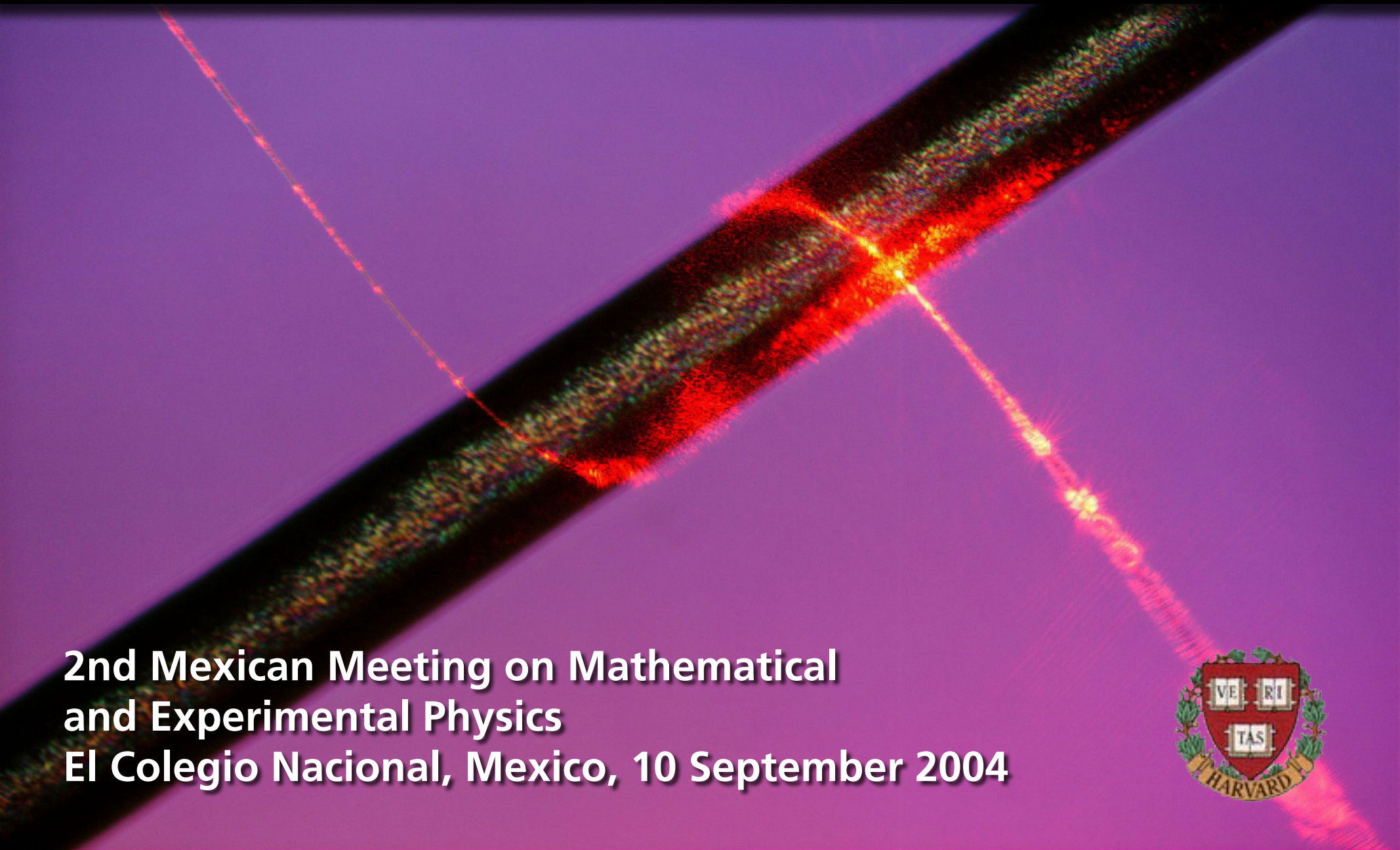
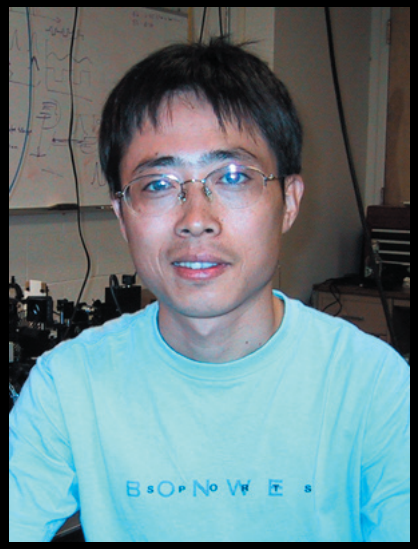
Wrapping light around a hair



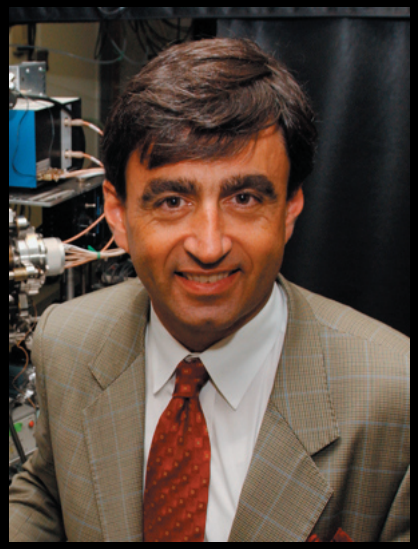
2nd Mexican Meeting on Mathematical
and Experimental Physics
El Colegio Nacional, Mexico, 10 September 2004



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

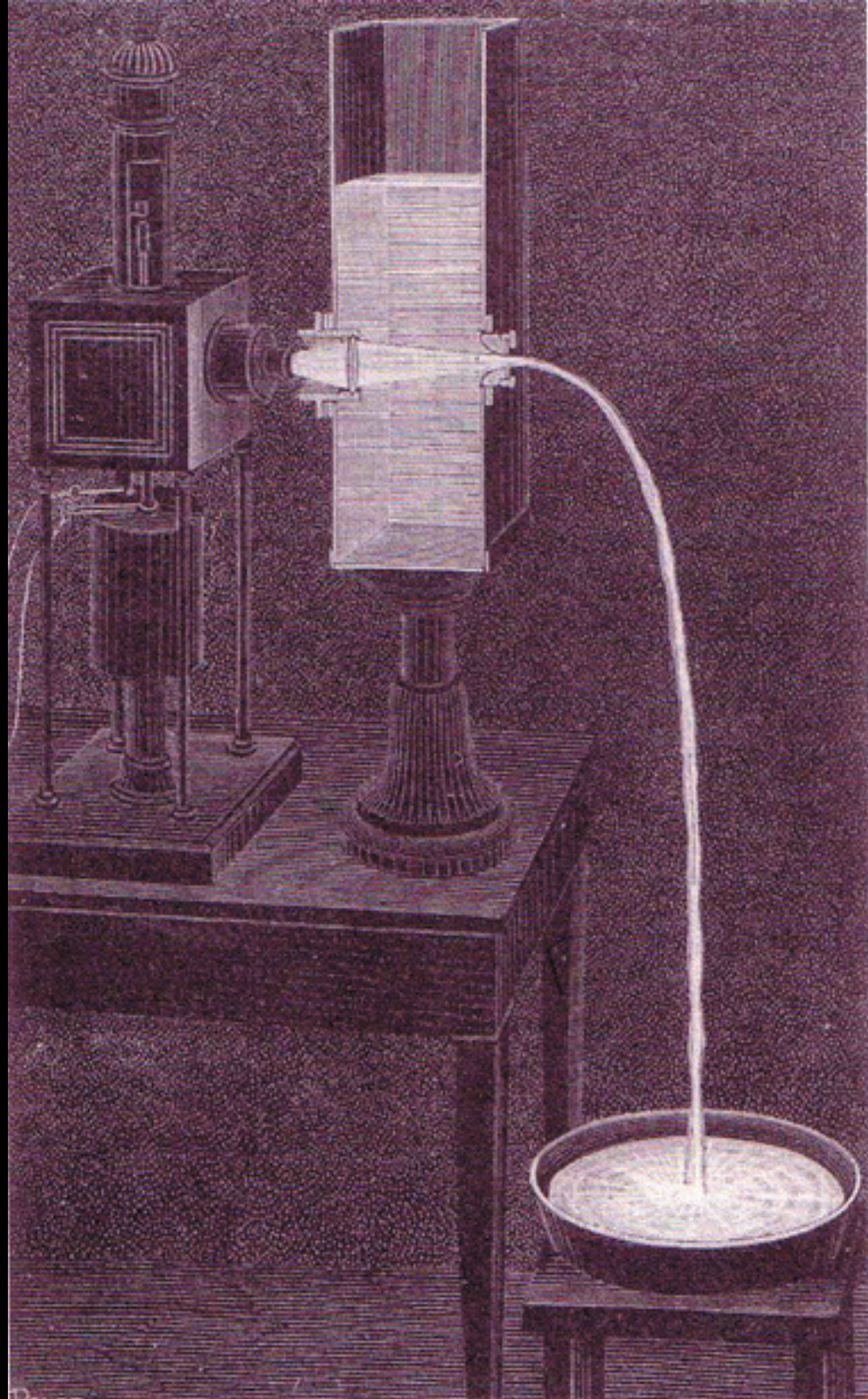
at Zhejiang University:

Dr. Sailing He
Dr. Jingyi Lou
Xuewen Chen
Liu Liu
Zhanghua Han

Dr. Ray Mariella (LLNL)

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

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



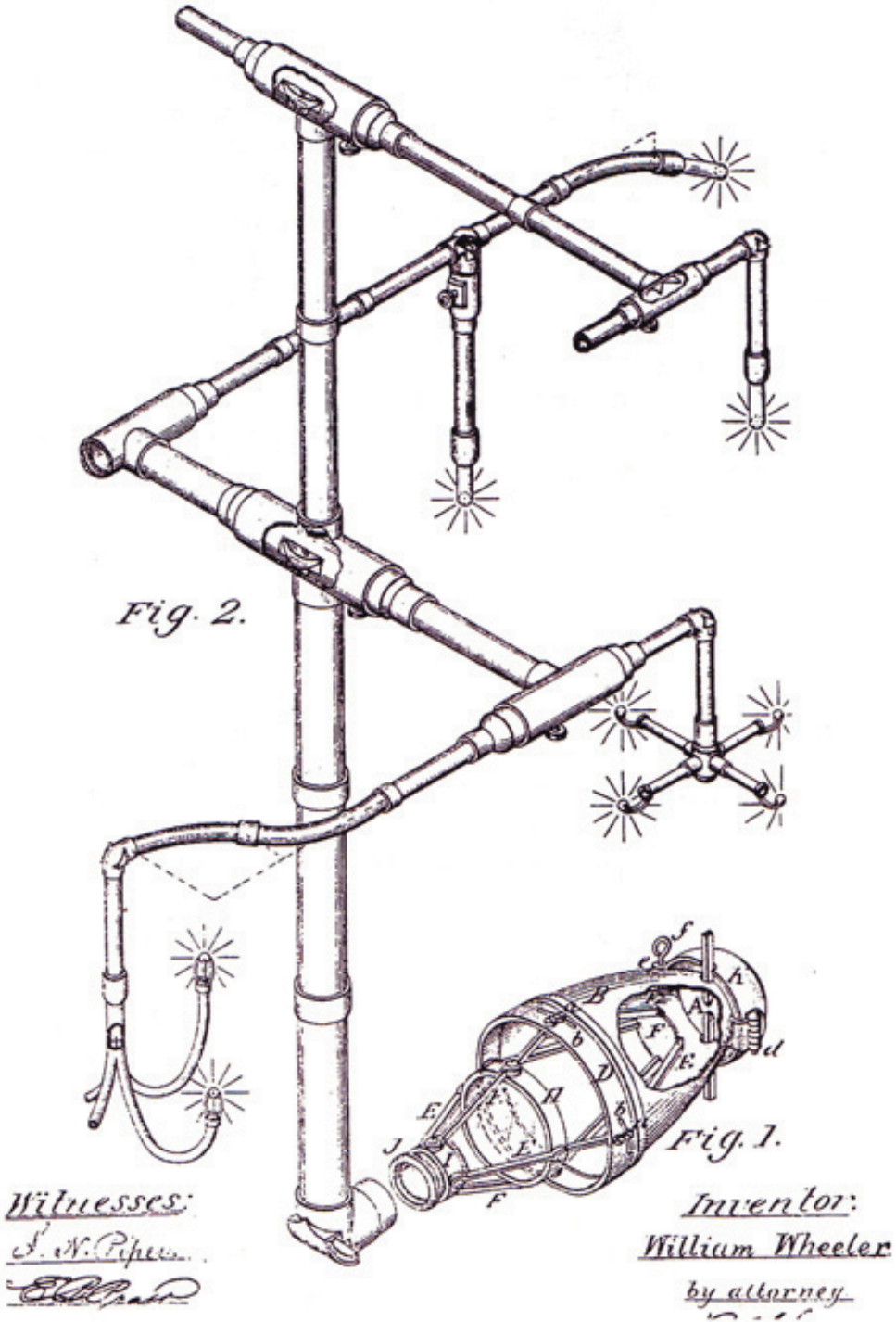
D. Colladon, *La Nature*, 325 (1884)

(No model.) 4 Sheets—Sheet

W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

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



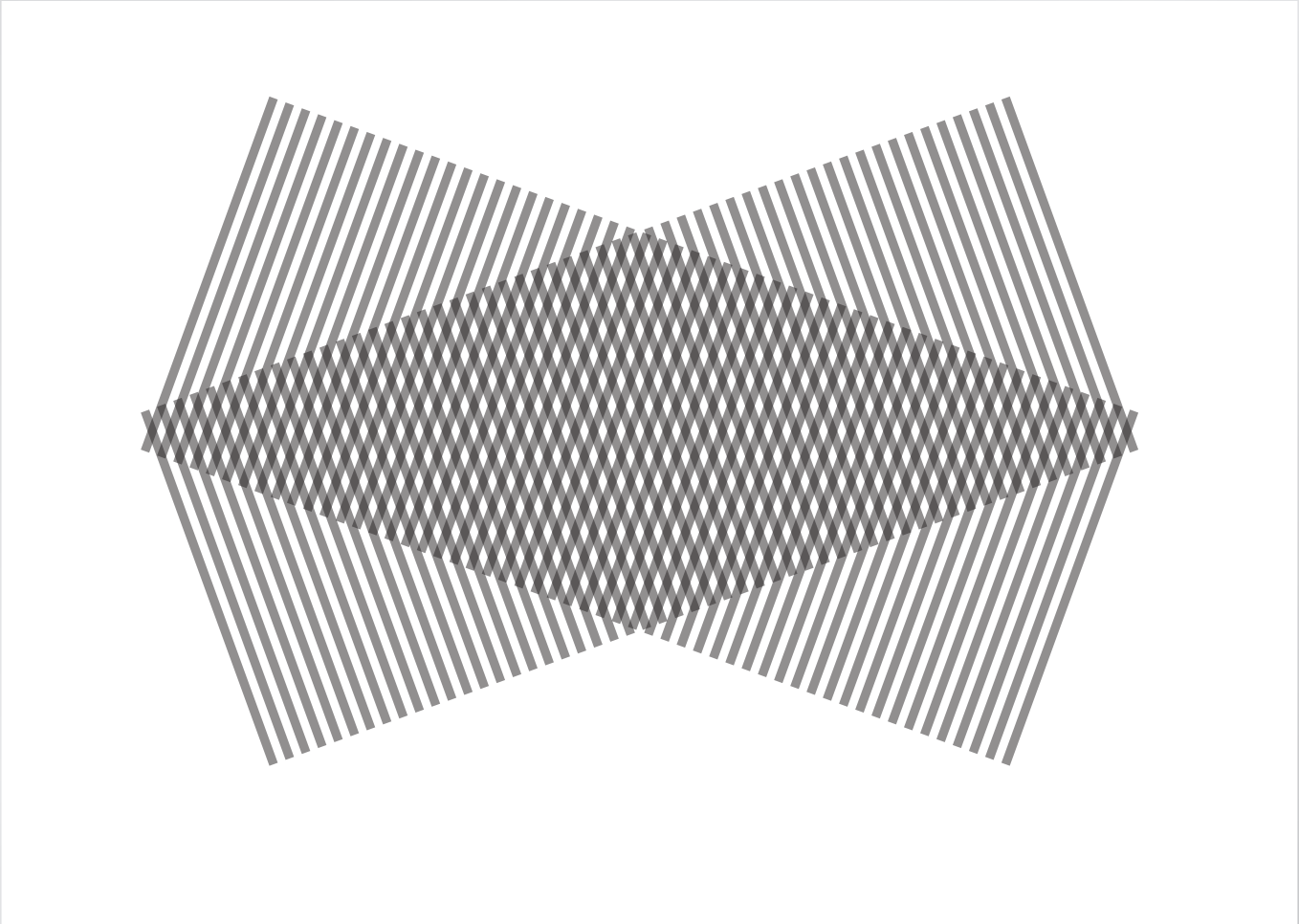
US Patent 247, 229 (1881)

Outline

- waveguiding
- nanowire fabrication
- optical properties

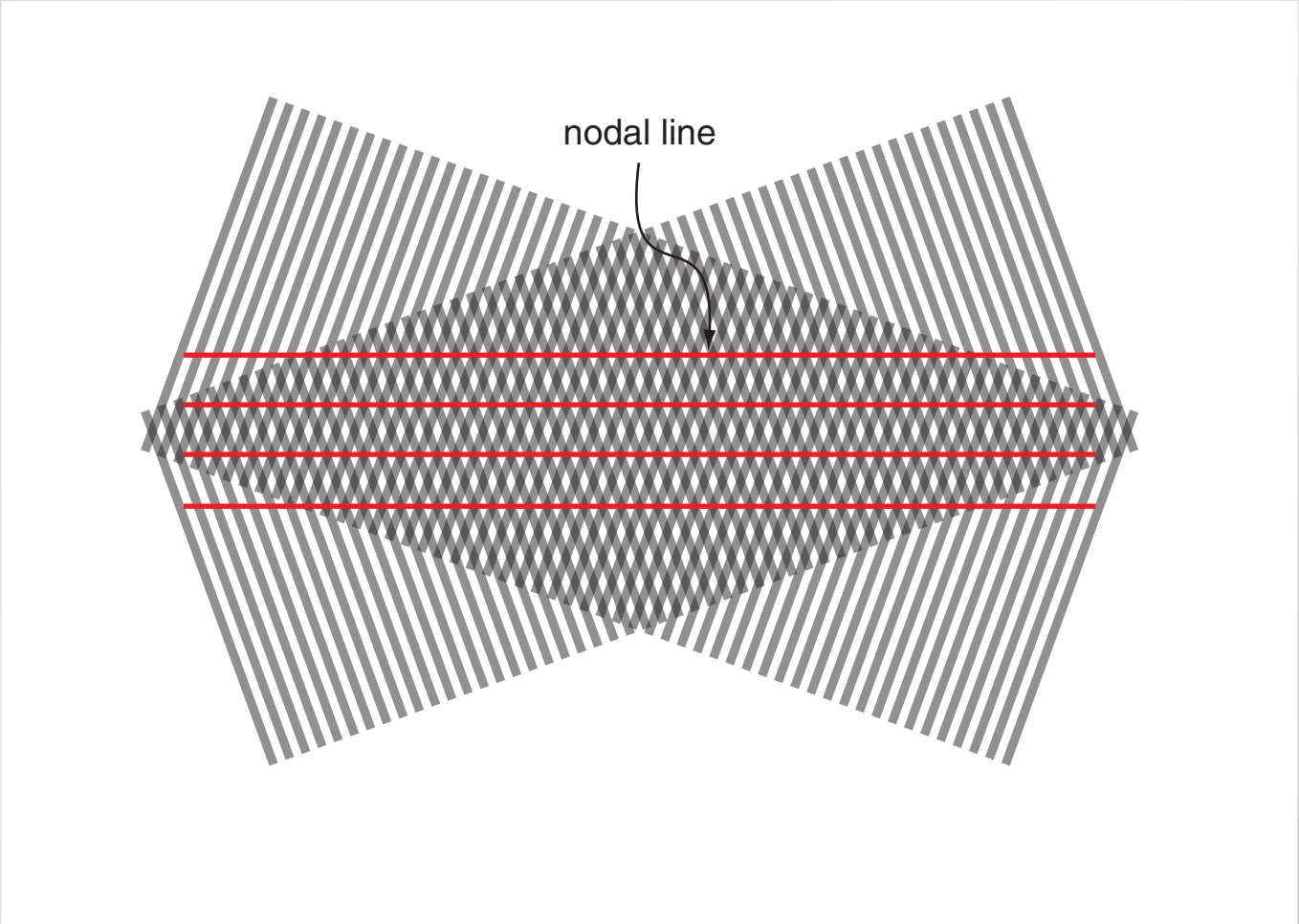
Waveguiding

two crossed planar waves…



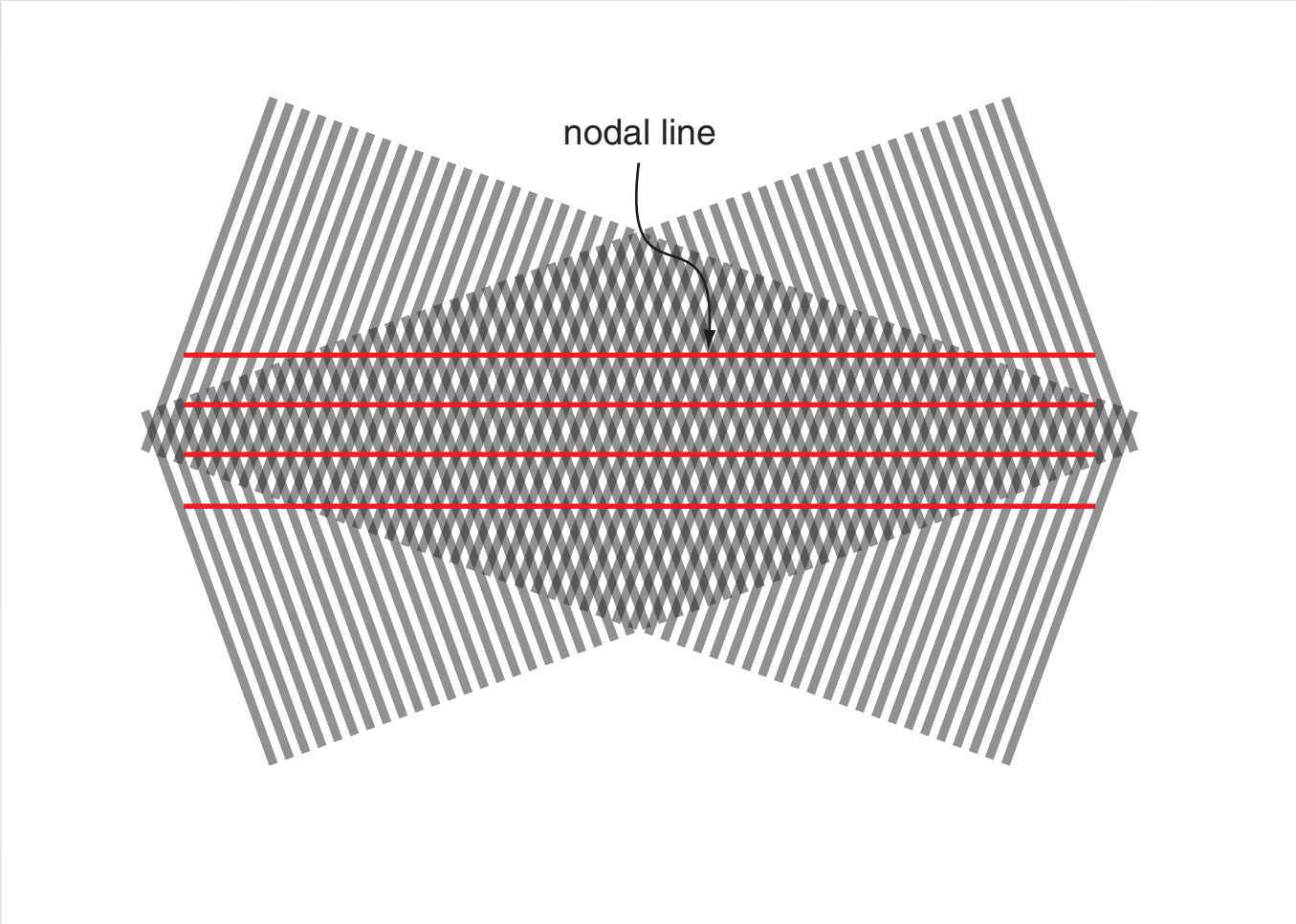
Waveguiding

…cause an interference pattern



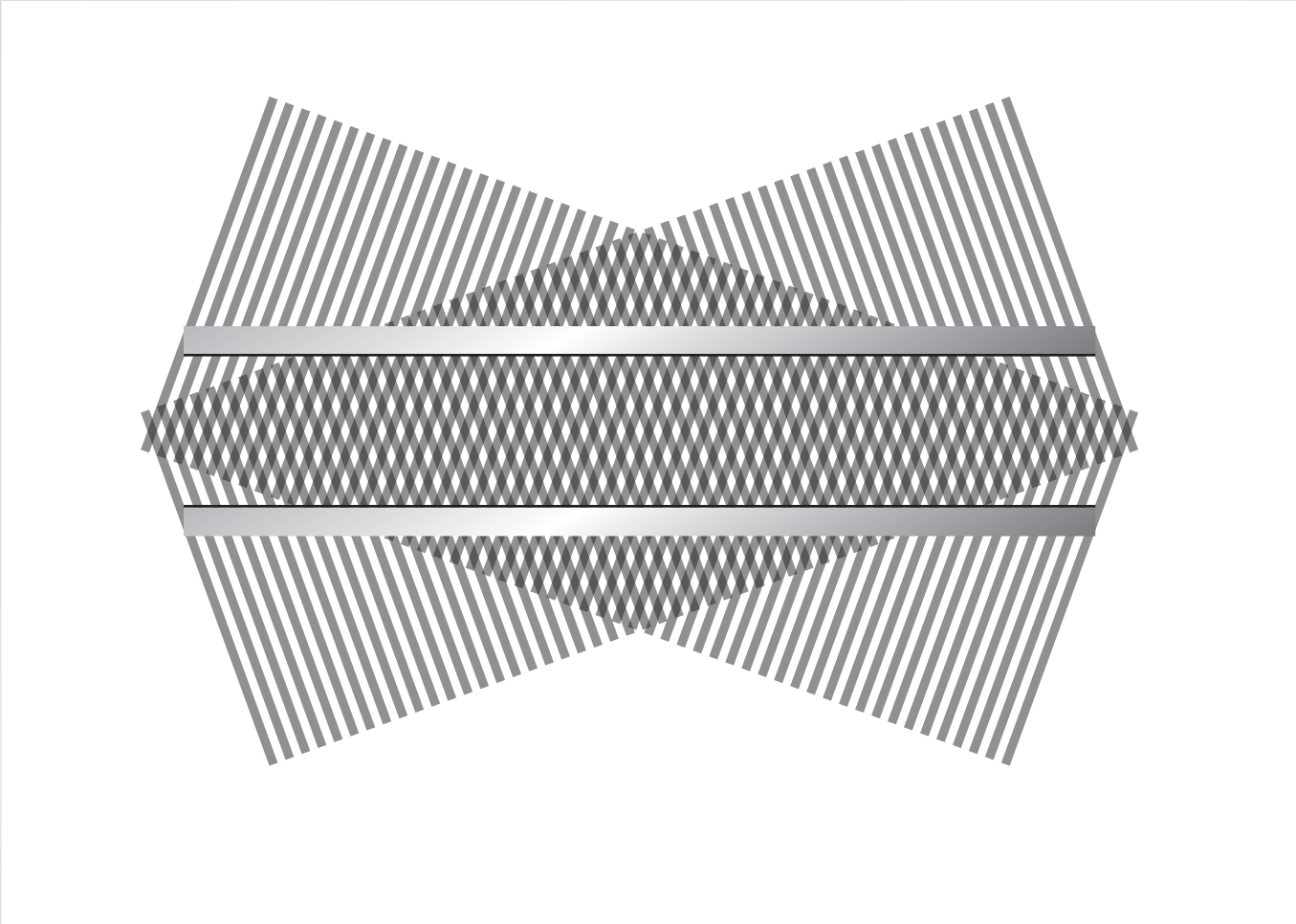
Waveguiding

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



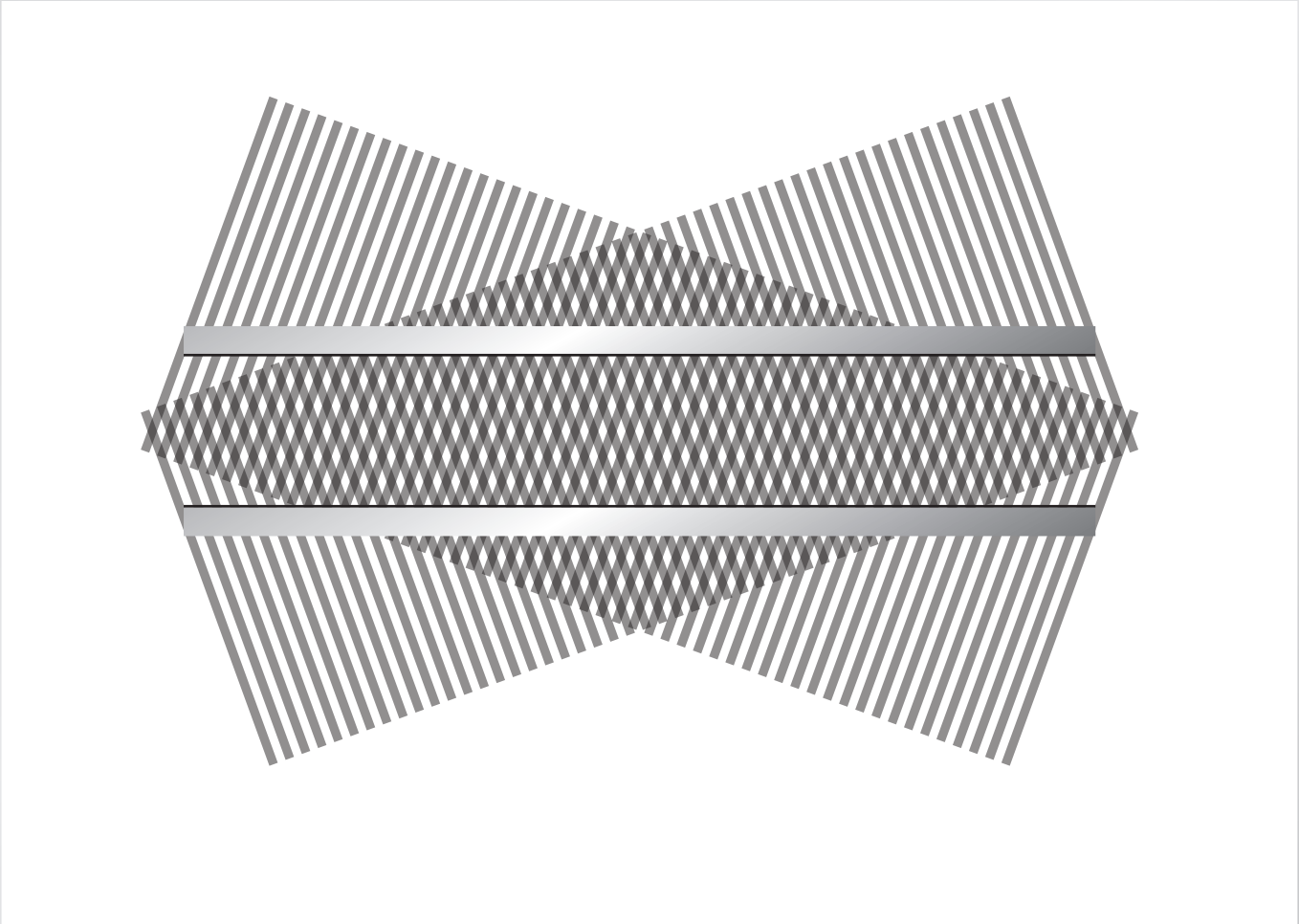
Waveguiding

…satisfying boundary conditions for planar-mirror waveguide



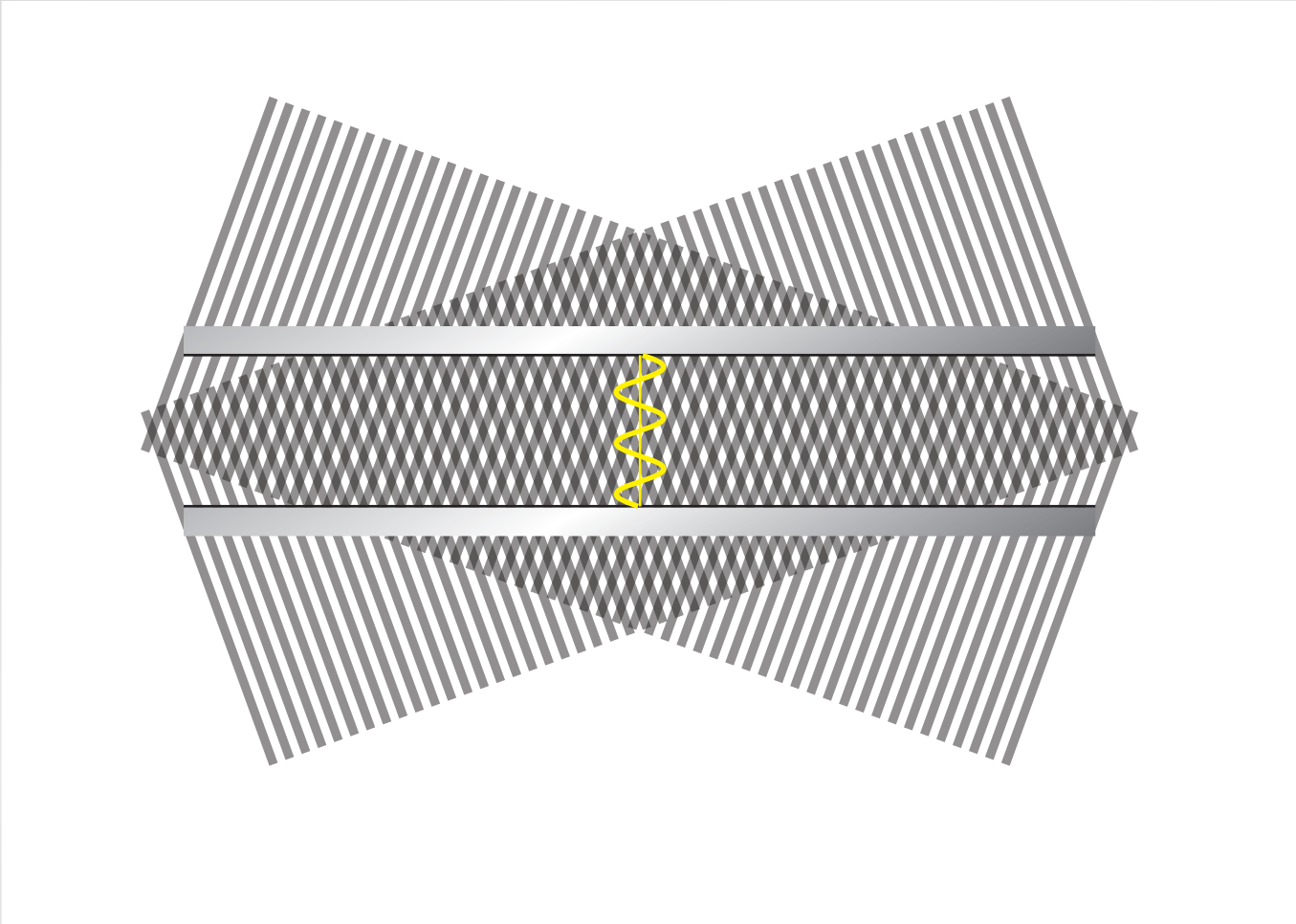
Waveguiding

transverse standing wave, traveling along axis



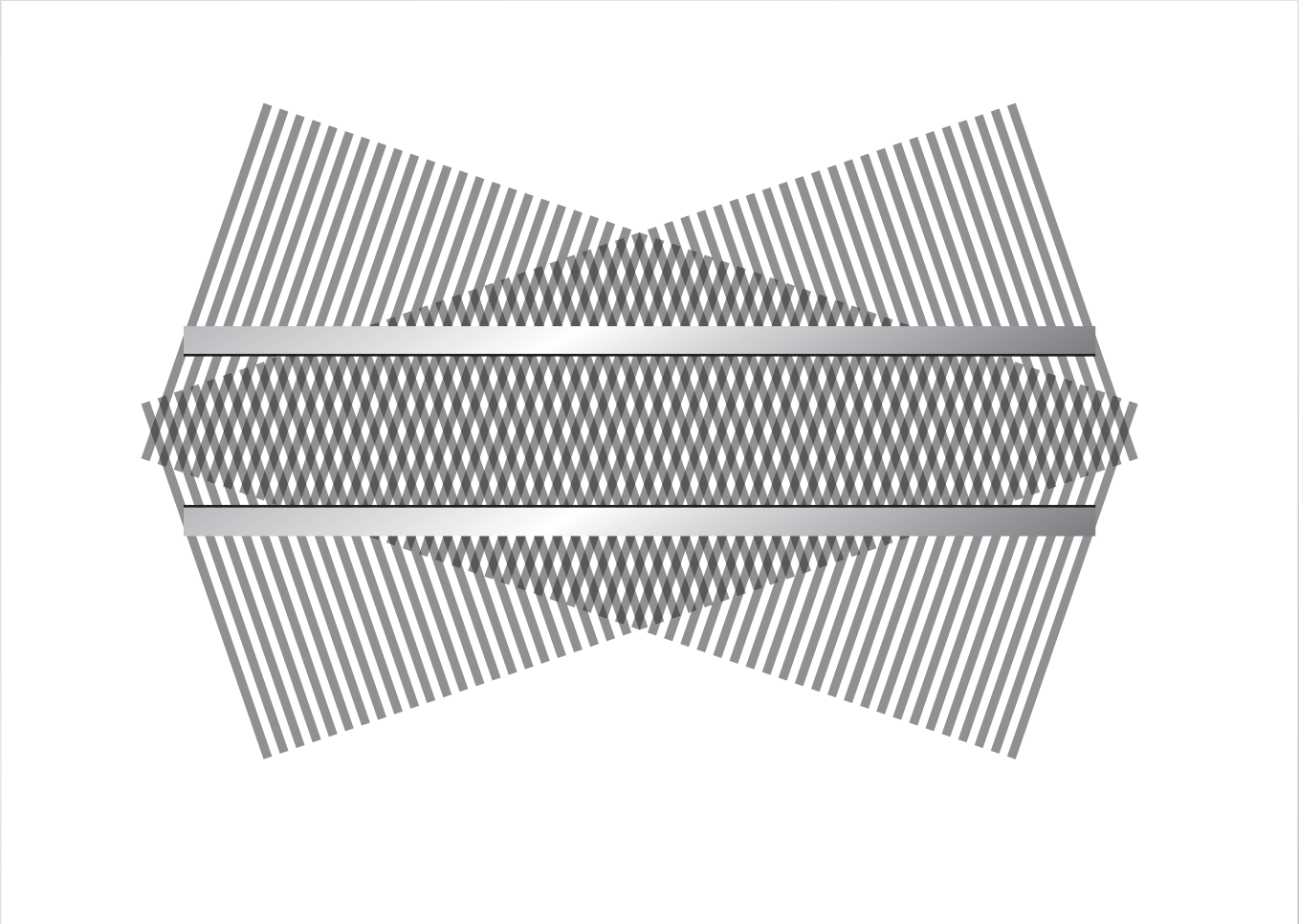
Waveguiding

transverse standing wave, traveling along axis



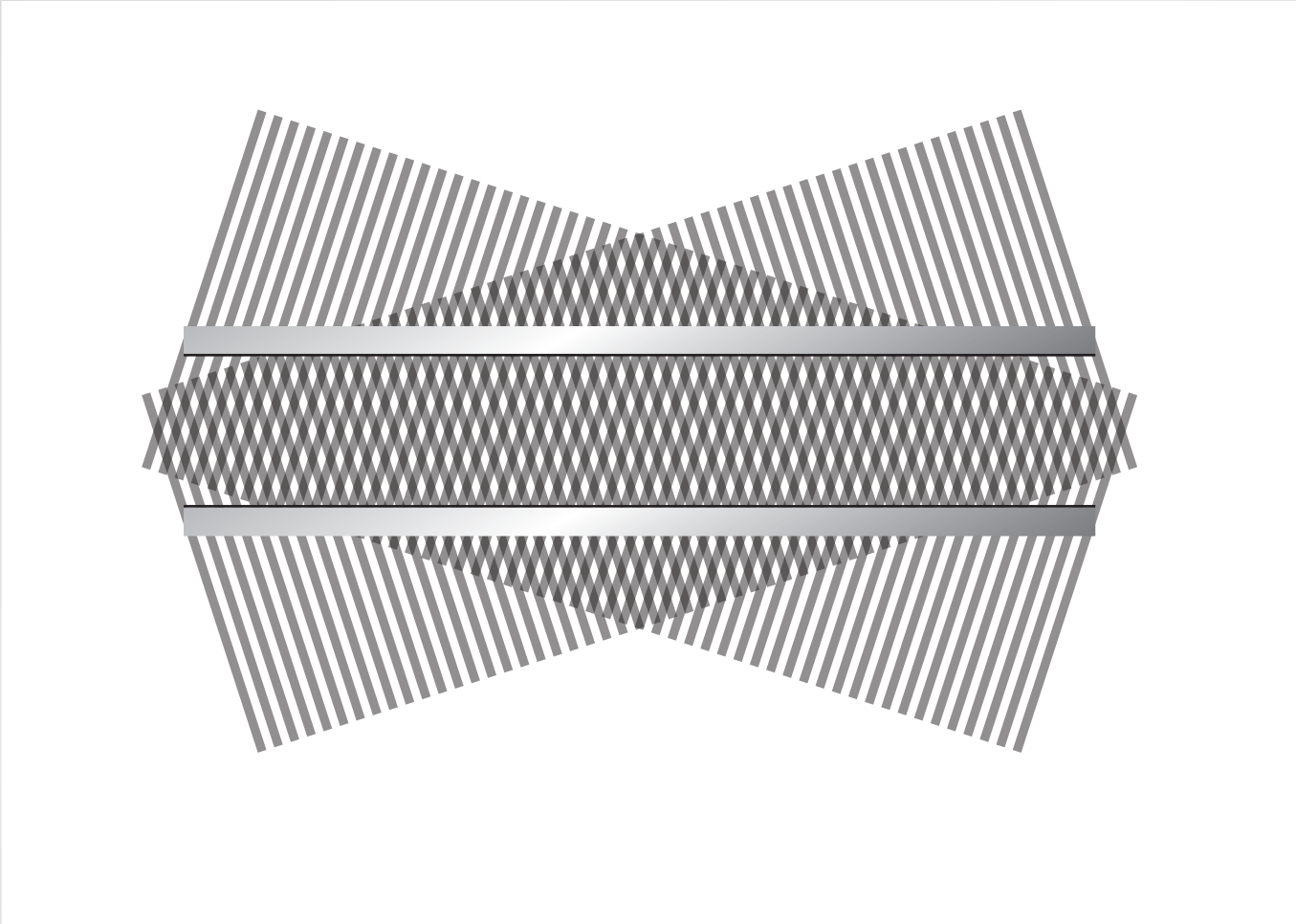
Waveguiding

change angle of incident waves…



Waveguiding

change angle of incident waves…



Waveguiding

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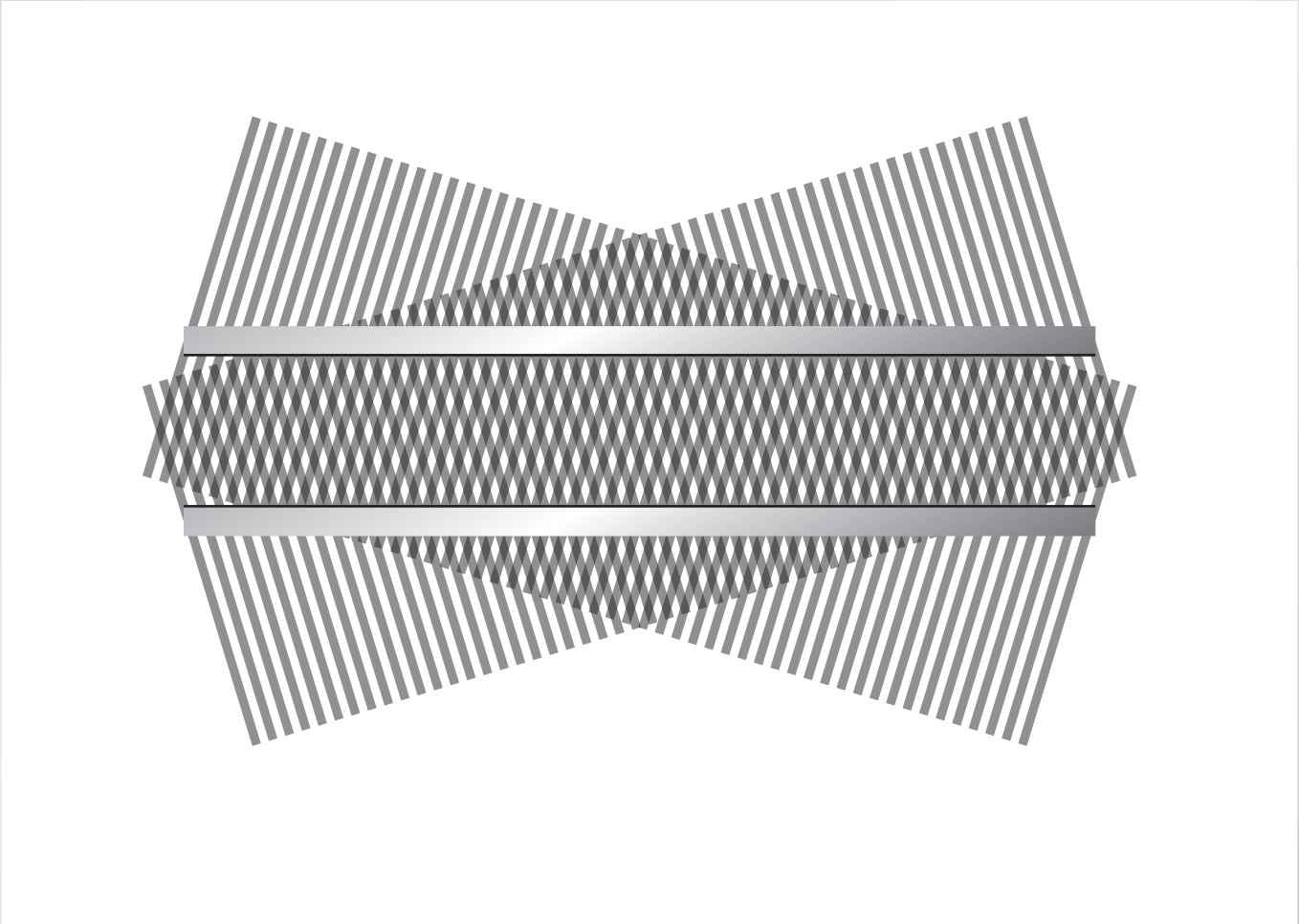
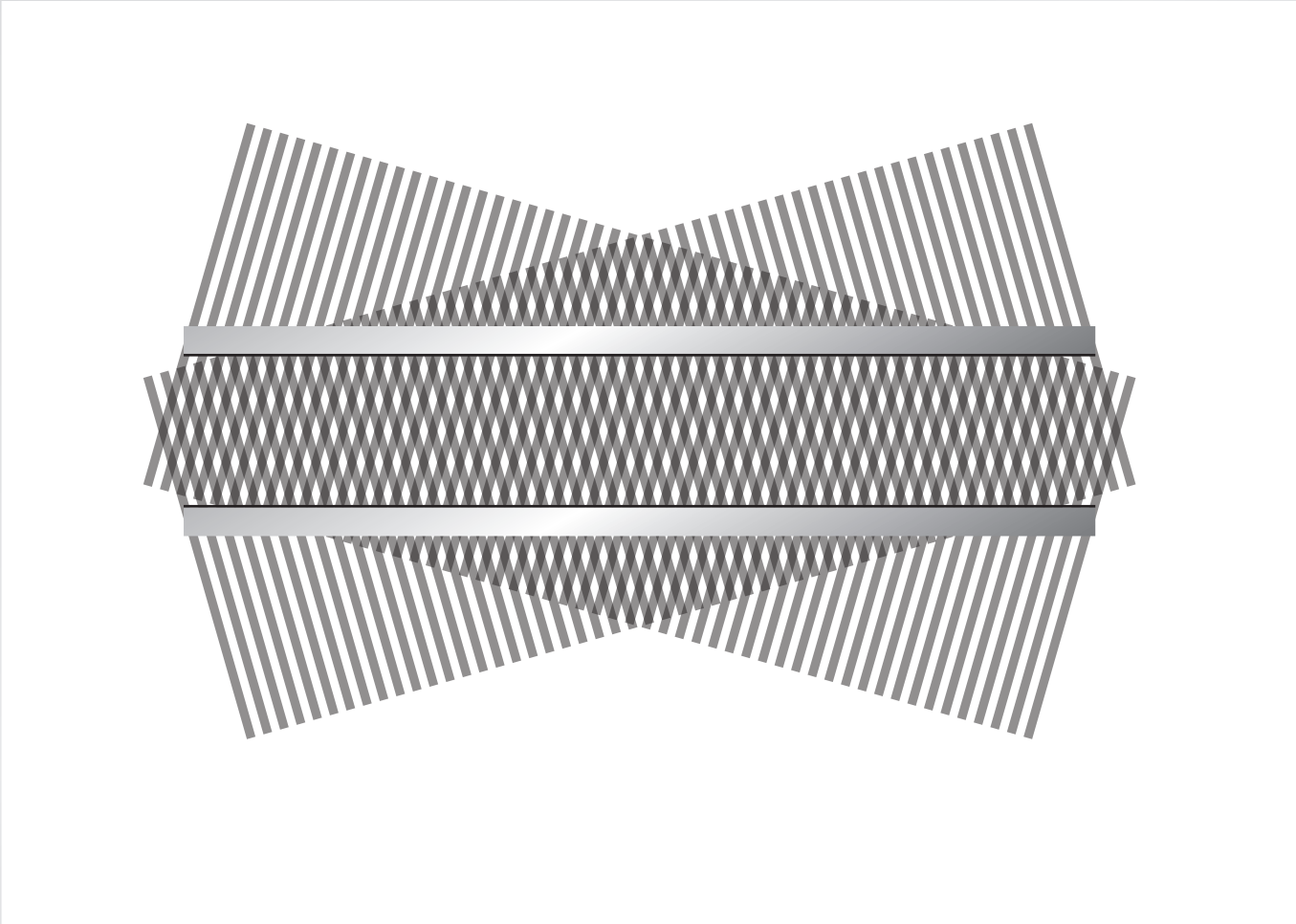


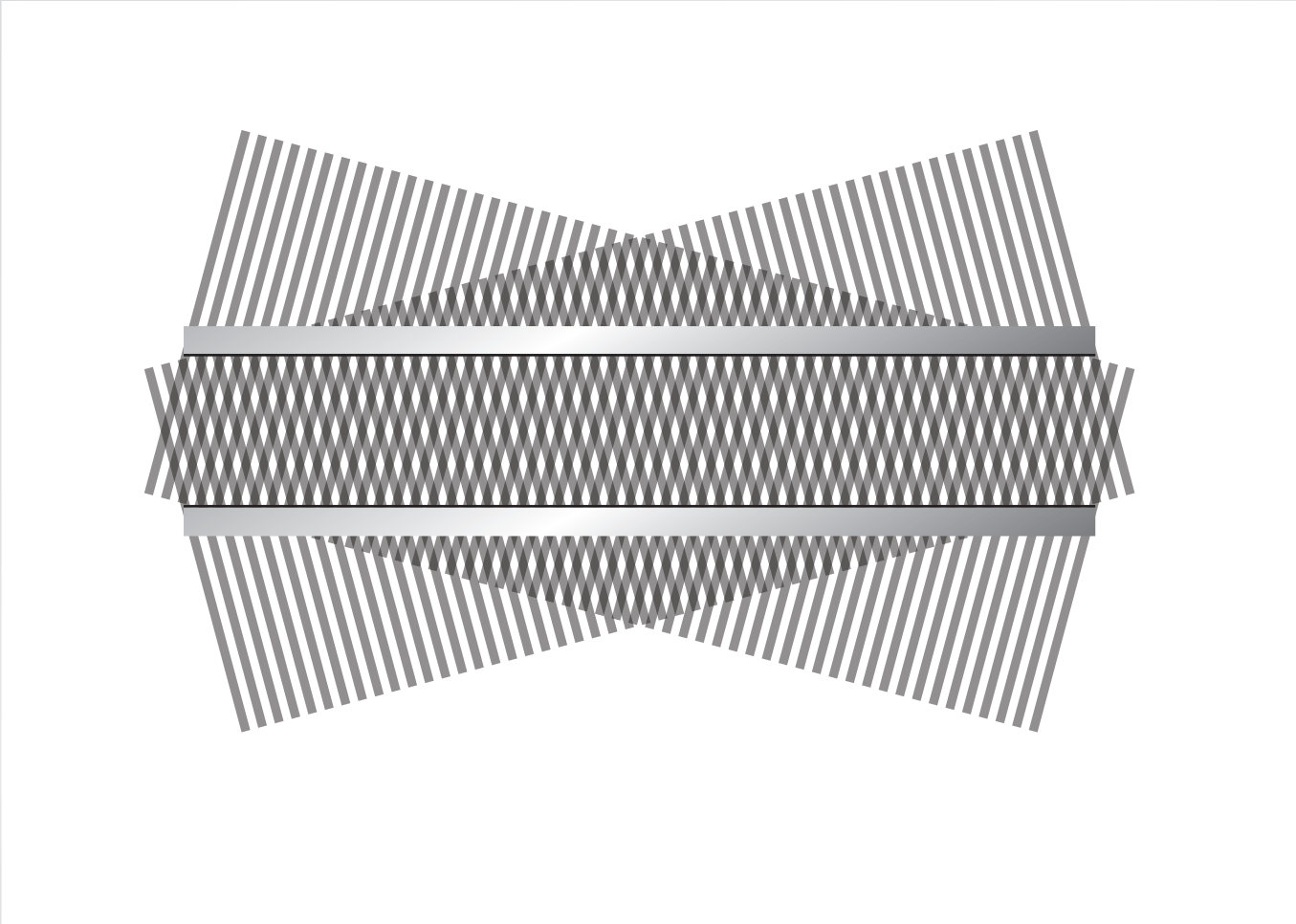
Waveguiding

change angle of incident waves…



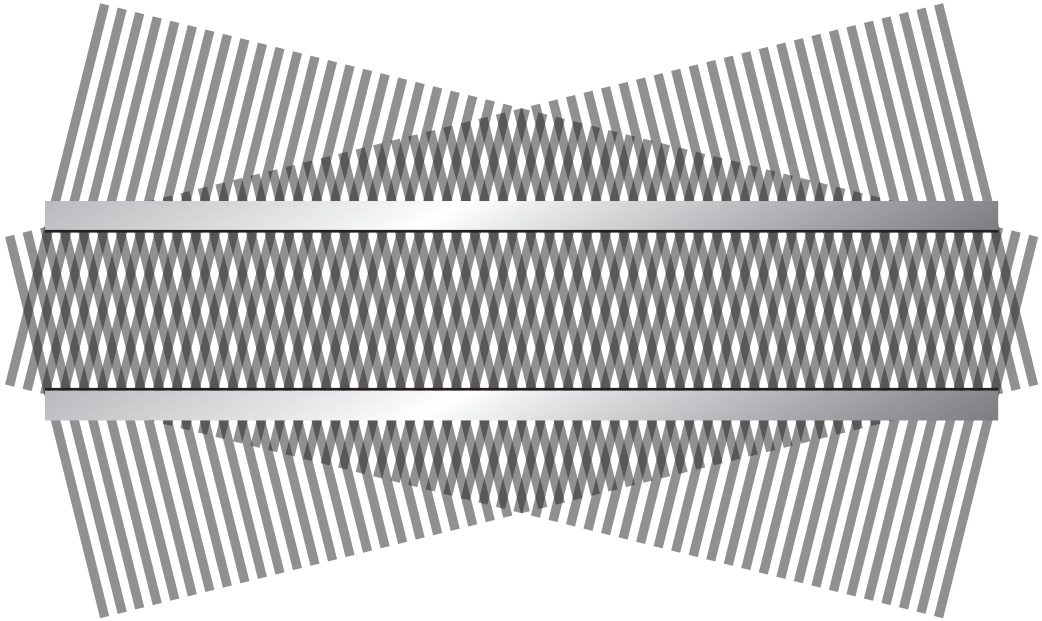
Waveguiding

change angle of incident waves…



Waveguiding

change angle of incident waves…



Waveguiding

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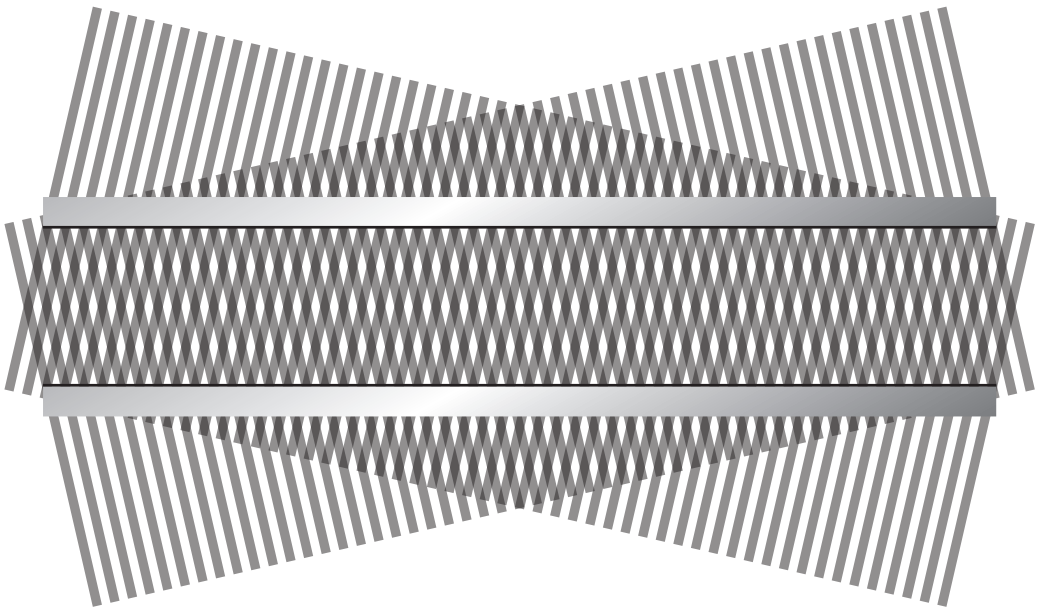
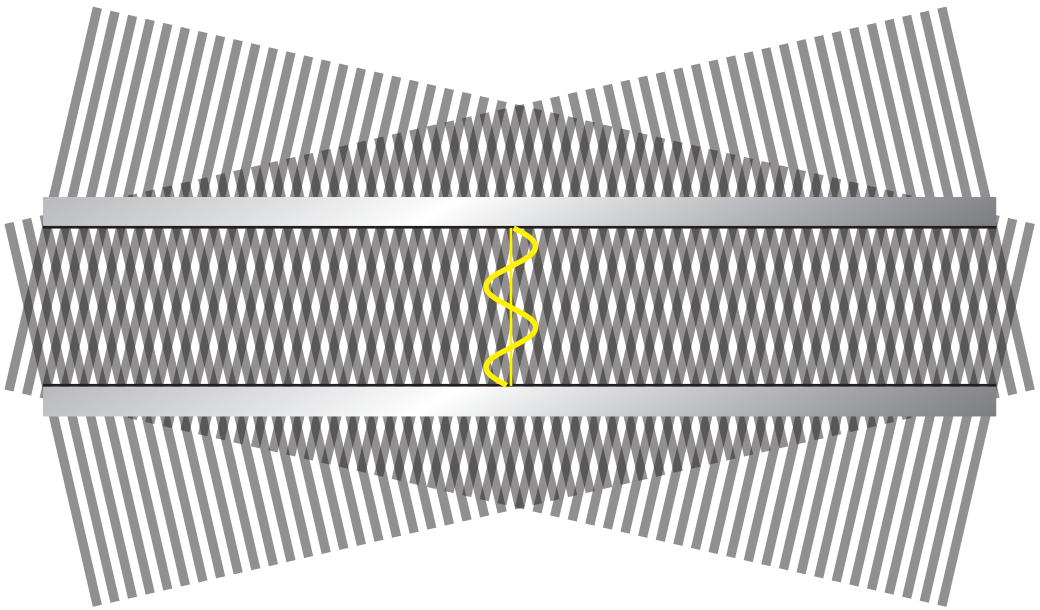


