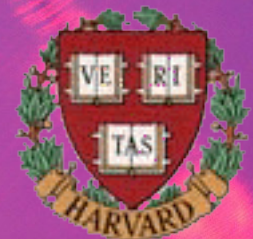


An introduction to femtosecond laser techniques: Part 2



XIII Escola de Verão Jorge André Swieca
de Ótica Quântica e Ótica Não Linear
São Carlos, SP, Brazil, 24 January 2012



Outline

- propagation of pulses
- nonlinear optics
- nanoscale optics
- nonlinear optics at the nanoscale

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- nonlinear optics
- **nanoscale optics**
- nonlinear optics at the nanoscale



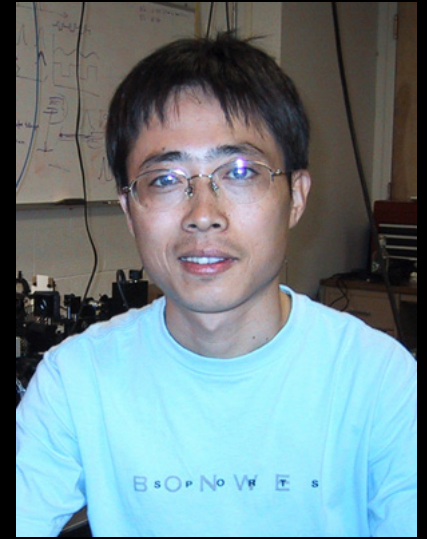
Geoff Svacha



Rafael Gattass



Tobias Voss



Limin Tong

and also....

Chris Evans

Jonathan Aschom

Mengyan Shen

Iva Maxwell

James Carey

Brian Tull

Dr. Yuan Lu

Dr. Richard Schalek

Prof. Federico Capasso

Prof. Cynthia Friend

Prof. Markus Pollnau (Twente)

Xuwen Chen (Zhejiang)

Zhanghua Han (Zhejiang)

Dr. Sailing He (Zhejiang)

Liu Liu (Zhejiang)

Dr. Jingyi Lou (Zhejiang)

Dr. Ray Mariella (LLNL)

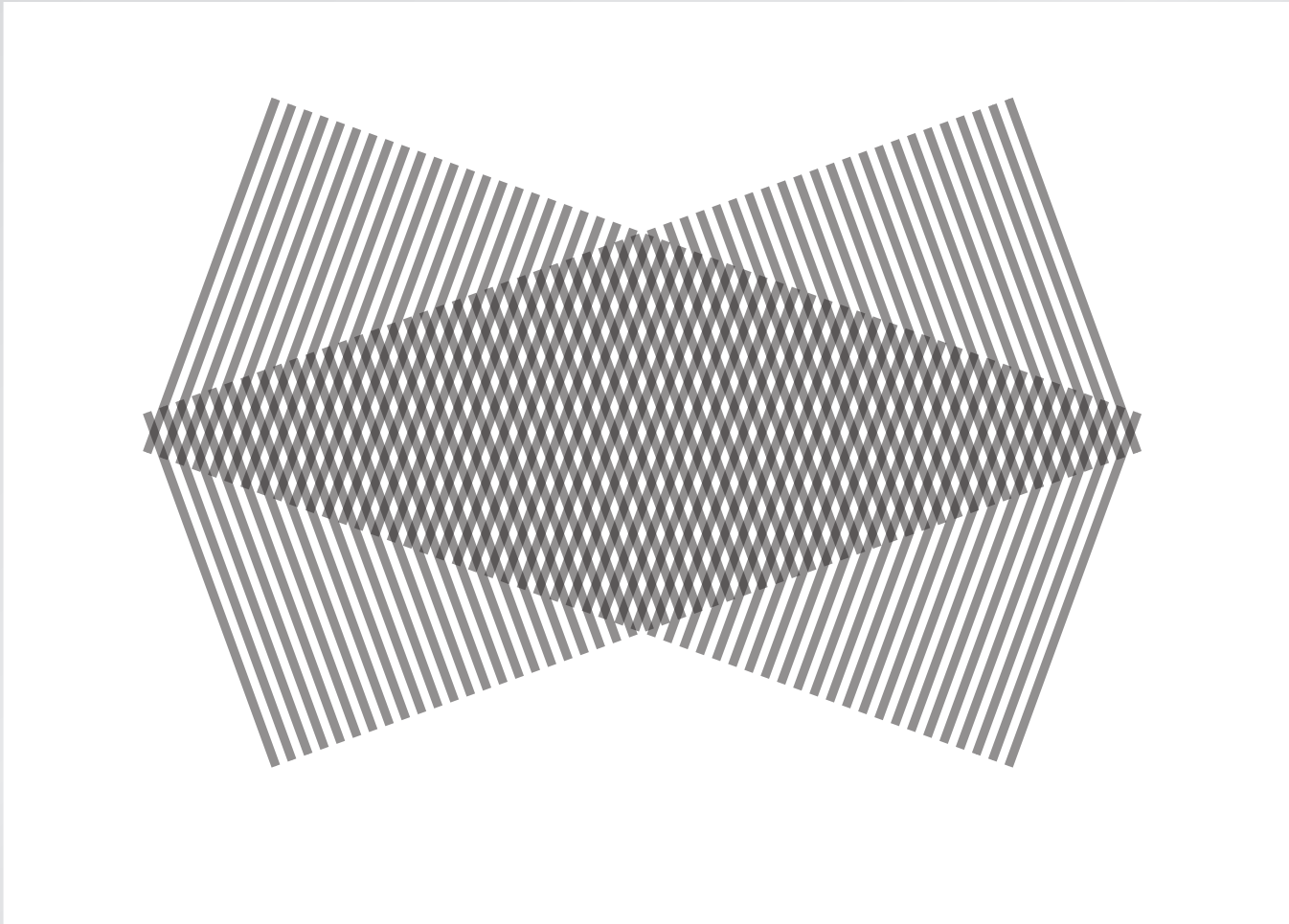
Prof. Frank Marlow (MPI Mülheim)

Prof. Sven Müller (Göttingen)

Prof. Carsten Ronning (Göttingen)

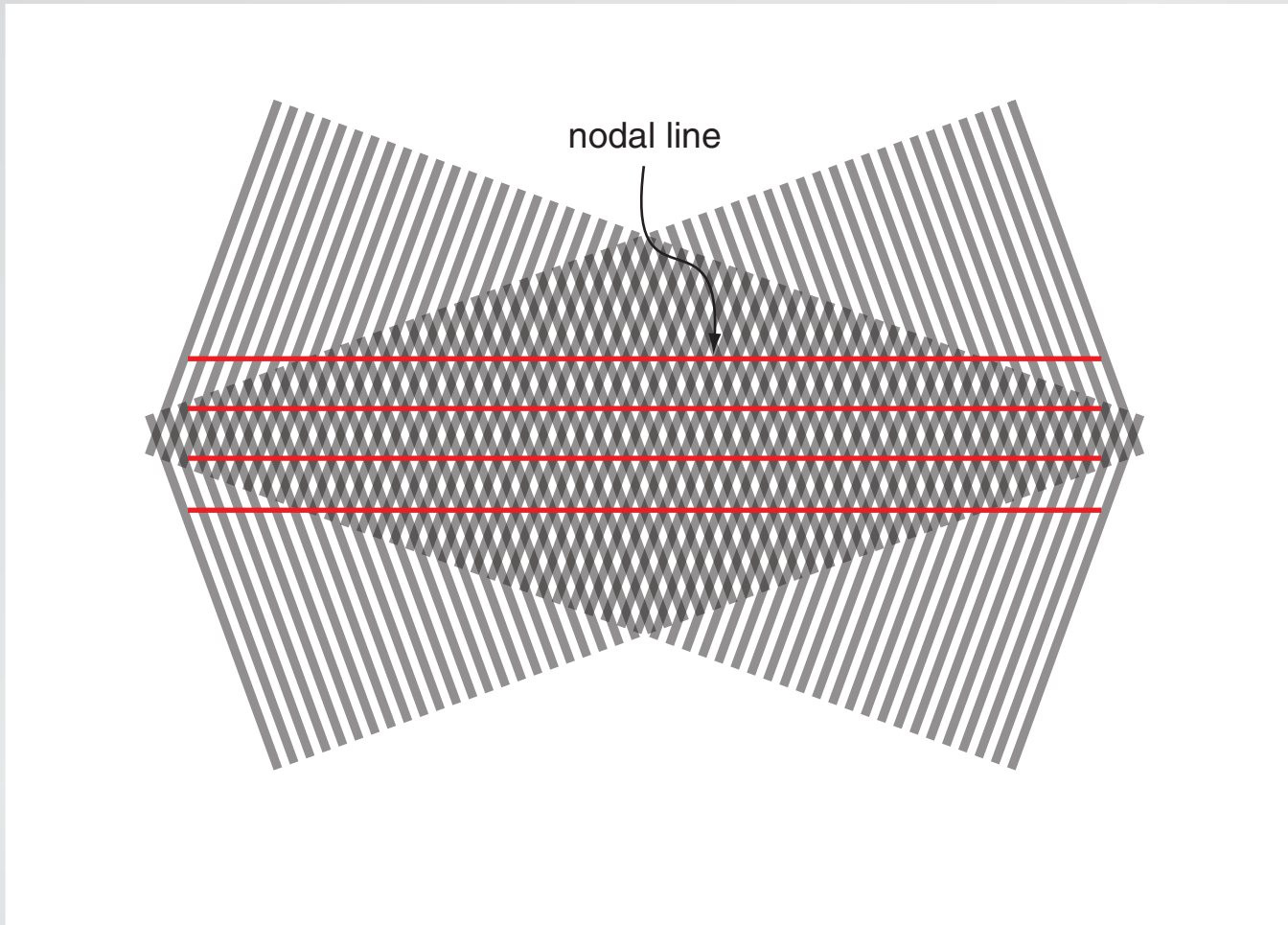
Waveguiding

two crossed planar waves...



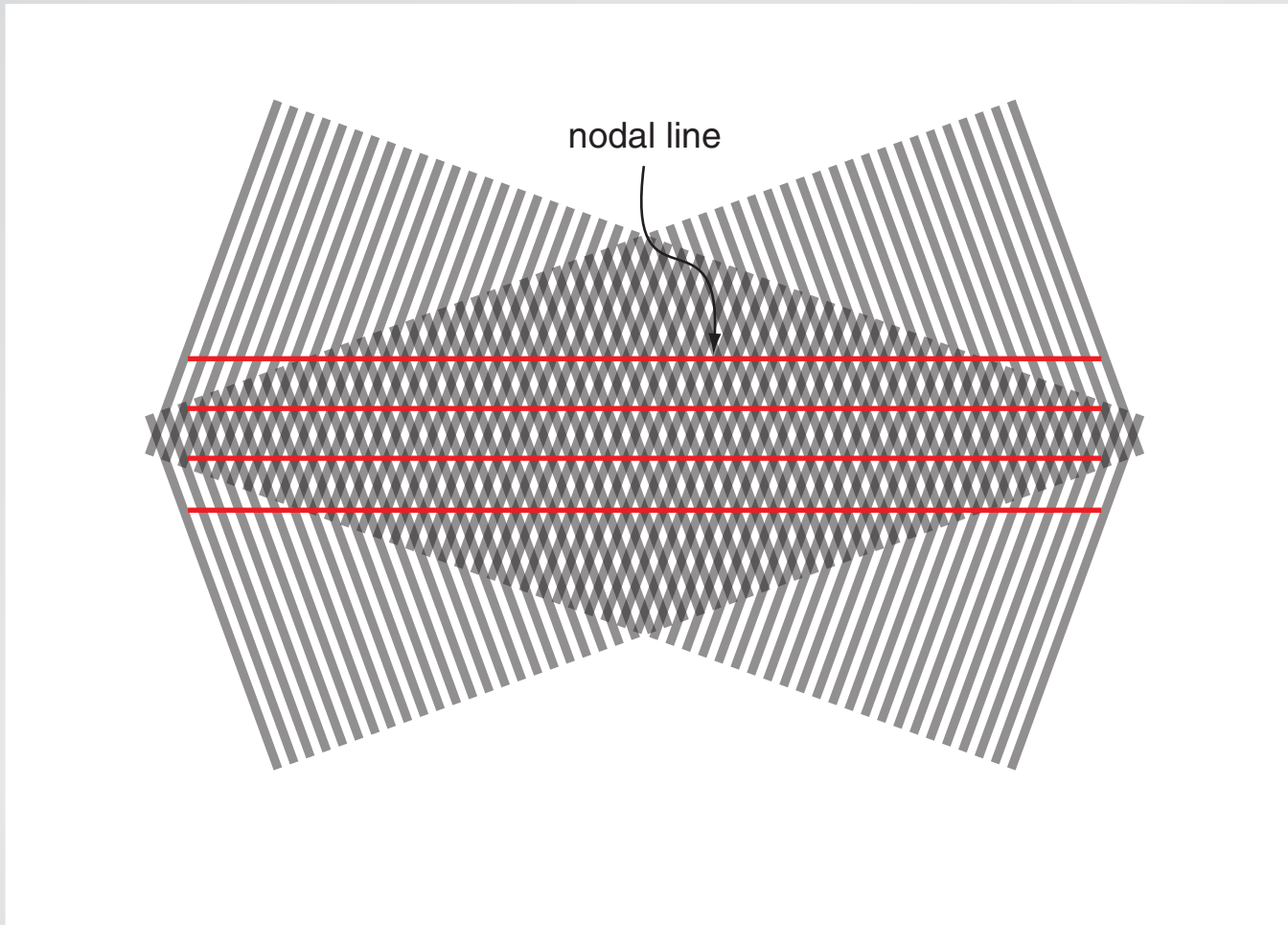
Waveguiding

...cause an interference pattern



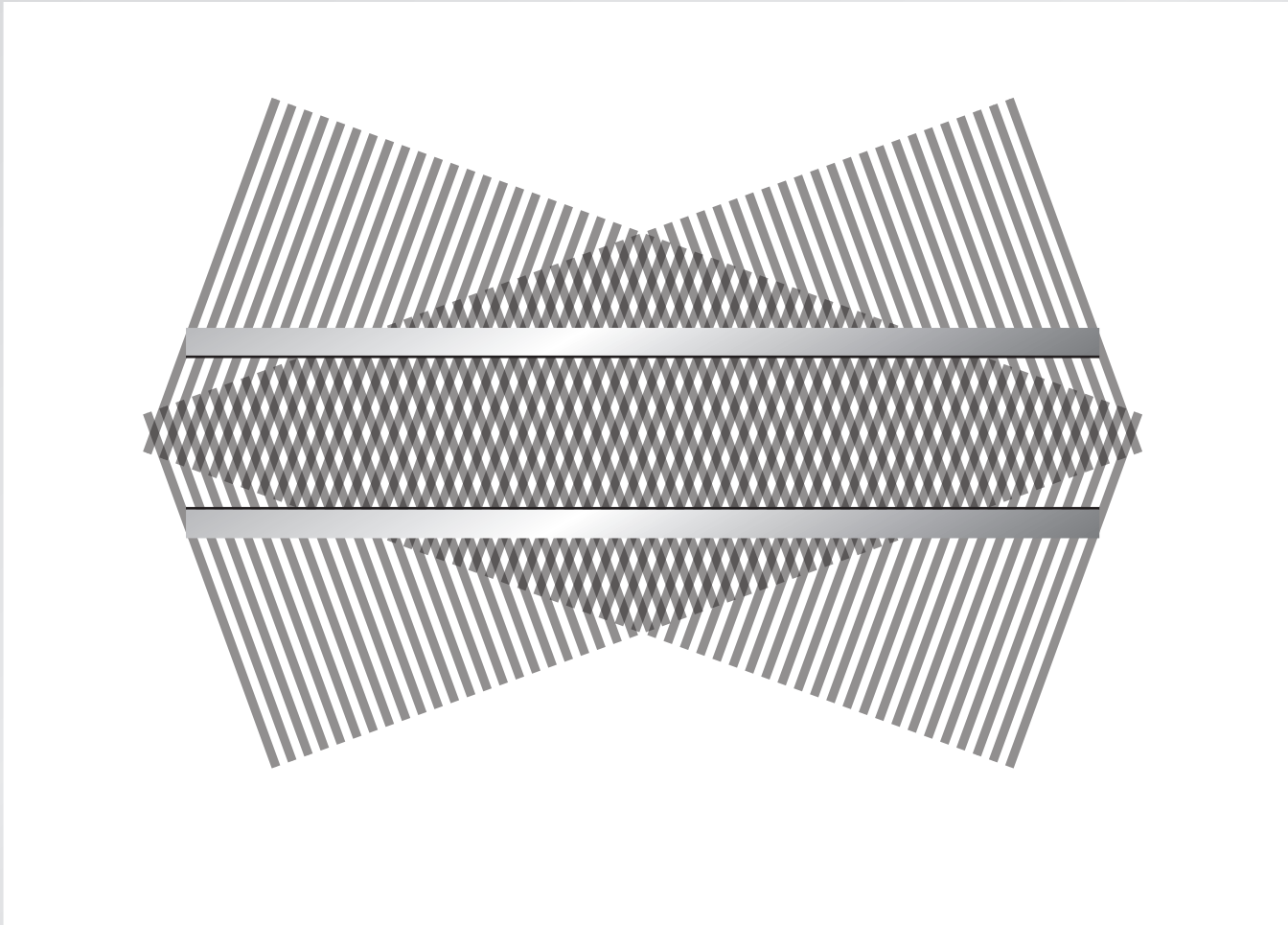
Waveguiding

$E = 0$ on the nodal lines



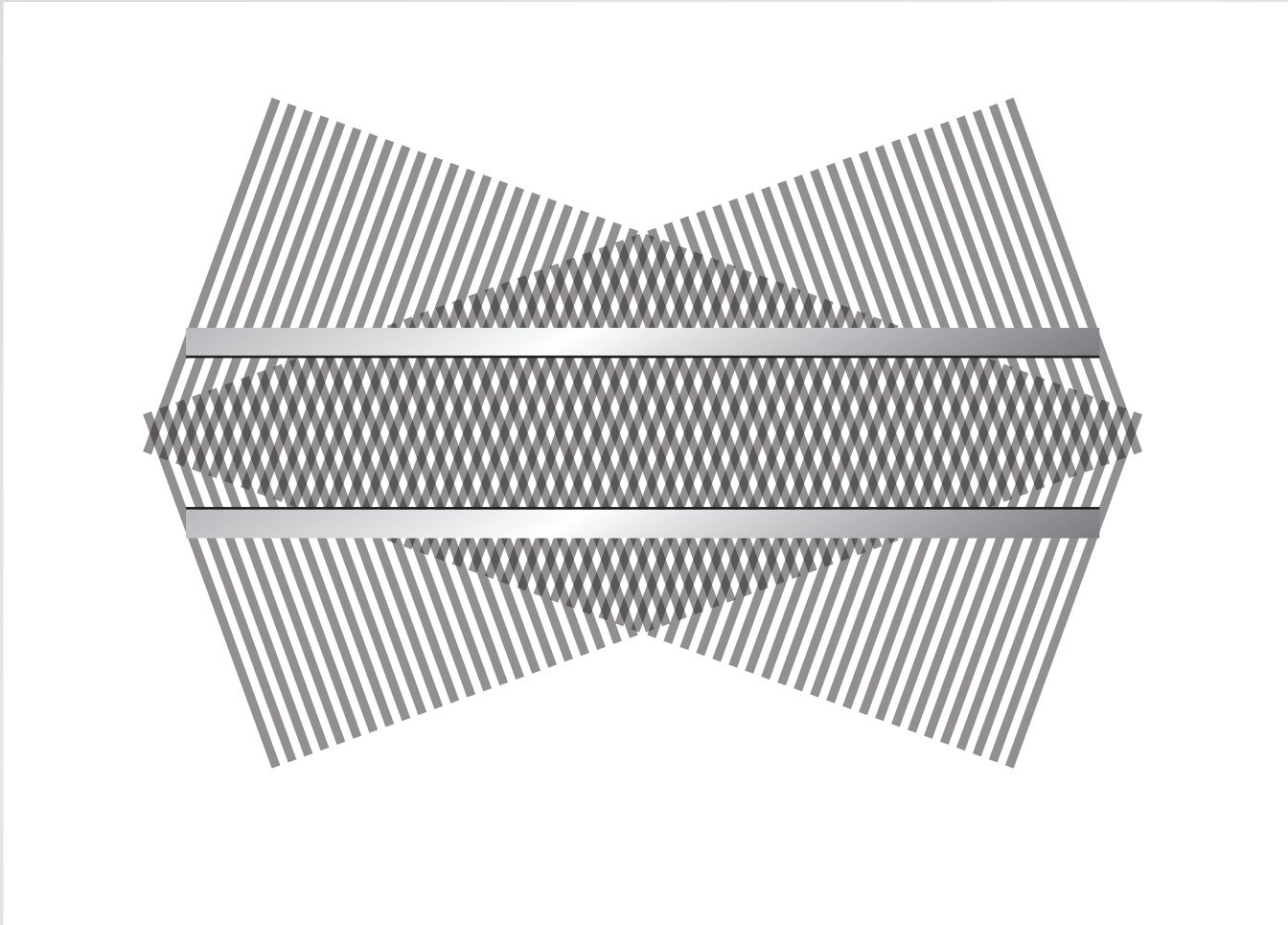
Waveguiding

...satisfying boundary conditions for planar-mirror waveguide



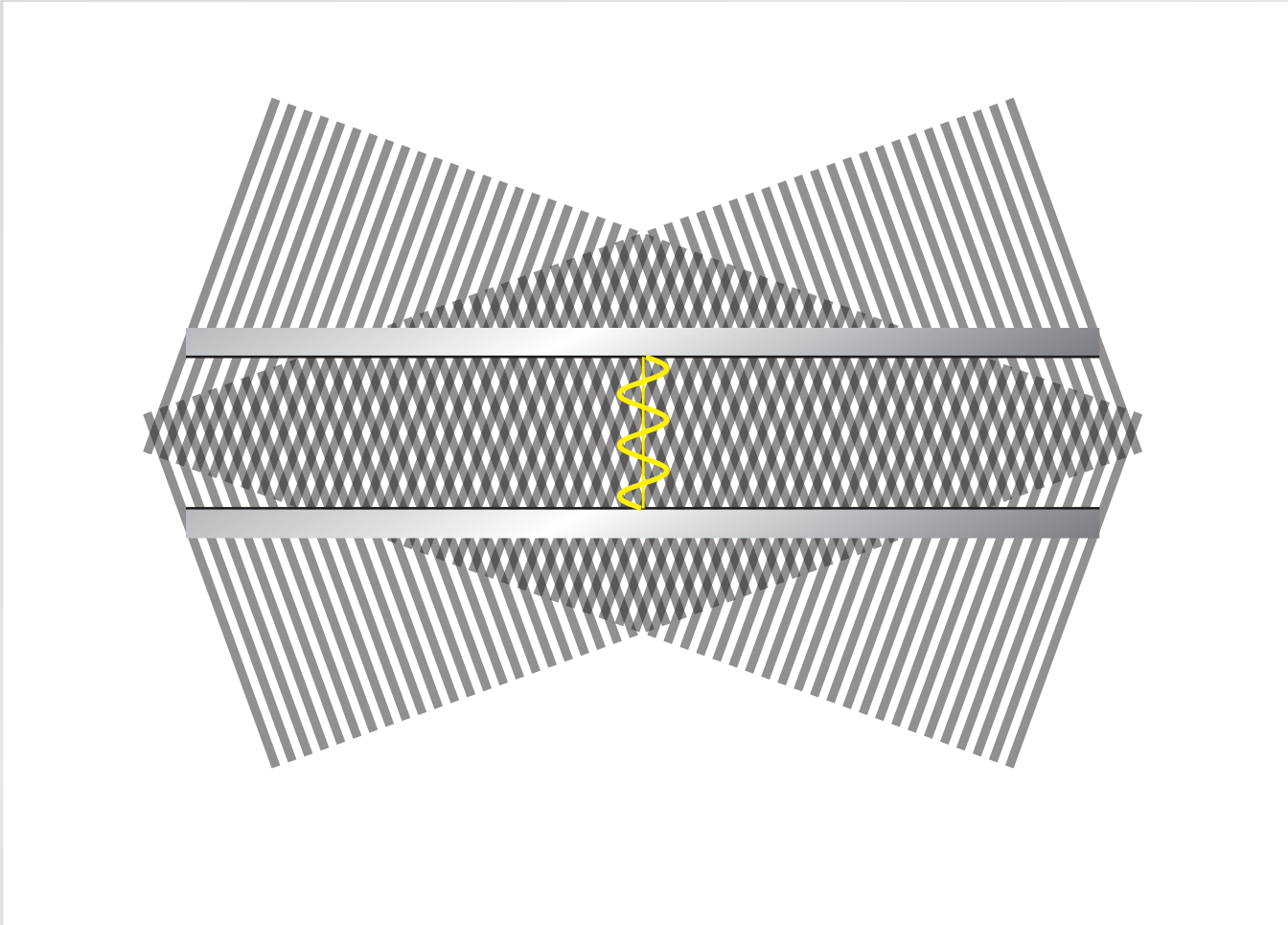
Waveguiding

transverse standing wave, traveling along axis



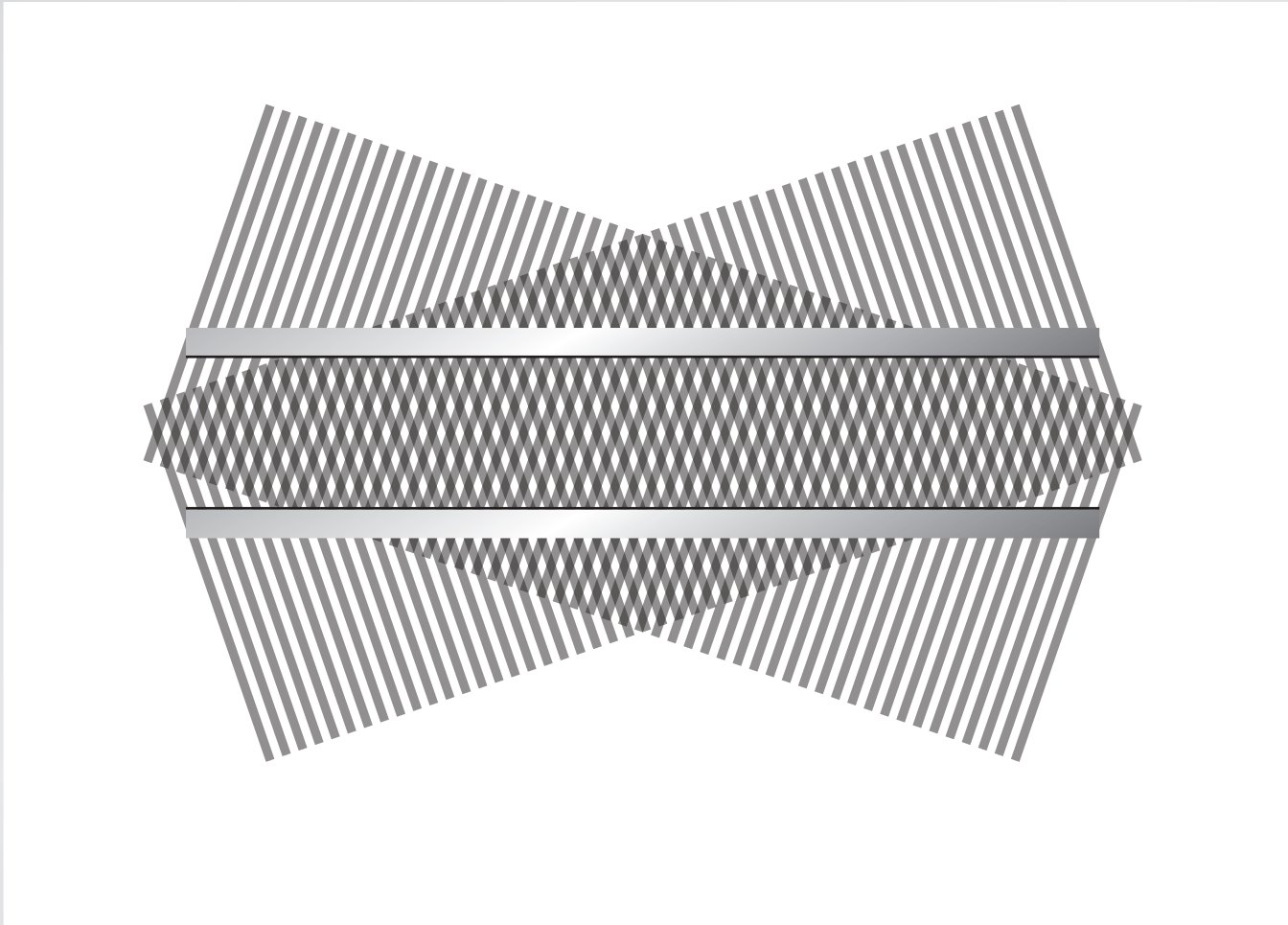
Waveguiding

transverse standing wave, traveling along axis



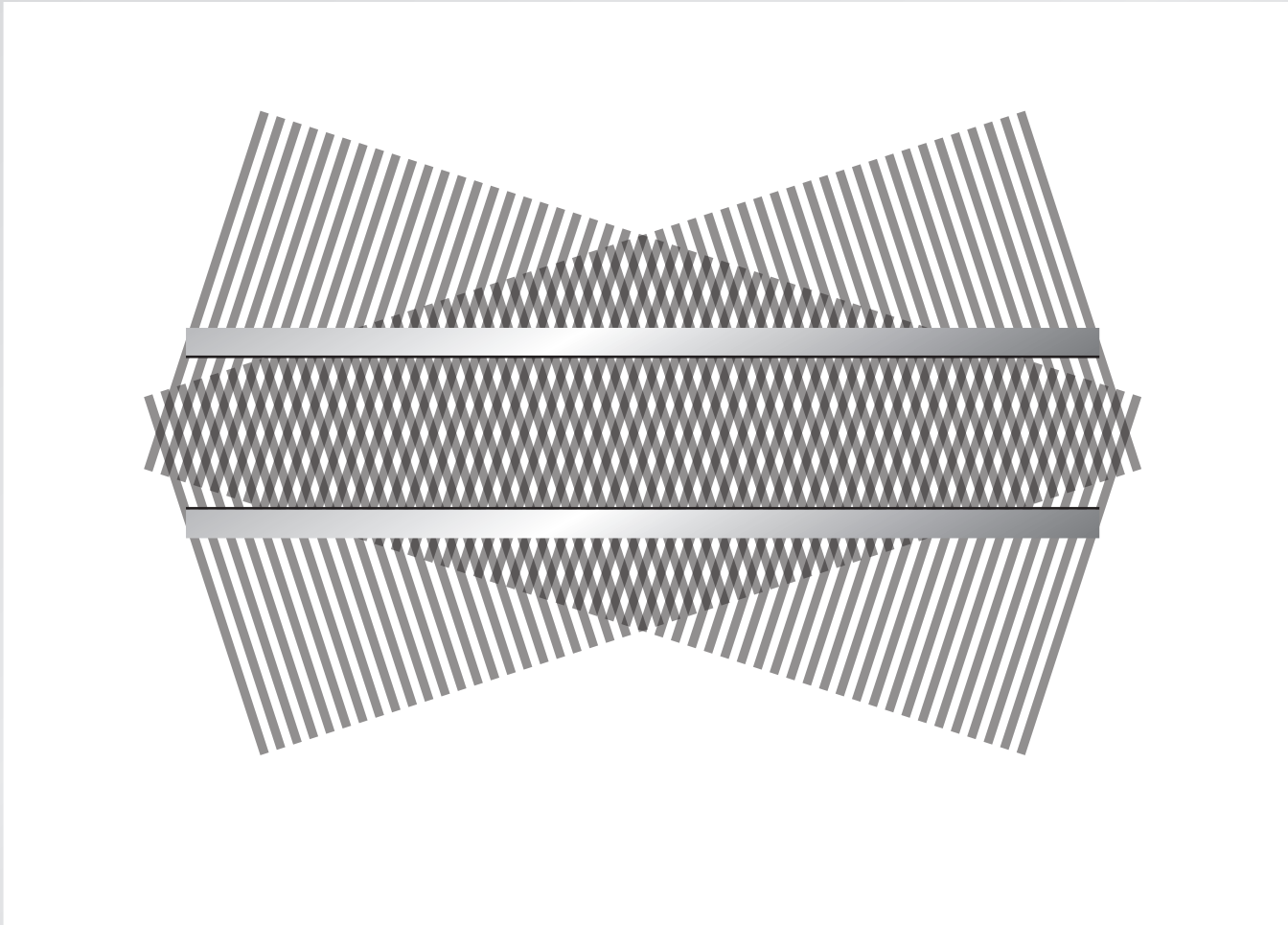
Waveguiding

change angle of incident waves...



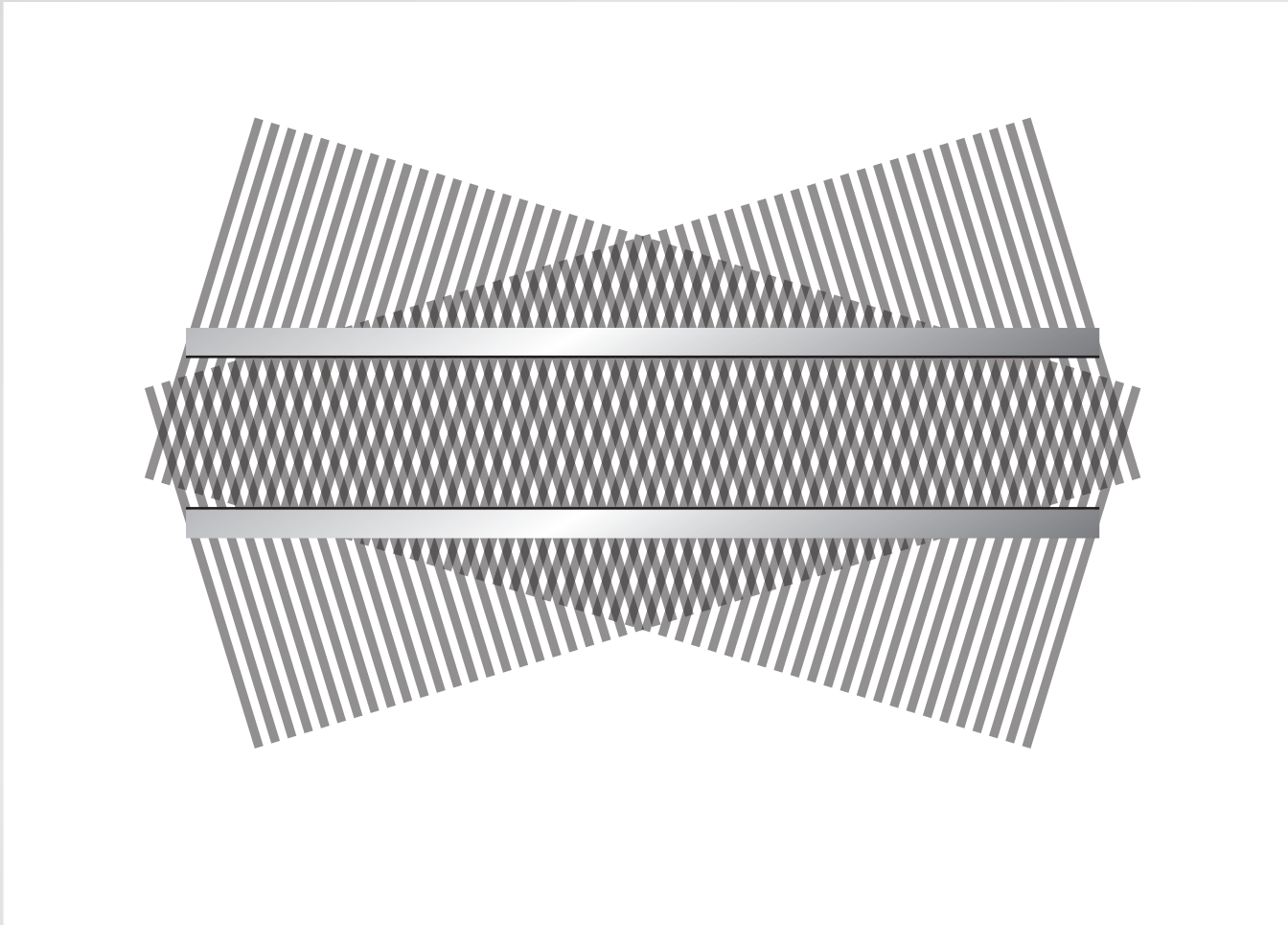
Waveguiding

change angle of incident waves...



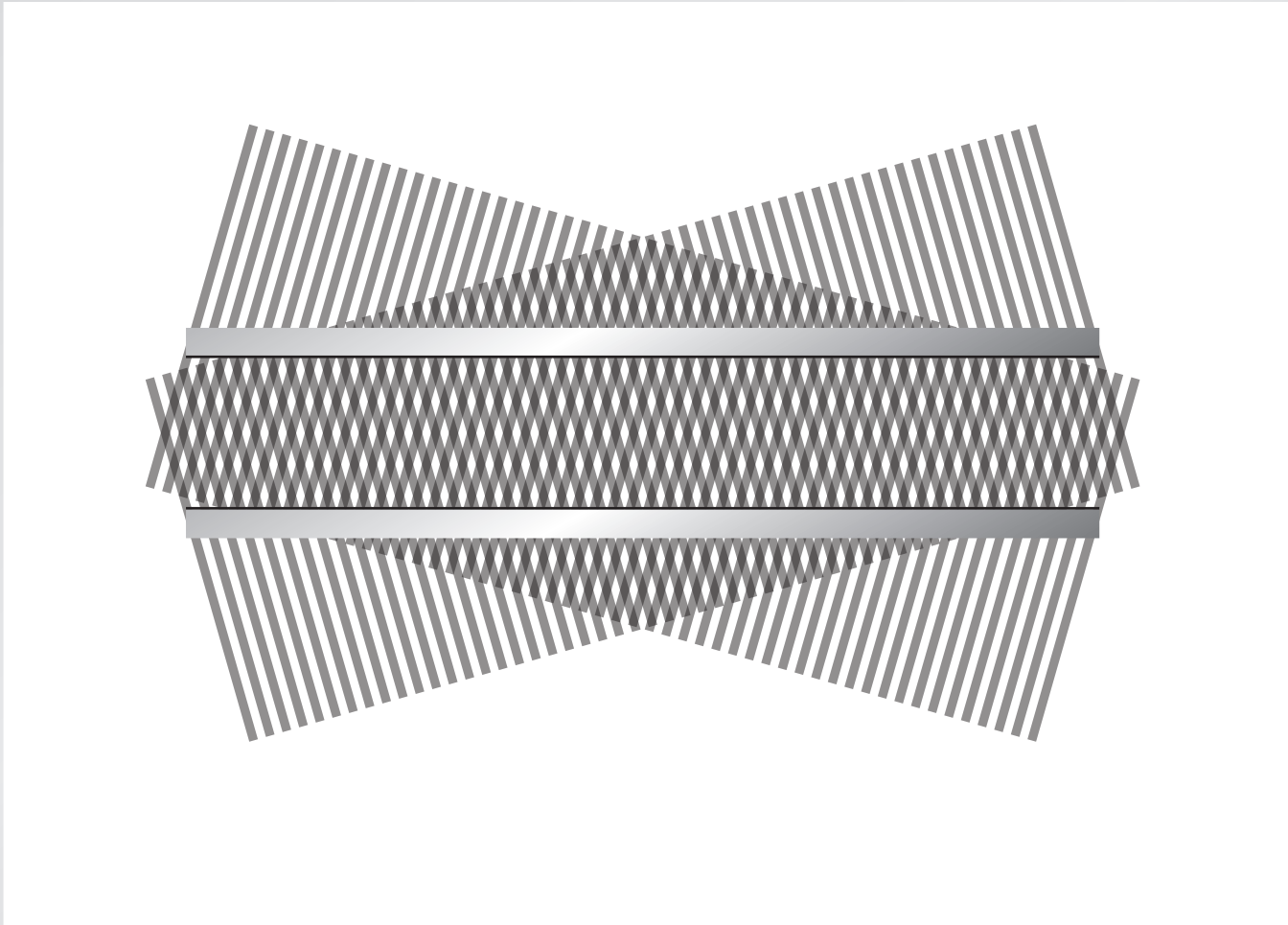
Waveguiding

change angle of incident waves...



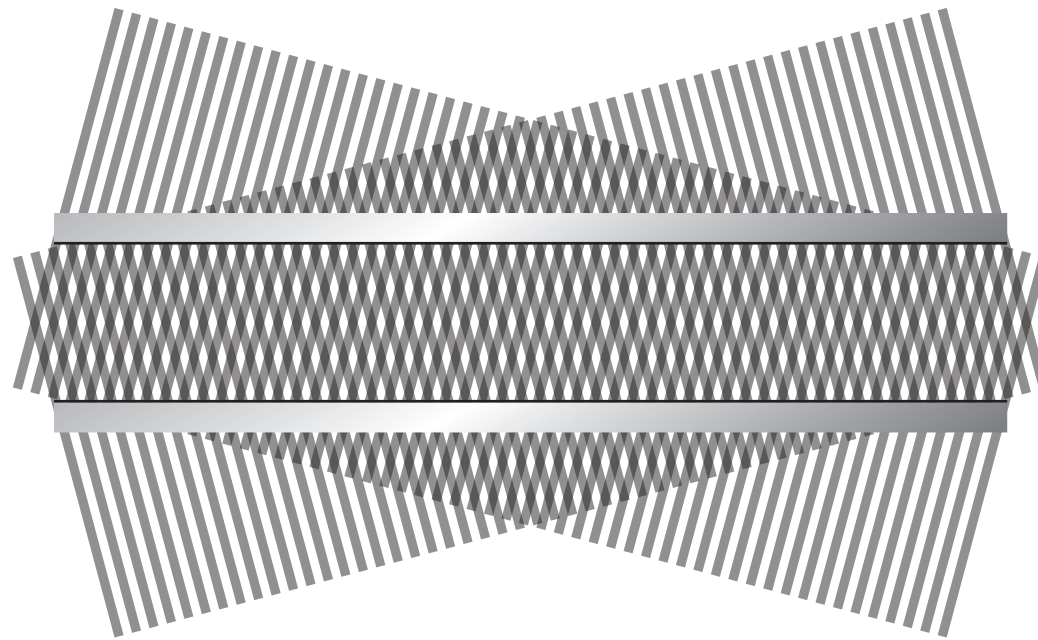
Waveguiding

change angle of incident waves...



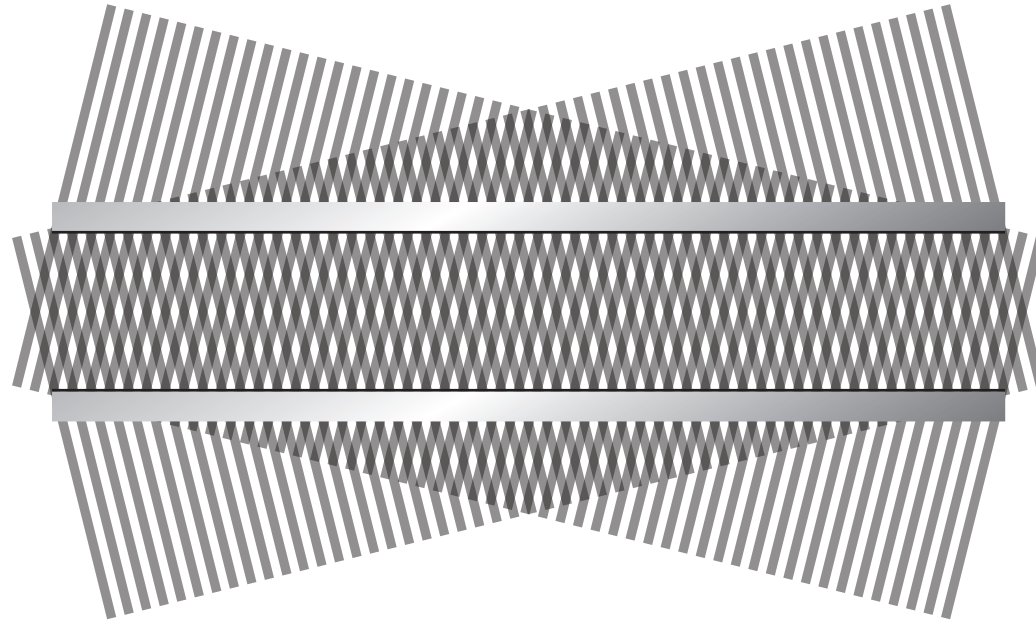
Waveguiding

change angle of incident waves...



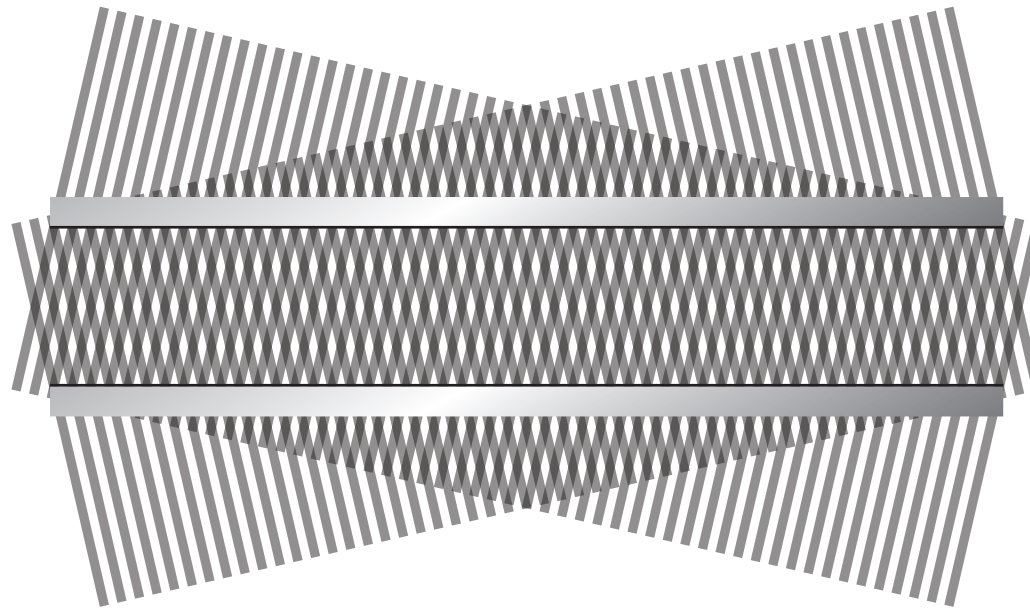
Waveguiding

change angle of incident waves...



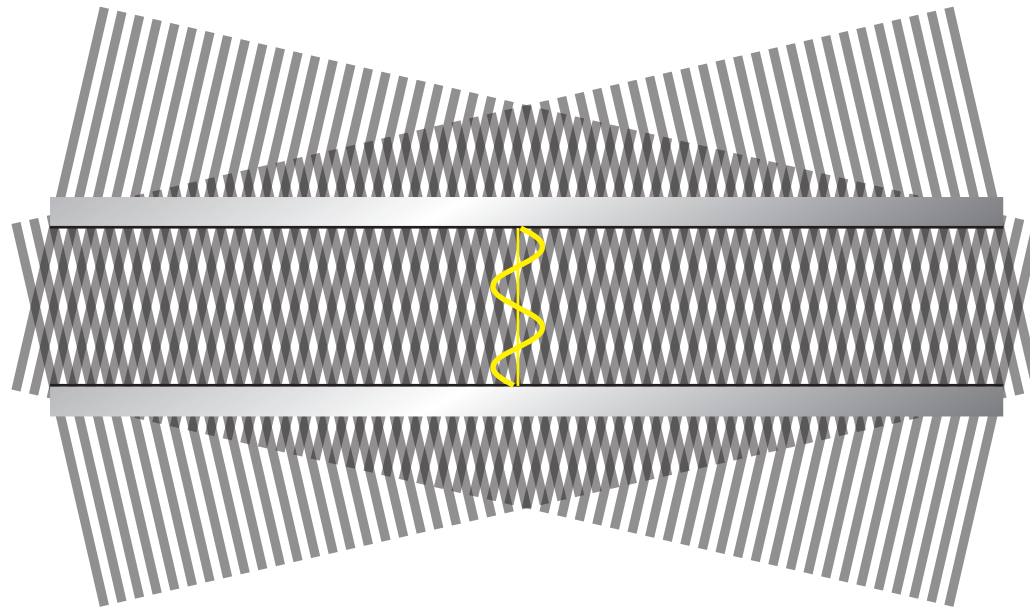
Waveguiding

change angle of incident waves...



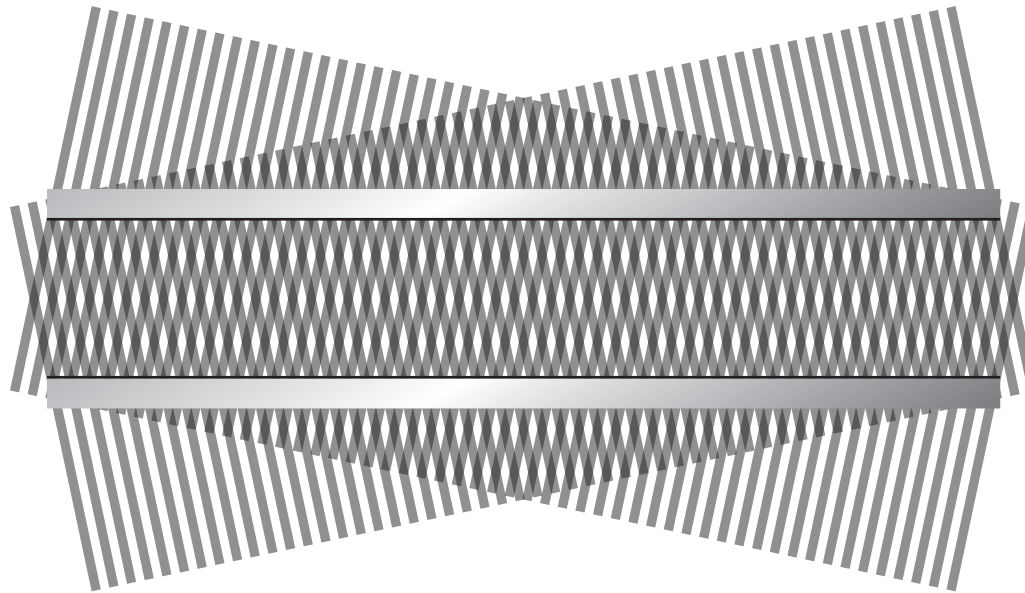
Waveguiding

change angle of incident waves...



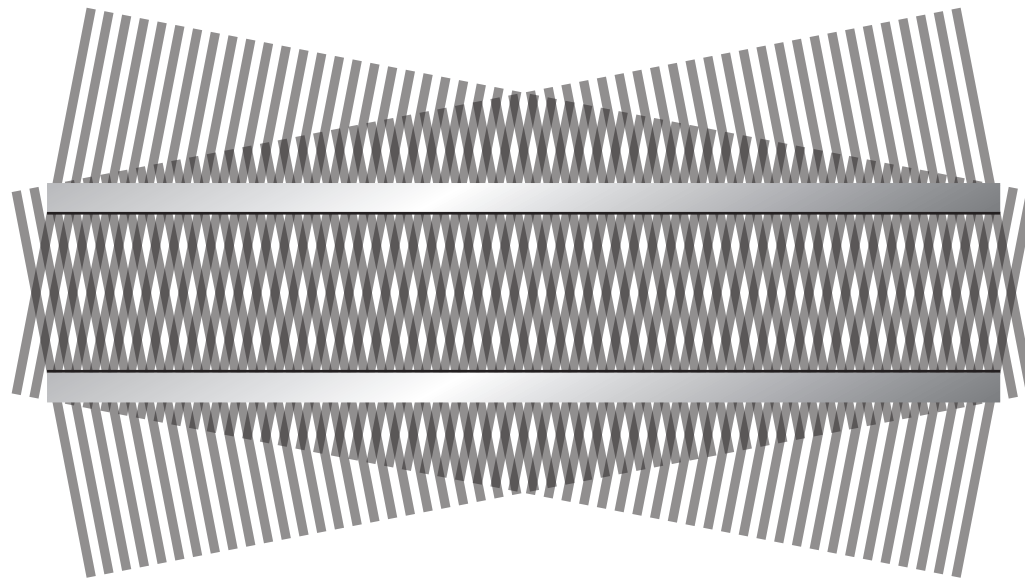
Waveguiding

change angle of incident waves...



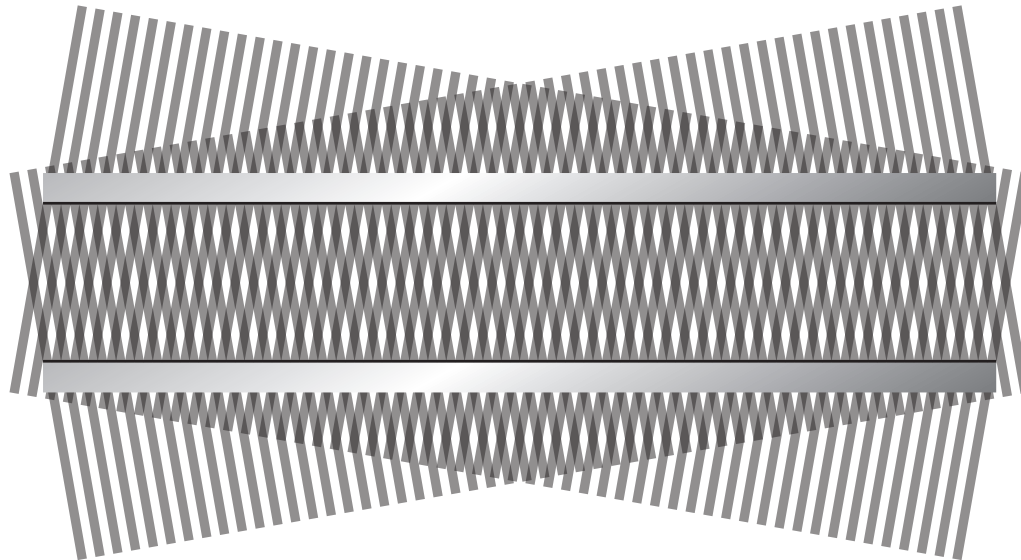
Waveguiding

change angle of incident waves...



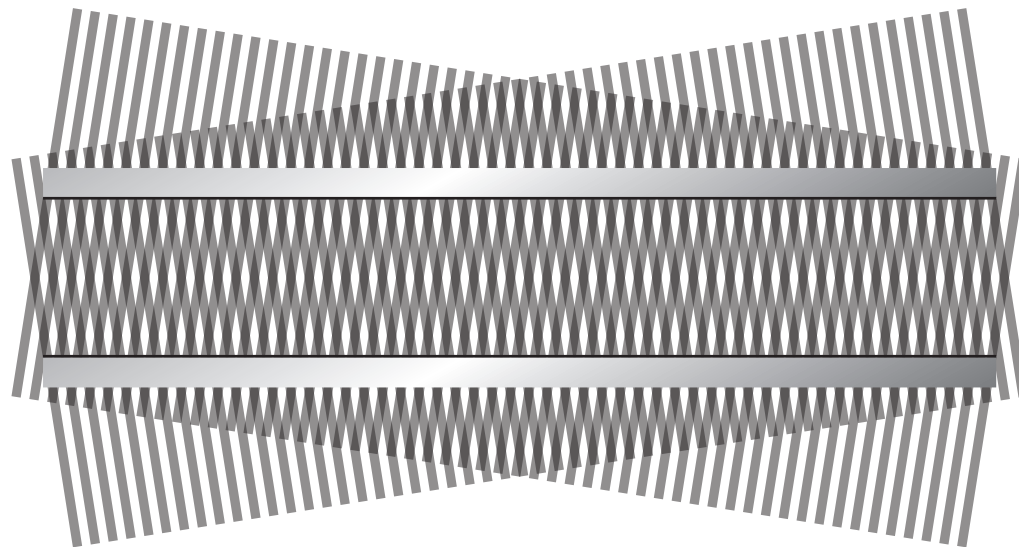
Waveguiding

change angle of incident waves...



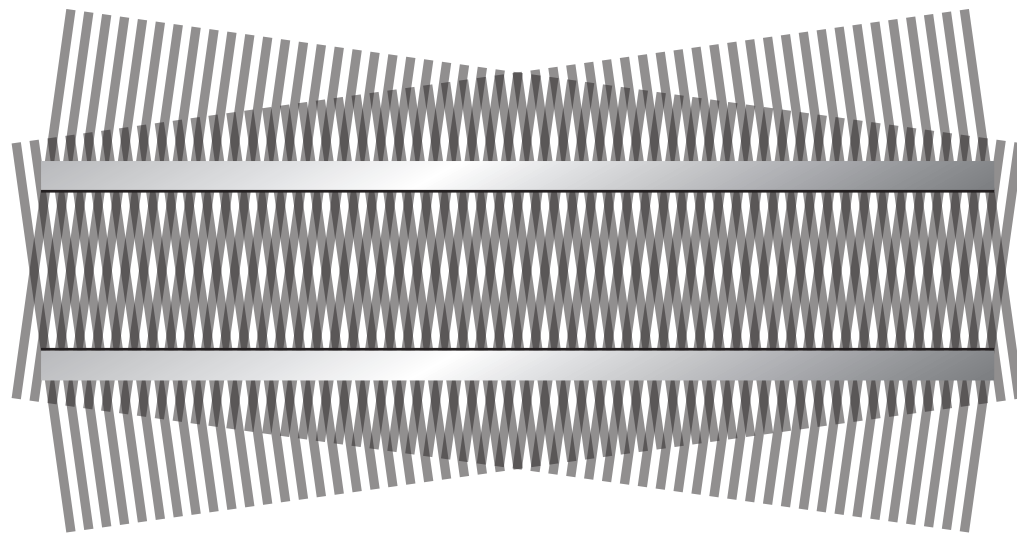
Waveguiding

change angle of incident waves...



