

Nonlinear optics at the nanoscale



PQE Meeting
Snowbird, UT, 9 January 2008

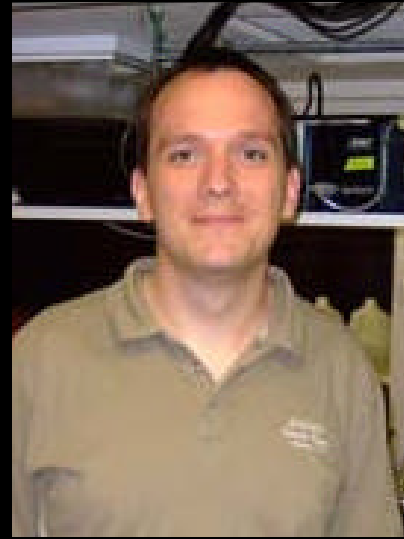




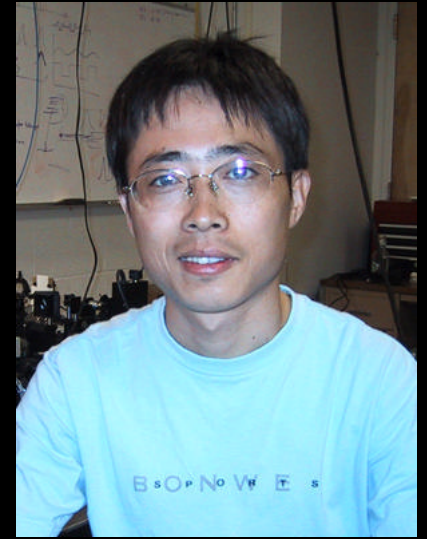
Geoff Svacha



Rafael Gattass



Tobias Voss



Limin Tong

and also....

Jonathan Aschom

Mengyan Shen

Iva Maxwell

James Carey

Brian Tull

Dr. Yuan Lu

Dr. Richard Schalek

Prof. Federico Capasso

Prof. Cynthia Friend

Xuwen Chen (Zhejiang)

Zhanghua Han (Zhejiang)

Dr. Sailing He (Zhejiang)

Liu Liu (Zhejiang)

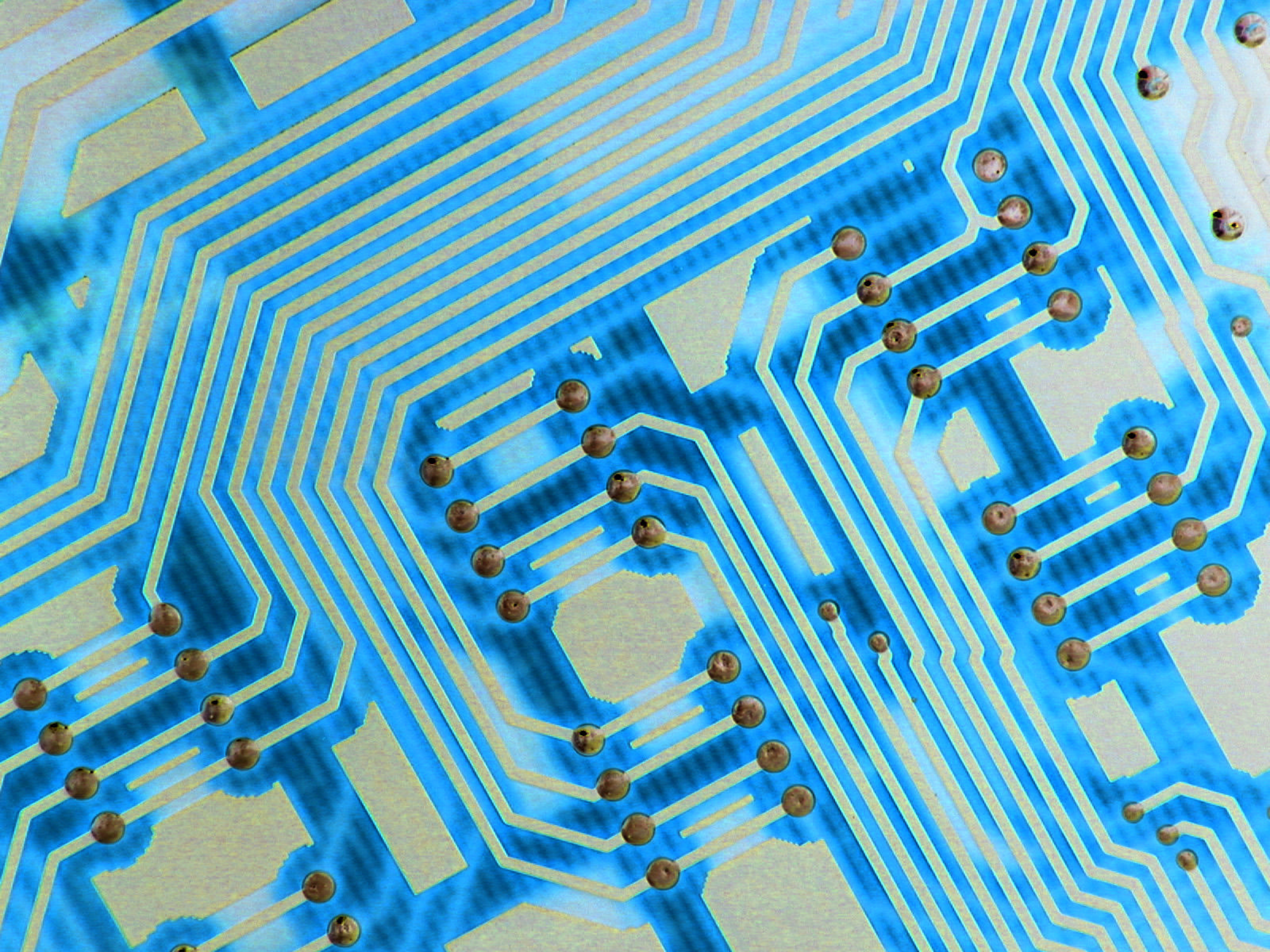
Dr. Jingyi Lou (Zhejiang)