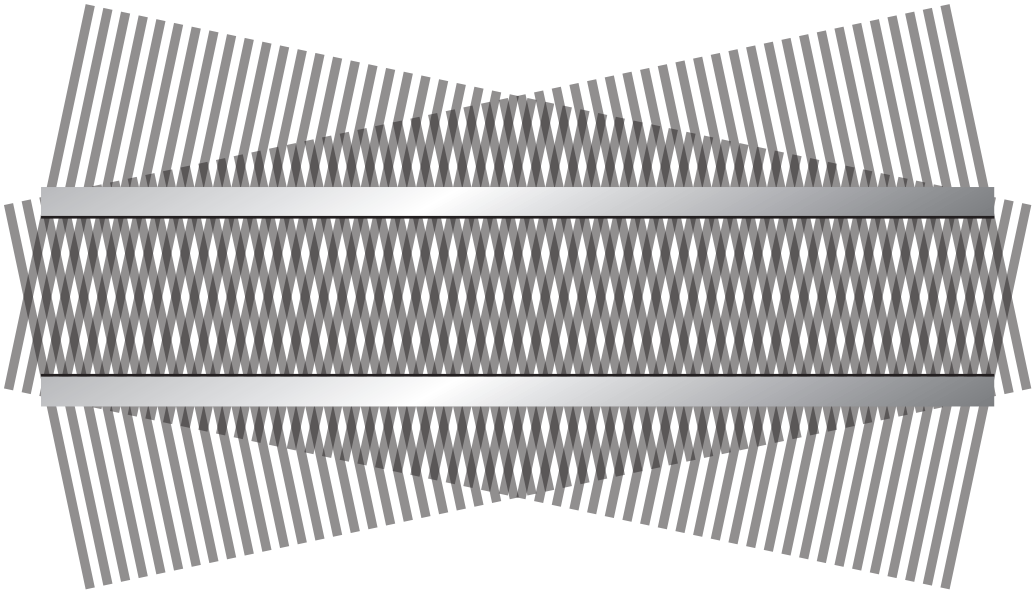
Waveguiding

change angle of incident waves…



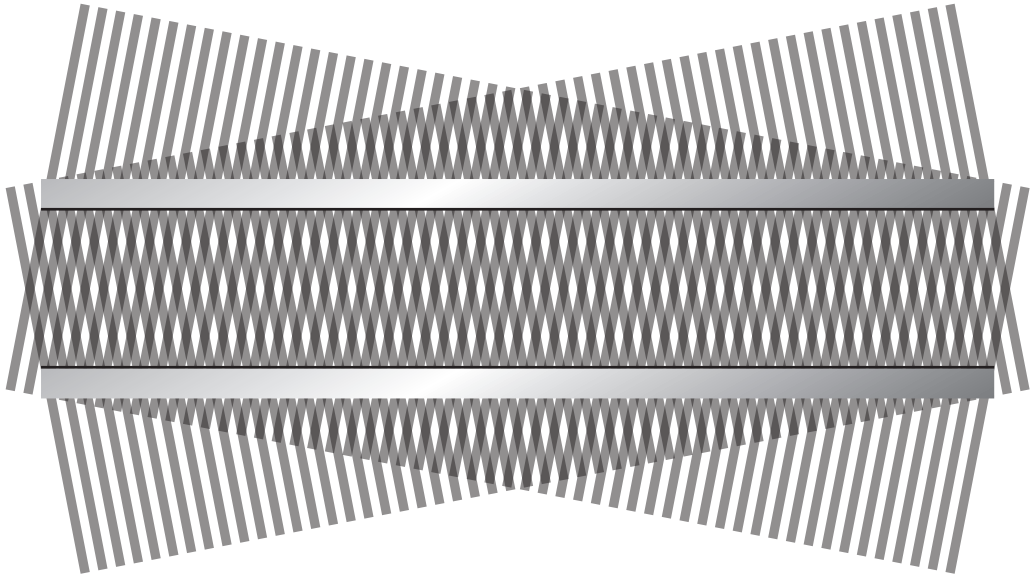
Waveguiding

change angle of incident waves…



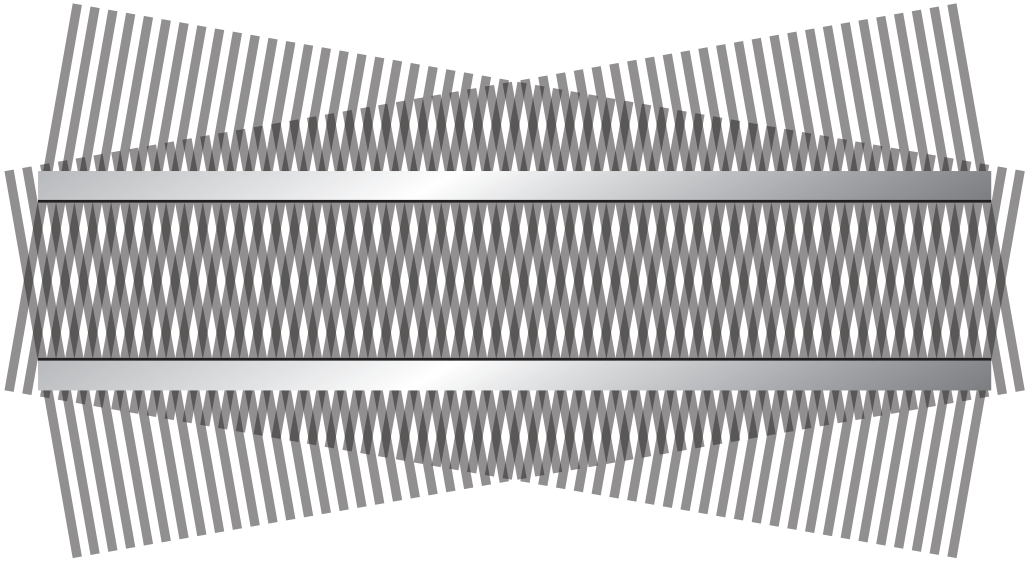
Waveguiding

change angle of incident waves…



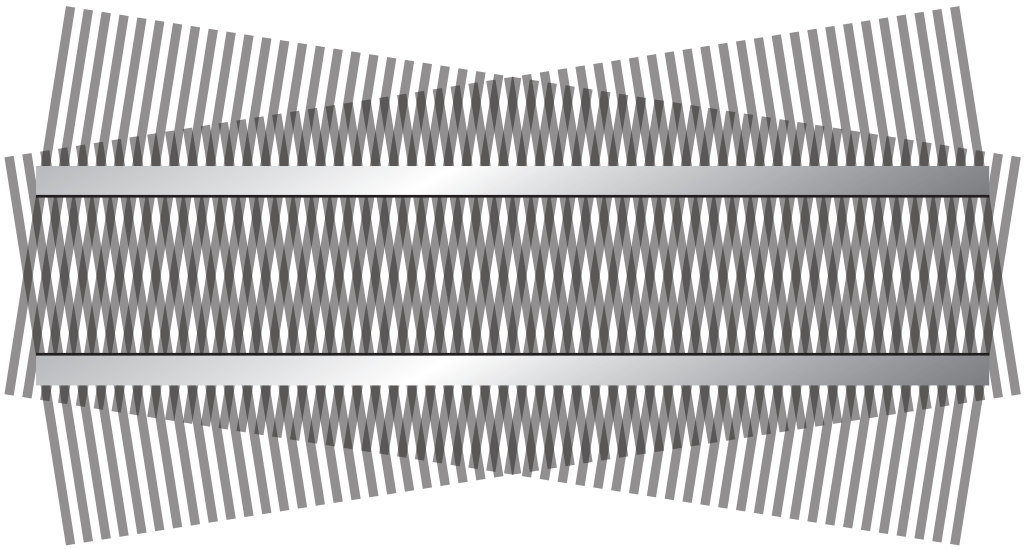
Waveguiding

change angle of incident waves…



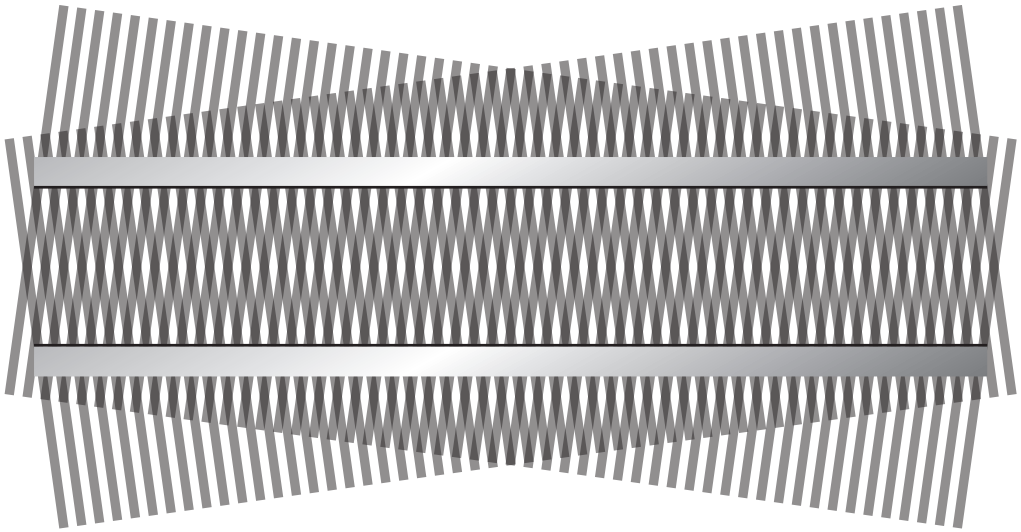
Waveguiding

change angle of incident waves…



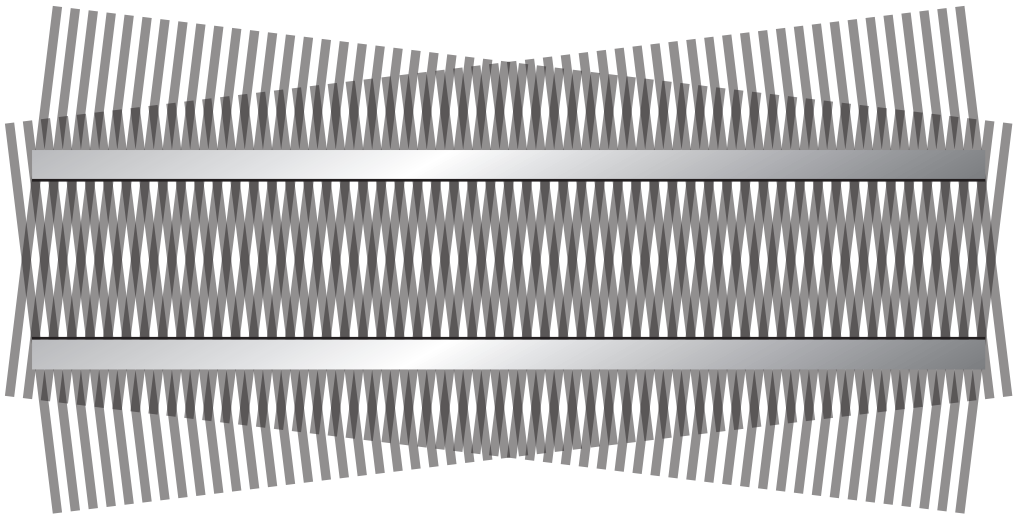
Waveguiding

change angle of incident waves…



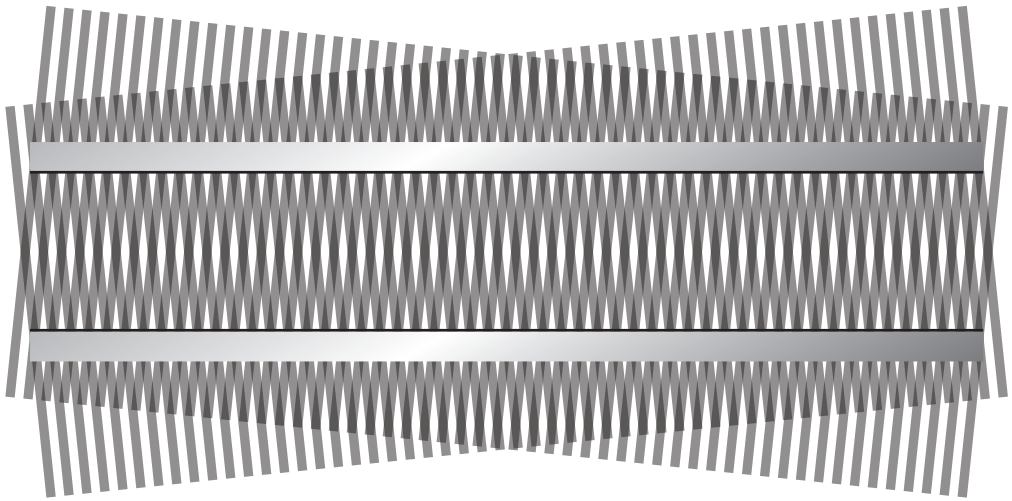
Waveguiding

change angle of incident waves…



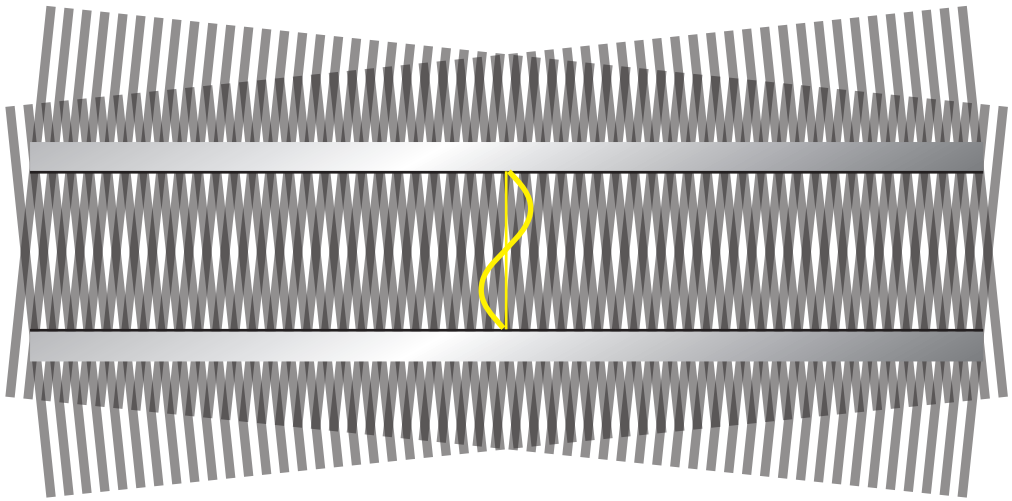
Waveguiding

change angle of incident waves…



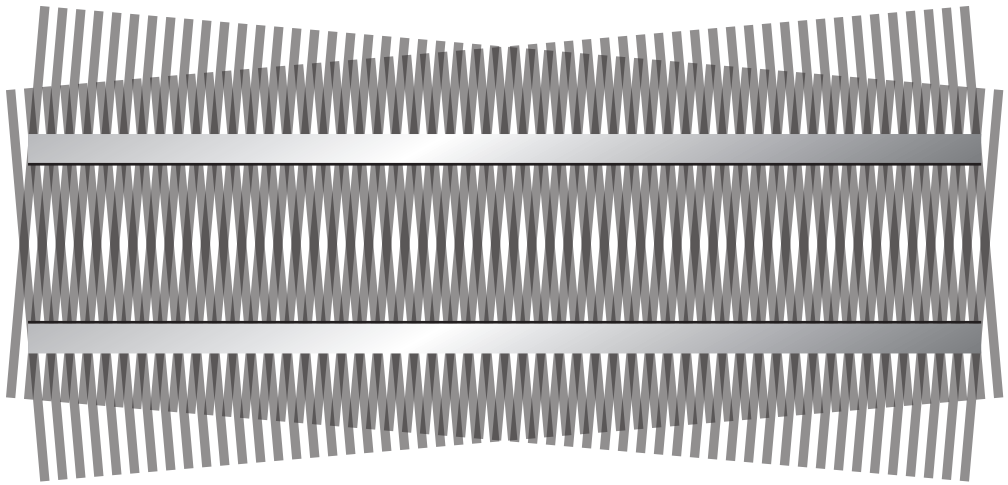
Waveguiding

change angle of incident waves…



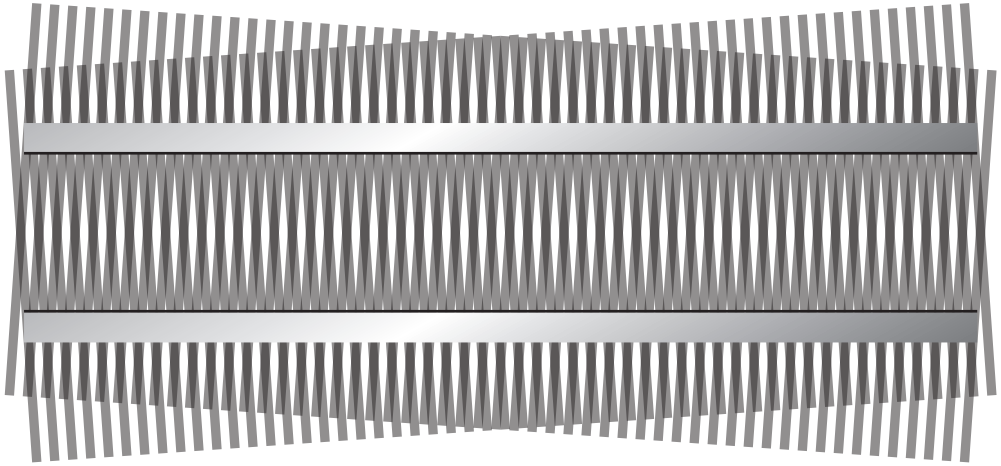
Waveguiding

change angle of incident waves…



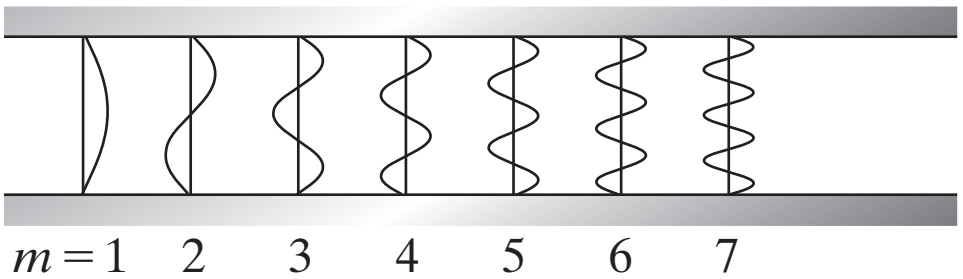
Waveguiding

change angle of incident waves…



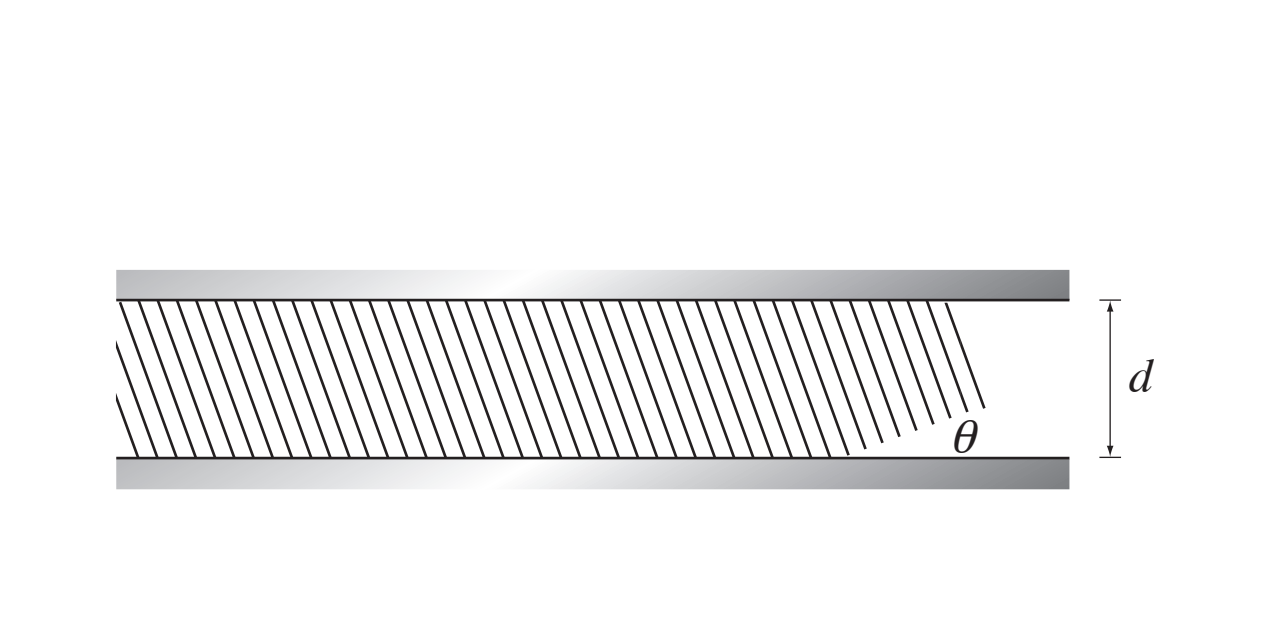
Waveguiding

boundary conditions only satisfied for certain θ



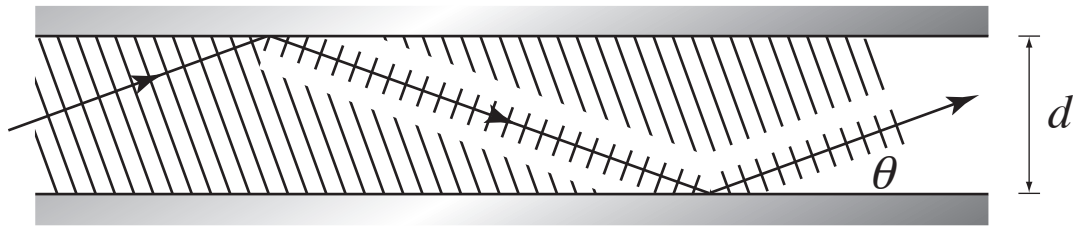
standing wave in *y*-direction, traveling in *z*-direction

Waveguiding



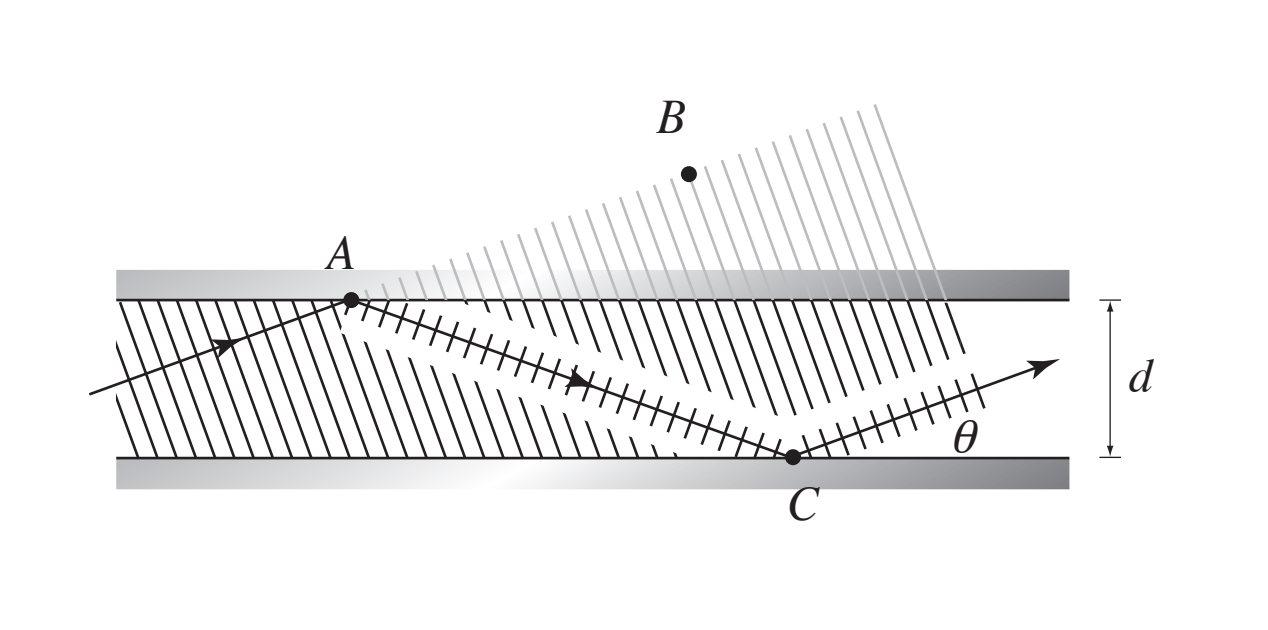
consider wave incident at angle θ

Waveguiding



twice-reflected wave

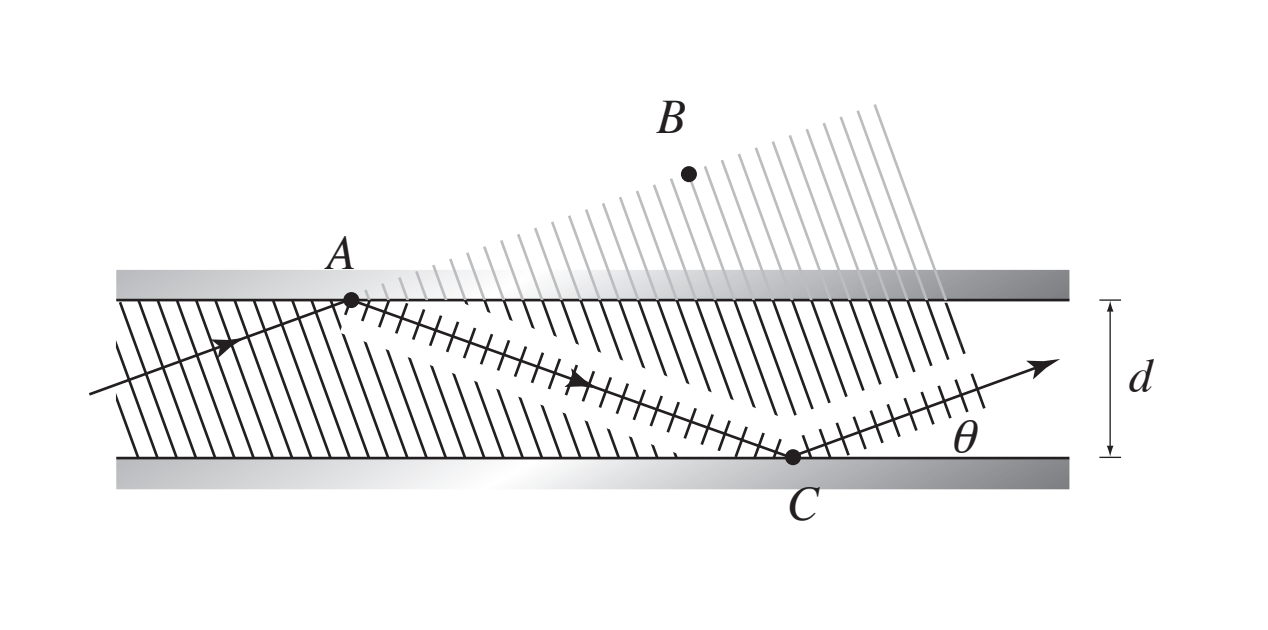
Waveguiding



self consistency:

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

Waveguiding



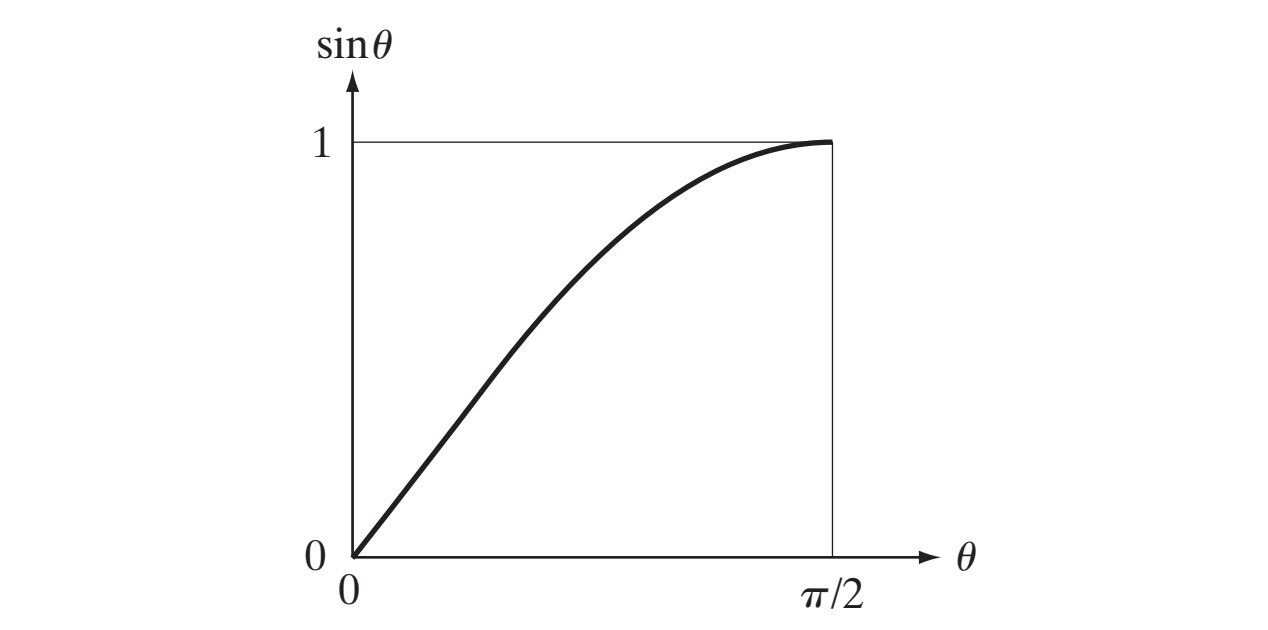
self consistency:

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

so:

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

Waveguiding



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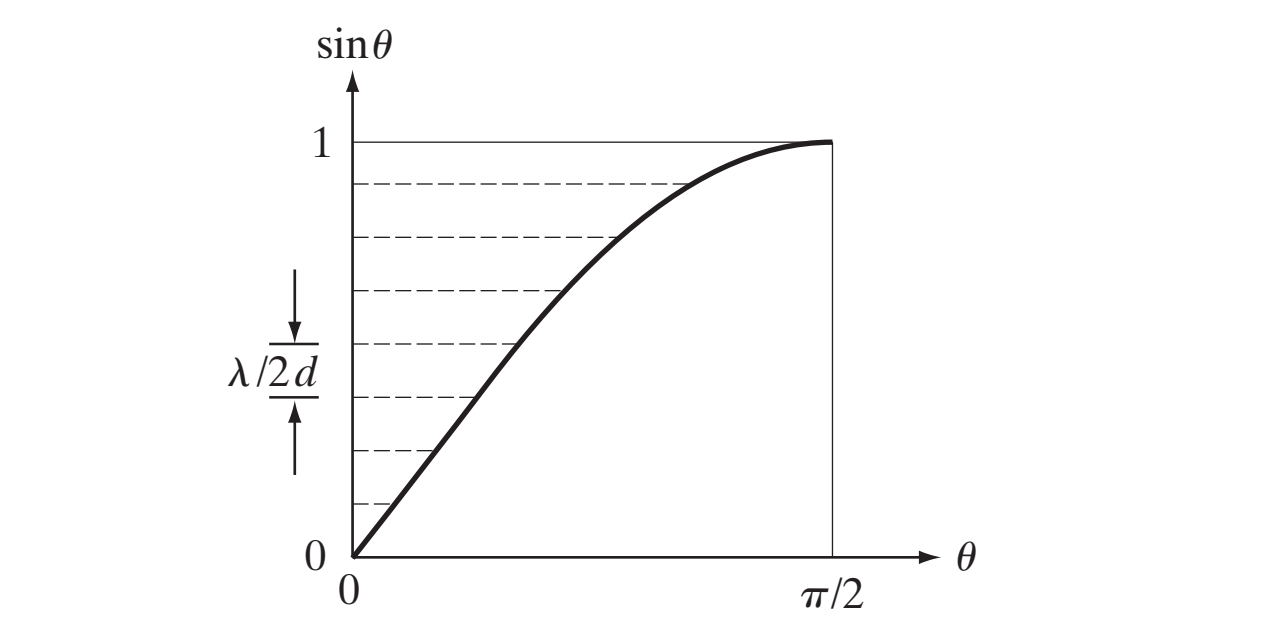
Waveguiding



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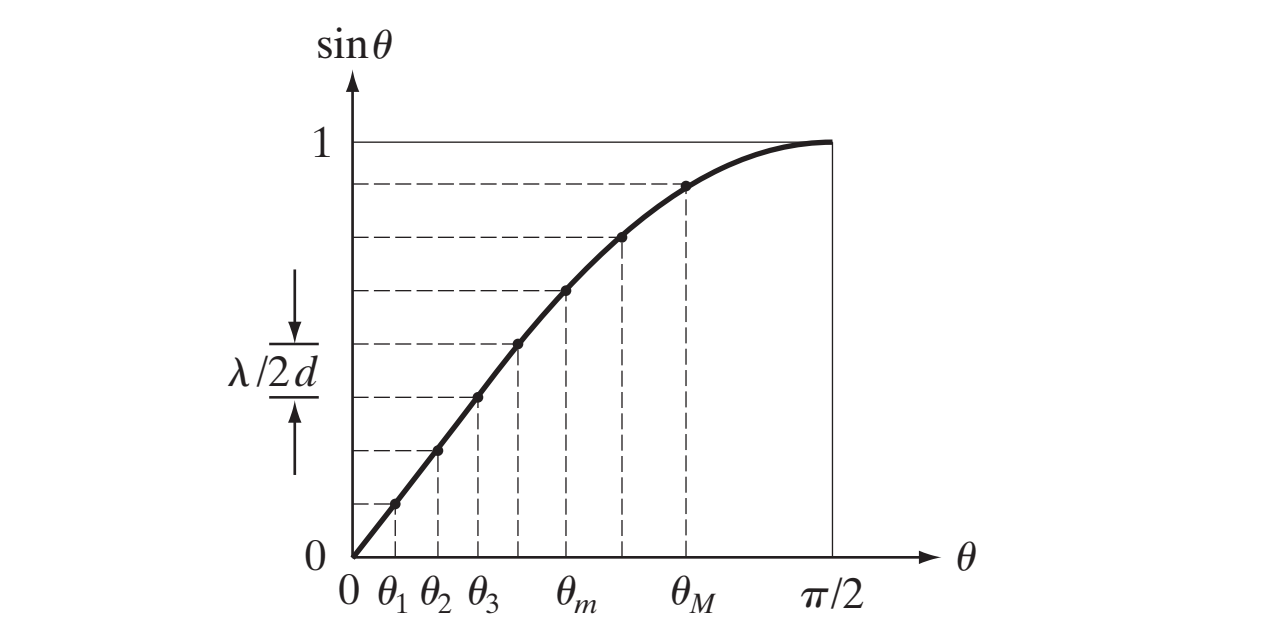
Waveguiding



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

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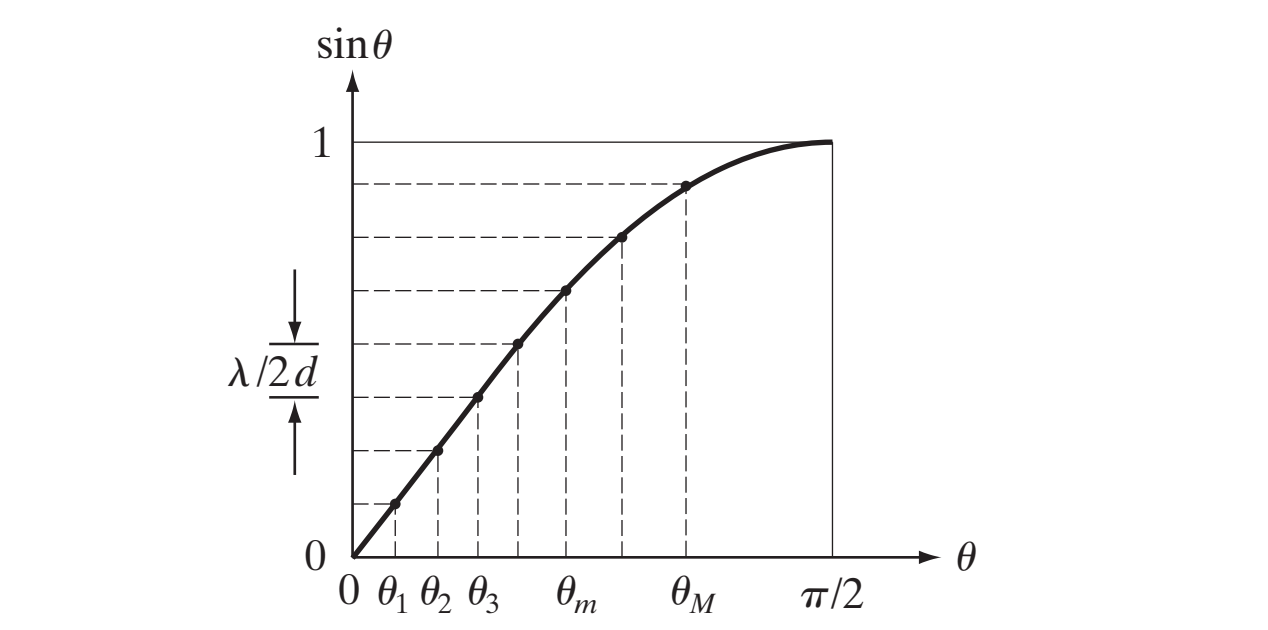
Waveguiding



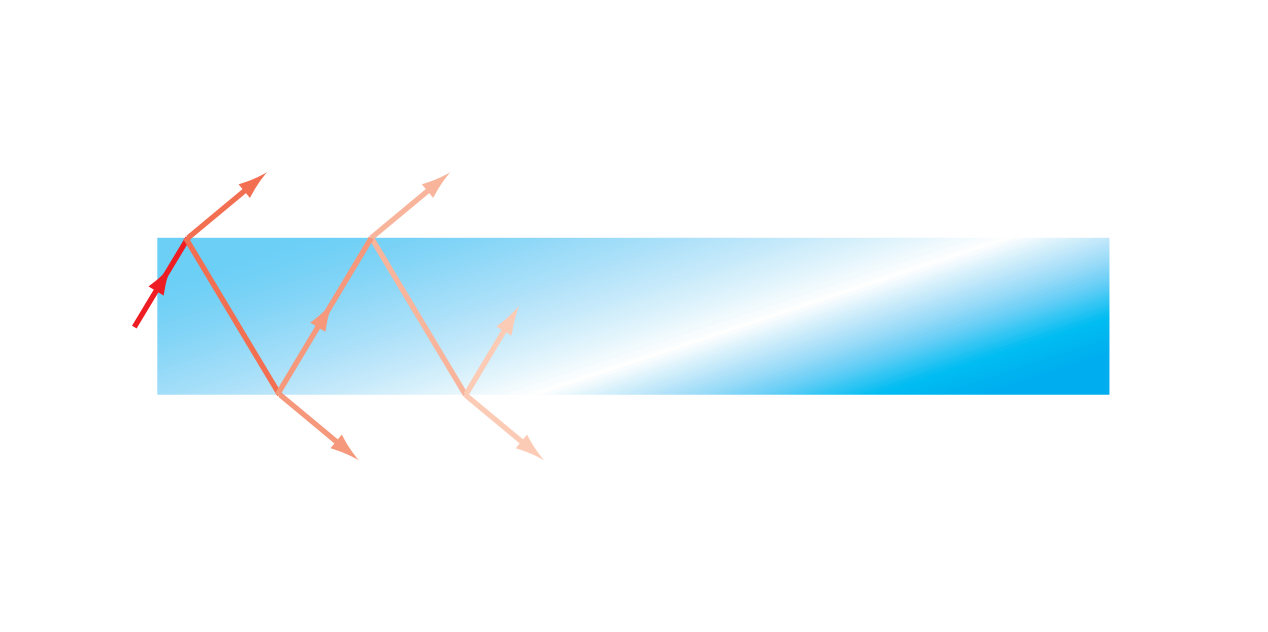
number of modes:

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

Waveguiding

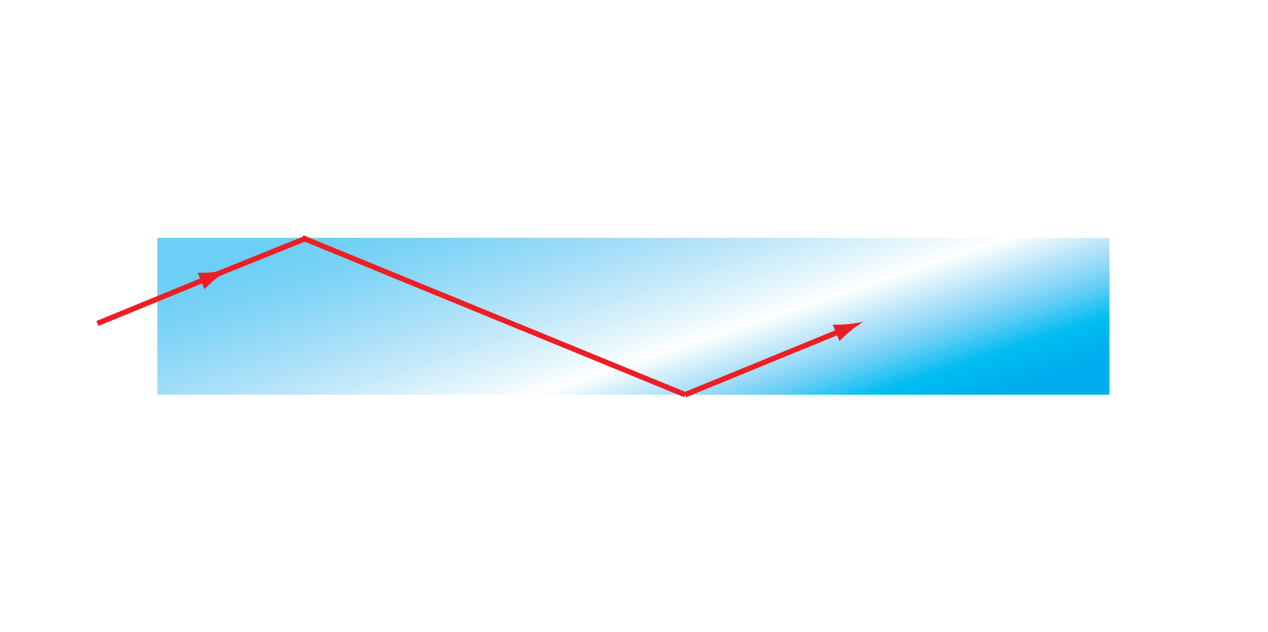
now consider a planar dielectric waveguide

Waveguiding



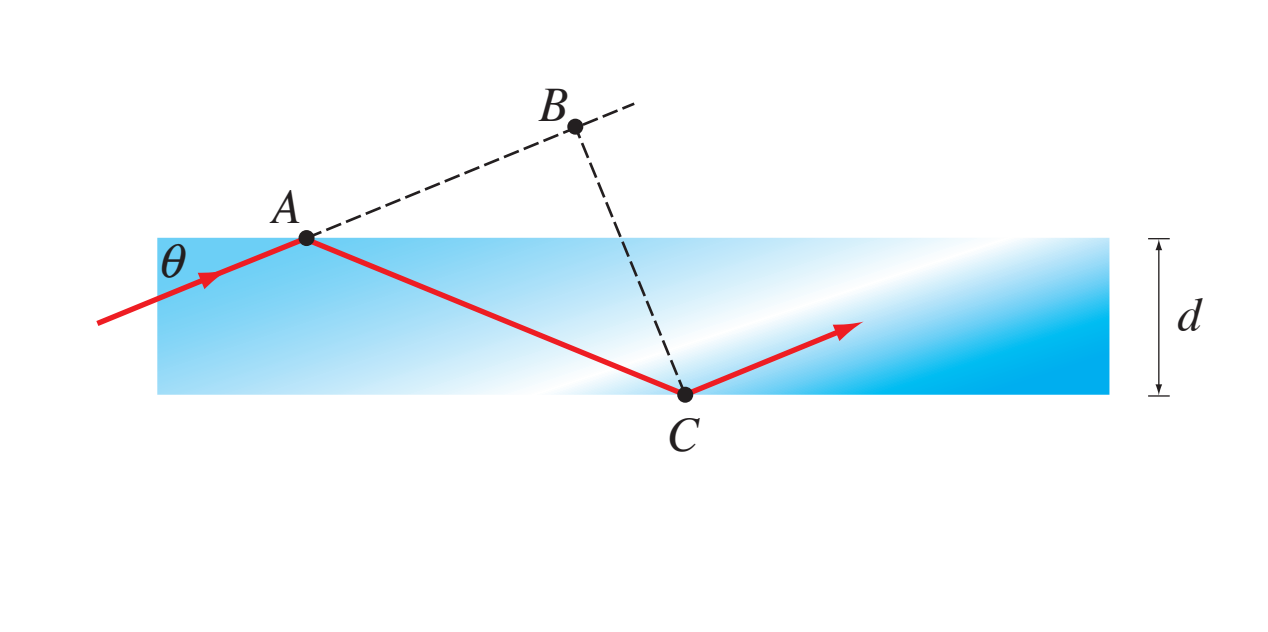
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



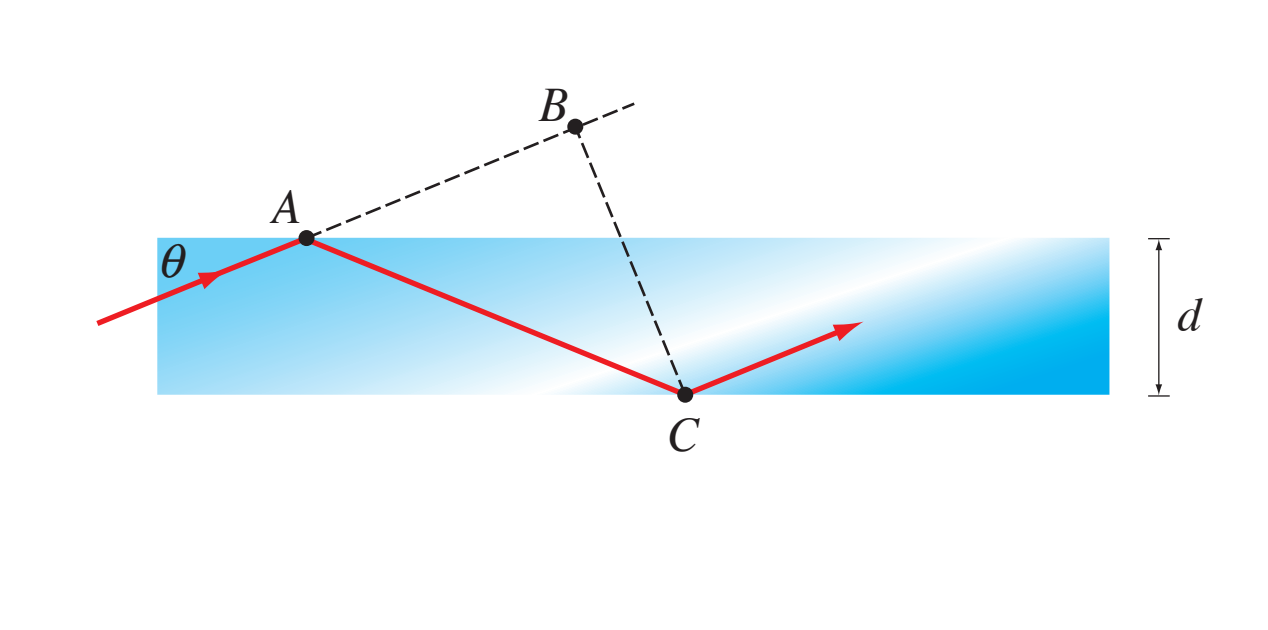
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

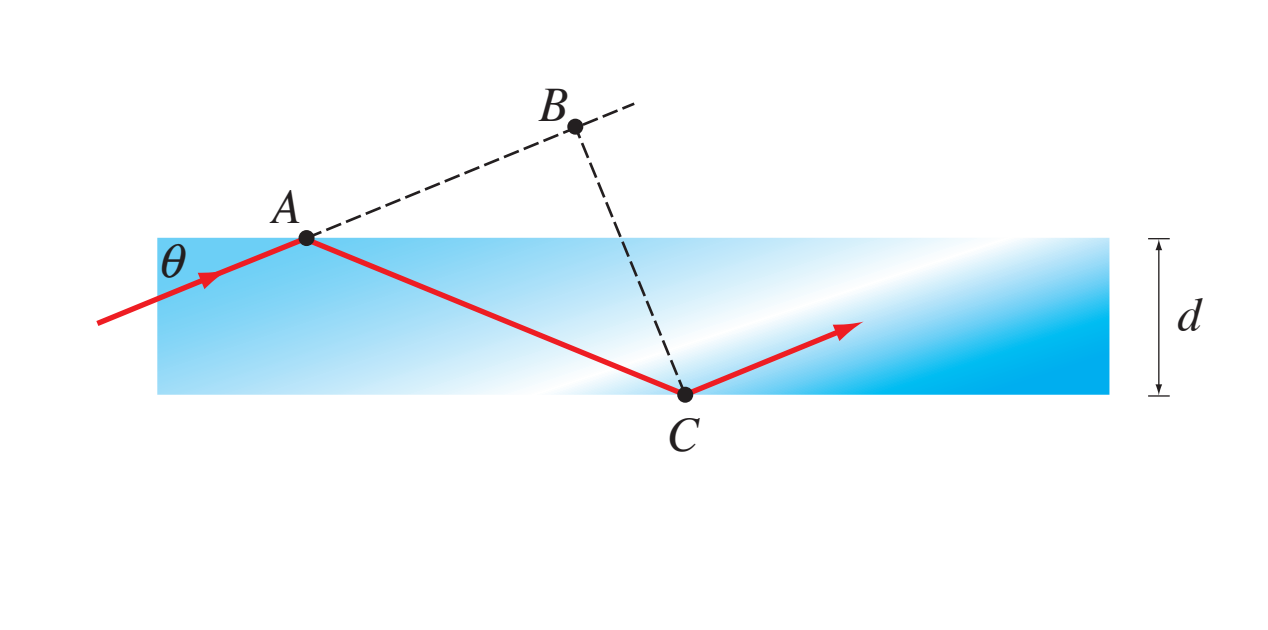
Waveguiding



self consistency:

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

Waveguiding



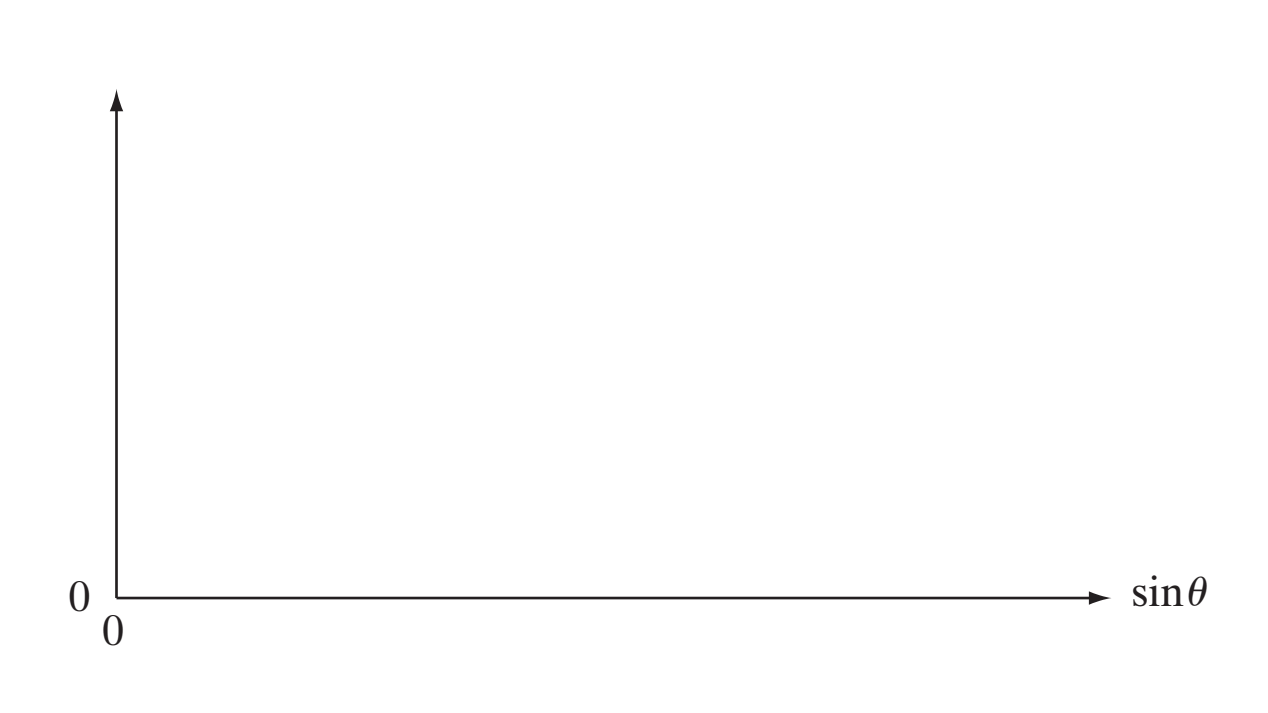
self consistency:

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

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



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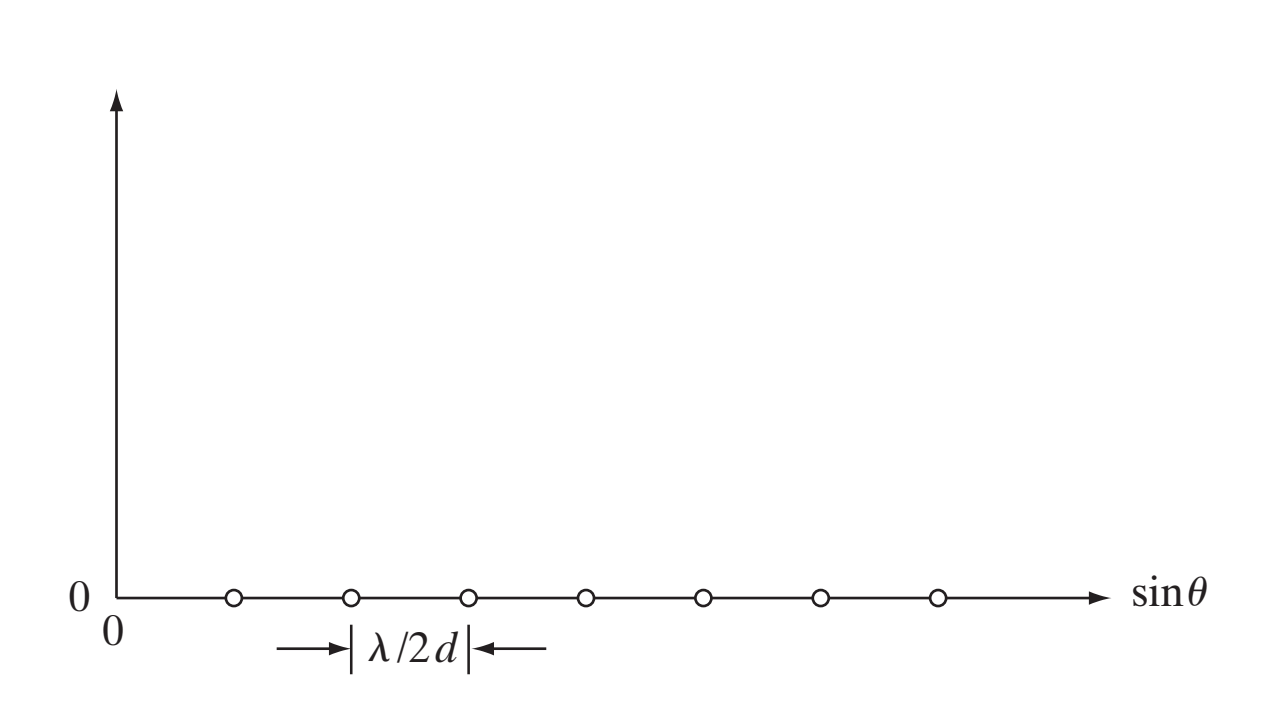

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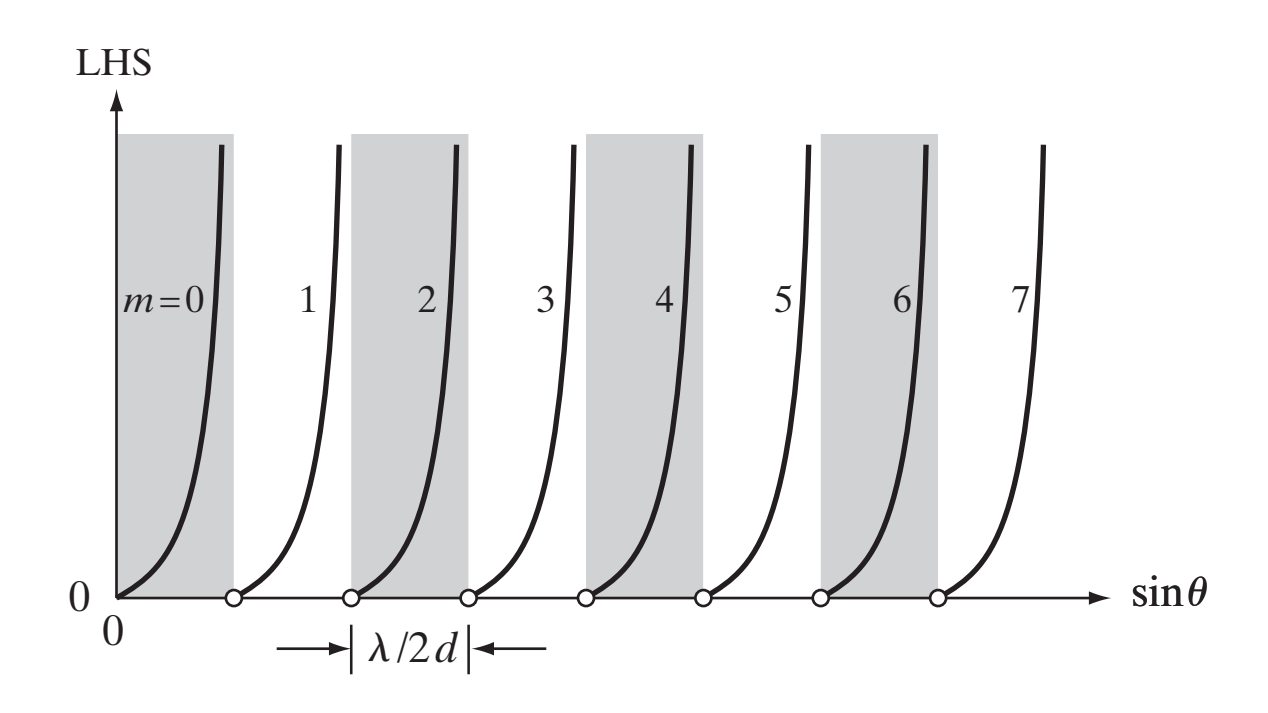
Waveguiding



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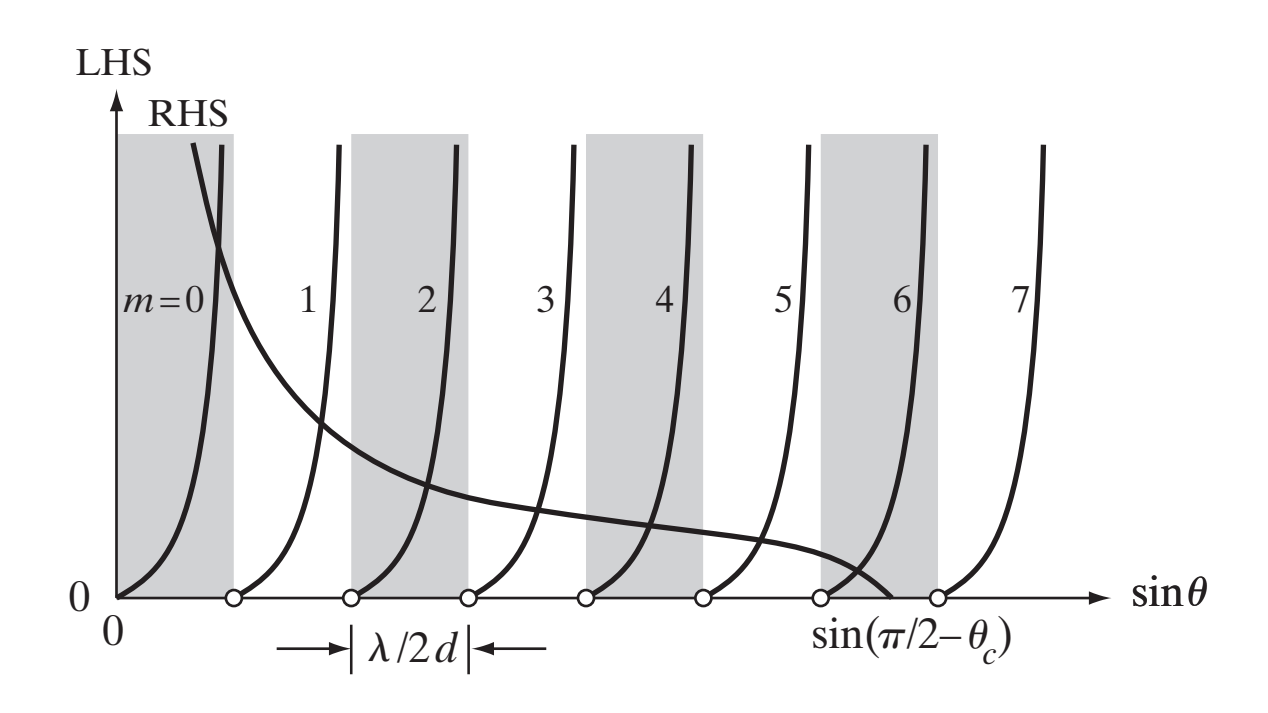
Waveguiding