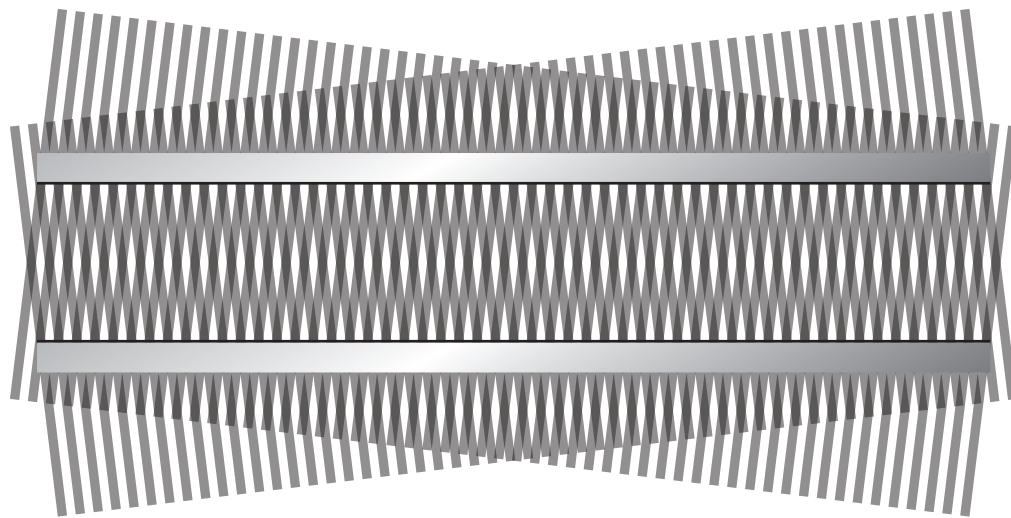
Waveguiding

change angle of incident waves...



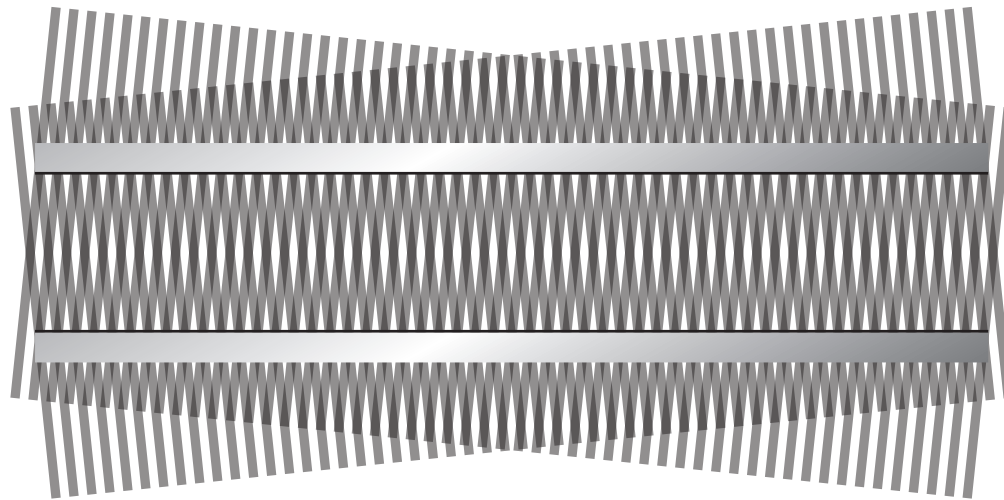
Waveguiding

change angle of incident waves...



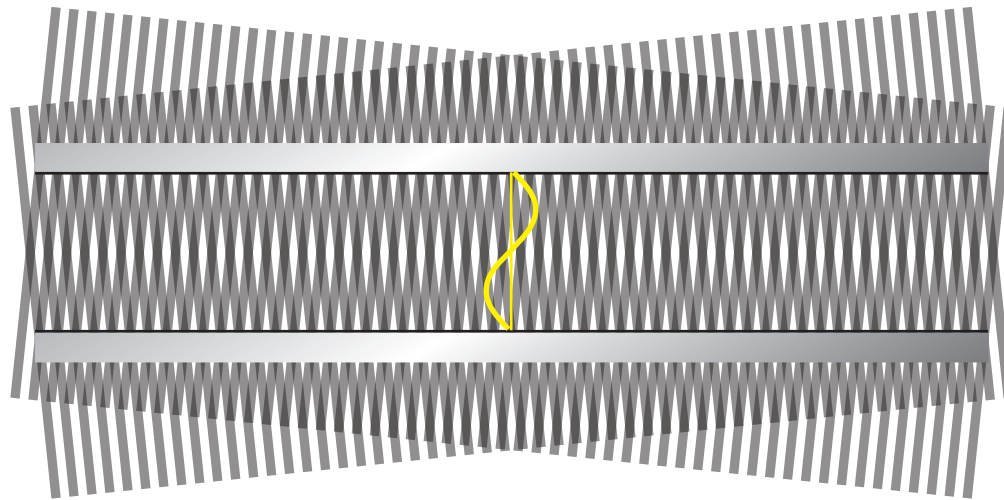
Waveguiding

change angle of incident waves...



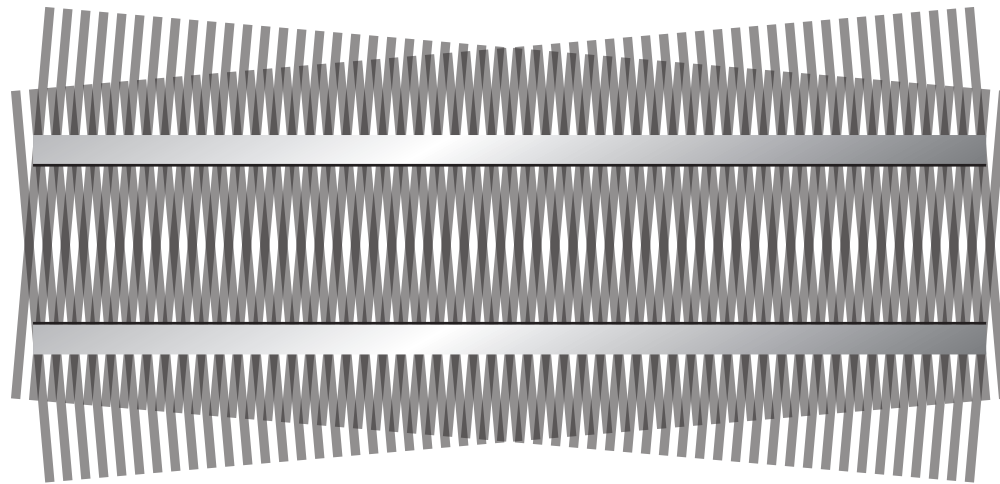
Waveguiding

change angle of incident waves...



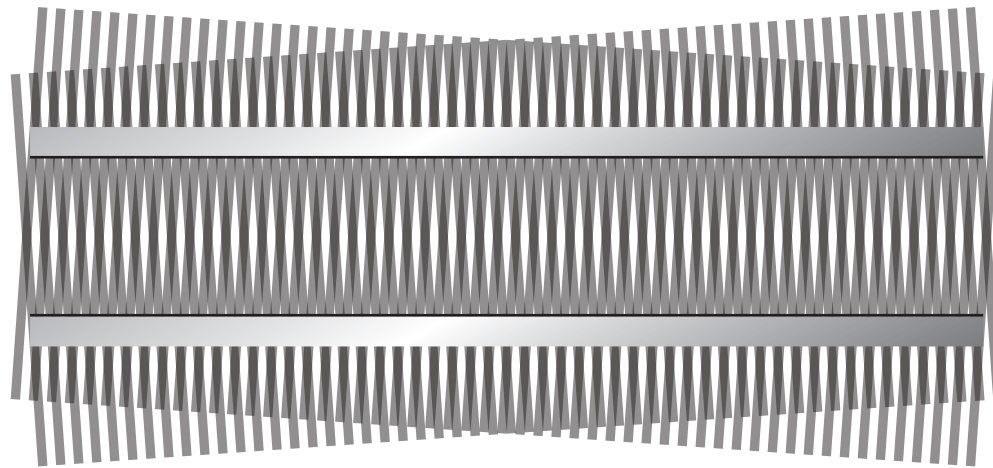
Waveguiding

change angle of incident waves...



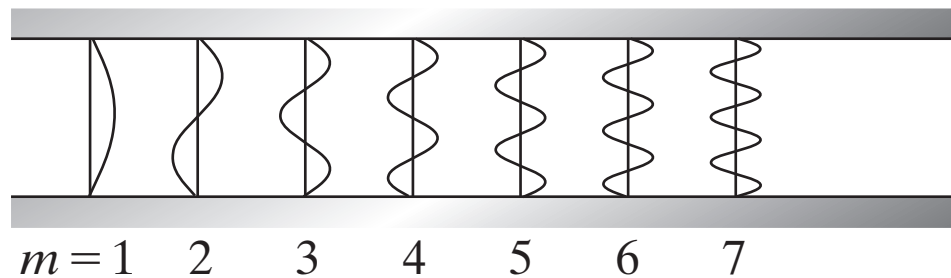
Waveguiding

change angle of incident waves...



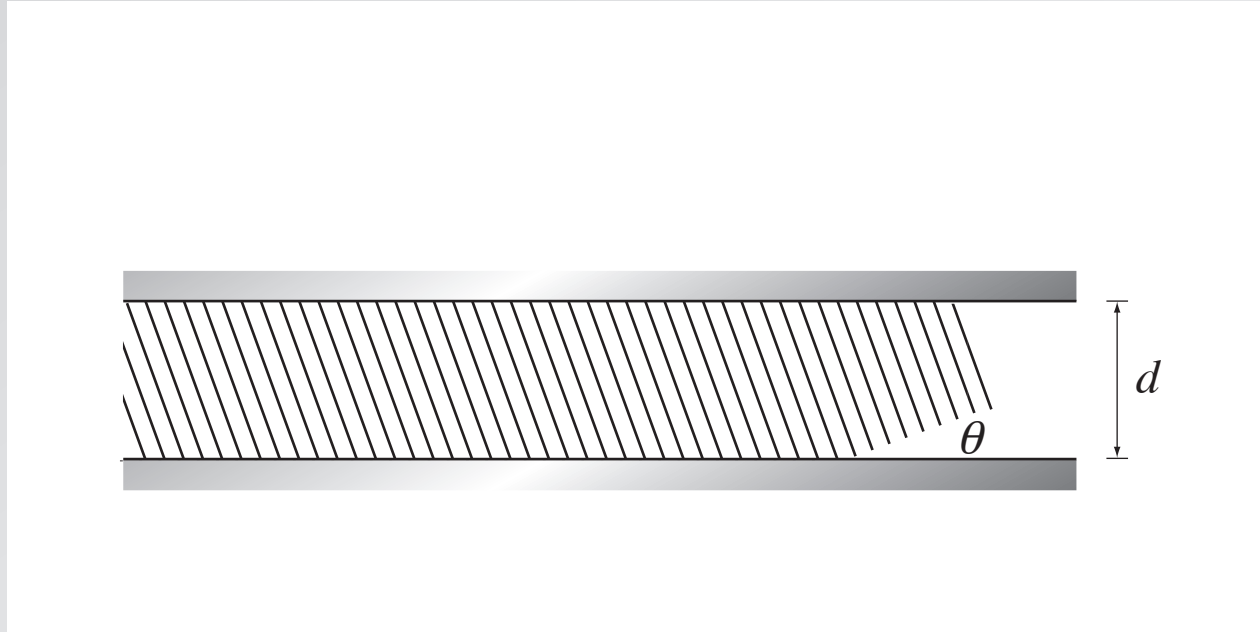
Waveguiding

boundary conditions only satisfied for certain θ



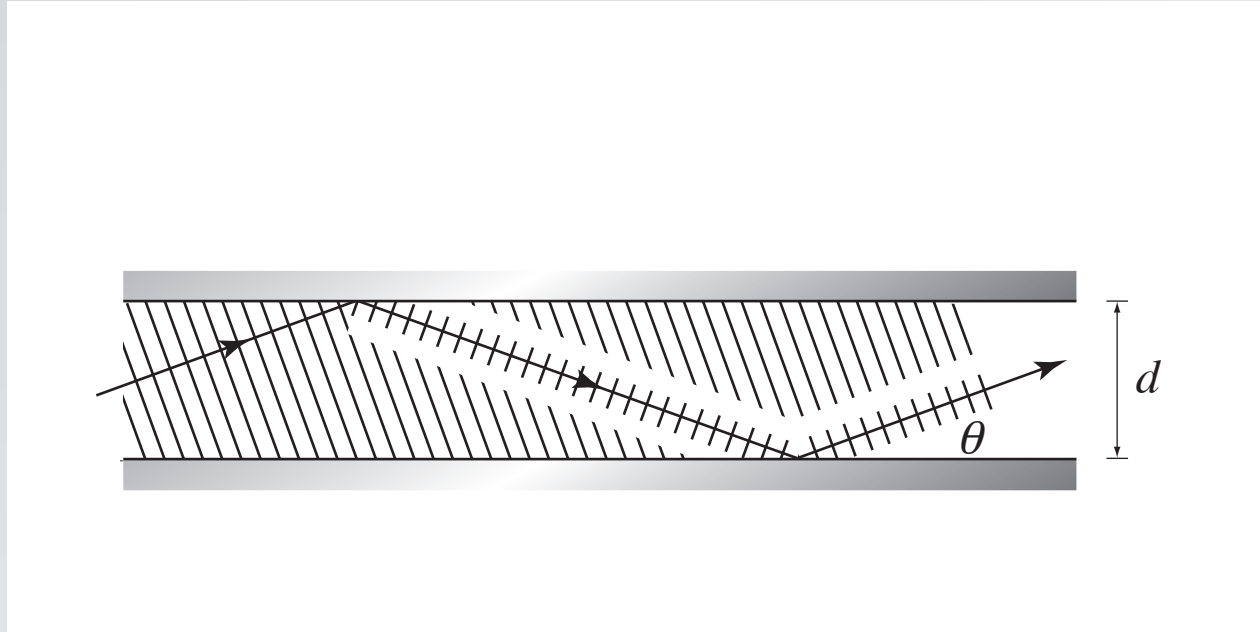
standing wave in y -direction, traveling in z -direction

Waveguiding



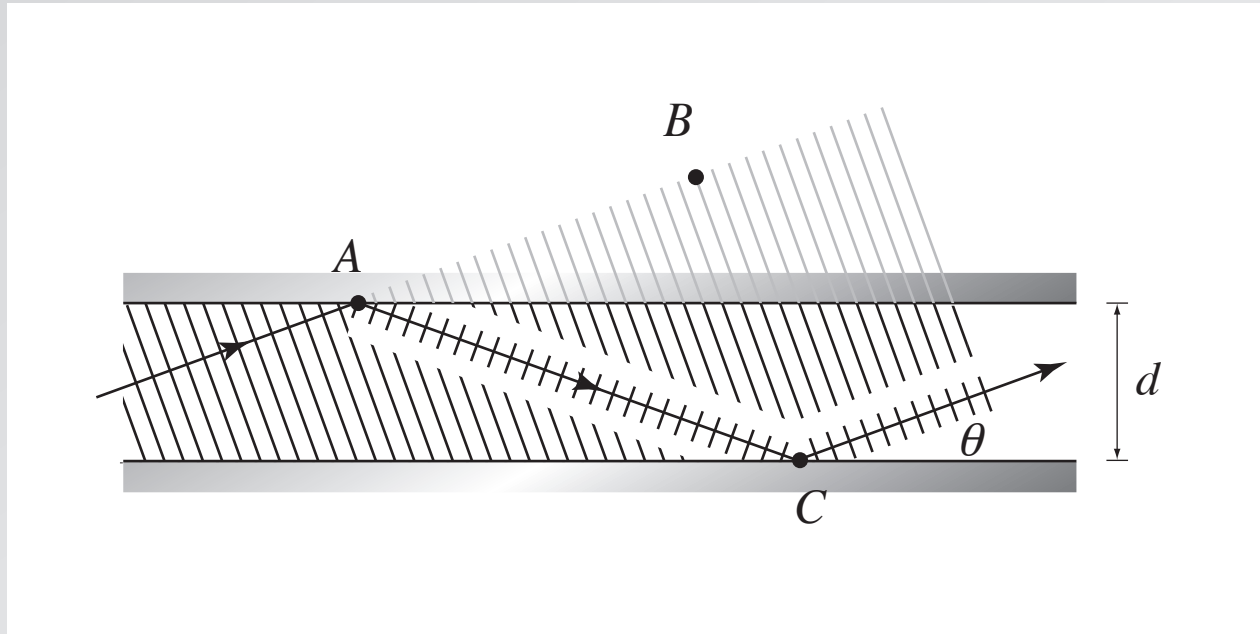
consider wave incident at angle θ

Waveguiding



twice-reflected wave

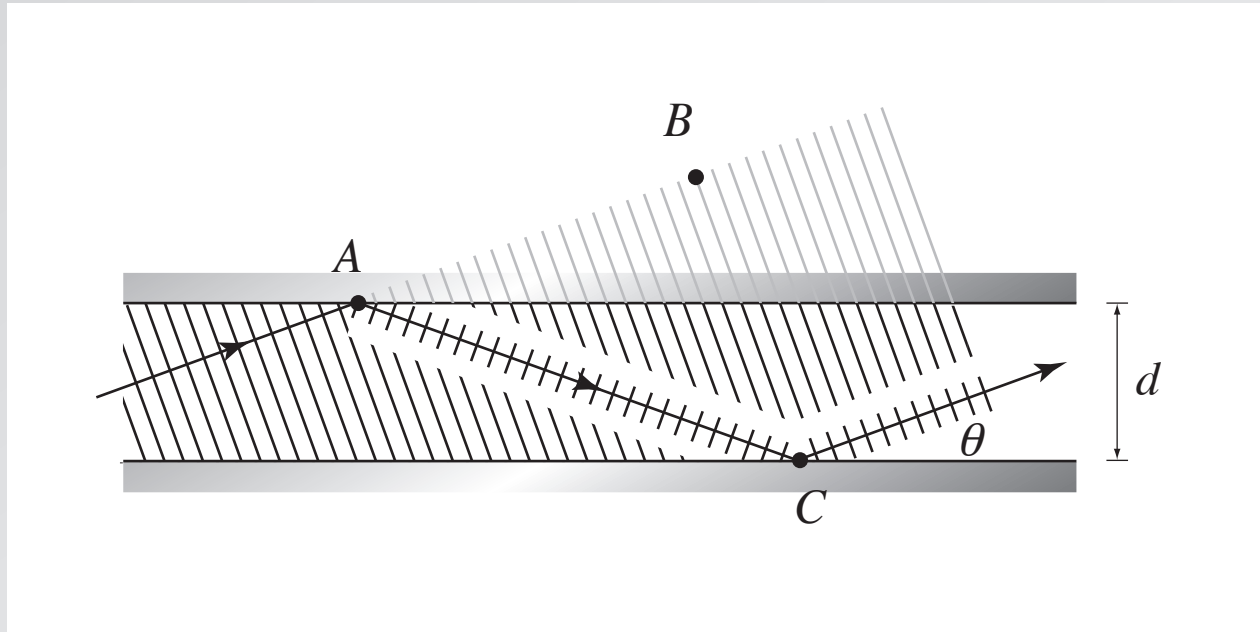
Waveguiding



self consistency:

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

Waveguiding



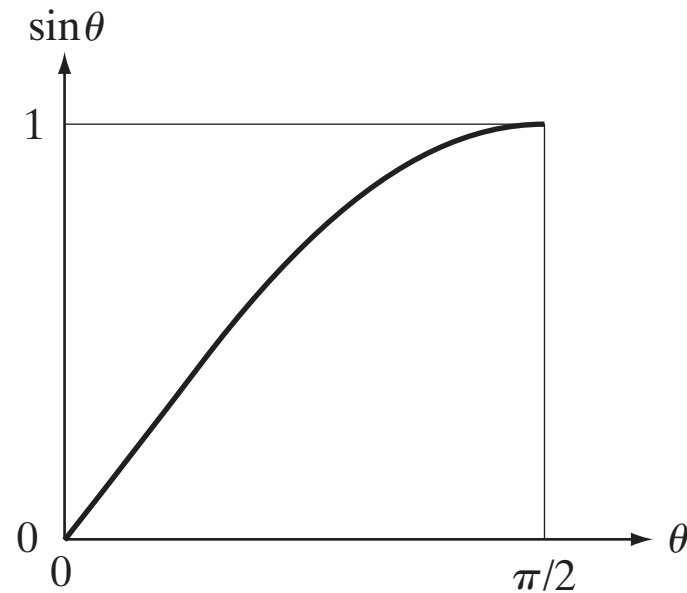
self consistency:

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

so:

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

Waveguiding



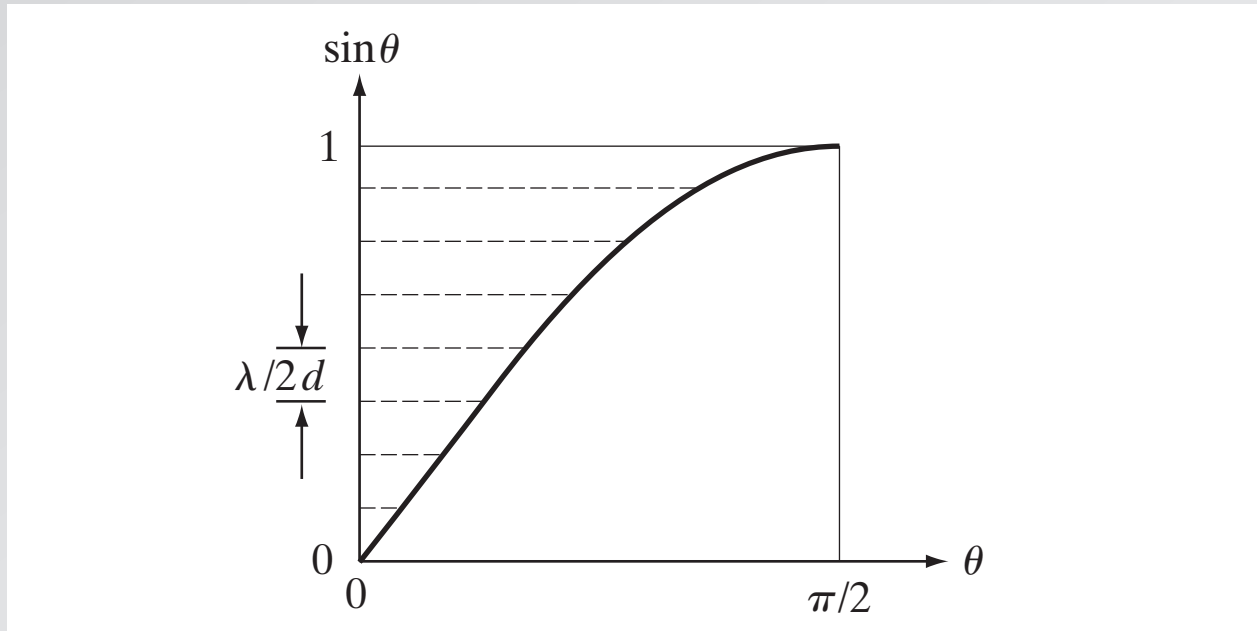
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Waveguiding



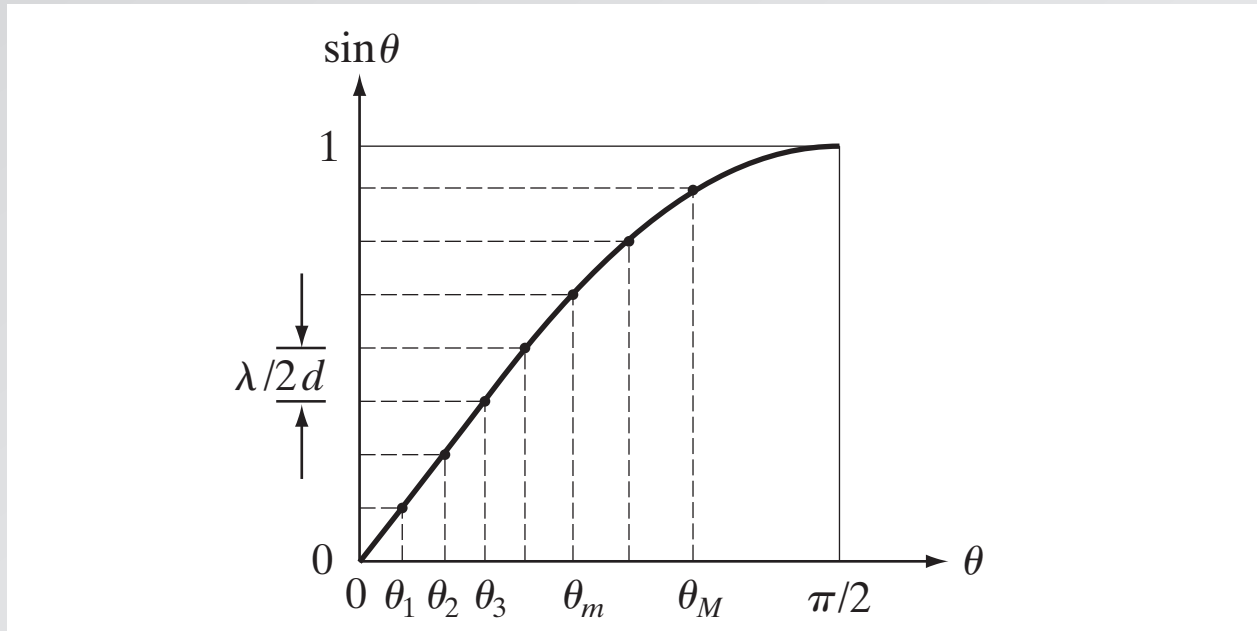
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Waveguiding



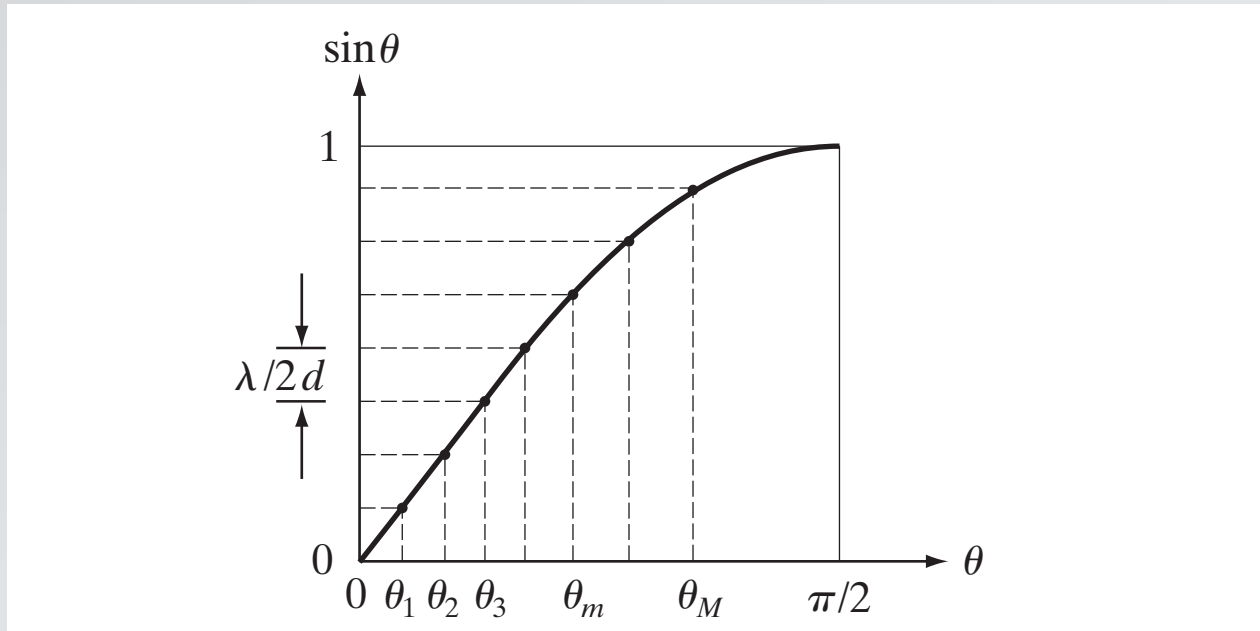
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Waveguiding



number of modes:

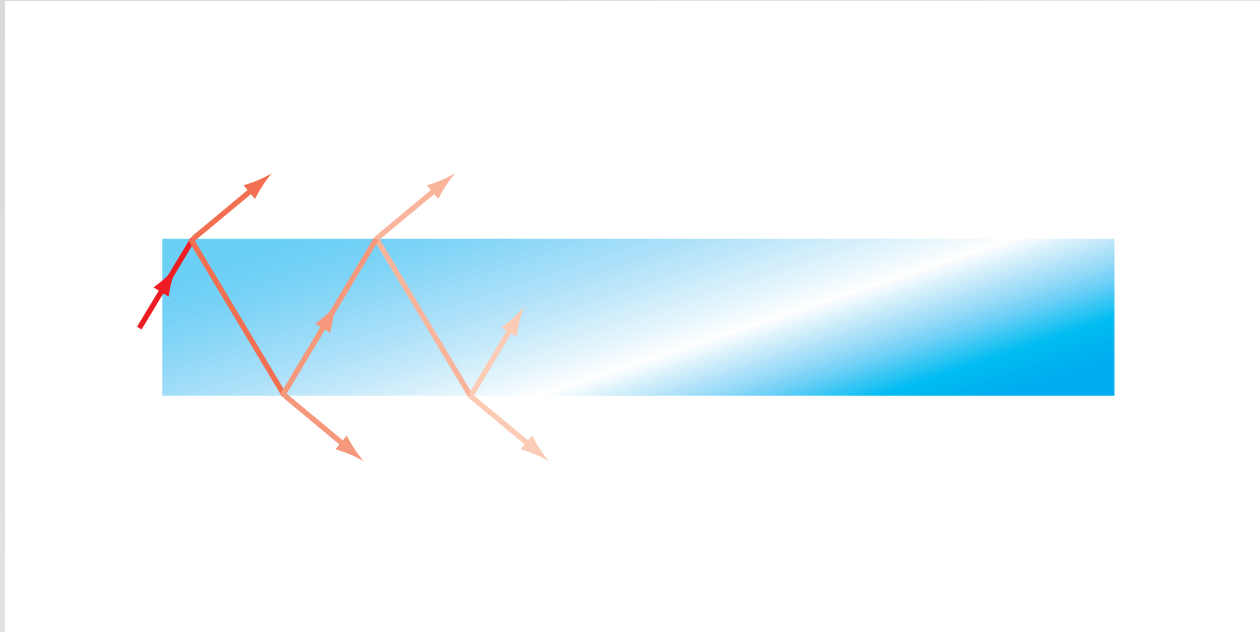
$$M = \frac{2d}{\lambda}$$

Waveguiding



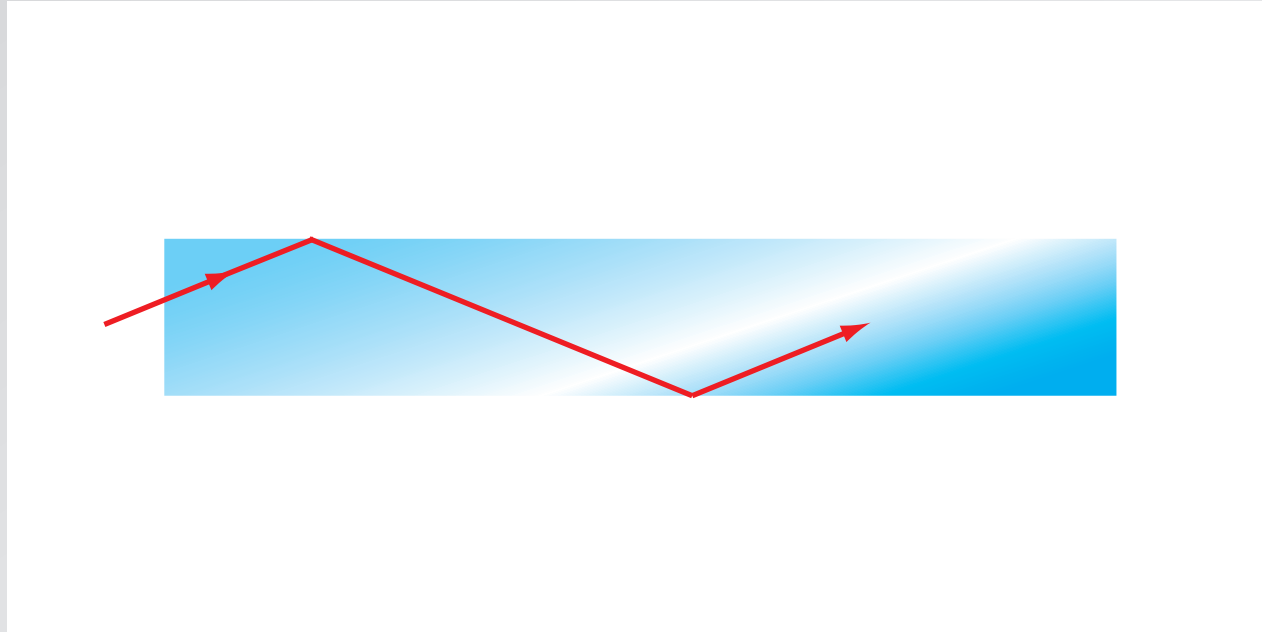
now consider a planar dielectric waveguide

Waveguiding



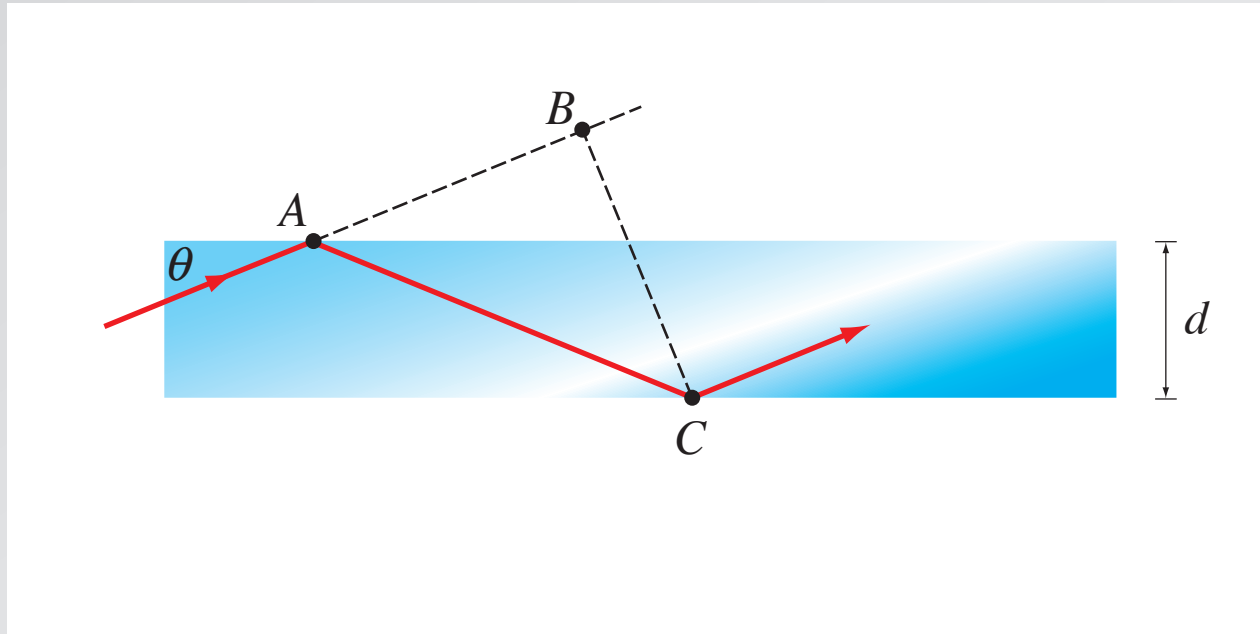
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided

Waveguiding



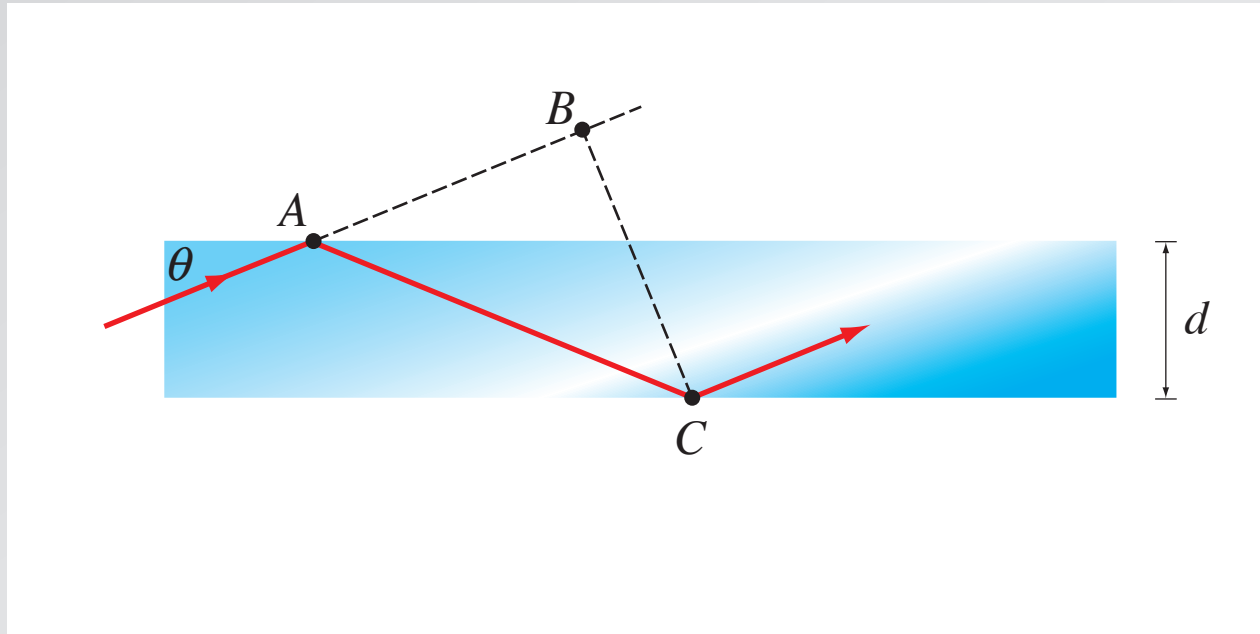
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided

Waveguiding



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

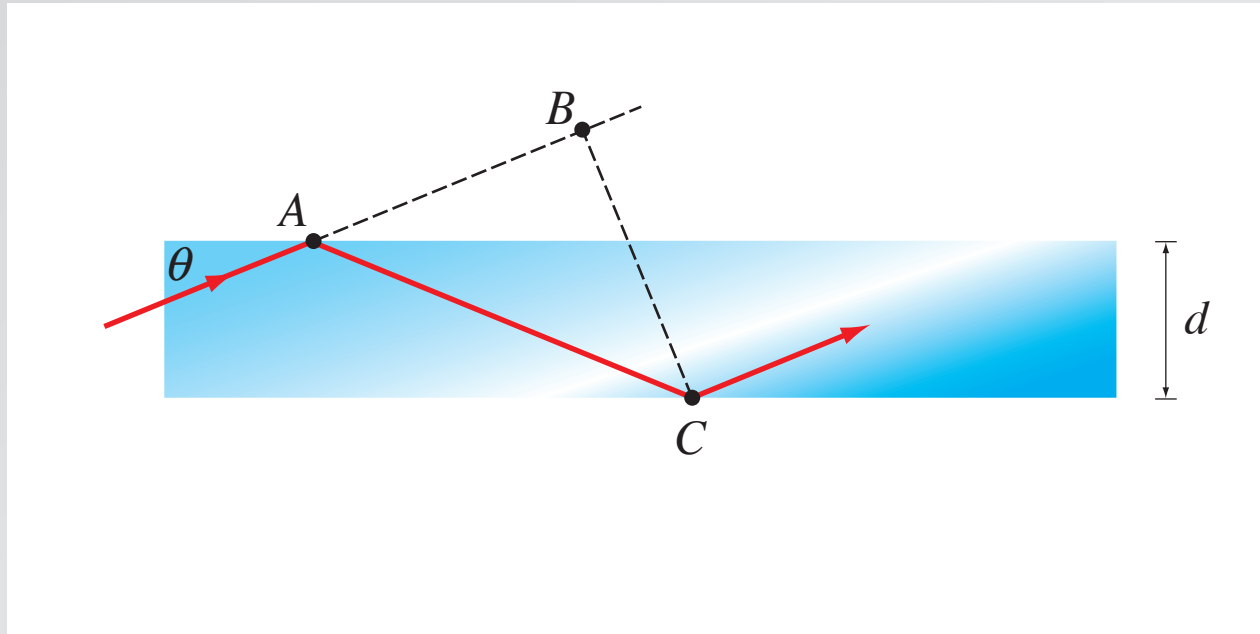
Waveguiding



self consistency:

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

Waveguiding



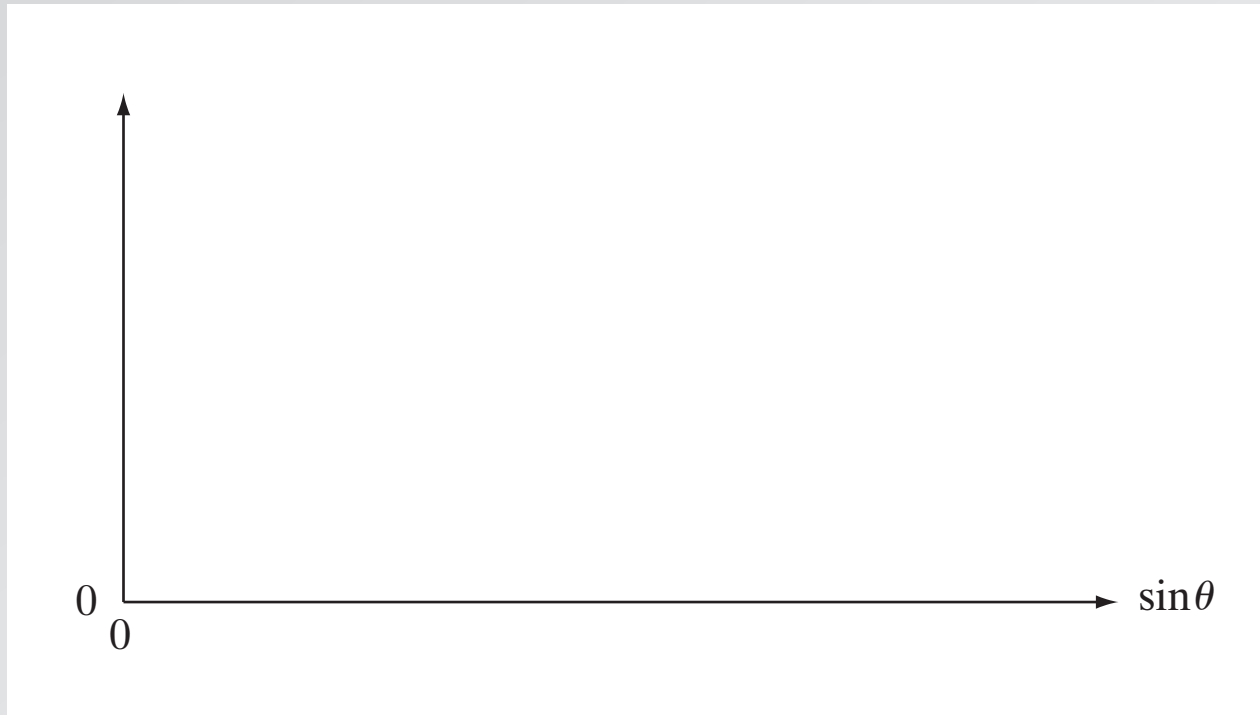
self consistency:

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

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



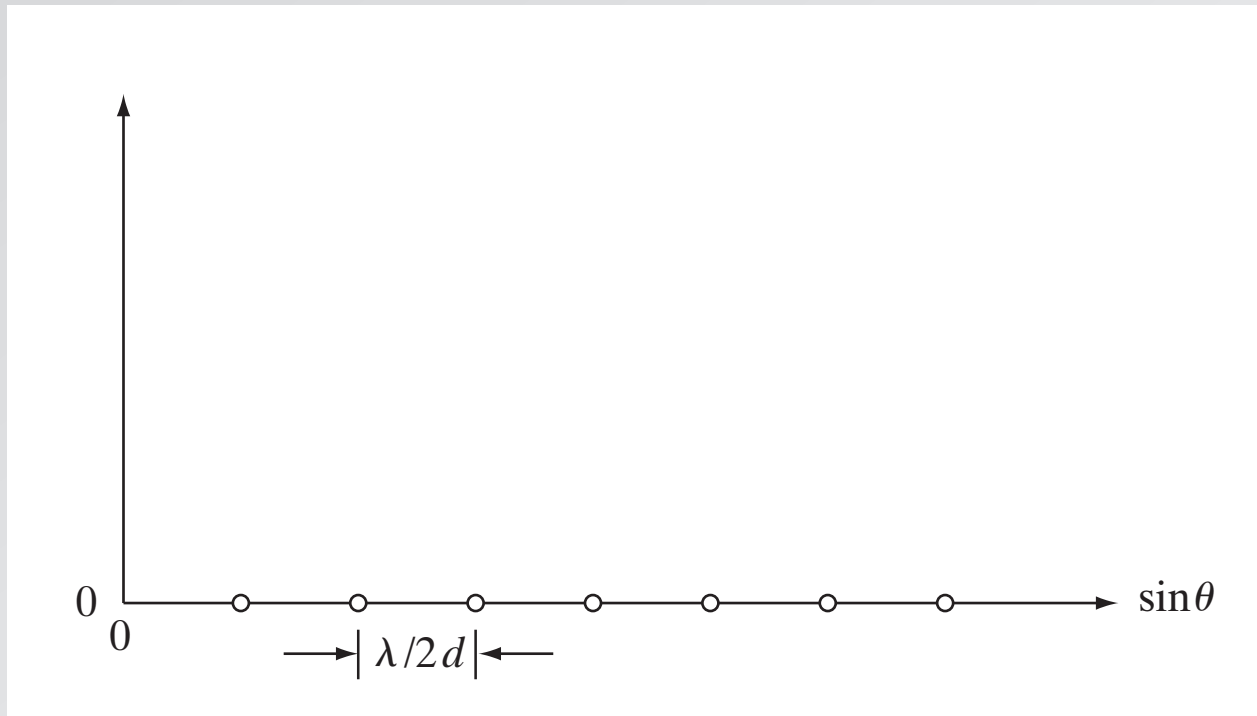
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Waveguiding



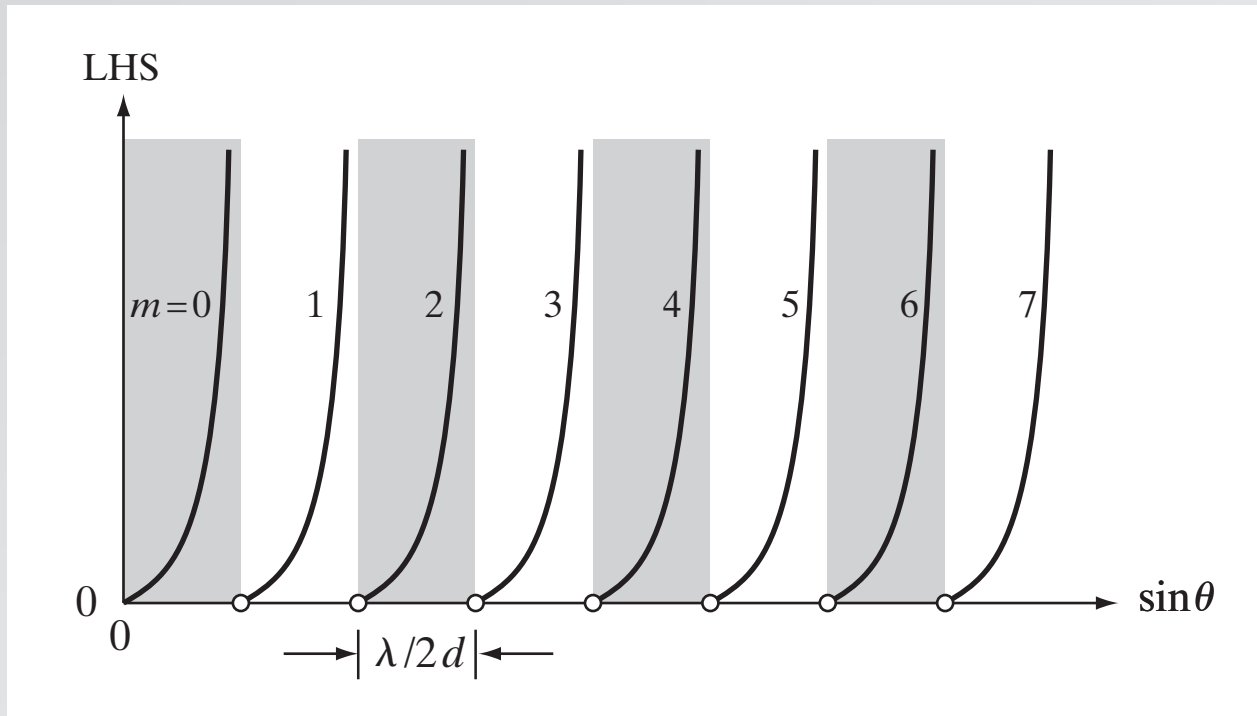
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Waveguiding



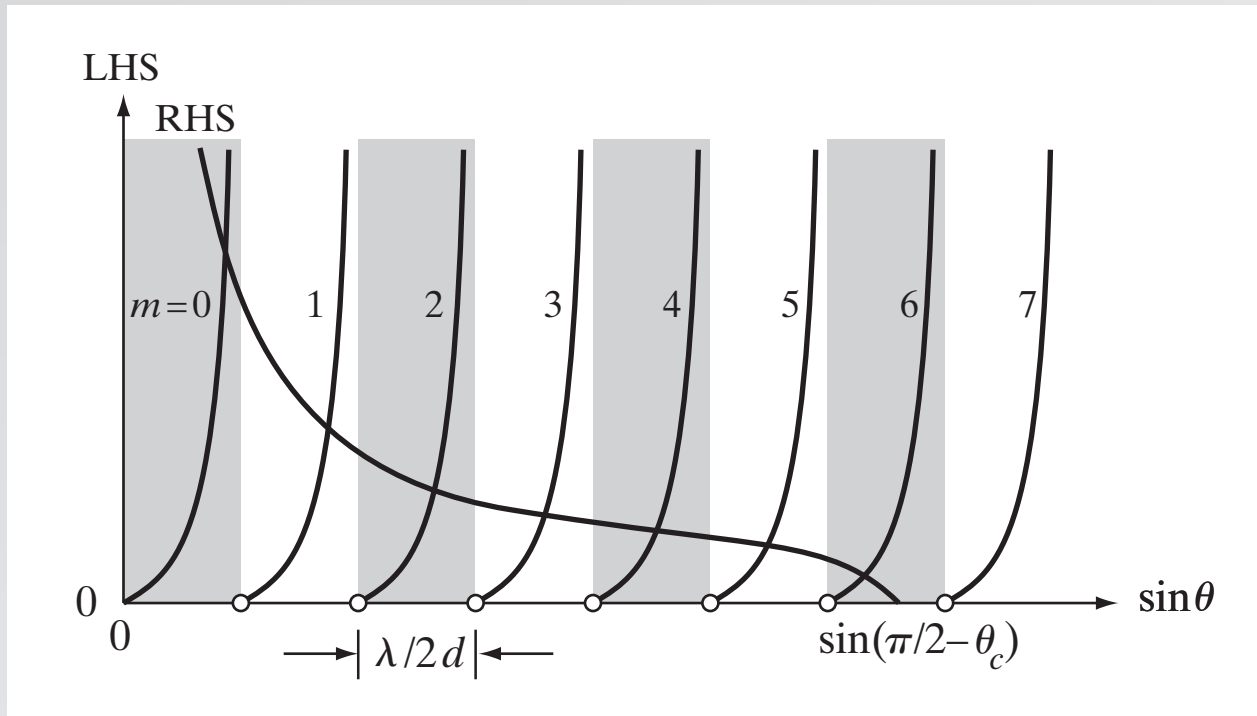
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Waveguiding



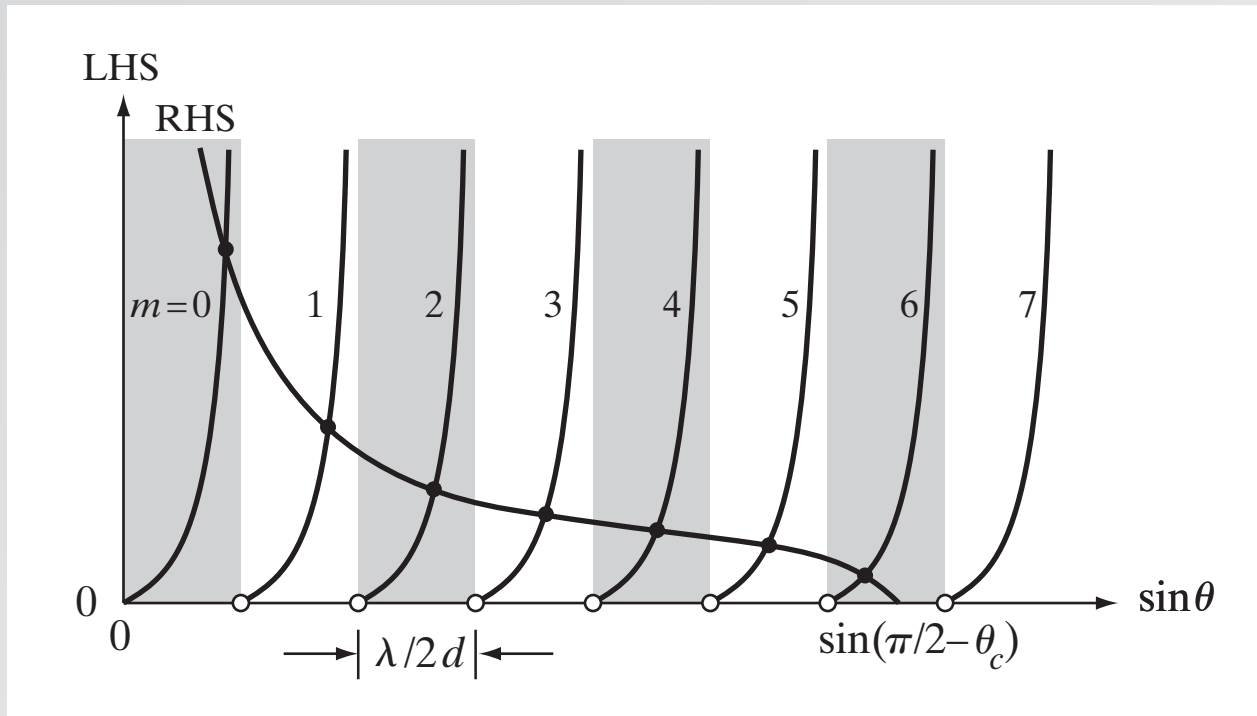
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Waveguiding



