

Nonlinear optics at the nanoscale



TU Delft
Delft, Netherlands, 21 September 2011



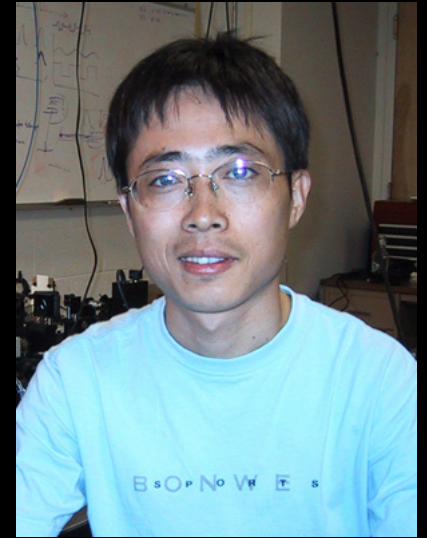
Geoff Svacha



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)

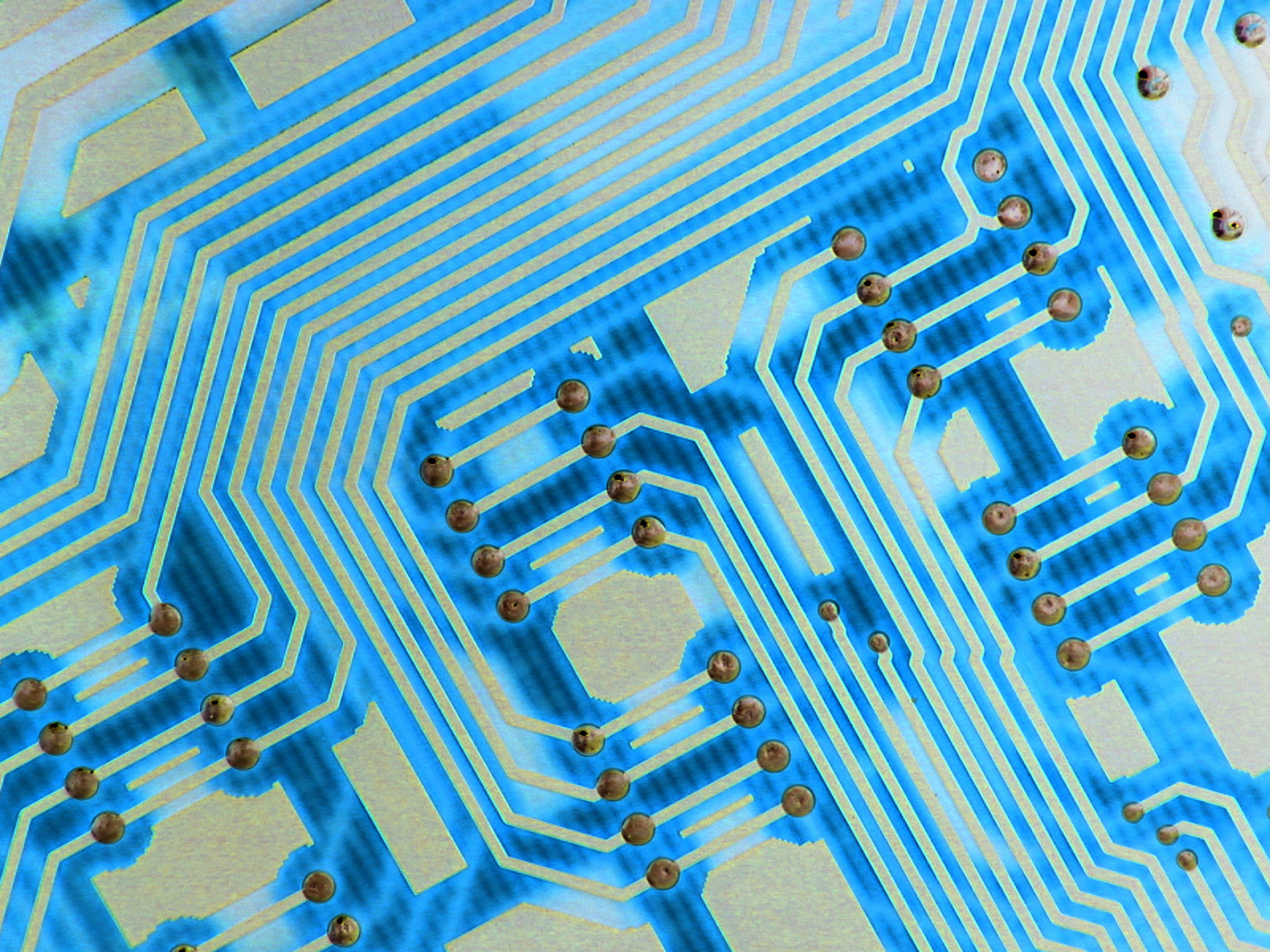
Dr. Jingyi Lou (Zhejiang)

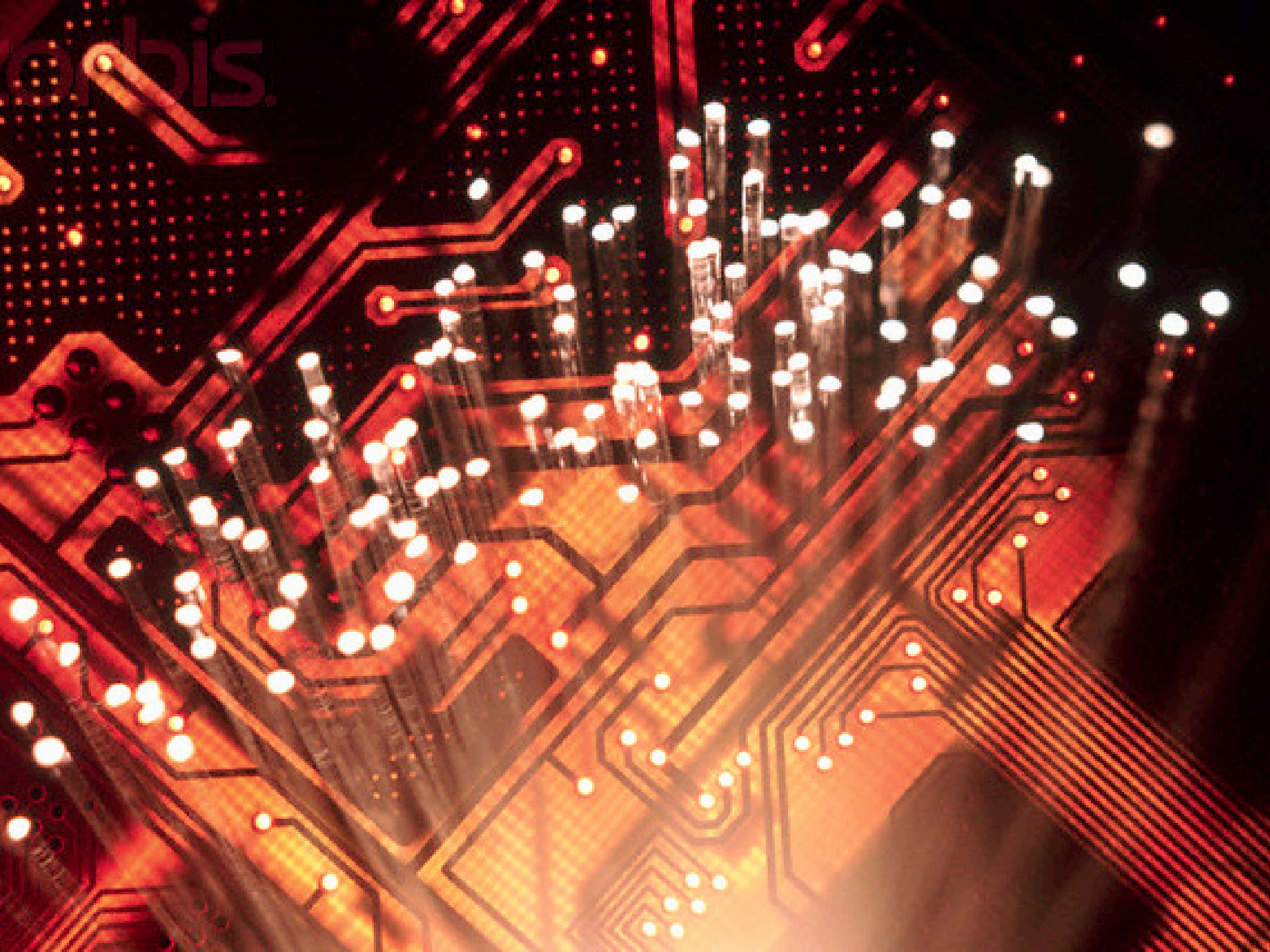
Dr. Ray Mariella (LLNL)

Prof. Frank Marlow (MPI Mülheim)

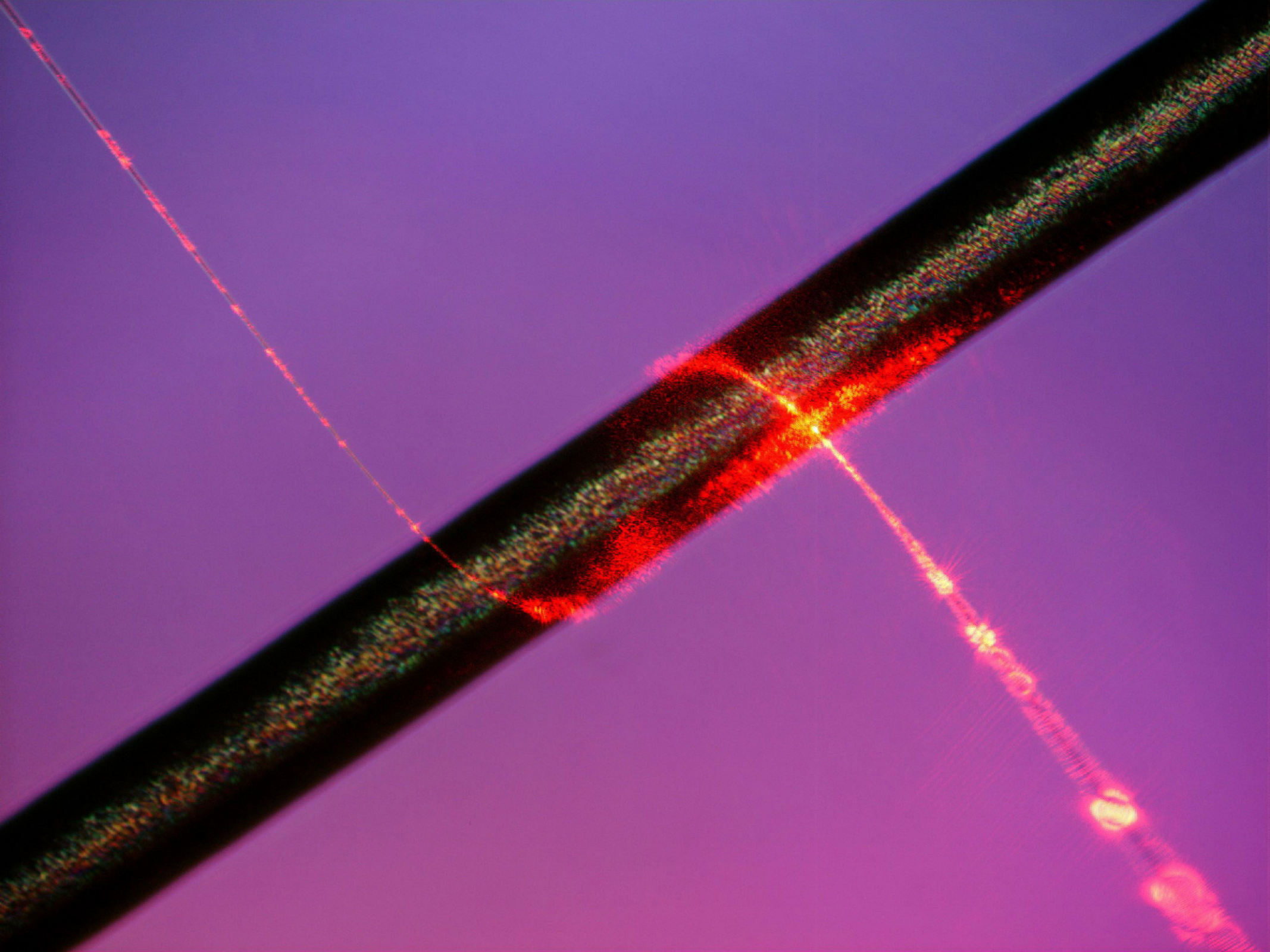
Prof. Sven Müller (Göttingen)

Prof. Carsten Ronning (Göttingen)





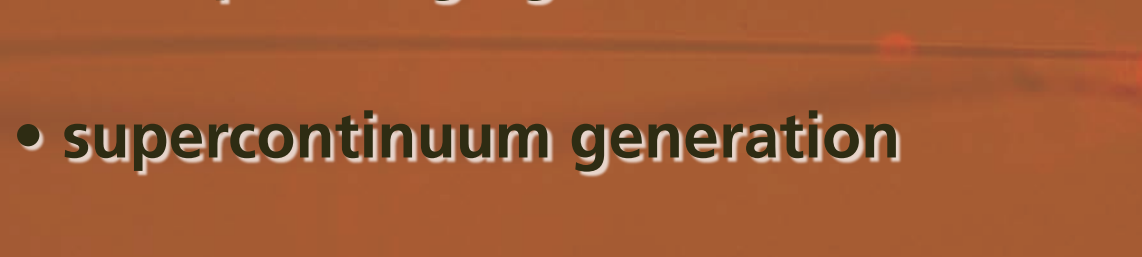
orbis.



Outline



Outline

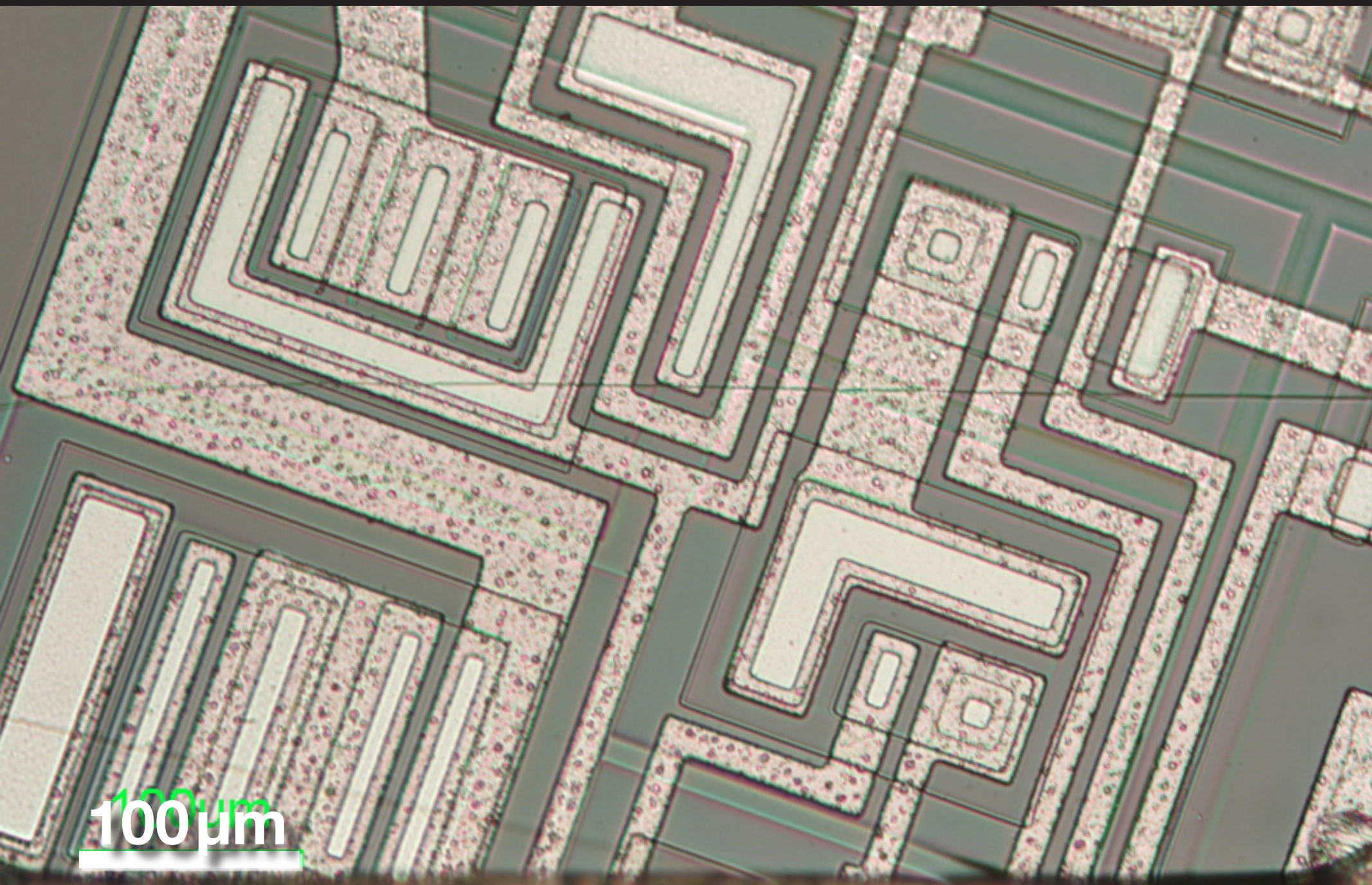
- **manipulating light at the nanoscale**
 - **supercontinuum generation**
 - **optical logic gates**
- 

Manipulating light at the nanoscale



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

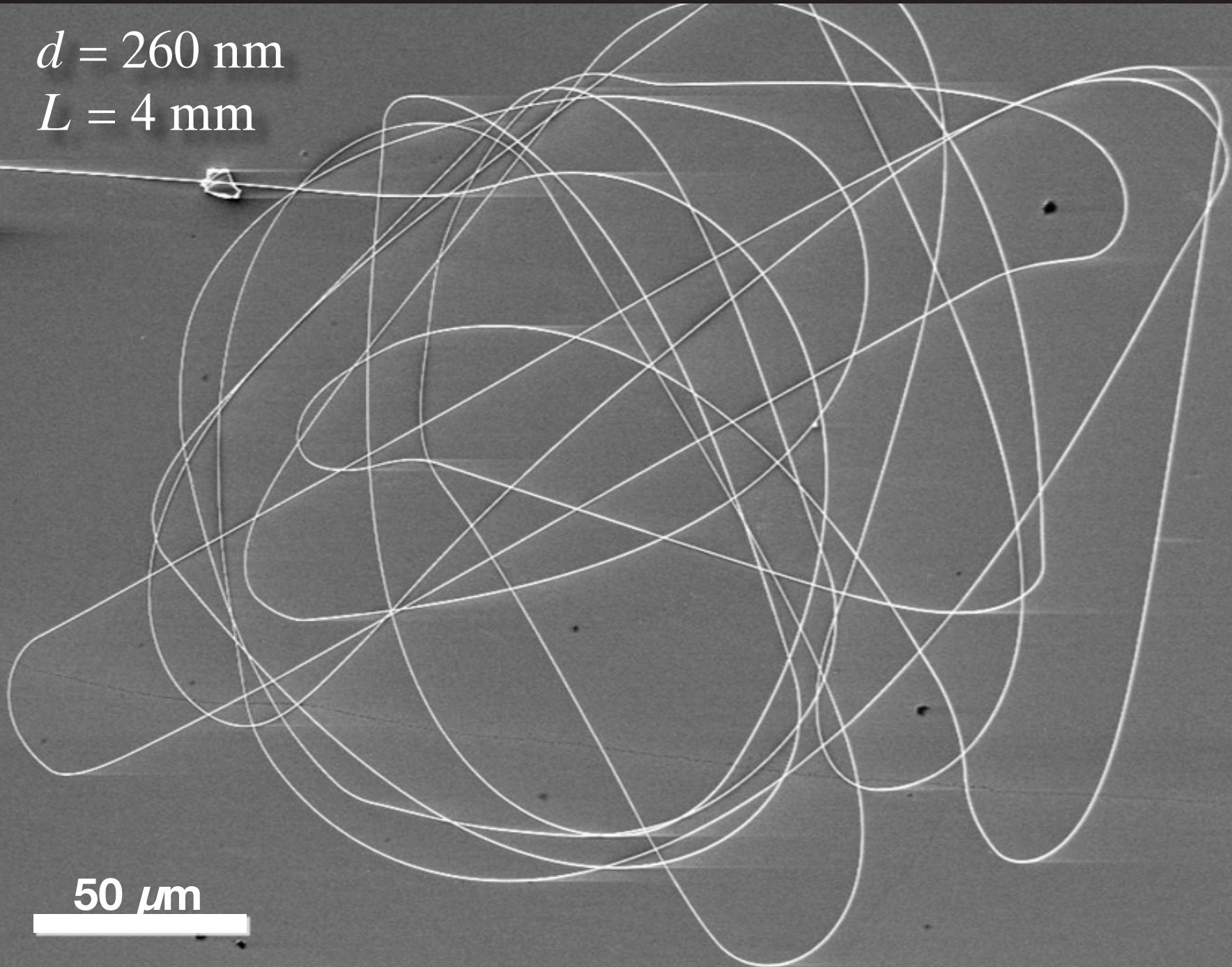
Manipulating light at the nanoscale



Manipulating light at the nanoscale

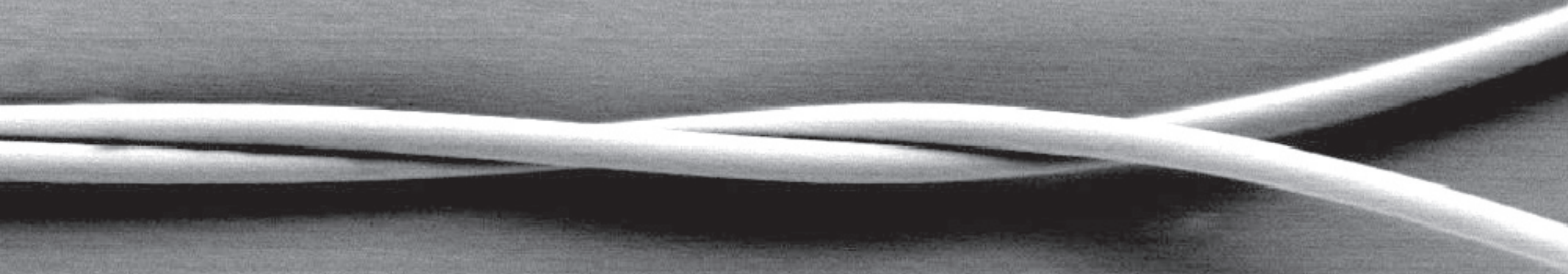
$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50 μm

