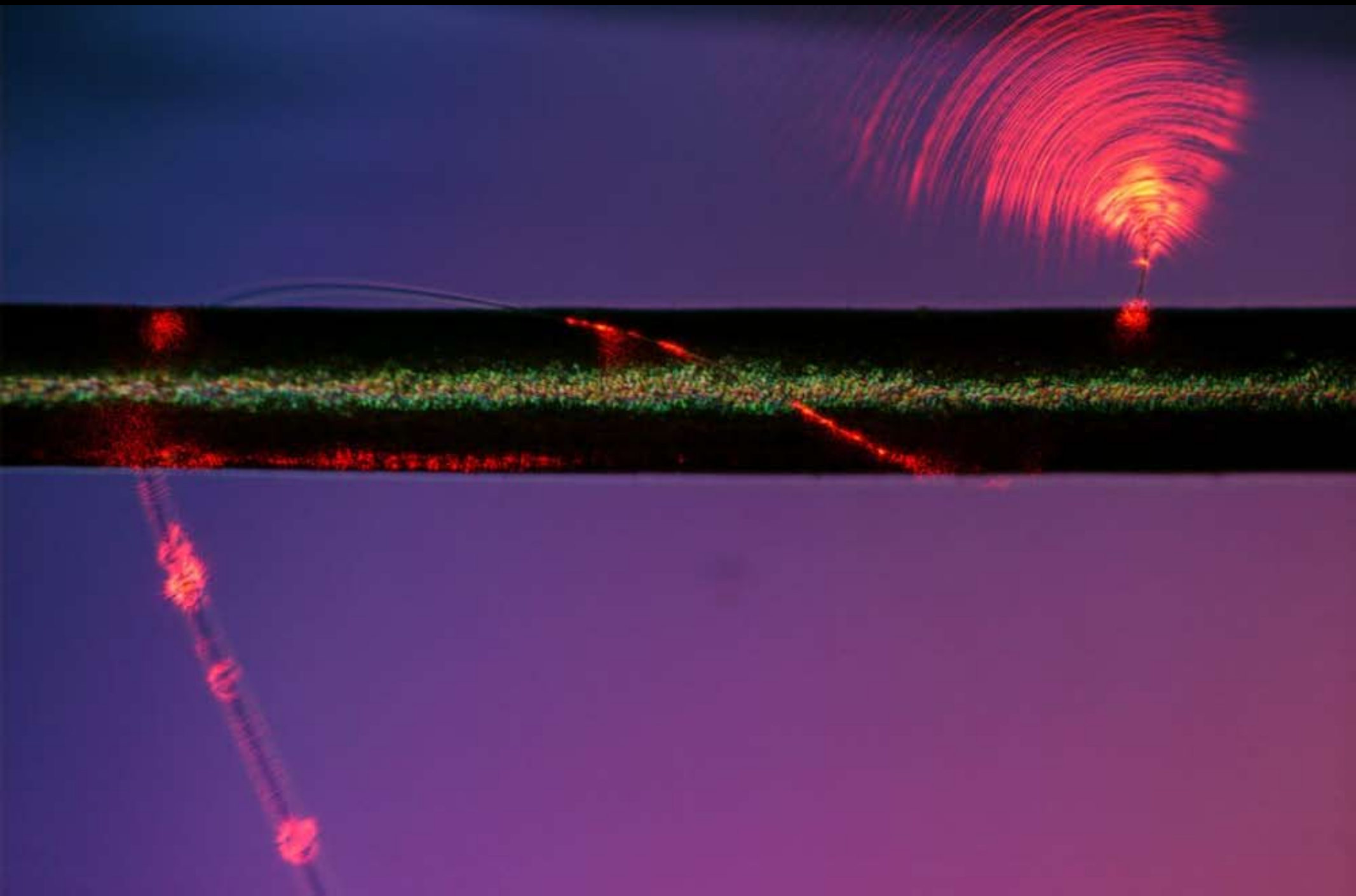


Nonlinear properties

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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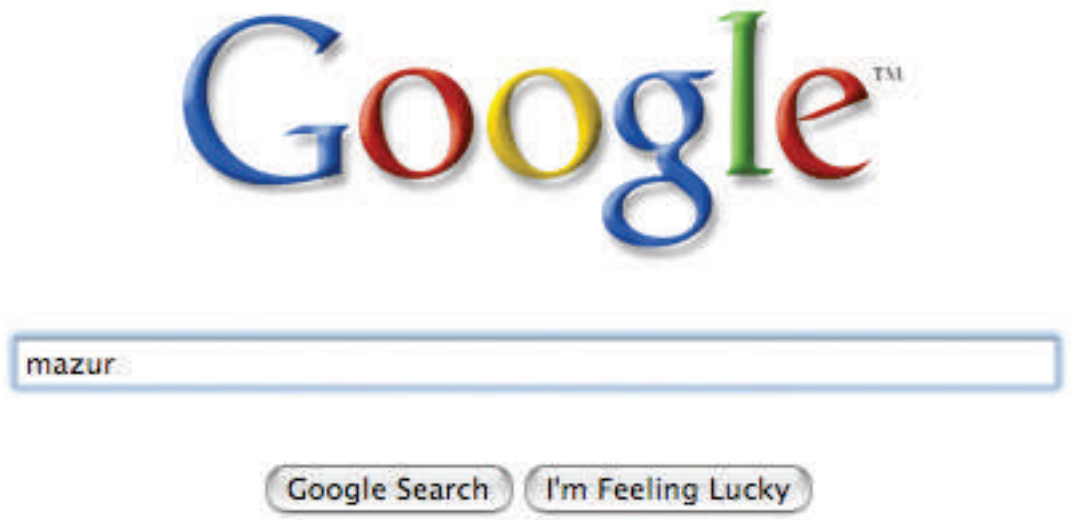