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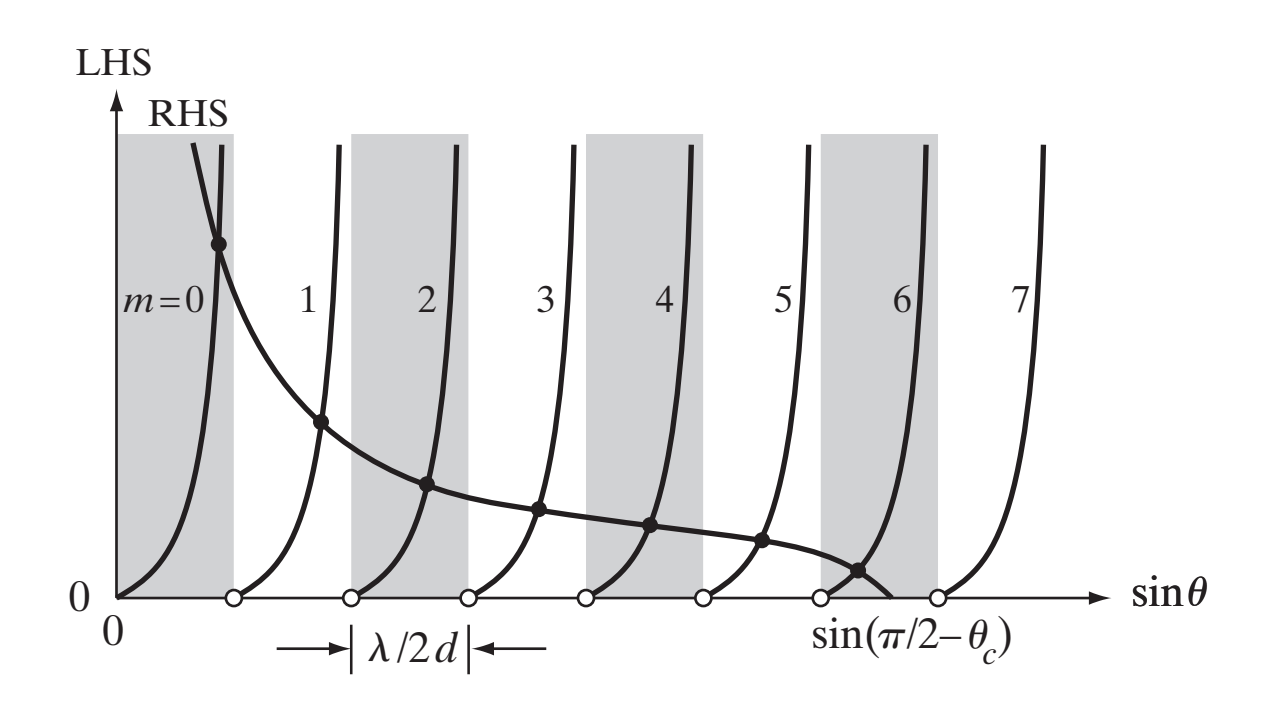
Waveguiding



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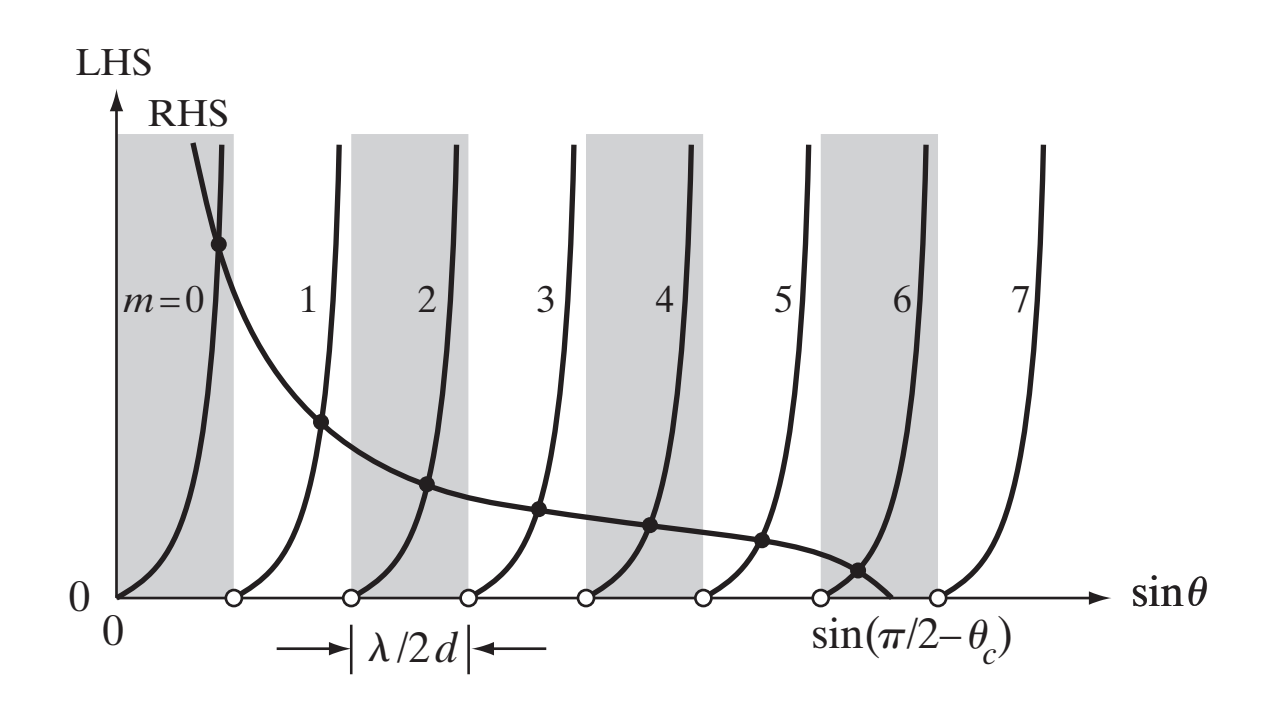
so:

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

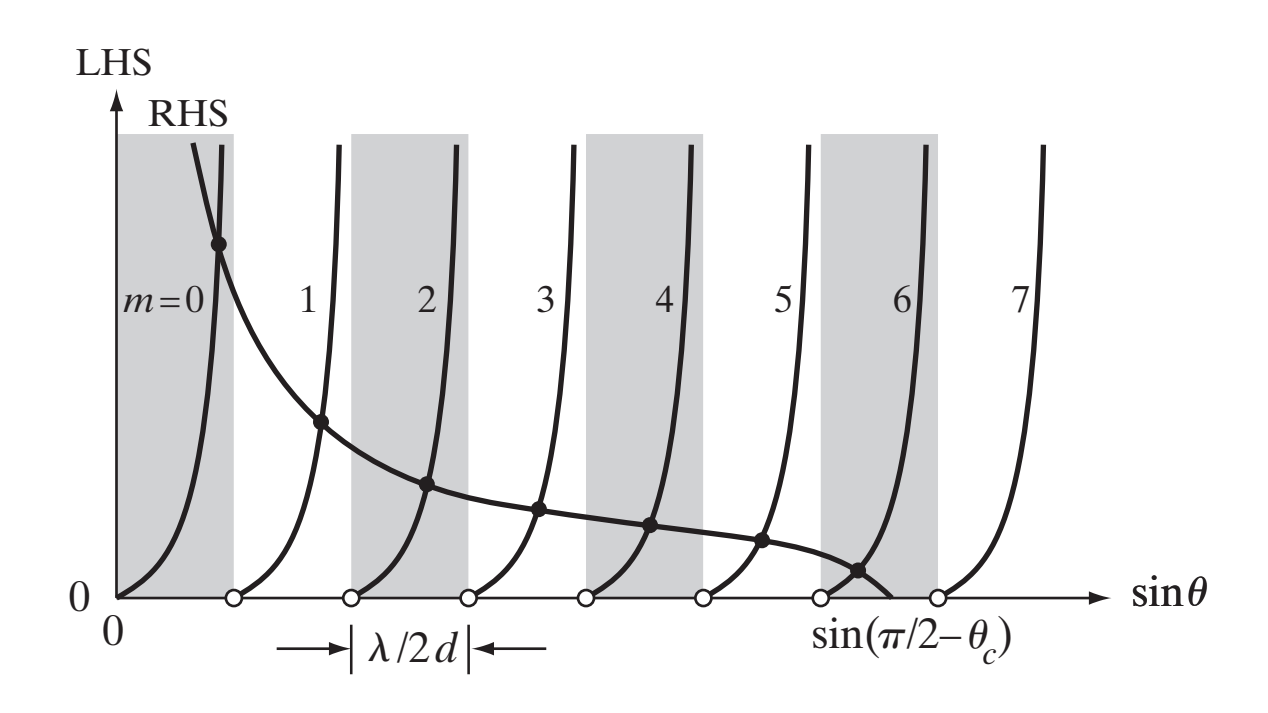
Waveguiding



number of modes:

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

Waveguiding



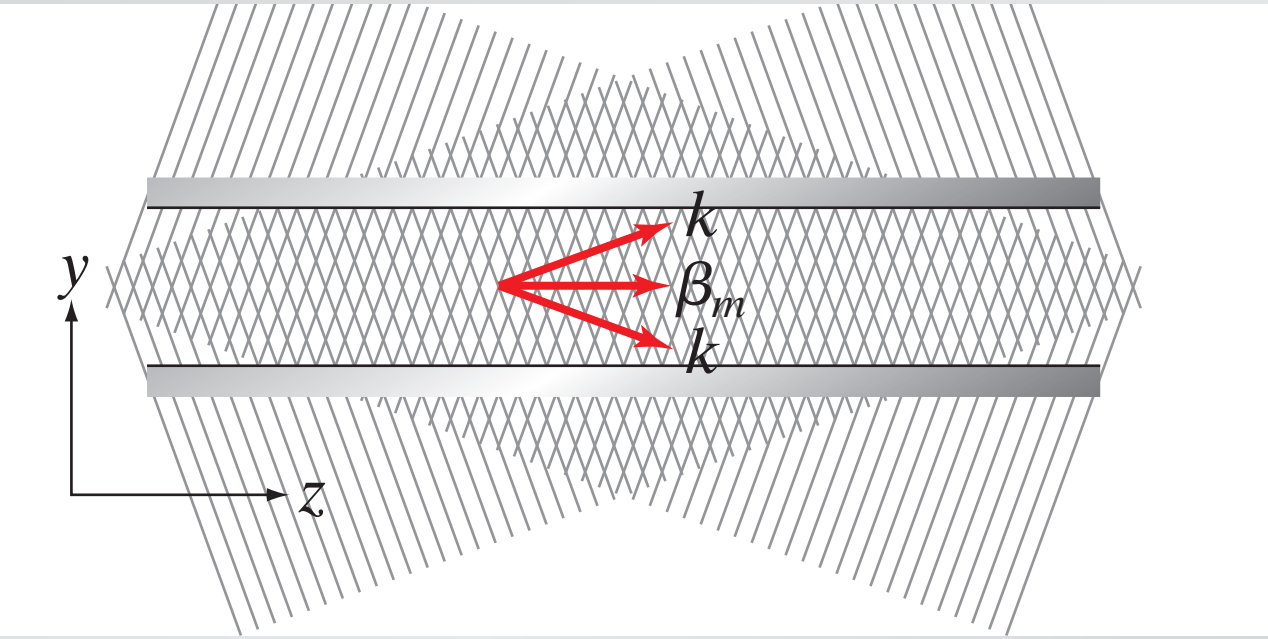
number of modes:

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

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 $$M \doteqdot \frac{2d}{\lambda}$$ $$300 < d < 600 \text{ nm}$$

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

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

Vector potential obeys:

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

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

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

yields:

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

Waveguiding

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

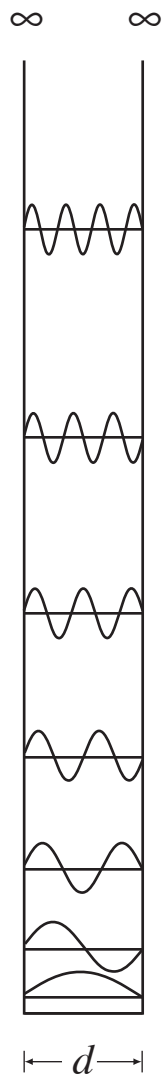
yields:

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

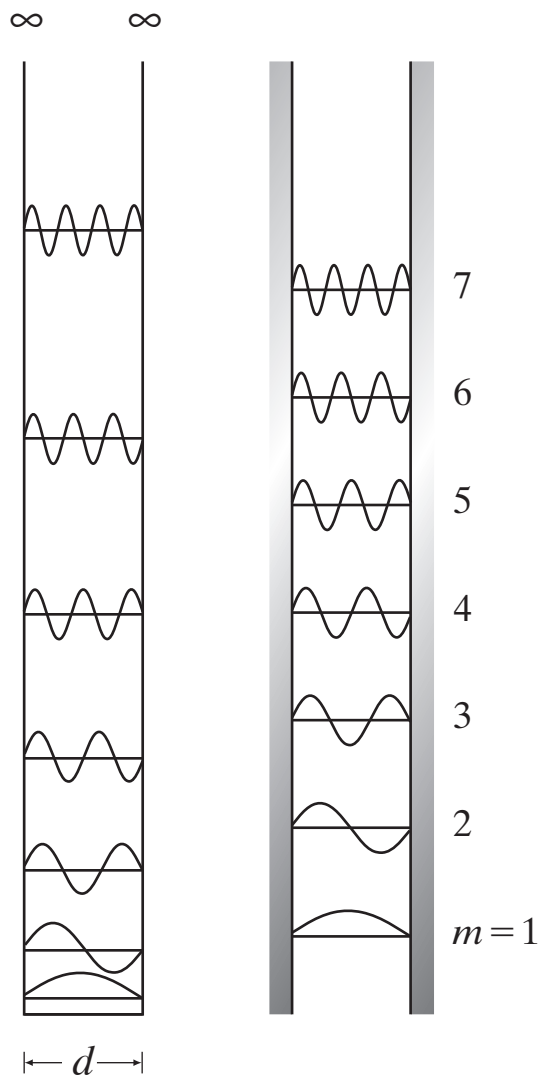
Compare to time-independent Schrödinger equation:

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

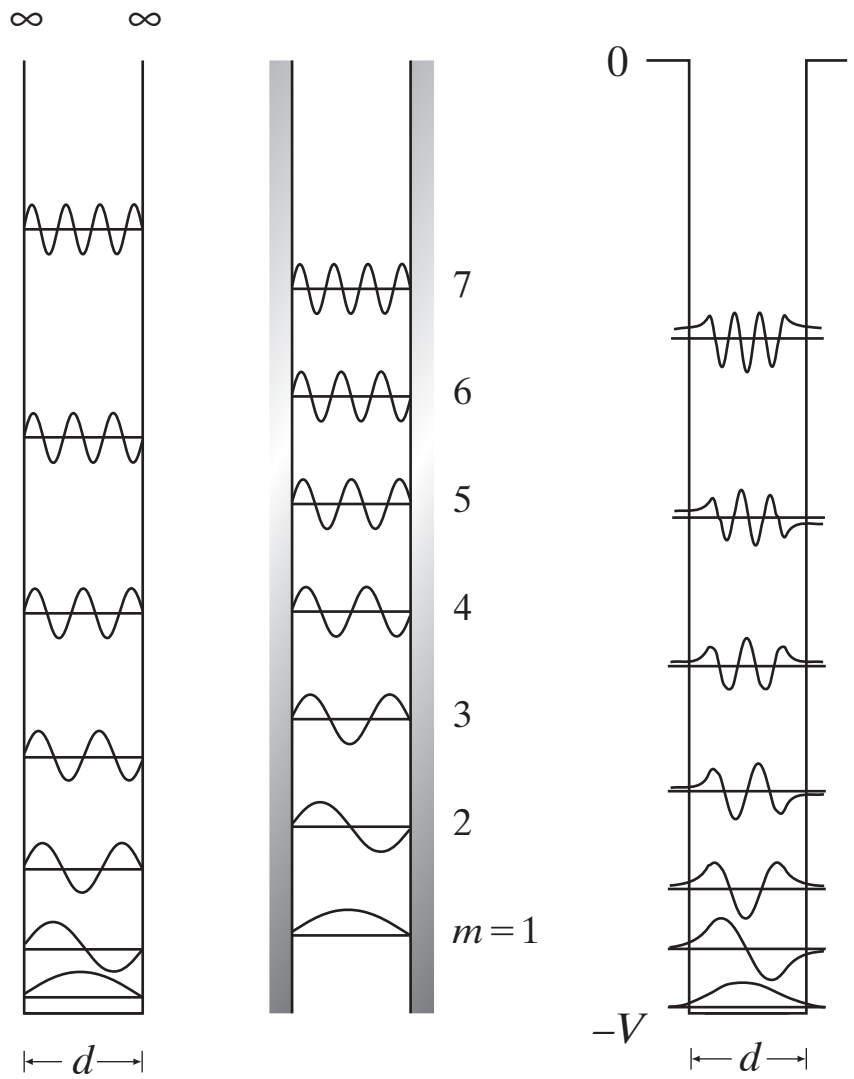
Waveguiding



Waveguiding



Waveguiding



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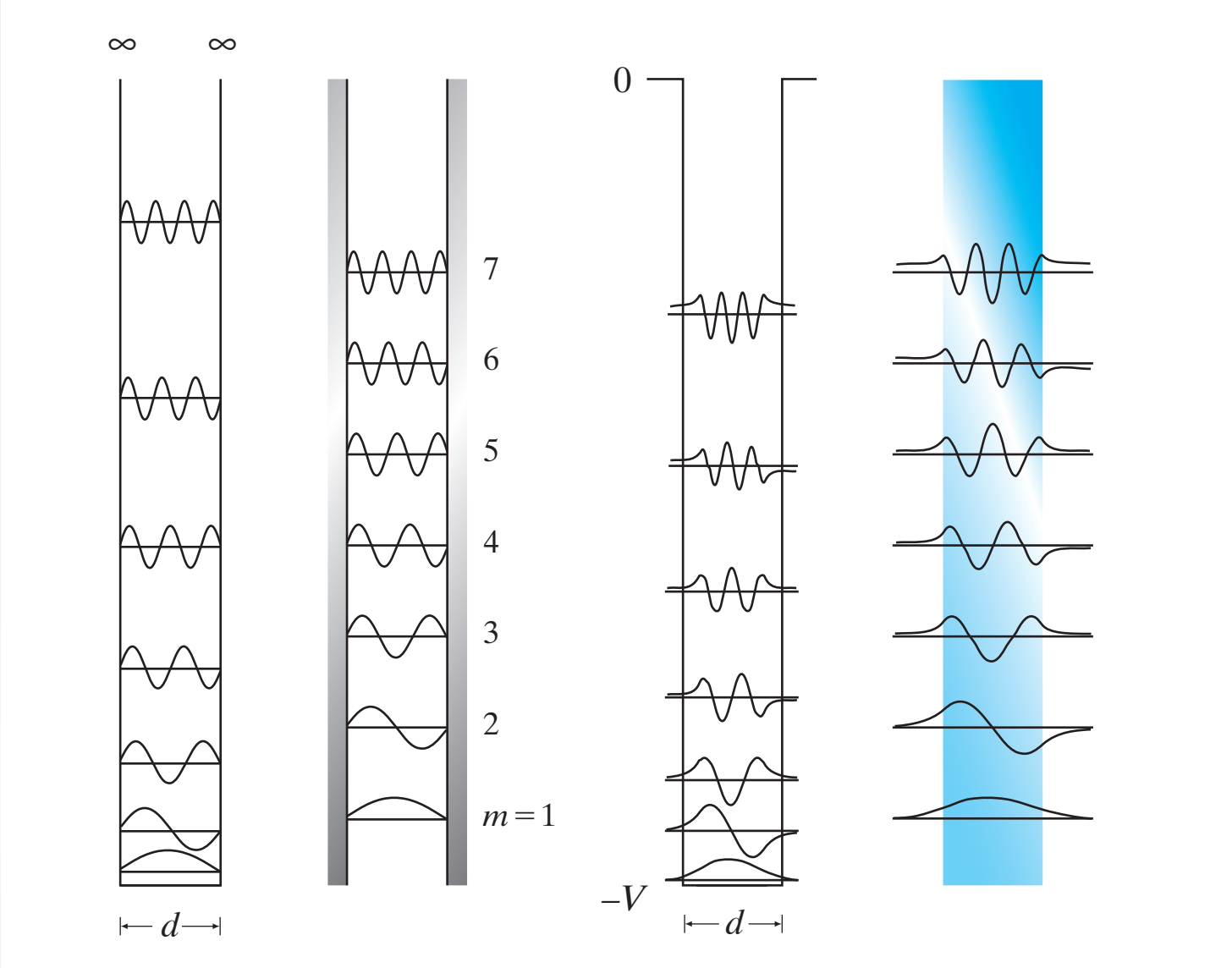
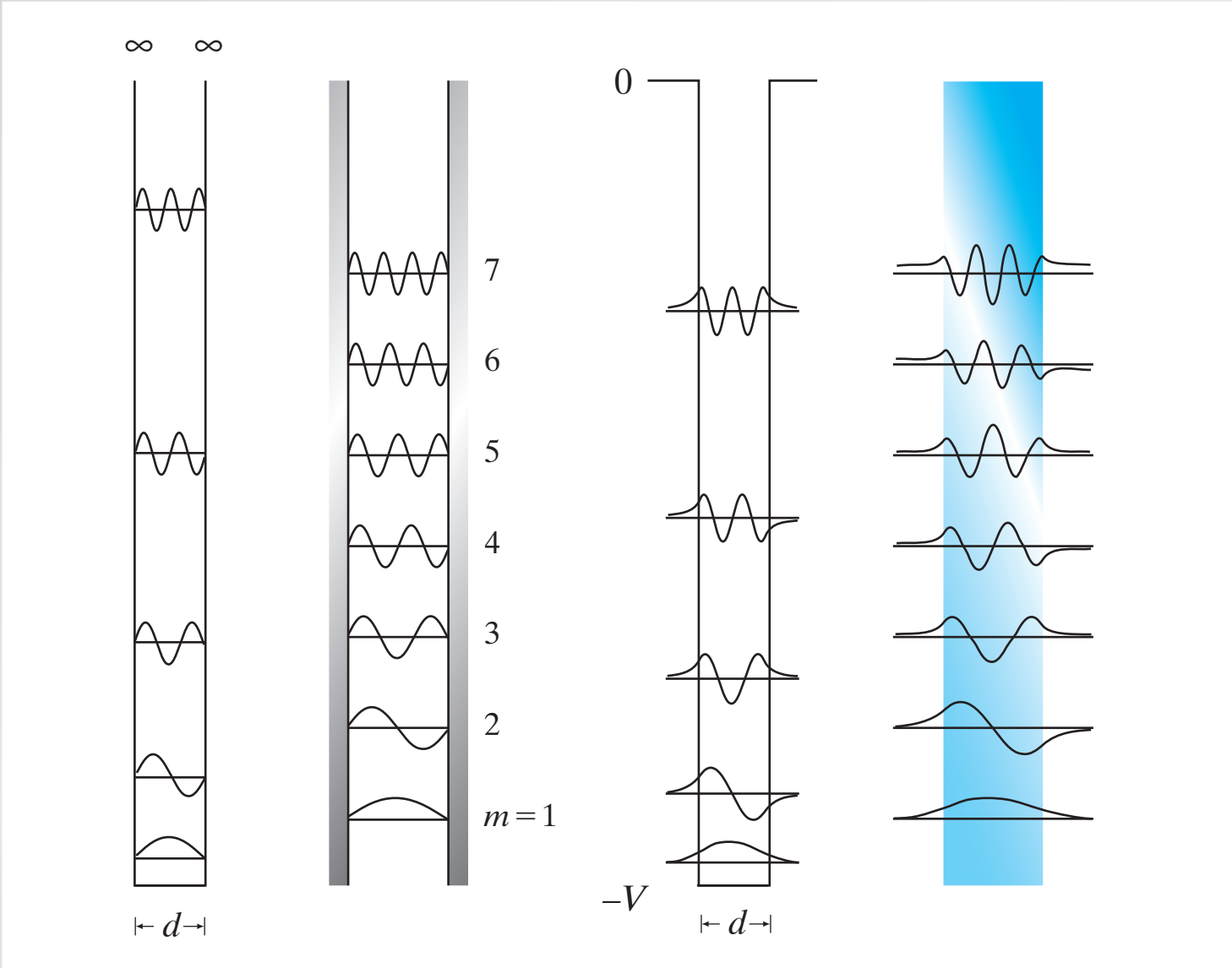


Waveguiding



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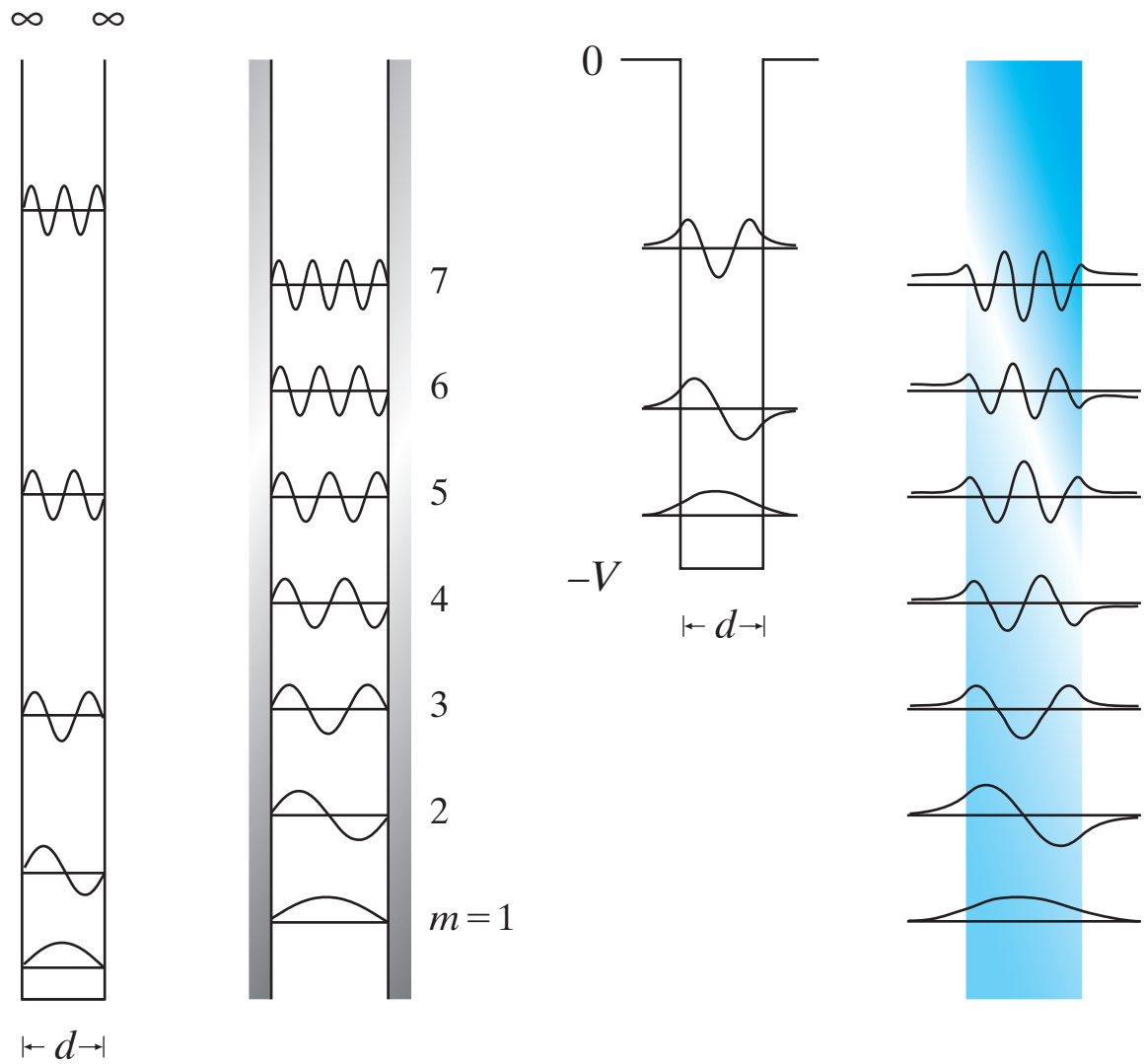
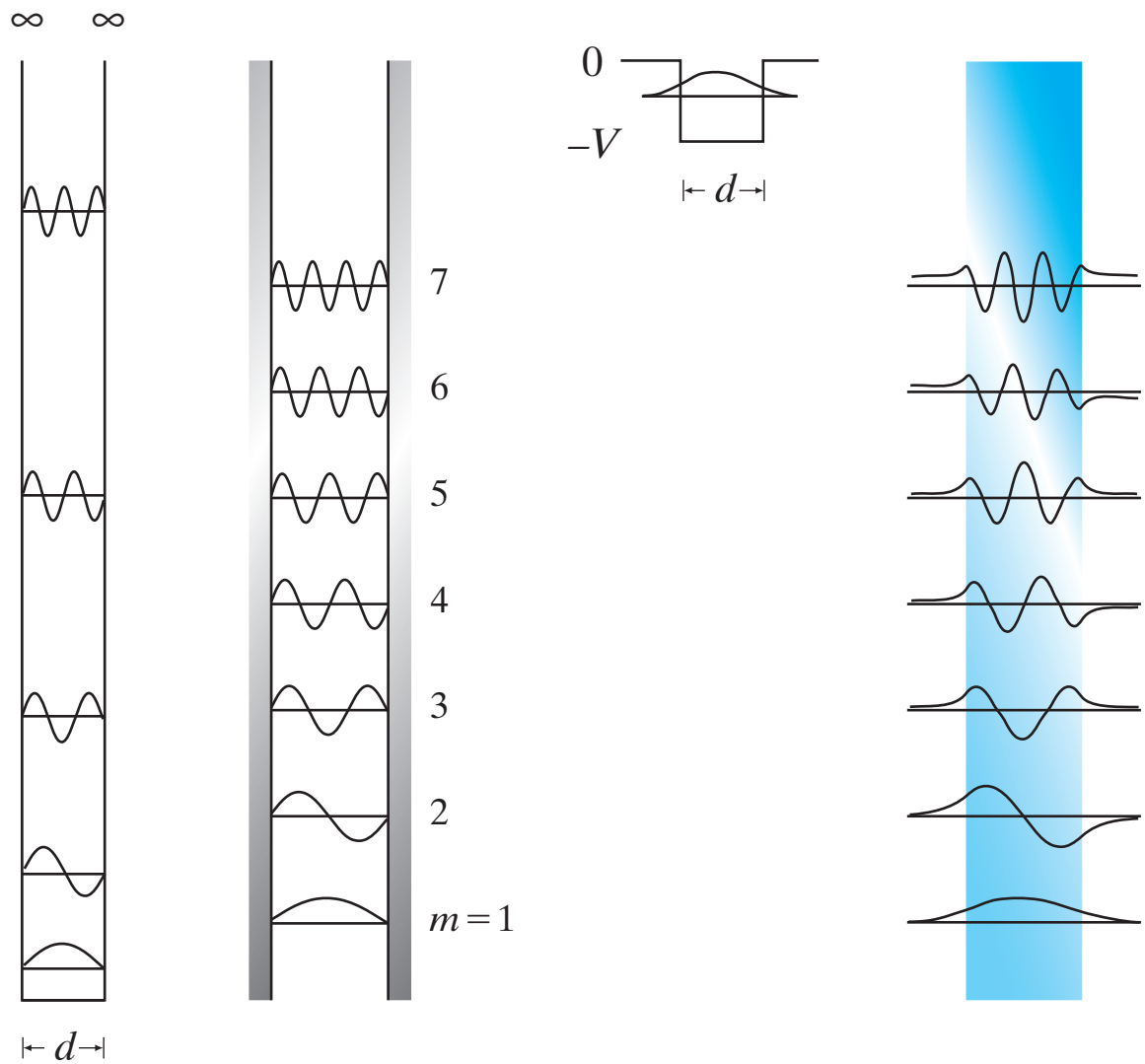
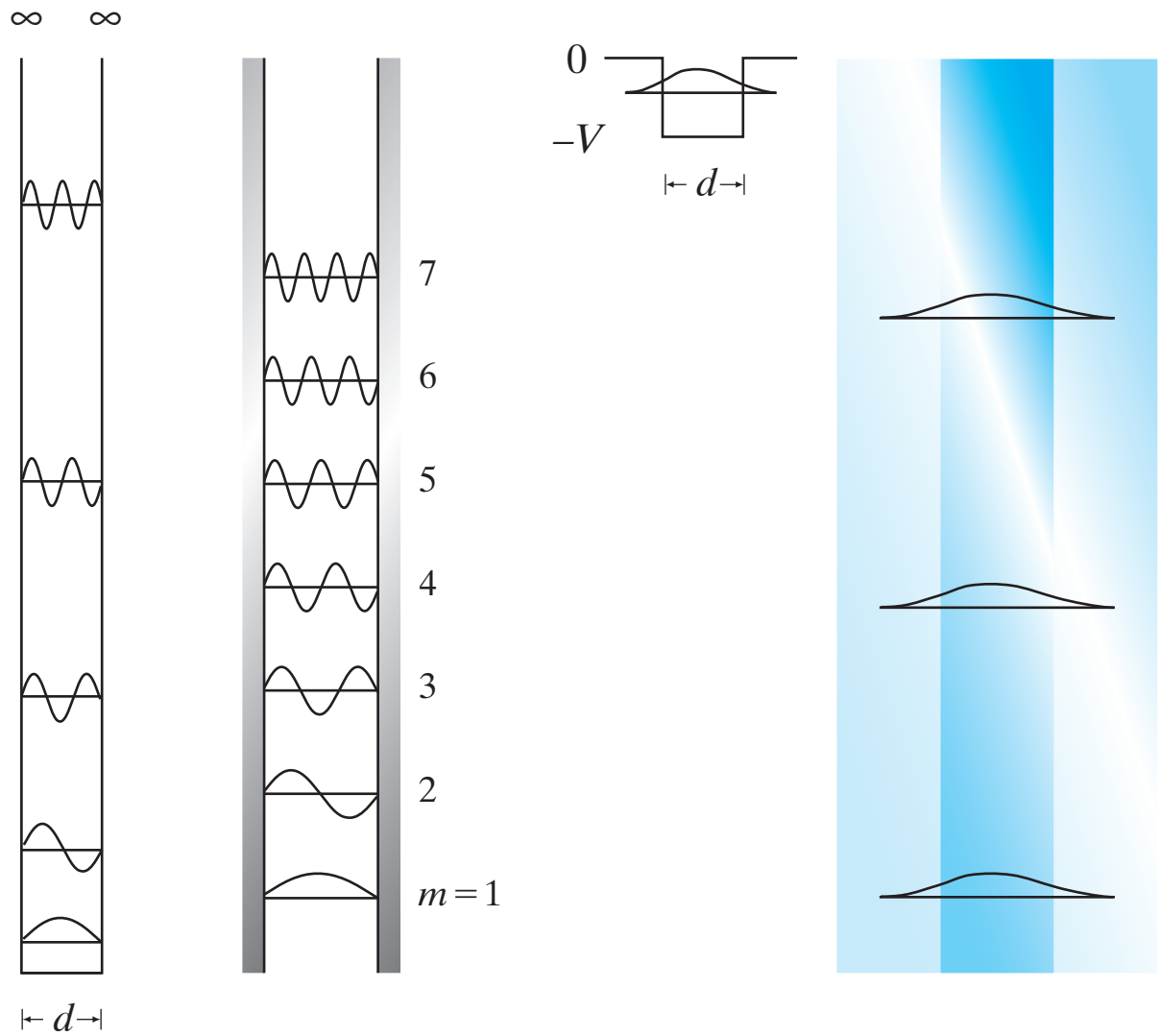


Waveguiding



Waveguiding



Waveguiding

single mode condition for 600-nm light:

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

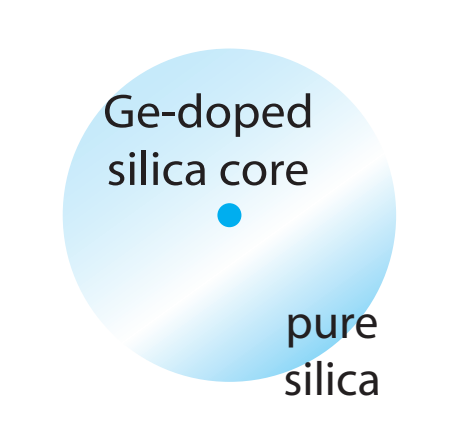
without cladding: $d < 268\ \mathrm{nm}$

Add cladding with 0.4% index difference:

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

Waveguiding

commercial single-mode fiber (Corning Titan®)



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

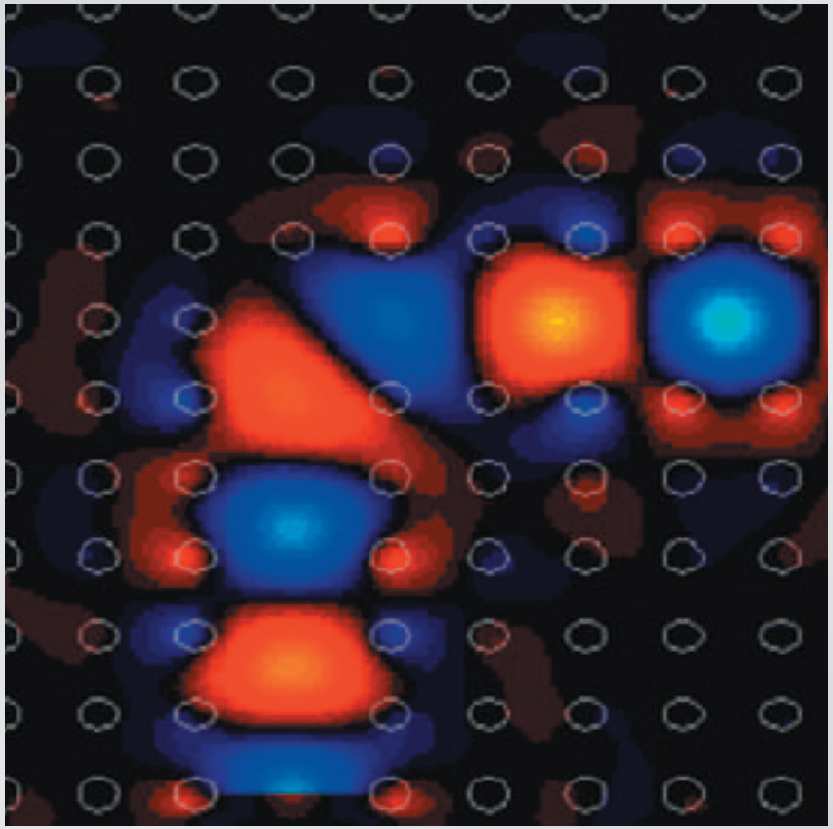
operating wavelength: $\lambda = 1310\ \text{nm}/1550\ \text{nm}$

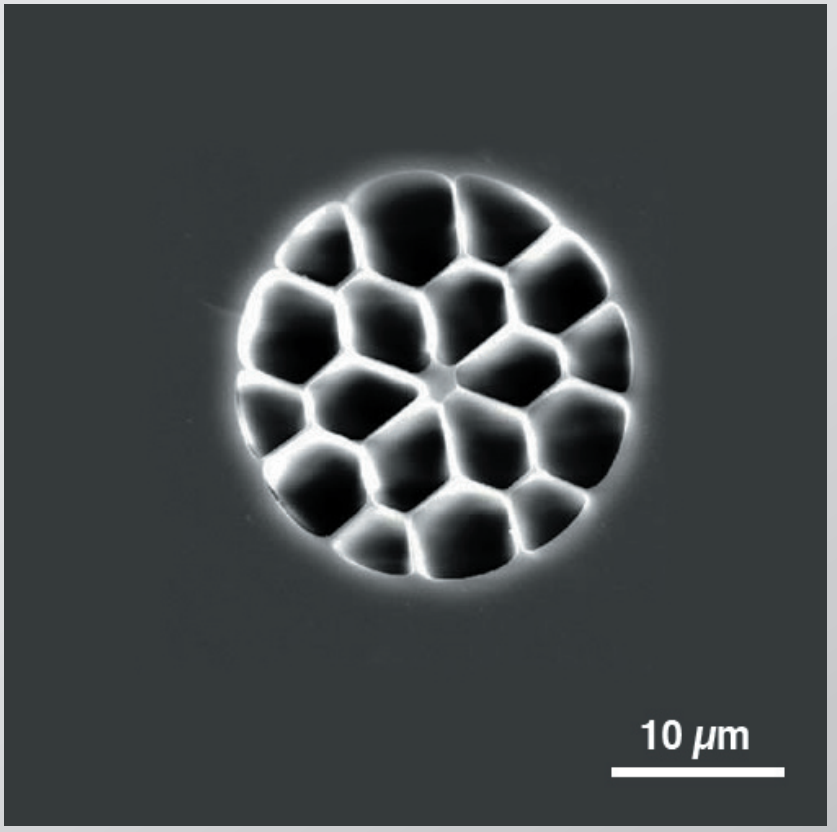
Waveguiding

drawbacks of clad fibers:

- weak confinement
- no tight bending
- coupling requires splicing

Waveguiding



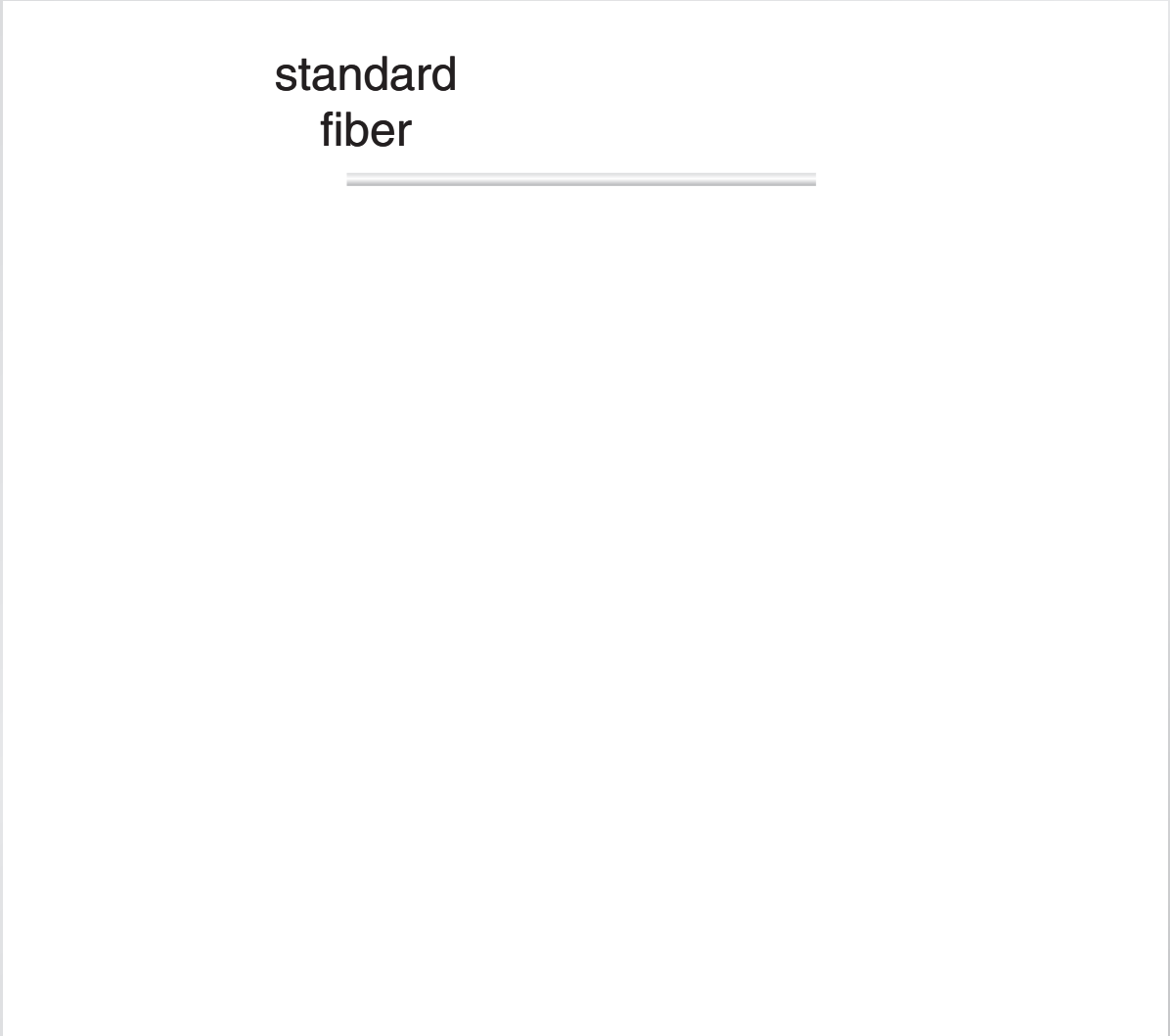


Outline

- waveguiding
- nanowire fabrication
- optical properties

Nanowire fabrication

two-step drawing process



Nanowire fabrication

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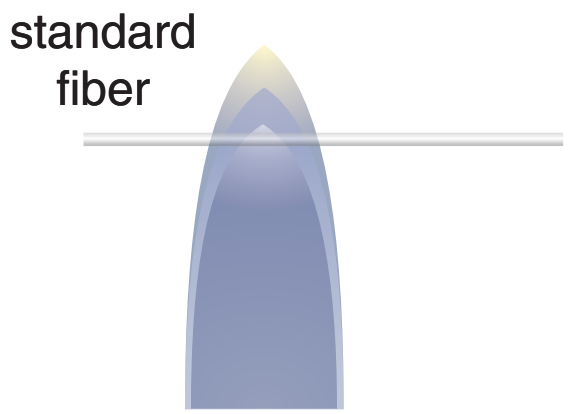

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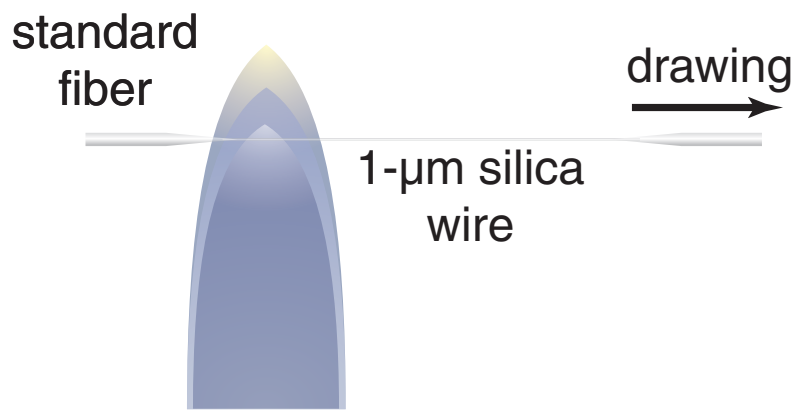

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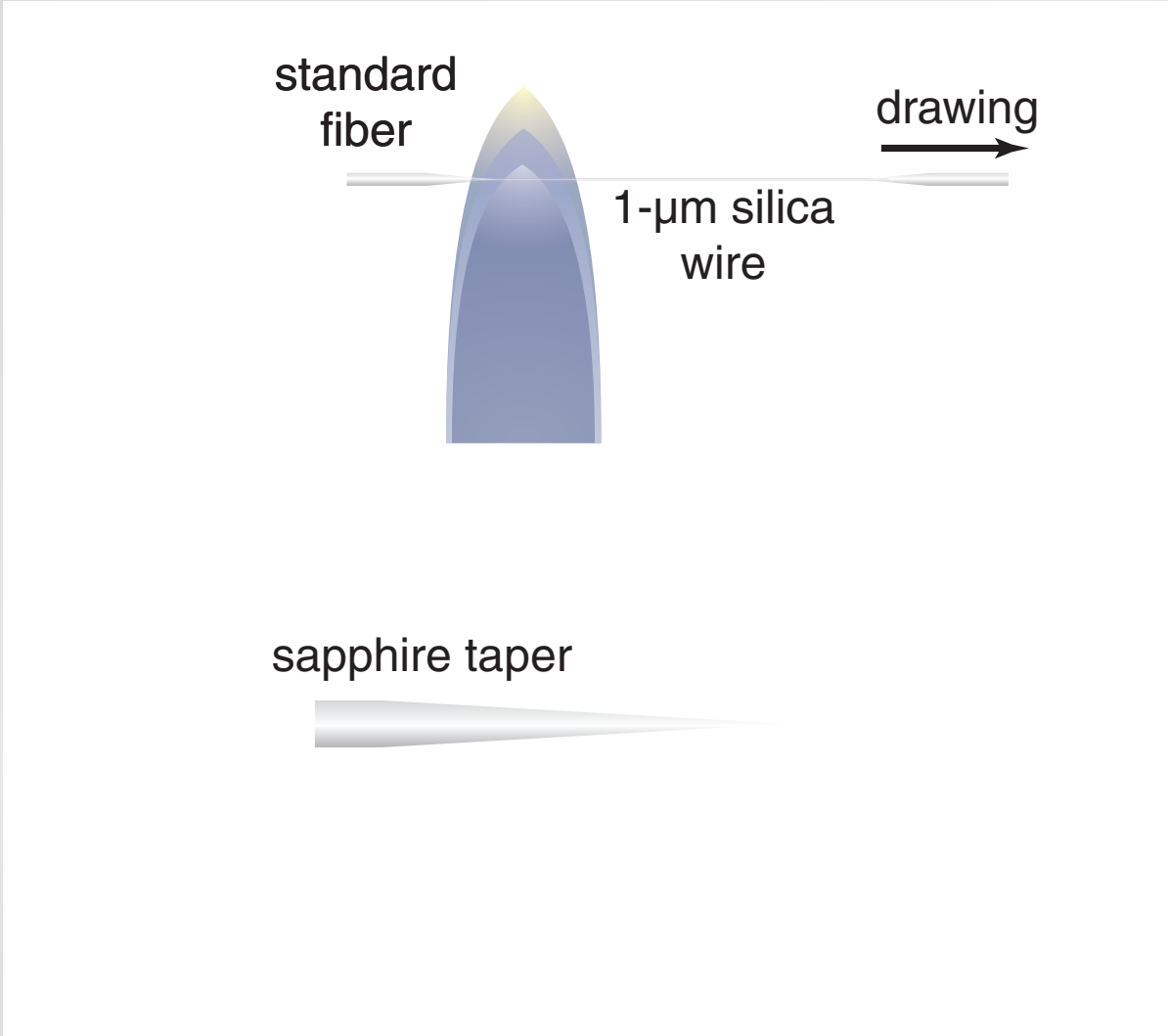

Nanowire fabrication

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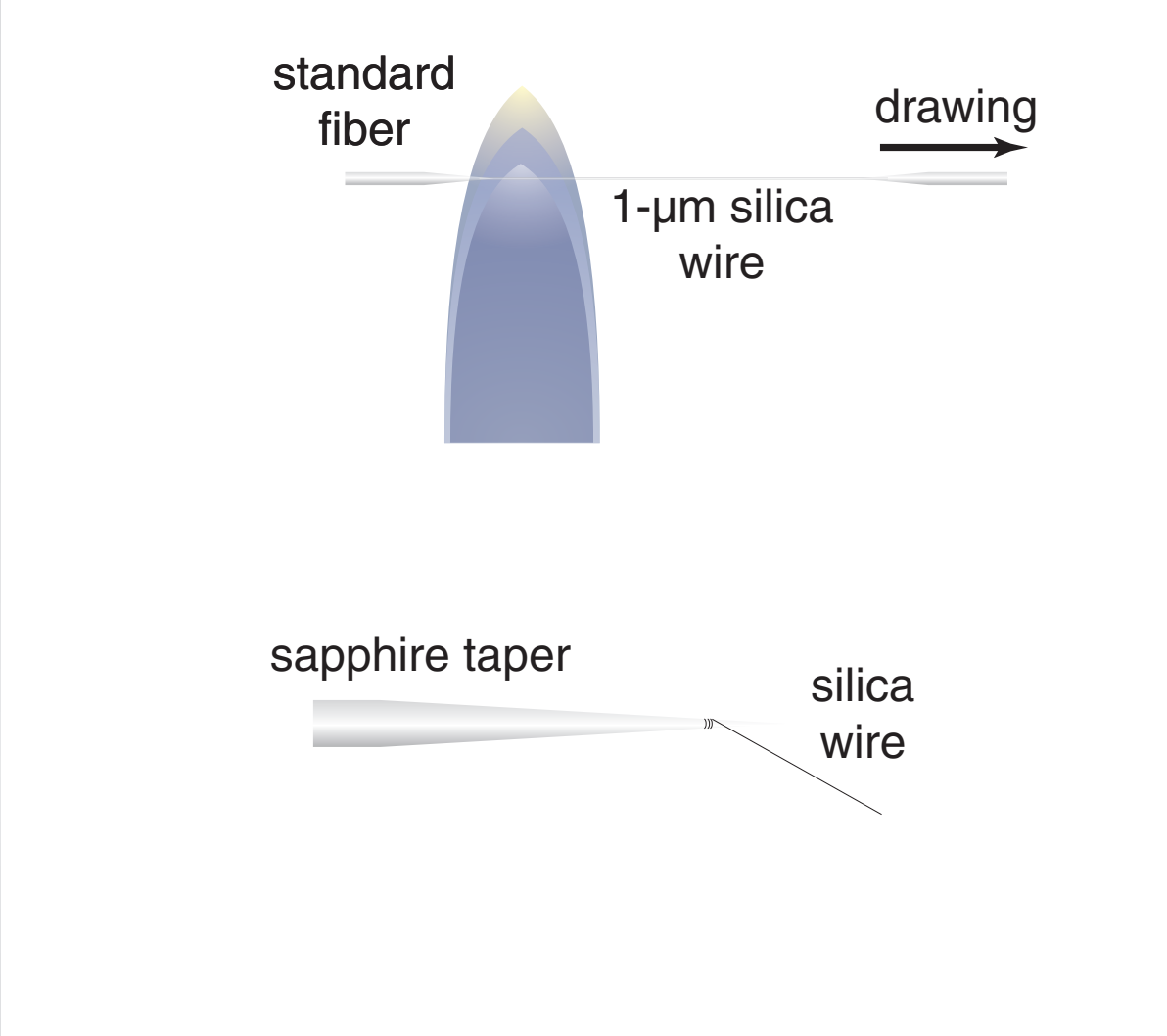

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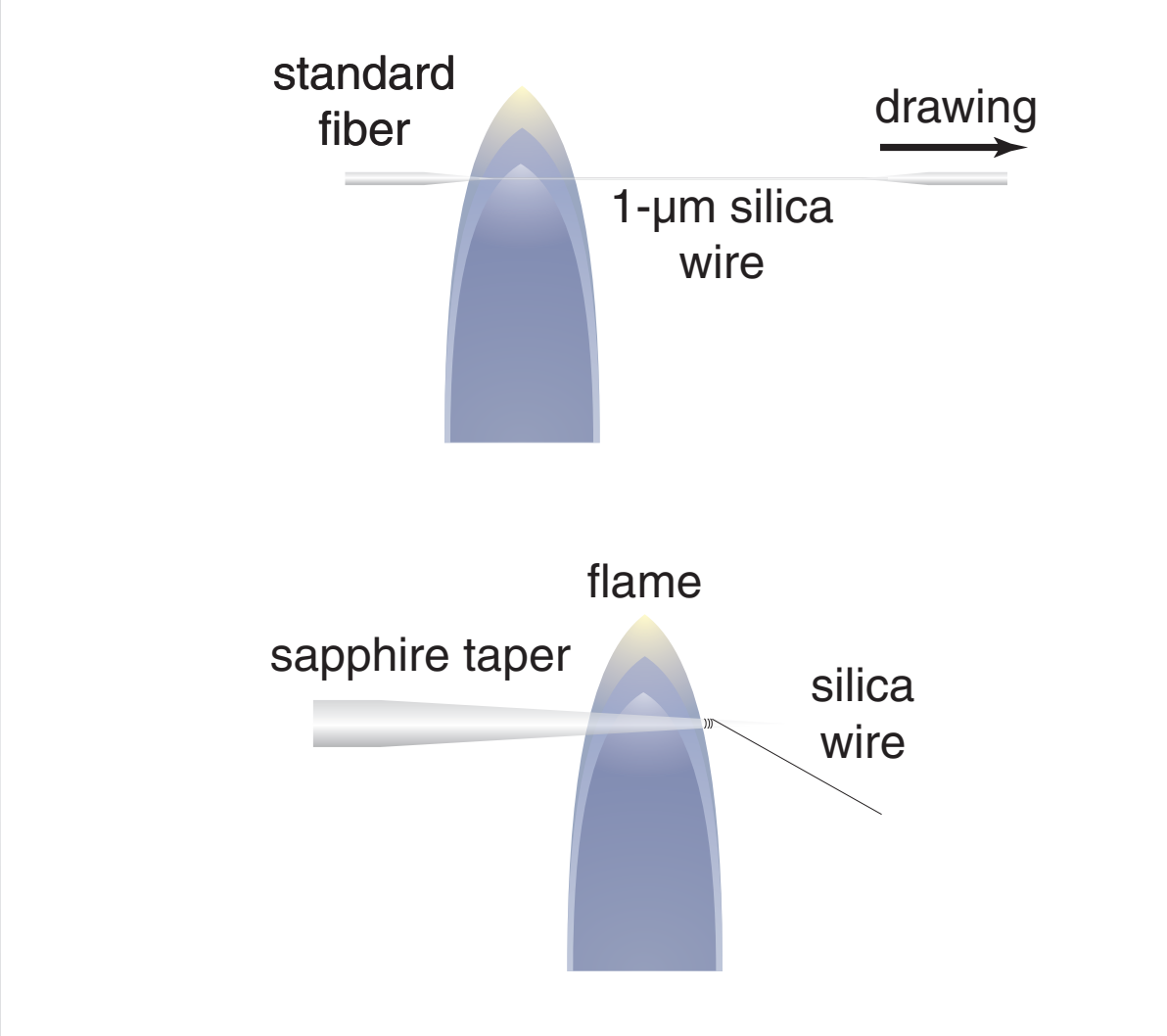

Nanowire fabrication

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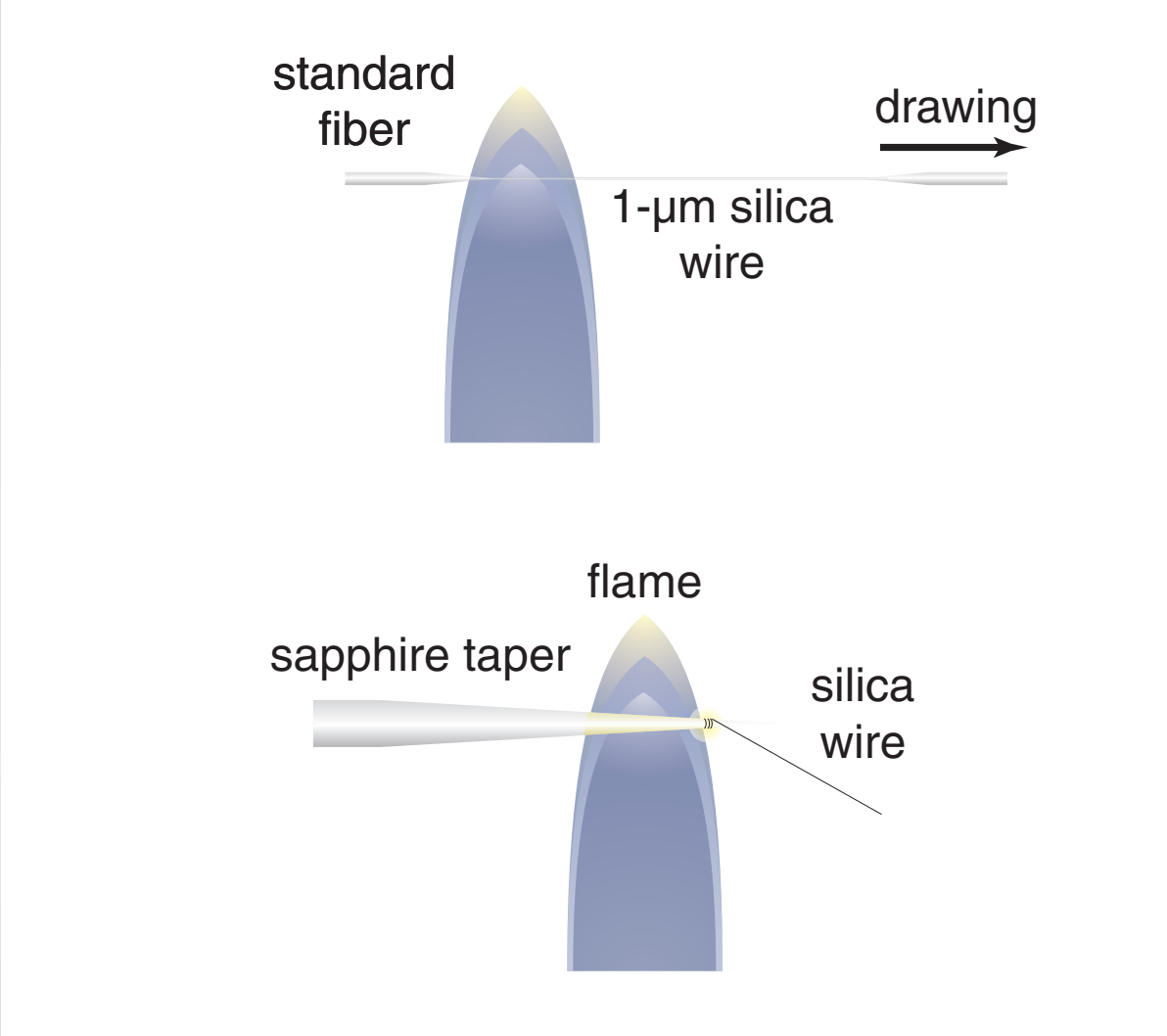