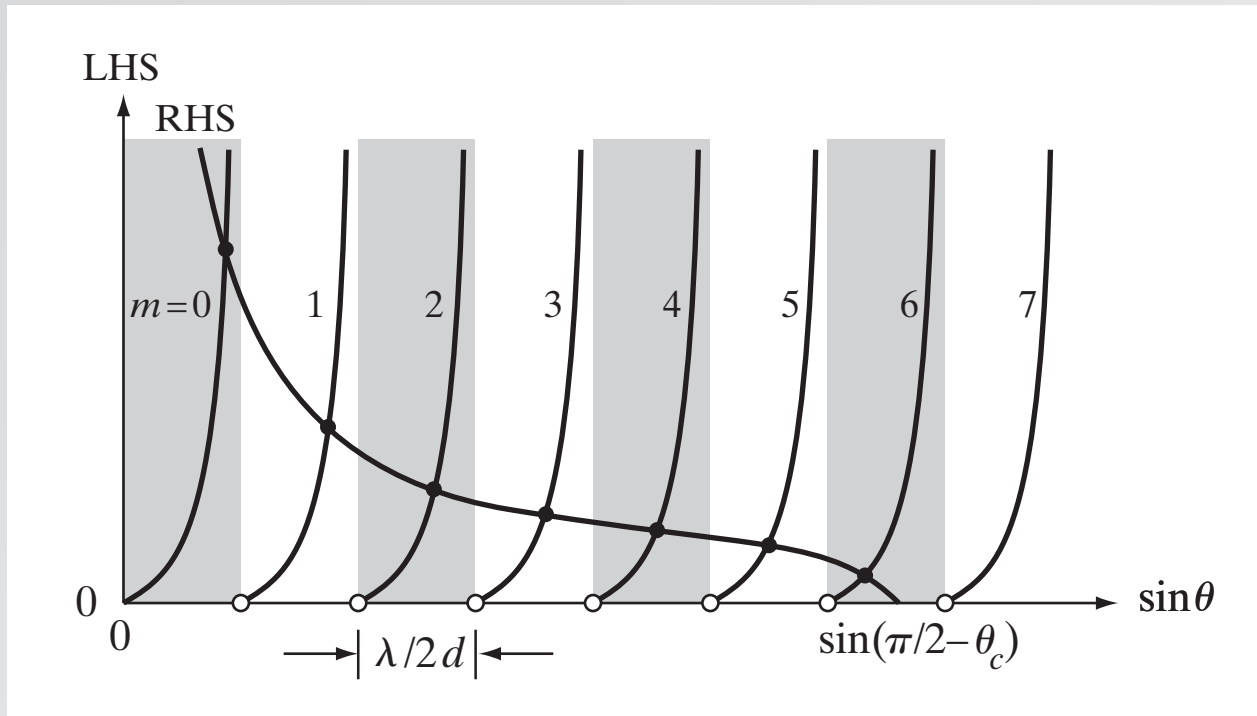
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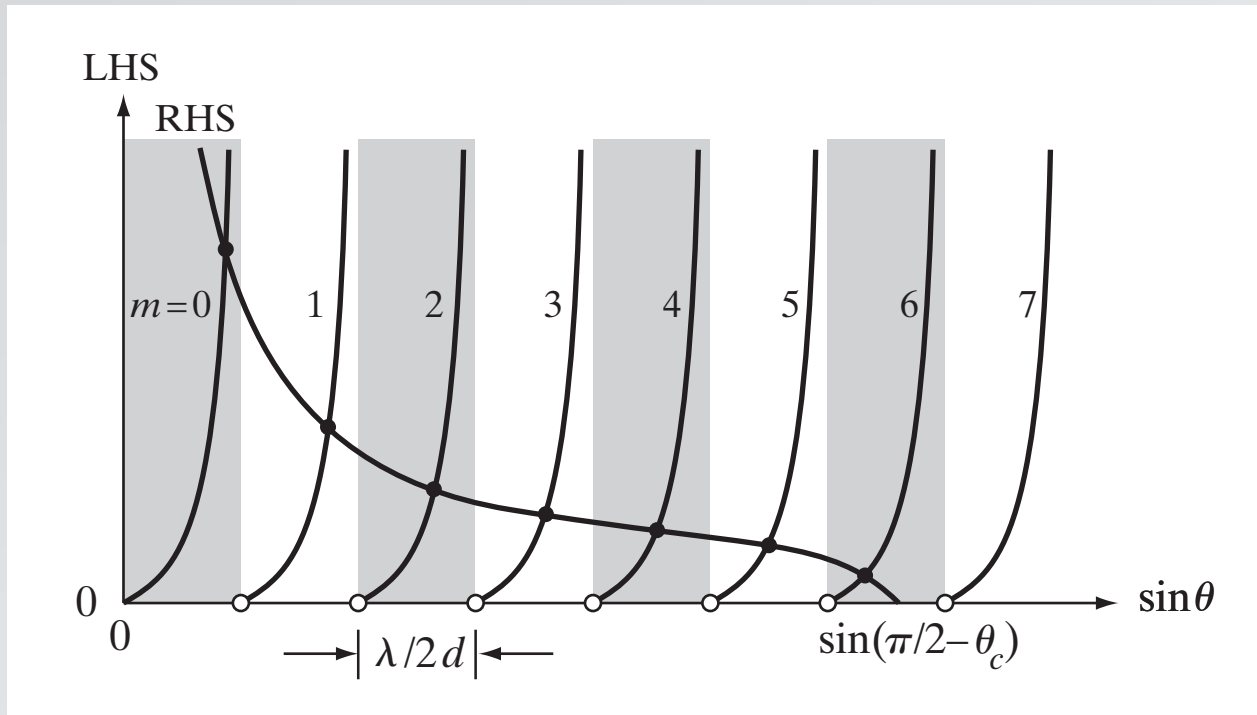
Waveguiding



number of modes:

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

Waveguiding



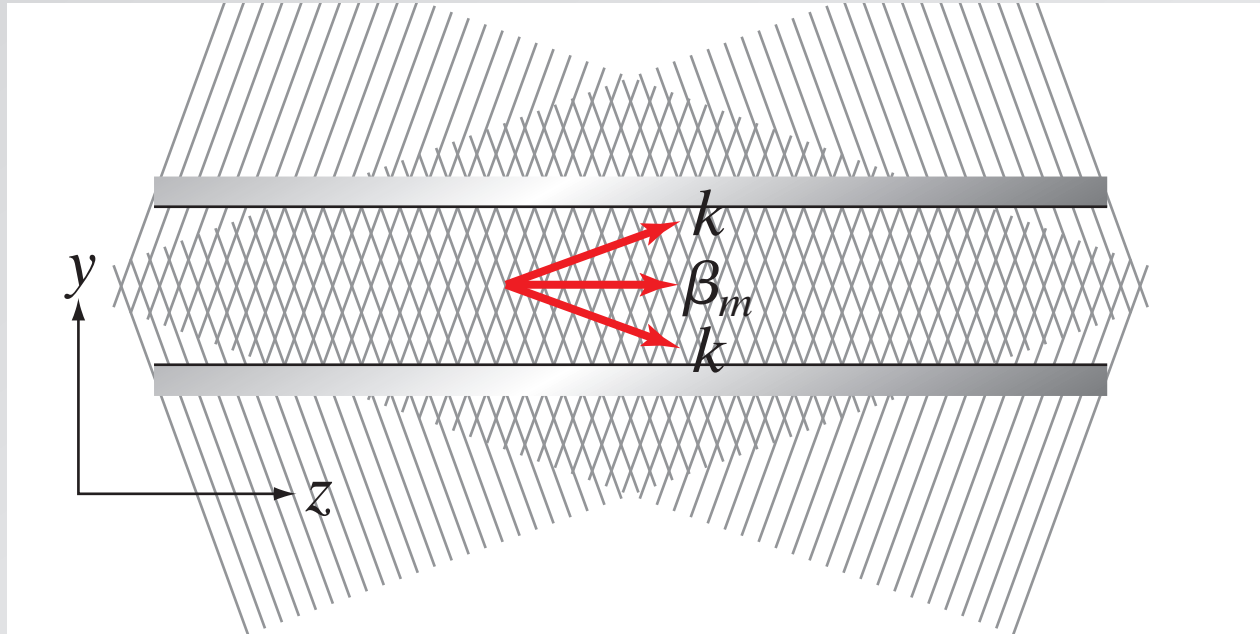
number of modes:

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

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:

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

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

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

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:

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

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:

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Substituting

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

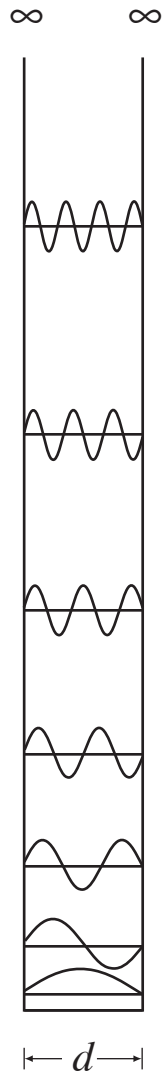
yields:

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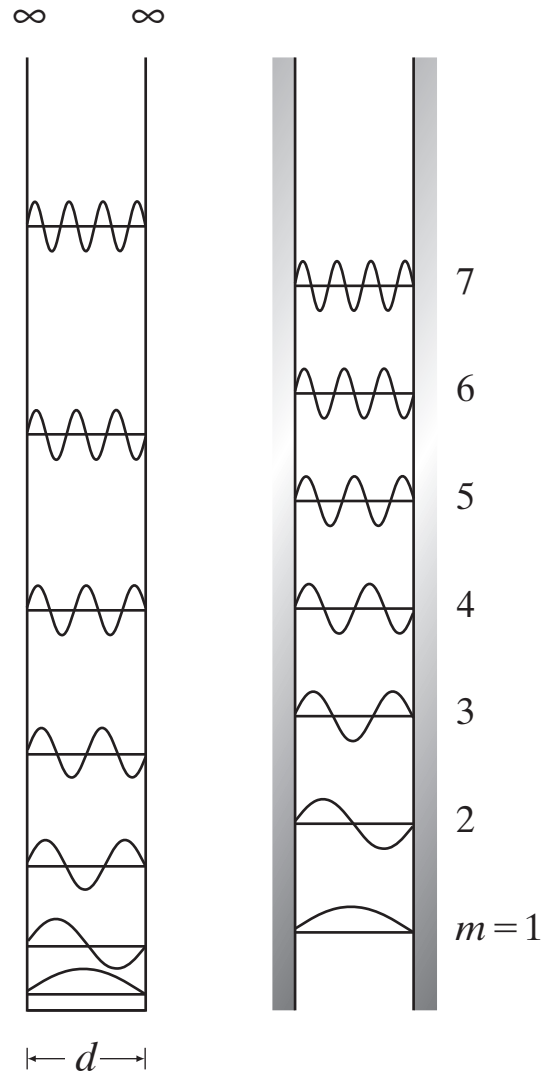
Compare to time-independent Schrödinger equation:

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

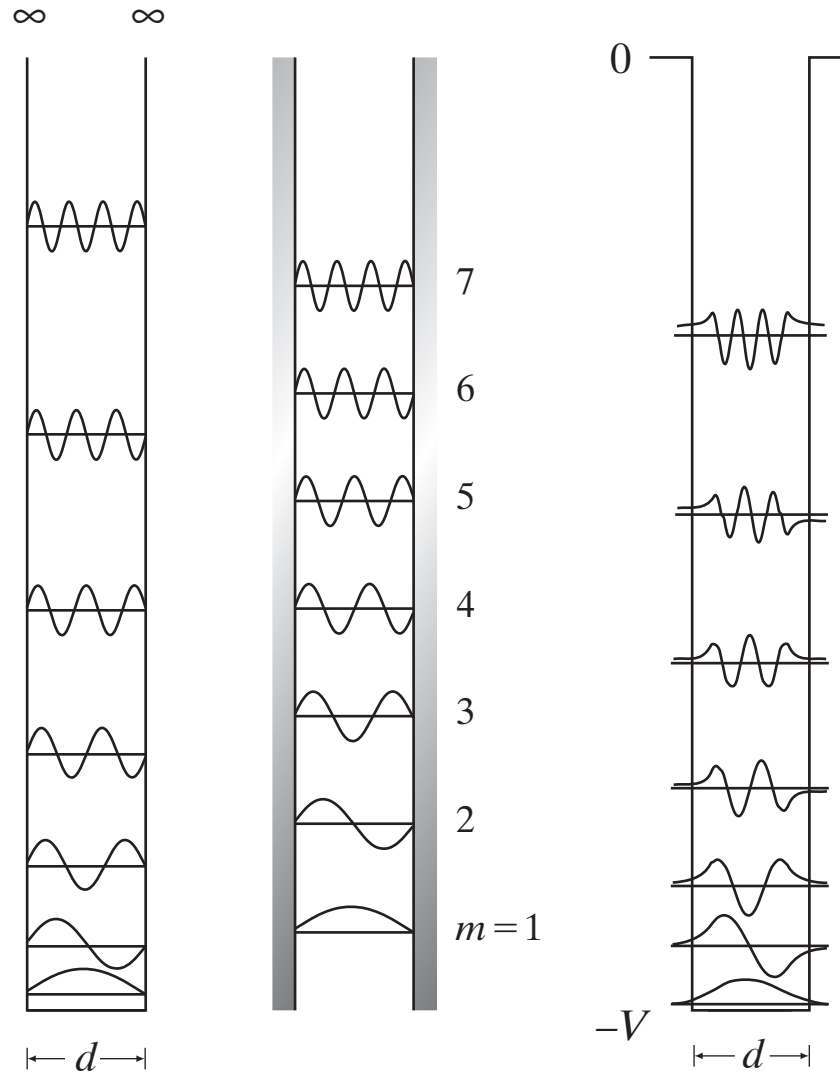
Waveguiding



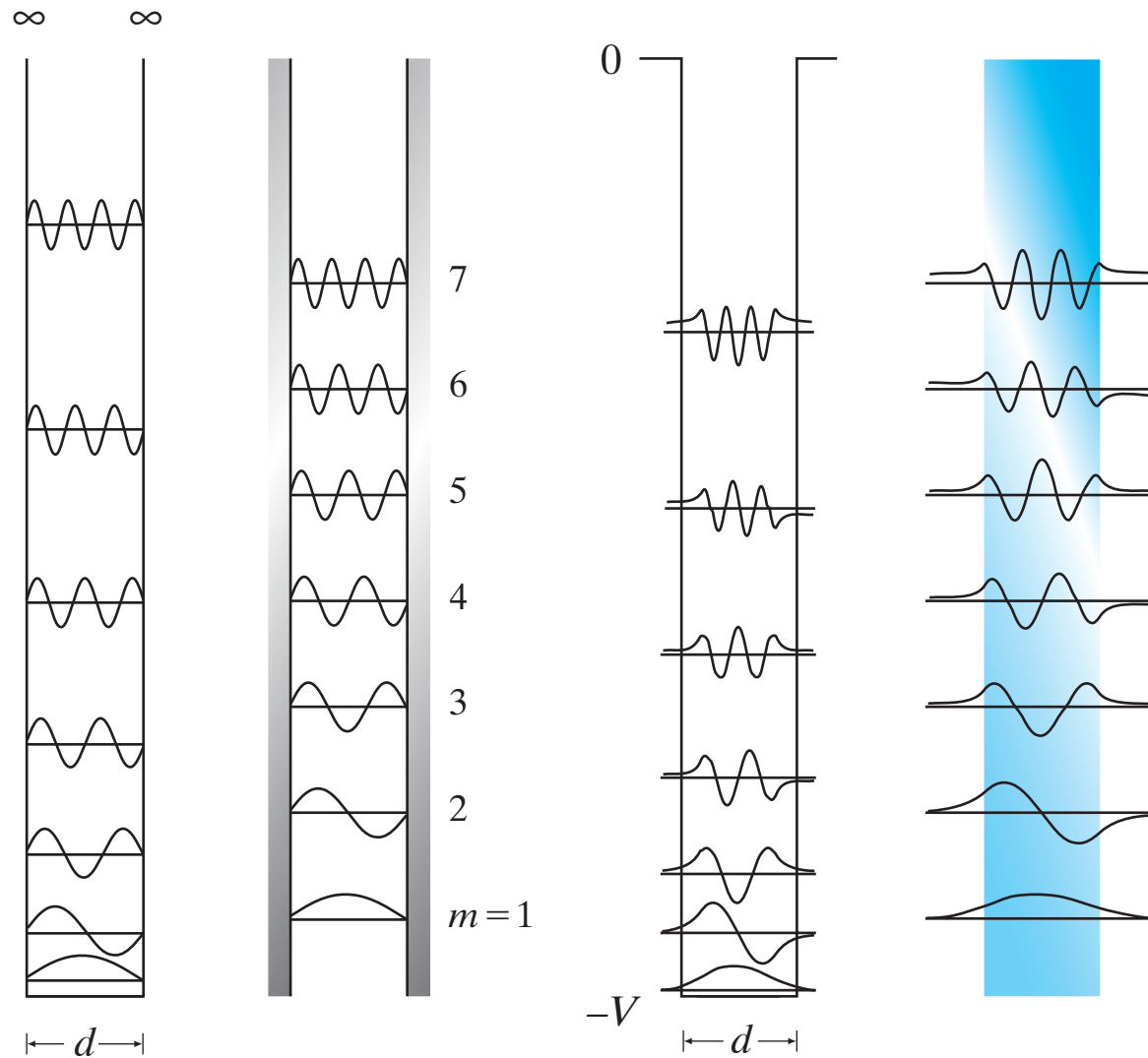
Waveguiding



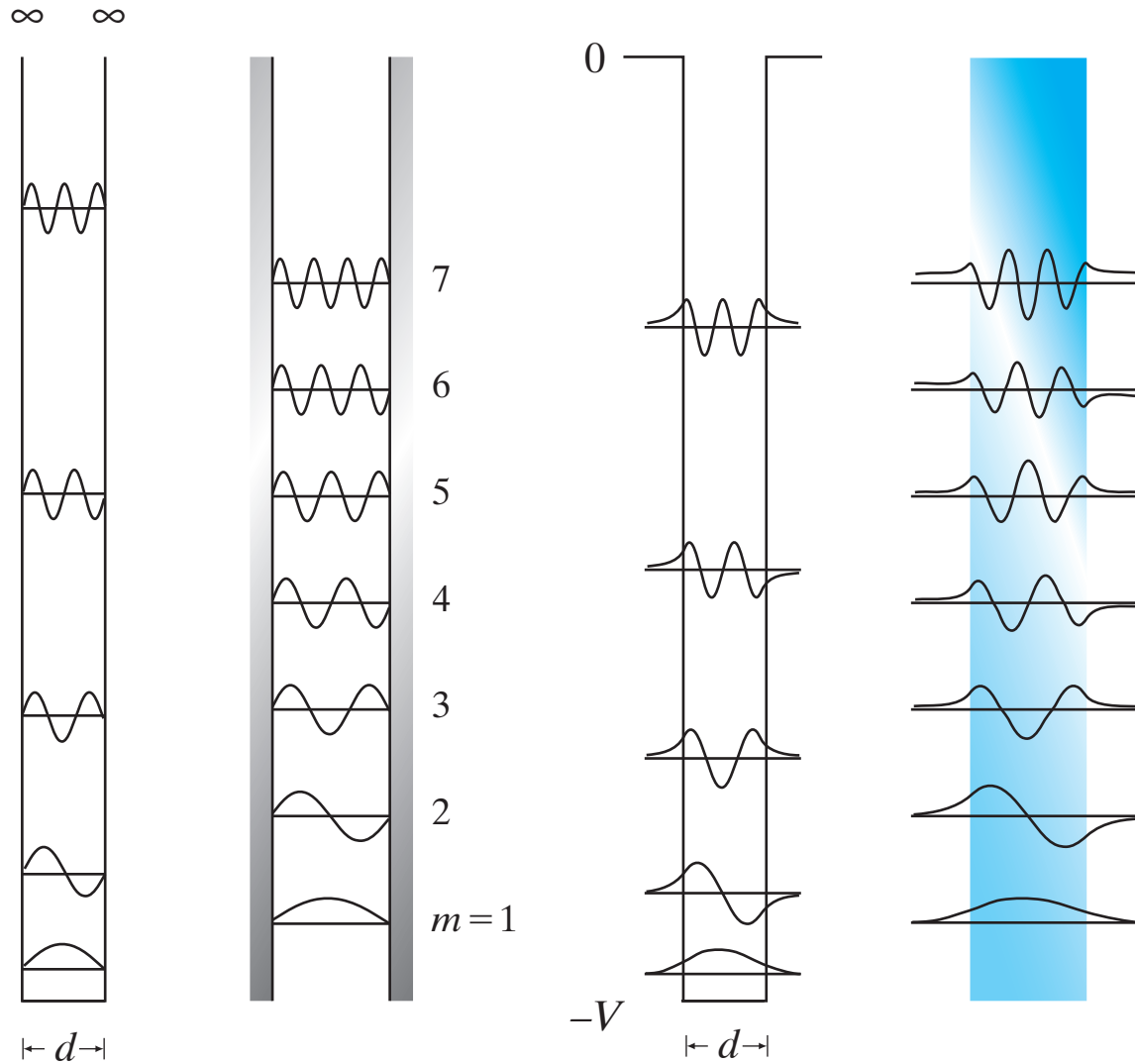
Waveguiding



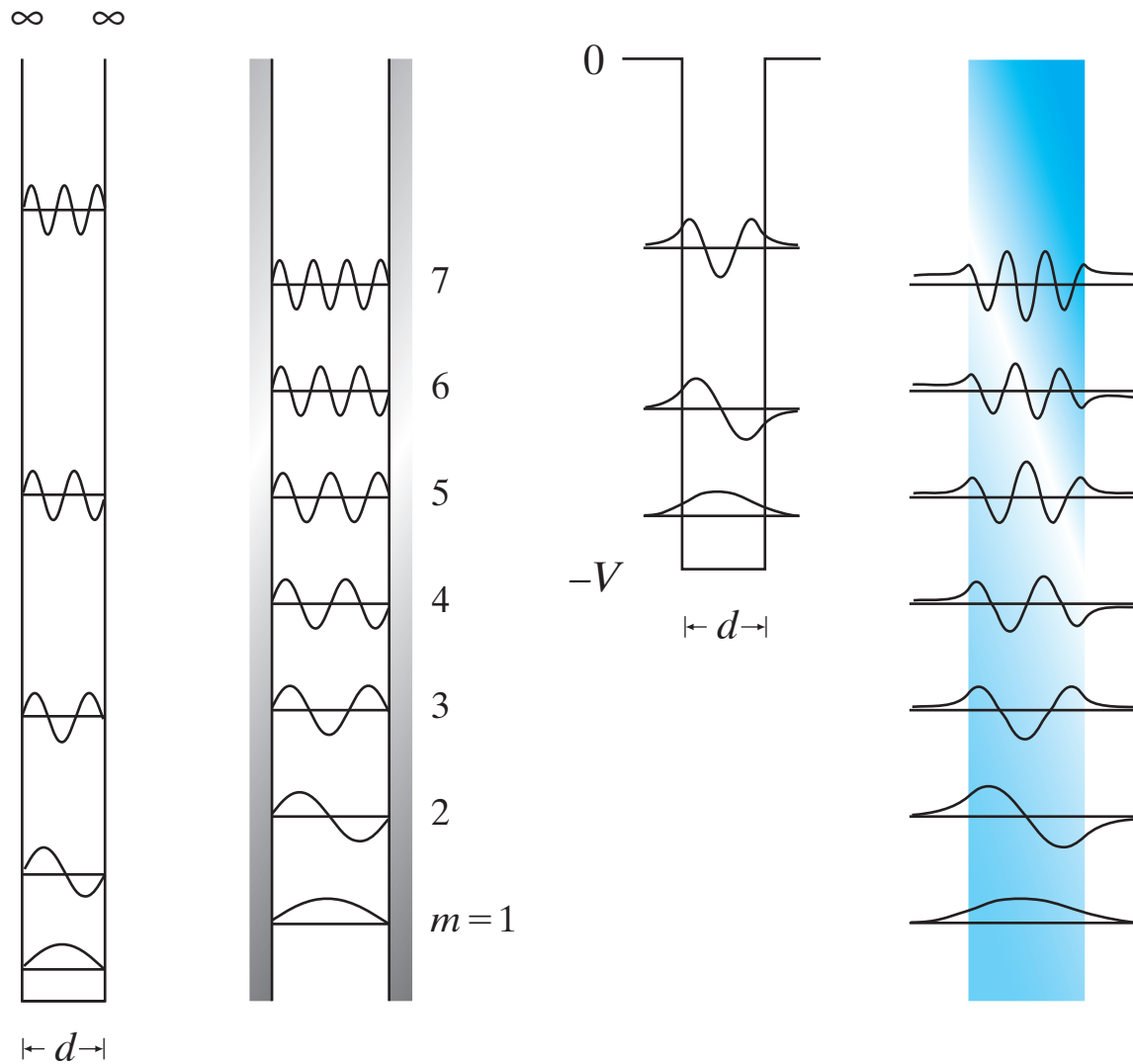
Waveguiding



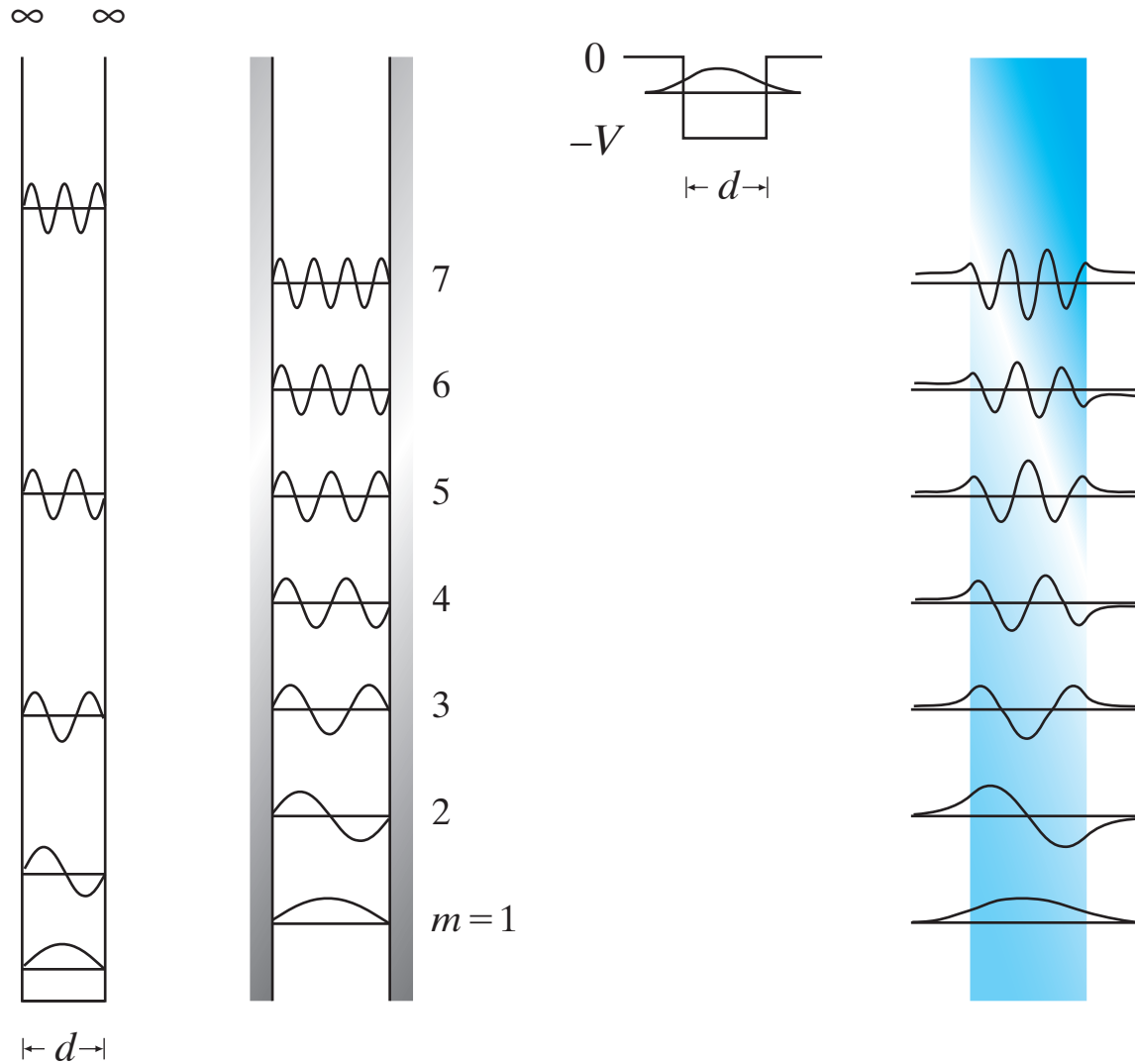
Waveguiding



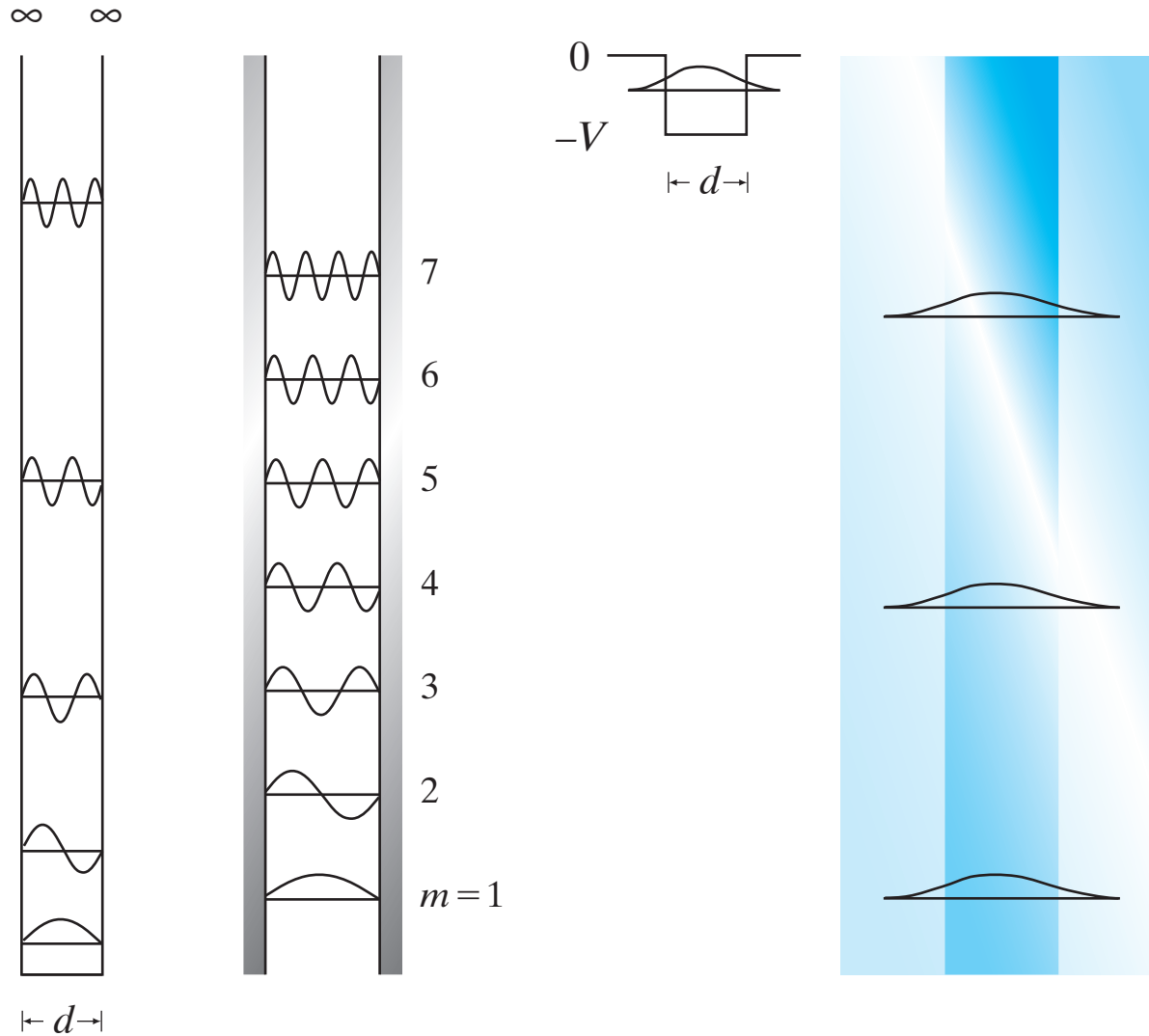
Waveguiding



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:

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

Waveguiding

single mode condition for 600-nm light:

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

without cladding:

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

Add cladding with 0.4% index difference:

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

Waveguiding

commercial single-mode fiber (Corning Titan[®])



	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**

Nanowire fabrication

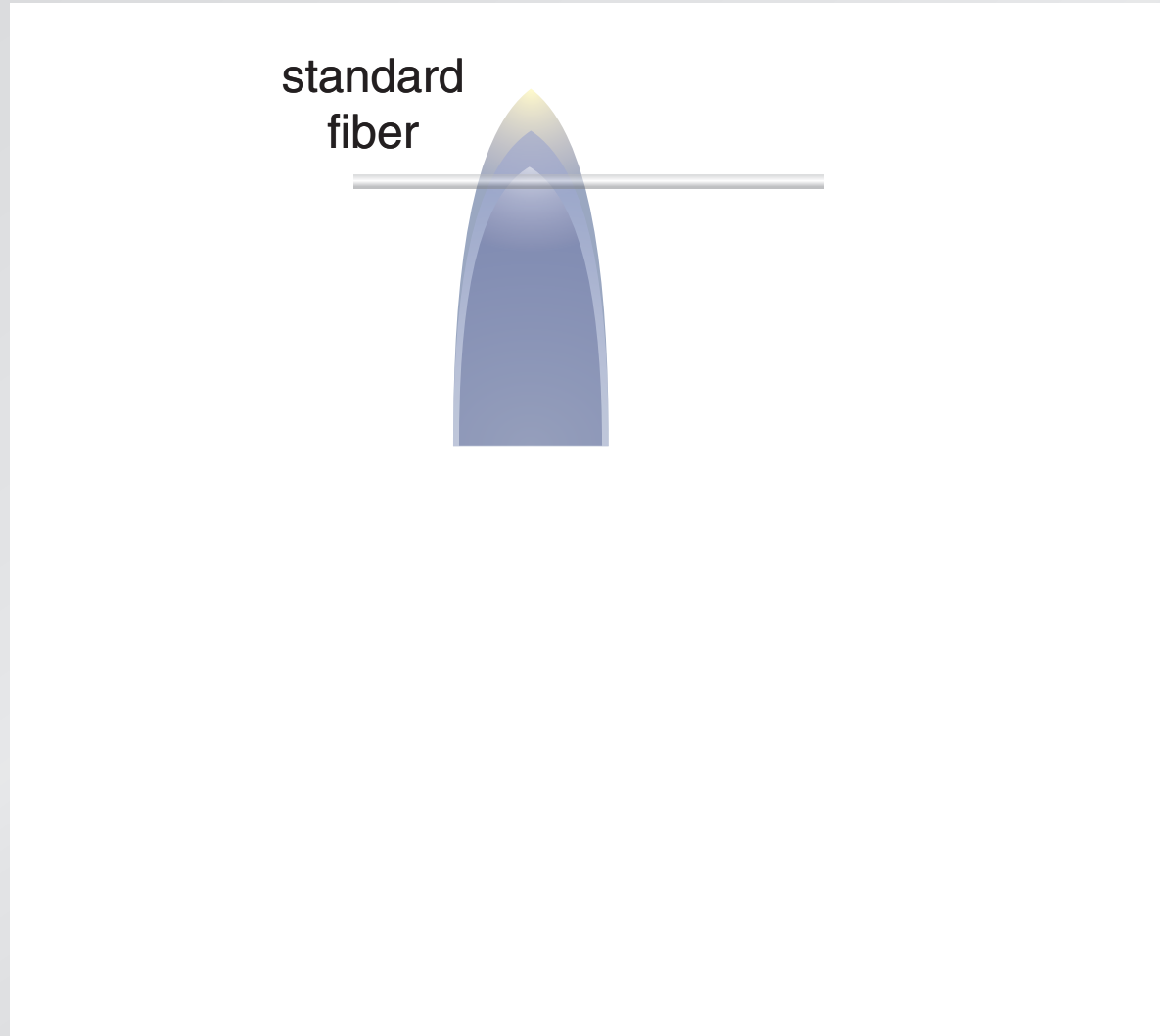
two-step drawing process

standard
fiber



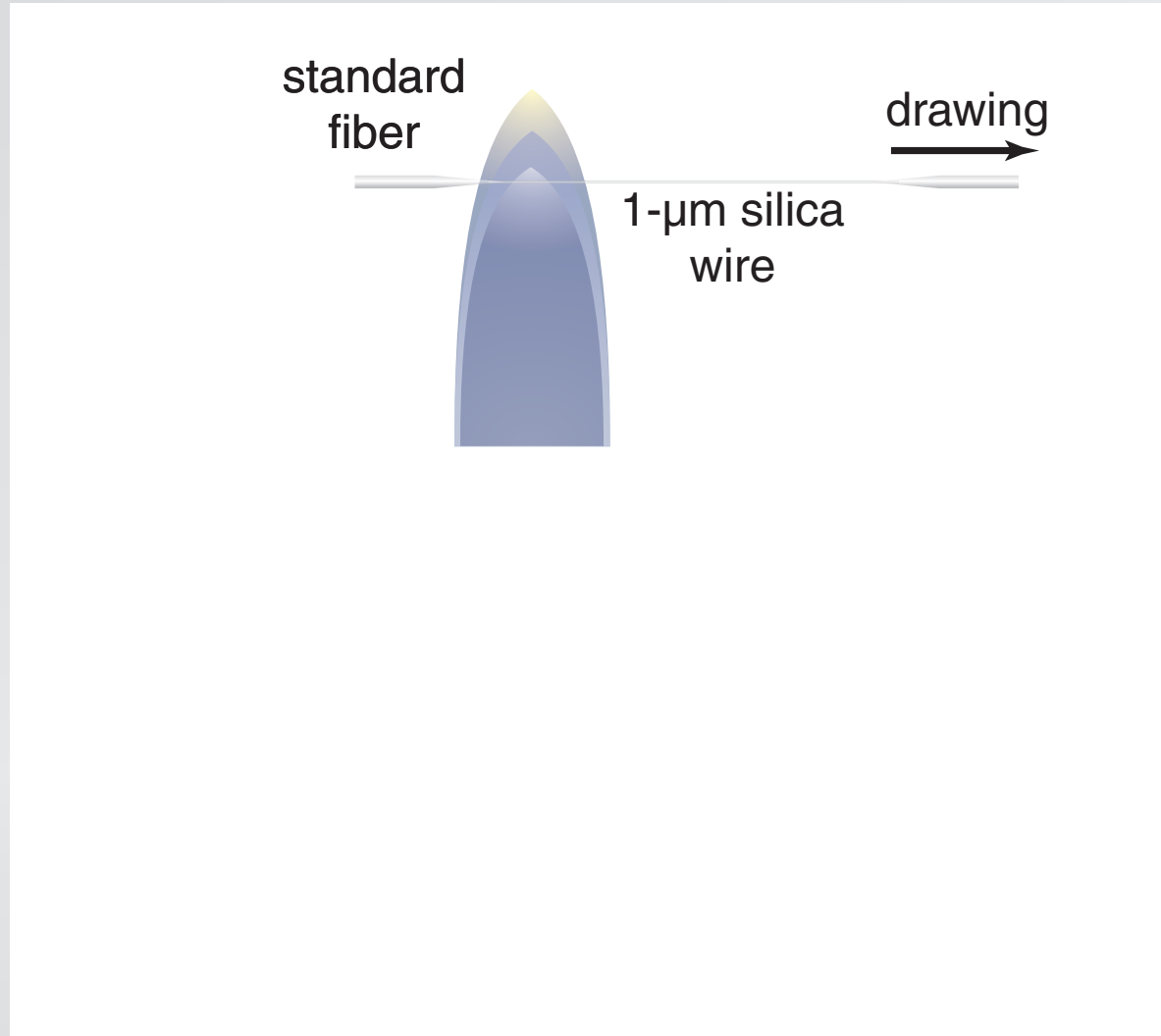
Nanowire fabrication

two-step drawing process



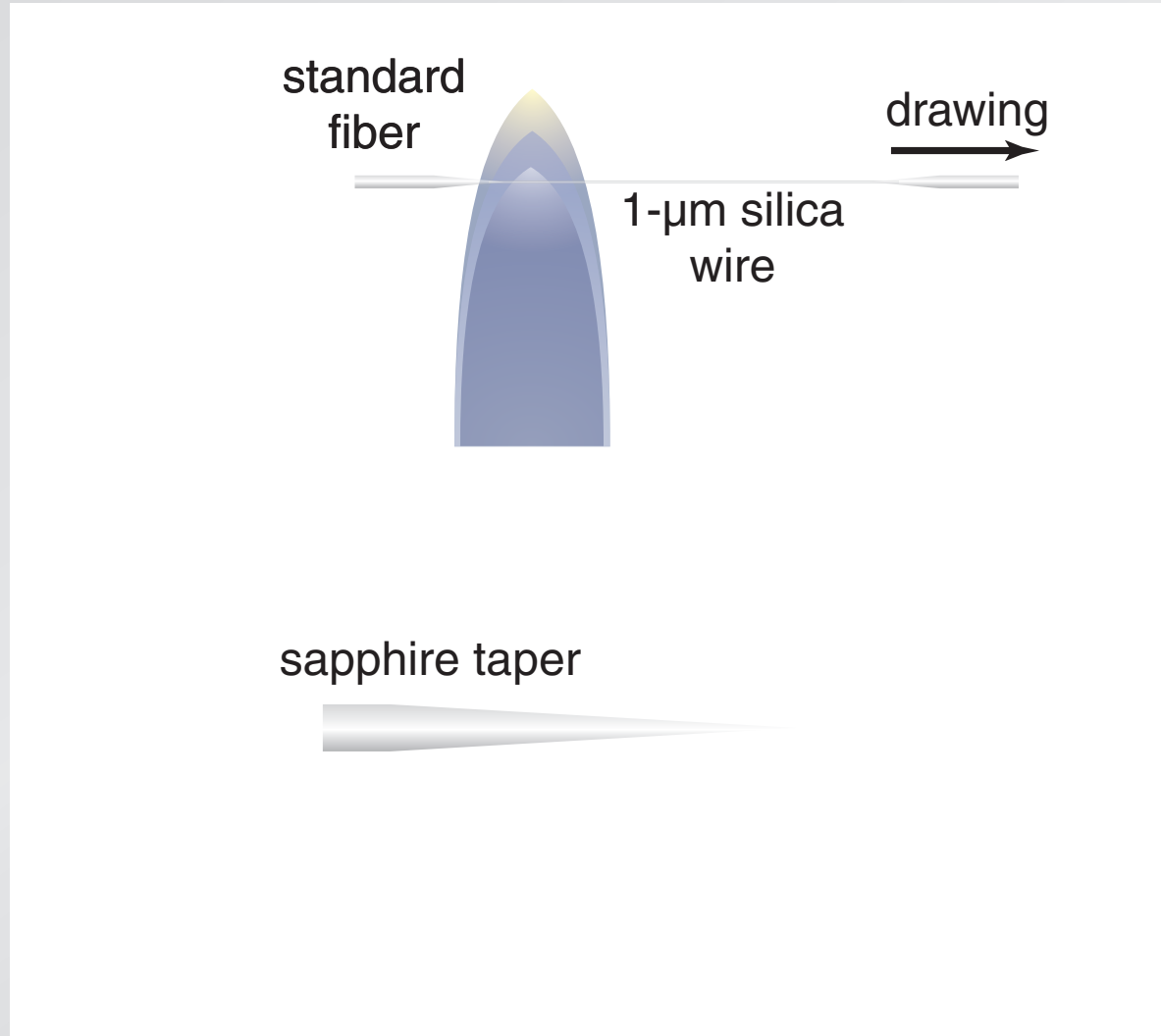
Nanowire fabrication

two-step drawing process



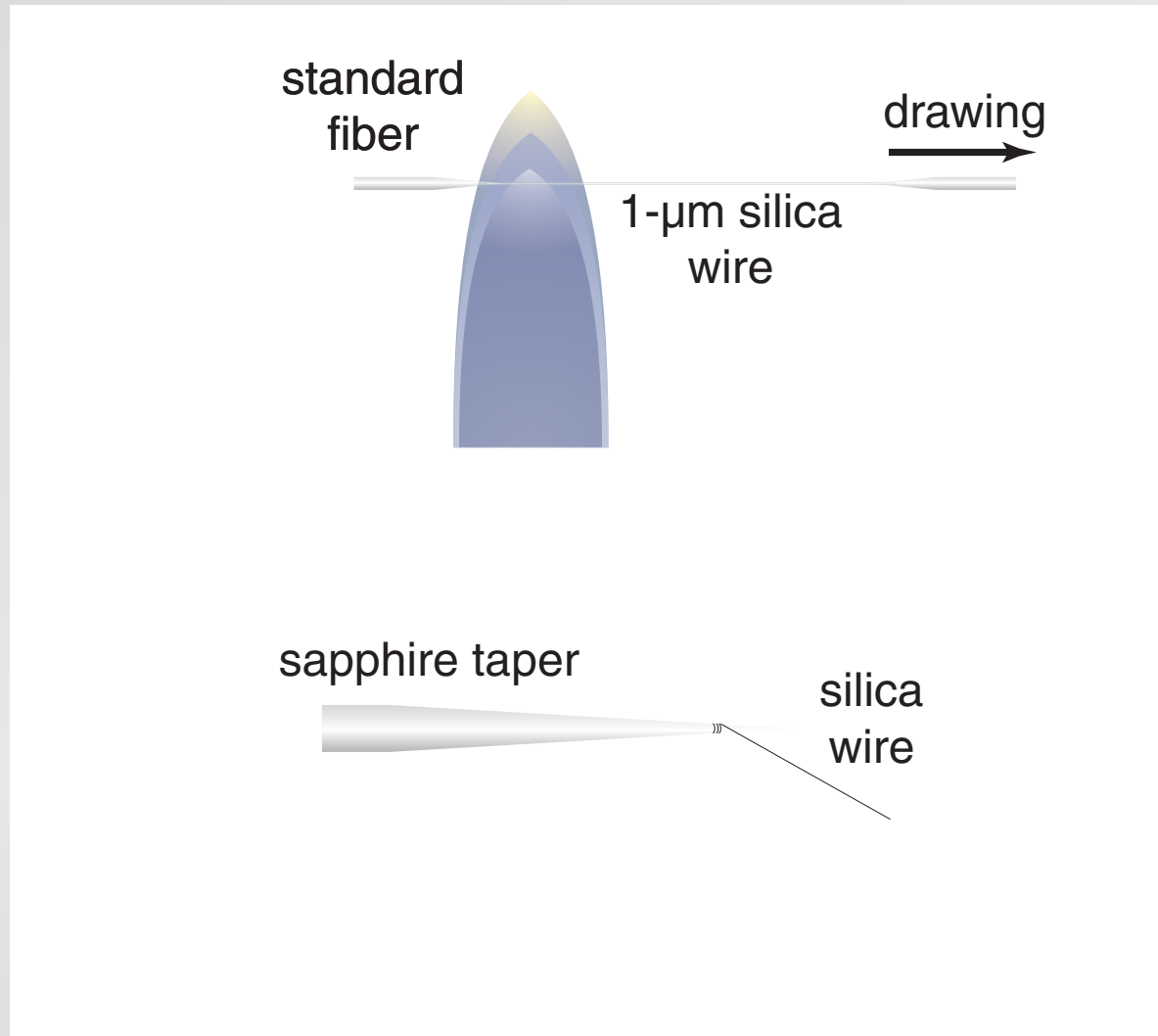
Nanowire fabrication

two-step drawing process



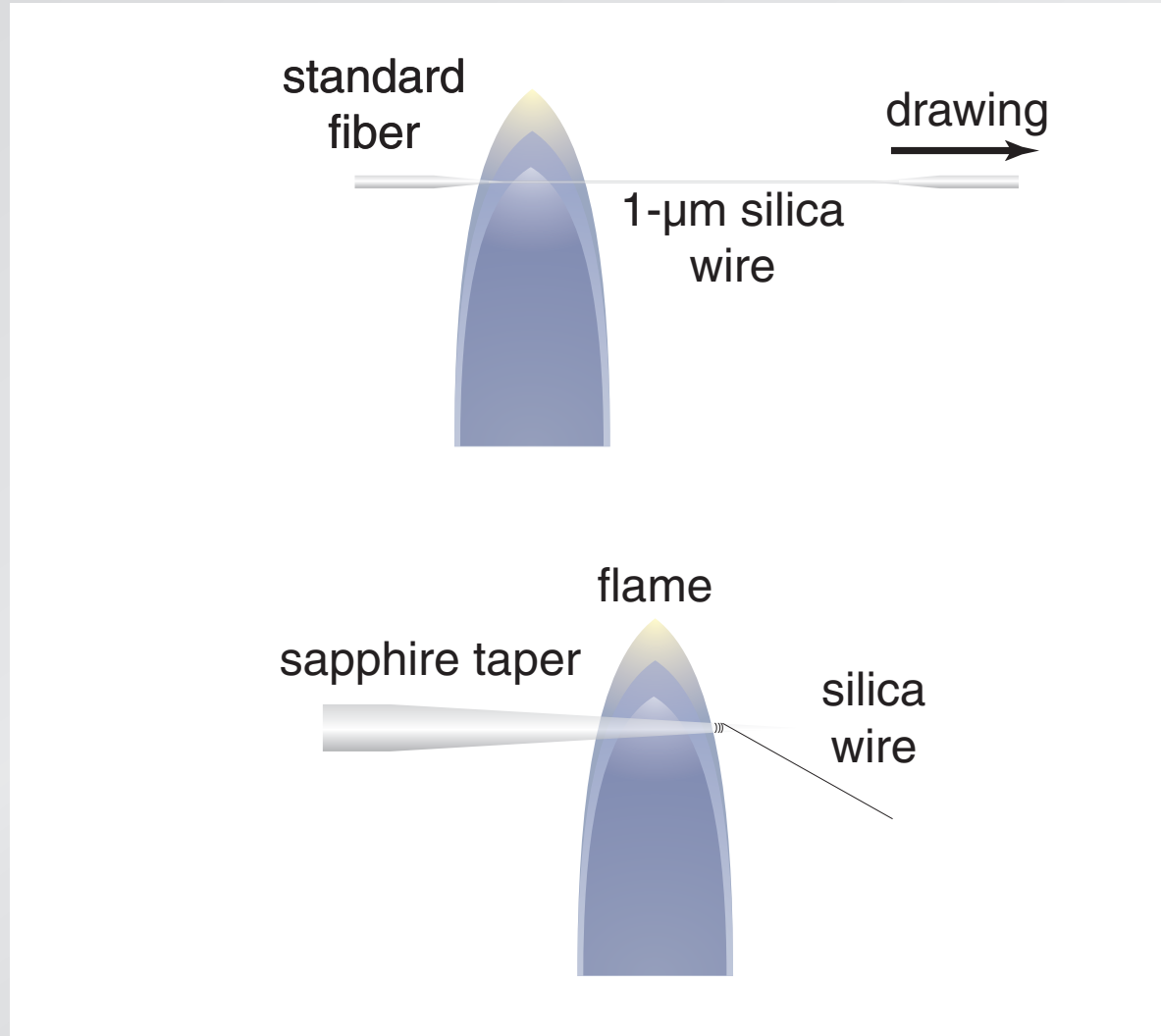
Nanowire fabrication

two-step drawing process



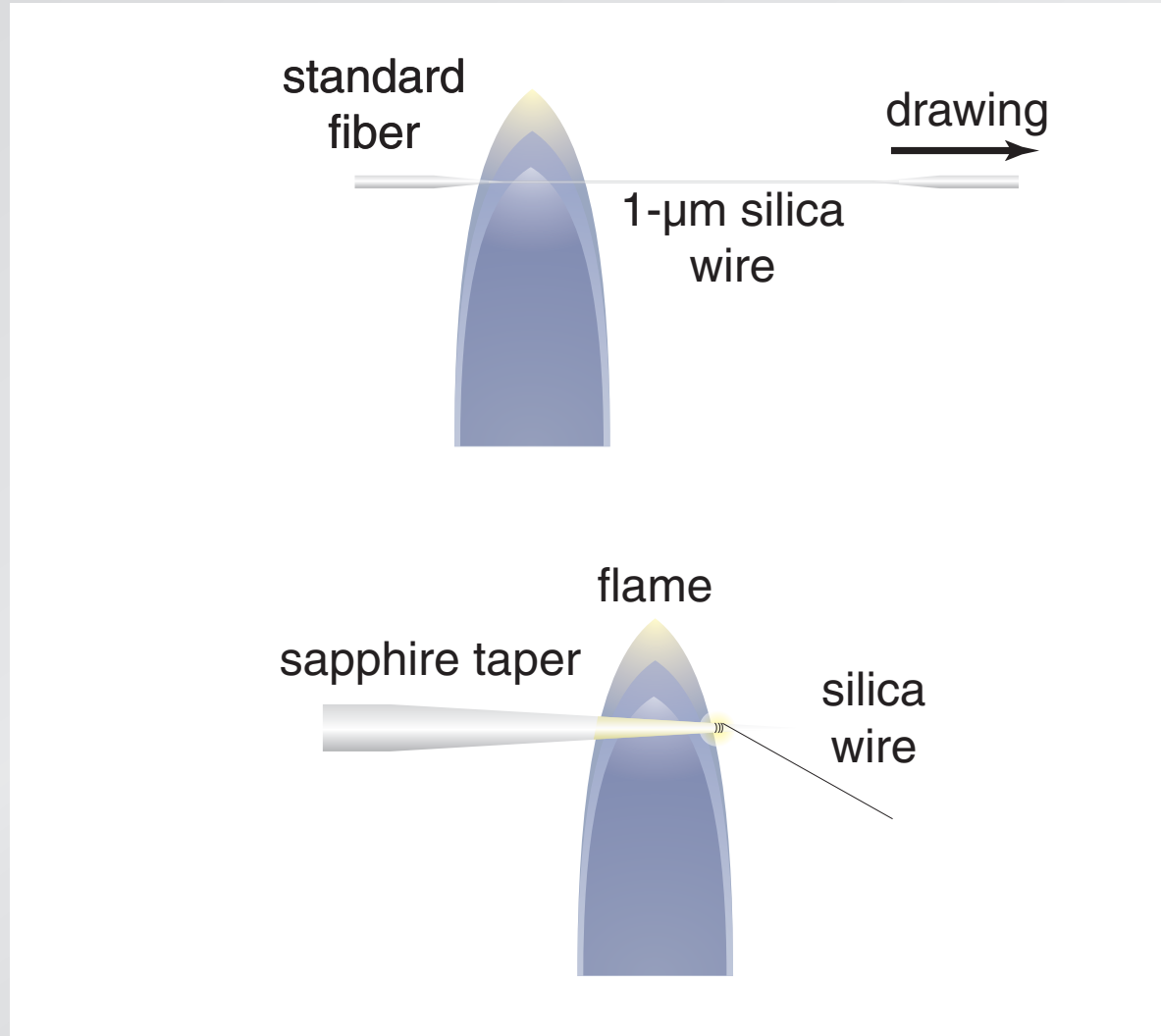
Nanowire fabrication

two-step drawing process



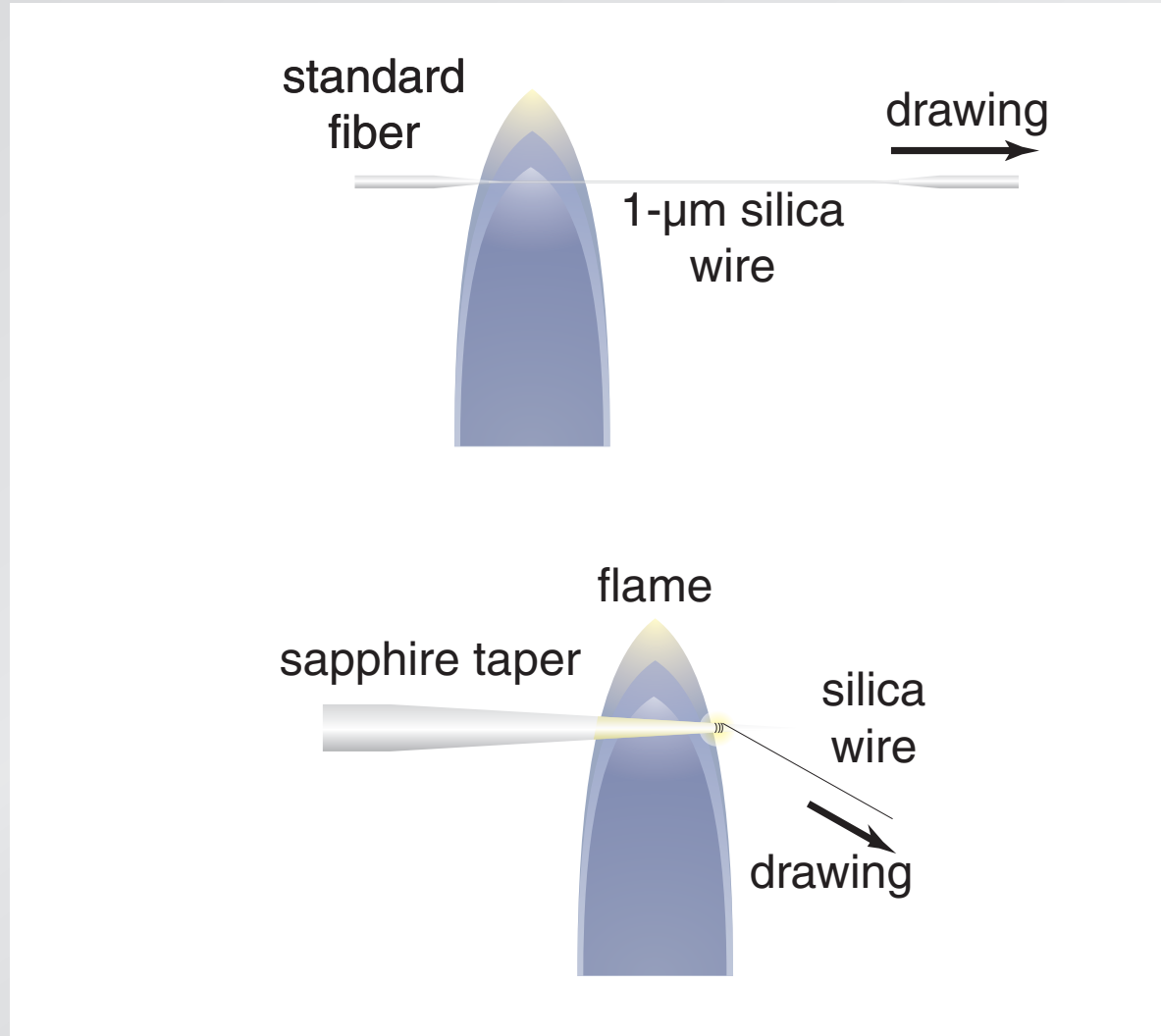
Nanowire fabrication

two-step drawing process



Nanowire fabrication

two-step drawing process



Manipulating light at the nanoscale



***Nature*, 426, 816 (2003)**

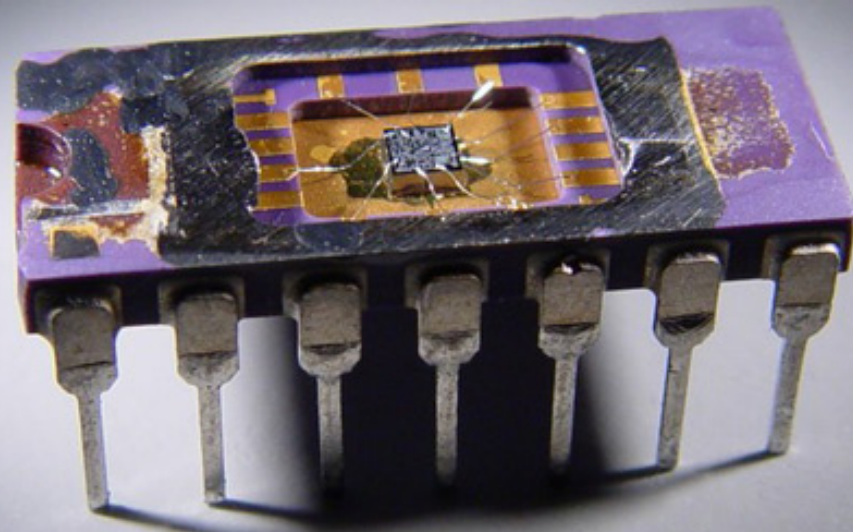
Nanowire fabrication

1 μm

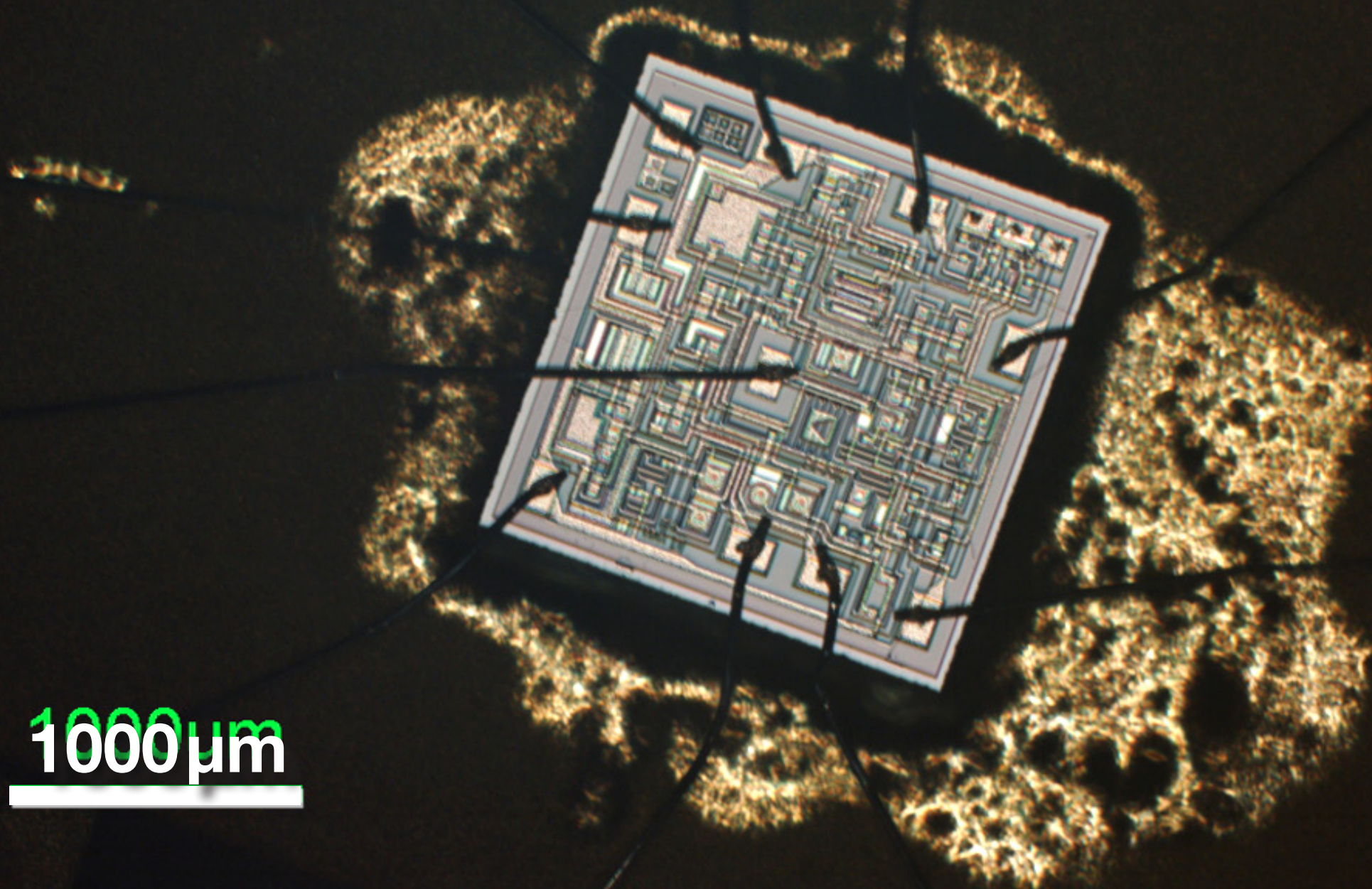


Nature, 426, 816 (2003)

