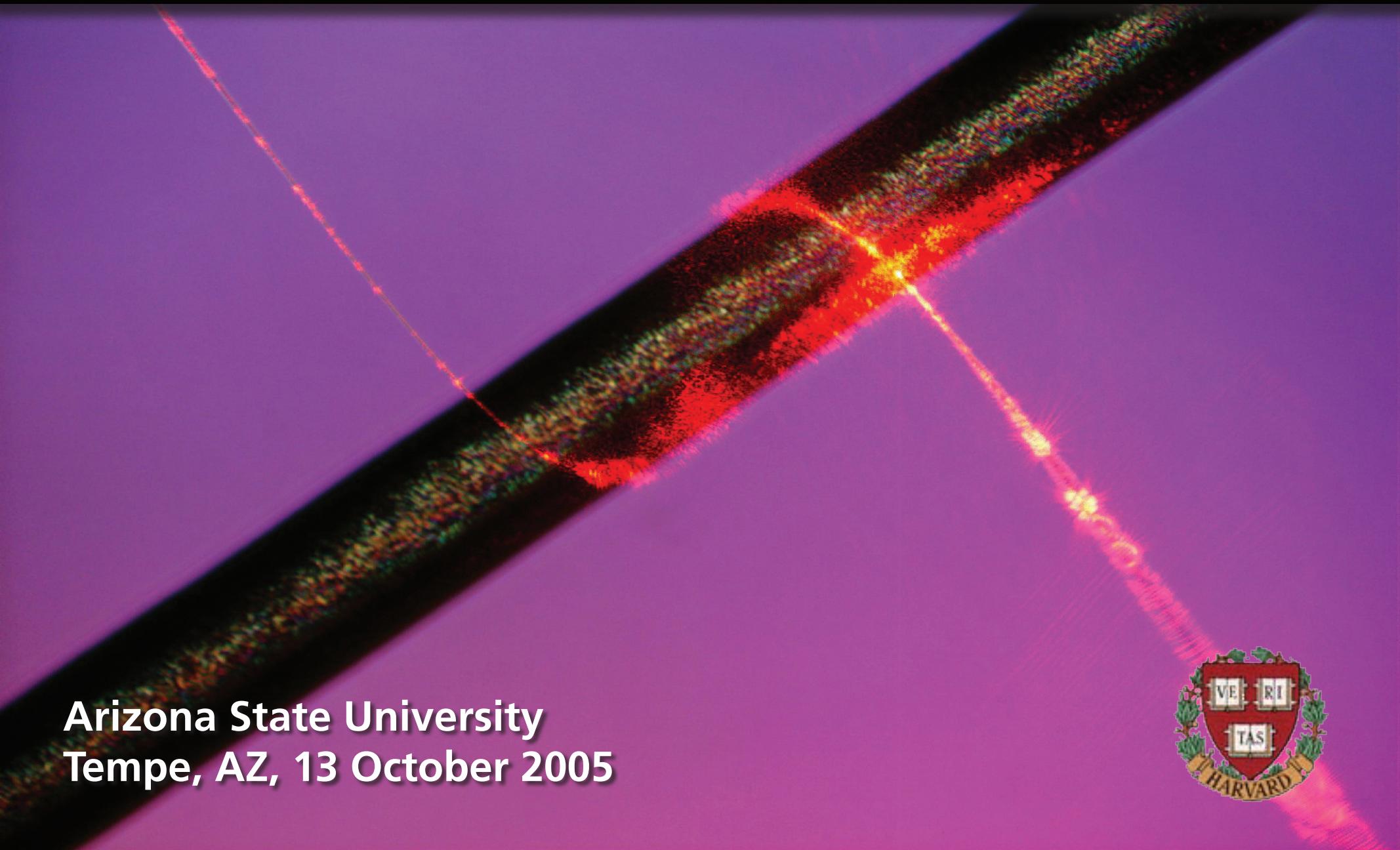
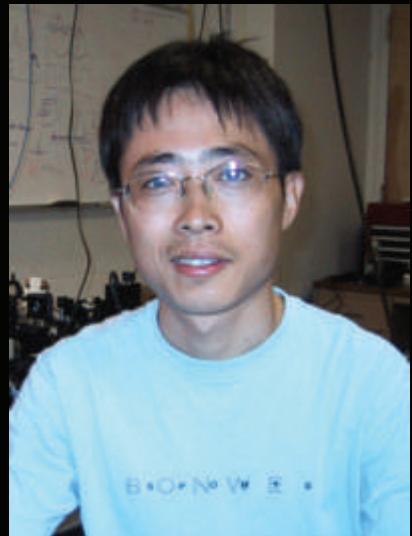


# Wrapping light around a hair: optics at the nanoscale



Arizona State University  
Tempe, AZ, 13 October 2005





**Limin Tong**



**Rafael Gattass**



**Geoff Svacha**



**Tommaso Baldacchini**

**and also....**

**at Harvard:**

**Jonathan Aschom**

**Mengyan Shen**

**Iva Maxwell**

**James Carey**

**Brian Tull**

**Dr. Yuan Lu**

**Dr. Richard Schalek**

**Prof. Federico Capasso**

**Prof. Cynthia Friend**

**and elsewhere:**

**Xuewen Chen (Zhejiang University)**

**Zhanghua Han (Zhejiang University)**

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

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

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

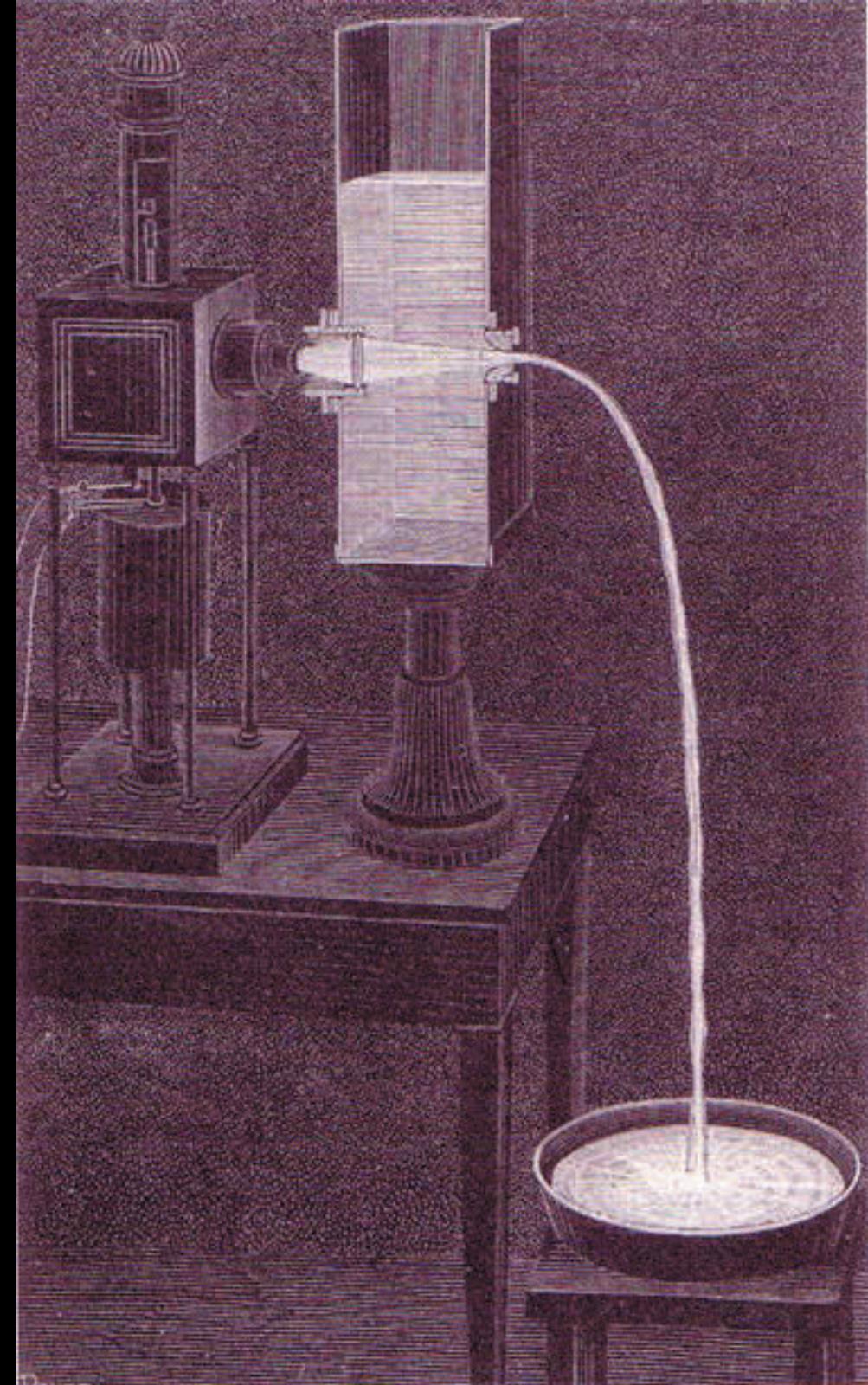
**Dr. Ray Mariella (LLNL)**

**Liu Liu (Zhejiang University)**

***"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)





(nu model.)

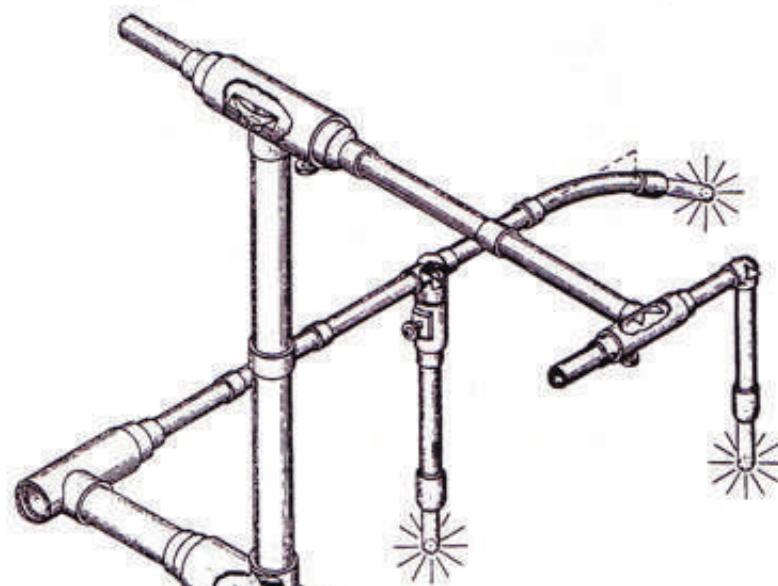
4 Sheets—Sheet

W. WHEELER.

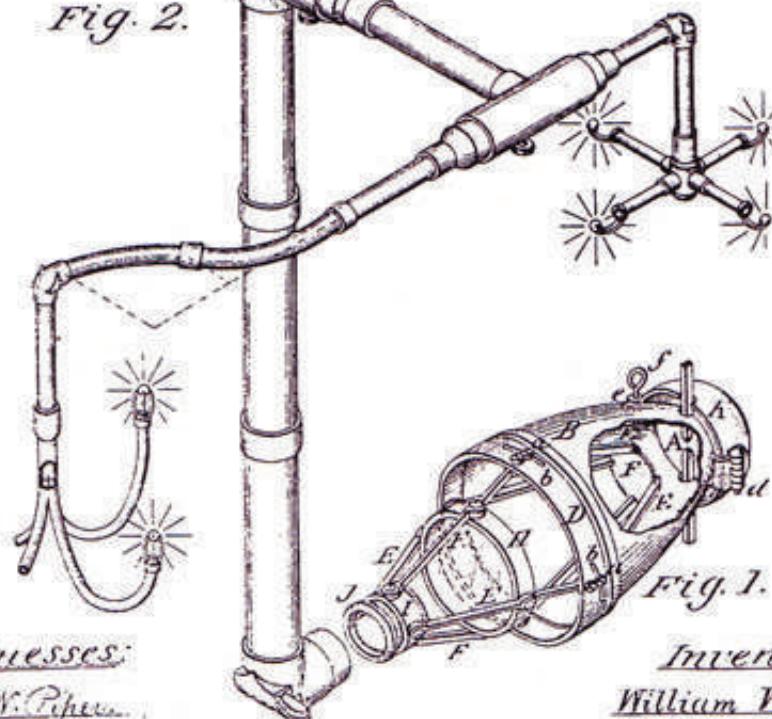
APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.



*Fig. 2.*



*Inventor:*

William Wheeler

by attorney

Witnesses:

J. W. Piper

E. D. Parker

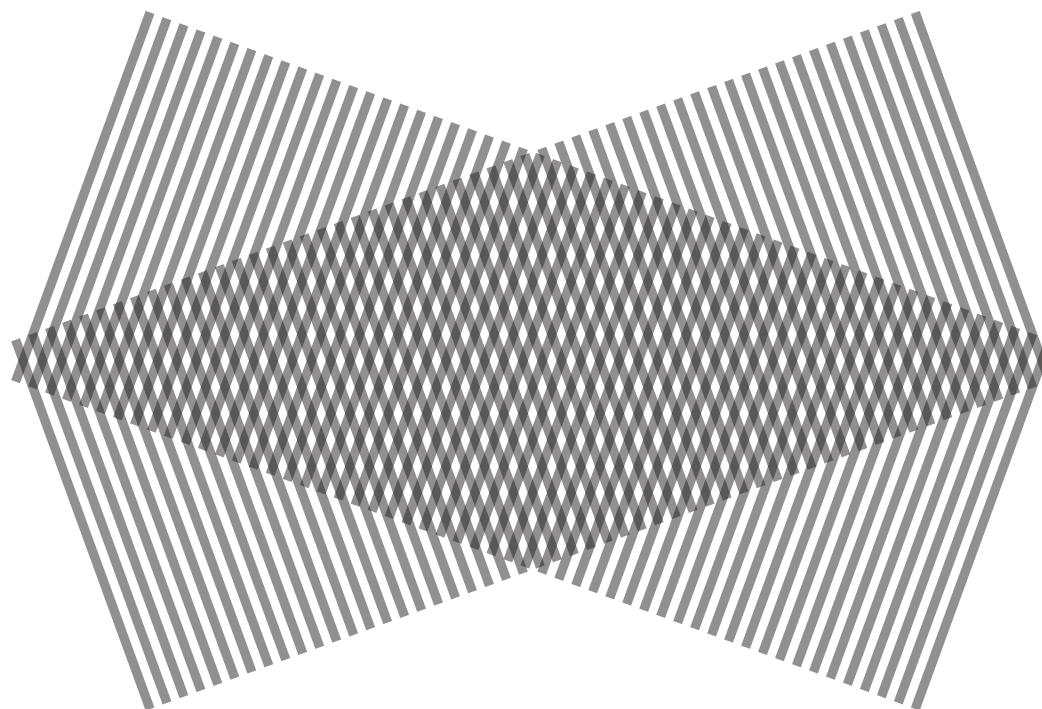
**US Patent 247, 229 (1881)**

# Outline

- waveguiding
- nanowire fabrication
- optical properties

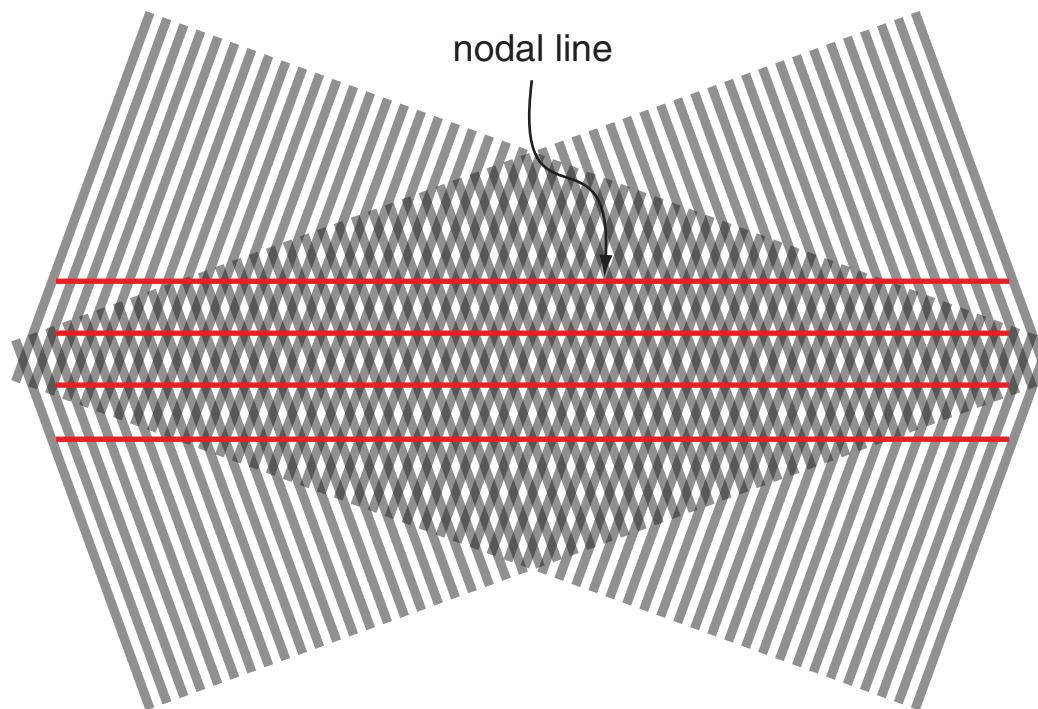
# Waveguiding

two crossed planar waves...



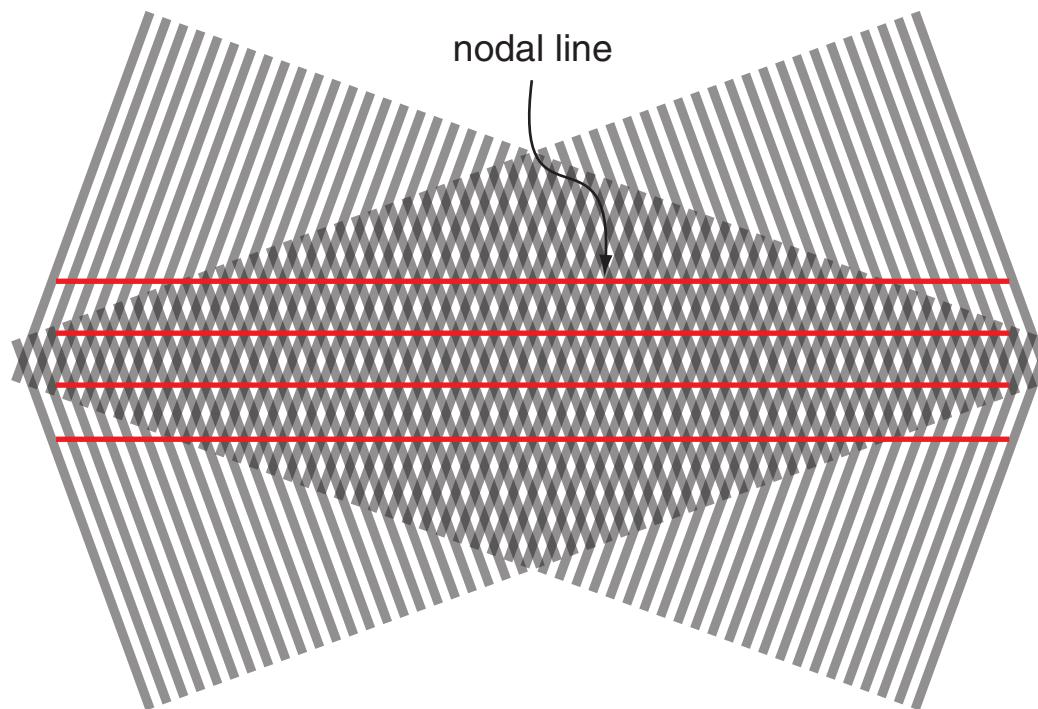
# Waveguiding

...cause an interference pattern



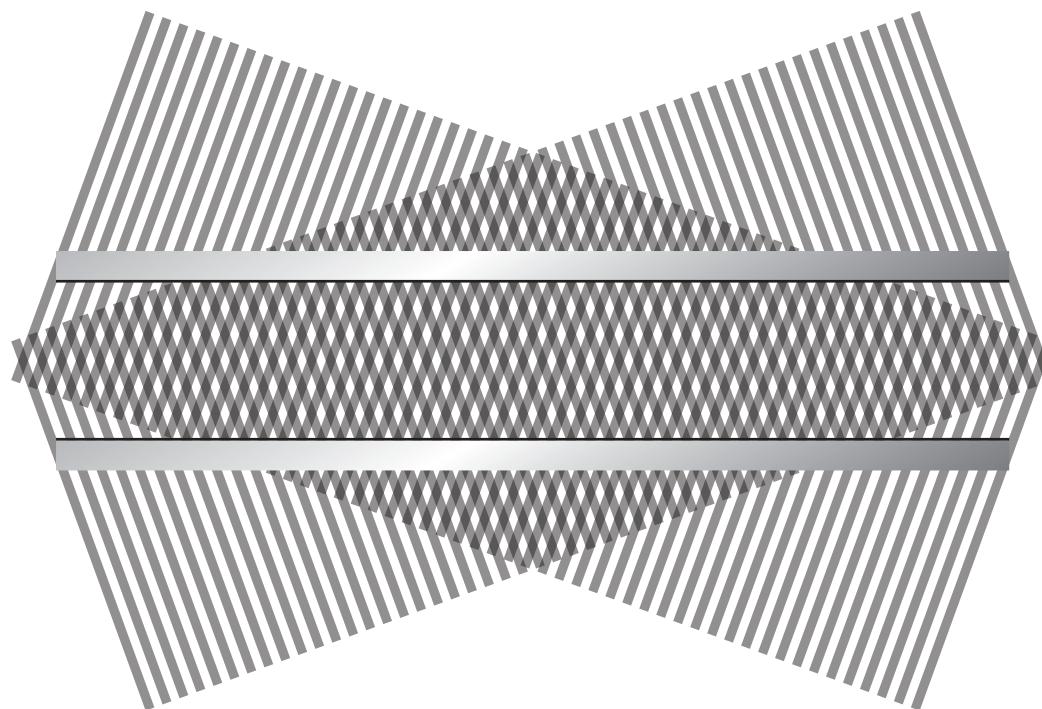
# Waveguiding

$E = 0$  on the nodal lines



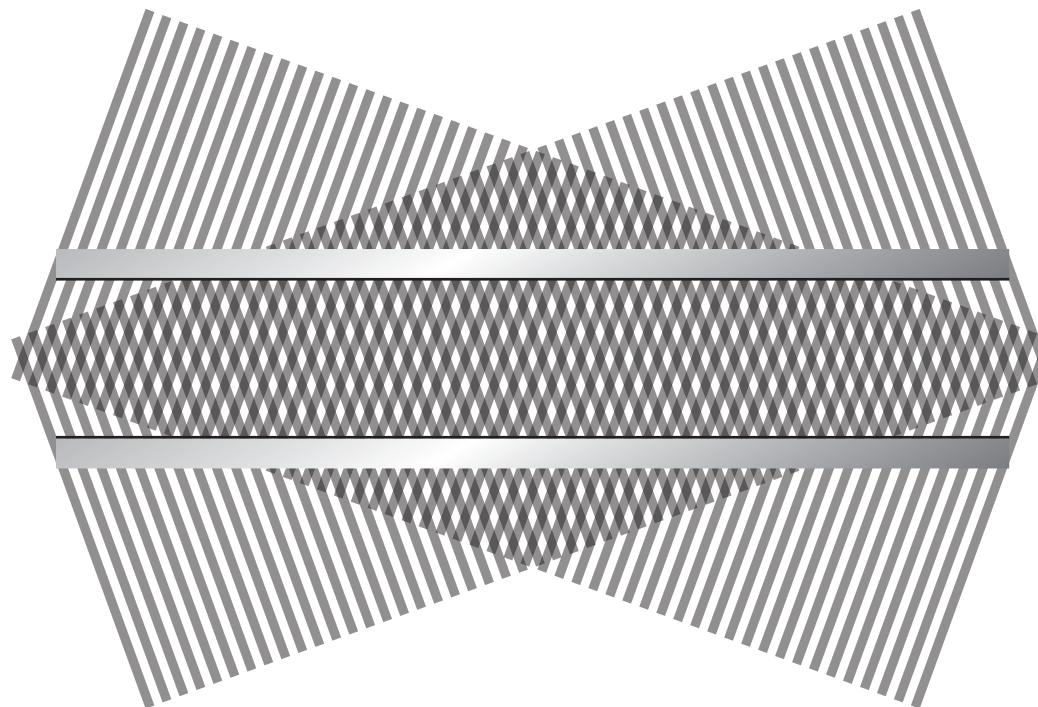
# Waveguiding

**...satisfying boundary conditions for planar-mirror waveguide**



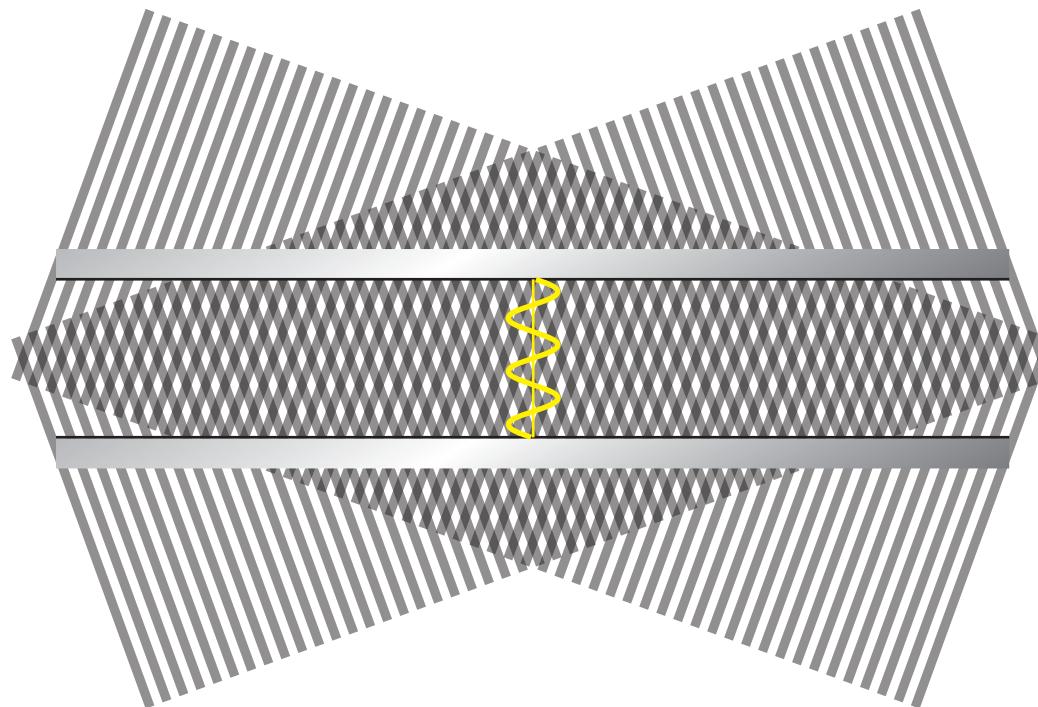
# Waveguiding

**transverse standing wave, traveling along axis**



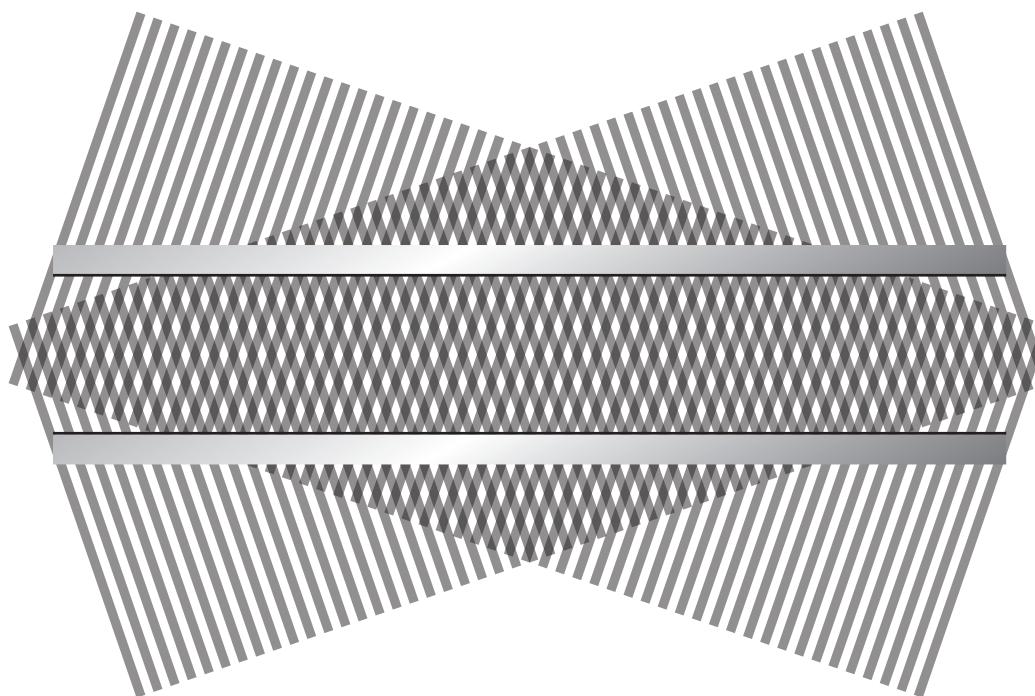
# Waveguiding

**transverse standing wave, traveling along axis**



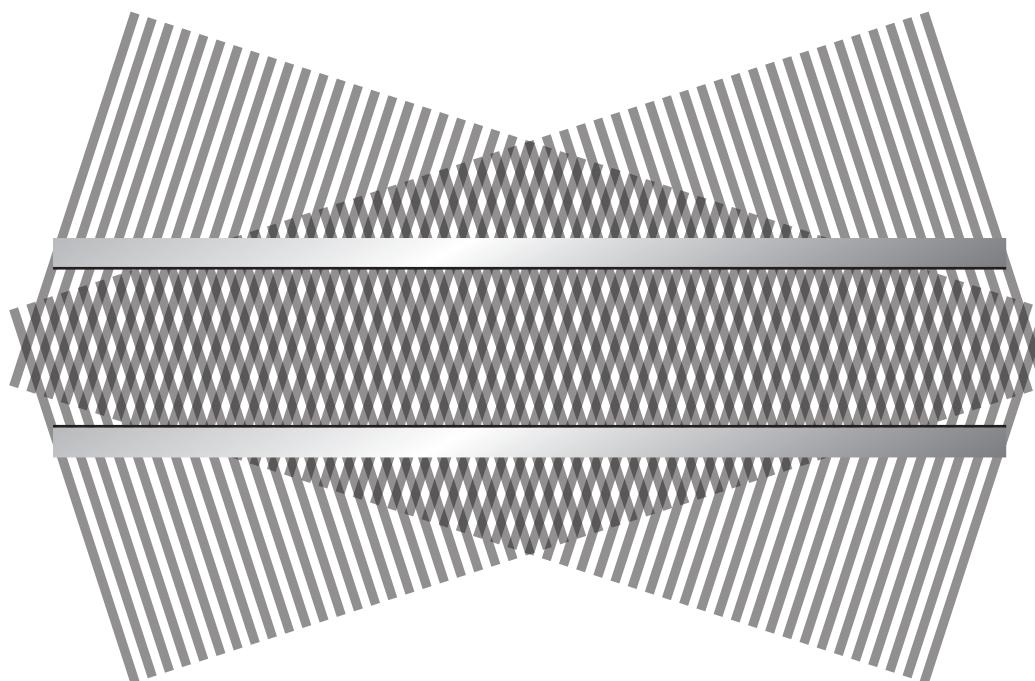
# Waveguiding

change angle of incident waves...



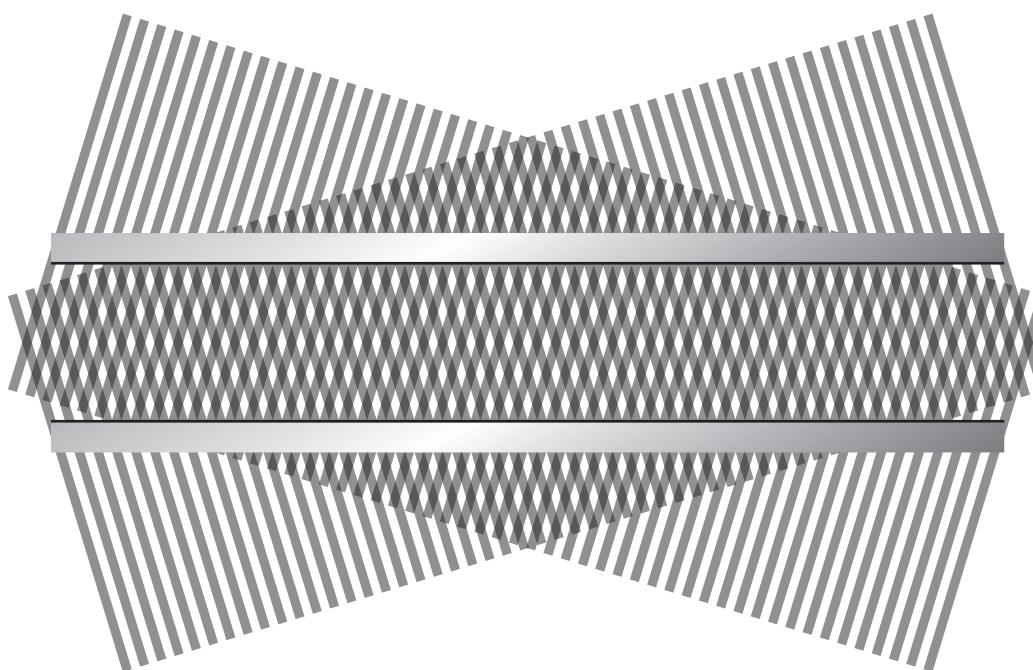
# Waveguiding

change angle of incident waves...



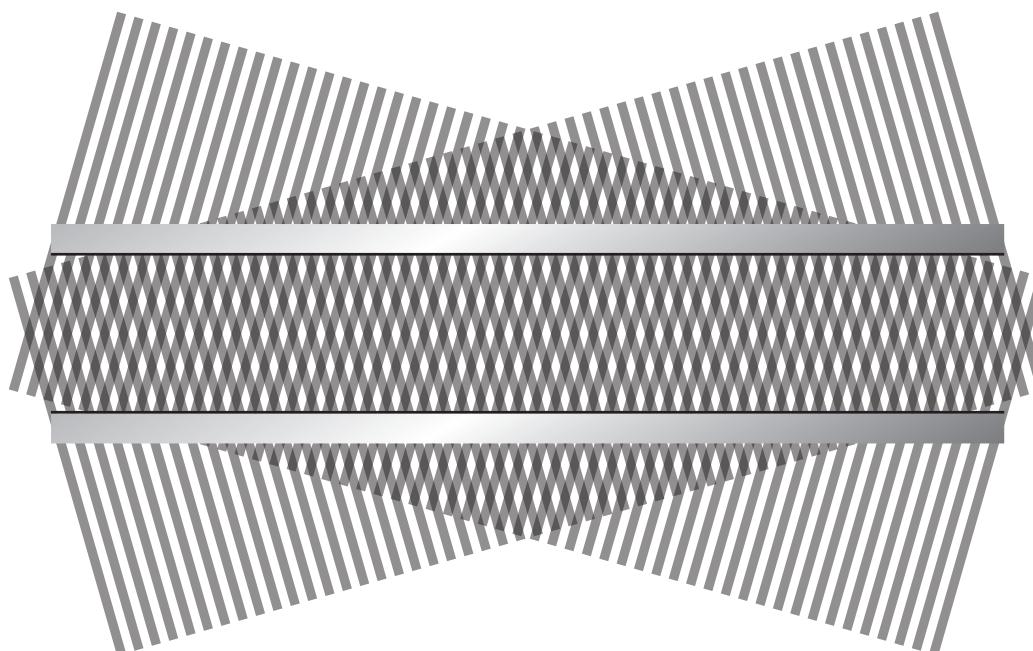
# Waveguiding

change angle of incident waves...



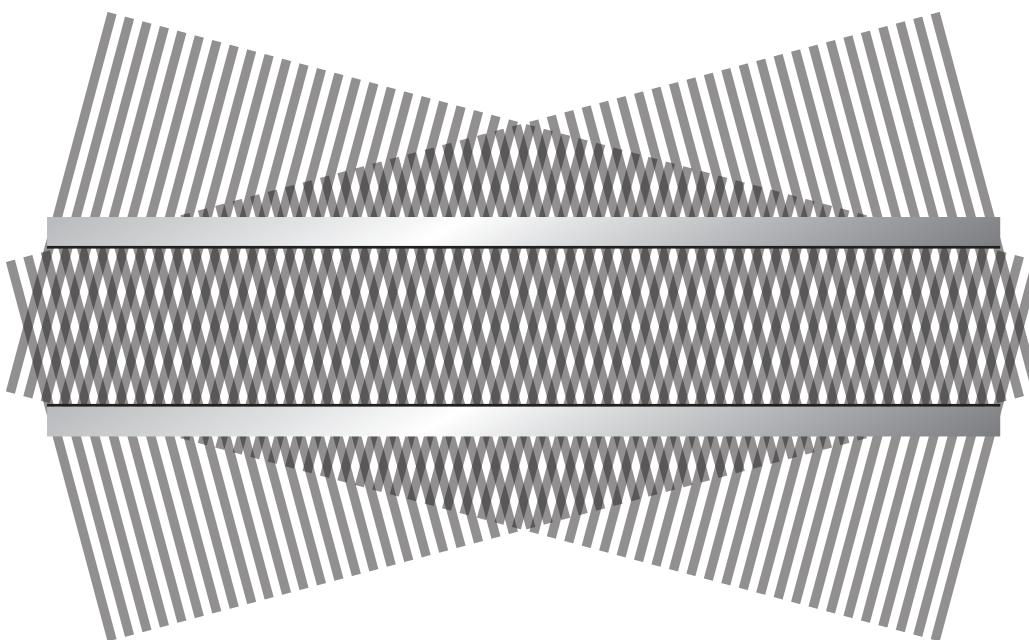
# Waveguiding

change angle of incident waves...



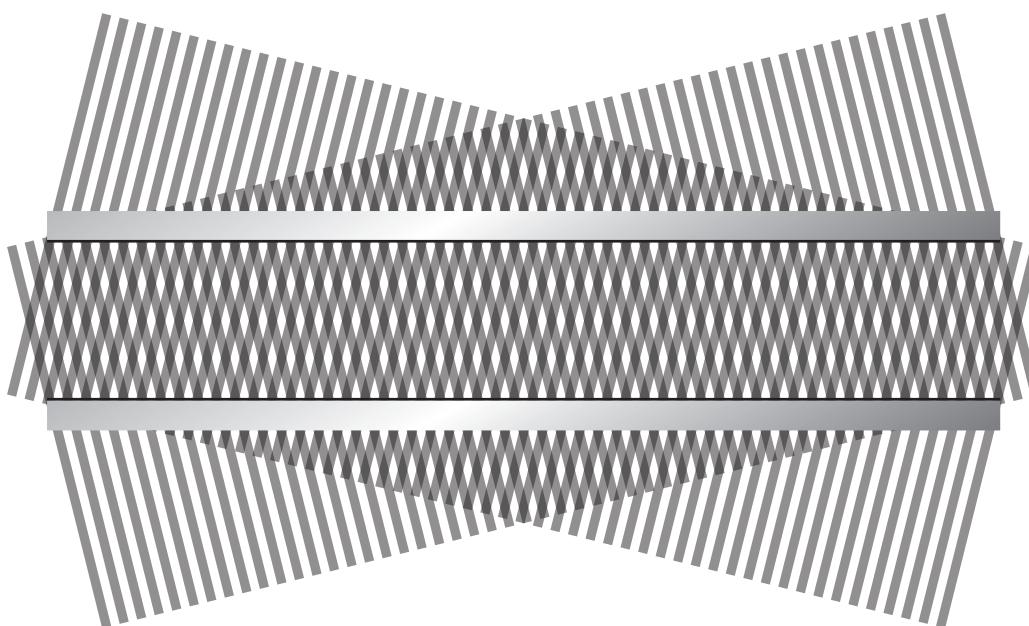
# Waveguiding

change angle of incident waves...



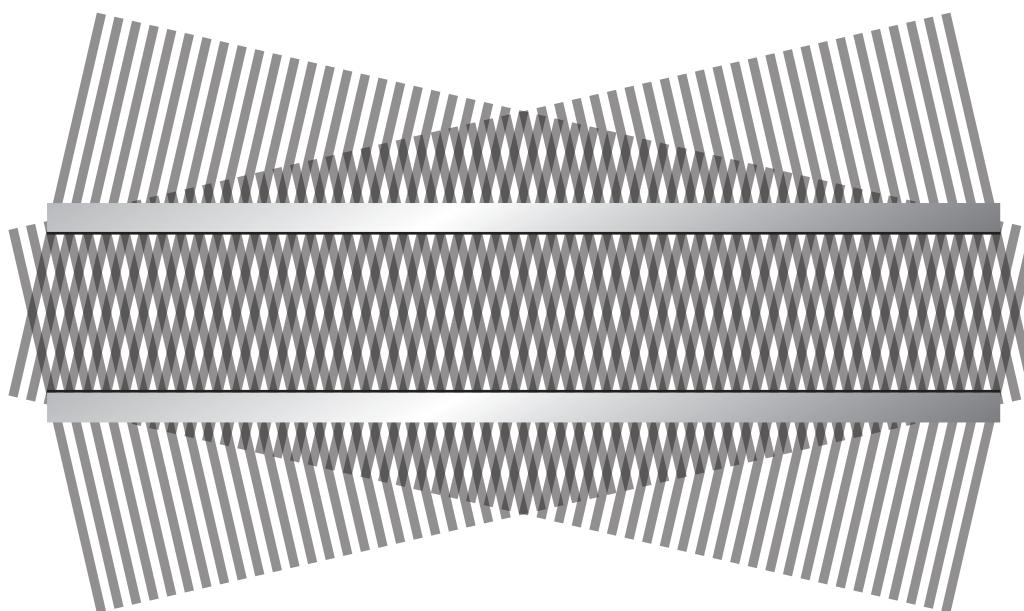
# Waveguiding

change angle of incident waves...



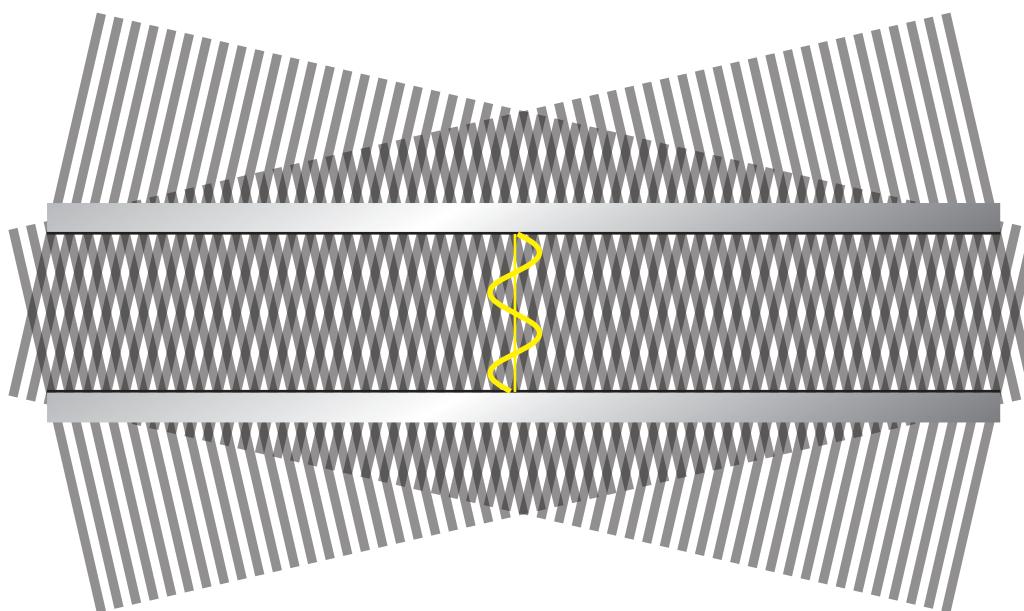
# Waveguiding

change angle of incident waves...



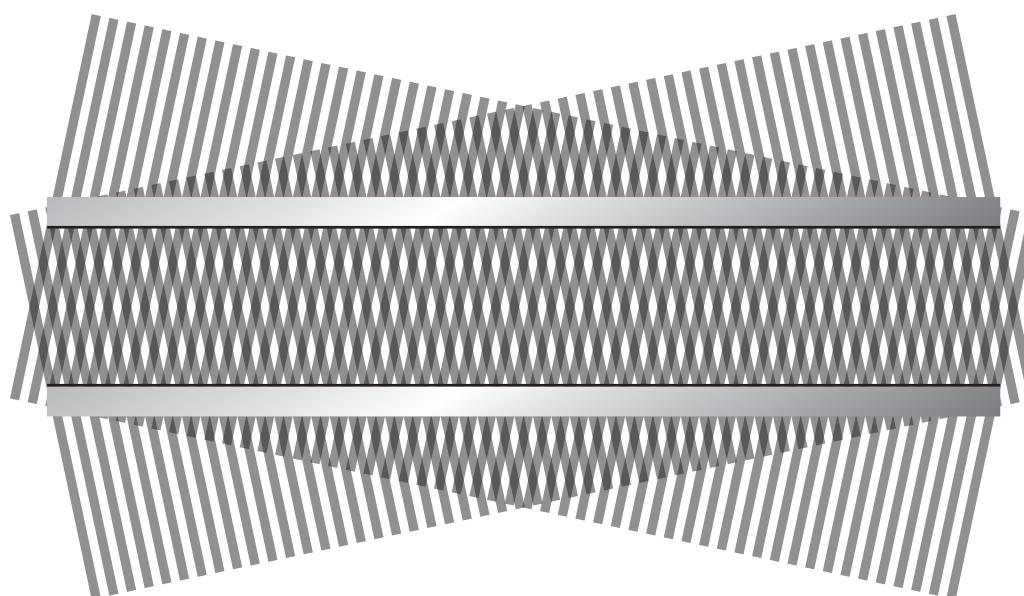
# Waveguiding

change angle of incident waves...



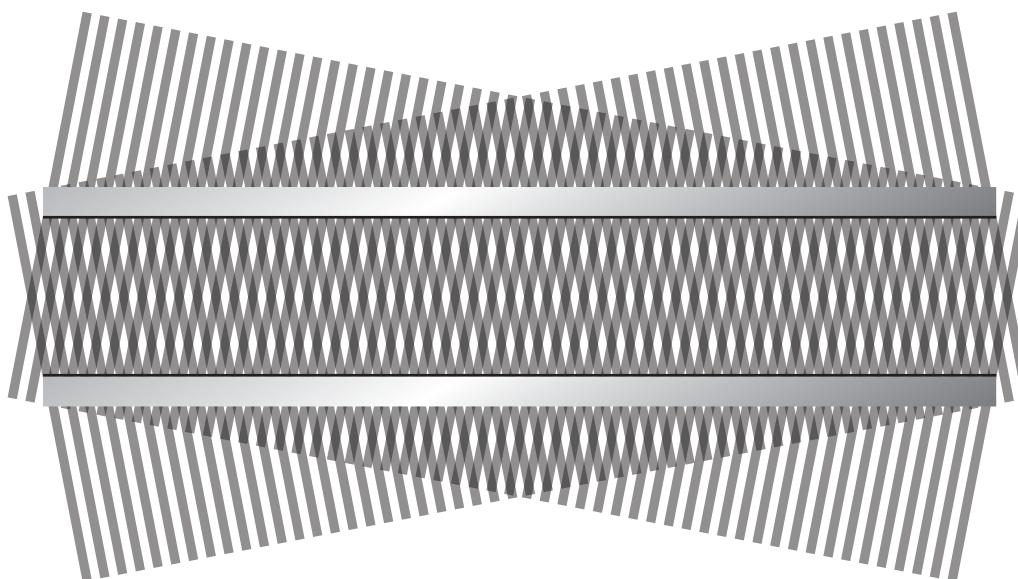
# Waveguiding

change angle of incident waves...



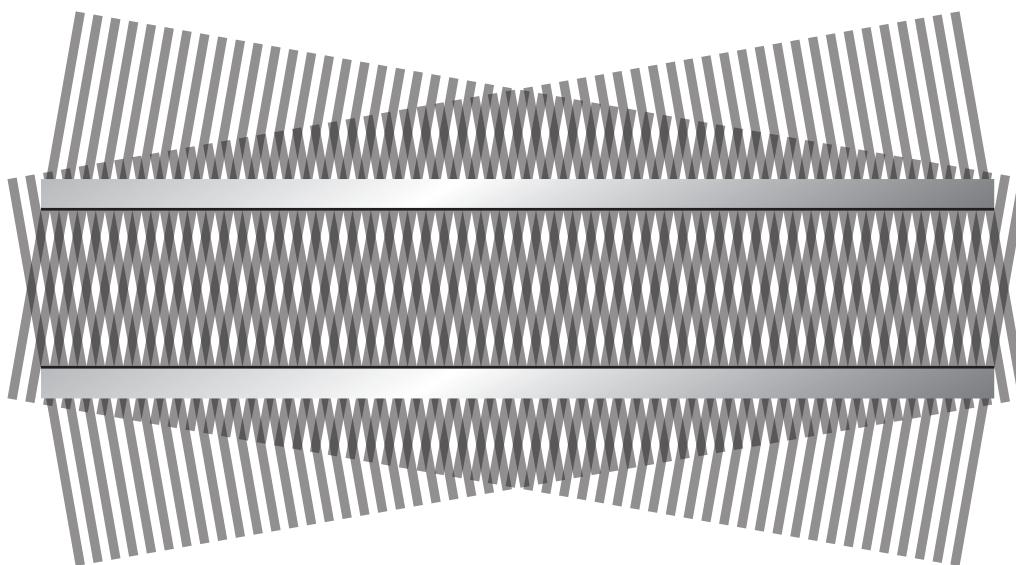
# Waveguiding

change angle of incident waves...



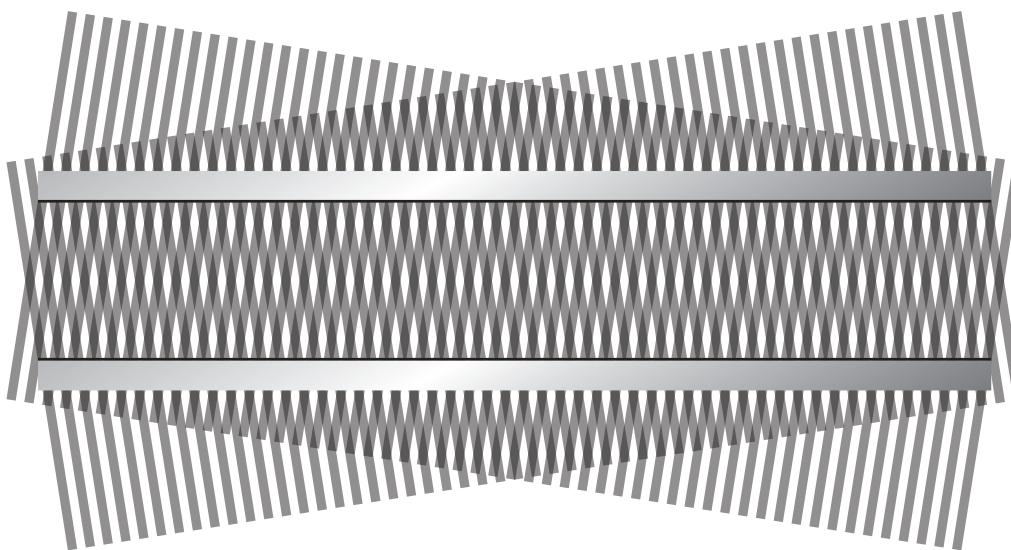
# Waveguiding

change angle of incident waves...



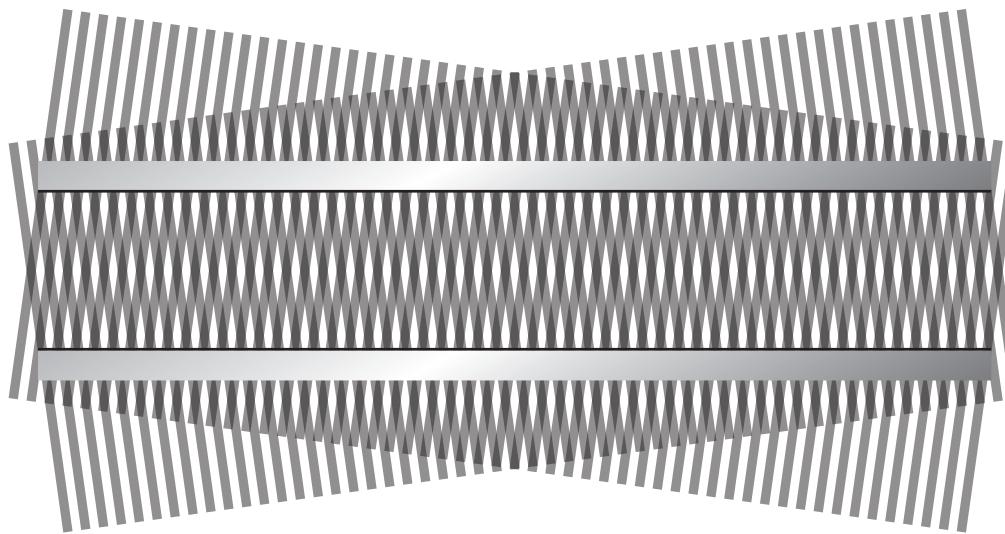
# Waveguiding

change angle of incident waves...