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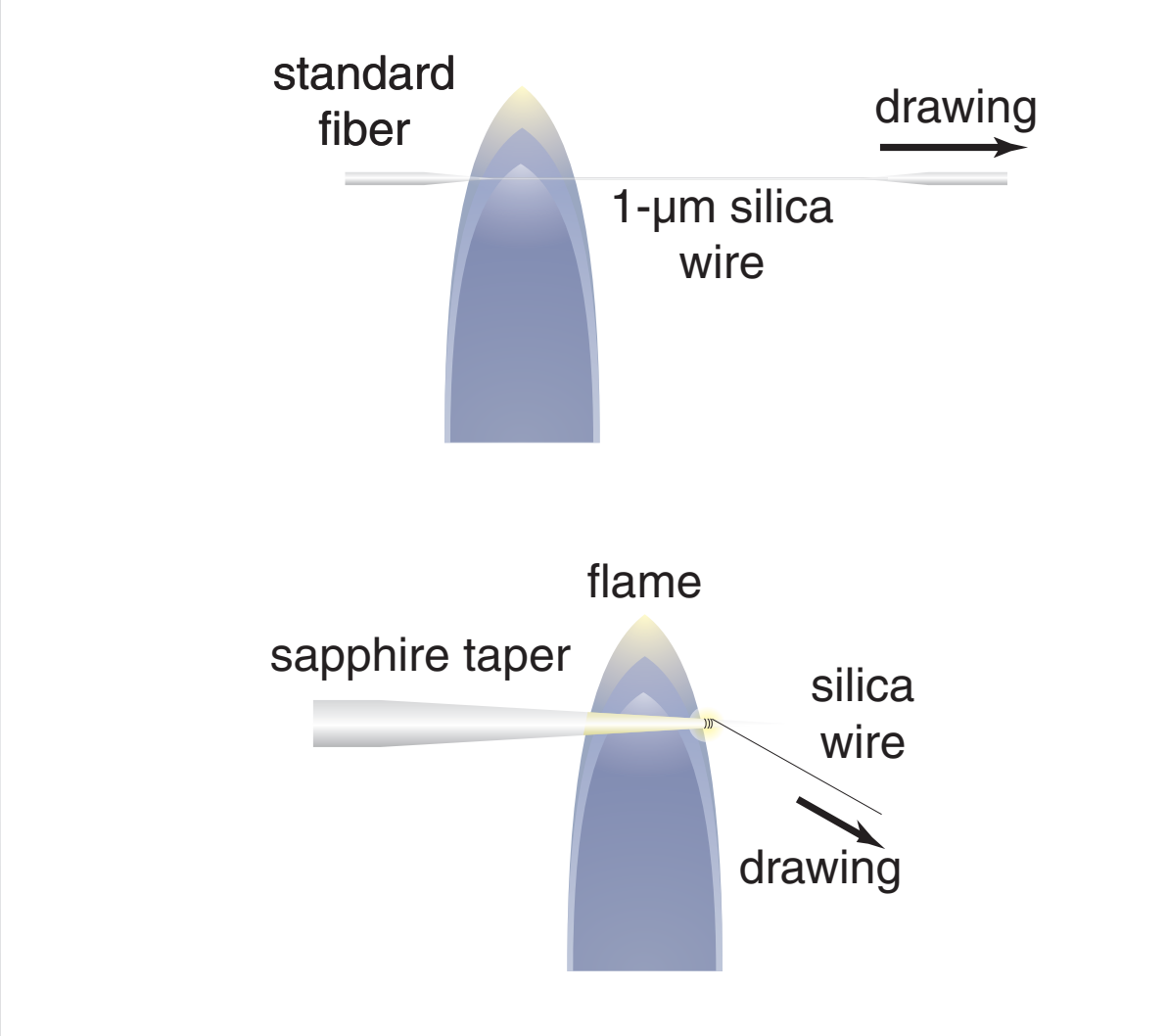

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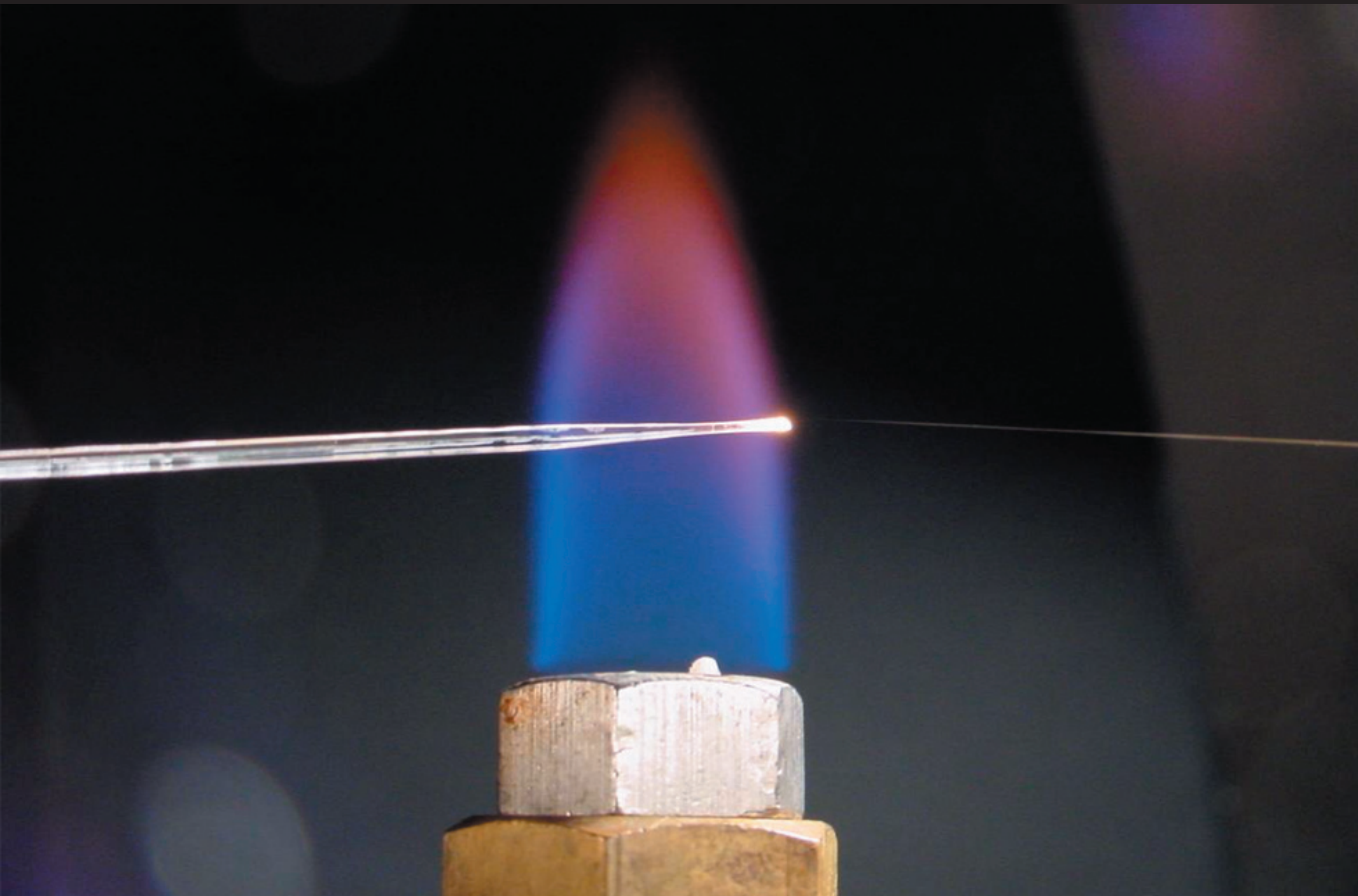

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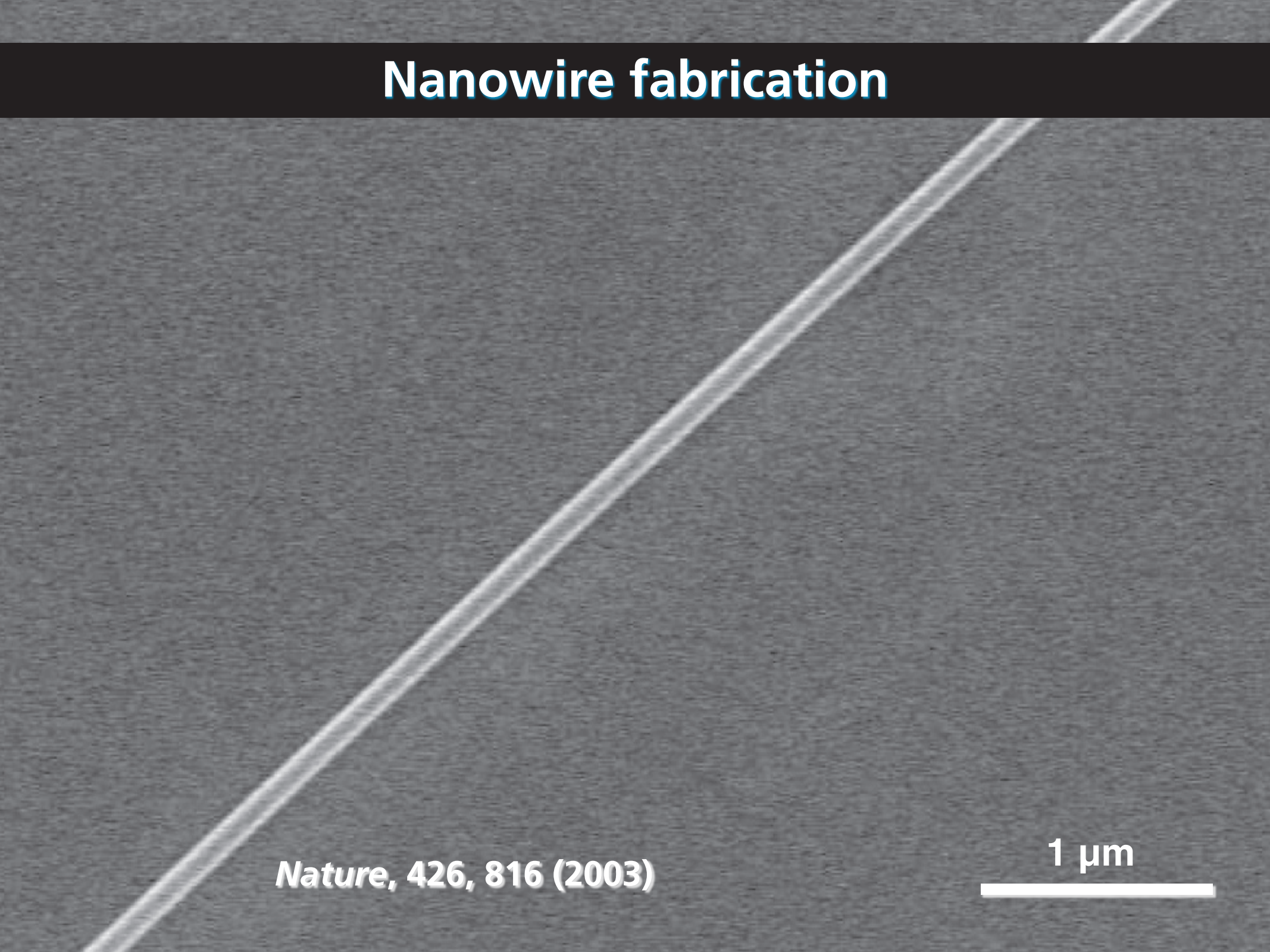
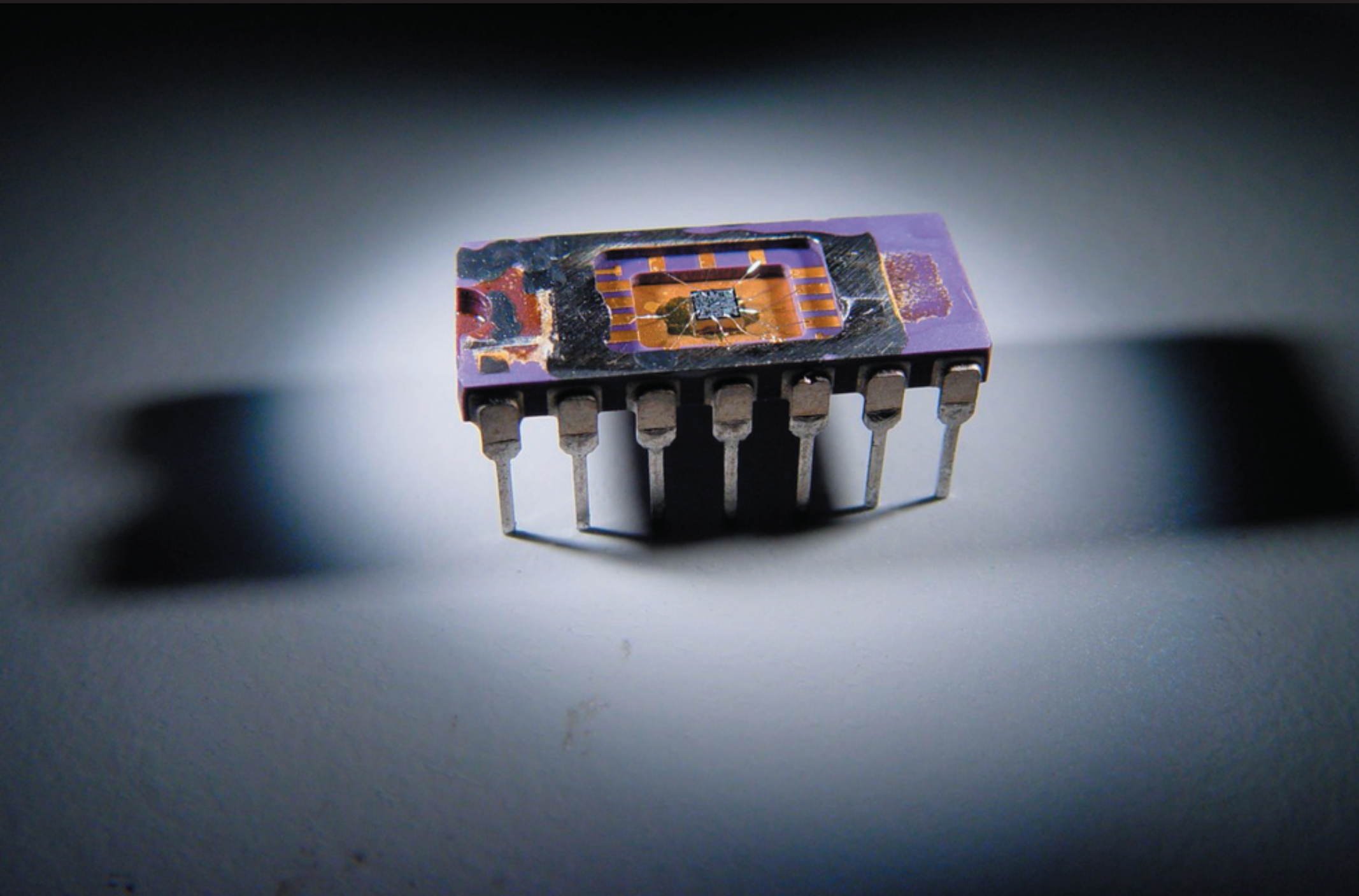
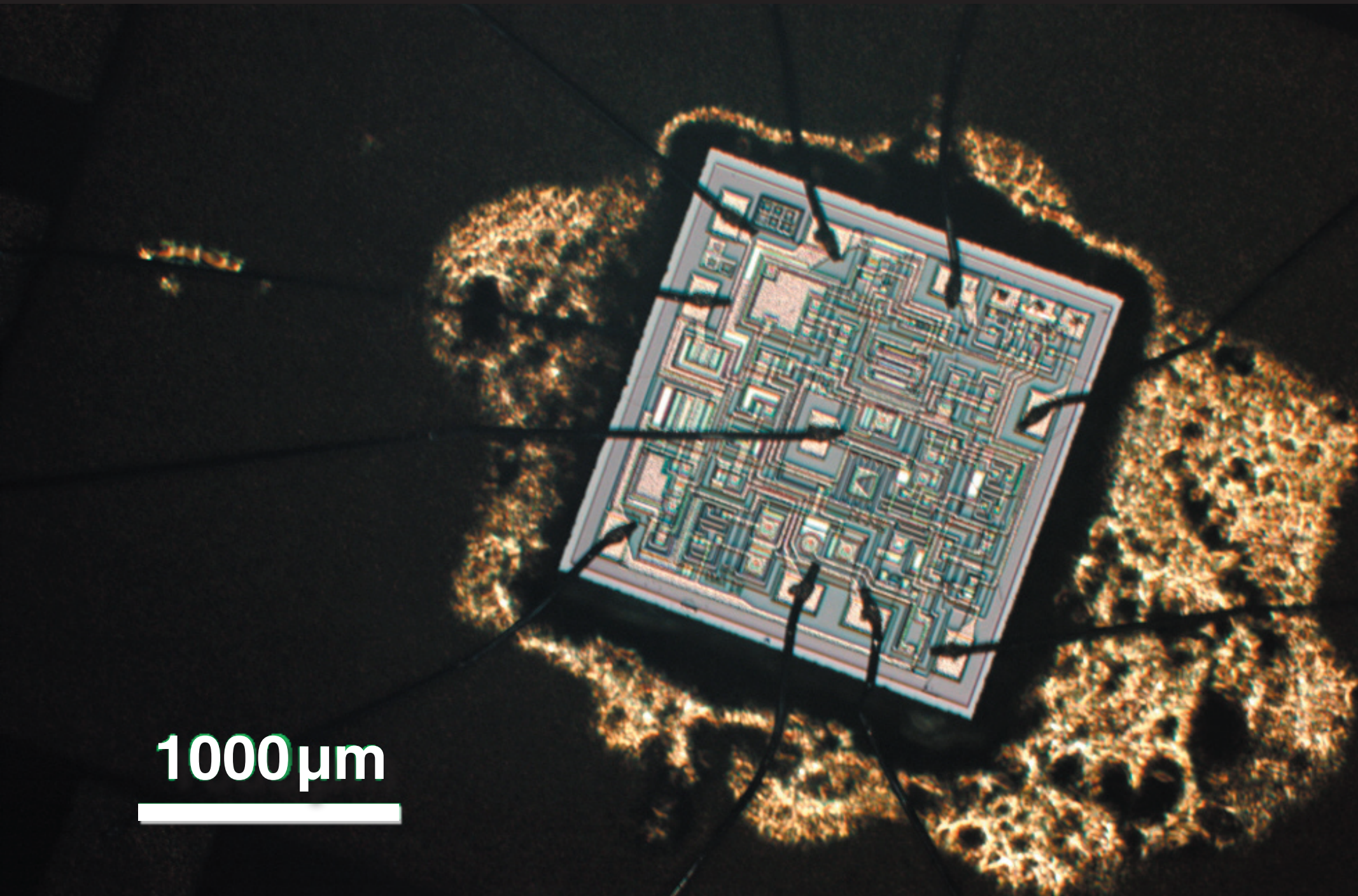


Nature, 426, 816 (2003)

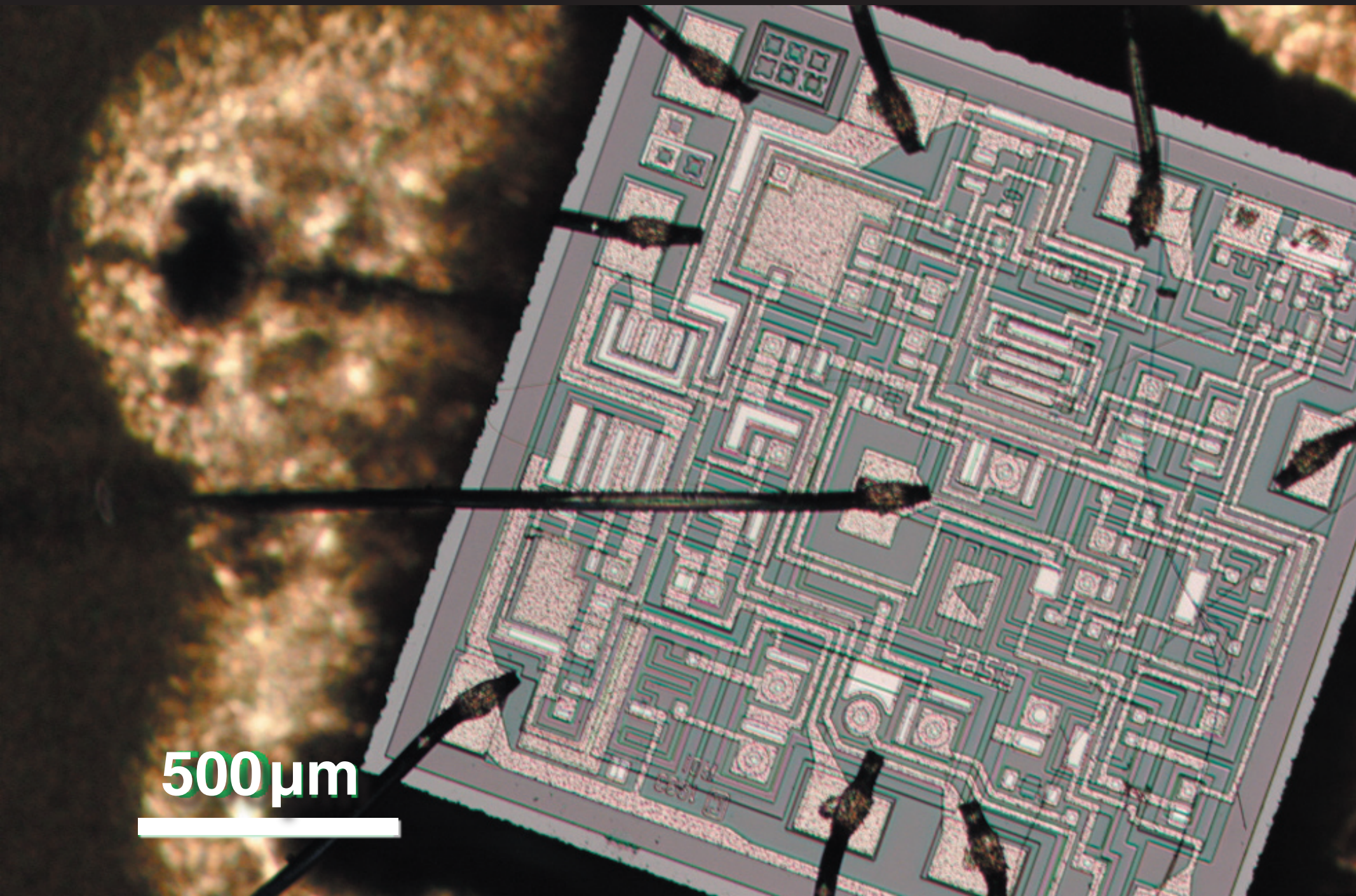
Nanowire fabrication



Nanowire fabrication



Nanowire fabrication



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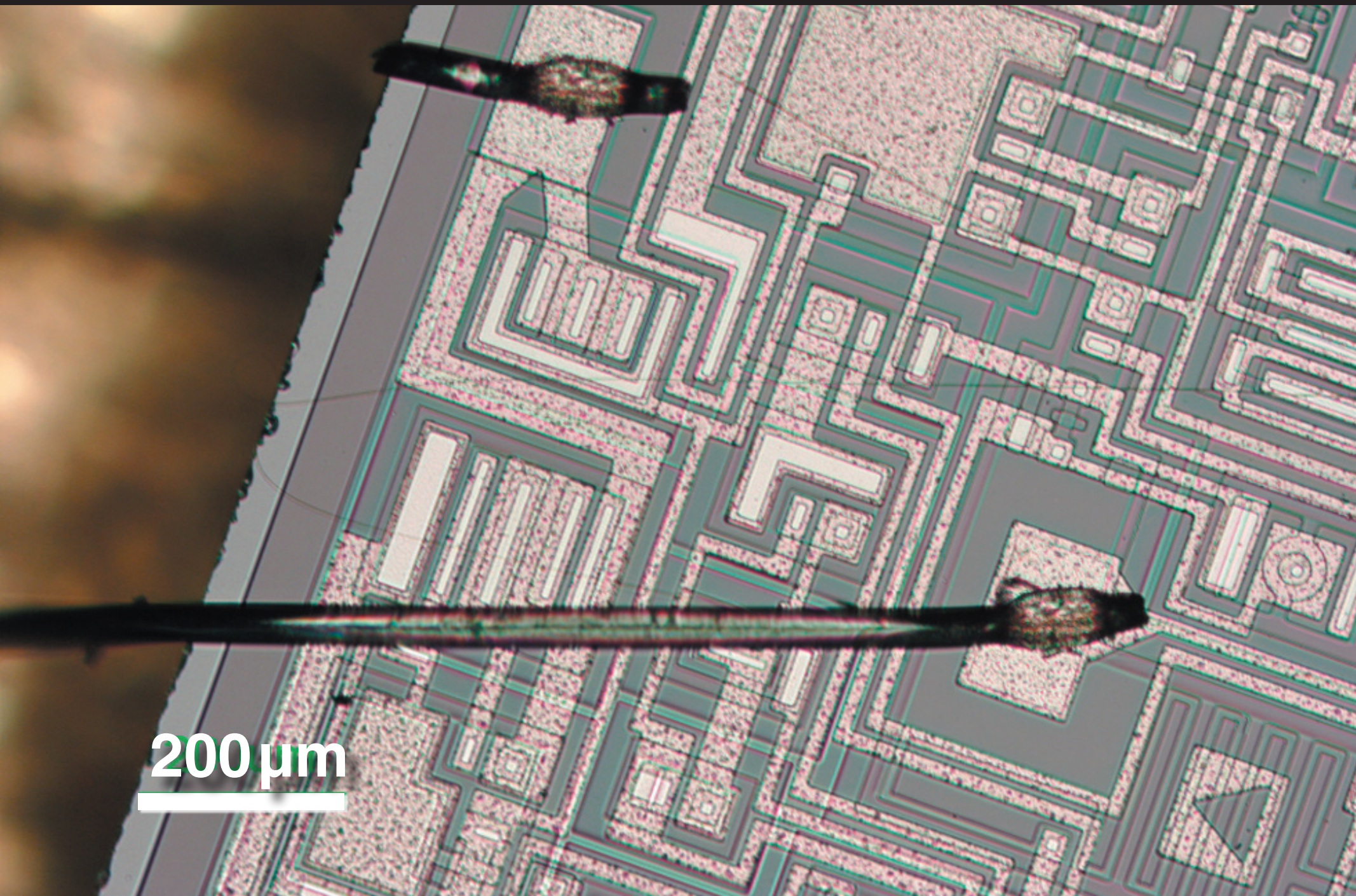

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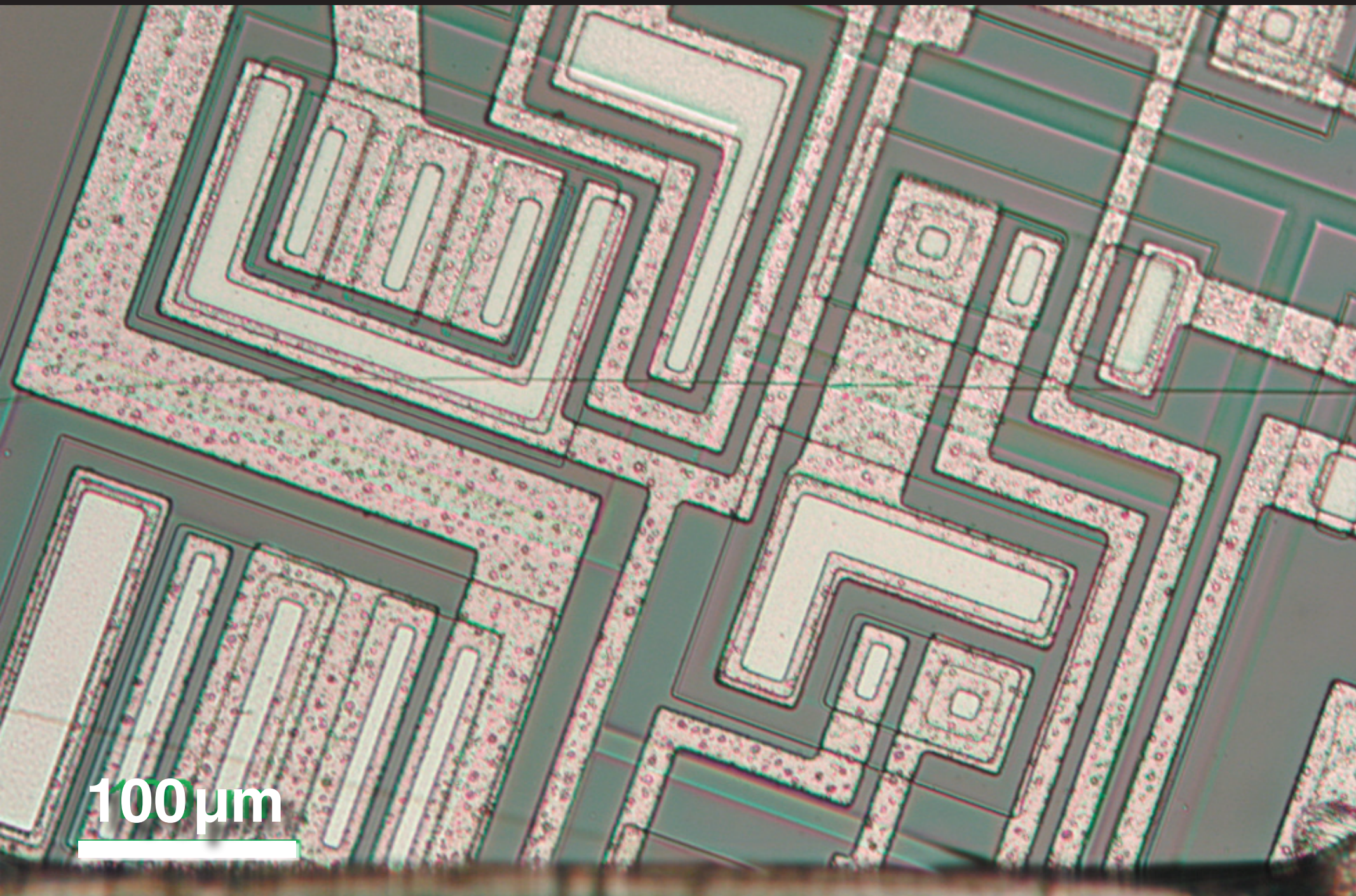

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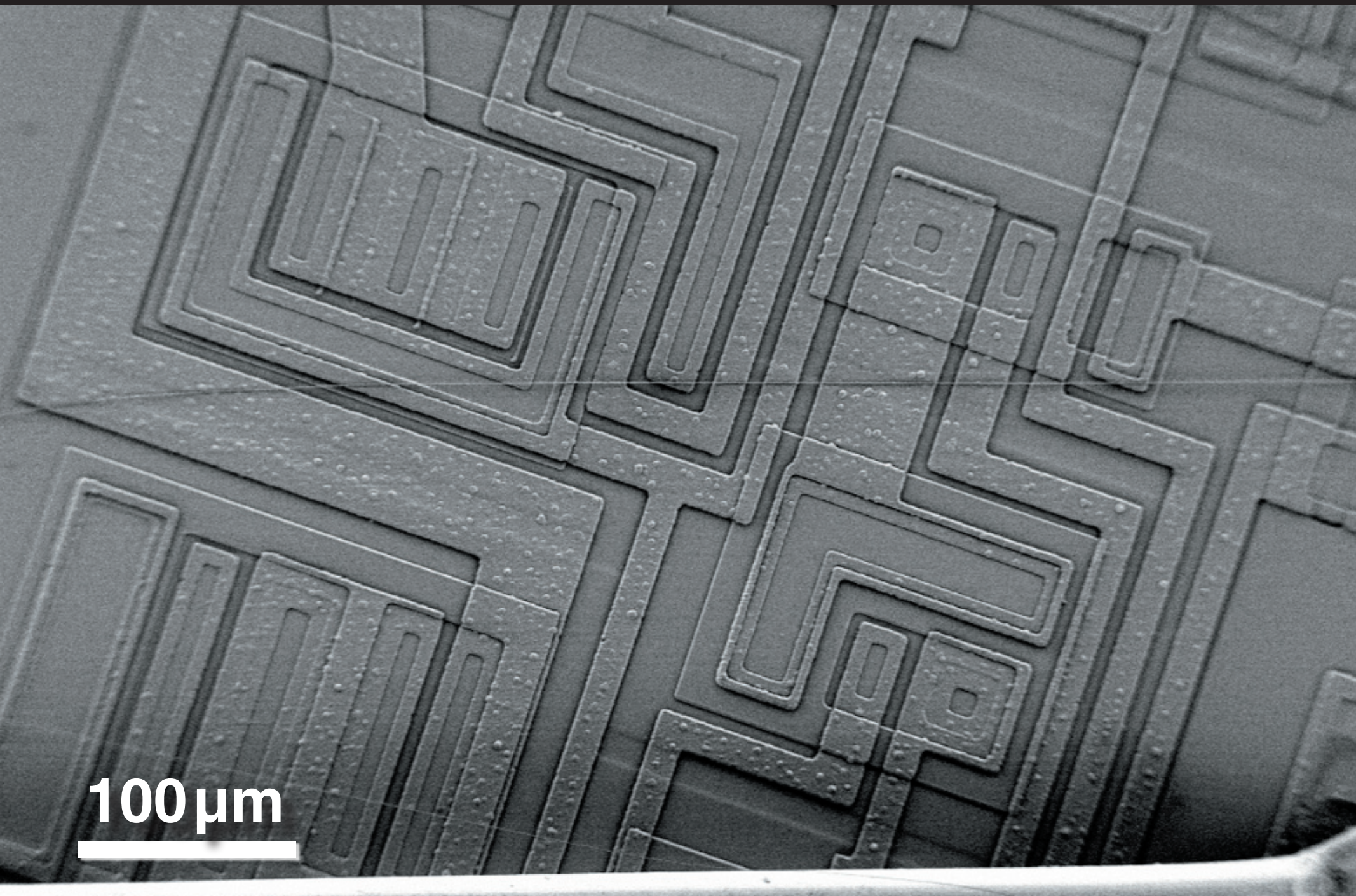

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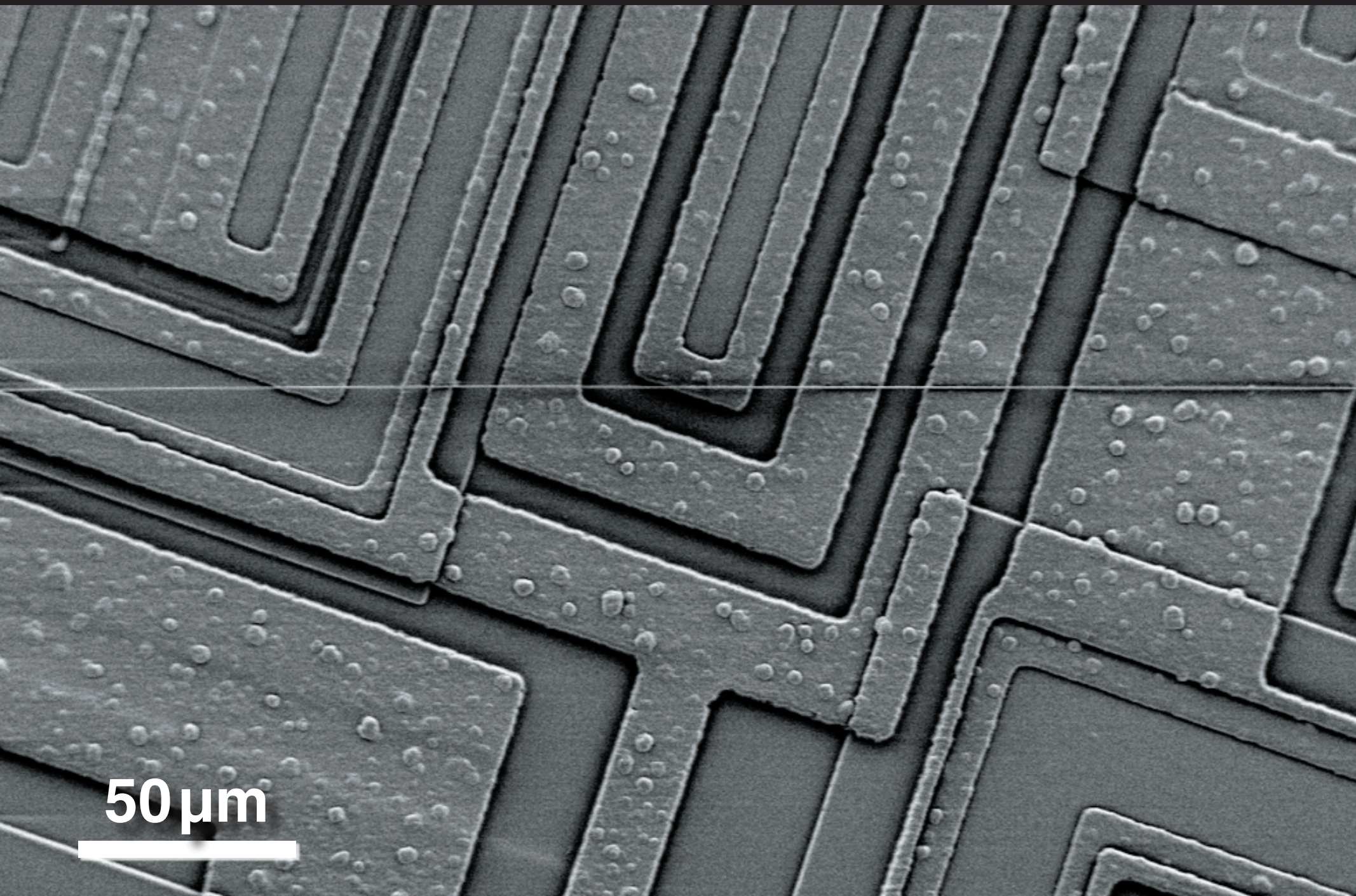
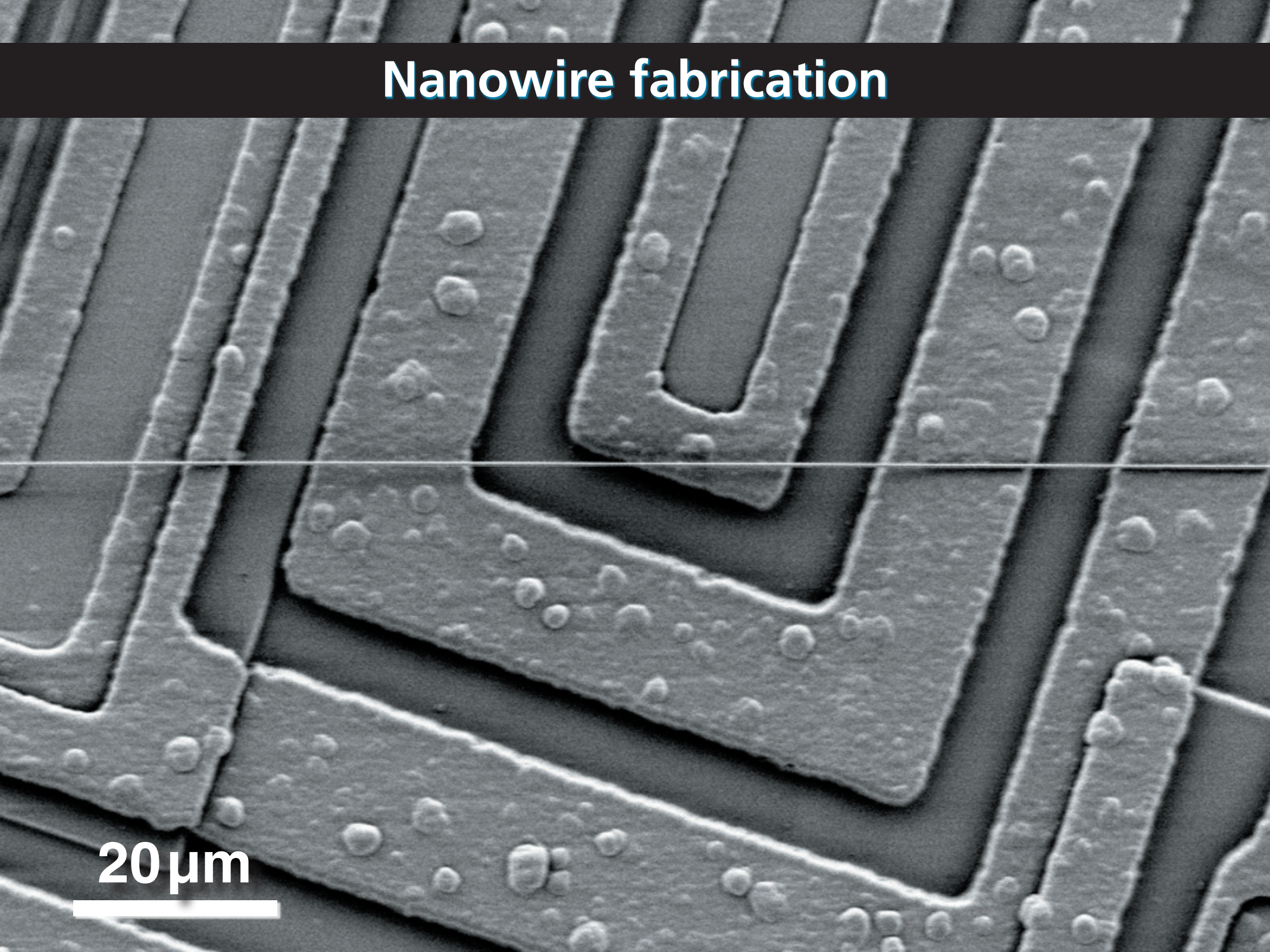


Nanowire fabrication



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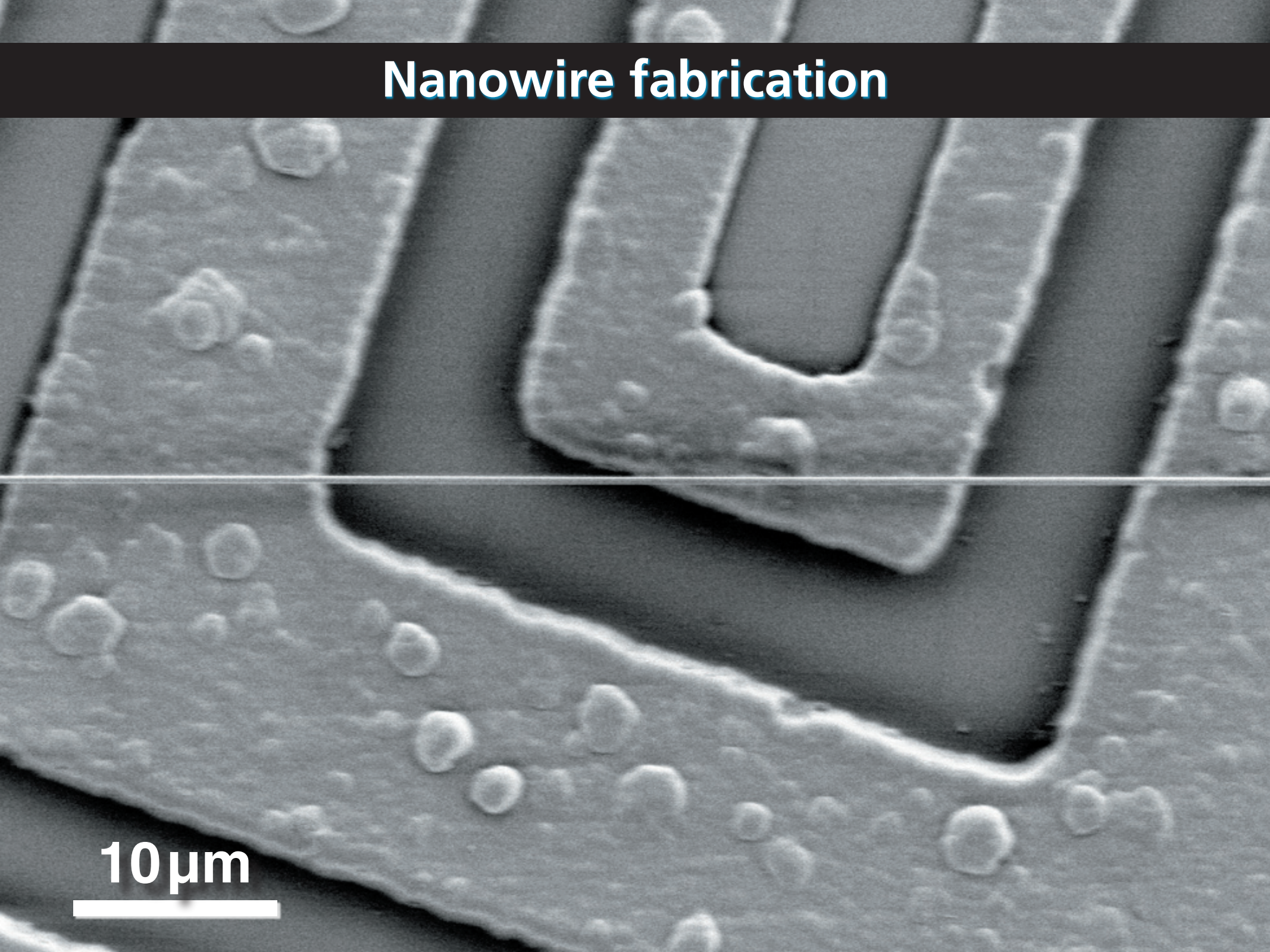
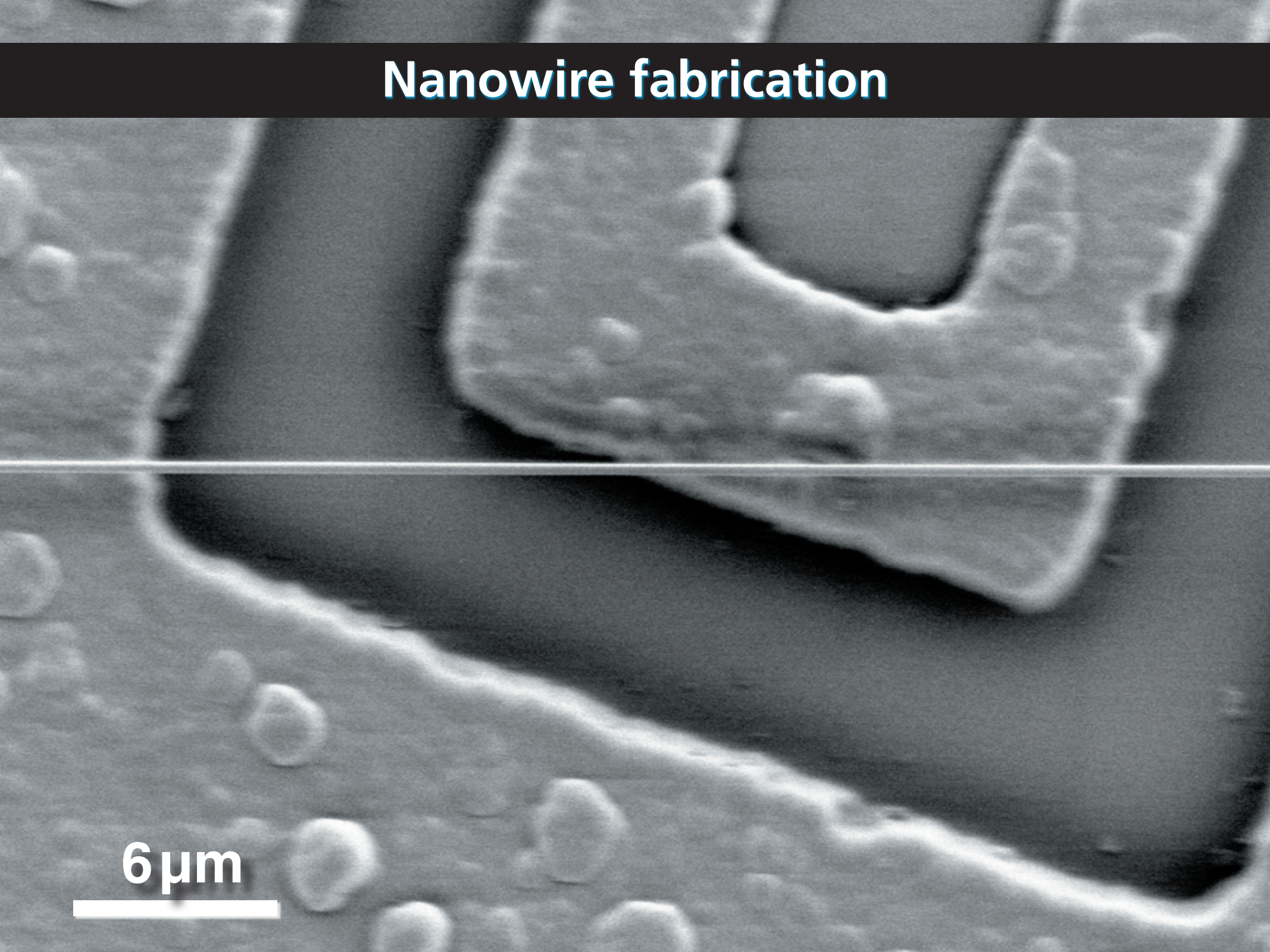


Nanowire fabrication



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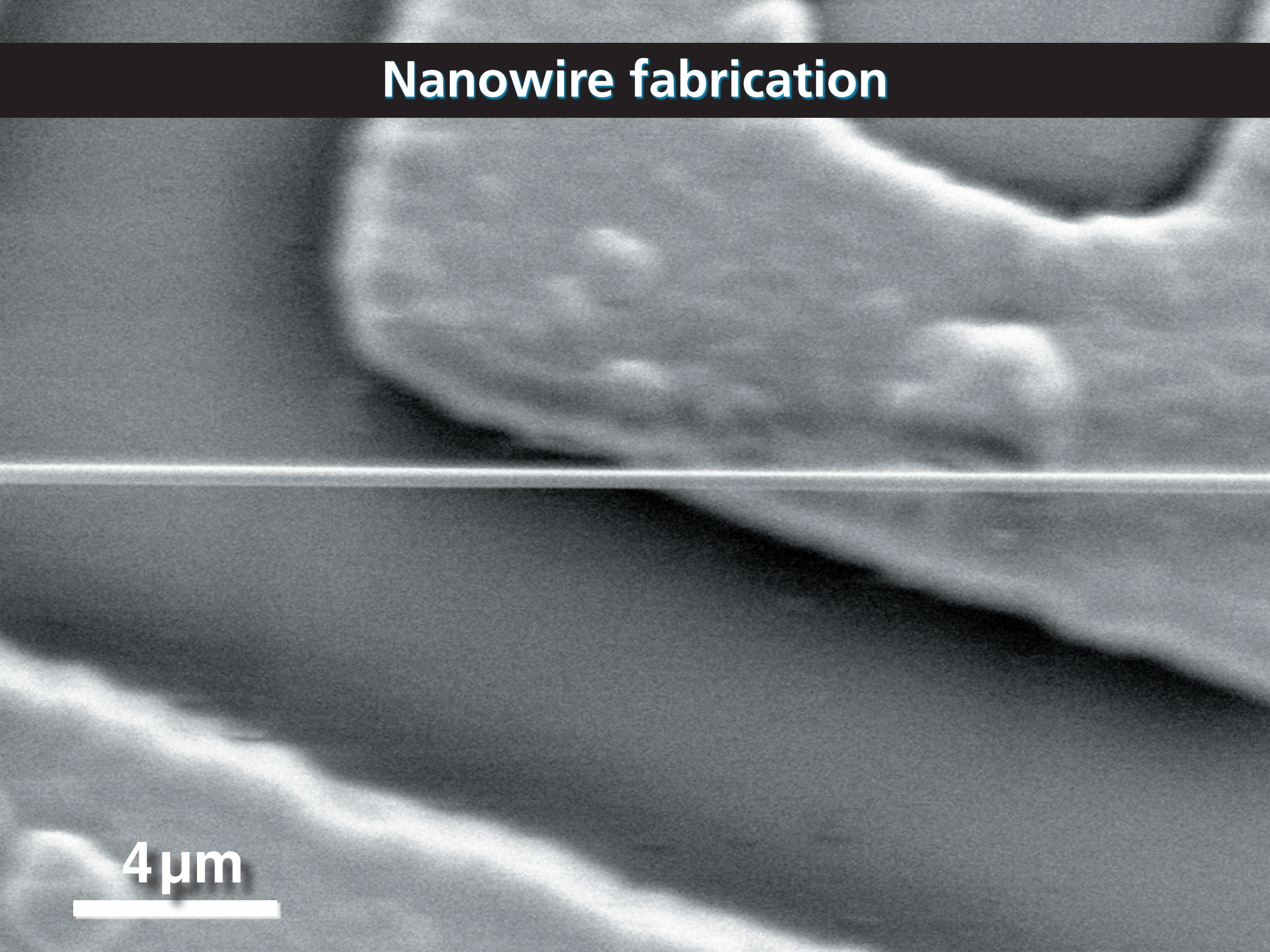

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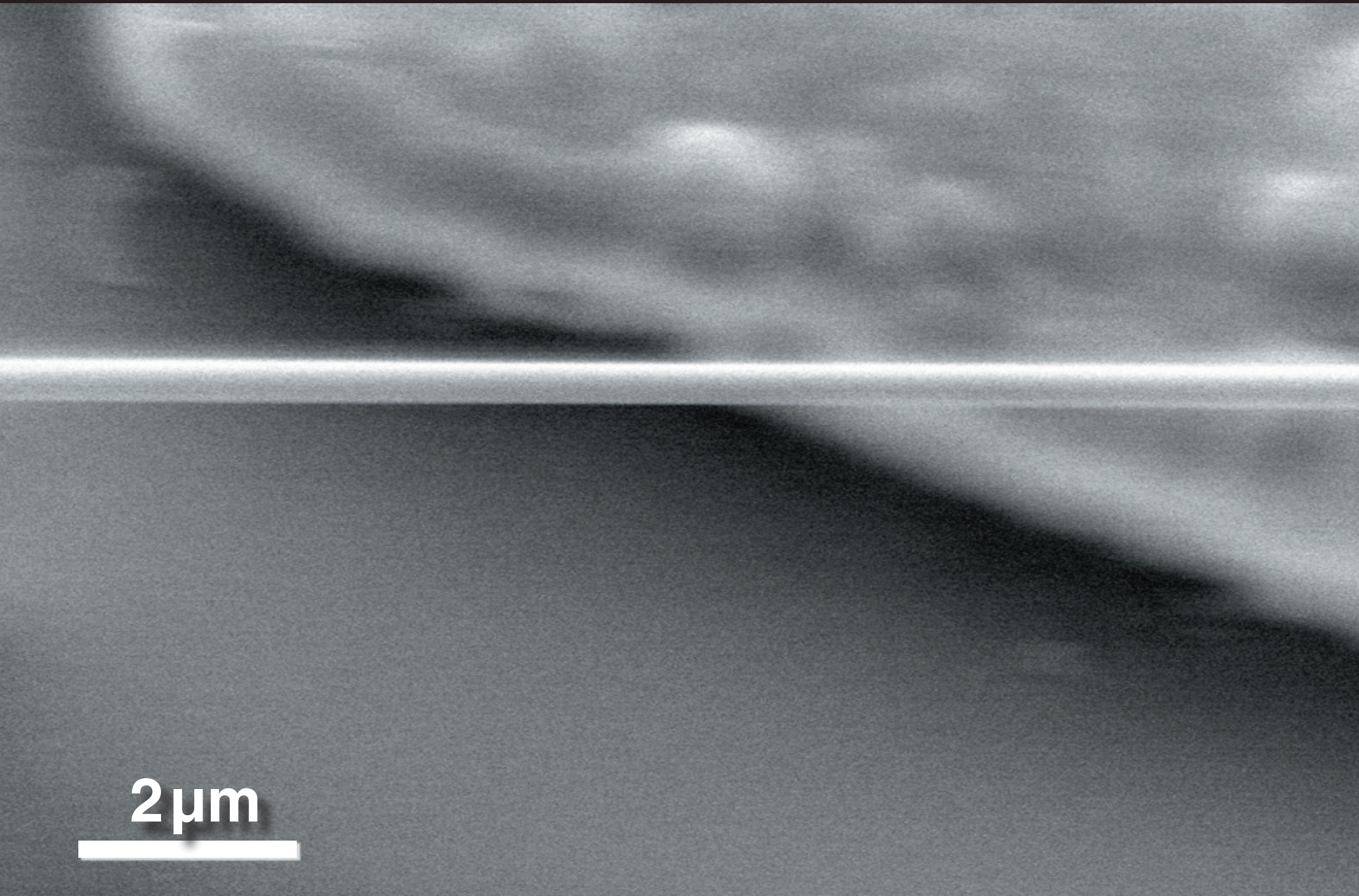

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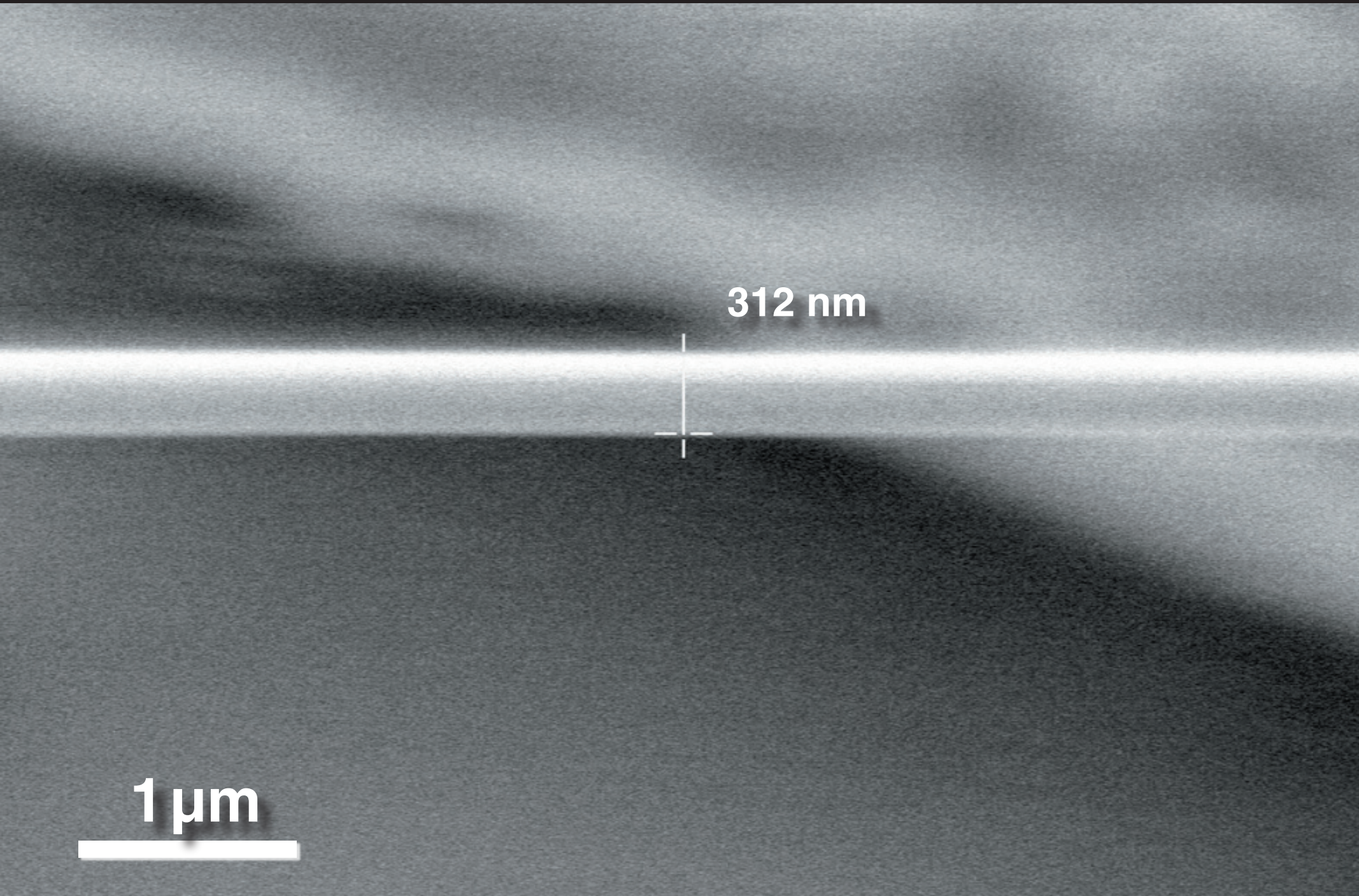