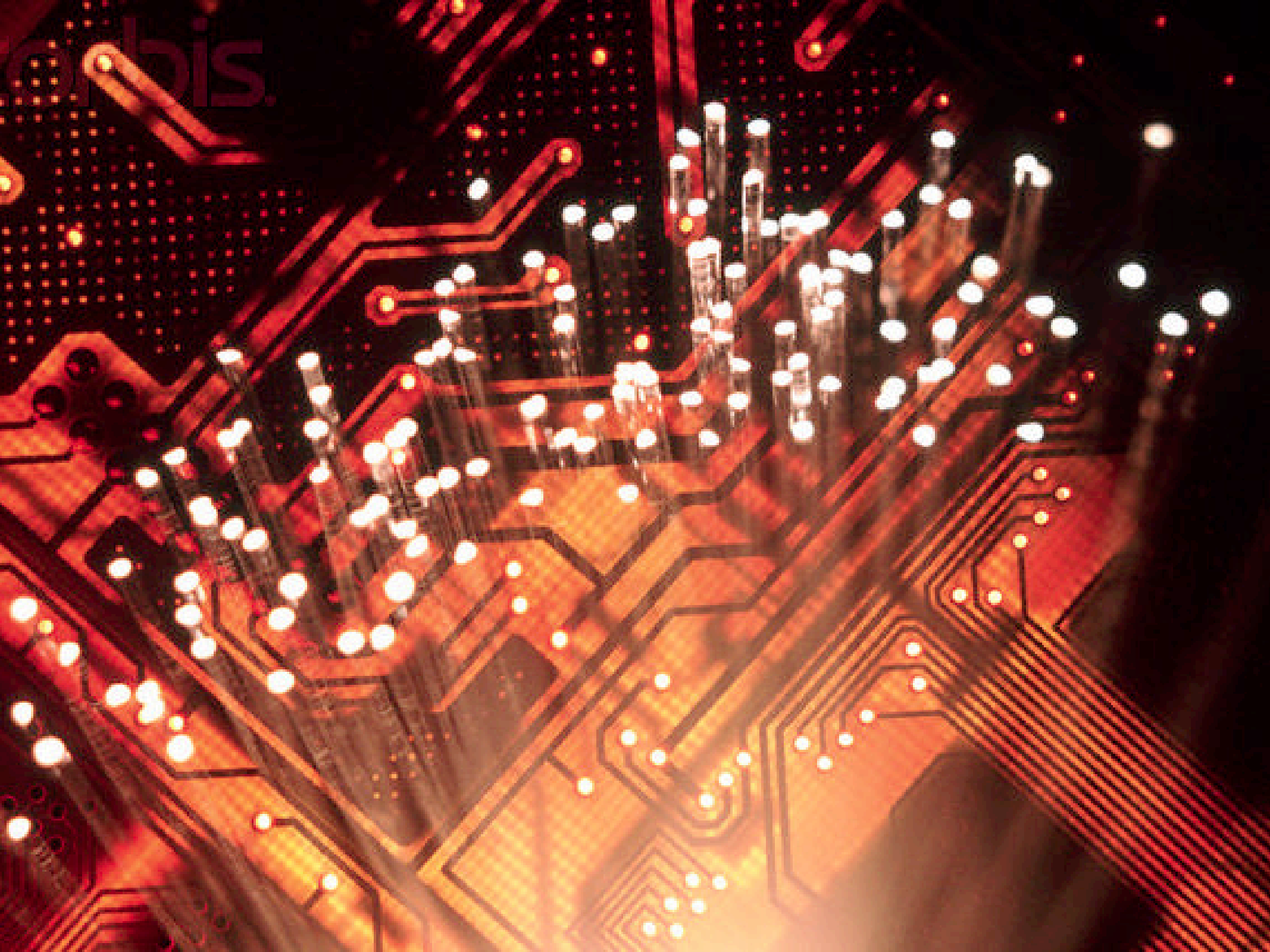
Dr. Ray Mariella (LLNL)

Prof. Frank Marlow (MPI Mülheim)

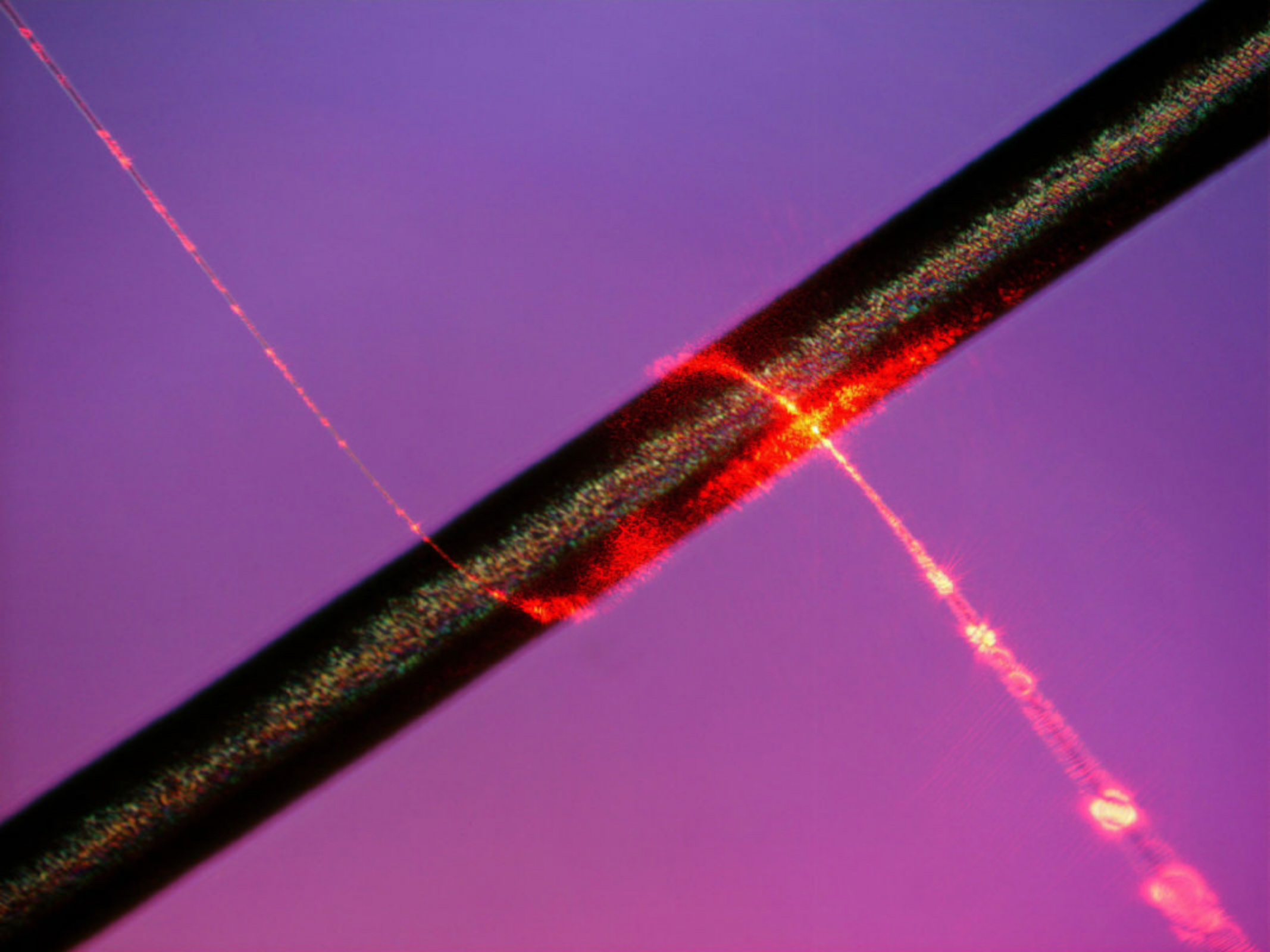
Prof. Sven Müller (Göttingen)

Prof. Carsten Ronning (Göttingen)