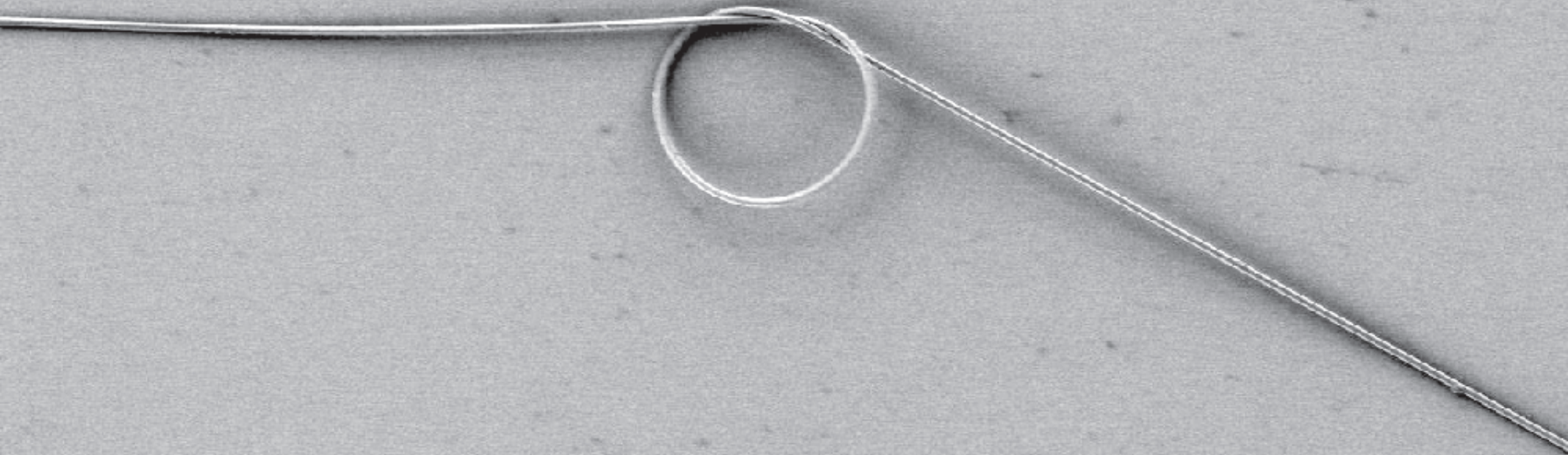
Manipulating light at the nanoscale



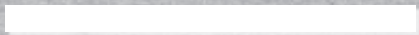
2 μm



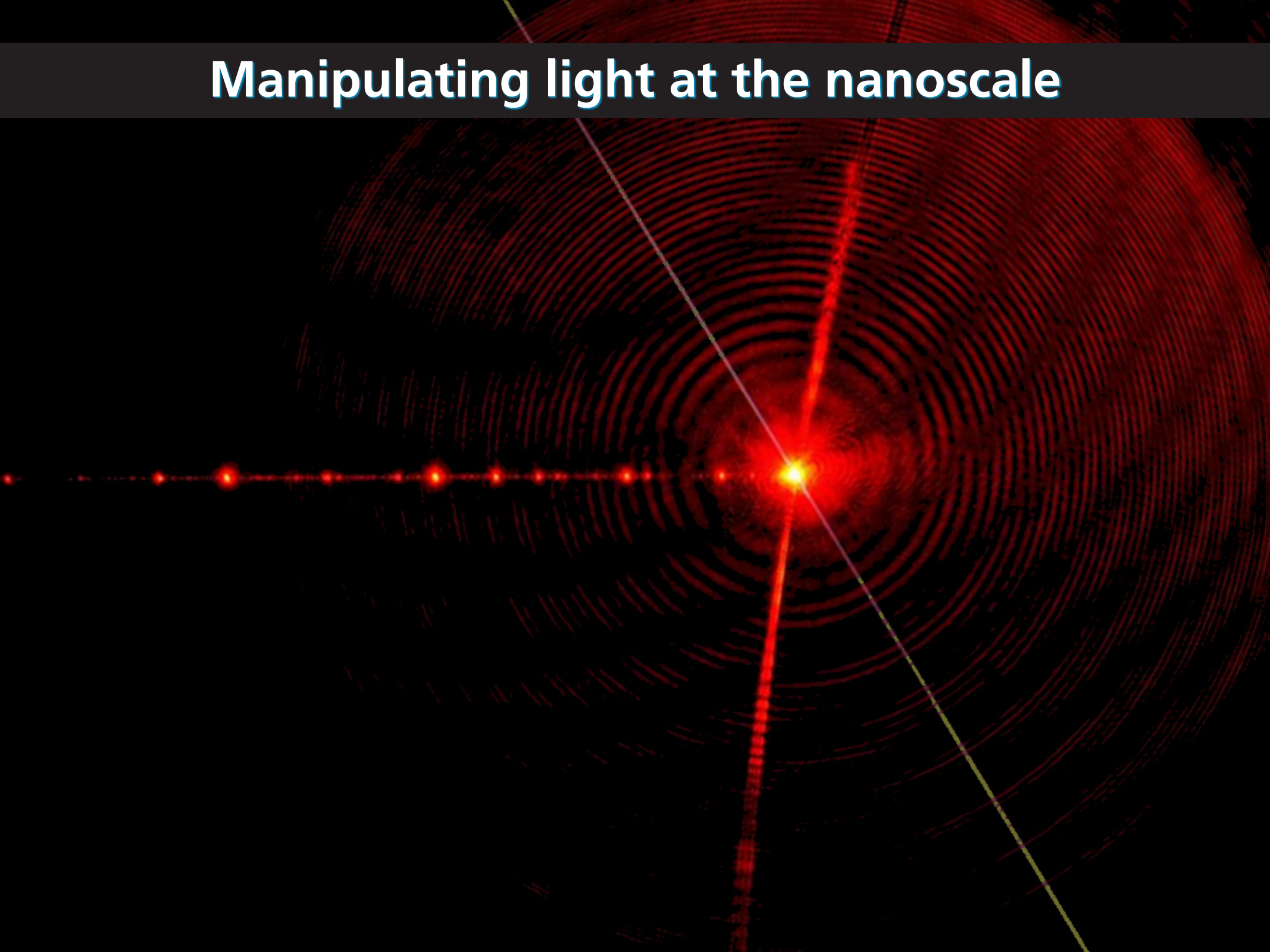
Manipulating light at the nanoscale



20 μm

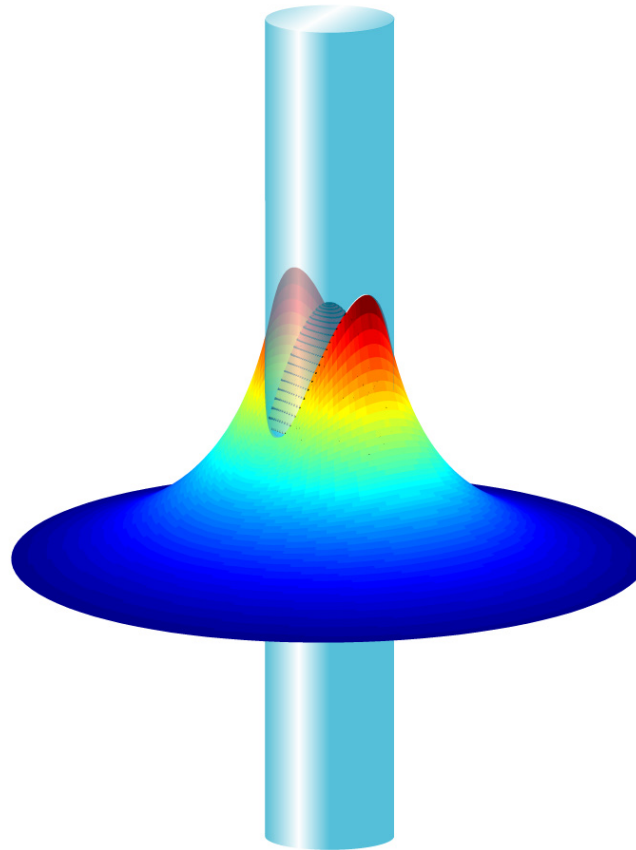


Manipulating light at the nanoscale

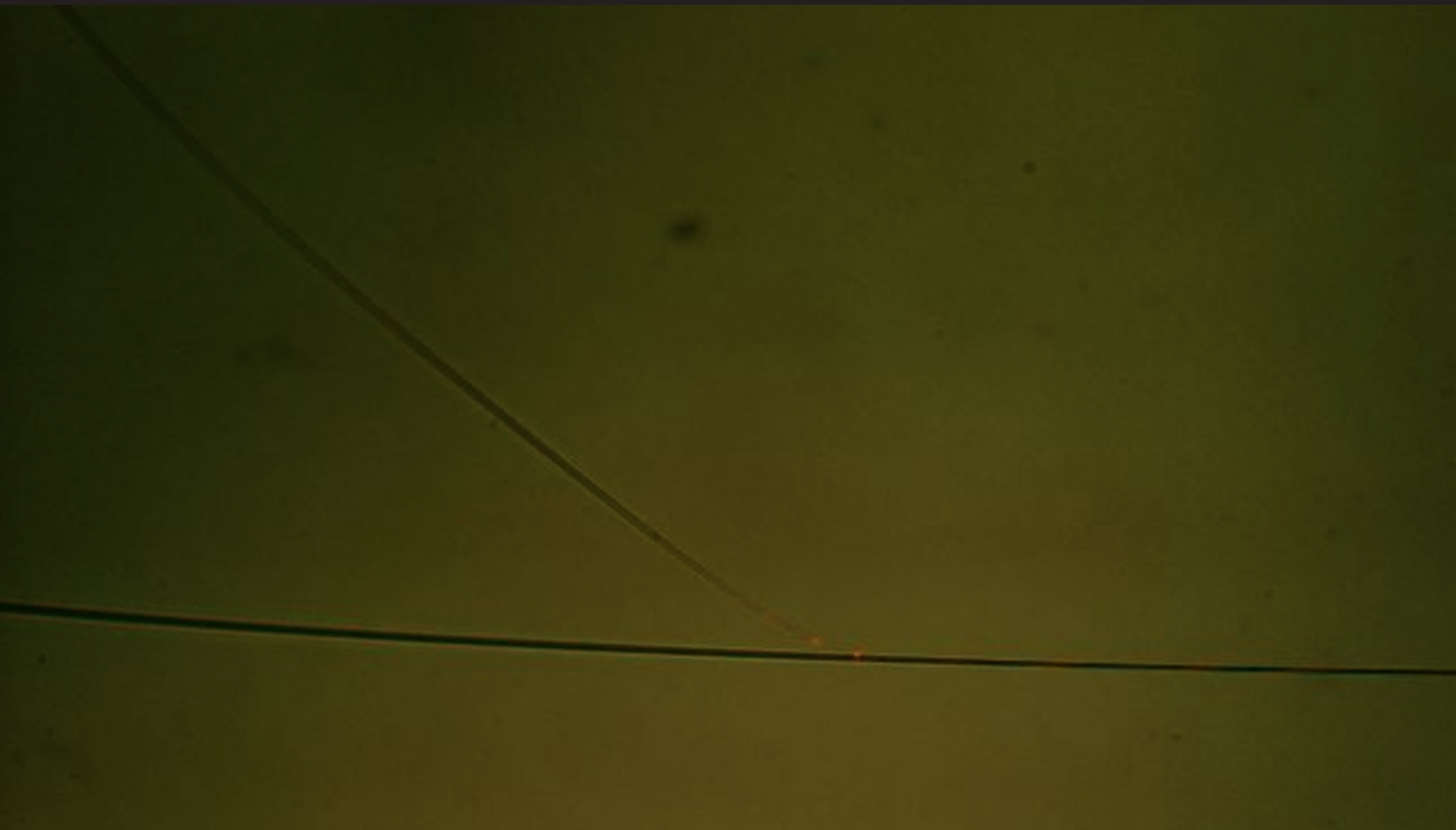


Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



Manipulating light at the nanoscale



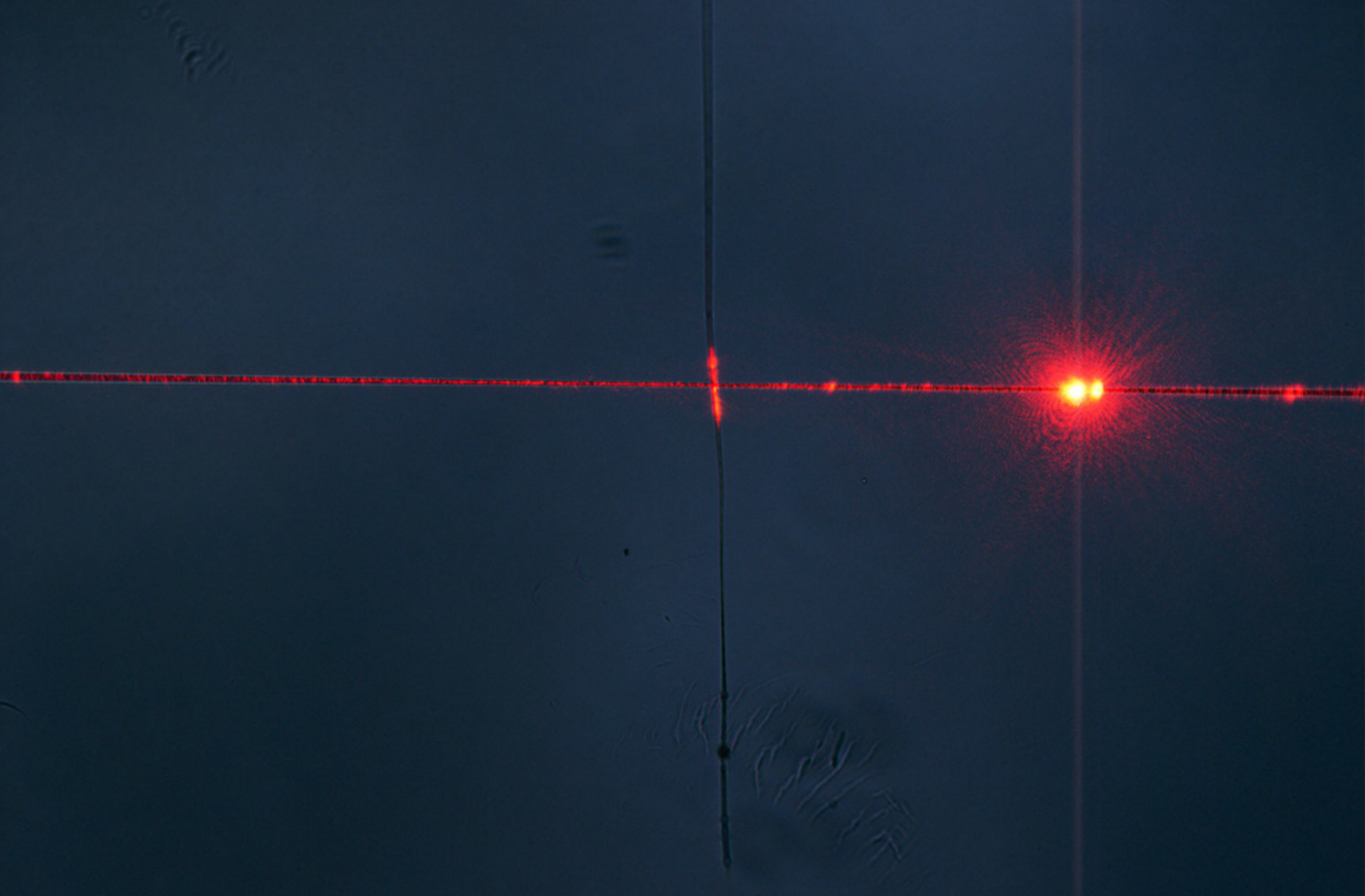
50 μm

Manipulating light at the nanoscale

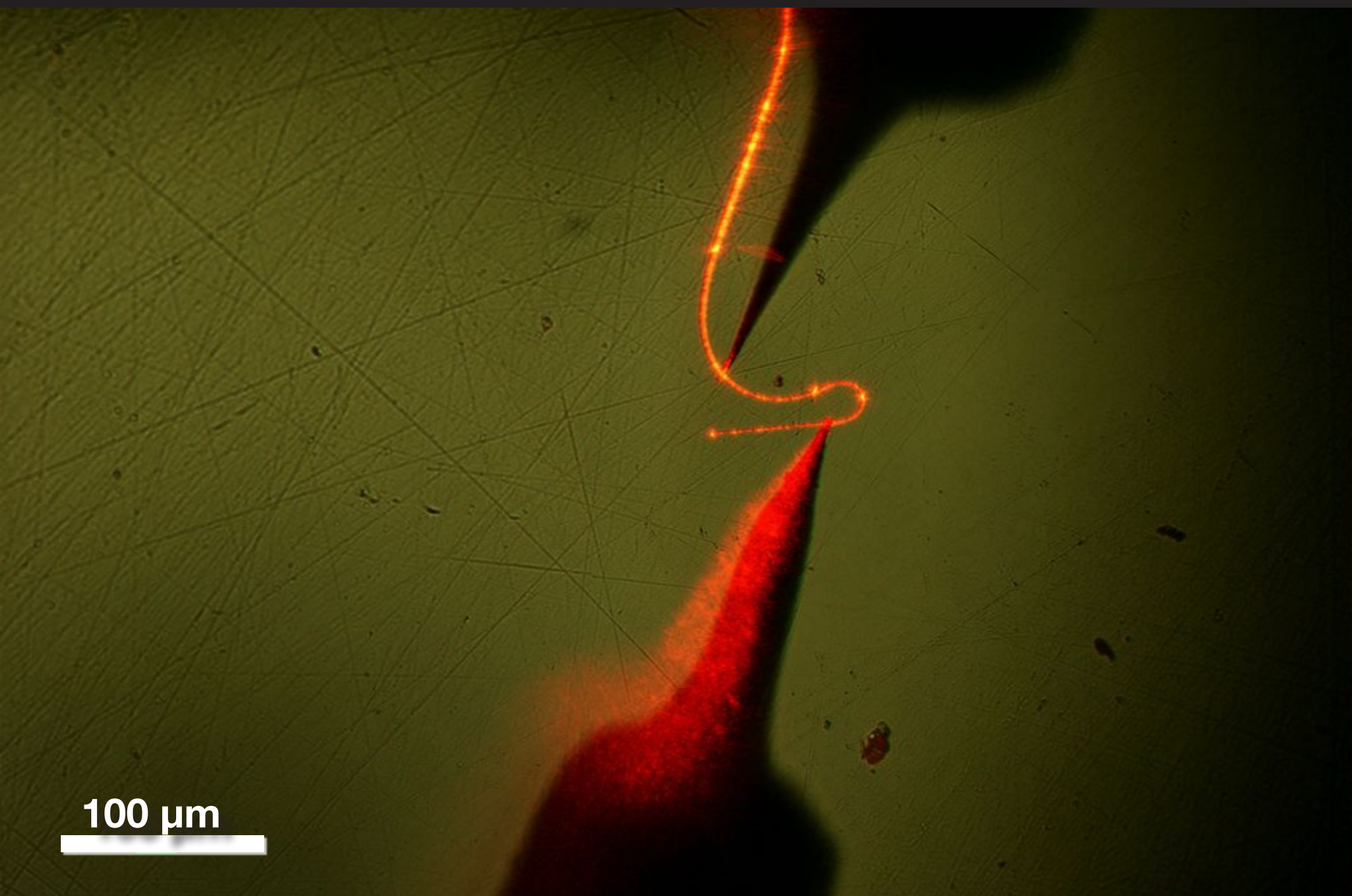


50 μm

Manipulating light at the nanoscale

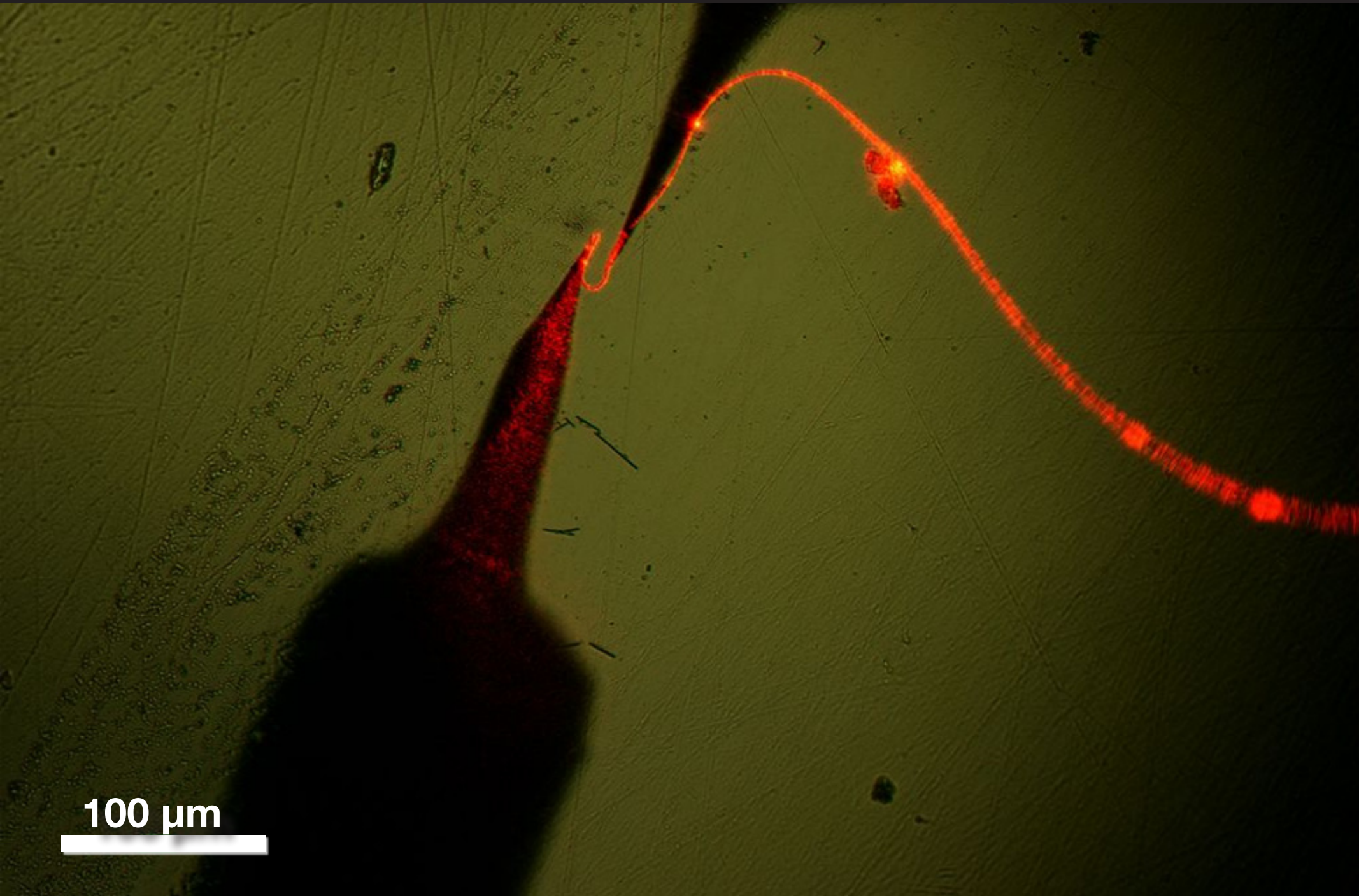


Manipulating light at the nanoscale



100 μm

Manipulating light at the nanoscale

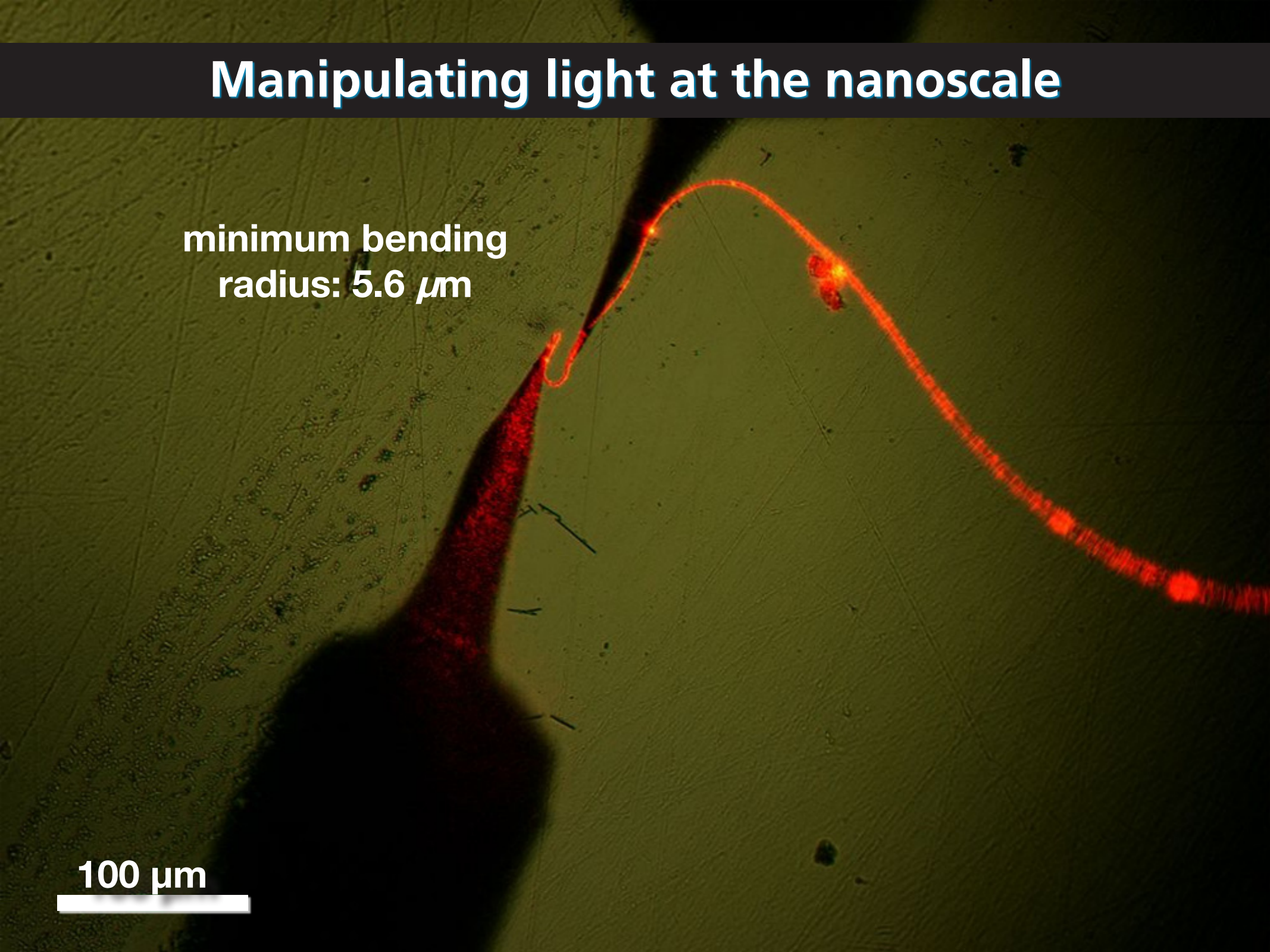


100 μm

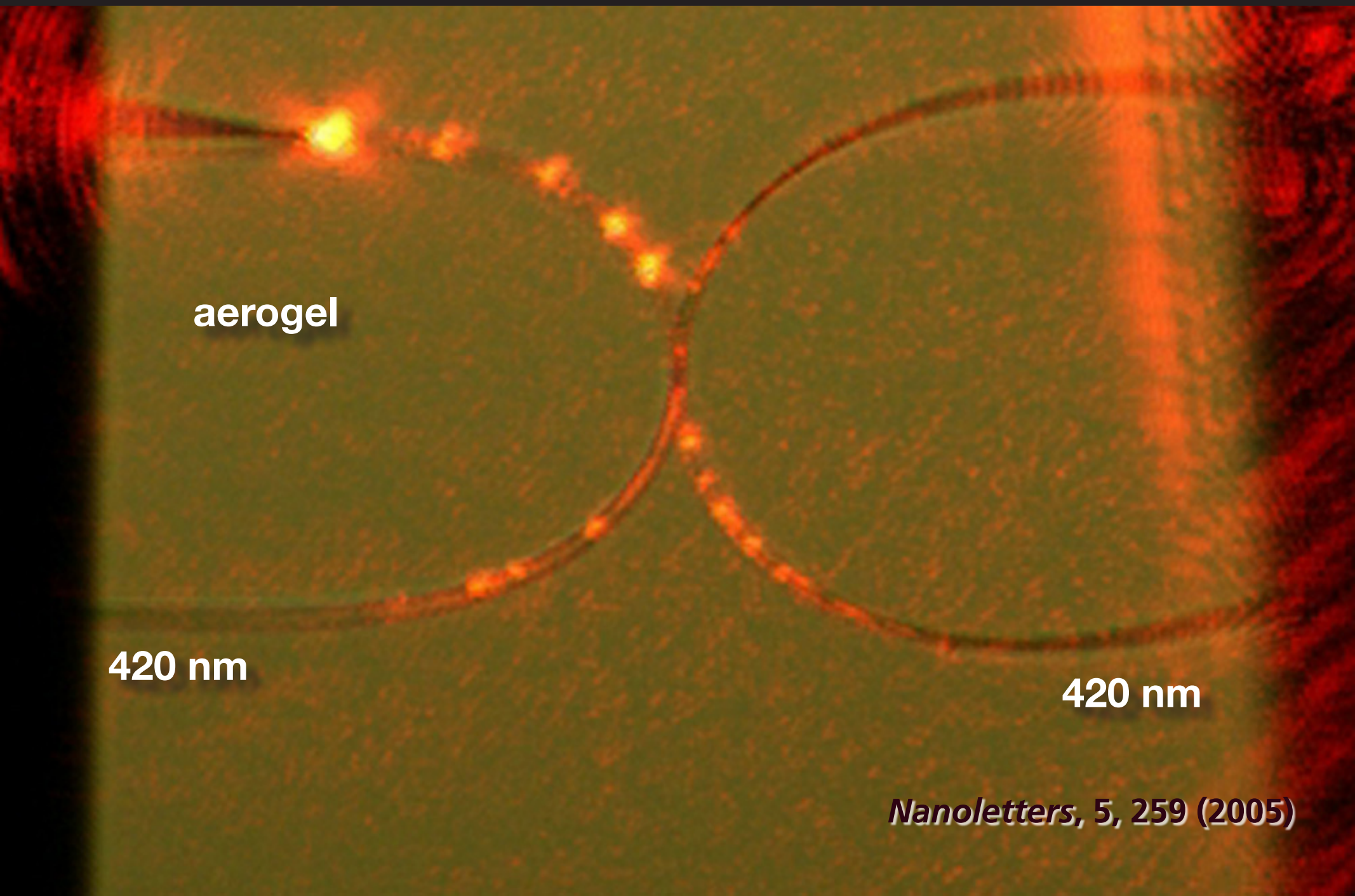
Manipulating light at the nanoscale

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

100 μm

A micrograph showing a fiber optic cable with a sharp bend. The cable is illuminated from the left, creating a bright red glow. The bend is sharp, and the light is visible as a bright red line. The background is dark green. A scale bar is located in the bottom left corner, and text is overlaid on the image.

Manipulating light at the nanoscale



aerogel

420 nm

420 nm

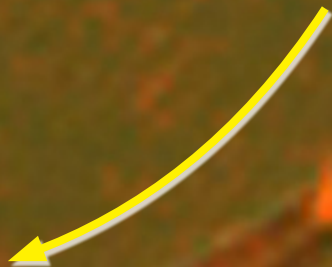
Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale

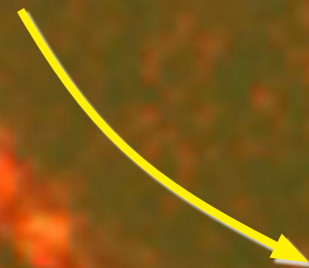
in



out

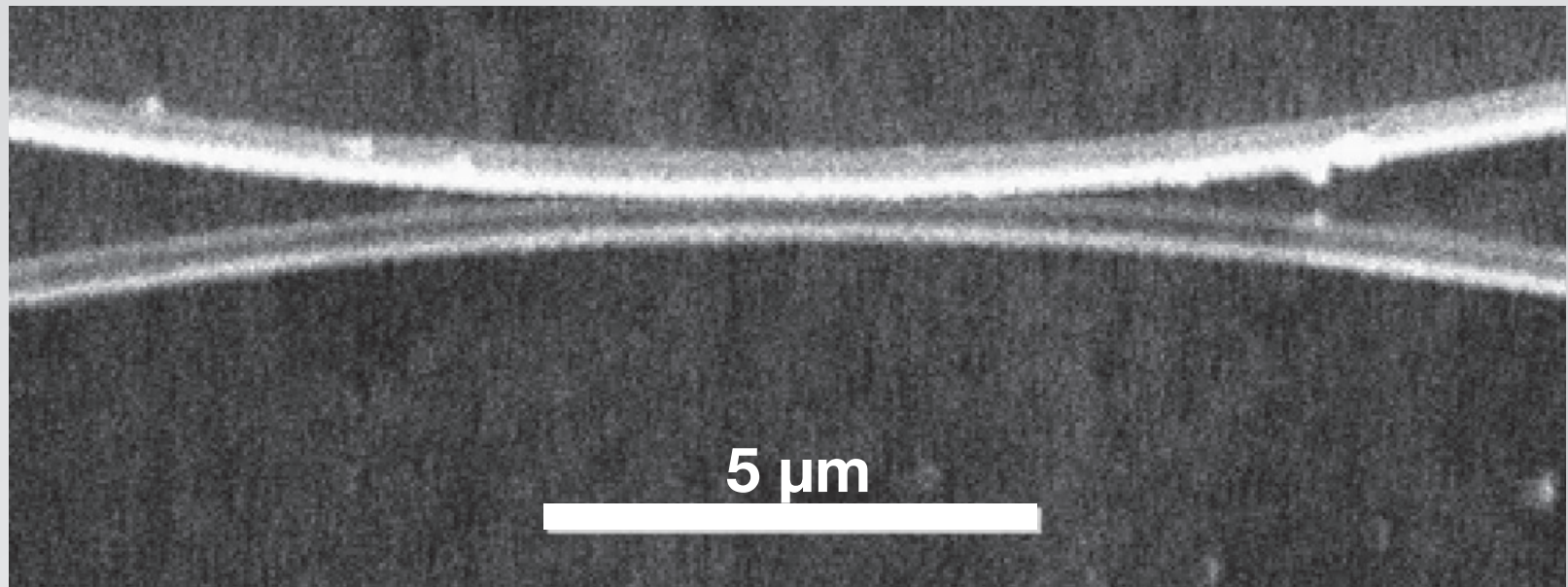


out



Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale

use tapered fibers to couple light to nanoscale objects

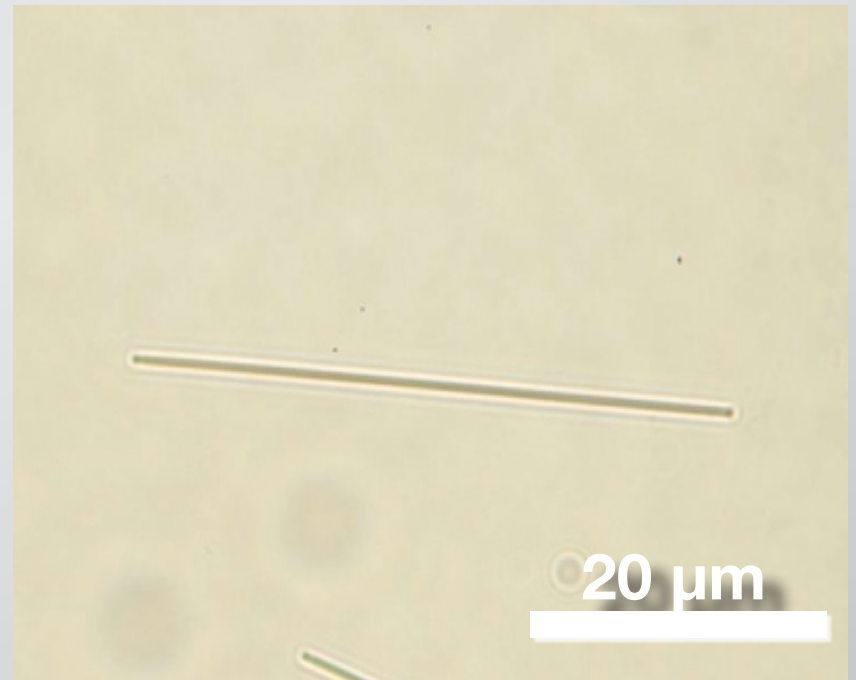
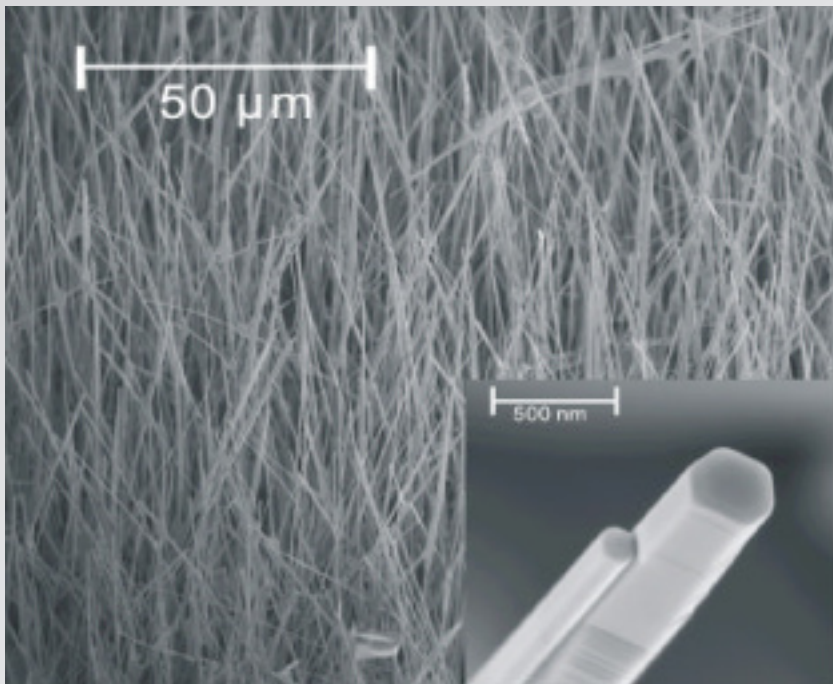
Manipulating light at the nanoscale

ZnO: non-toxic, wide bandgap semiconductor

A top-down view of a clear glass petri dish containing a mound of fine, white, powdery particles. The particles are piled in the center and have a slightly irregular, clumpy appearance. The background is a dark, textured surface, possibly a lab bench. The lighting is bright, casting soft shadows around the mound of powder.