Nanowire fabrication



Nanowire fabrication



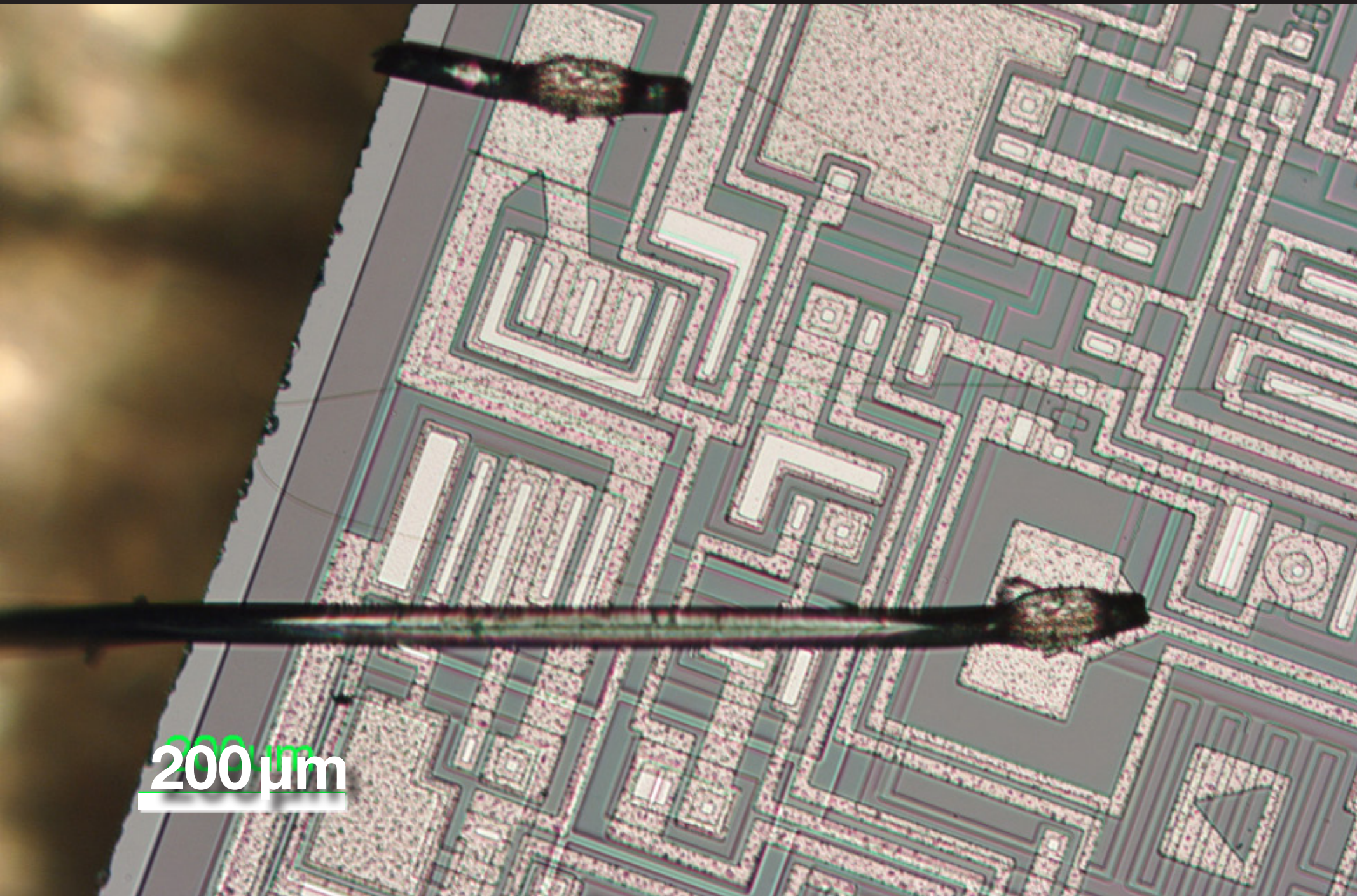
1000 μm

Nanowire fabrication

500 μm

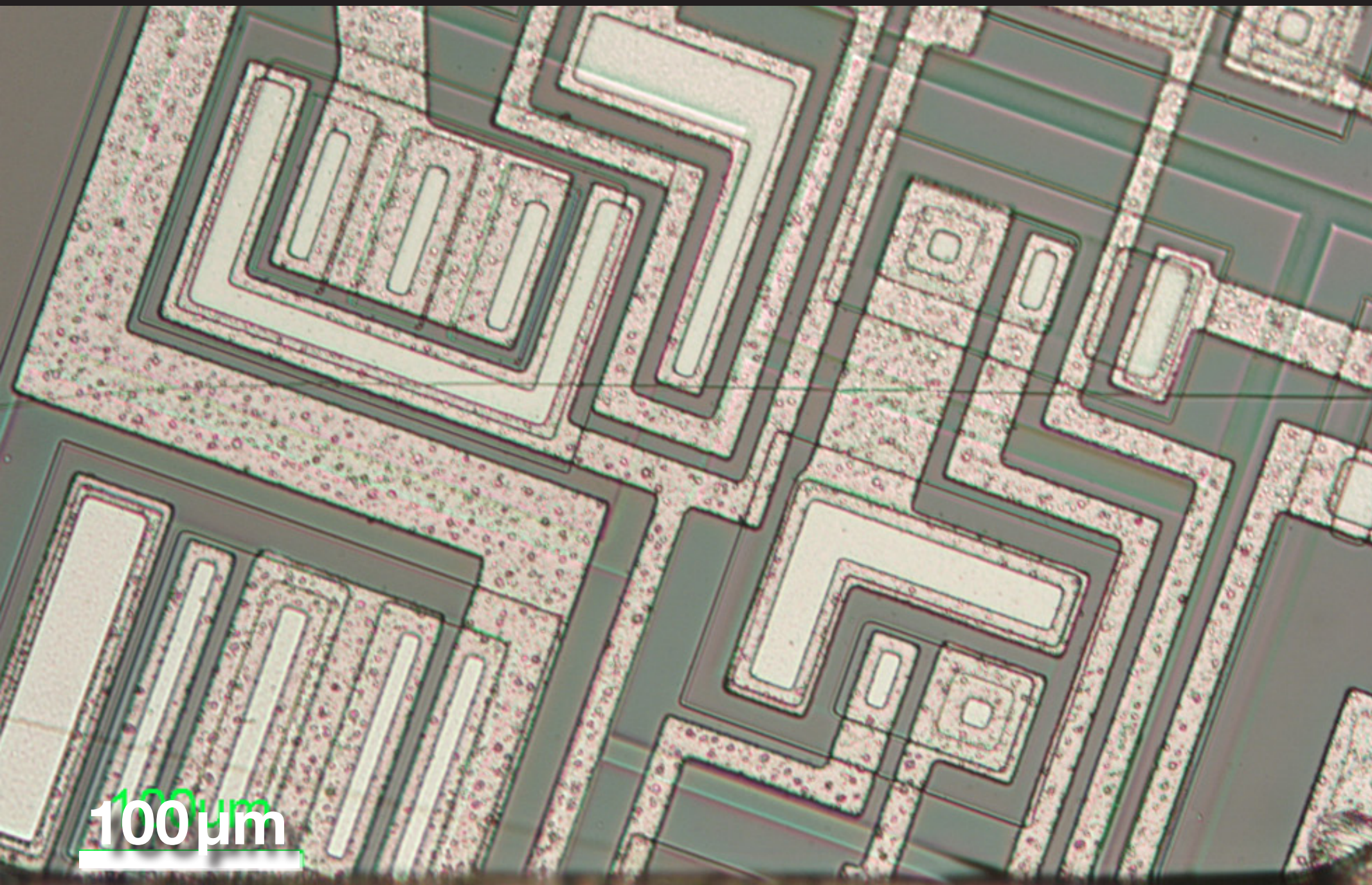
A scanning electron micrograph (SEM) of a nanowire fabrication chip. The chip is a square substrate with a complex, dense network of nanowires and various microstructures. The nanowires are thin, light-colored lines forming a grid and connecting various components. The background is a darker, textured surface. A white scale bar in the bottom left corner is labeled "500 μm".

Nanowire fabrication

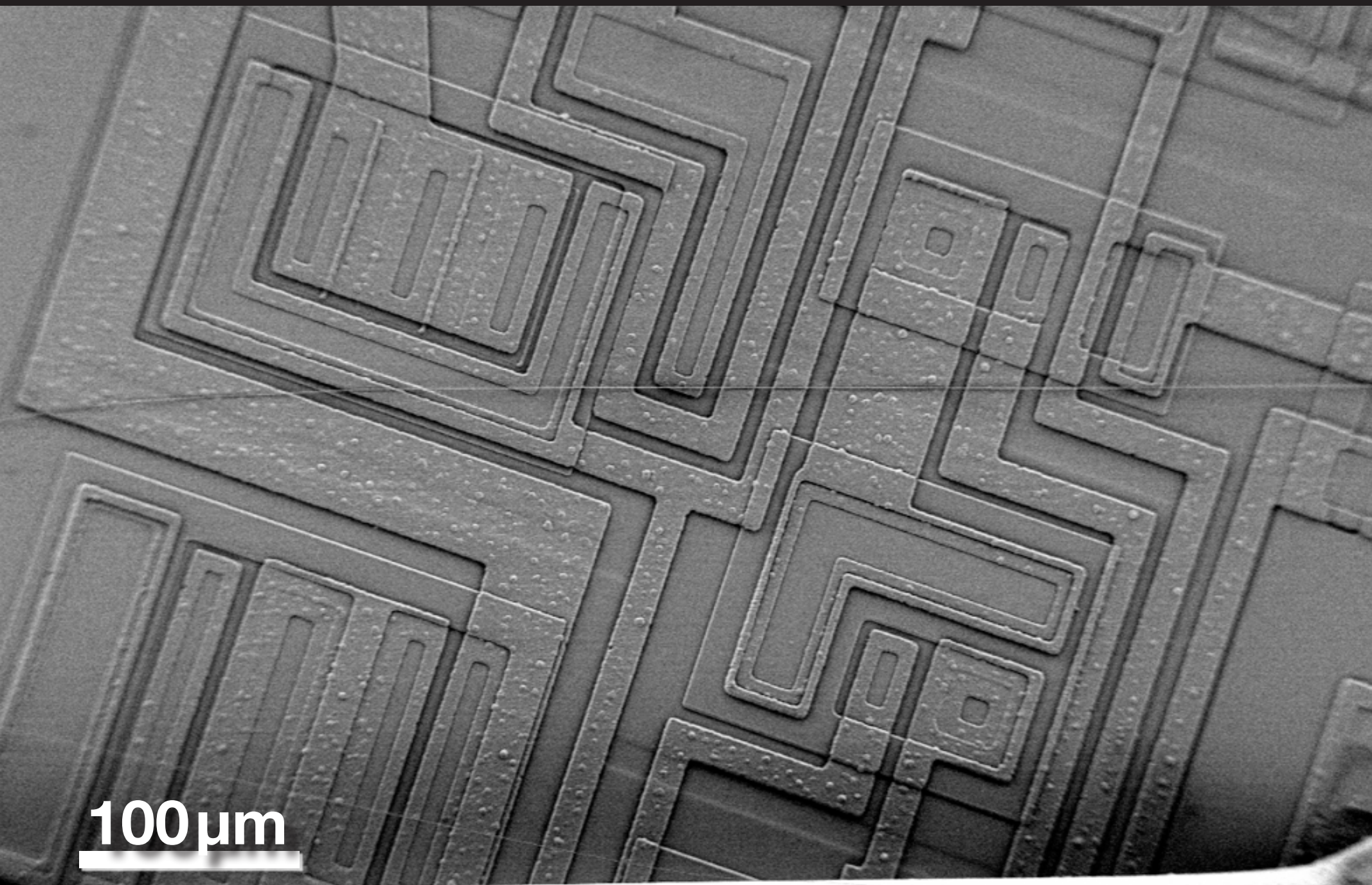


200 μm

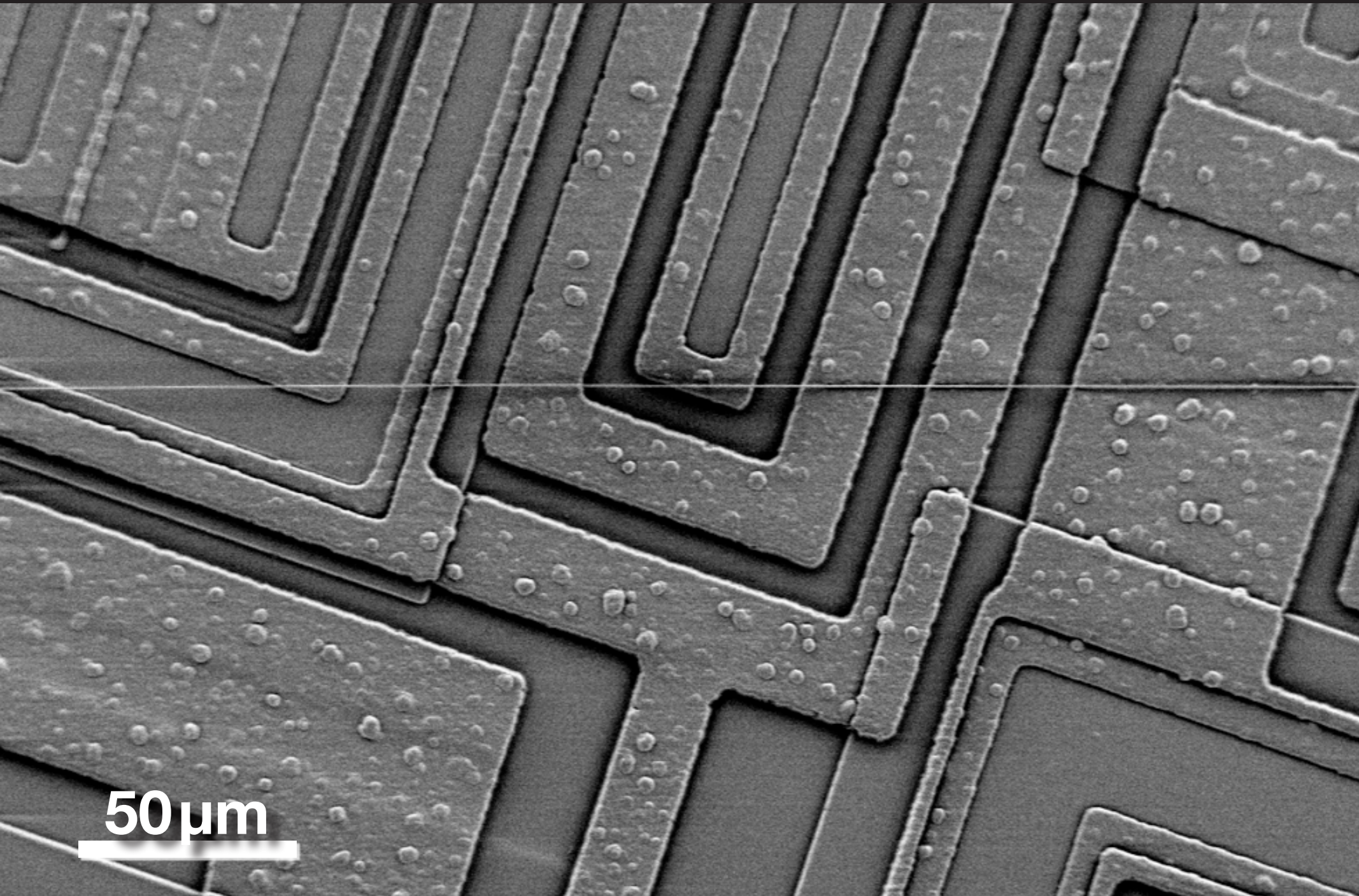
Nanowire fabrication



Nanowire fabrication



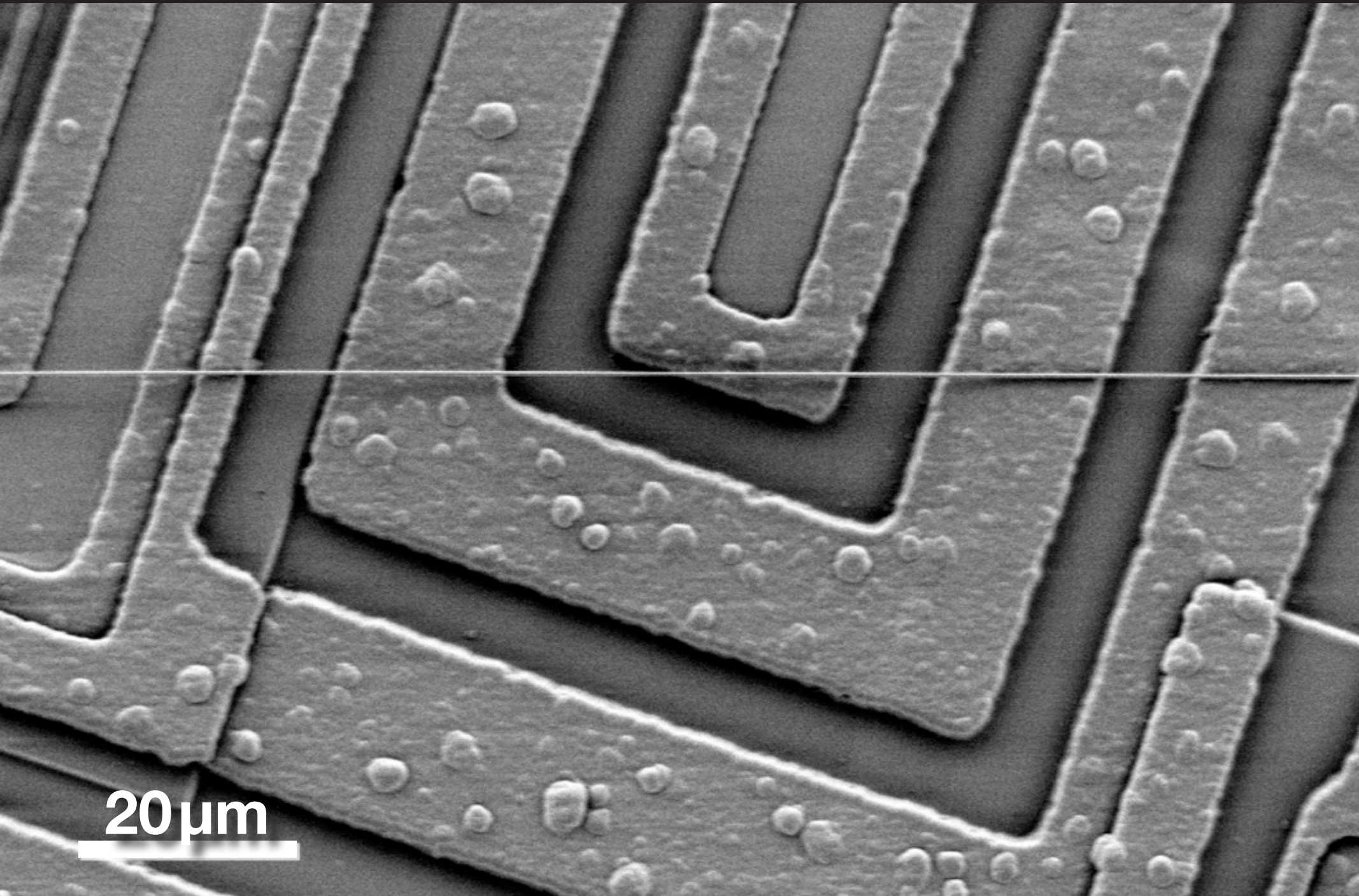
Nanowire fabrication



50 μm

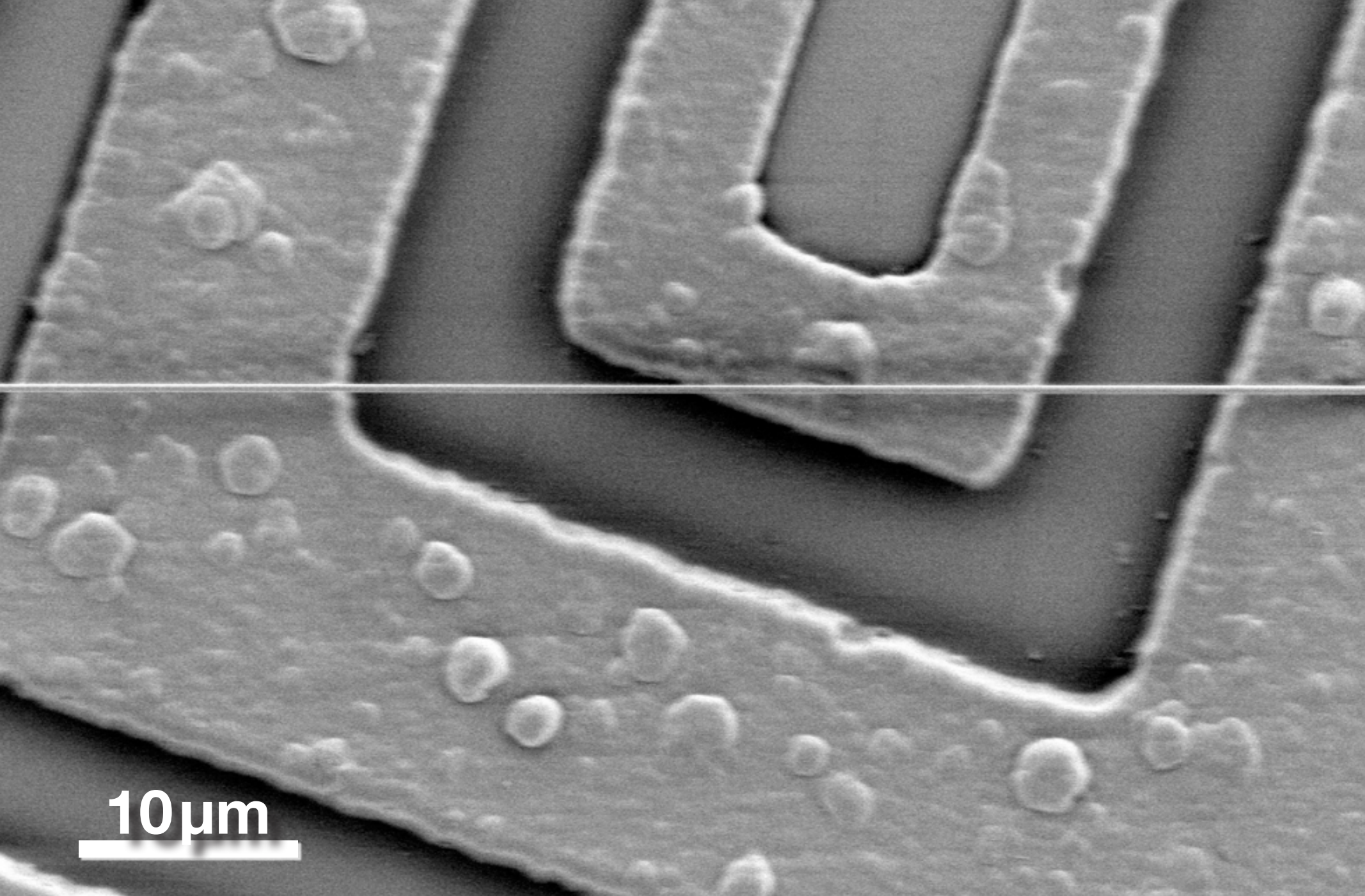


Nanowire fabrication



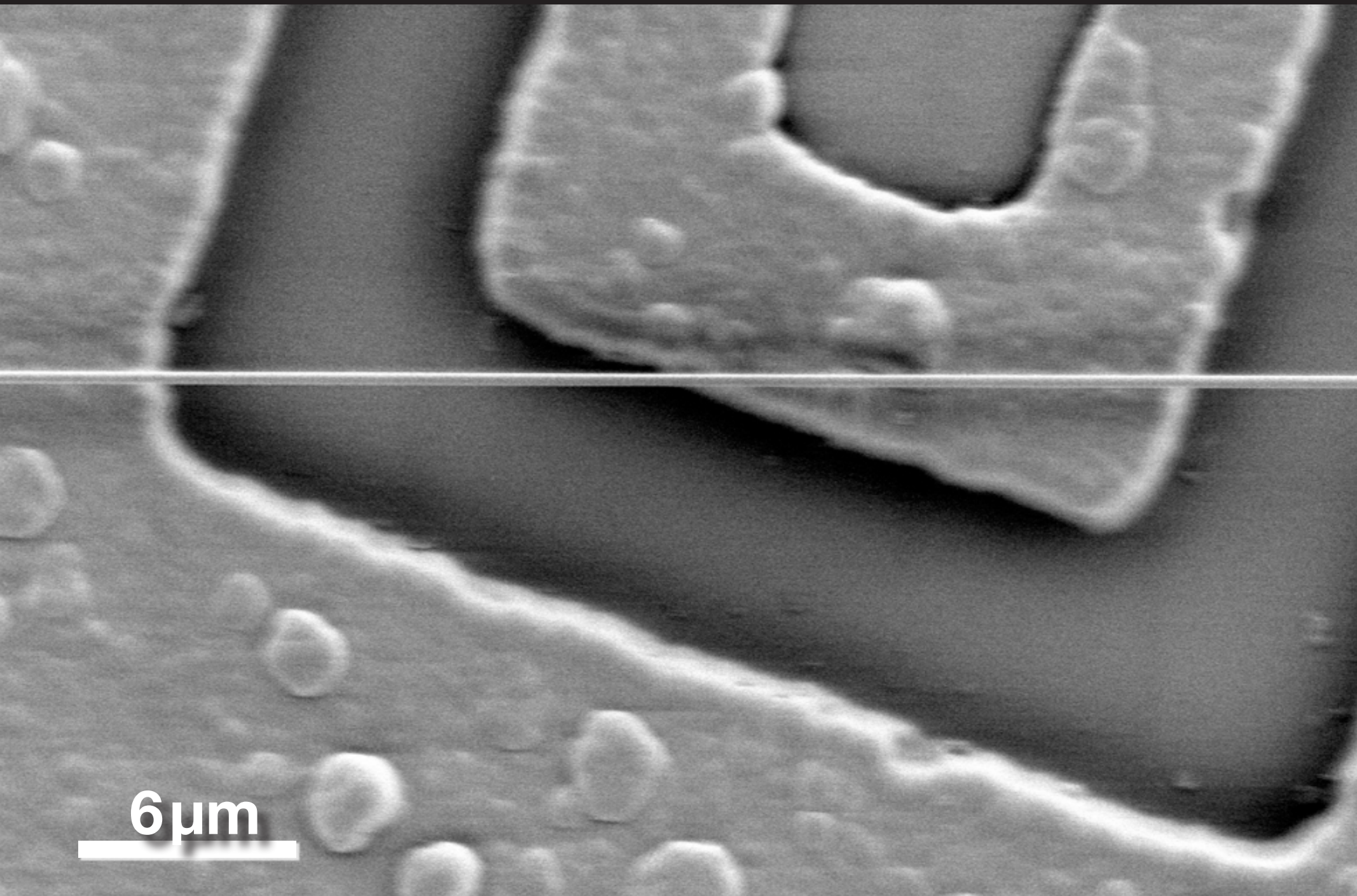
20 μm

Nanowire fabrication



10 μm

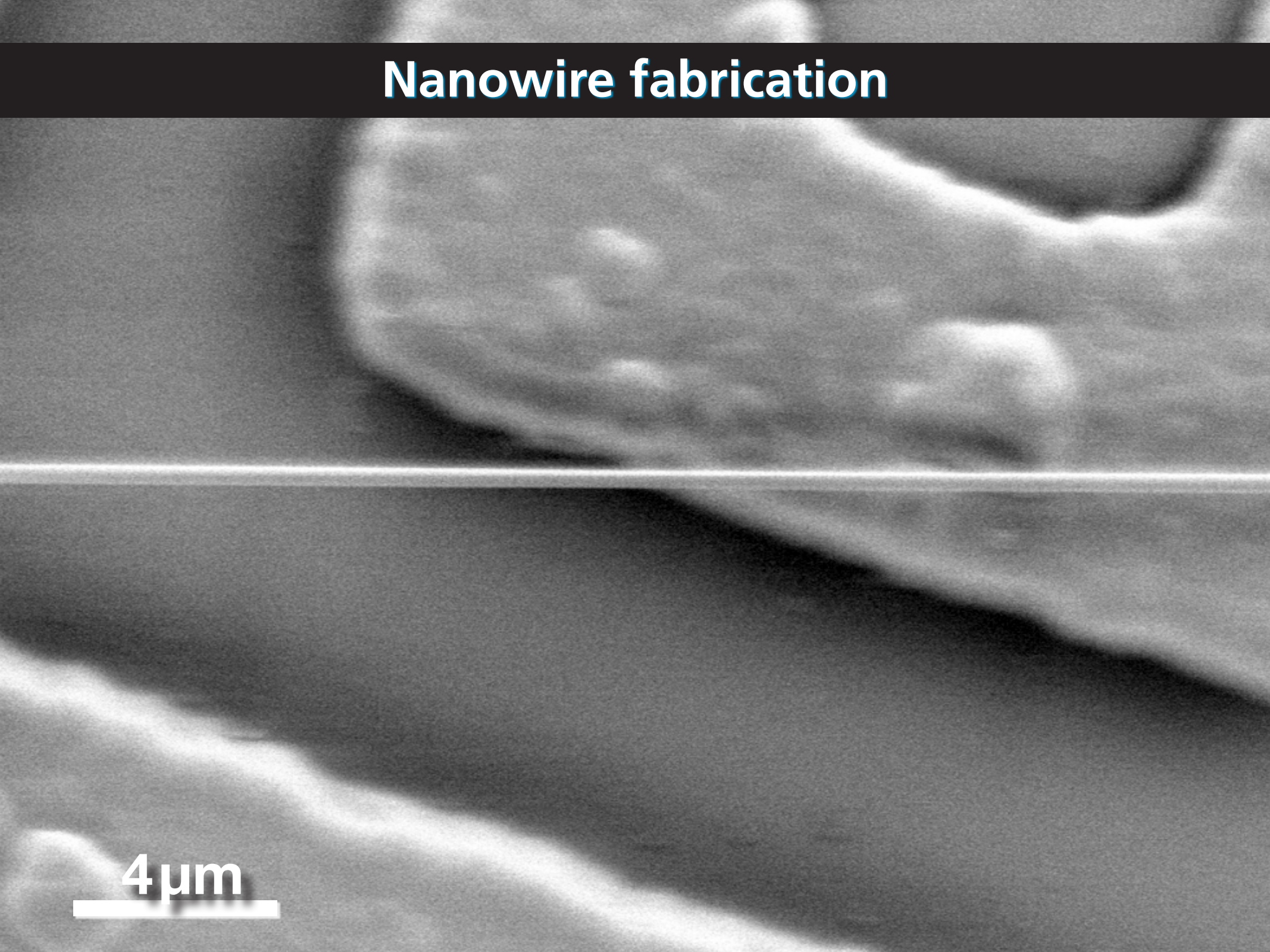
Nanowire fabrication



6 μm



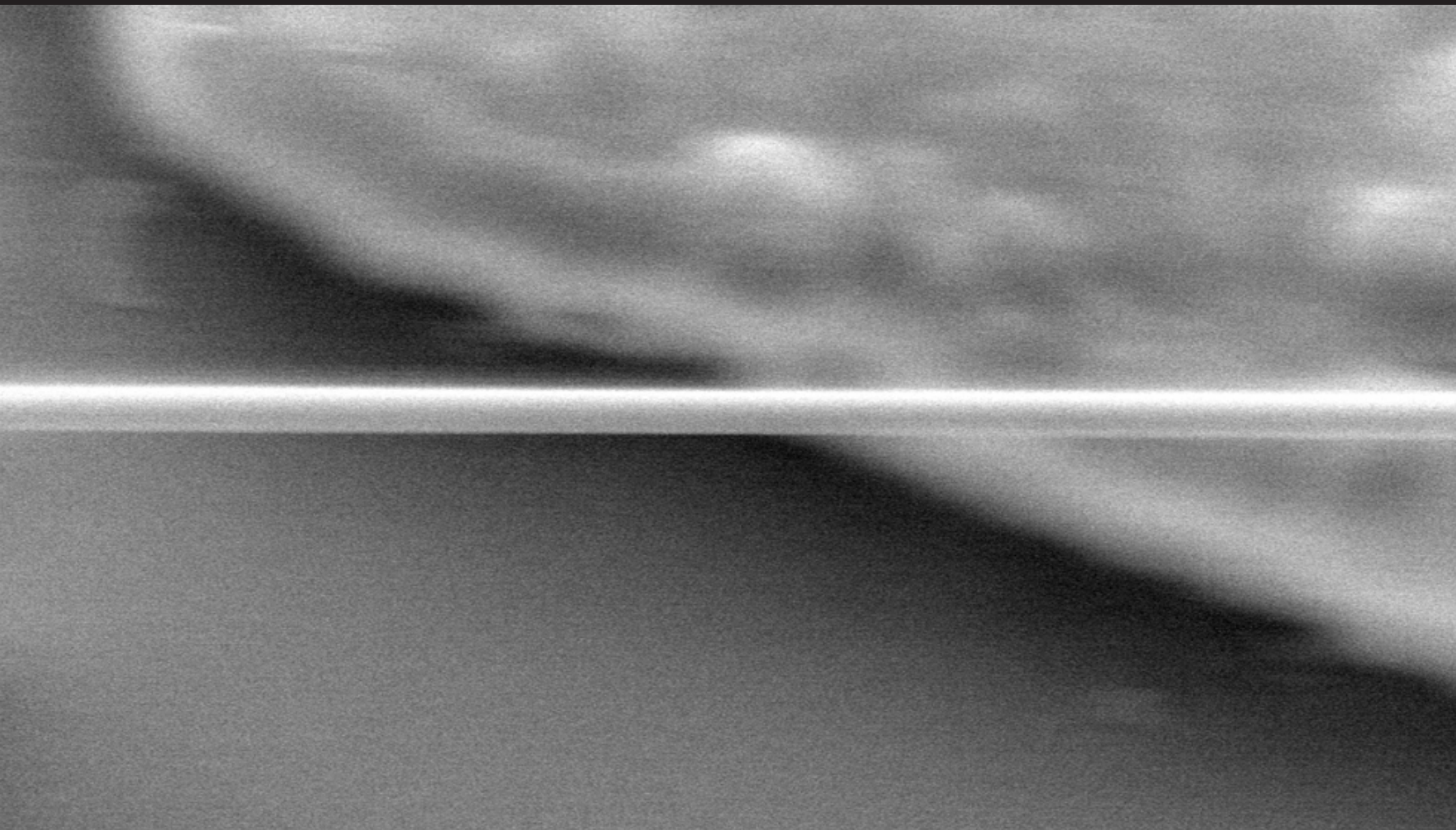
Nanowire fabrication



4 μm



Nanowire fabrication



2 μm

Nanowire fabrication

312 nm

A transmission electron micrograph (TEM) showing a single, long, cylindrical nanowire. The nanowire is oriented horizontally and appears as a bright, uniform line against a dark background. A vertical white line with a crossbar at the bottom is drawn across the nanowire to indicate its diameter. The text '312 nm' is placed above this vertical line. In the bottom left corner, there is a horizontal white scale bar with the text '1 μm' above it.