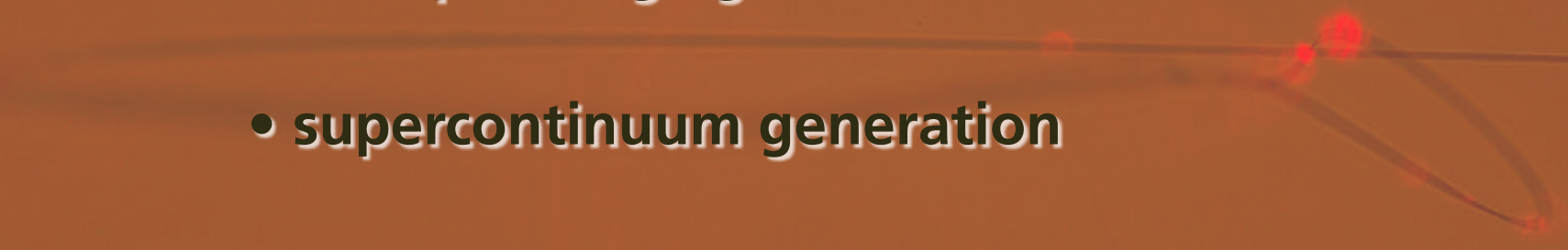
Orbis



Outline



Outline

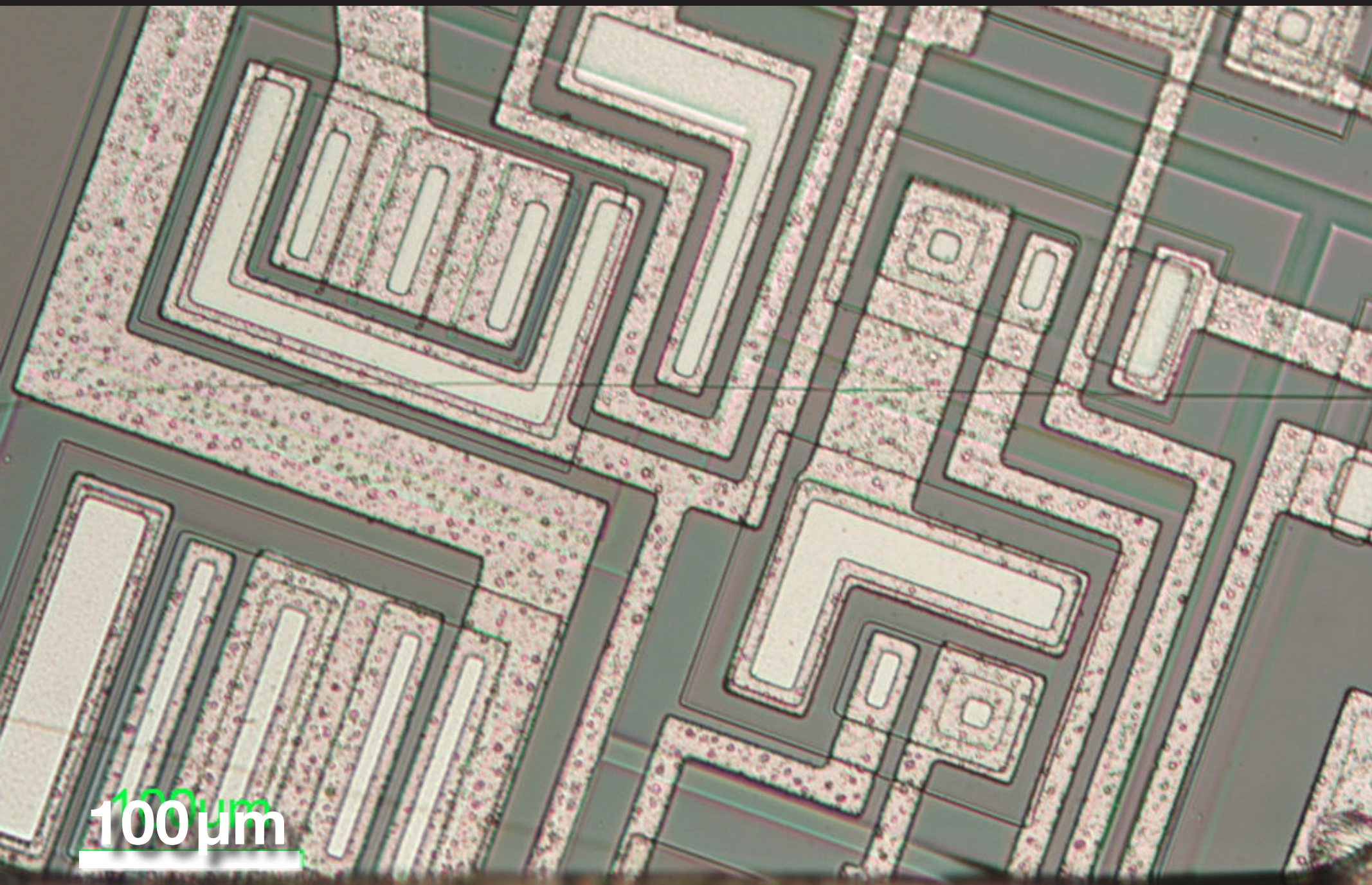
- **manipulating light at the nanoscale**
 - **supercontinuum generation**
 - **optical logic gates**
- 
- A decorative graphic consisting of several red, glowing, curved lines that resemble light trails or fiber optic paths, extending from the right side of the slide towards the center.

Manipulating light at the nanoscale



Nature, 426, 816 (2003)