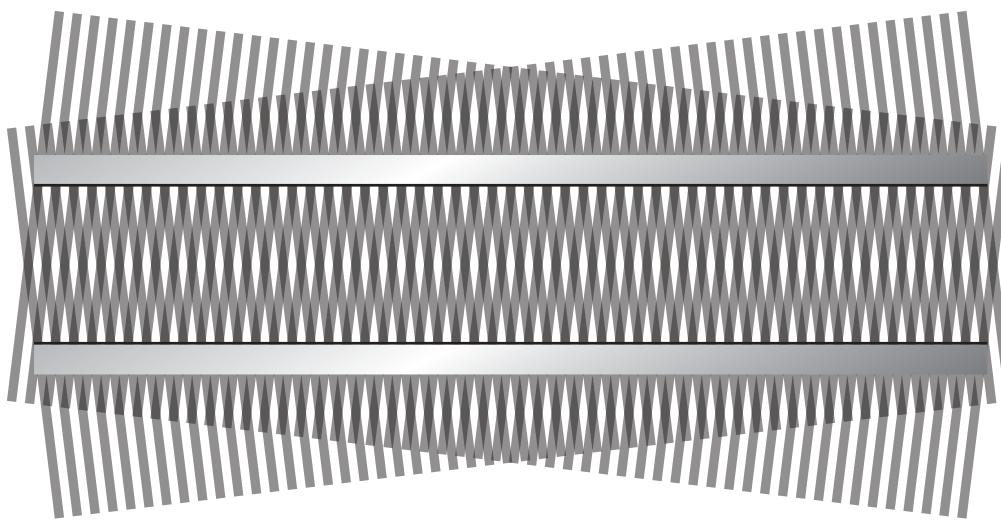
# Waveguiding

change angle of incident waves...



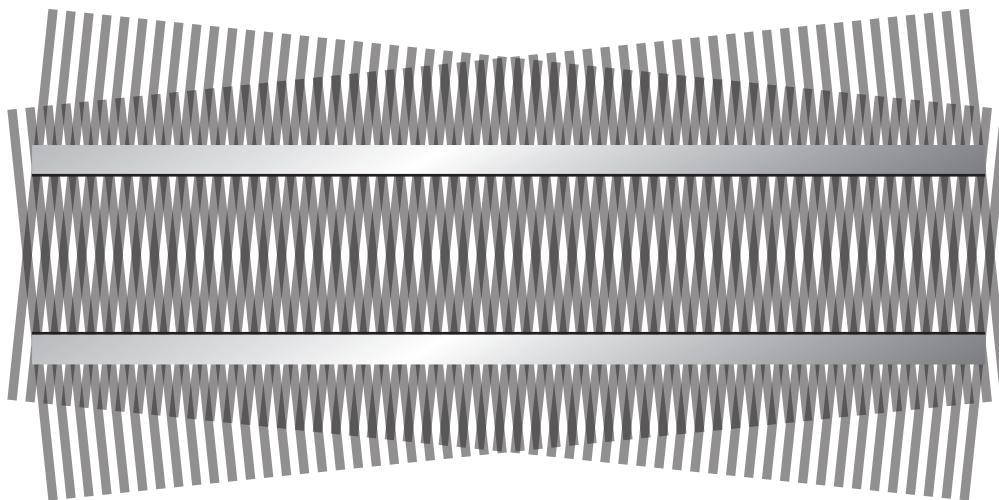
# Waveguiding

change angle of incident waves...



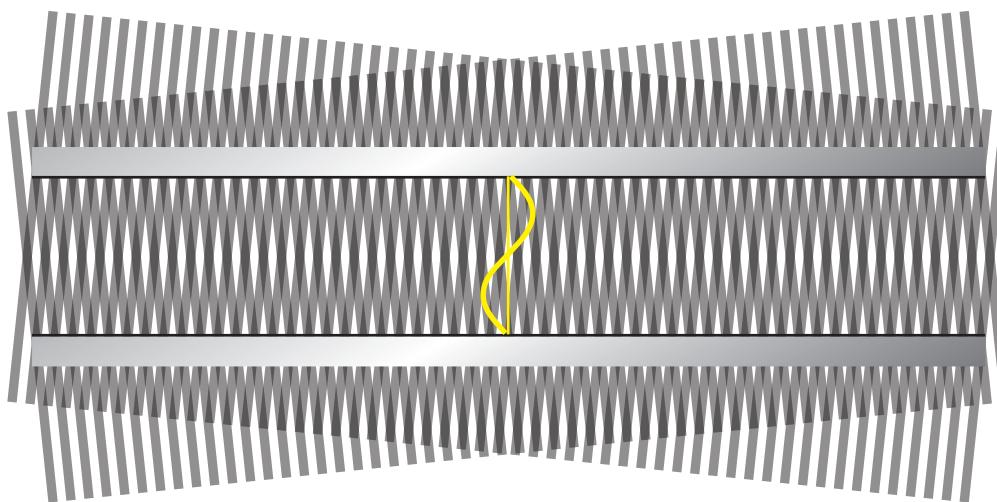
# Waveguiding

change angle of incident waves...



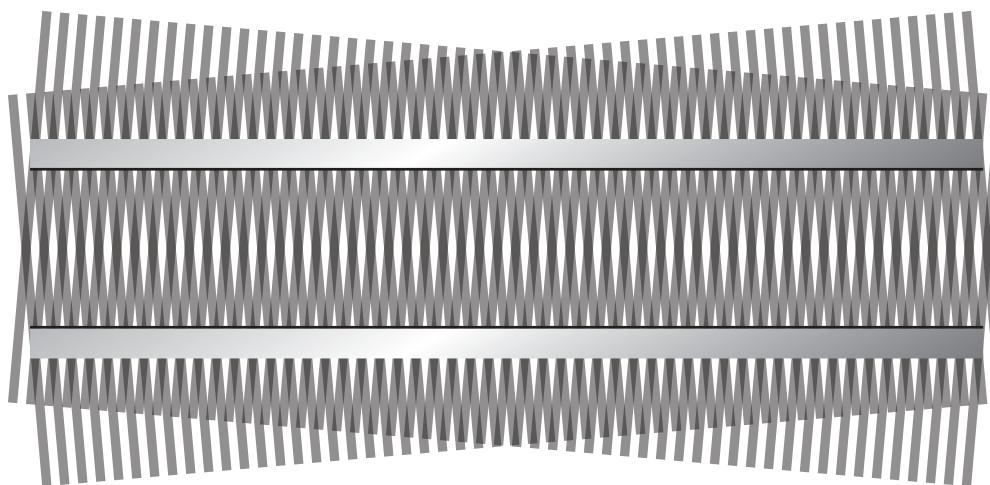
# Waveguiding

change angle of incident waves...



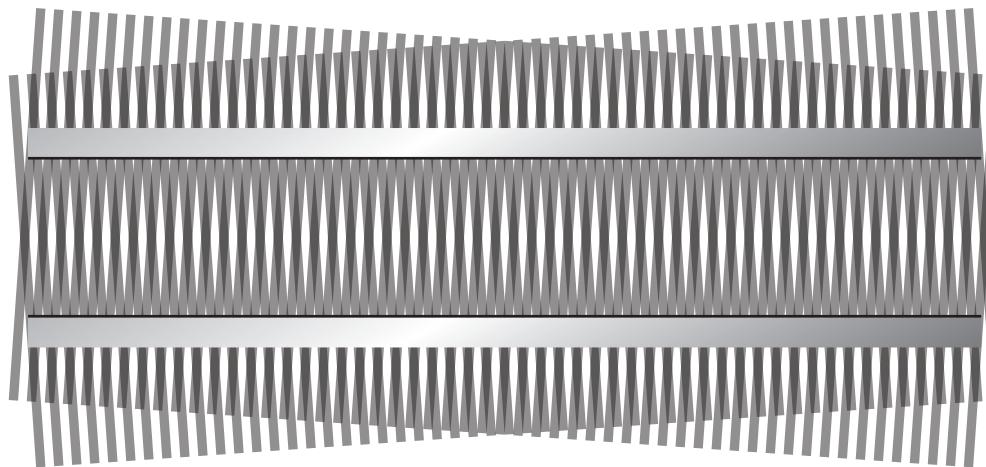
# Waveguiding

change angle of incident waves...



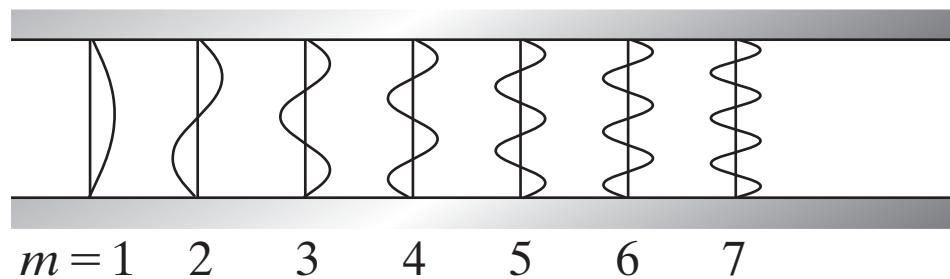
# Waveguiding

change angle of incident waves...



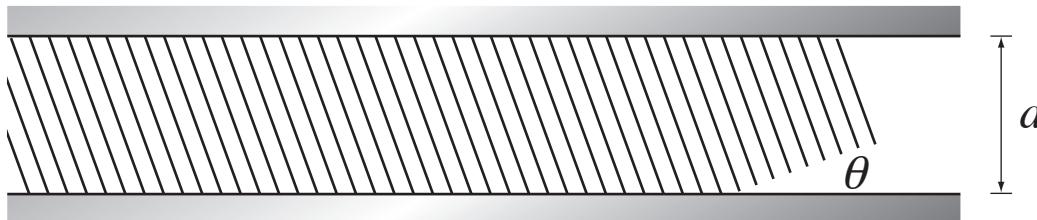
# Waveguiding

**boundary conditions only satisfied for certain  $\theta$**



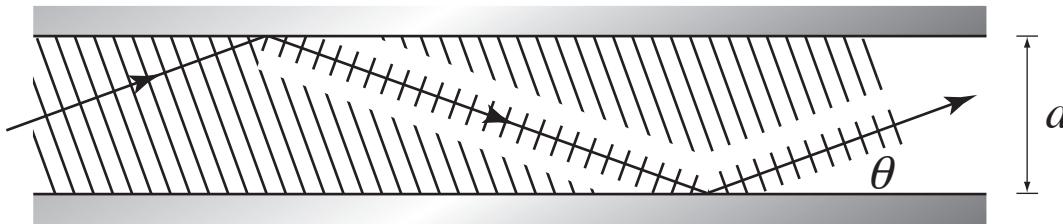
**standing wave in y-direction, traveling in z-direction**

# Waveguiding



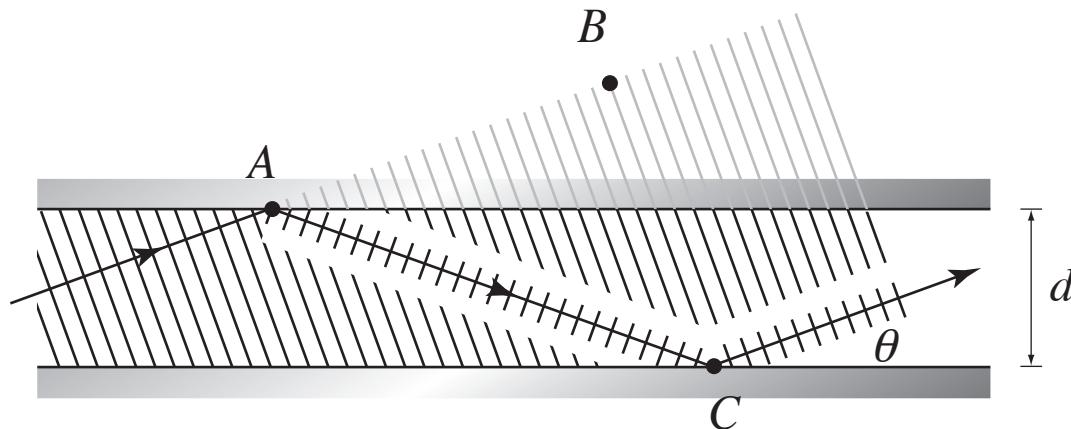
consider wave incident at angle  $\theta$

# Waveguiding



**twice-reflected wave**

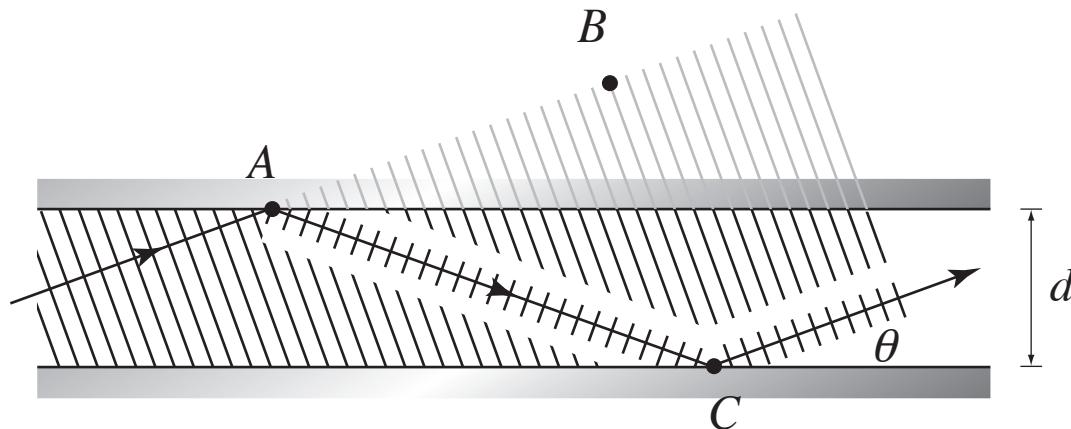
# Waveguiding



**self consistency:**

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

# Waveguiding



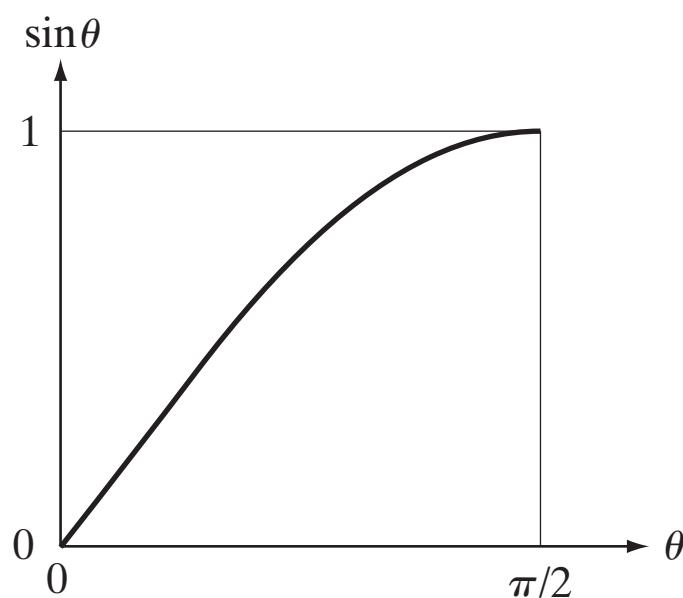
**self consistency:**

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

**so:**

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

# Waveguiding



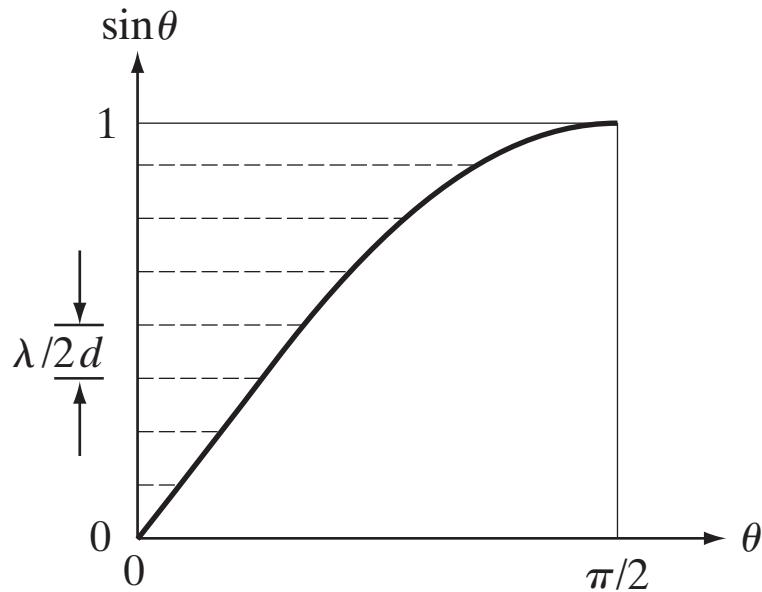
**self consistency:**

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

**so:**

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

# Waveguiding



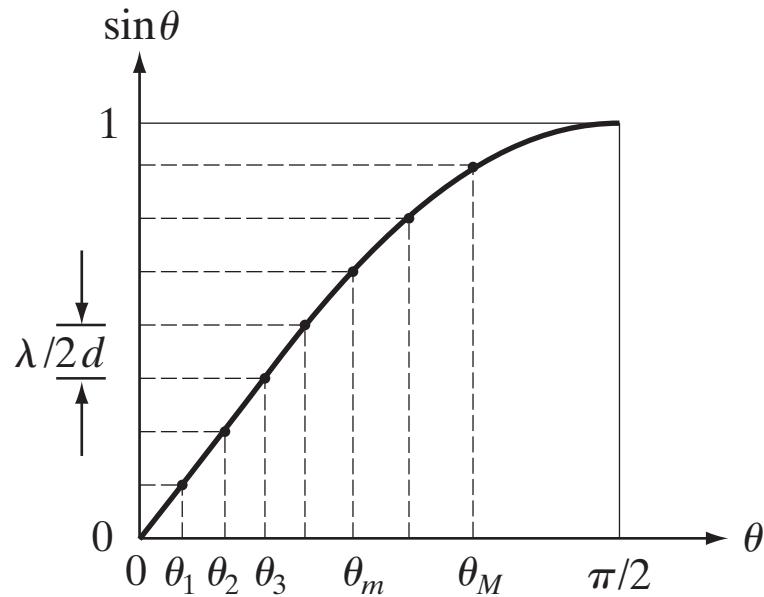
**self consistency:**

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

**so:**

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

# Waveguiding



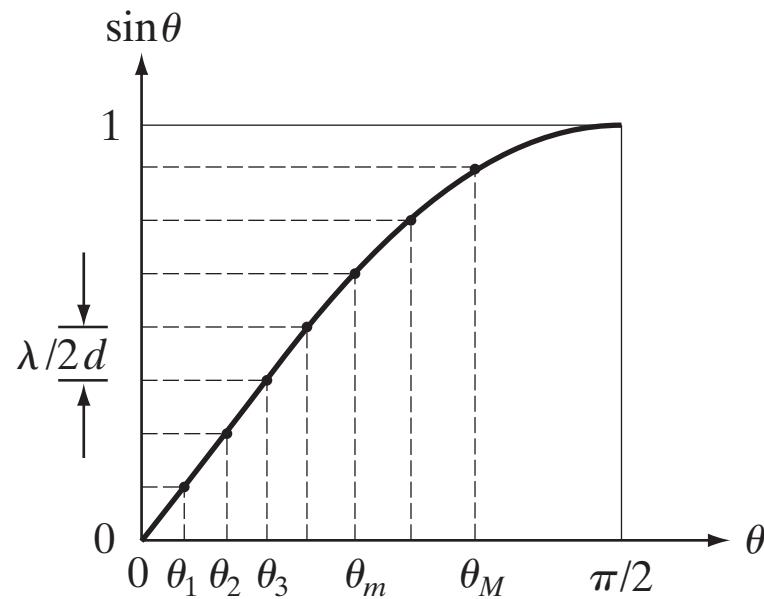
**self consistency:**

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

**so:**

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

# Waveguiding



number of modes:

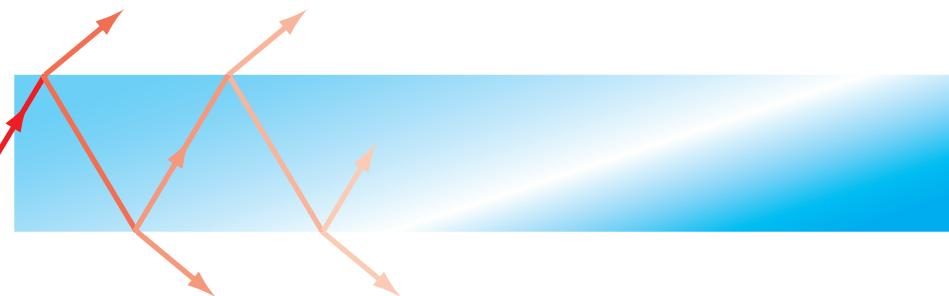
$$M \doteq \frac{2d}{\lambda}$$

# Waveguiding



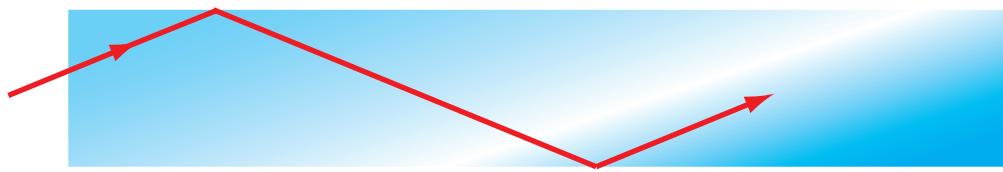
**now consider a planar dielectric waveguide**

# Waveguiding



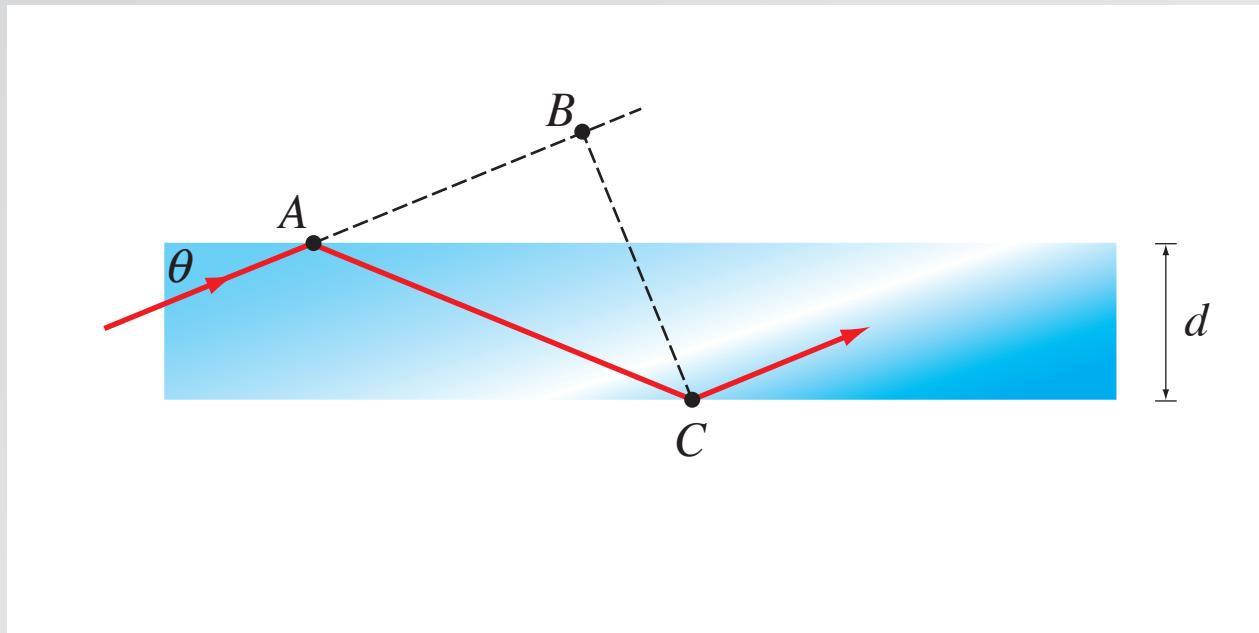
**rays incident at angle  $\theta > \pi/2 - \theta_c$  are unguided**

# Waveguiding



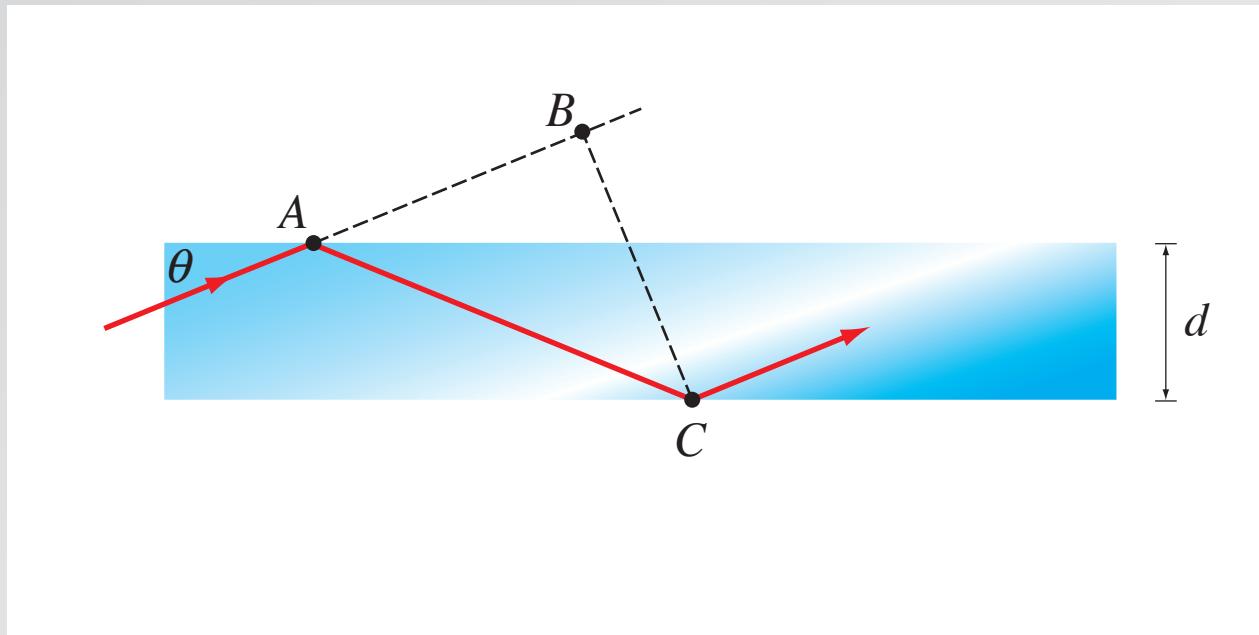
**rays incident at angle  $\theta < \pi/2 - \theta_c$  are guided**

# Waveguiding



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

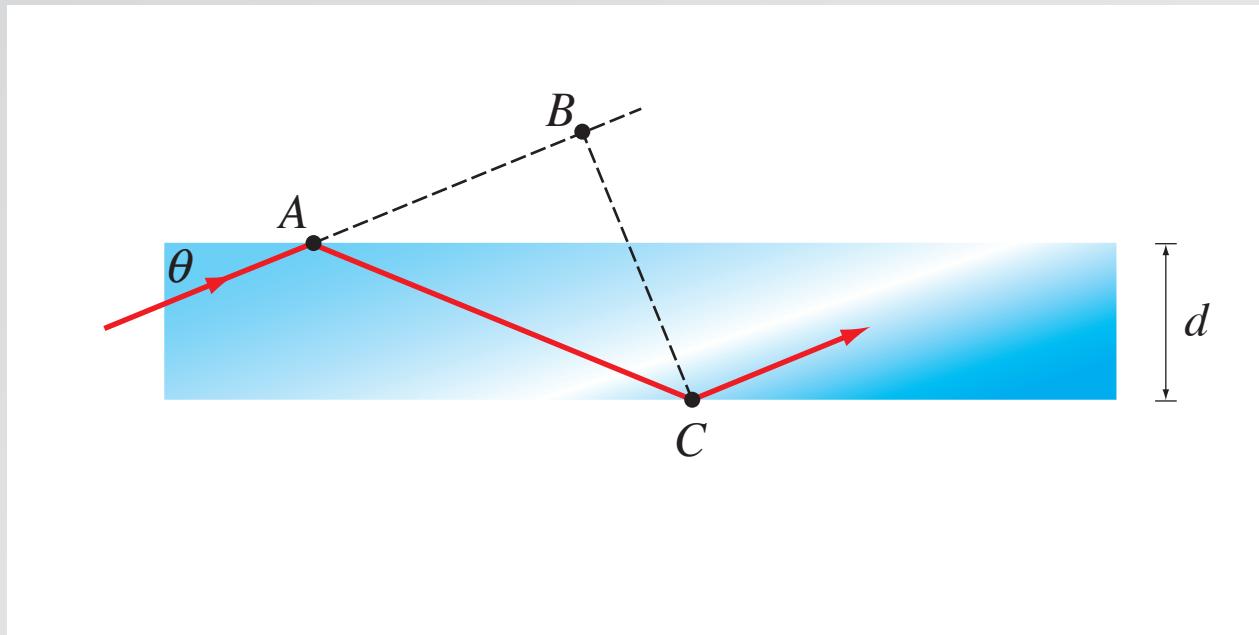
# Waveguiding



**self consistency:**

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

# Waveguiding



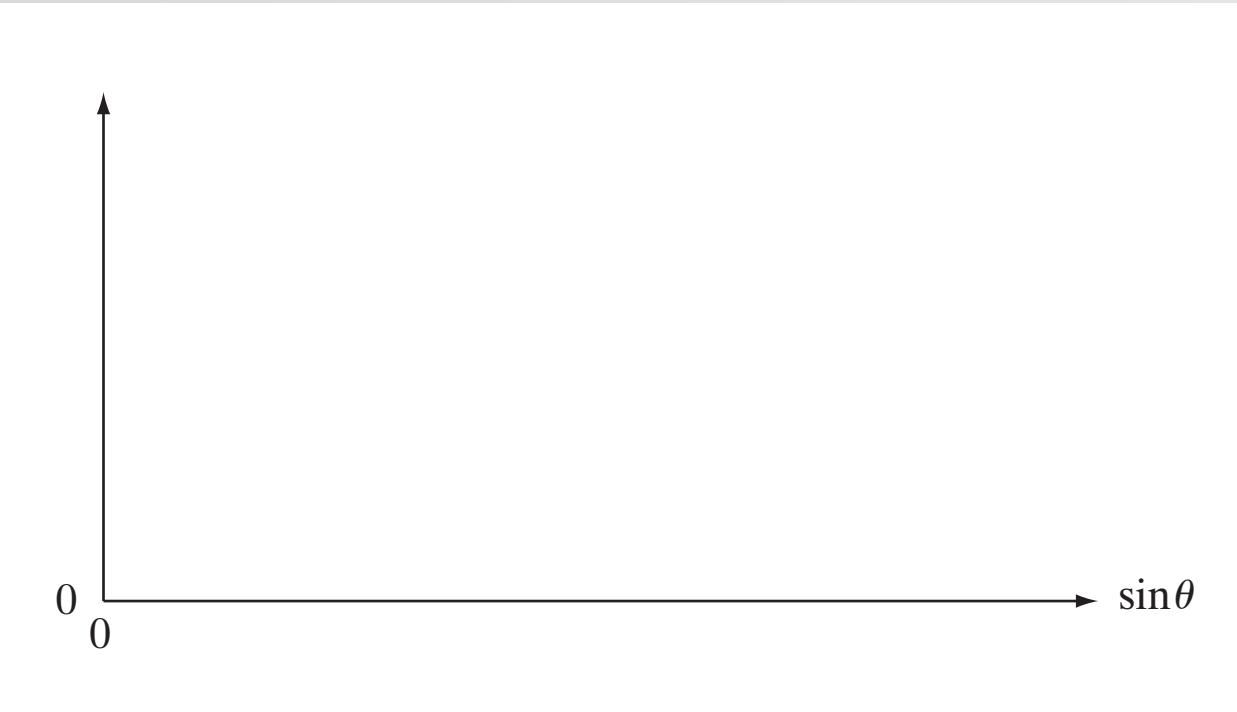
**self consistency:**

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

**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



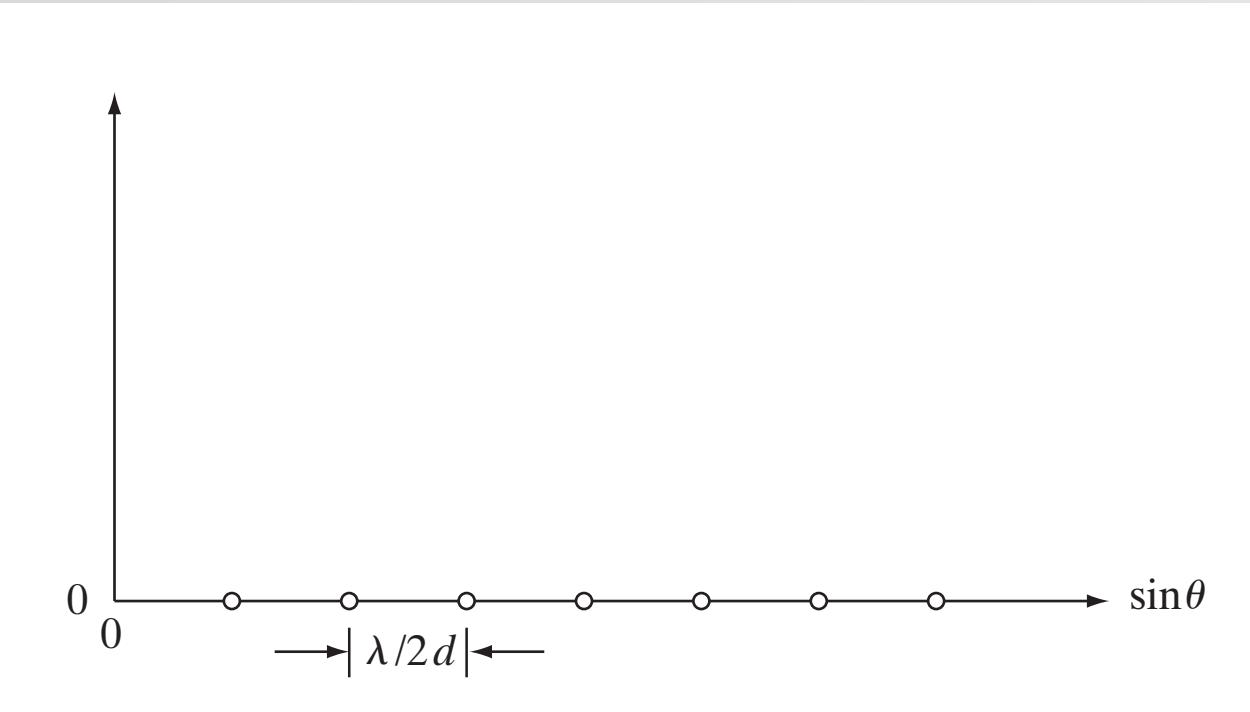
**self consistency:**

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

**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



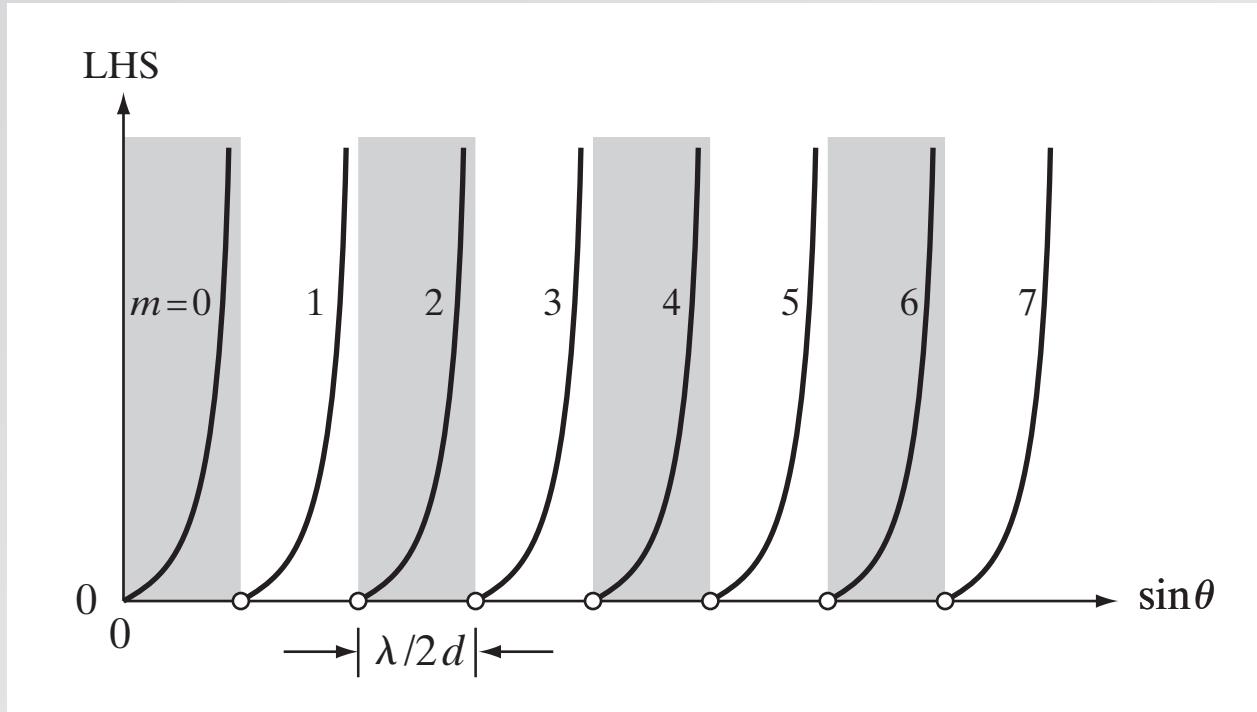
**self consistency:**

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

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# Waveguiding



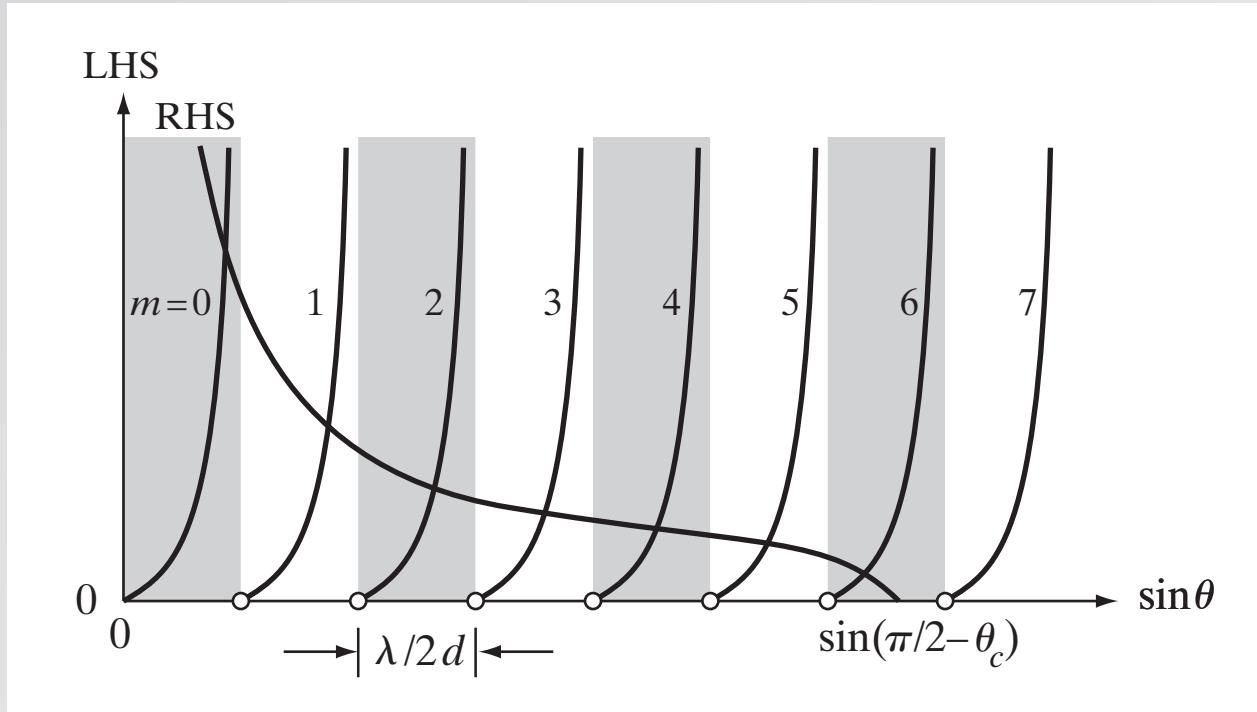
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$$AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m\lambda \quad (m = 0, 1, 2\dots)$$

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# Waveguiding



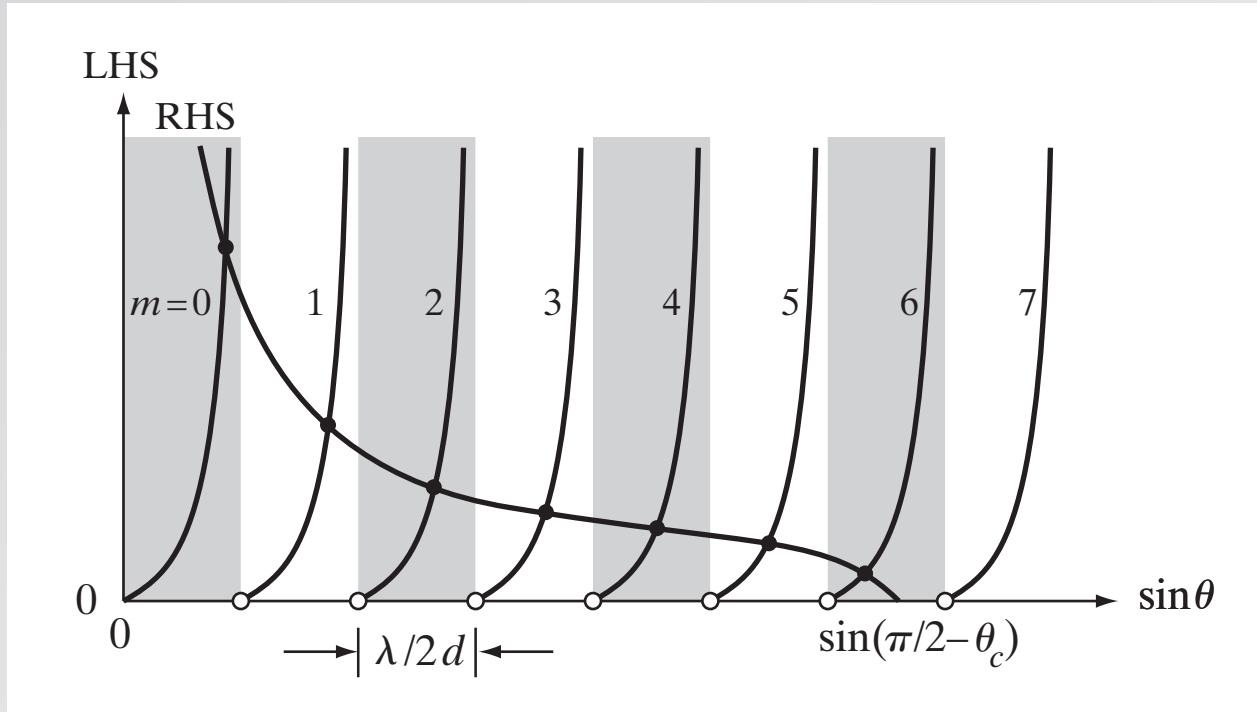
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# Waveguiding



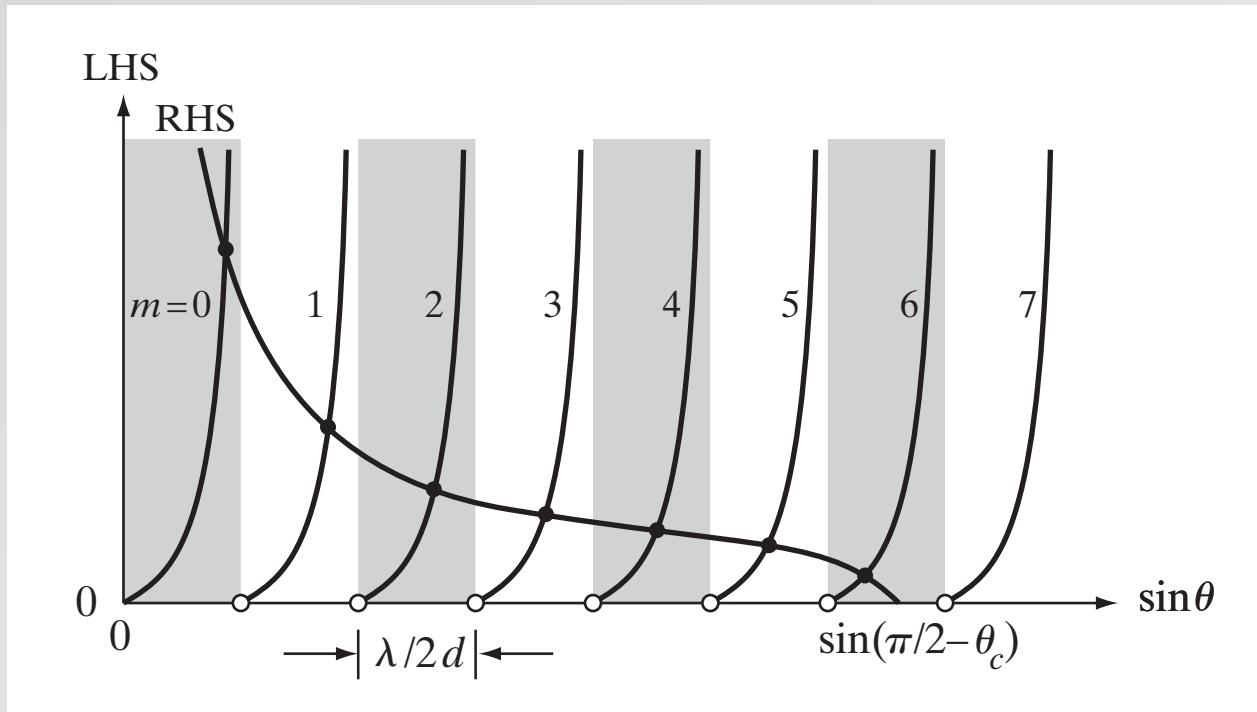
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**so:**

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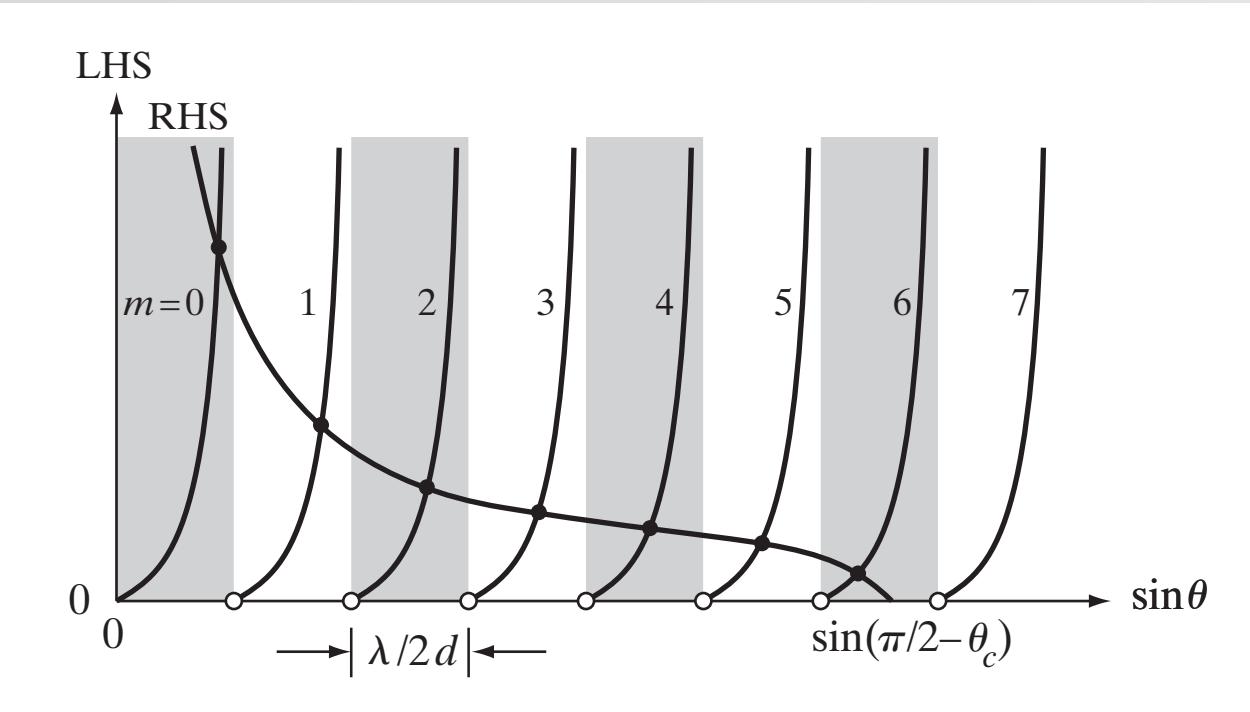
# Waveguiding



**number of modes:**

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

# Waveguiding



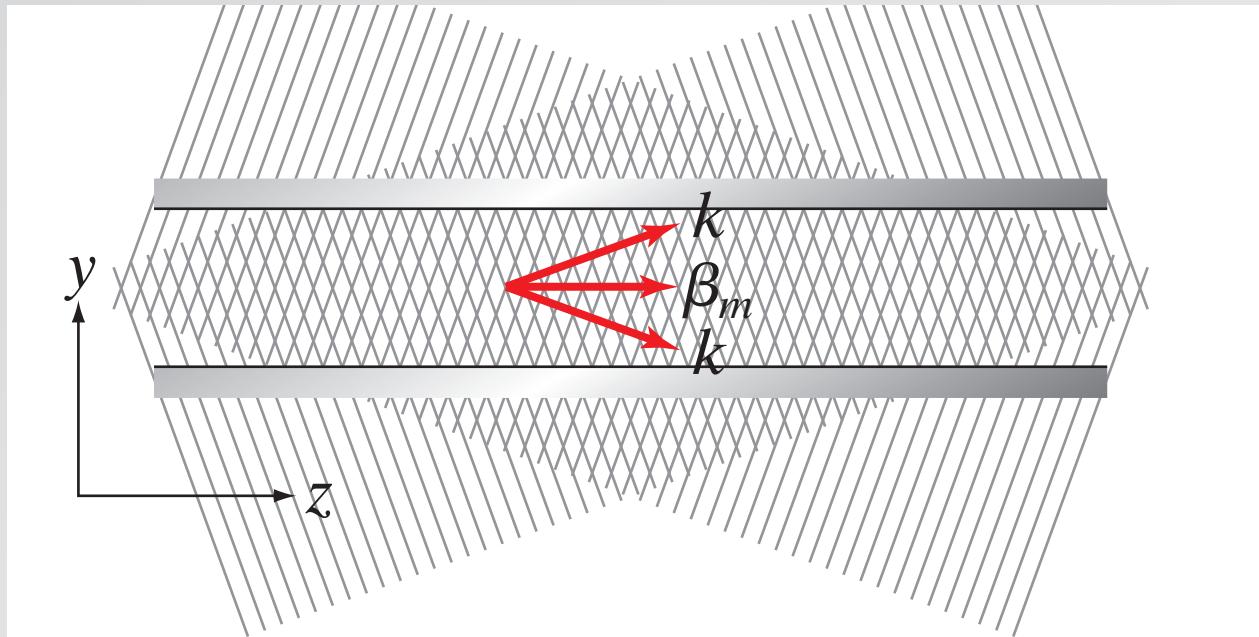
**number of modes:**

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

**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

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

$$300 < d < 600 \text{ nm}$$

dielectric

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

$$d < 268 \text{ nm}$$

# Waveguiding

single mode condition for 600-nm light:

planar mirror

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

dielectric

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

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:

$$\nabla^2 \vec{A} + \omega^2 \mu_0 \epsilon \vec{A} = 0$$

Substituting

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

# Waveguiding

Vector potential obeys:

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

Substituting

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

yields:

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

# Waveguiding

Vector potential obeys:

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

Substituting

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

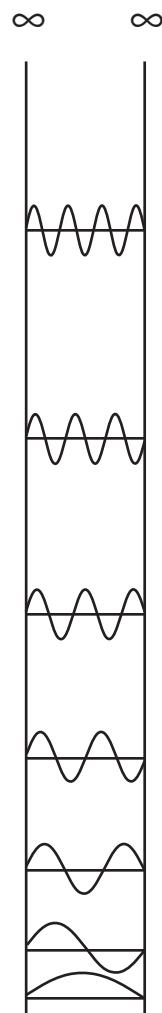
yields:

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

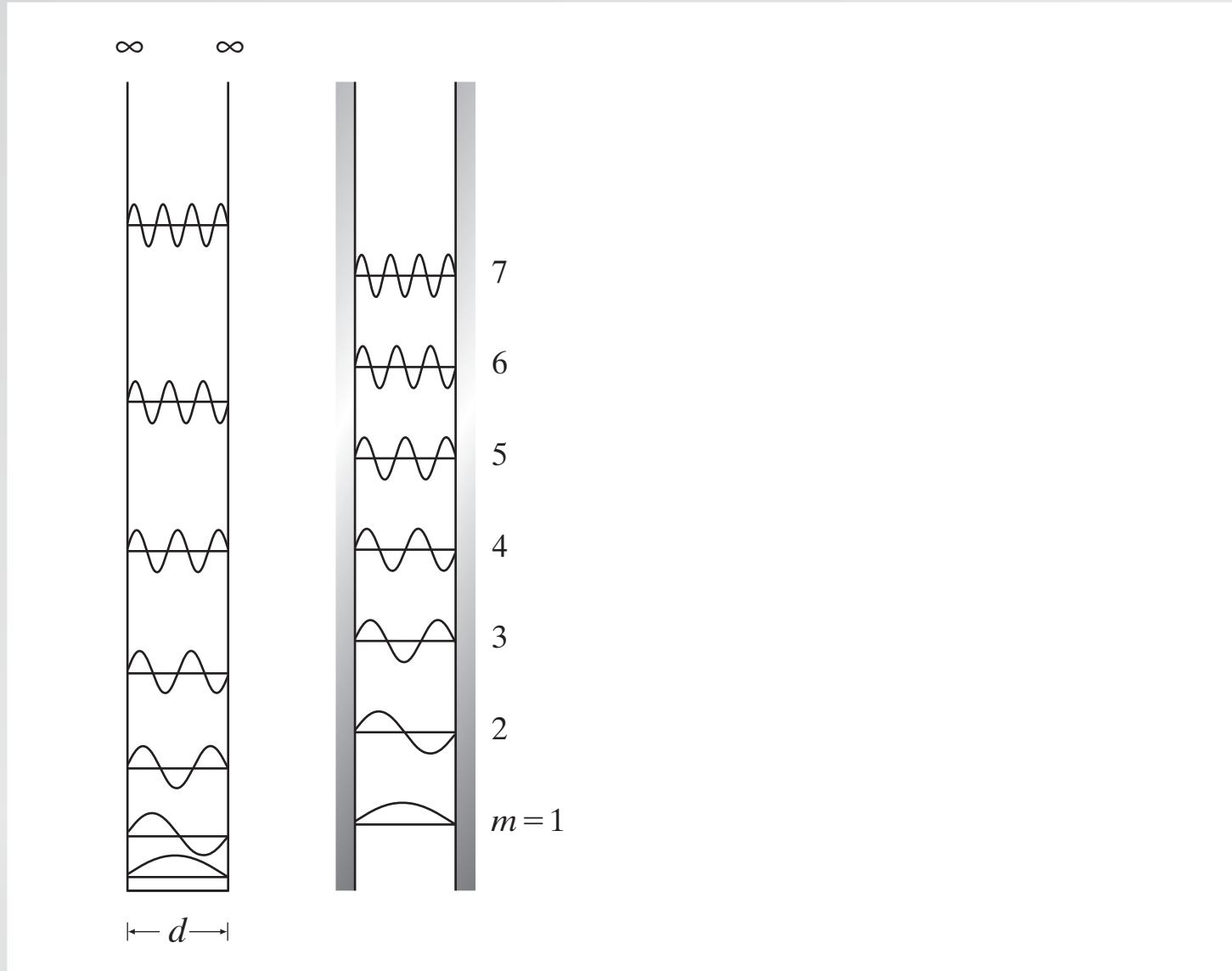
Compare to time-independent Schrödinger equation:

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

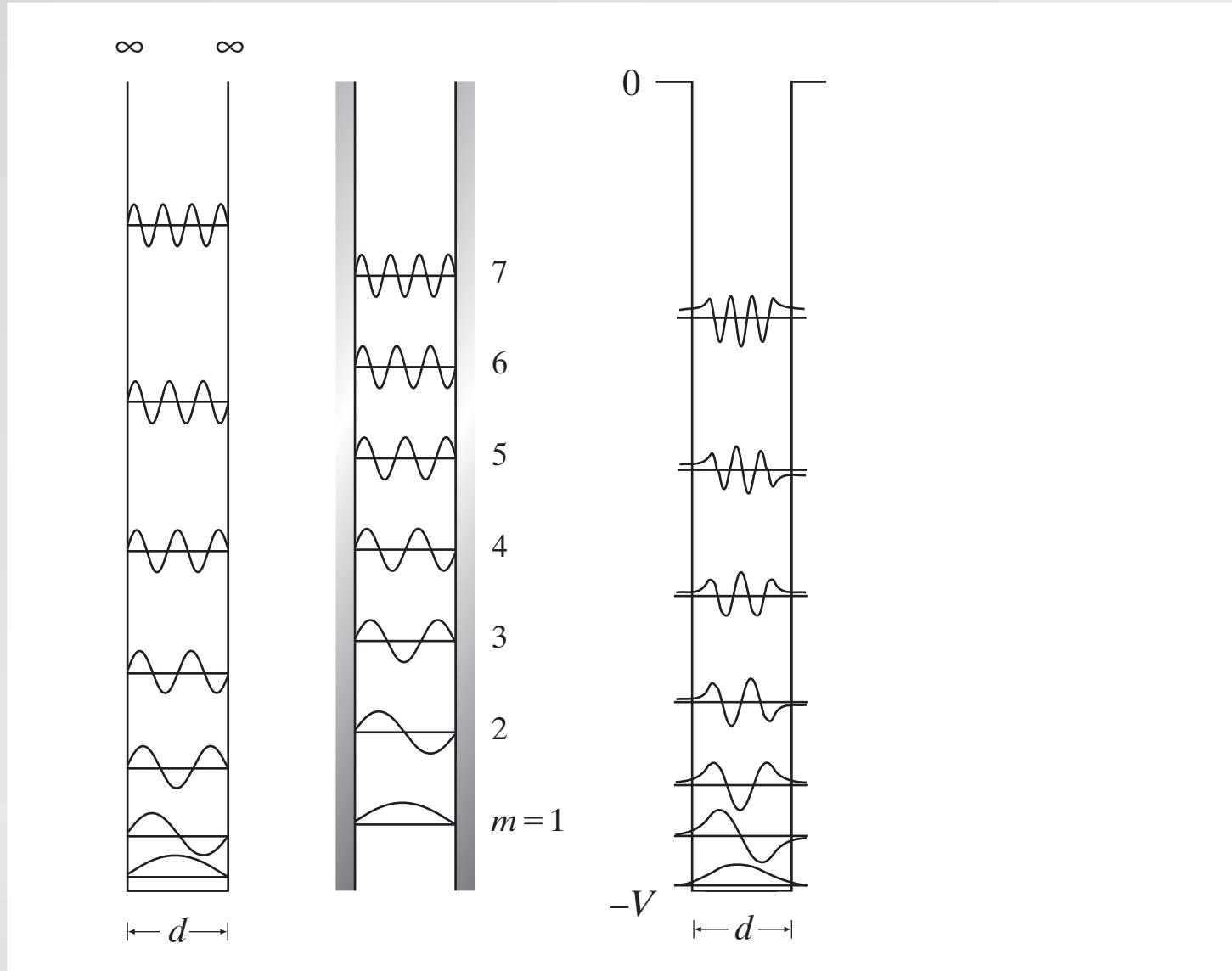
# Waveguiding



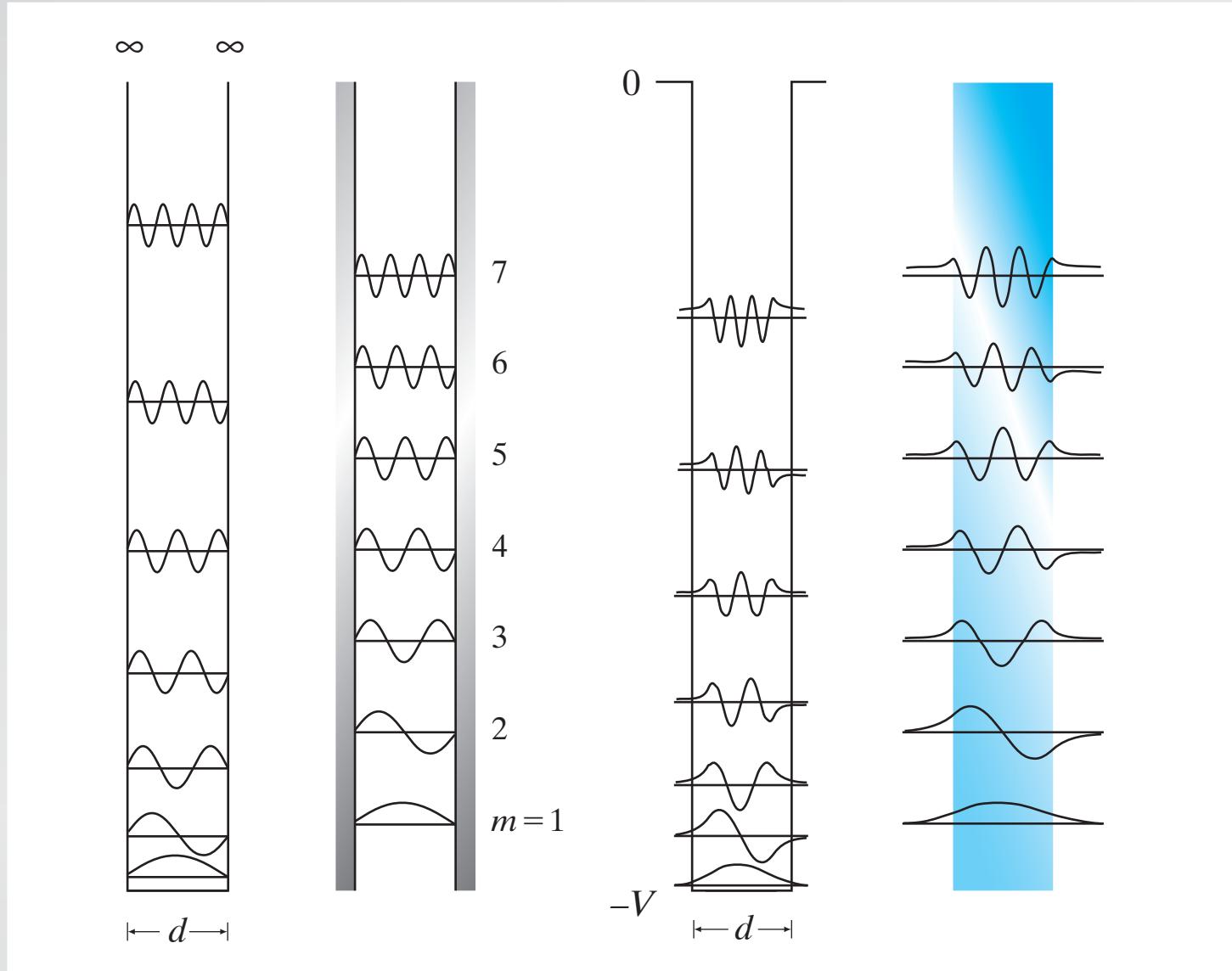
# Waveguiding



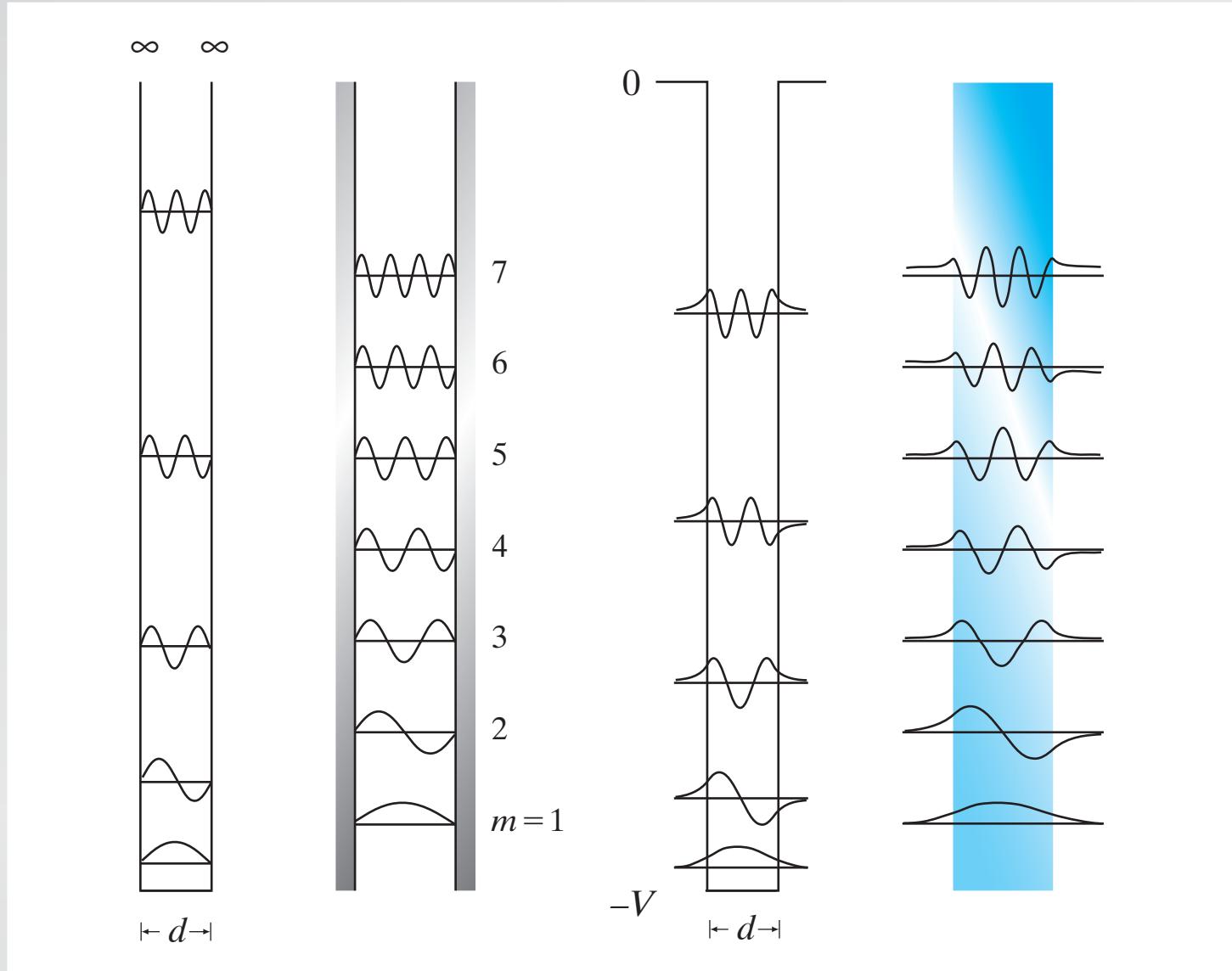
# Waveguiding



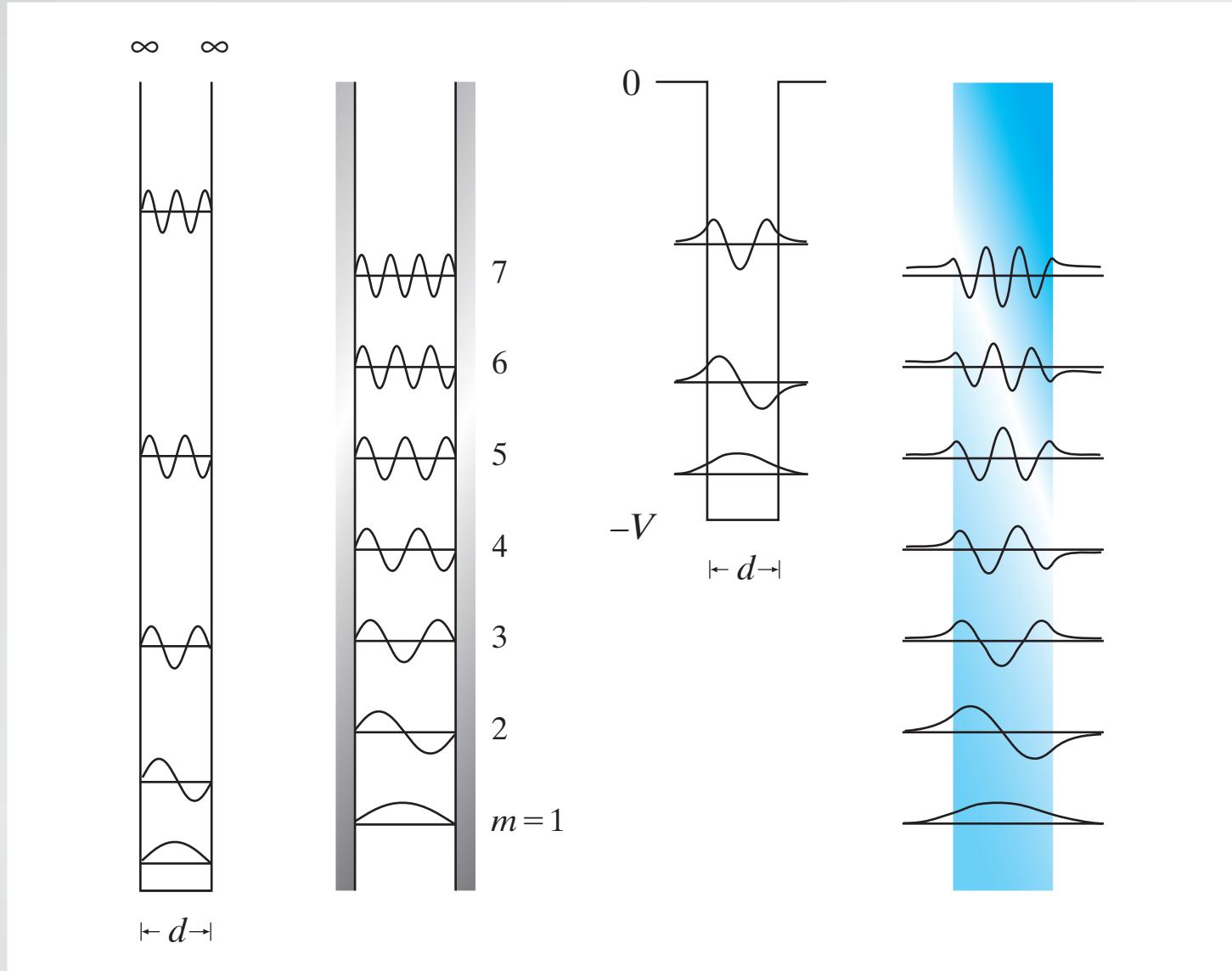
# Waveguiding



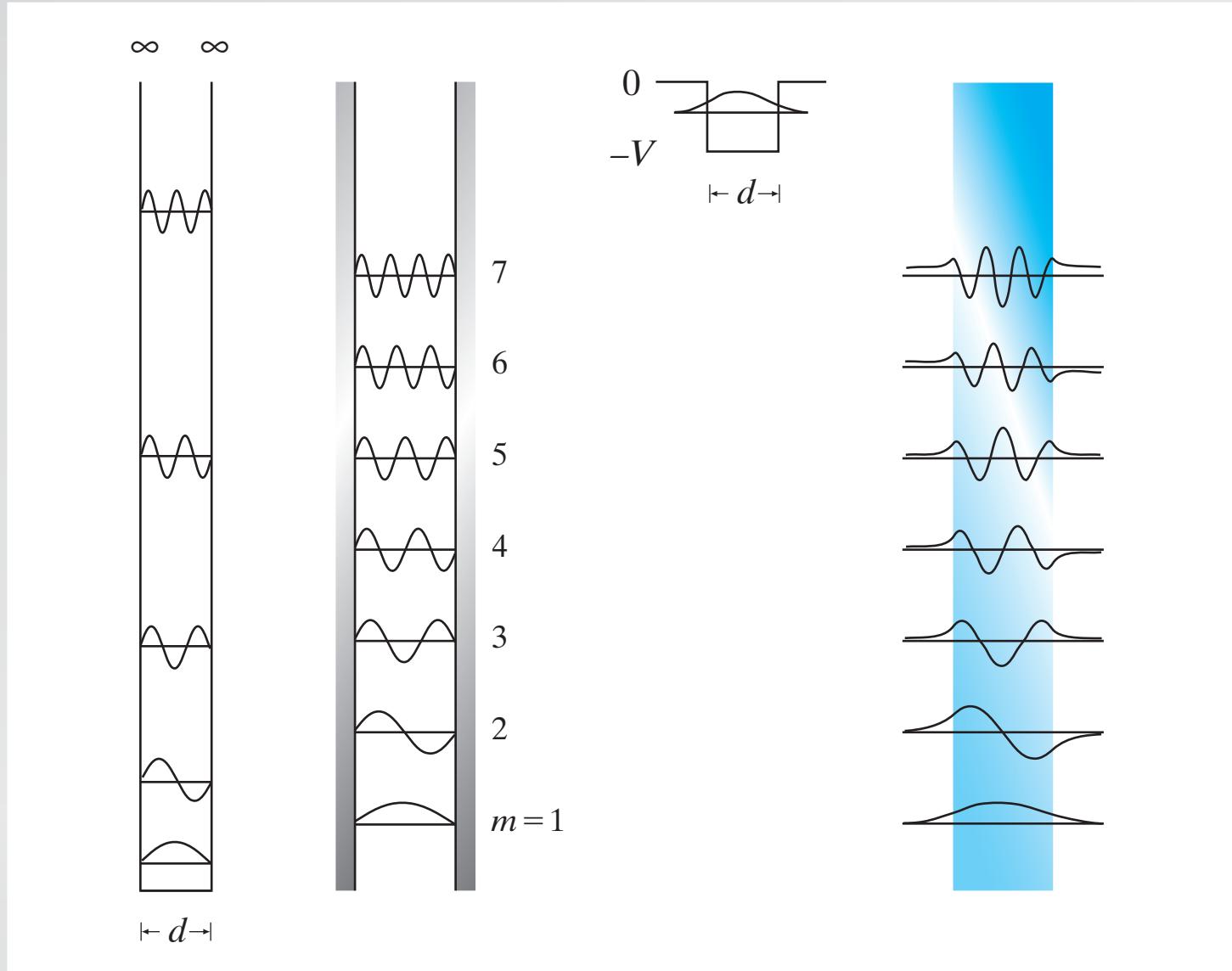
# Waveguiding



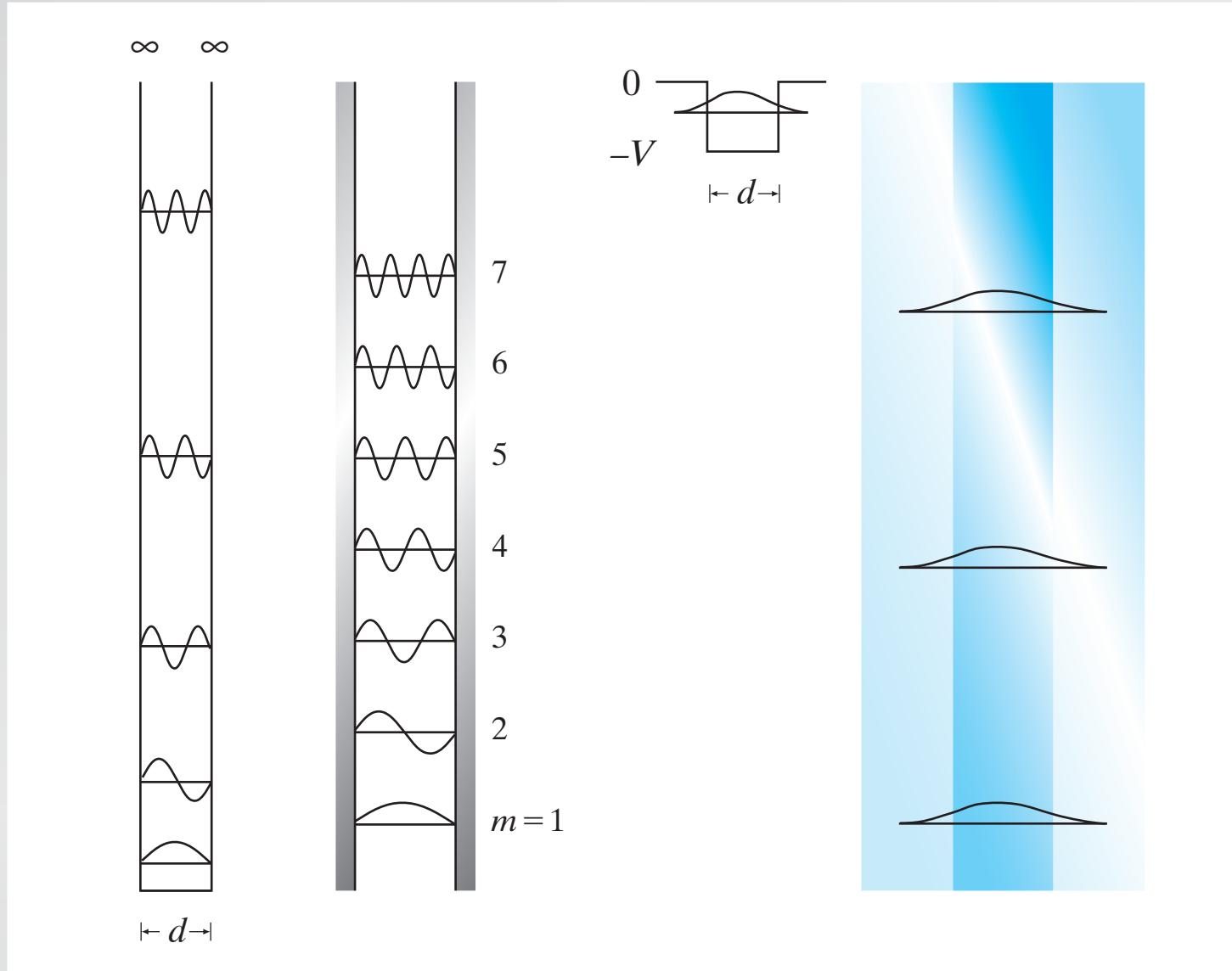
# Waveguiding



# 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:**

$8.3 \mu\text{m}$

$125.0 \pm 1.0 \mu\text{m}$

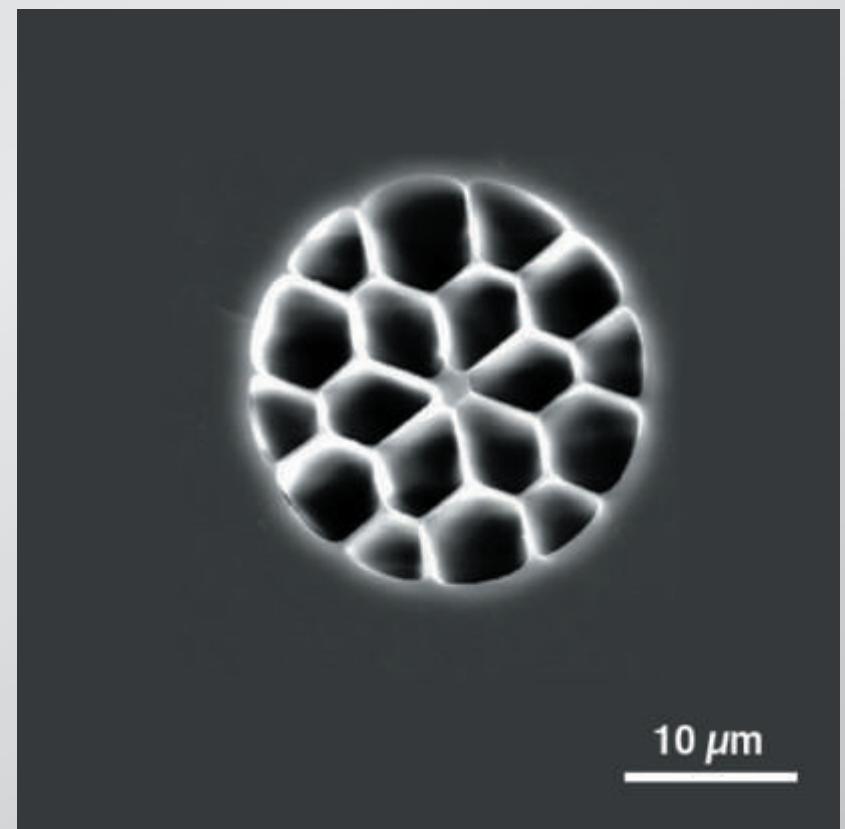
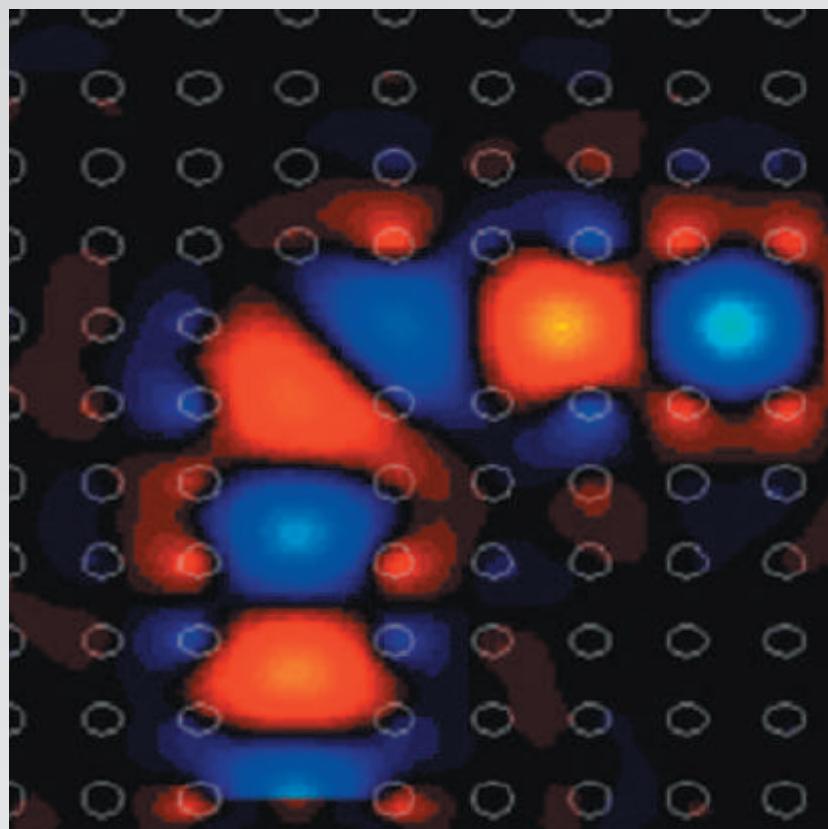
**operating wavelength:**  $\lambda = 1310 \text{ nm}/1550 \text{ nm}$