1 μm

Waveguiding

Specifications

diameter D : down to 20 nm

length L : up to 90 mm

aspect ratio D/L : up to 10^6

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

Nanowire fabrication

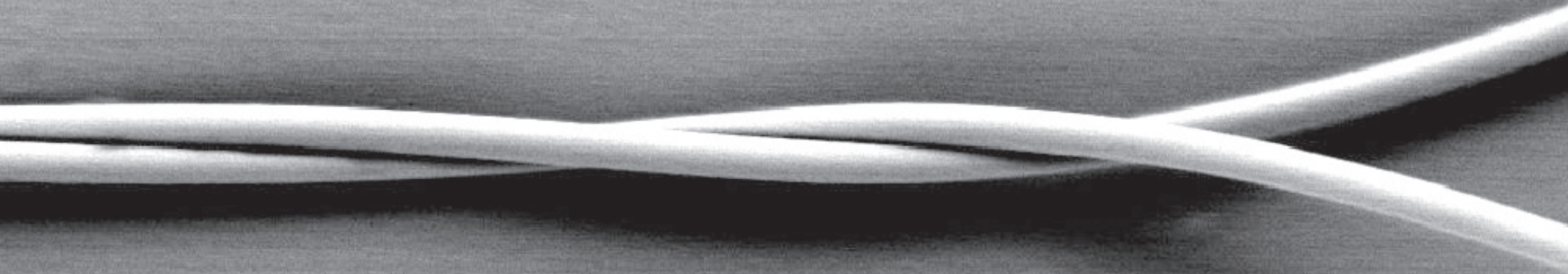
$d = 260 \text{ nm}$

$L = 4 \text{ mm}$

50 μm



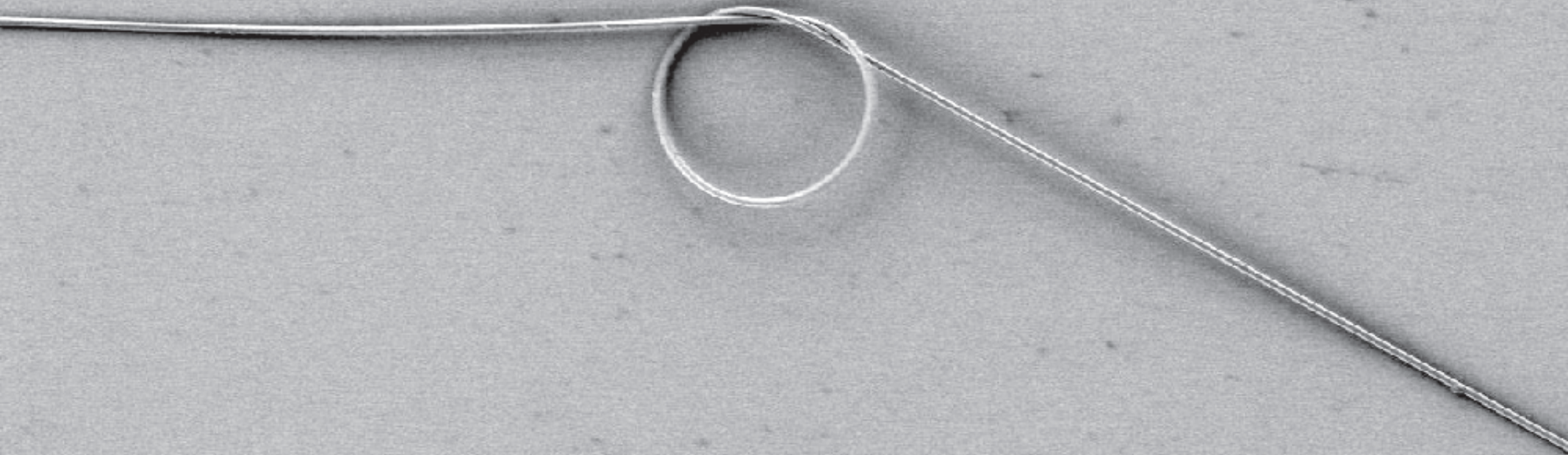
Nanowire fabrication



2 μm



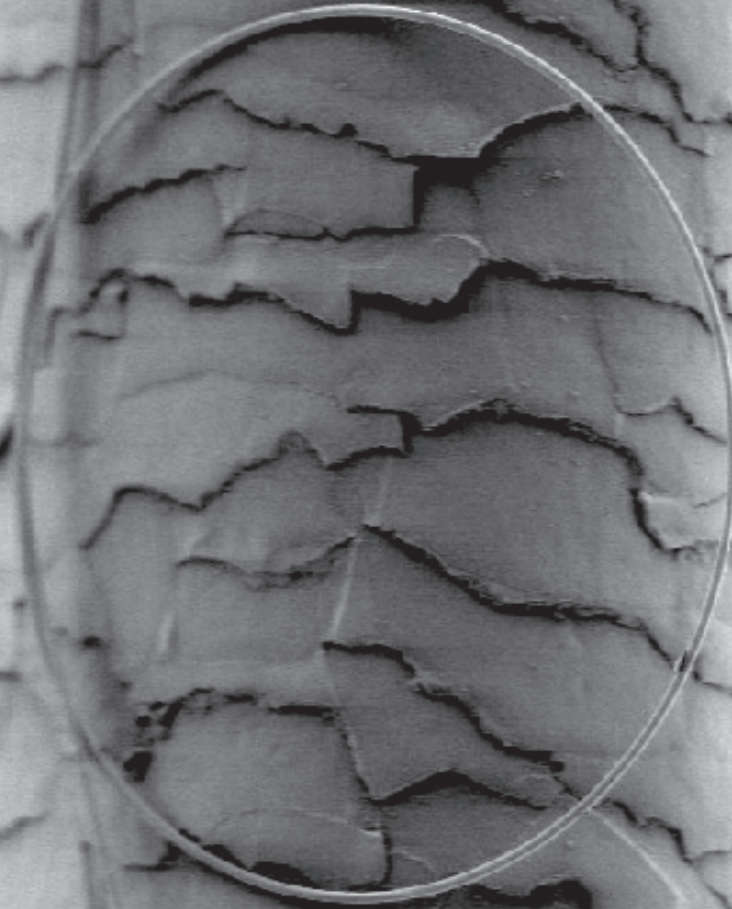
Nanowire fabrication



20 μm



Nanowire fabrication

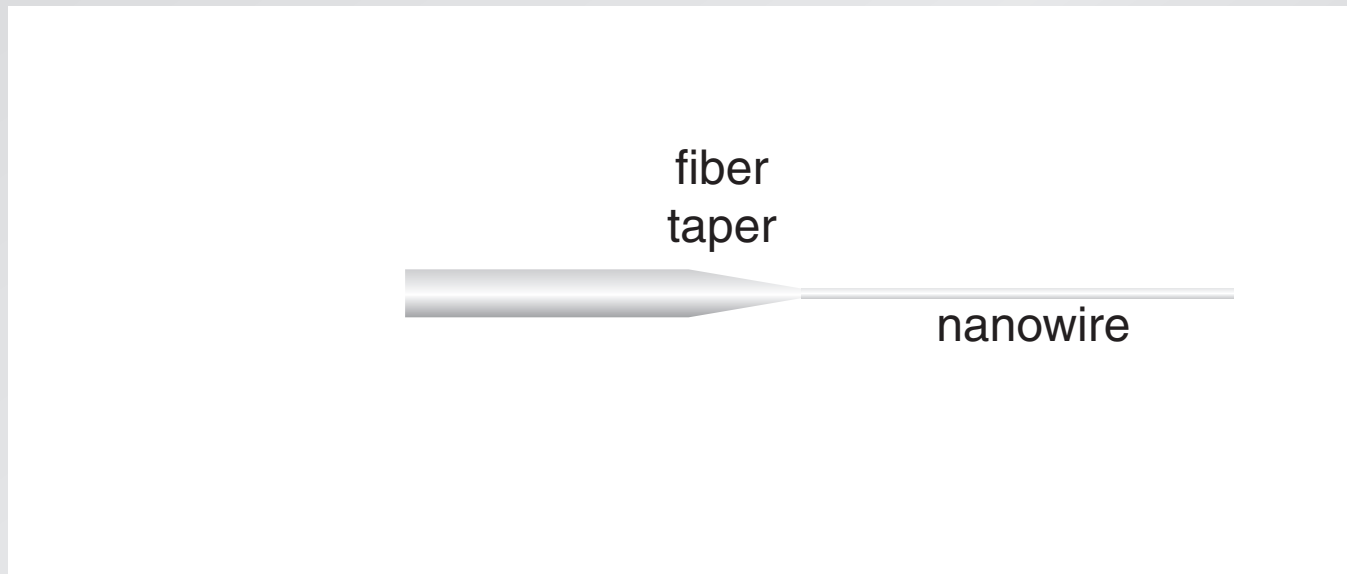


20 μm



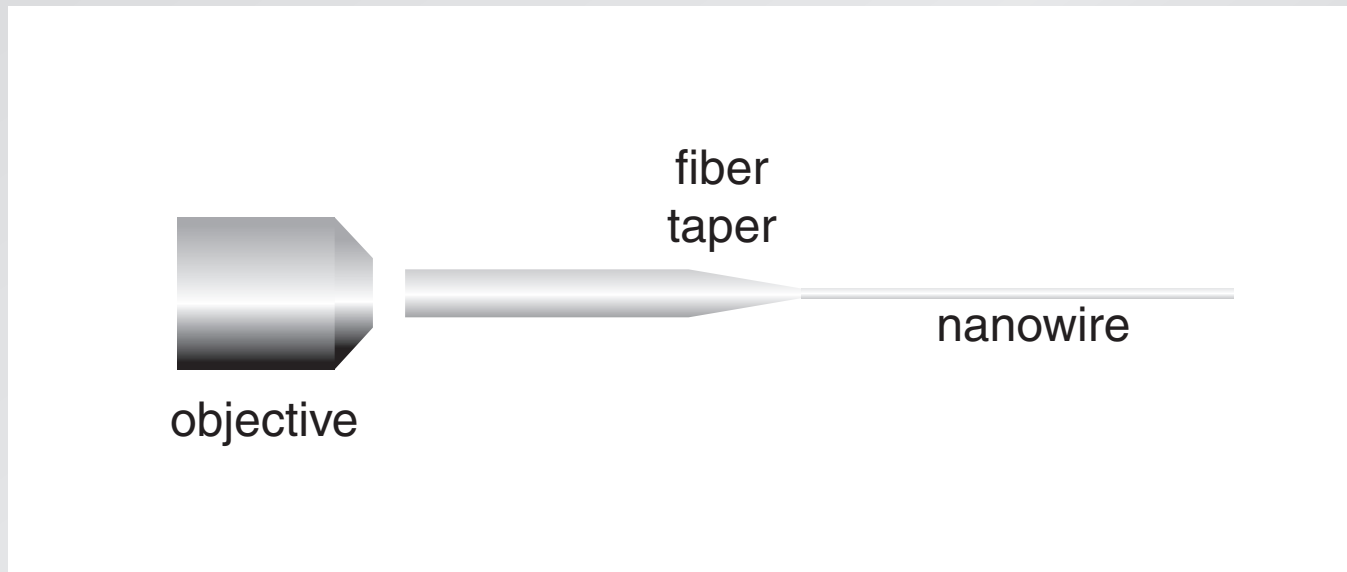
Optical properties

coupling light into nanowires



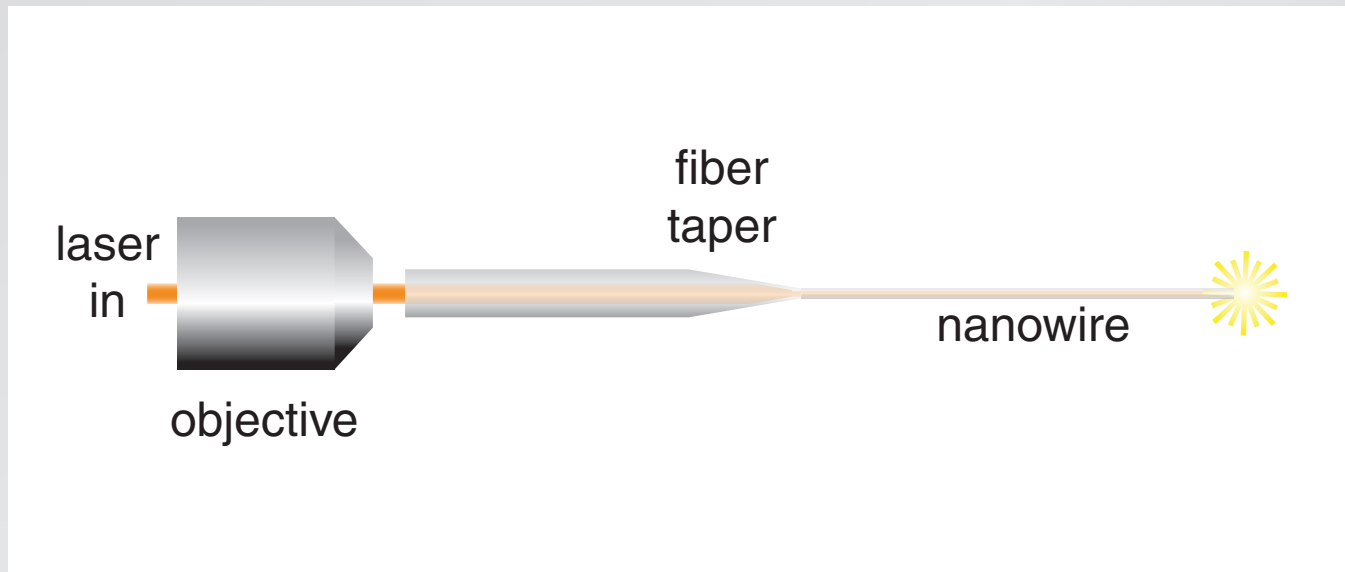
Optical properties

coupling light into nanowires



Optical properties

coupling light into nanowires



Optical properties

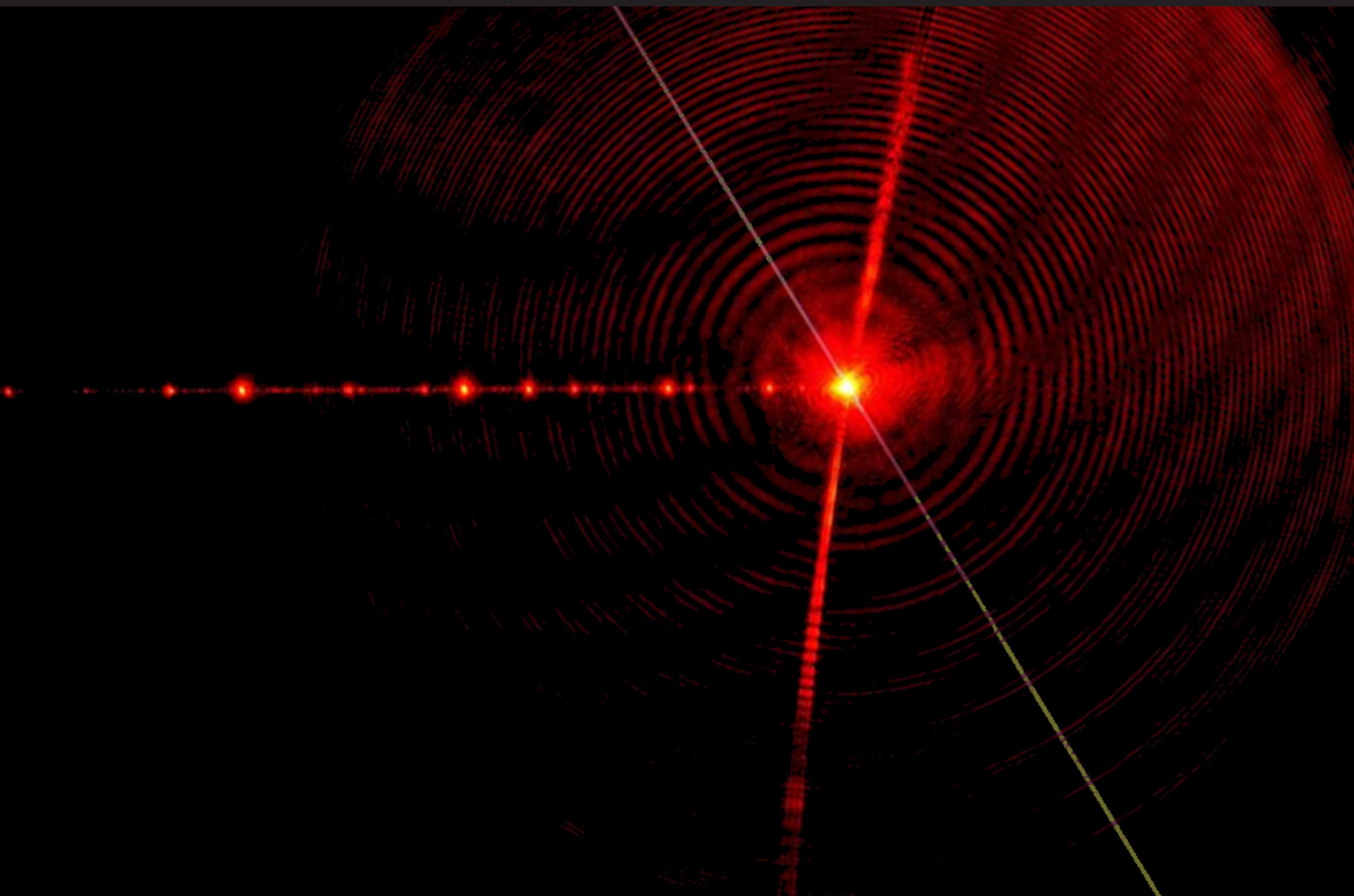
280-nm nanowire



360 nm

450 nm

Optical properties

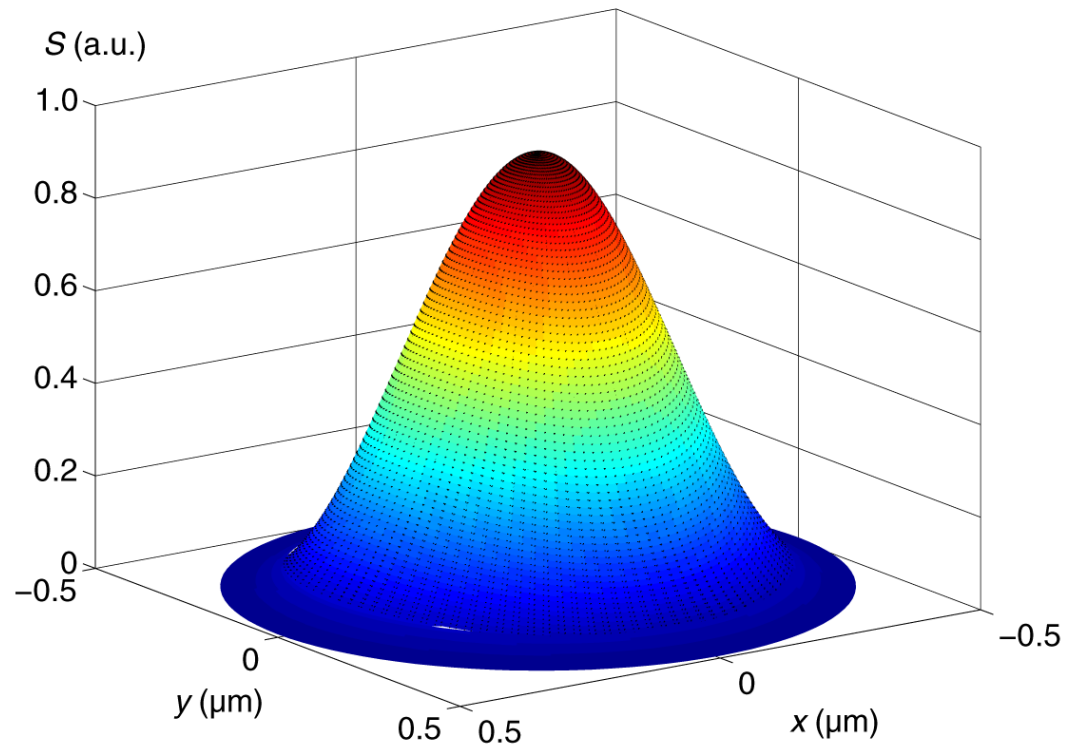


Optical properties



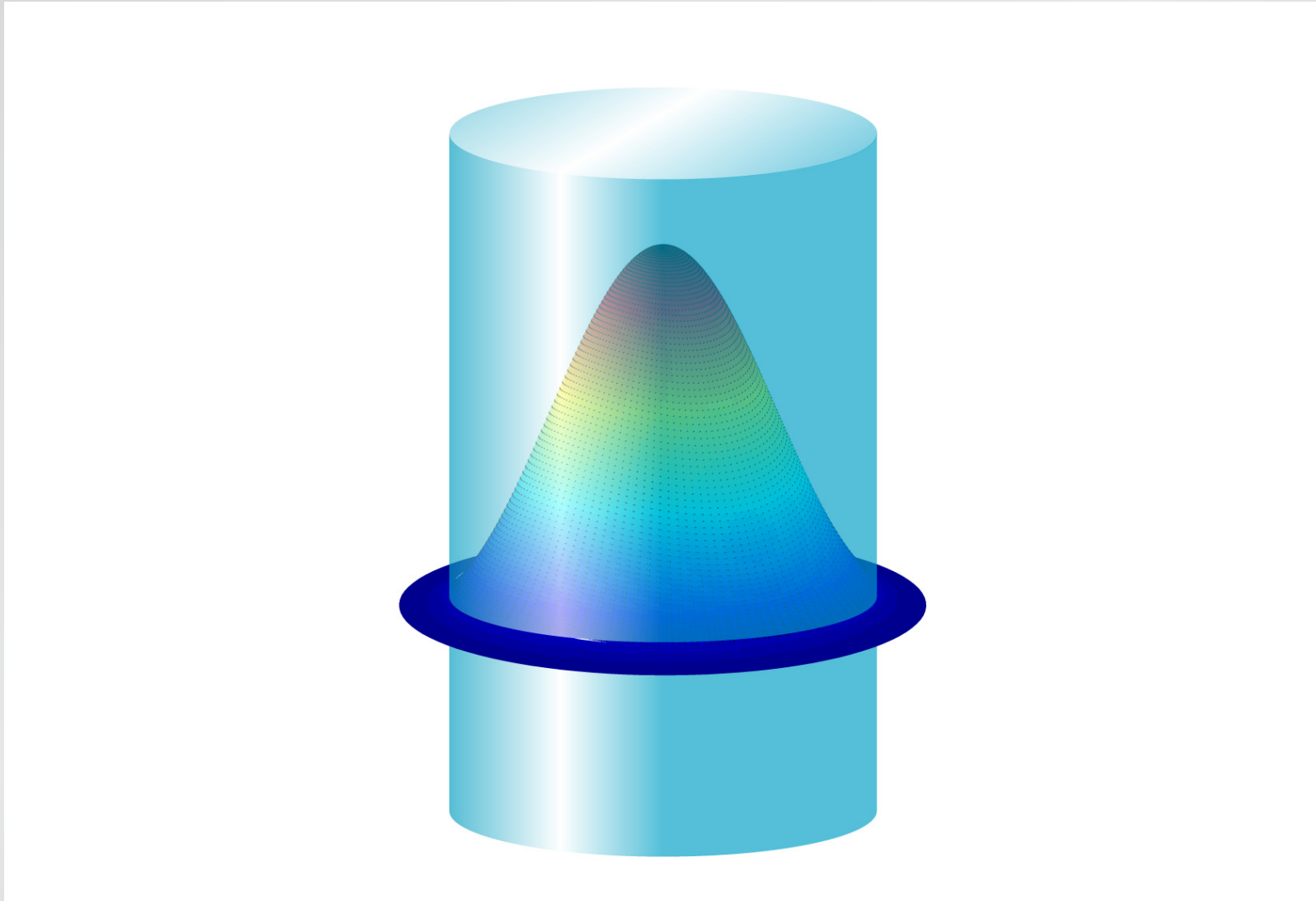
Optical properties

Poynting vector profile for 800-nm nanowire



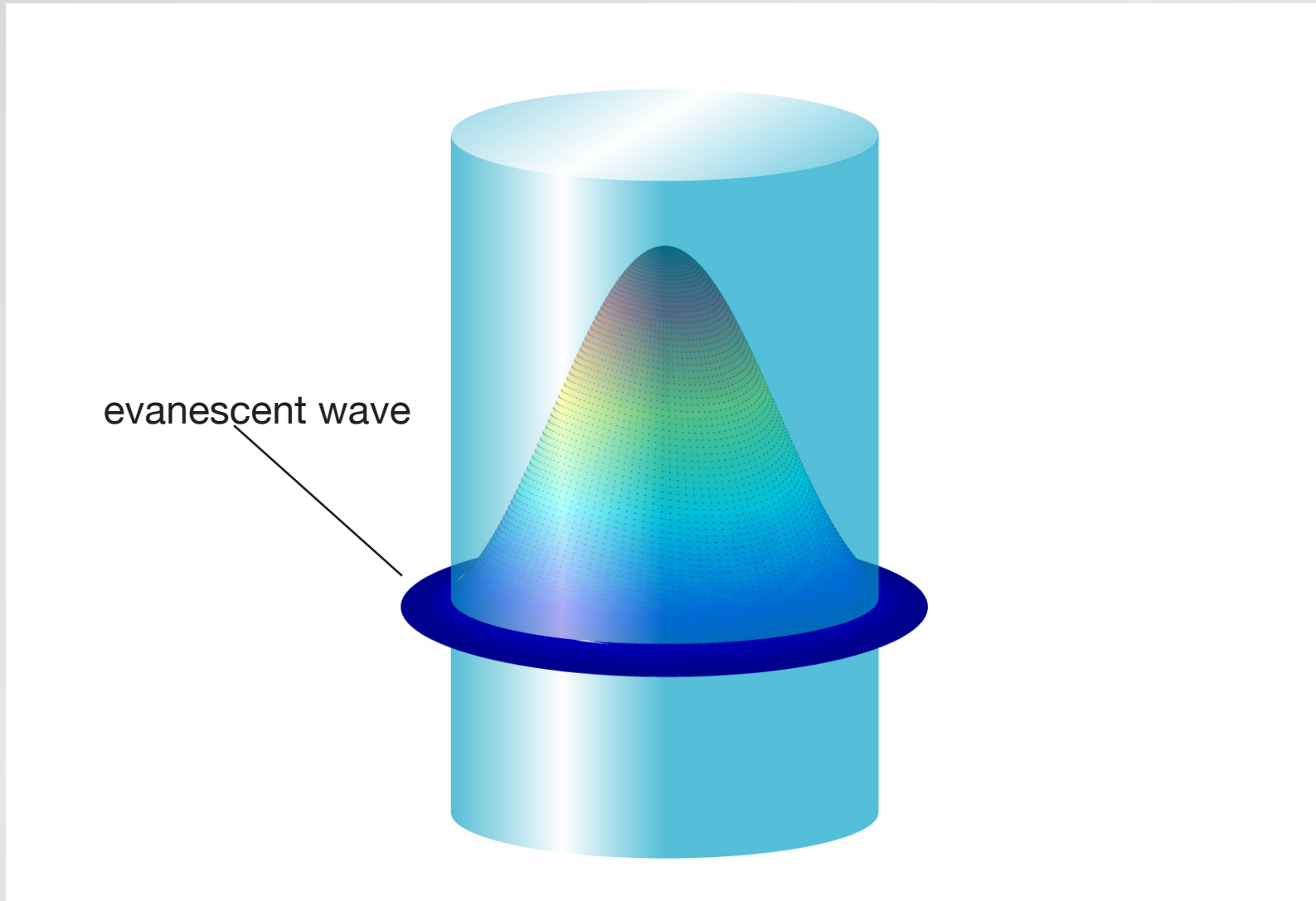
Optical properties

Poynting vector profile for 800-nm nanowire



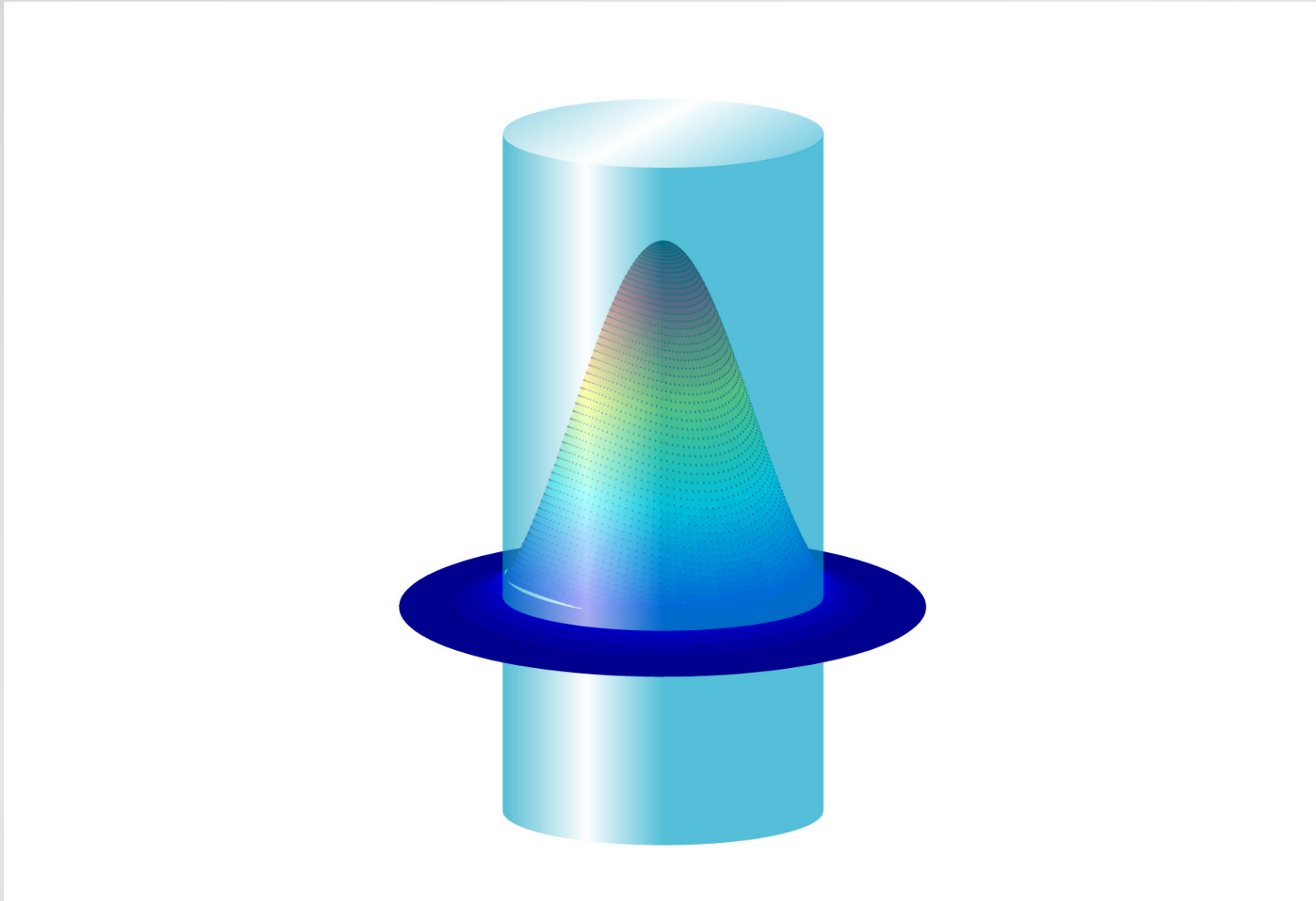
Optical properties

Poynting vector profile for 800-nm nanowire



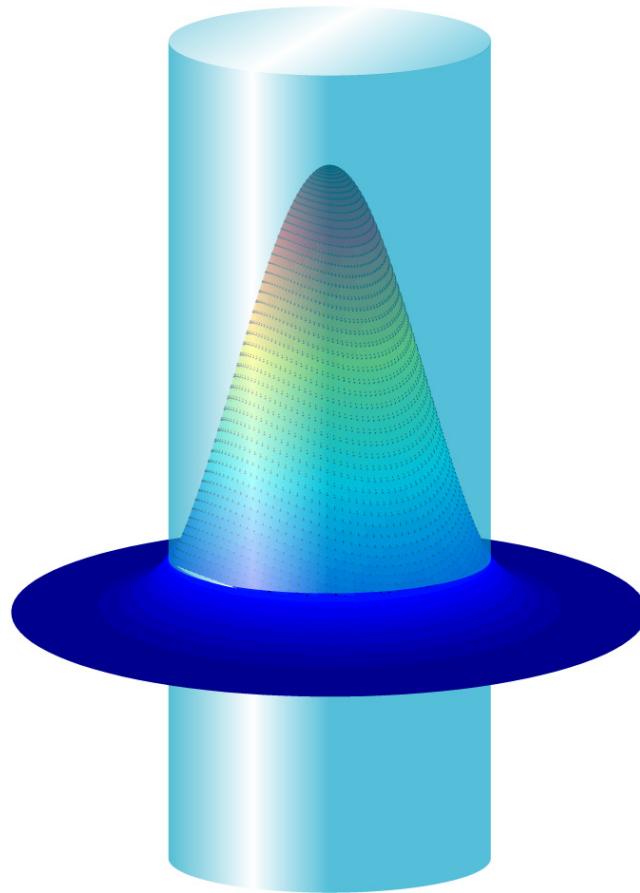
Optical properties

Poynting vector profile for 600-nm nanowire



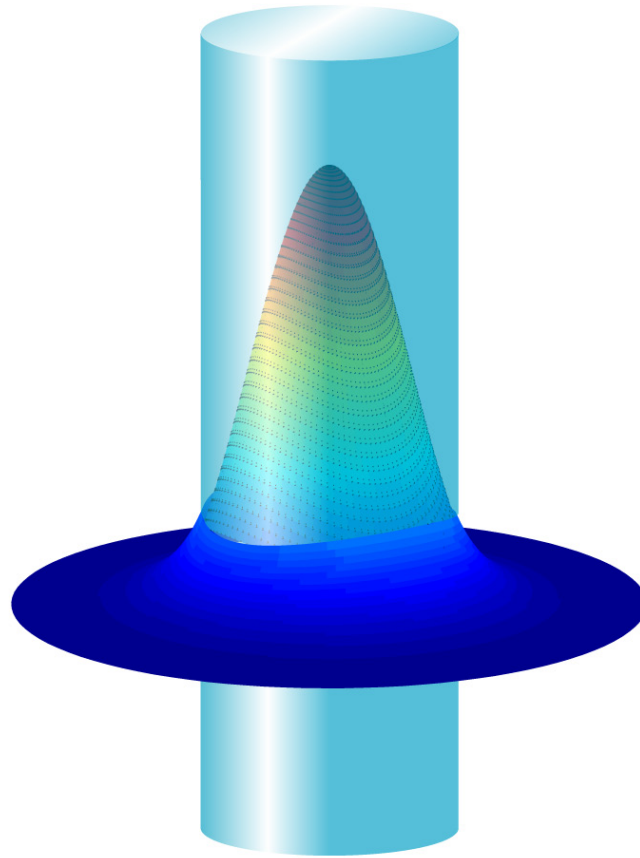
Optical properties

Poynting vector profile for 500-nm nanowire



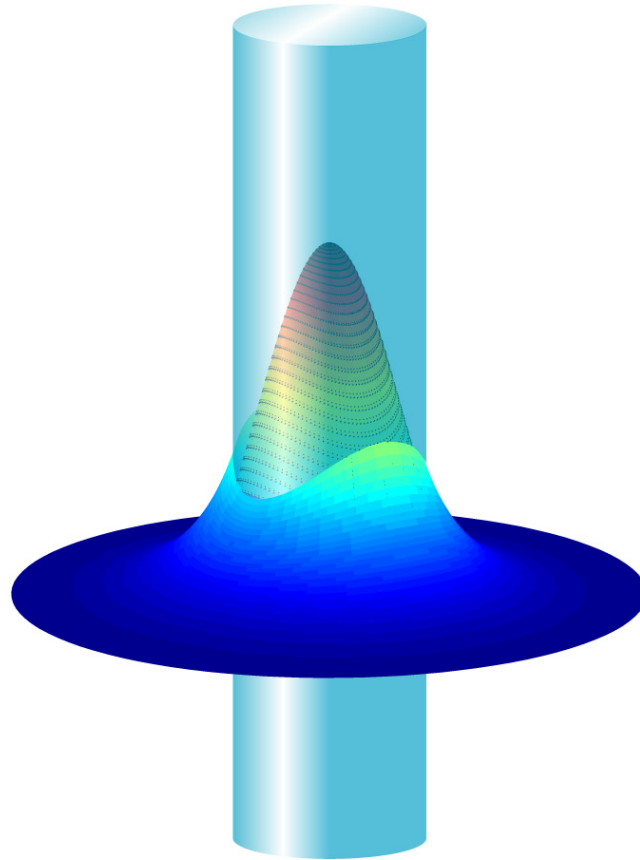
Optical properties

Poynting vector profile for 400-nm nanowire



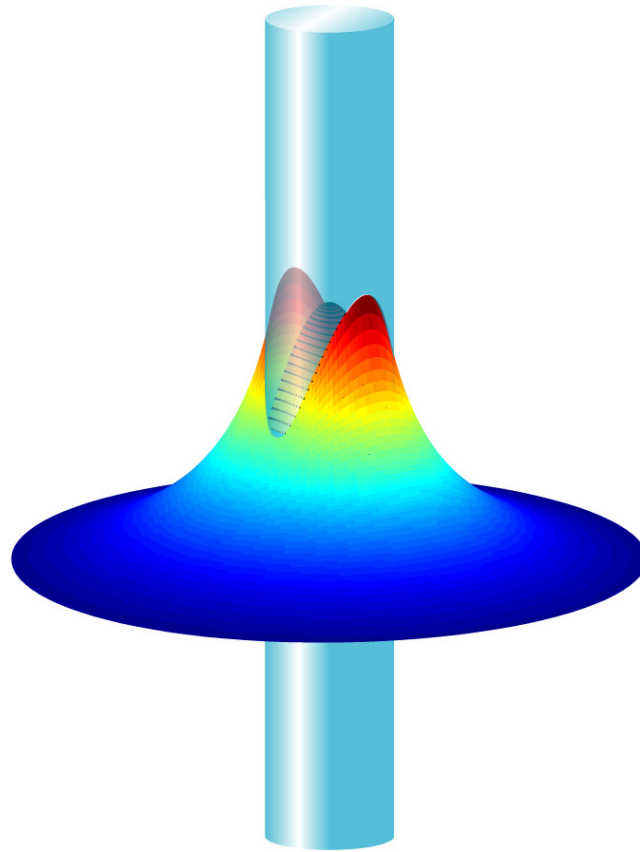
Optical properties

Poynting vector profile for 300-nm nanowire



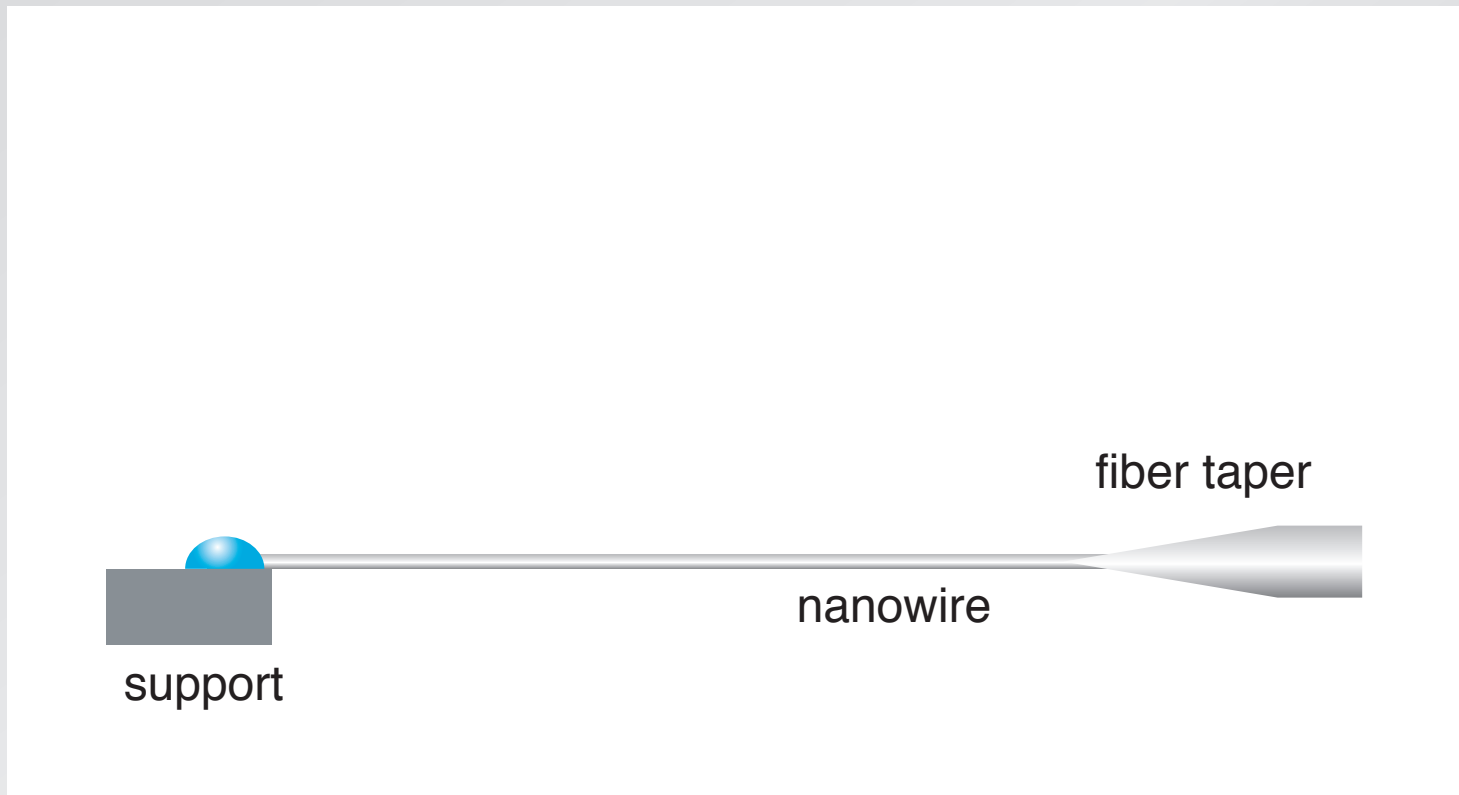
Optical properties

Poynting vector profile for 200-nm nanowire



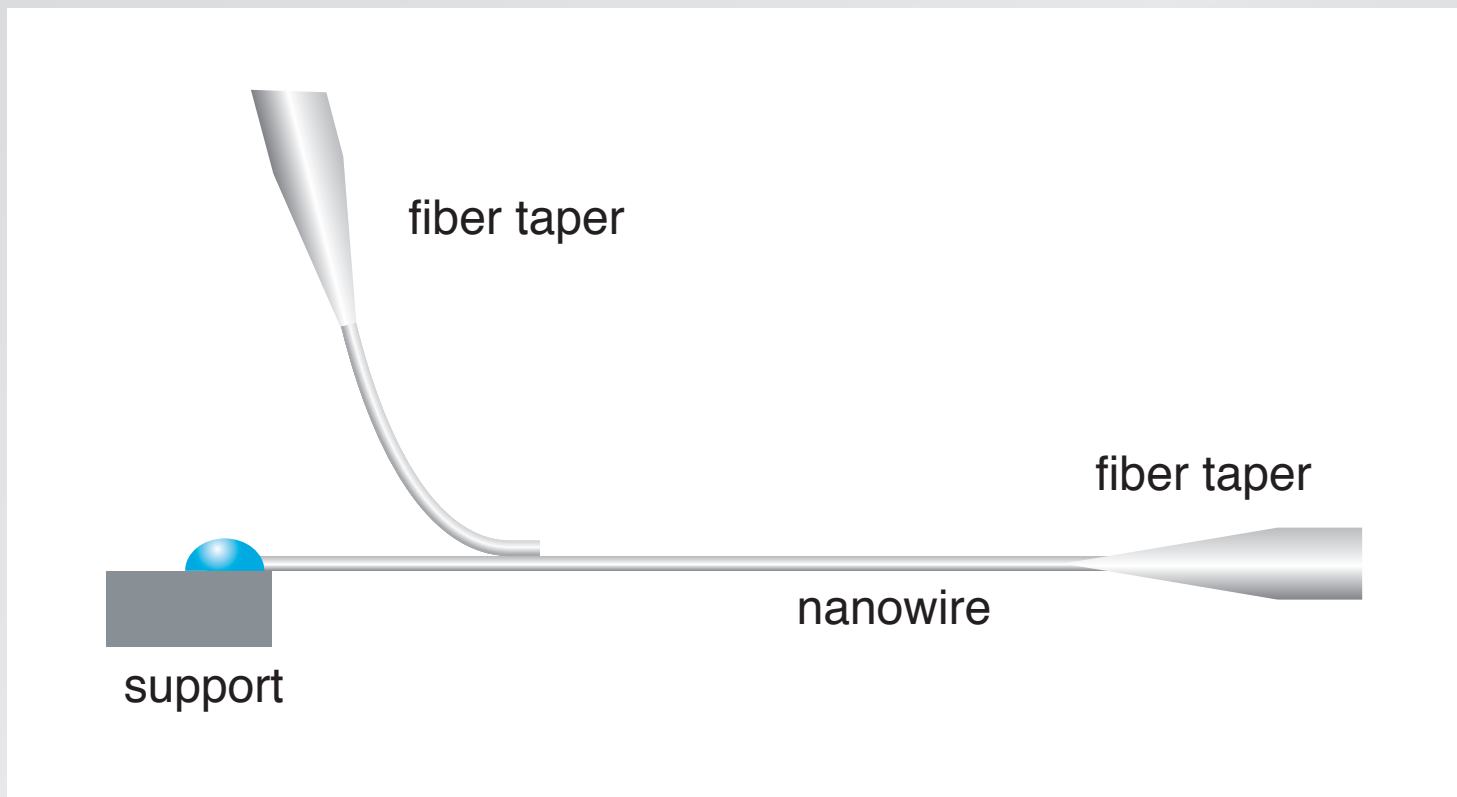
Optical properties

coupling light between nanowires



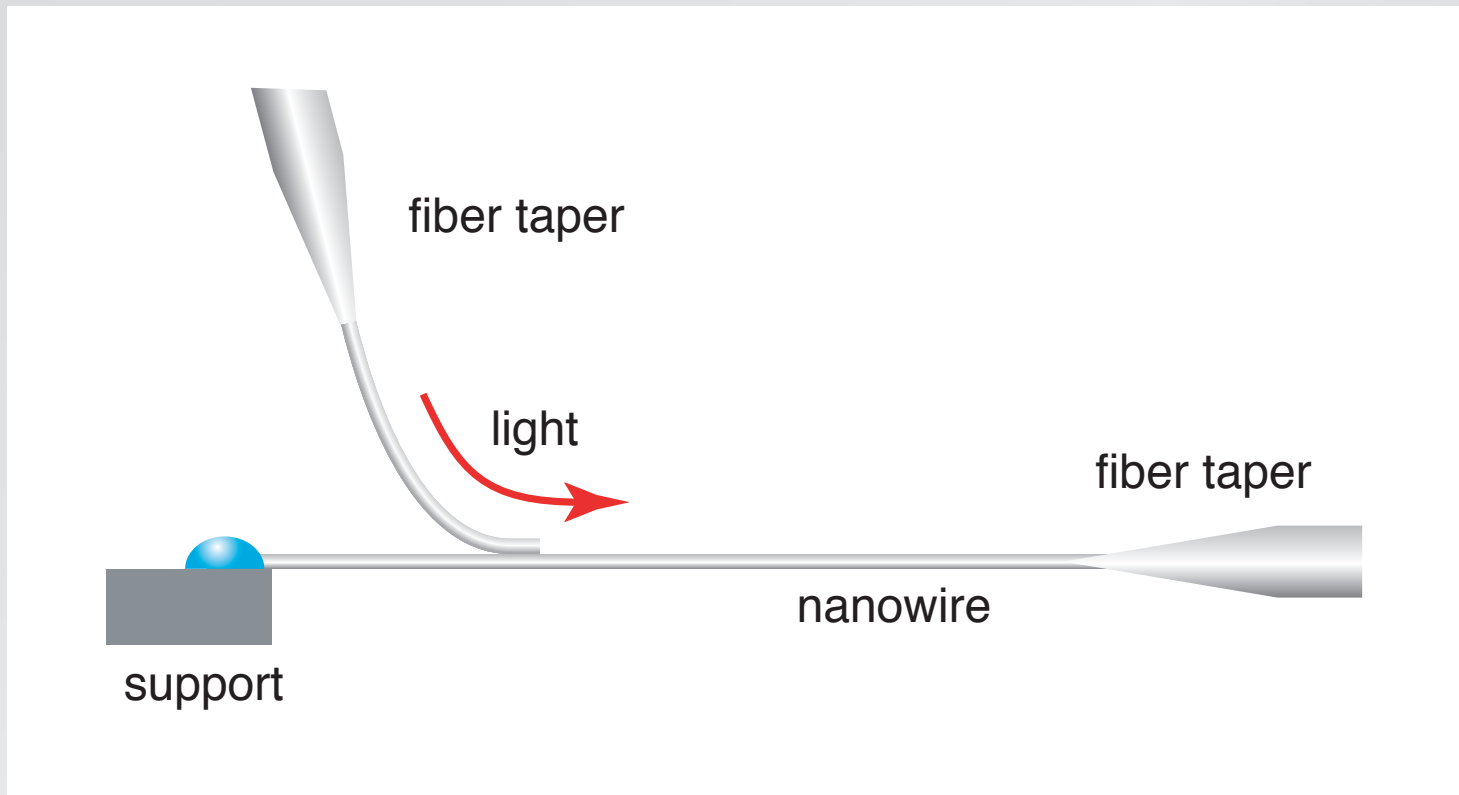
Optical properties

coupling light between nanowires

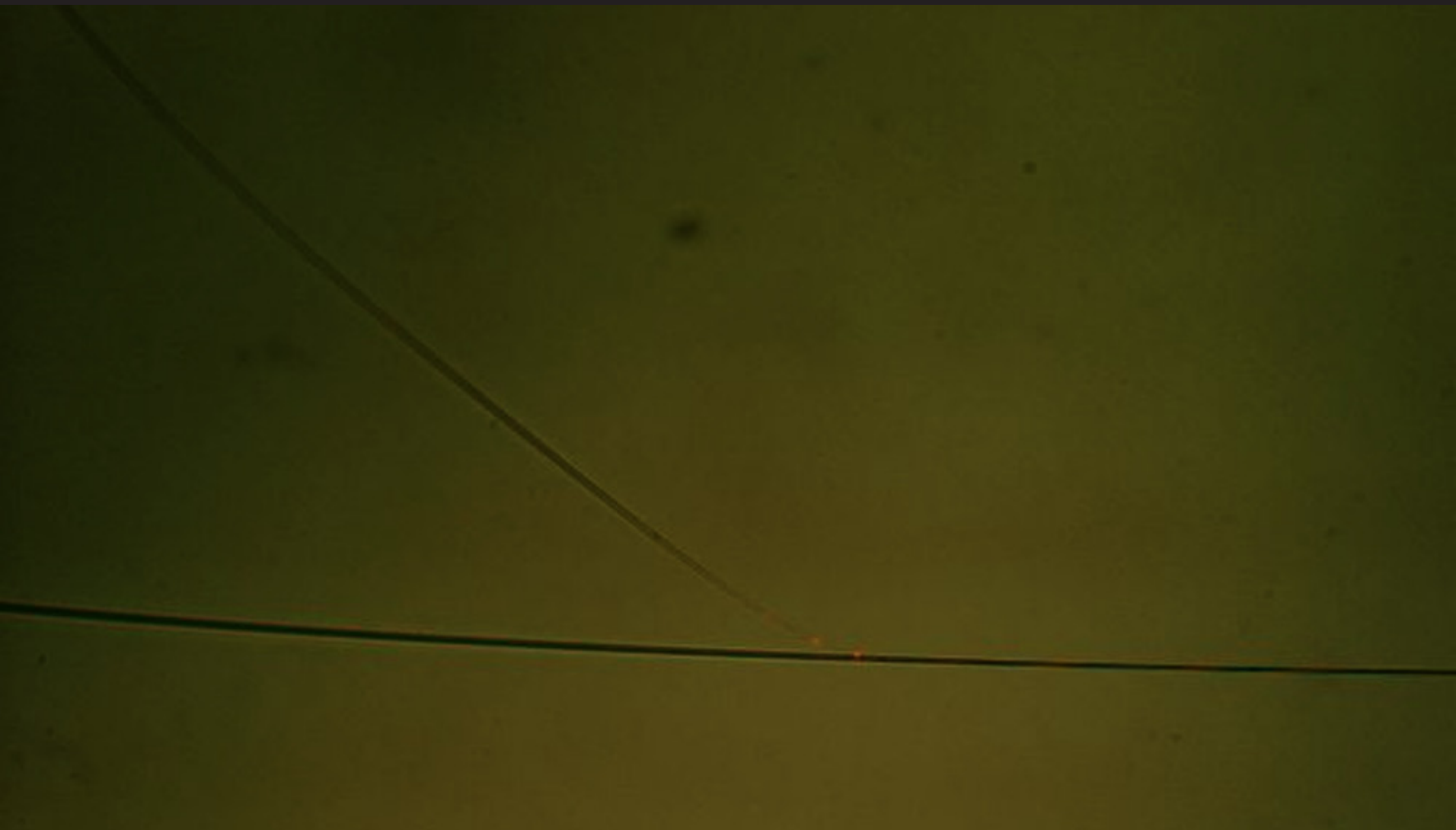


Optical properties

coupling light between nanowires



Optical properties



50 μm

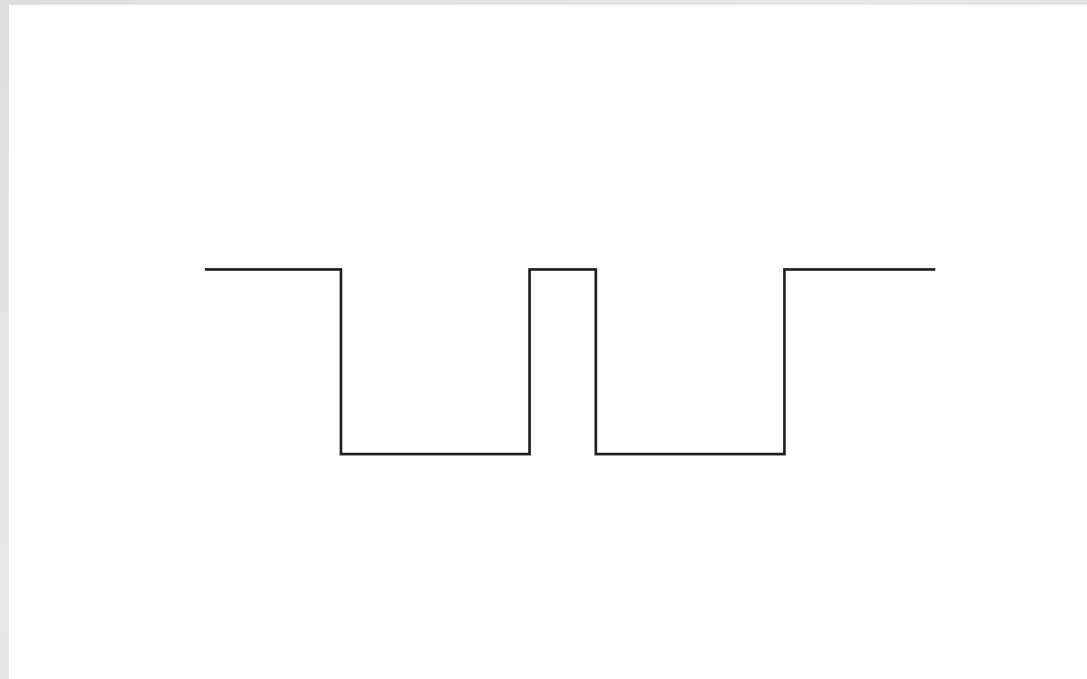
Optical properties



50 μm

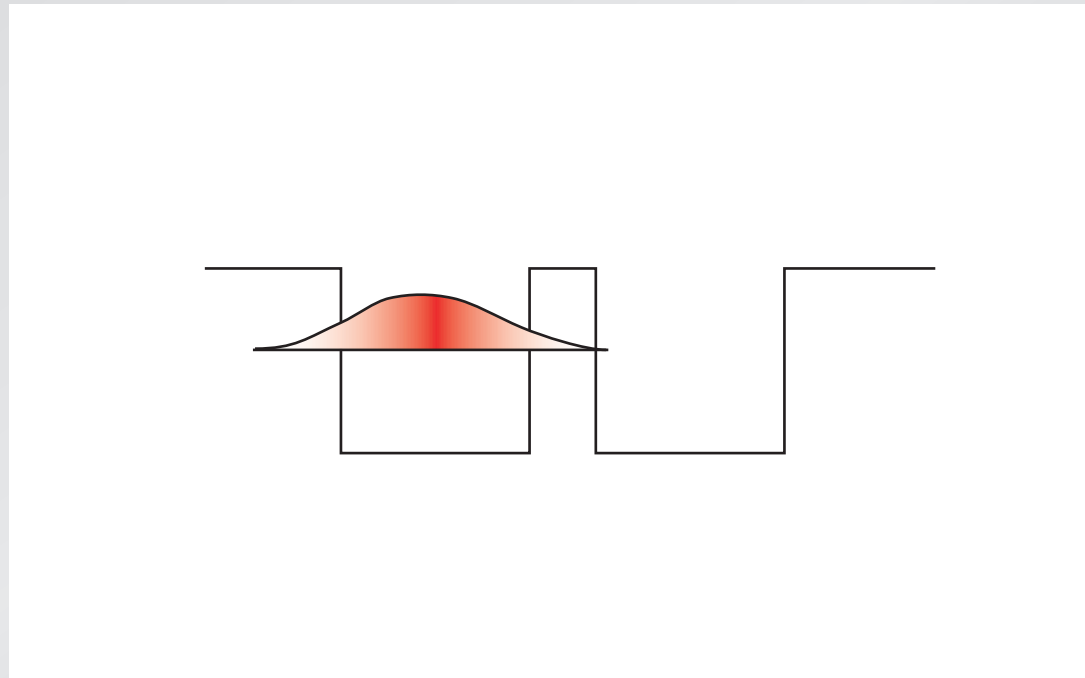
Optical properties

coupling light between nanowires



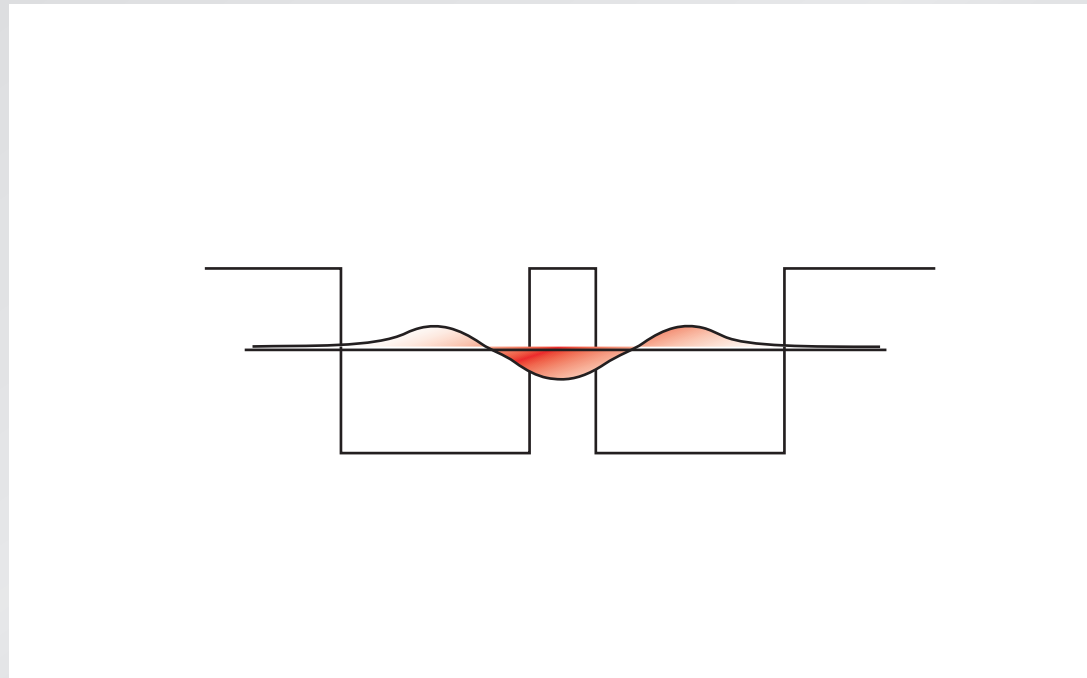
Optical properties

coupling light between nanowires



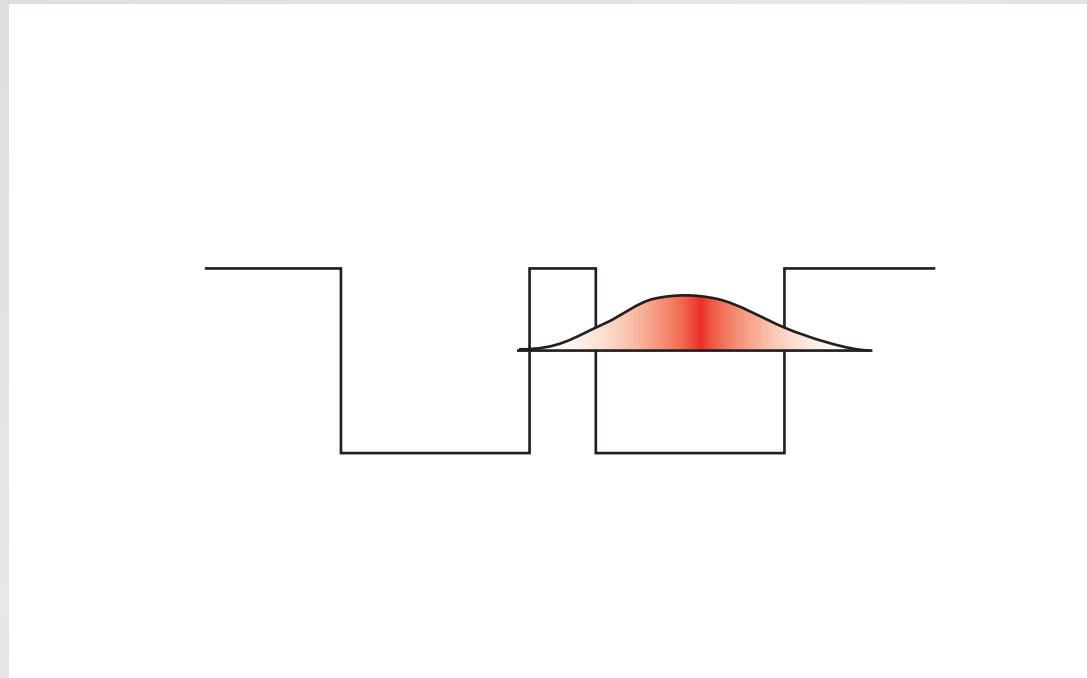
Optical properties

“tunneling” of light



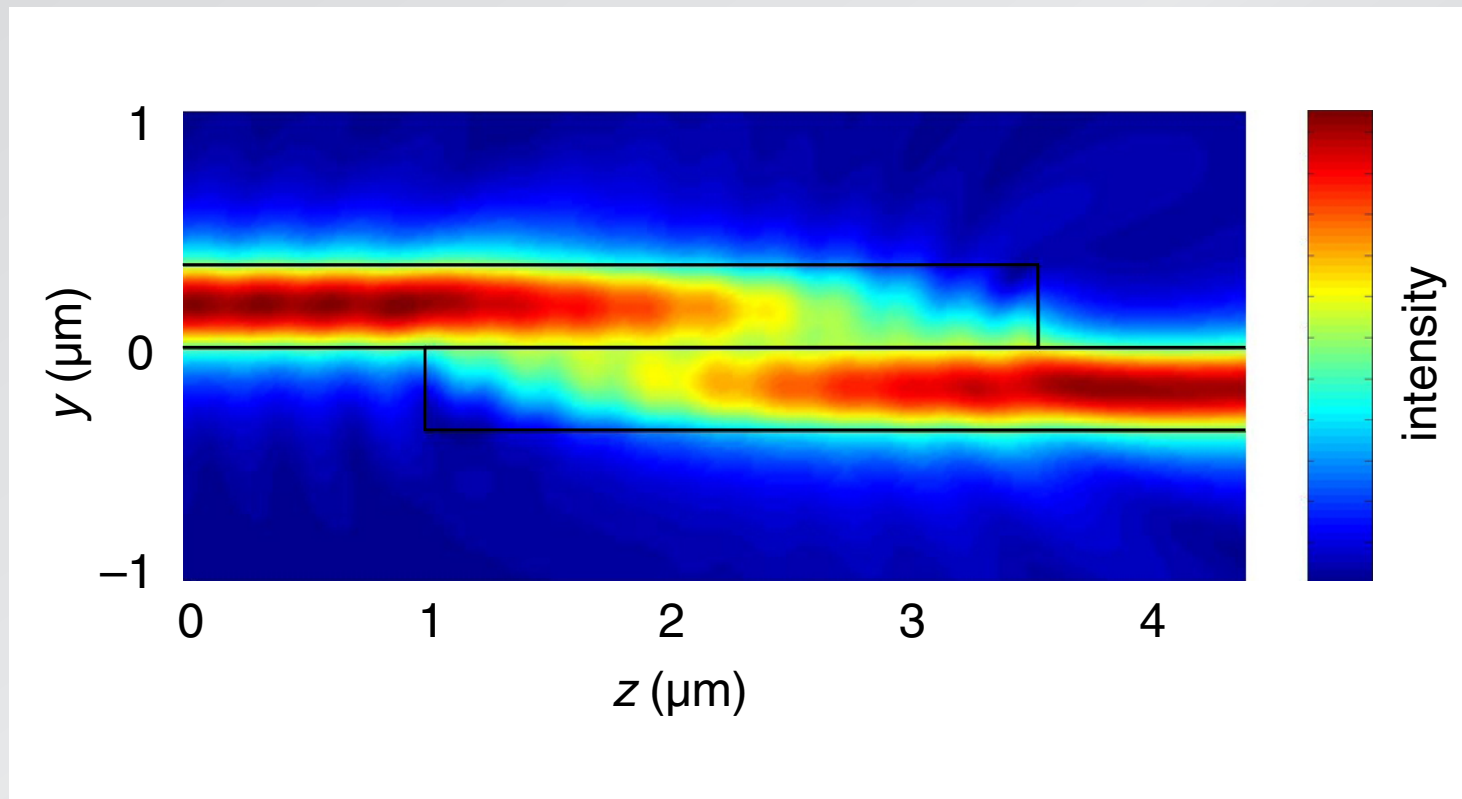
Optical properties

“tunneling” of light

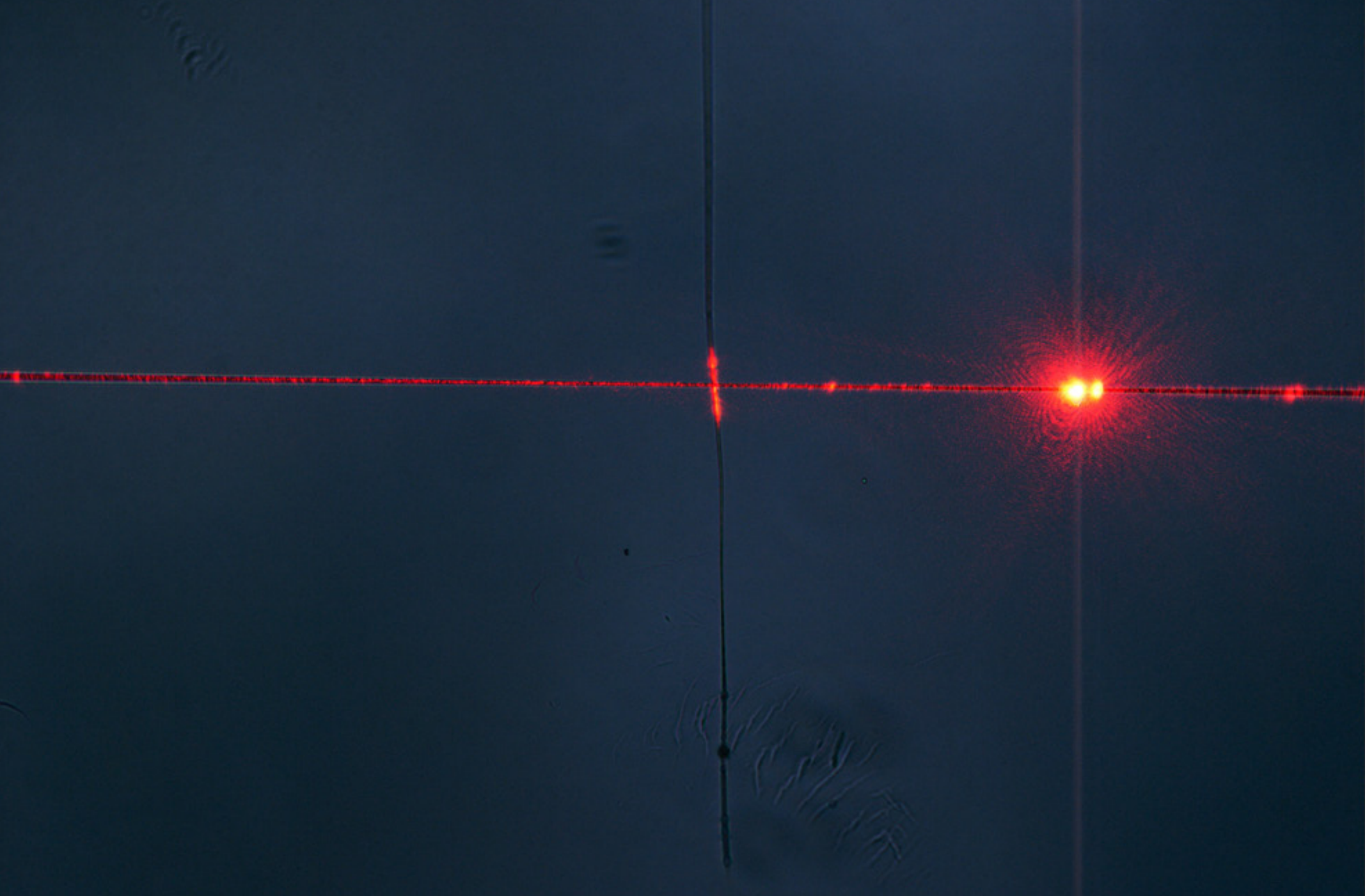


Optical properties

intensity distribution

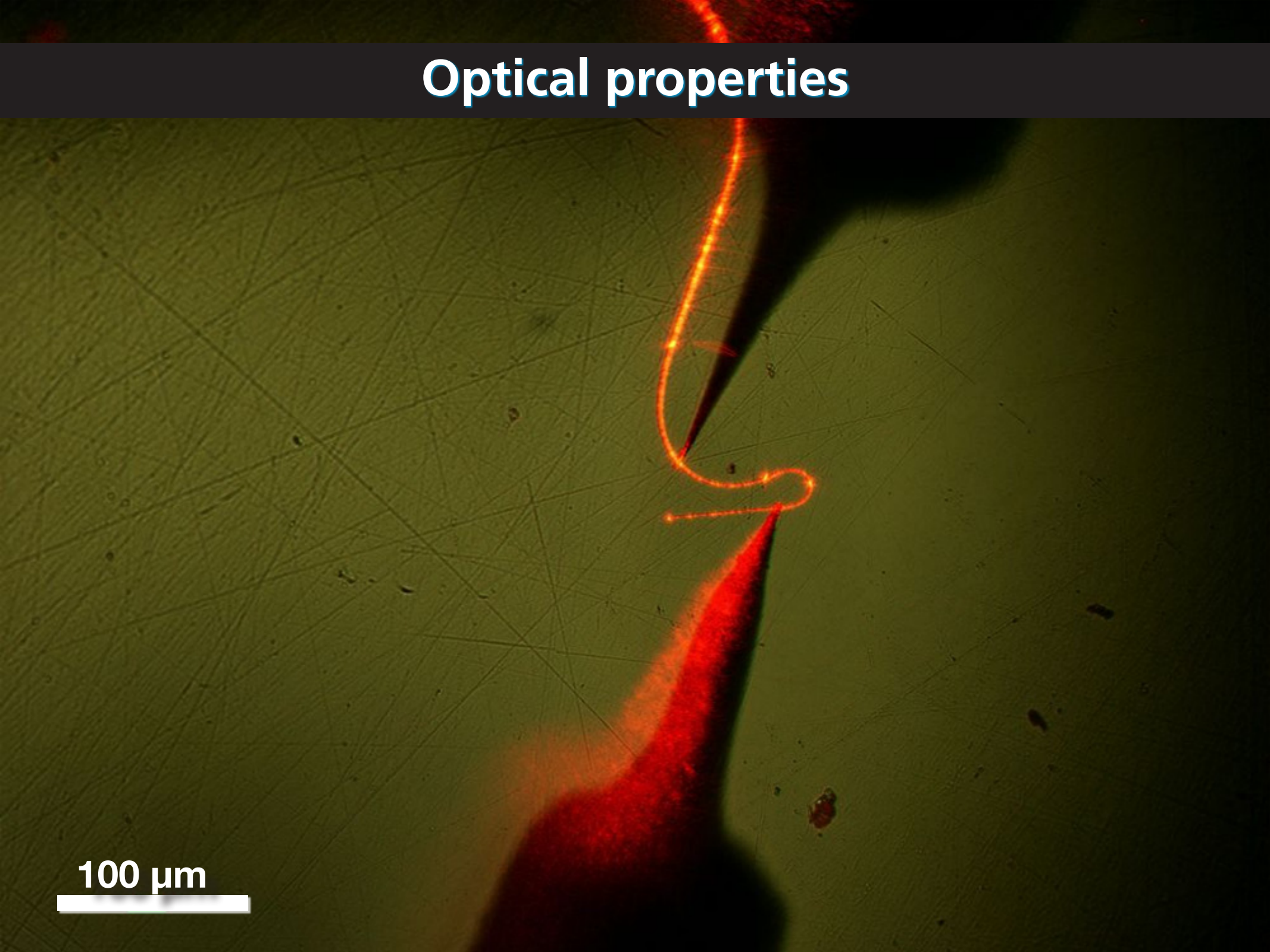


Optical properties

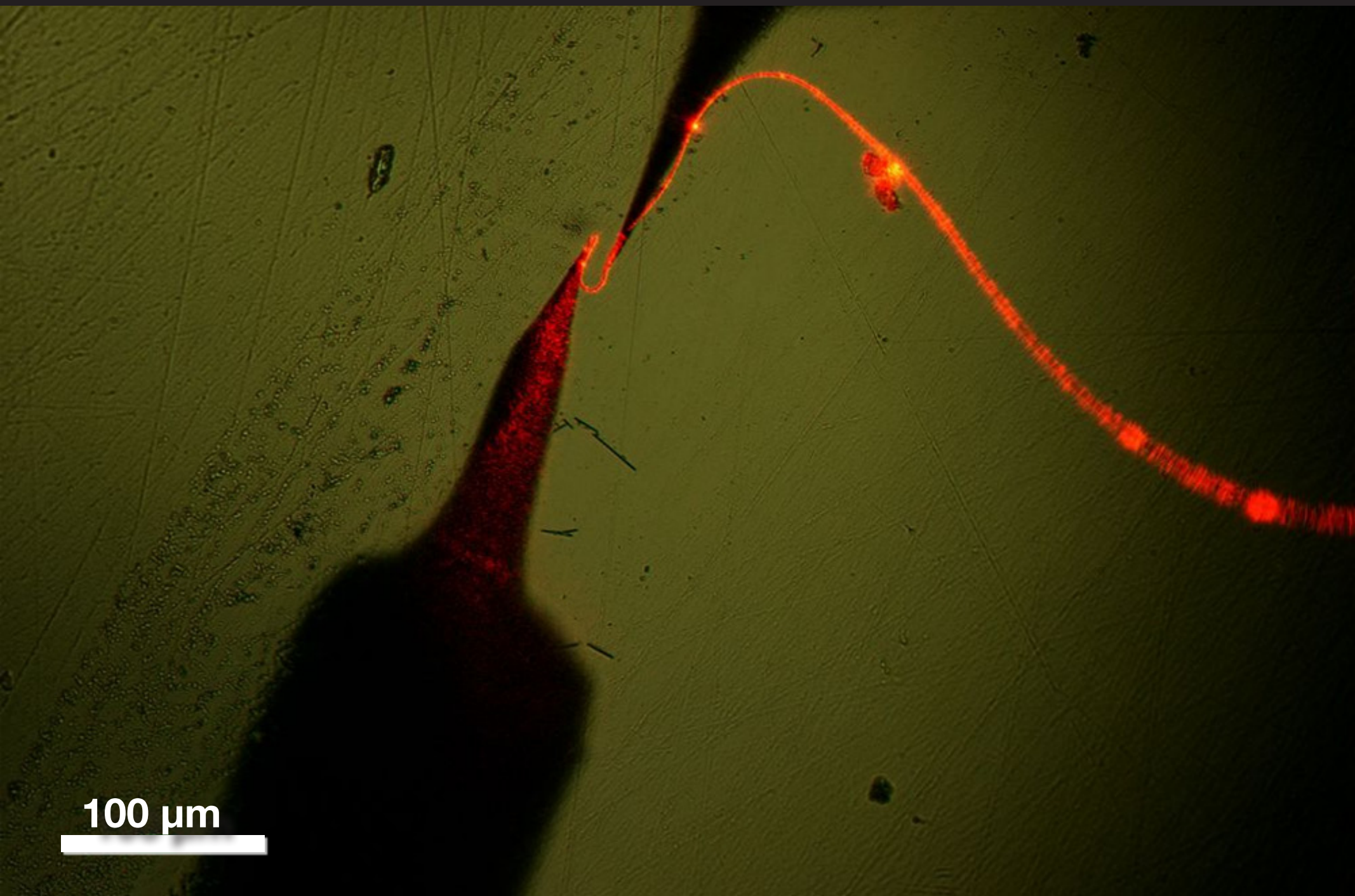


Optical properties

100 μm

An optical micrograph showing a fiber optic tip on the right side. A bright red laser beam is directed at the tip, and its path is visible as a glowing red line that curves and loops back. The background is a dark, textured surface with fine scratches. A white scale bar in the bottom left corner indicates a length of 100 micrometers.