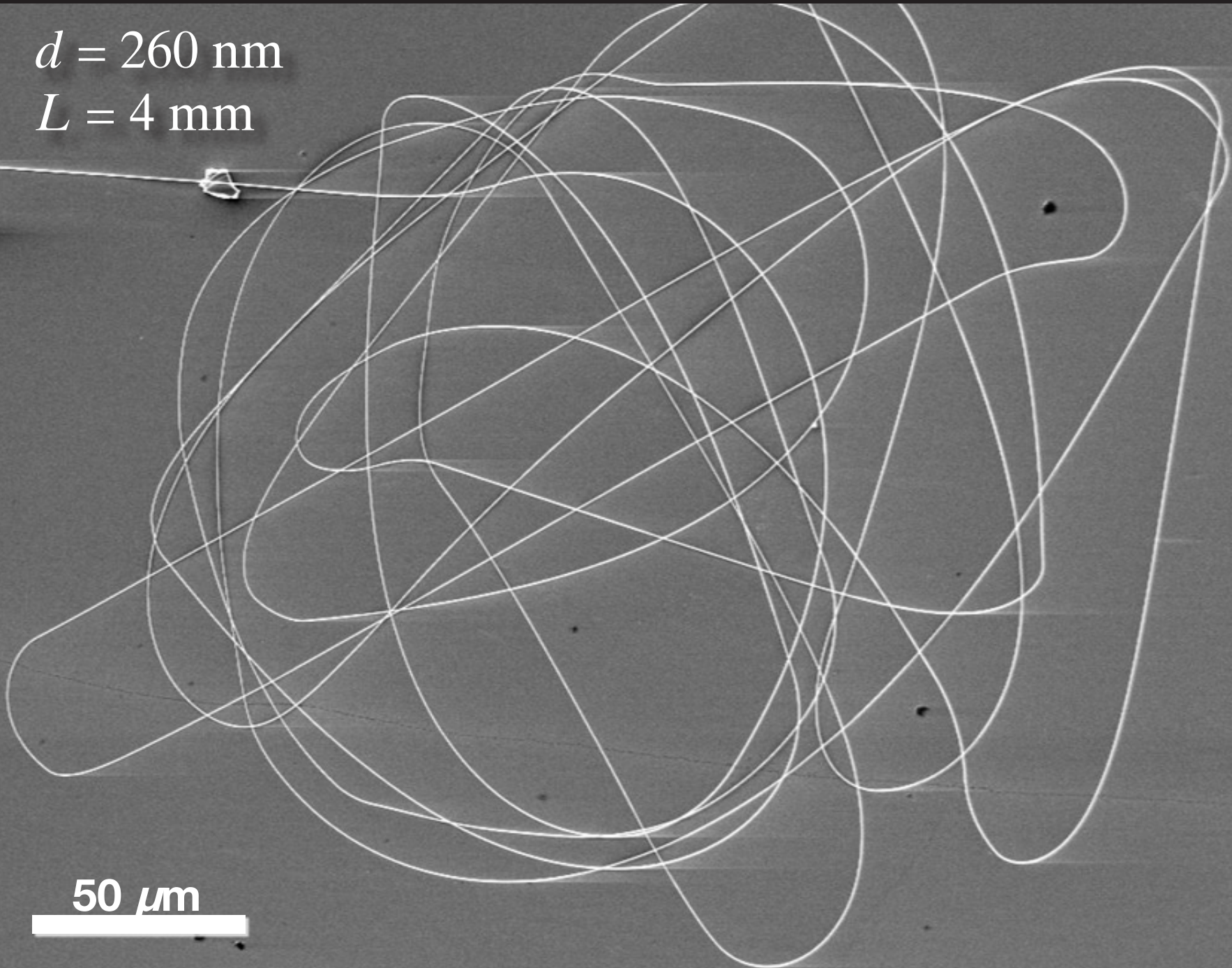
Manipulating light at the nanoscale



Manipulating light at the nanoscale

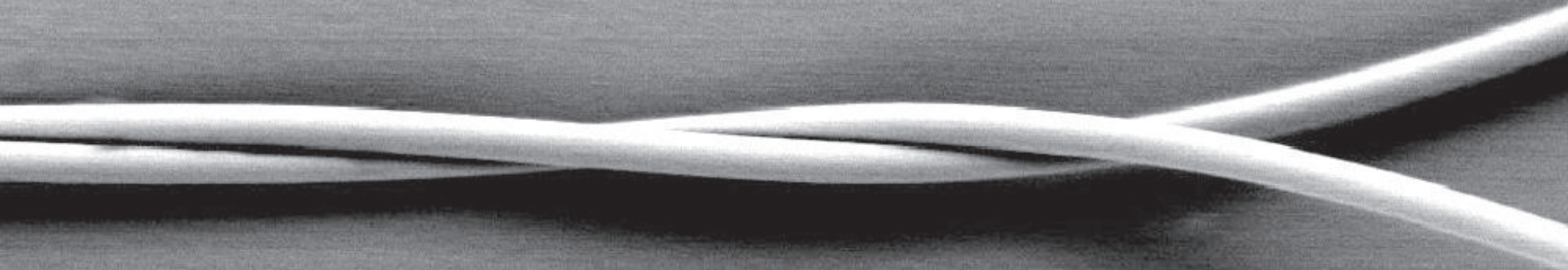
$d = 260 \text{ nm}$

$L = 4 \text{ mm}$

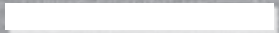