# Waveguiding

**drawbacks of clad fibers:**

- weak confinement
- no tight bending
- coupling requires splicing

# Waveguiding



# Outline

- waveguiding
- nanowire fabrication
- optical properties

# Nanowire fabrication

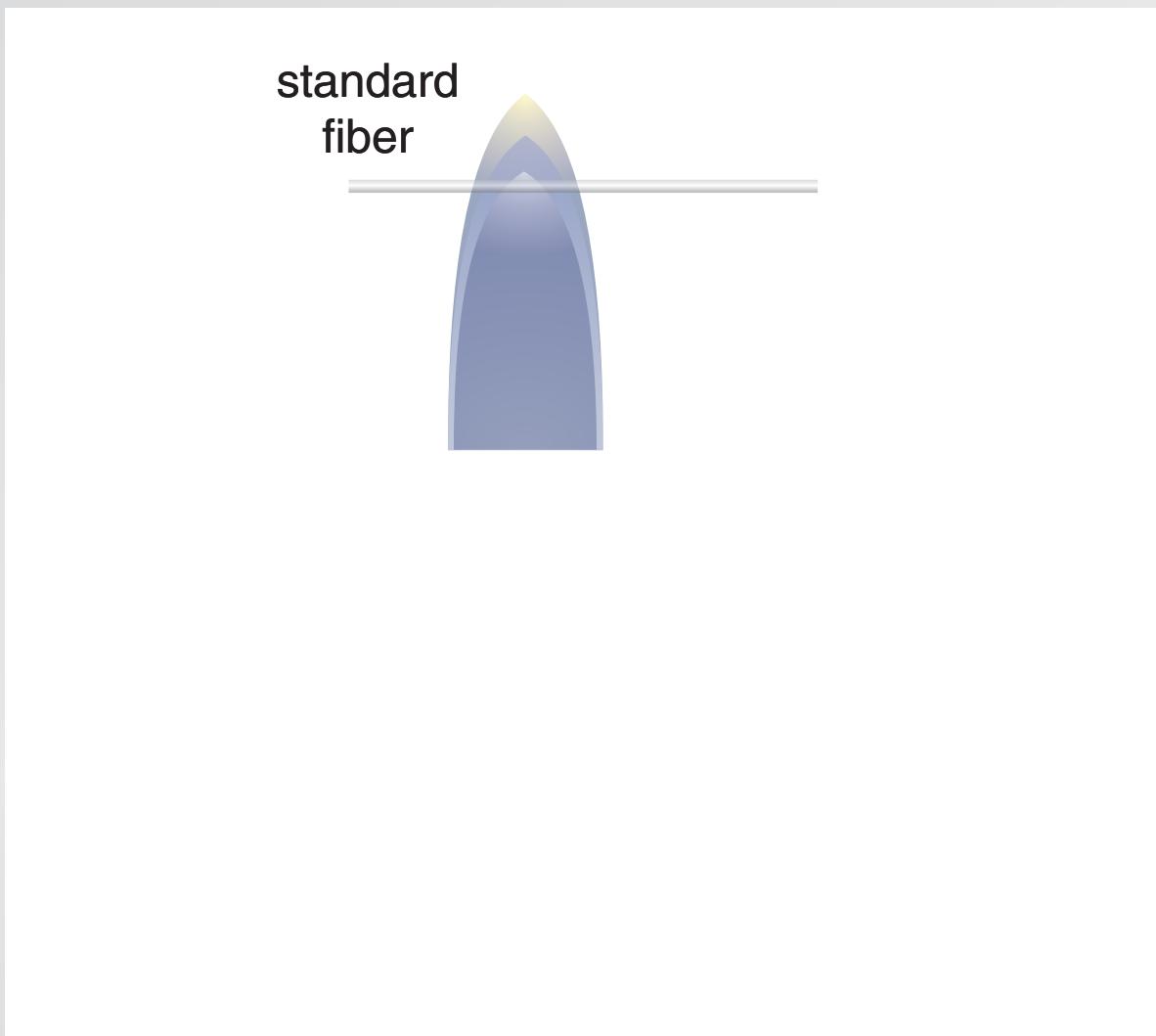
## two-step drawing process

standard  
fiber

---

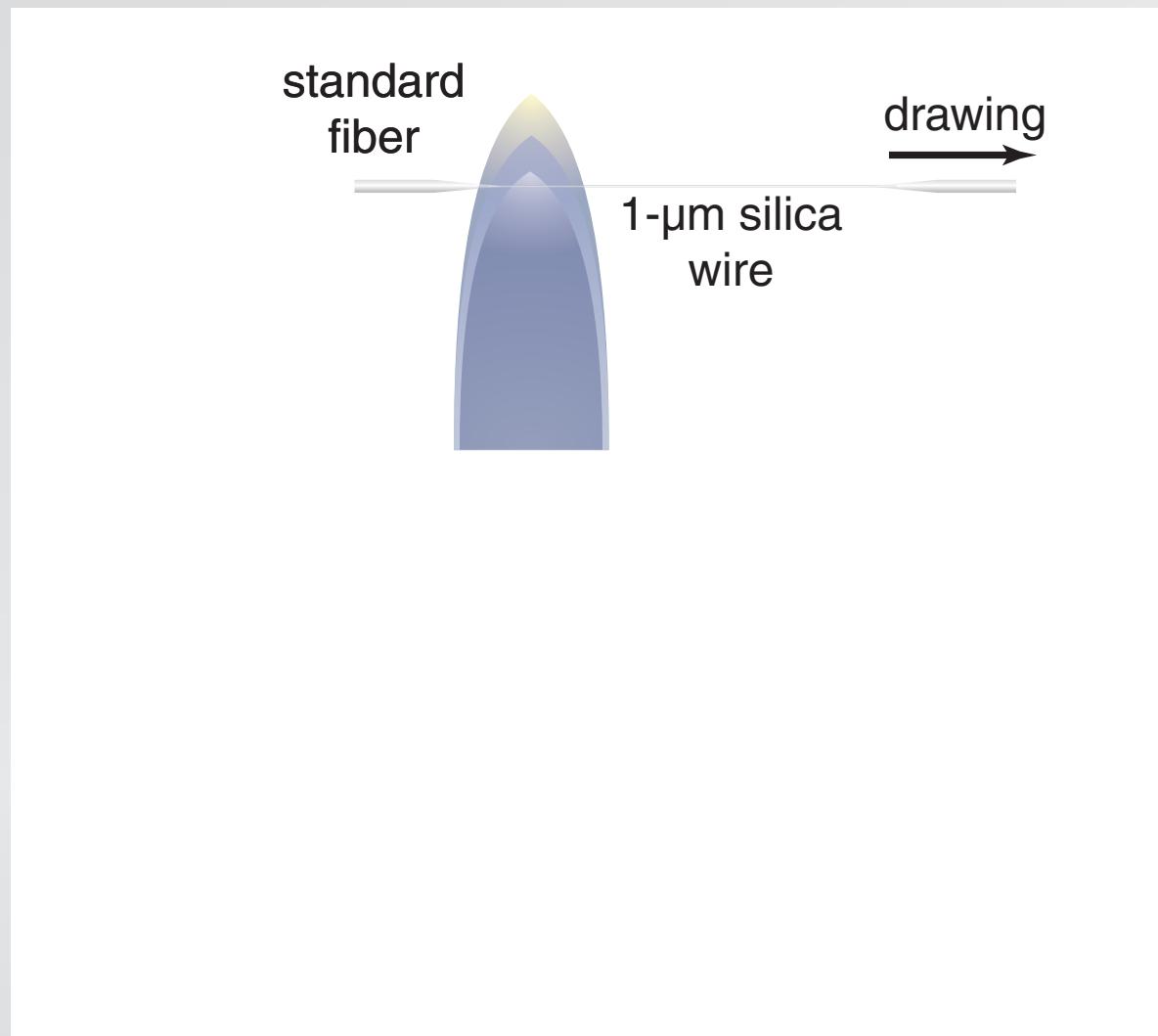
# Nanowire fabrication

two-step drawing process



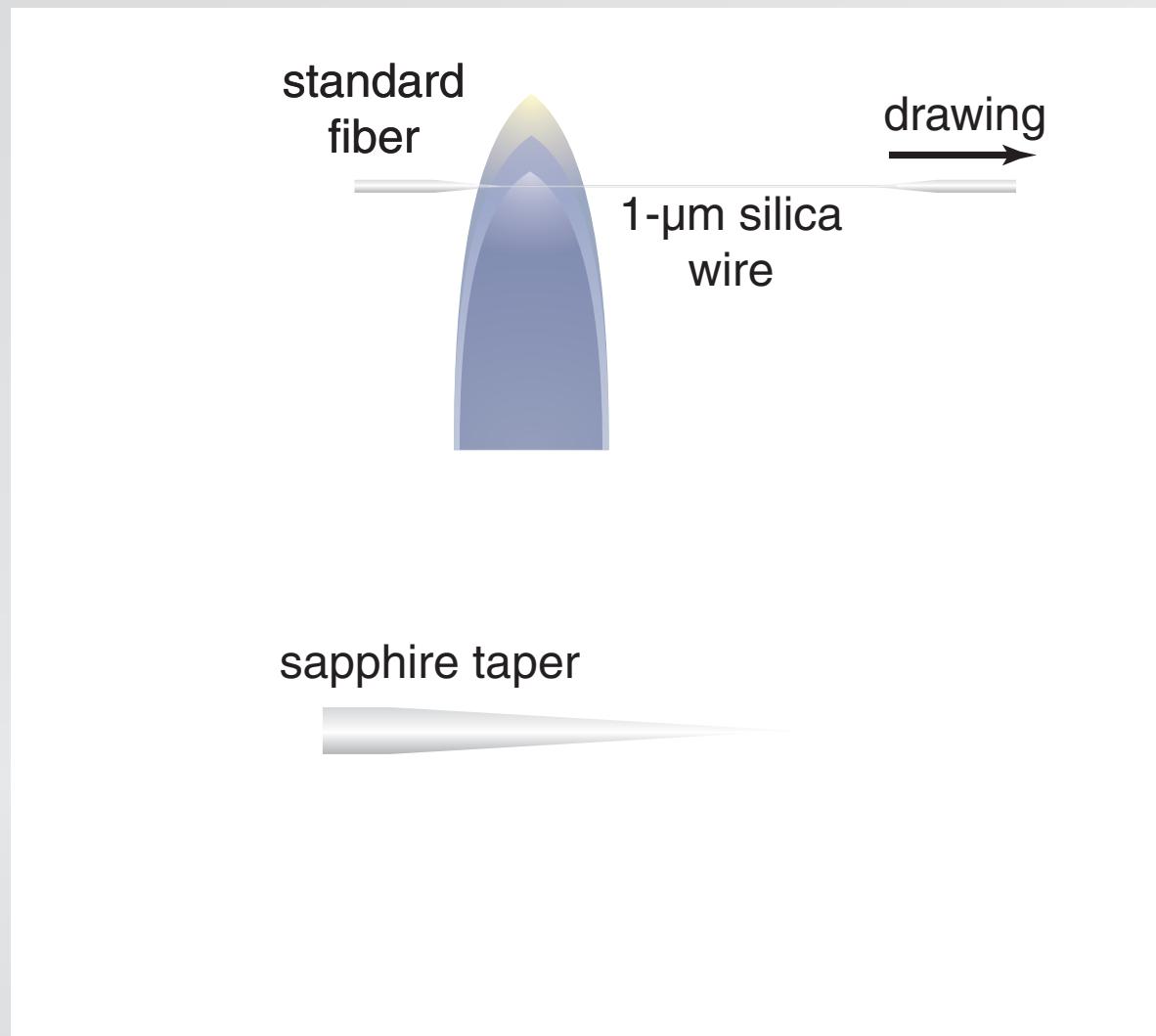
# Nanowire fabrication

two-step drawing process



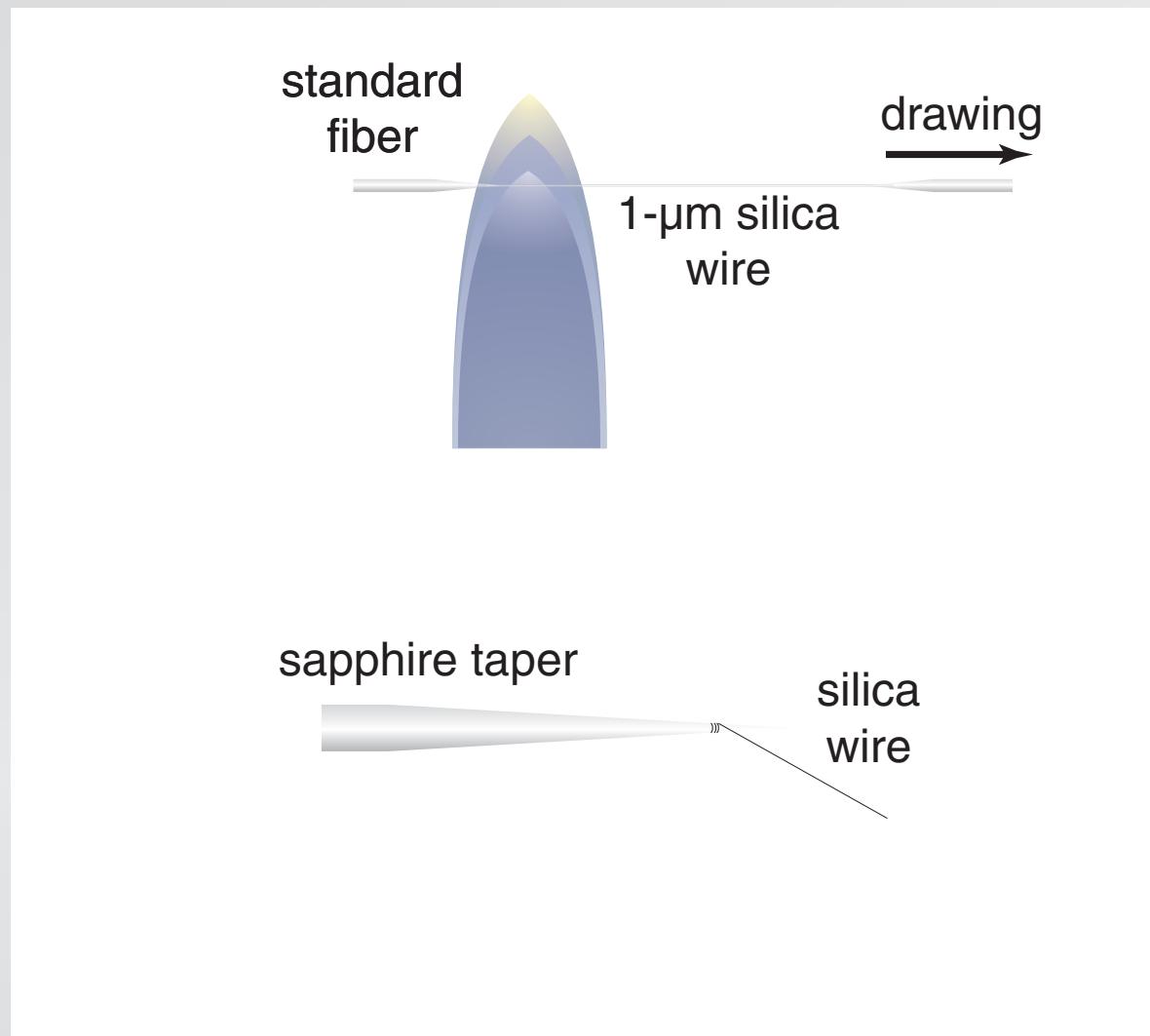
# Nanowire fabrication

## two-step drawing process



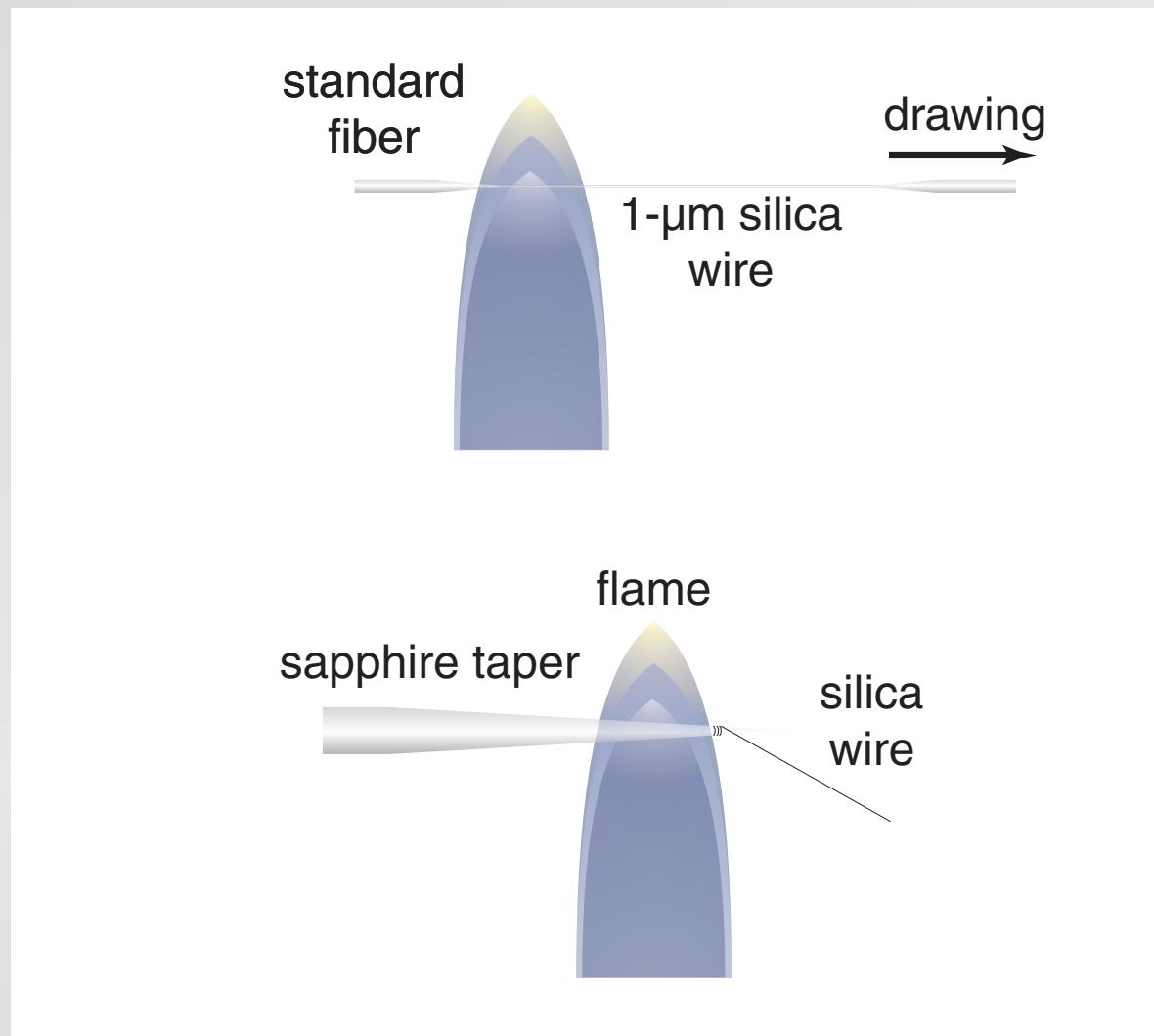
# Nanowire fabrication

## two-step drawing process



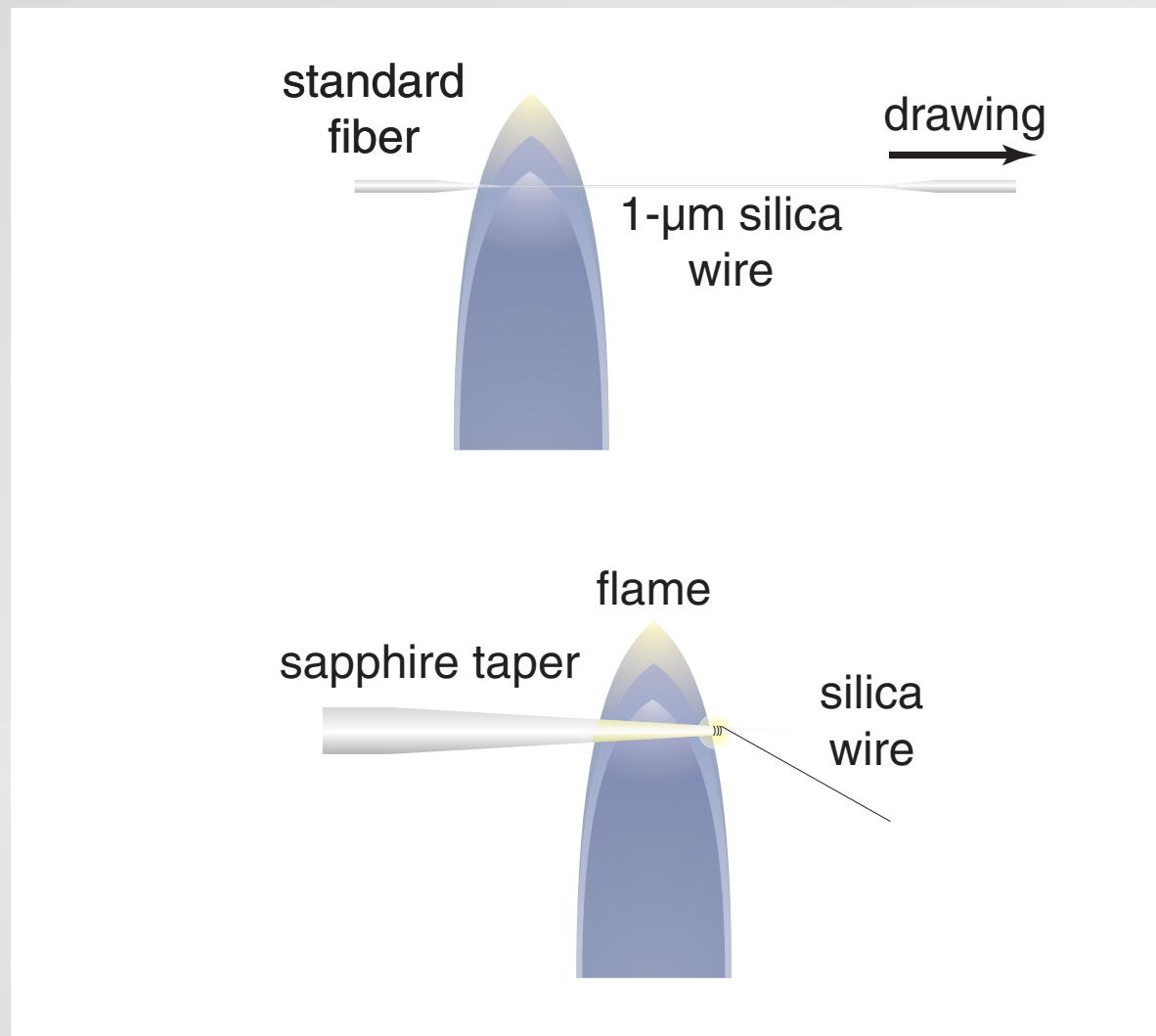
# Nanowire fabrication

## two-step drawing process



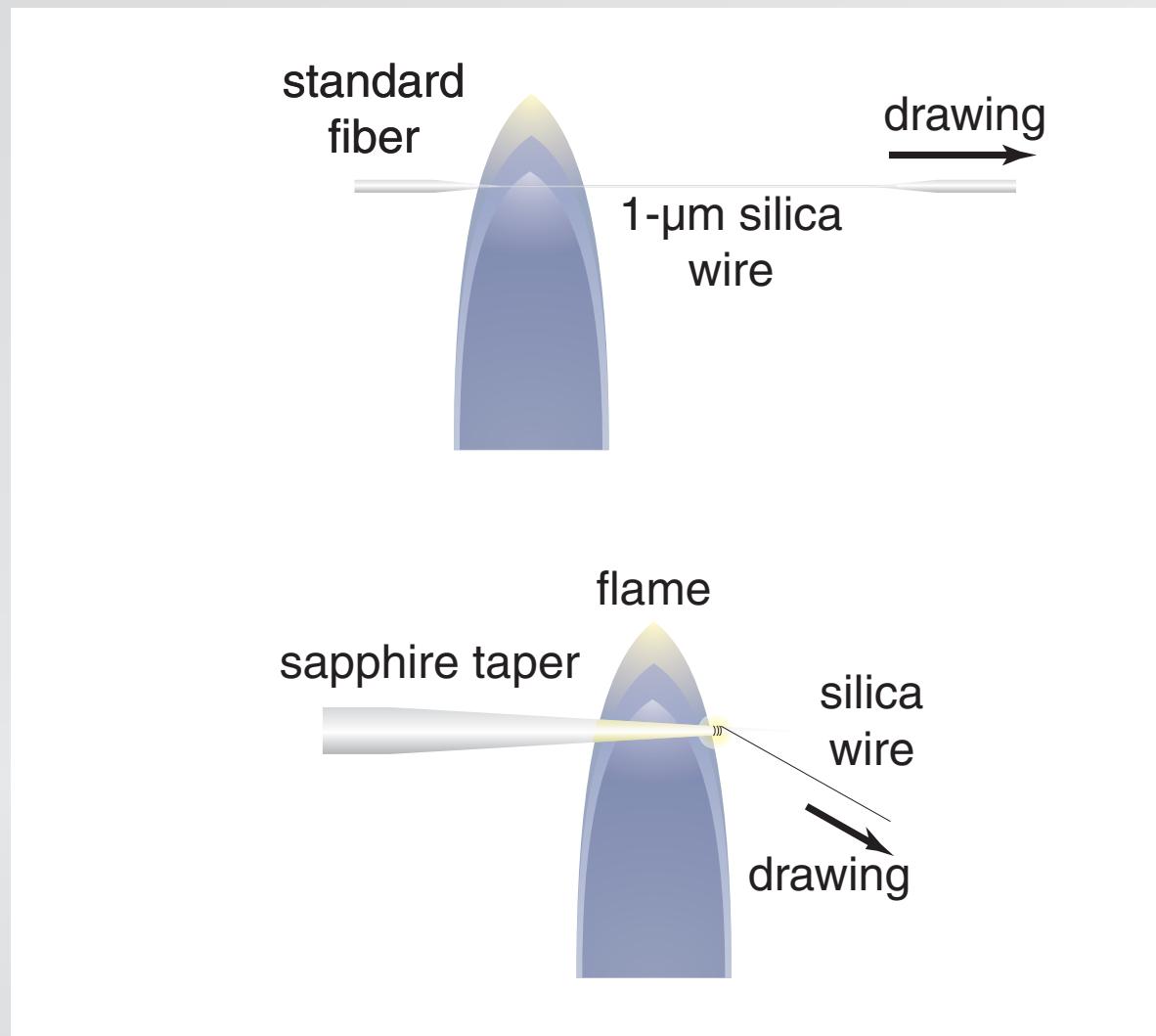
# Nanowire fabrication

## two-step drawing process

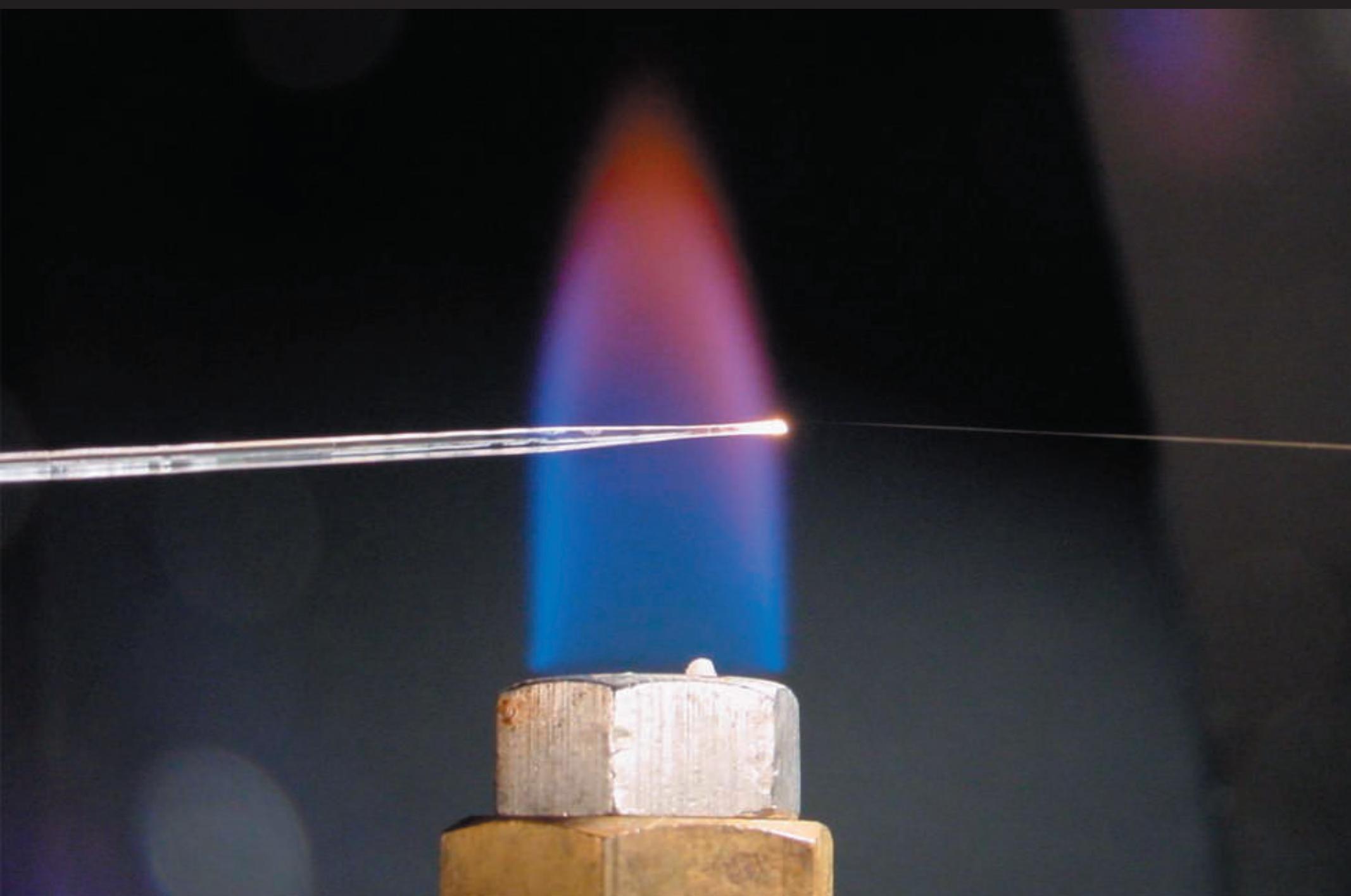


# Nanowire fabrication

## two-step drawing process



# Nanowire fabrication



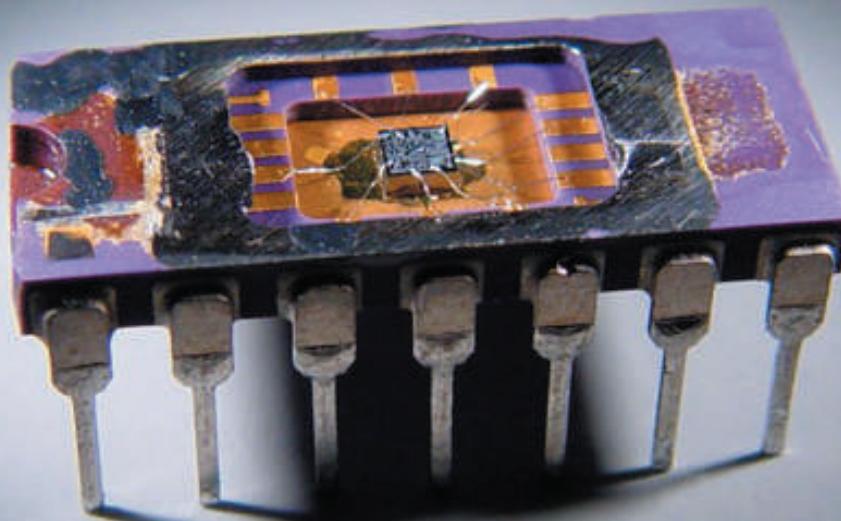
# Nanowire fabrication

1 μm

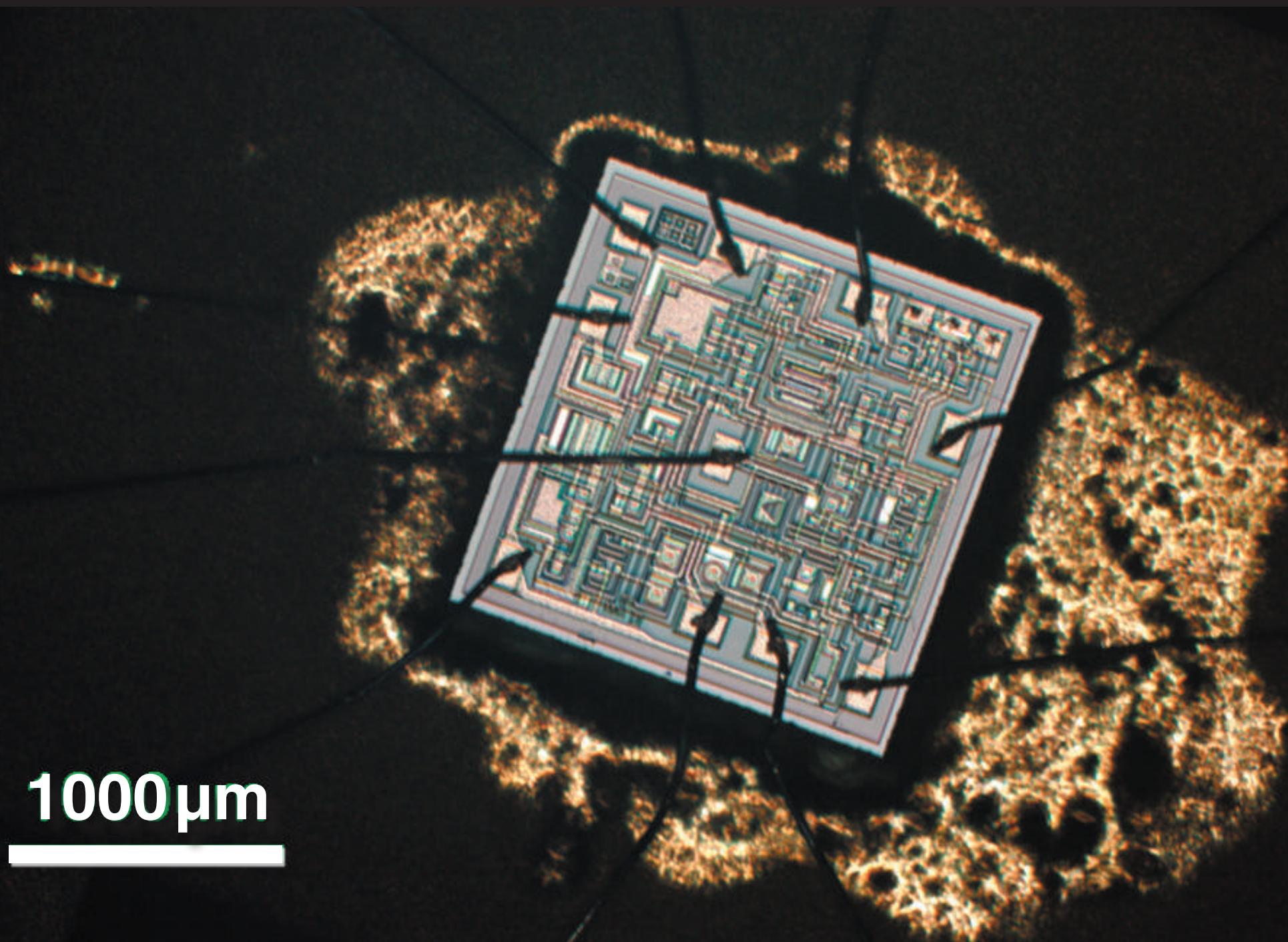


*Nature*, 426, 816 (2003)

# Nanowire fabrication



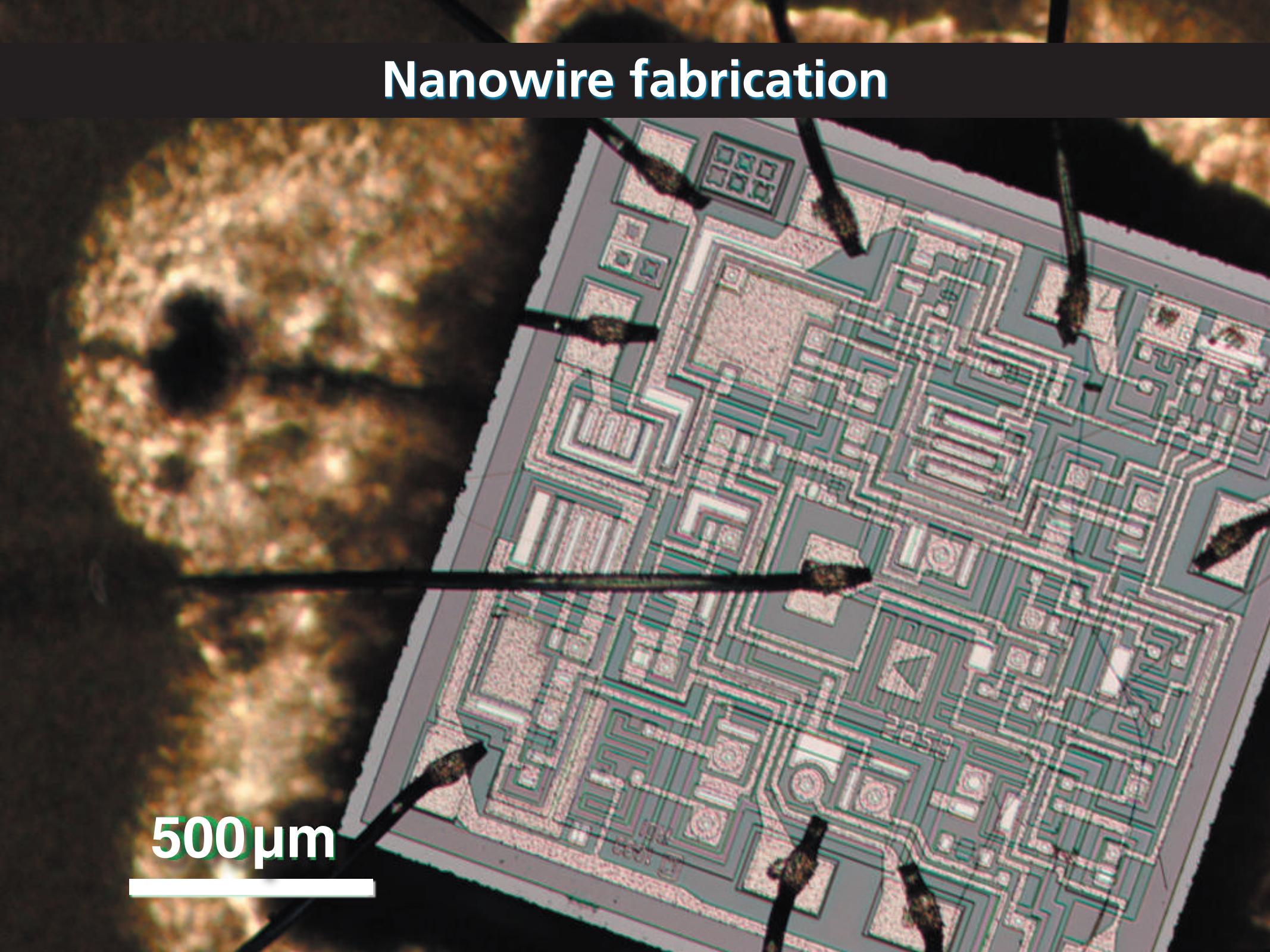
# Nanowire fabrication



1000  $\mu\text{m}$

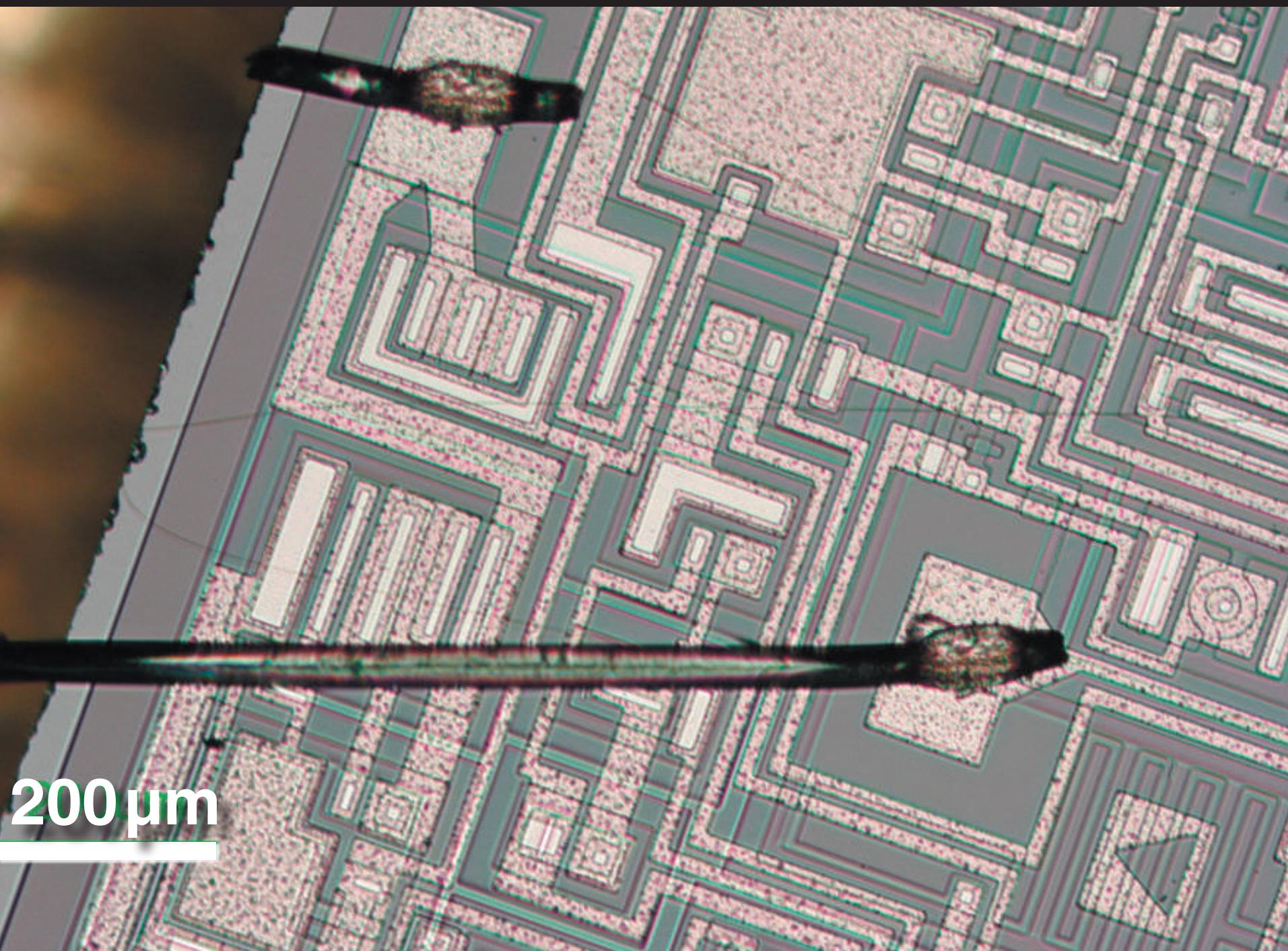
# Nanowire fabrication

500  $\mu\text{m}$

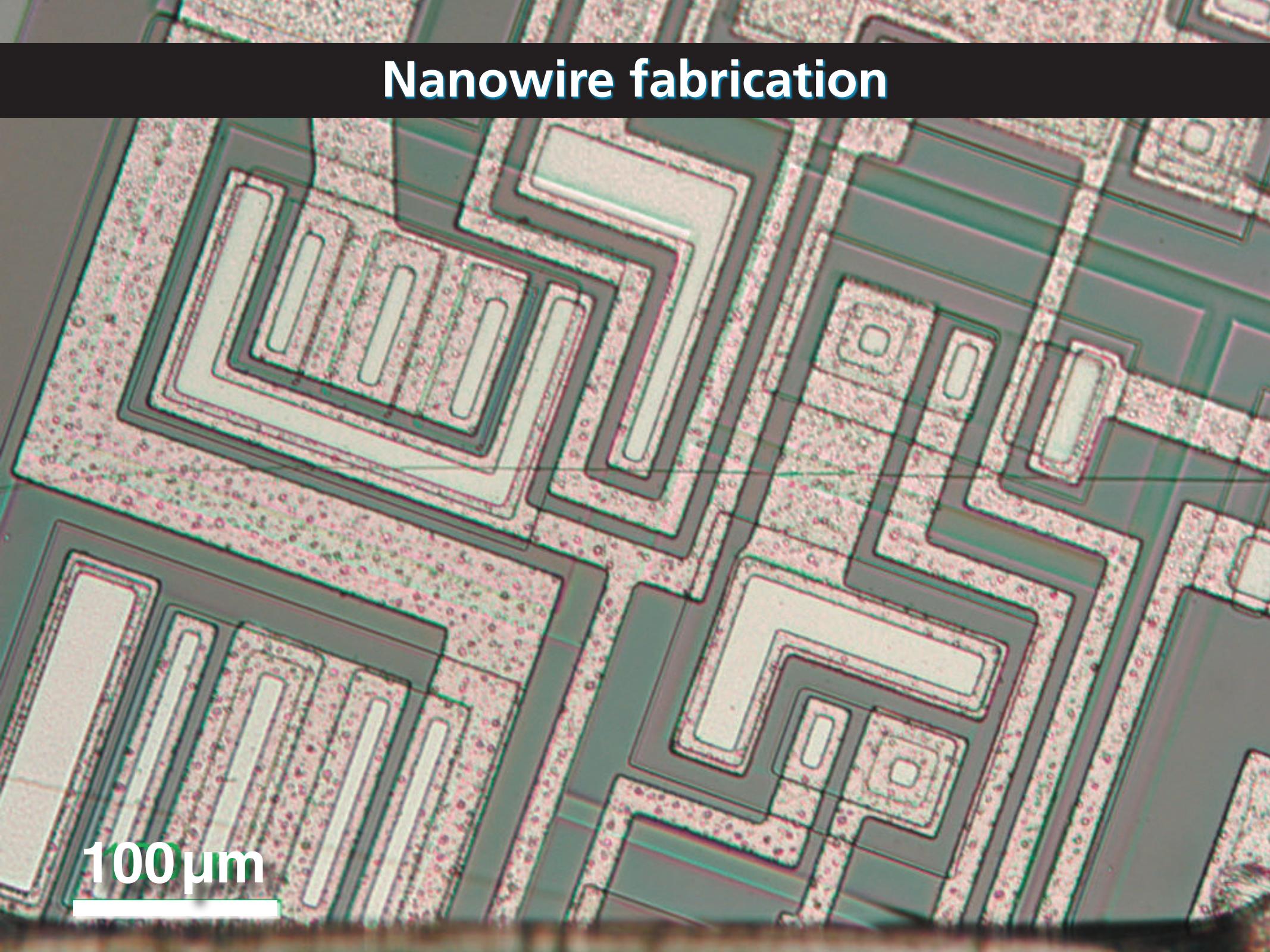


# Nanowire fabrication

200  $\mu\text{m}$



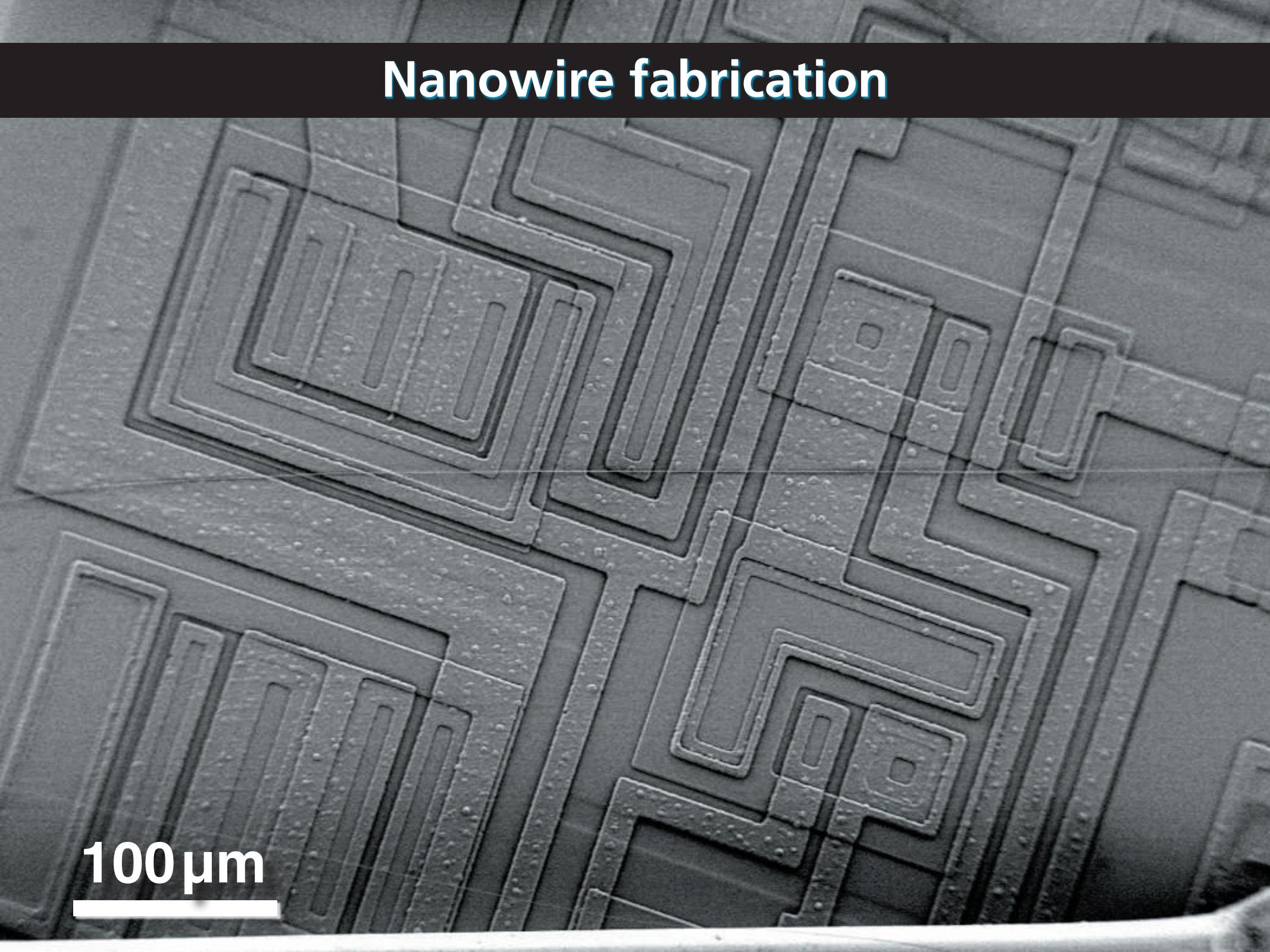
# Nanowire fabrication



100 $\mu\text{m}$

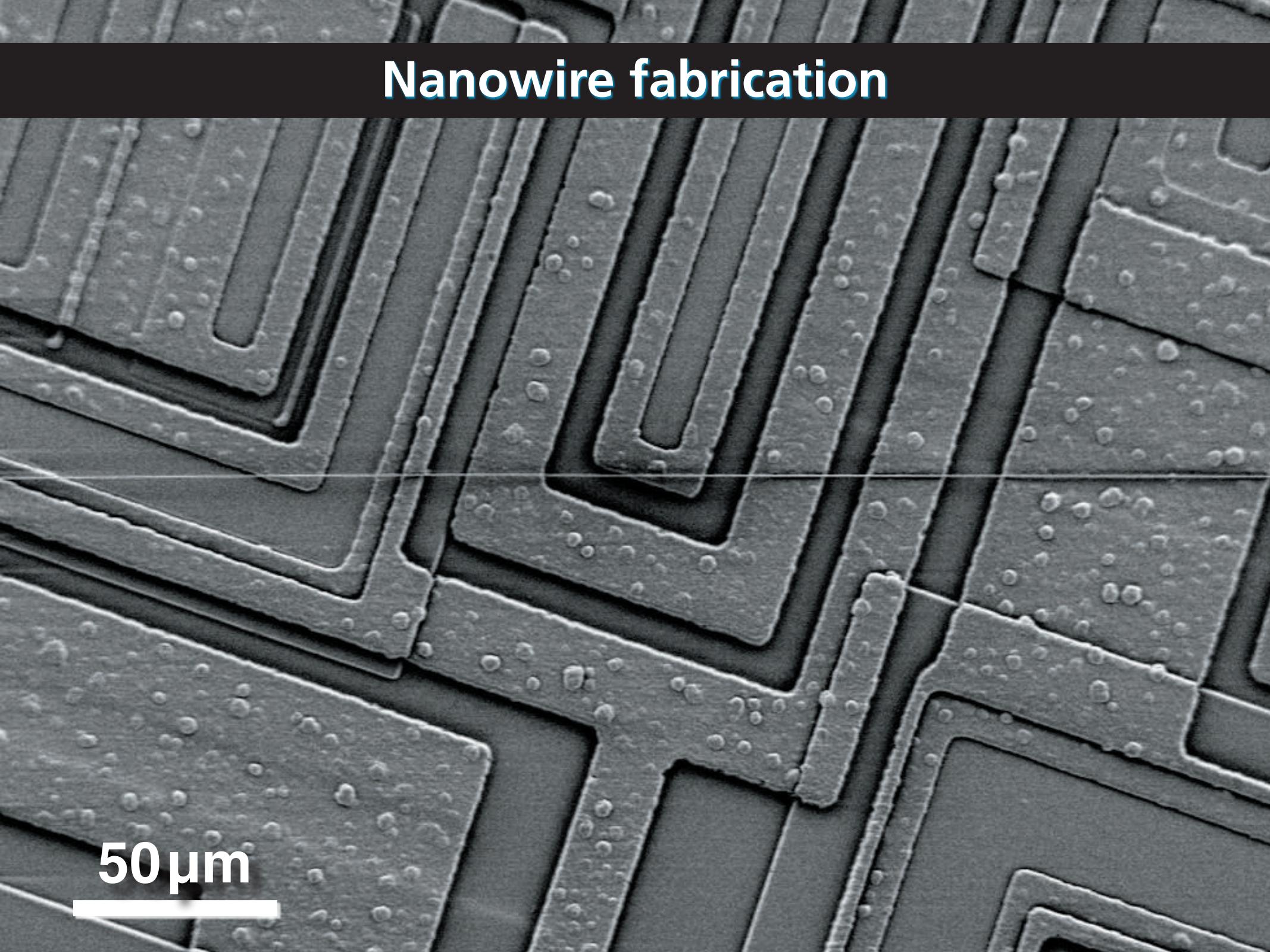
# Nanowire fabrication

100  $\mu\text{m}$

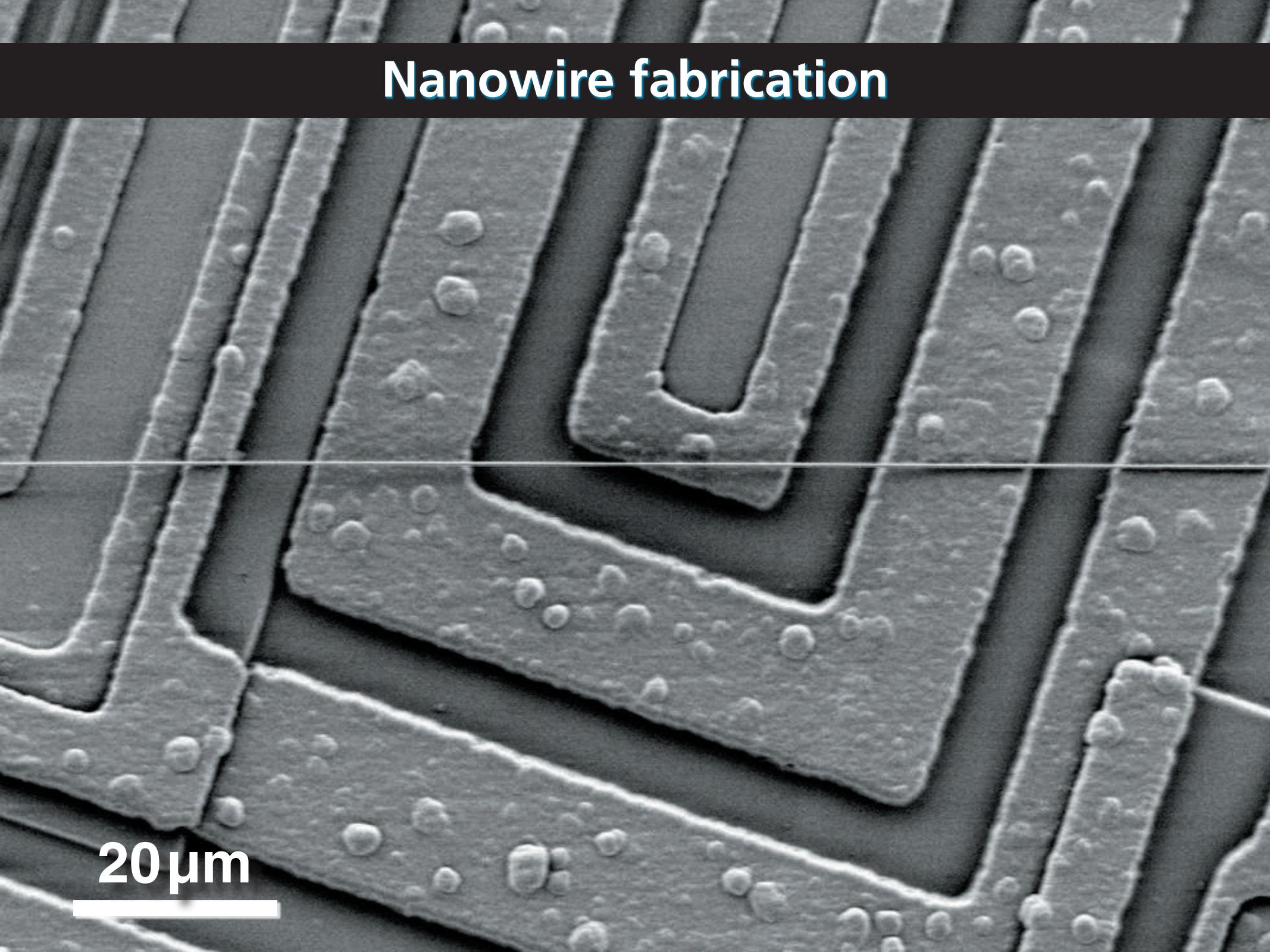


# Nanowire fabrication

50  $\mu\text{m}$

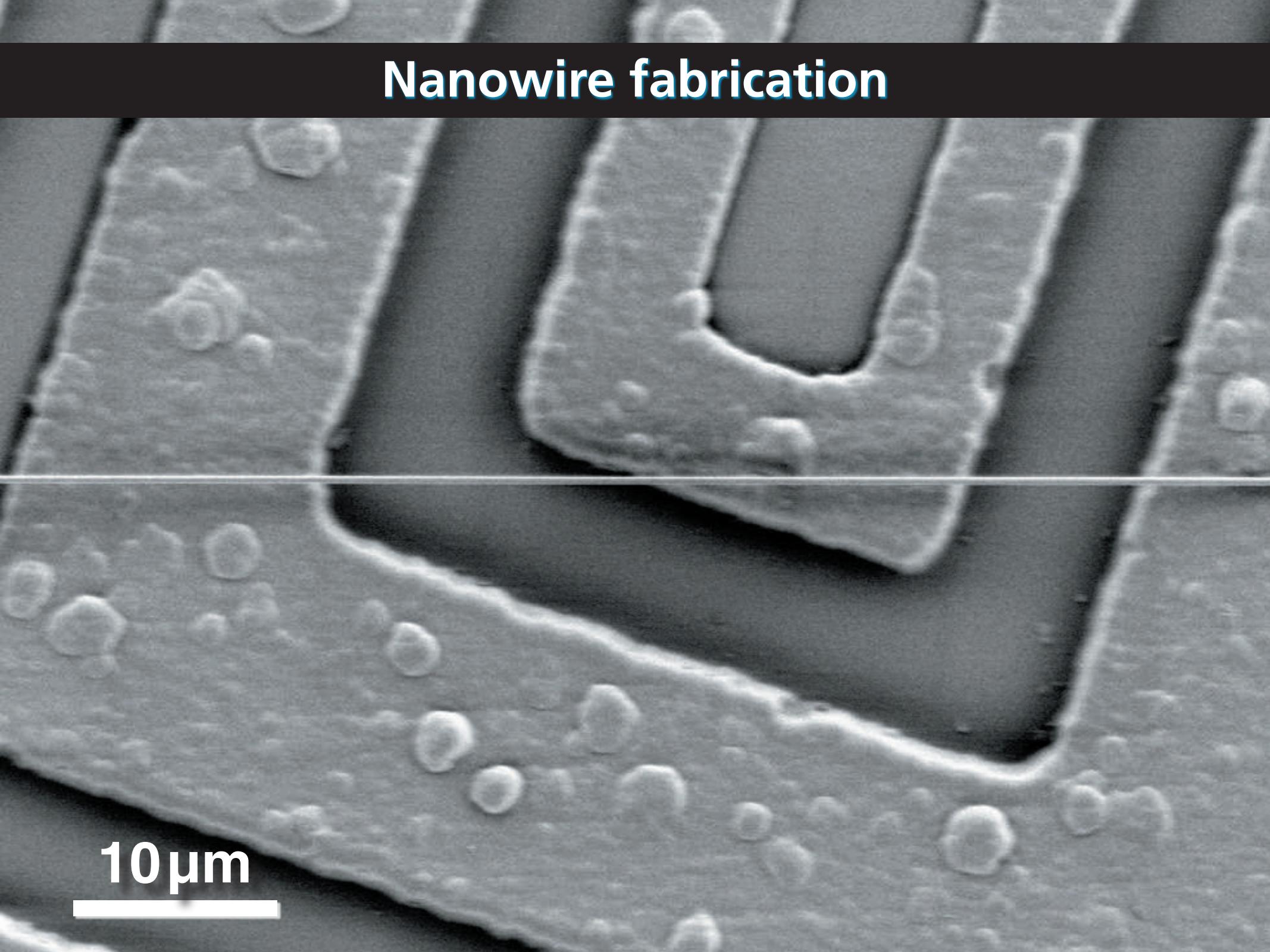


# Nanowire fabrication



20  $\mu\text{m}$

# Nanowire fabrication



10  $\mu\text{m}$

# Nanowire fabrication

6  $\mu$ m



# Nanowire fabrication

4  $\mu\text{m}$

# Nanowire fabrication

2  $\mu\text{m}$

# Nanowire fabrication

312 nm



1  $\mu$ m



# Waveguiding

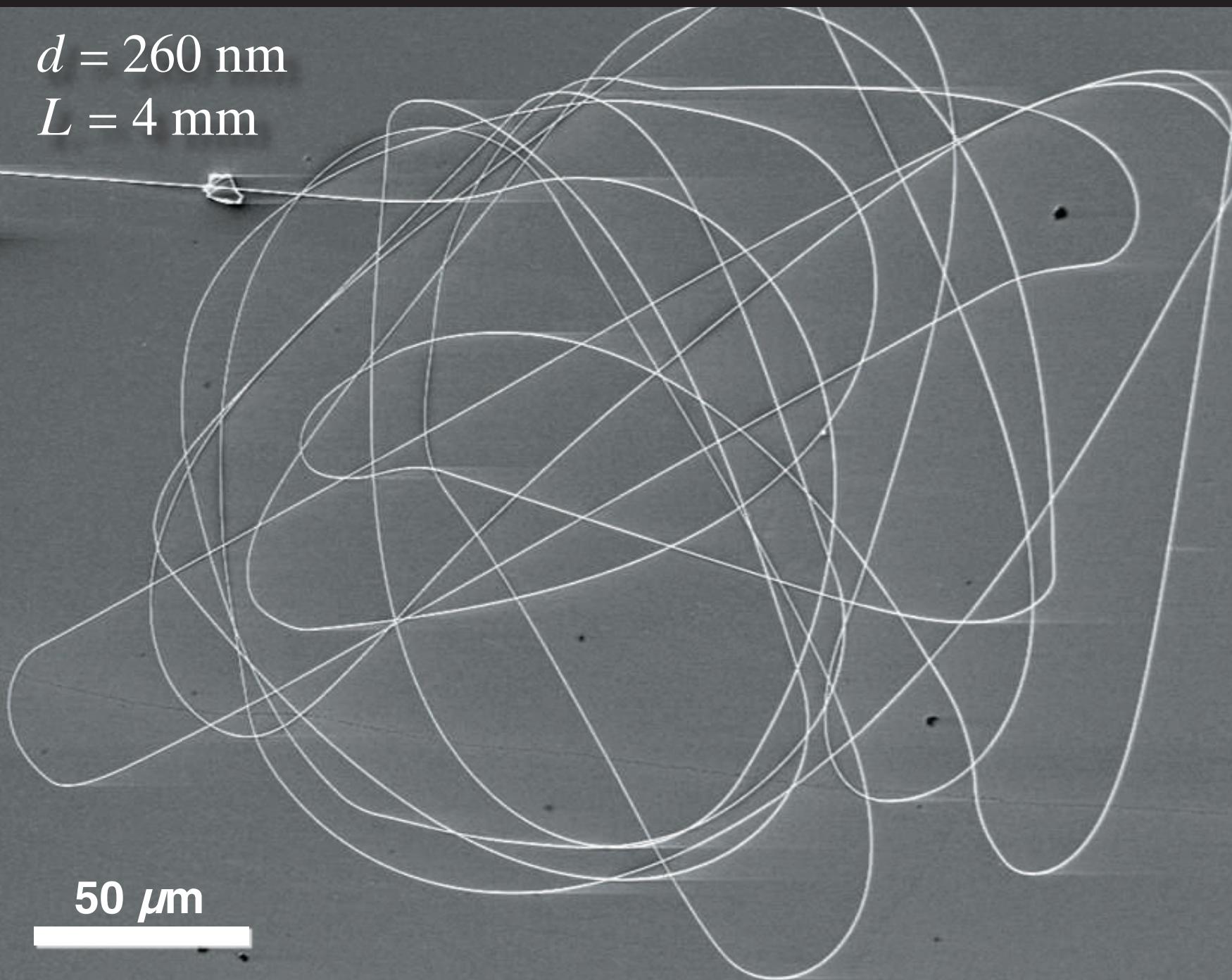
## Specifications

<b>diameter <math>D</math>:</b>	<b>down to 20 nm</b>
<b>length <math>L</math>:</b>	<b>up to 90 mm</b>
<b>aspect ratio <math>D/L</math>:</b>	<b>up to <math>10^6</math></b>
<b>diameter uniformity <math>\Delta D/L</math>:</b>	<b><math>2 \times 10^{-6}</math></b>

# Nanowire fabrication

$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



# Nanowire fabrication

240-nm wire

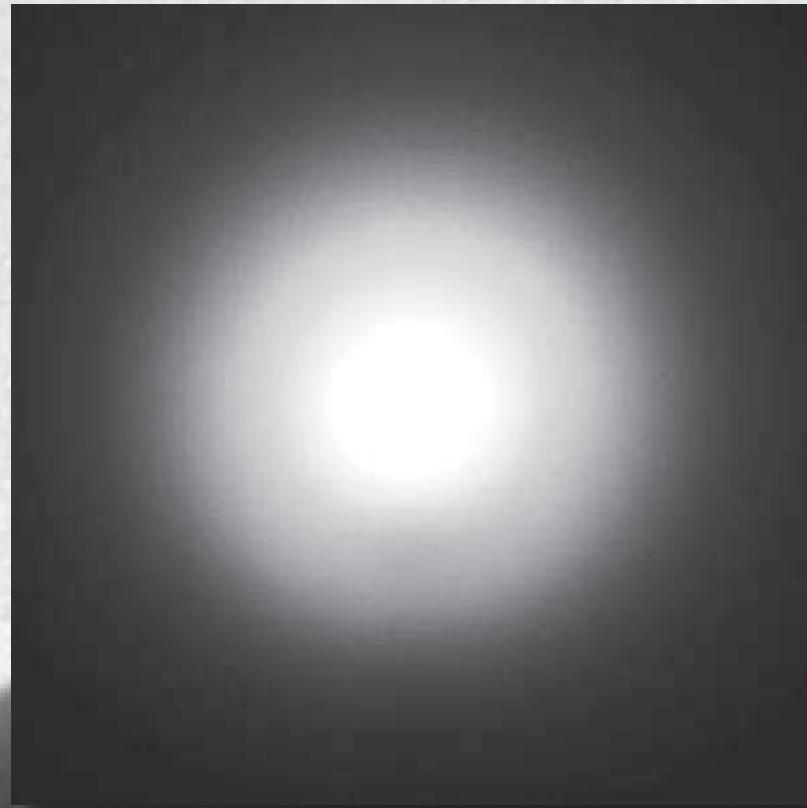
200 nm

# Nanowire fabrication

RMS roughness < 0.5 nm

20 nm

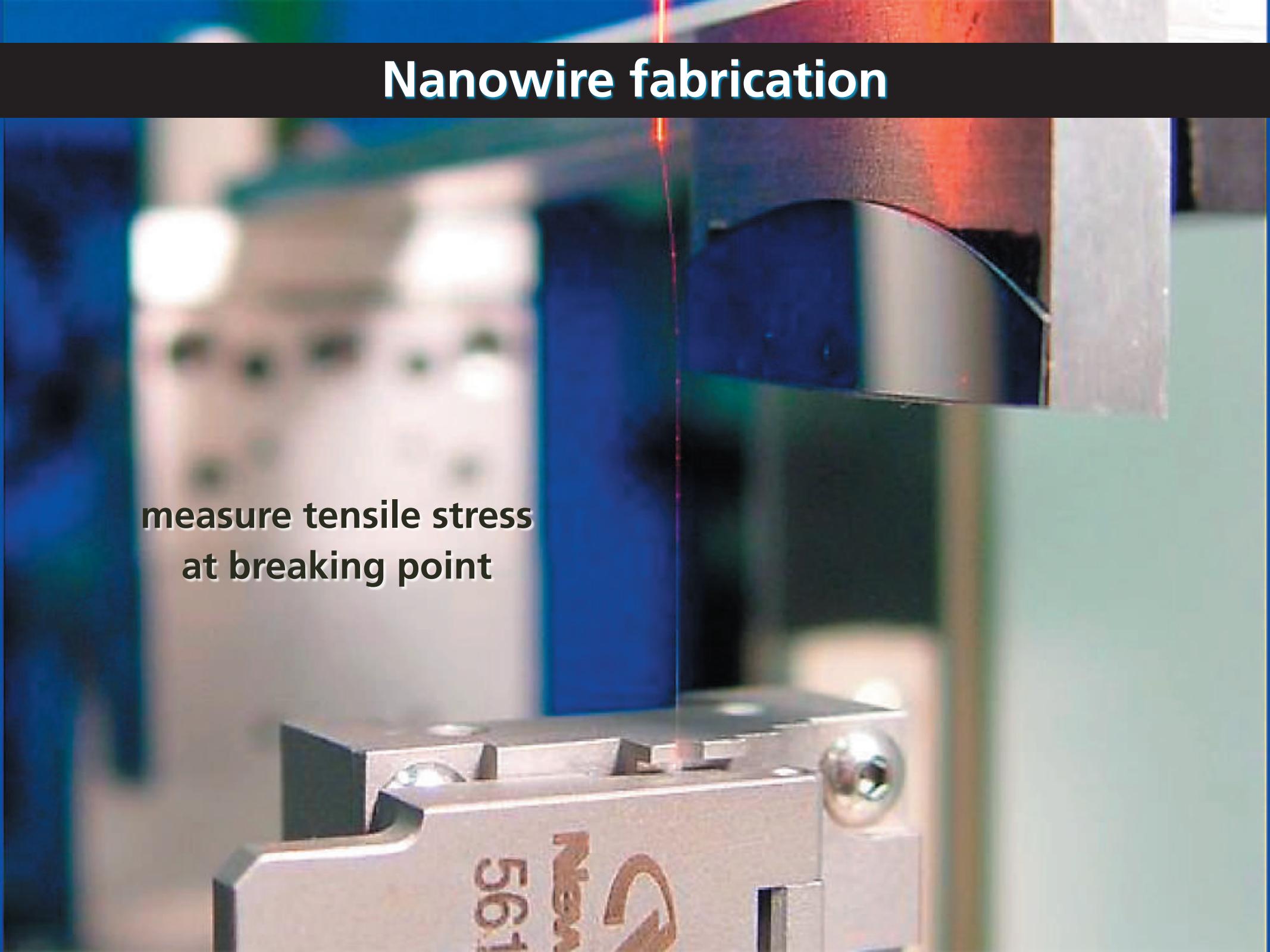
# Nanowire fabrication



20 nm

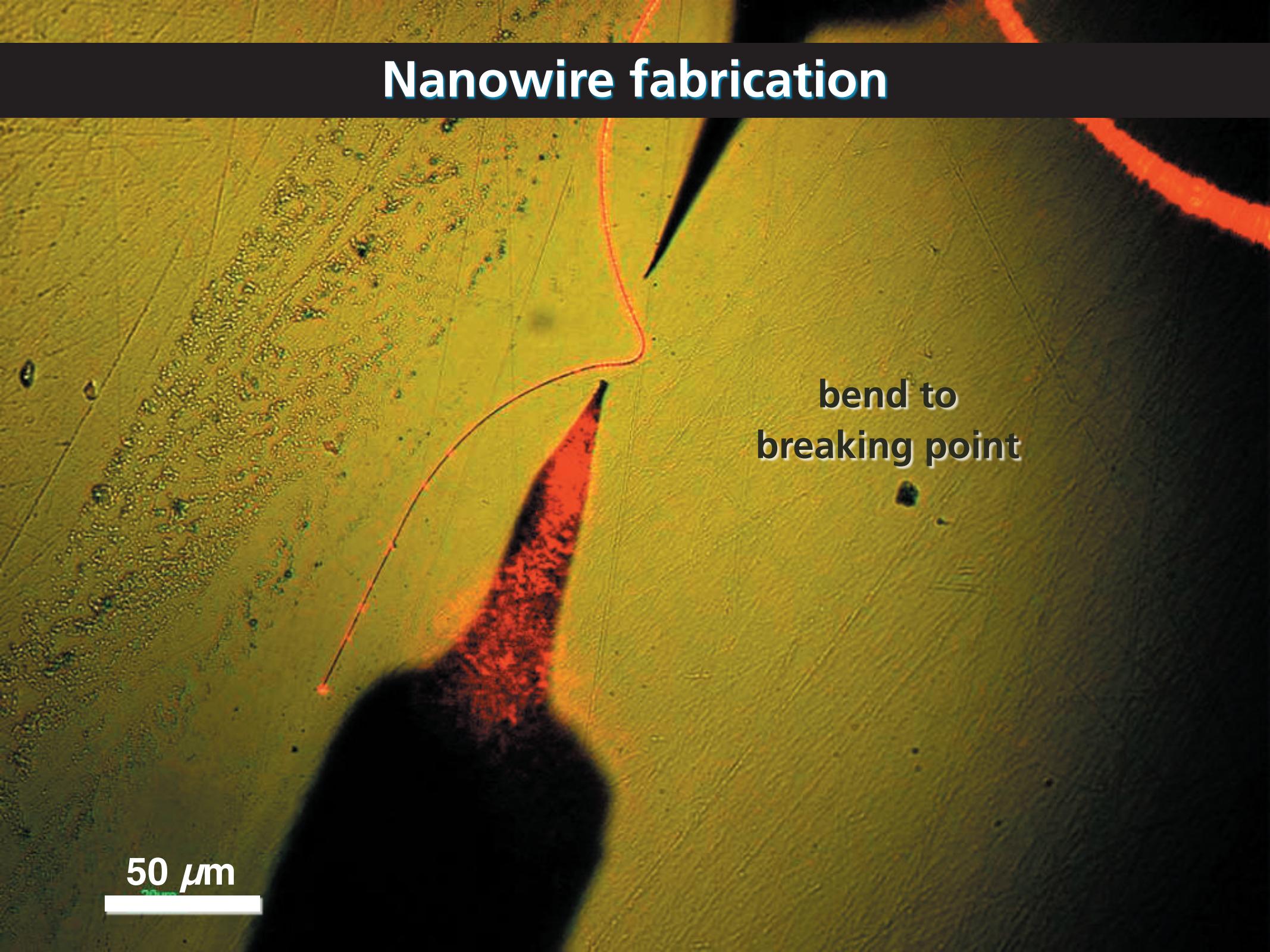


# Nanowire fabrication

A close-up photograph of a nanowire being pulled from a substrate by a mechanical gripper. The nanowire is thin and dark, appearing to be made of carbon nanotubes. It is being stretched between two metal clamps. The background is blurred, showing laboratory equipment.