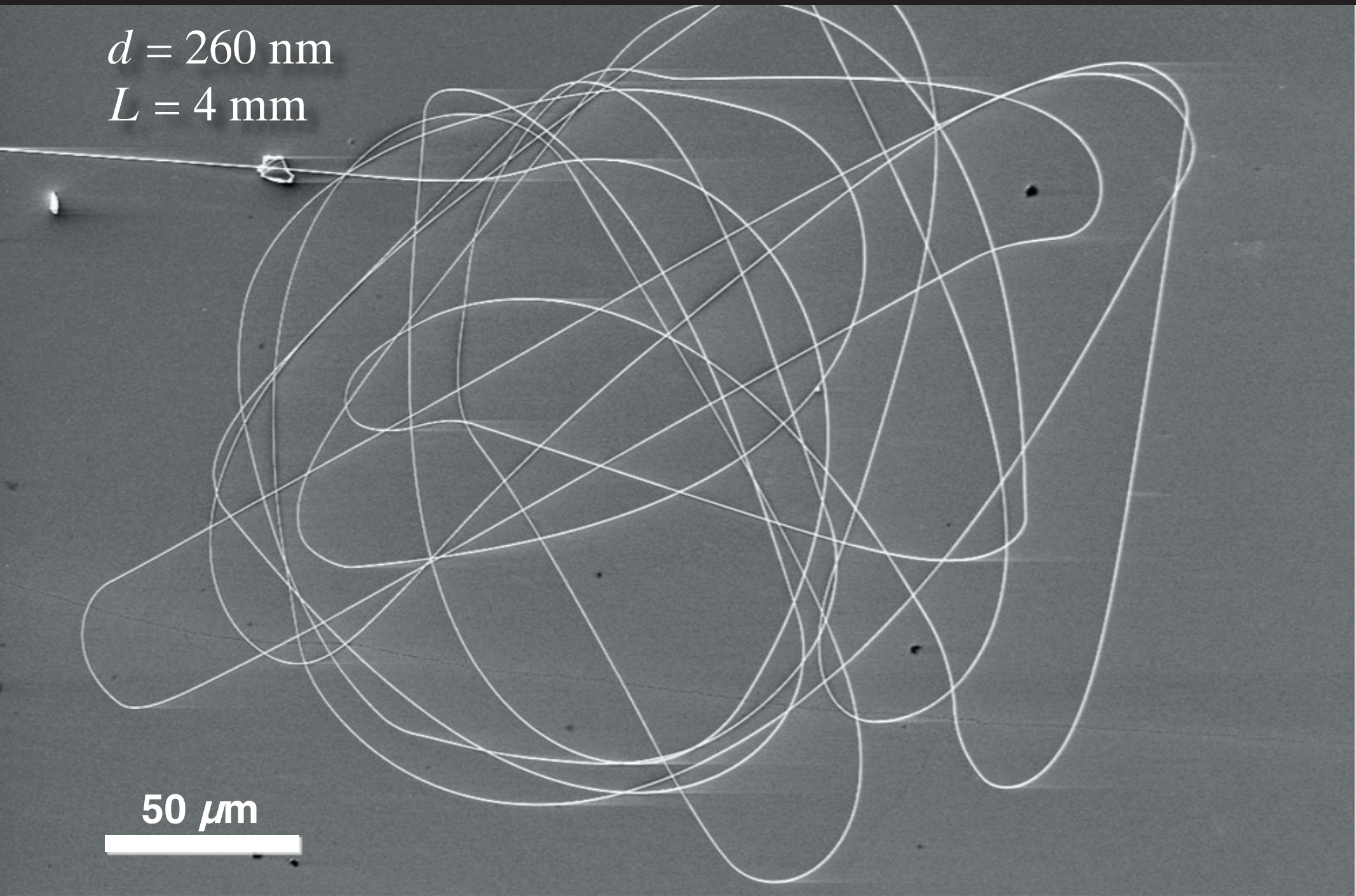
Waveguiding

Specifications

diameter D:	down to 50 nm
length L:	up to 40 mm
aspect ratio D/L:	up to 2×10^5
diameter uniformity $\Delta D/L$:	2×10^{-6}

Nature, 426, 816 (2003)

Nanowire fabrication



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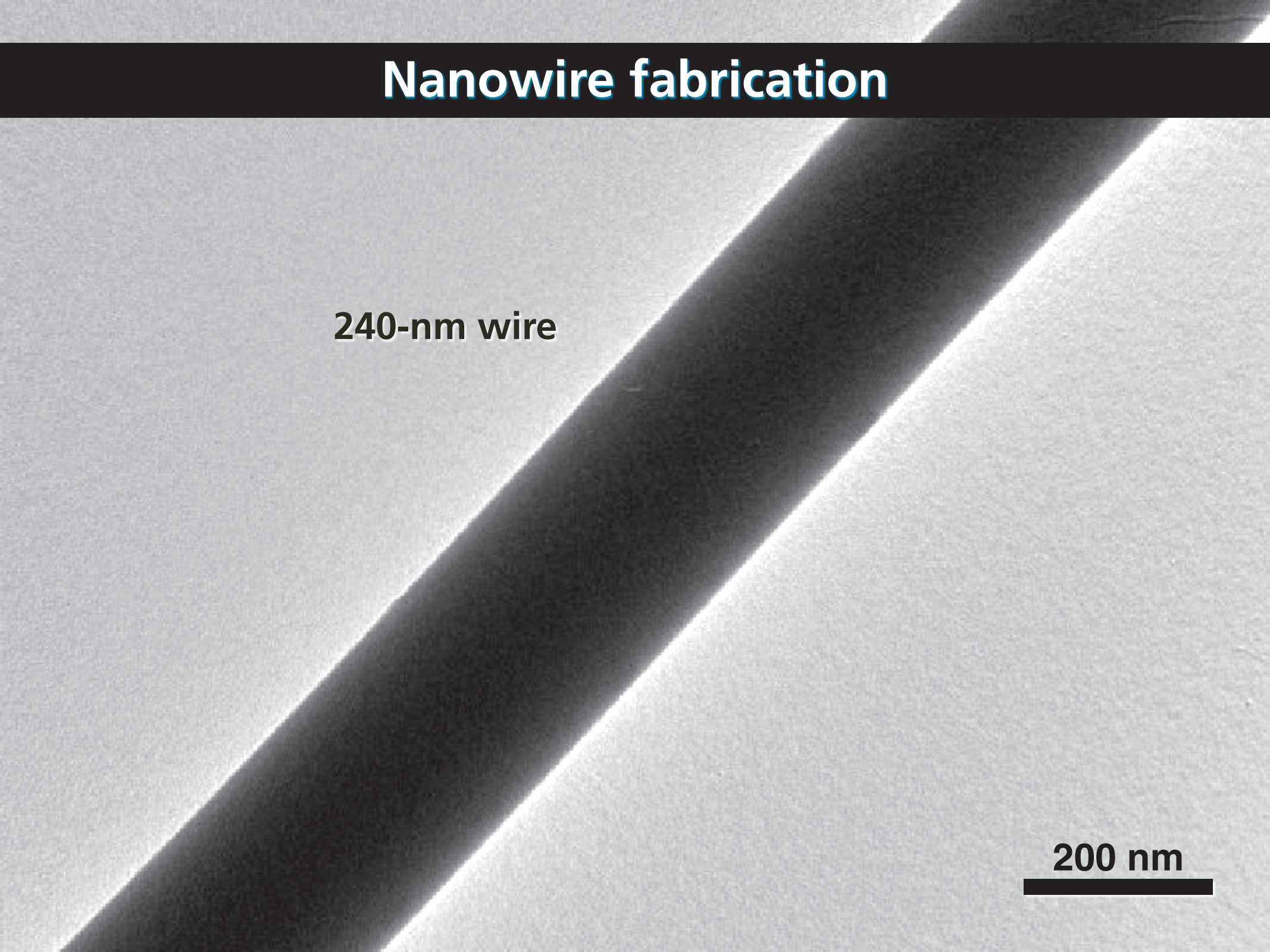

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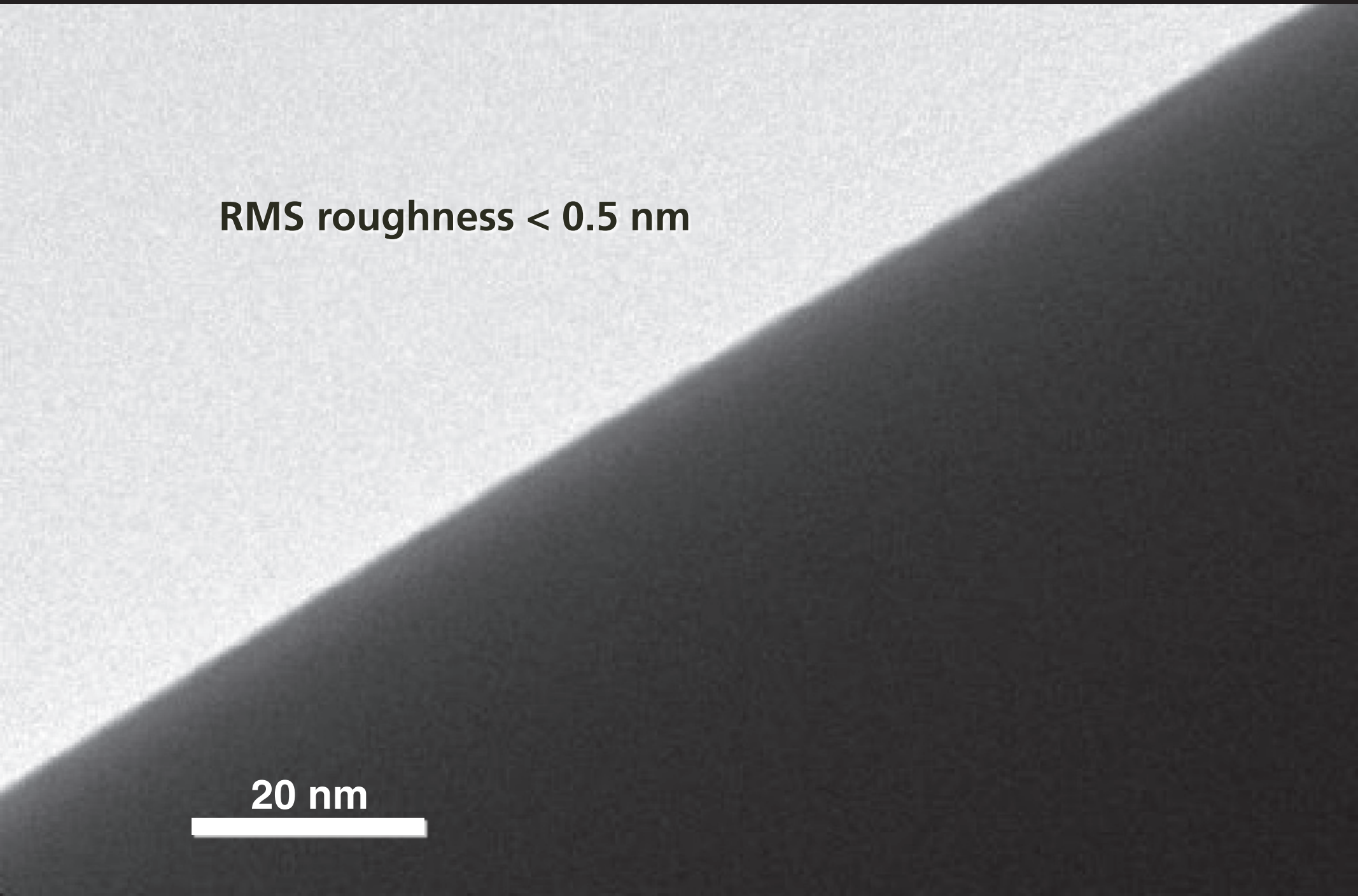

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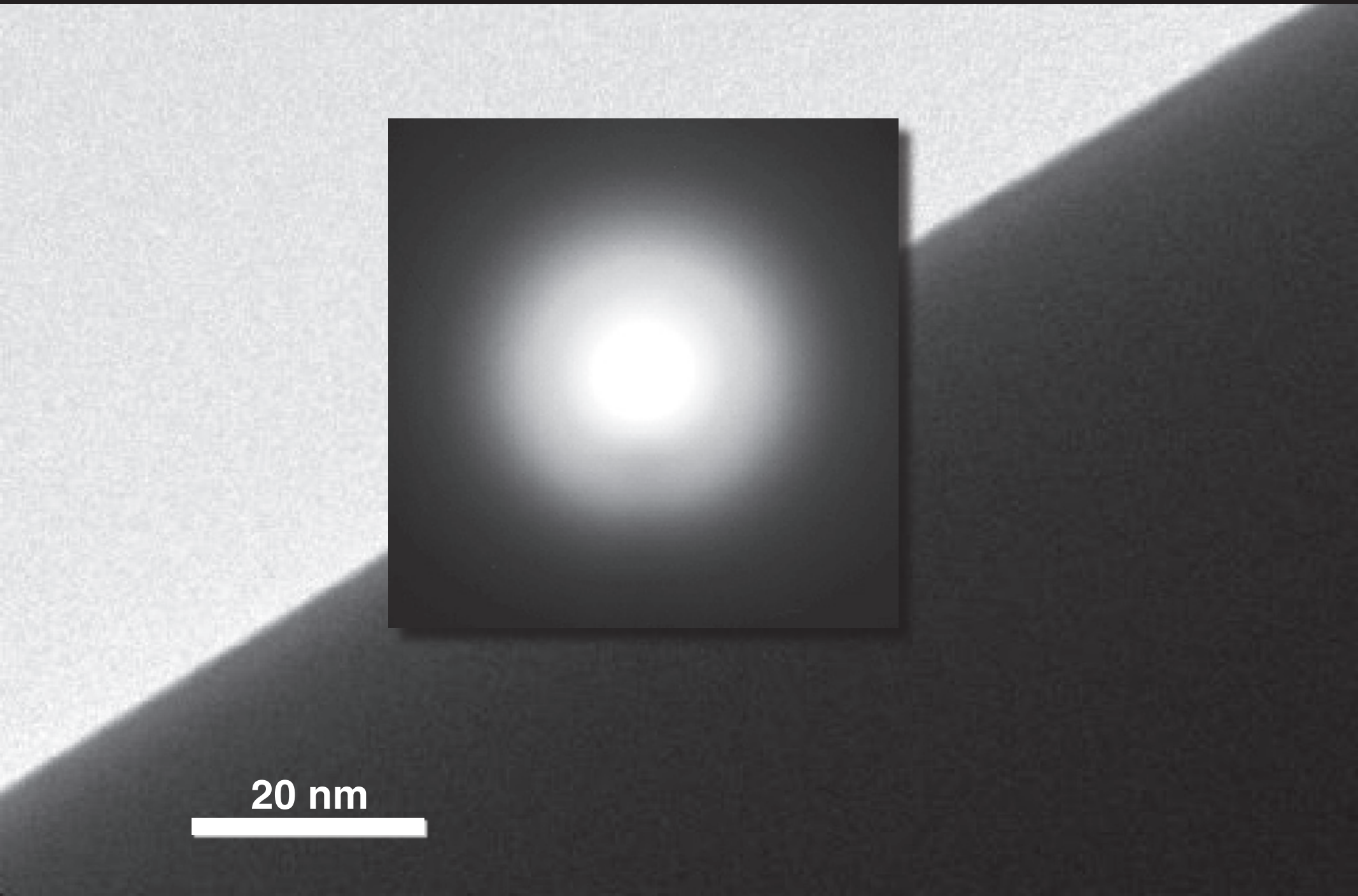

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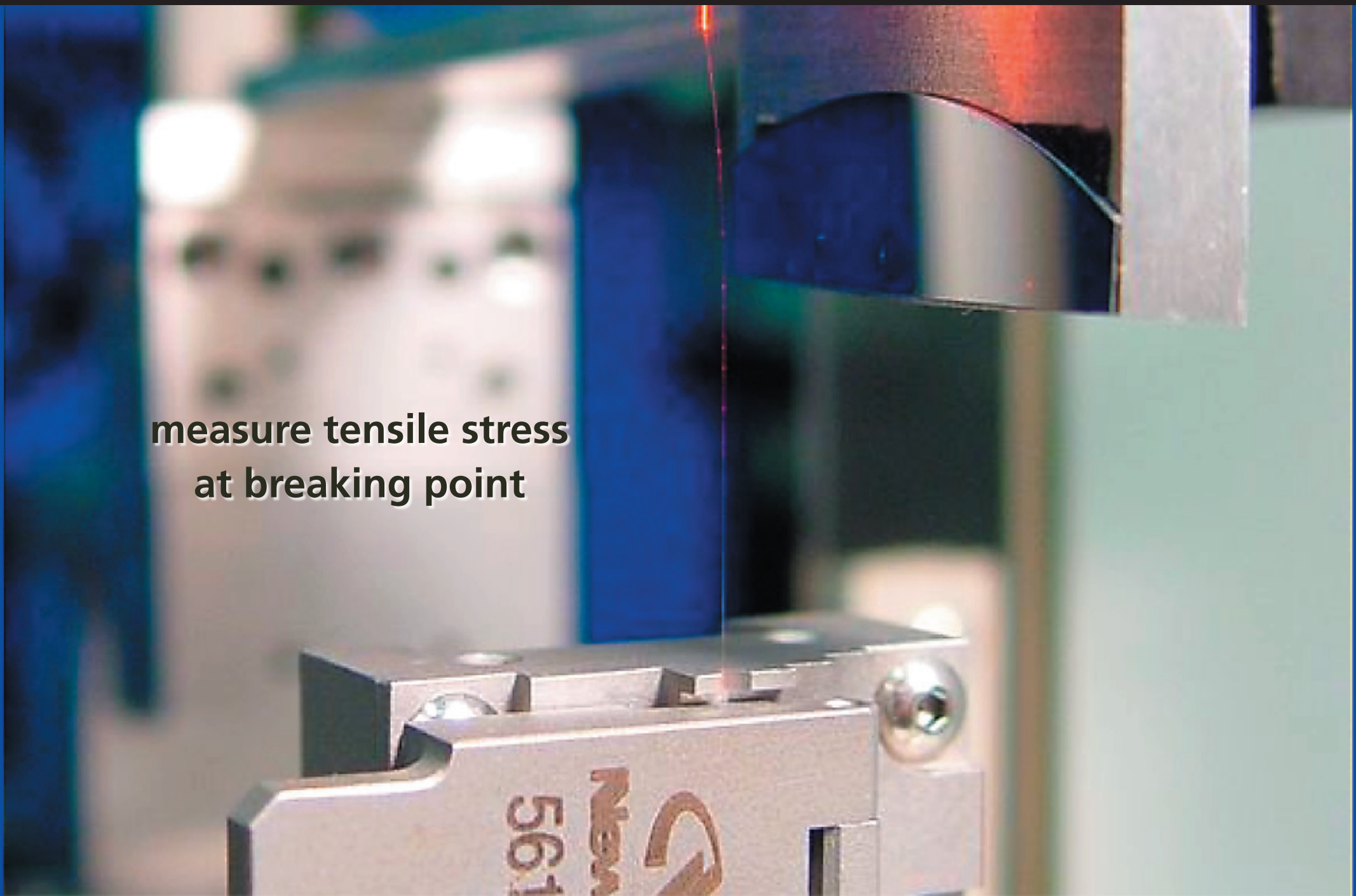

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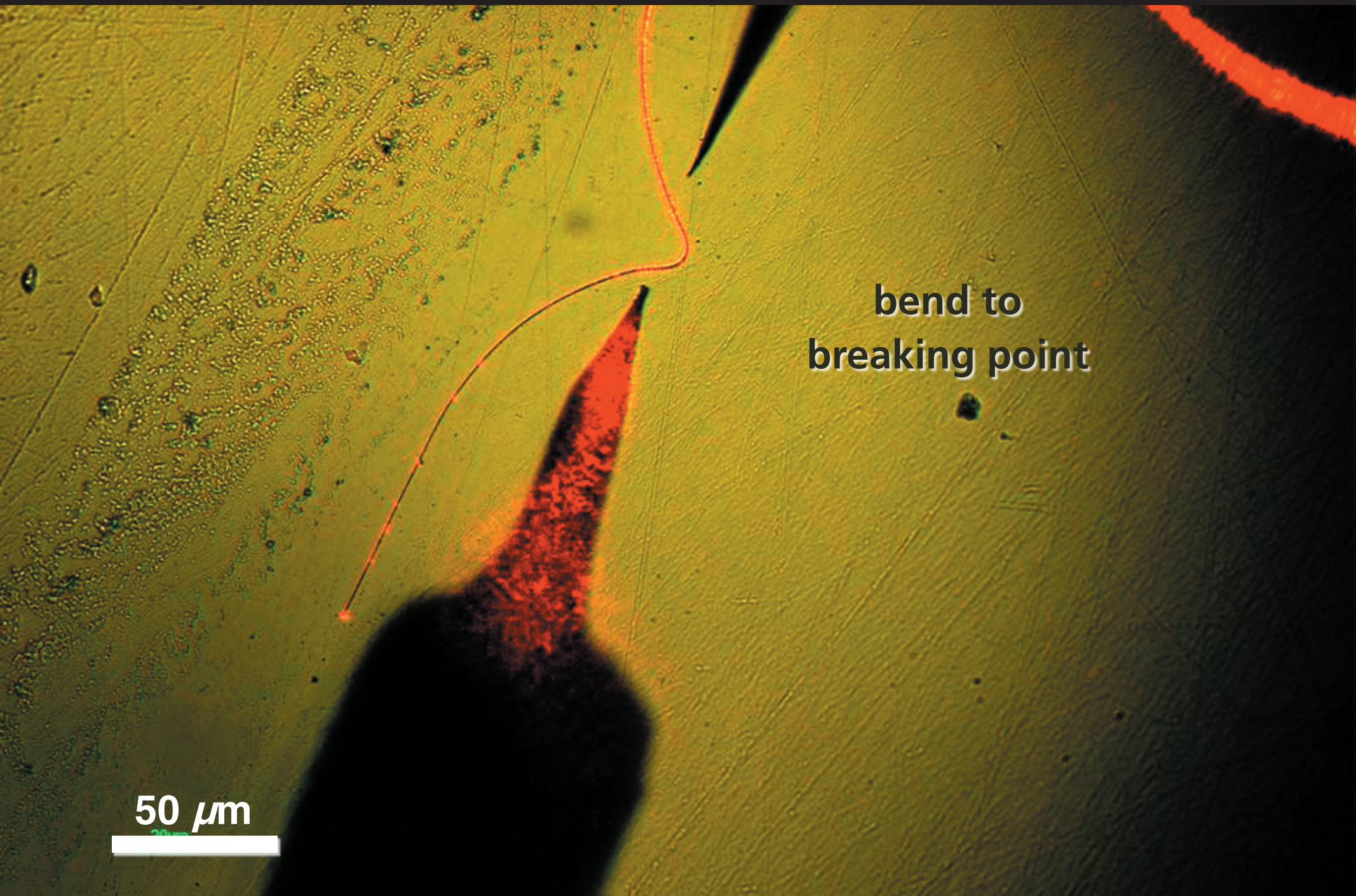

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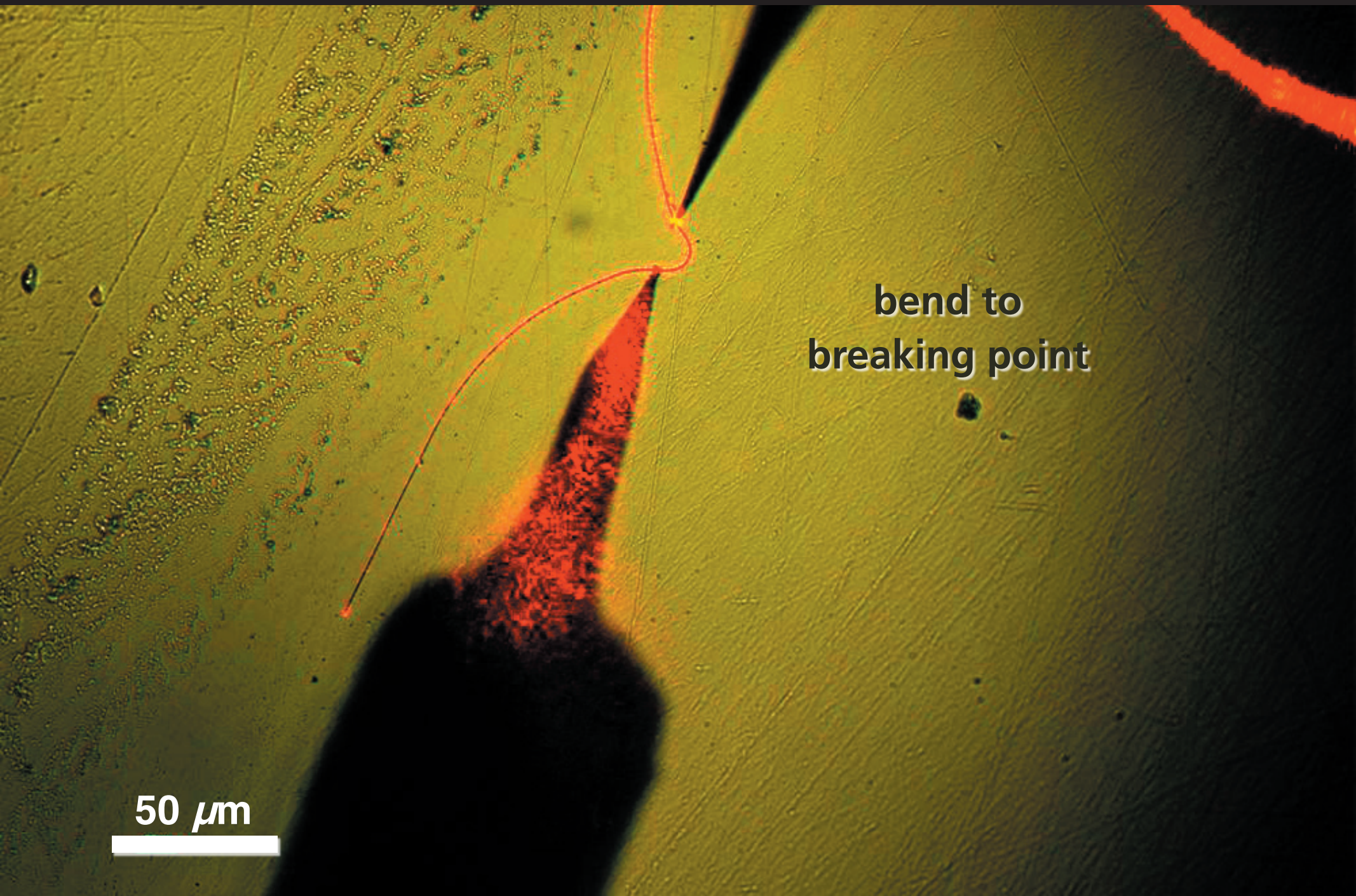
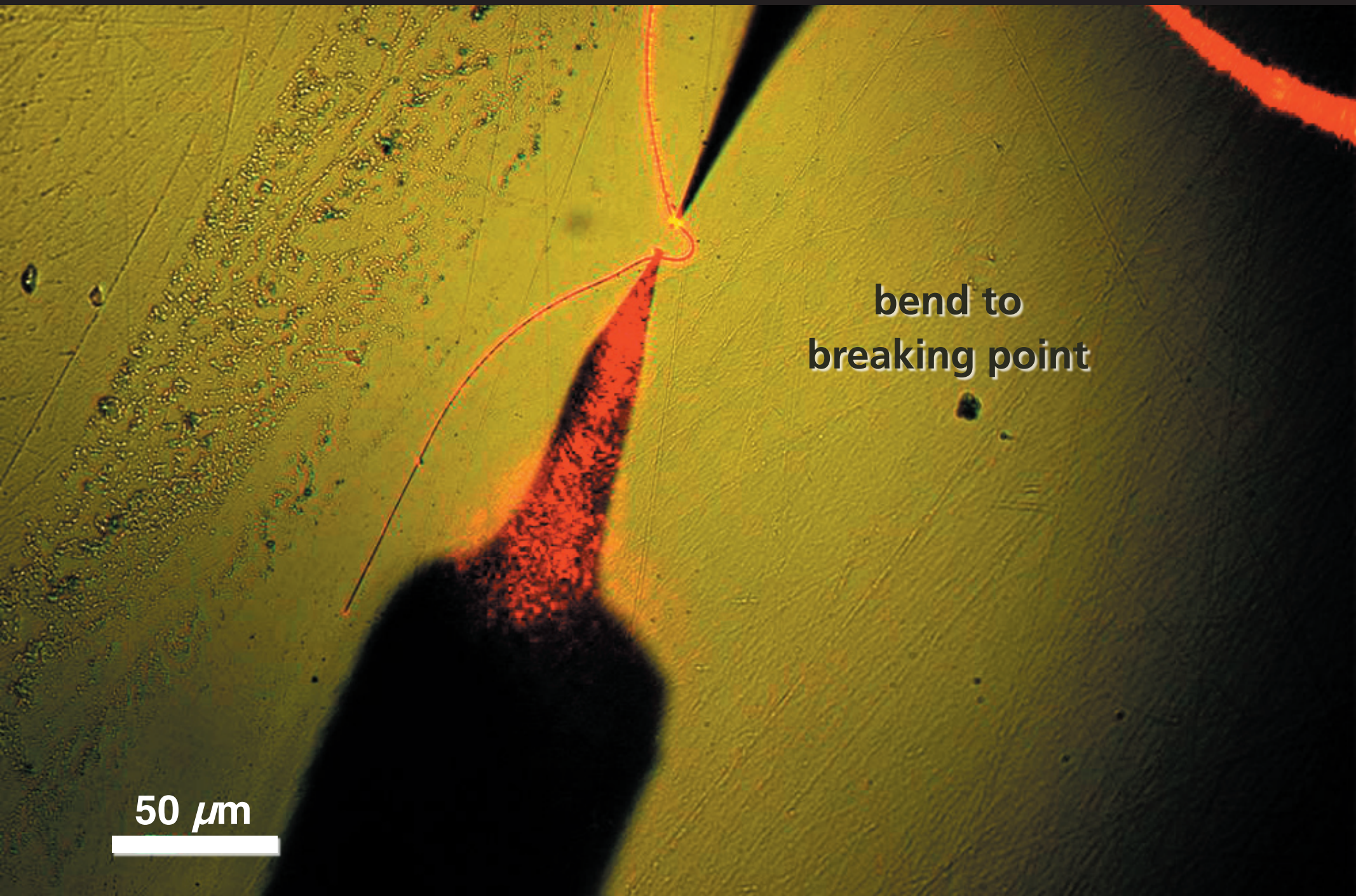
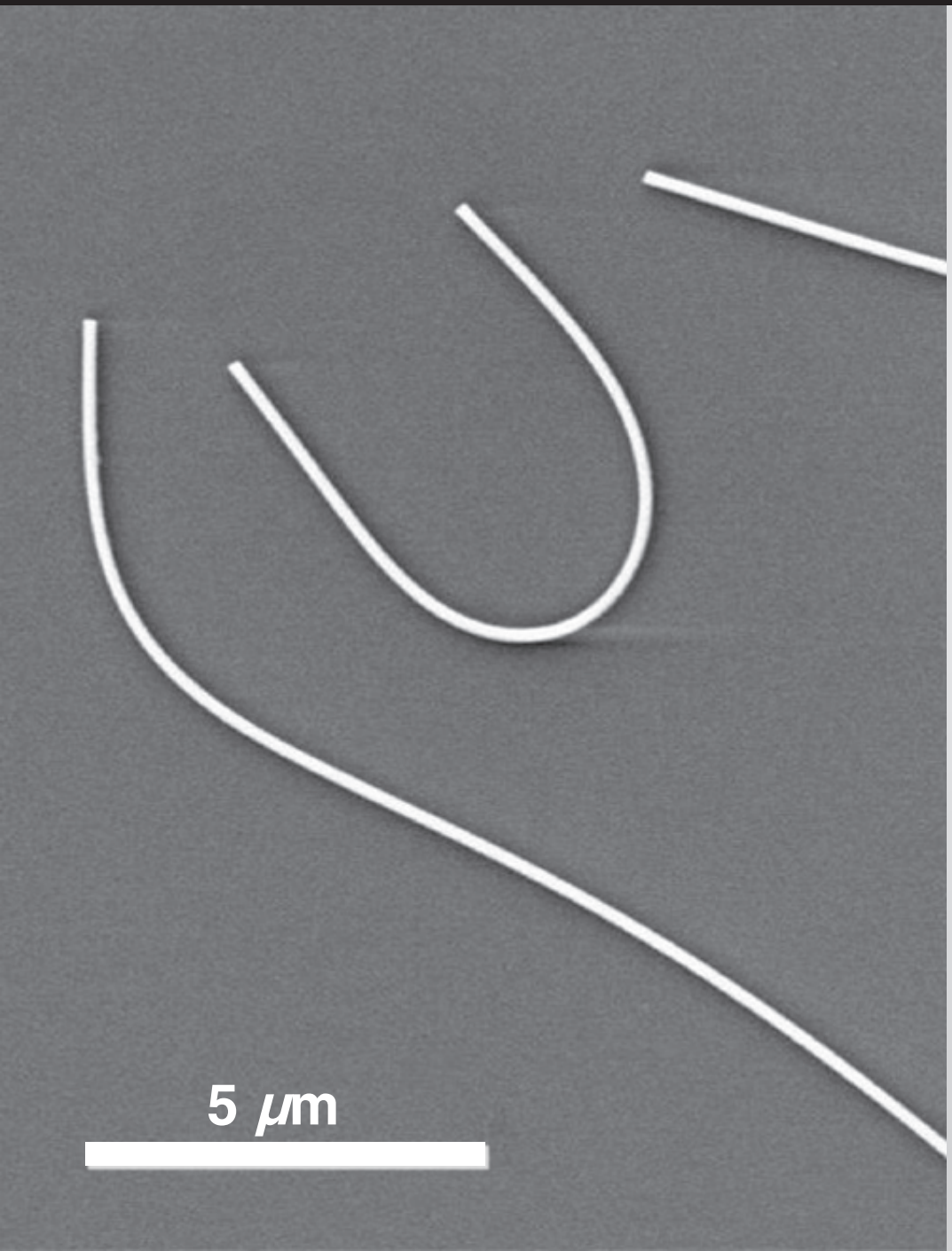


Nanowire fabrication



Nanowire fabrication



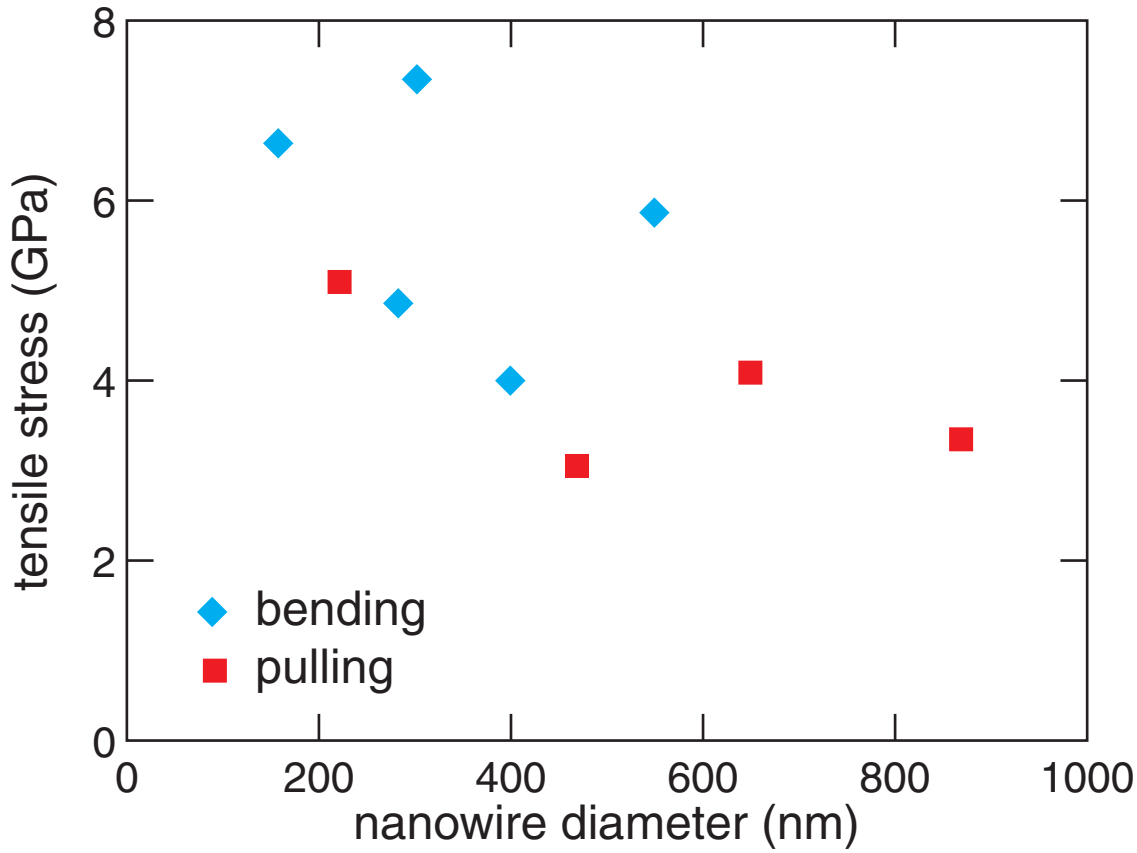
minimum bending radius R_{EB} gives tensile stress:

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

E = **Young's modulus**
D = **wire diameter**

Waveguiding

tensile strength



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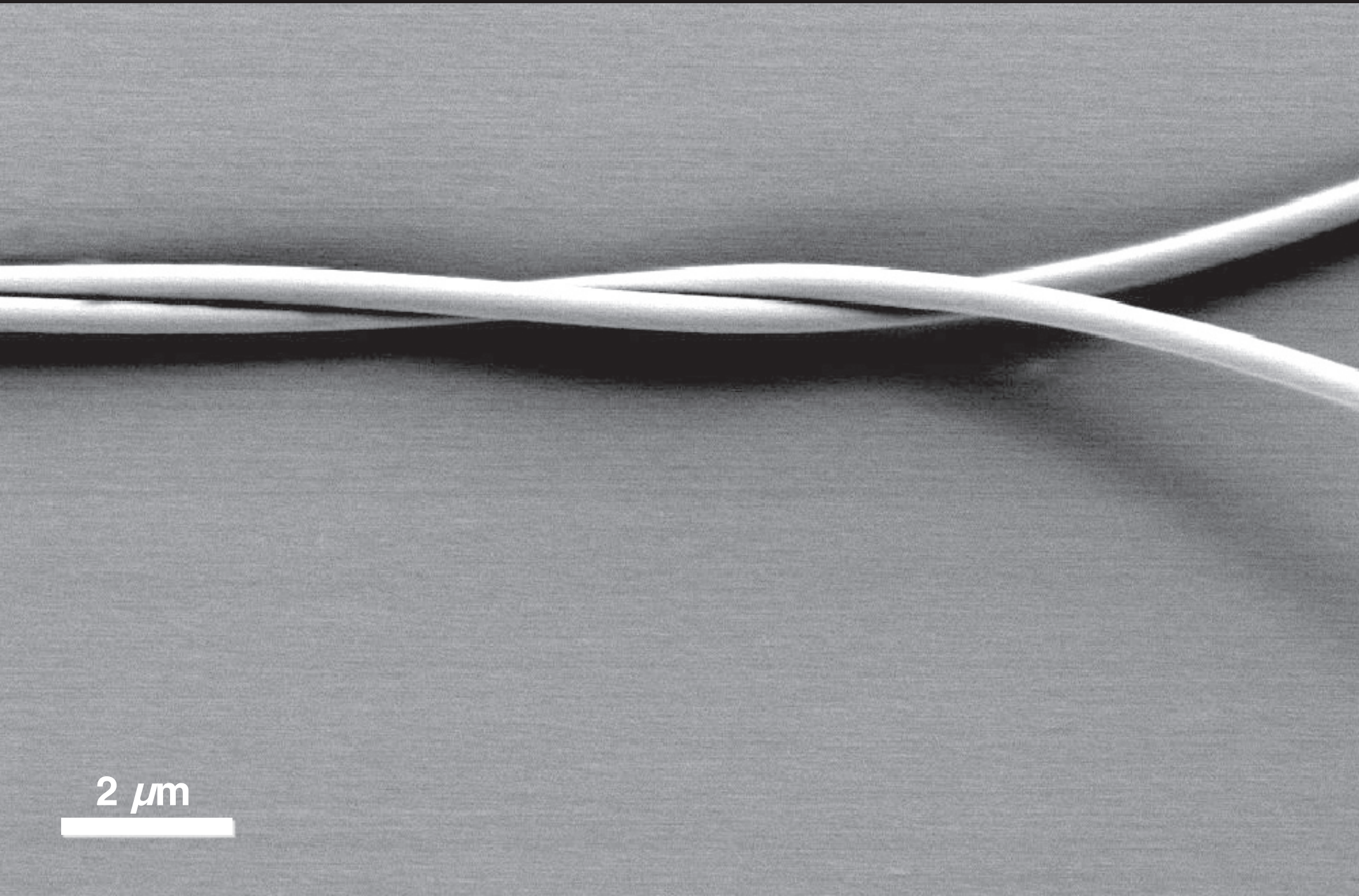

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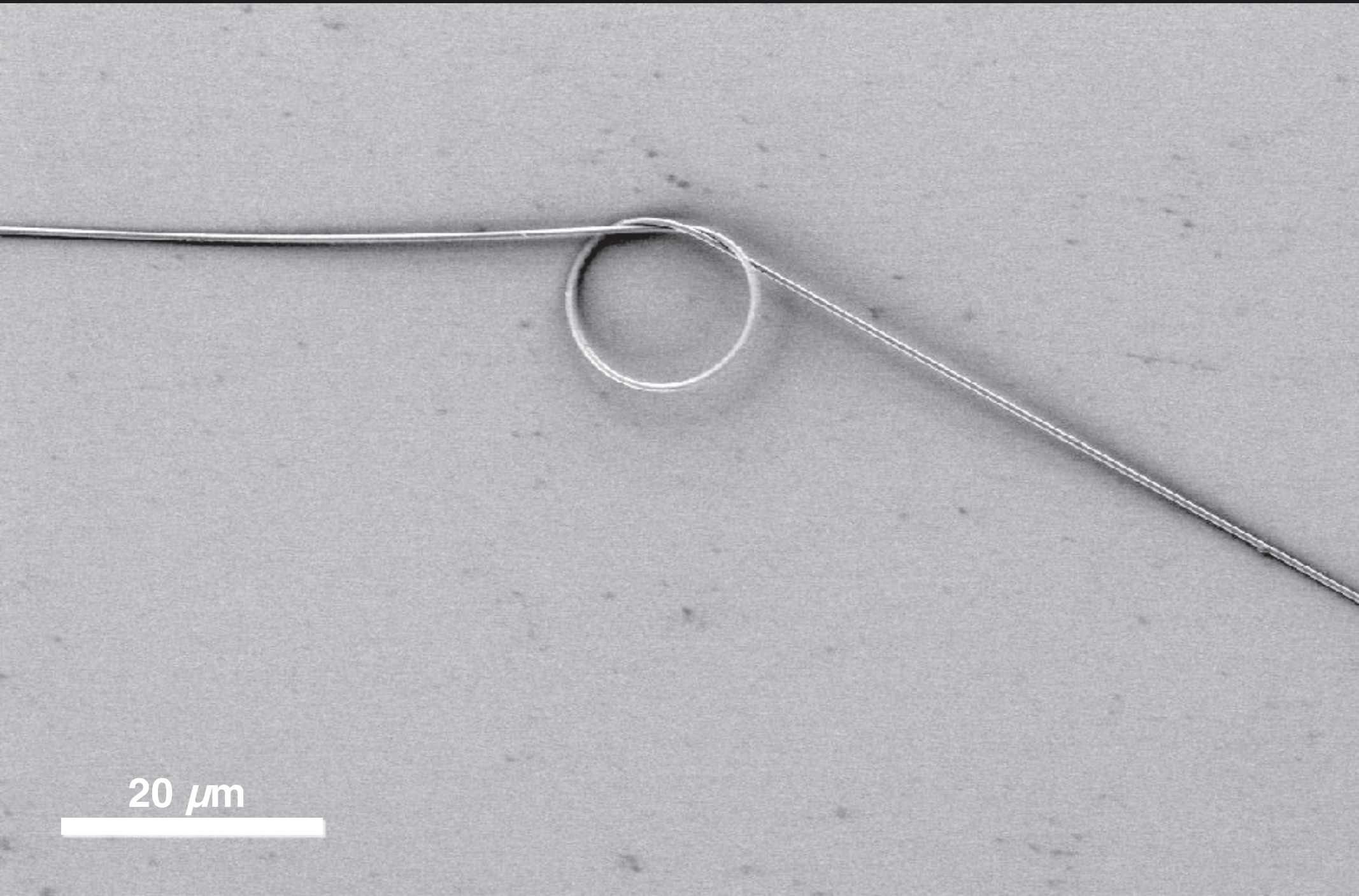
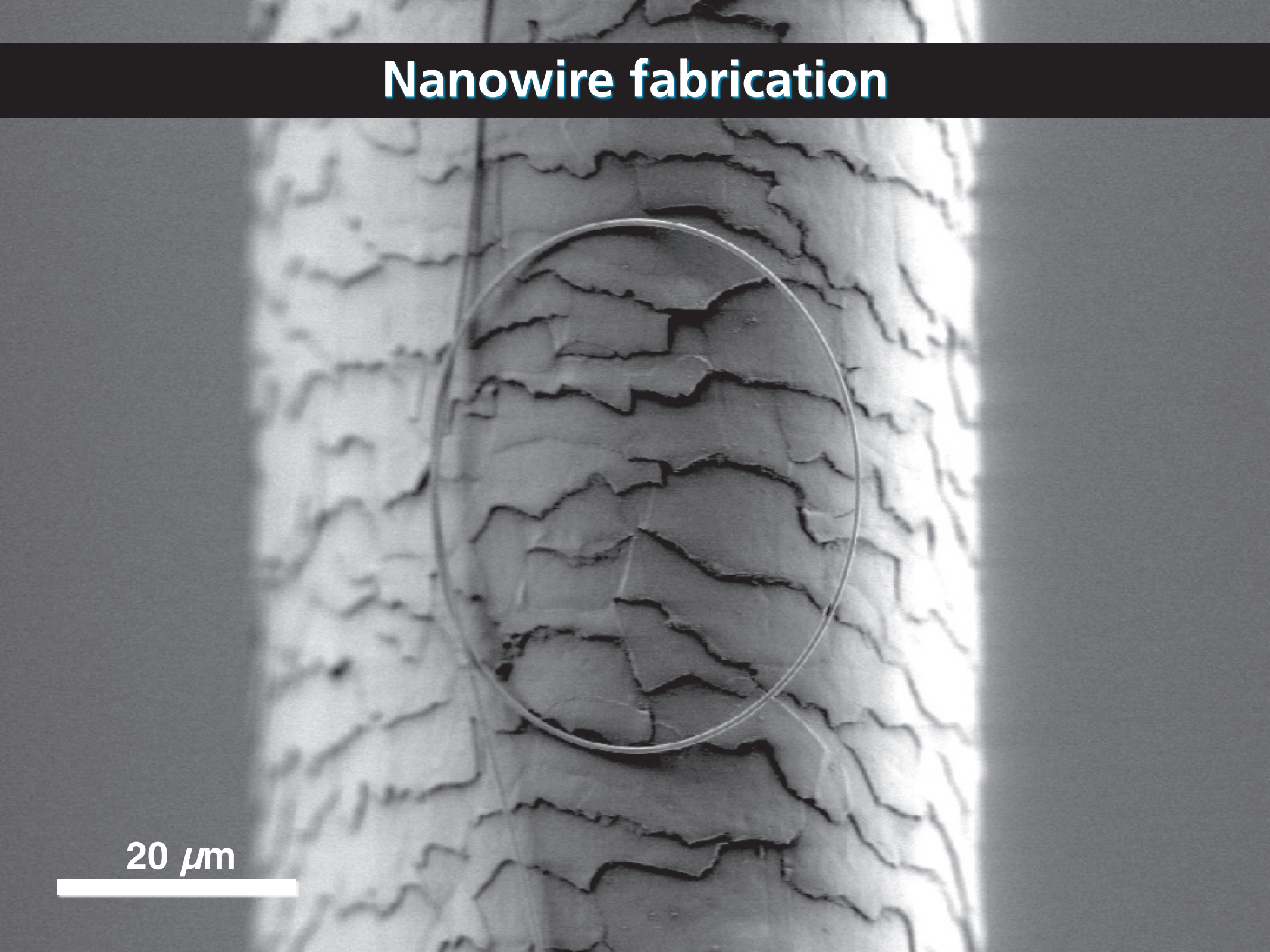


Nanowire fabrication



Outline

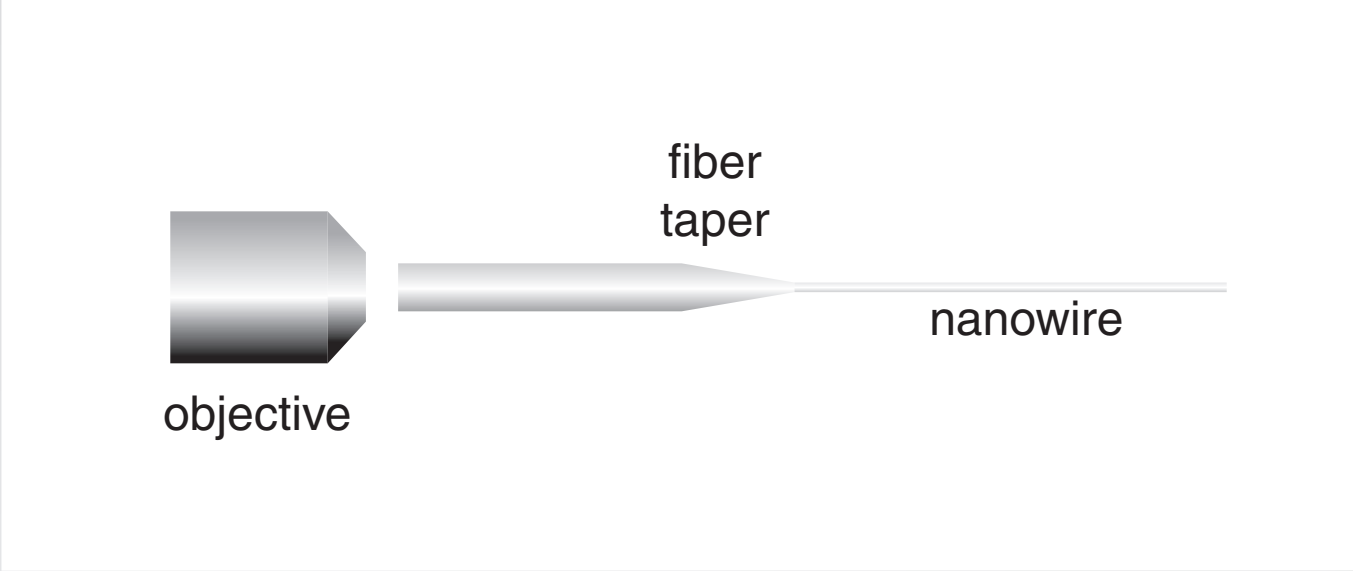
- waveguiding
- nanowire fabrication
- optical properties