50 μm

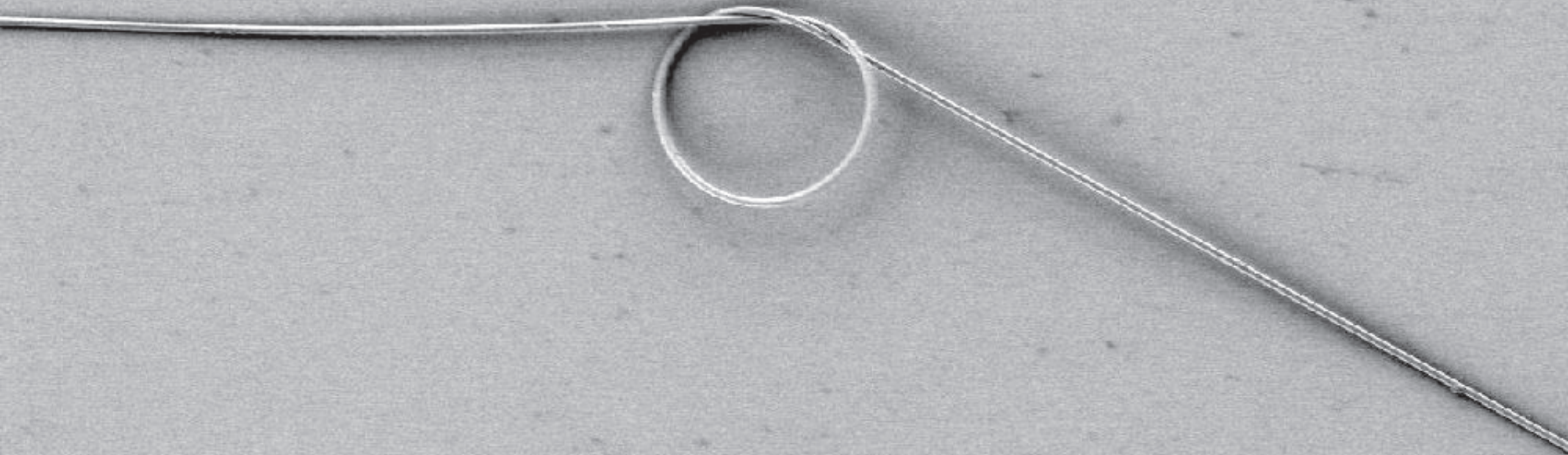
Manipulating light at the nanoscale



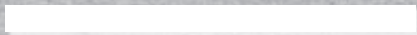
2 μm



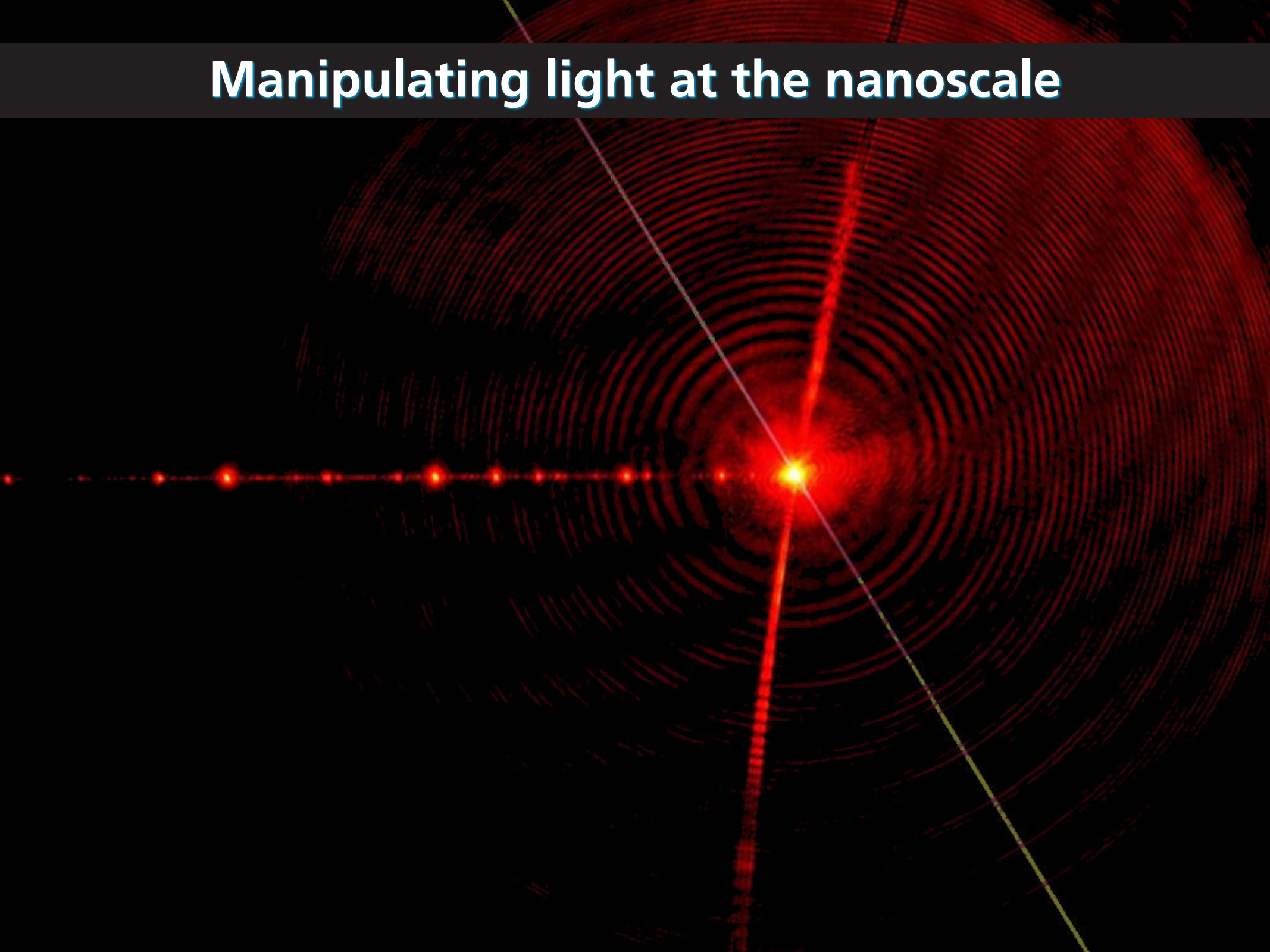
Manipulating light at the nanoscale



20 μm