measure tensile stress  
at breaking point

# Nanowire fabrication

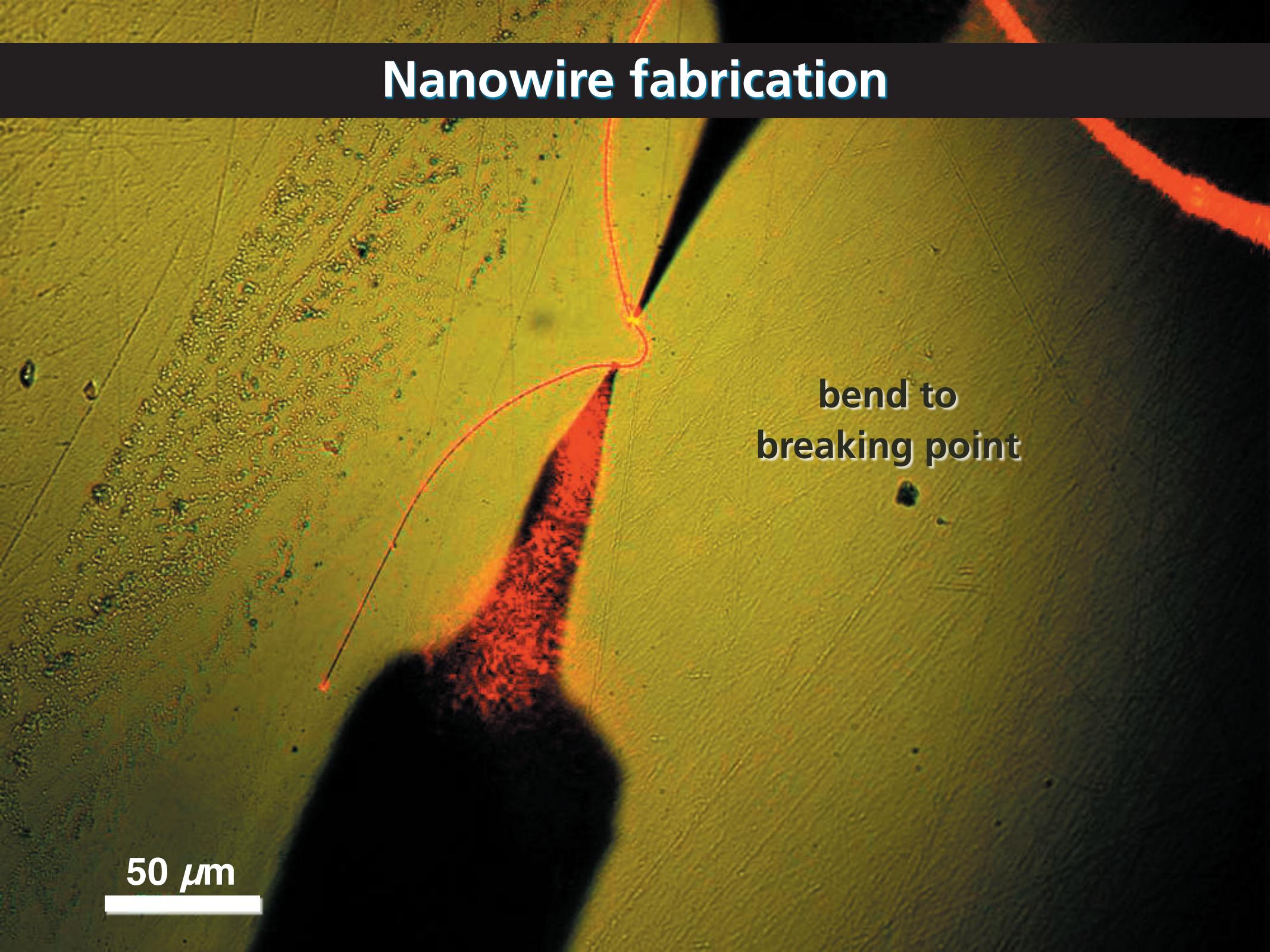


A scanning electron micrograph showing a single nanowire being bent. The nanowire is red and yellow, with a dark shadow cast by the probe. It is being bent at its left end, which is highlighted with a red circle. The background is a textured green surface. A black arrow points towards the bend point. The text "bend to breaking point" is located in the lower right area of the image.

bend to  
breaking point

50  $\mu\text{m}$

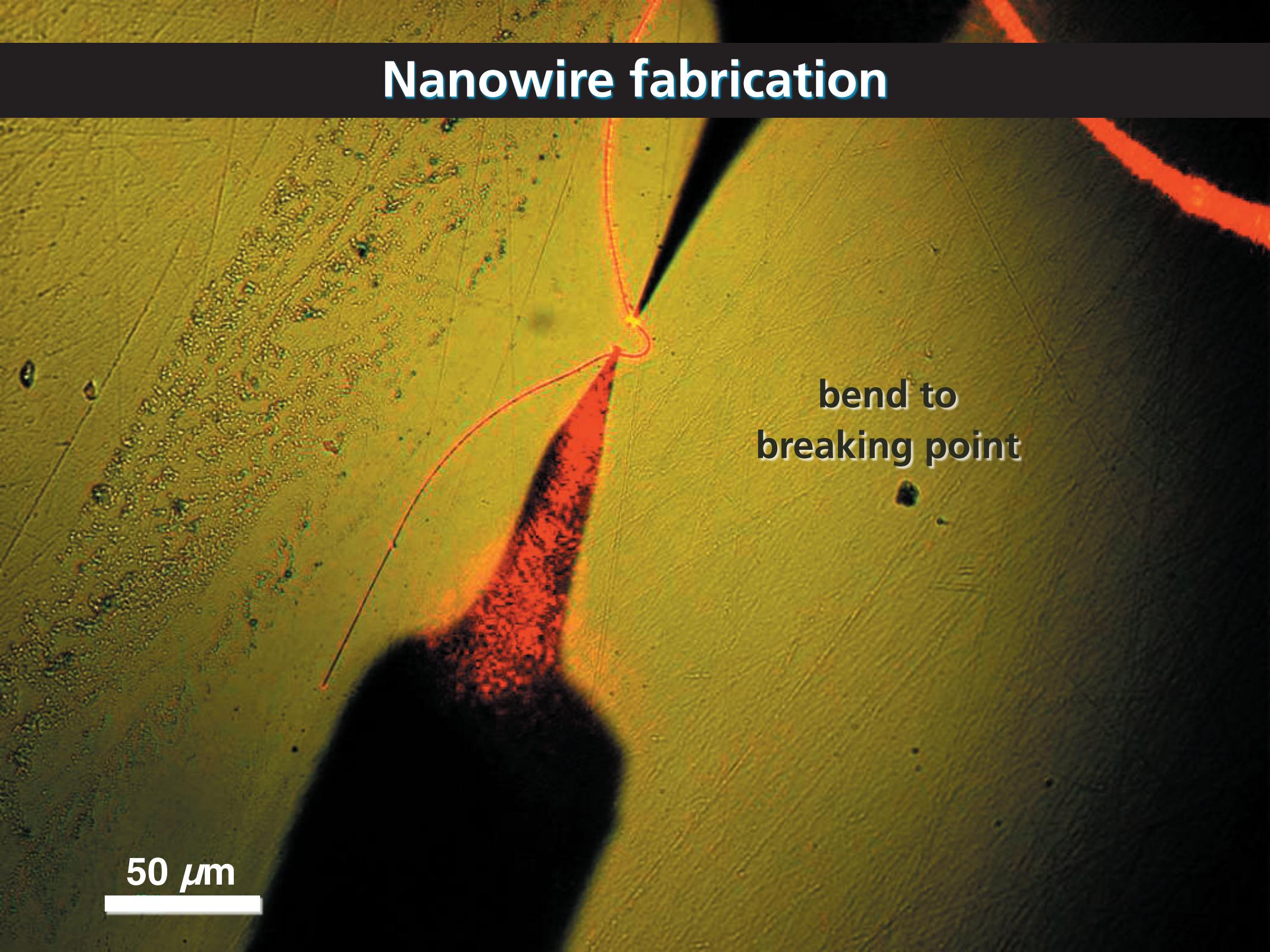
# Nanowire fabrication



bend to  
breaking point

50  $\mu\text{m}$

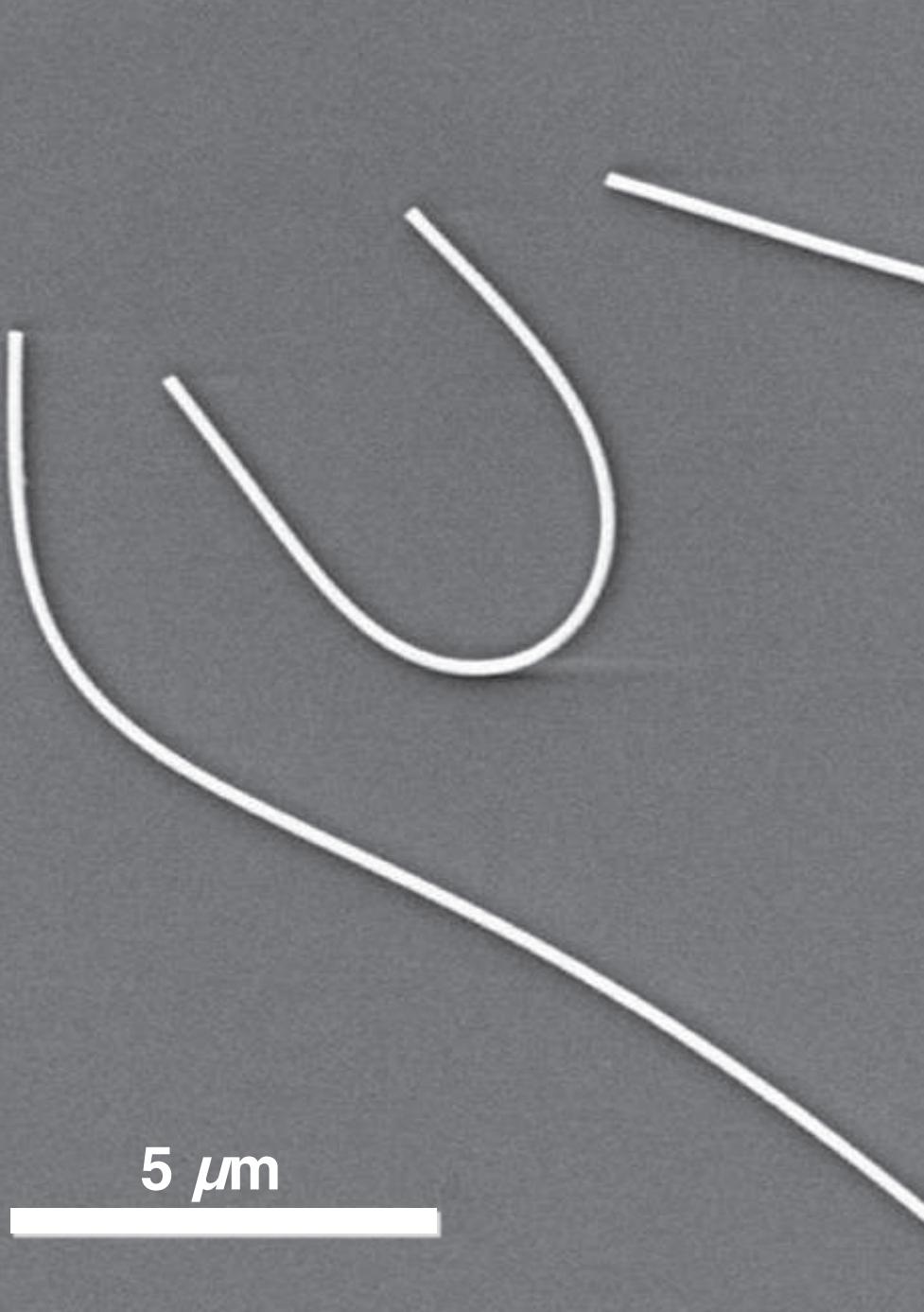
# Nanowire fabrication

A scanning electron micrograph showing the fabrication of a nanowire. A red line traces the path of the nanowire as it is being pulled from a source at the bottom left. The nanowire is thin and red at its tip, transitioning to a thicker, more textured red/orange segment as it extends upwards and to the right. A black beam-like shape originates from the top center and points towards the nanowire's tip. The background is a textured greenish-yellow.

bend to  
breaking point

50  $\mu\text{m}$

# Nanowire fabrication



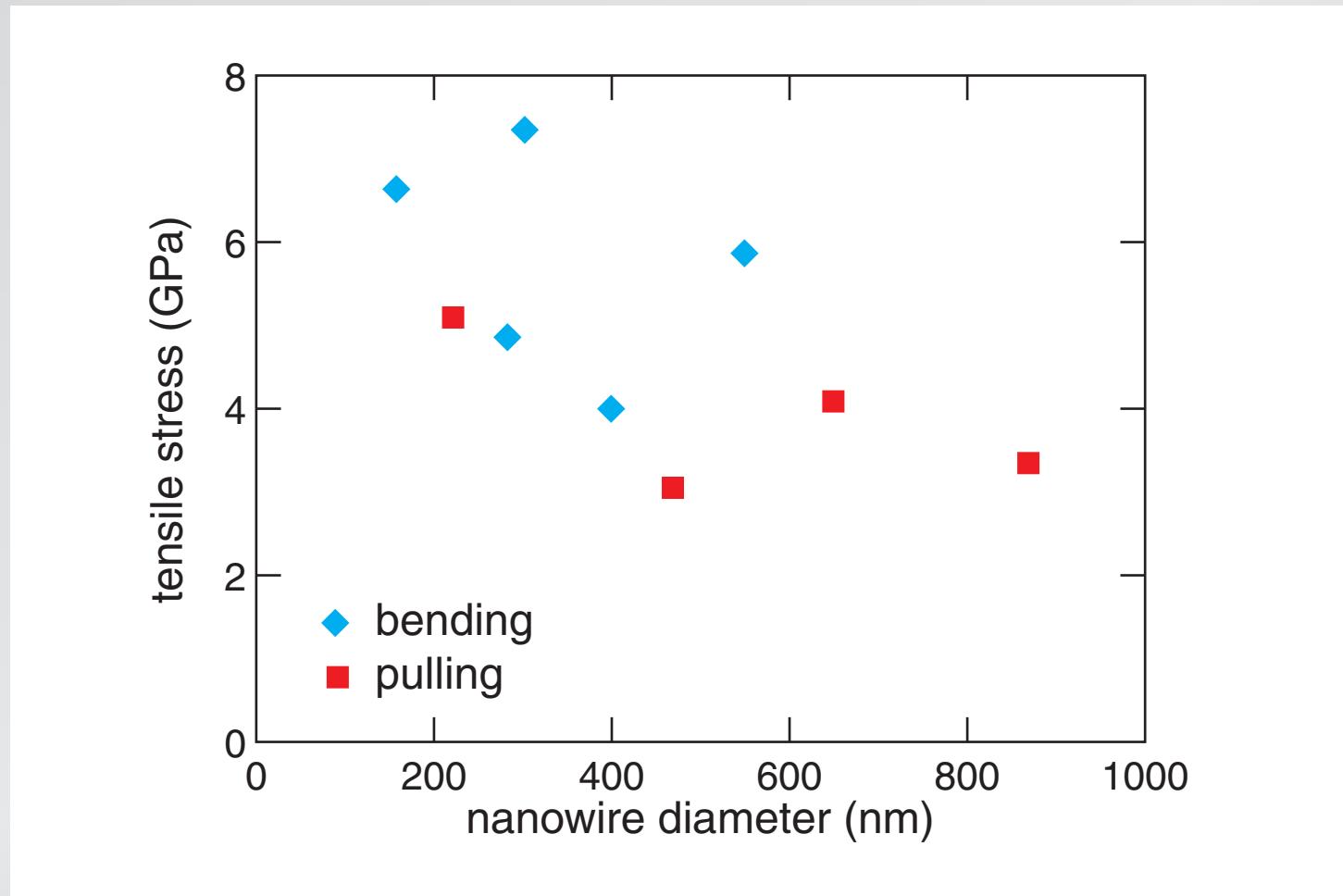
minimum bending radius  $R_{EB}$   
gives tensile stress:

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

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

# Waveguiding

## tensile strength



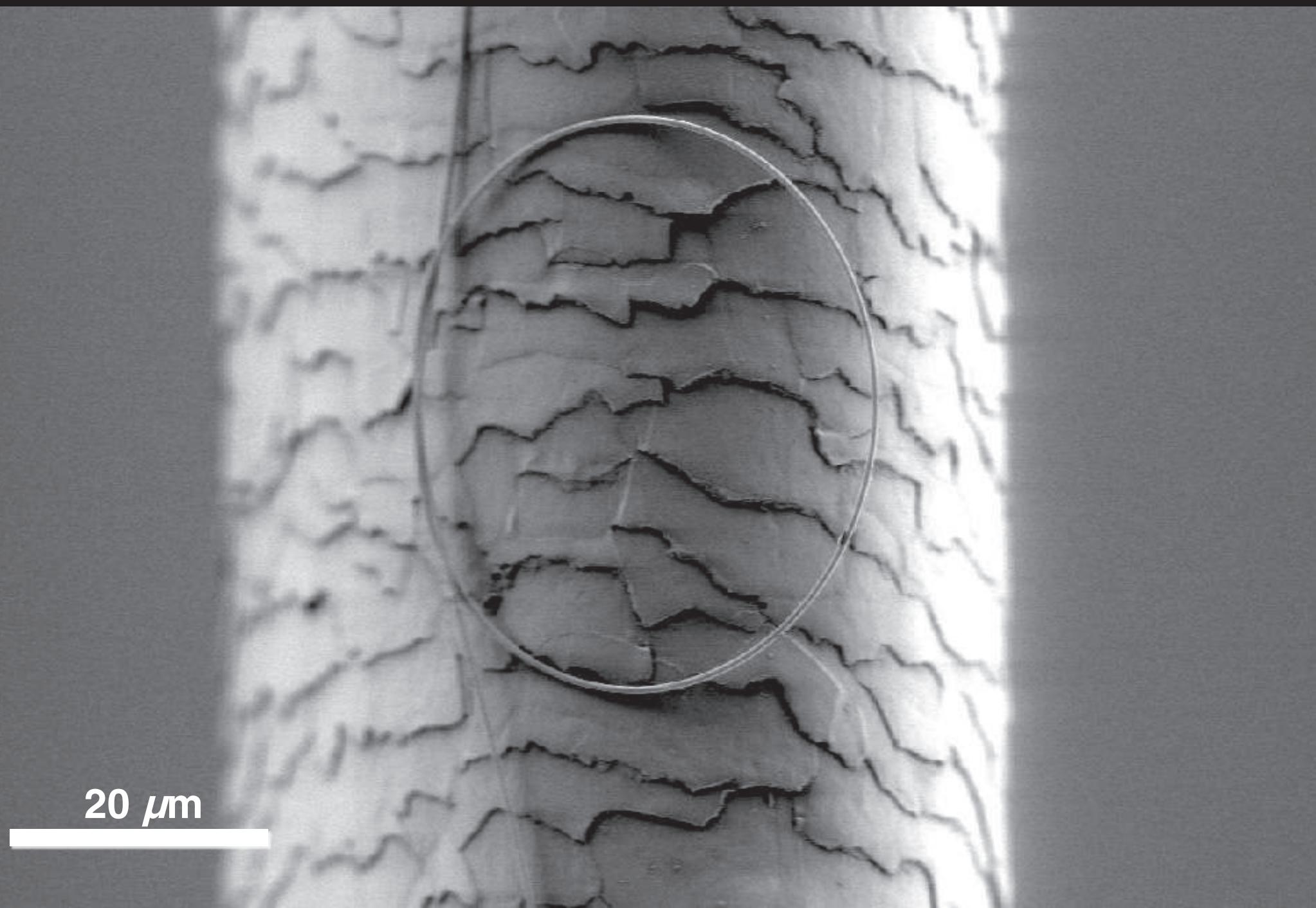
# Nanowire fabrication

2  $\mu\text{m}$

# Nanowire fabrication

20  $\mu\text{m}$

# Nanowire fabrication



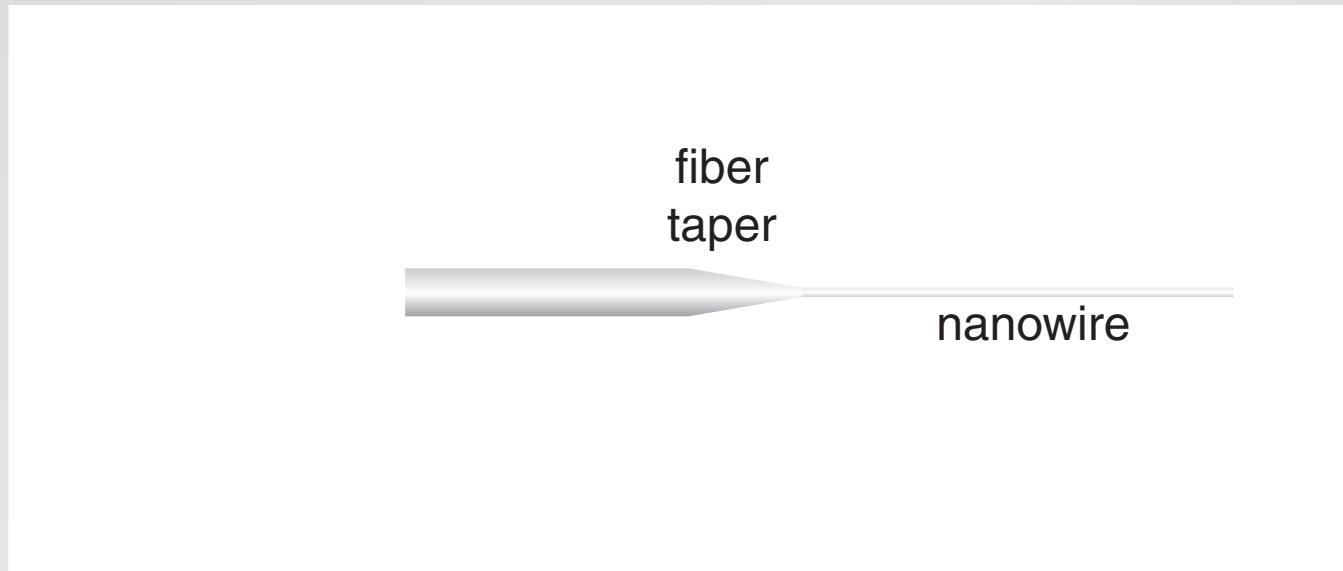
20  $\mu\text{m}$

# Outline

- waveguiding
- nanowire fabrication
- optical properties

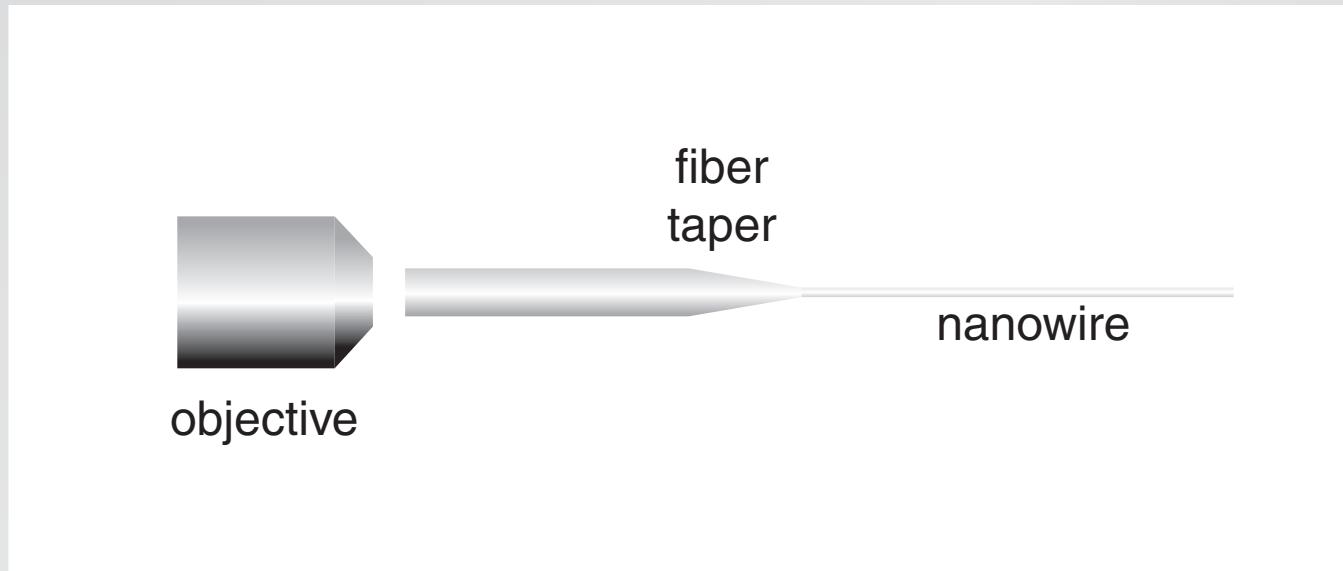
# Optical properties

coupling light into nanowires



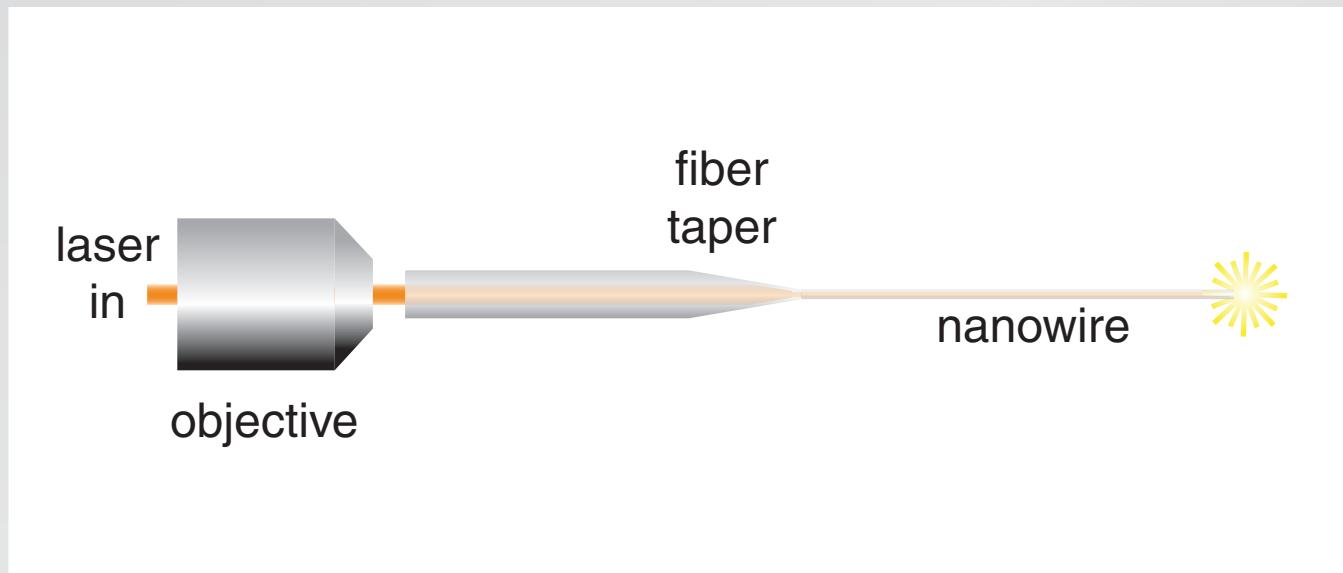
# Optical properties

coupling light into nanowires



# Optical properties

## coupling light into nanowires



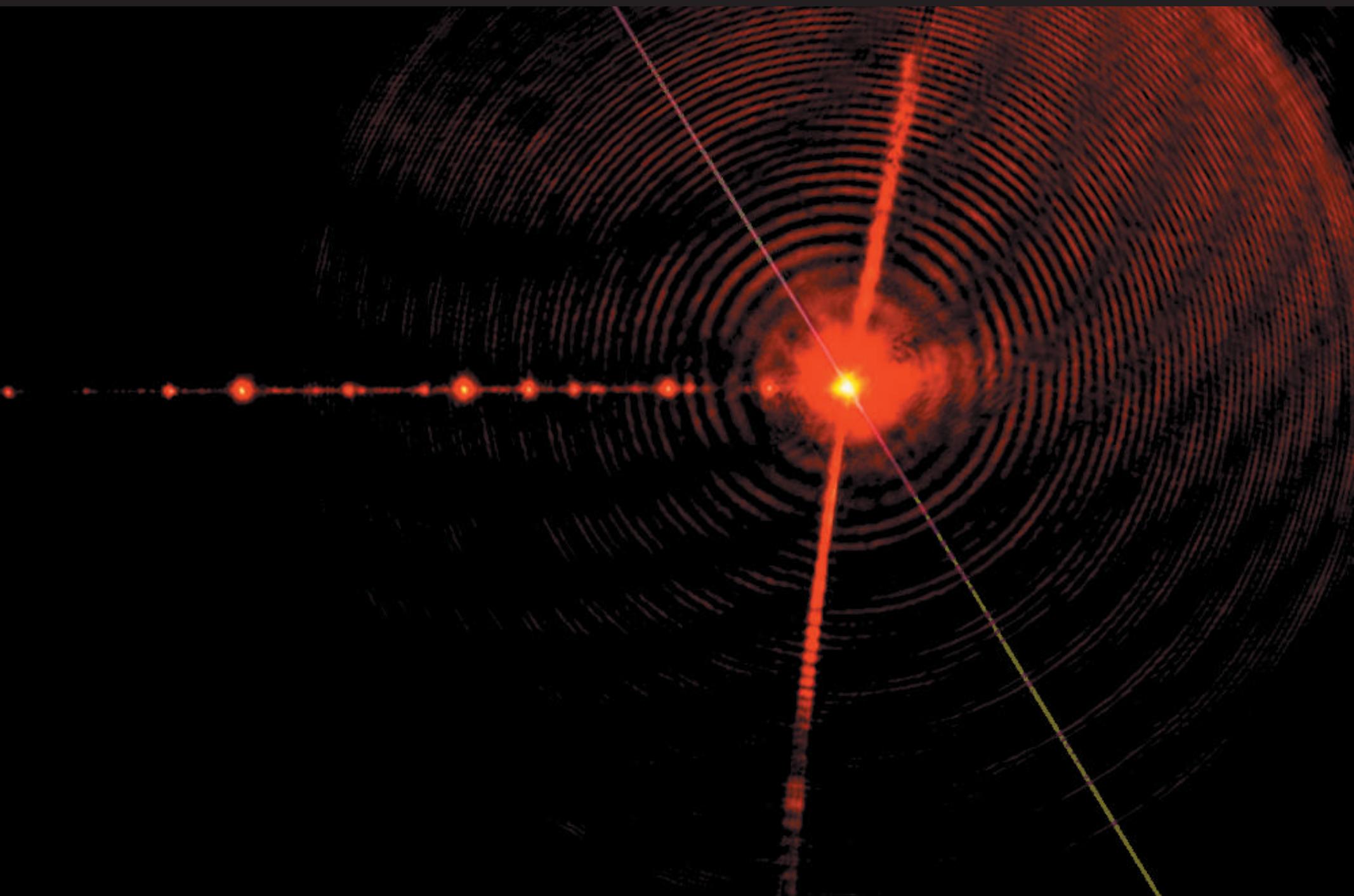
# Optical properties

280-nm nanowire

360 nm

450 nm

# Optical properties

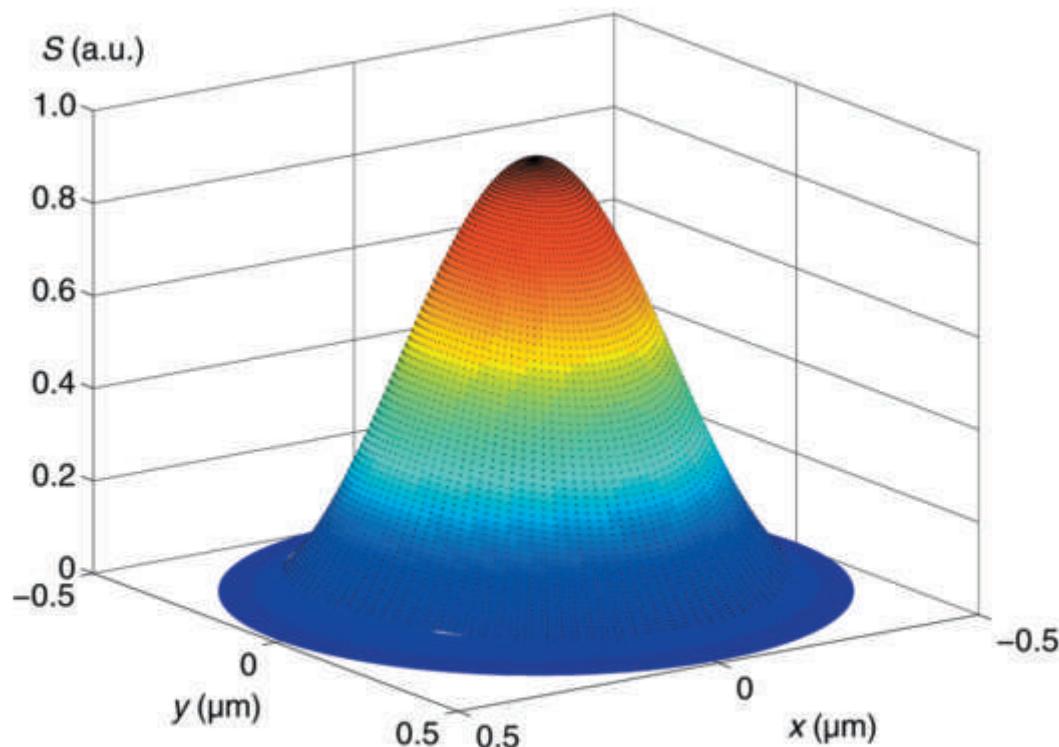


# Optical properties



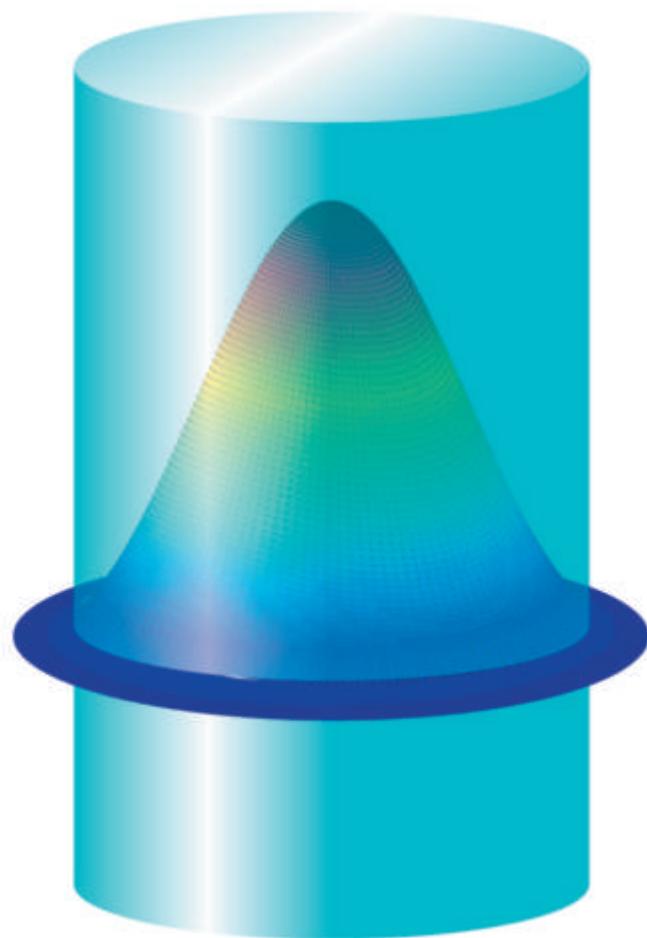
# Optical properties

Poynting vector profile for 800-nm nanowire



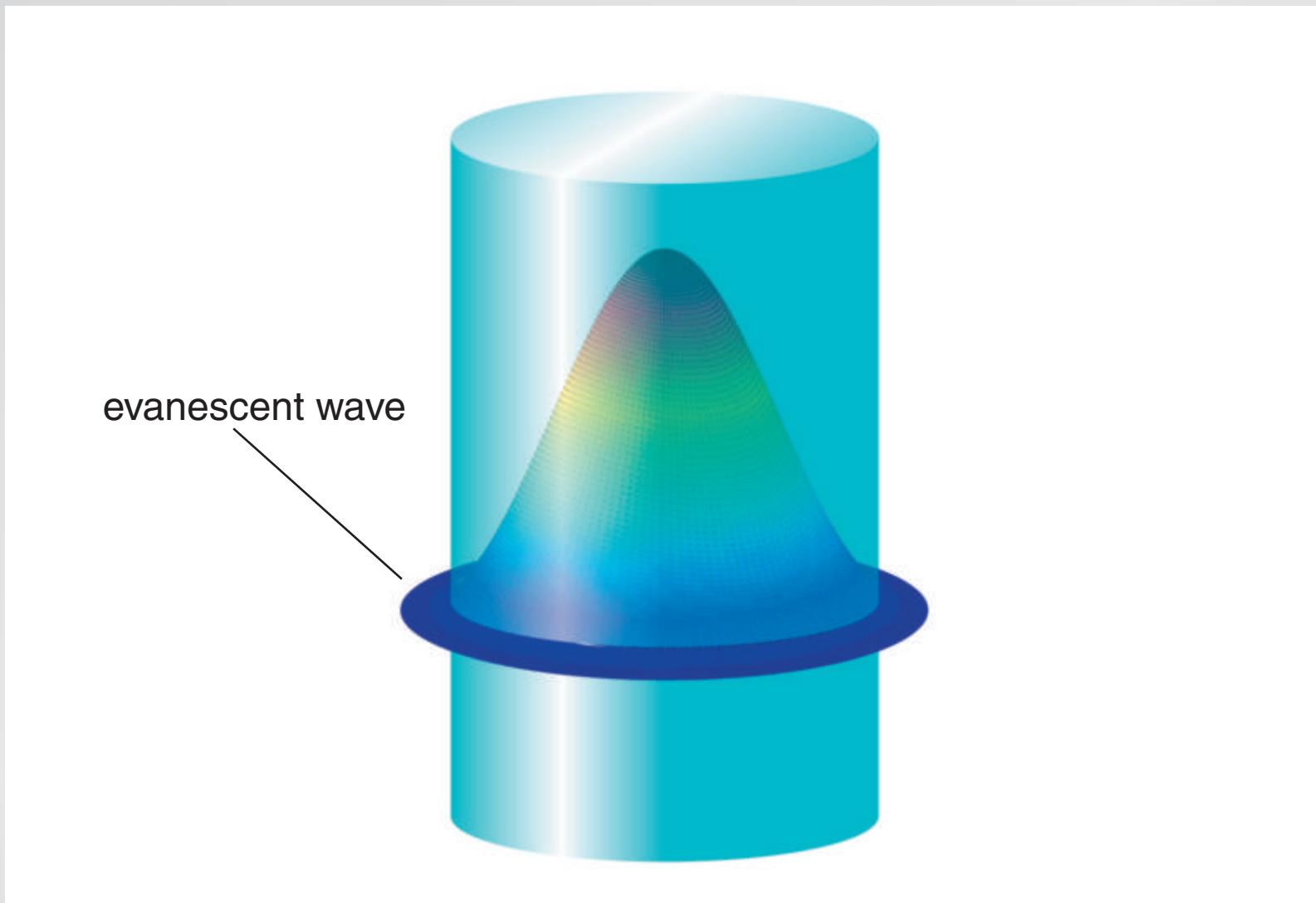
# Optical properties

Poynting vector profile for 800-nm nanowire



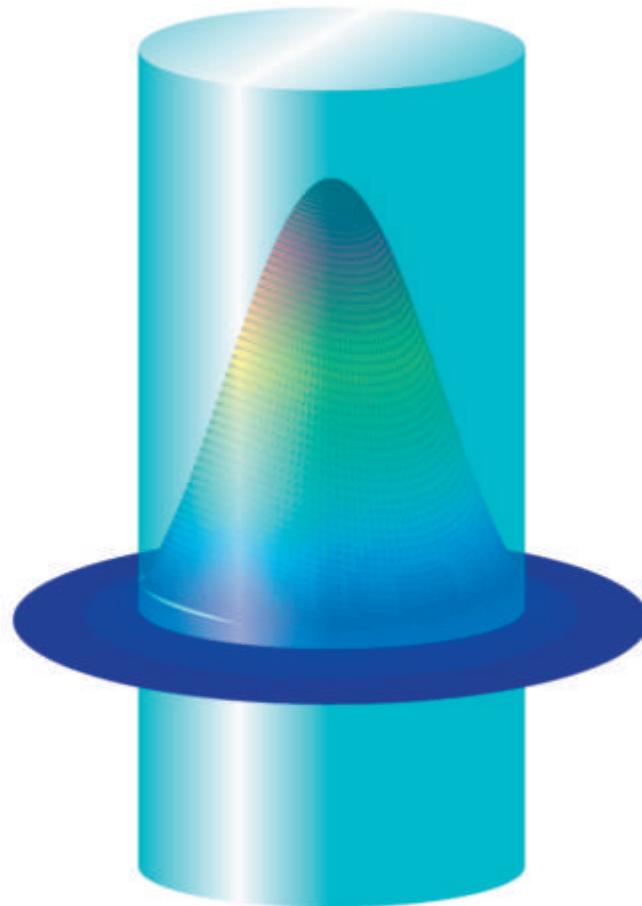
# Optical properties

Poynting vector profile for 800-nm nanowire



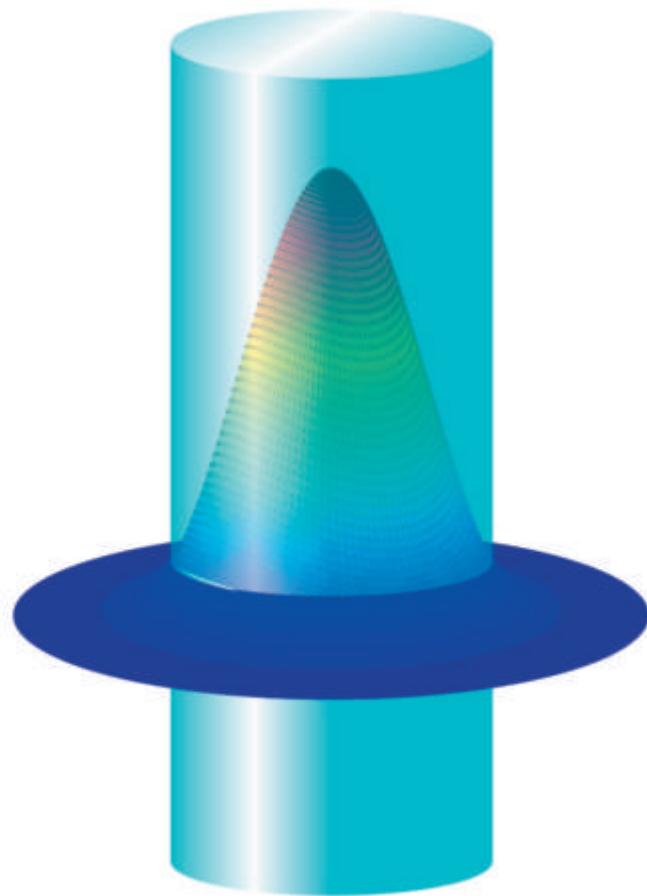
# Optical properties

Poynting vector profile for 600-nm nanowire



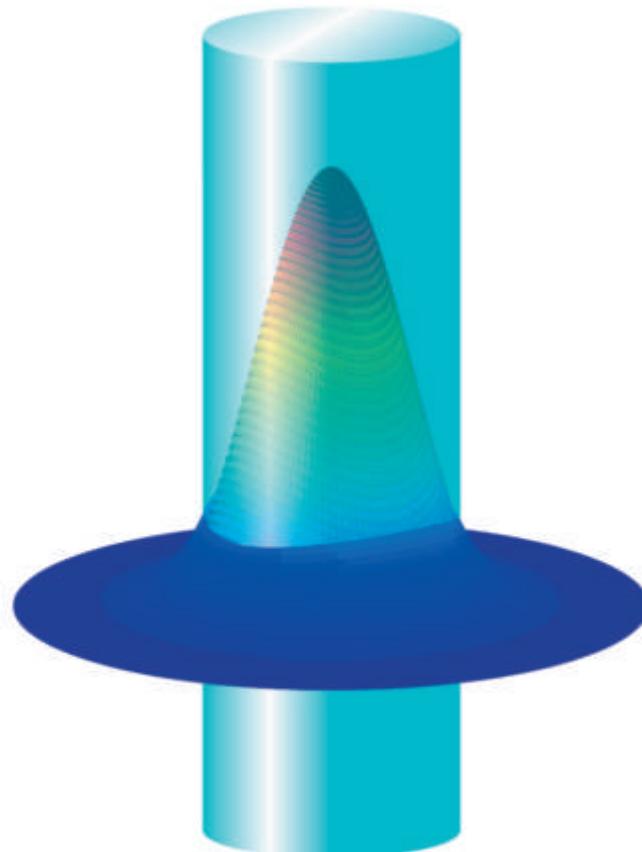
# Optical properties

Poynting vector profile for 500-nm nanowire



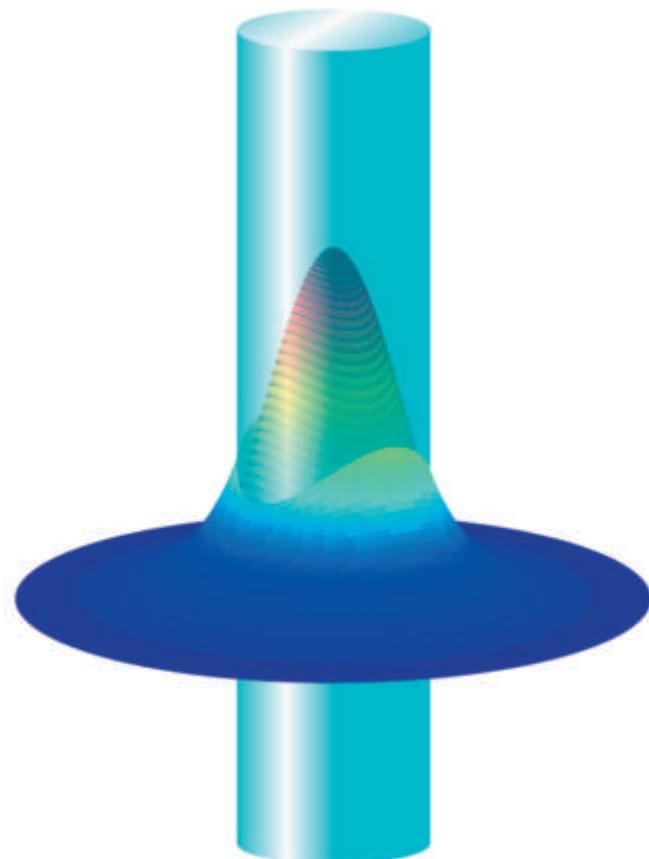
# Optical properties

Poynting vector profile for 400-nm nanowire



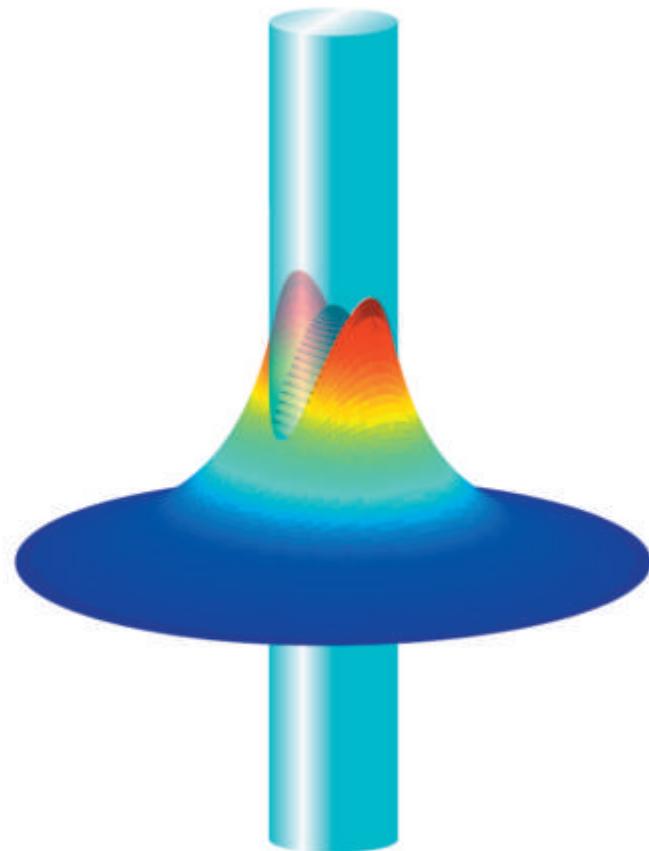
# Optical properties

Poynting vector profile for 300-nm nanowire



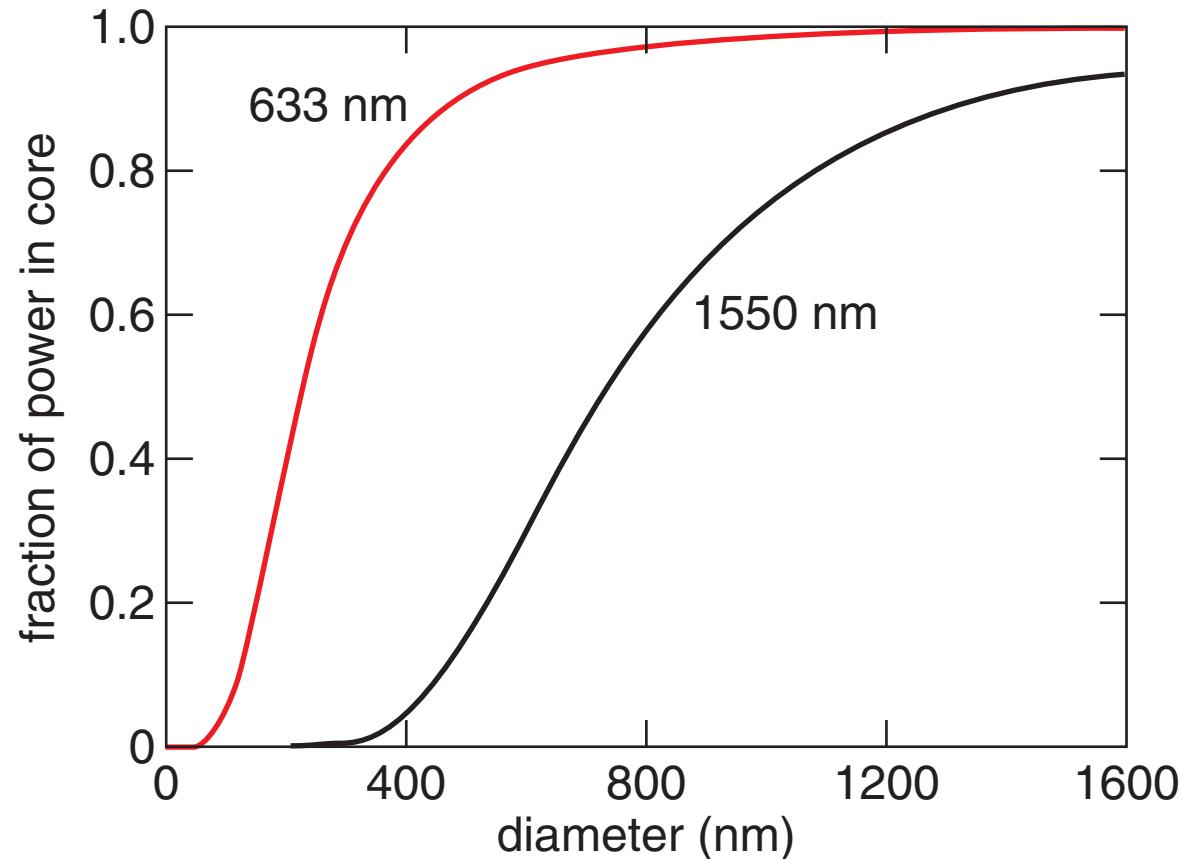
# Optical properties

Poynting vector profile for 200-nm nanowire



# Waveguiding

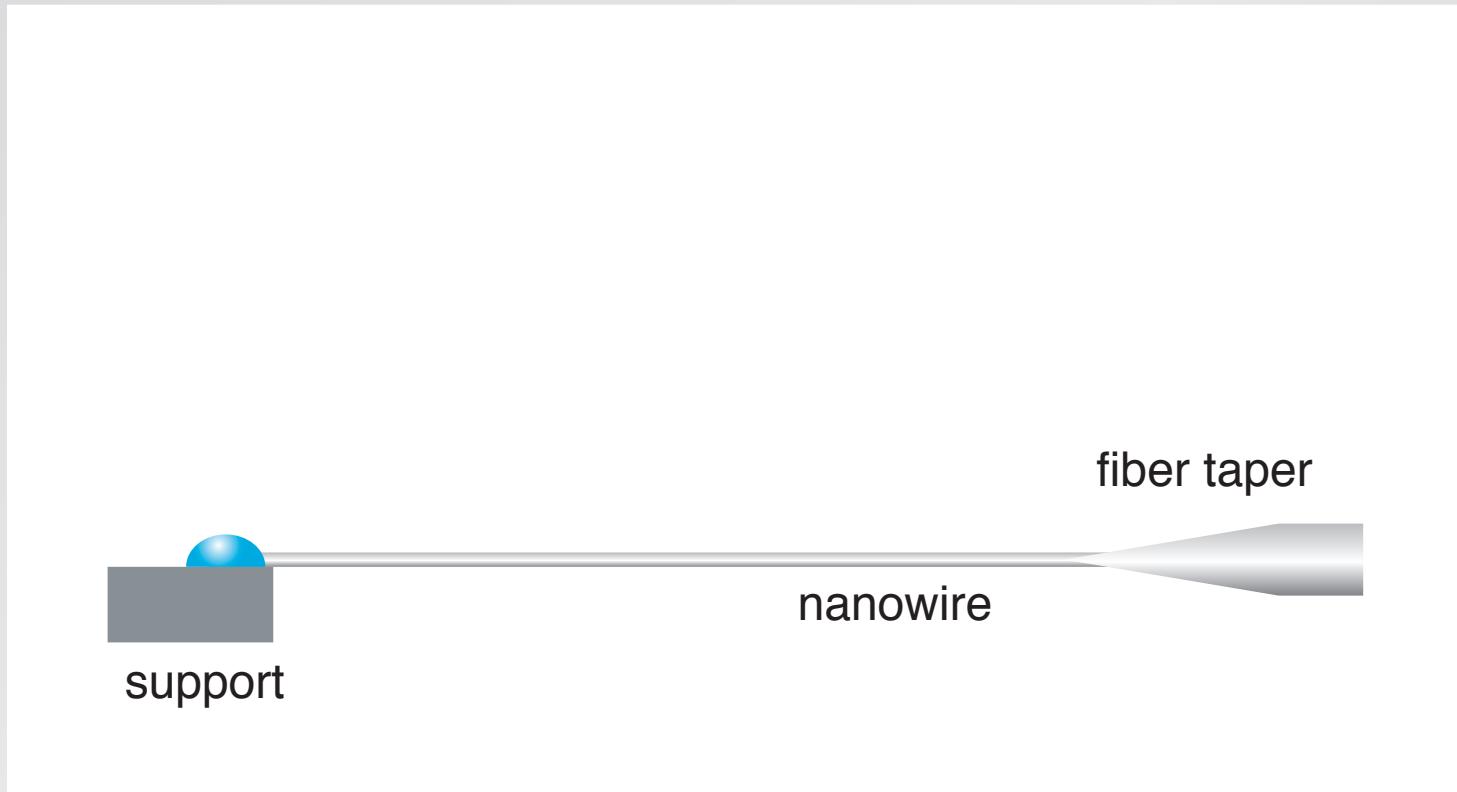
fraction of power carried in core





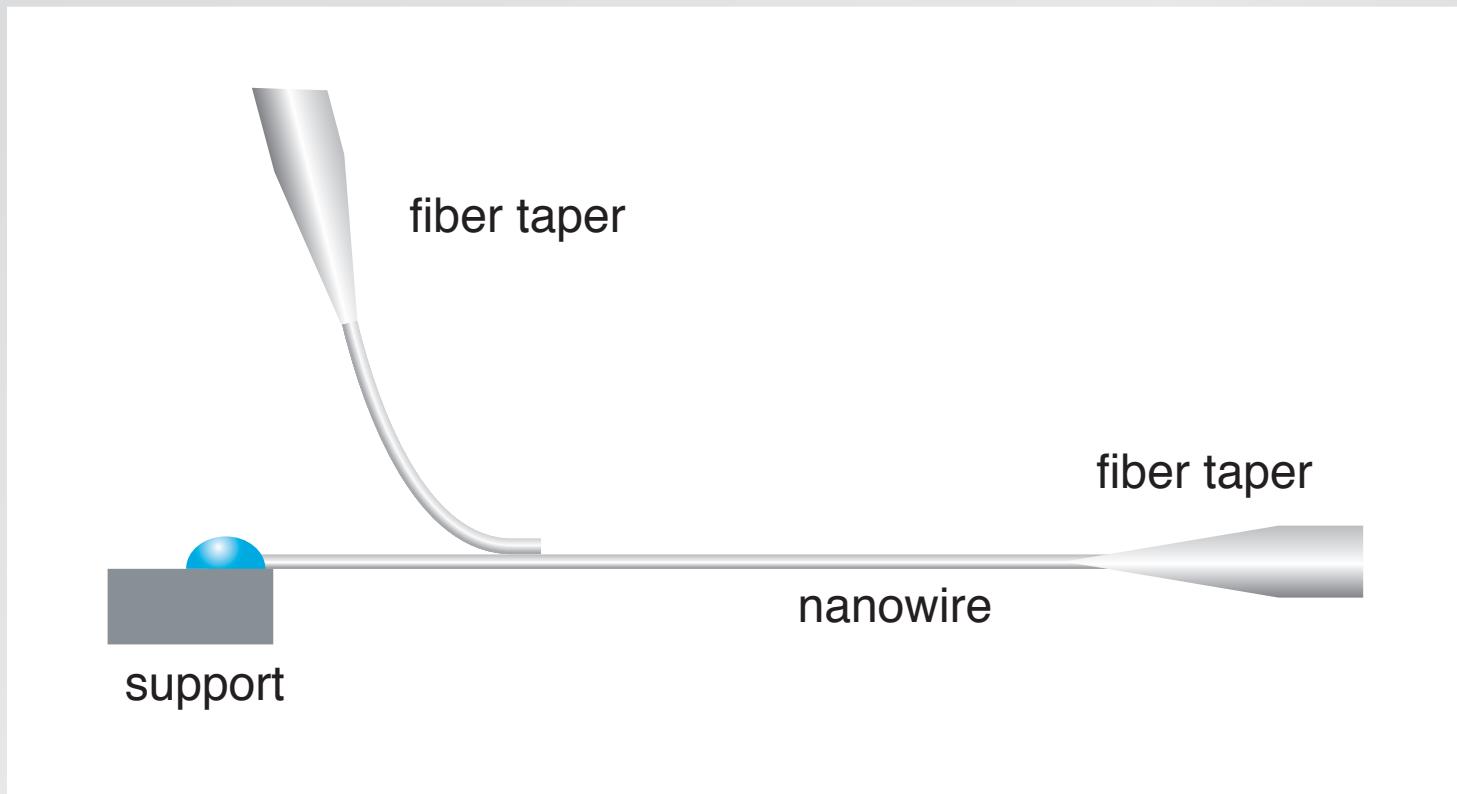
# Optical properties

coupling light between nanowires



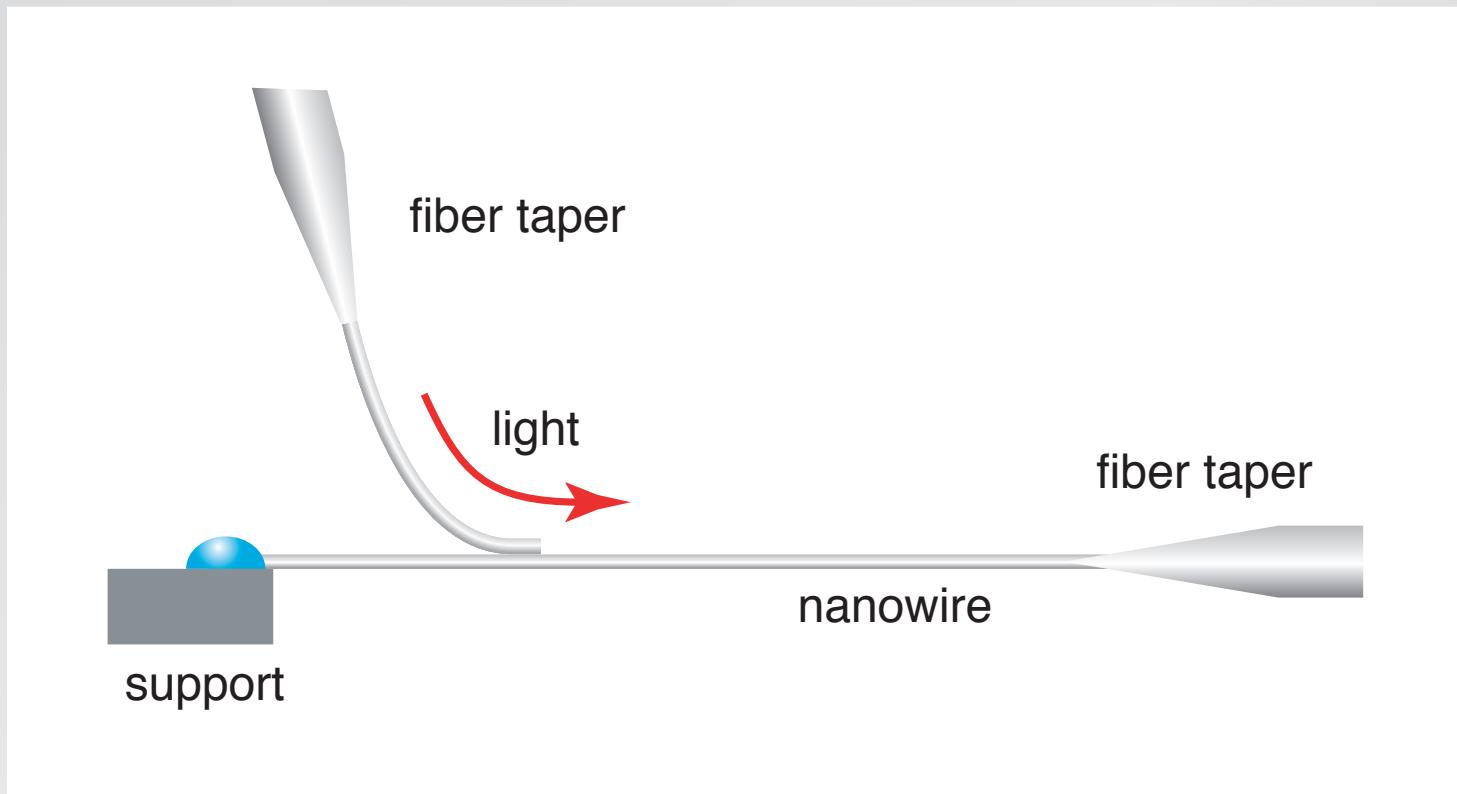
# Optical properties

coupling light between nanowires



# Optical properties

coupling light between nanowires



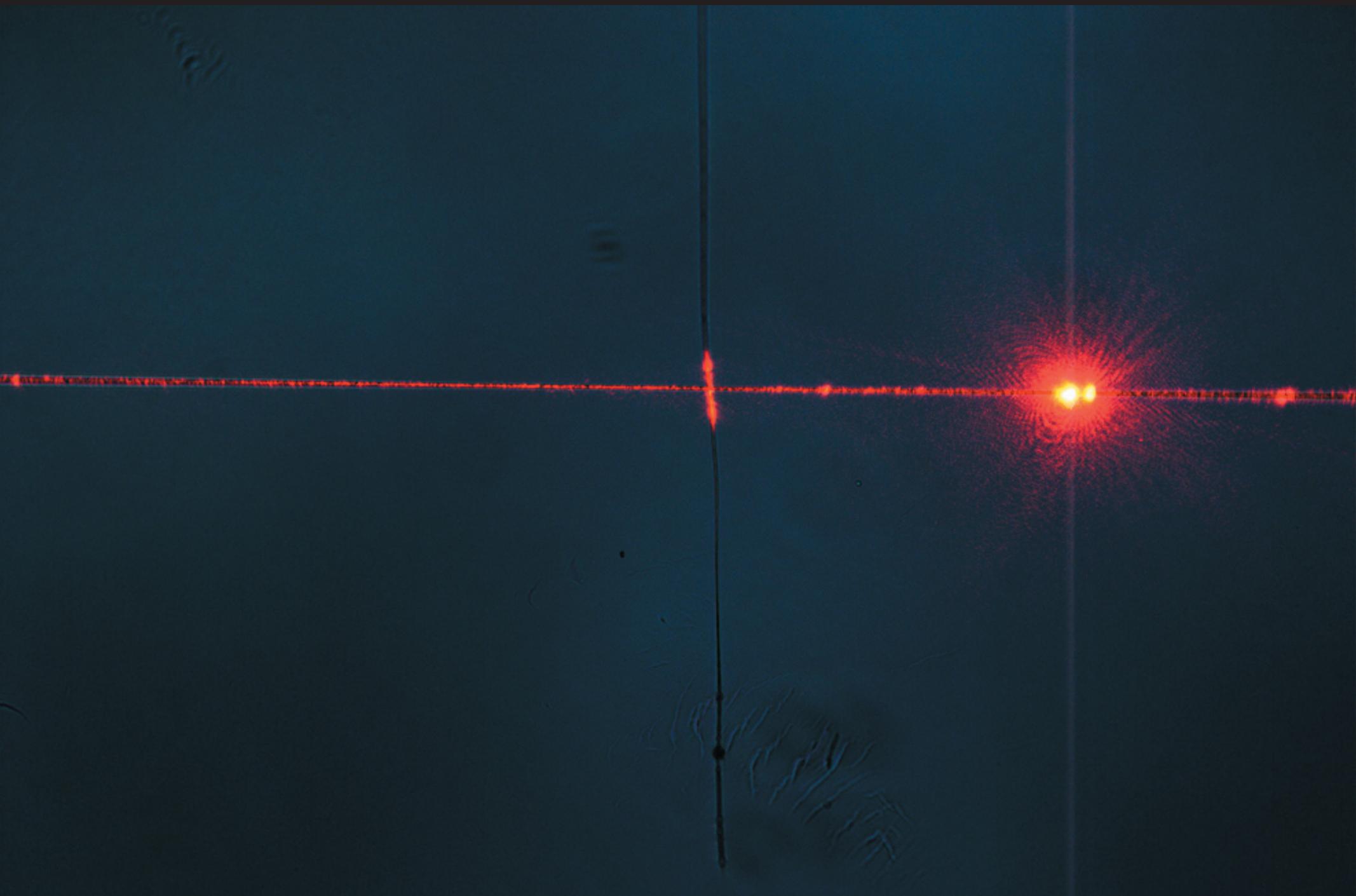
# Optical properties

50µm

# Optical properties

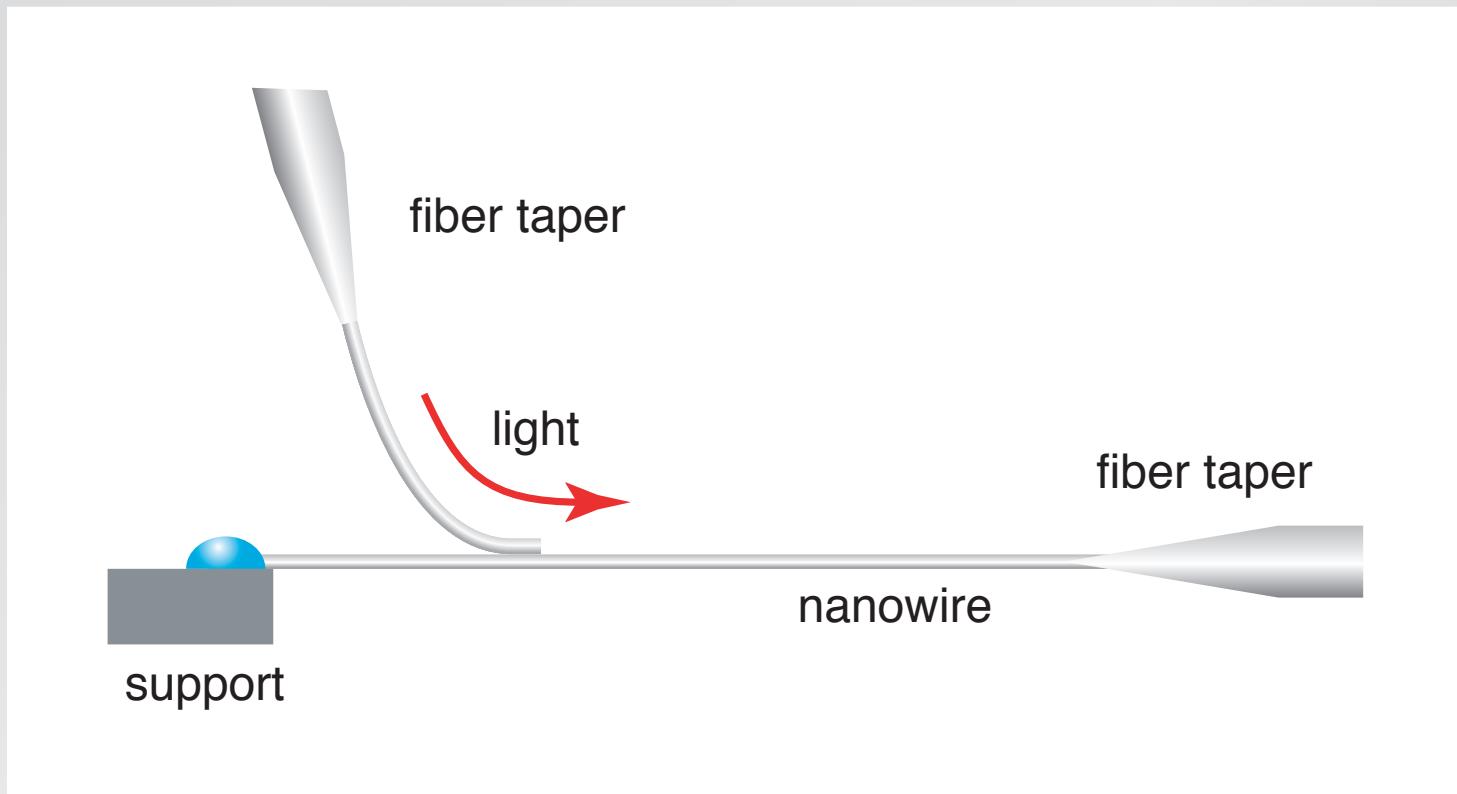


# Optical properties



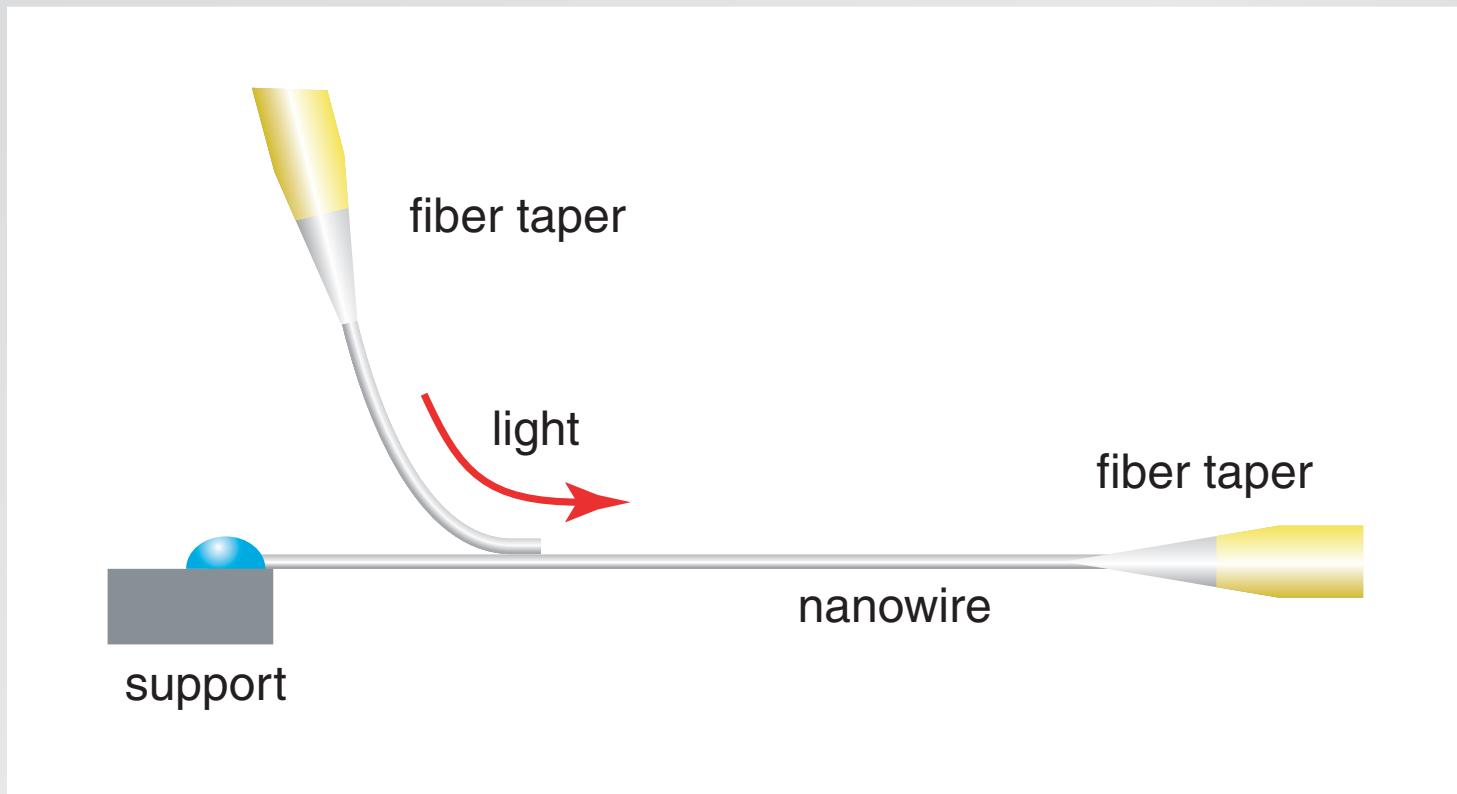
# Optical properties

## loss measurement



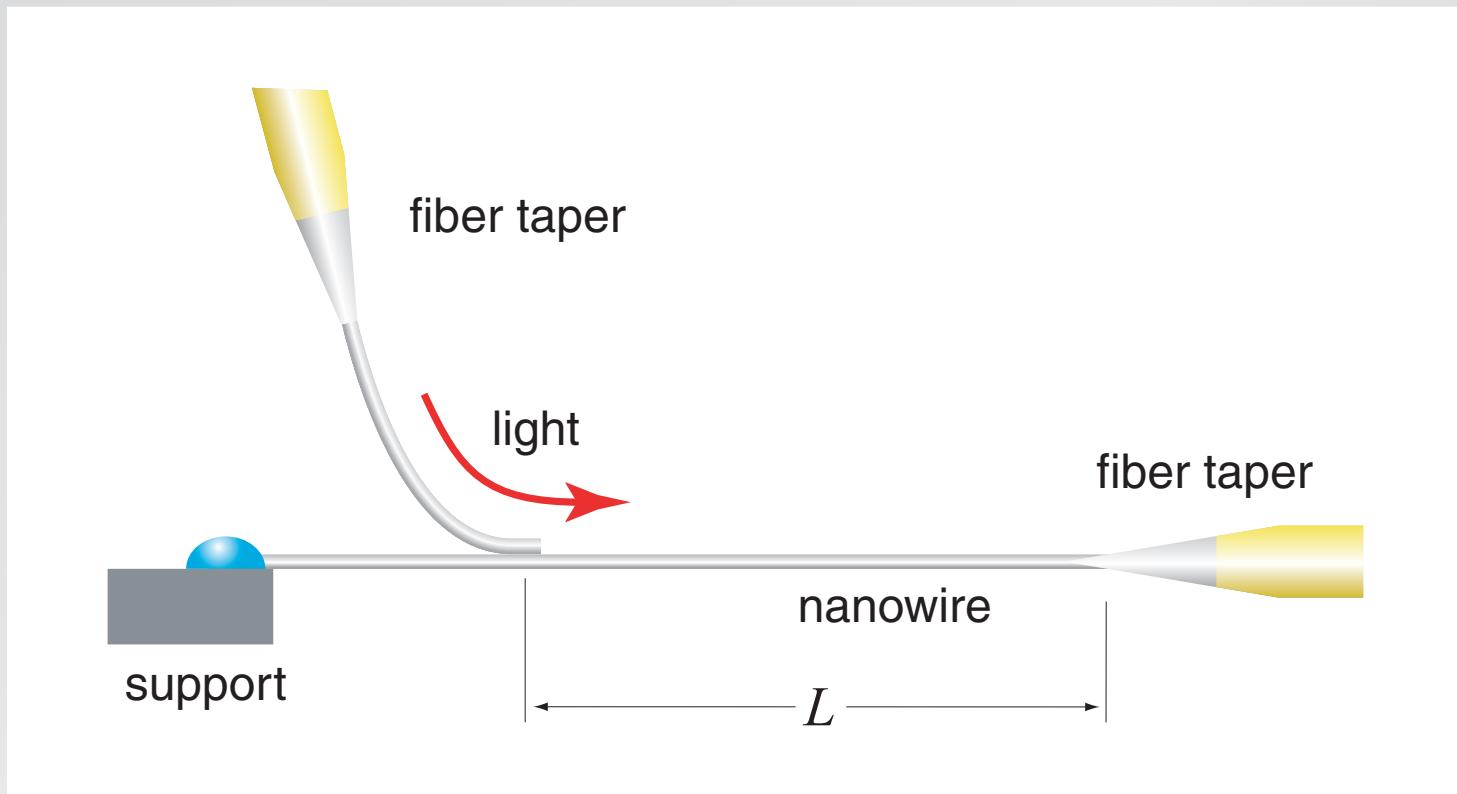
# Optical properties

## loss measurement



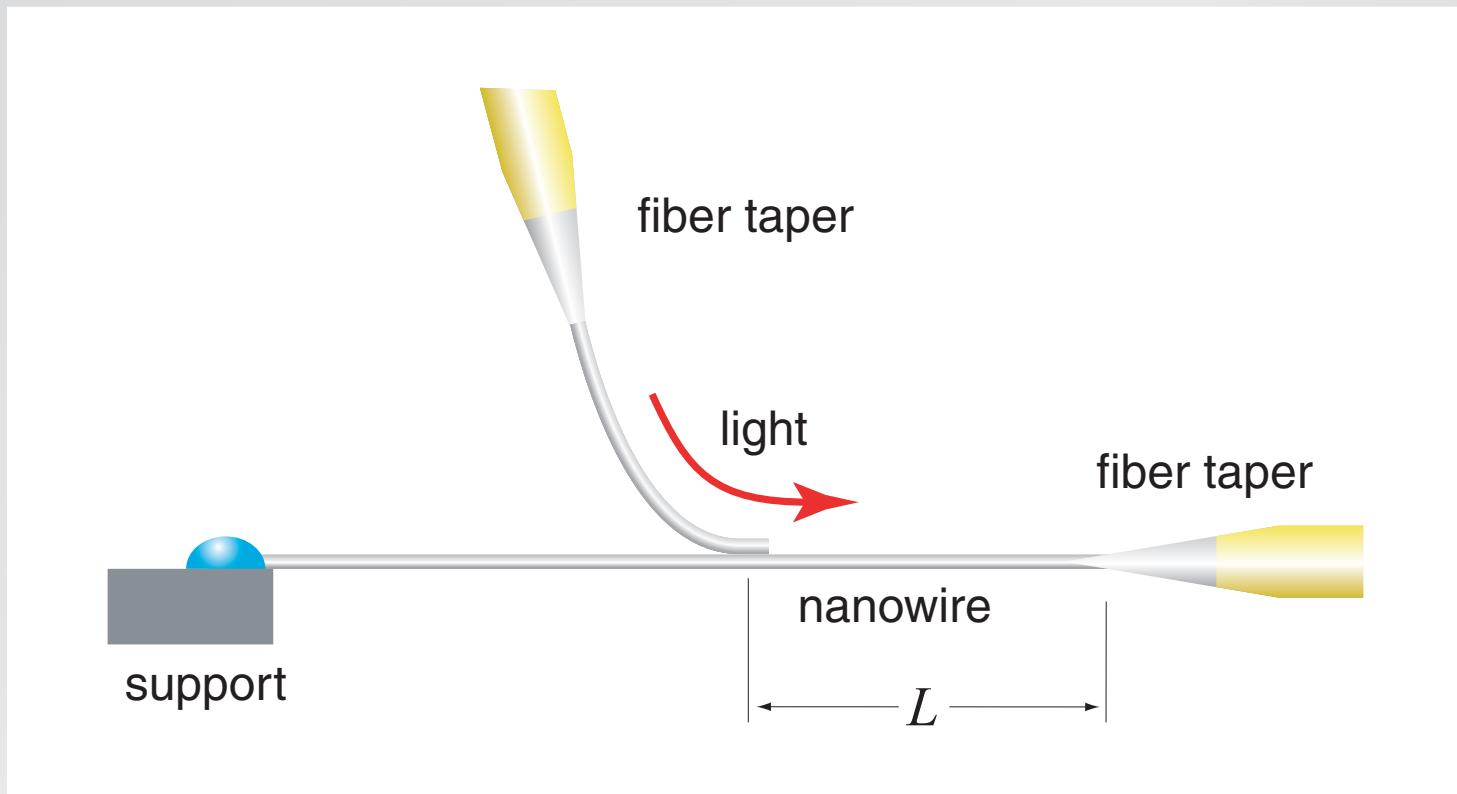
# Optical properties

## loss measurement



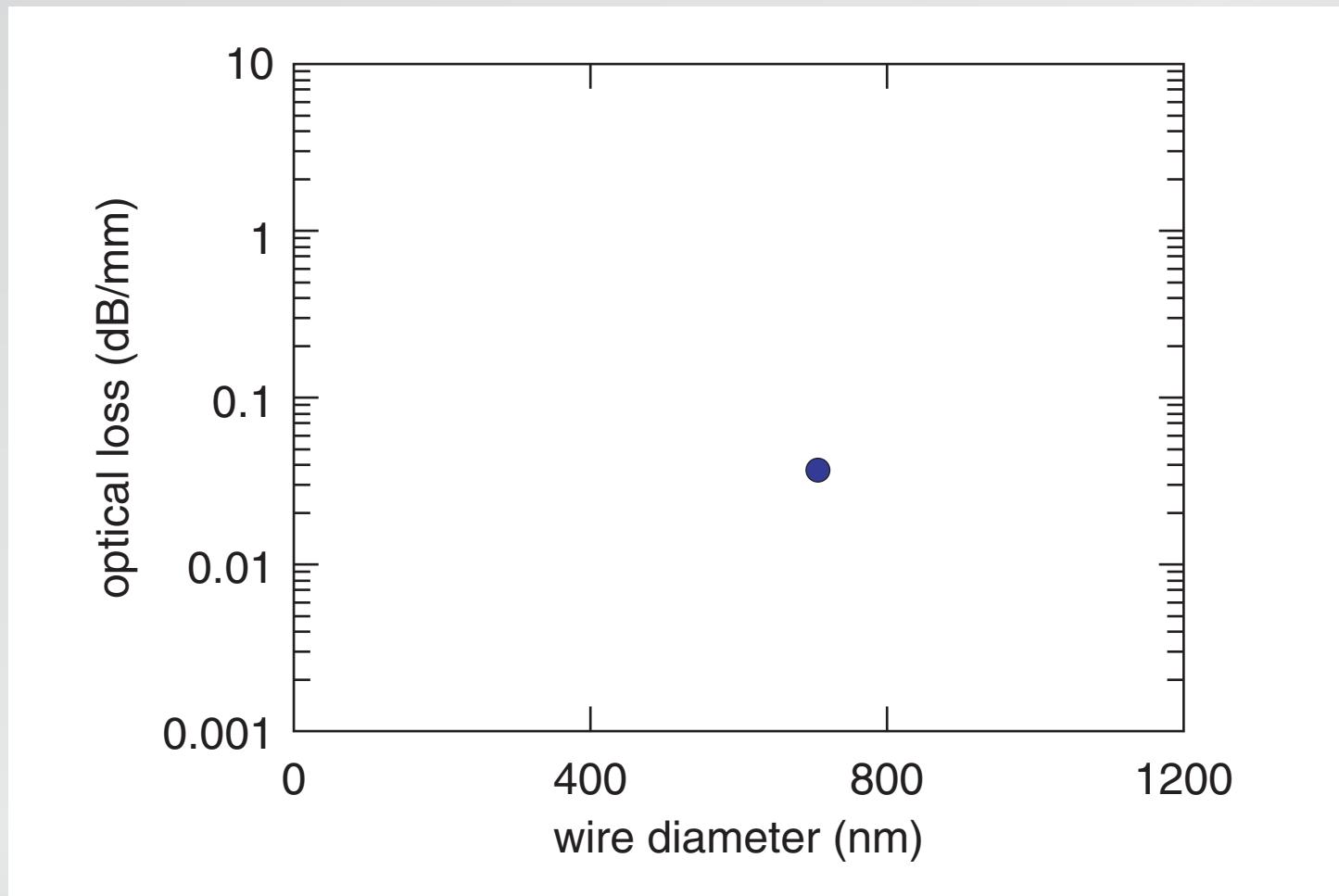
# Optical properties

## loss measurement



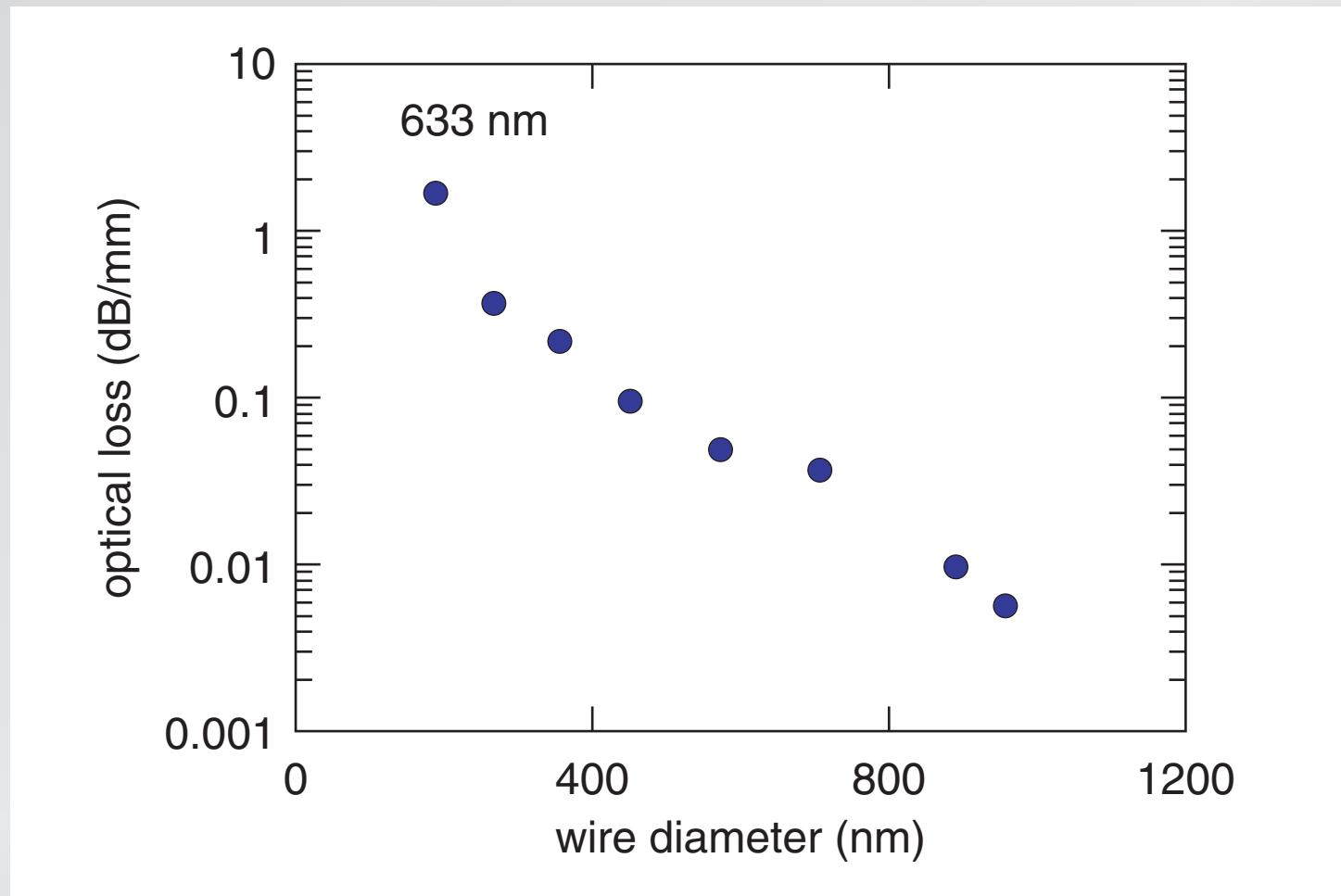
# Optical properties

## loss measurement



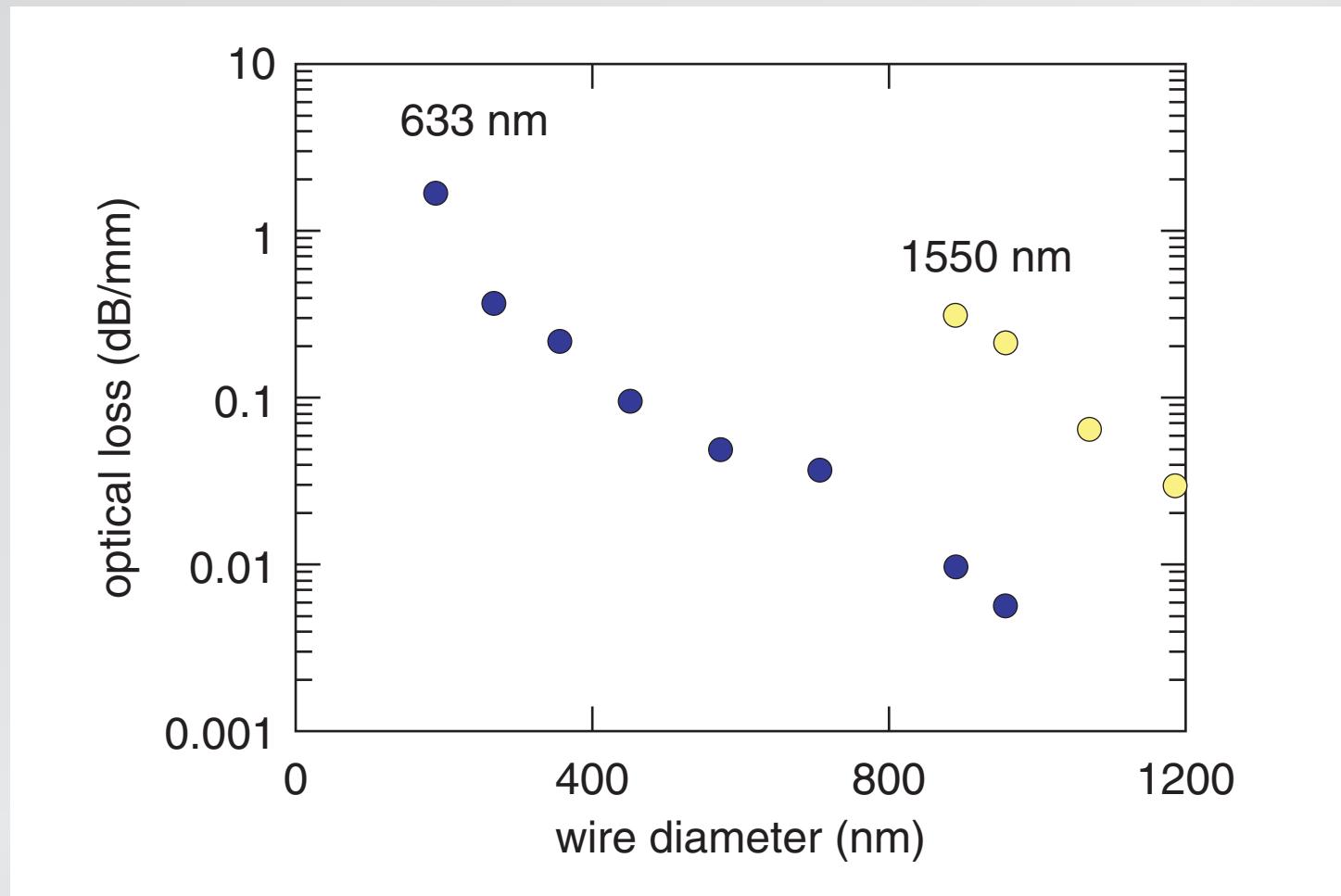
# Optical properties

## loss measurement



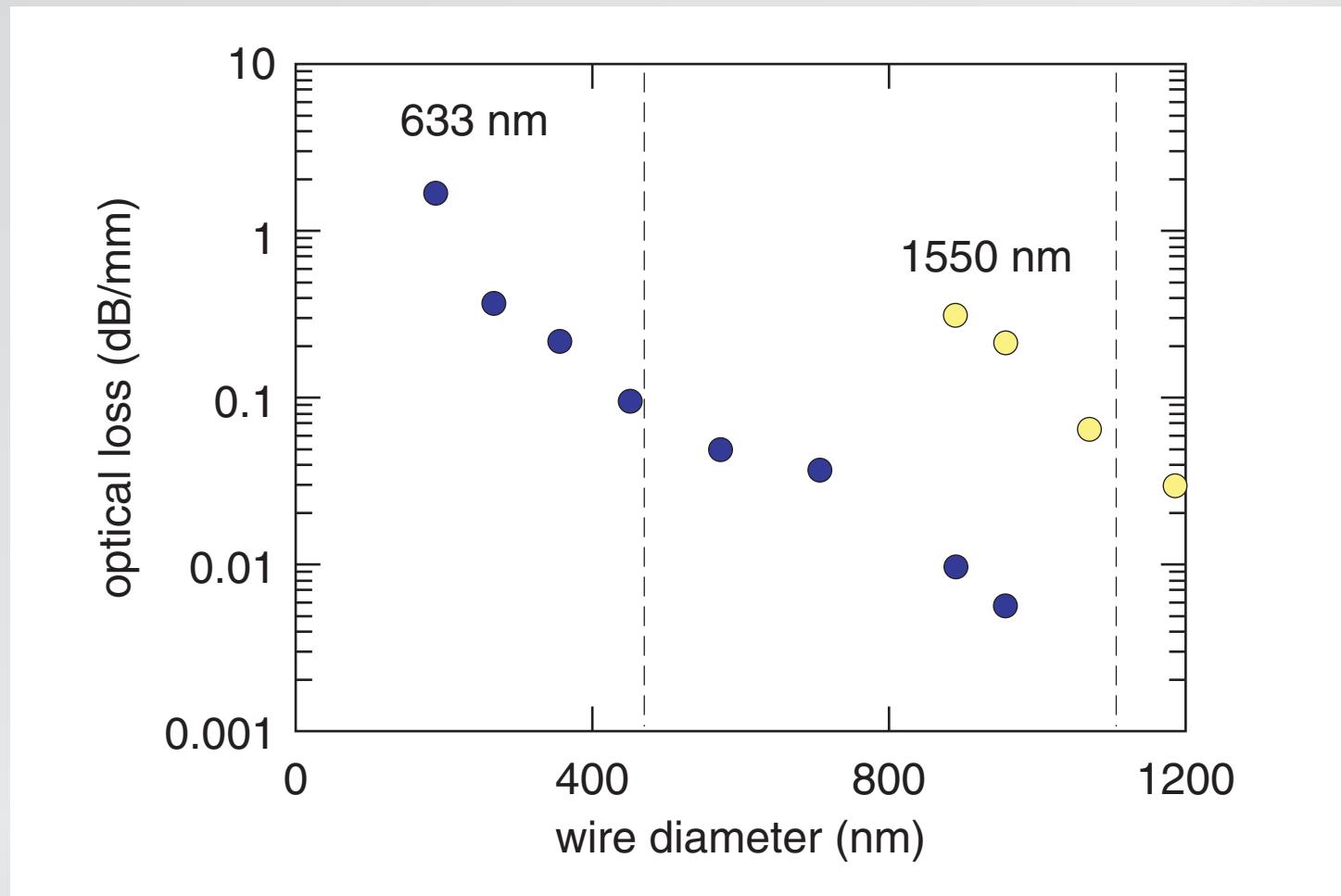
# Optical properties

## loss measurement

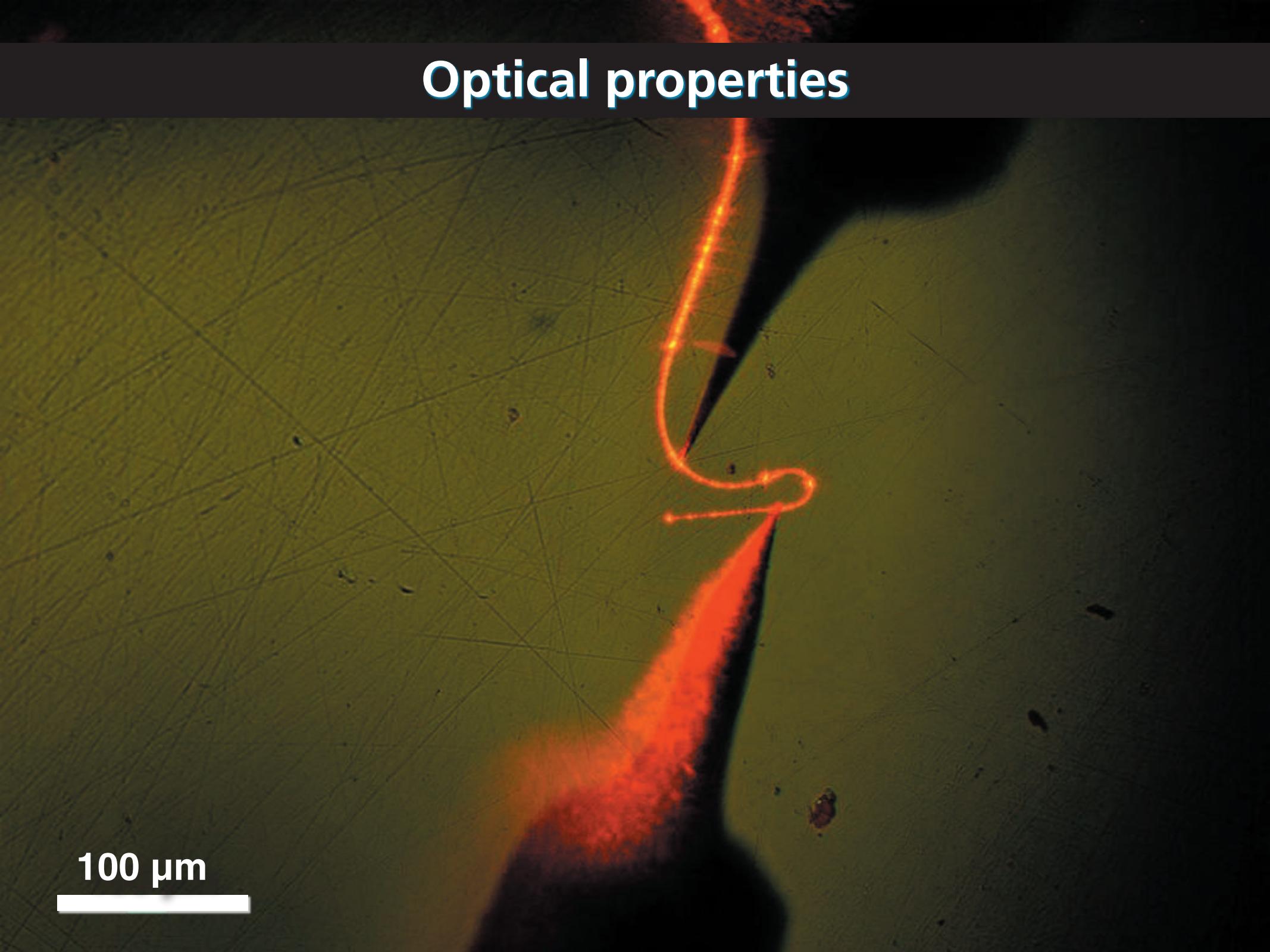


# Optical properties

loss at single-mode diameter < 0.1 dB/mm

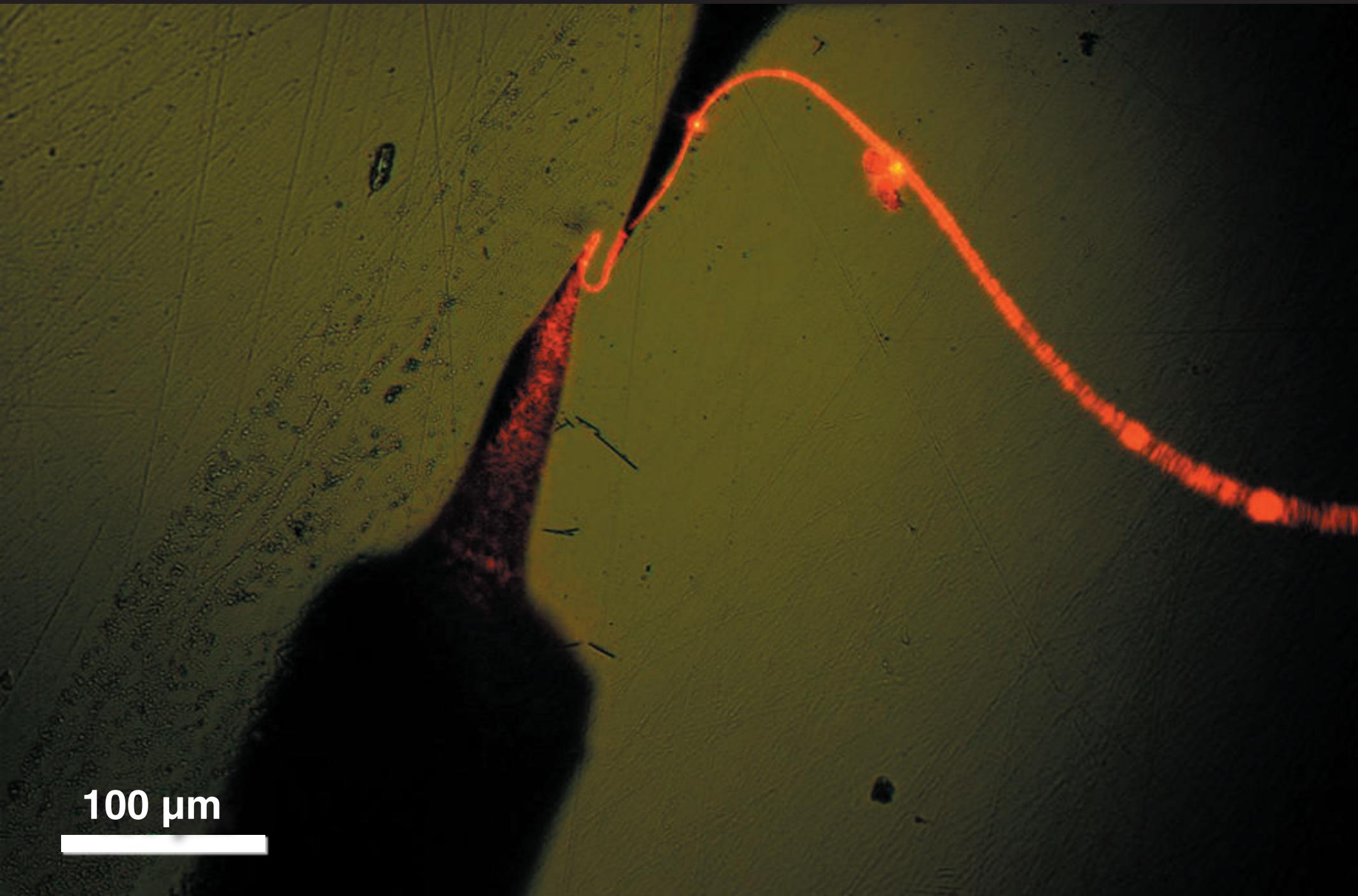


# Optical properties



100  $\mu\text{m}$

# Optical properties



100  $\mu\text{m}$

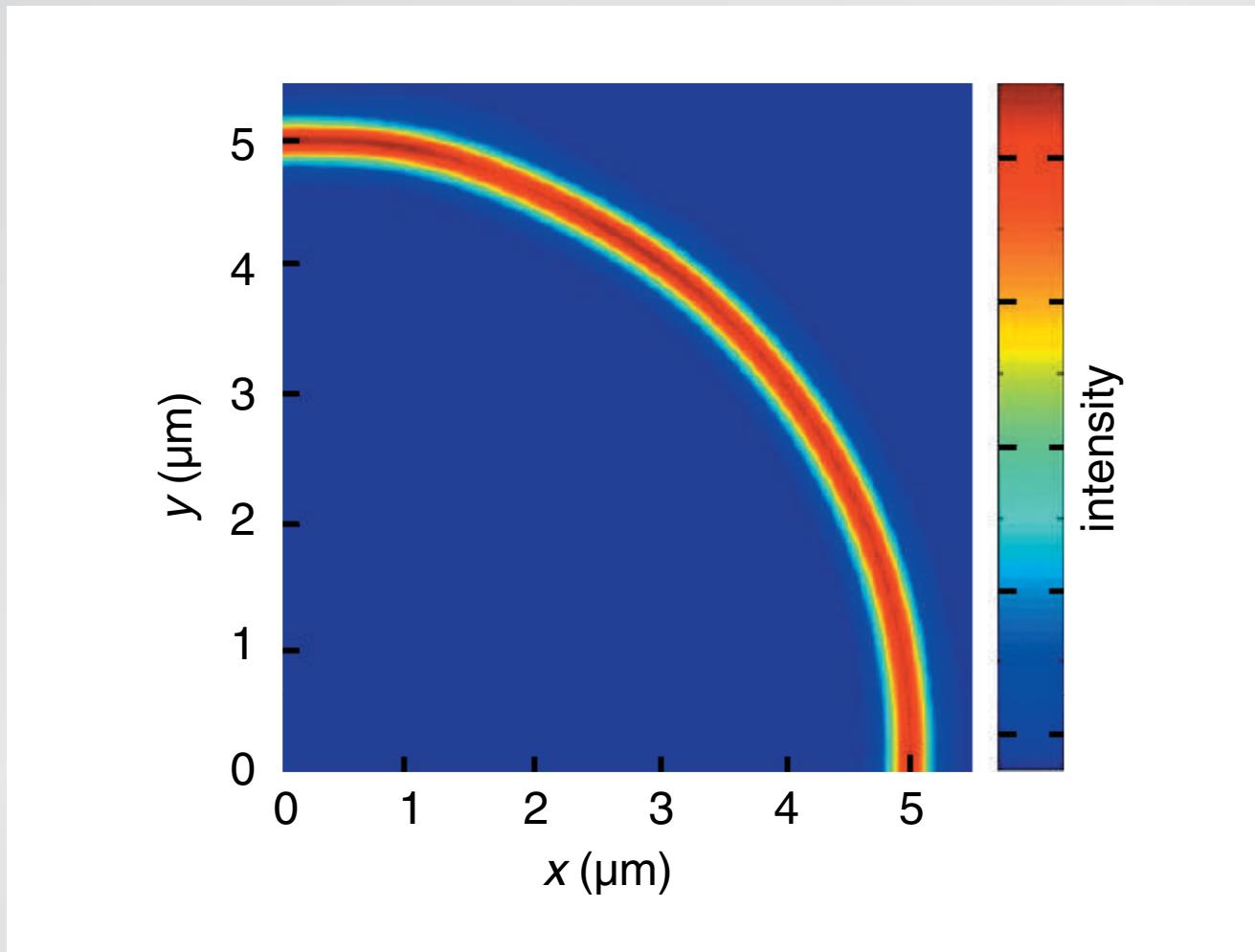
# Optical properties

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

100  $\mu\text{m}$

# Optical properties

virtually no loss through 5  $\mu\text{m}$  corner!