Optical properties

coupling light into nanowires

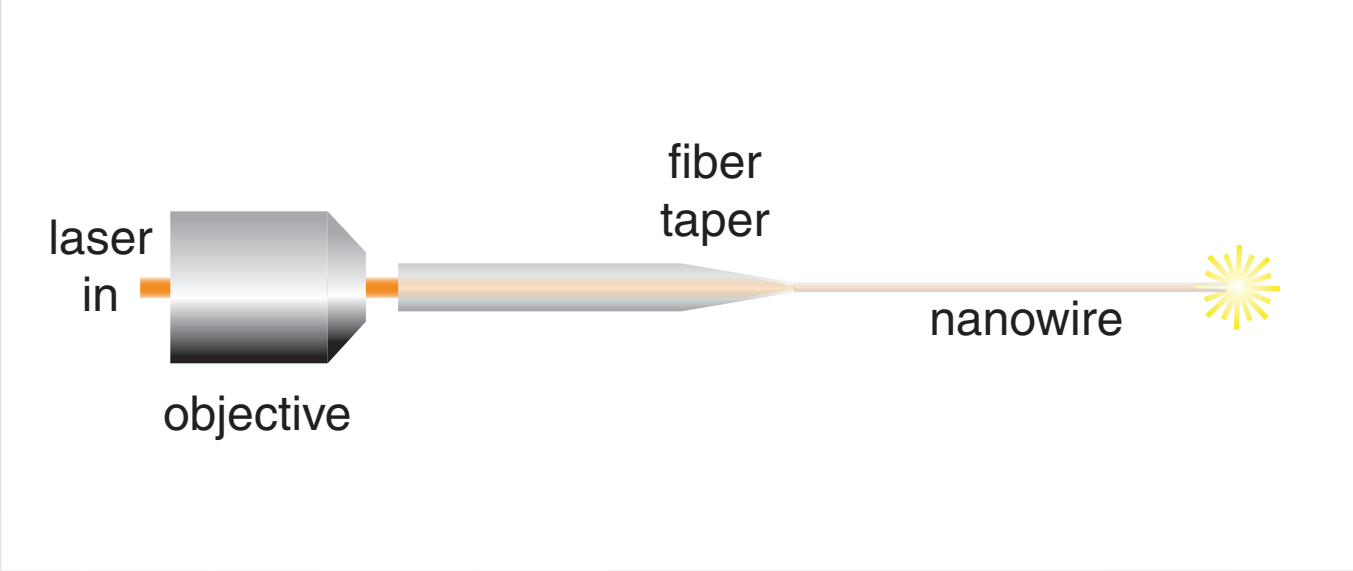
Optical properties

coupling light into nanowires

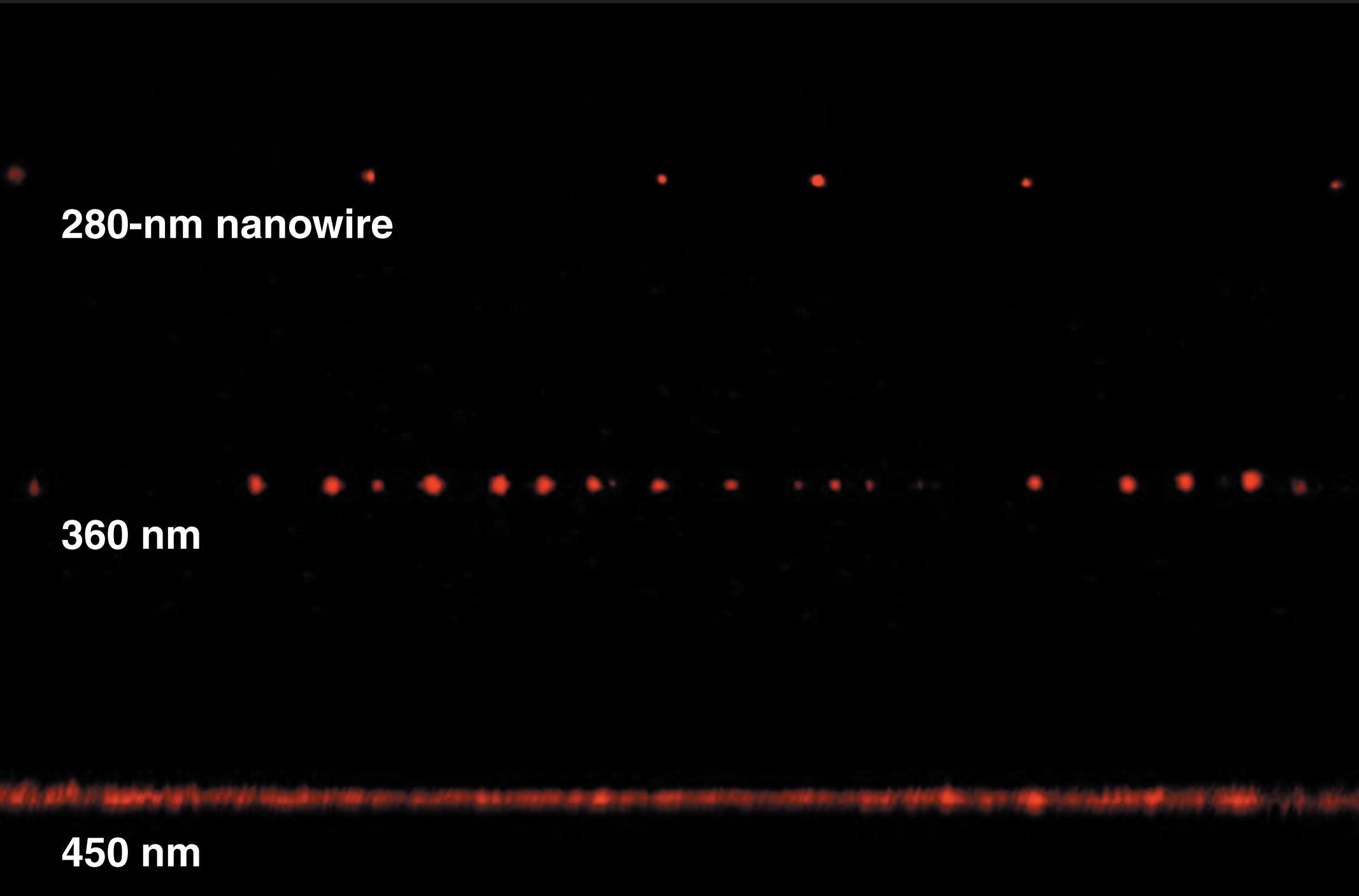


Optical properties

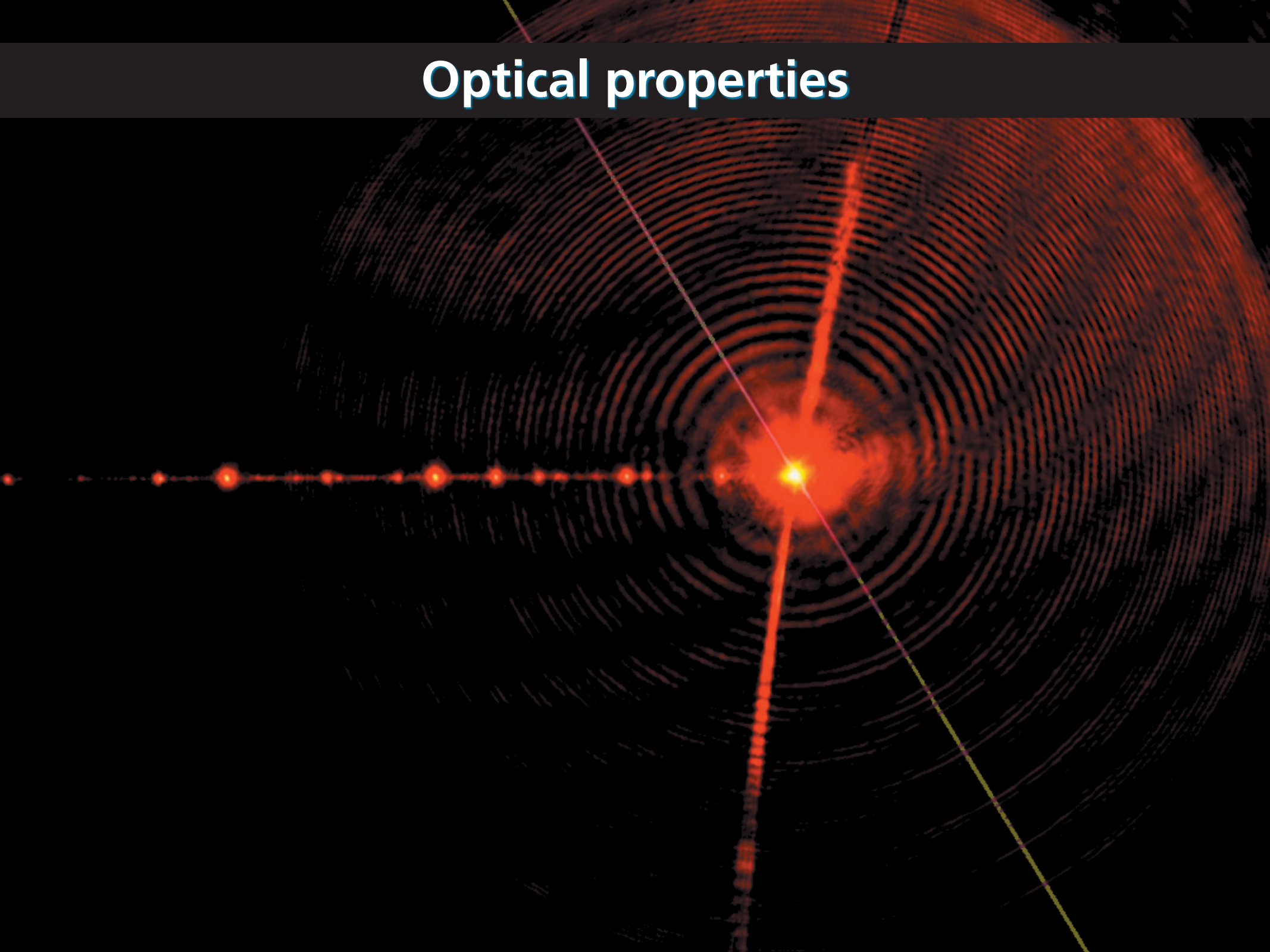
coupling light into nanowires



Optical properties



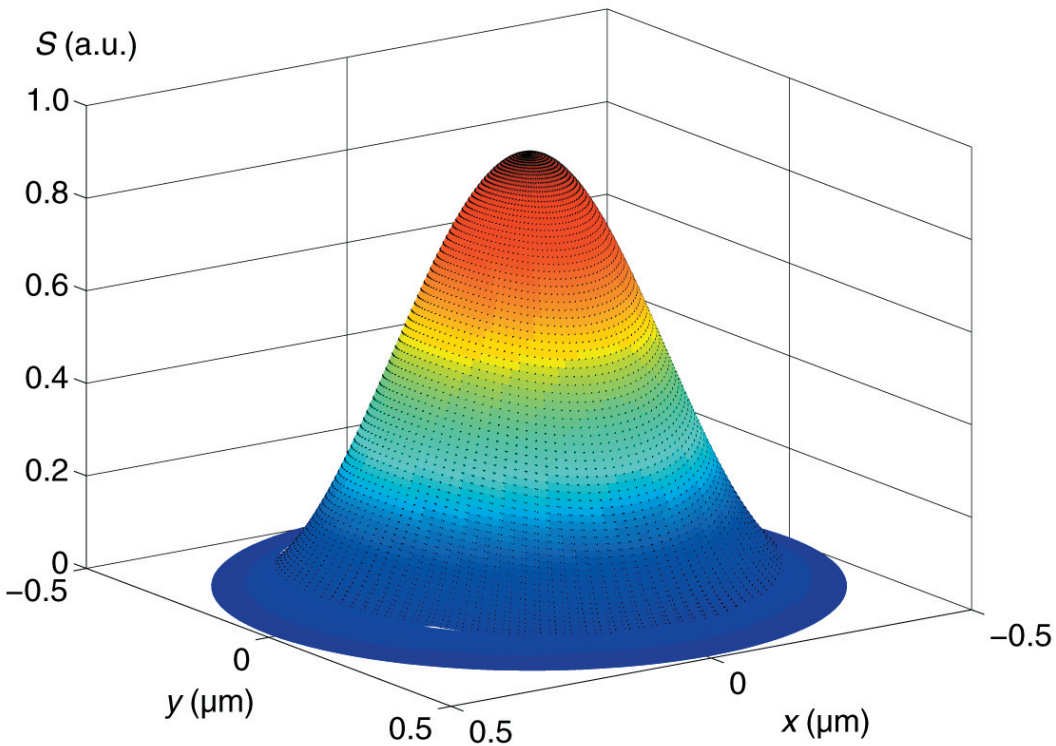
Optical properties



Optical properties

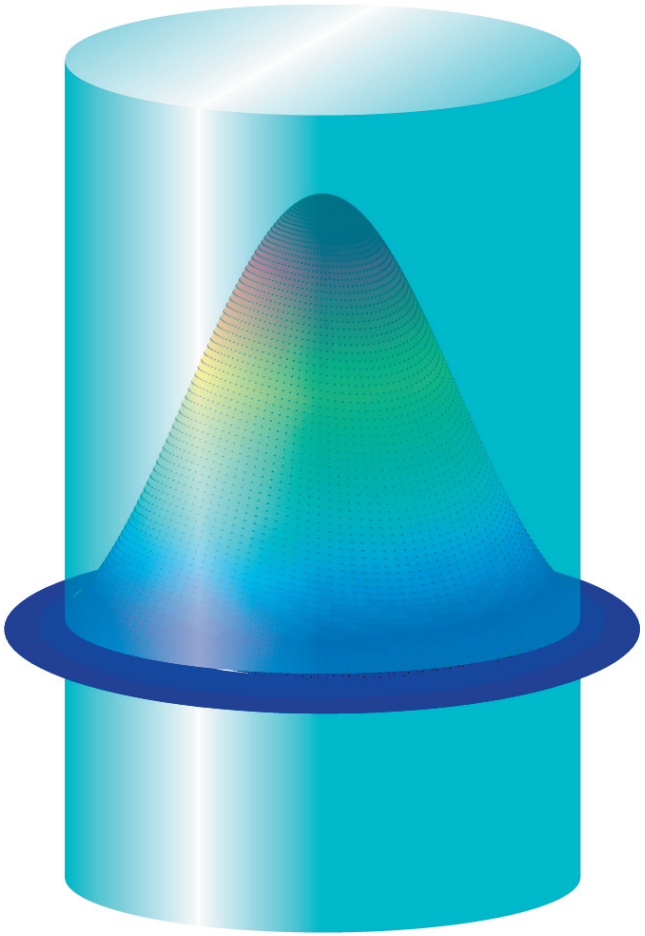
Optical properties

Poynting vector profile for 800-nm nanowire



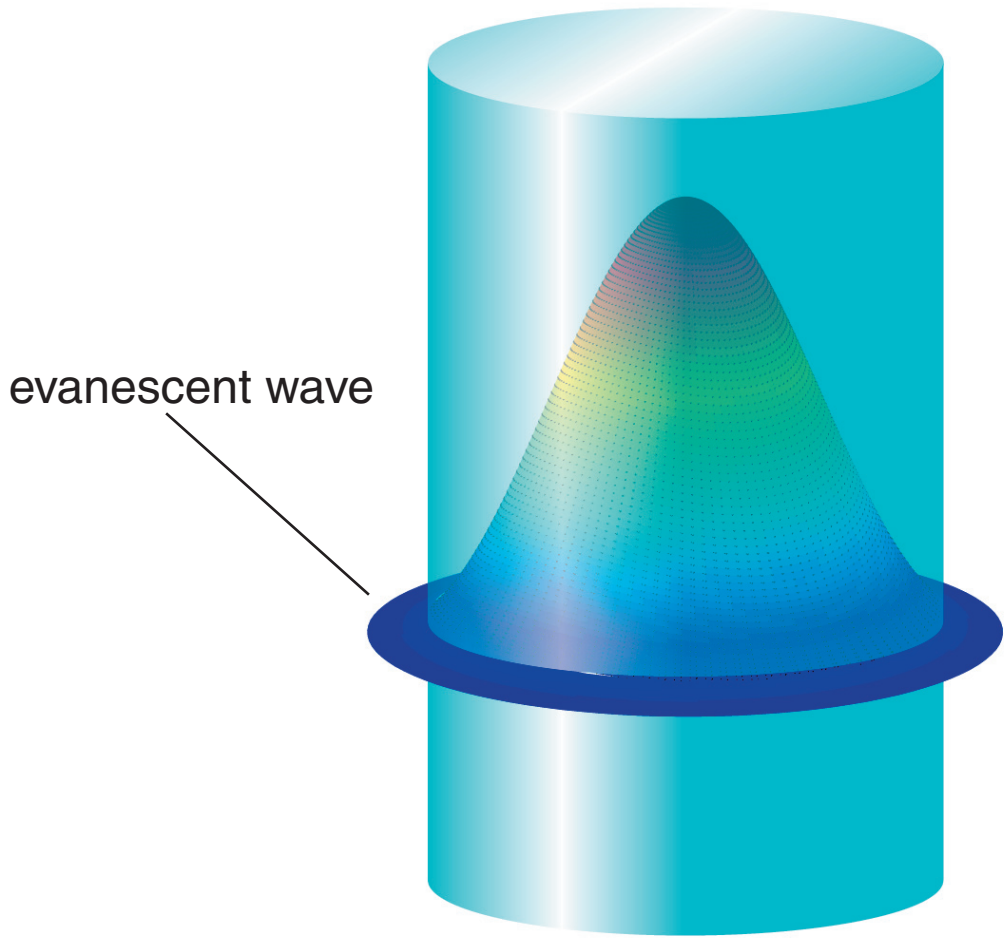
Optical properties

Poynting vector profile for 800-nm nanowire



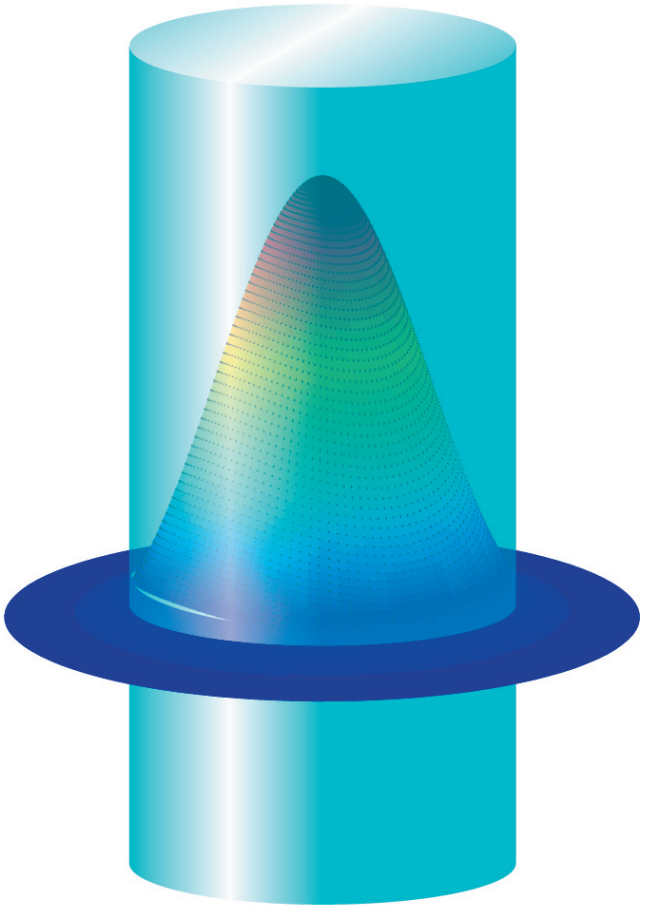
Optical properties

Poynting vector profile for 800-nm nanowire



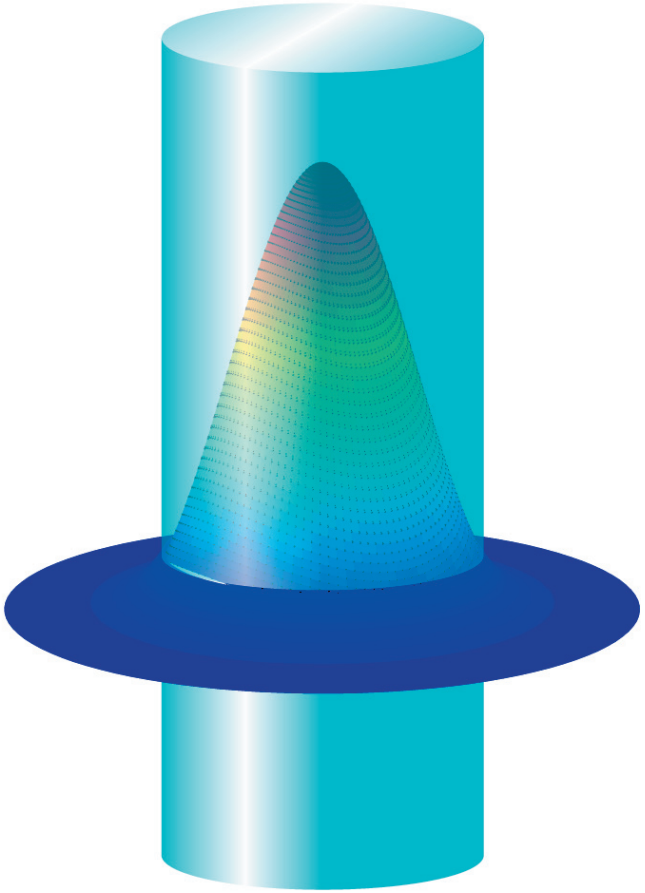
Optical properties

Poynting vector profile for 600-nm nanowire



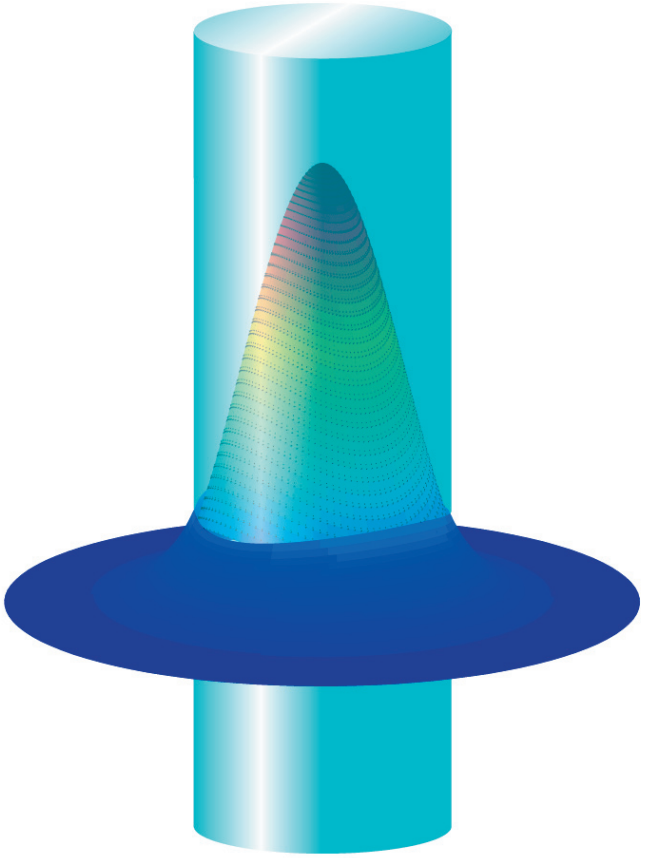
Optical properties

Poynting vector profile for 500-nm nanowire



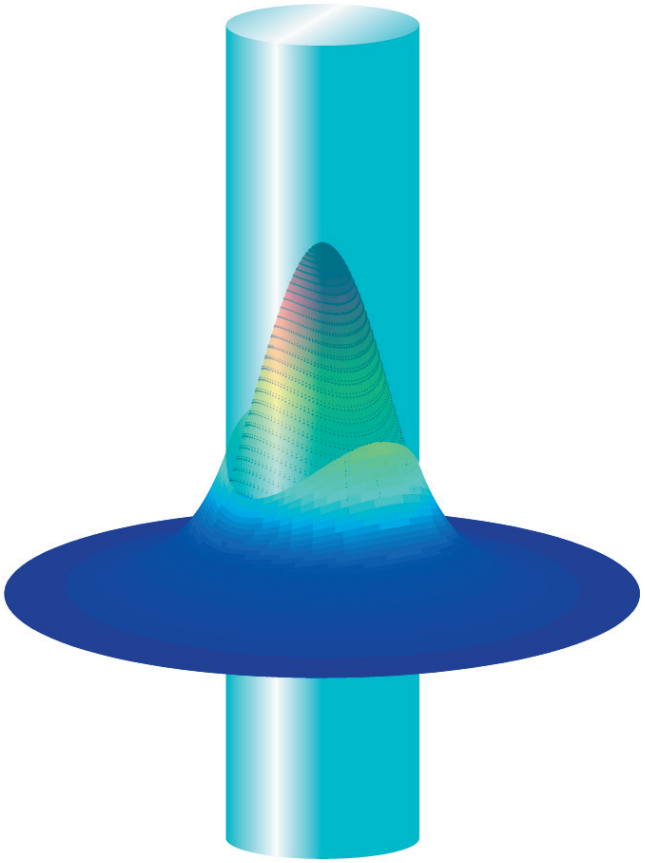
Optical properties

Poynting vector profile for 400-nm nanowire



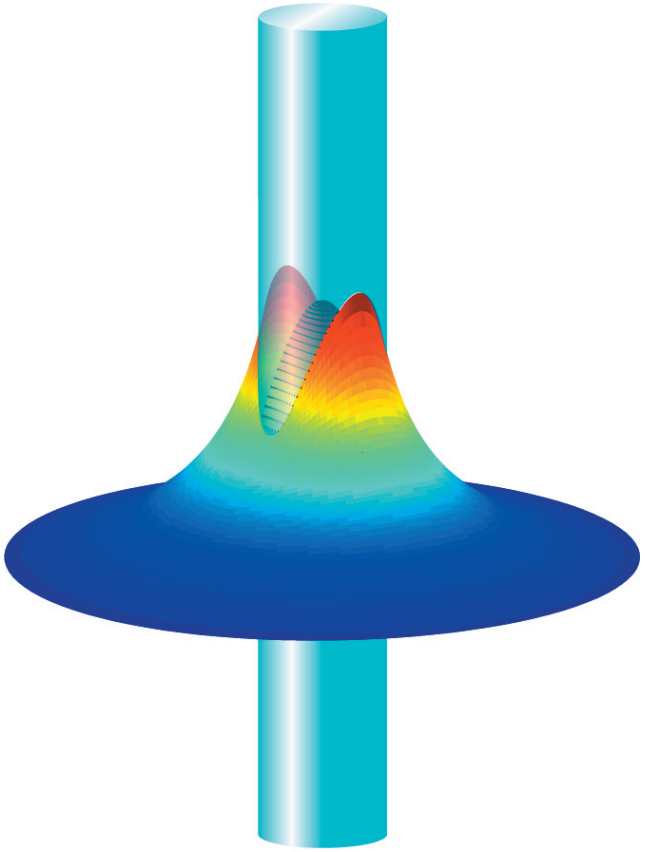
Optical properties

Poynting vector profile for 300-nm nanowire



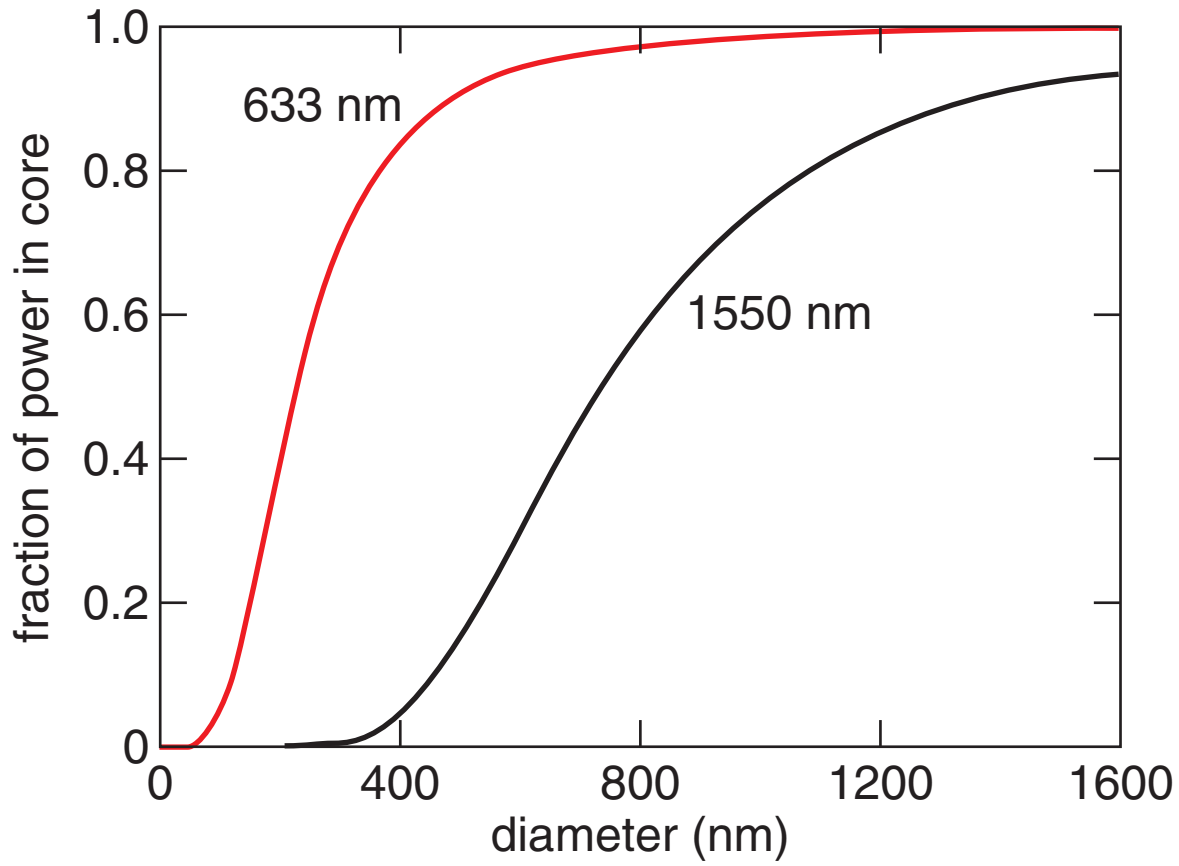
Optical properties

Poynting vector profile for 200-nm nanowire

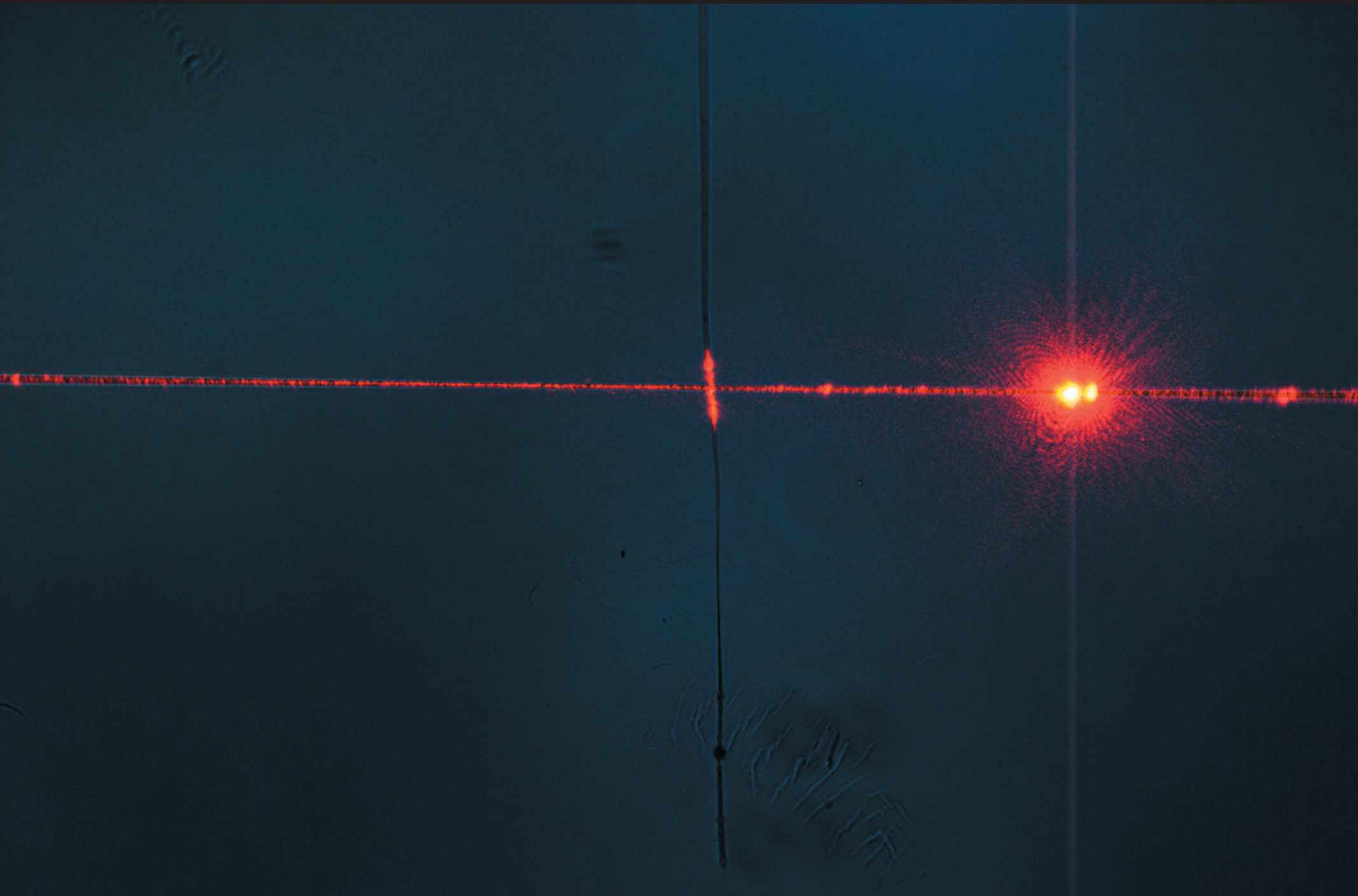


Waveguiding

fraction of power carried in core

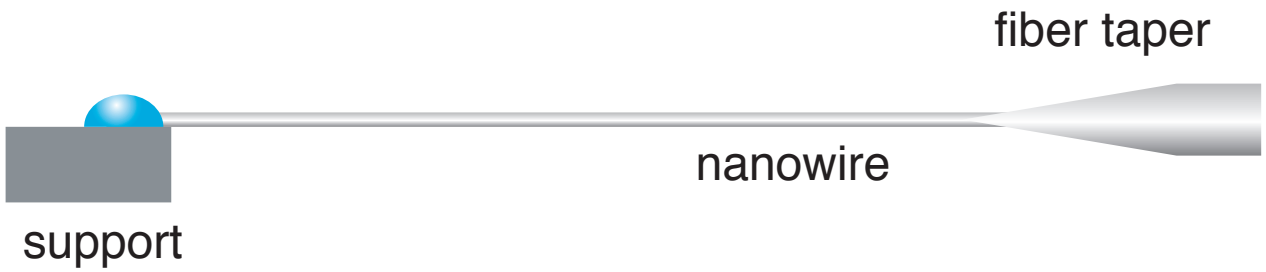


Optical properties



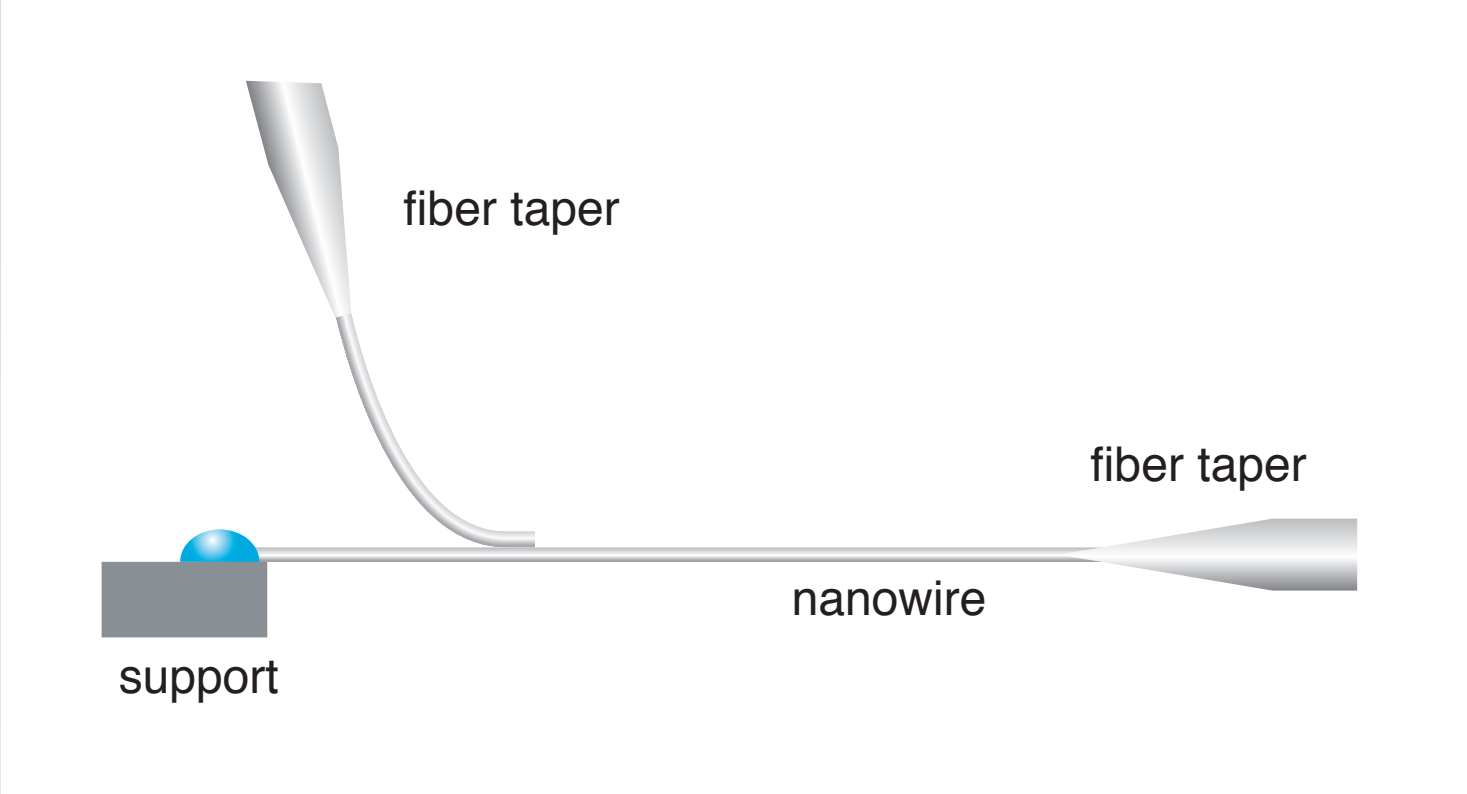
Optical properties

coupling light between nanowires



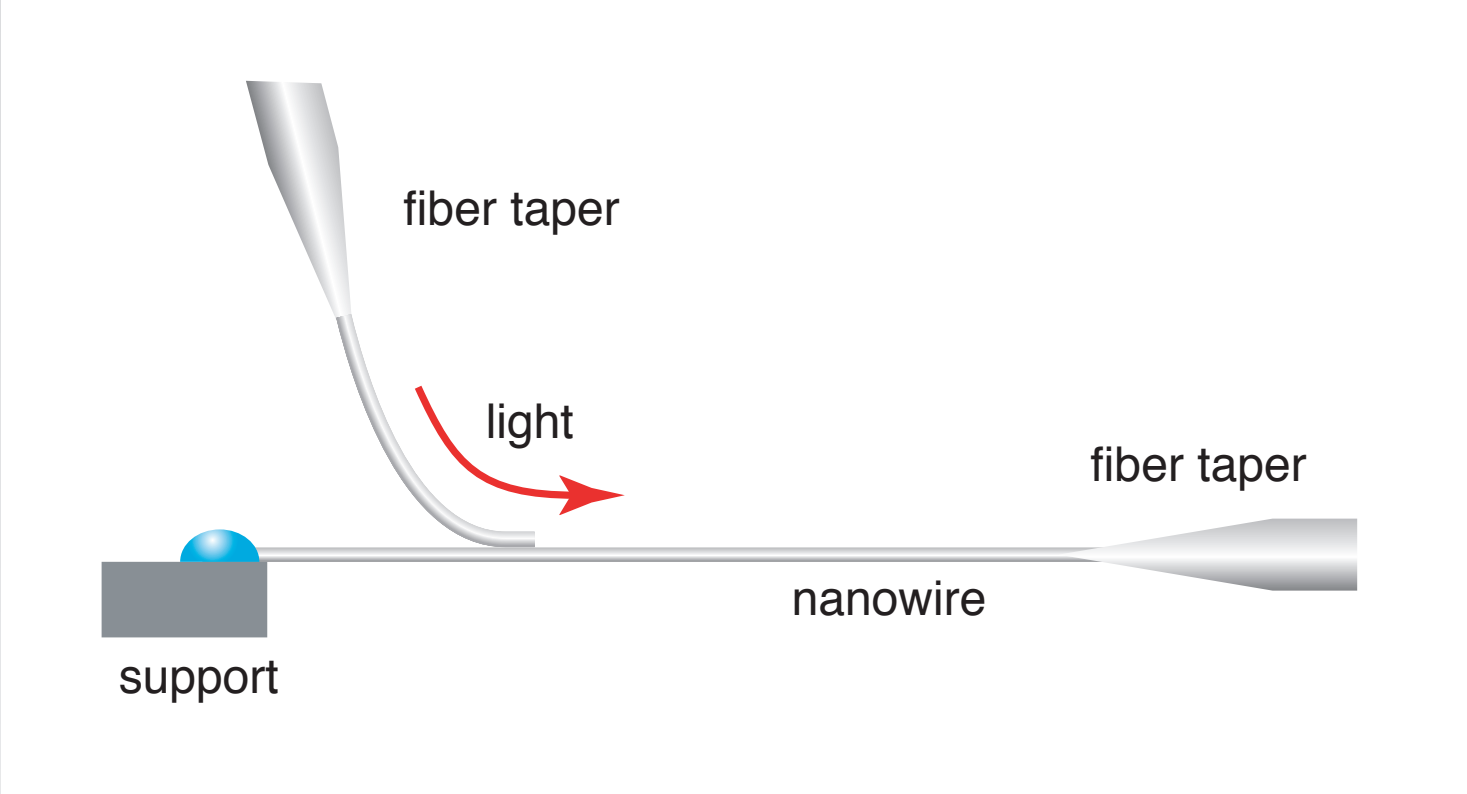
Optical properties

coupling light between nanowires



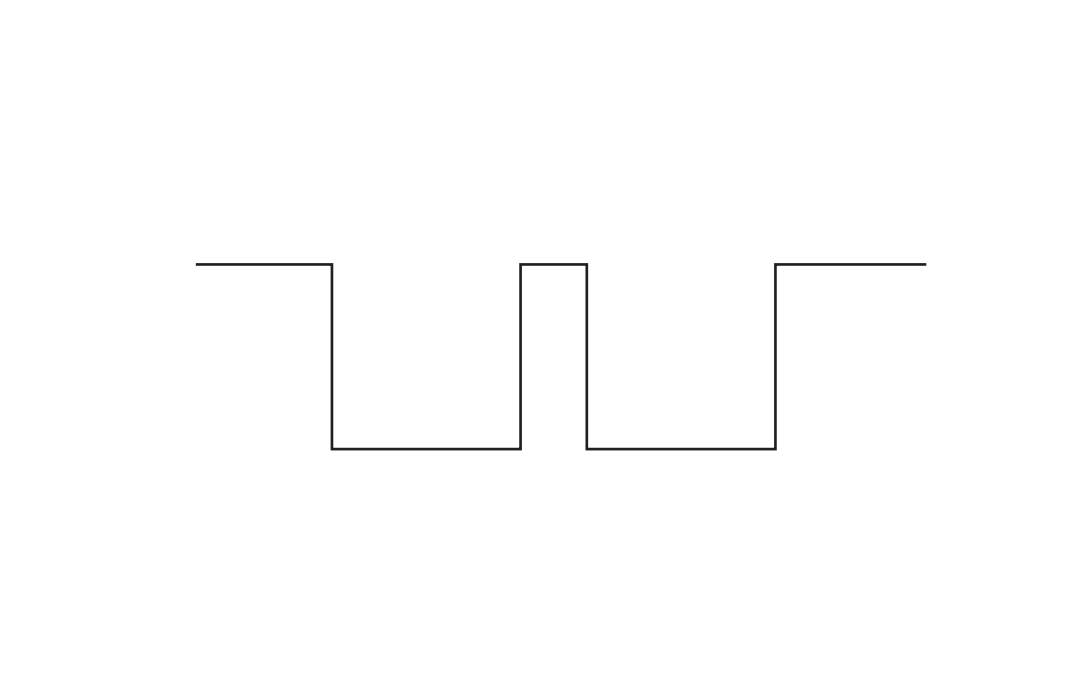
Optical properties

coupling light between nanowires



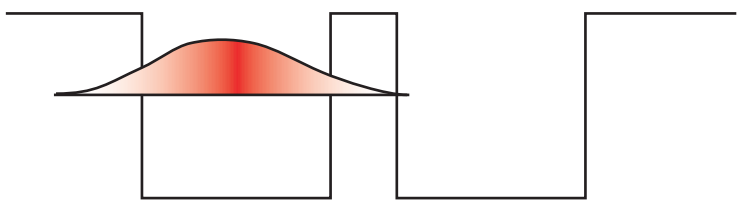
Optical properties

coupling light between nanowires



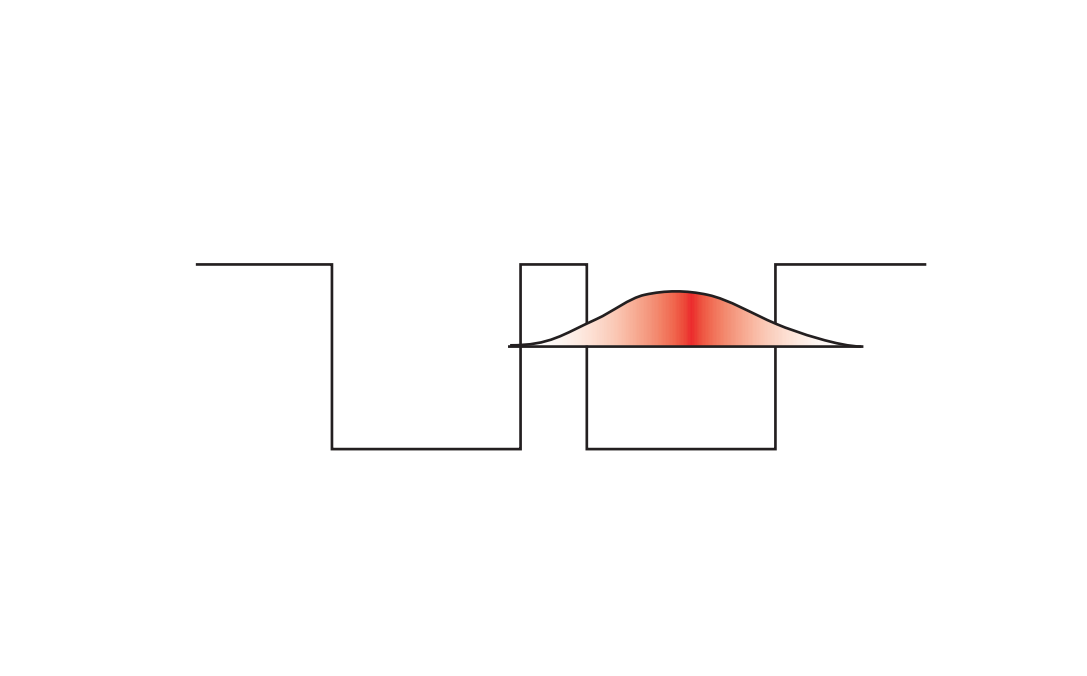
Optical properties

coupling light between nanowires

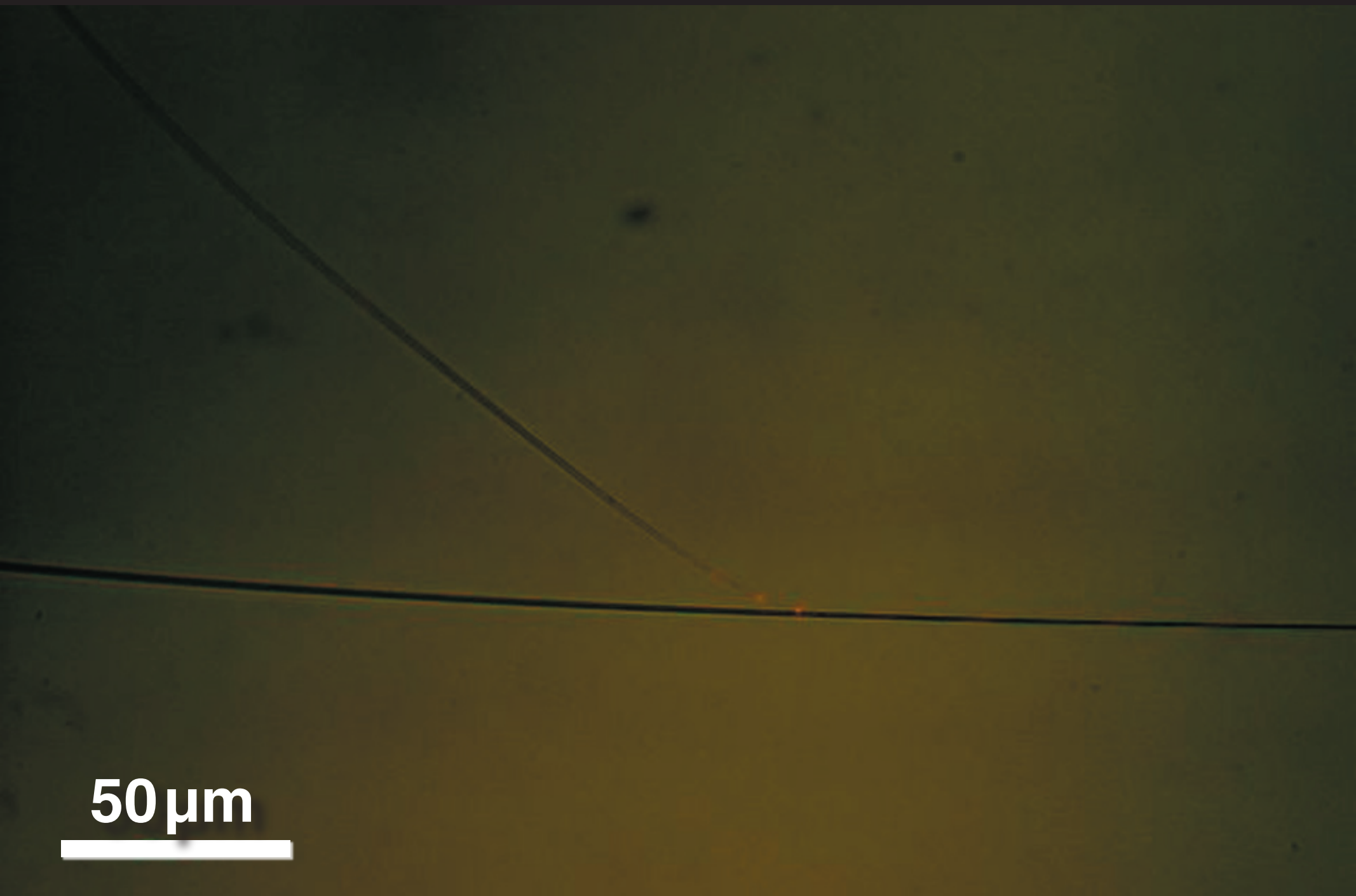


Optical properties

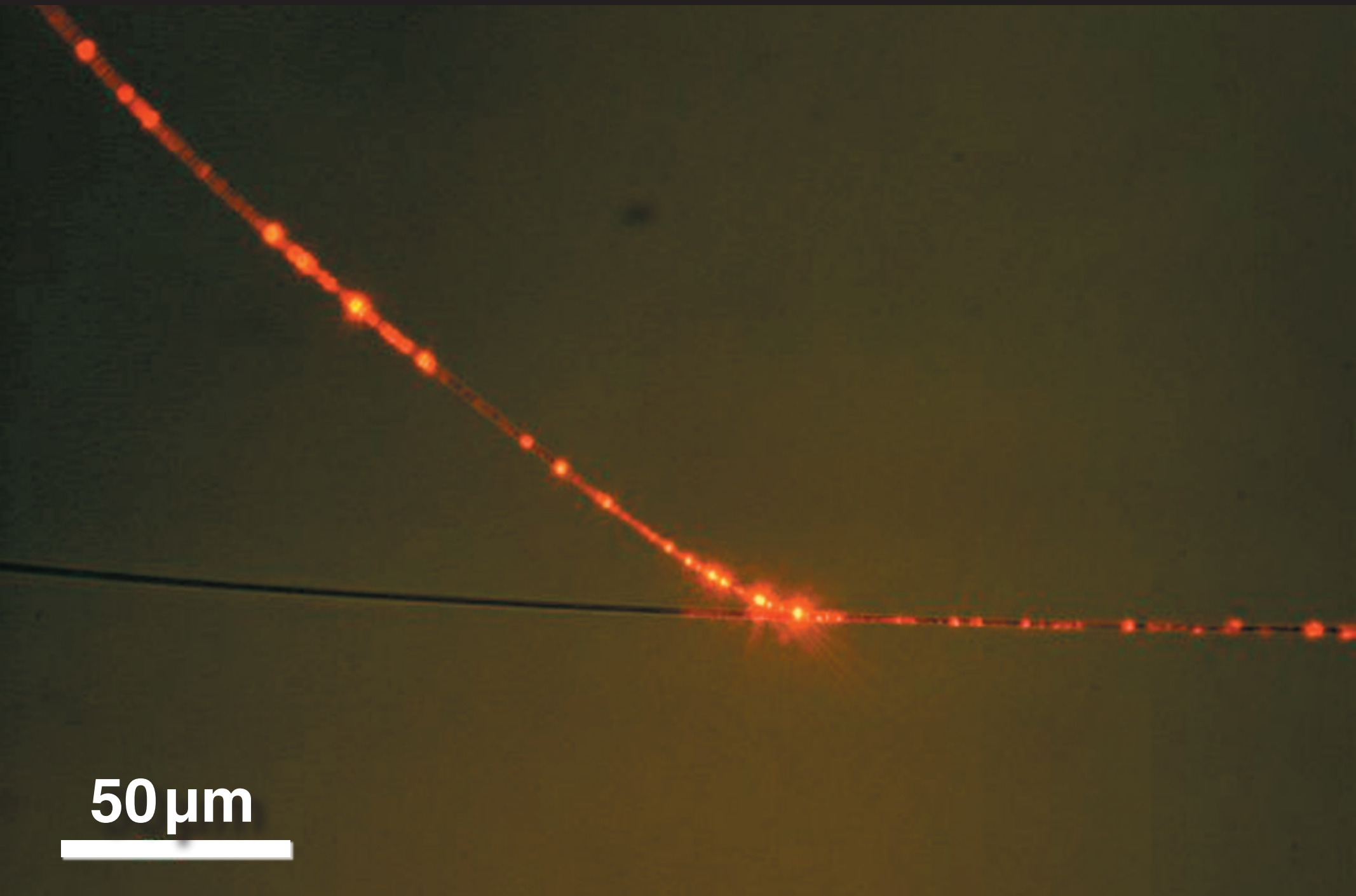
“tunneling” of light



Optical properties

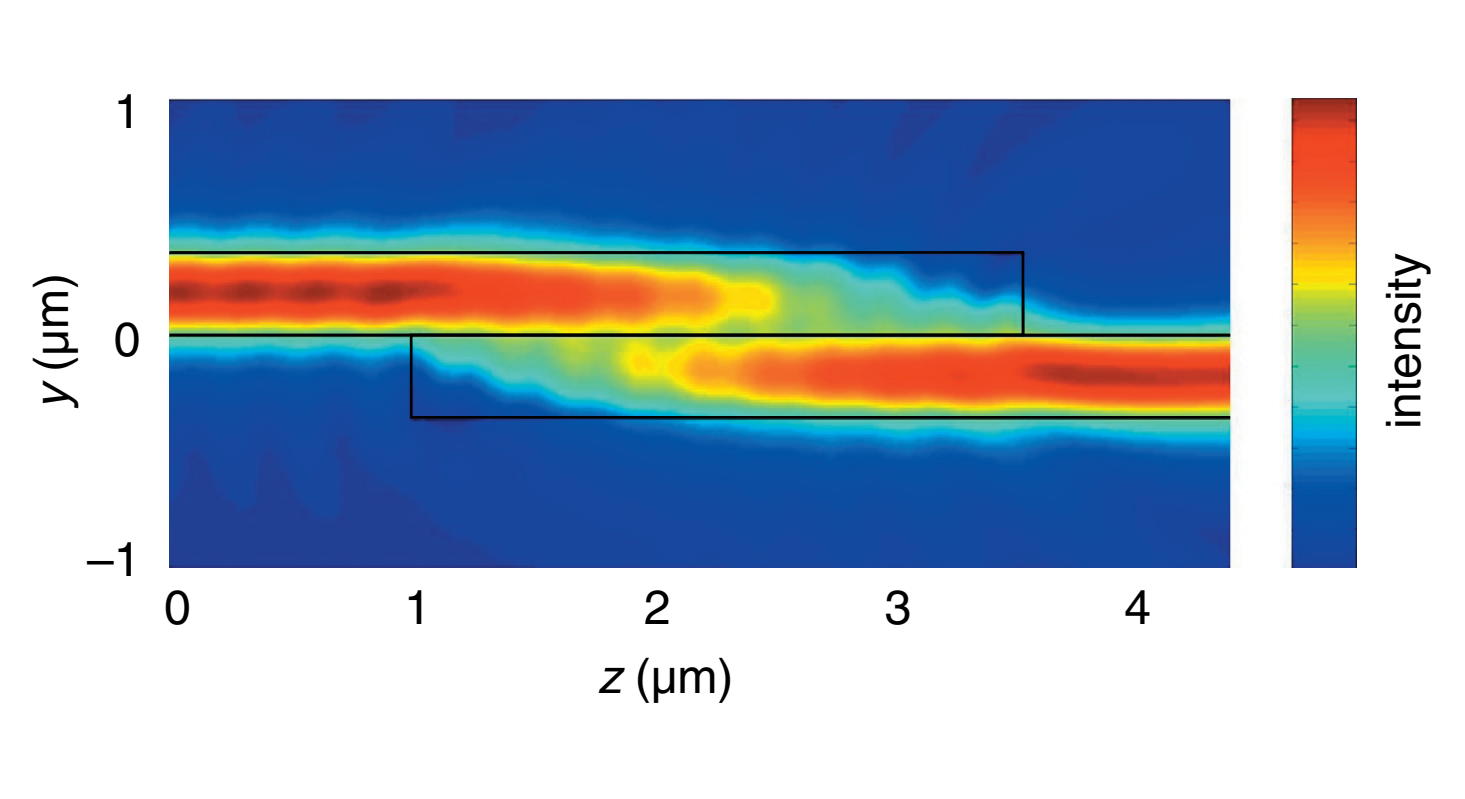


Optical properties



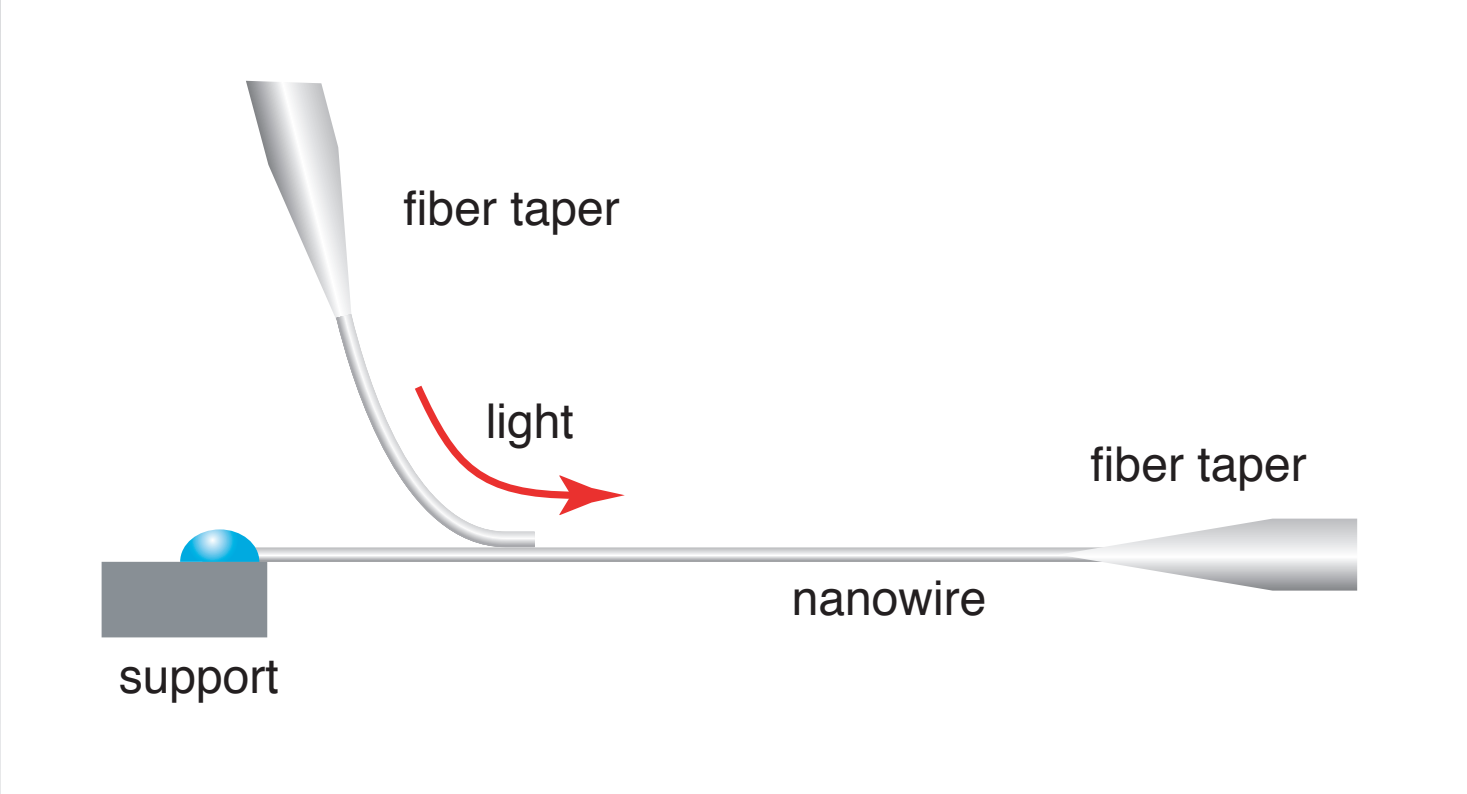
Optical properties

intensity distribution



Optical properties

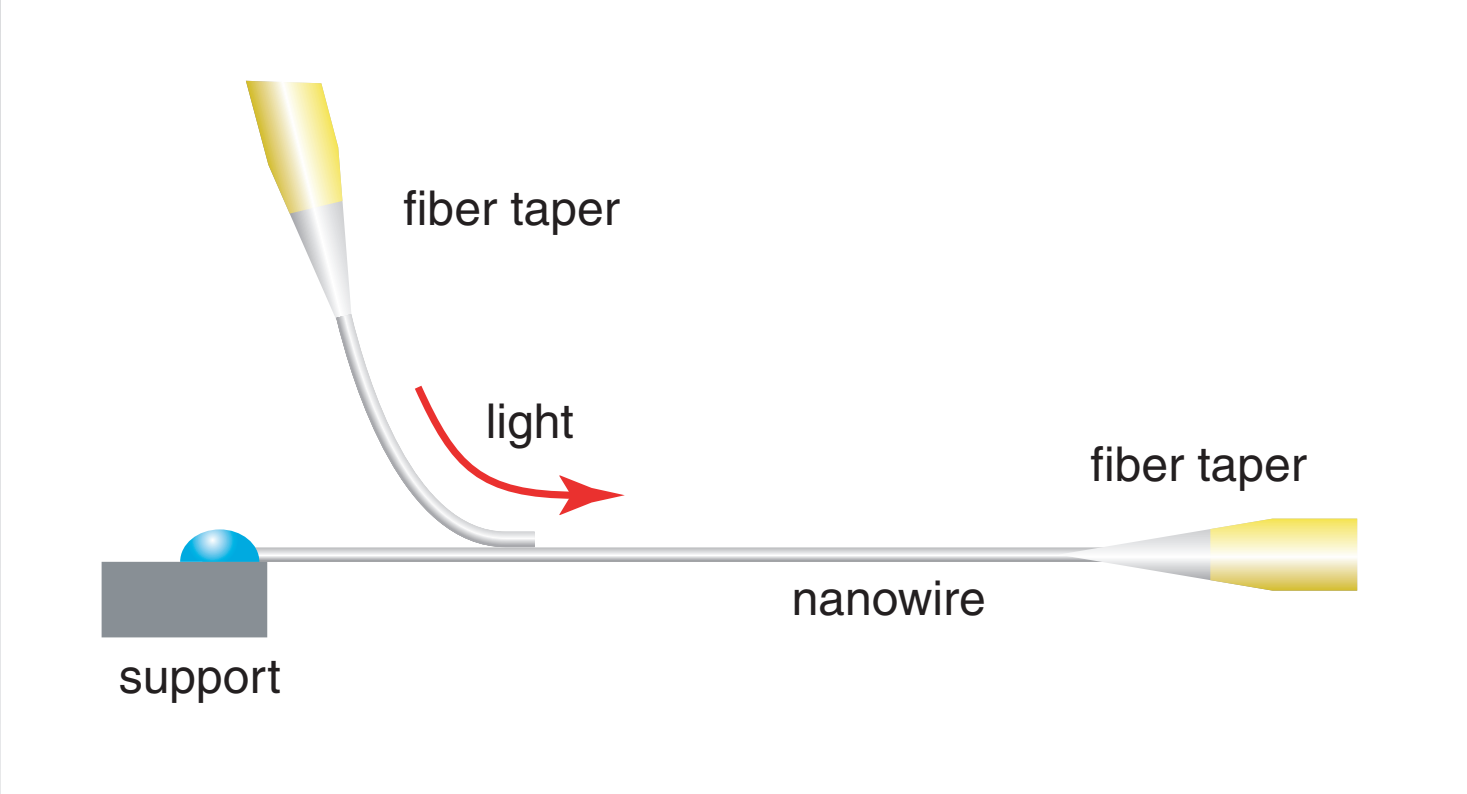
loss measurement



Nature, 426, 816 (2003)

Optical properties

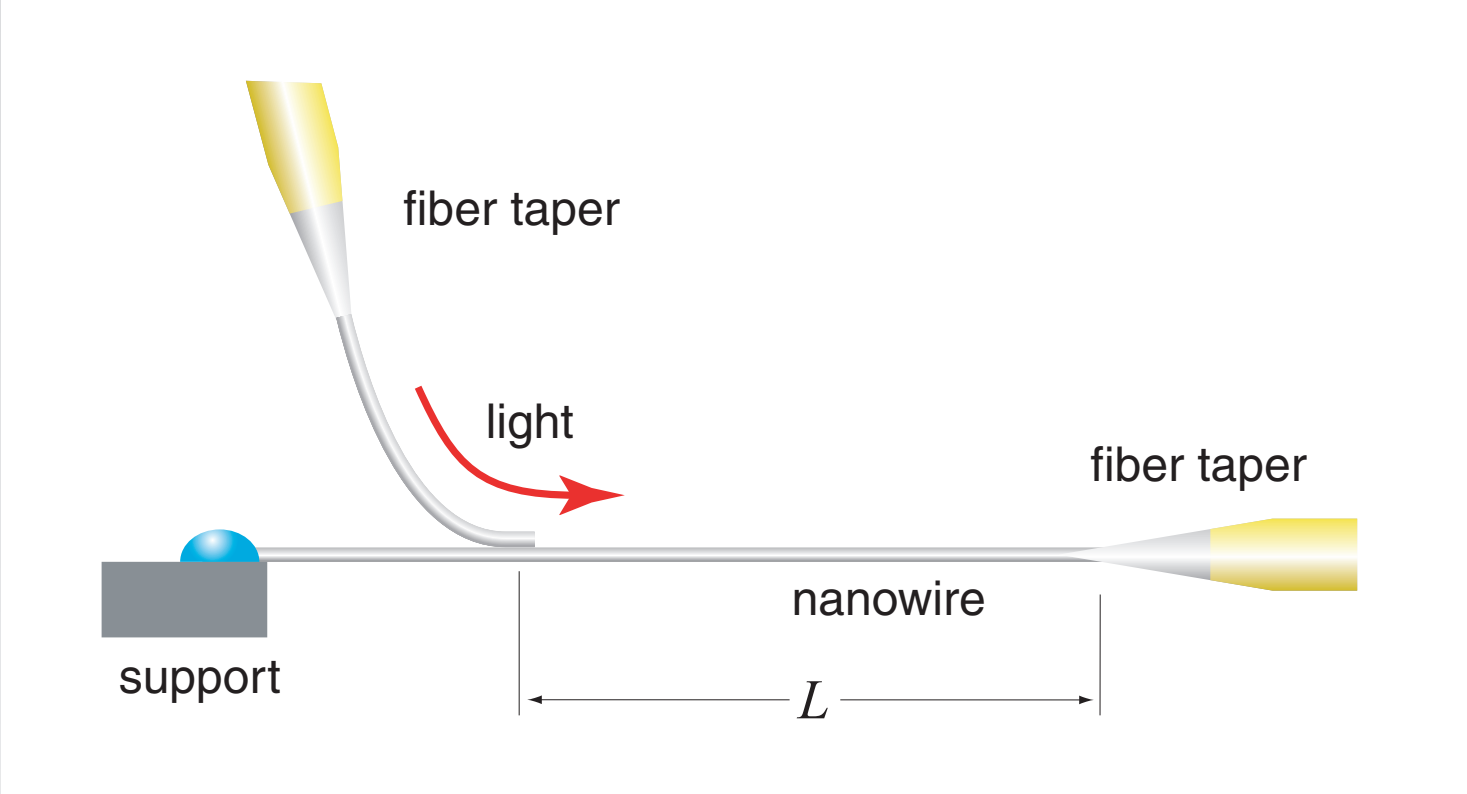
loss measurement



Nature, 426, 816 (2003)

Optical properties

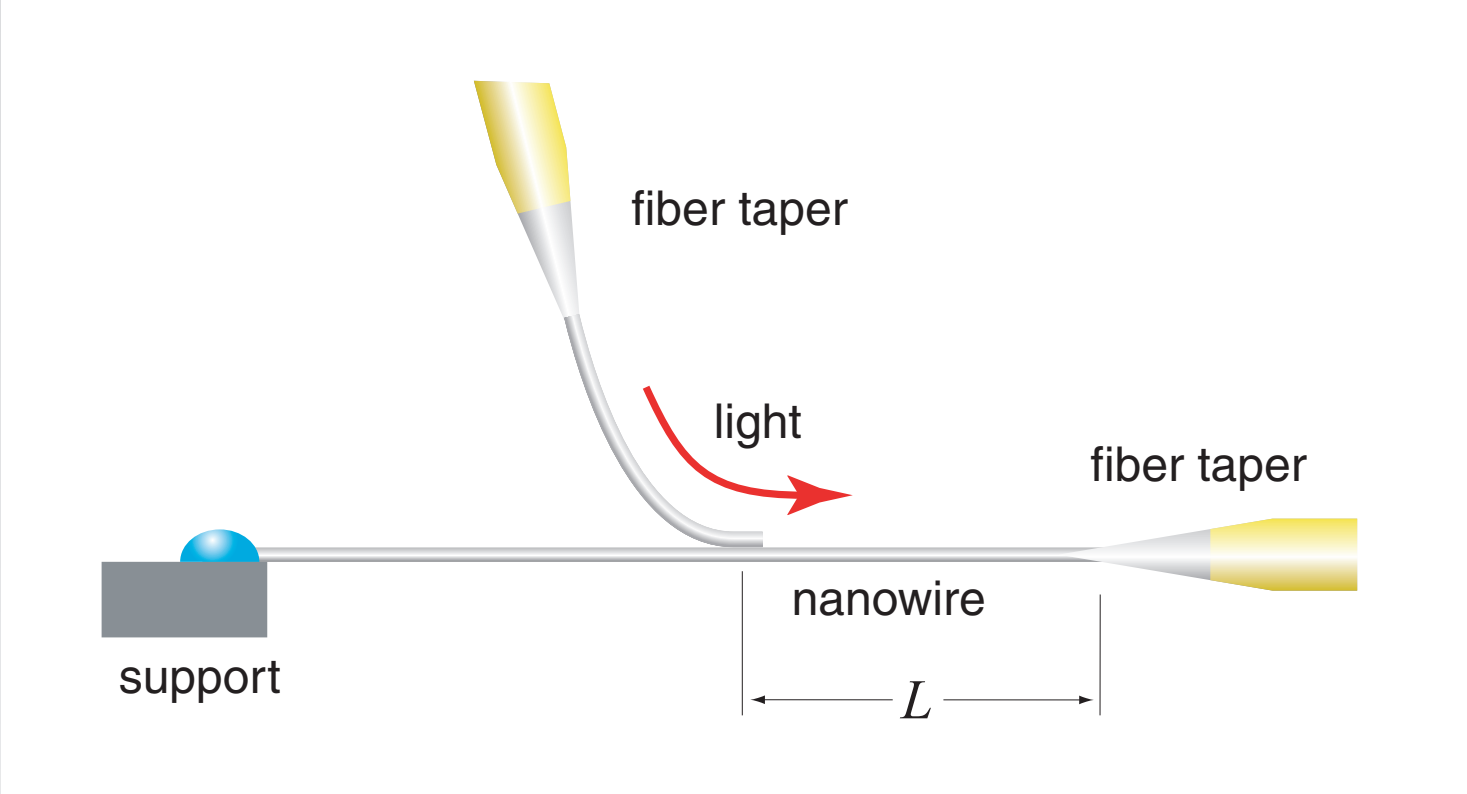
loss measurement



Nature, 426, 816 (2003)