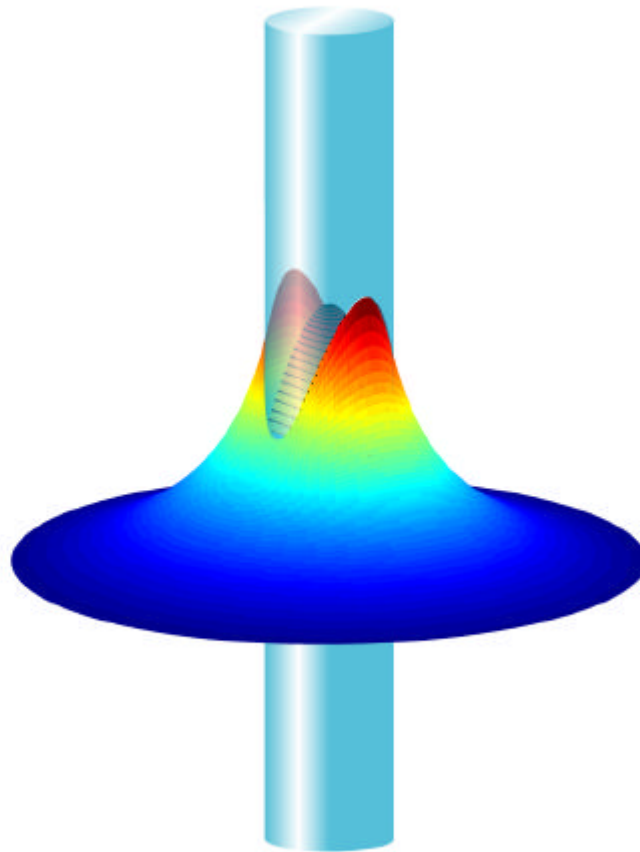


Manipulating light at the nanoscale

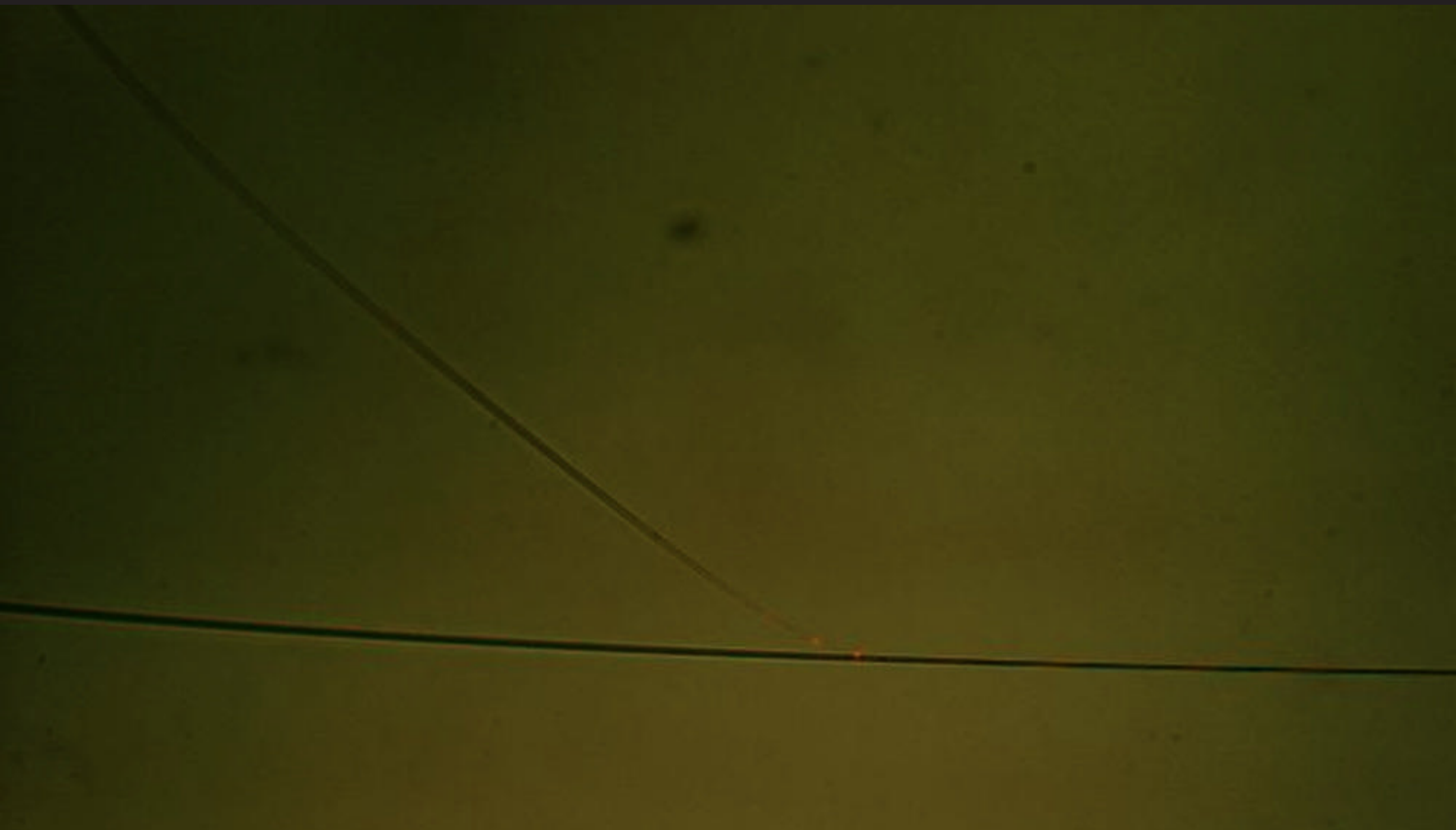


Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



Manipulating light at the nanoscale