Manipulating light at the nanoscale

vapor transport grown ZnO nanowires



80–400 nm diameter, up to 80 μm long

Manipulating light at the nanoscale

best of both worlds

ZnO

silica

bottom-up

top-down

semiconductor

glass

active photonic devices

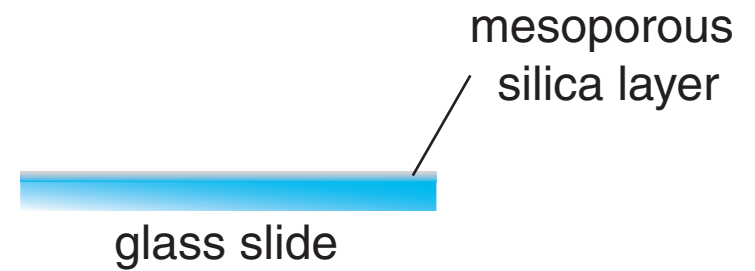
passive waveguides

electrical operation

link to macroworld

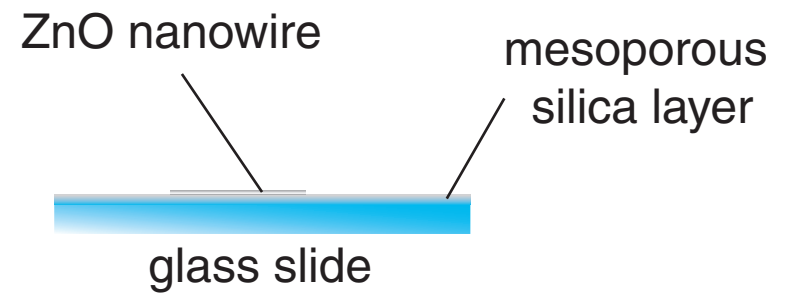
Manipulating light at the nanoscale

coupling to ZnO nanowires



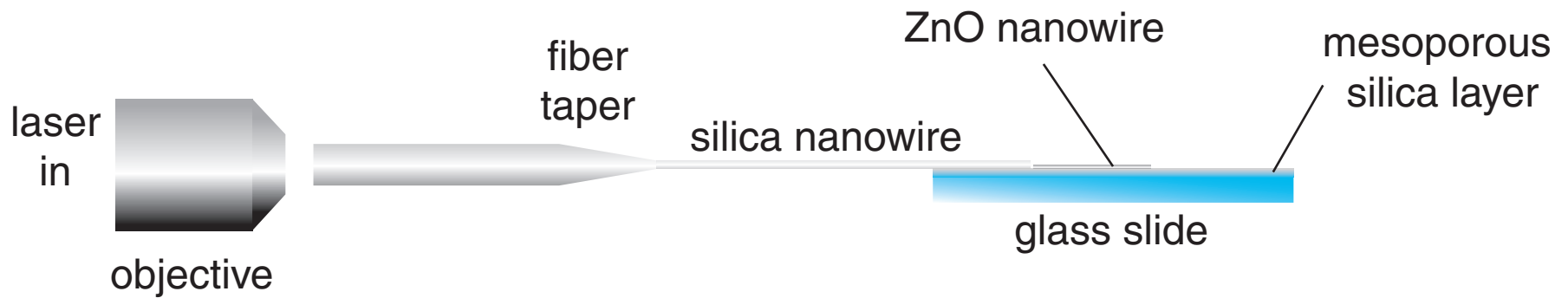
Manipulating light at the nanoscale

coupling to ZnO nanowires



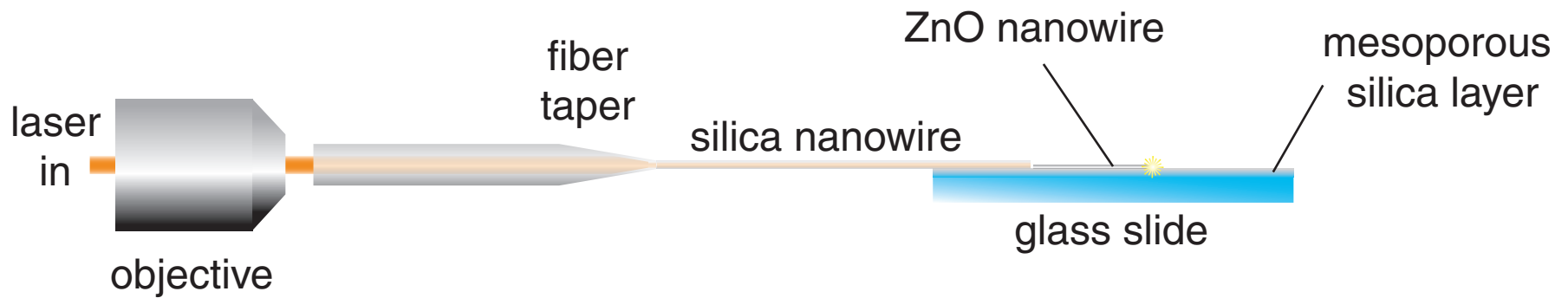
Manipulating light at the nanoscale

coupling to ZnO nanowires

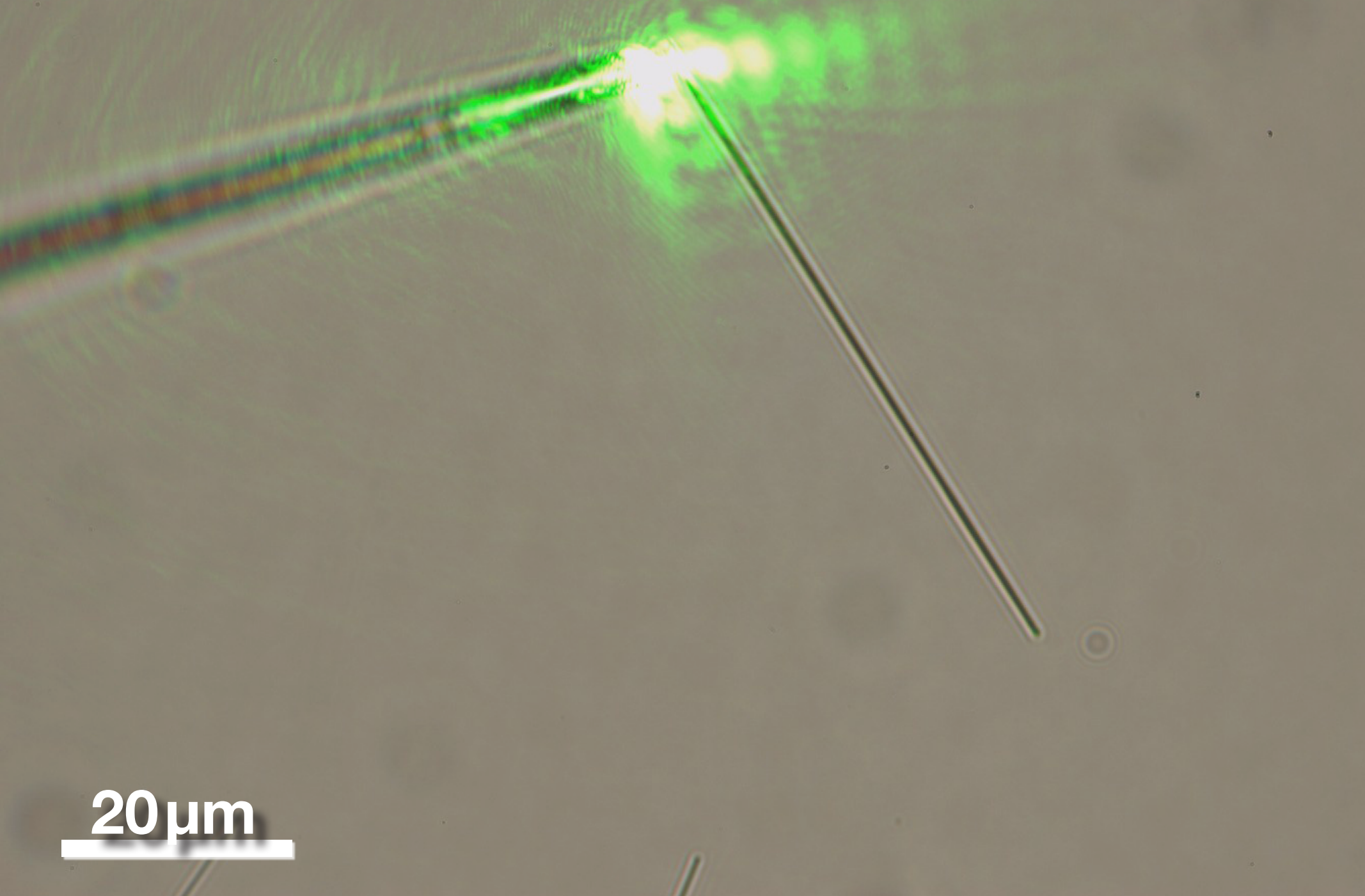


Manipulating light at the nanoscale

coupling to ZnO nanowires

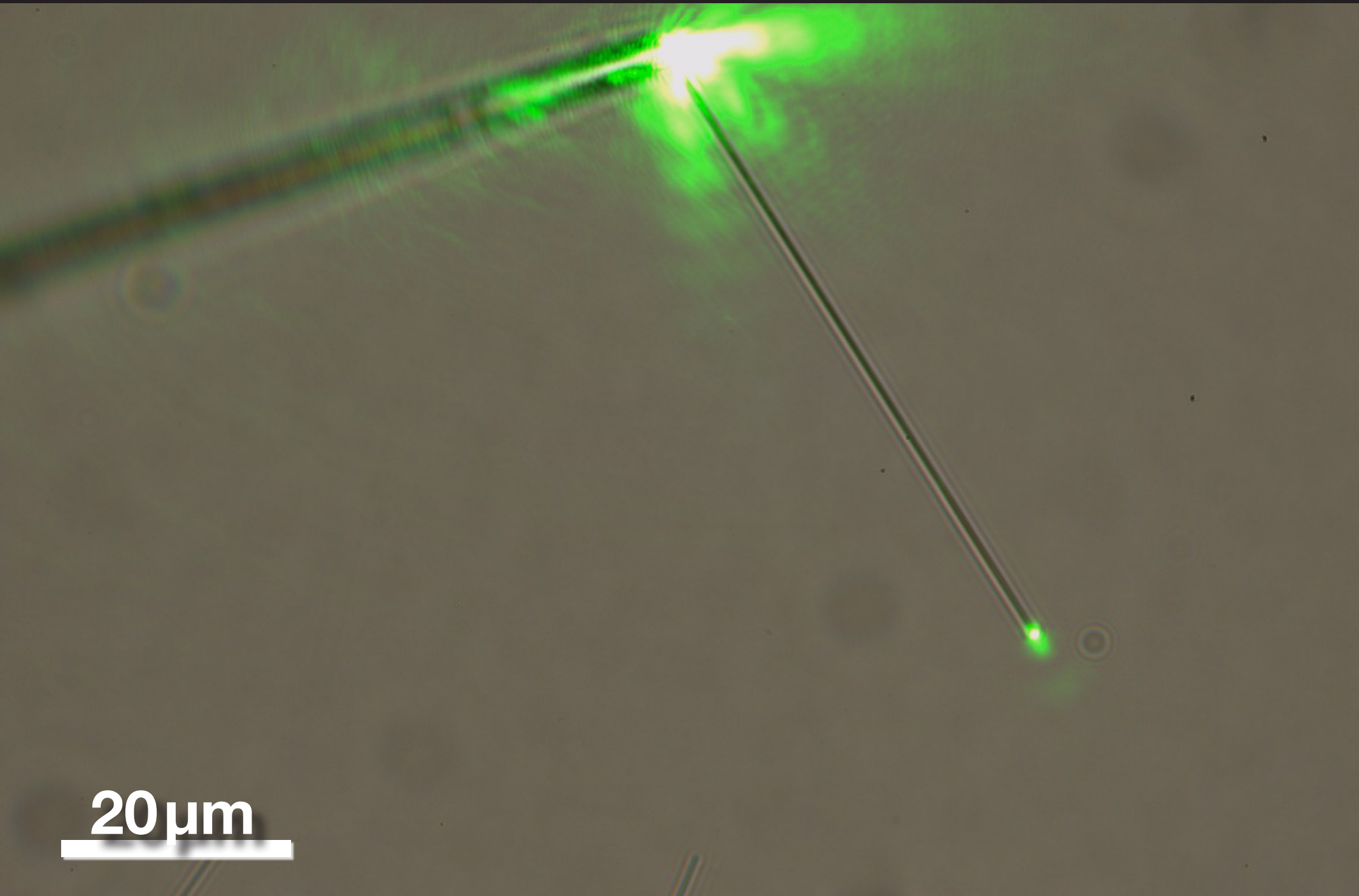


Manipulating light at the nanoscale



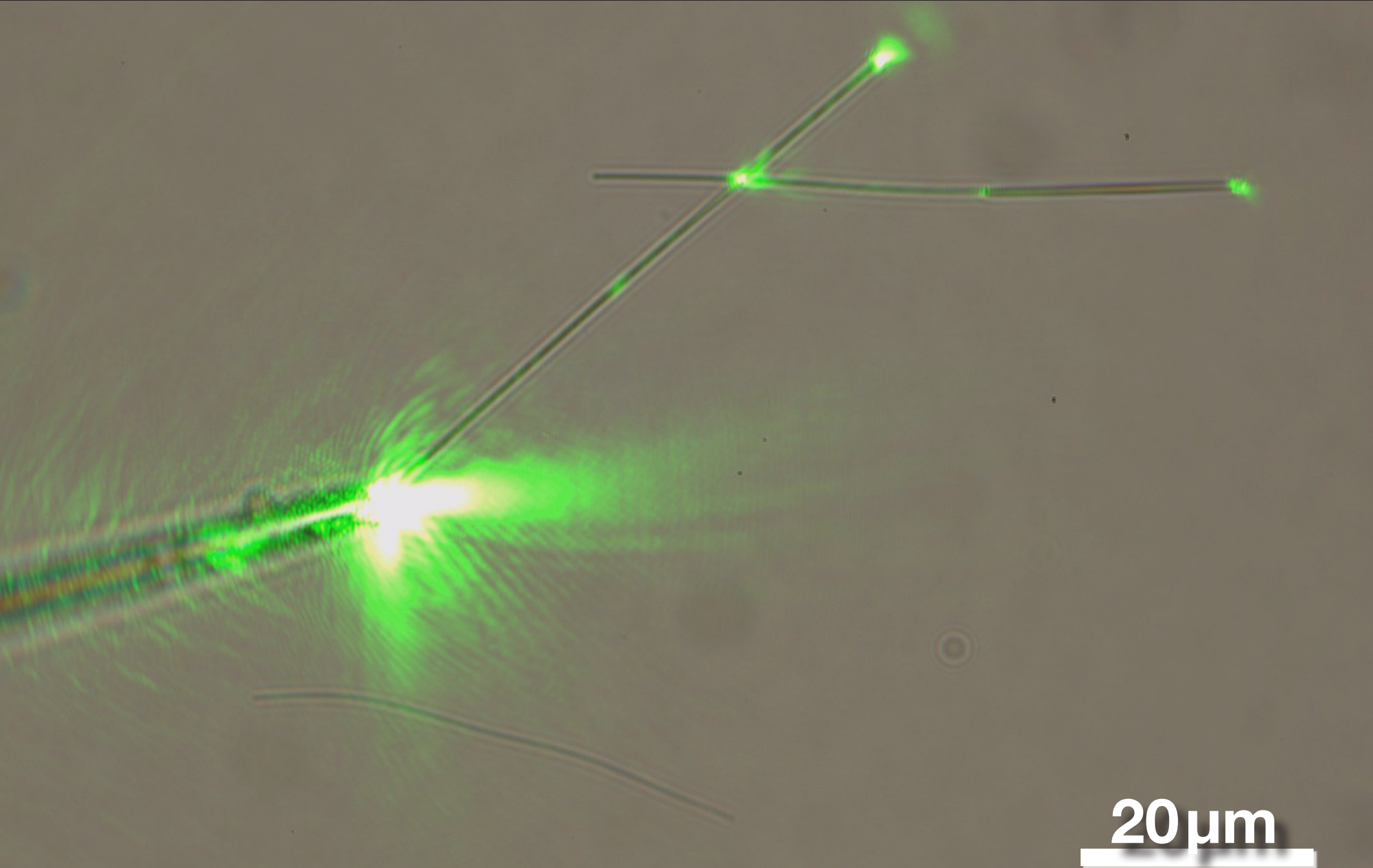
20 μm

Manipulating light at the nanoscale

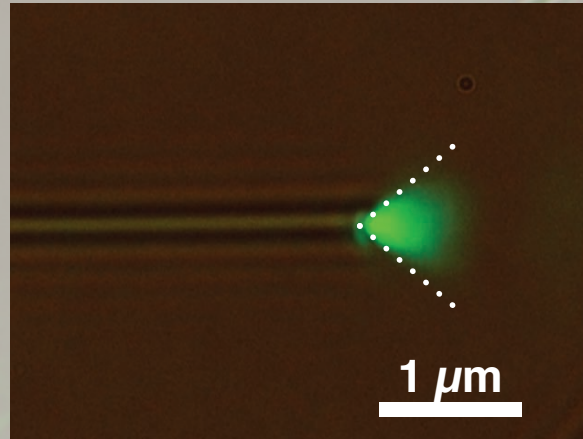


20 μm

Manipulating light at the nanoscale

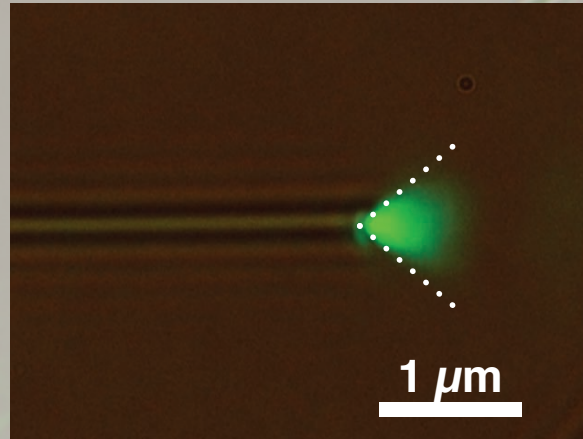


Manipulating light at the nanoscale

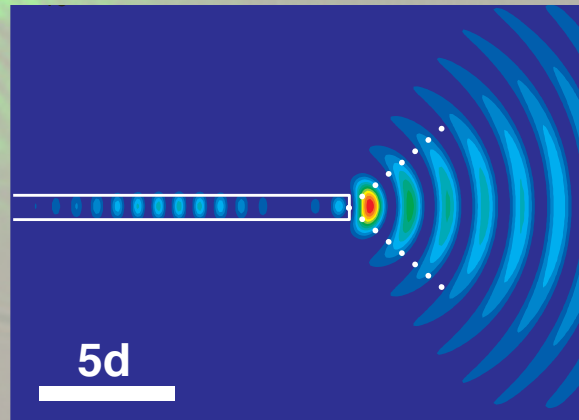


Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

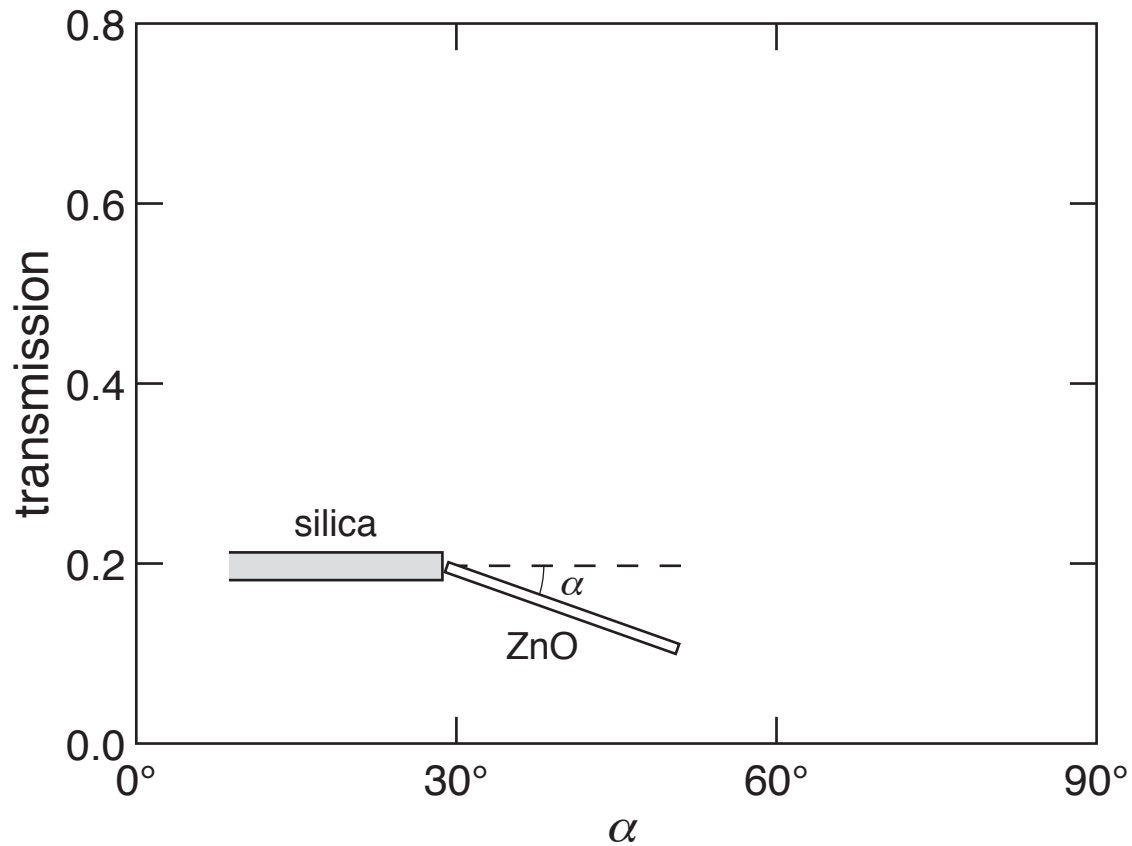


FDTD simulation



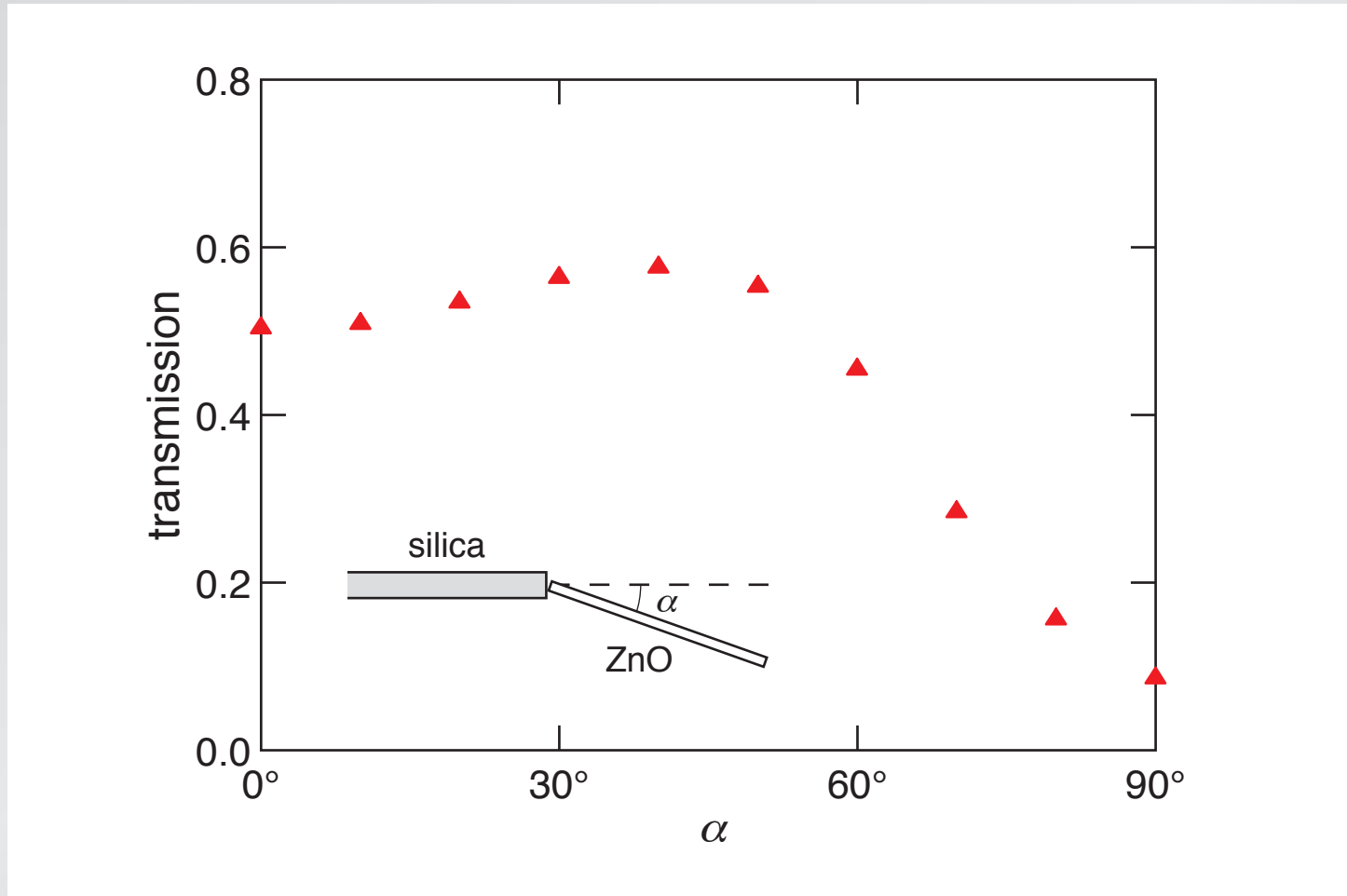
Manipulating light at the nanoscale

coupling efficiency

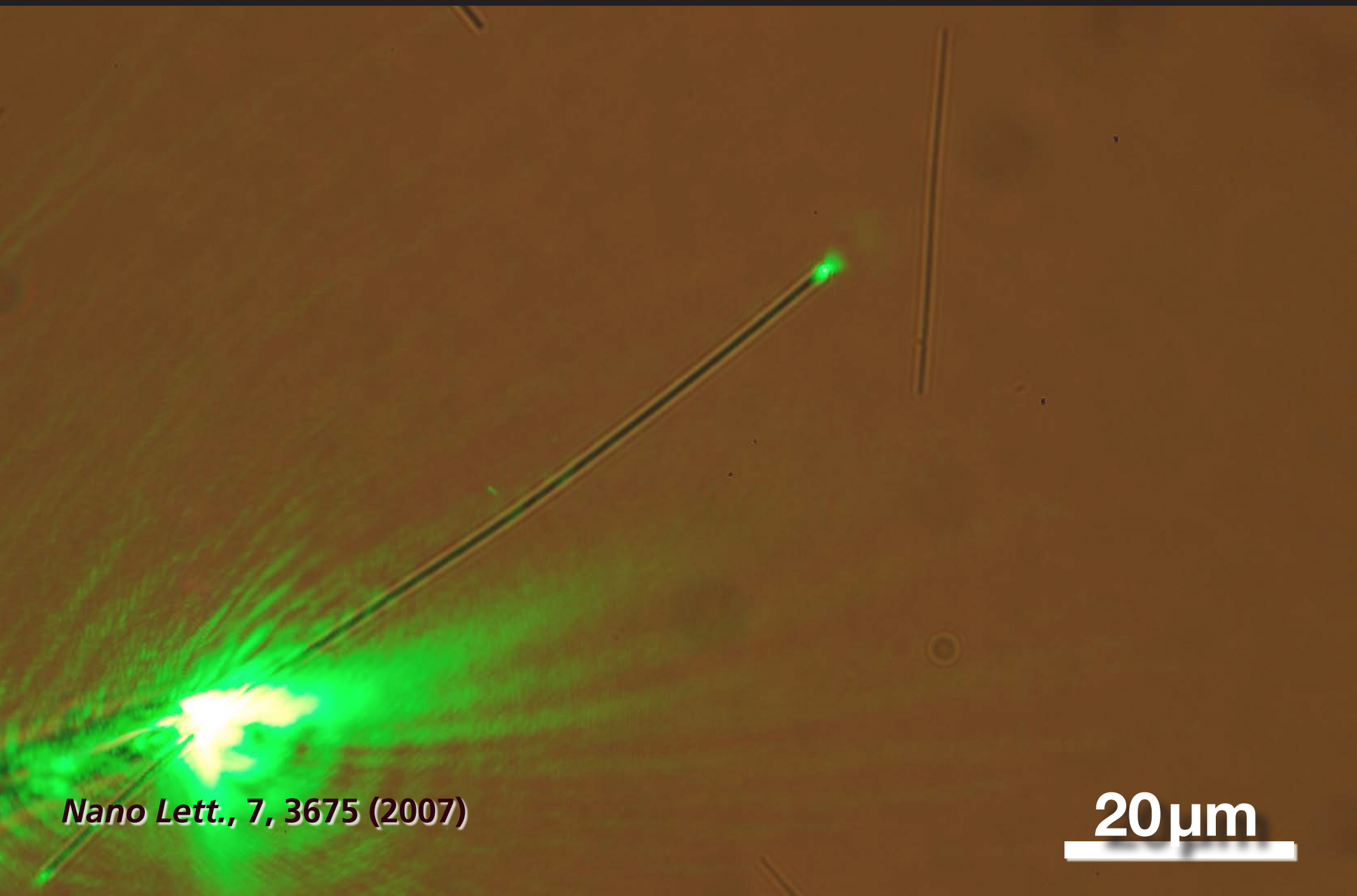


Manipulating light at the nanoscale

coupling efficiency



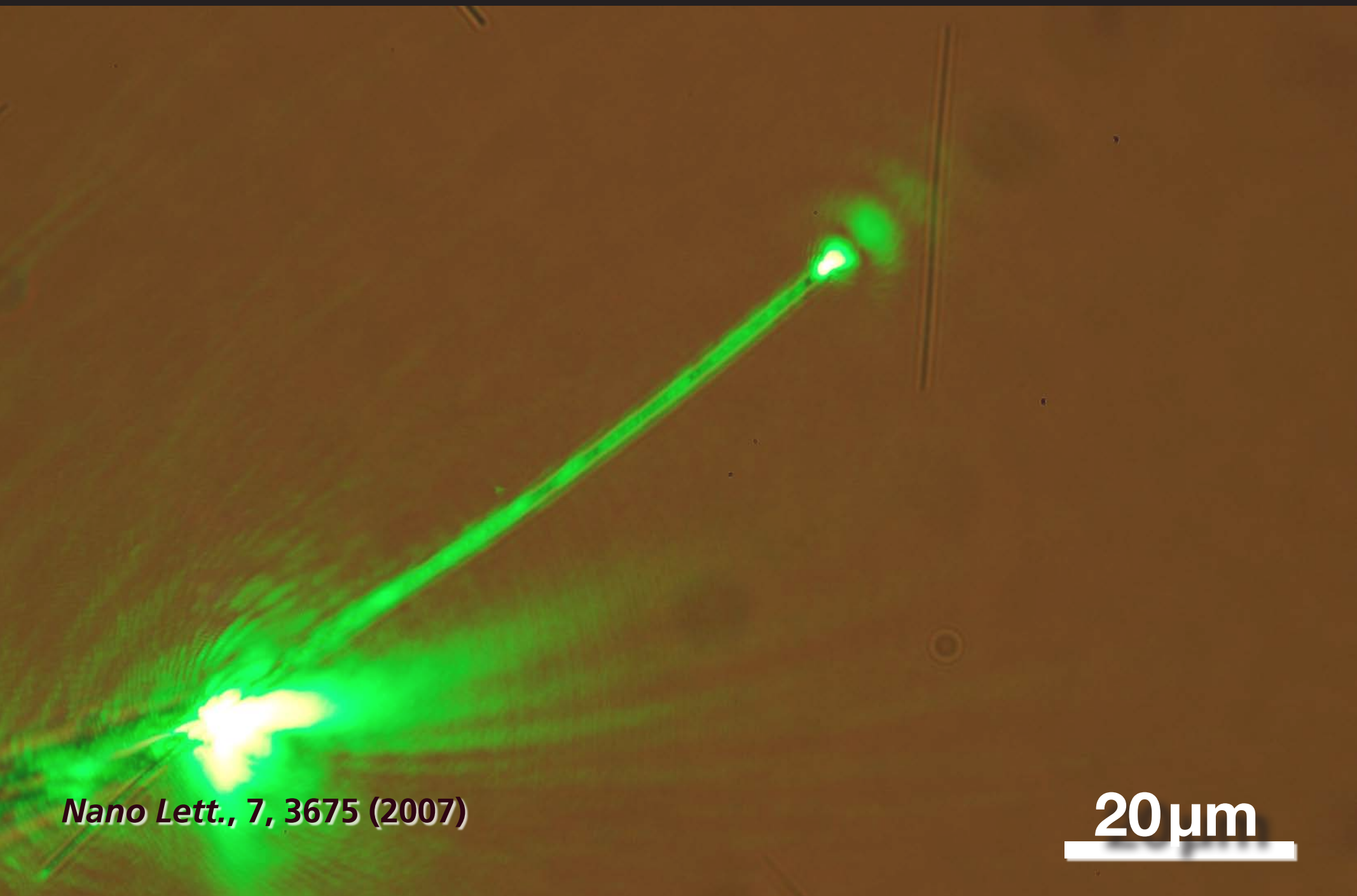
Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

20 μm

Manipulating light at the nanoscale

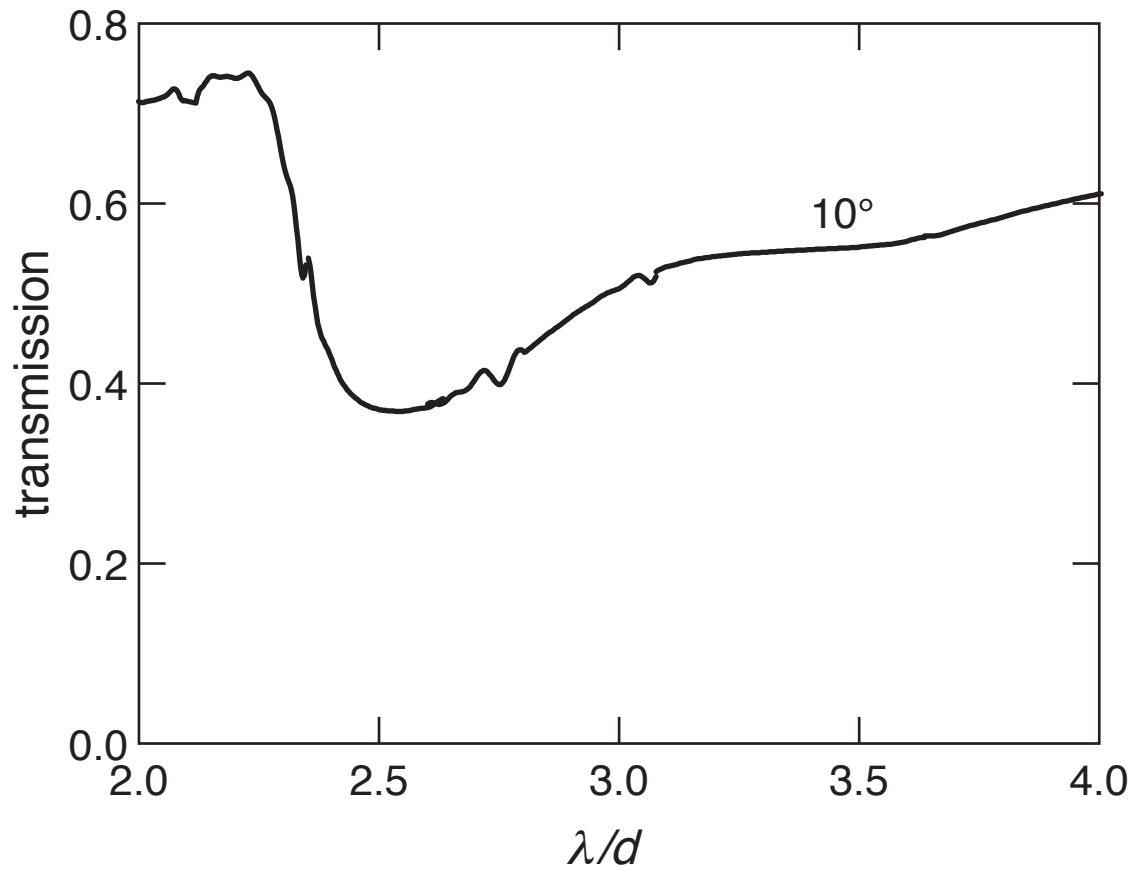


Nano Lett., 7, 3675 (2007)

20 μm

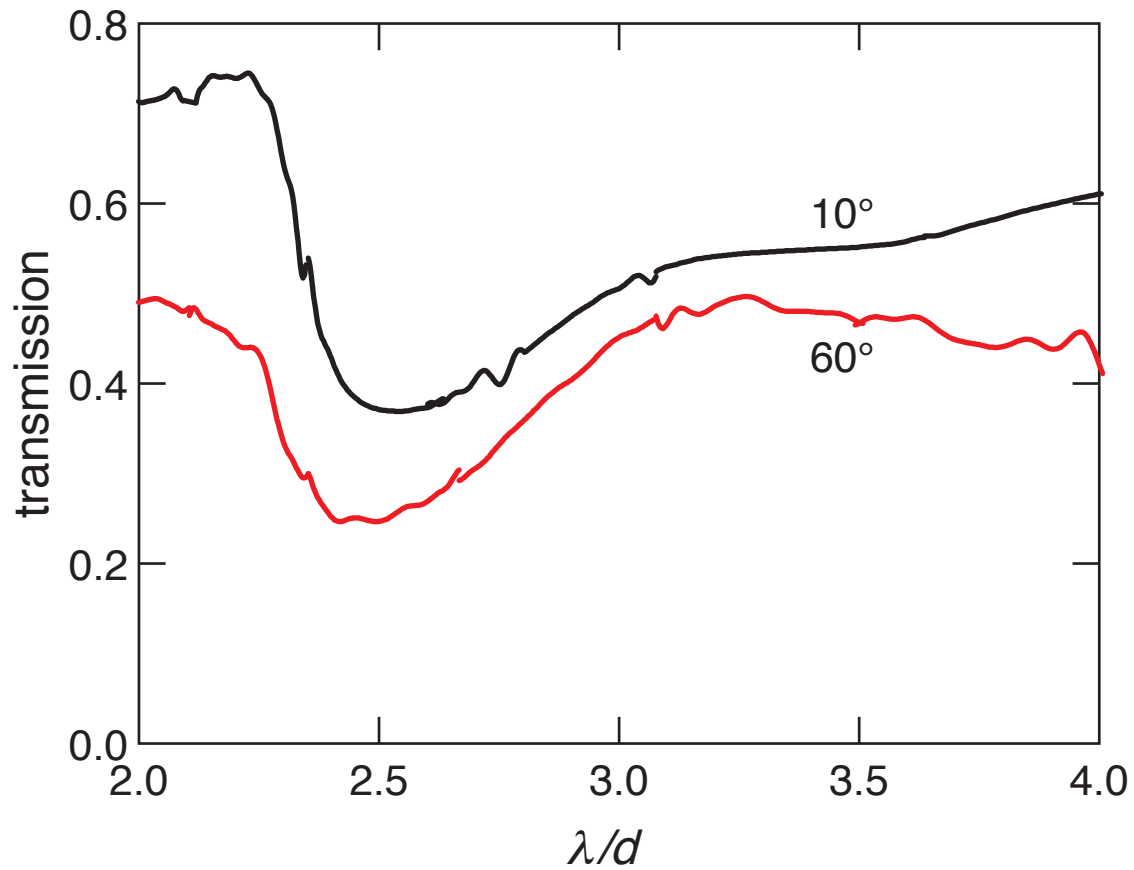
Manipulating light at the nanoscale

transmission spectrum



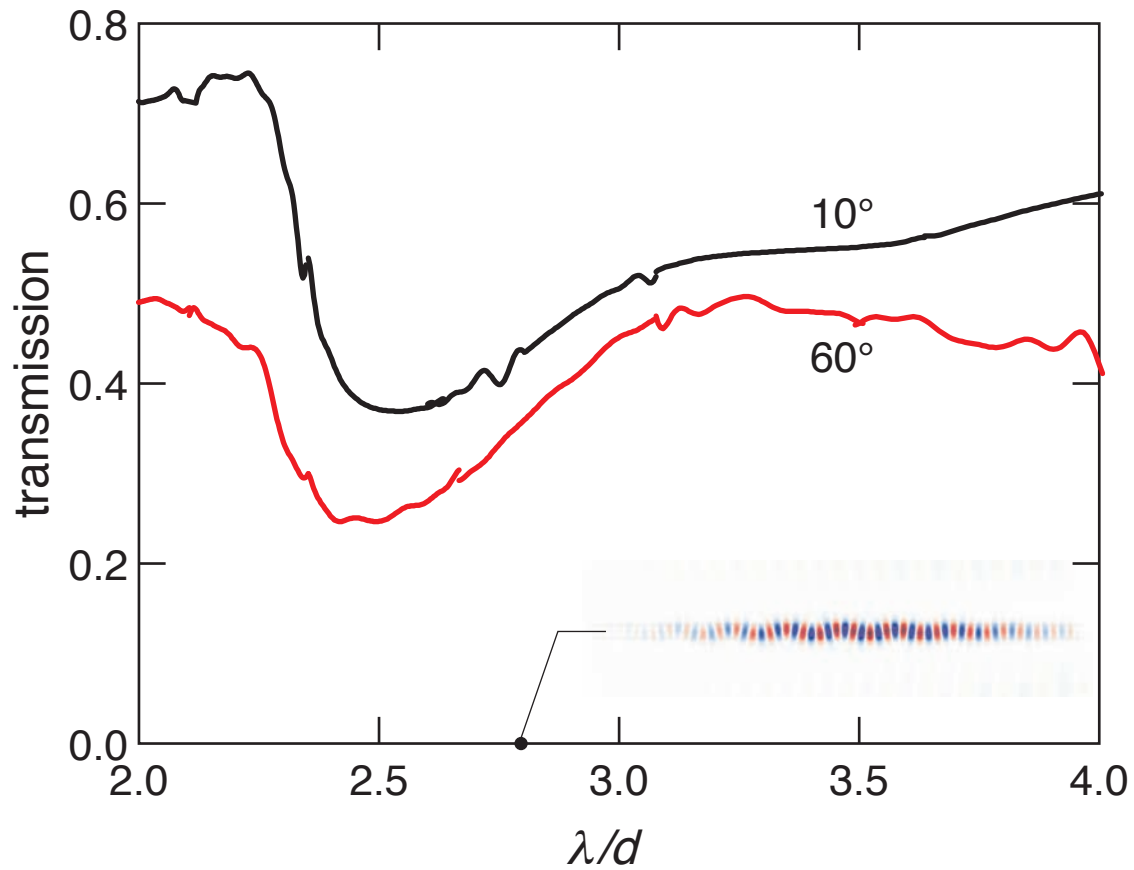
Manipulating light at the nanoscale

transmission spectrum



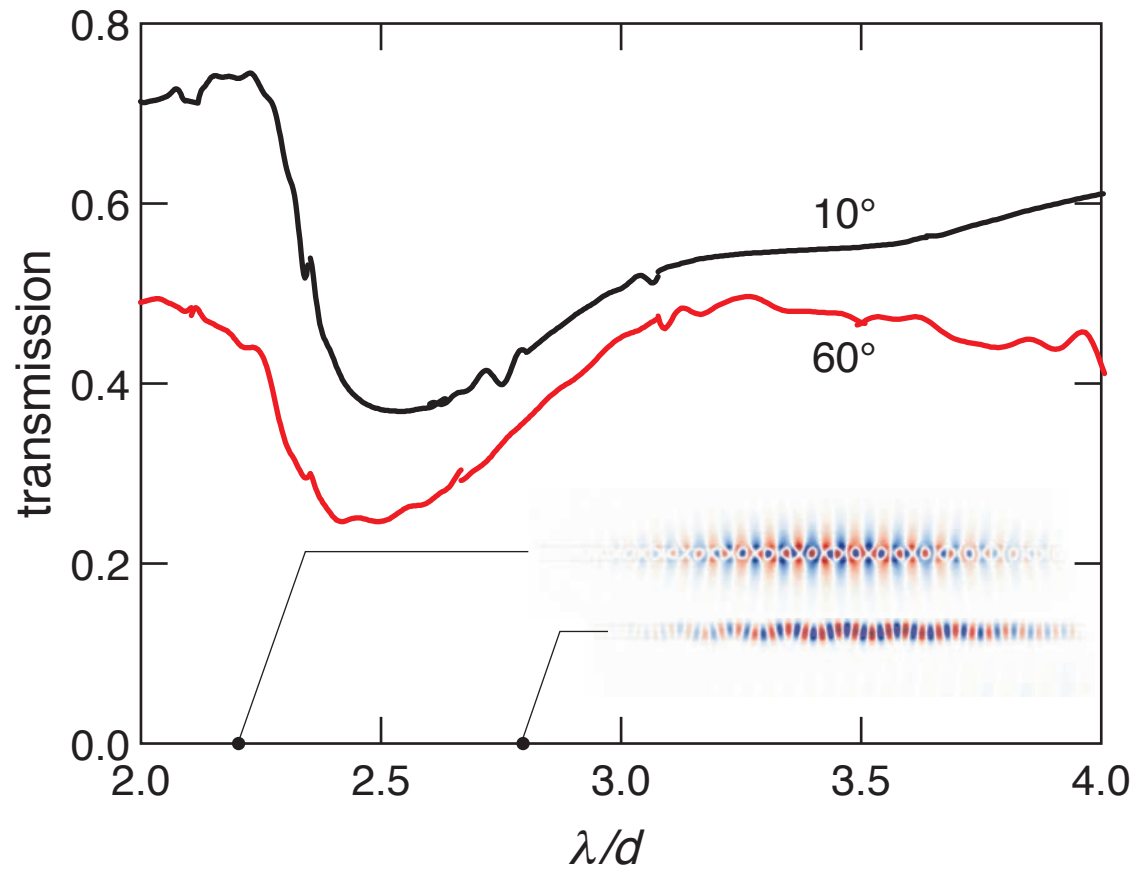
Manipulating light at the nanoscale

transmission spectrum

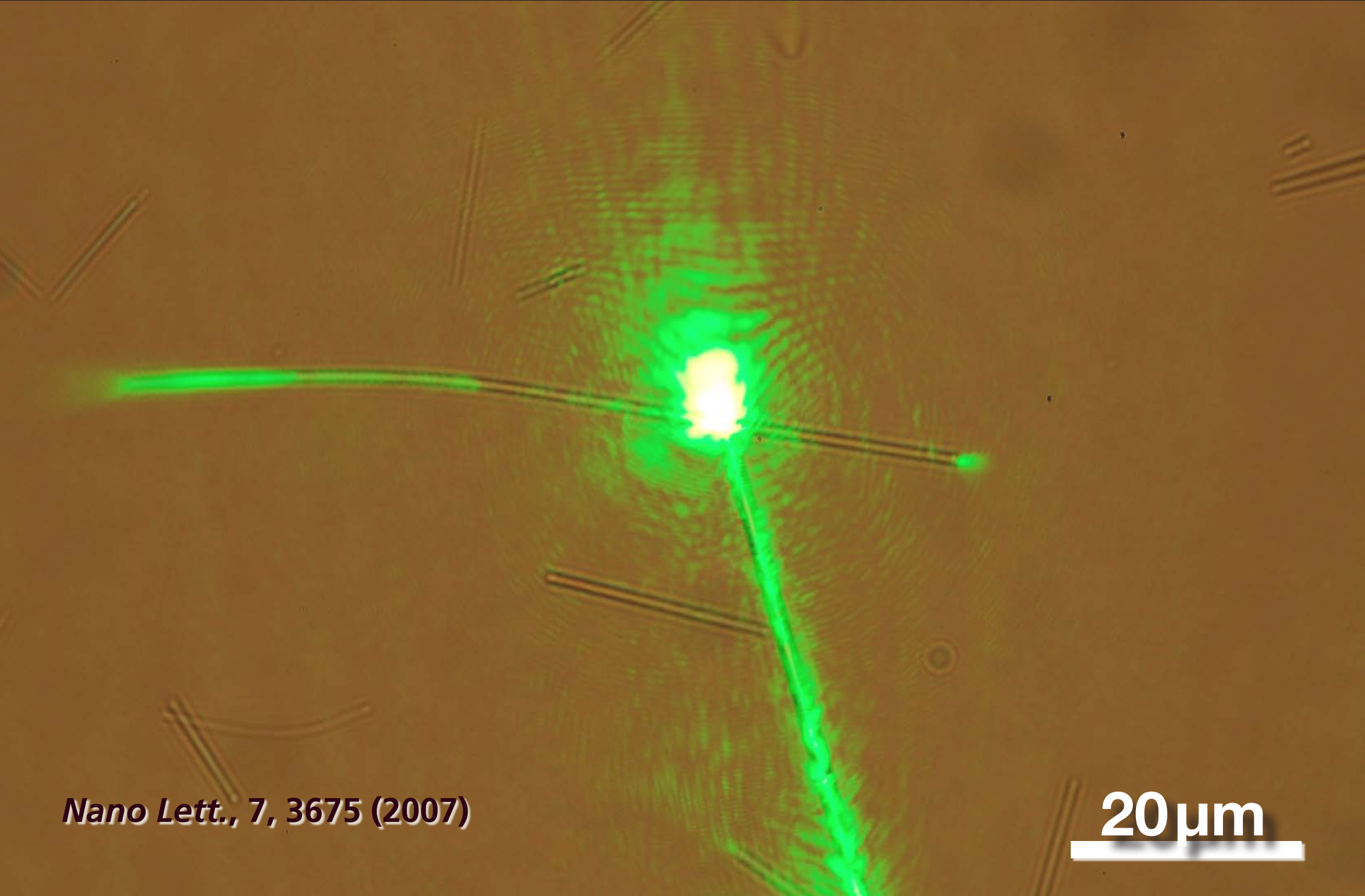


Manipulating light at the nanoscale

transmission spectrum



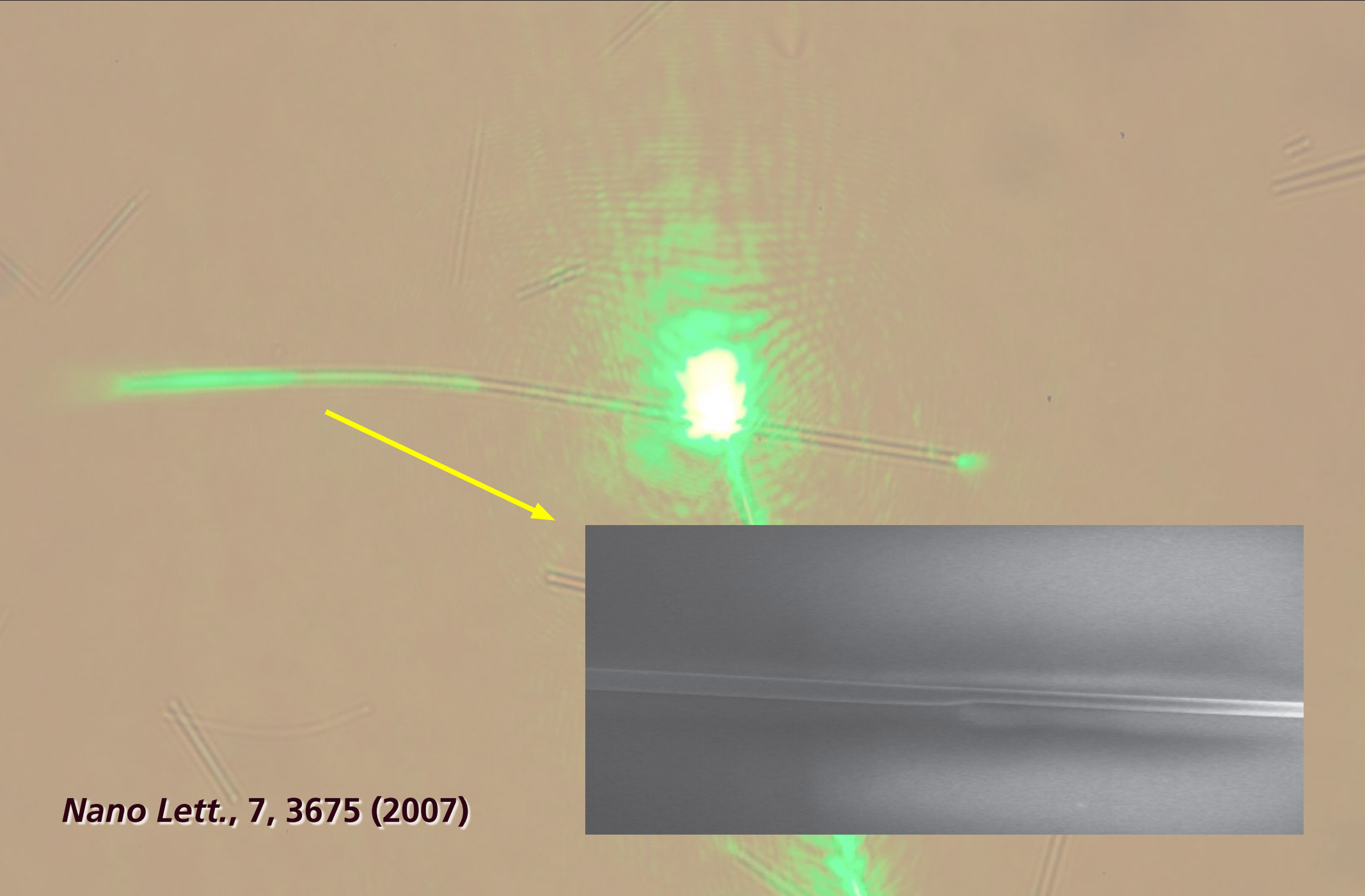
Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

20 μm

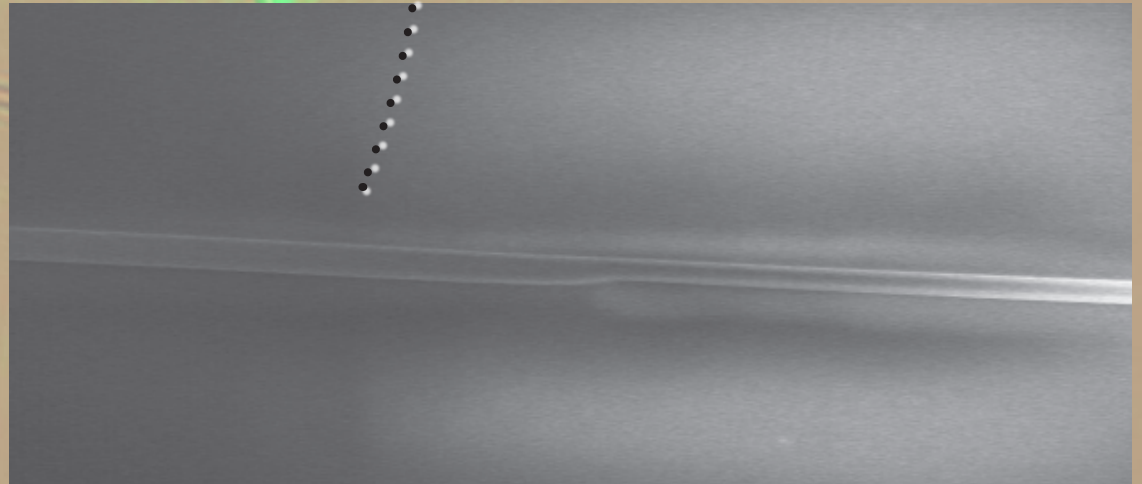
Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

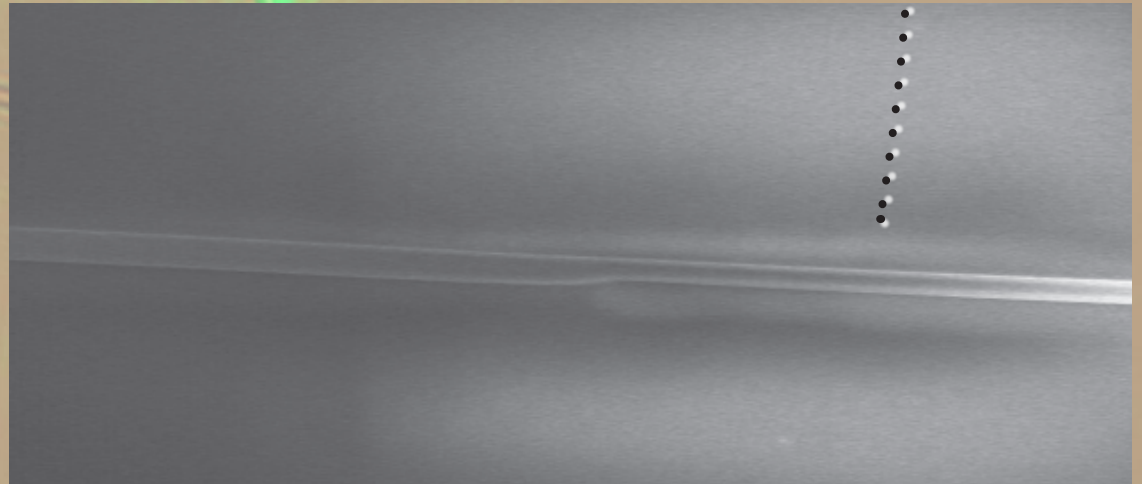
large diameter:
multimode



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

small diameter:
single mode



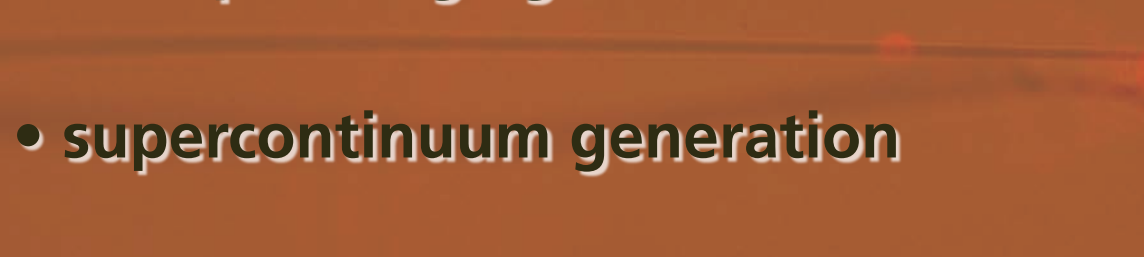
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

Points to keep in mind:

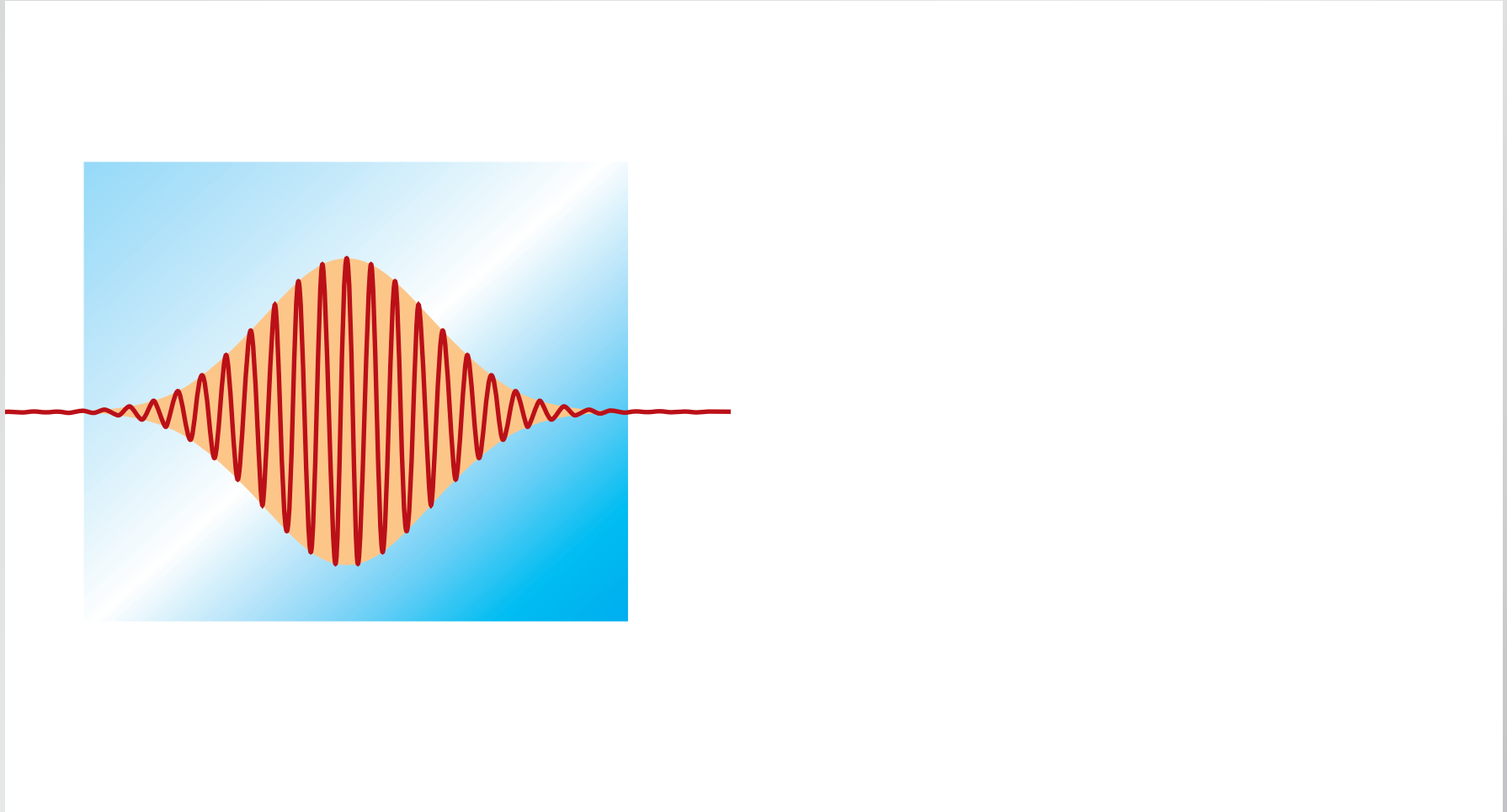
- **low-loss guiding**
- **convenient evanescent coupling**
- **attached to ordinary fiber**

Outline

- **manipulating light at the nanoscale**
 - **supercontinuum generation**
 - **optical logic gates**
- 

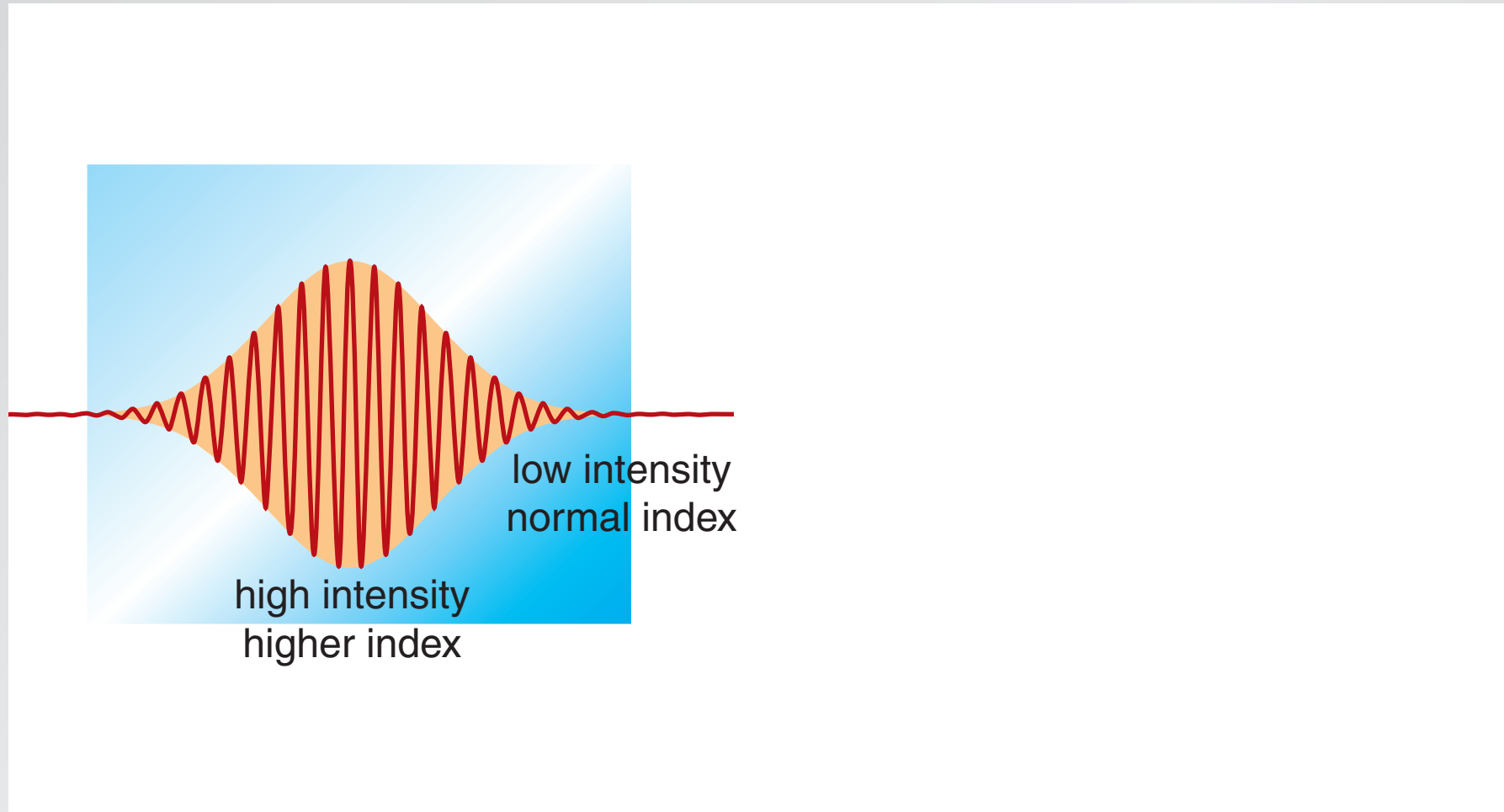
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



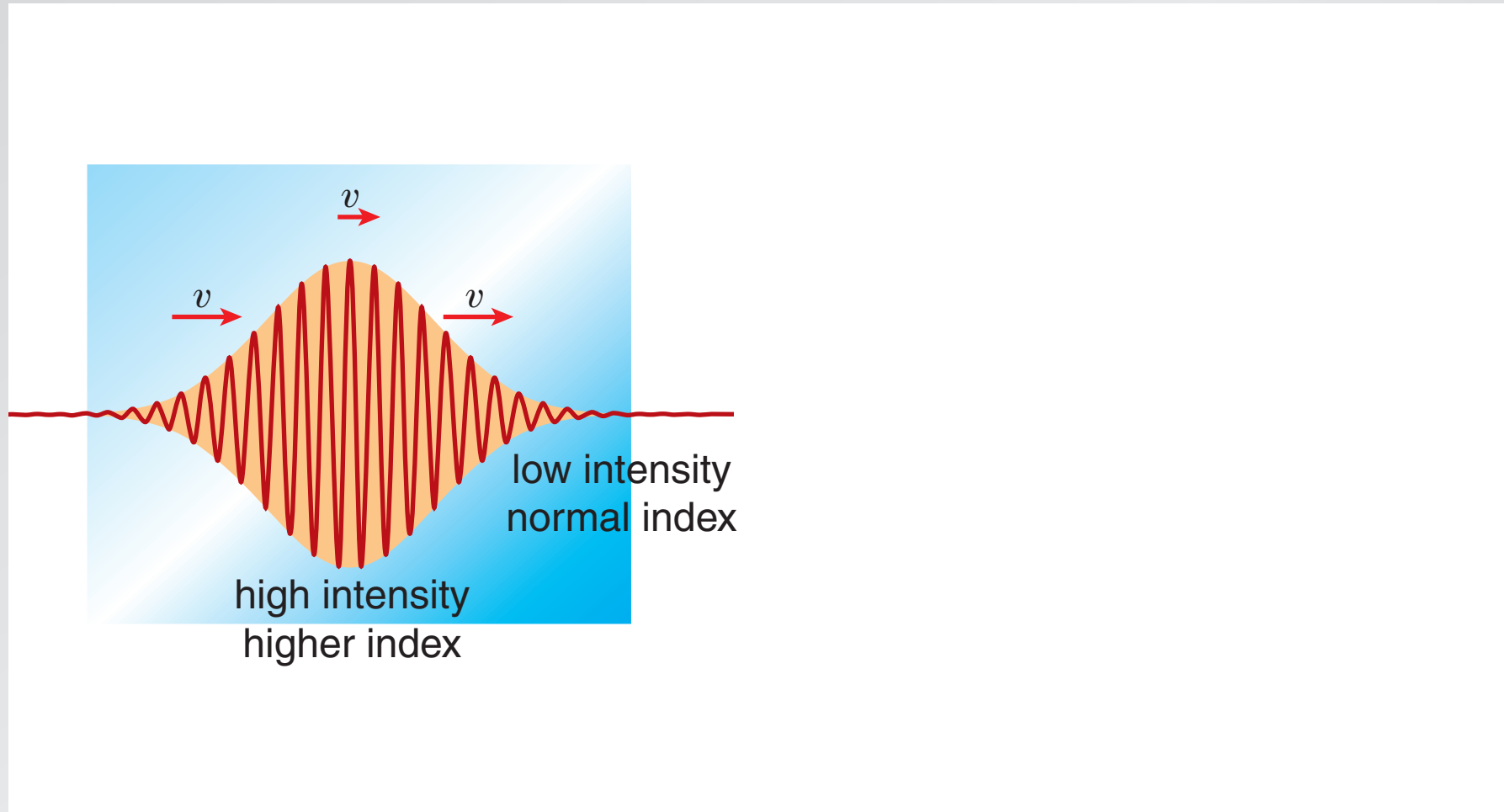
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



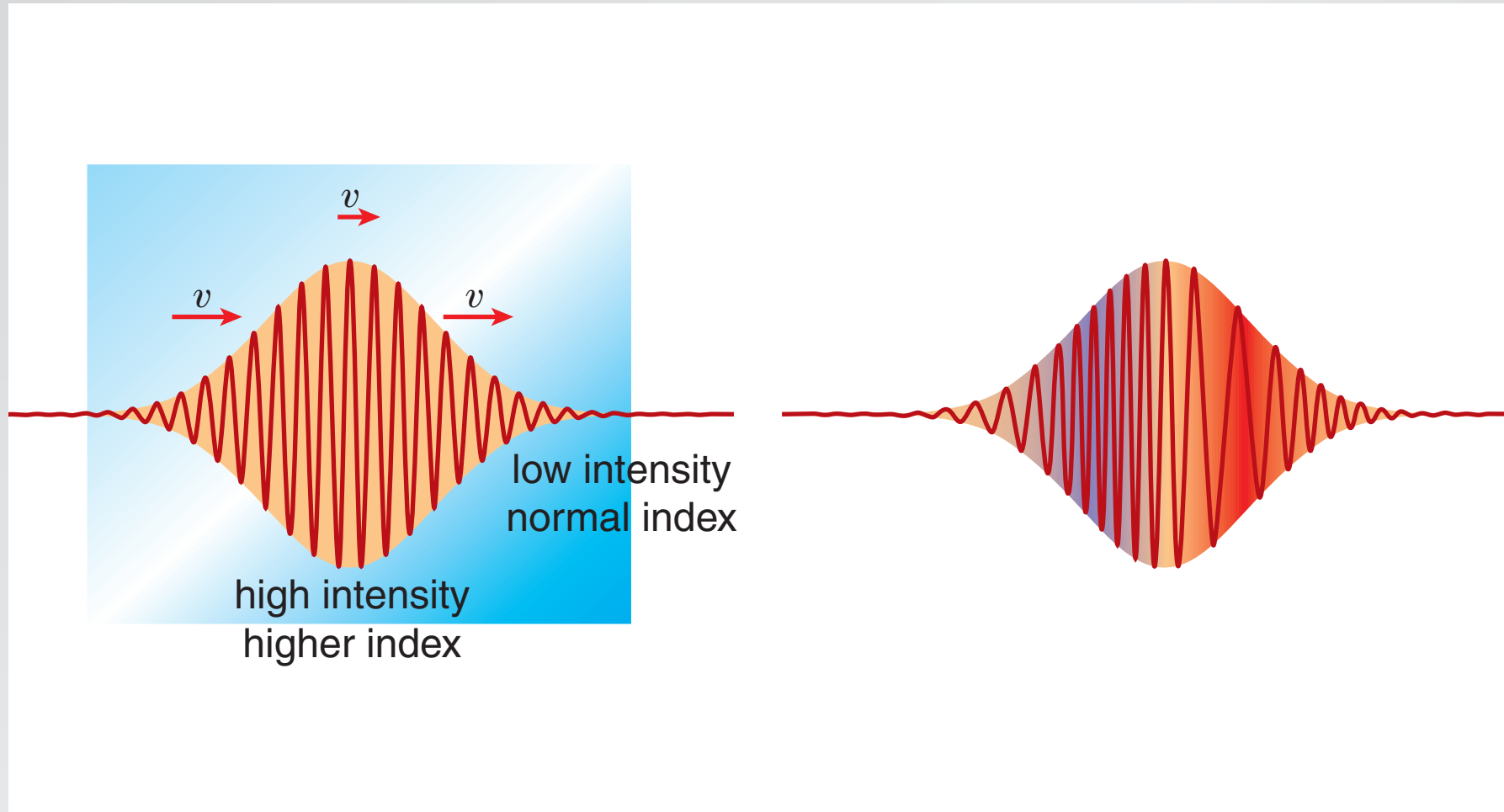
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



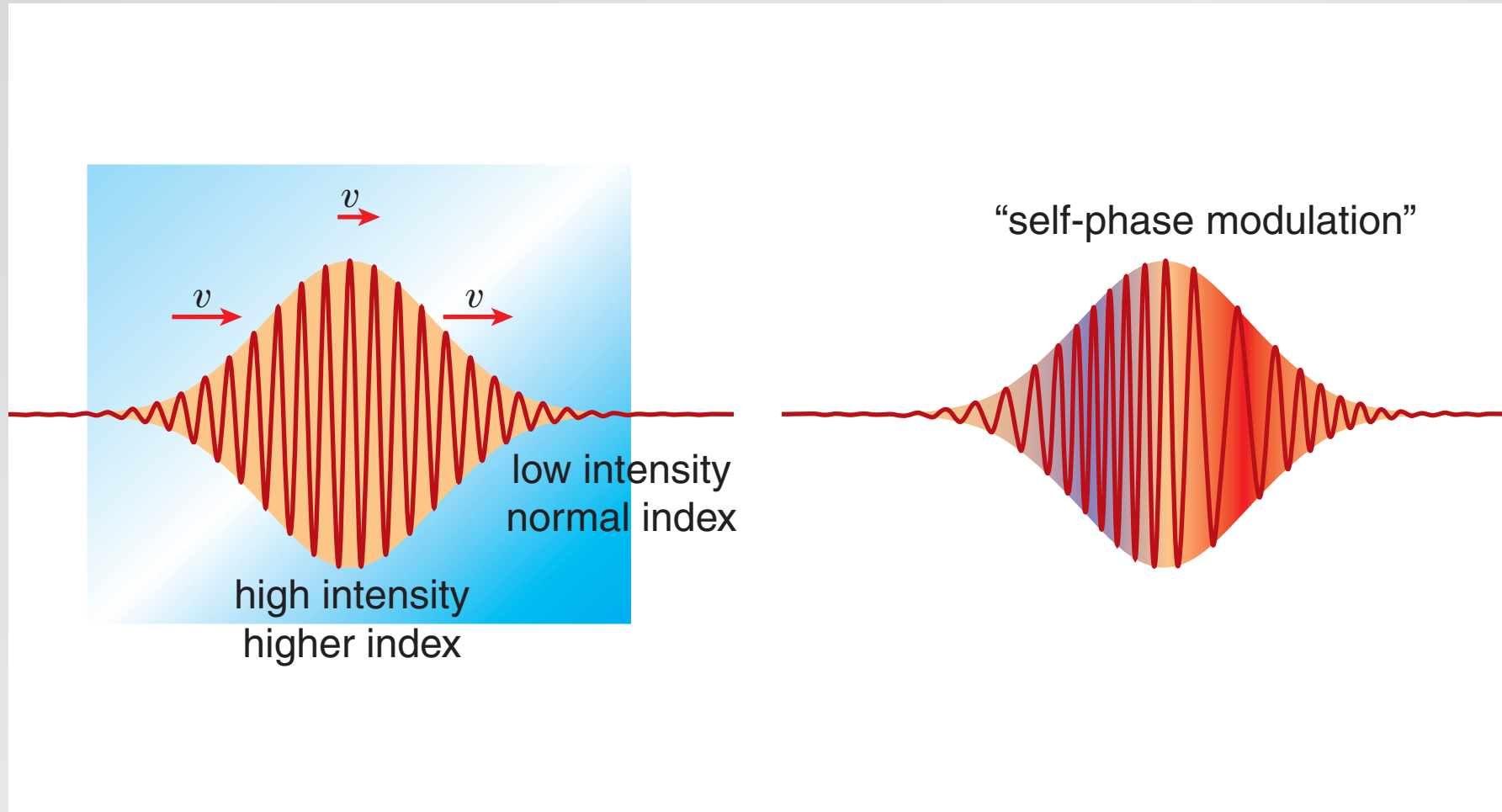
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



Supercontinuum generation

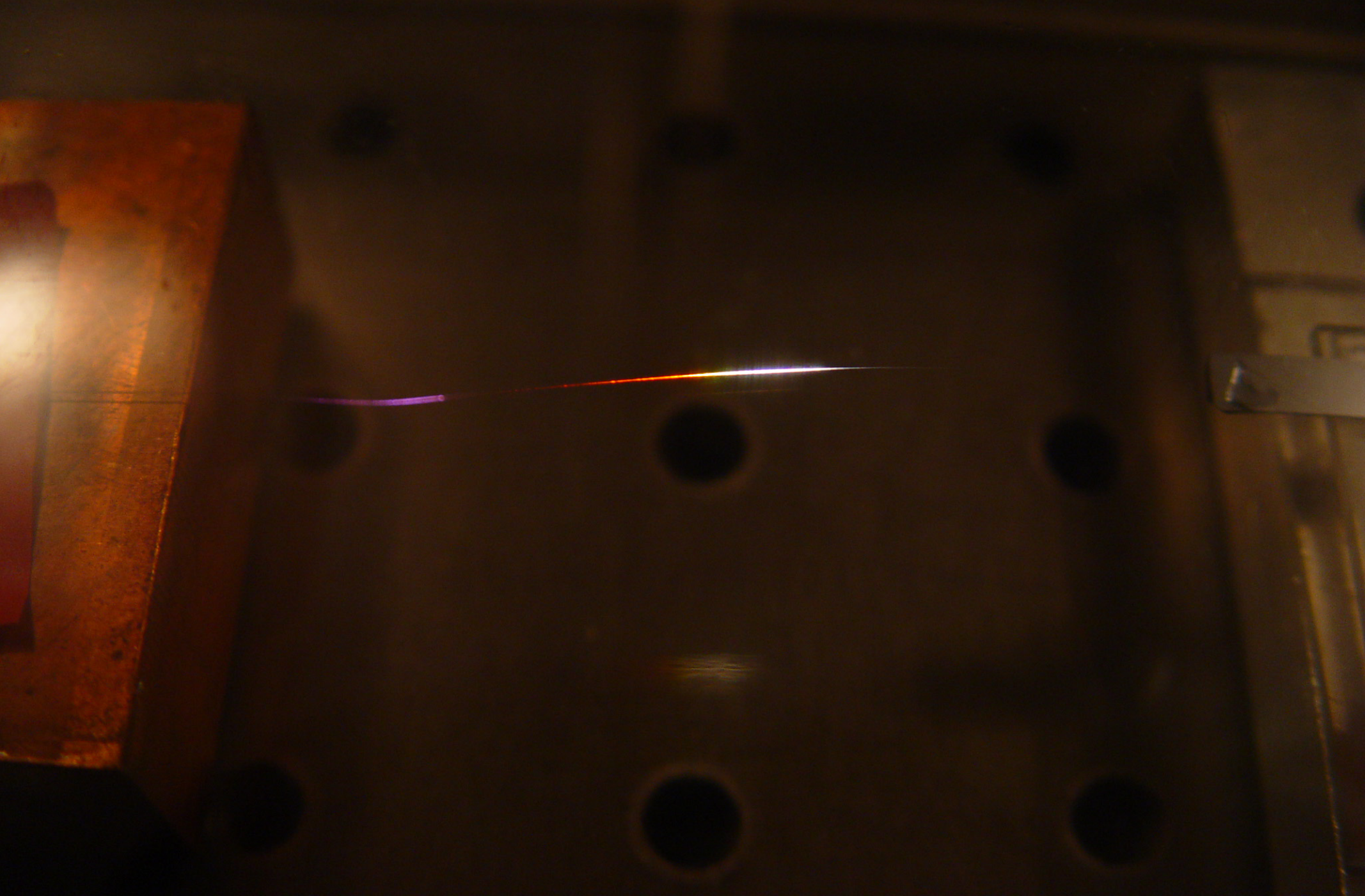
nonlinear dispersion: $n = n_0 + n_2 I$



Supercontinuum generation

strong confinement \longrightarrow **high intensity**

Supercontinuum generation

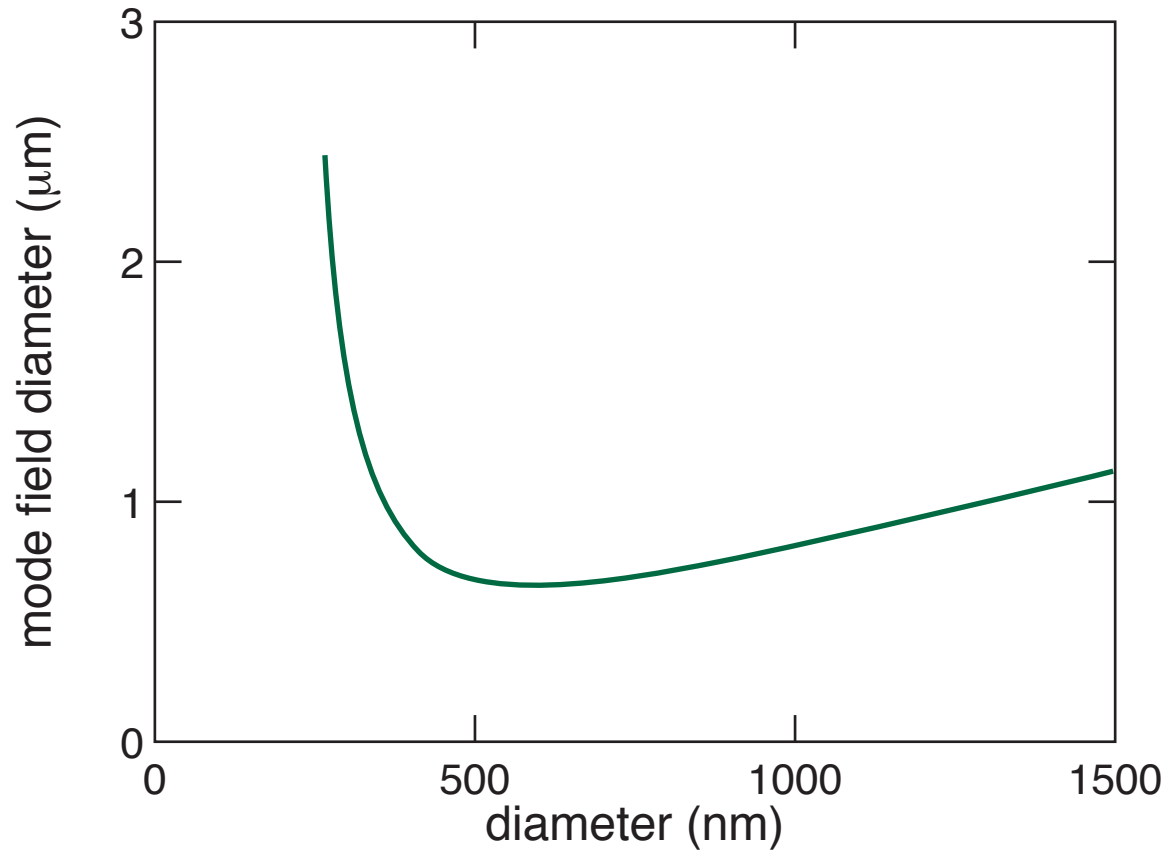


Supercontinuum generation



Supercontinuum generation

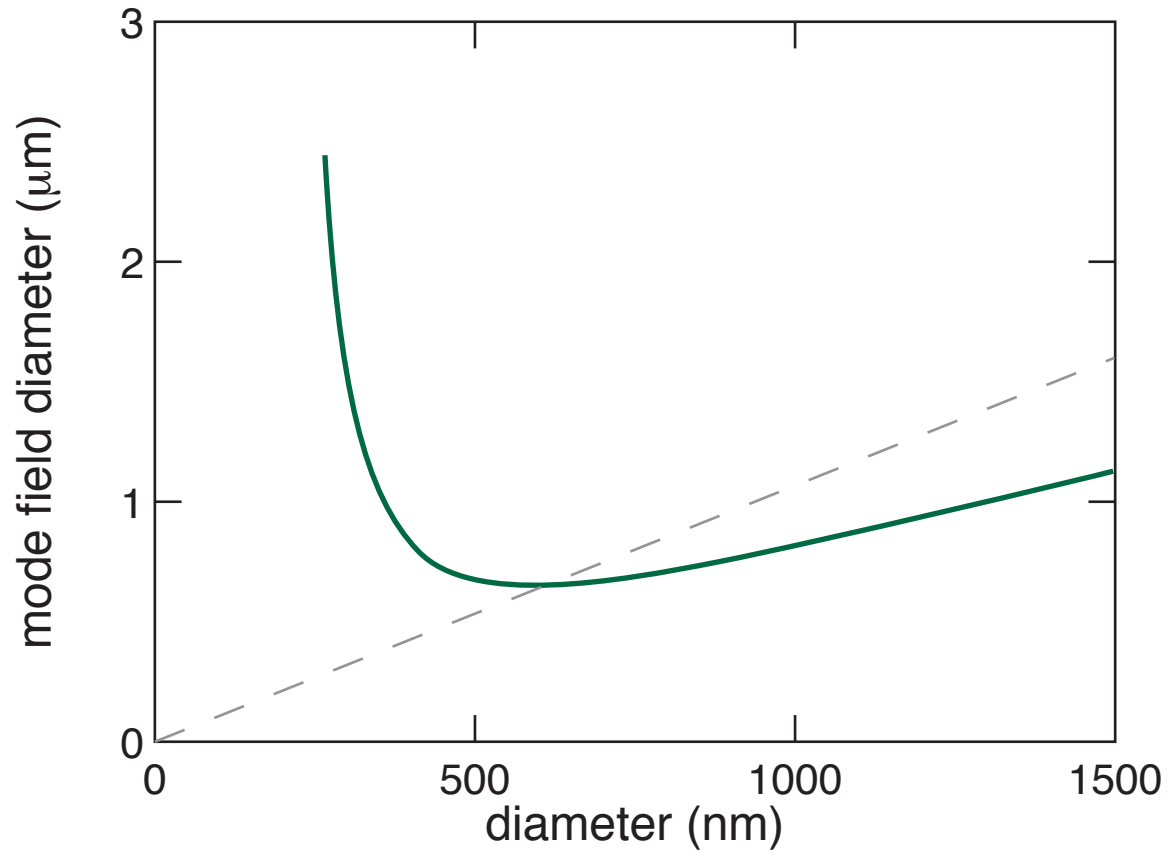
mode field diameter ($\lambda = 800$ nm)



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

Supercontinuum generation

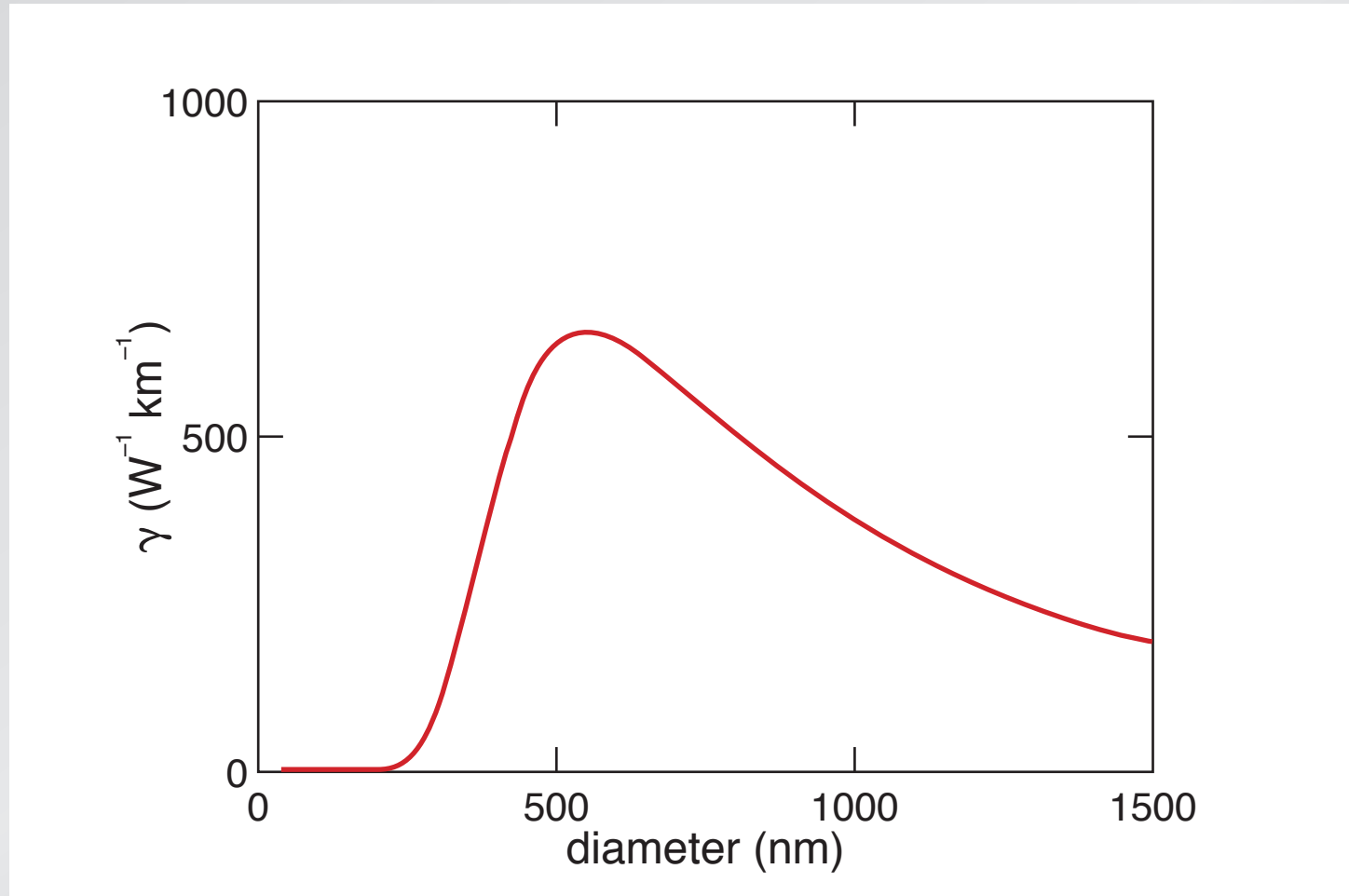
mode field diameter ($\lambda = 800$ nm)



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!

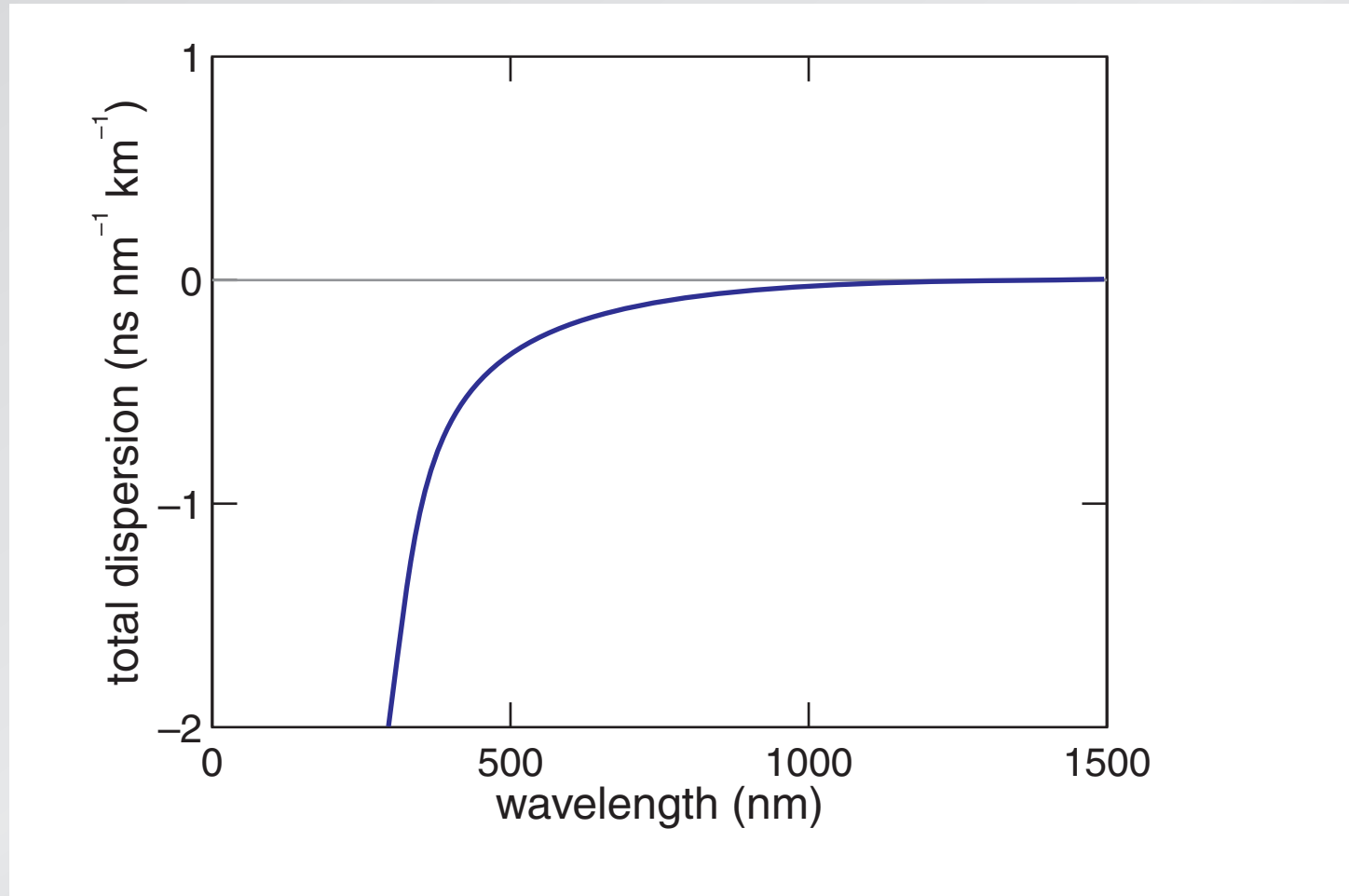
Supercontinuum generation

dispersion:

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

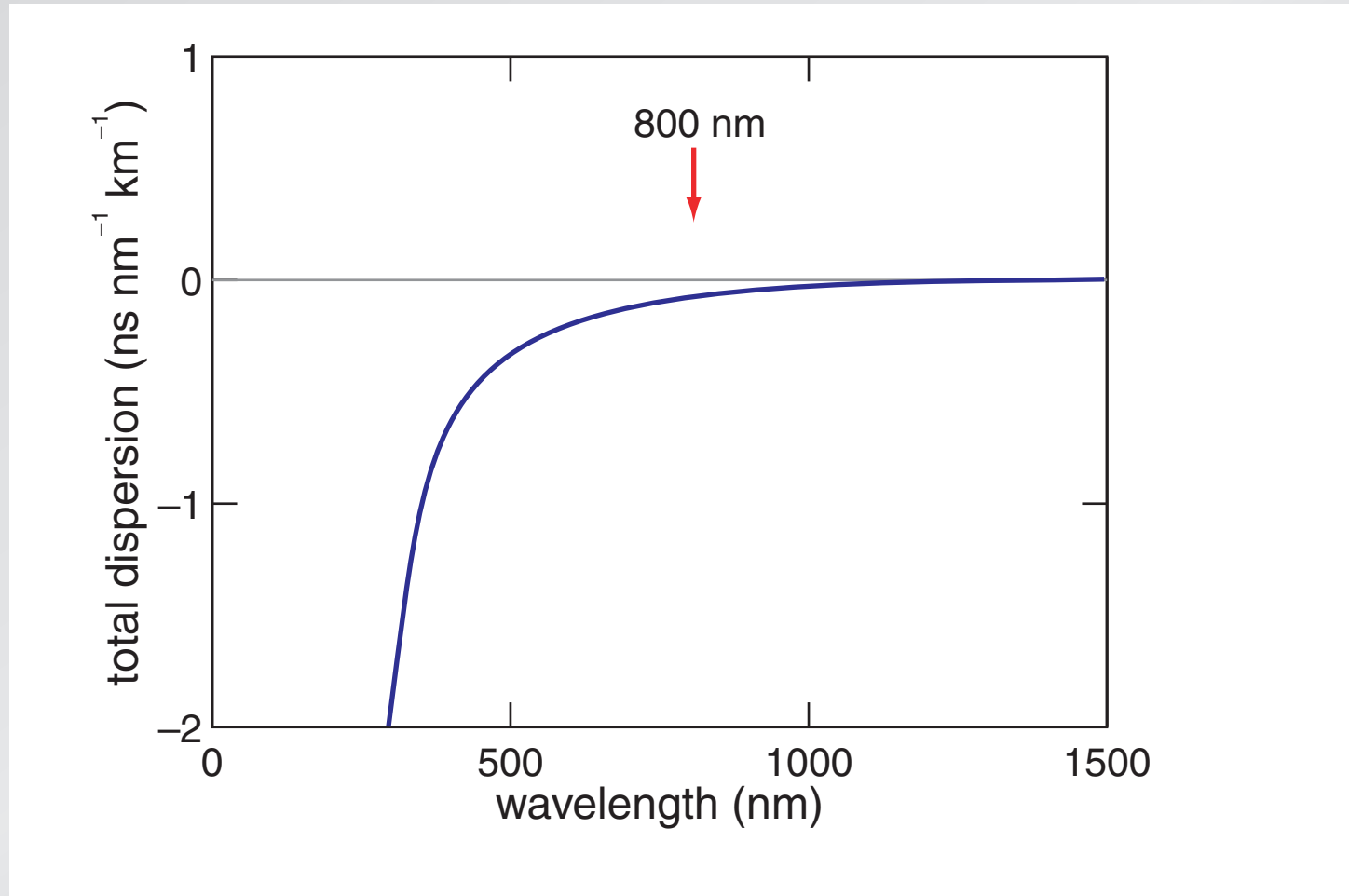
Supercontinuum generation

waveguide dispersion



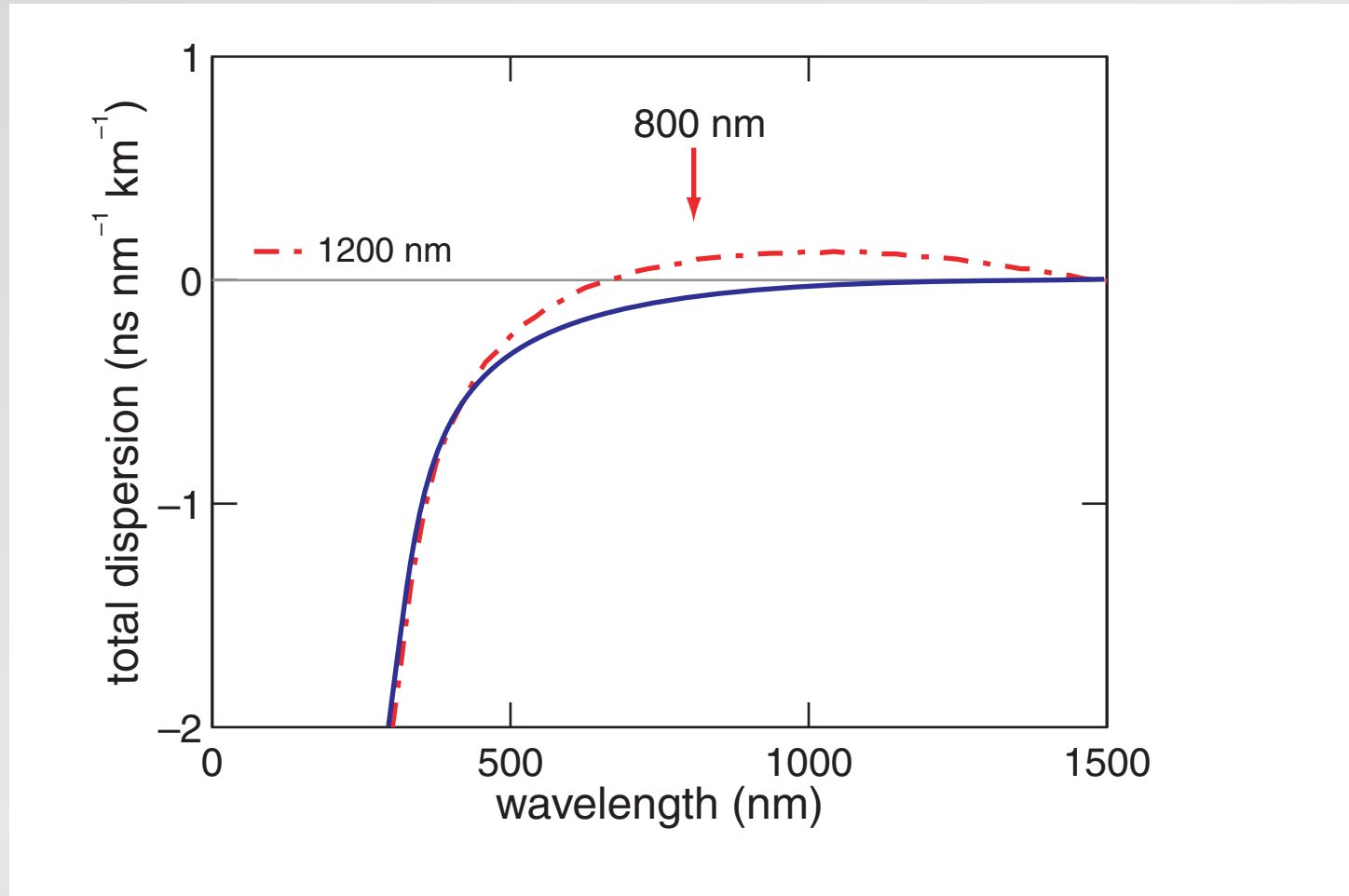
Supercontinuum generation

waveguide dispersion



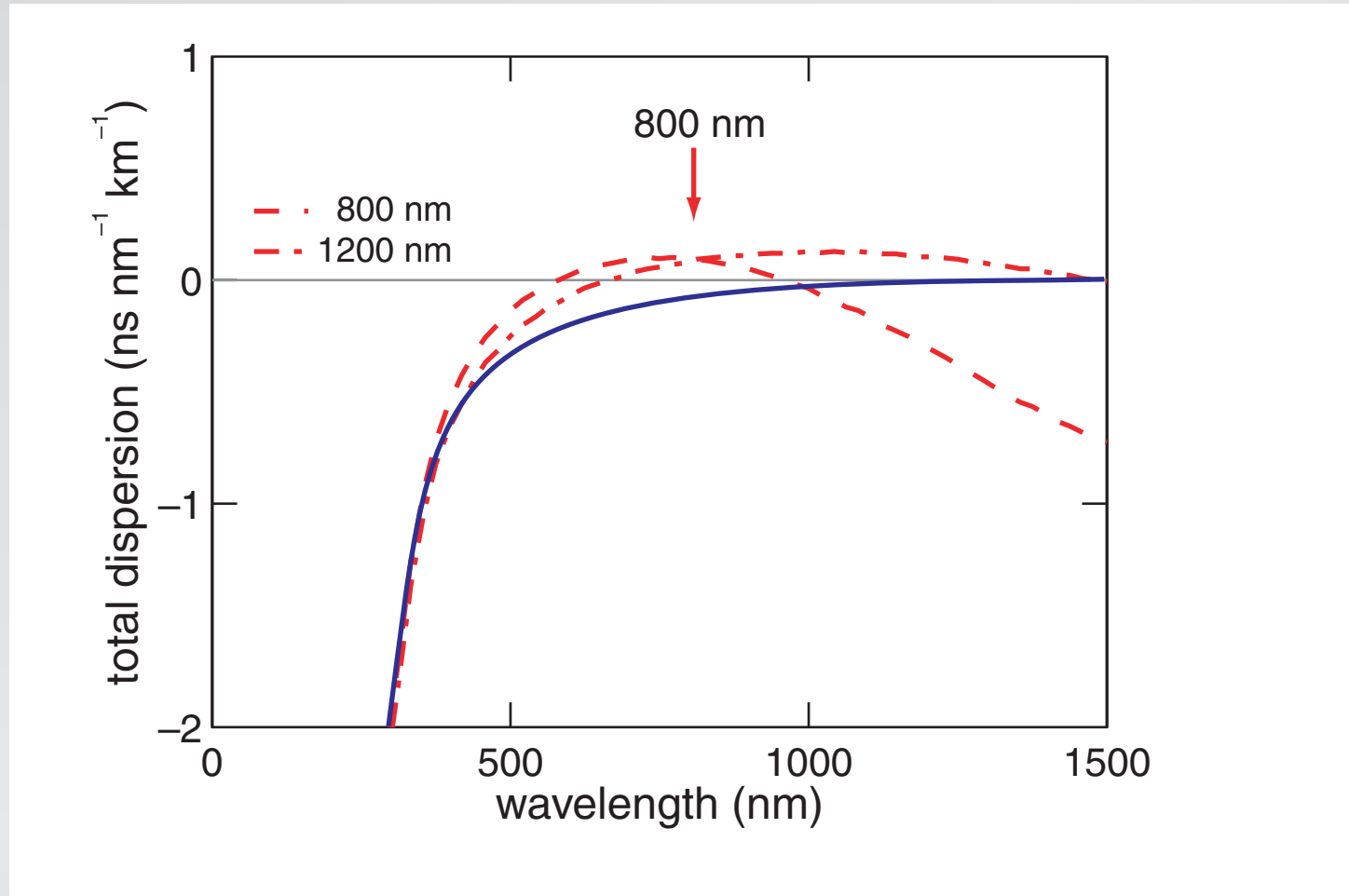
Supercontinuum generation

waveguide dispersion



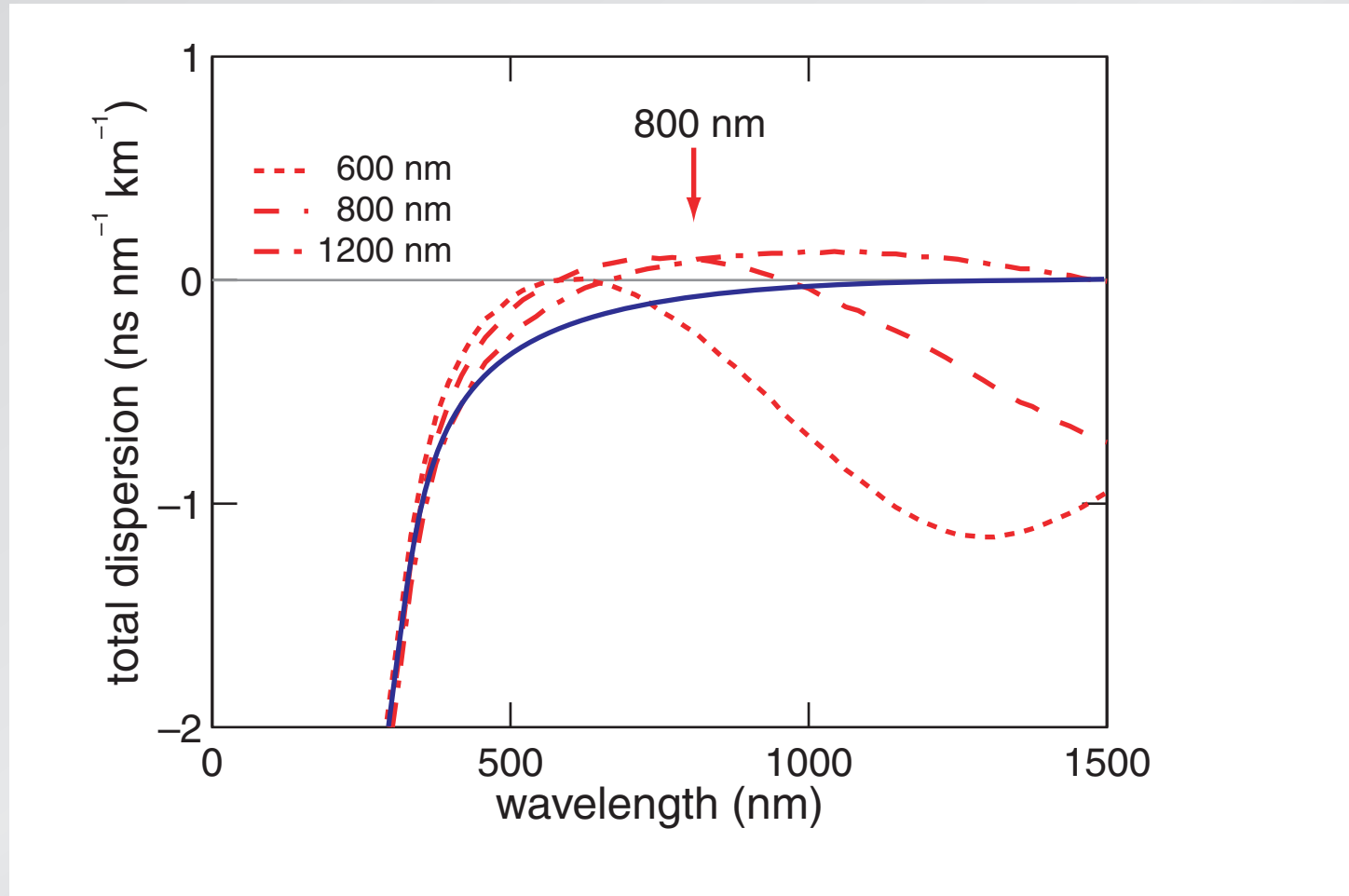
Supercontinuum generation

waveguide dispersion



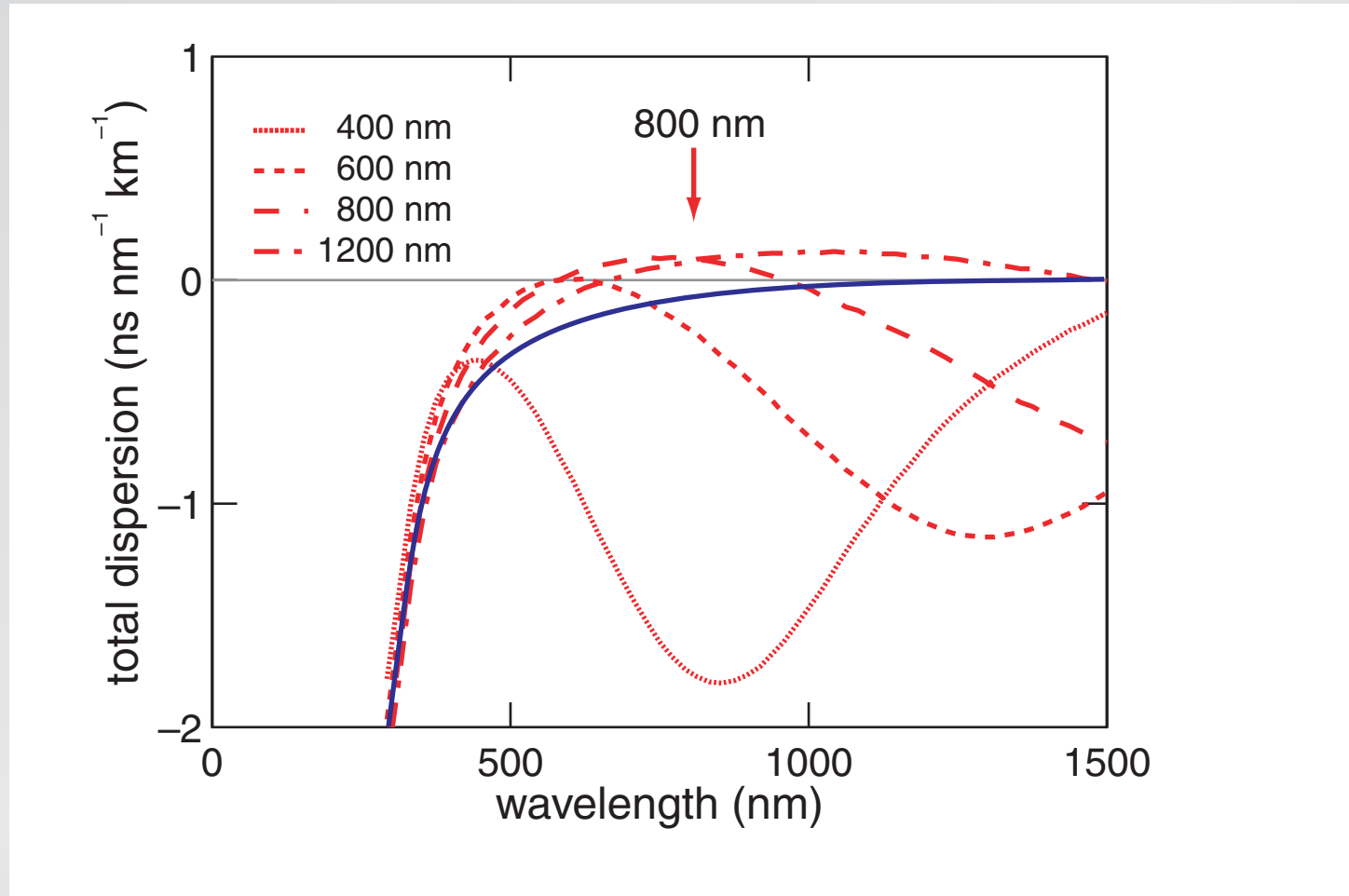
Supercontinuum generation

waveguide dispersion



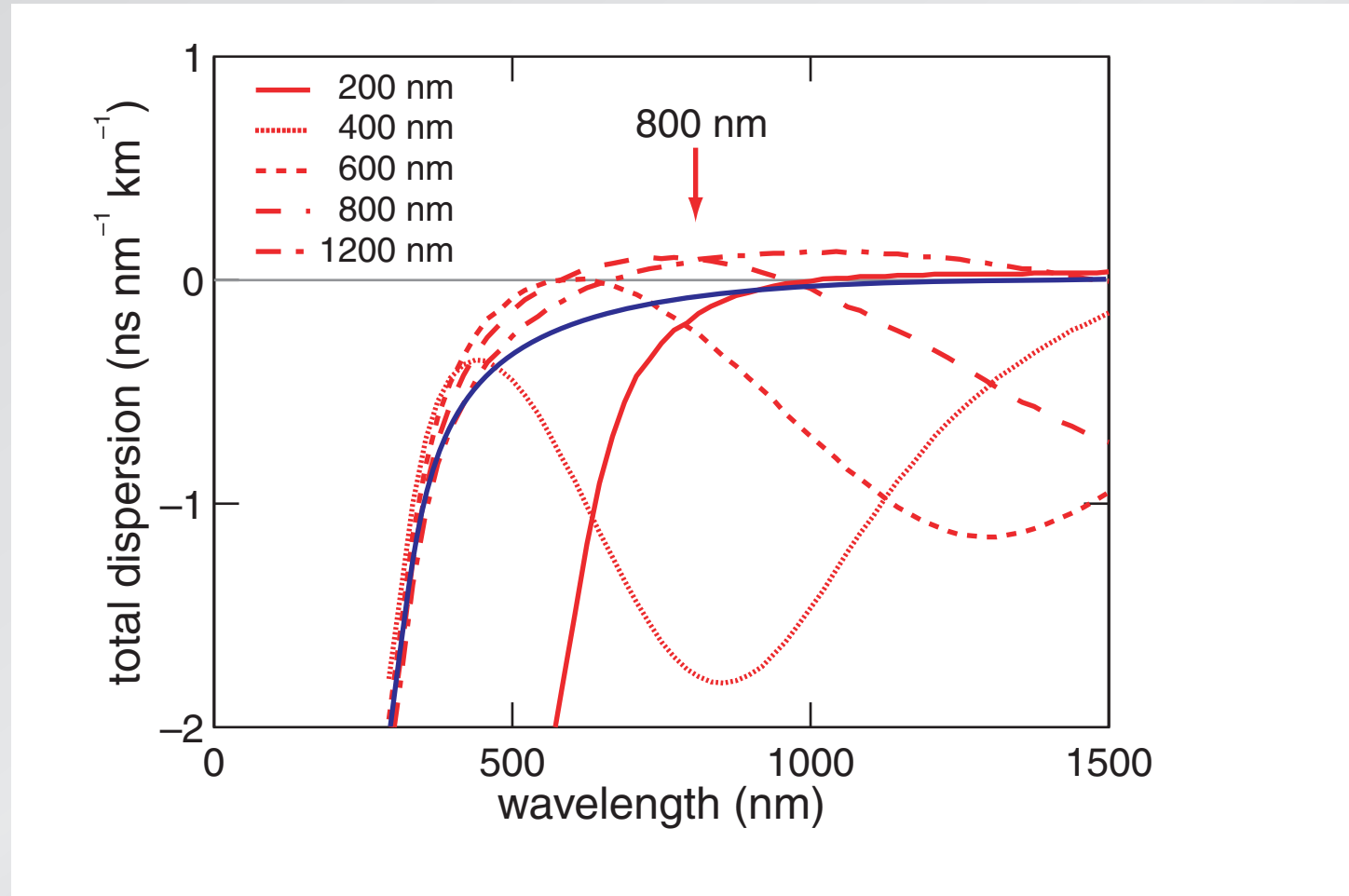
Supercontinuum generation

waveguide dispersion



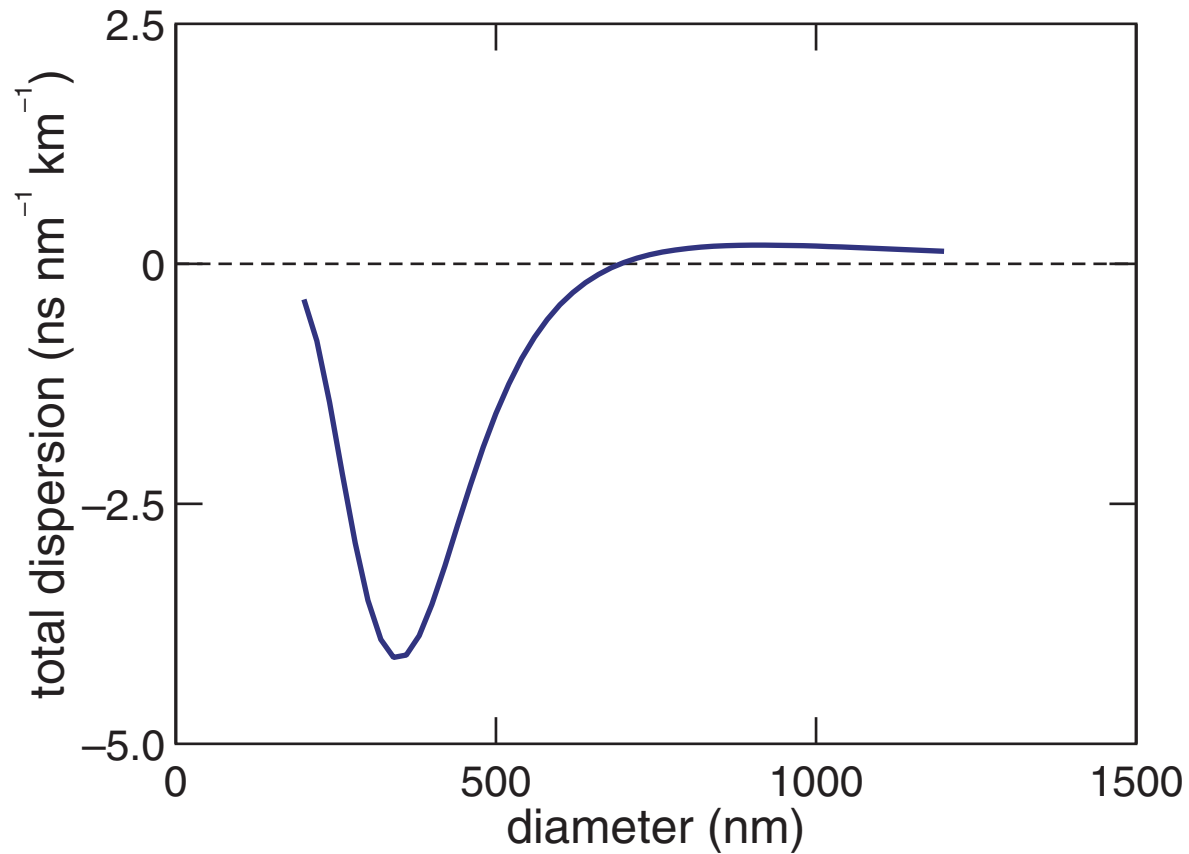
Supercontinuum generation

waveguide dispersion



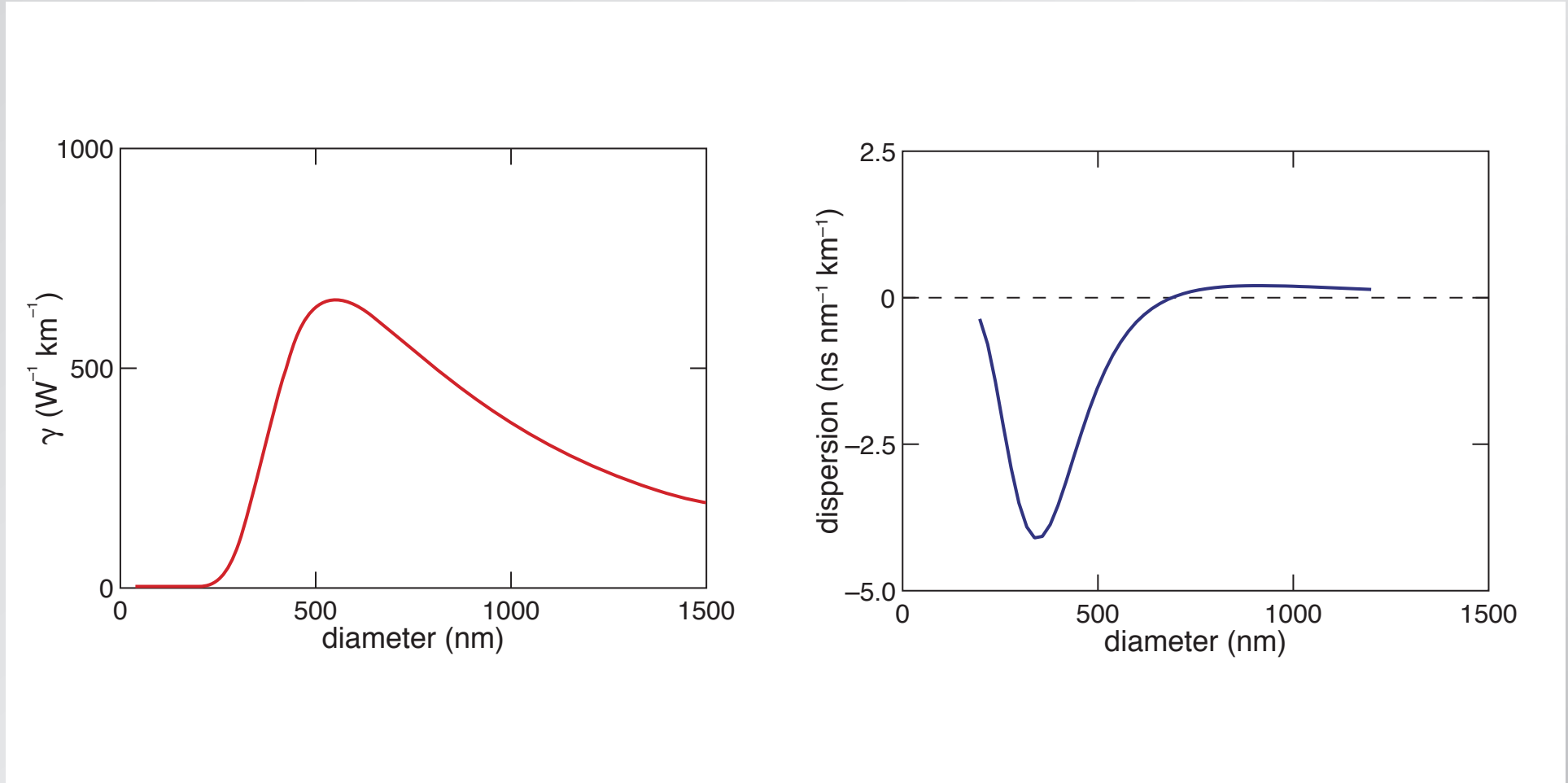
Supercontinuum generation

waveguide dispersion



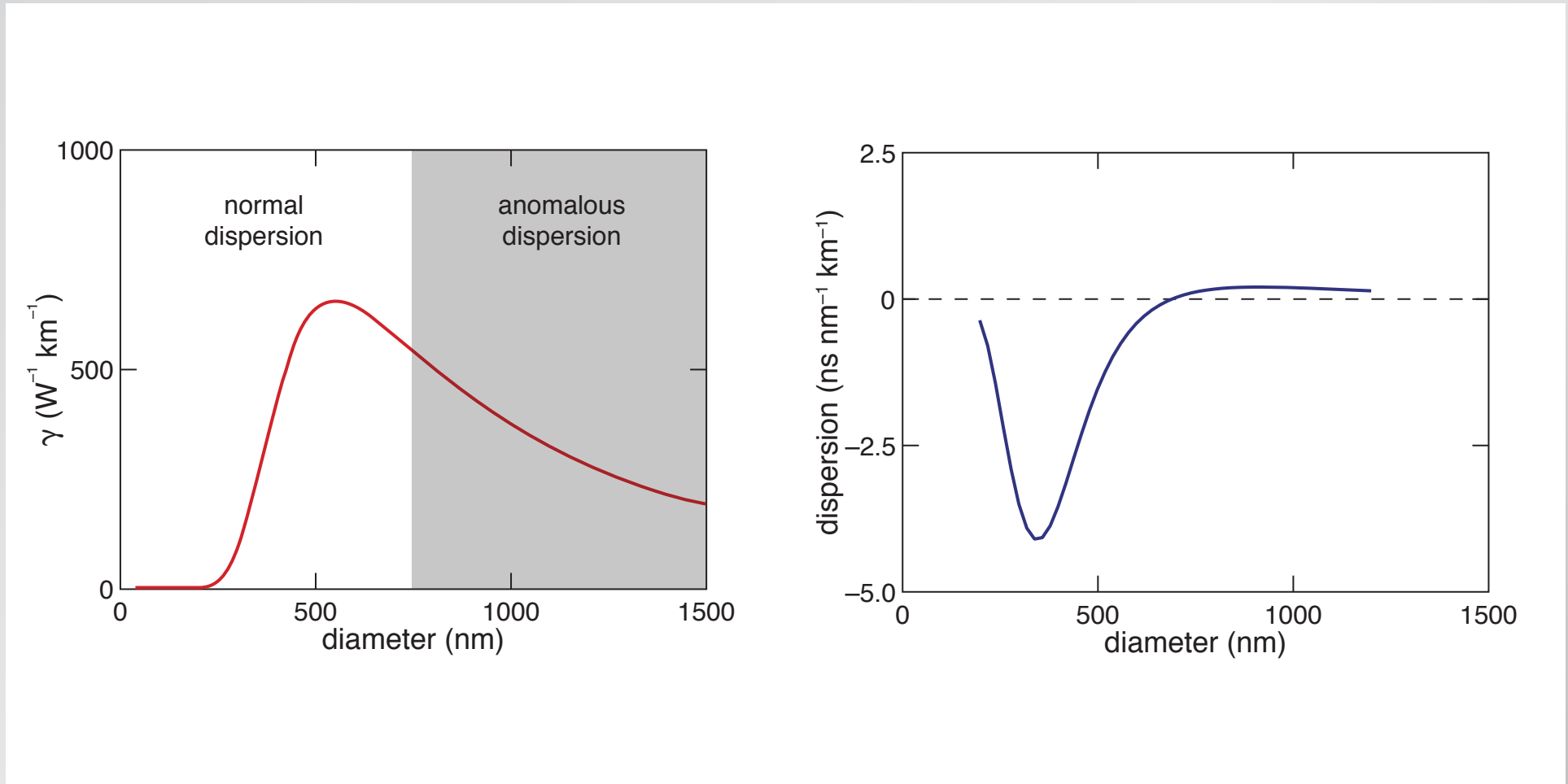
Supercontinuum generation

waveguide dispersion



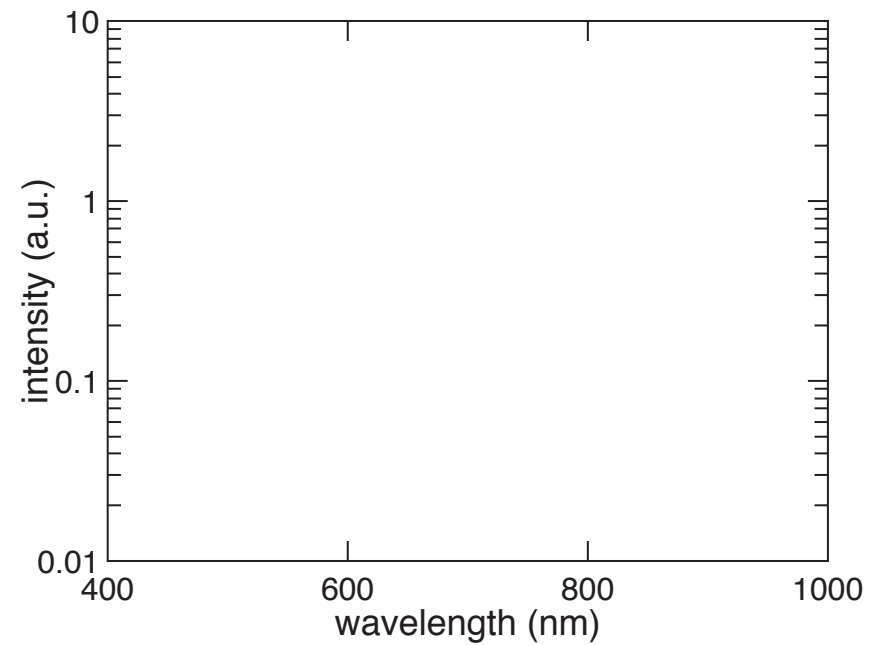
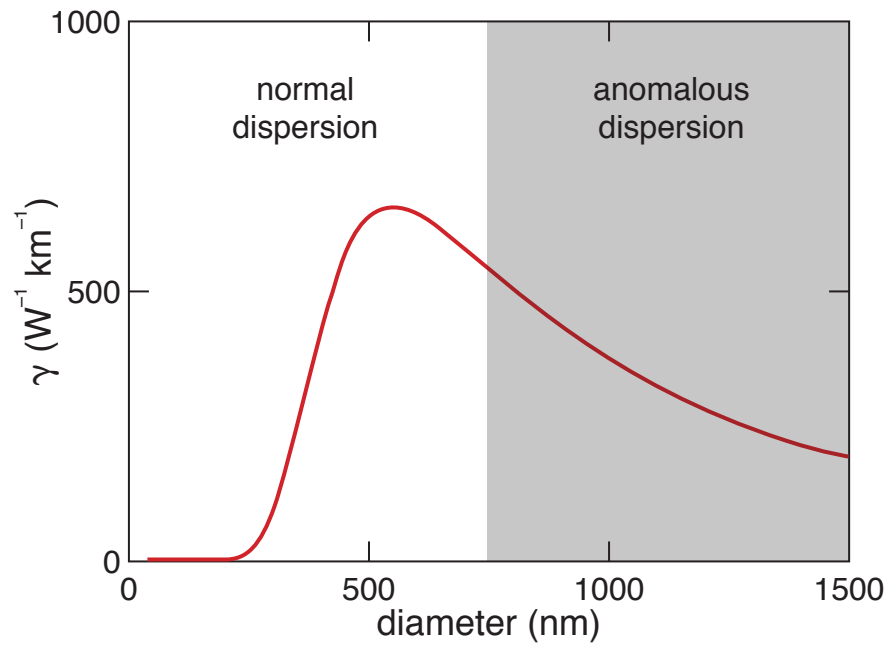
Supercontinuum generation