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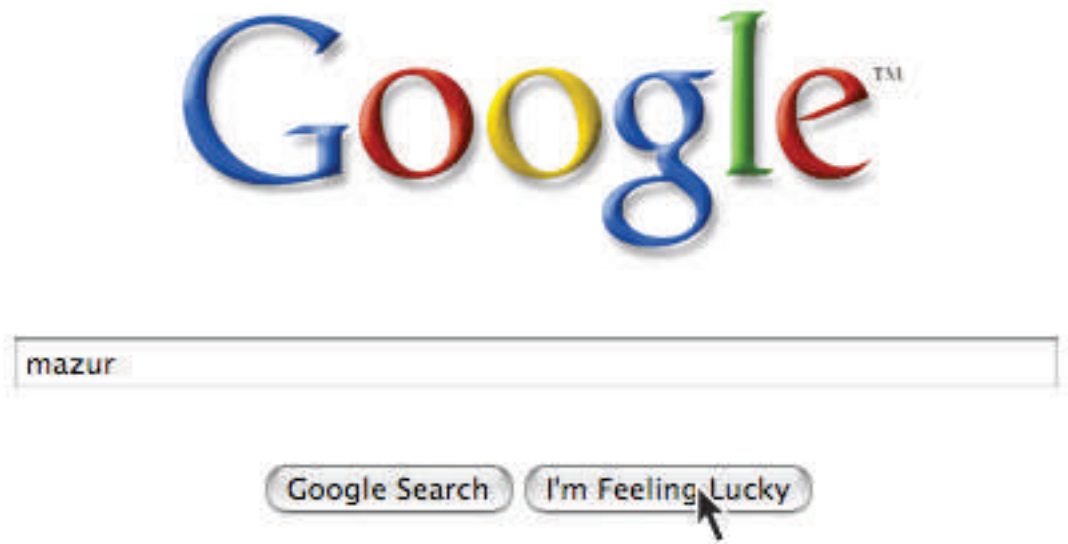
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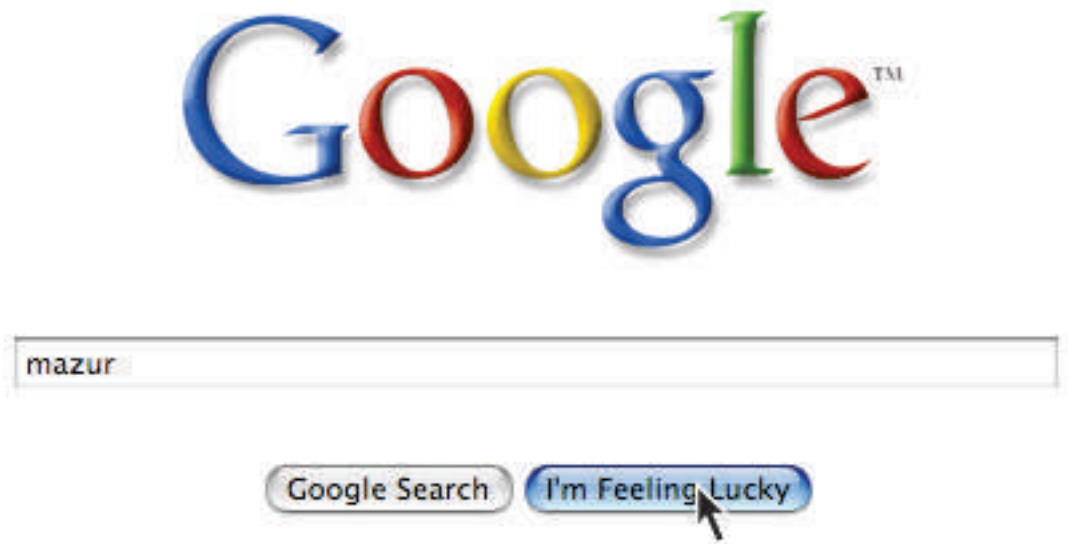
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