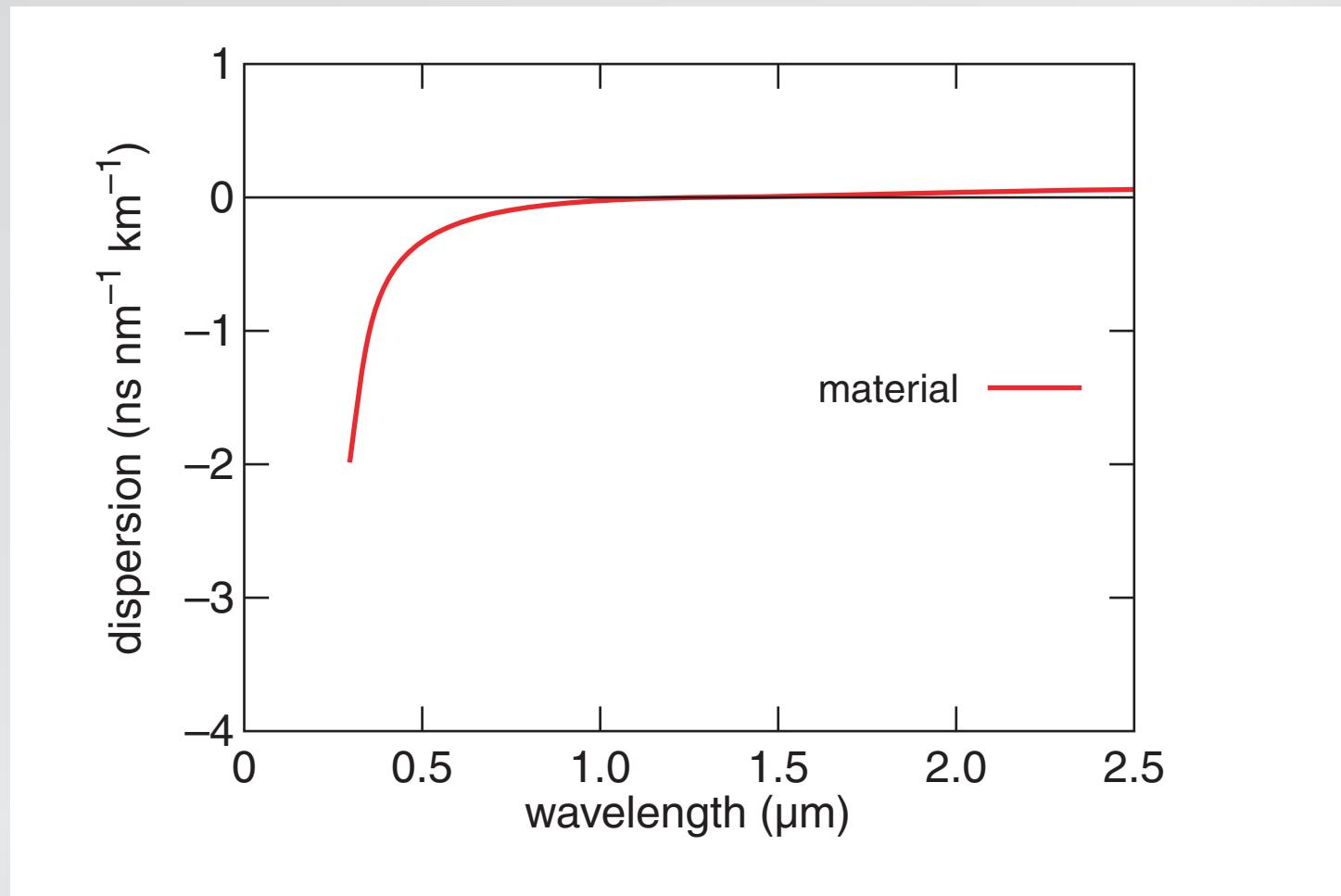
# Optical properties

dispersion:

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

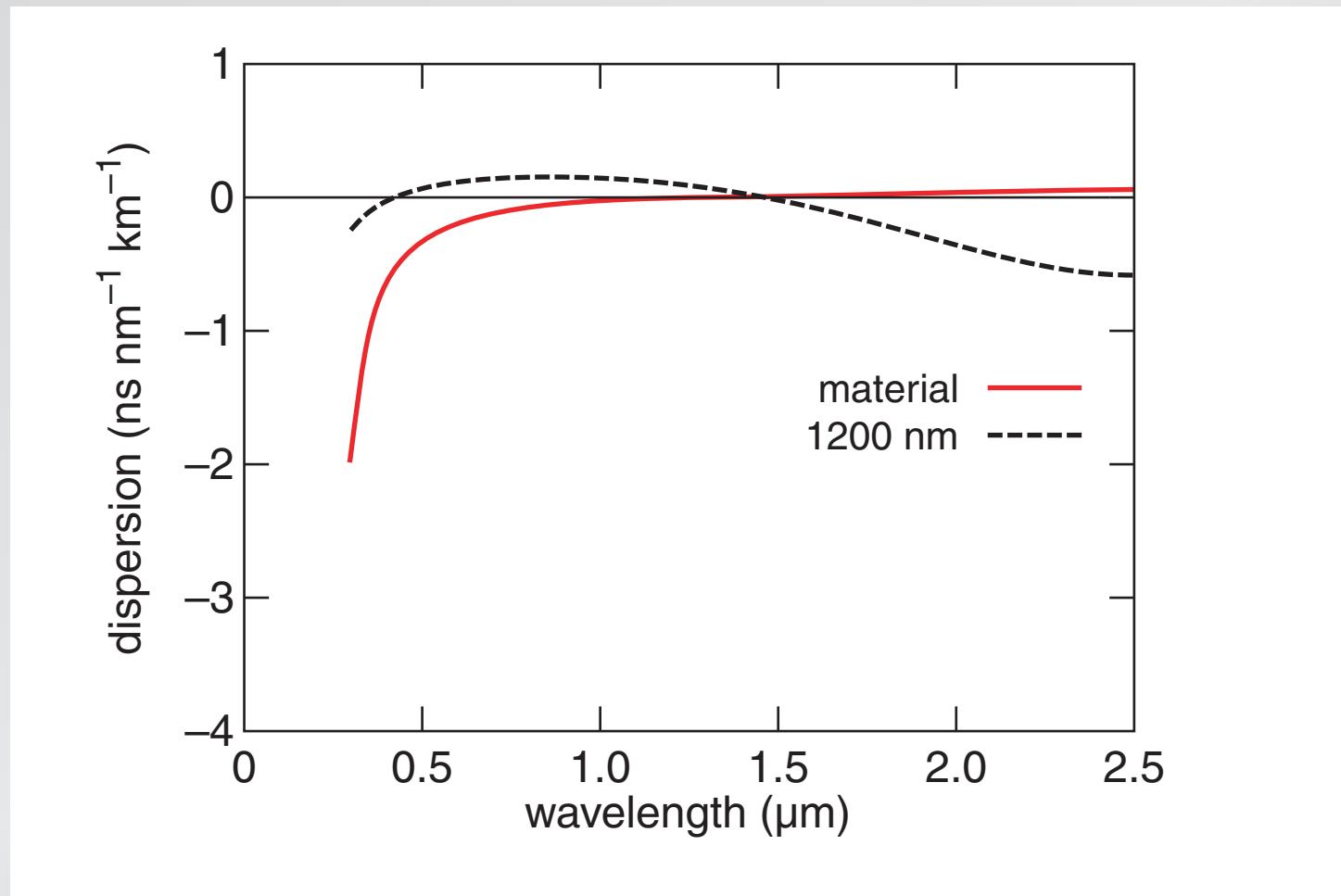
# Optical properties

## waveguide dispersion



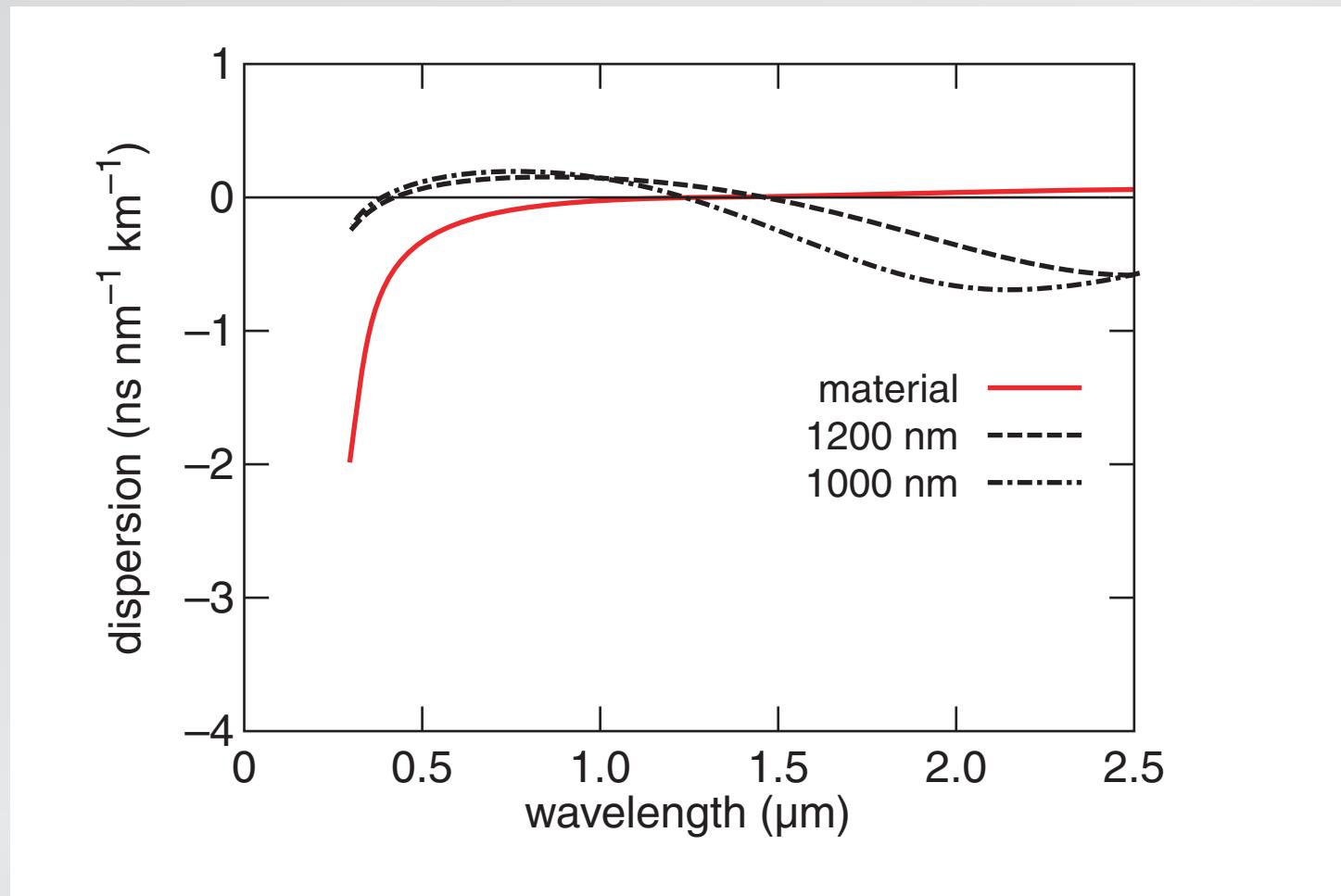
# Optical properties

## waveguide dispersion



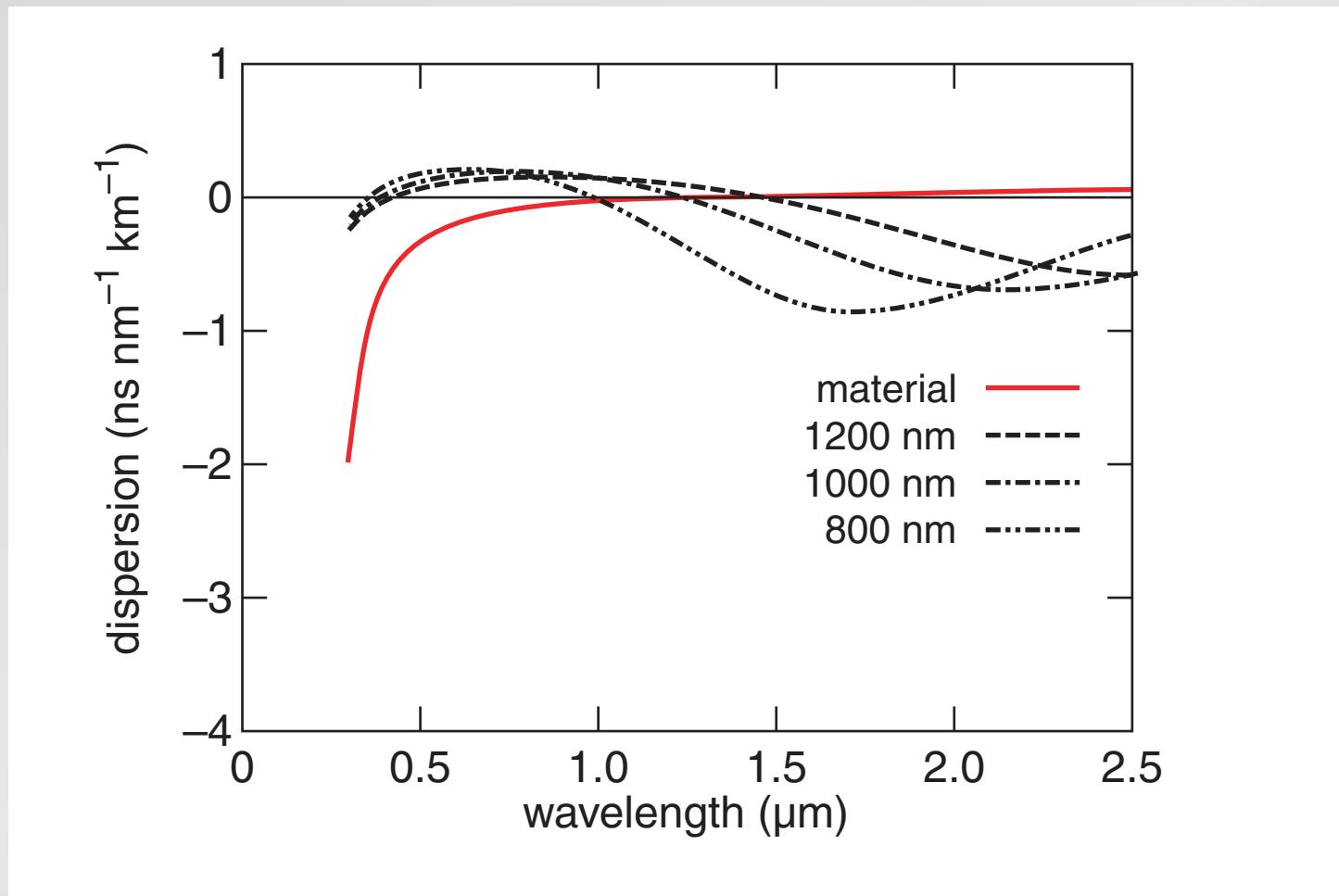
# Optical properties

## waveguide dispersion



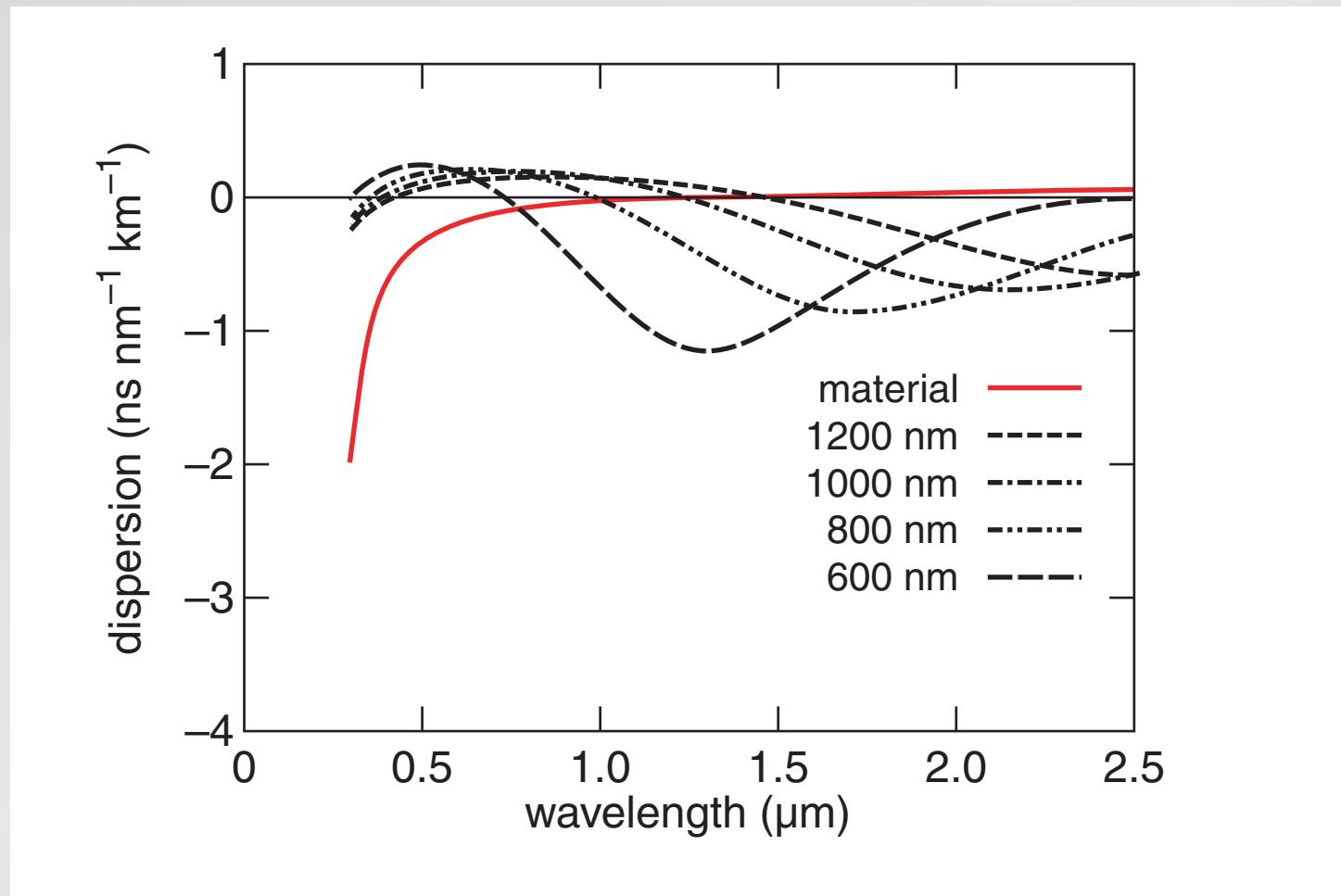
# Optical properties

## waveguide dispersion



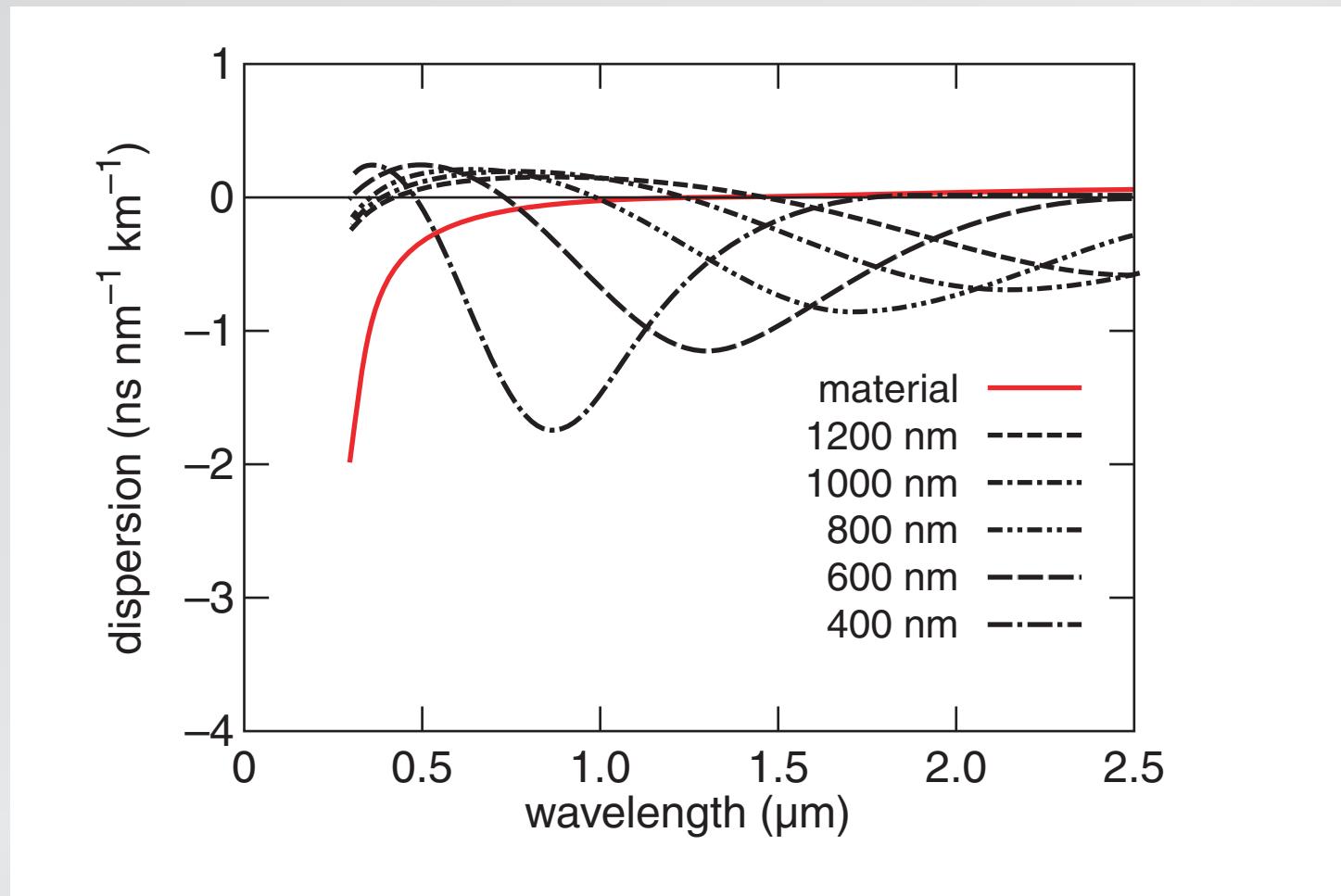
# Optical properties

## waveguide dispersion



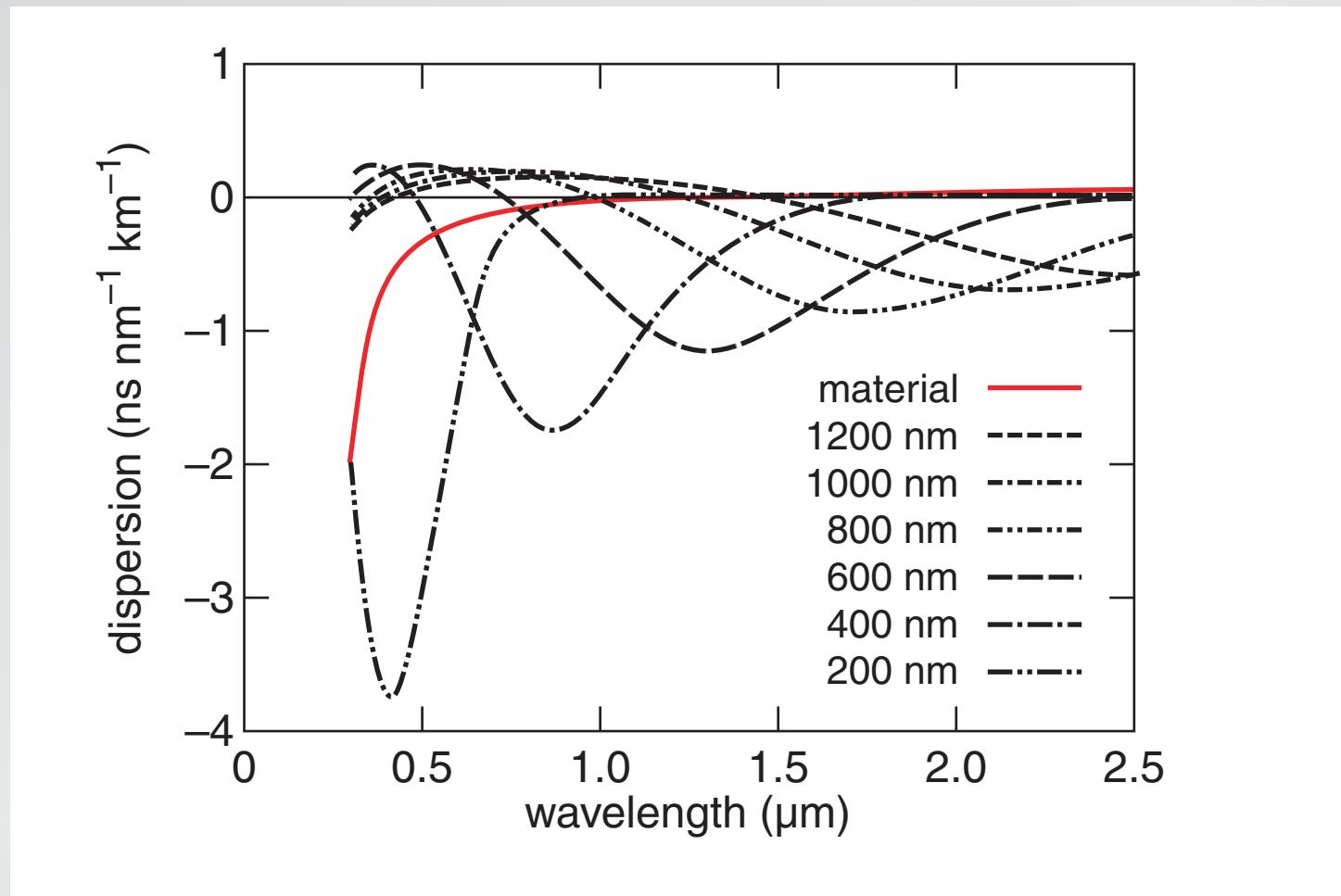
# Optical properties

## waveguide dispersion



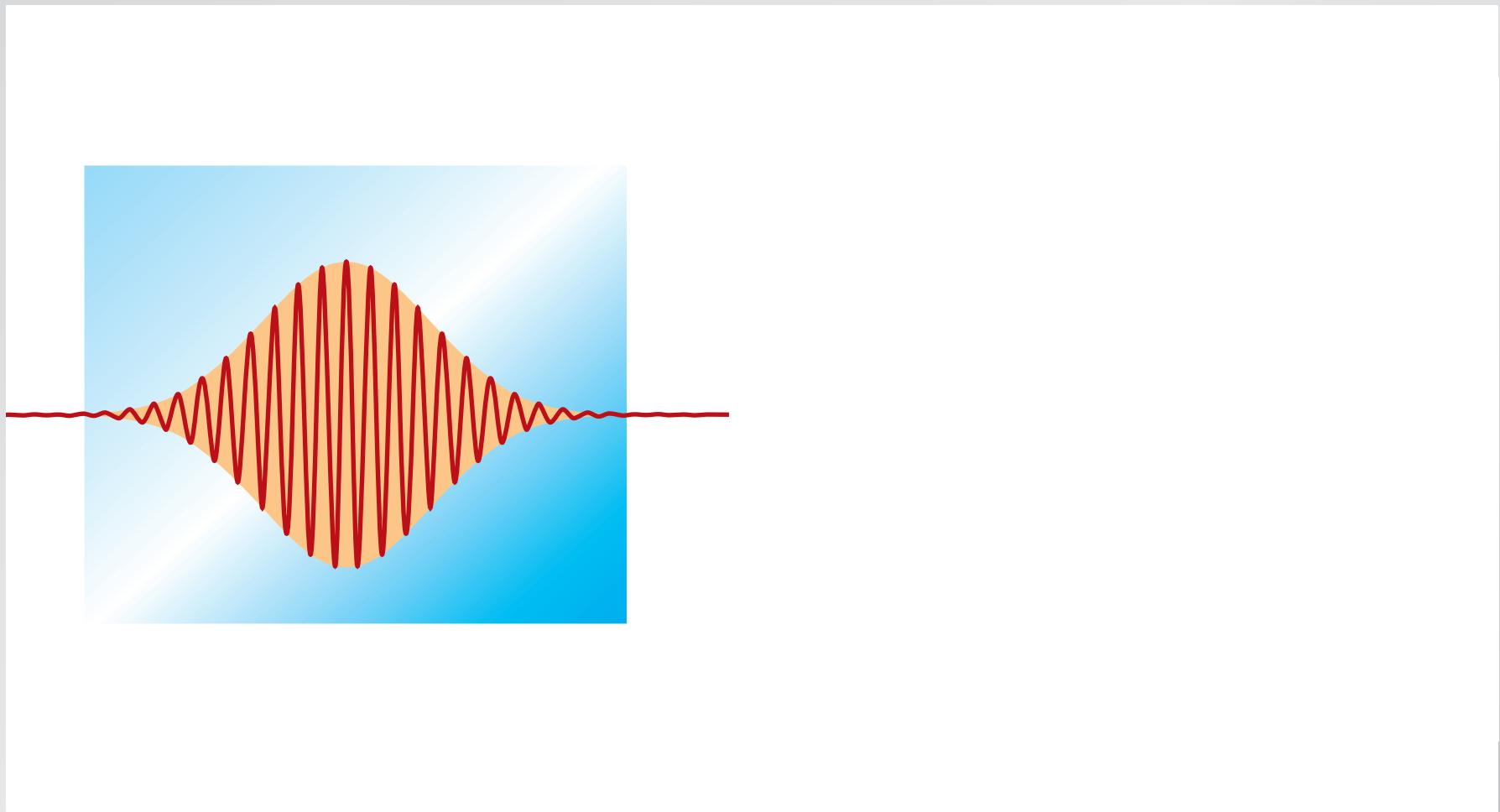
# Optical properties

## waveguide dispersion



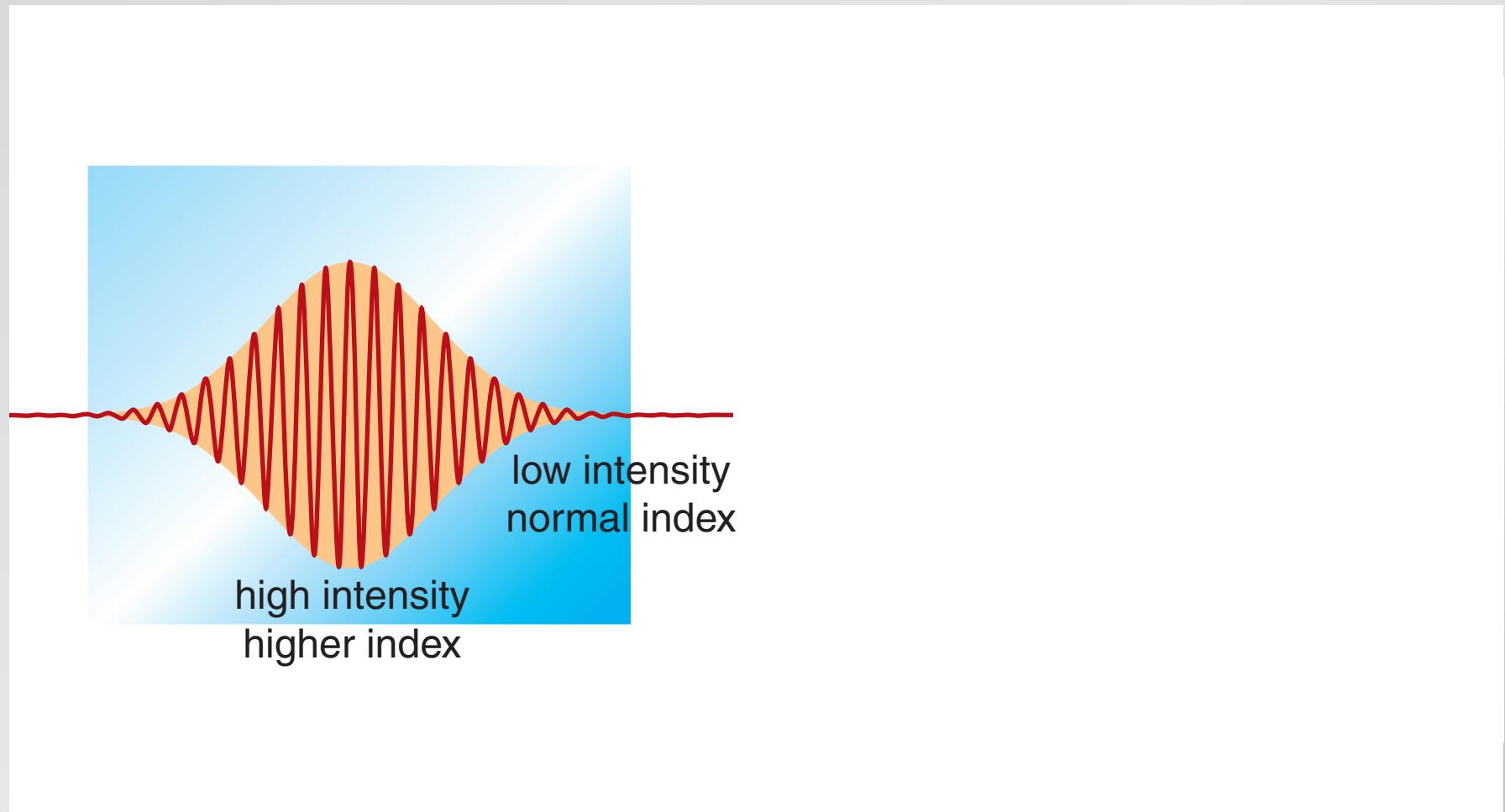
# Optical properties

**nonlinear dispersion:**  $n = n_0 + n_2 I$



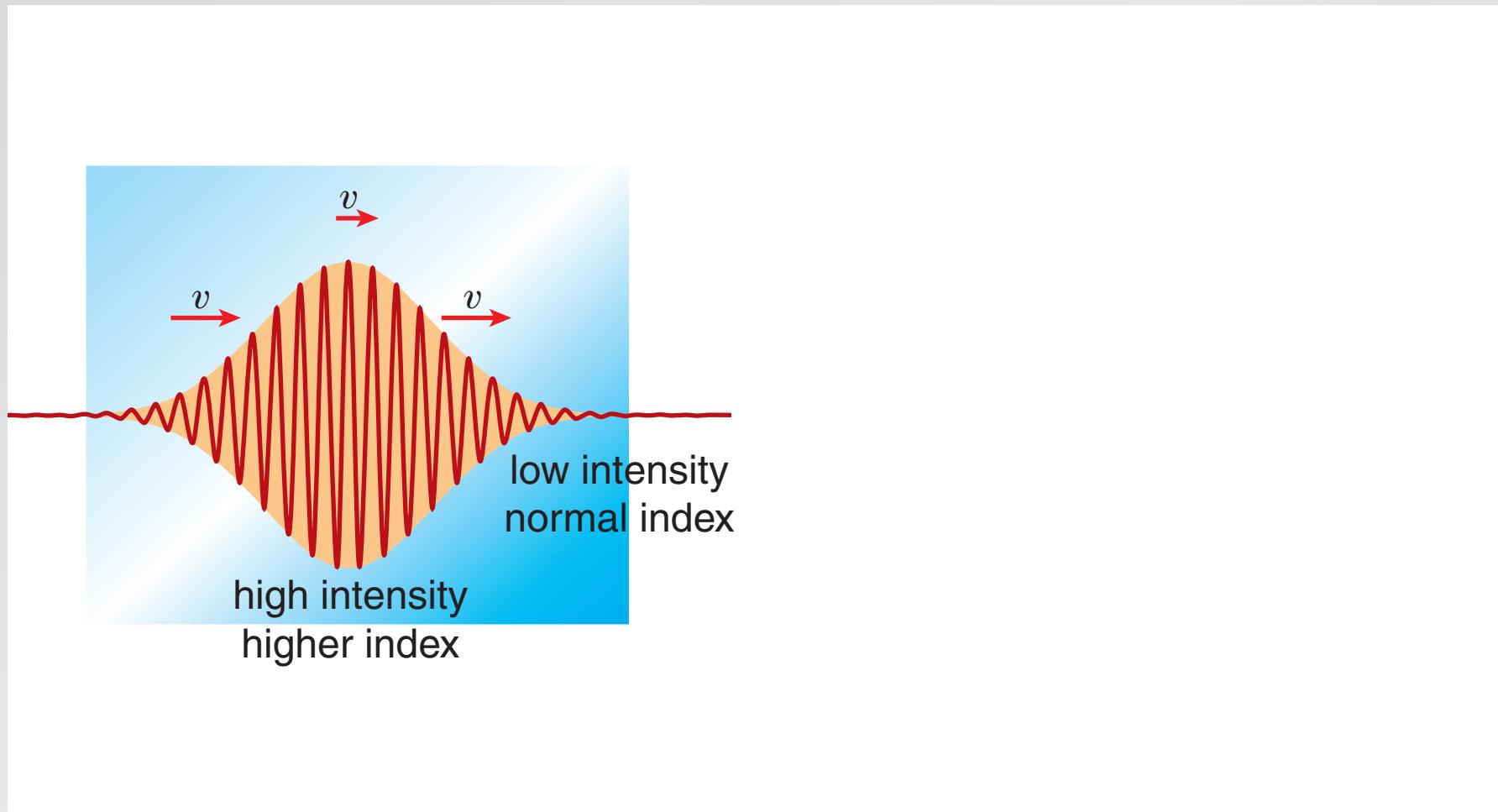
# Optical properties

**nonlinear dispersion:**  $n = n_0 + n_2 I$



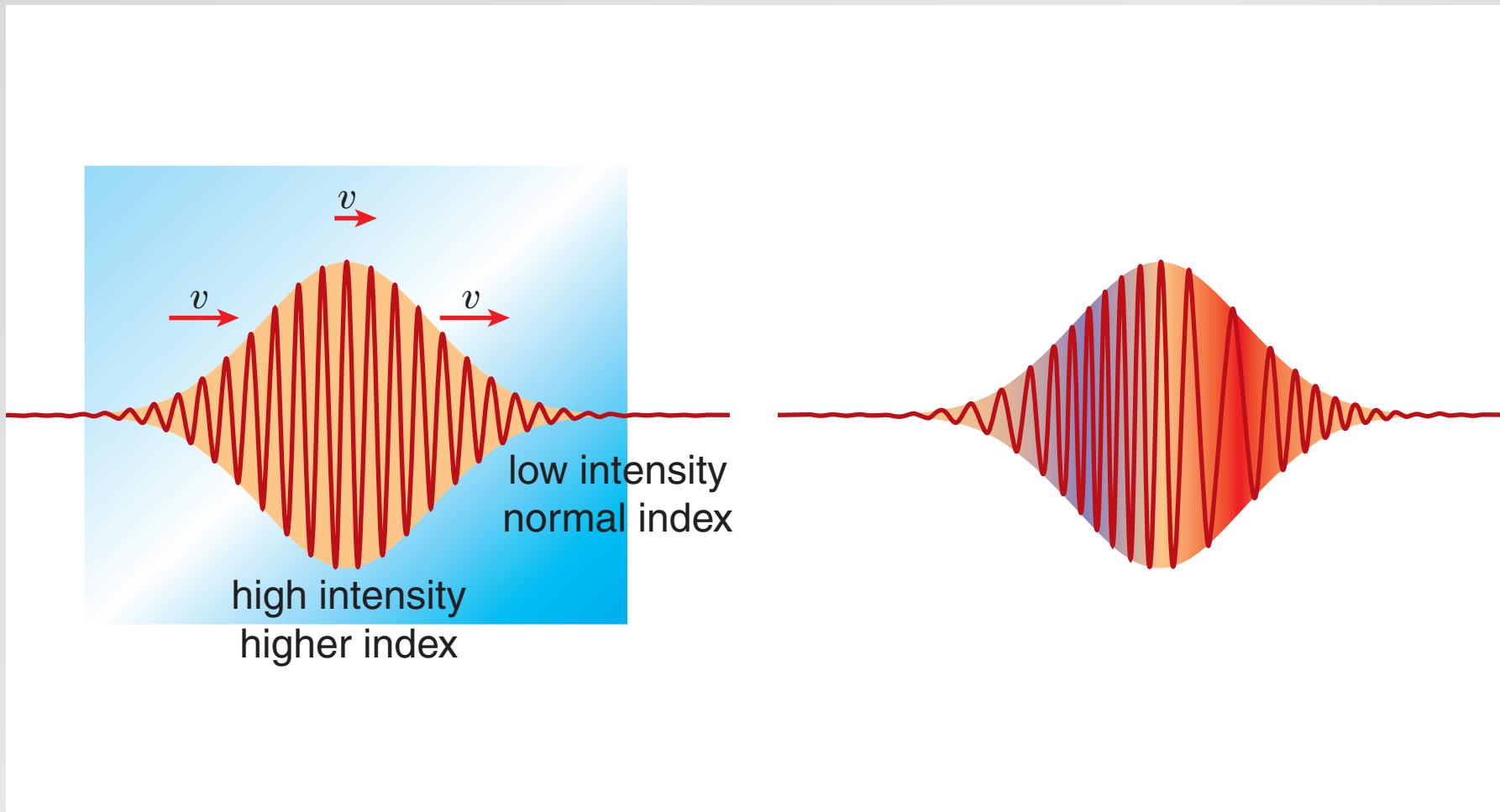
# Optical properties

**nonlinear dispersion:**  $n = n_0 + n_2 I$



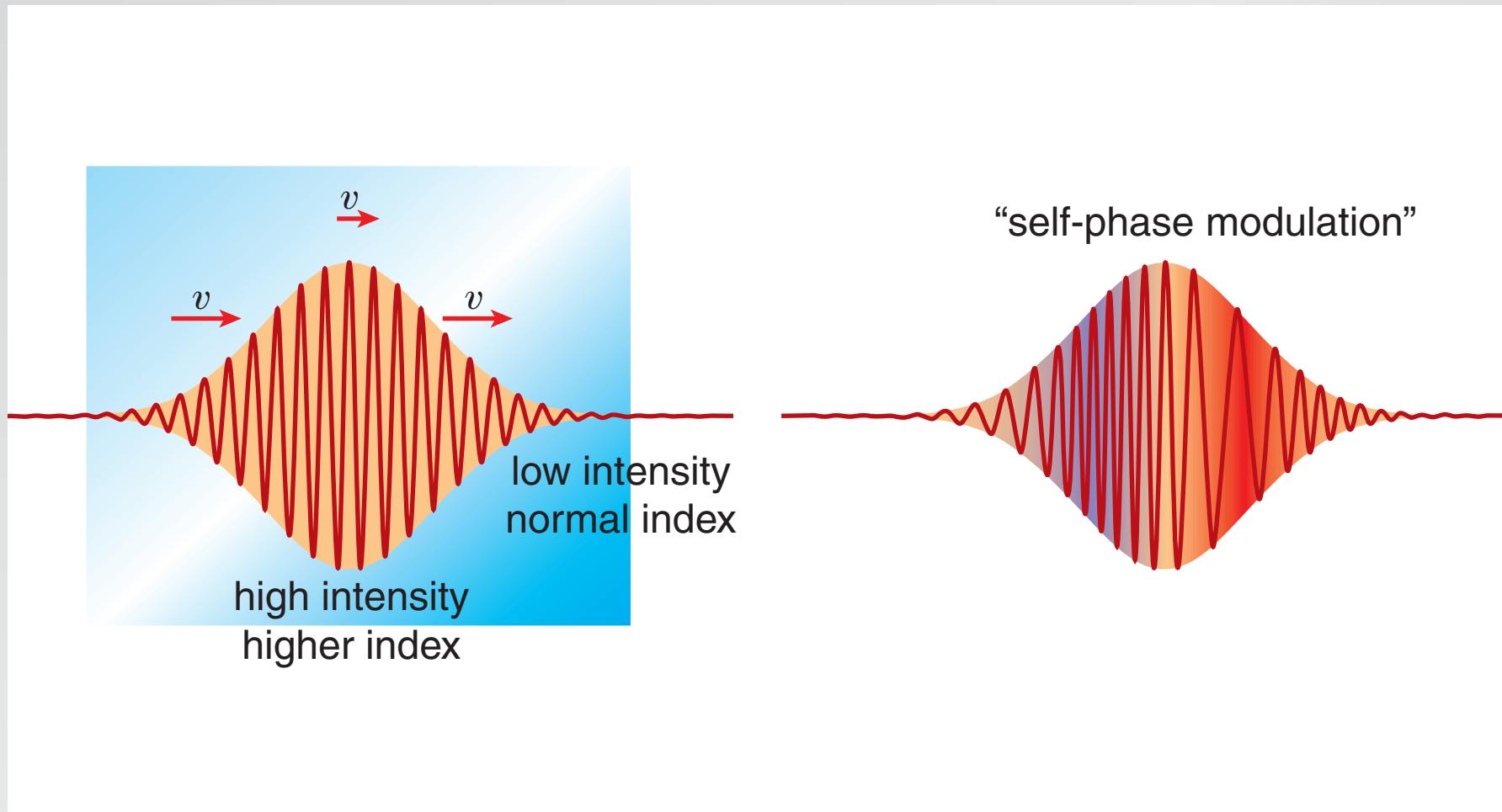
# Optical properties

**nonlinear dispersion:**  $n = n_0 + n_2 I$

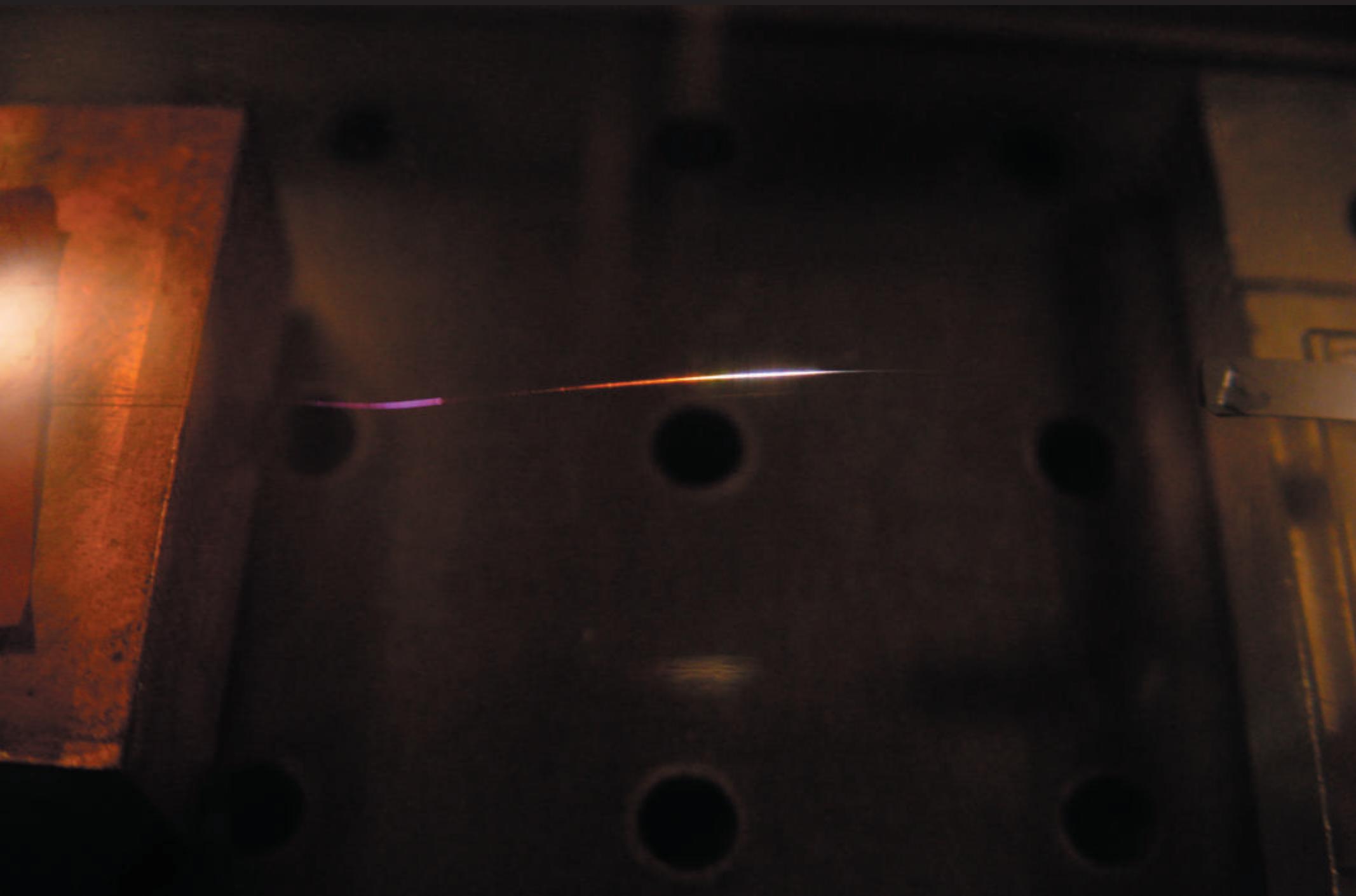


# Optical properties

**nonlinear dispersion:**  $n = n_0 + n_2 I$



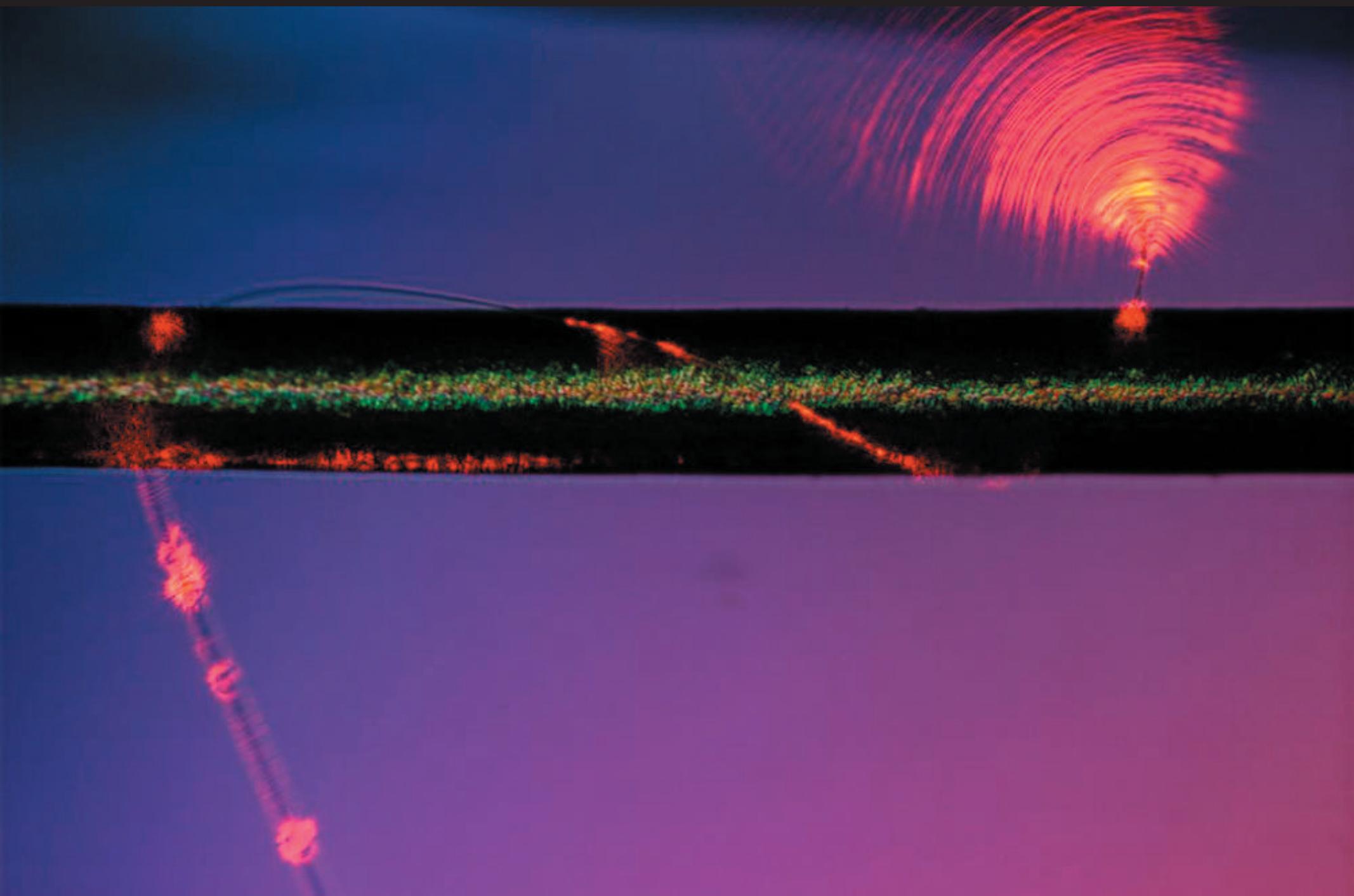
# Optical properties



# Optical properties



# Summary



# Summary

- strong confinement
- very tight bending
- large evanescent wave

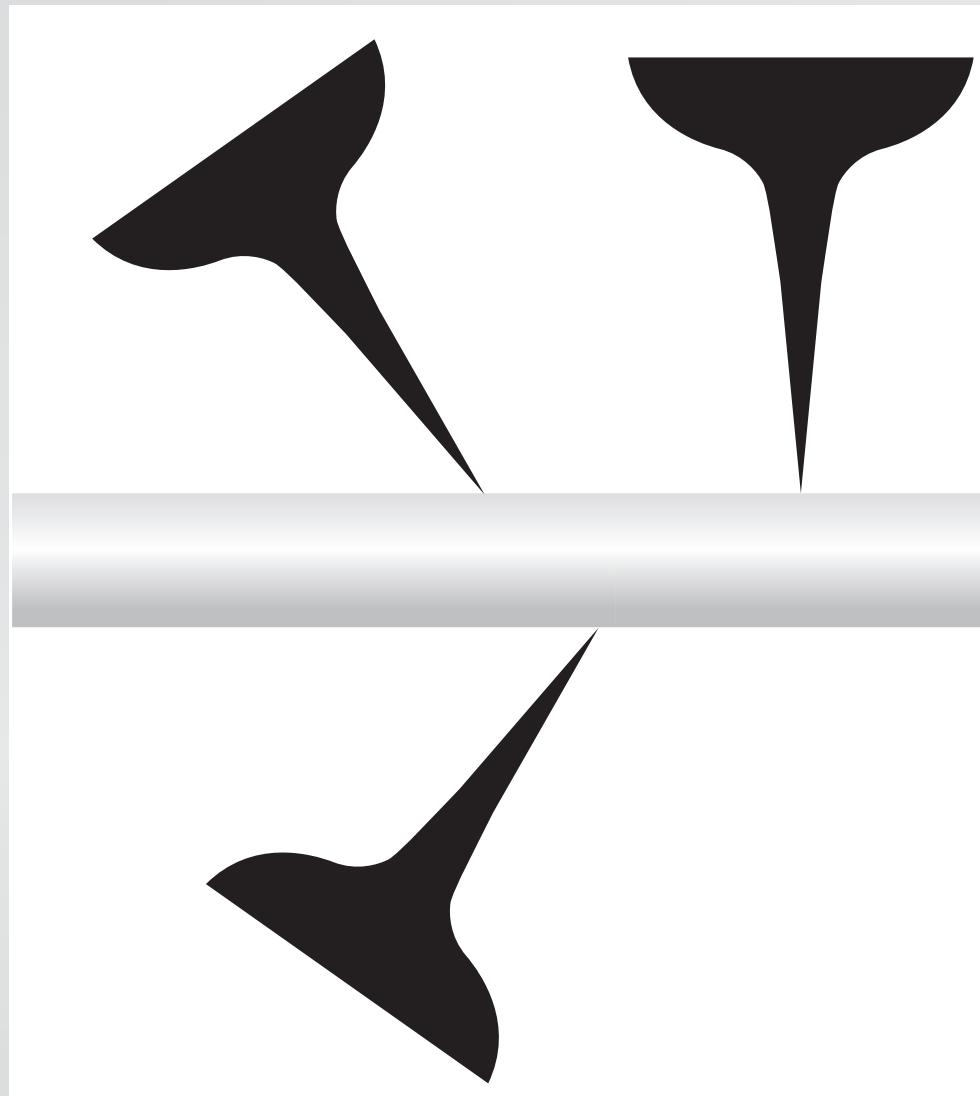
# Outlook

## microphtonic components



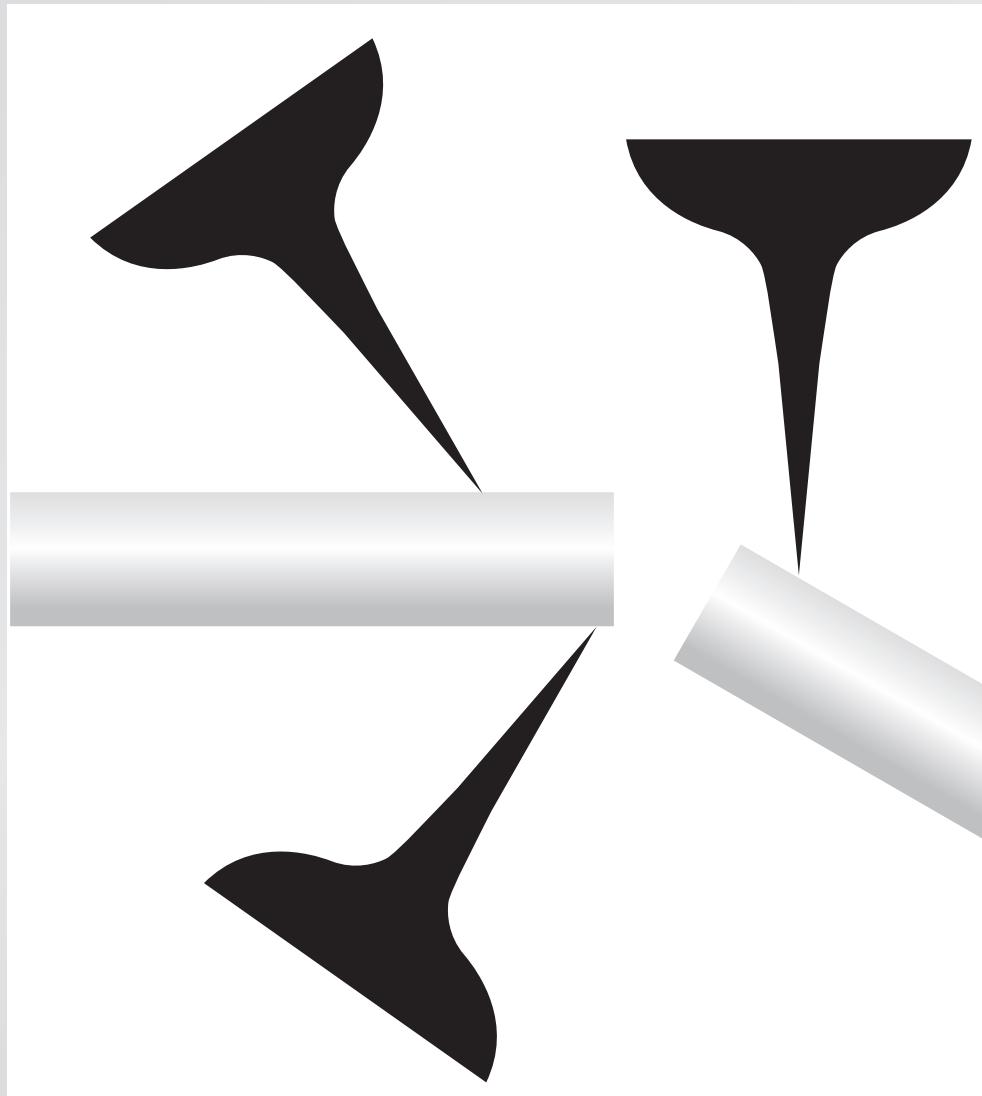
# Outlook

**microphotonic components**



# Outlook

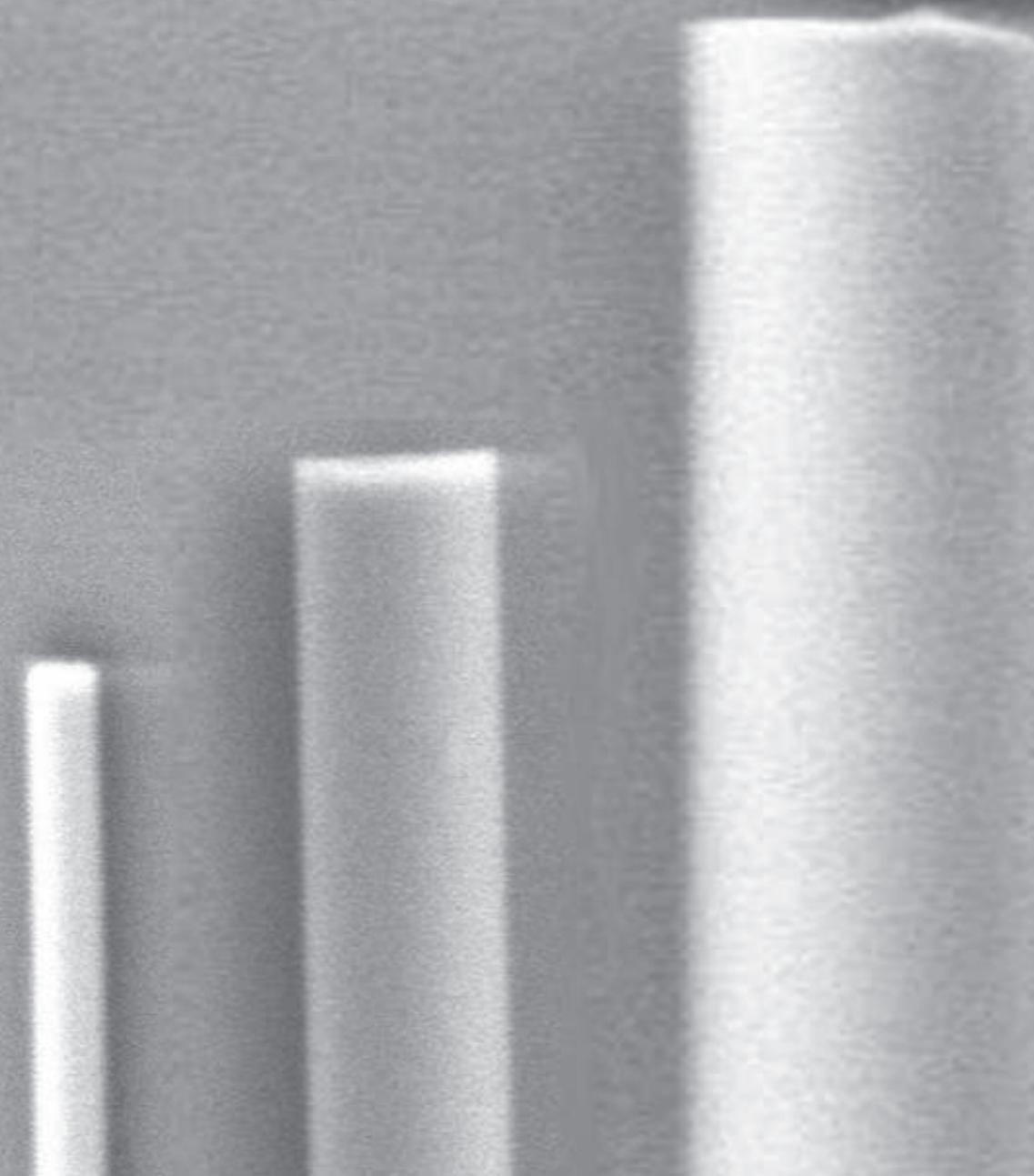
**microphotonic components**



# Outlook

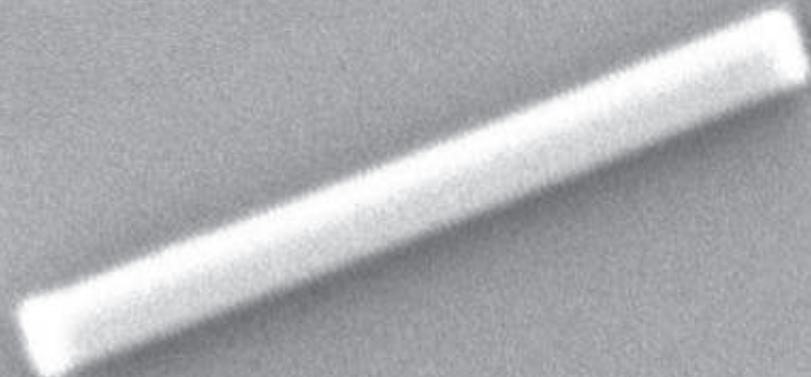
1  $\mu\text{m}$

# Outlook



500 nm

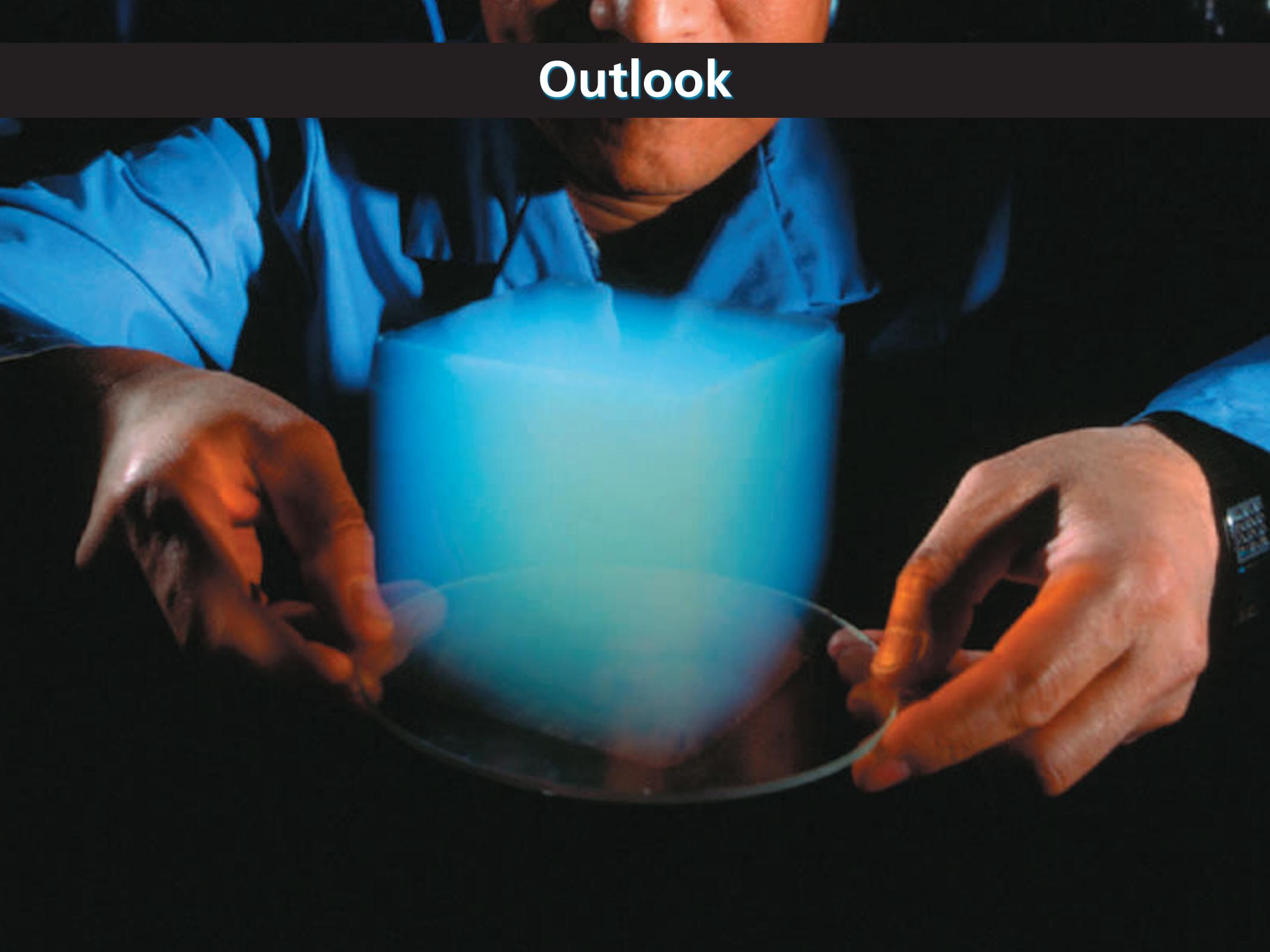
# Outlook



500 nm

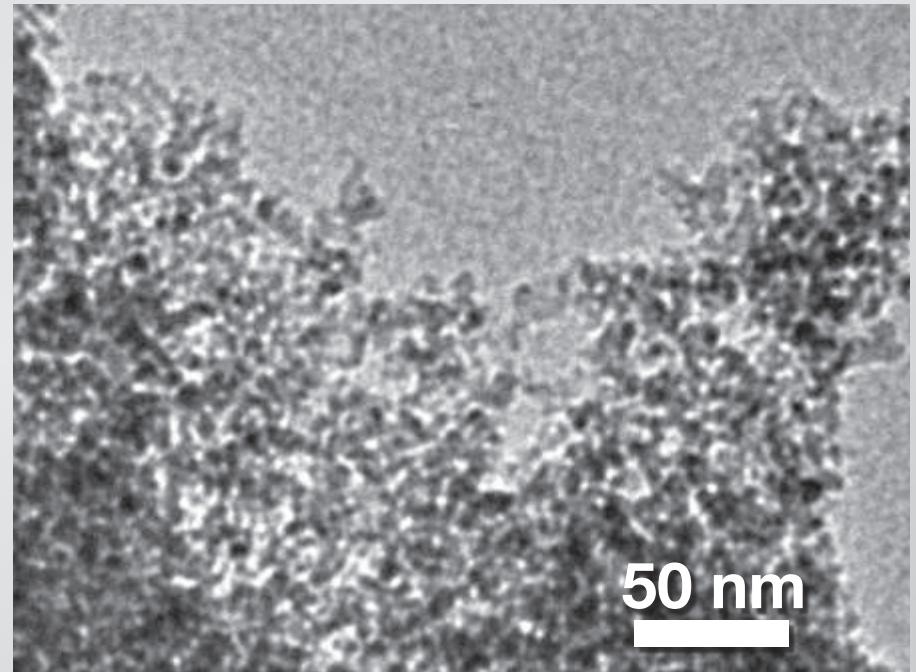
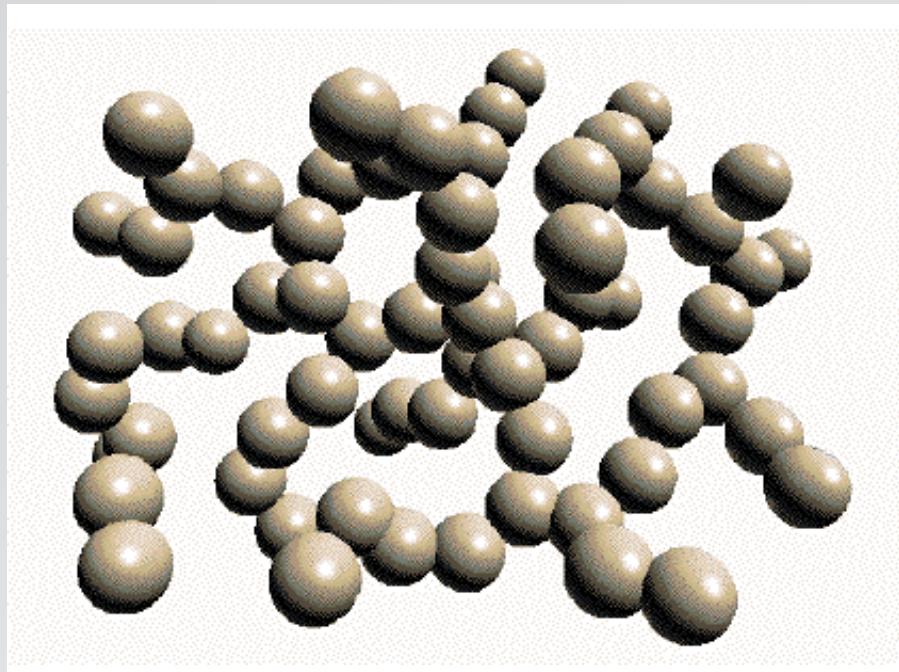


# Outlook

A close-up photograph of a person's hands and torso. The person is wearing a blue short-sleeved shirt and blue latex gloves. They are holding a glowing, translucent blue cylindrical object, possibly a light stick or a glowing rock, which illuminates their hands and part of their shirt. The background is dark, making the blue glow stand out.

# Outlook

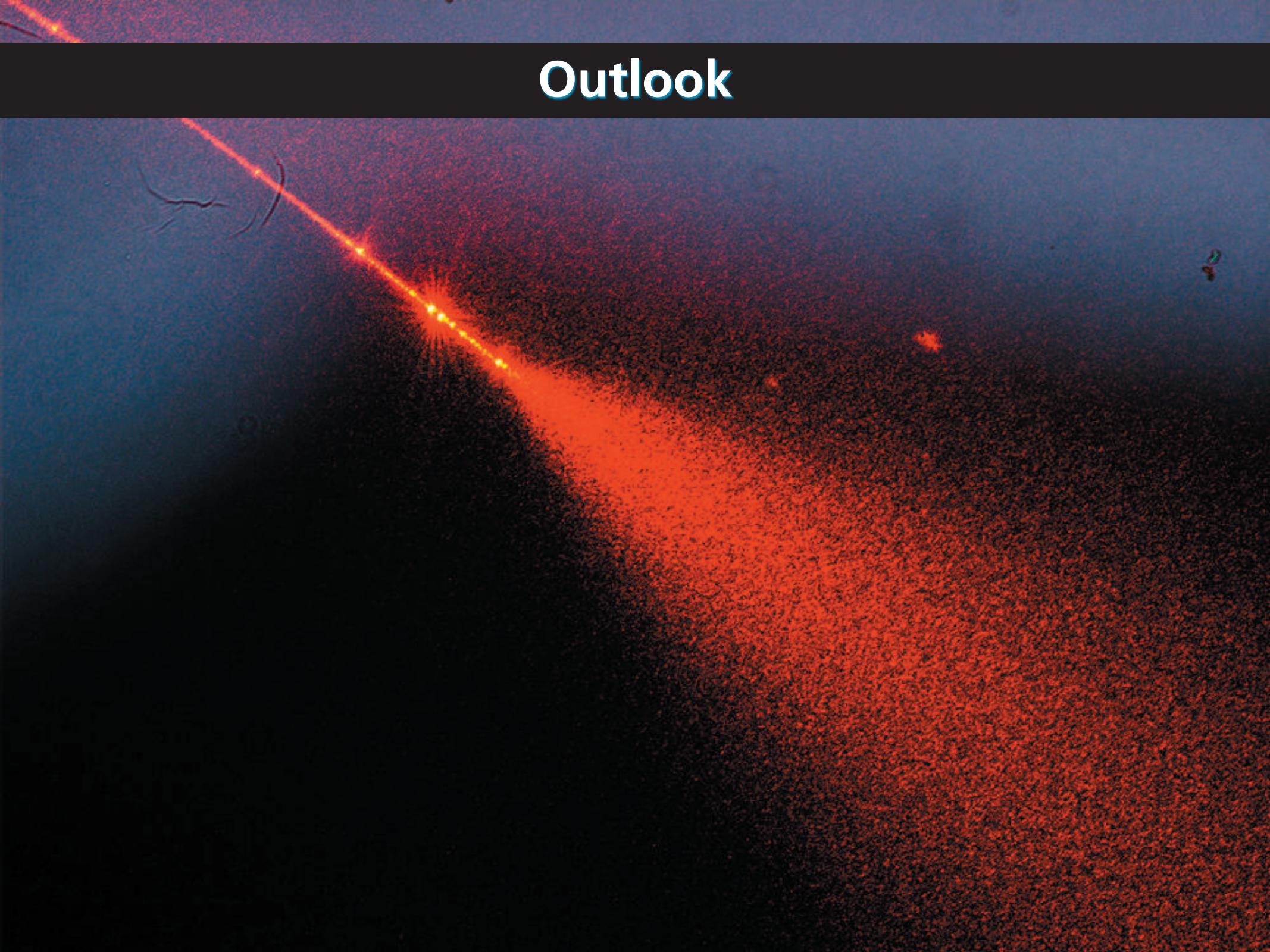
## Aerogel



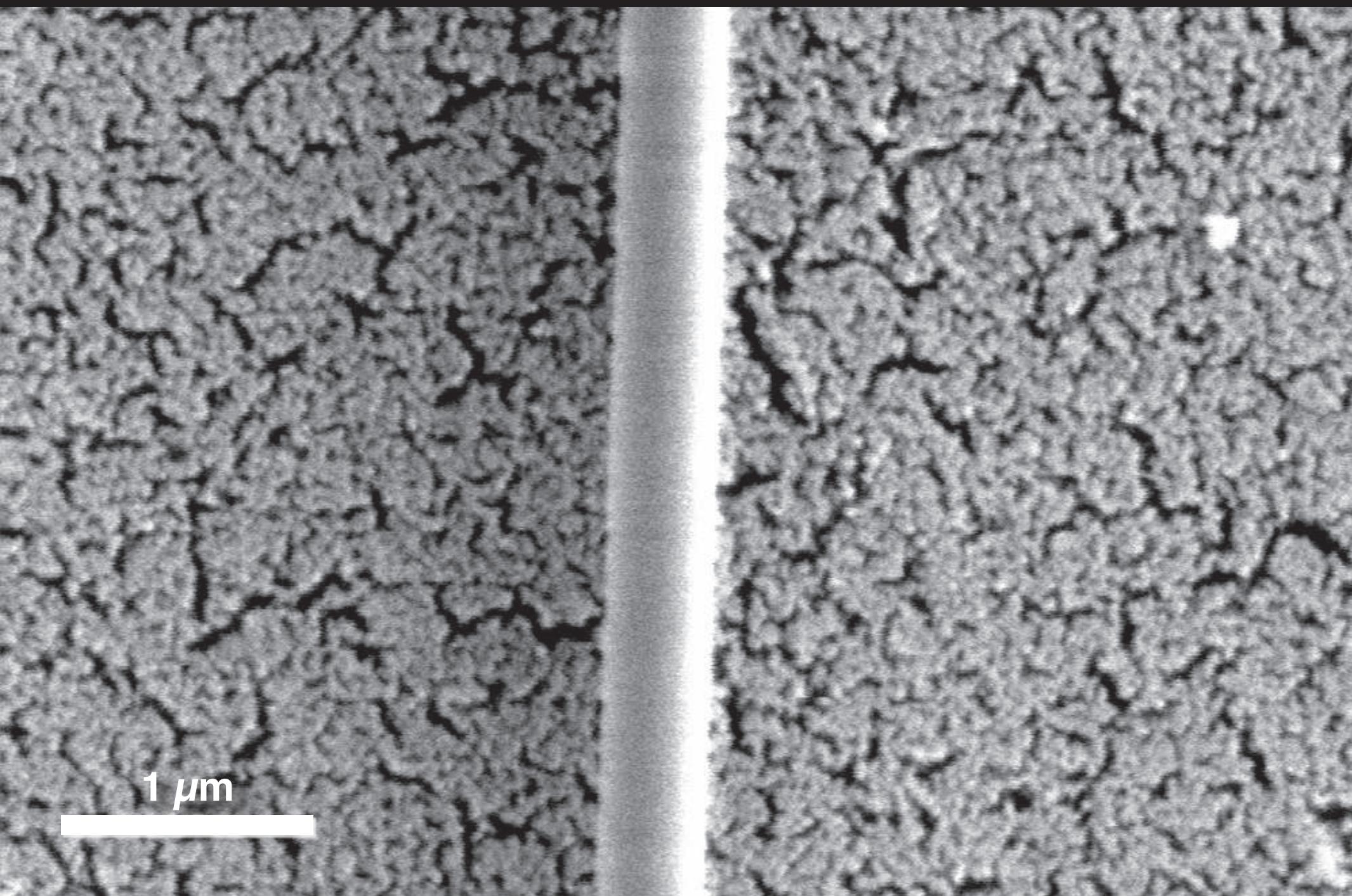
density:  $1.9 \text{ kg/m}^3$

index of refraction: 1.03–1.08

# Outlook

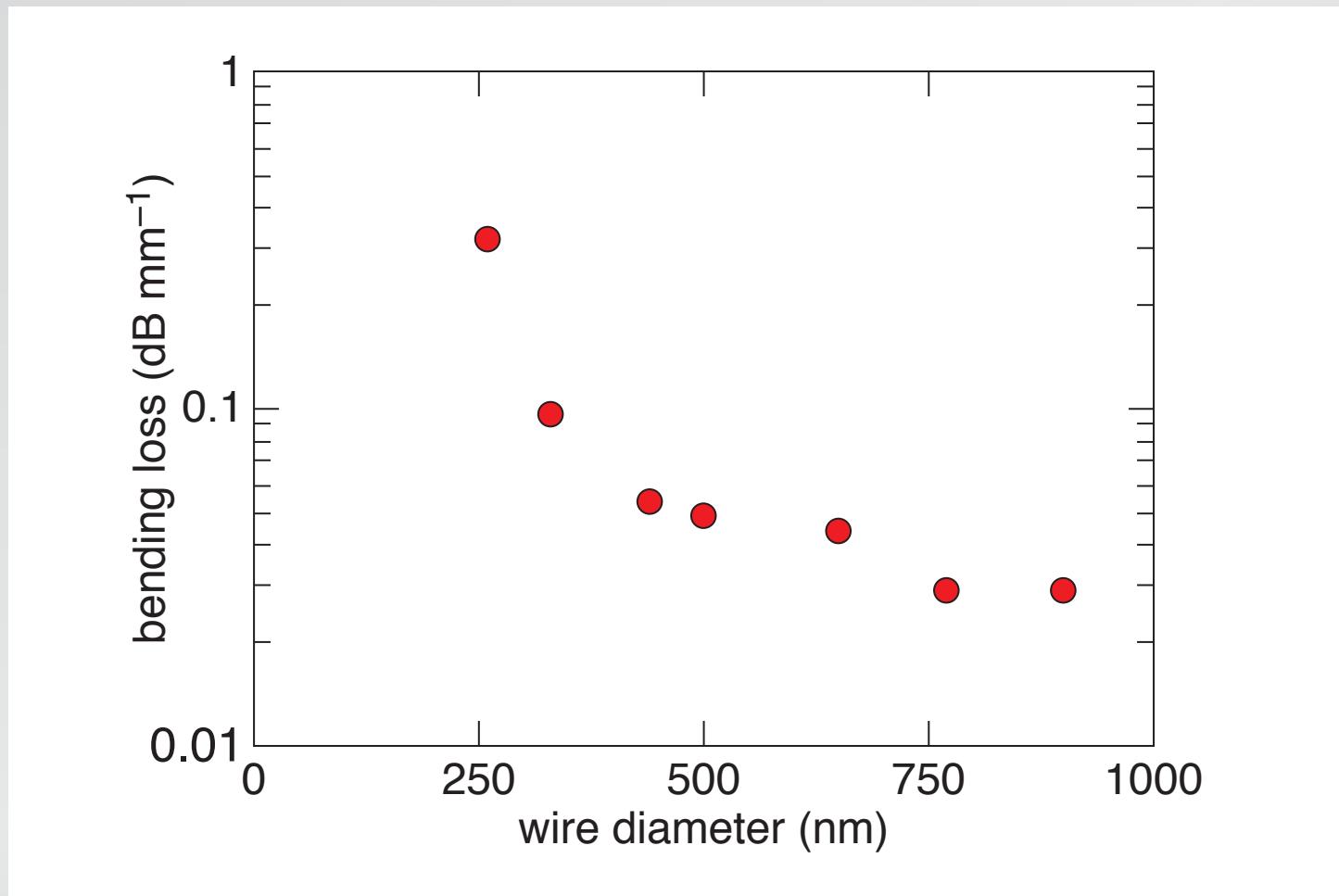


# Outlook



# Outlook

loss measurement @ 633 nm

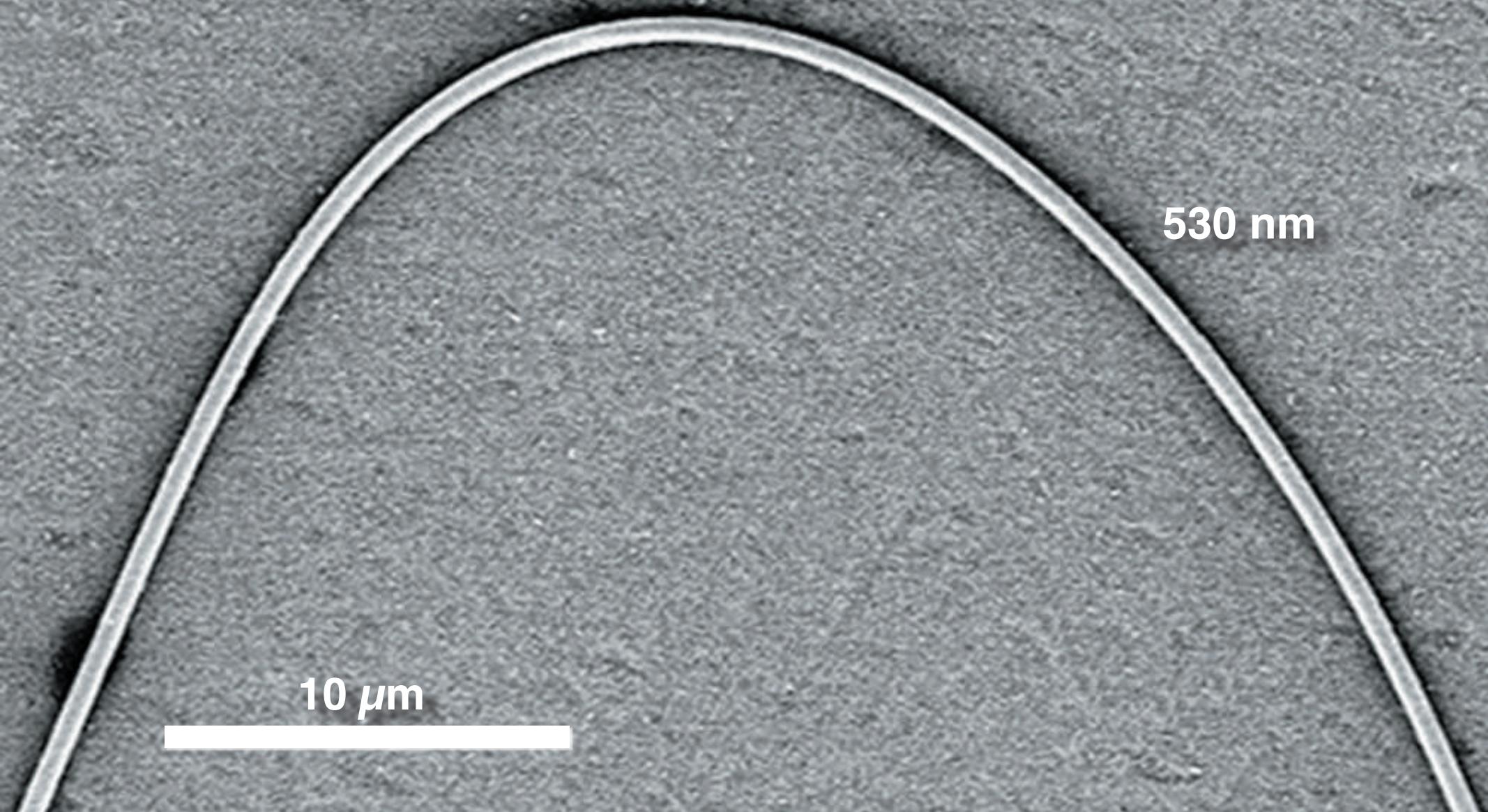


# Outlook

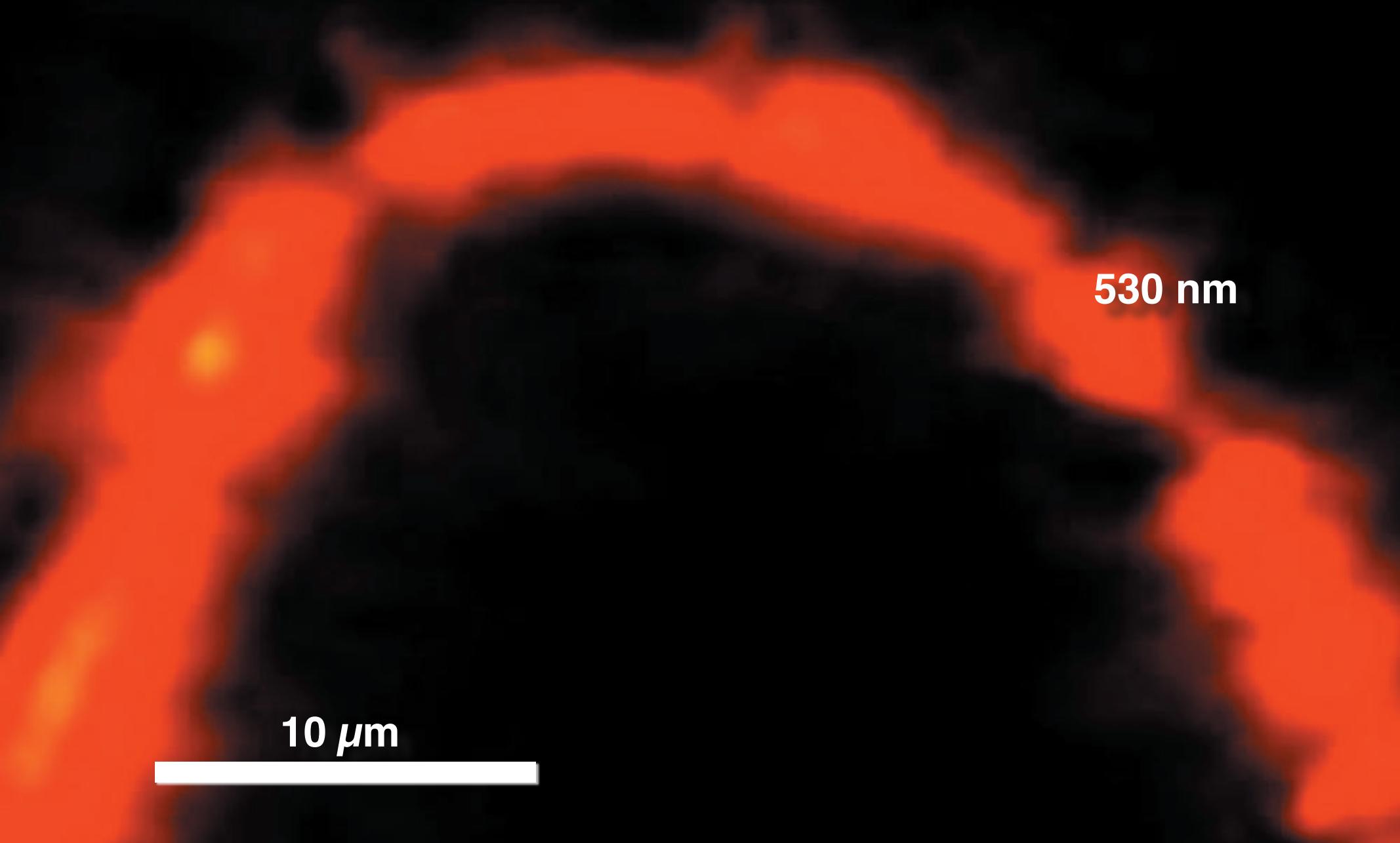
530 nm

50  $\mu$ m

# Outlook



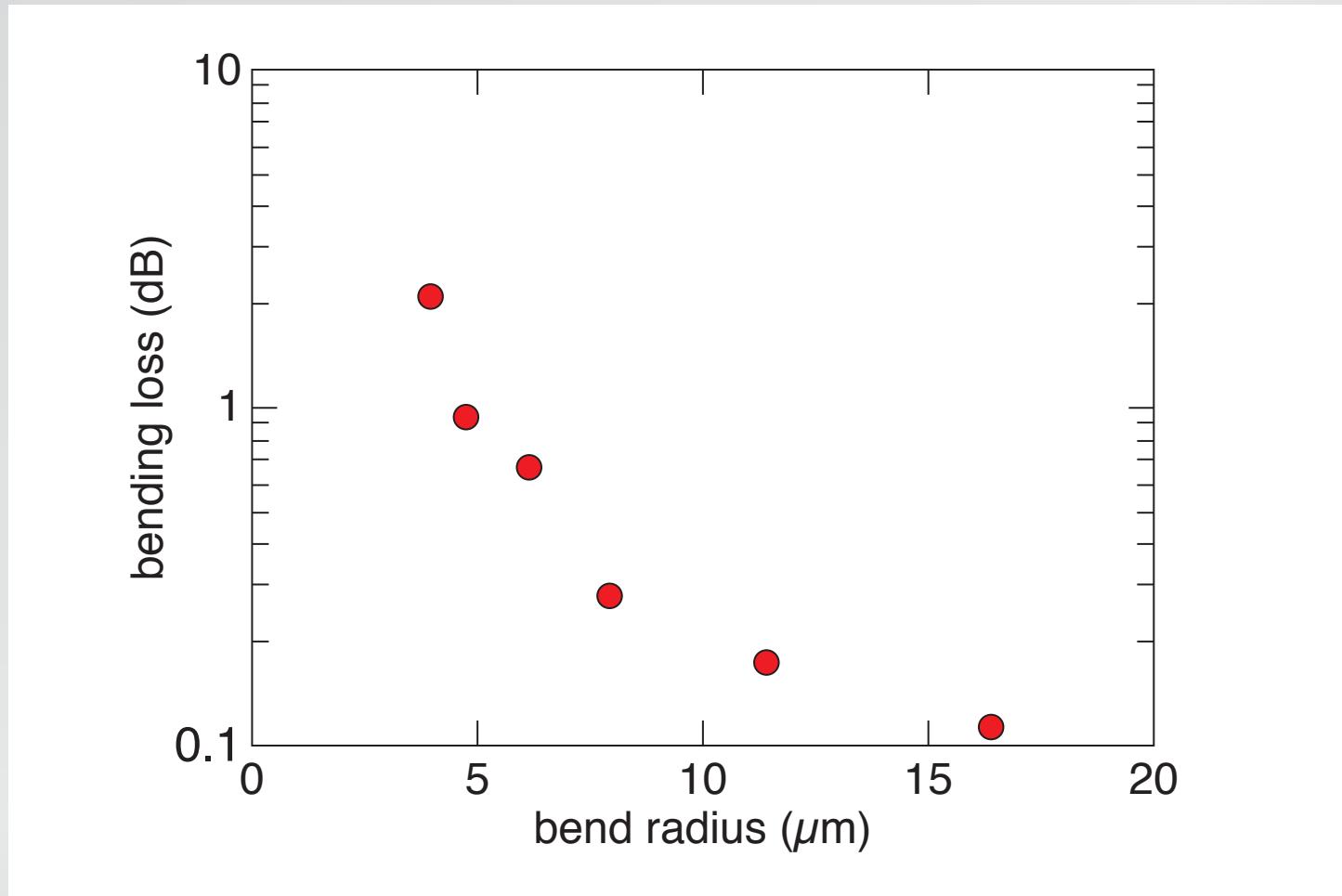
# Outlook



10  $\mu\text{m}$

# Outlook

bending loss @ 633 nm



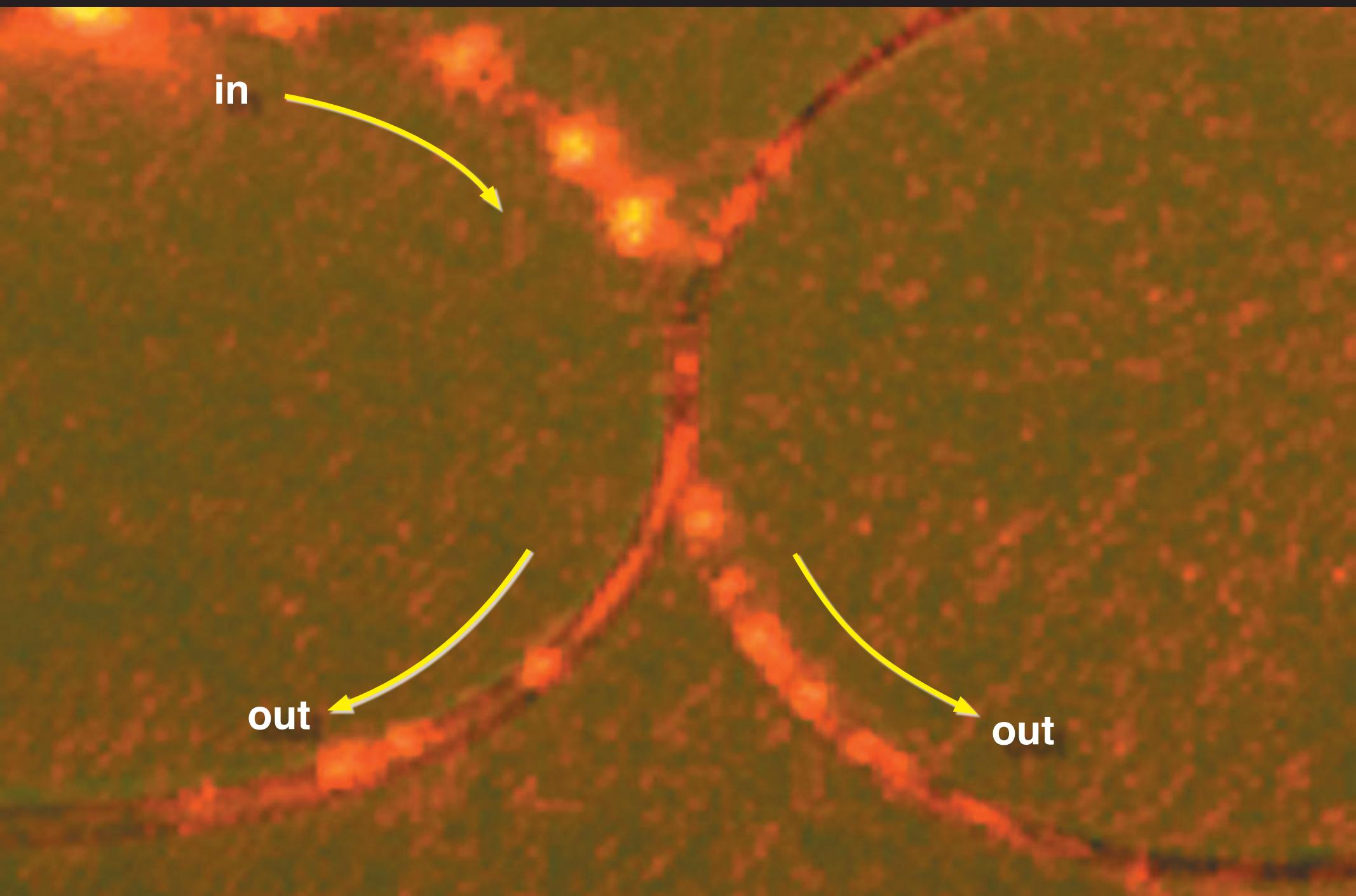
# Outlook

420 nm

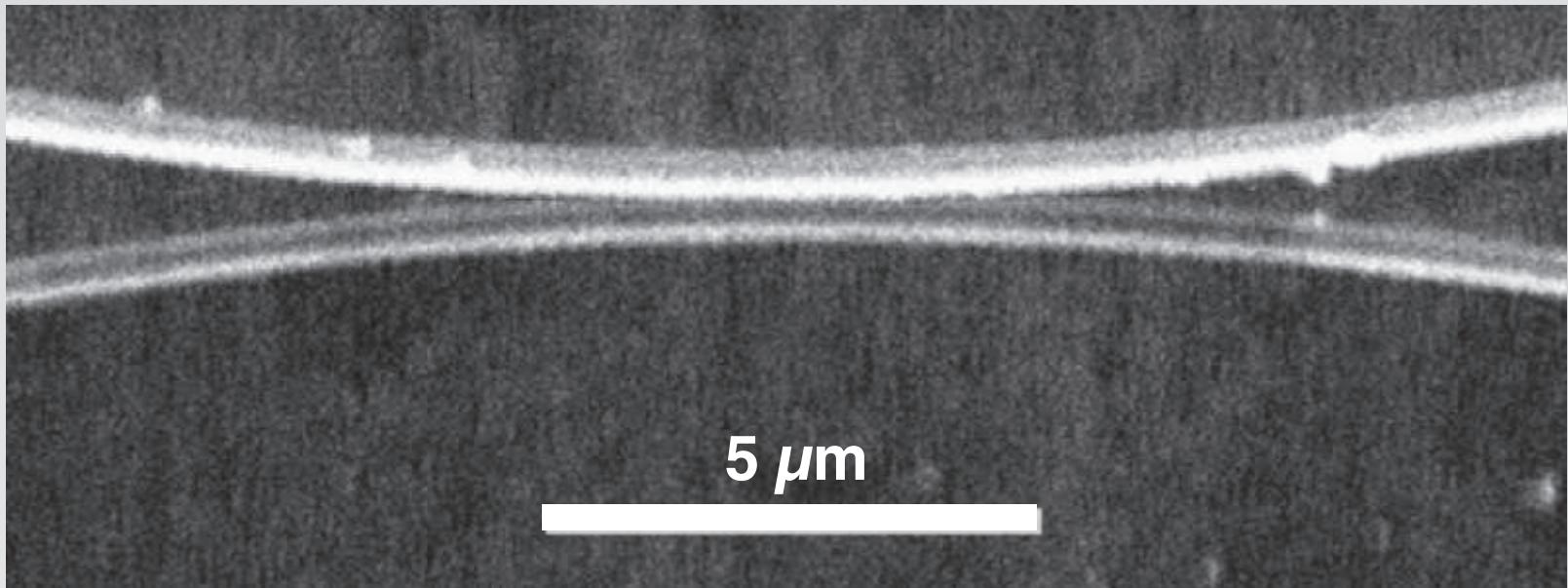
420 nm

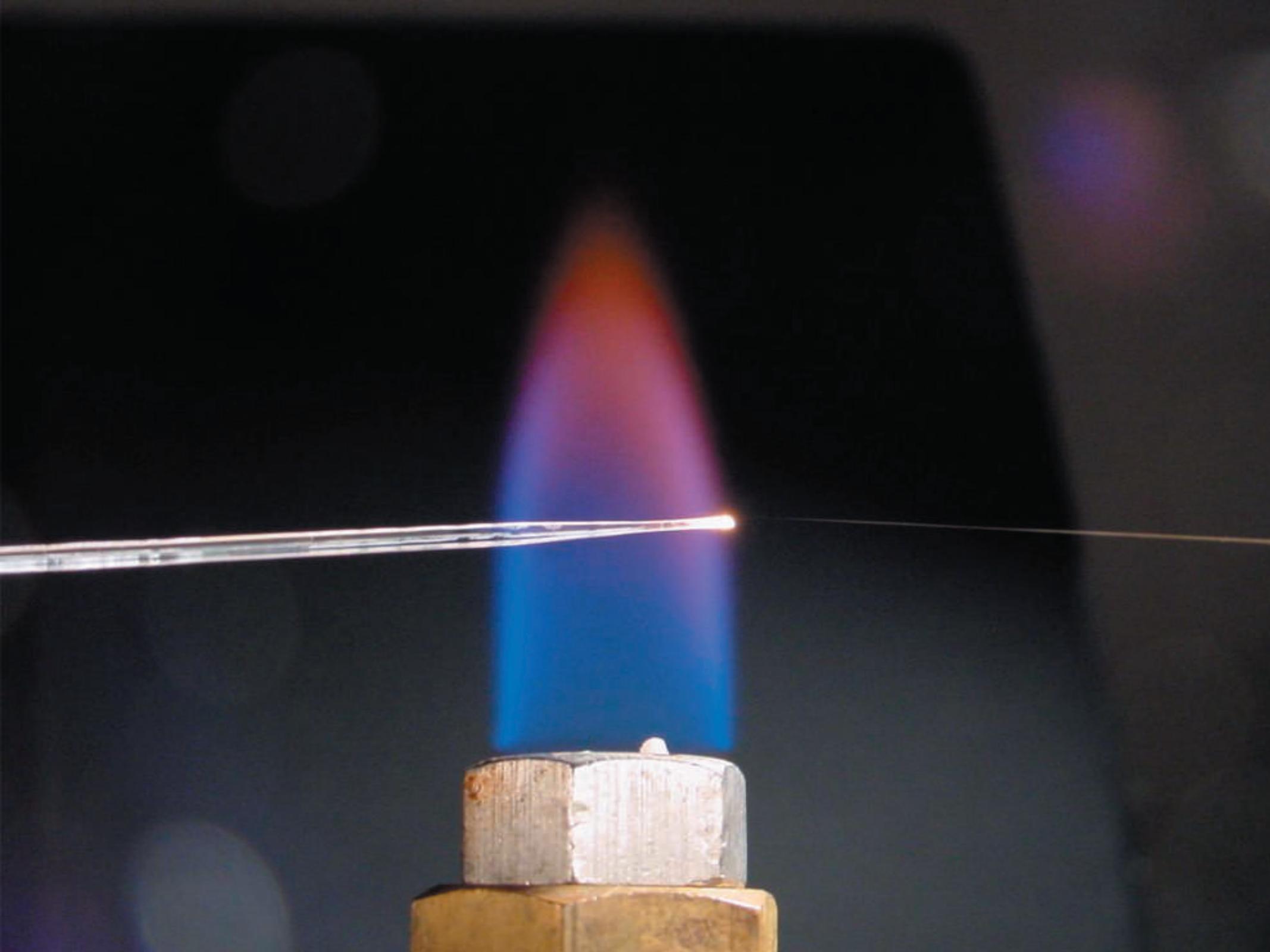
aerogel

# Outlook



# Outlook









**Funding:**

**Harvard Center for Imaging and Mesoscopic Structures**

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