waveguide dispersion



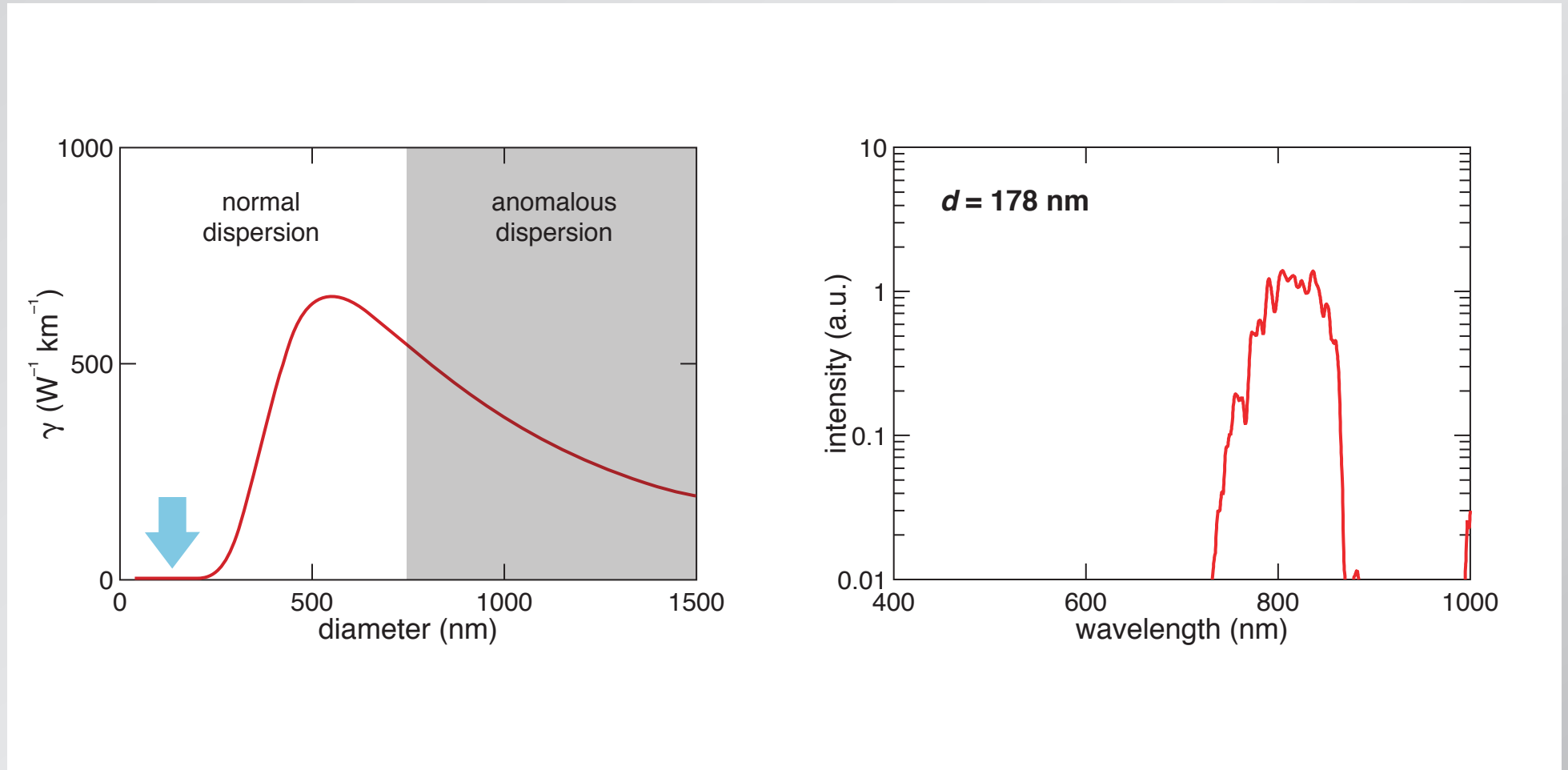
Supercontinuum generation

nanowire continuum generation



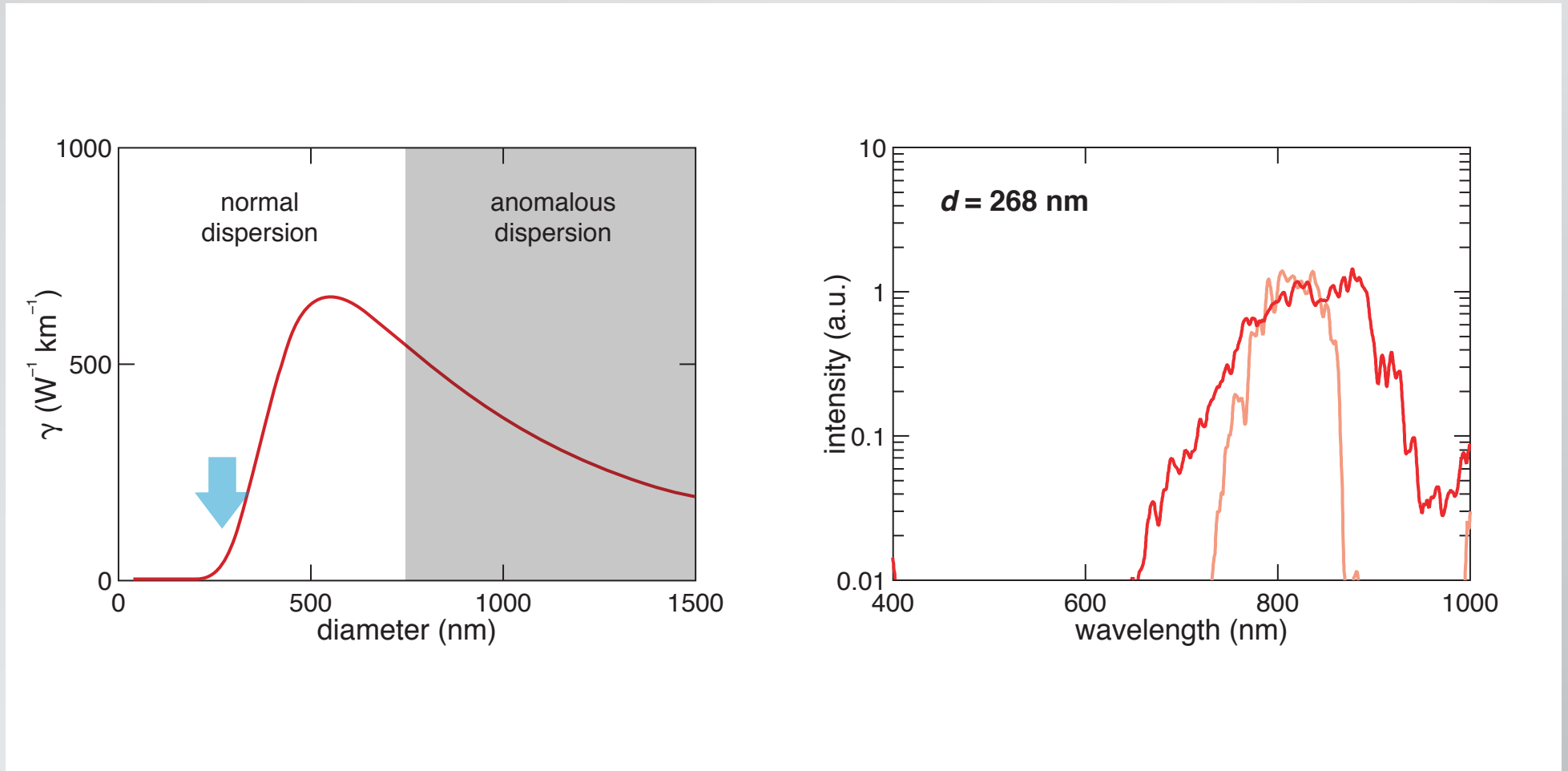
Supercontinuum generation

nanowire continuum generation



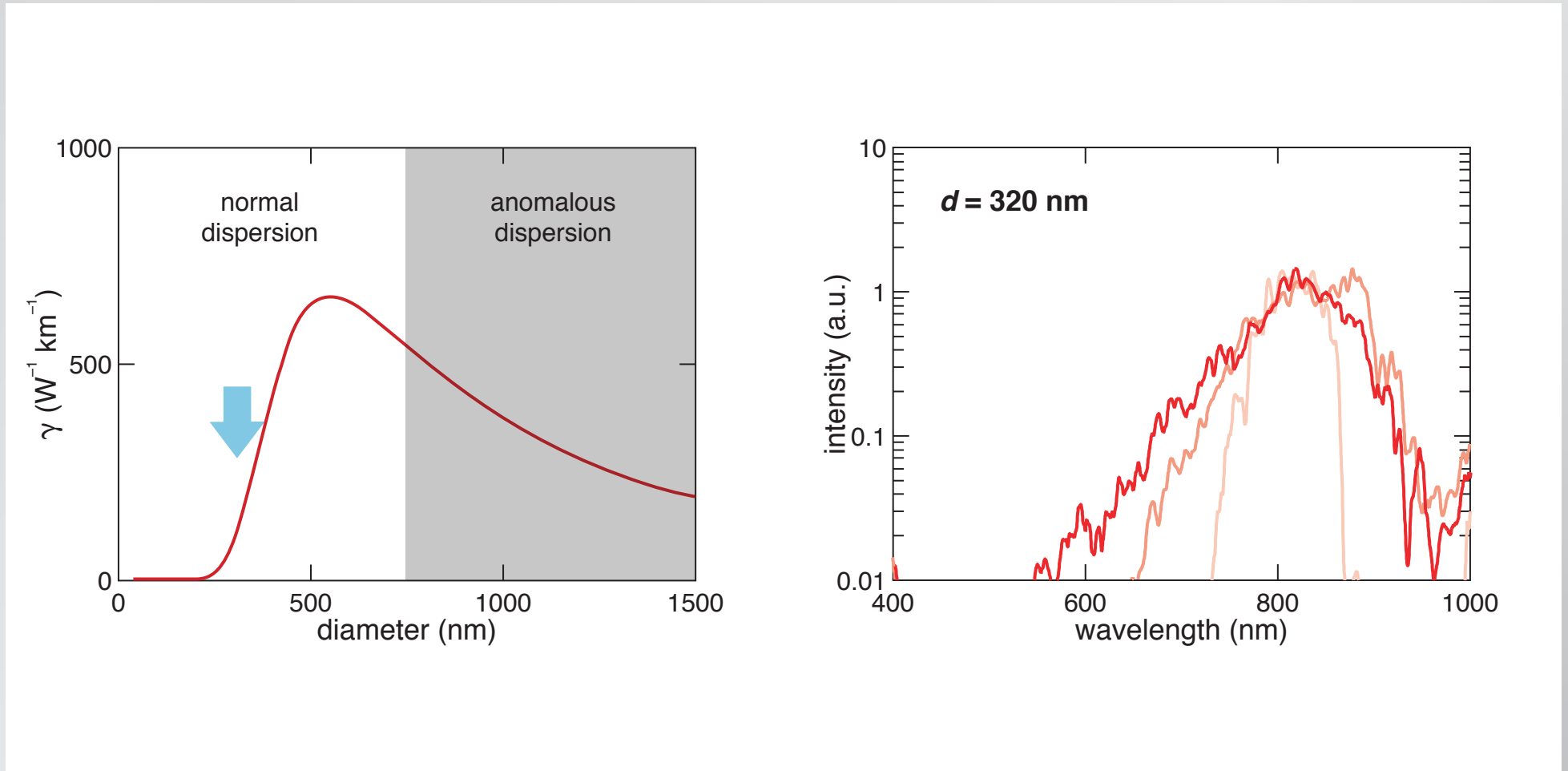
Supercontinuum generation

nanowire continuum generation



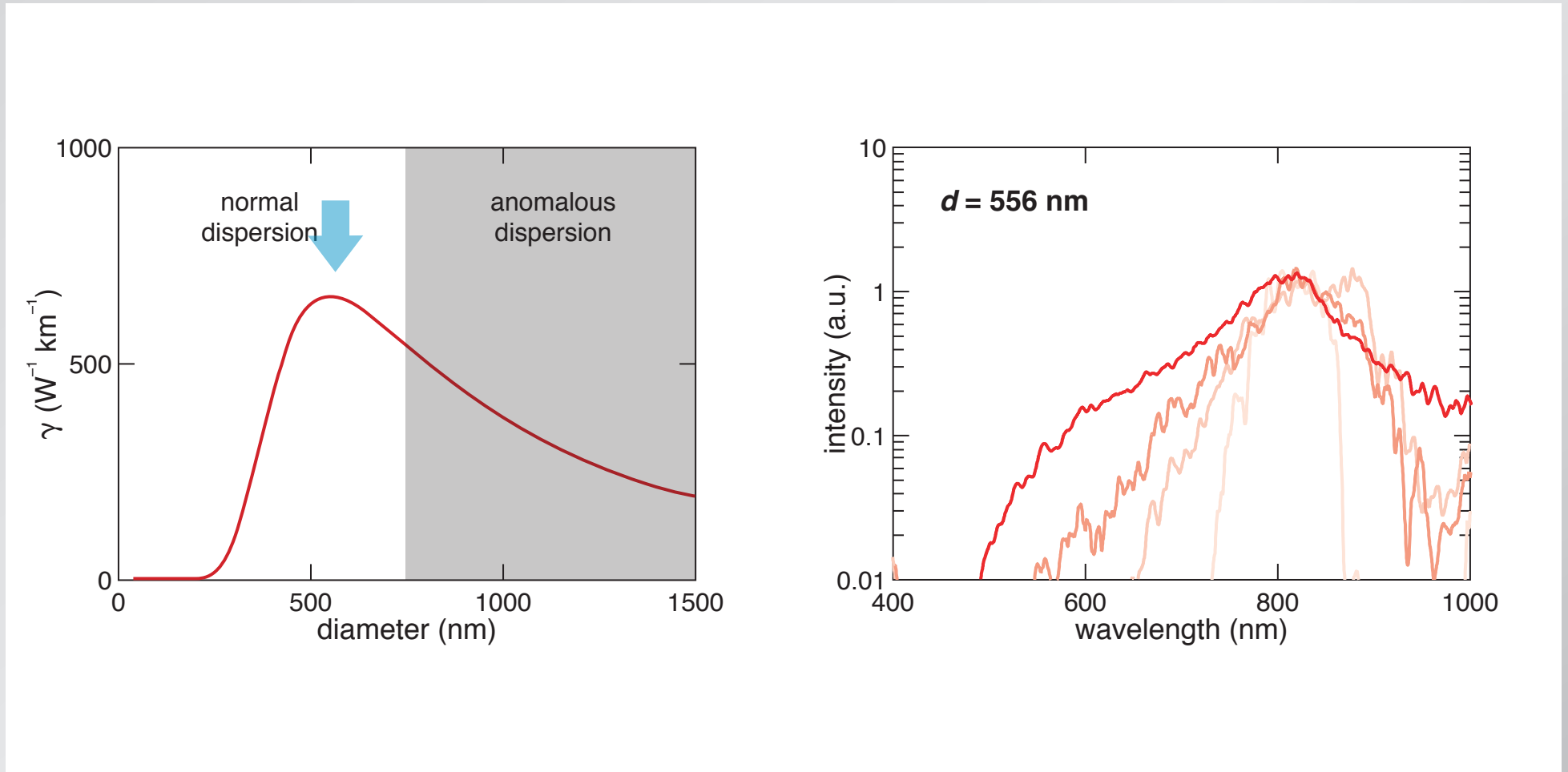
Supercontinuum generation

nanowire continuum generation



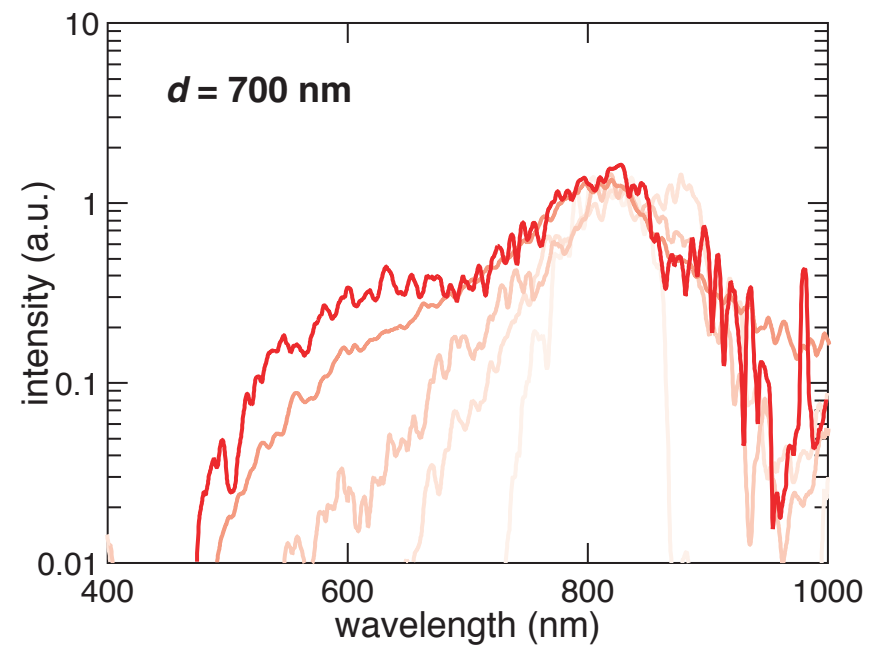
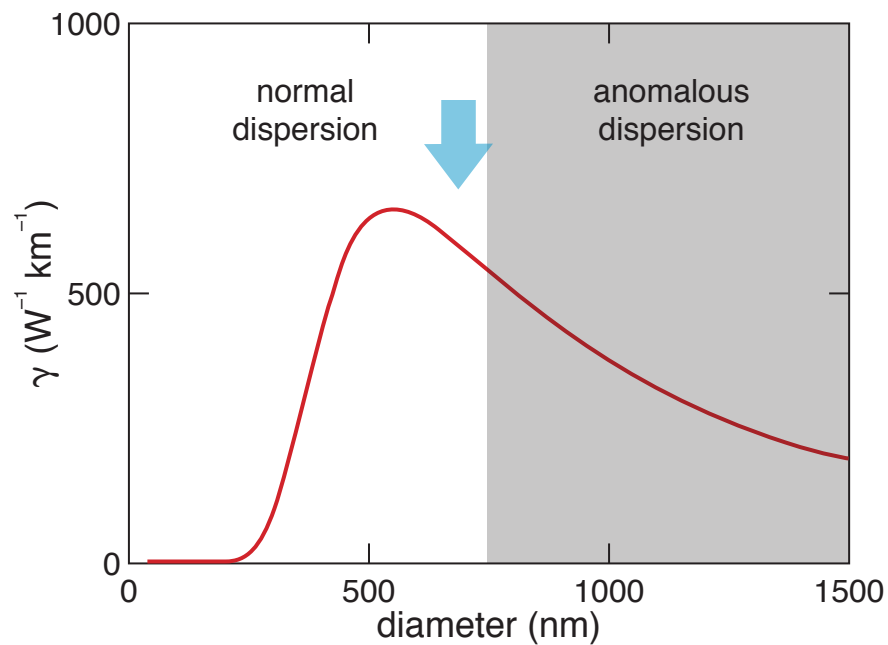
Supercontinuum generation

nanowire continuum generation



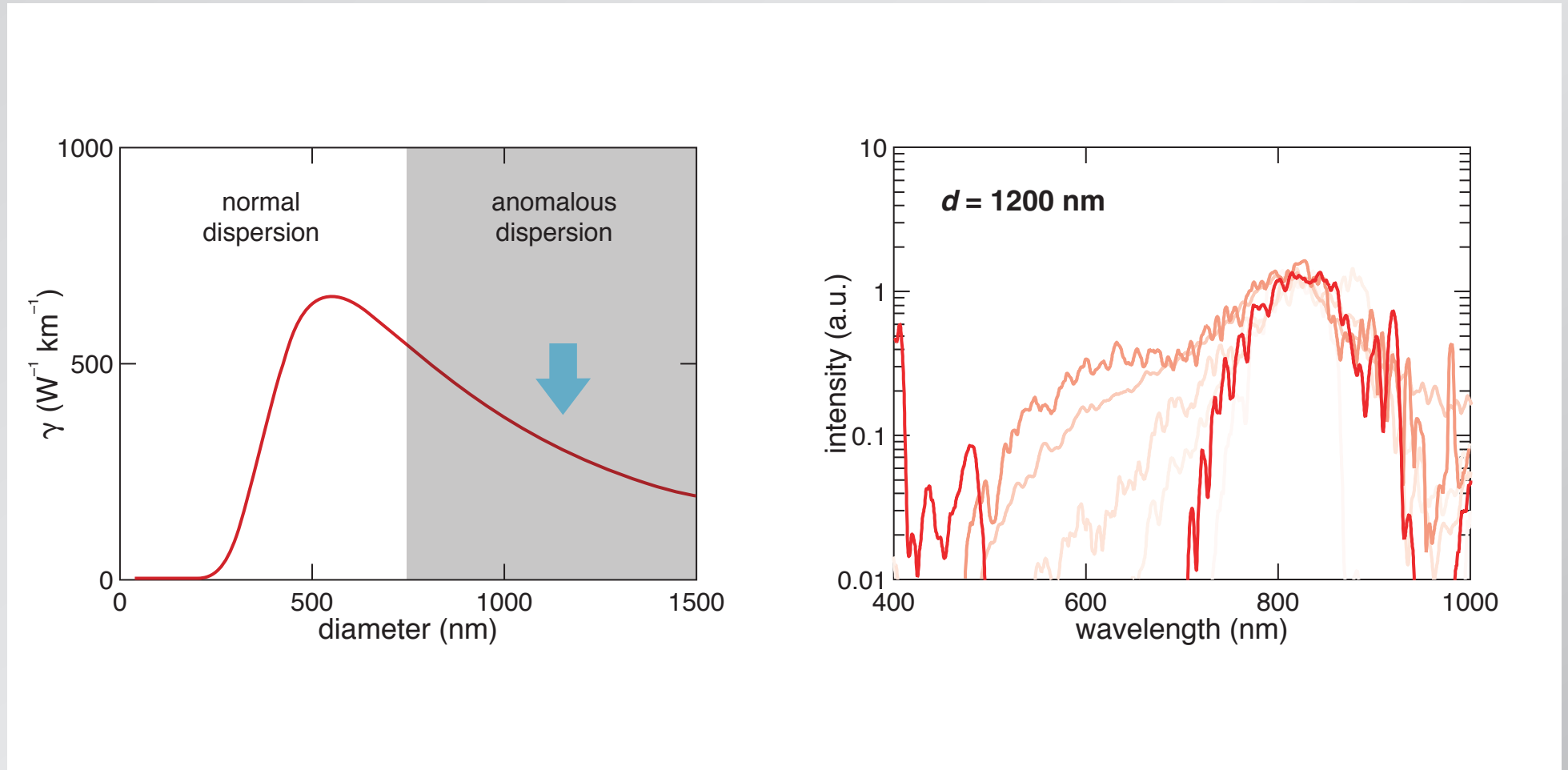
Supercontinuum generation

nanowire continuum generation



Supercontinuum generation

nanowire continuum generation



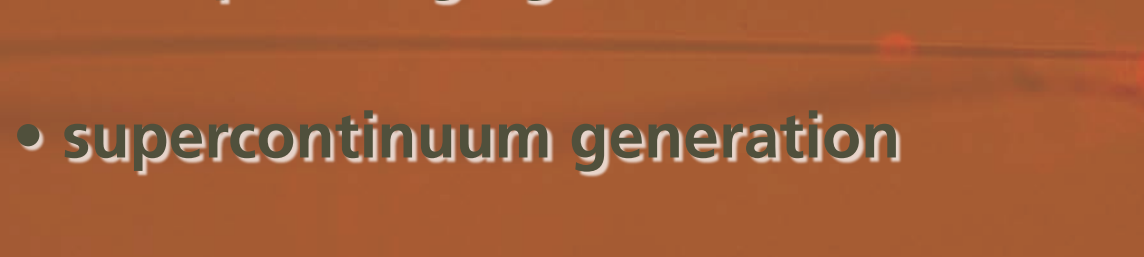
Supercontinuum generation

energy in nanowire < 100 pJ!

Supercontinuum generation

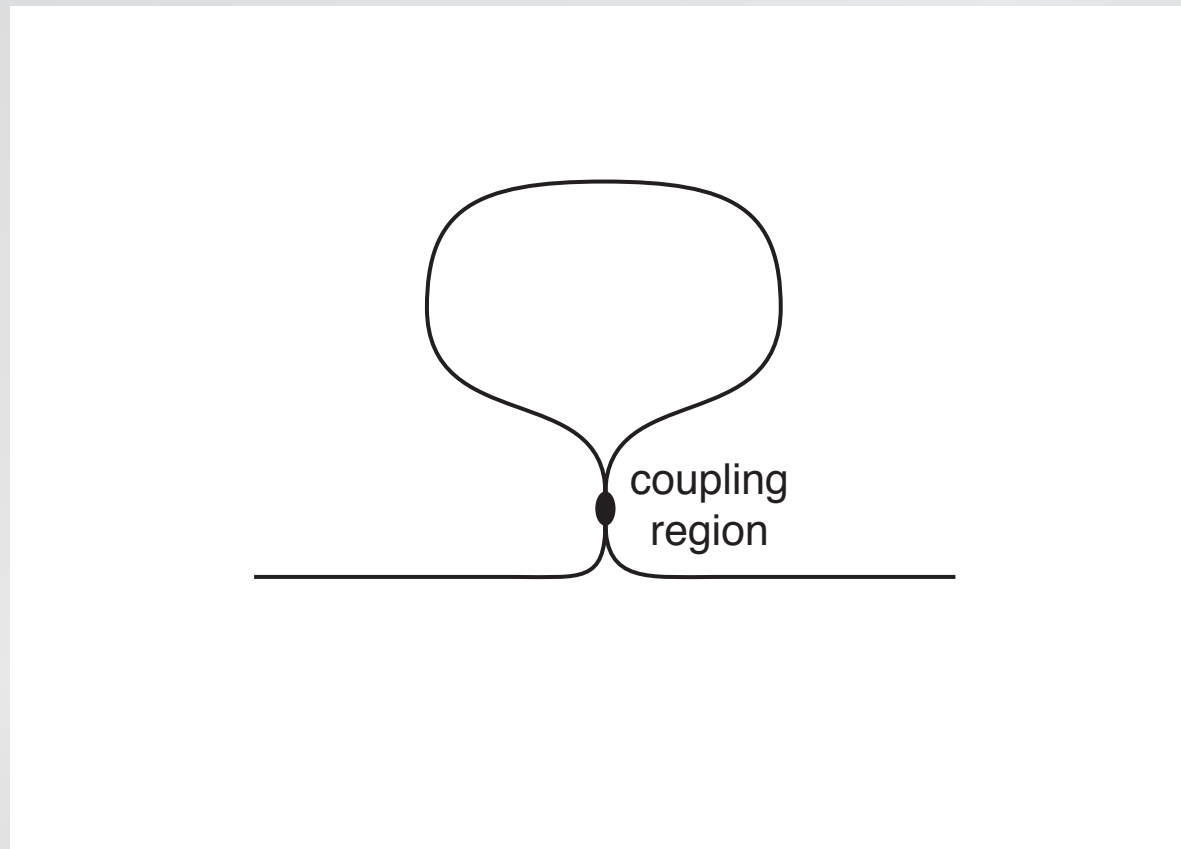
- **picojoule nonlinear optics**
- **optimum diameter for silica 500–600 nm**
- **low dispersion**

Outline

- **manipulating light at the nanoscale**
 - **supercontinuum generation**
 - **optical logic gates**
- 