Optical properties

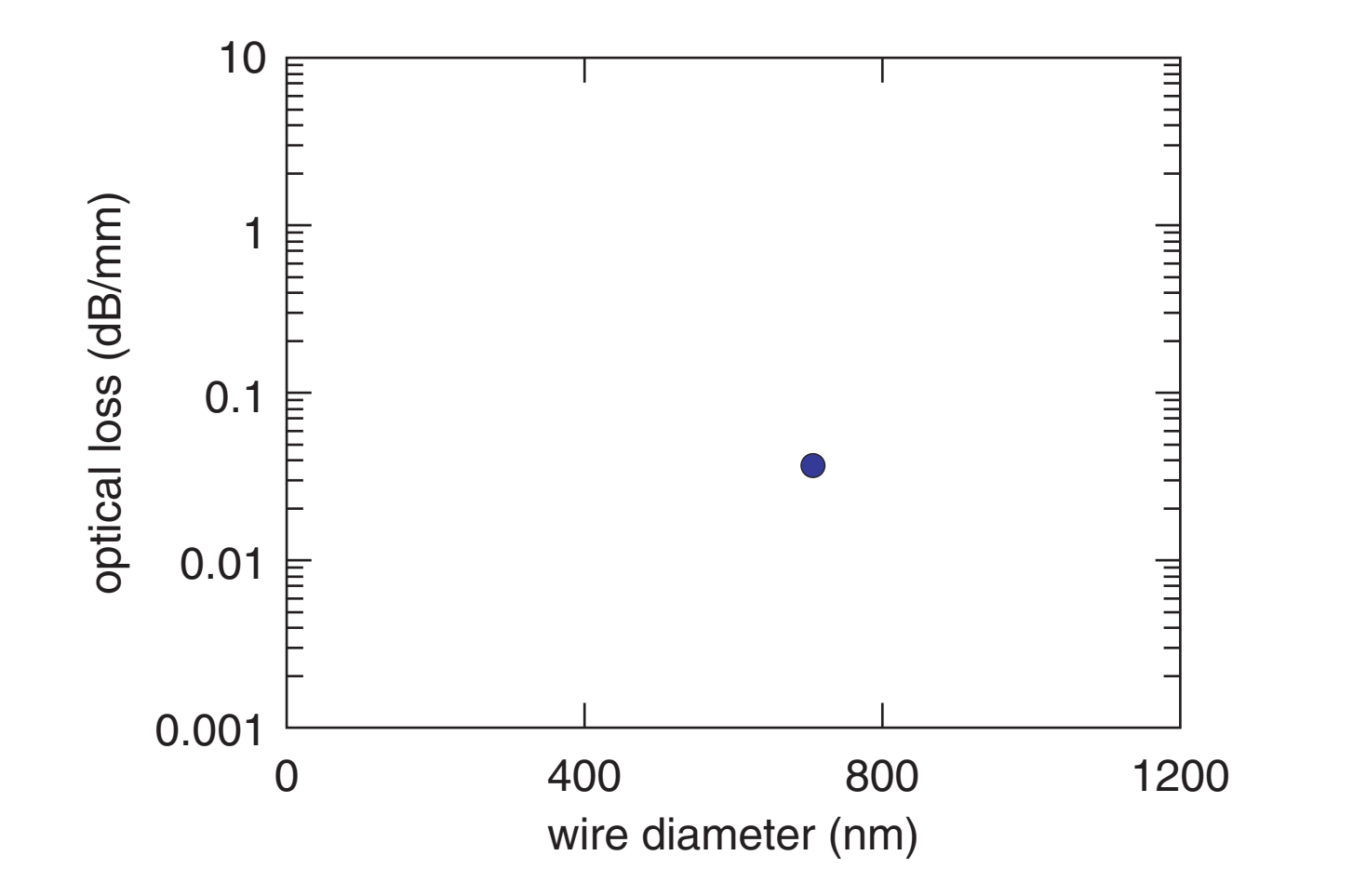
loss measurement



Nature, 426, 816 (2003)

Optical properties

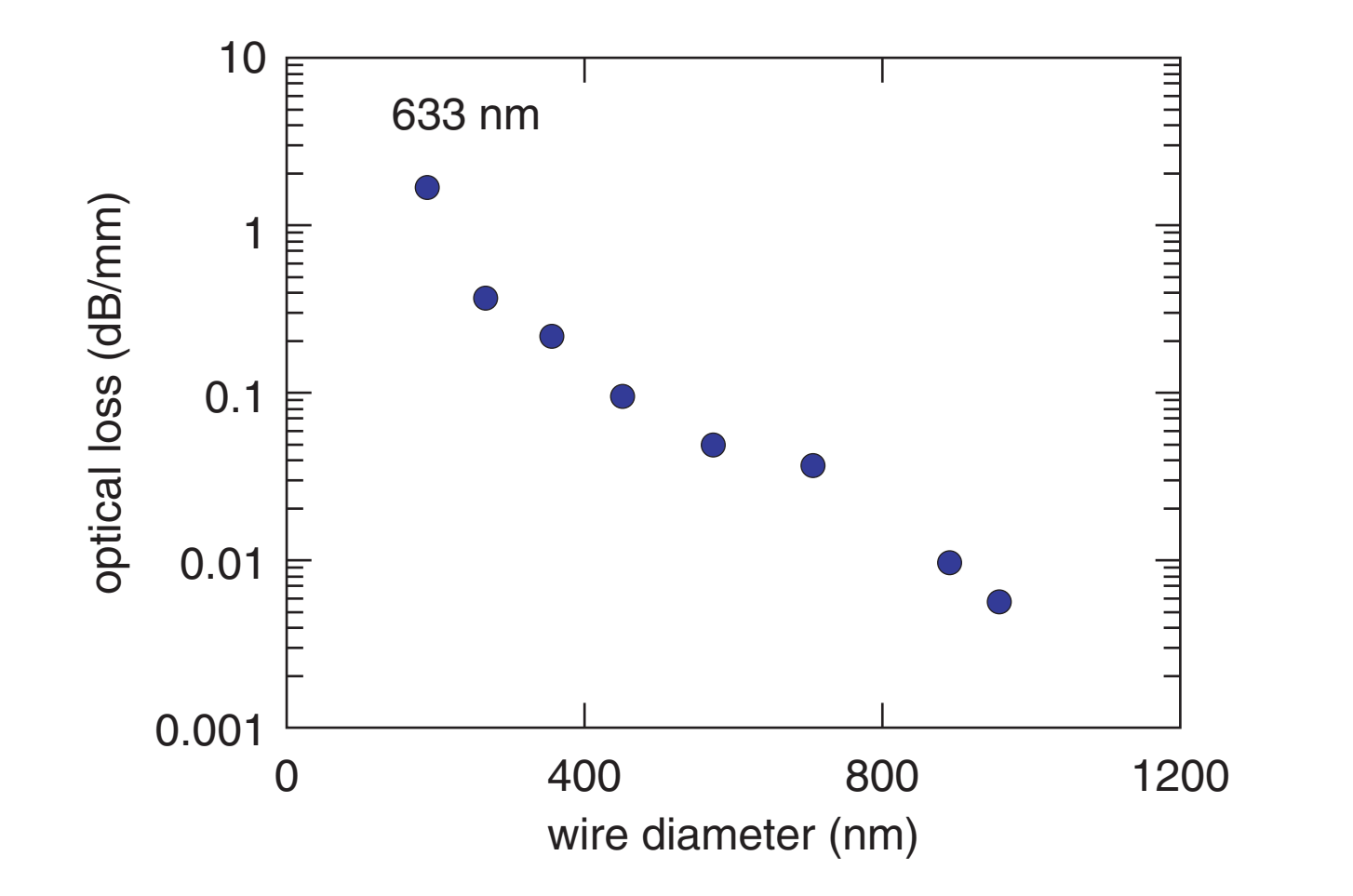
loss measurement



Nature, 426, 816 (2003)

Optical properties

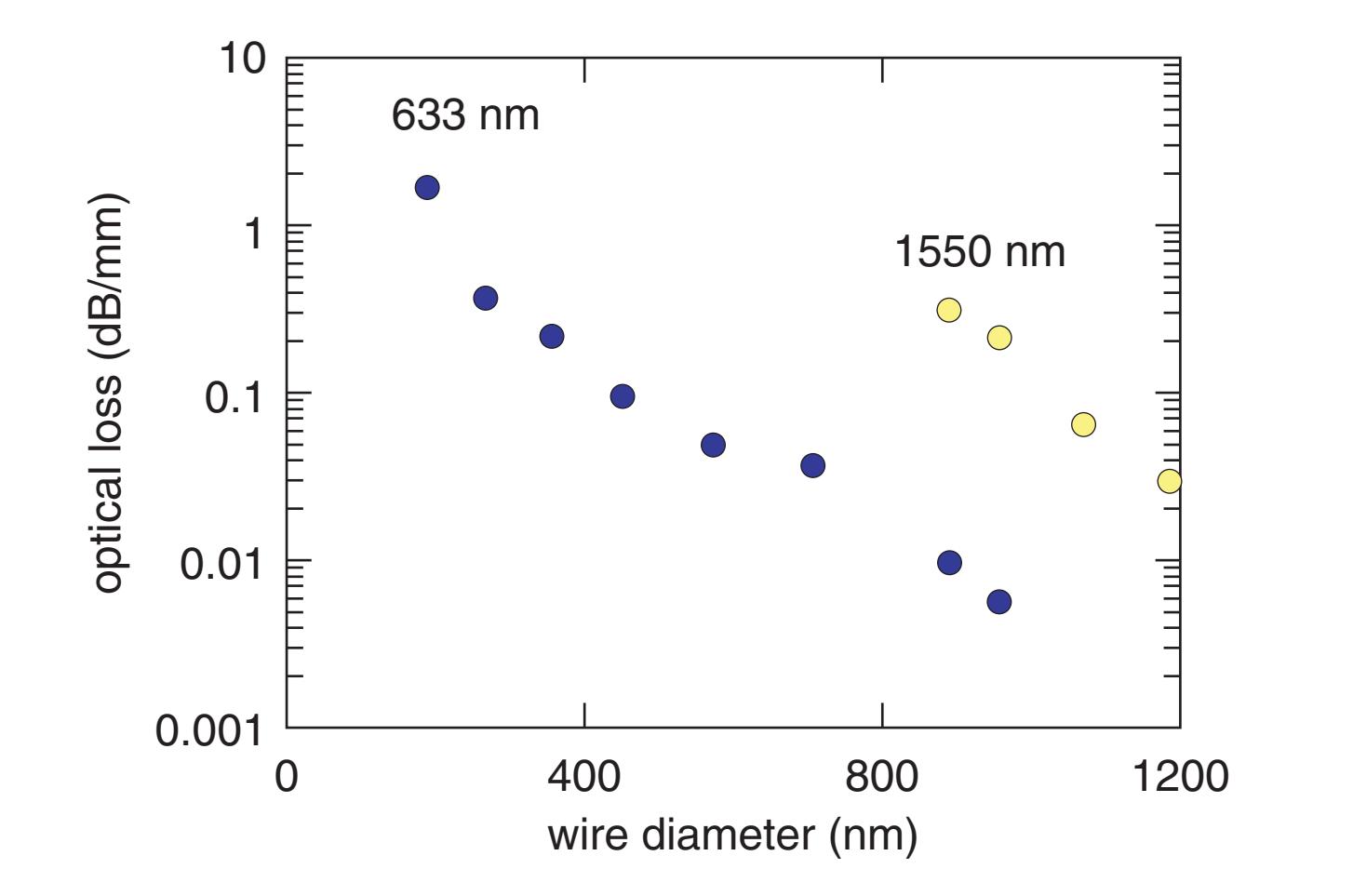
loss measurement



Nature, 426, 816 (2003)

Optical properties

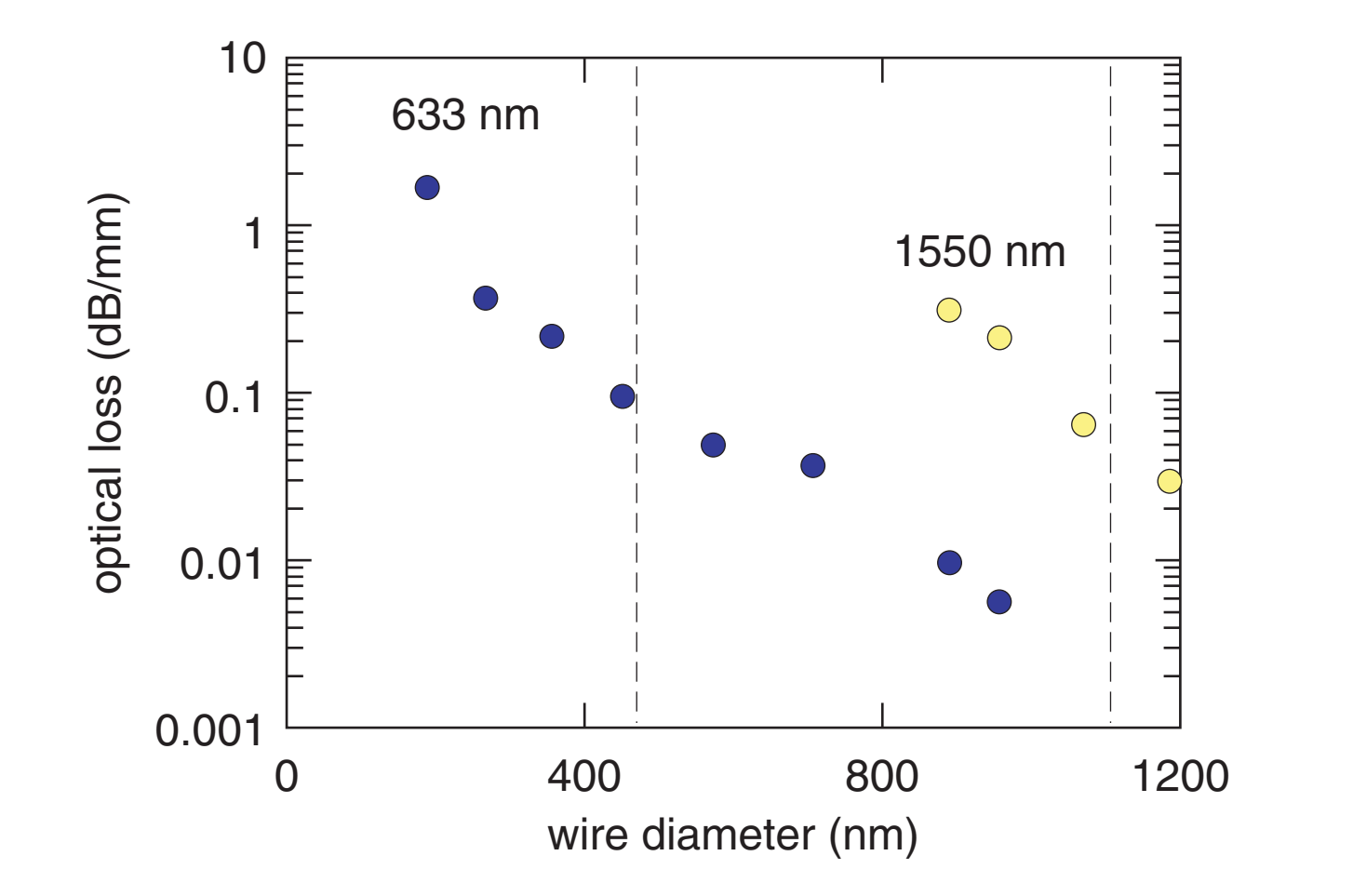
loss measurement



Nature, 426, 816 (2003)

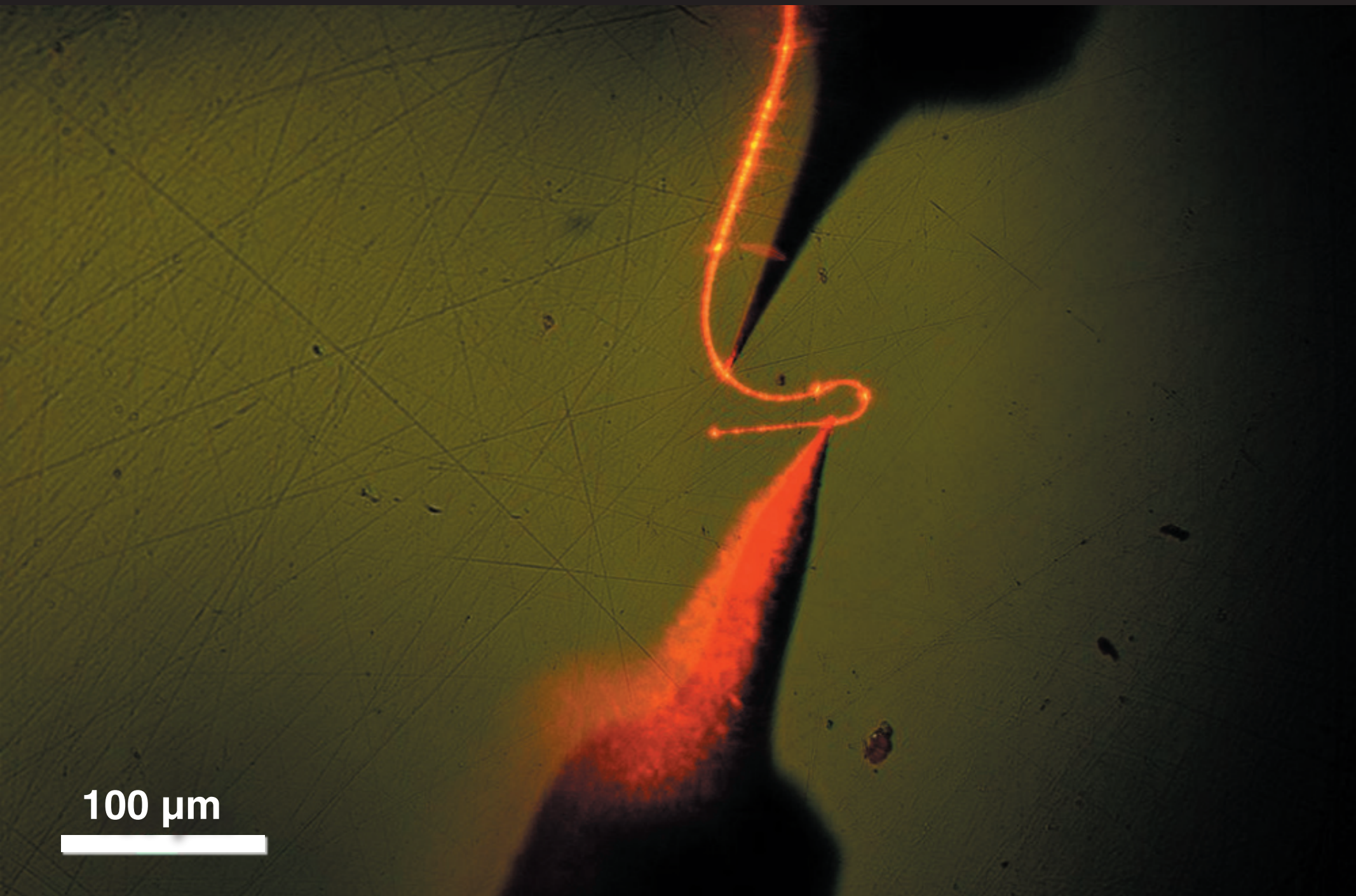
Optical properties

loss a single-mode diameter < 0.1 dB/mm

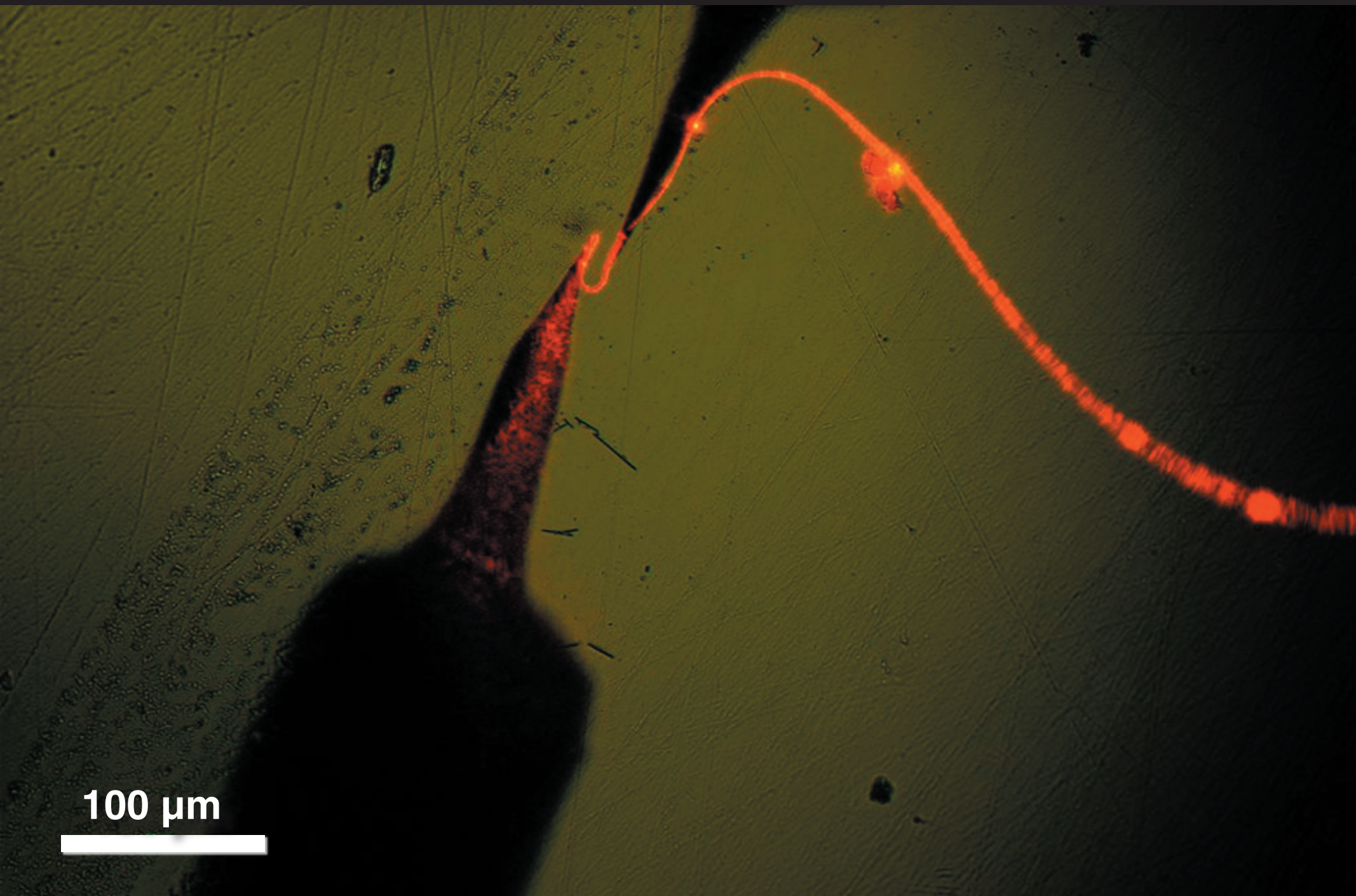


Nature, 426, 816 (2003)

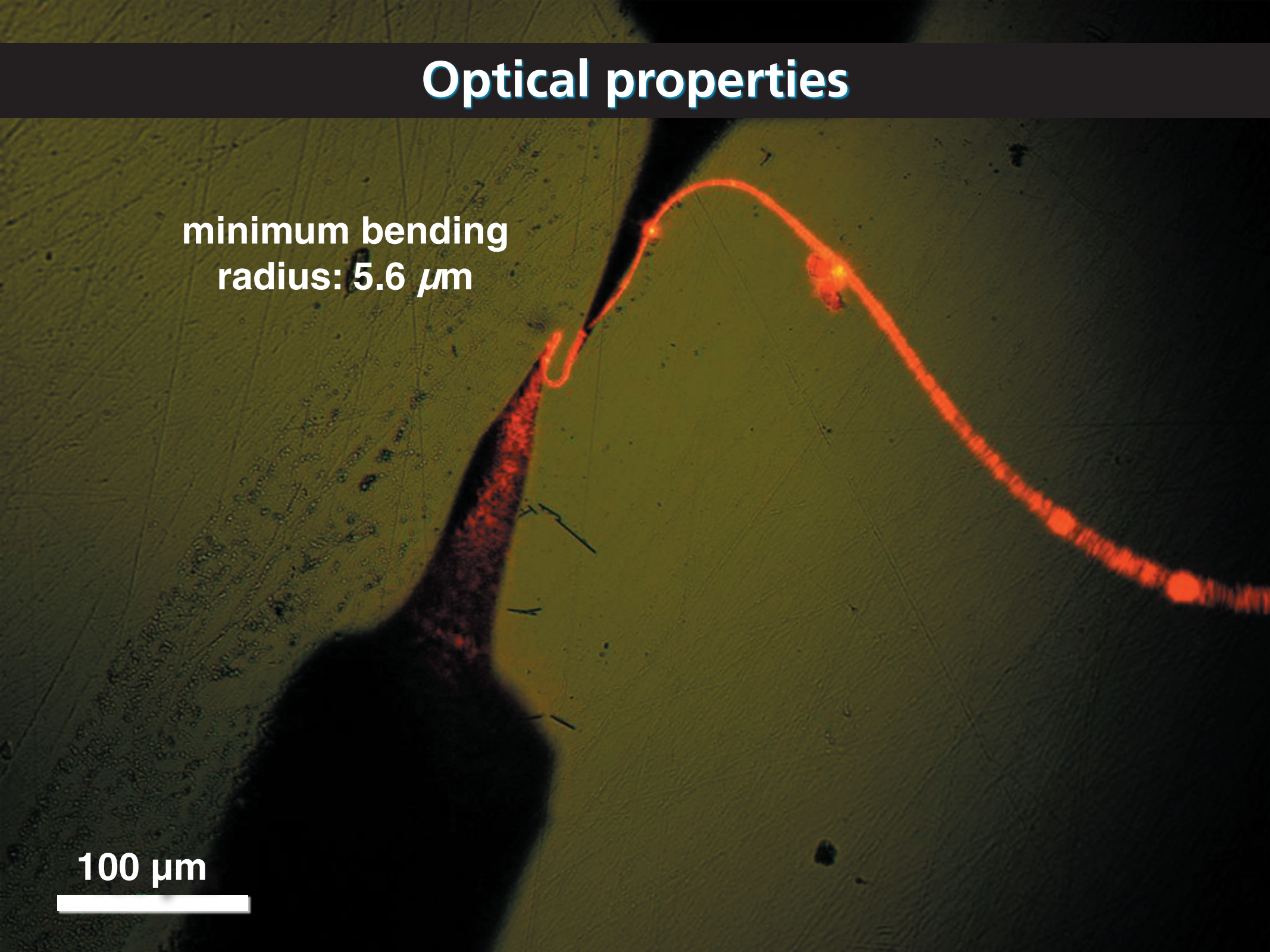
Optical properties



Optical properties

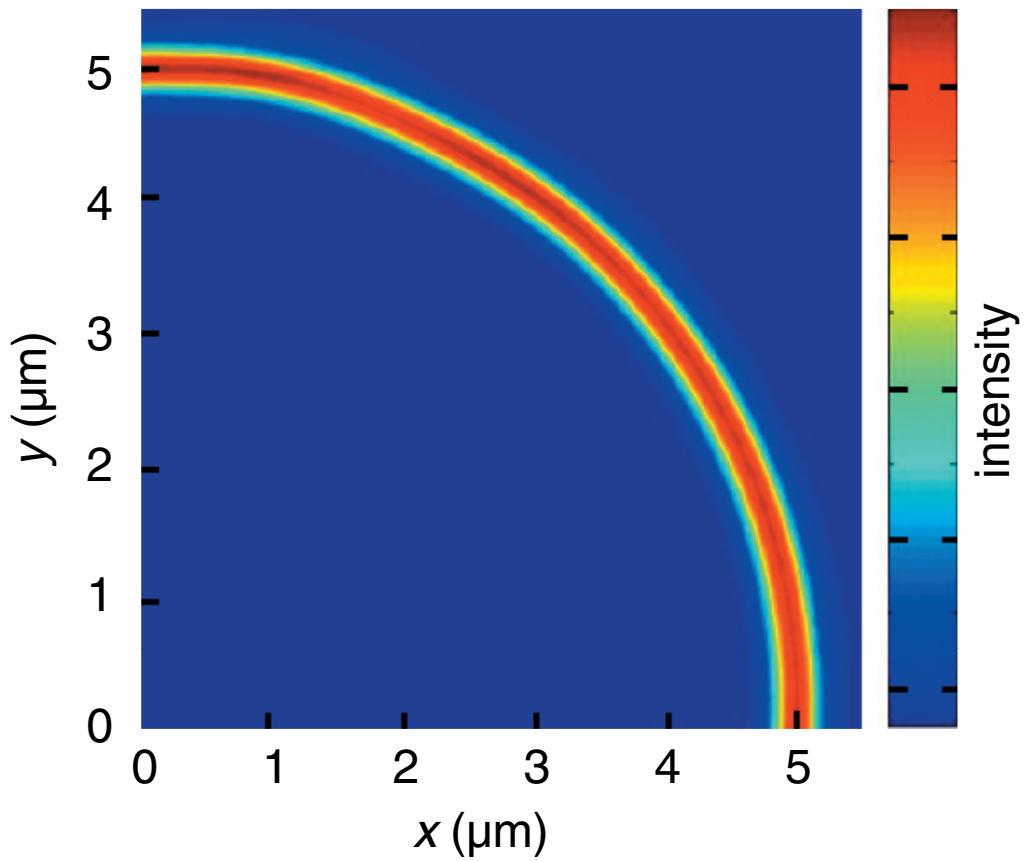


Optical properties



Optical properties

virtually no loss through 5 μm corner!



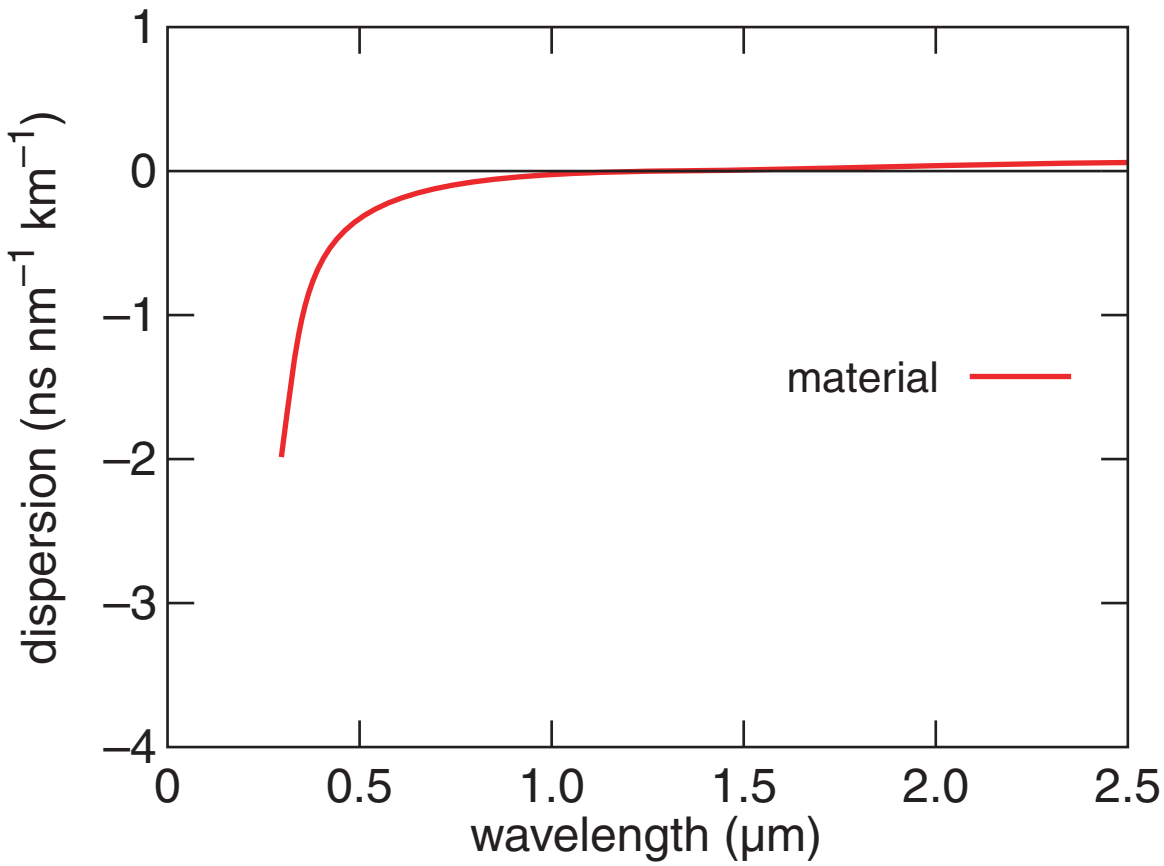
Optical properties

dispersion:

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

Optical properties

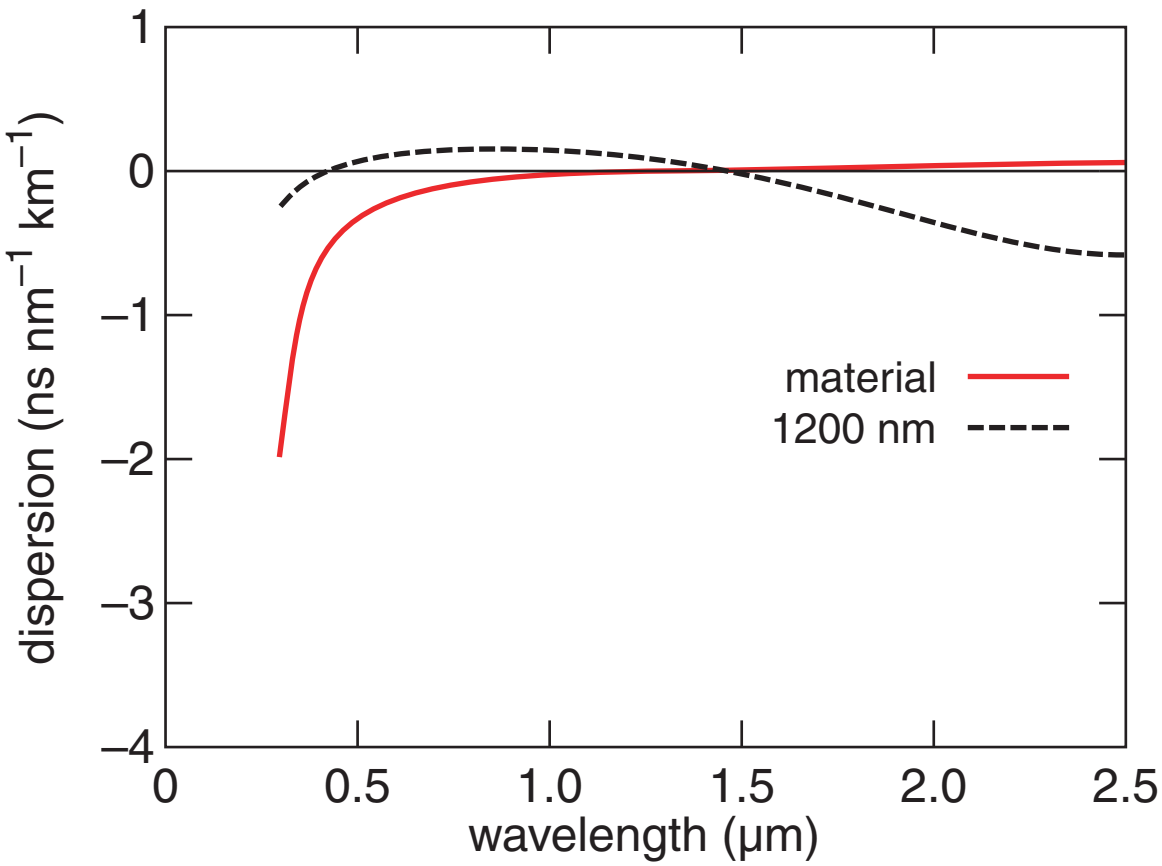
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

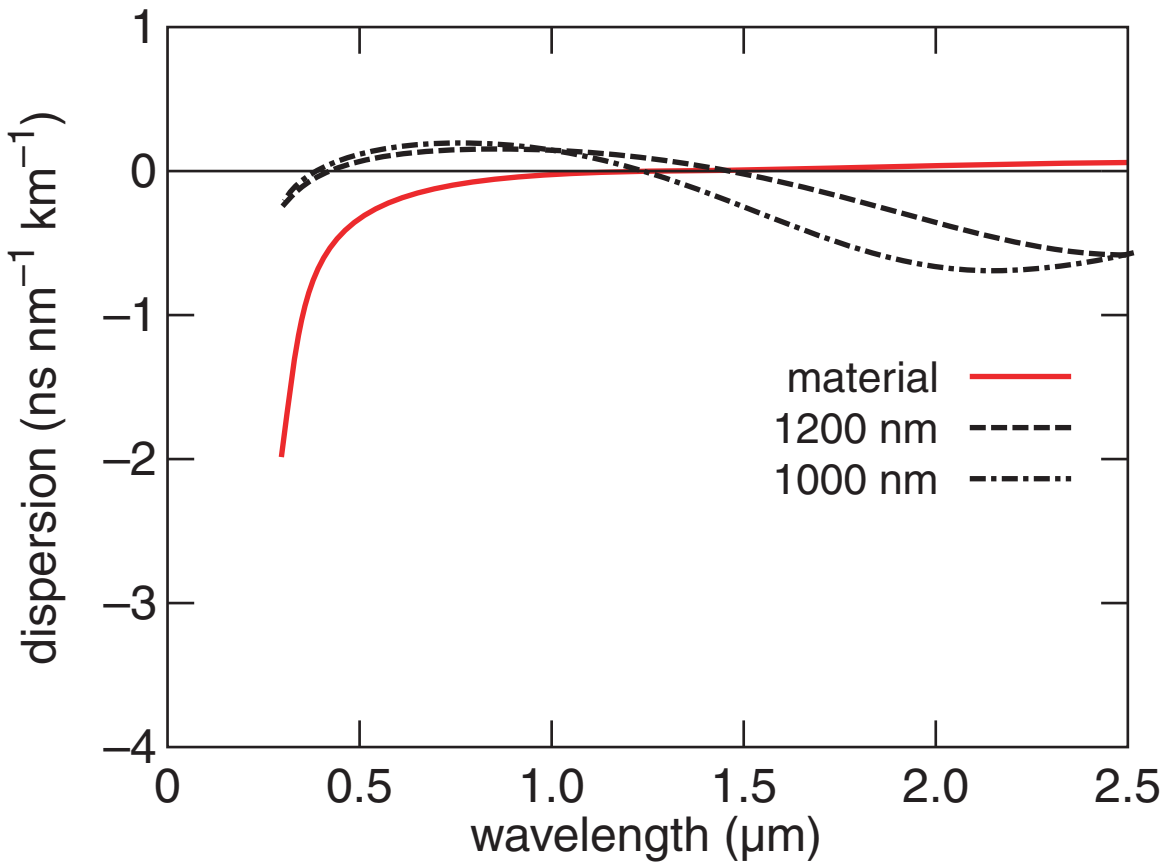
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

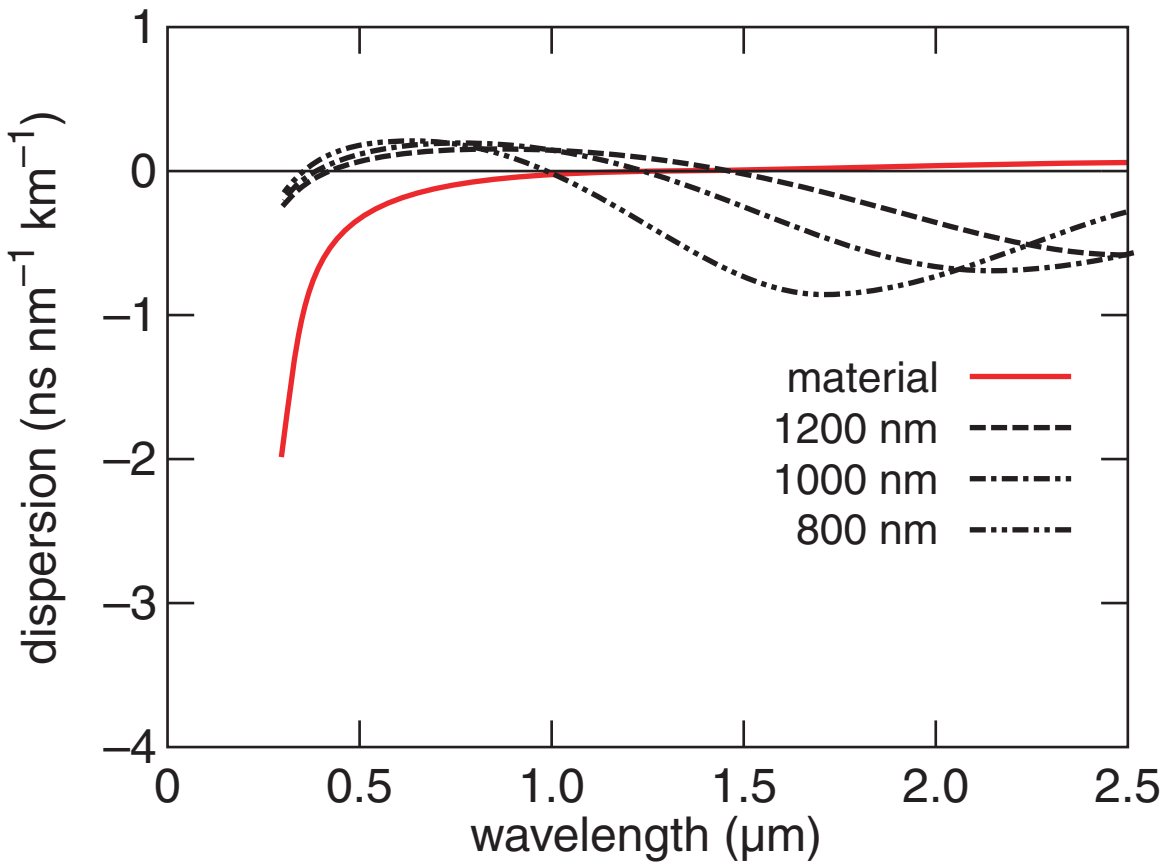
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

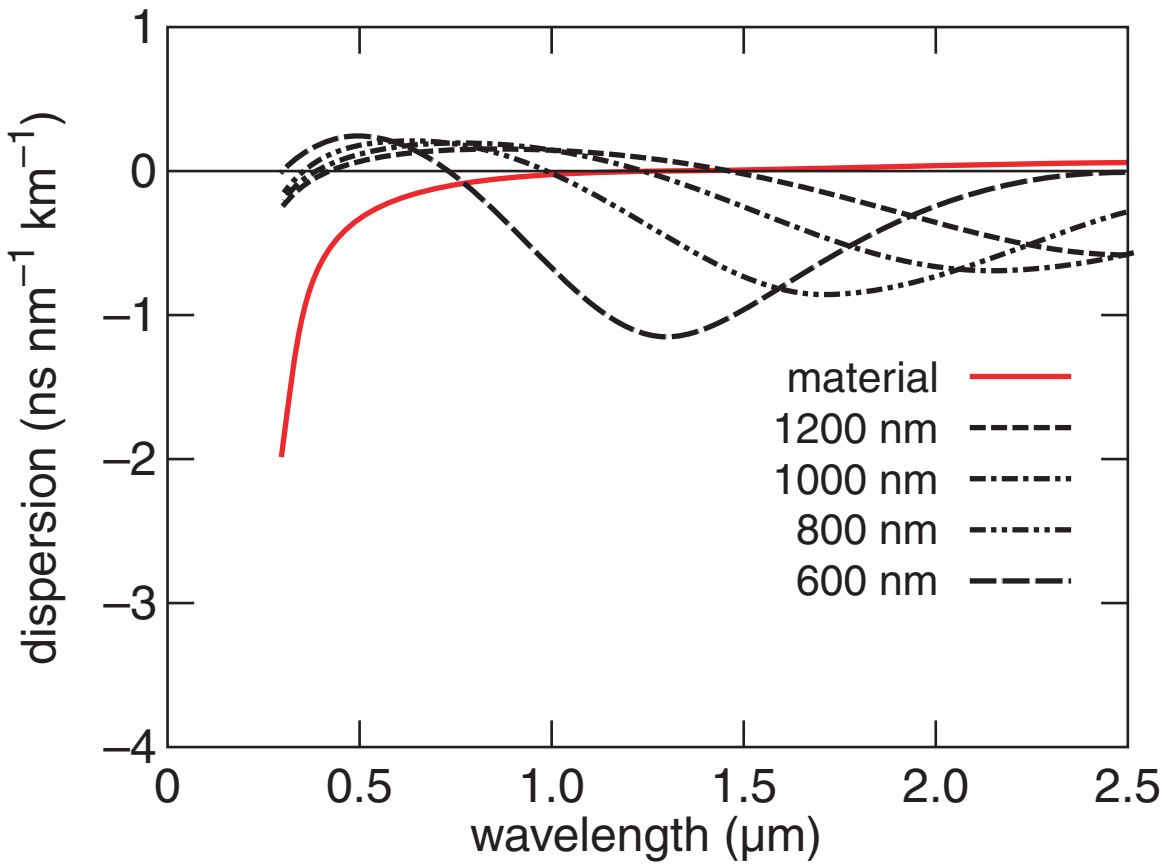
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

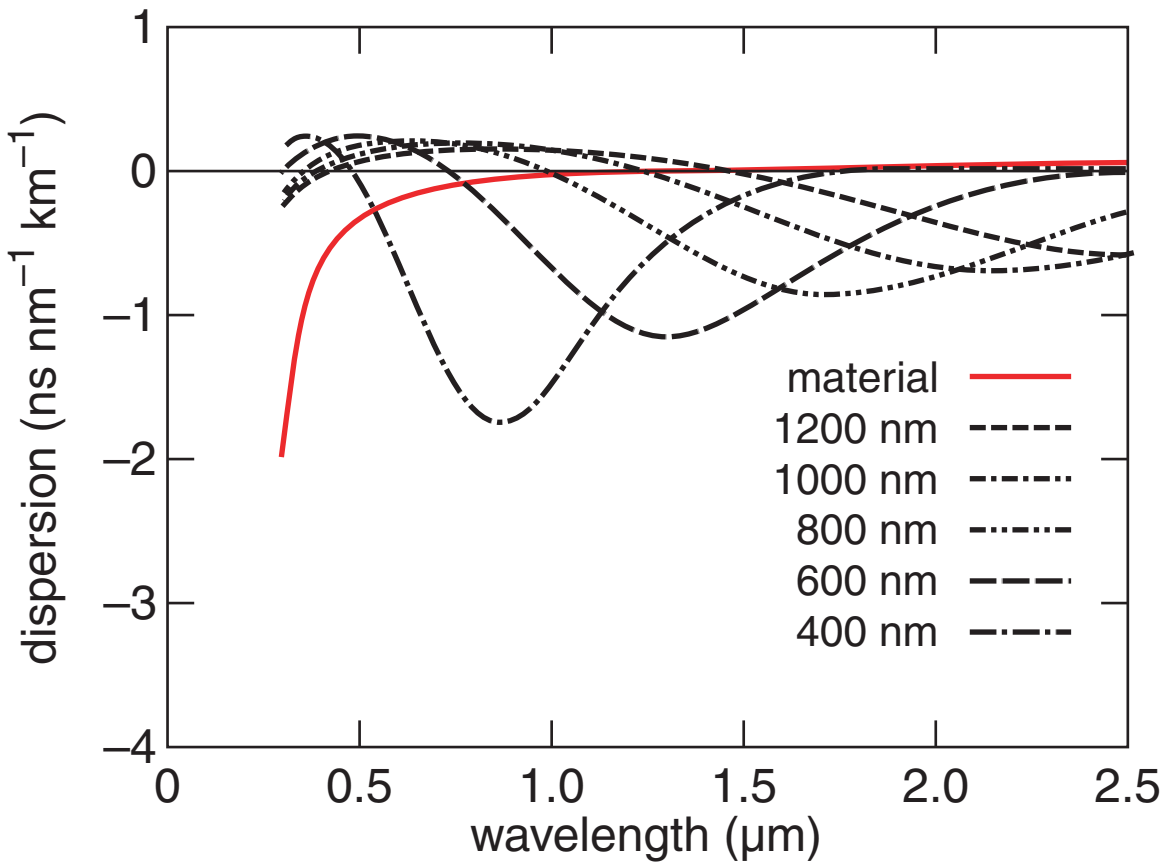
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

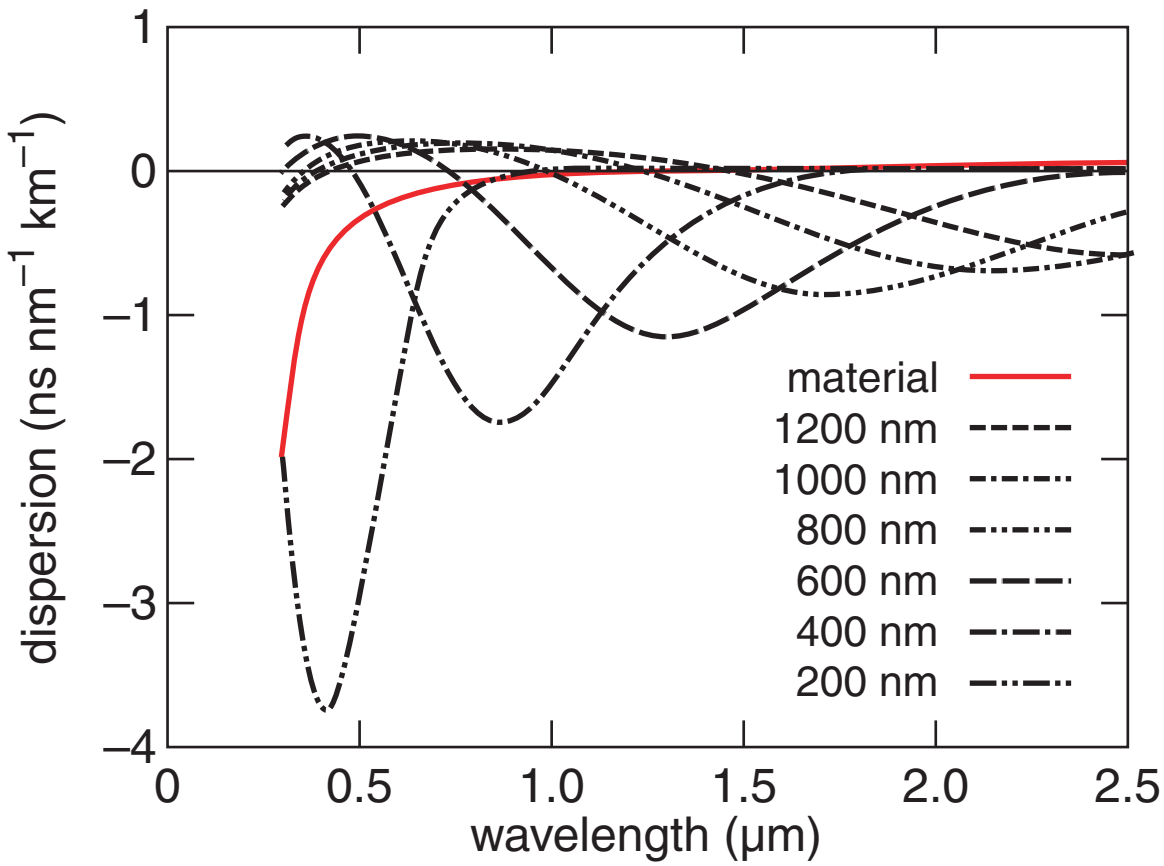
waveguide dispersion



Optics Express, 12, 1025 (2004)

Optical properties

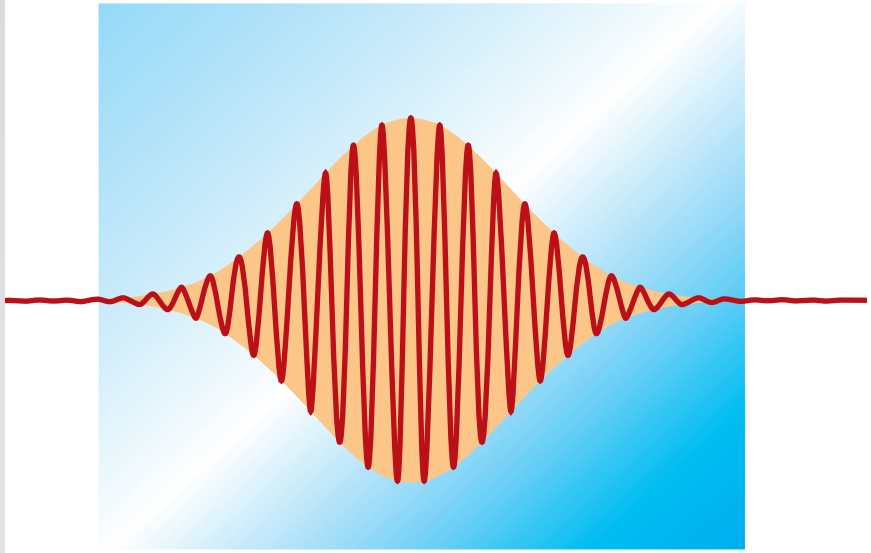
waveguide dispersion



Optics Express, 12, 1025 (2004)