Optical properties

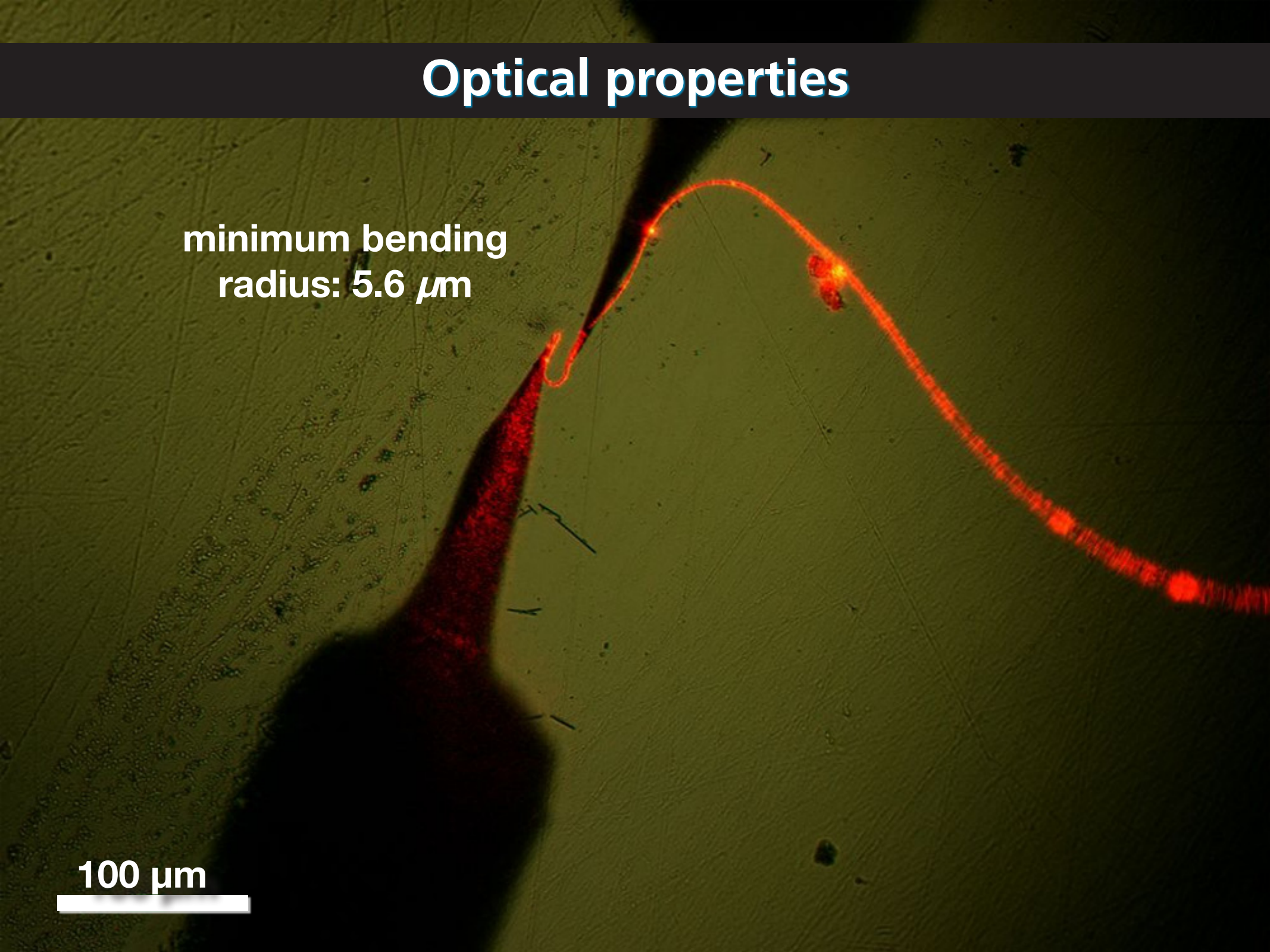


100 μm

Optical properties

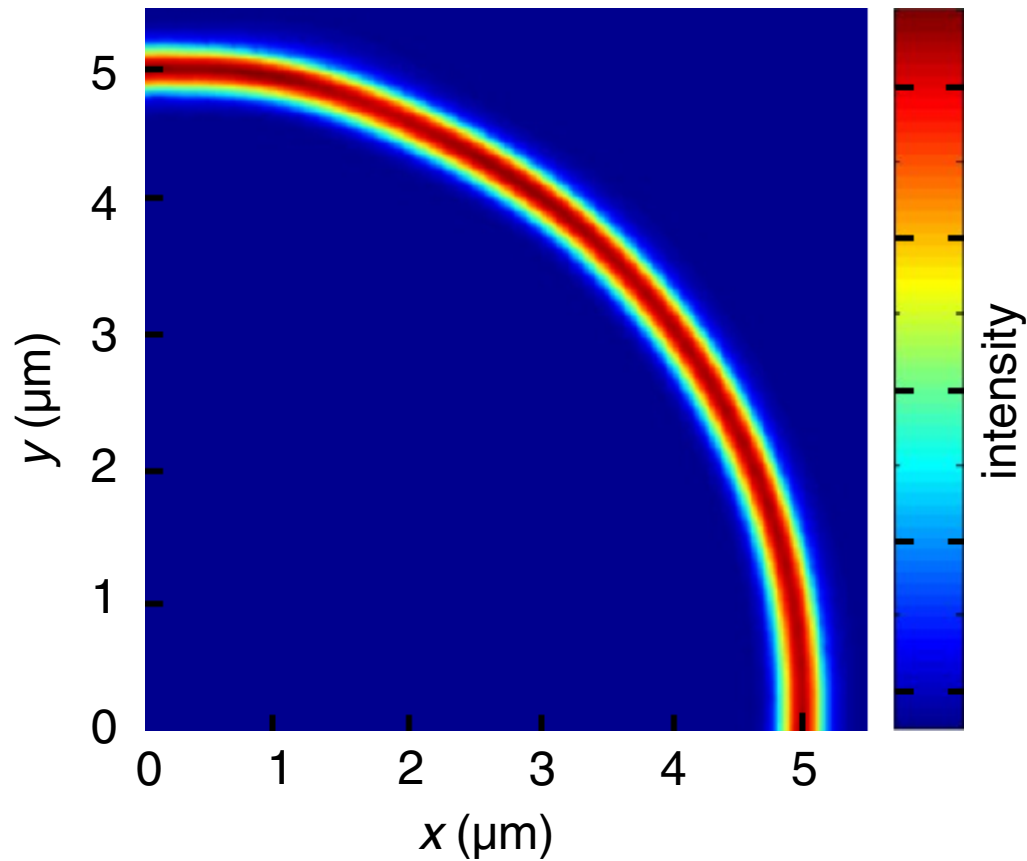
minimum bending
radius: $5.6 \mu\text{m}$

100 μm

An optical micrograph showing a fiber optic cable. A bright red laser spot is focused on the fiber, creating a visible light path that curves through the fiber. The fiber is dark against a light green background. A scale bar in the bottom left corner indicates 100 micrometers. Text in the upper left corner states the minimum bending radius is 5.6 micrometers.

Optical properties

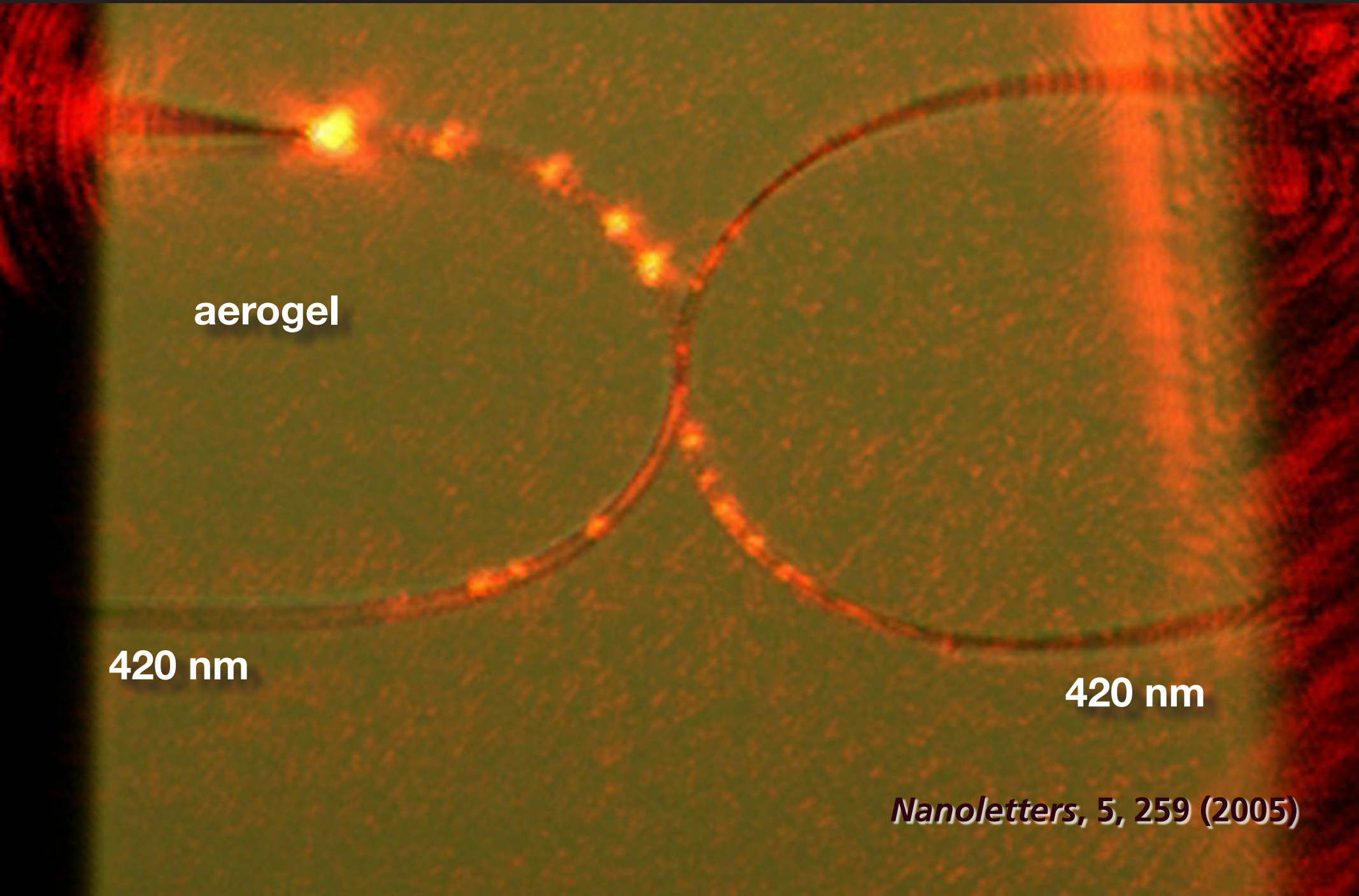
virtually no loss through 5 μm corner!



Manipulating light at the nanoscale



Manipulating light at the nanoscale



aerogel

420 nm

420 nm

Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale

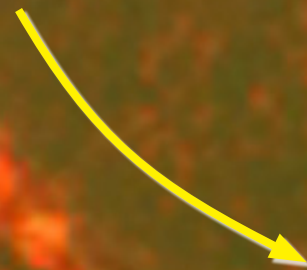
in



out

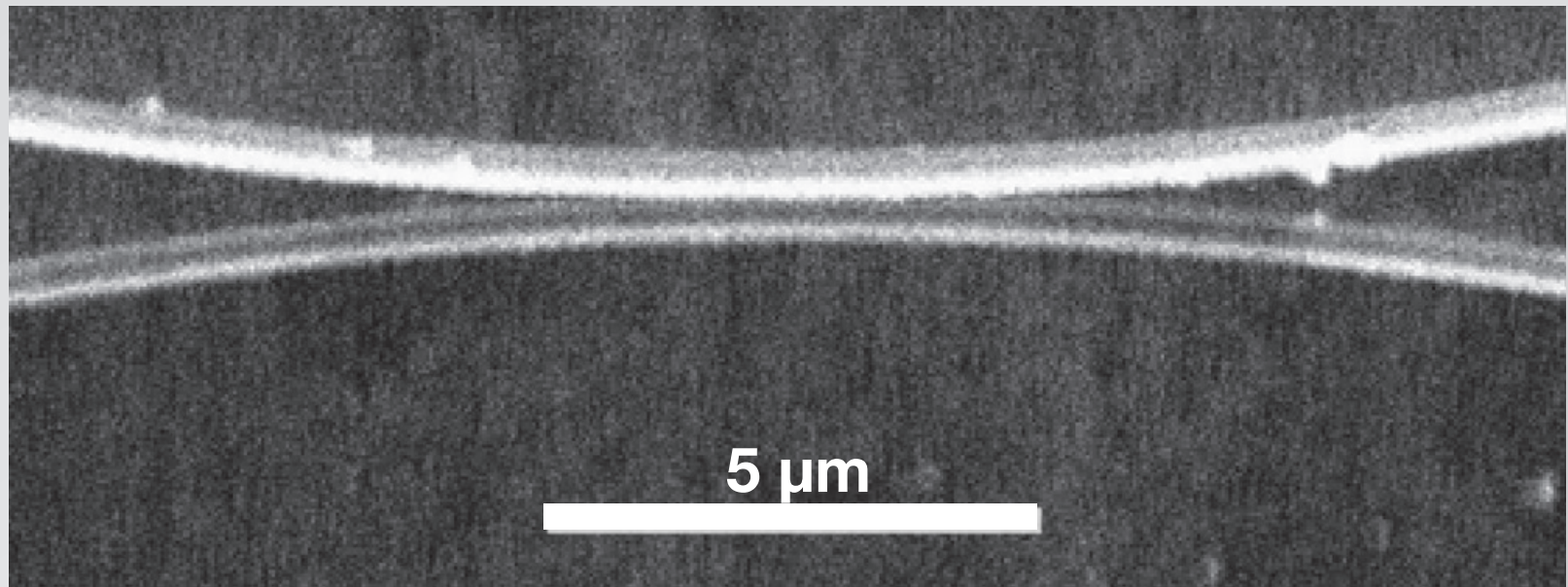


out



Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

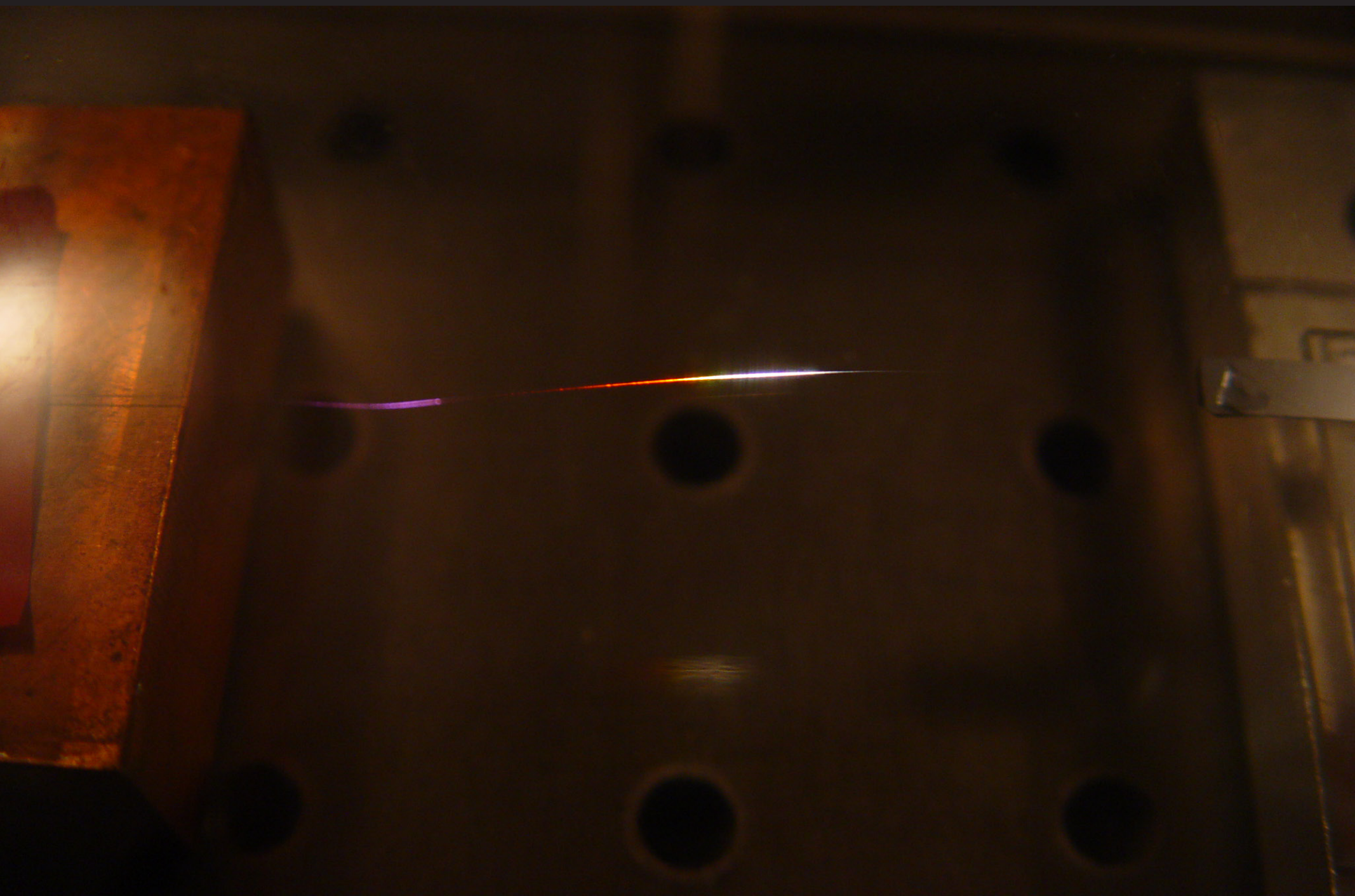
Outline

- propagation of pulses
- nonlinear optics
- nanoscale optics
- **nonlinear optics at the nanoscale**

Supercontinuum generation

strong confinement \longrightarrow high intensity

Supercontinuum generation

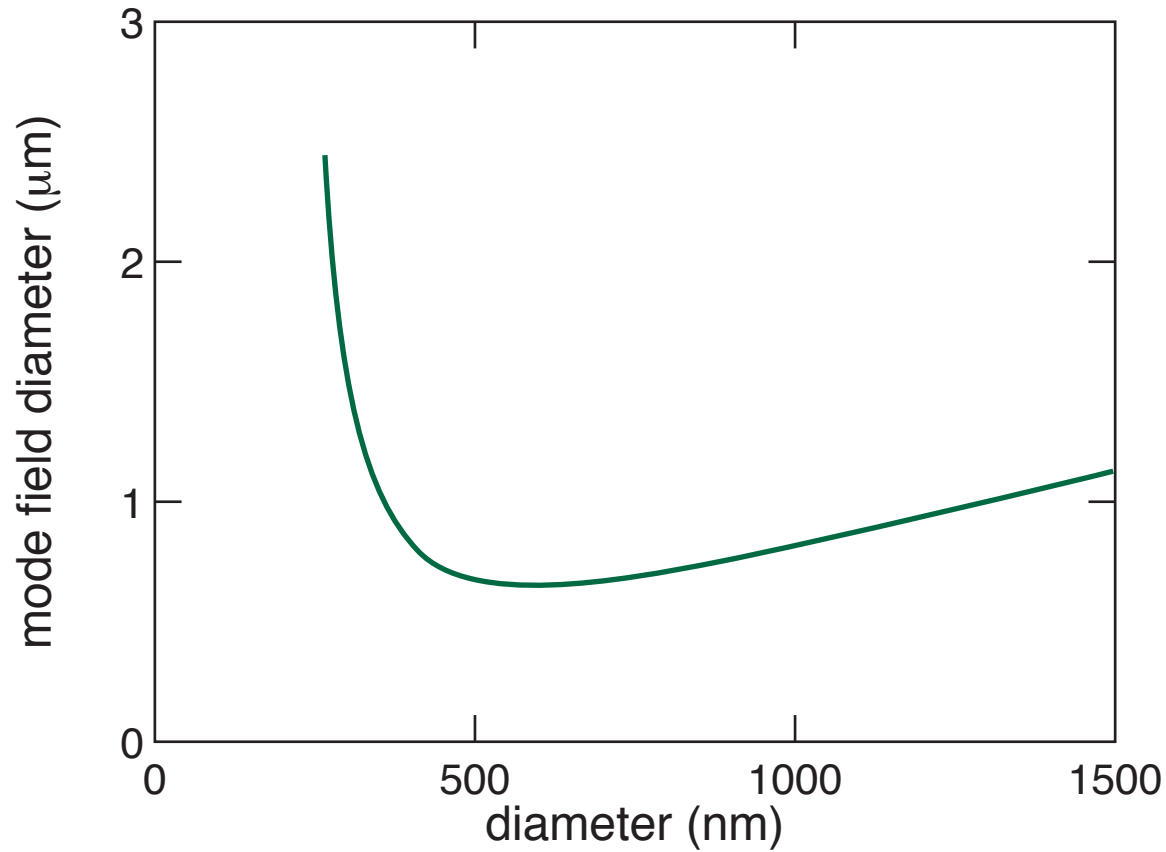


Supercontinuum generation



Supercontinuum generation

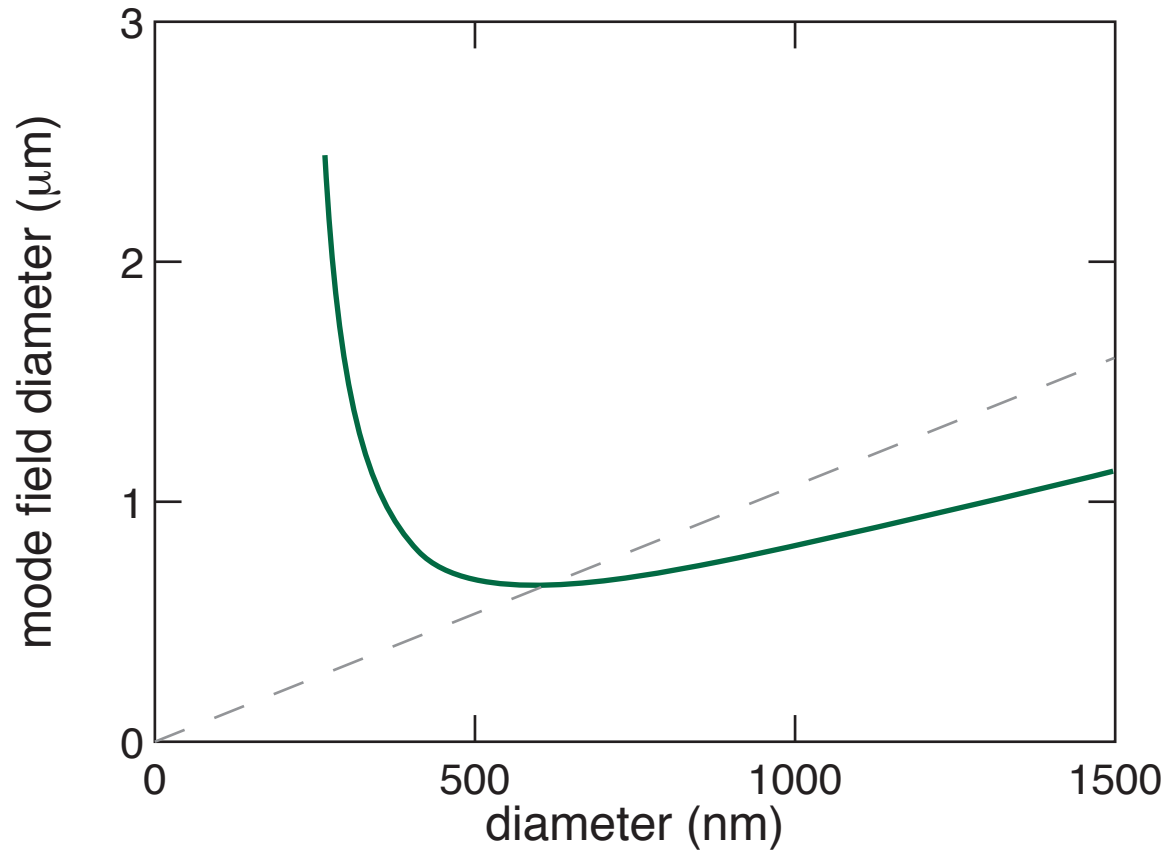
mode field diameter ($\lambda = 800$ nm)



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

Supercontinuum generation

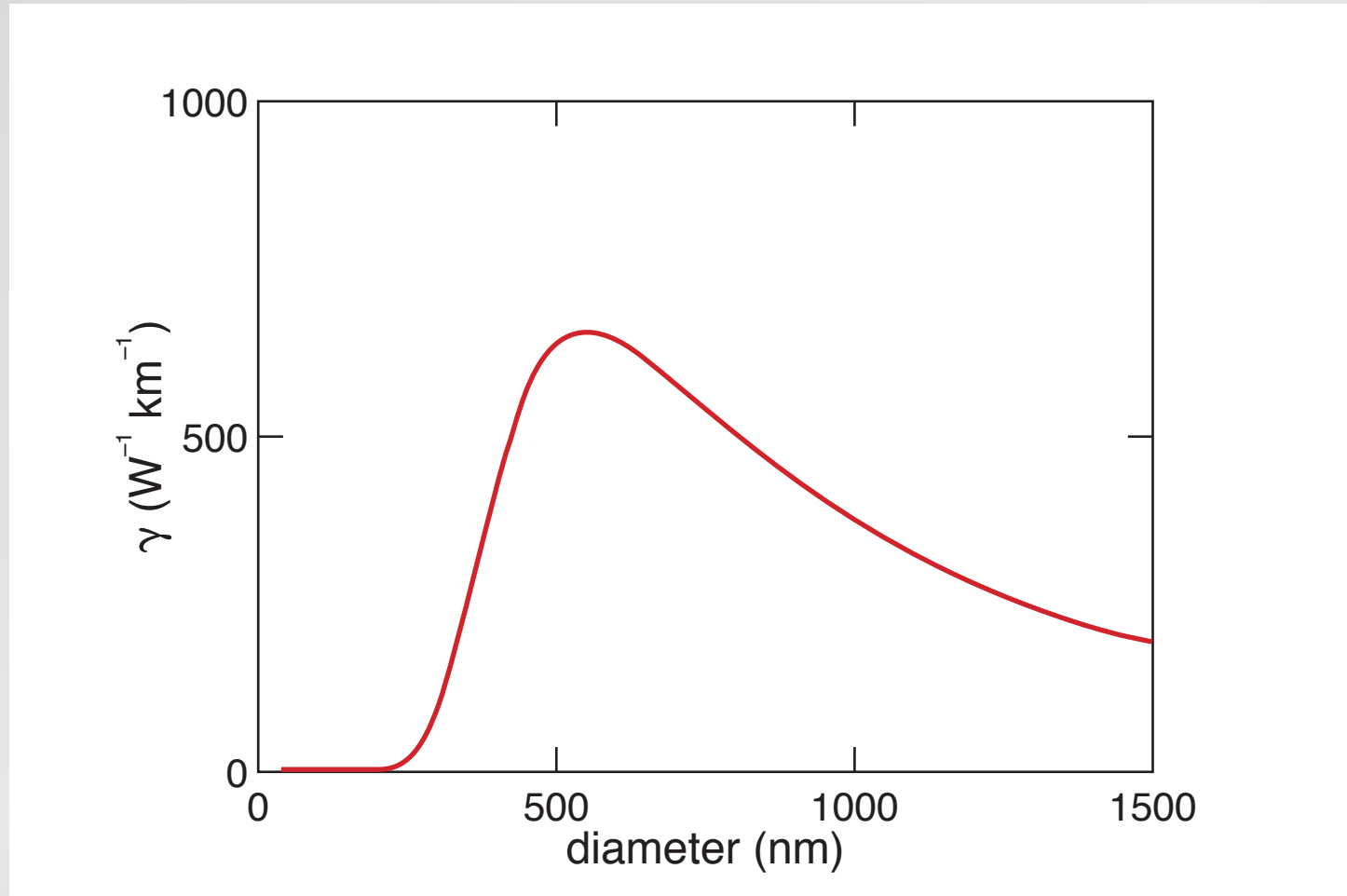
mode field diameter ($\lambda = 800$ nm)



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

Supercontinuum generation

nonlinear parameter



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

Supercontinuum generation

dispersion important!

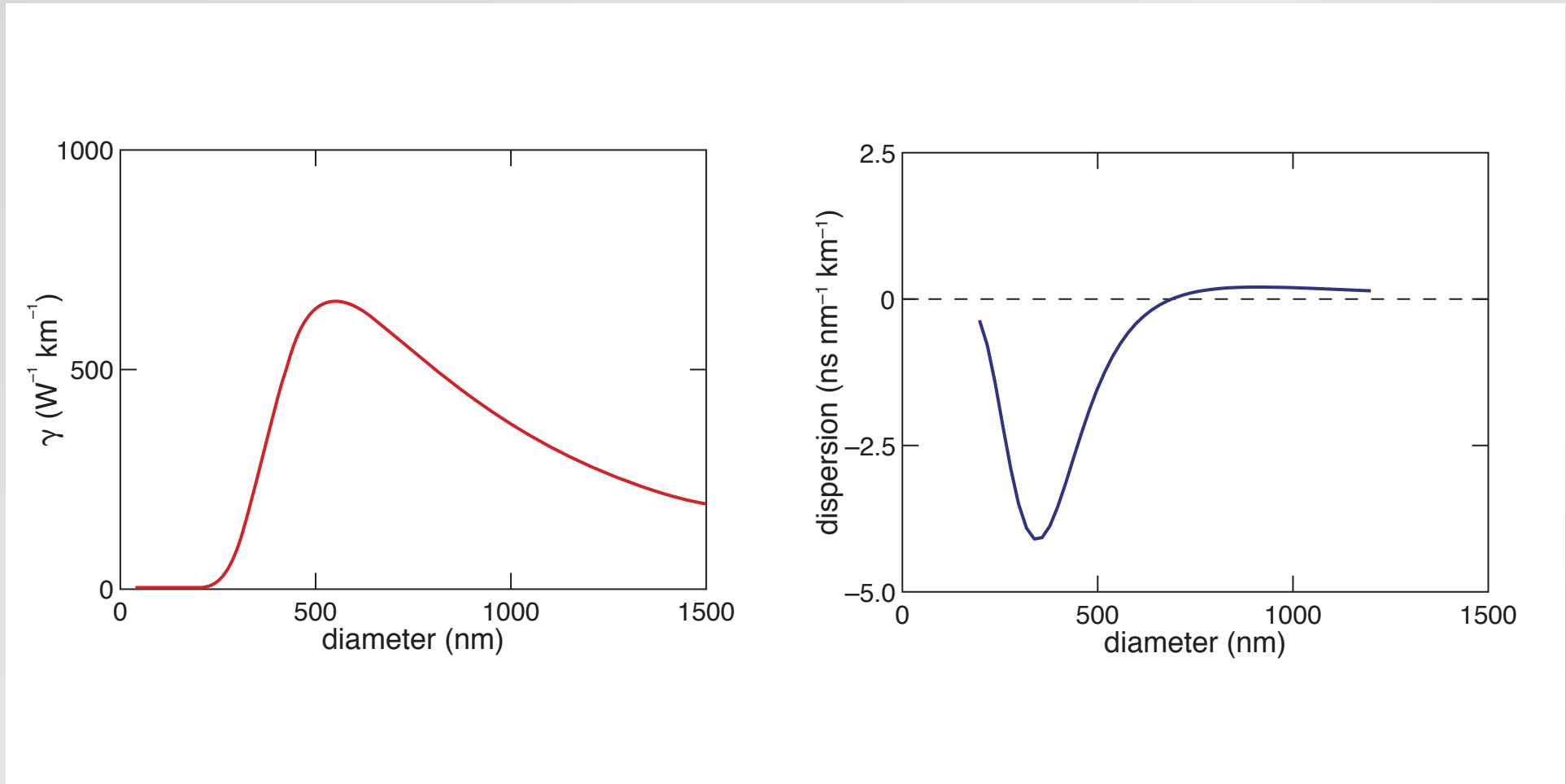
Supercontinuum generation

dispersion:

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

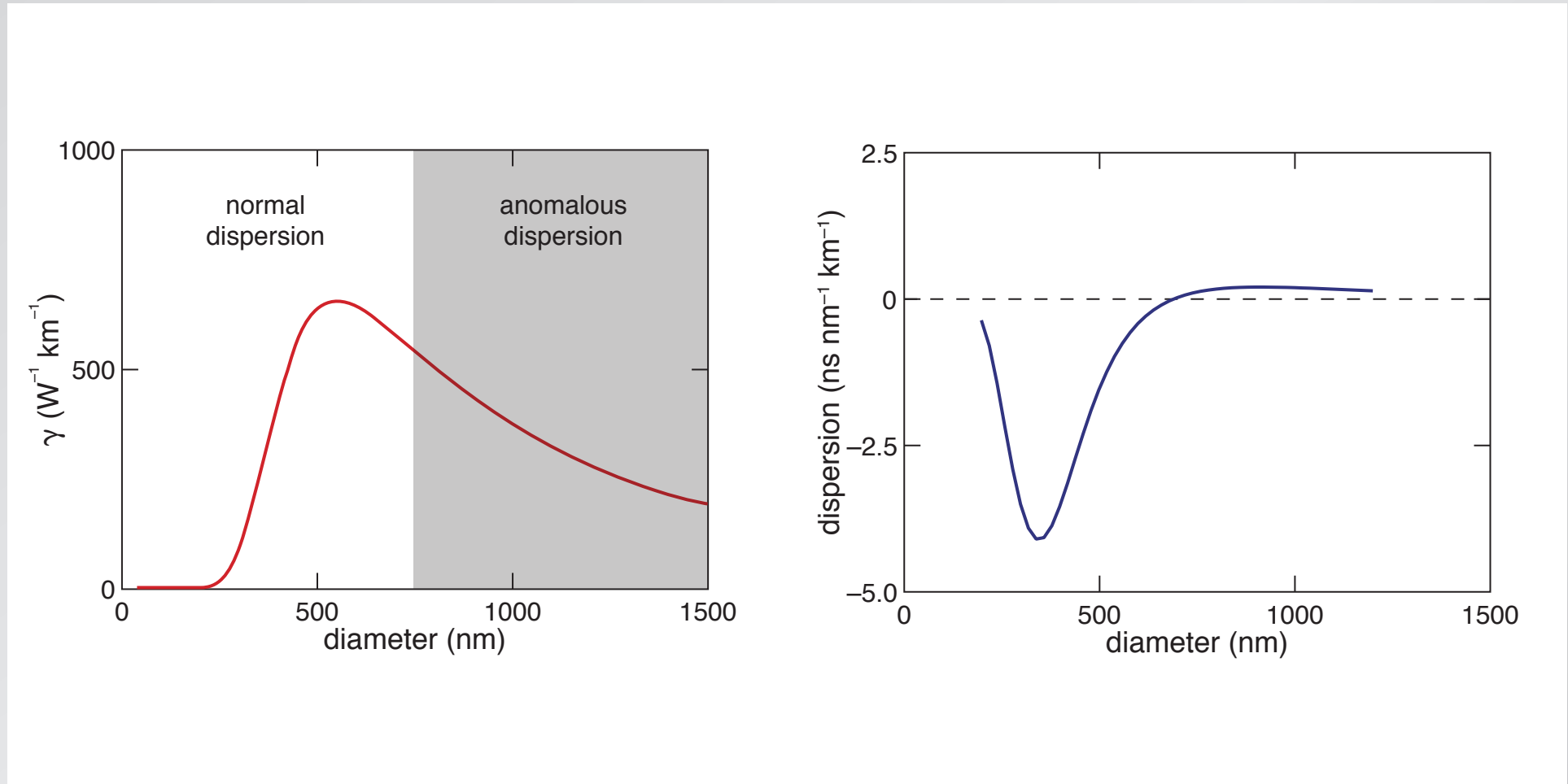
Supercontinuum generation

waveguide dispersion



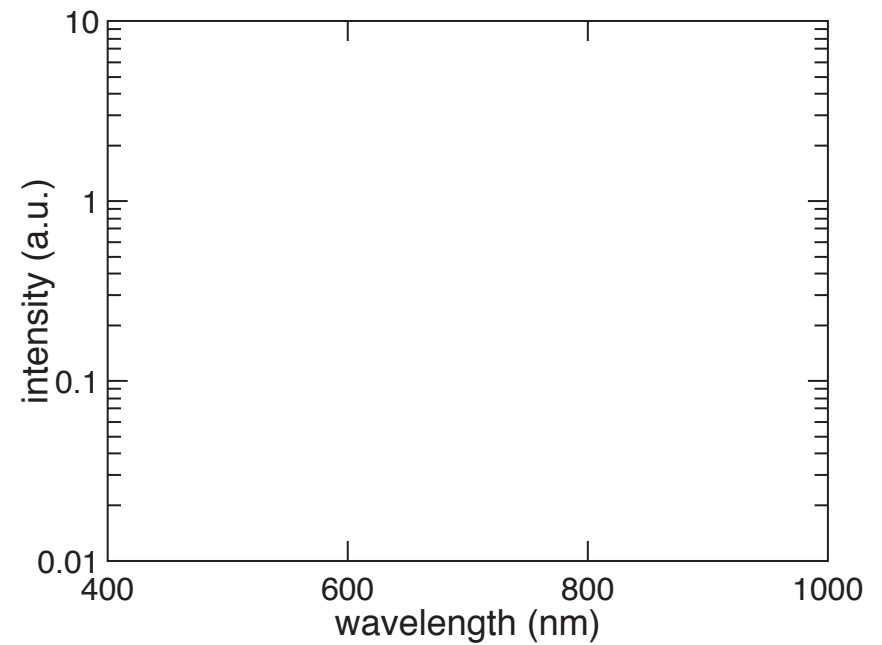
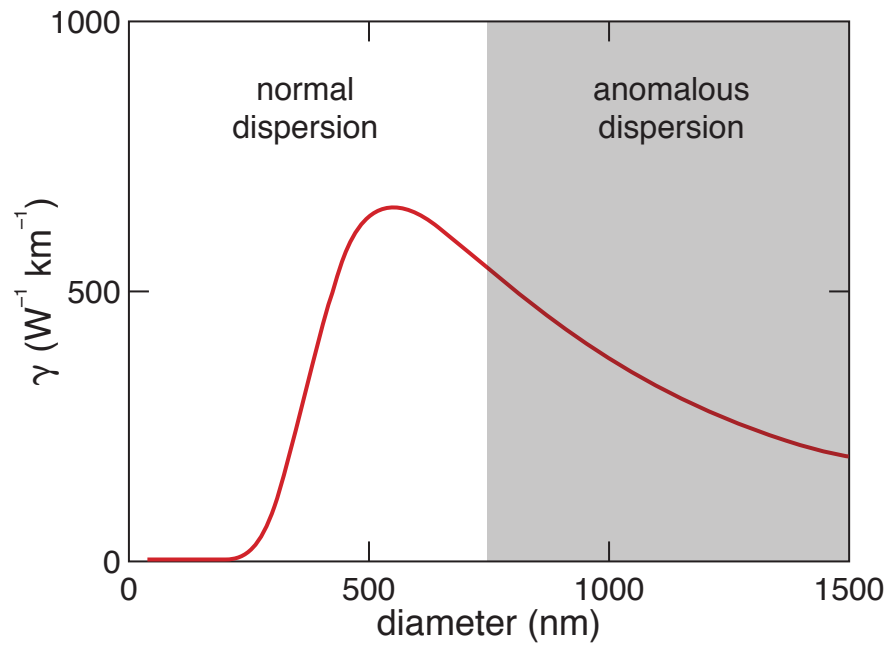
Supercontinuum generation

waveguide dispersion



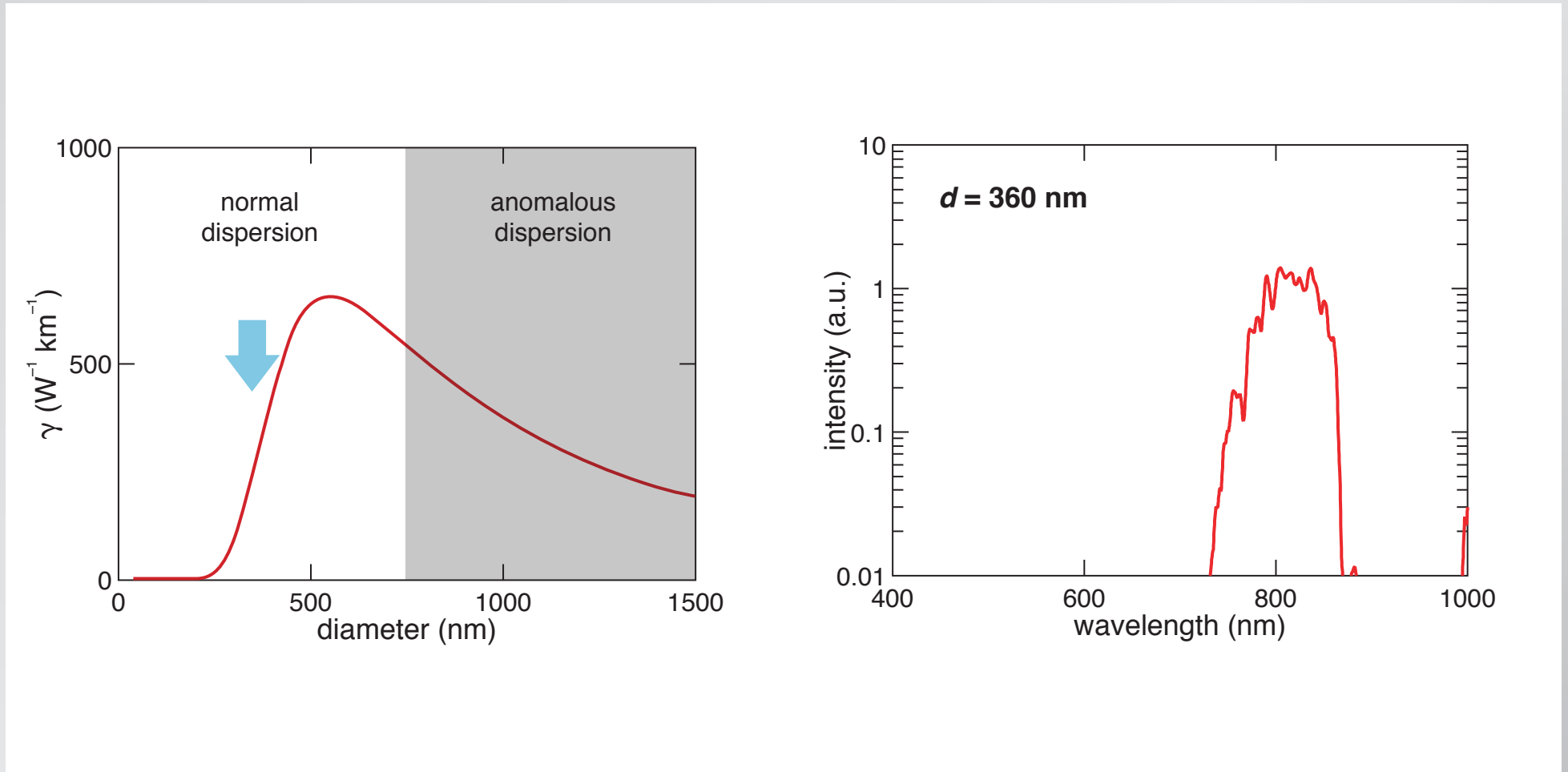
Supercontinuum generation

nanowire continuum generation



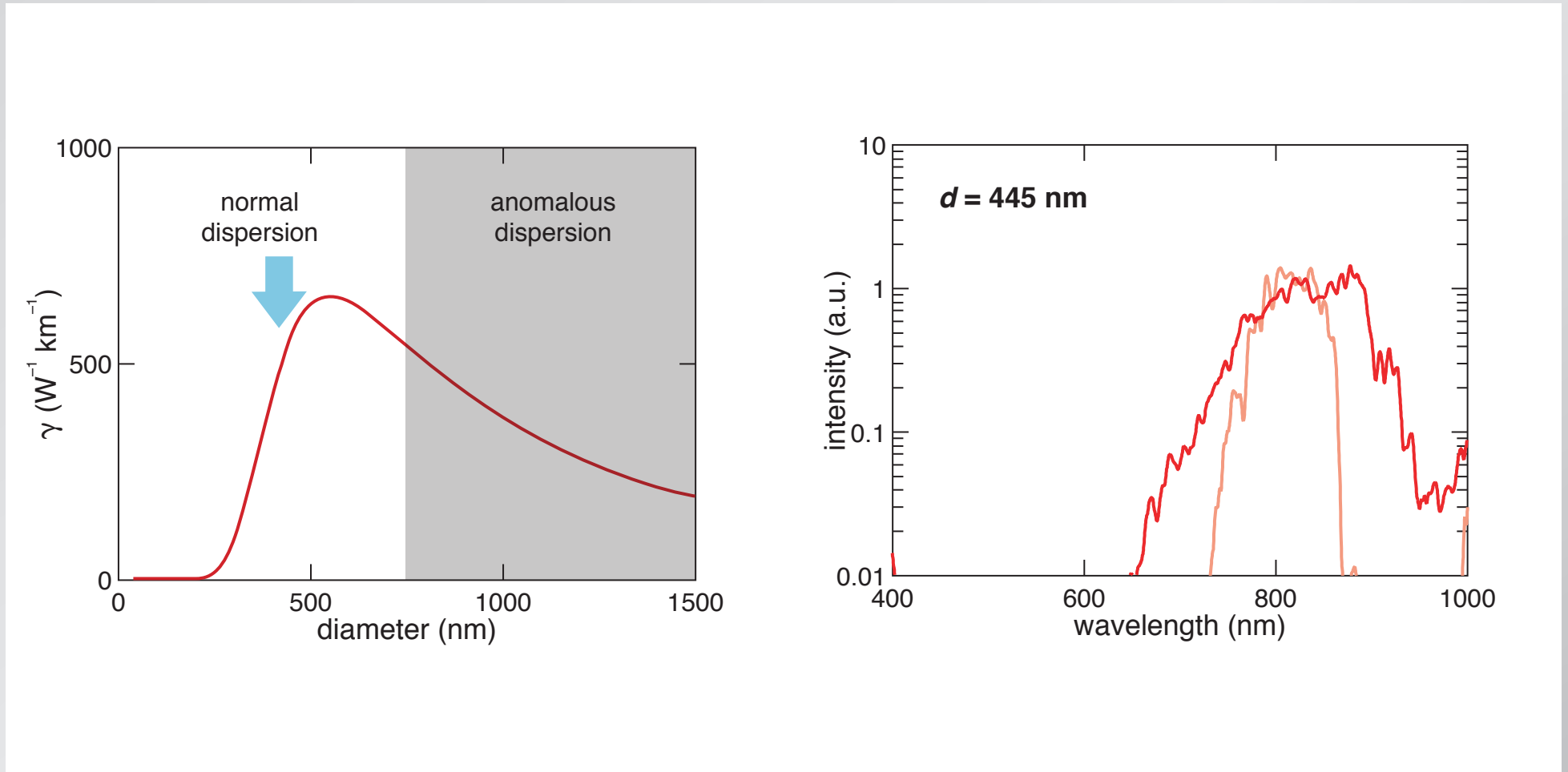
Supercontinuum generation

nanowire continuum generation



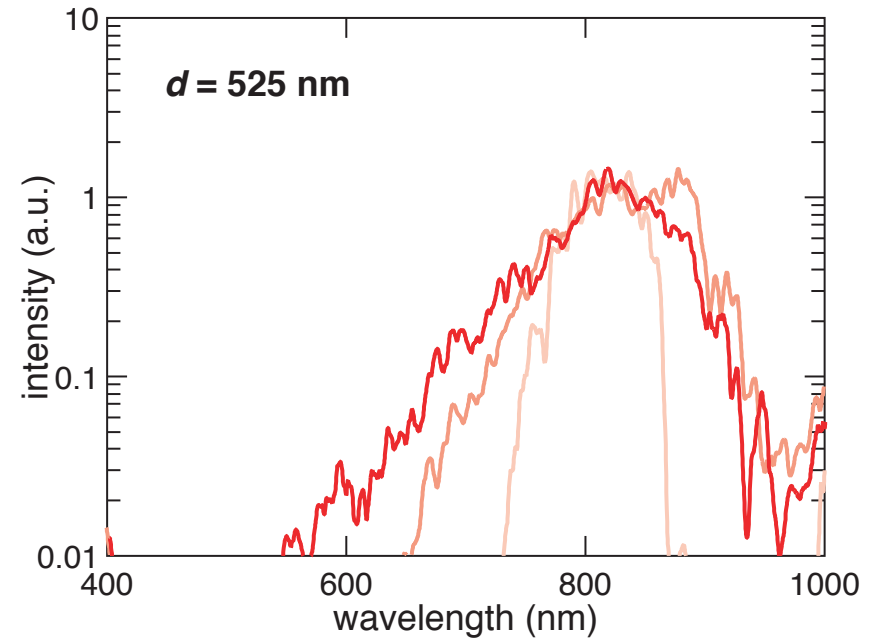
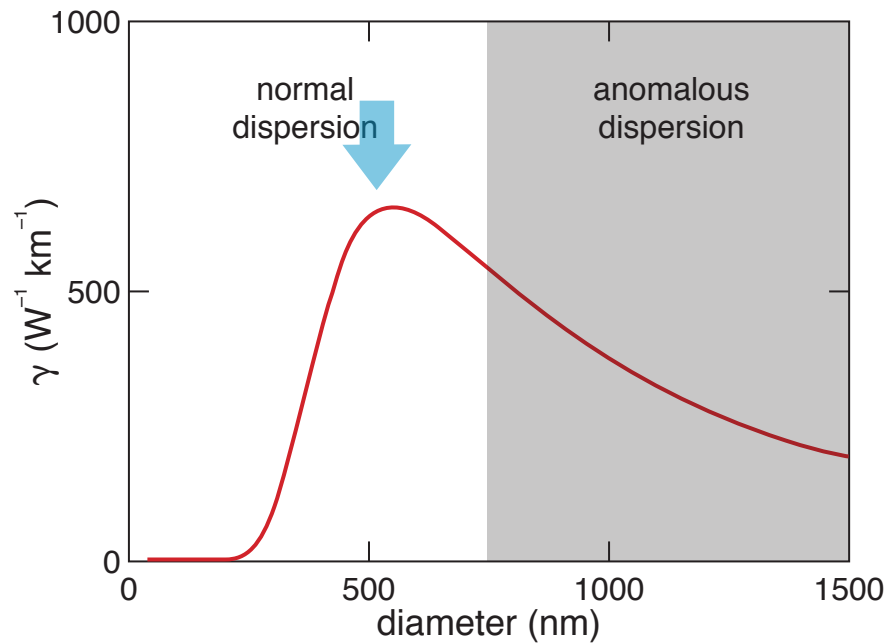
Supercontinuum generation