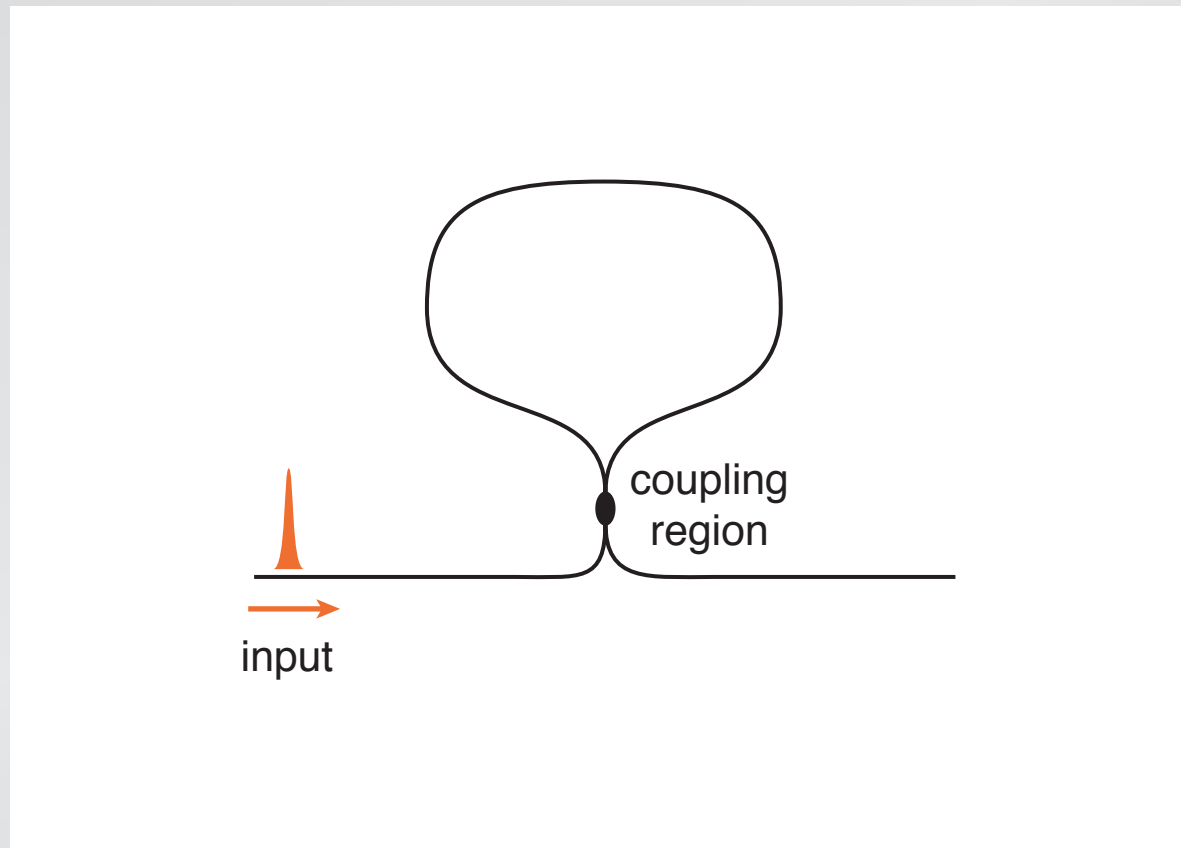
Optical logic gates

nanowire Sagnac interferometer



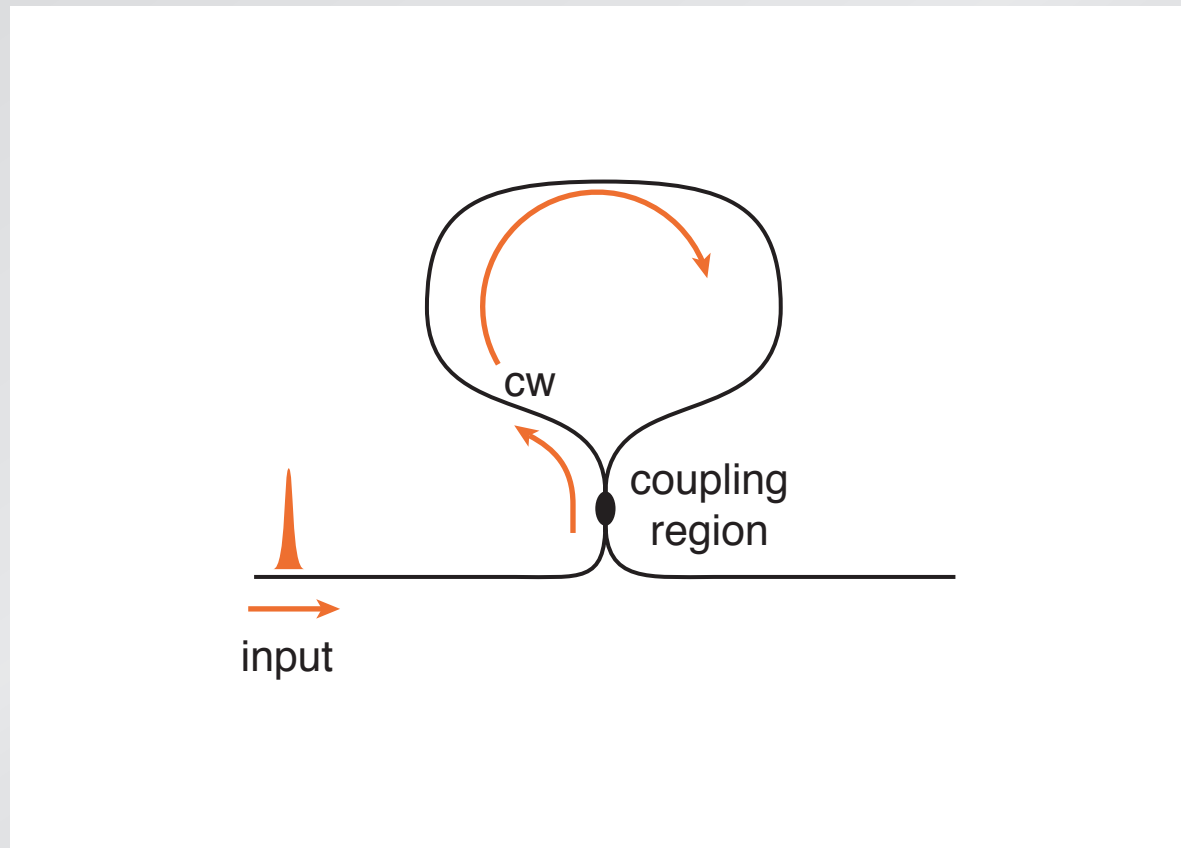
Optical logic gates

nanowire Sagnac interferometer



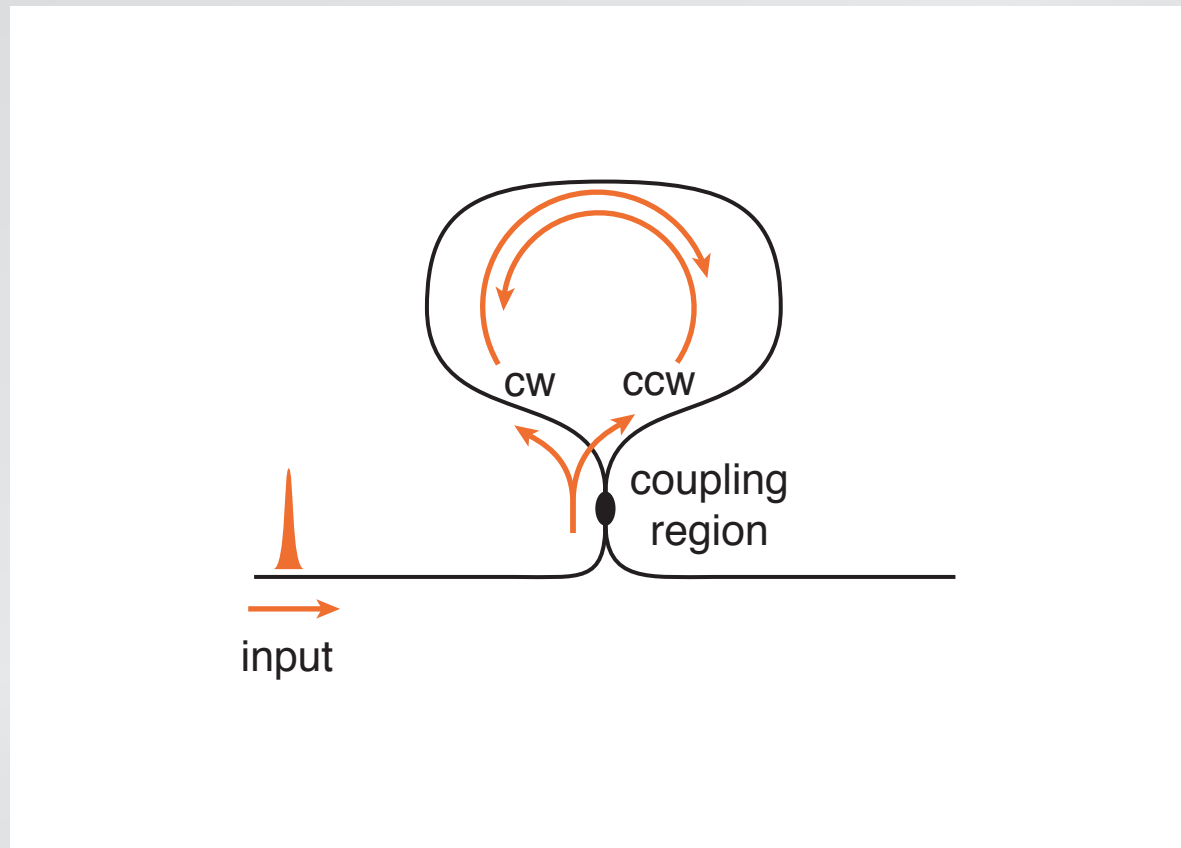
Optical logic gates

nanowire Sagnac interferometer



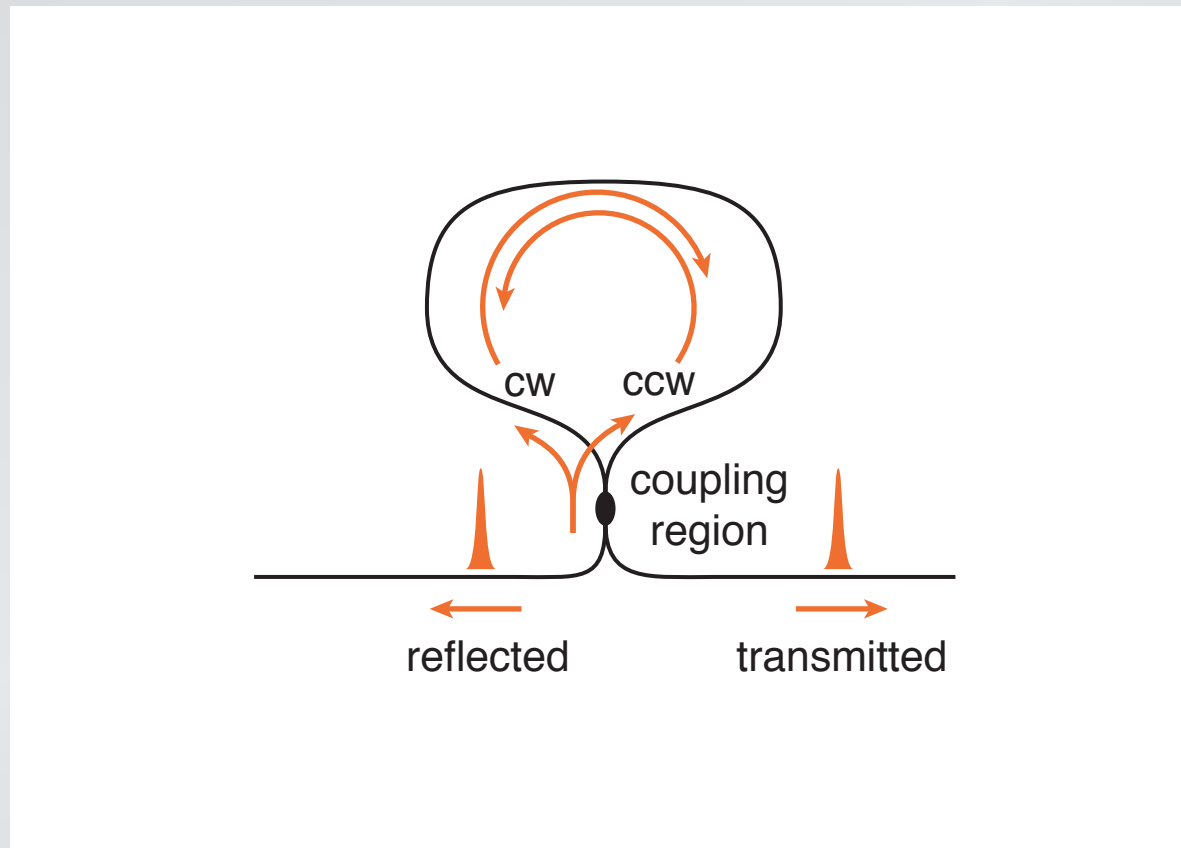
Optical logic gates

nanowire Sagnac interferometer



Optical logic gates

nanowire Sagnac interferometer



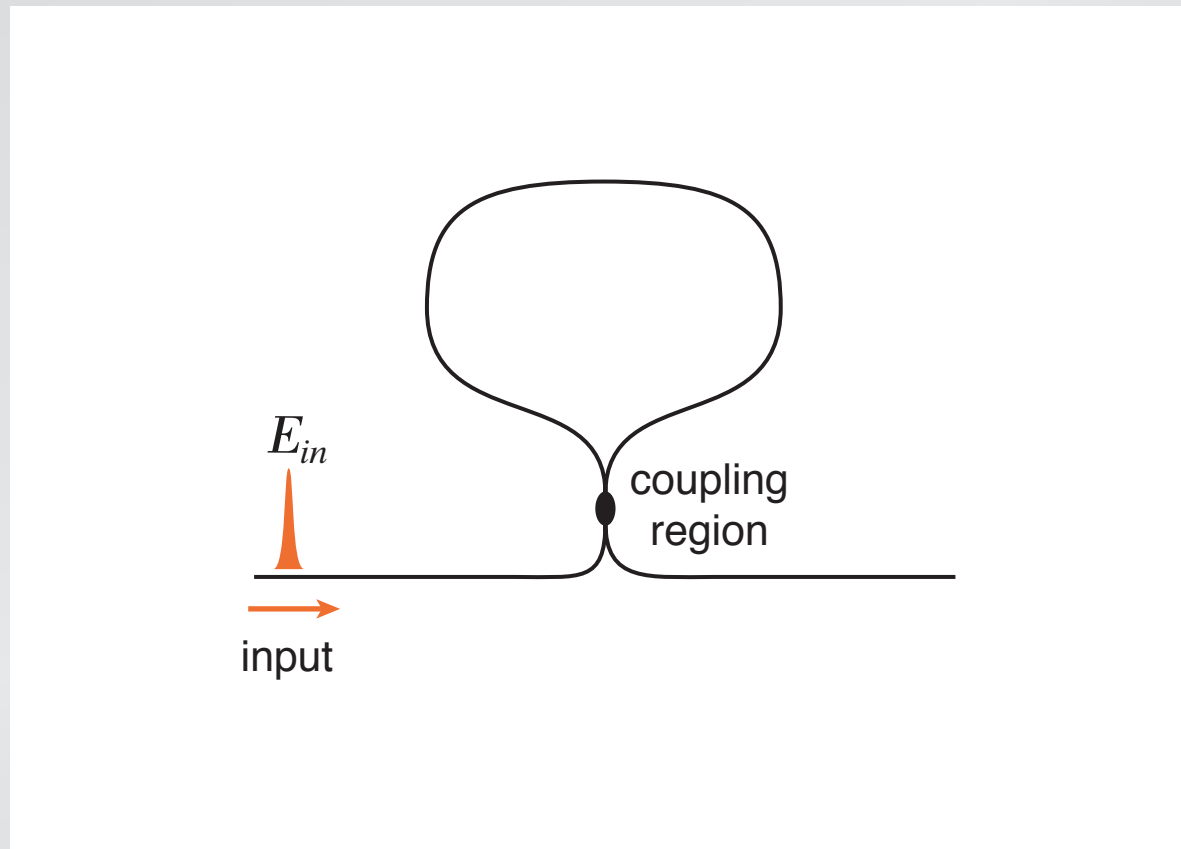
Optical logic gates

output = transmitted cw + ccw power



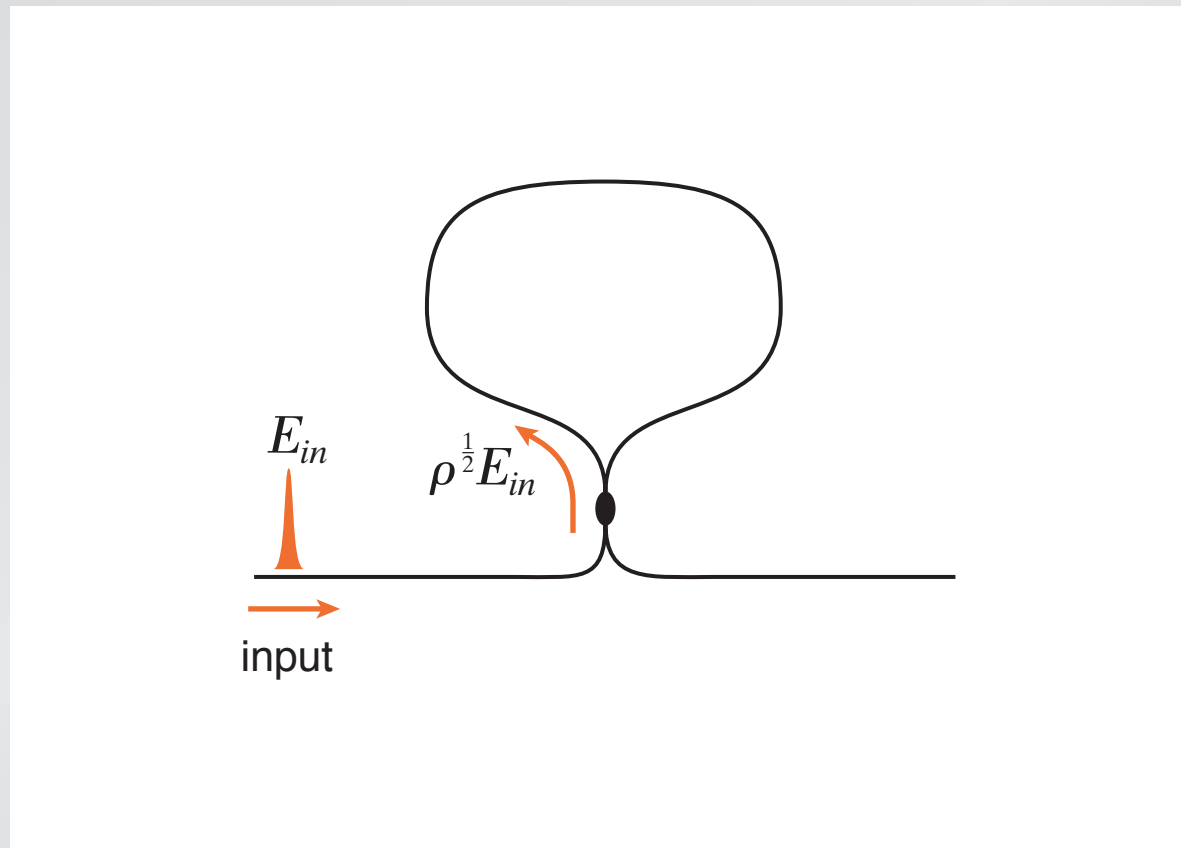
Optical logic gates

input electric field amplitude E_{in}



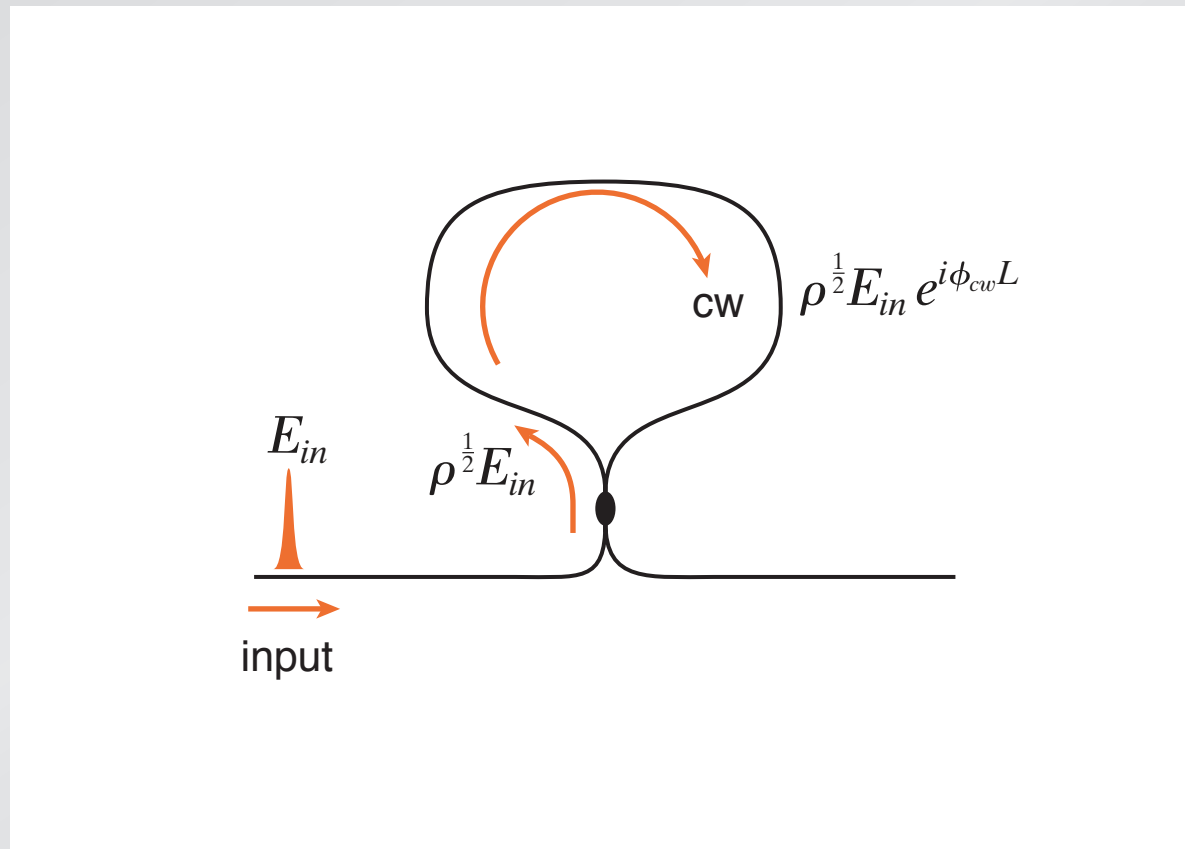
Optical logic gates

coupling parameter: ρ



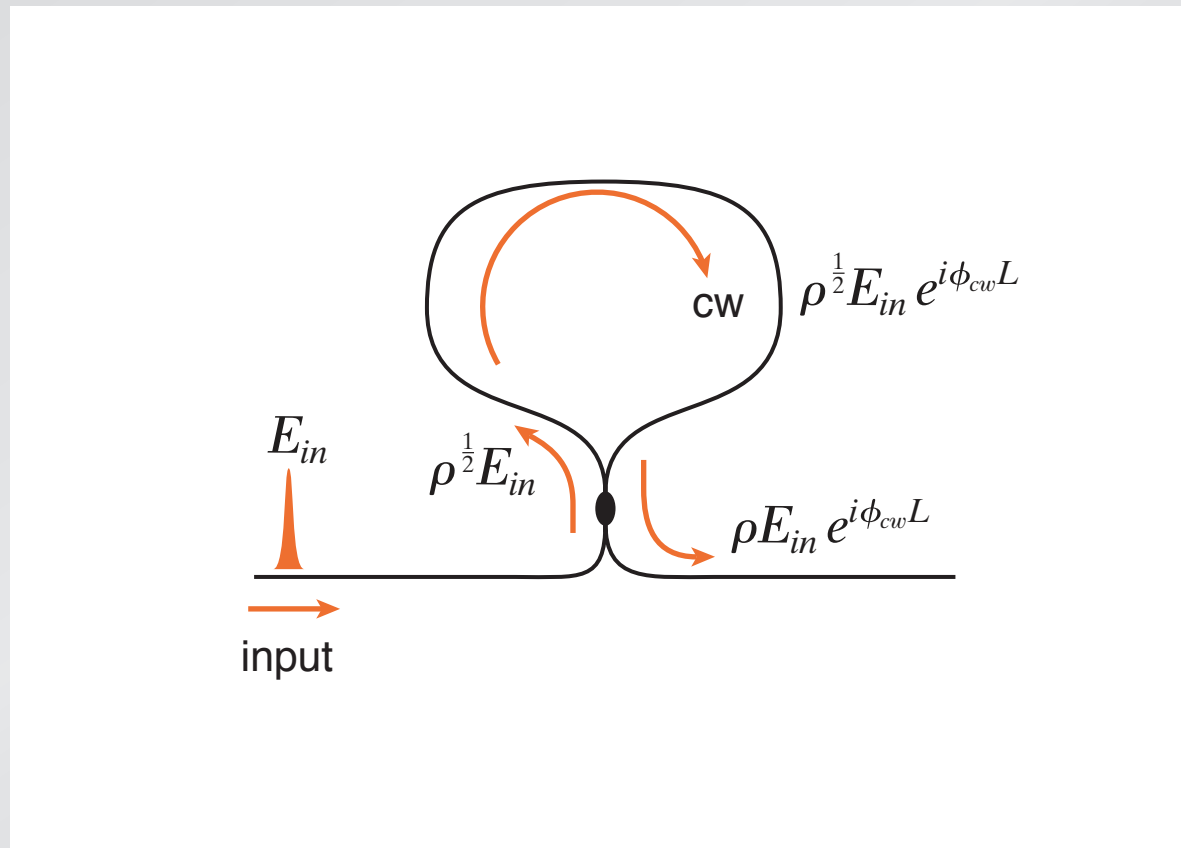
Optical logic gates

phase accumulation over path length of loop L



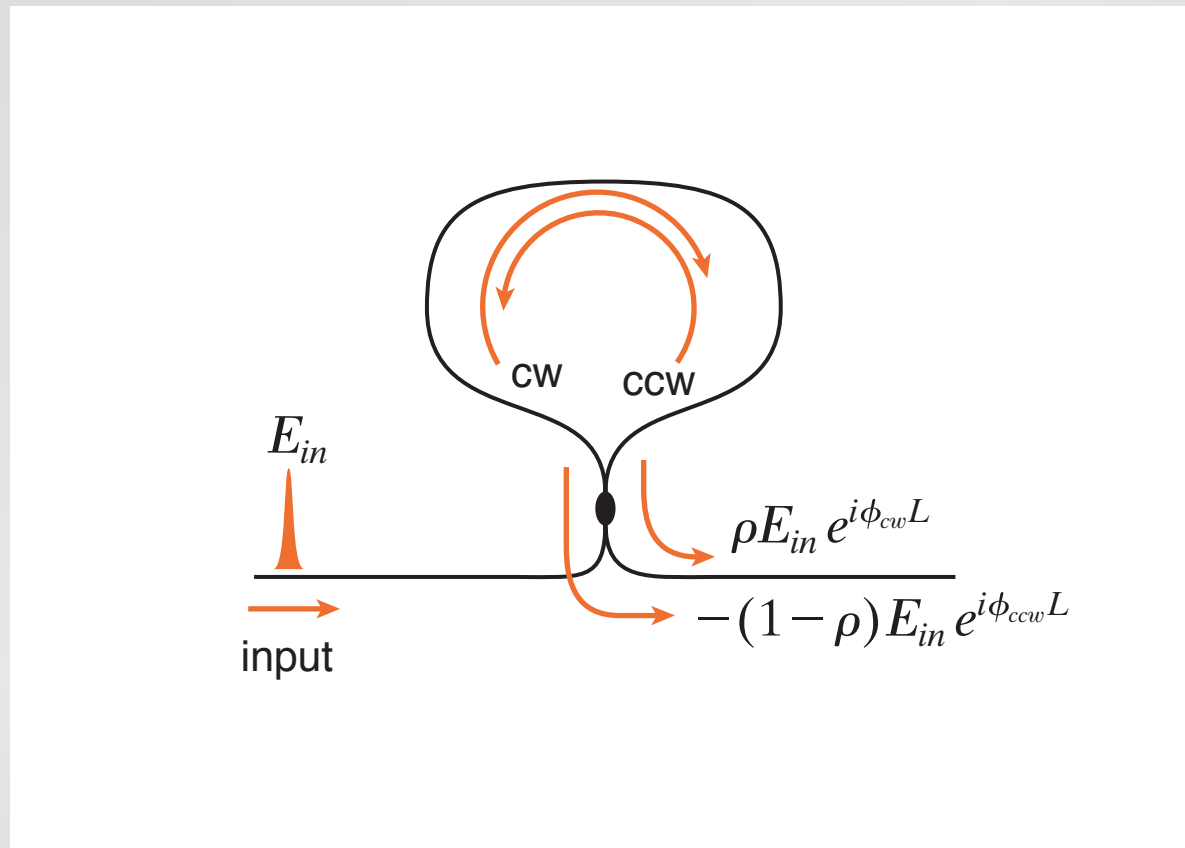
Optical logic gates

coupling parameter: ρ



Optical logic gates

output is sum of transmitted cw and ccw



Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_0 n$$

Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n$$

nonlinear index:

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

Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n$$

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:

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

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:

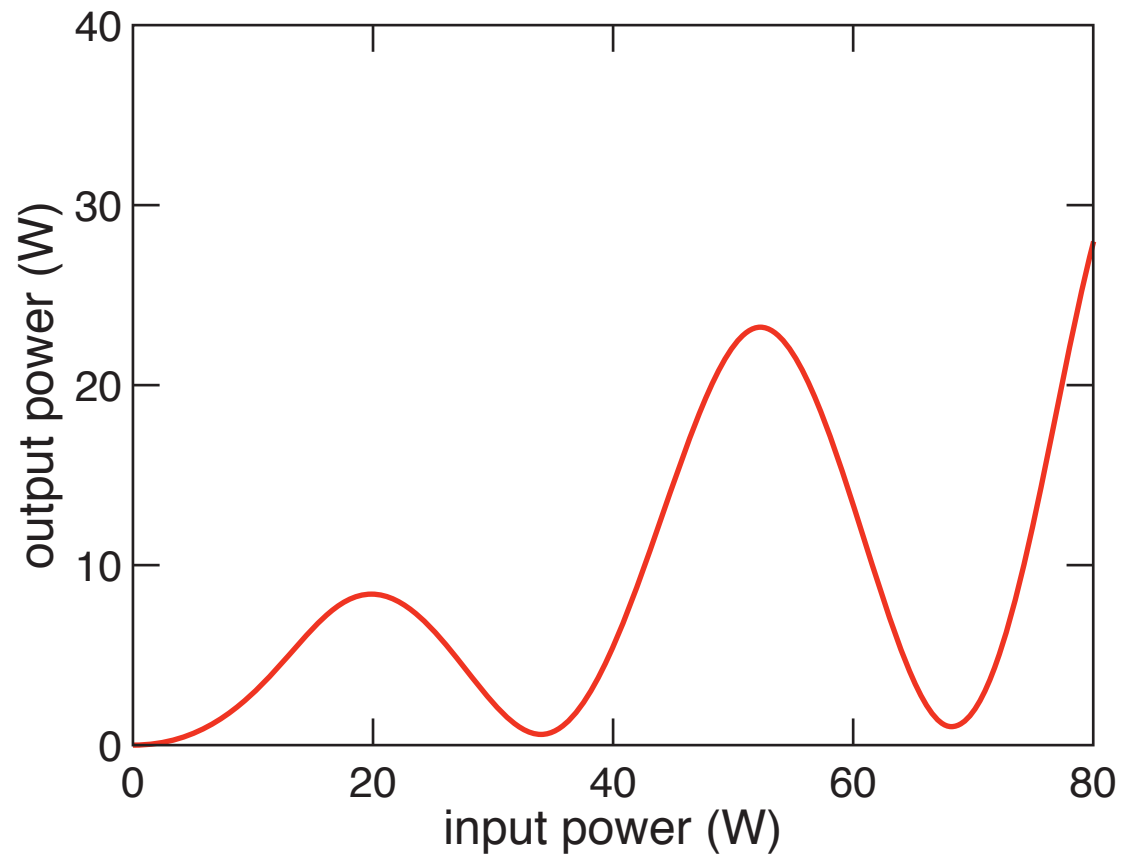
$$\rho = 0.5$$

no transmission:

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

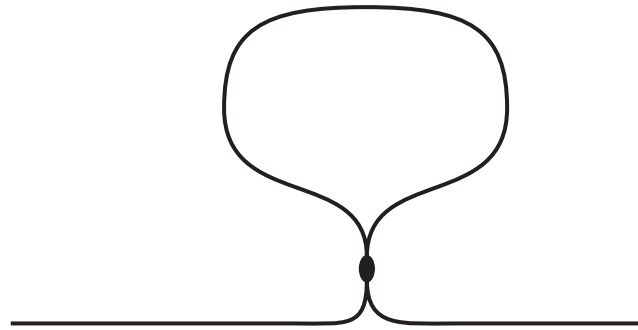
Optical logic gates

when $\rho \neq 0.5$:



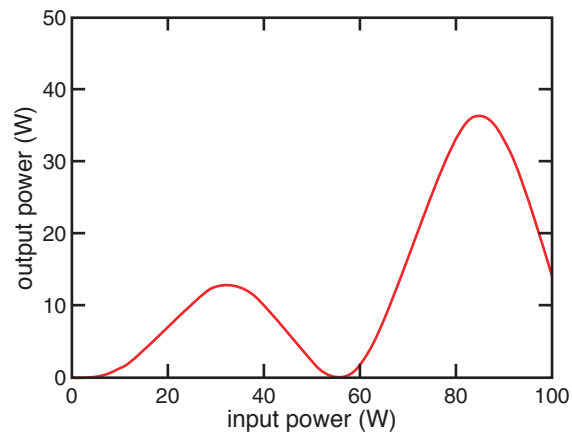
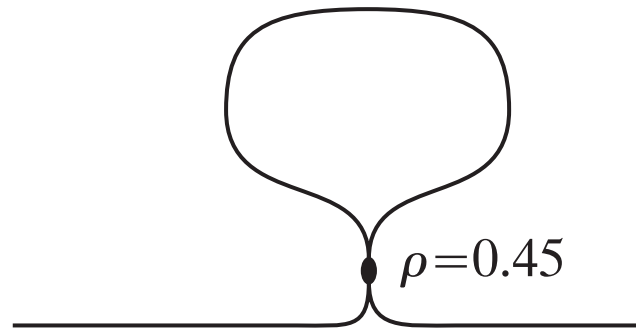
Optical logic gates

nonlinear nanogate



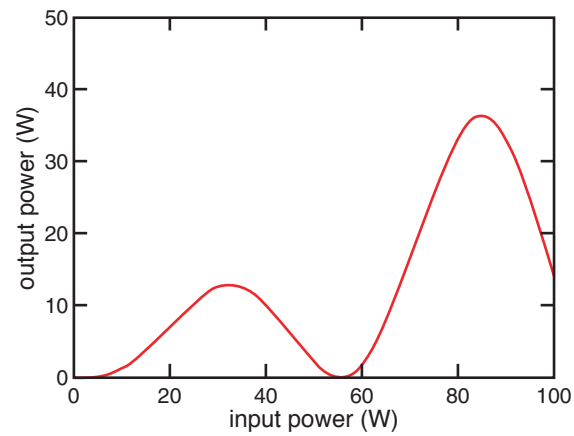
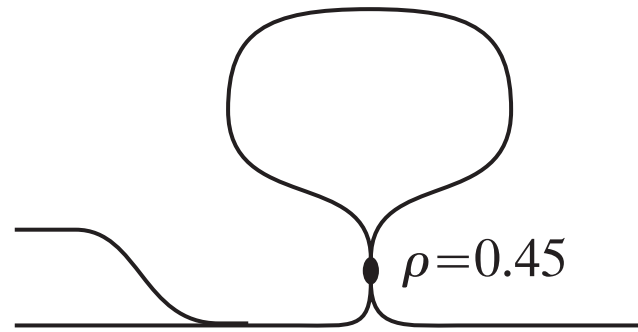
Optical logic gates

nonlinear nanogate



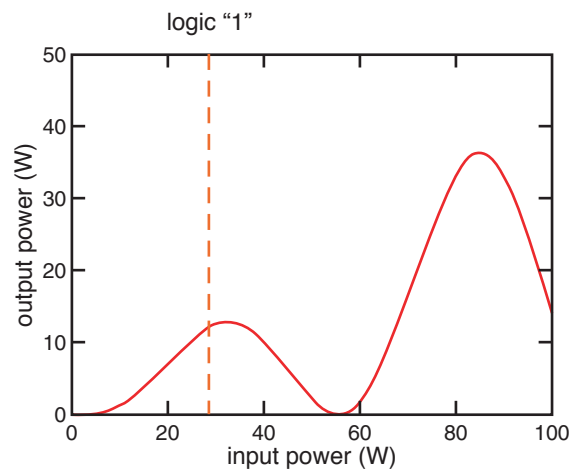
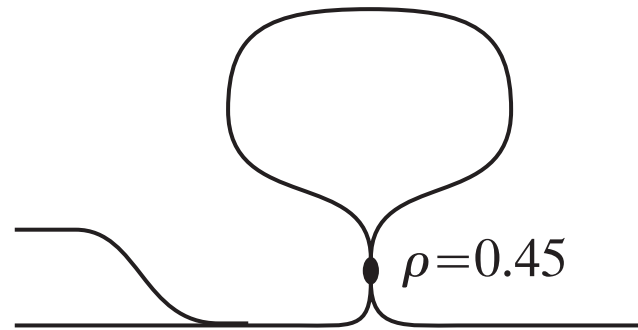
Optical logic gates

nonlinear nanogate



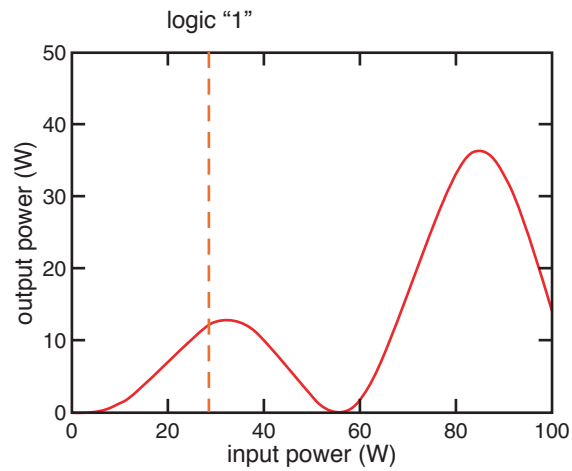
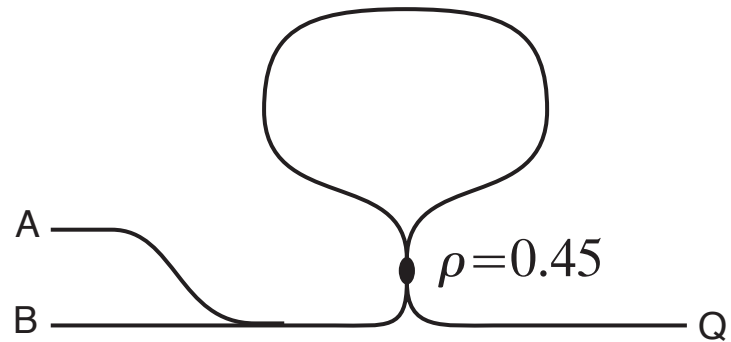
Optical logic gates

nonlinear nanogate



Optical logic gates

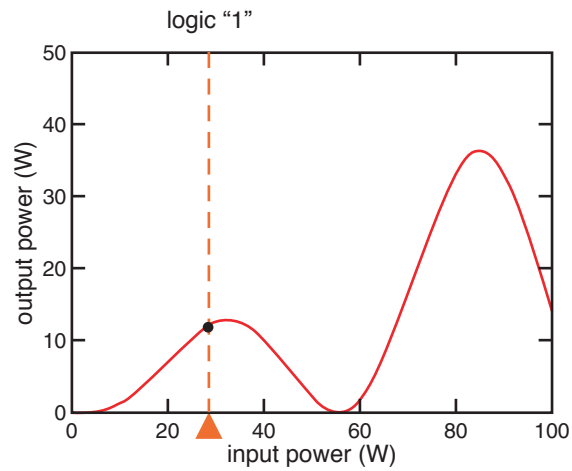
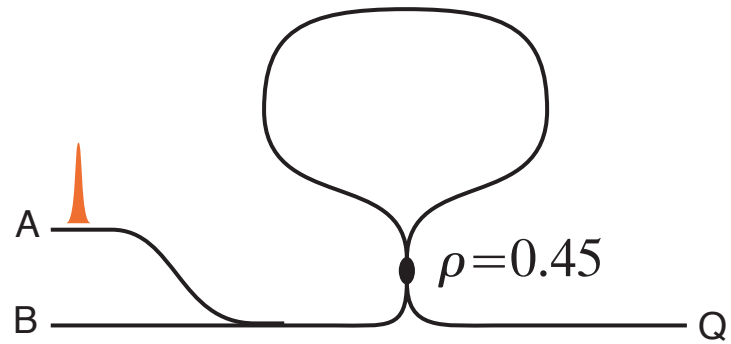
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

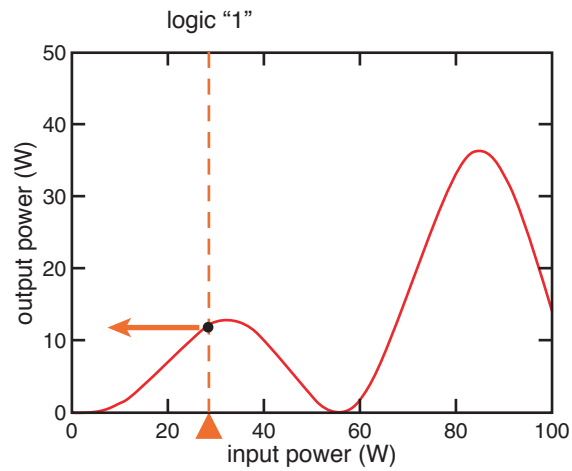
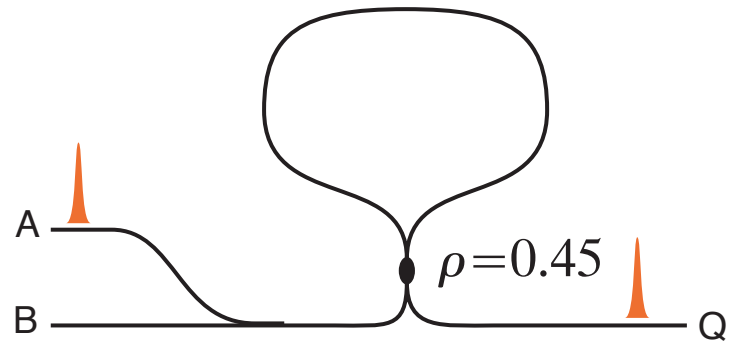
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

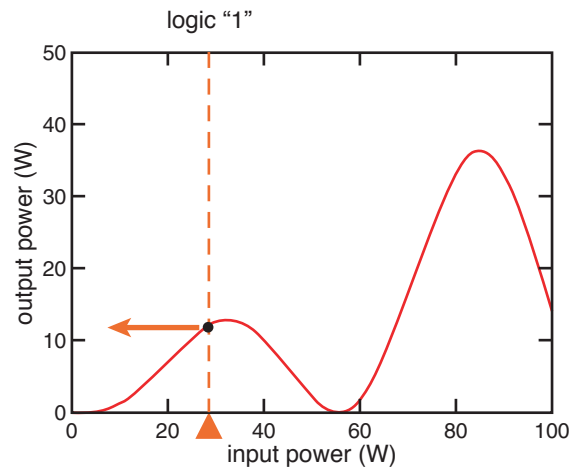
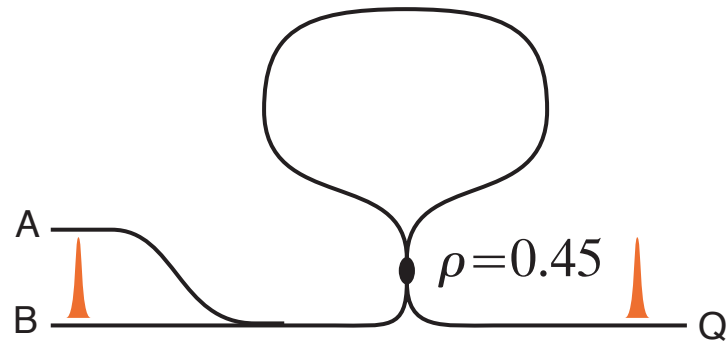
nonlinear nanogate



A	B	Q
0	0	0
1	0	1

Optical logic gates

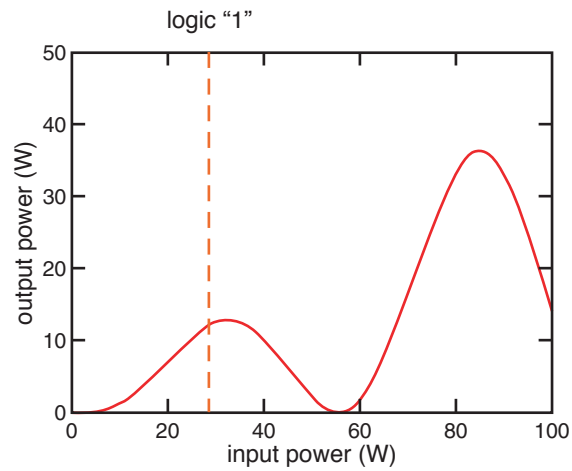
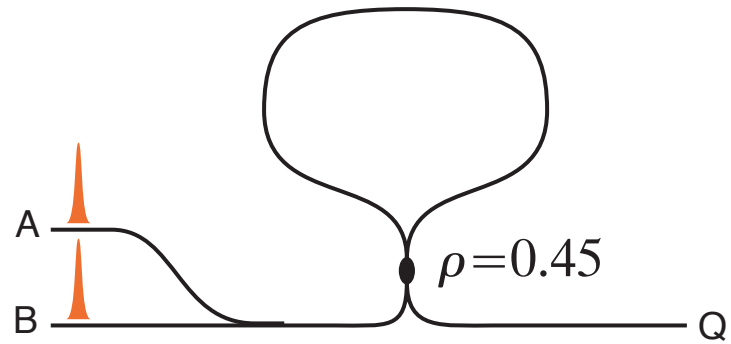
nonlinear nanogate



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

Optical logic gates

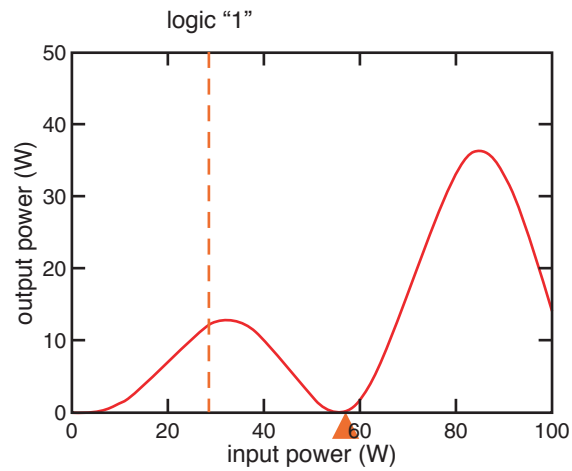
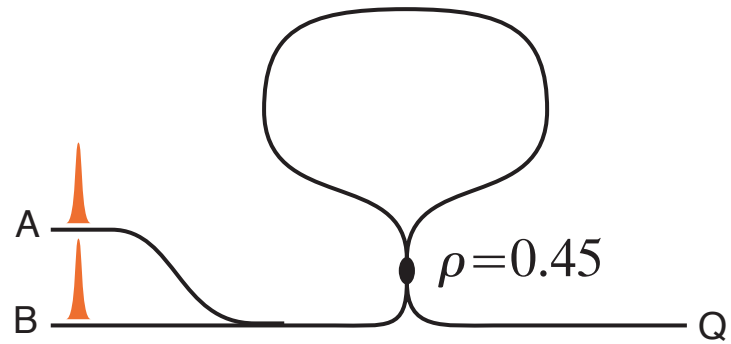
nonlinear nanogate



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

Optical logic gates

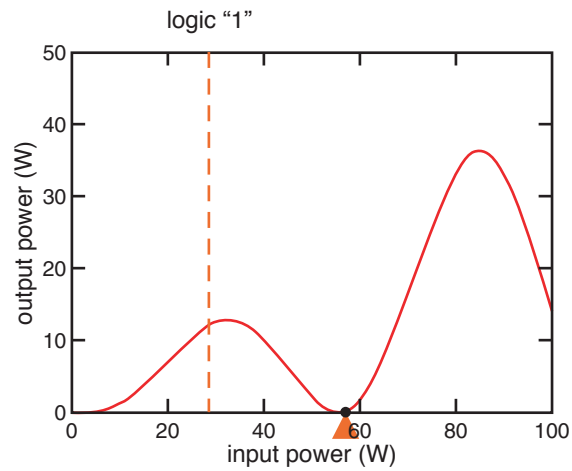
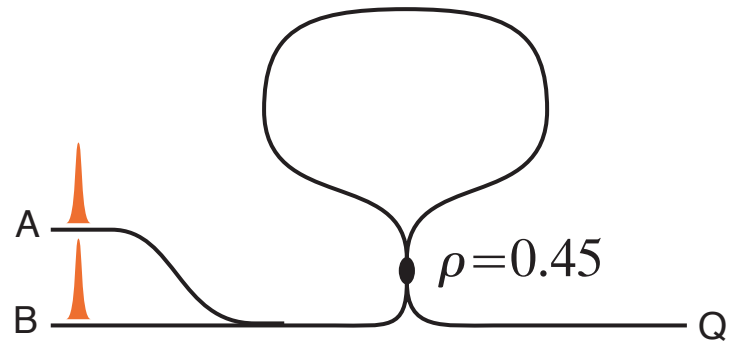
nonlinear nanogate



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

Optical logic gates

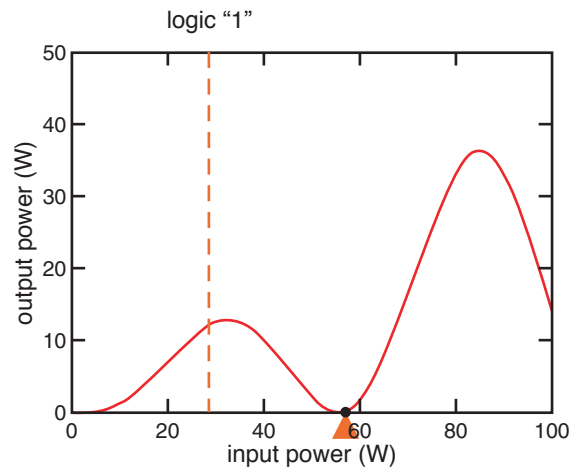
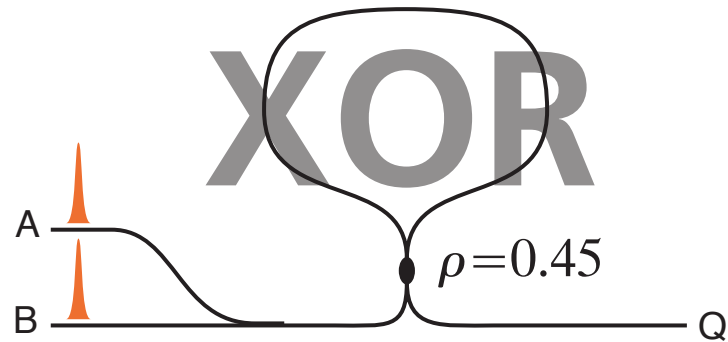
nonlinear nanogate



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

Optical logic gates

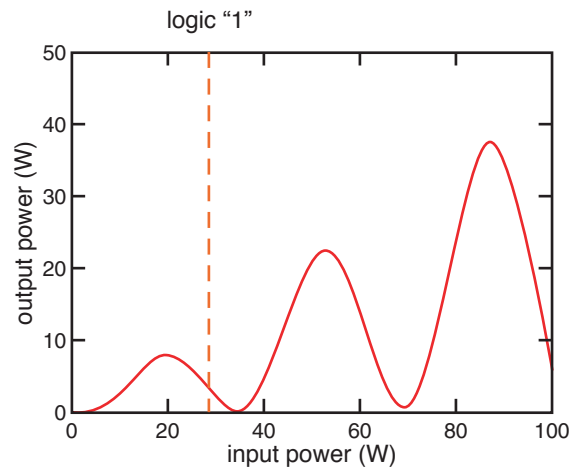
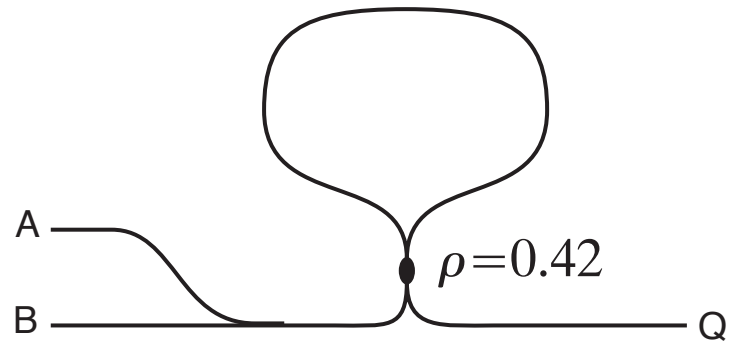
nonlinear nanogate



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

Optical logic gates

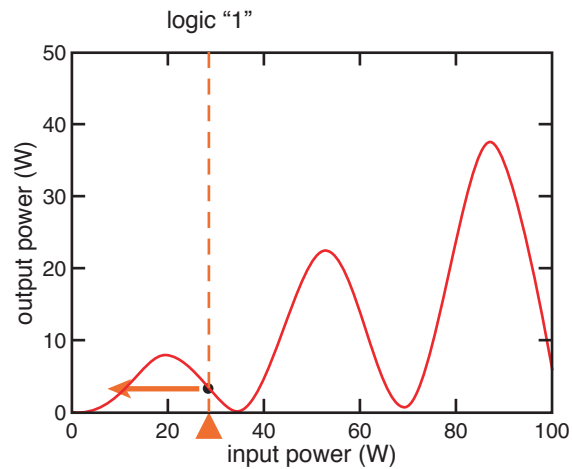
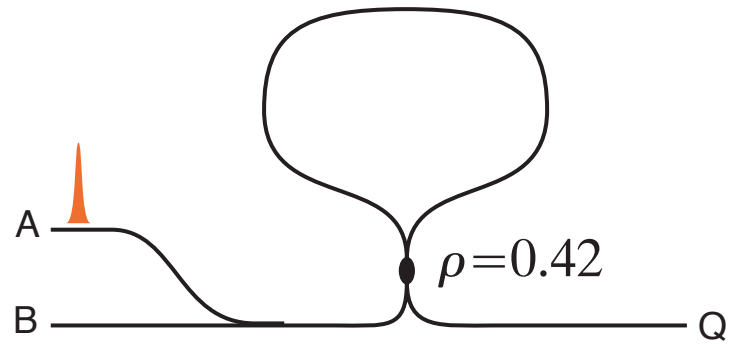
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

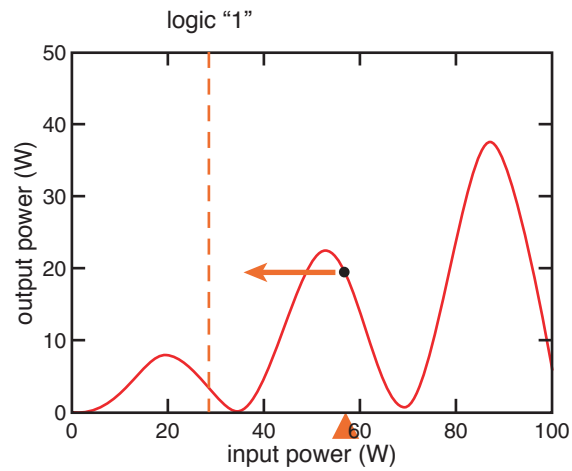
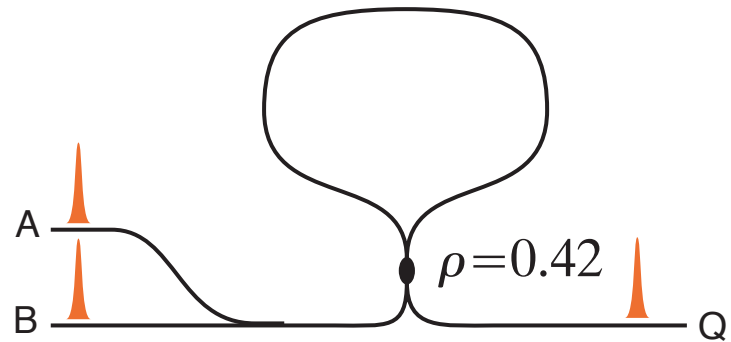
nonlinear nanogate



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

Optical logic gates

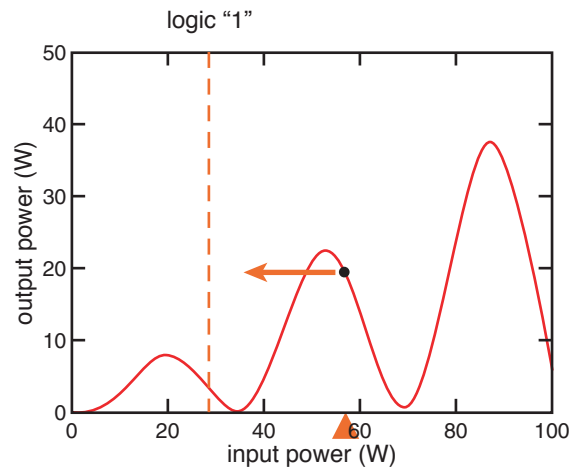
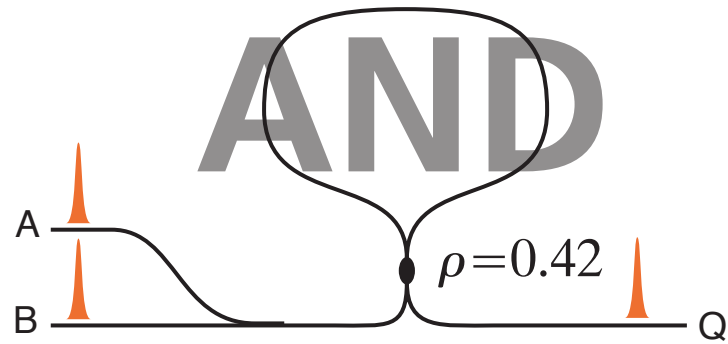
nonlinear nanogate