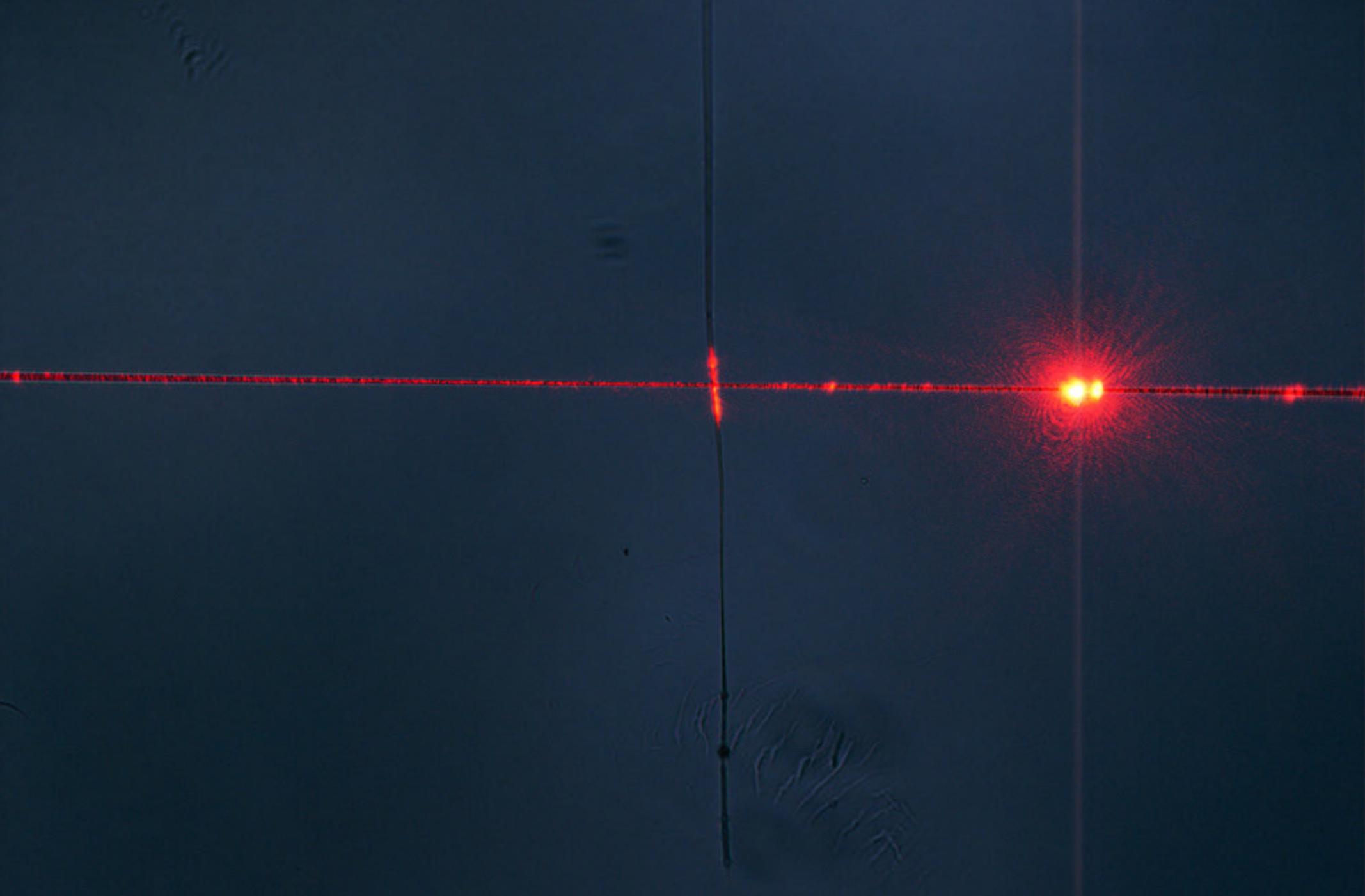
50 μm

Manipulating light at the nanoscale

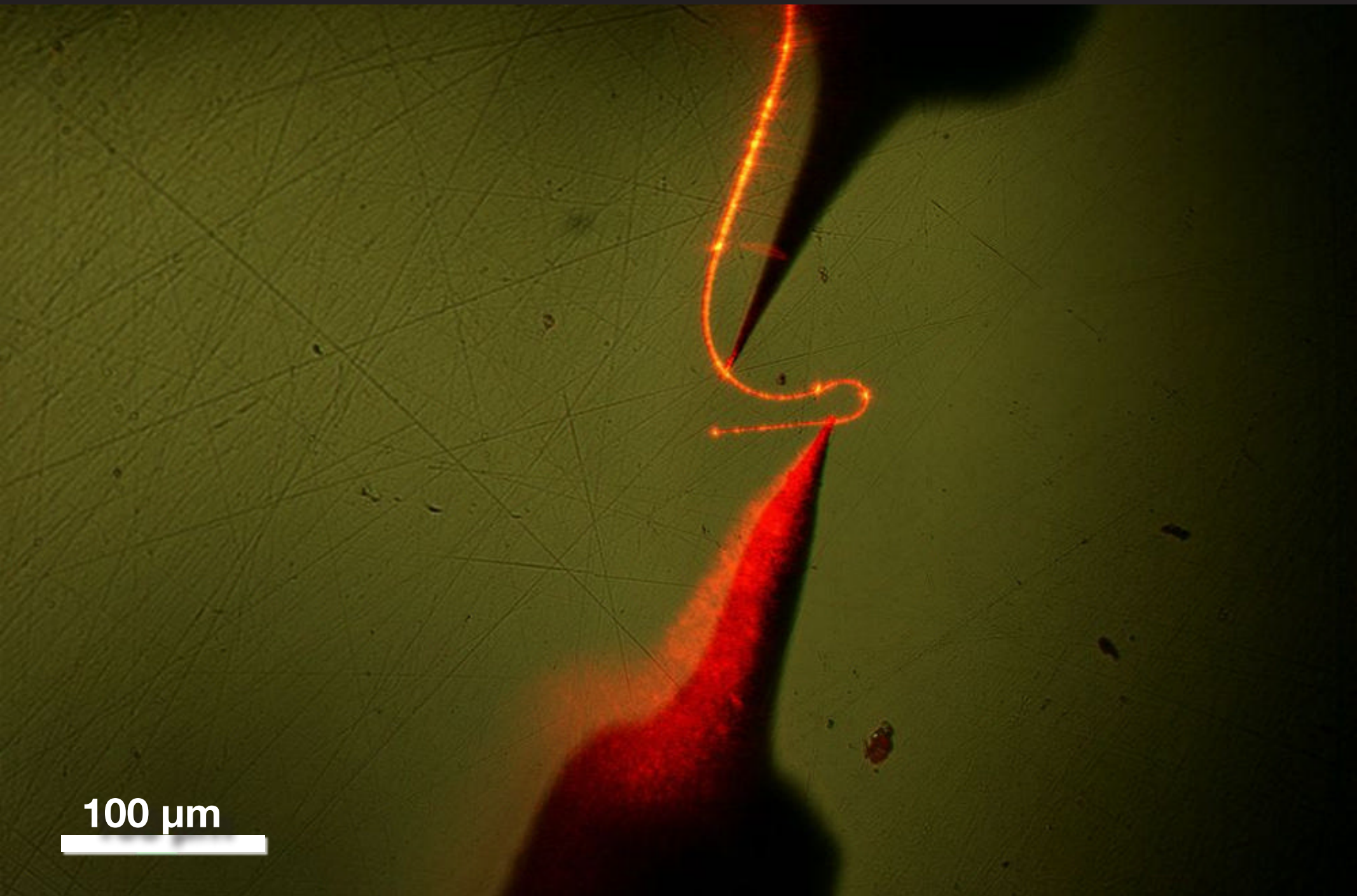


50 μm

Manipulating light at the nanoscale

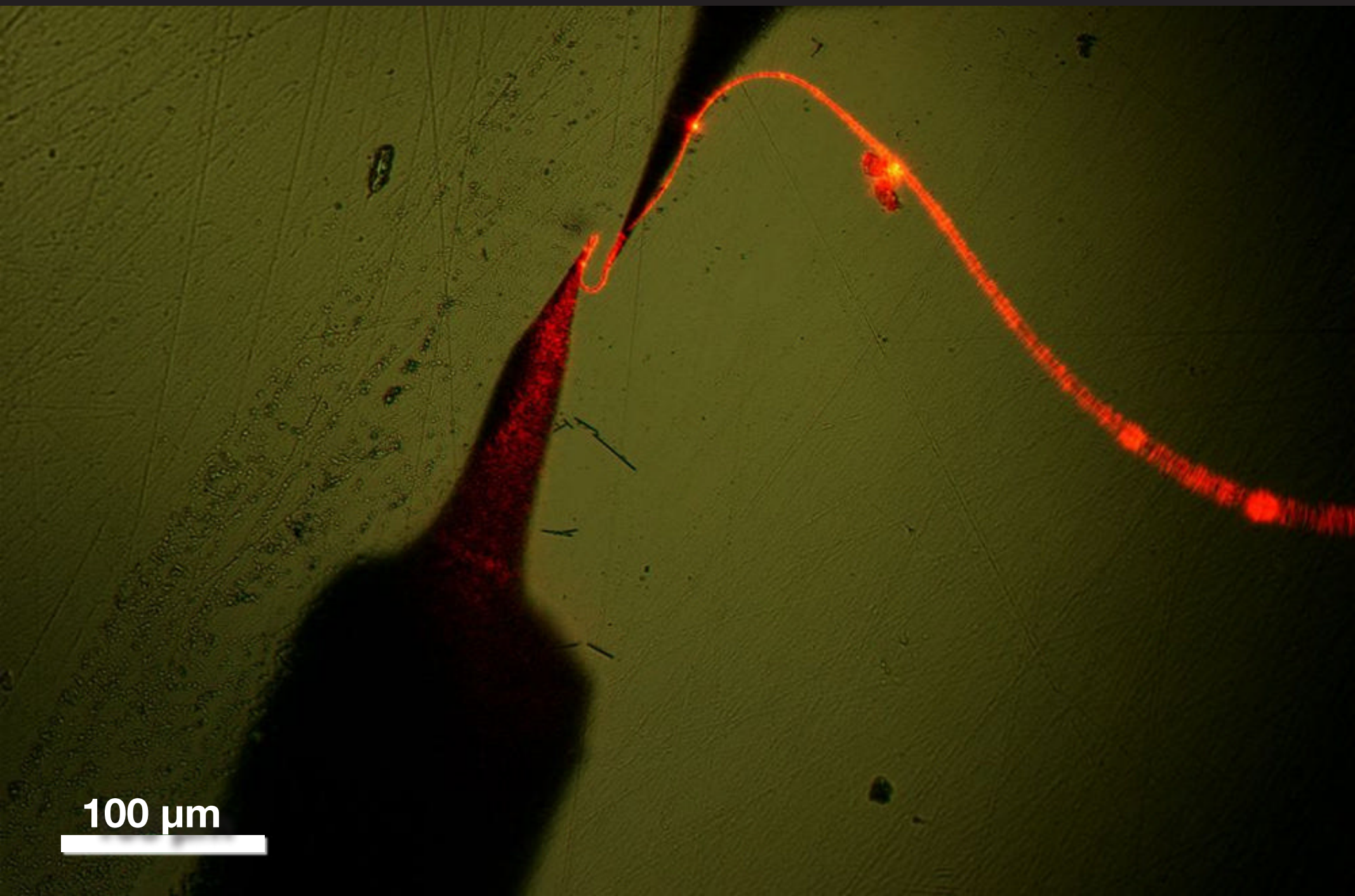


Manipulating light at the nanoscale