nanowire continuum generation



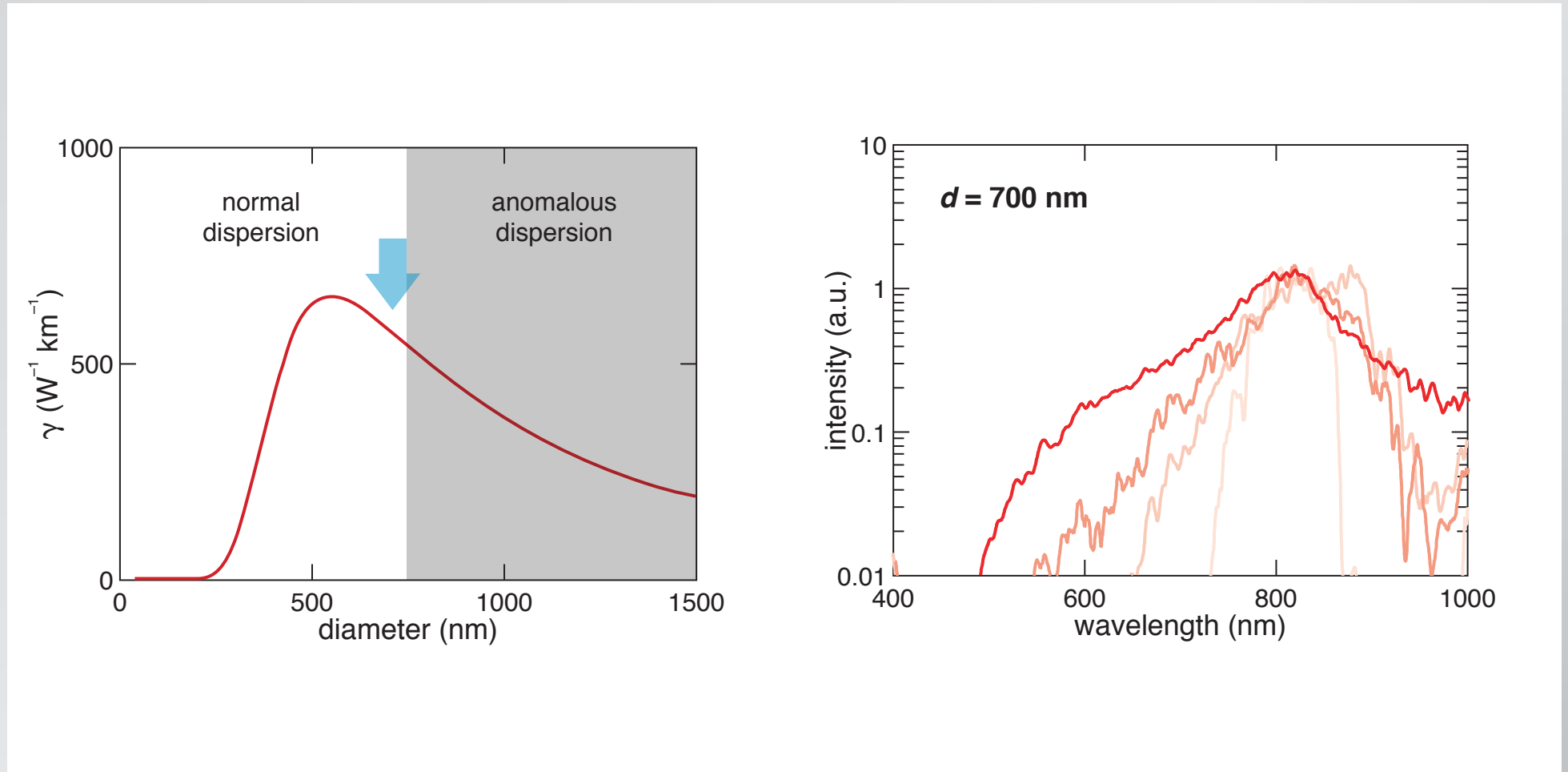
Supercontinuum generation

nanowire continuum generation



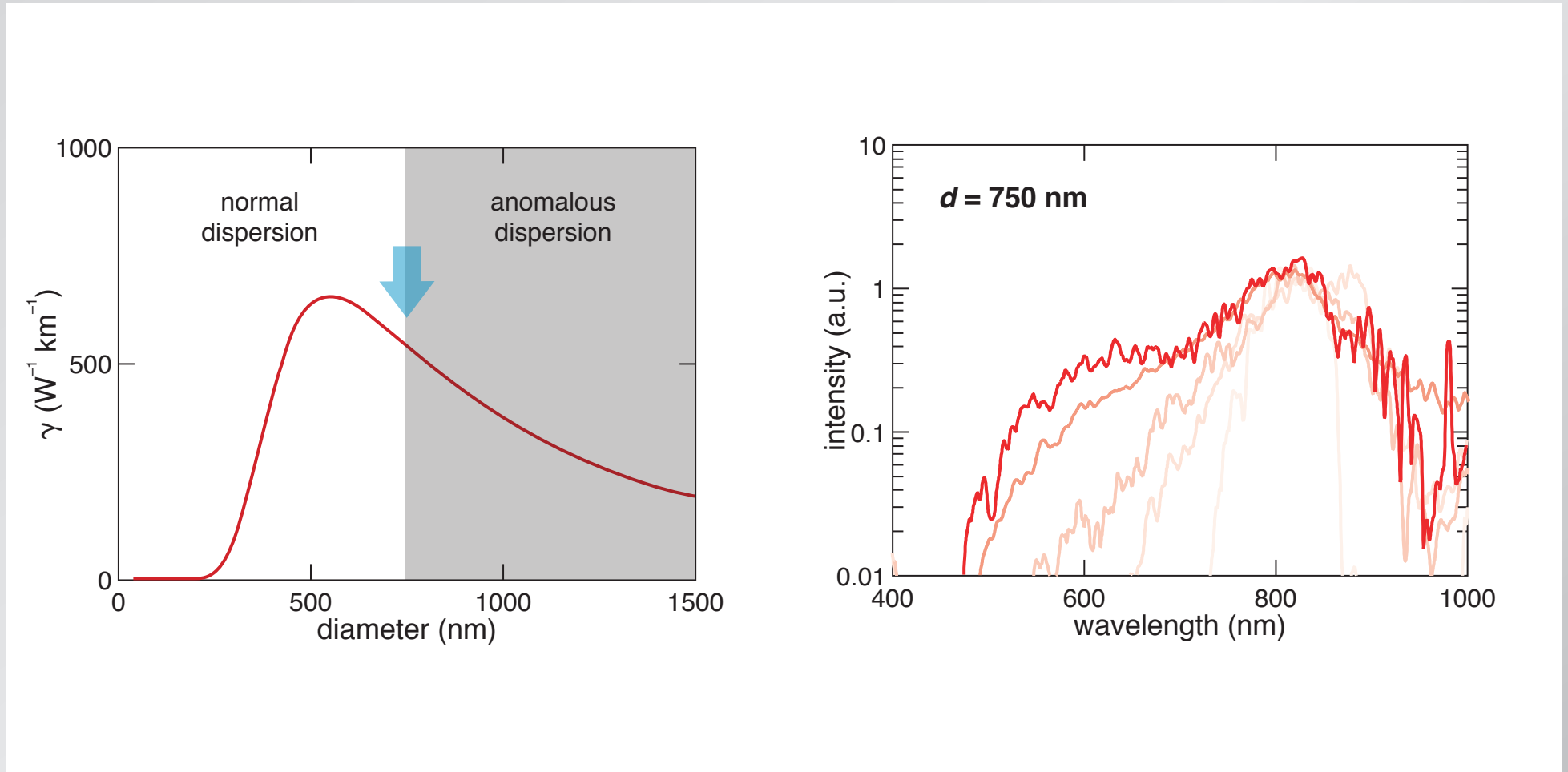
Supercontinuum generation

nanowire continuum generation



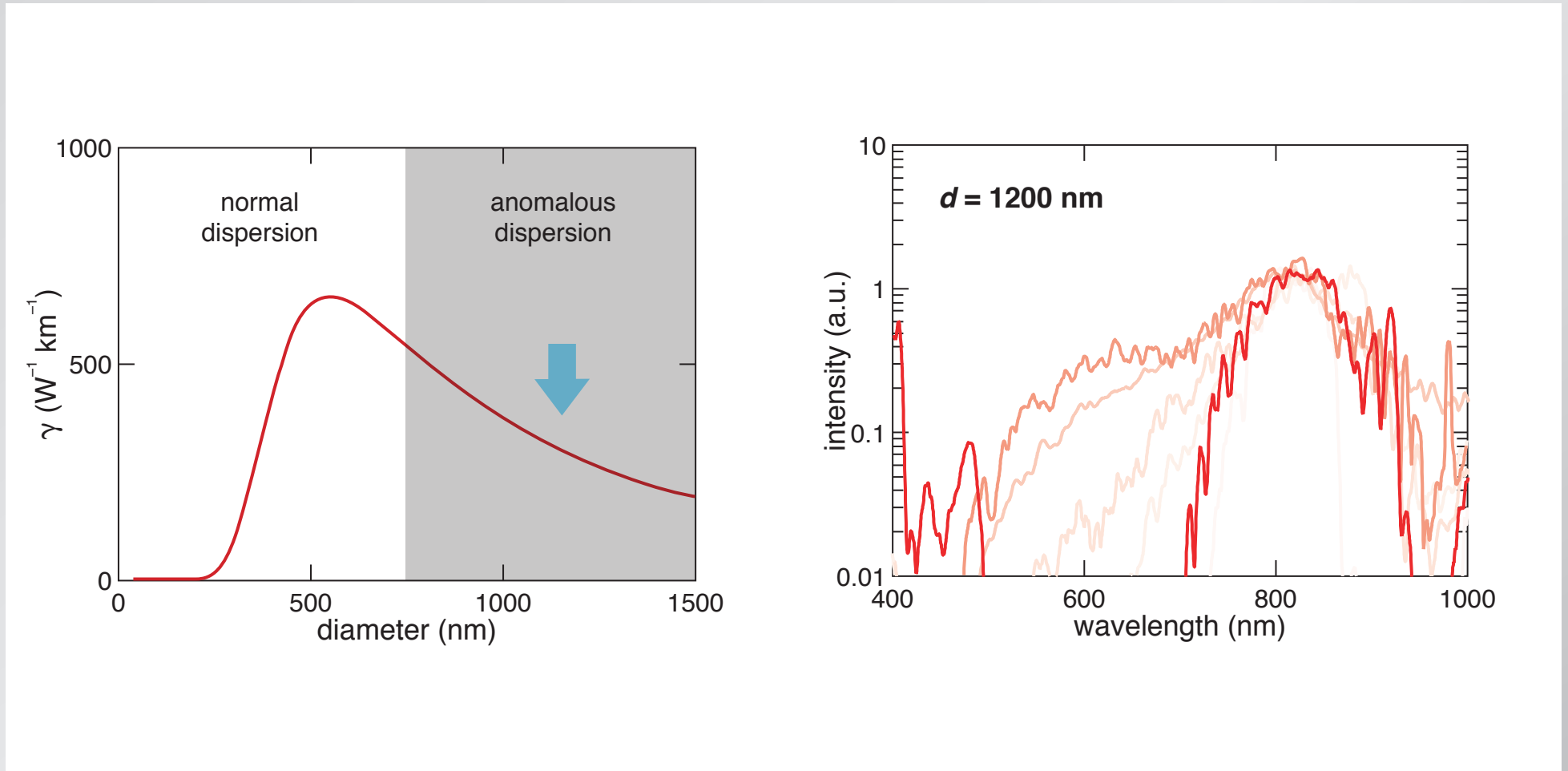
Supercontinuum generation

nanowire continuum generation



Supercontinuum generation

nanowire continuum generation



Supercontinuum generation

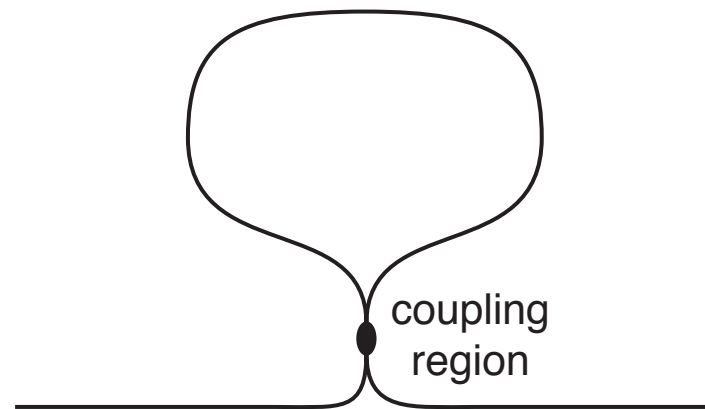
energy in nanowire \approx 1 nJ!

Supercontinuum generation

- **nanojoule nonlinear optics**
- **optimum diameter for silica 500–600 nm**
- **low dispersion**

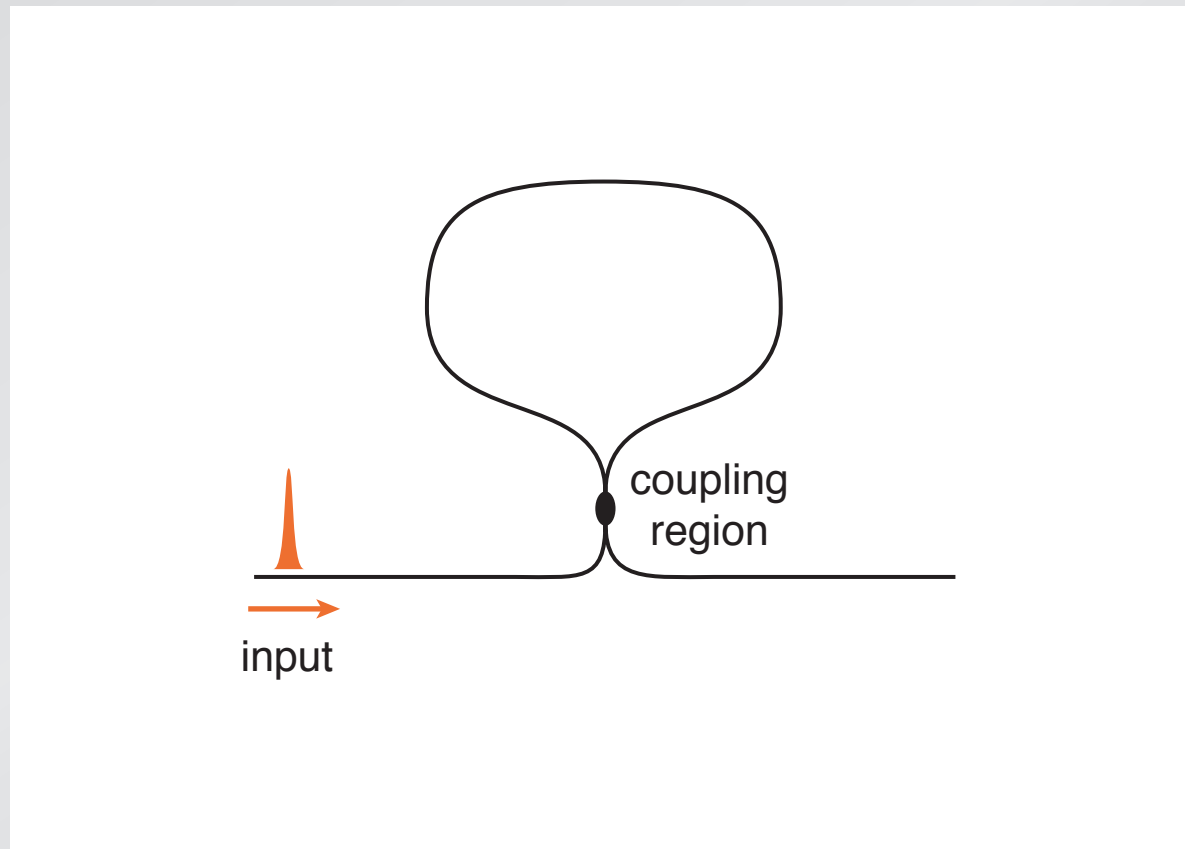
Optical logic gates

nanowire Sagnac interferometer



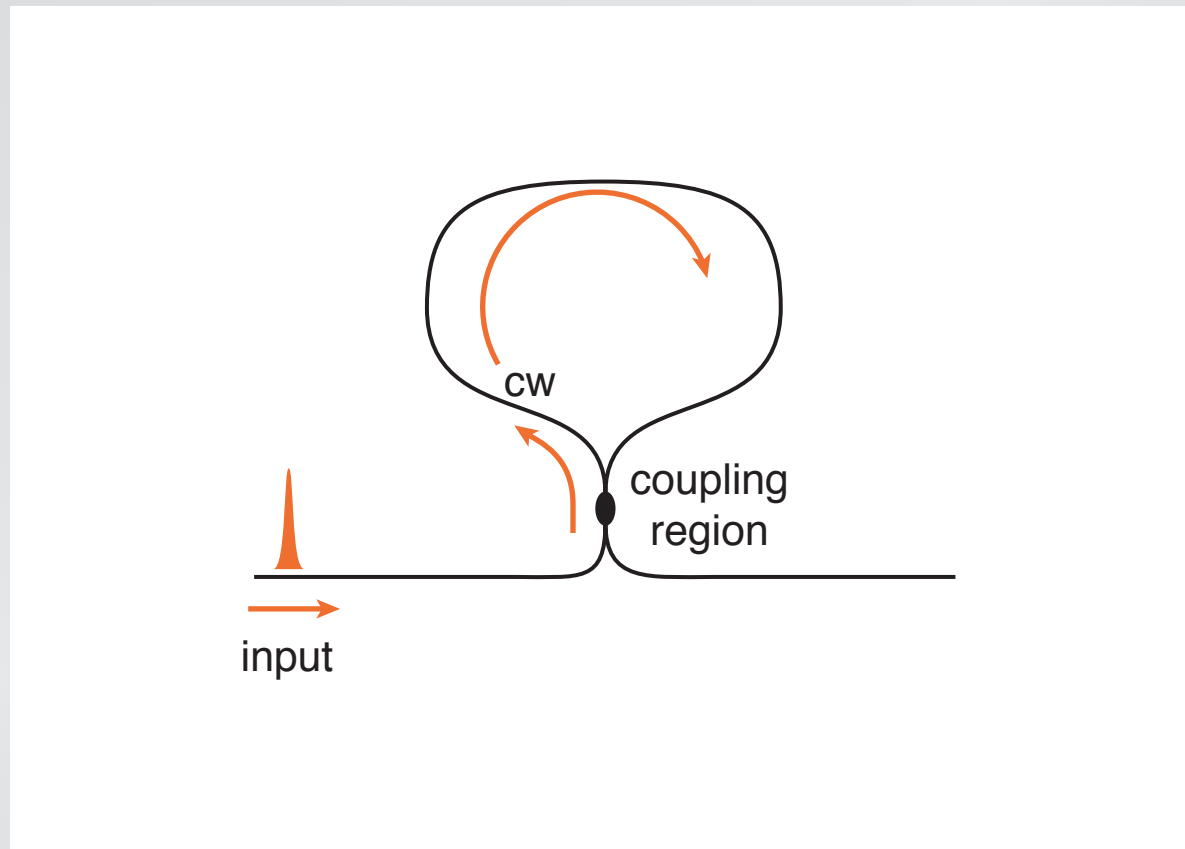
Optical logic gates

nanowire Sagnac interferometer



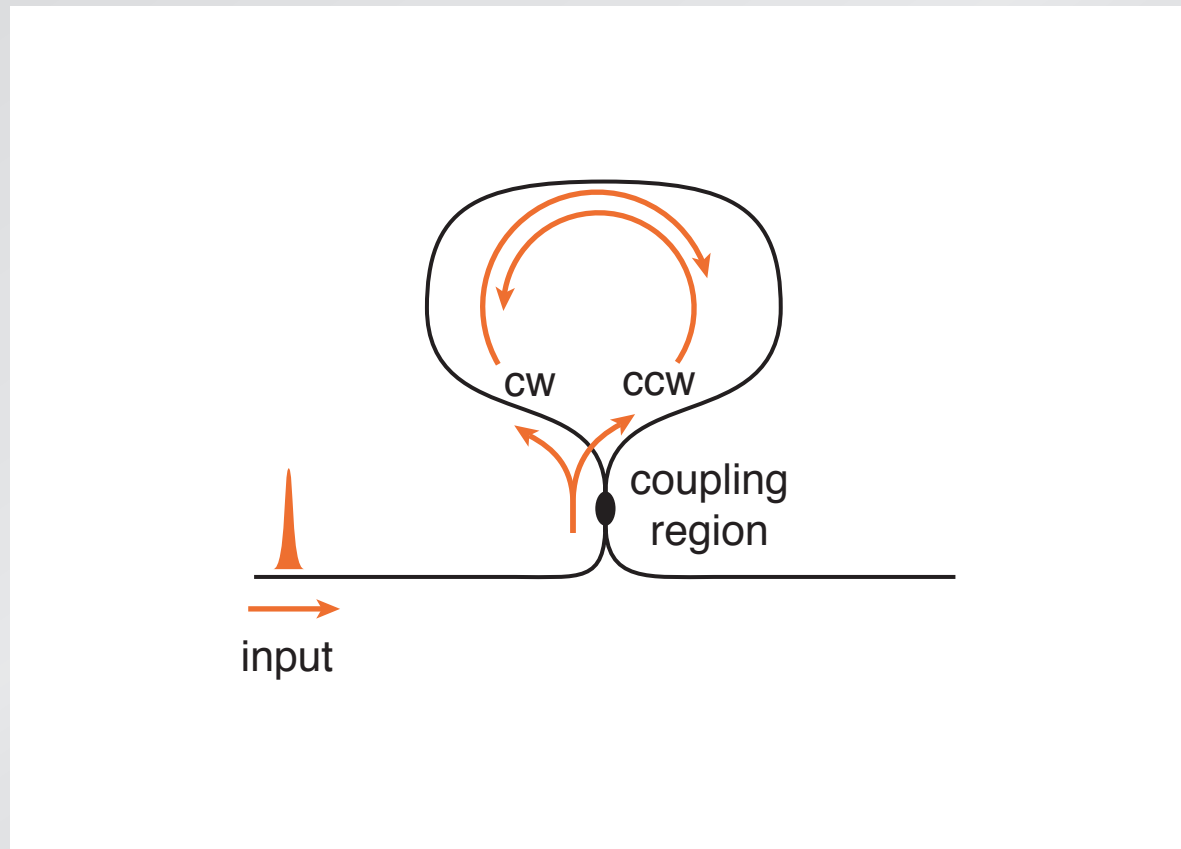
Optical logic gates

nanowire Sagnac interferometer



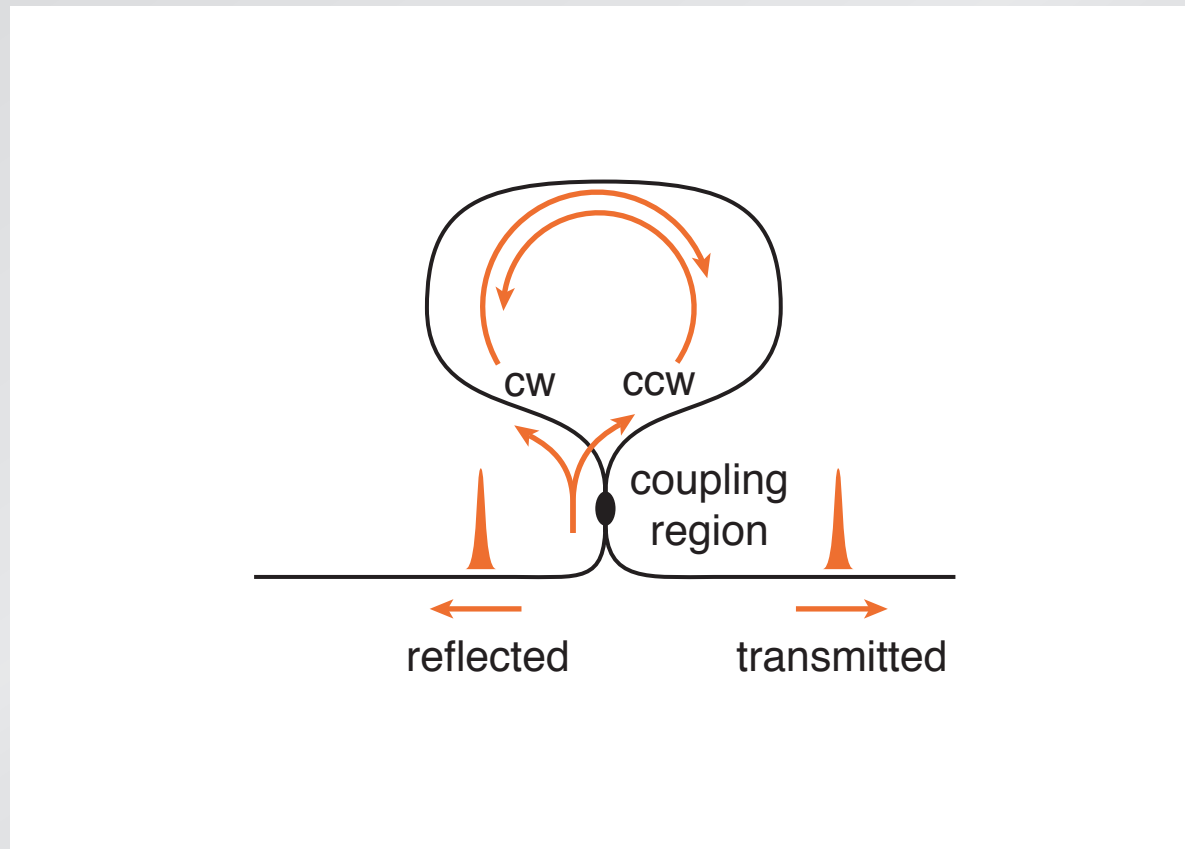
Optical logic gates

nanowire Sagnac interferometer



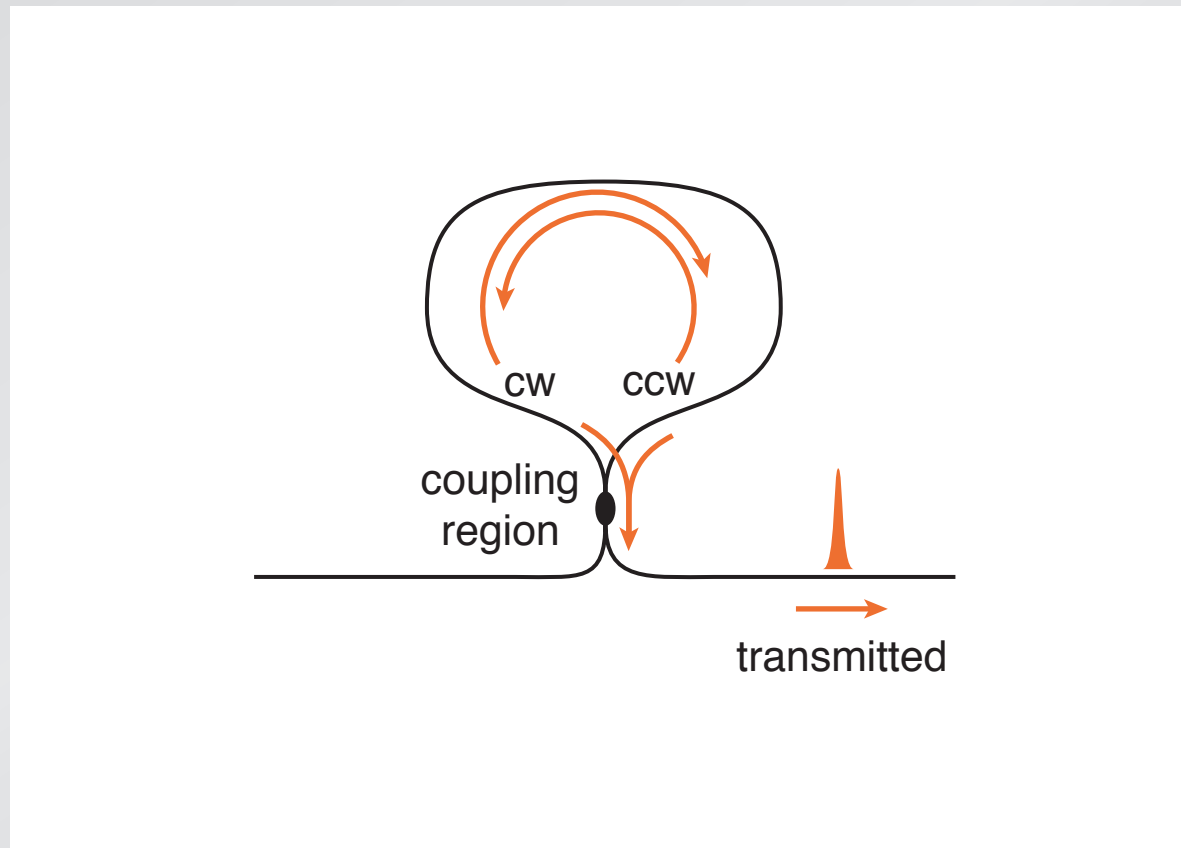
Optical logic gates

nanowire Sagnac interferometer



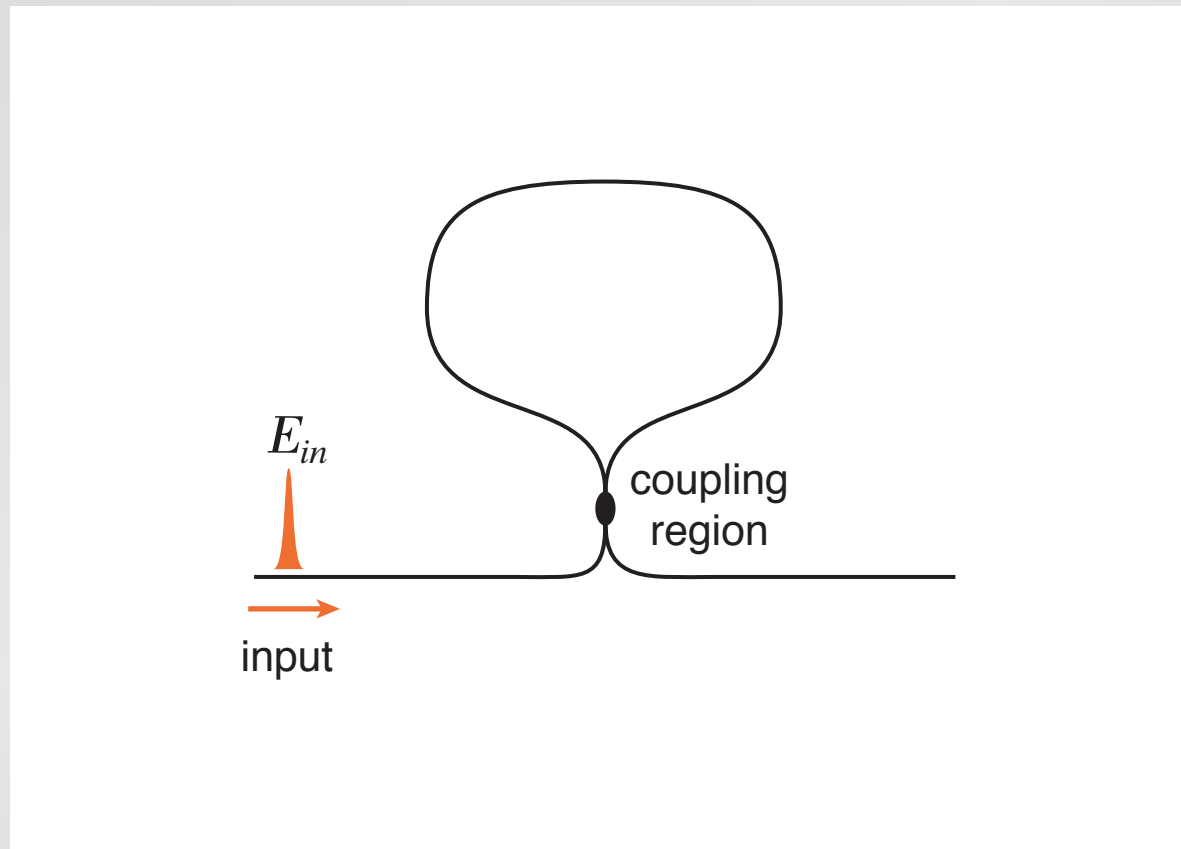
Optical logic gates

output = transmitted cw + ccw power



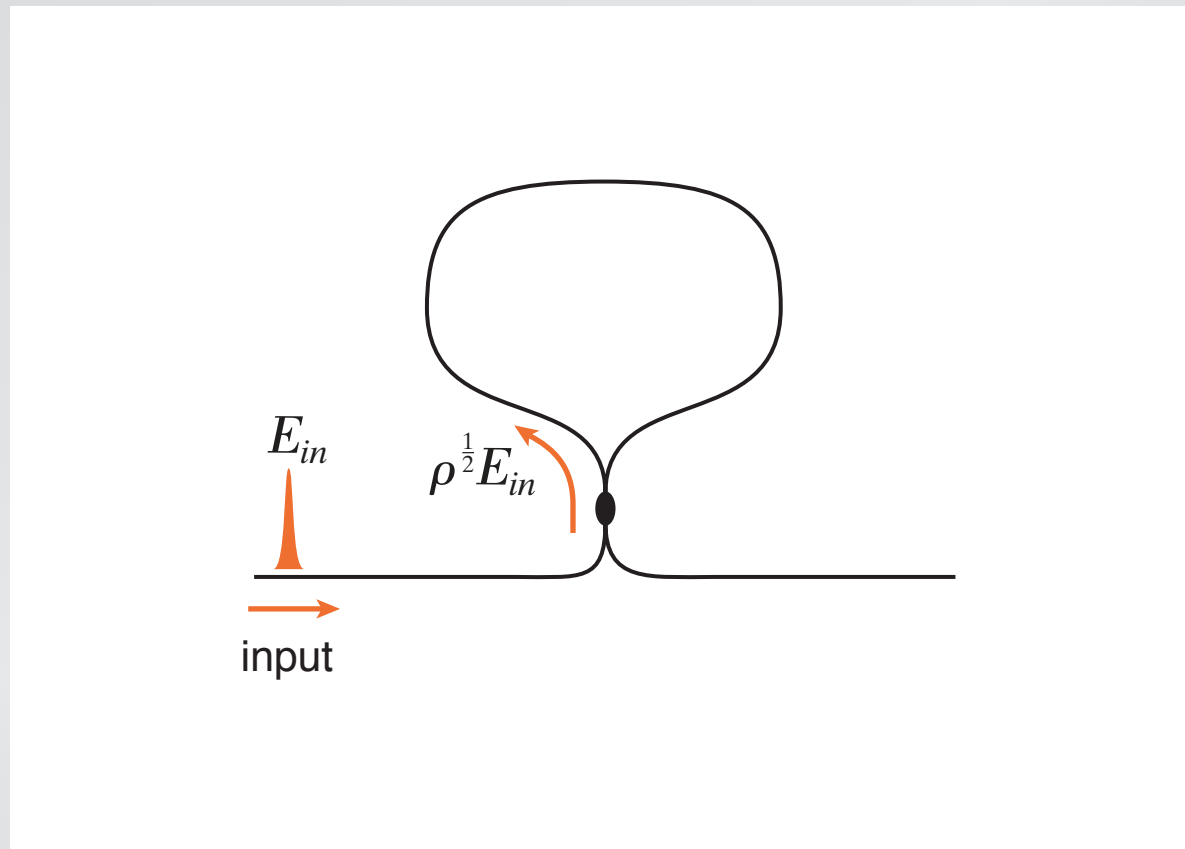
Optical logic gates

input electric field amplitude E_{in}



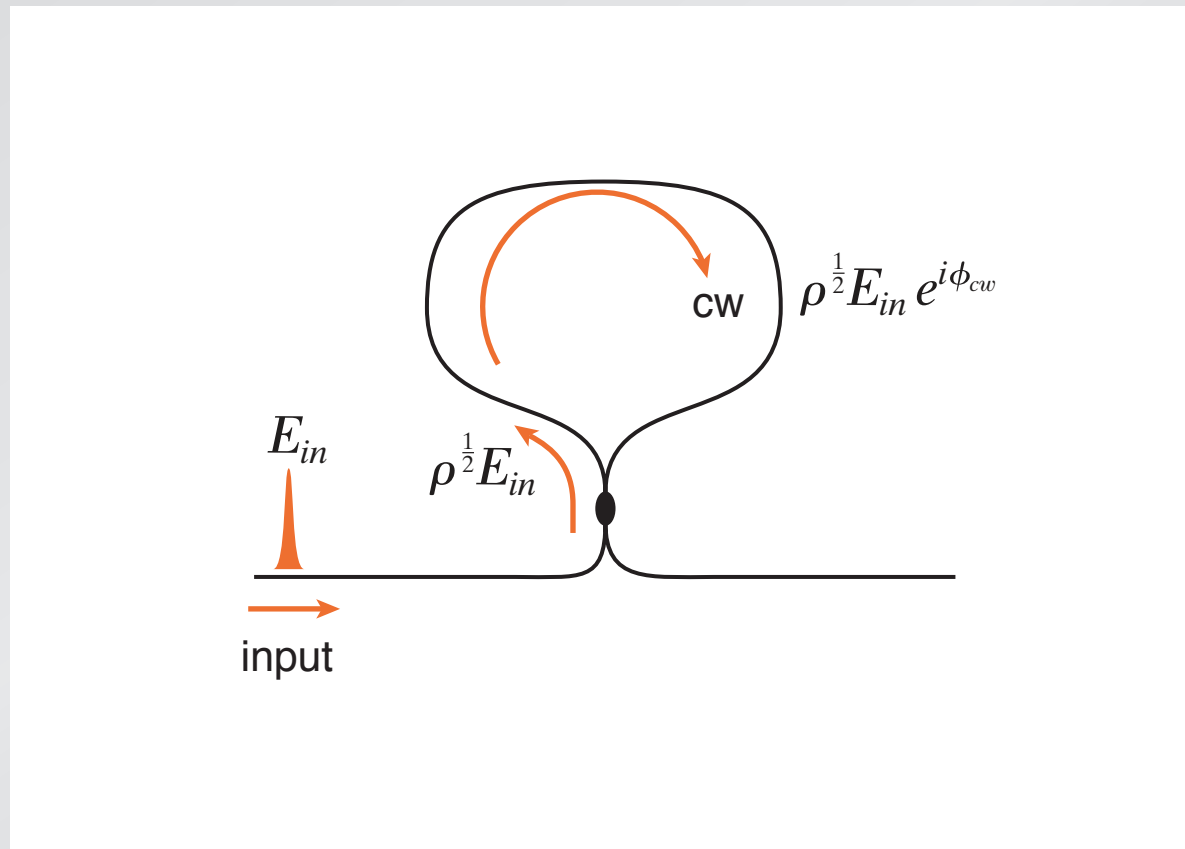
Optical logic gates

coupling parameter: ρ



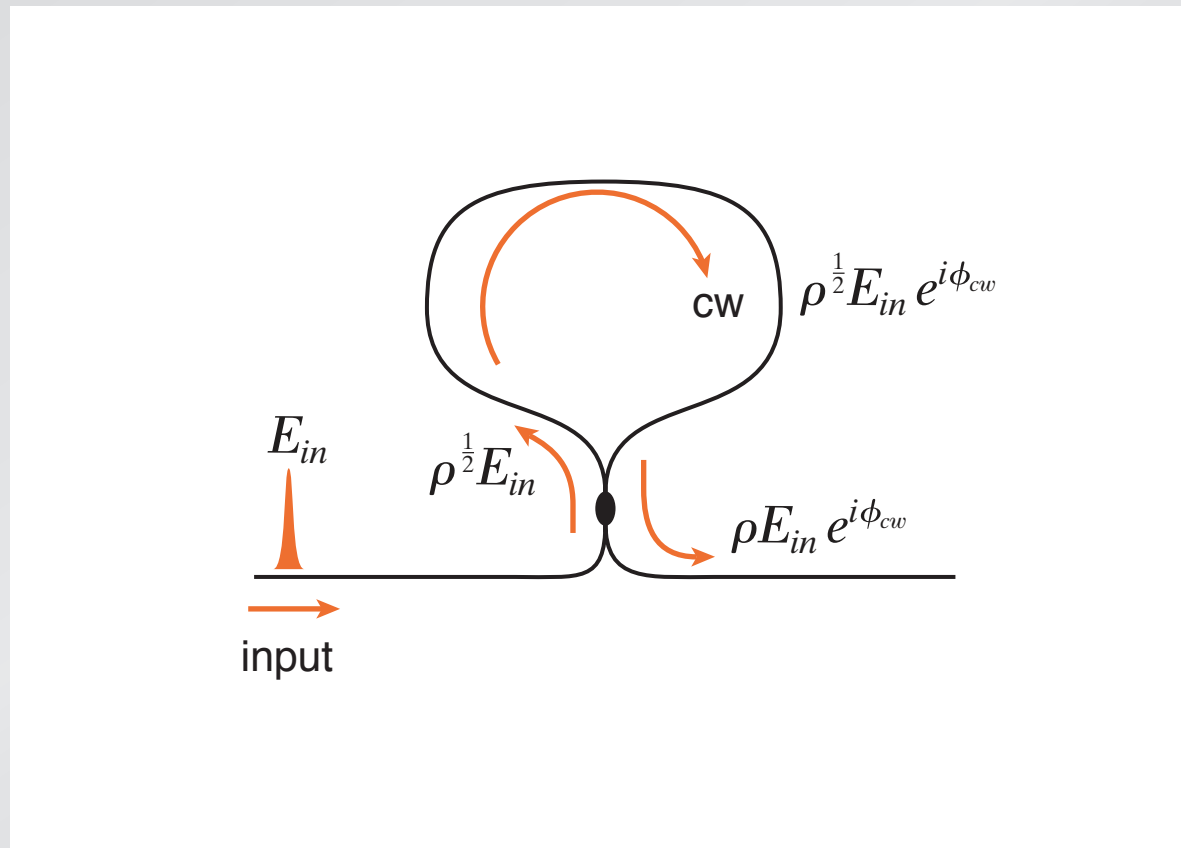
Optical logic gates

phase accumulation over path length of loop L



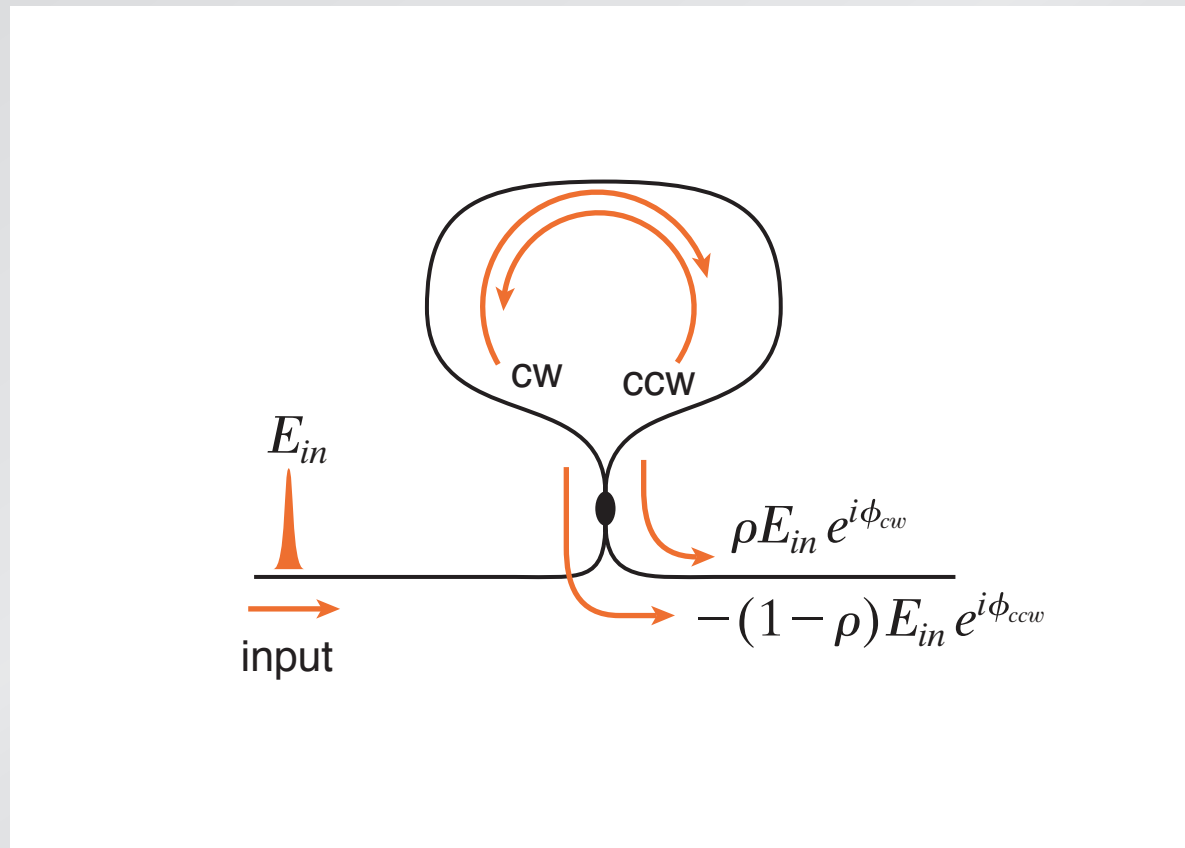
Optical logic gates

coupling parameter: ρ



Optical logic gates

output is sum of transmitted cw and ccw



Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_0 n L$$

Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n L$$

nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n L$$

nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

nonlinear parameter:

$$\gamma = n_2 \frac{k_o}{A_{eff}}$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

Q: What happens for a 50-50 coupler?

- 1. All the light is transmitted.**
- 2. Half the light is transmitted.**
- 3. No light is transmitted.**
- 4. The transmission depends on the input power P_o .**
- 5. Other**

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

Q: What happens for a 50-50 coupler?

1. All the light is transmitted.
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Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

for 50-50 coupler:

$$\rho = 0.5$$

Manipulating light at the nanoscale

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

for 50-50 coupler:

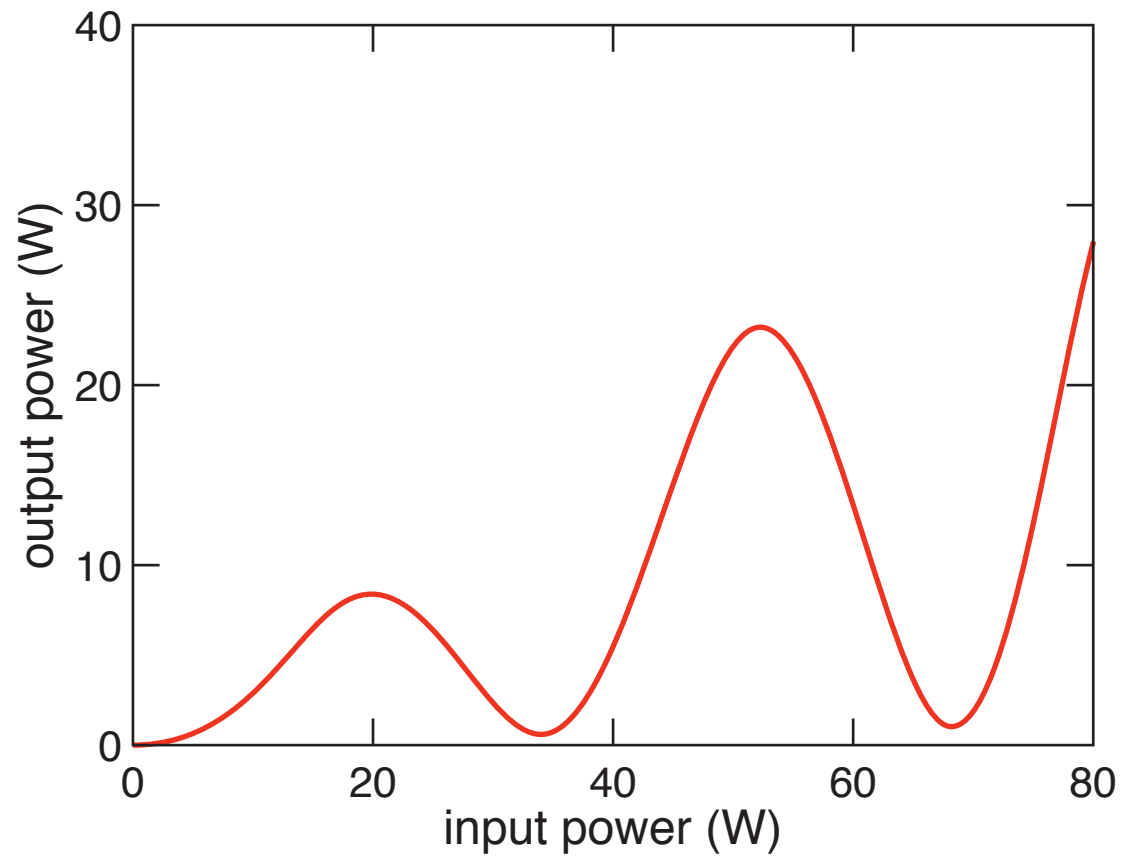
$$\rho = 0.5$$

no transmission:

$$\frac{E_{out}^2}{E_{in}^2} = 0$$

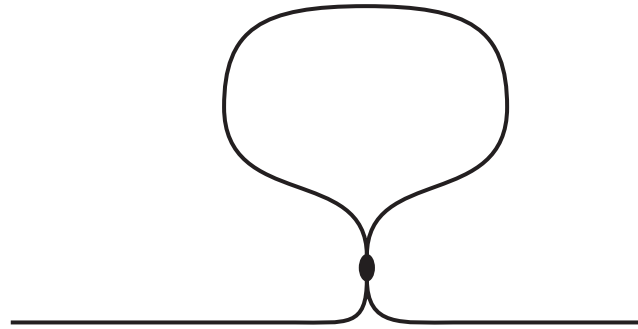
Optical logic gates

when $\rho \neq 0.5$:



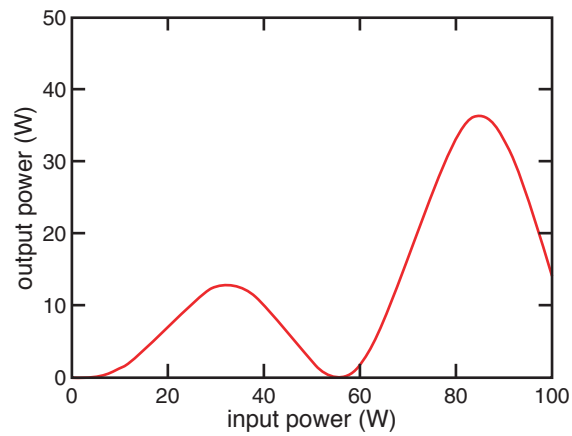
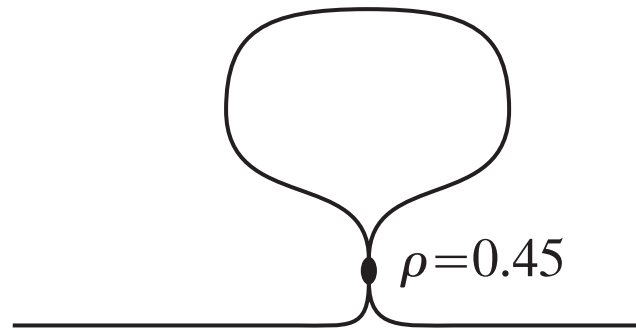
Optical logic gates

nonlinear nanogate



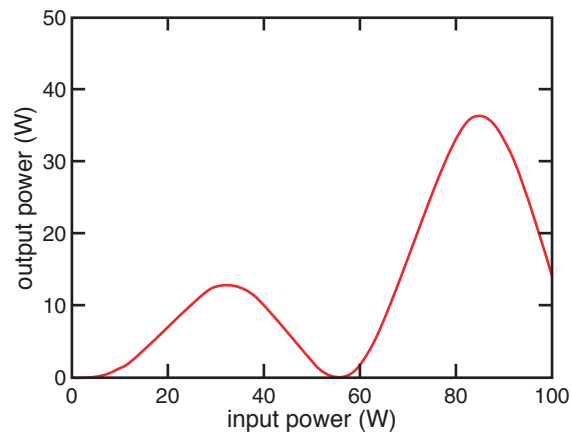
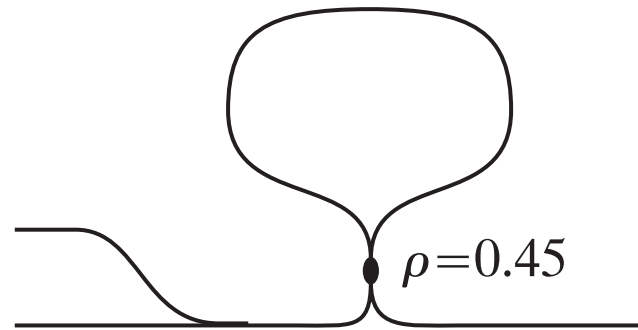
Optical logic gates

nonlinear nanogate



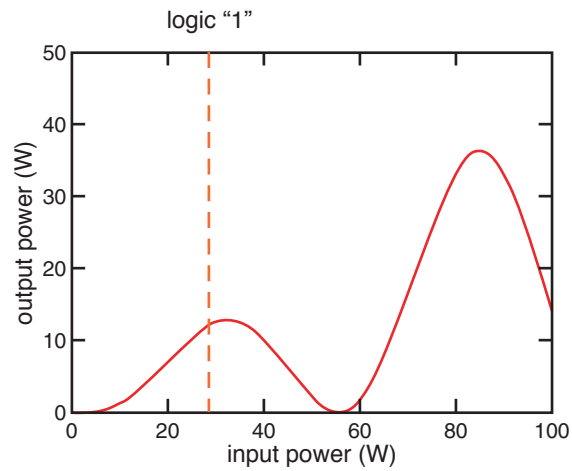
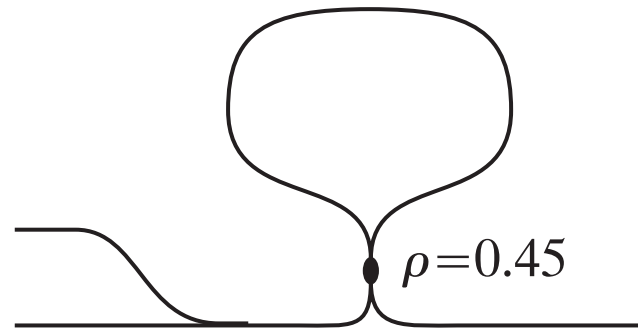
Optical logic gates

nonlinear nanogate



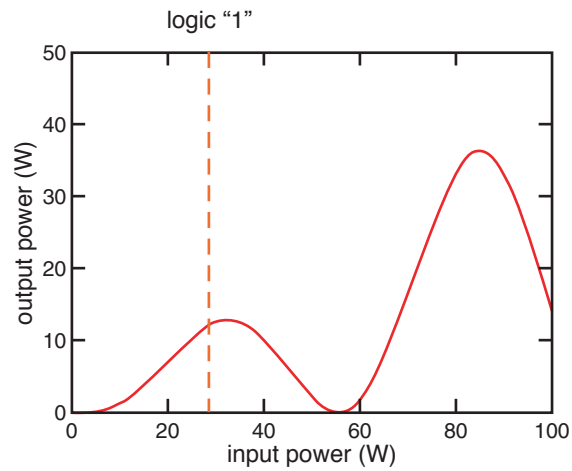
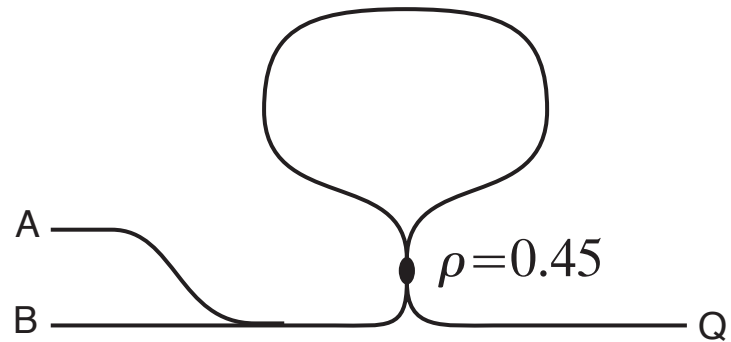
Optical logic gates

nonlinear nanogate



Optical logic gates

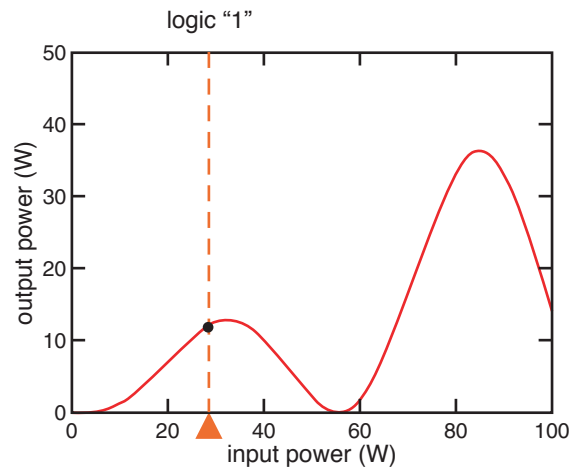
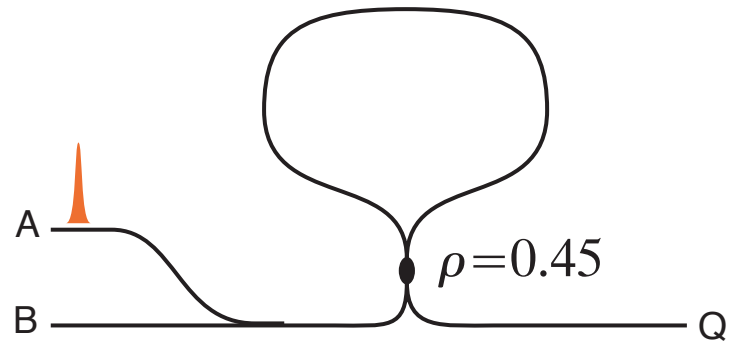
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

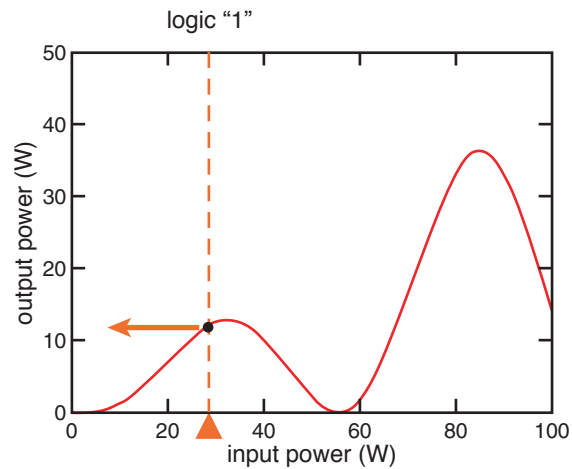
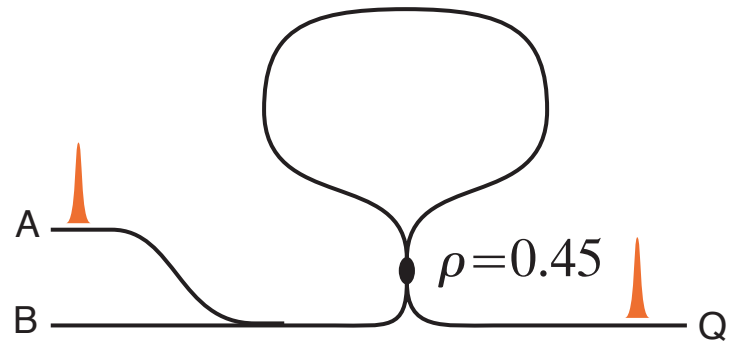
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

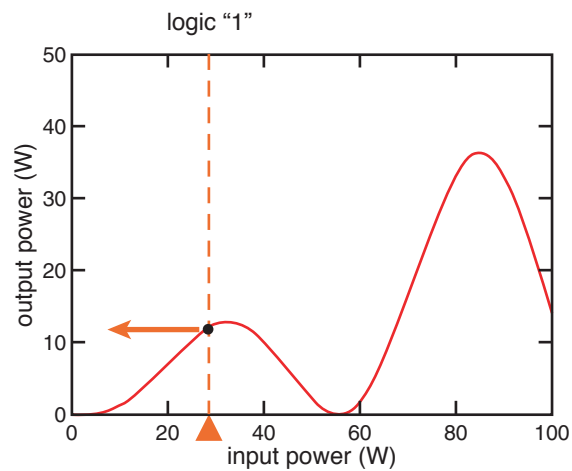
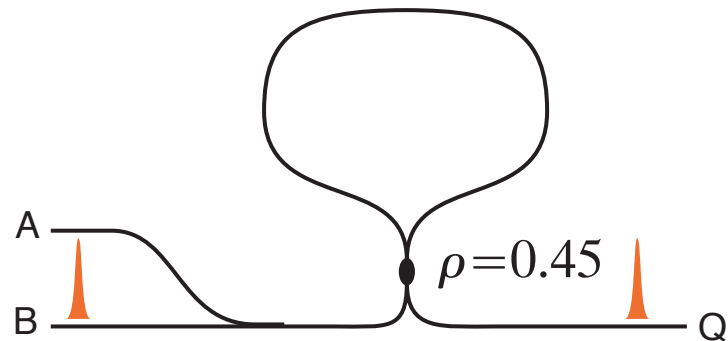
nonlinear nanogate