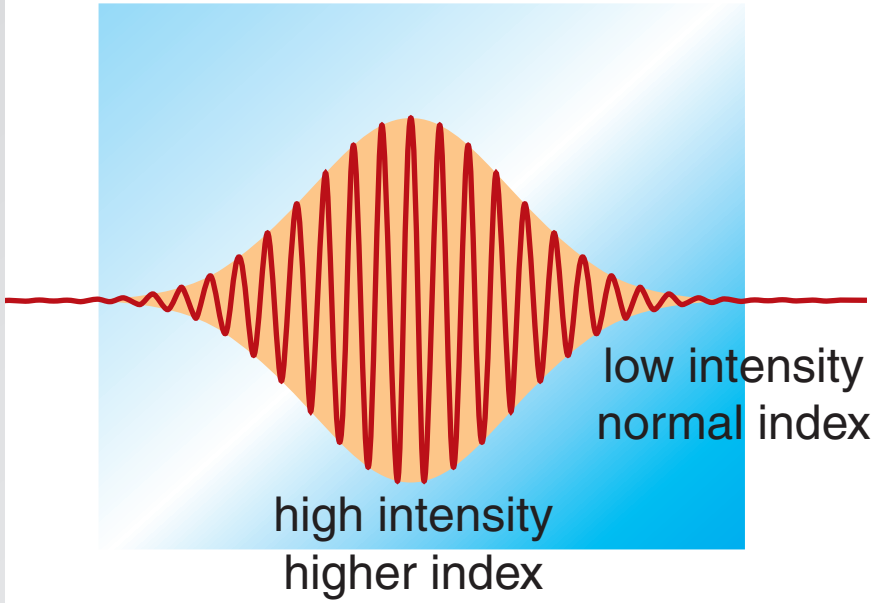
Optical properties

nonlinear dispersion: $n = n_o + n_2 I$



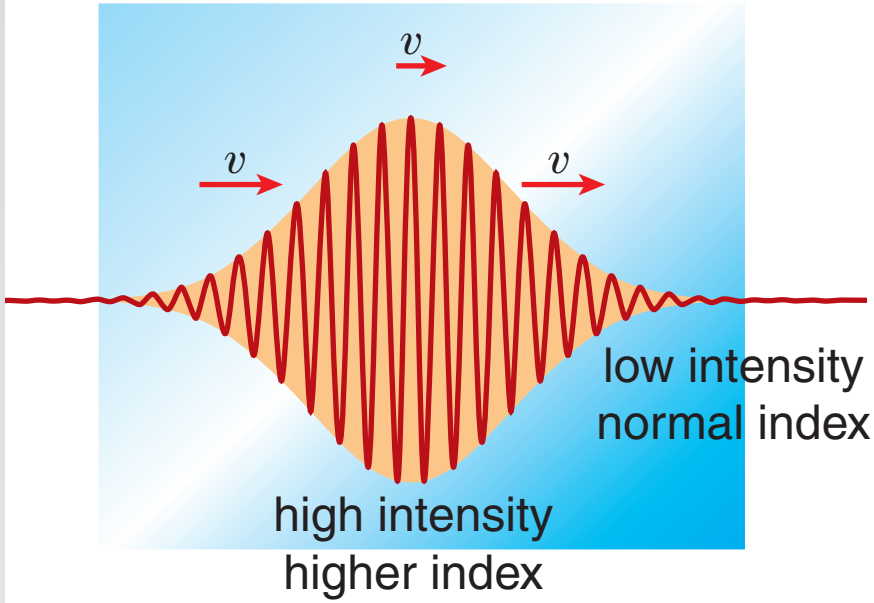
Optical properties

nonlinear dispersion: $n = n_o + n_2 I$



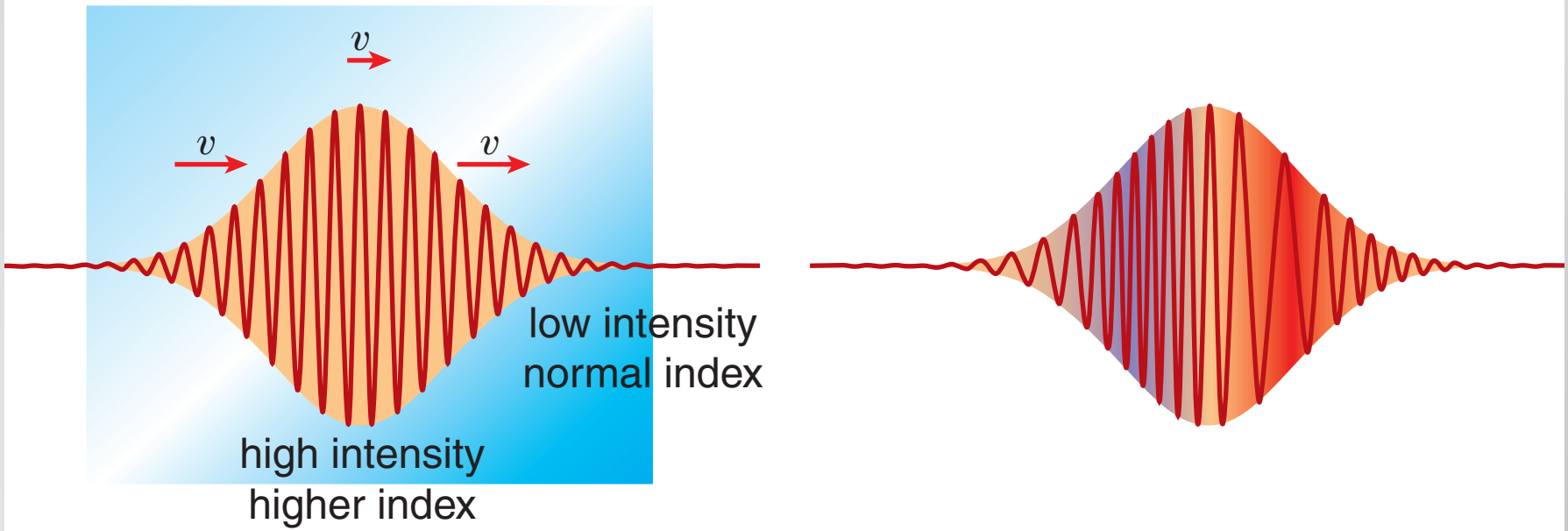
Optical properties

nonlinear dispersion: $n = n_o + n_2 I$



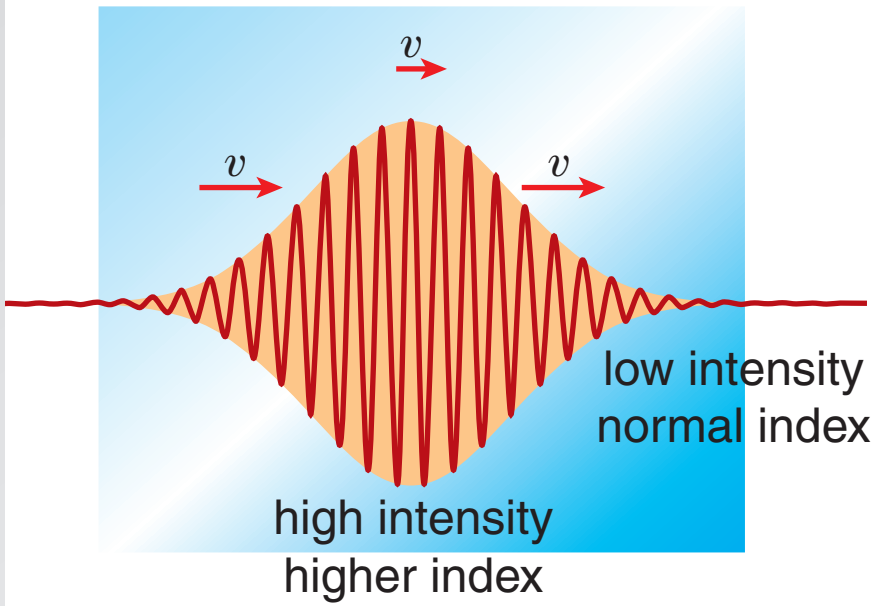
Optical properties

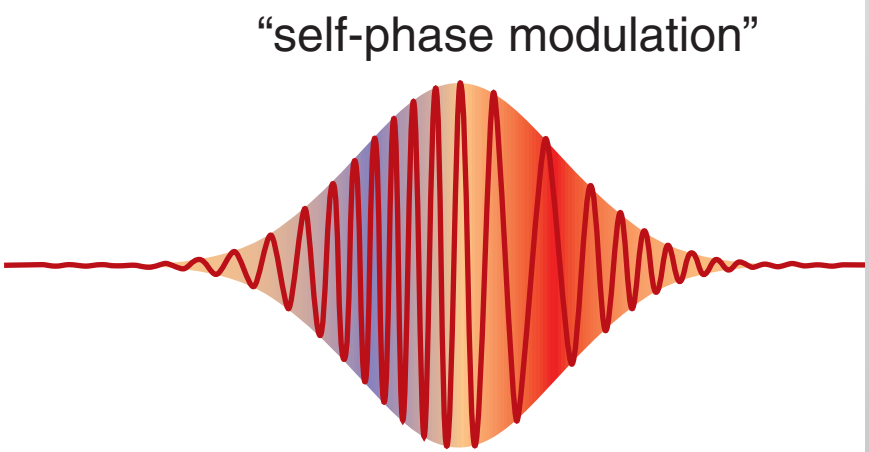
nonlinear dispersion: $n = n_o + n_2 I$



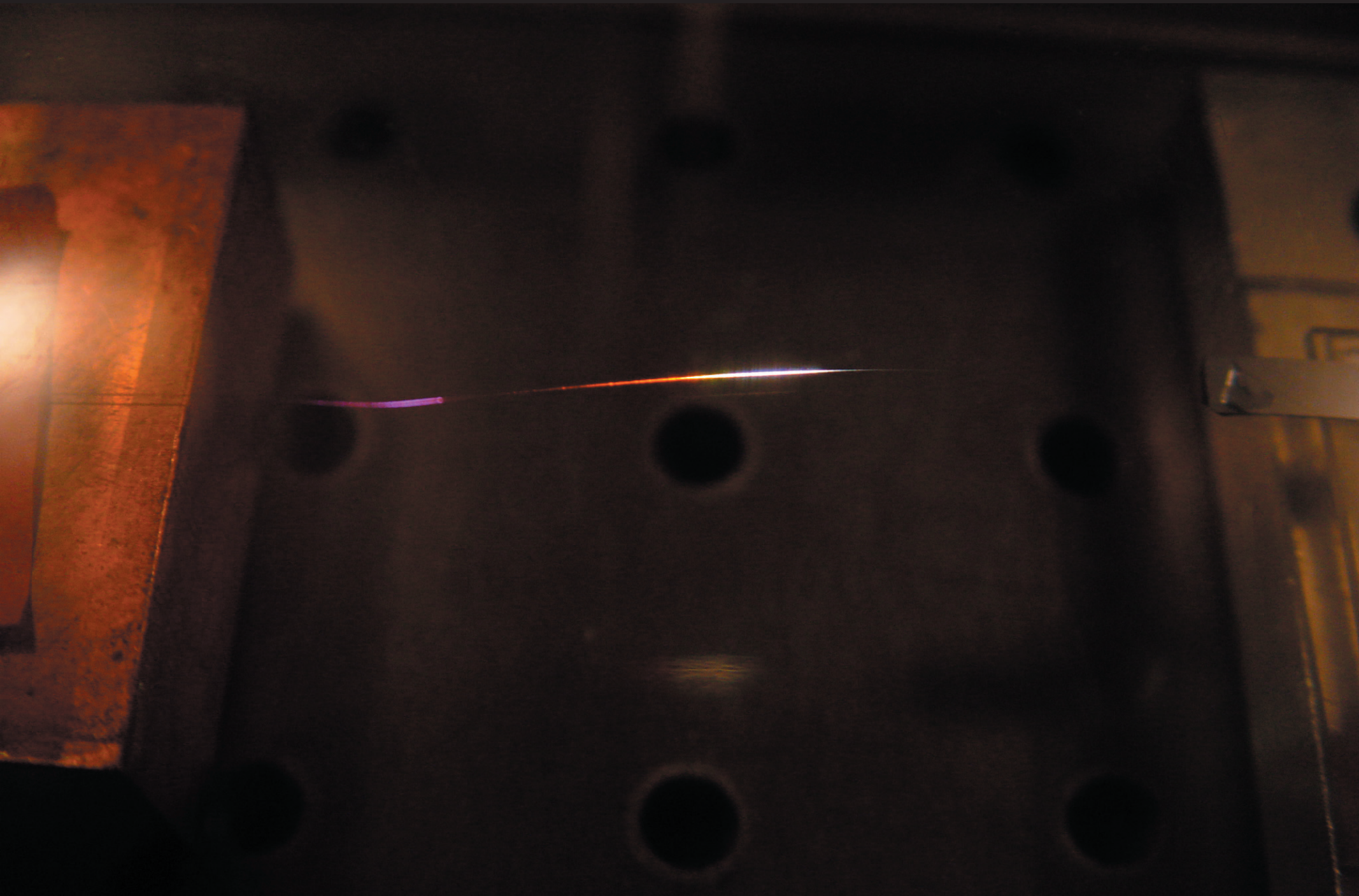
Optical properties

nonlinear dispersion: $n = n_o + n_2 I$

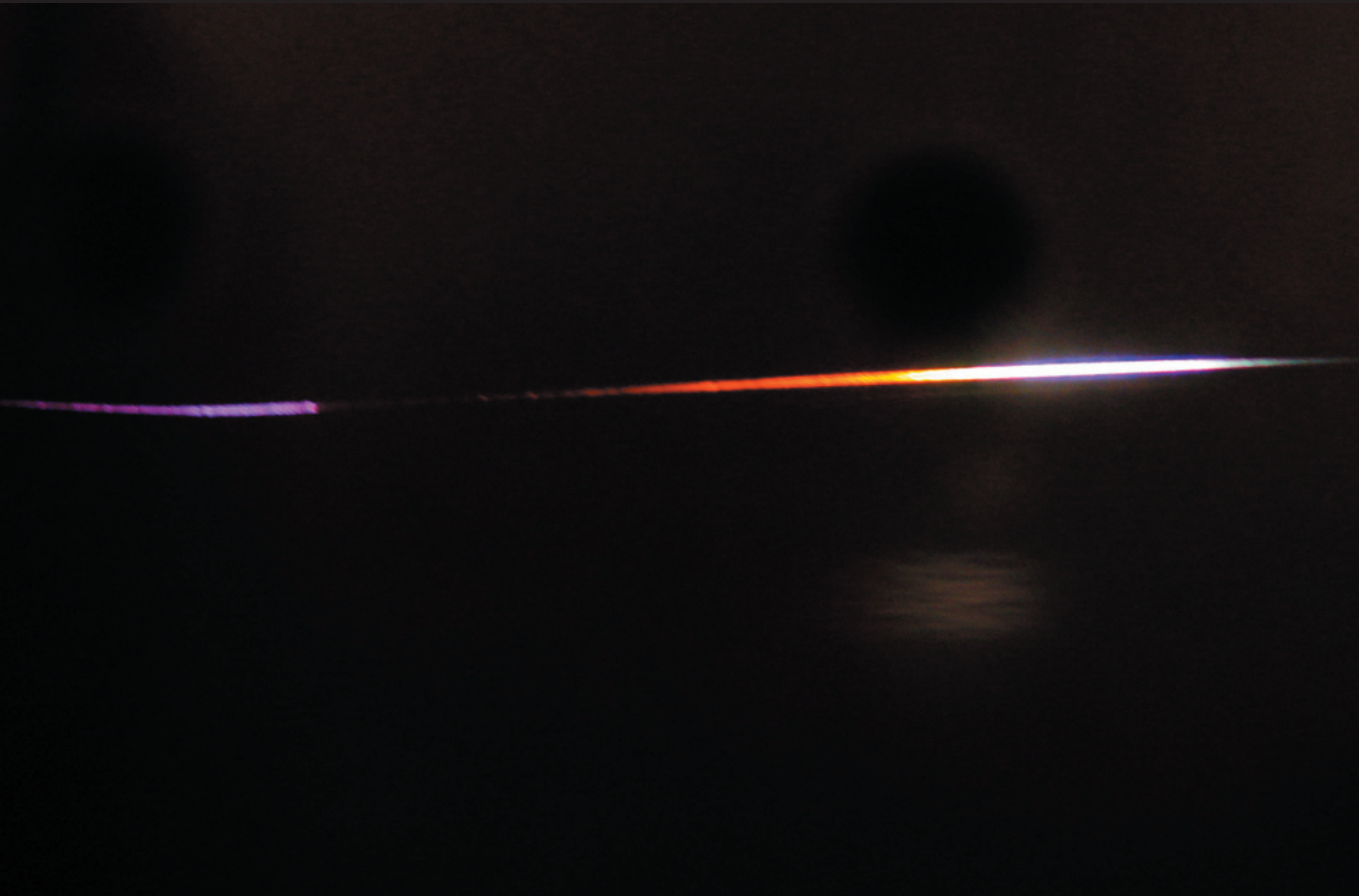




Optical properties

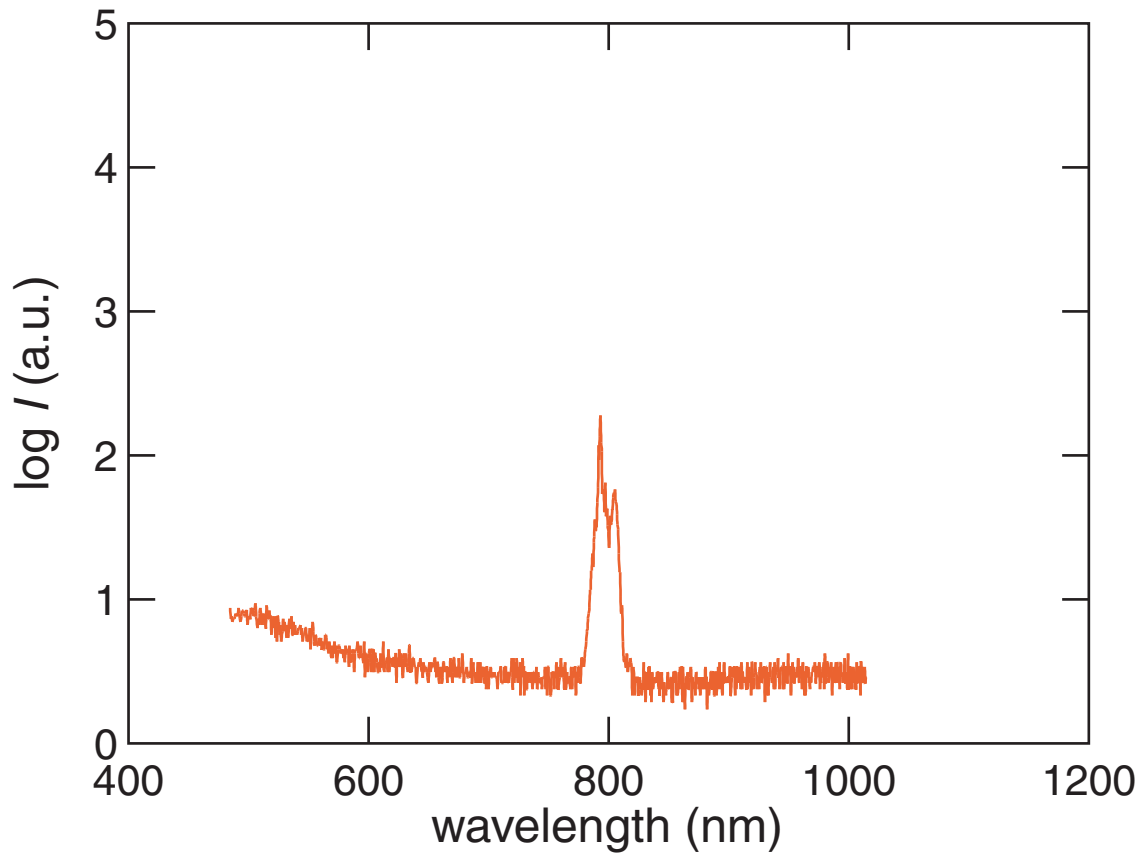


Optical properties



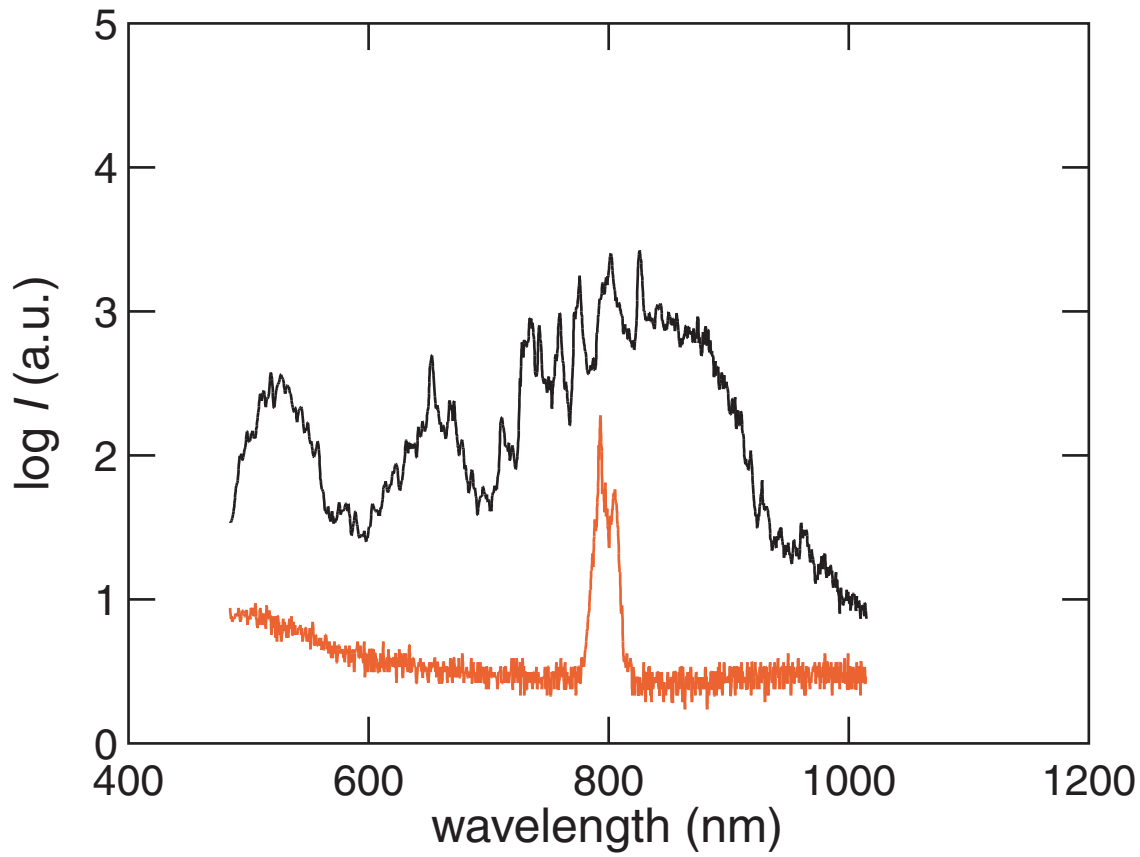
Optical properties

self-phase modulation



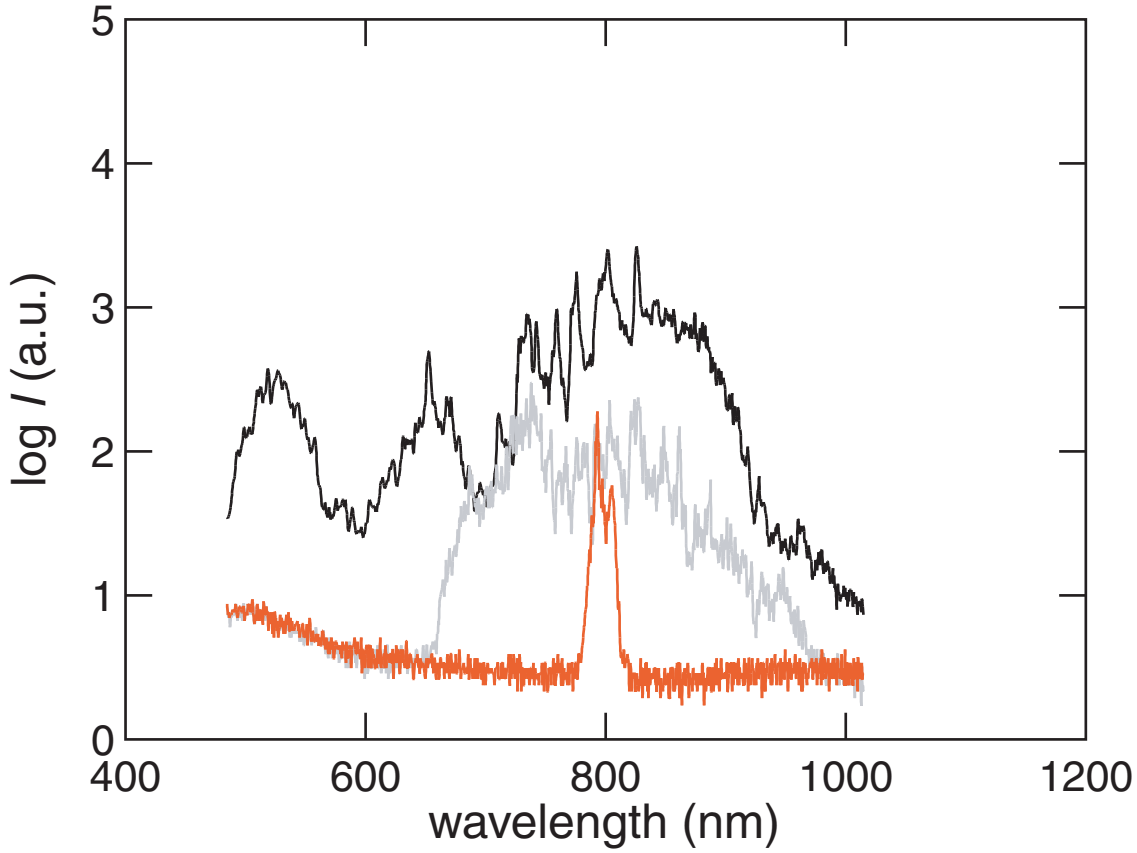
Optical properties

self-phase modulation

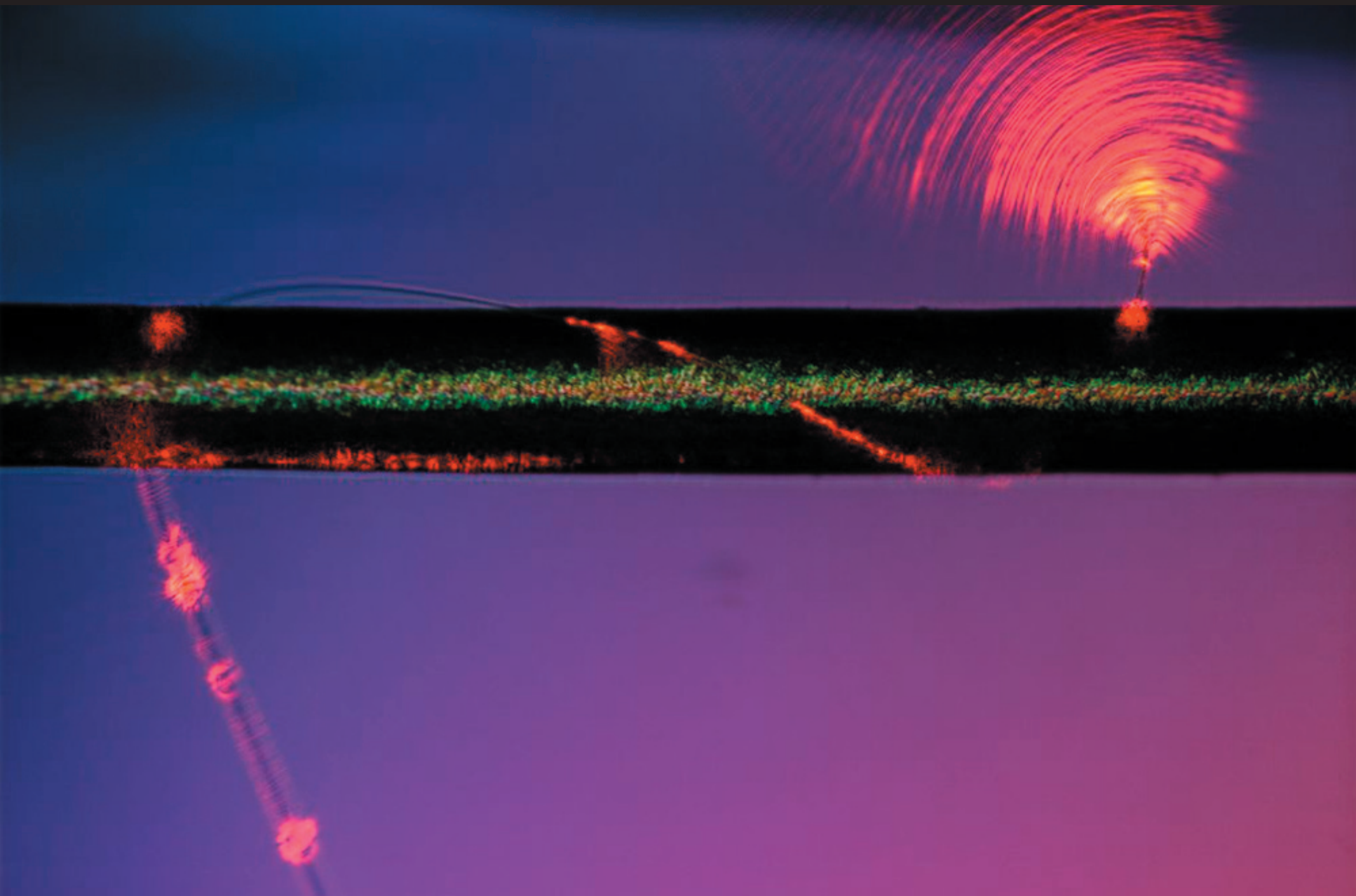


Optical properties

self-phase modulation



Summary



Summary

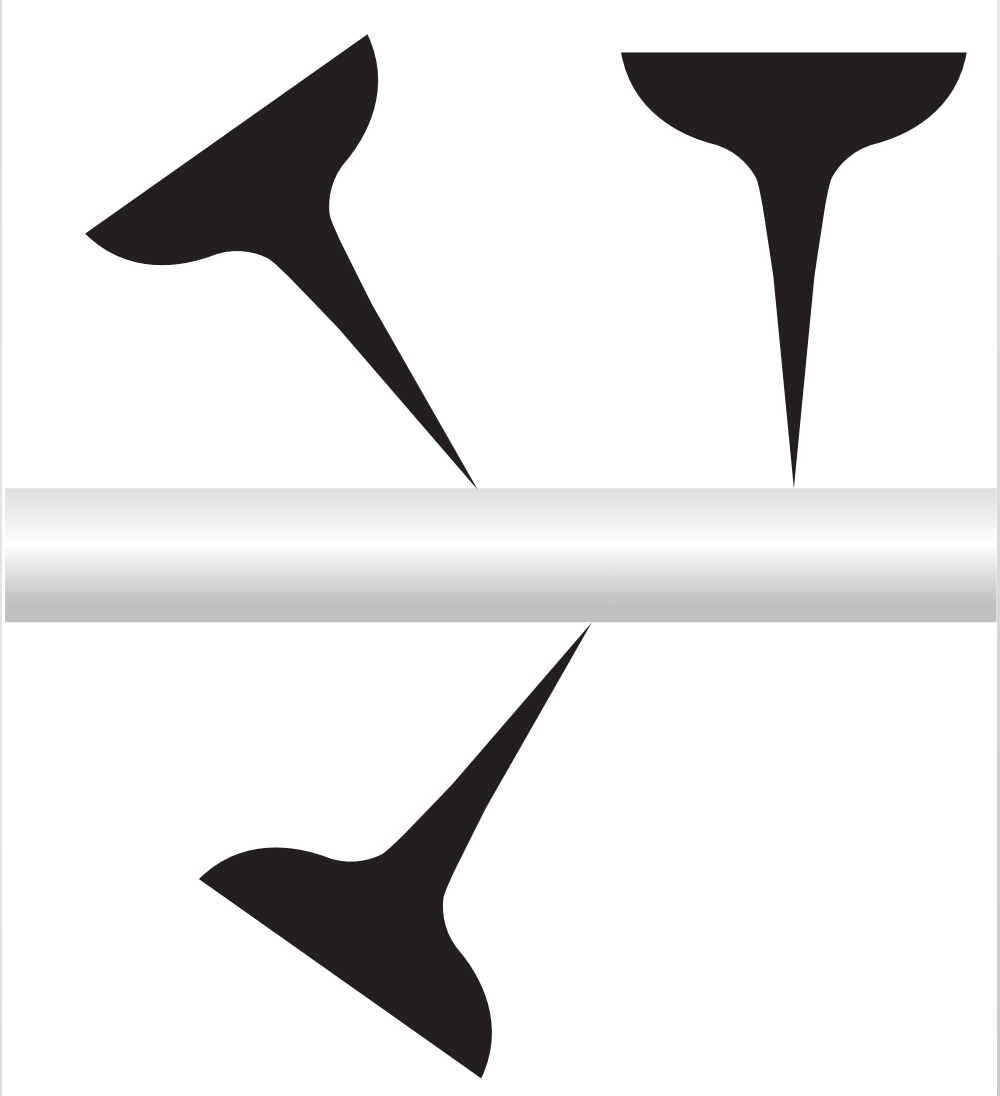
- strong confinement
- very tight bending
- large evanescent wave

Outlook

microphotonic components

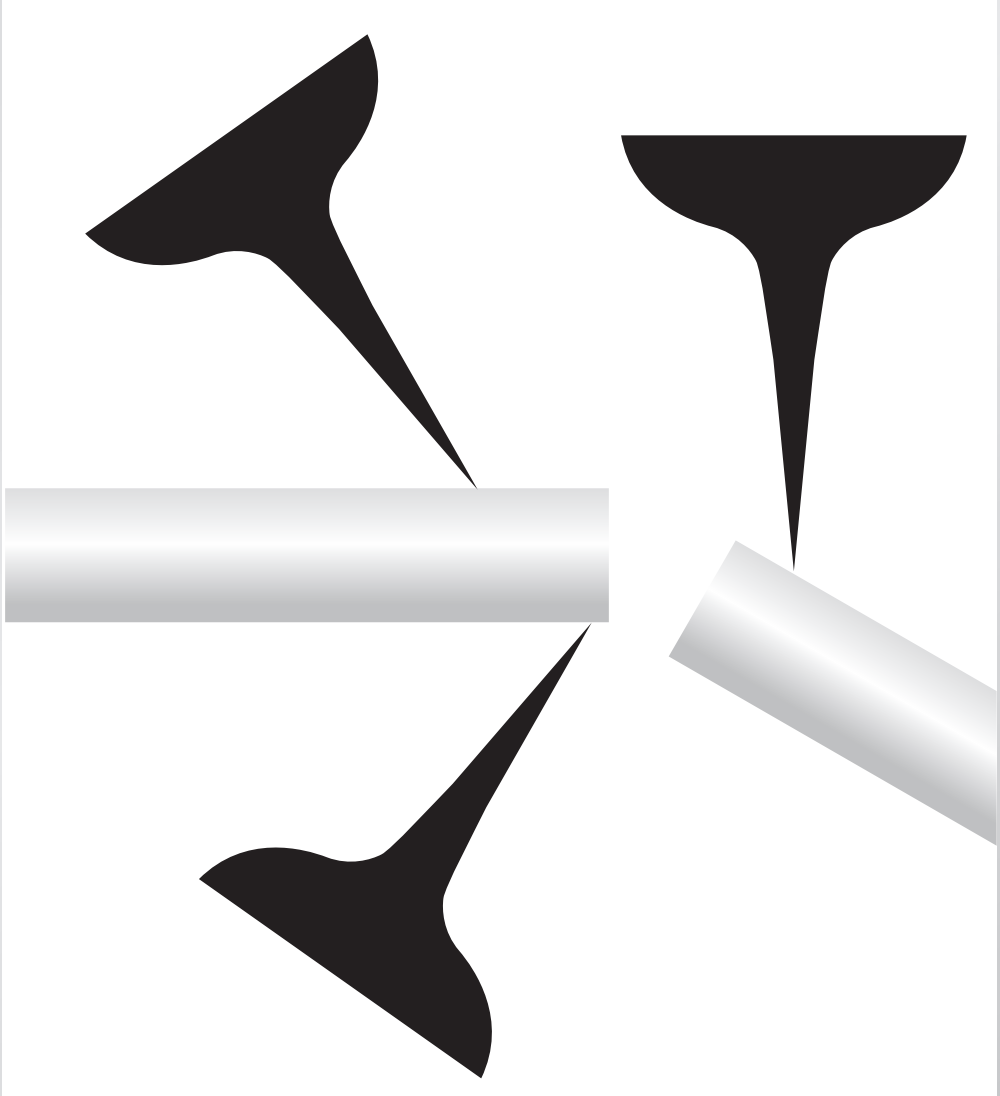
Outlook

microphotonic components

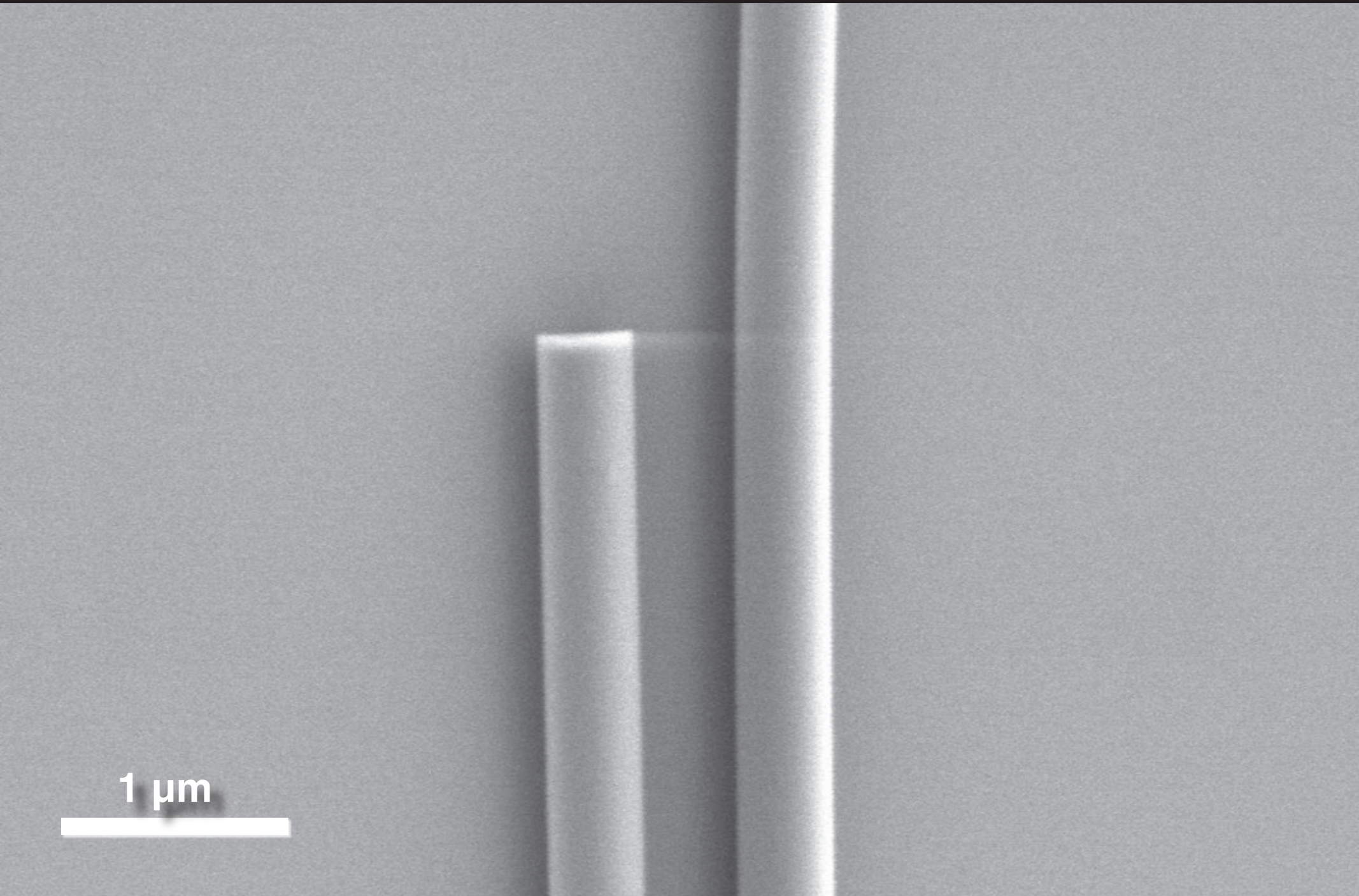


Outlook

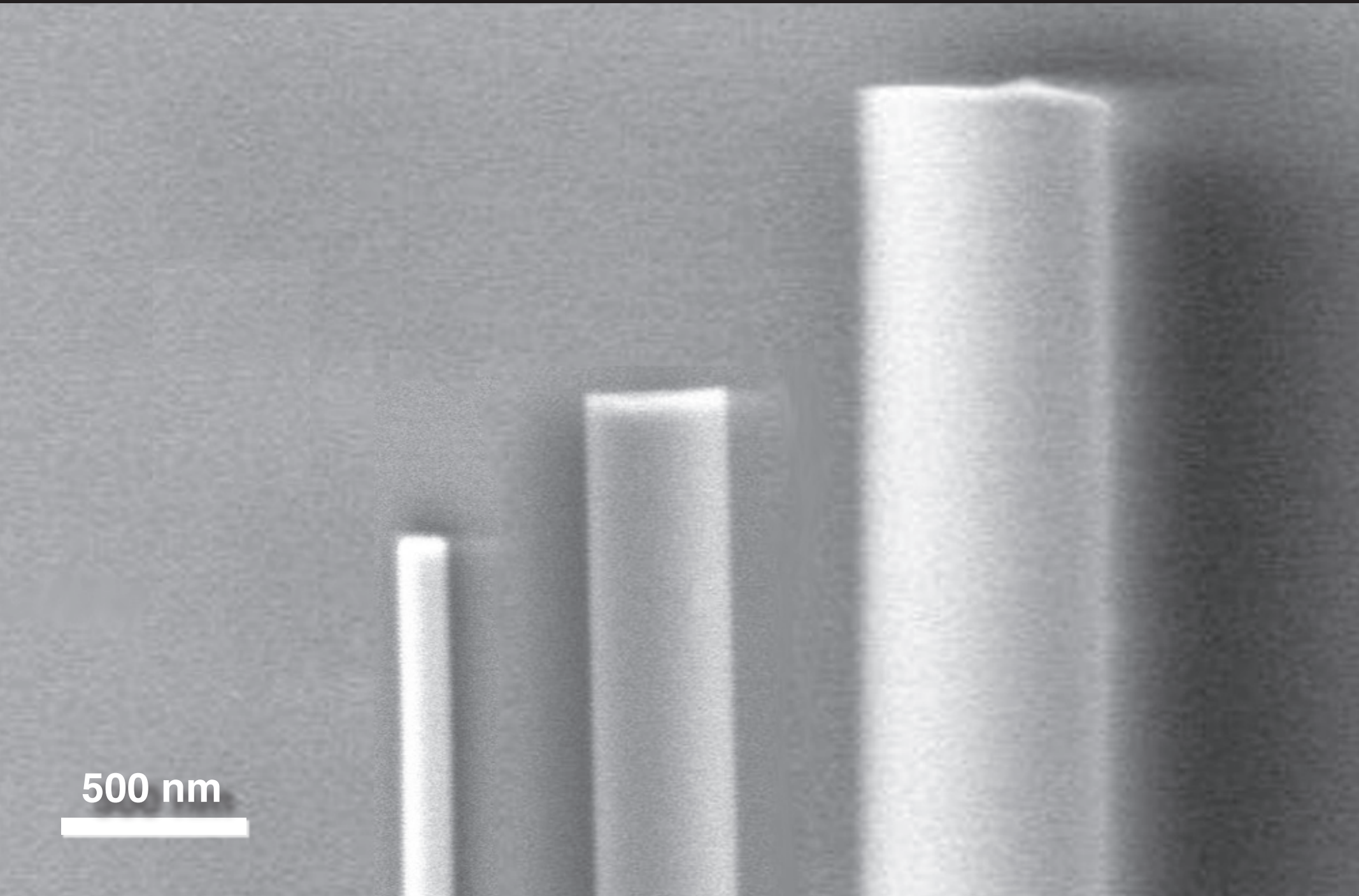
microphotonic components



Outlook



Outlook



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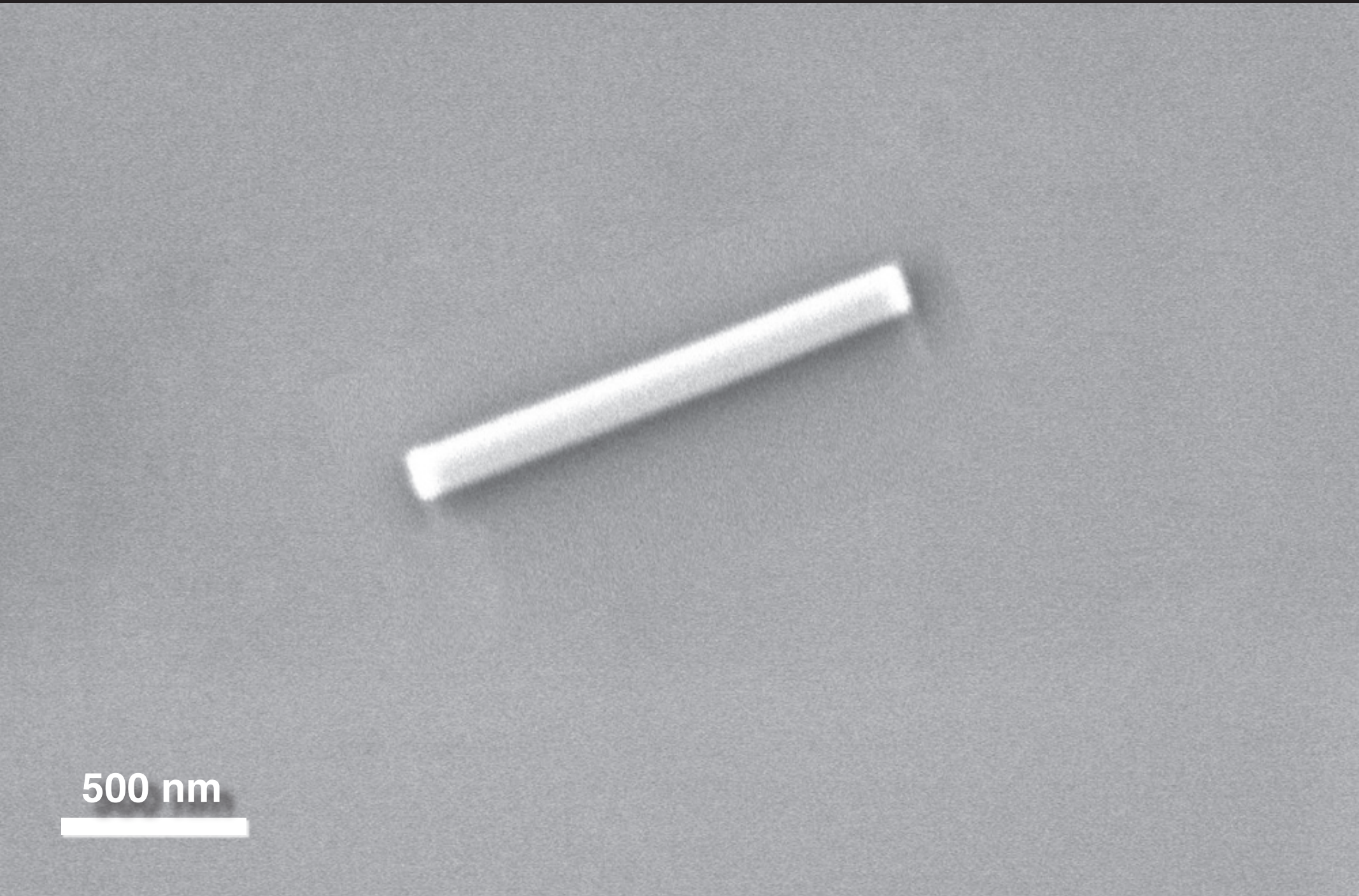

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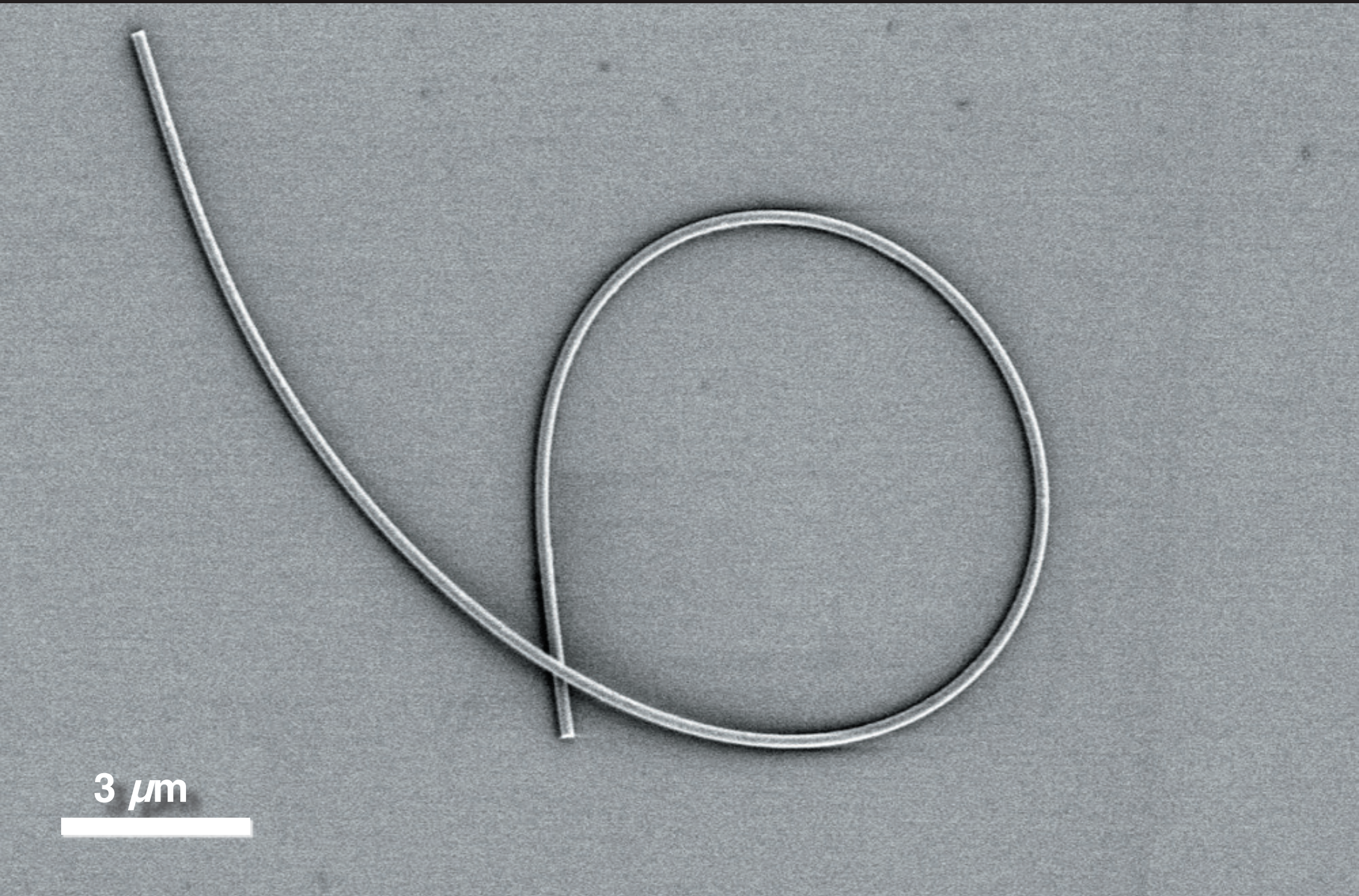

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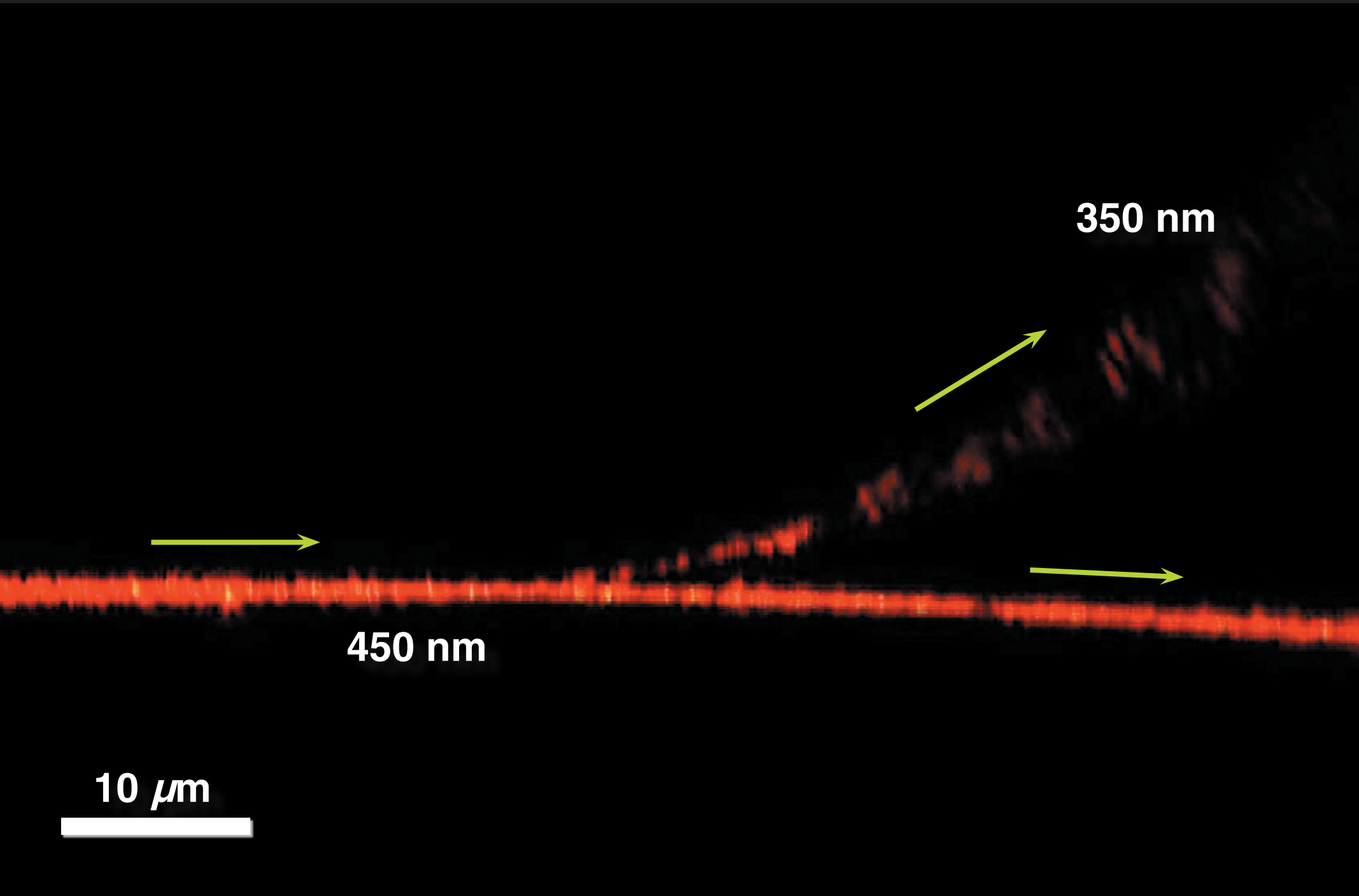

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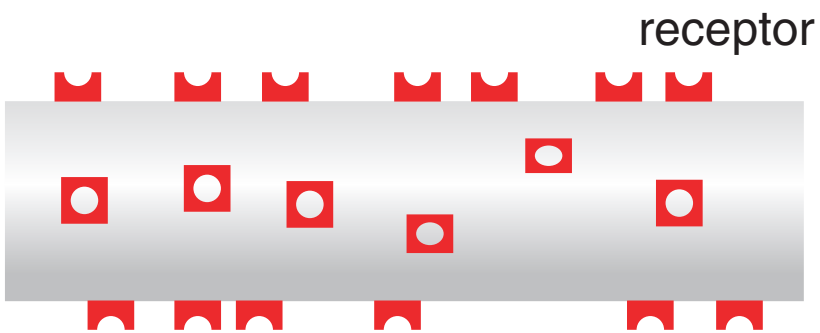

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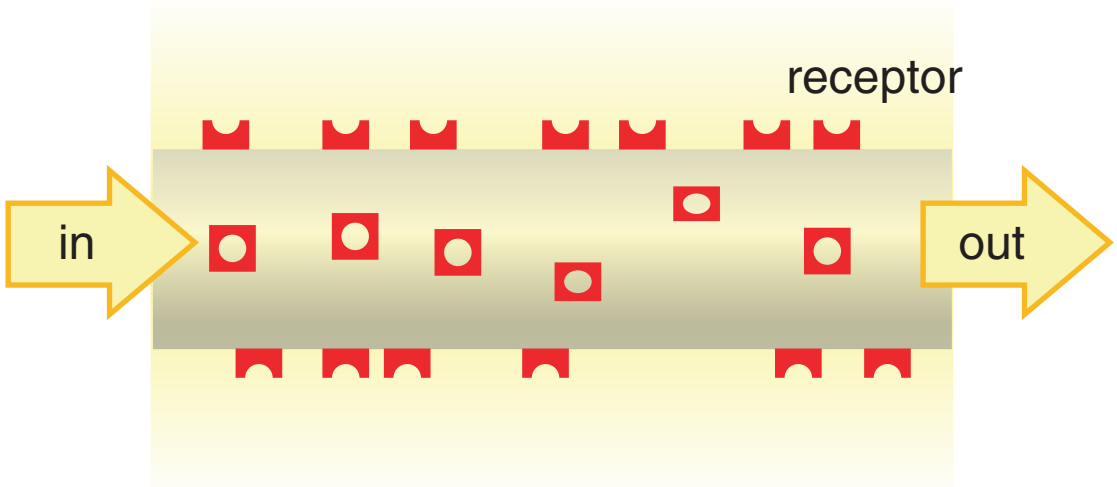

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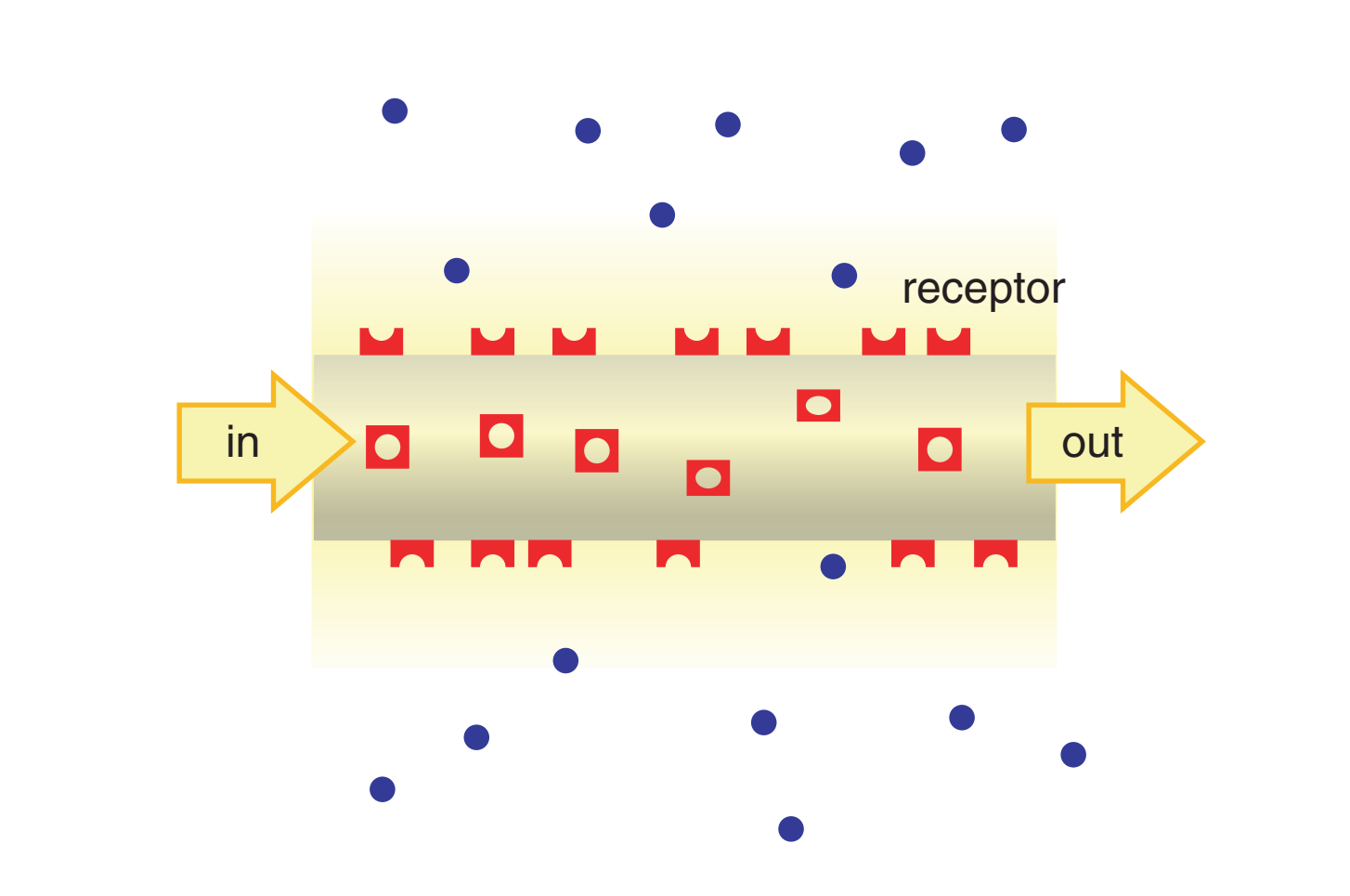

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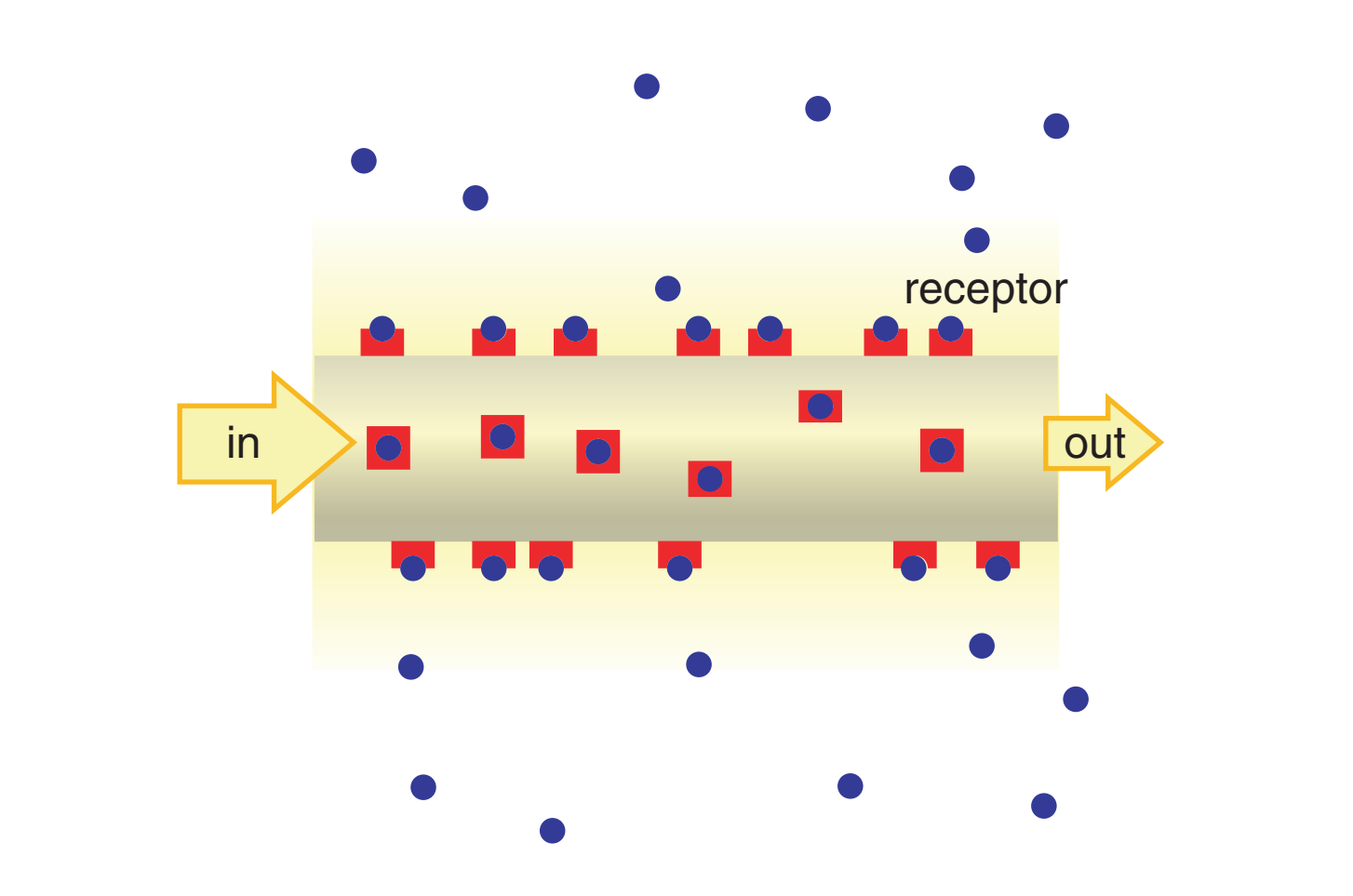

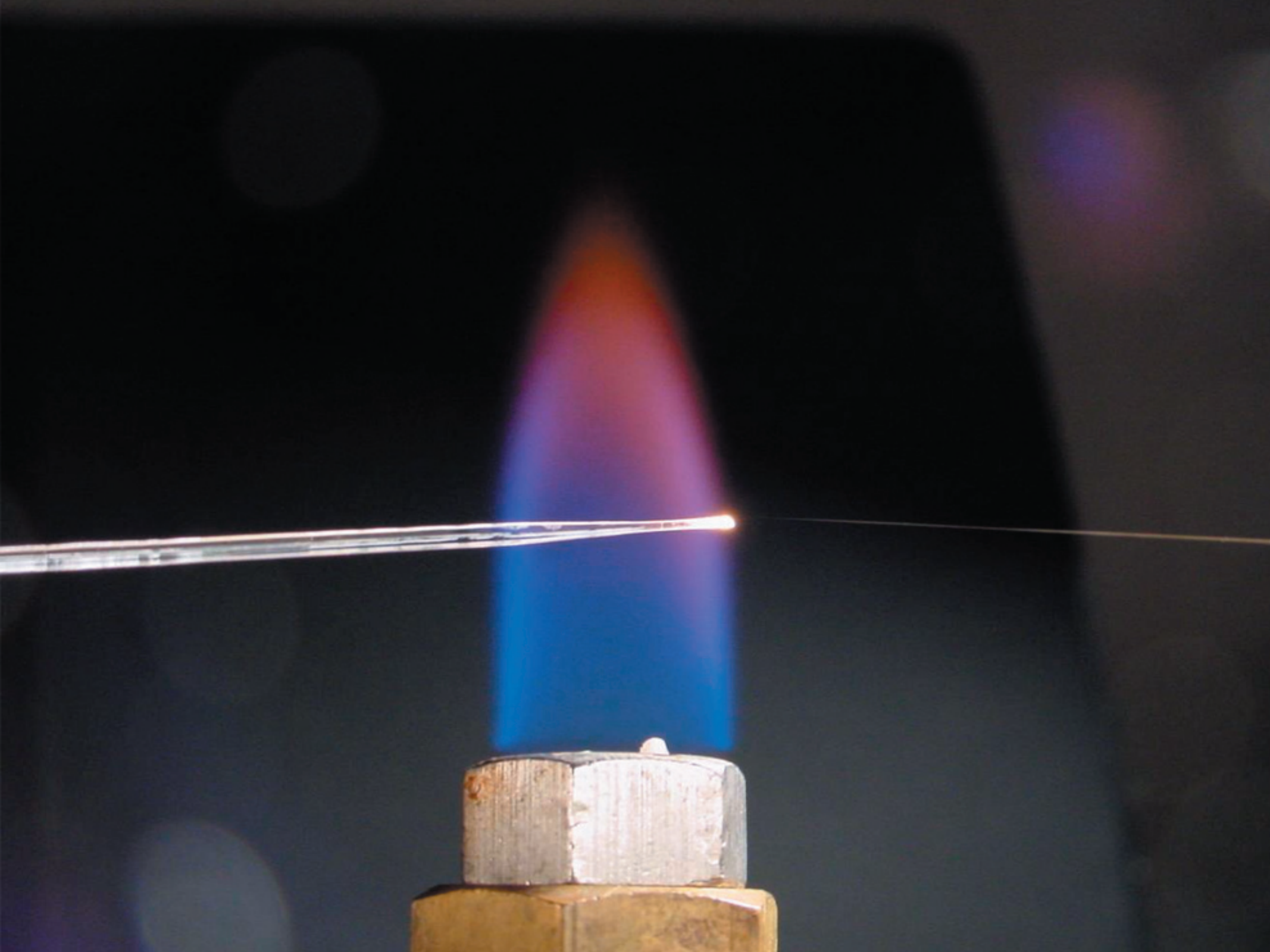

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