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

Optical logic gates

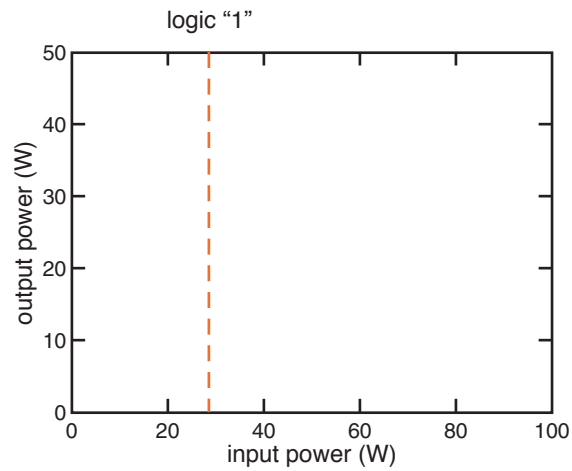
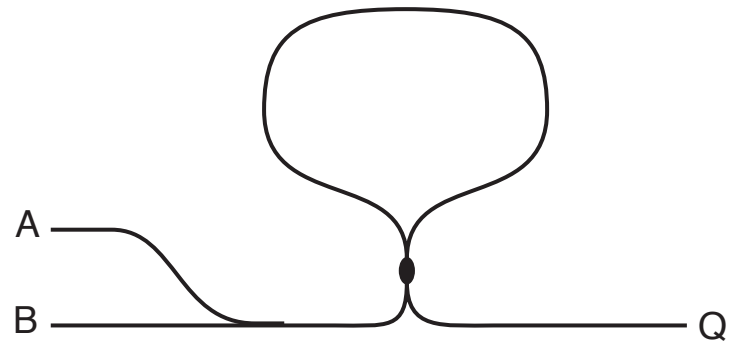
nonlinear nanogate



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

Optical logic gates

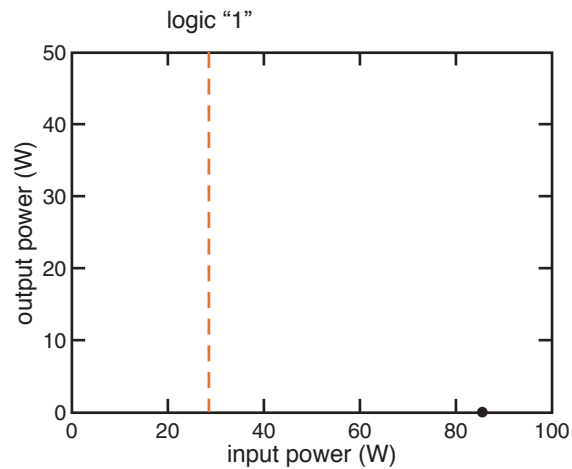
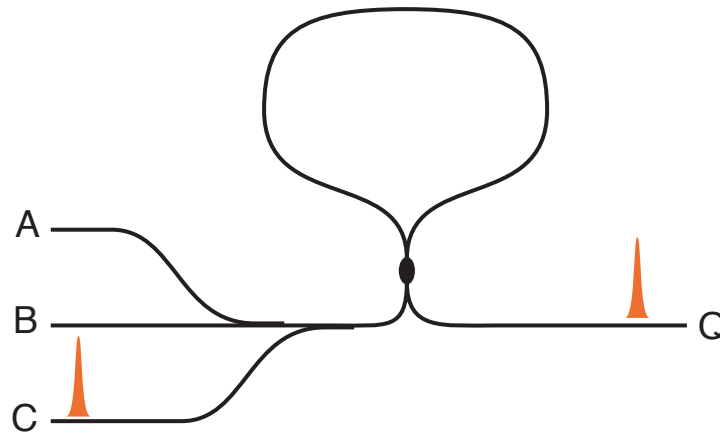
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

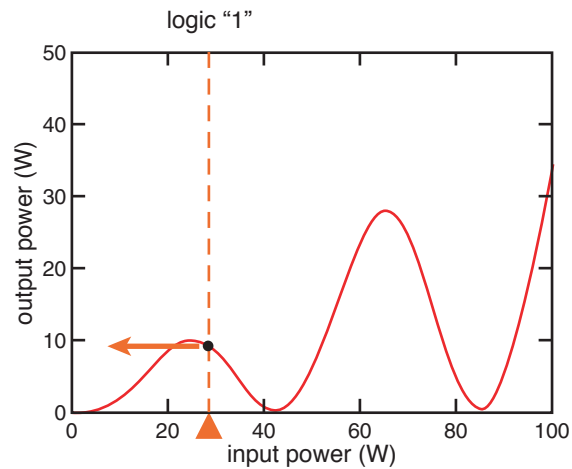
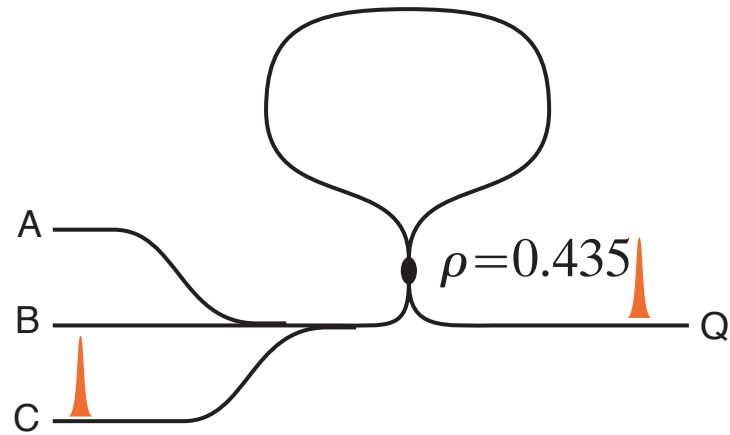
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

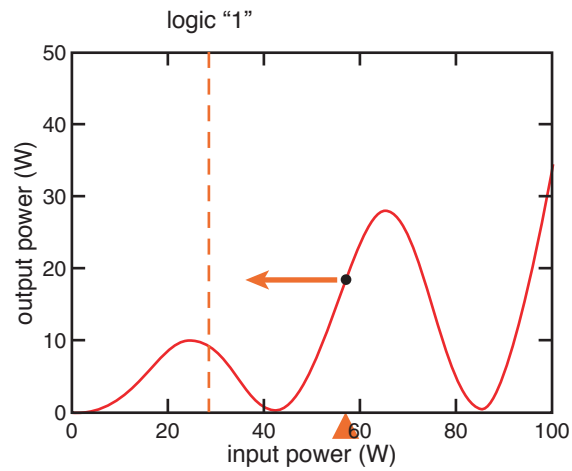
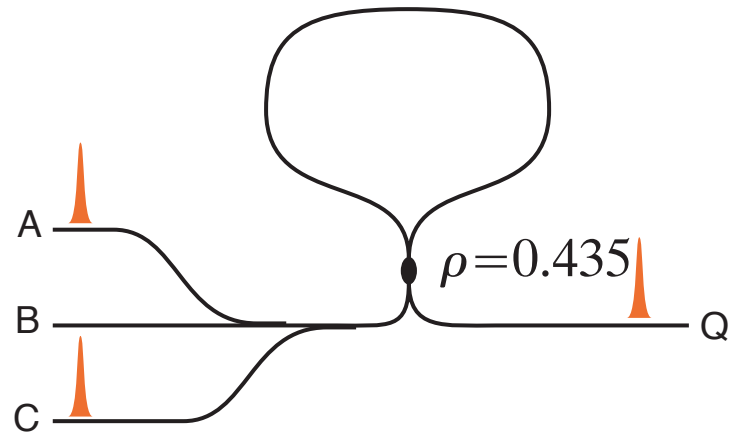
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

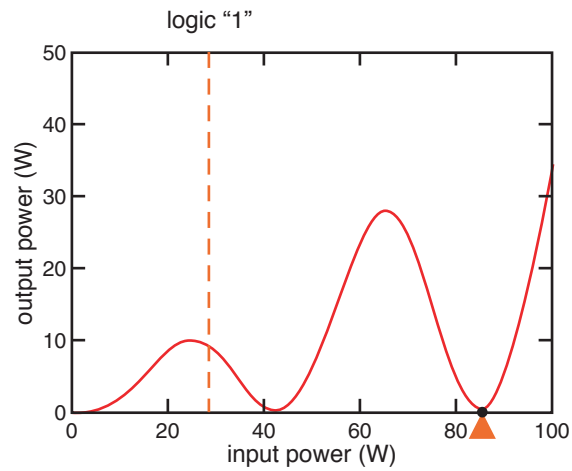
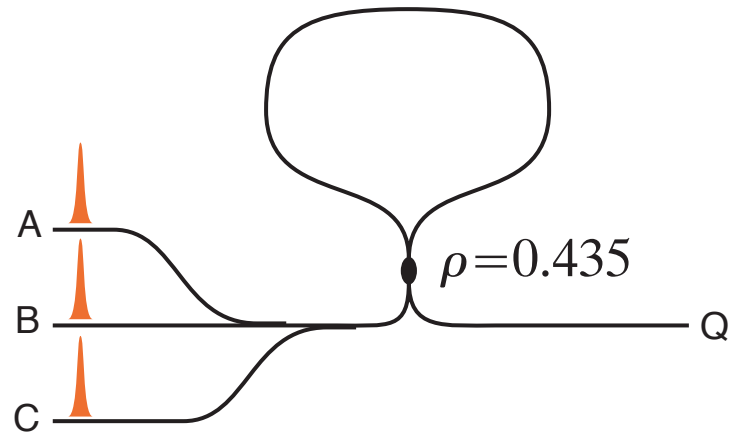
universal NAND gate



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

Optical logic gates

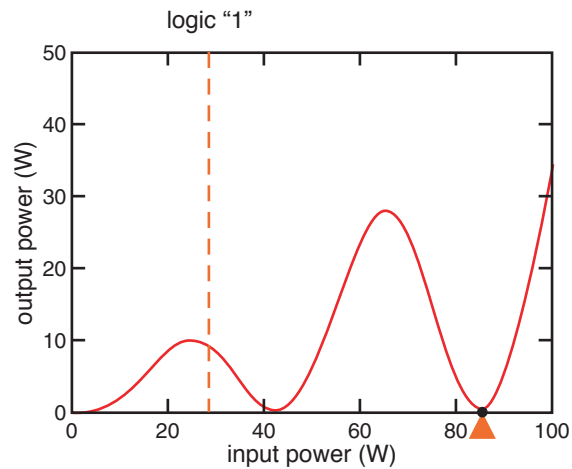
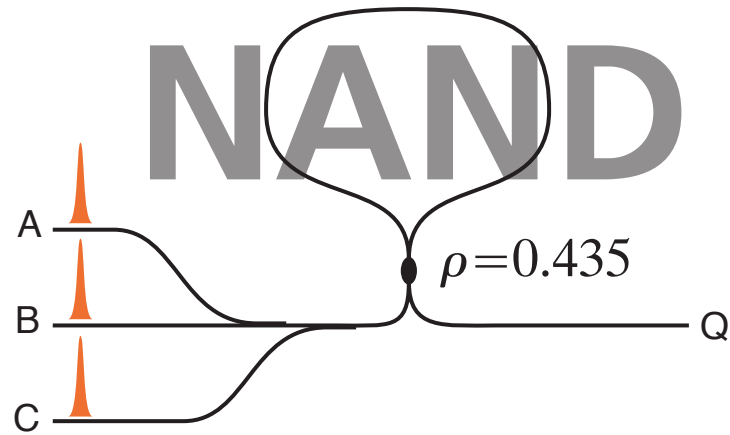
universal NAND gate



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

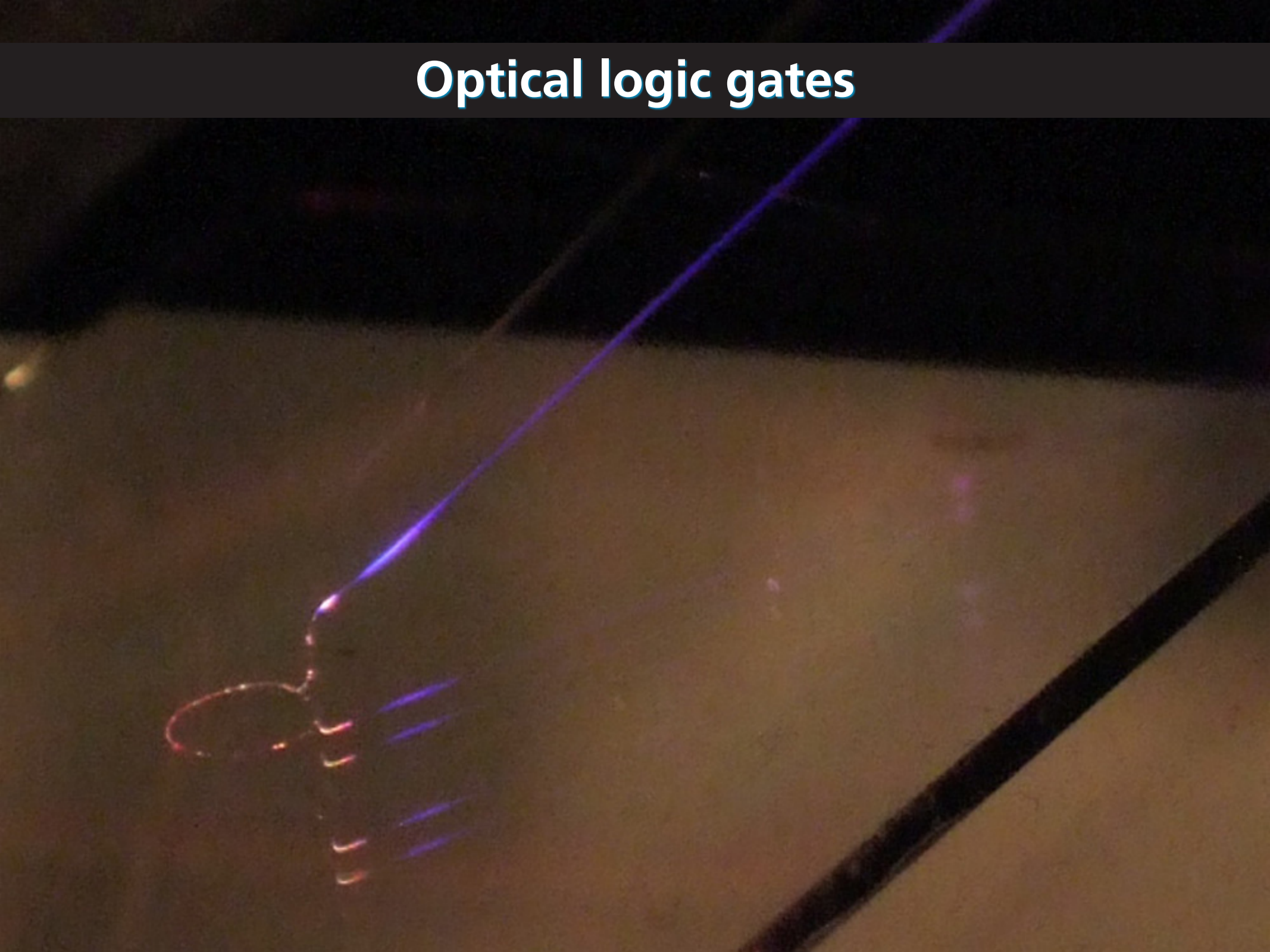
Optical logic gates

universal NAND gate



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

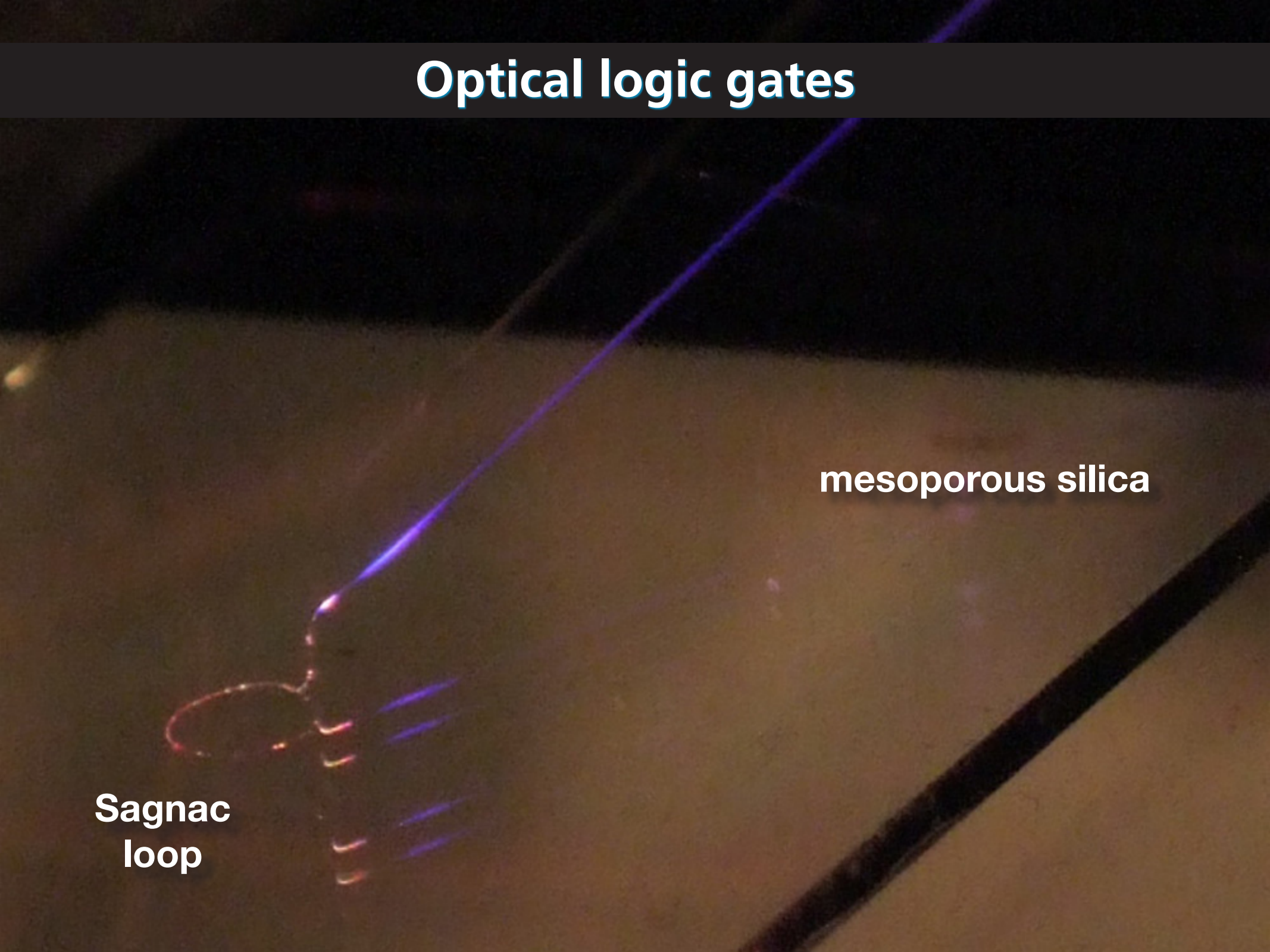
Optical logic gates



Optical logic gates

mesoporous silica

Sagnac
loop



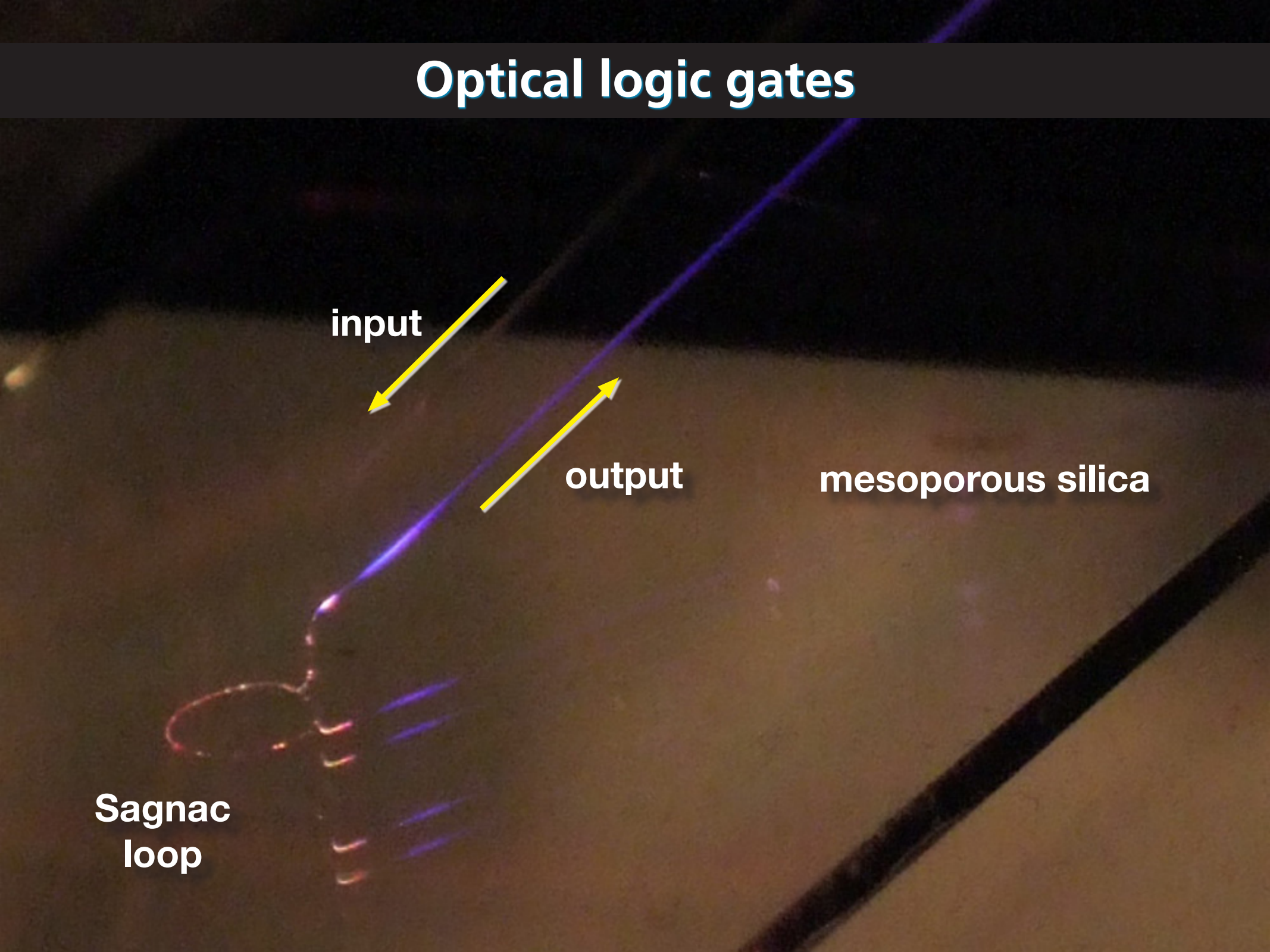
Optical logic gates

input

output

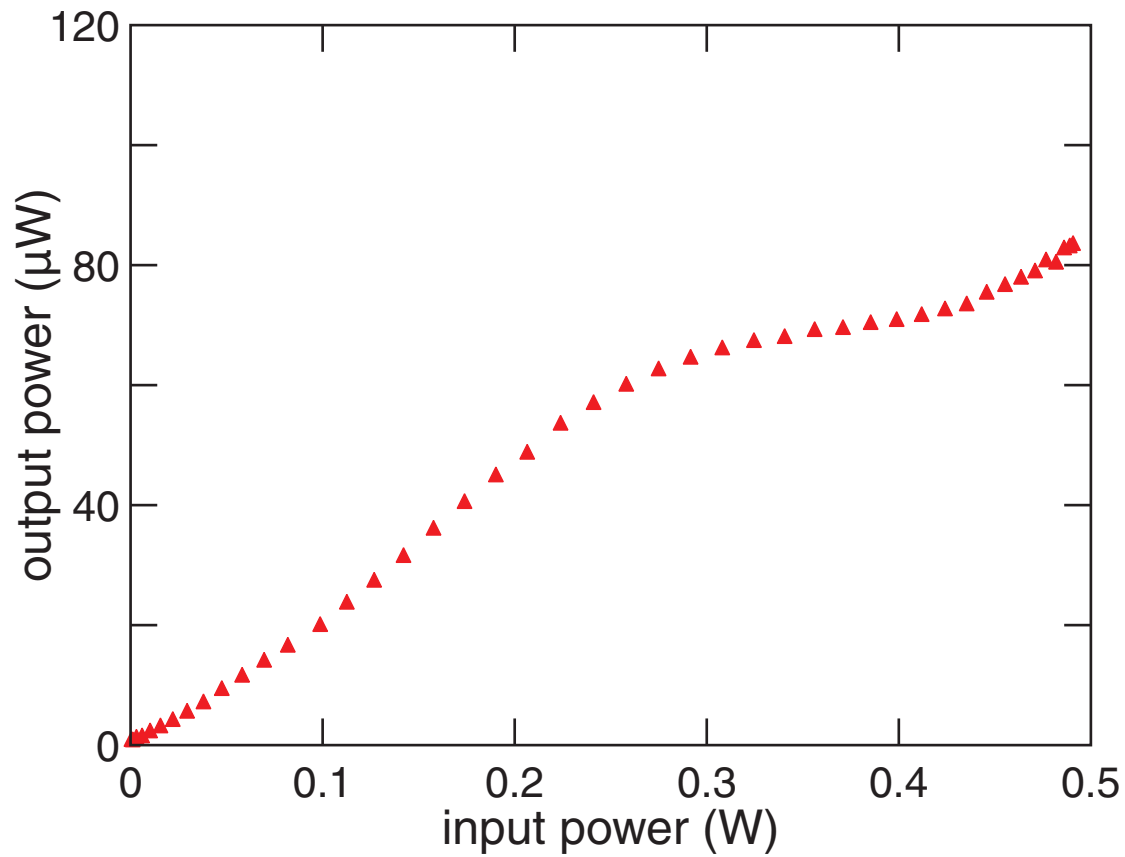
mesoporous silica

Sagnac
loop



Optical logic gates

very preliminary data

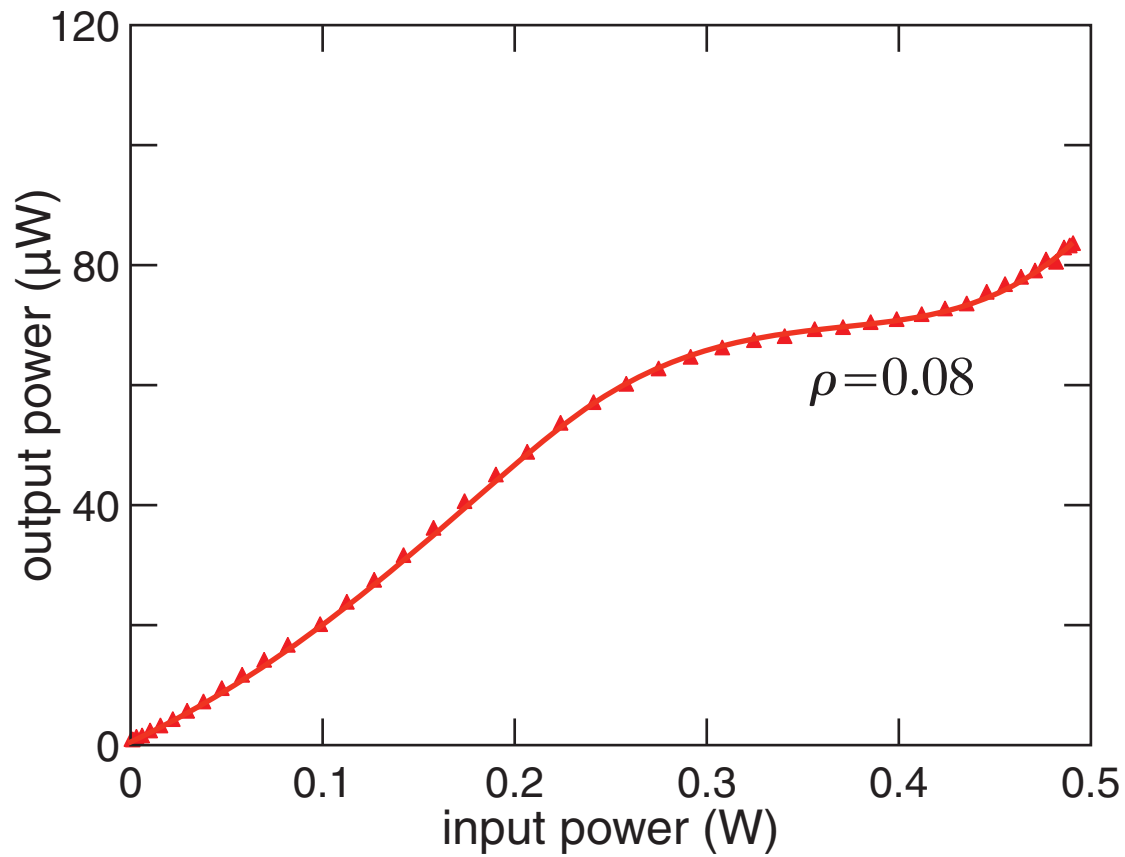


Optical logic gates

light-by-light modulation!

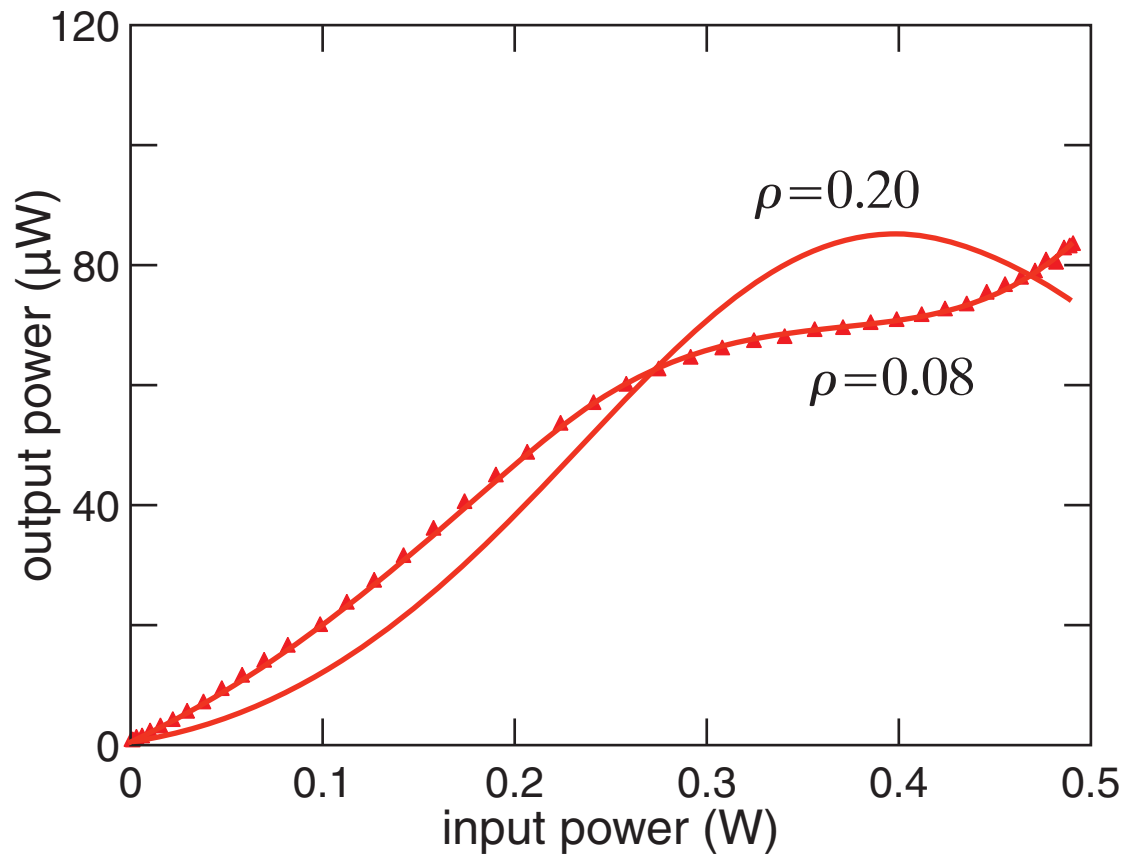
Optical logic gates

very preliminary data

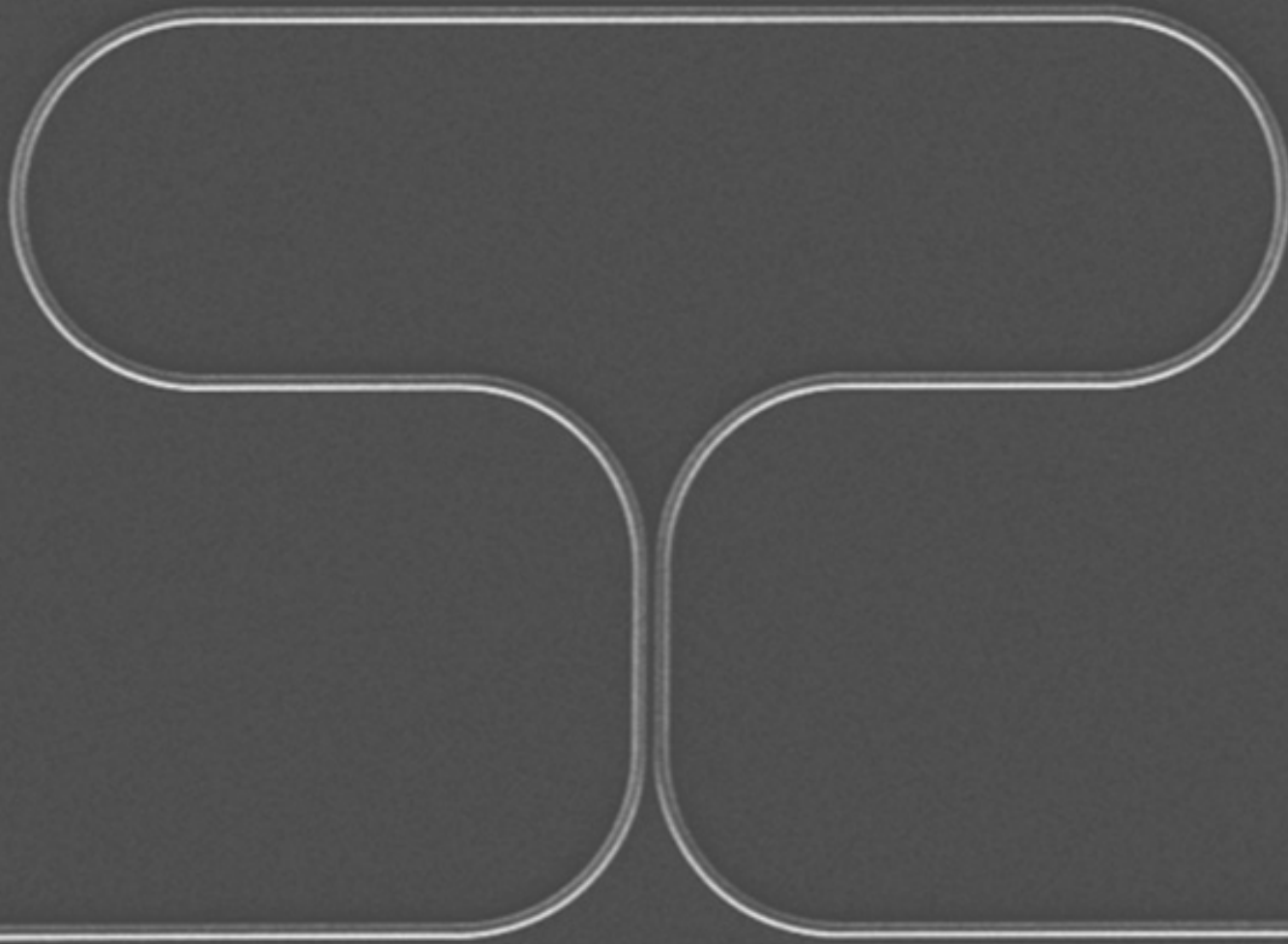


Optical logic gates

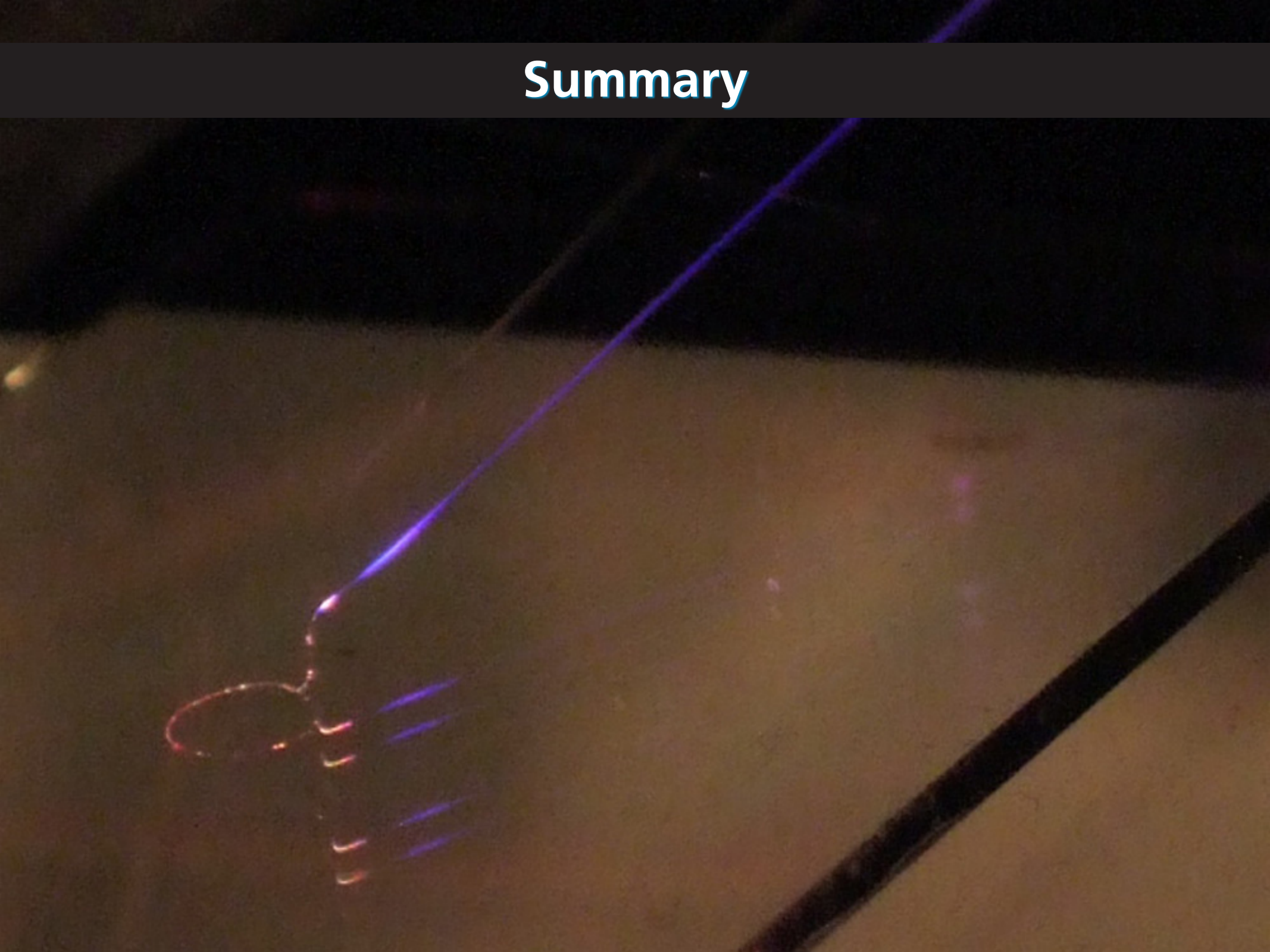
very preliminary data



Optical logic gates



Summary



Summary

- several nanodevices demonstrated
- large γ permits miniature Sagnac loops
- switching energy < 10 pJ



Funding:

Harvard Center for Imaging and Mesoscopic Structures

National Science Foundation

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