A	B	Q
0	0	0
1	0	1

Optical logic gates

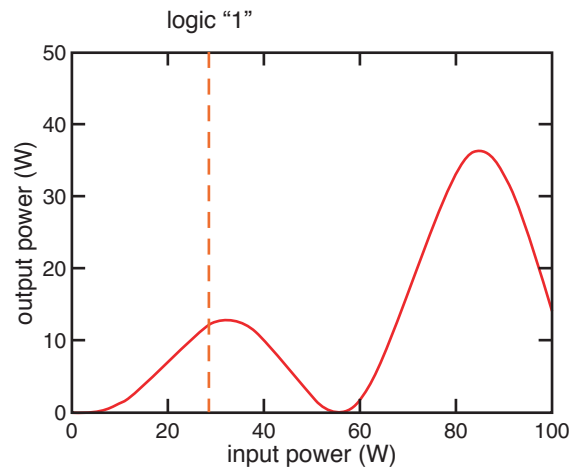
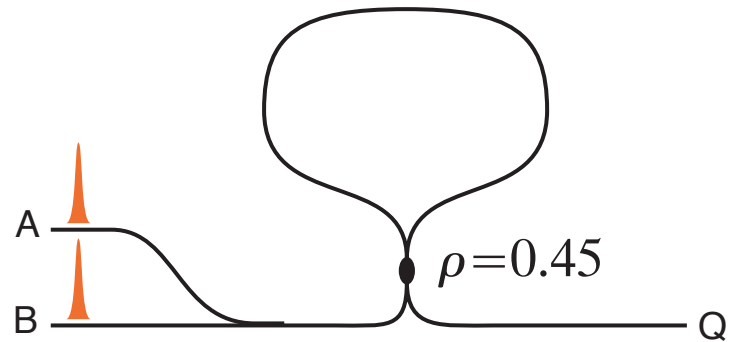
nonlinear nanogate



A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

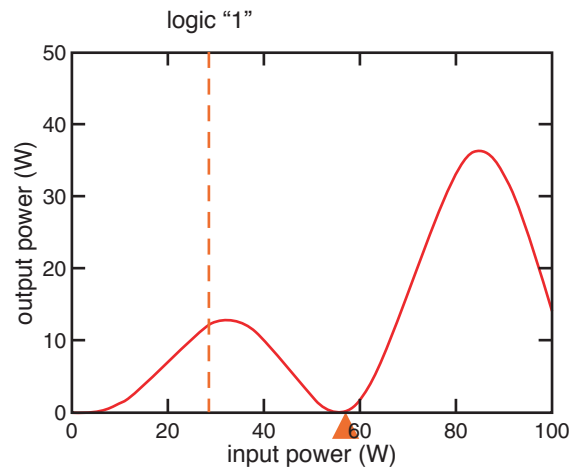
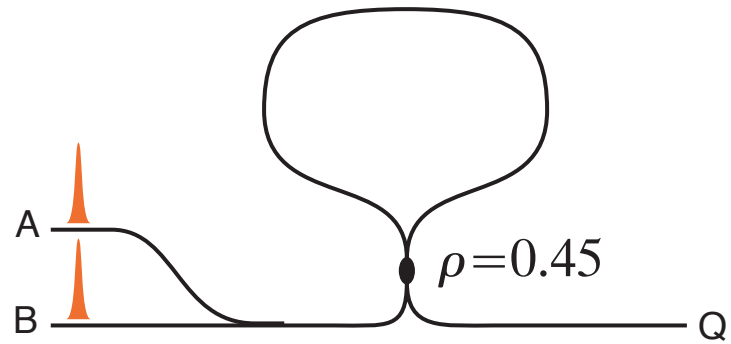
nonlinear nanogate



A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

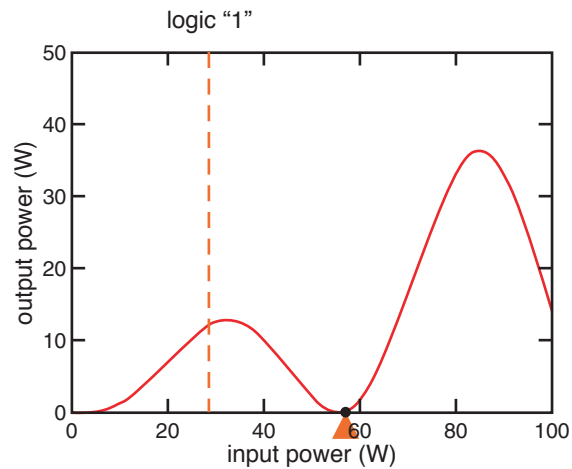
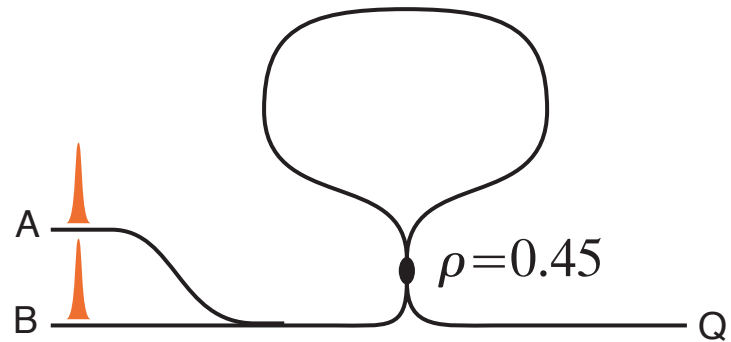
nonlinear nanogate



A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

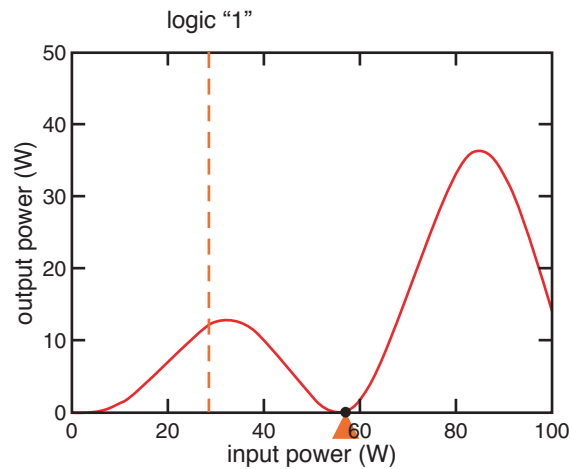
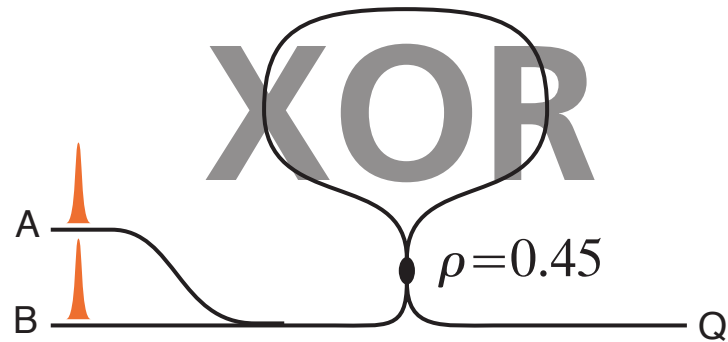
nonlinear nanogate



A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

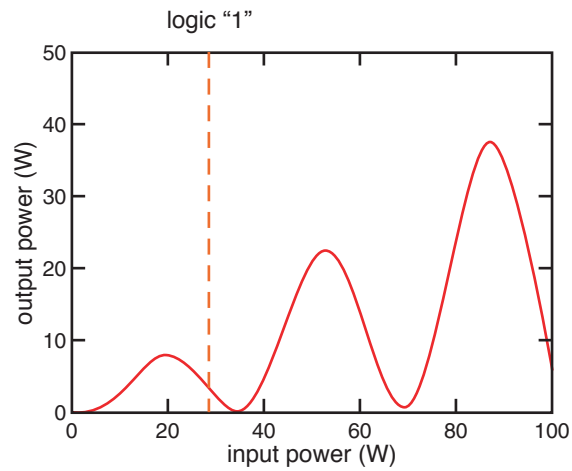
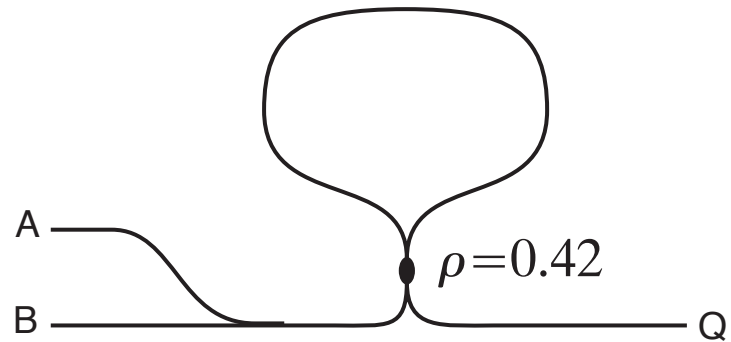
nonlinear nanogate



A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

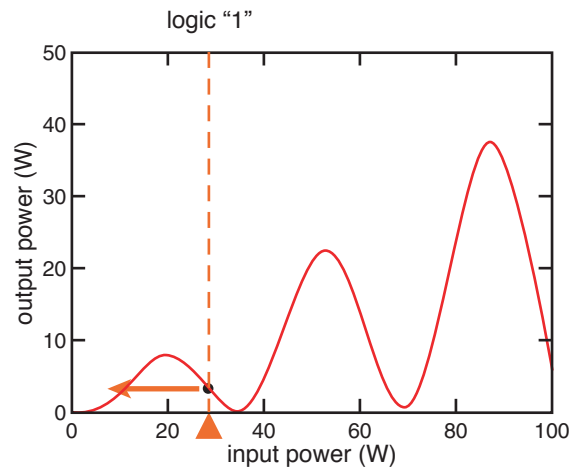
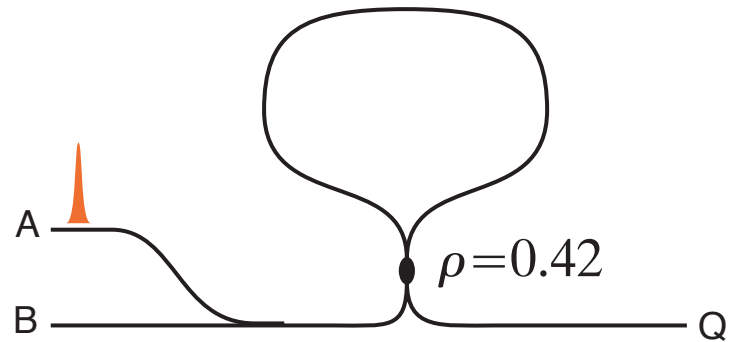
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

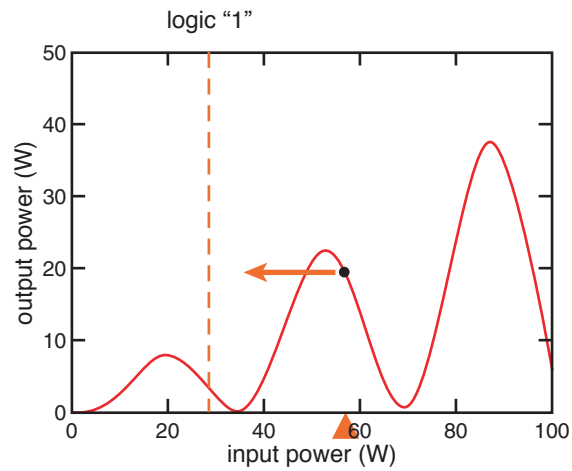
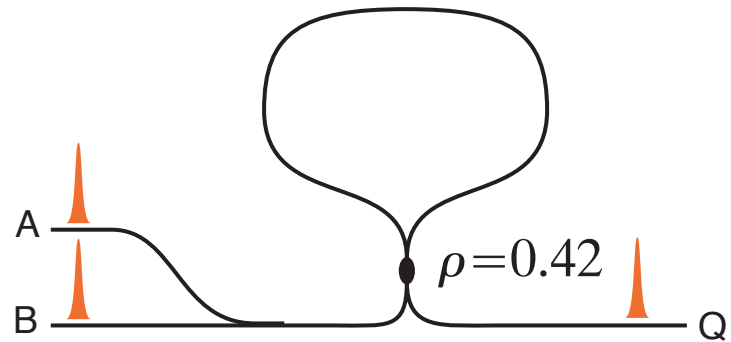
nonlinear nanogate



A	B	Q
0	0	0
1	0	0
0	1	0

Optical logic gates

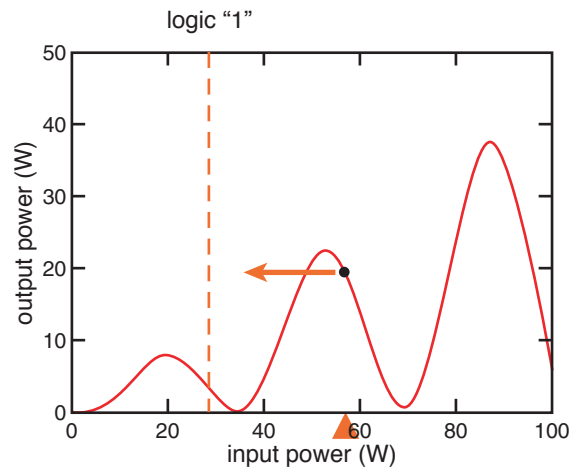
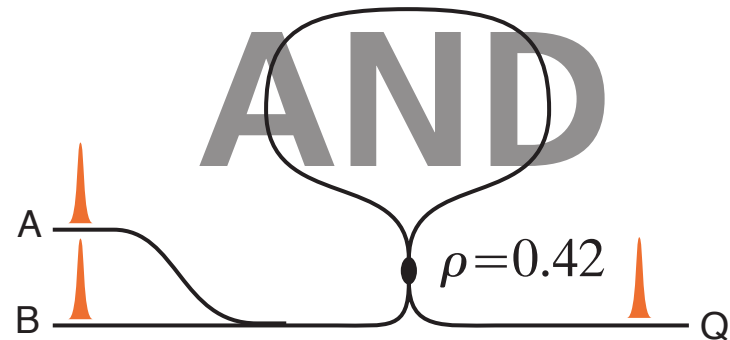
nonlinear nanogate



A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

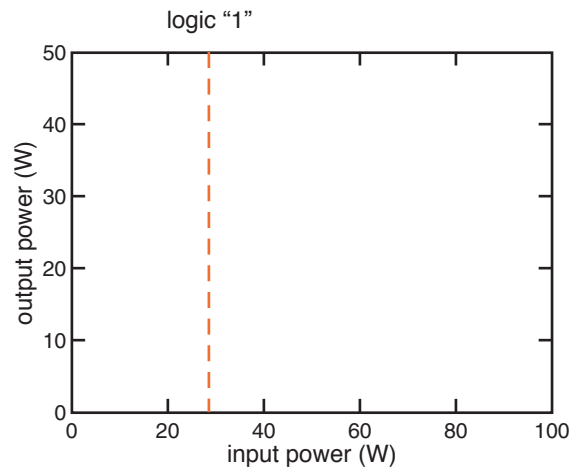
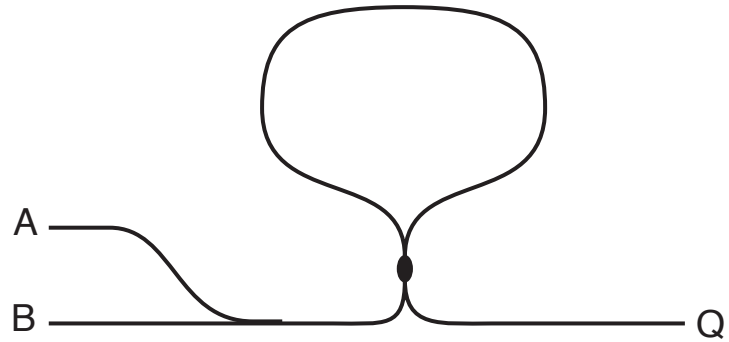
nonlinear nanogate



A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

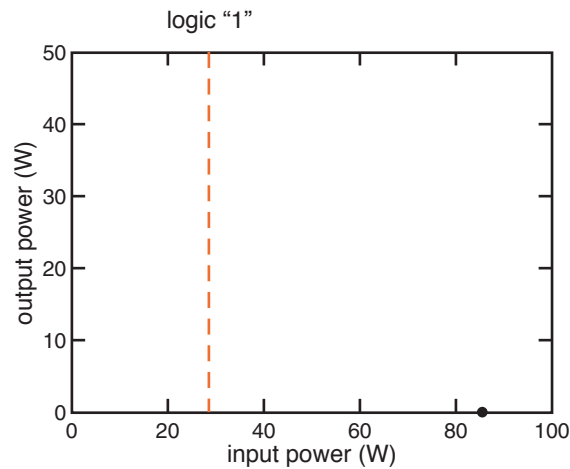
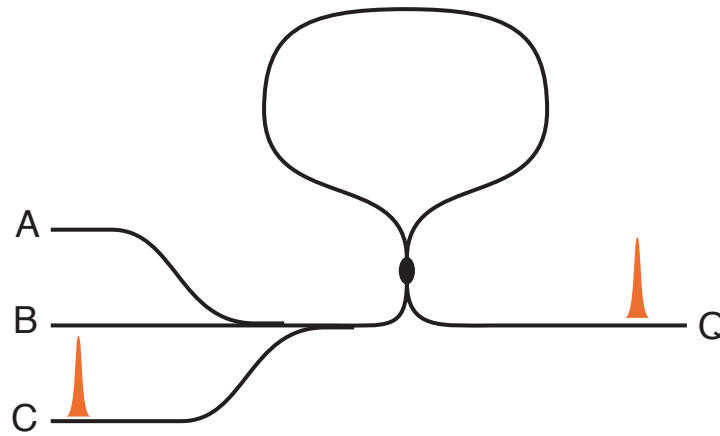
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

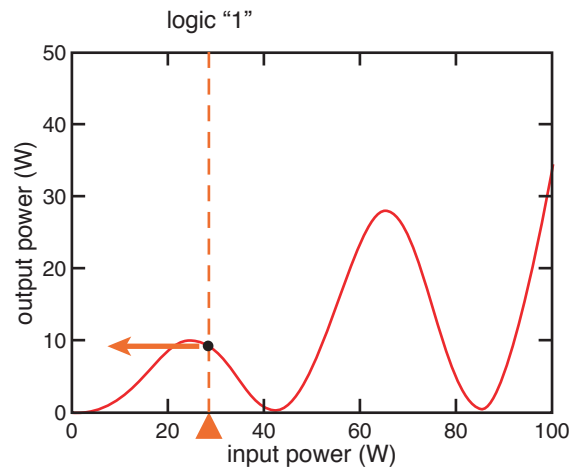
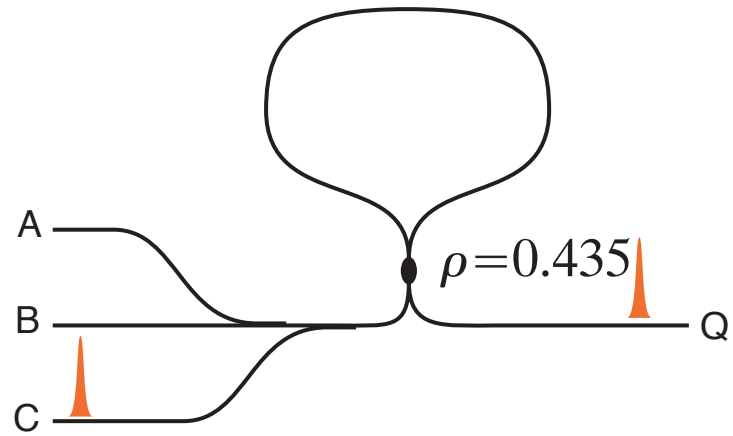
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

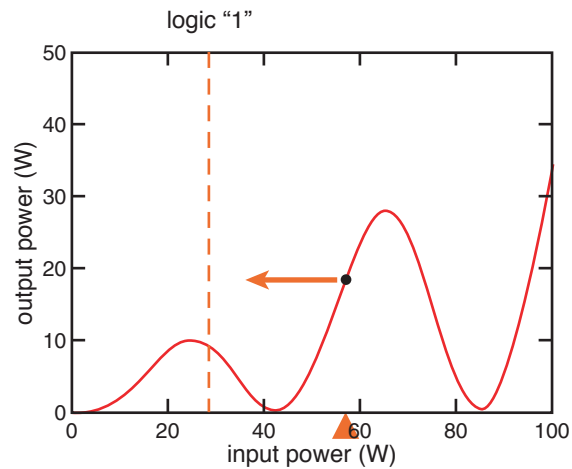
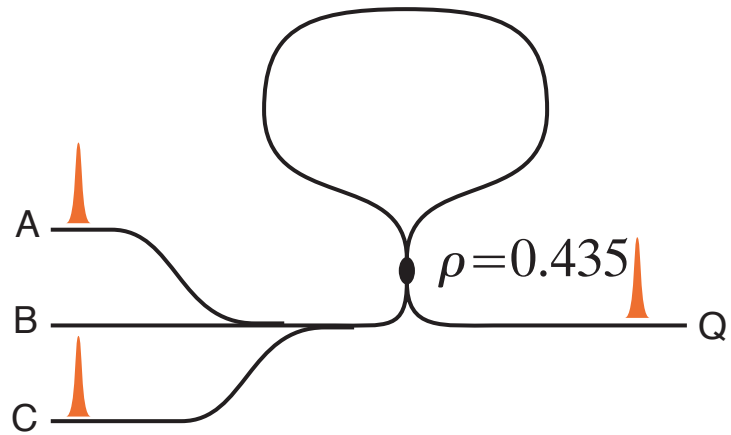
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

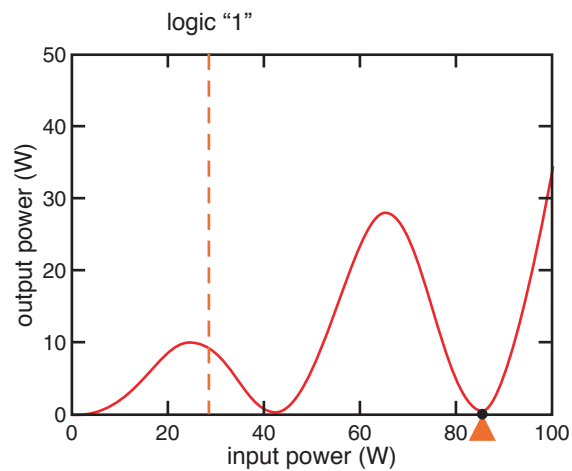
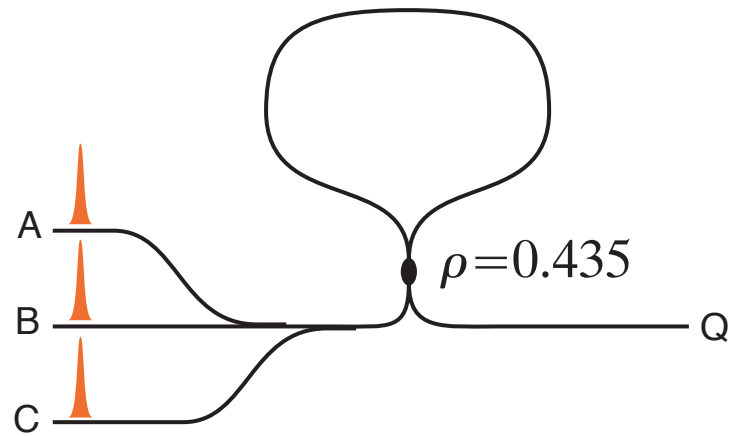
universal NAND gate



A	B	Q
0	0	1
1	0	1
0	1	1

Optical logic gates

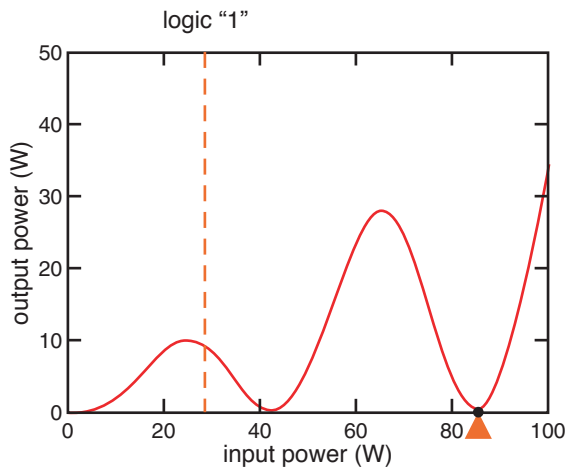
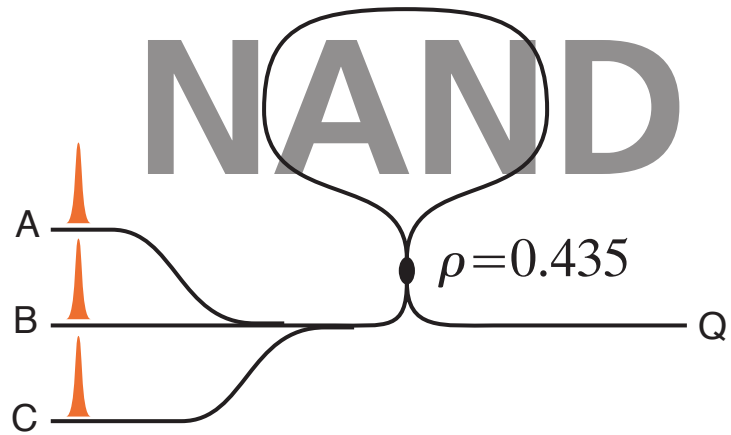
universal NAND gate



A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

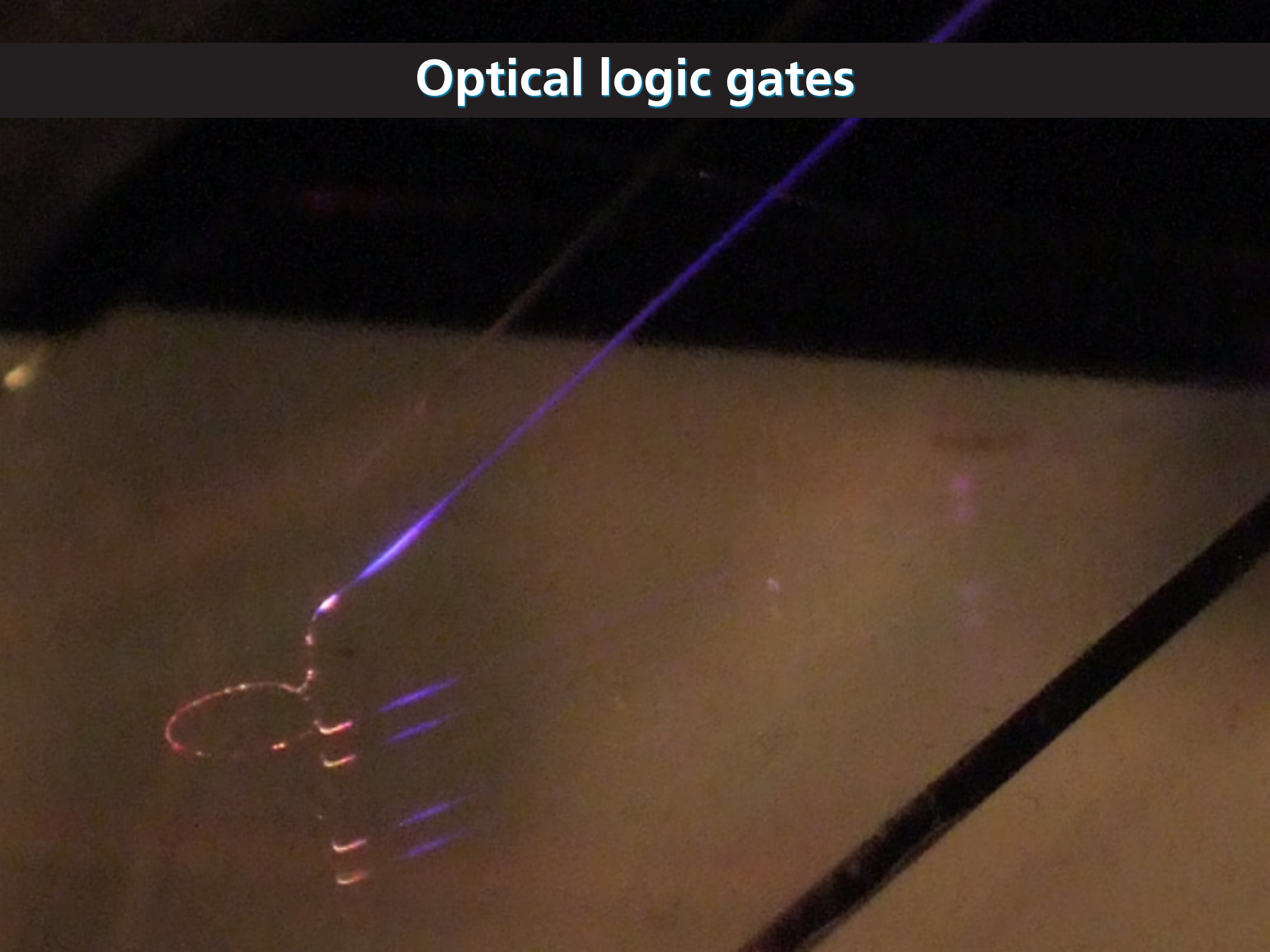
Optical logic gates

universal NAND gate



A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

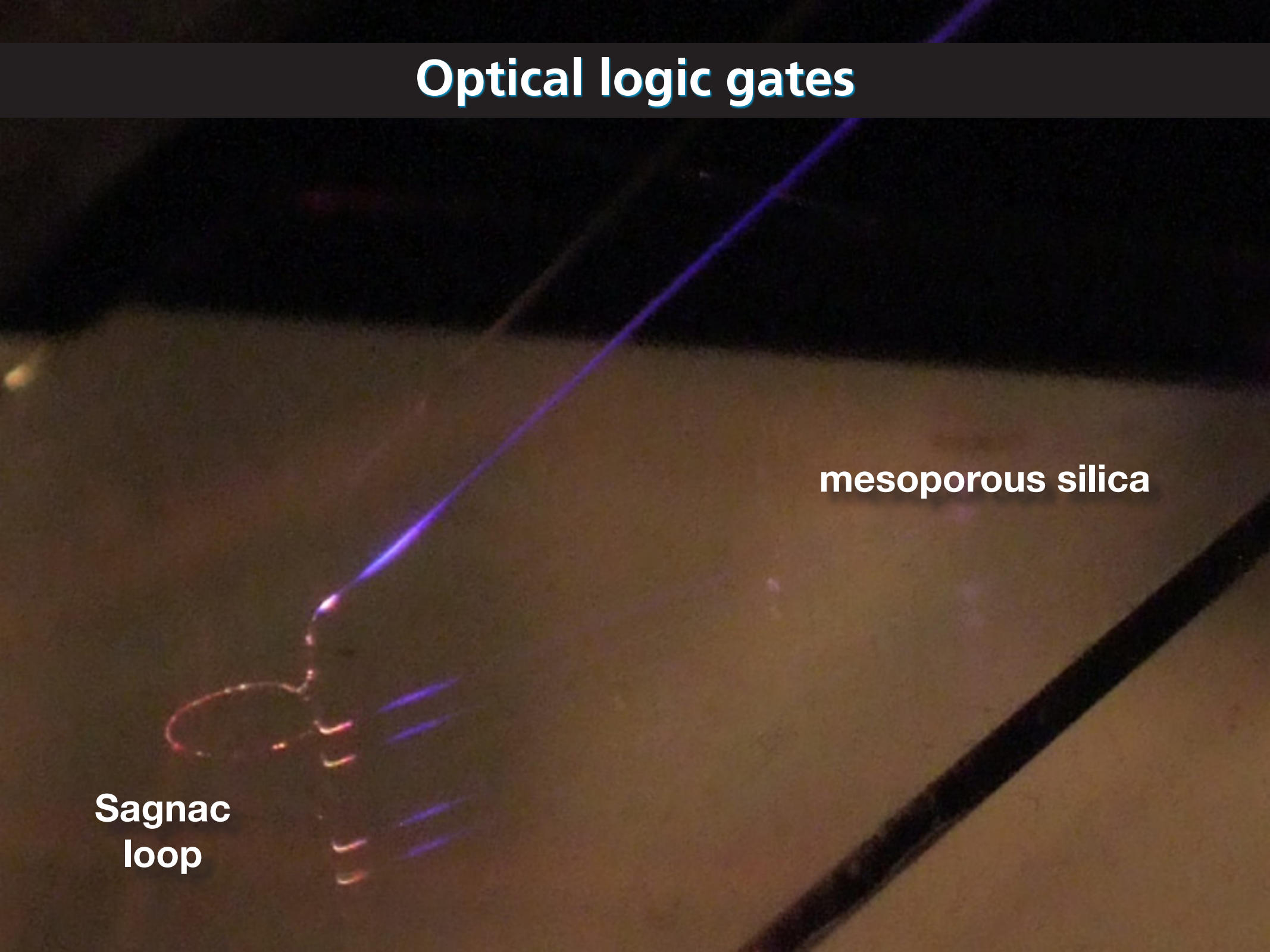
Optical logic gates



Optical logic gates

mesoporous silica

Sagnac
loop



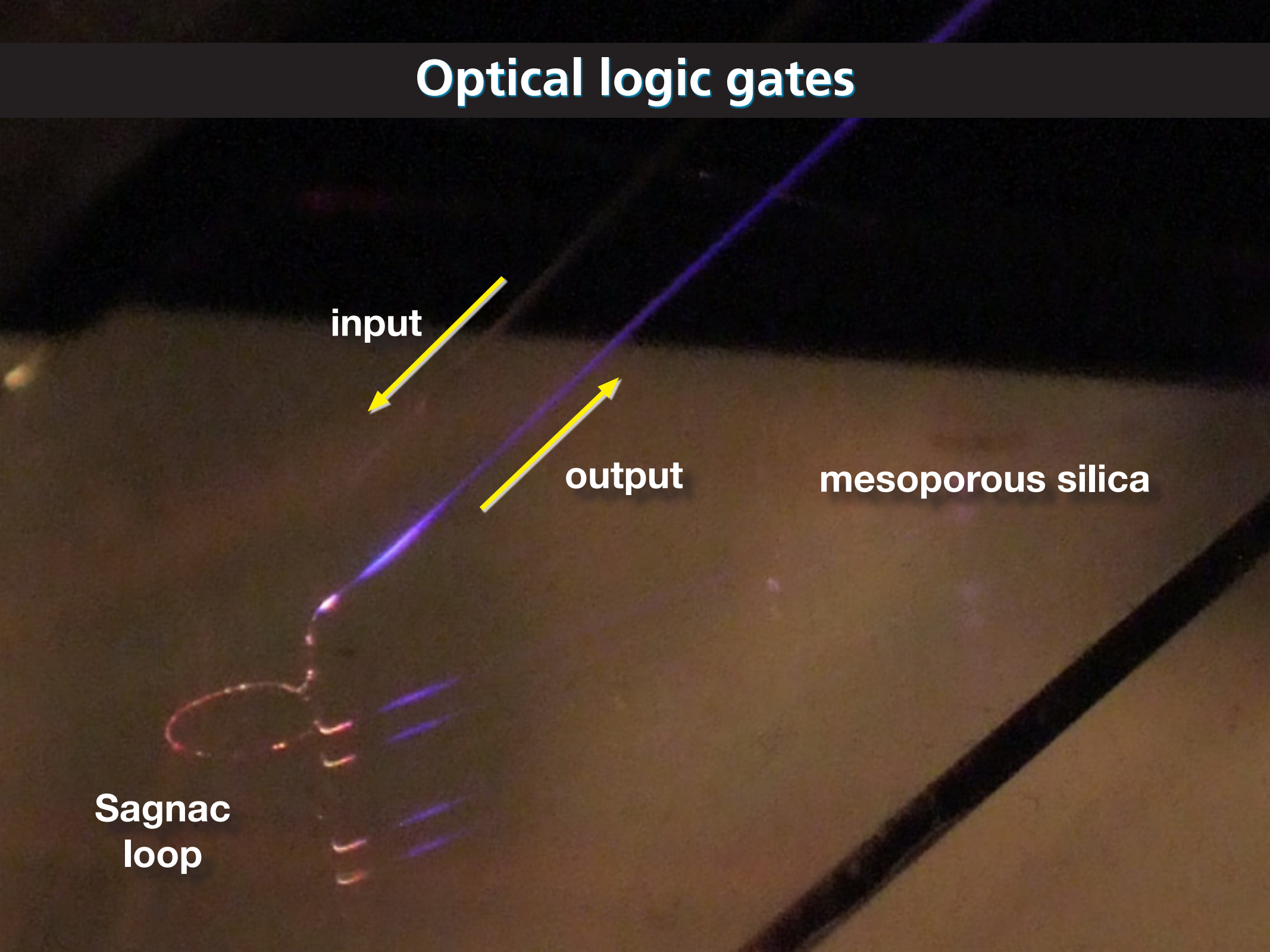
Optical logic gates

input

output

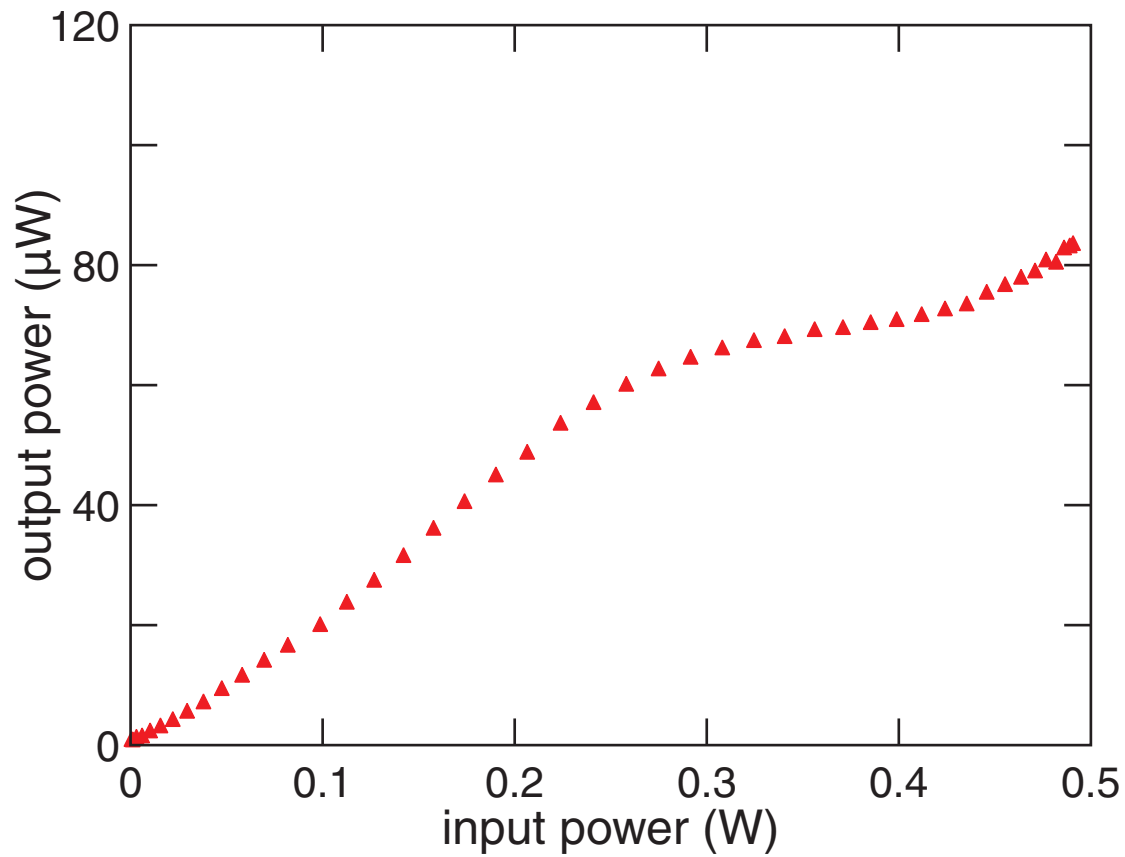
mesoporous silica

Sagnac
loop



Optical logic gates

very preliminary data

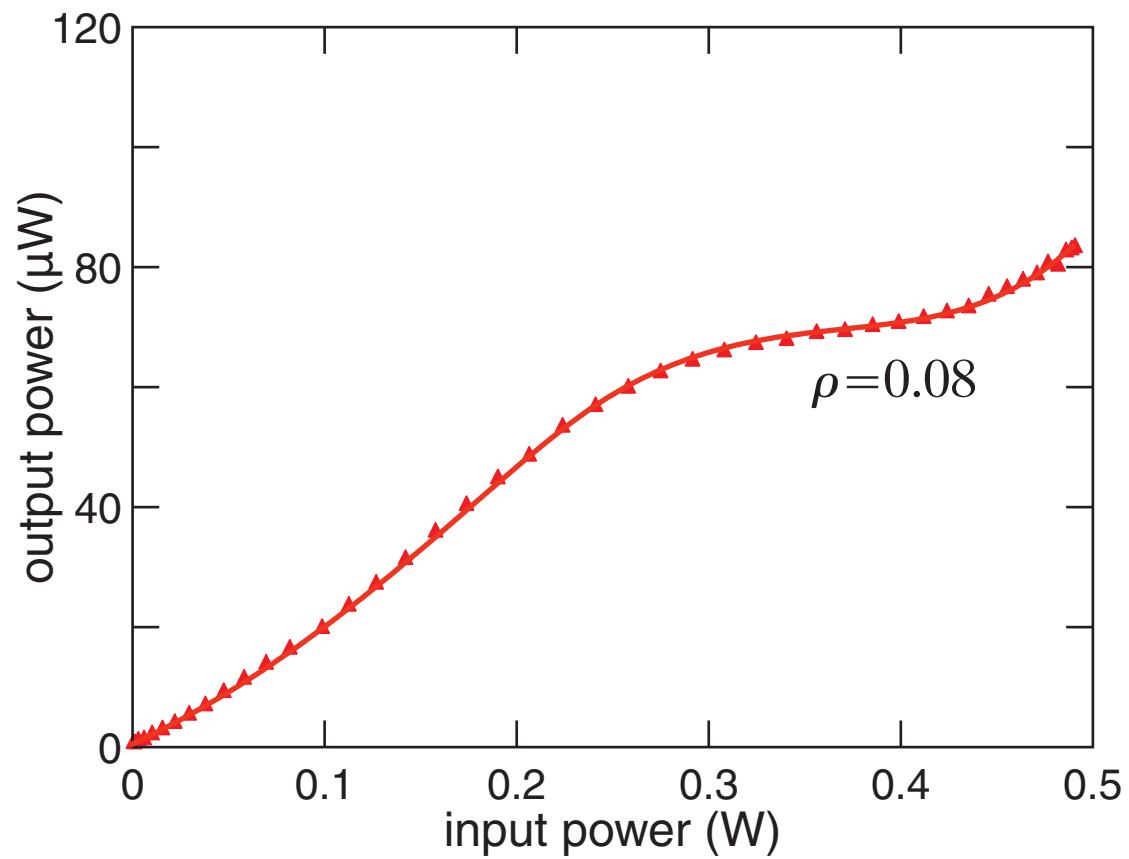


Optical logic gates

light-by-light modulation!

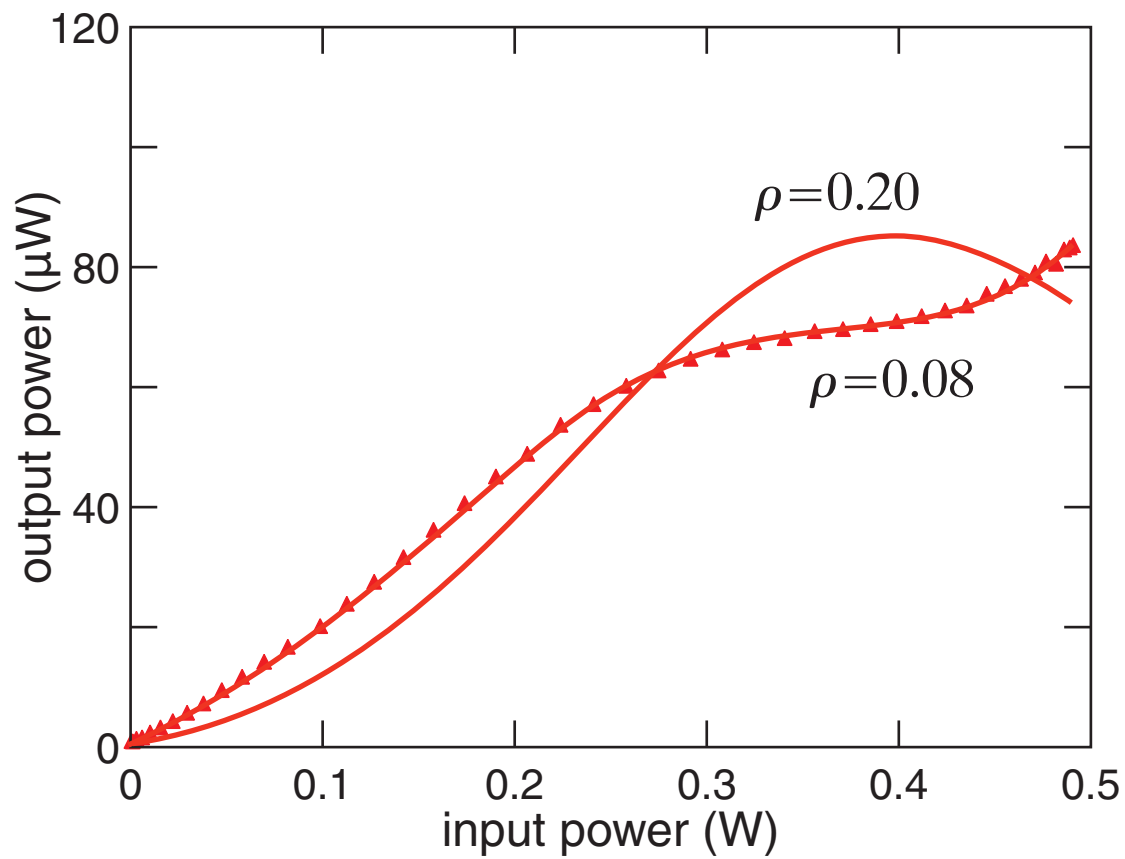
Optical logic gates

very preliminary data

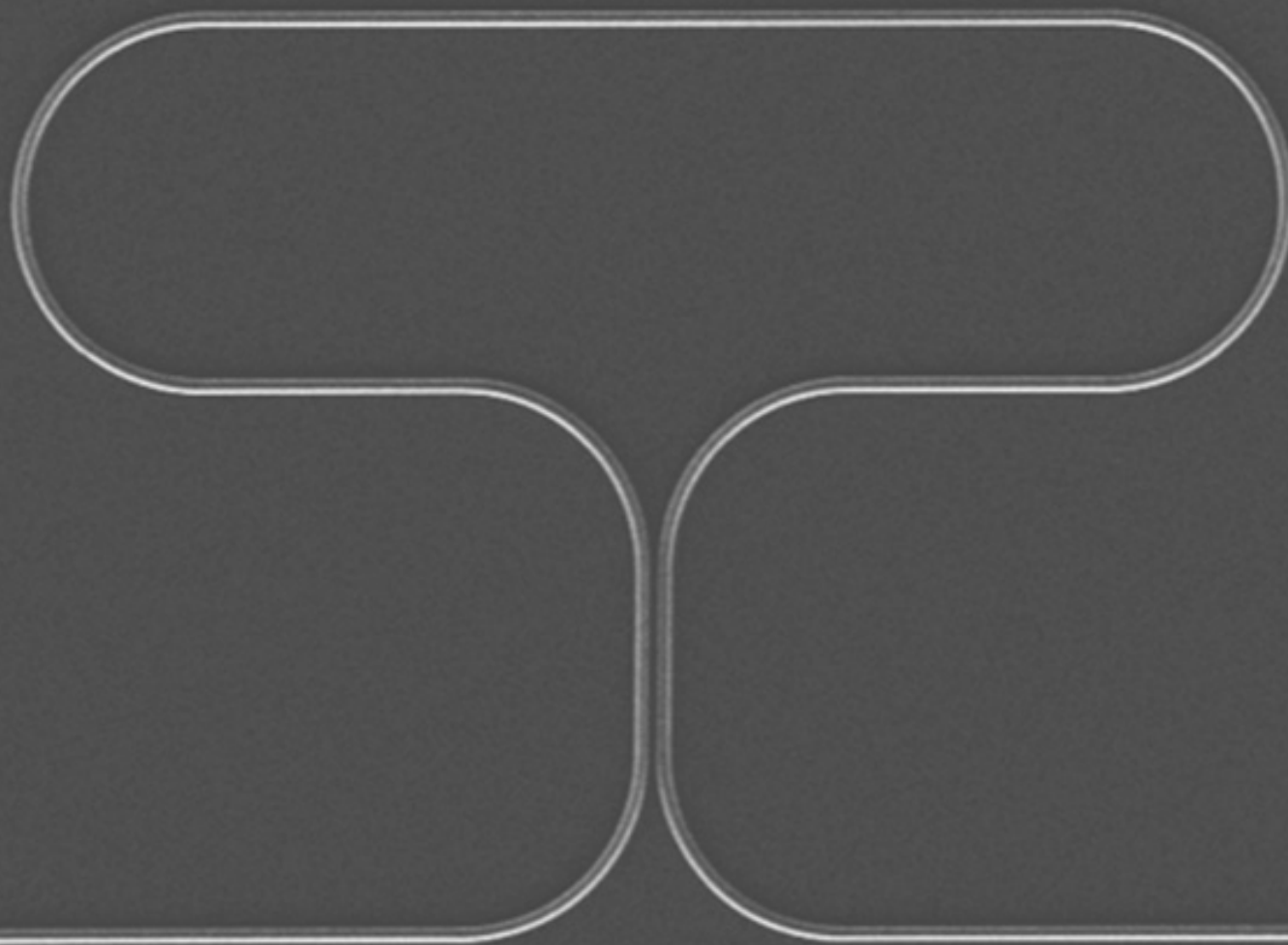


Optical logic gates

very preliminary data



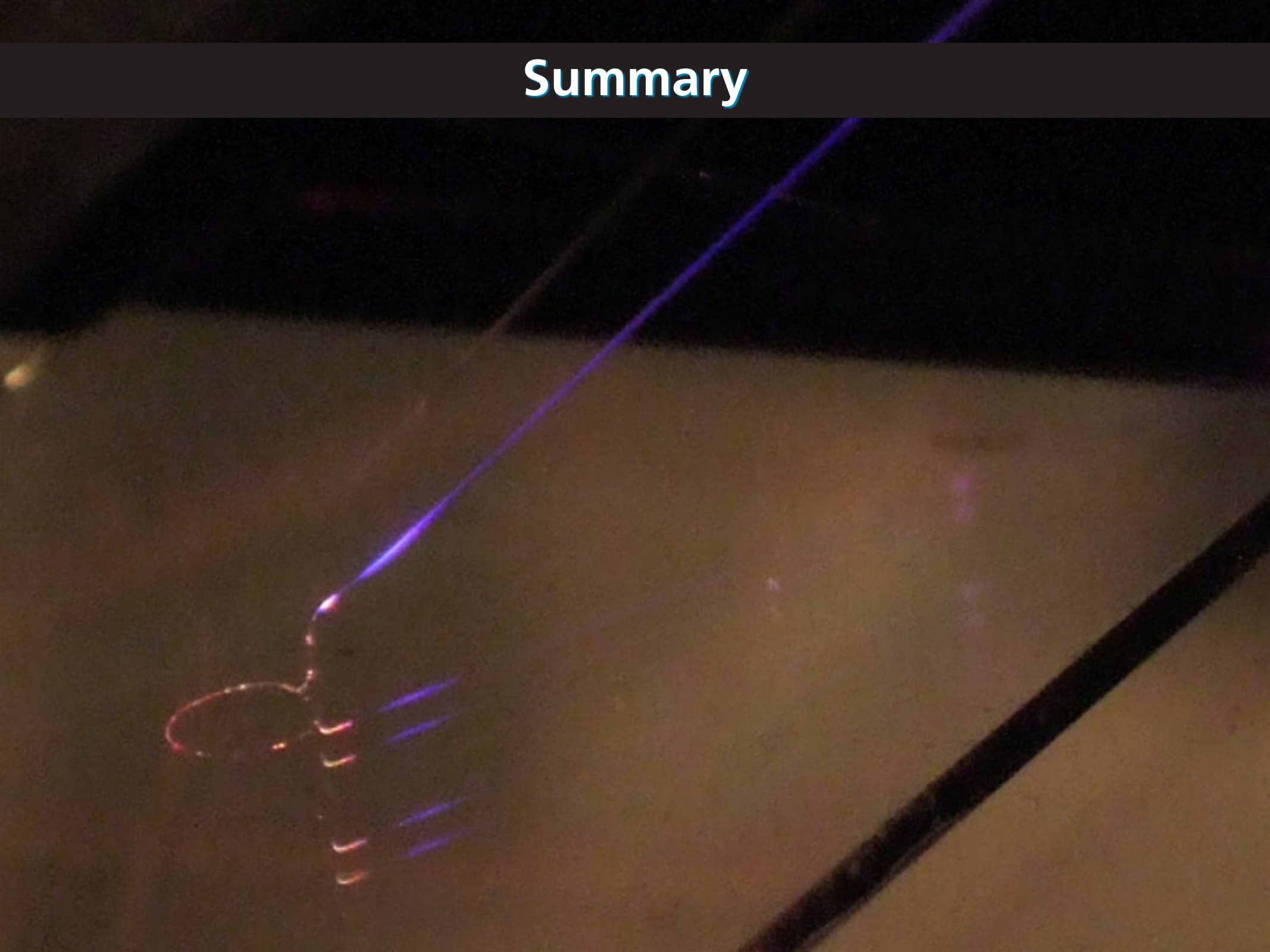
Optical logic gates



10 μm



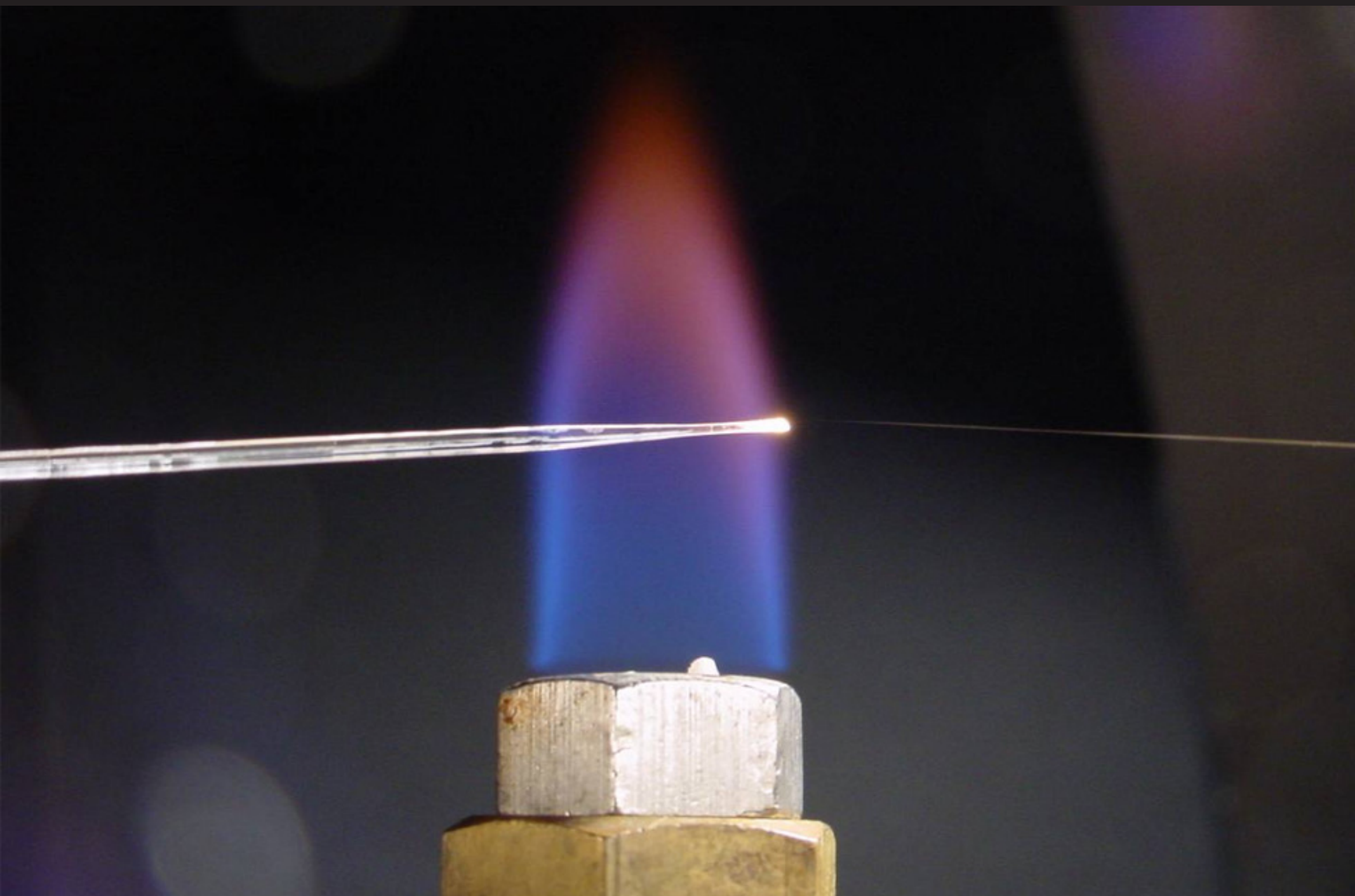
Summary



Summary

- several nanodevices demonstrated
- large γ permits miniature Sagnac loops
- switching energy ≈ 100 pJ

Summary





Funding:

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