100 μm

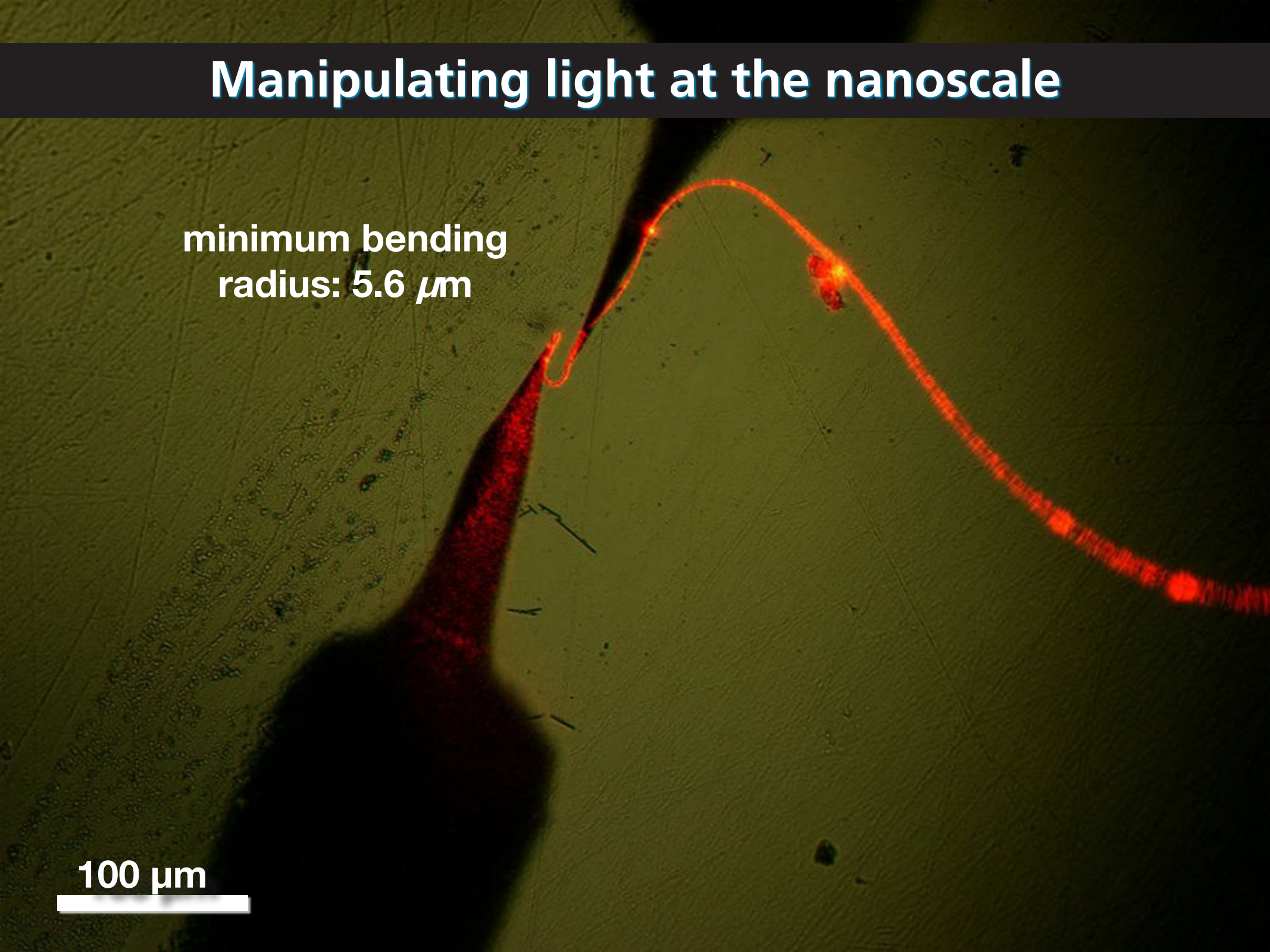
Manipulating light at the nanoscale



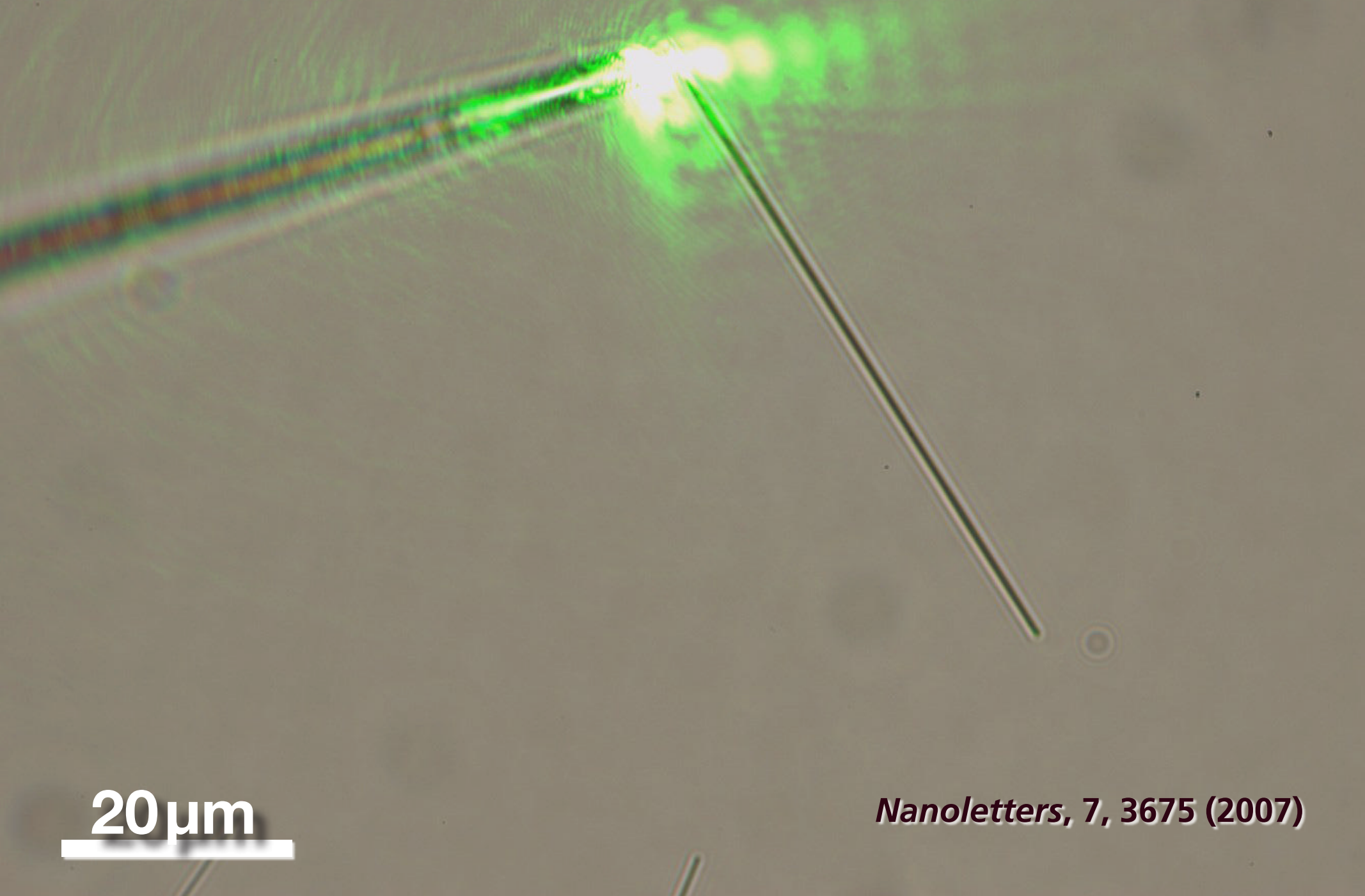
Manipulating light at the nanoscale

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.

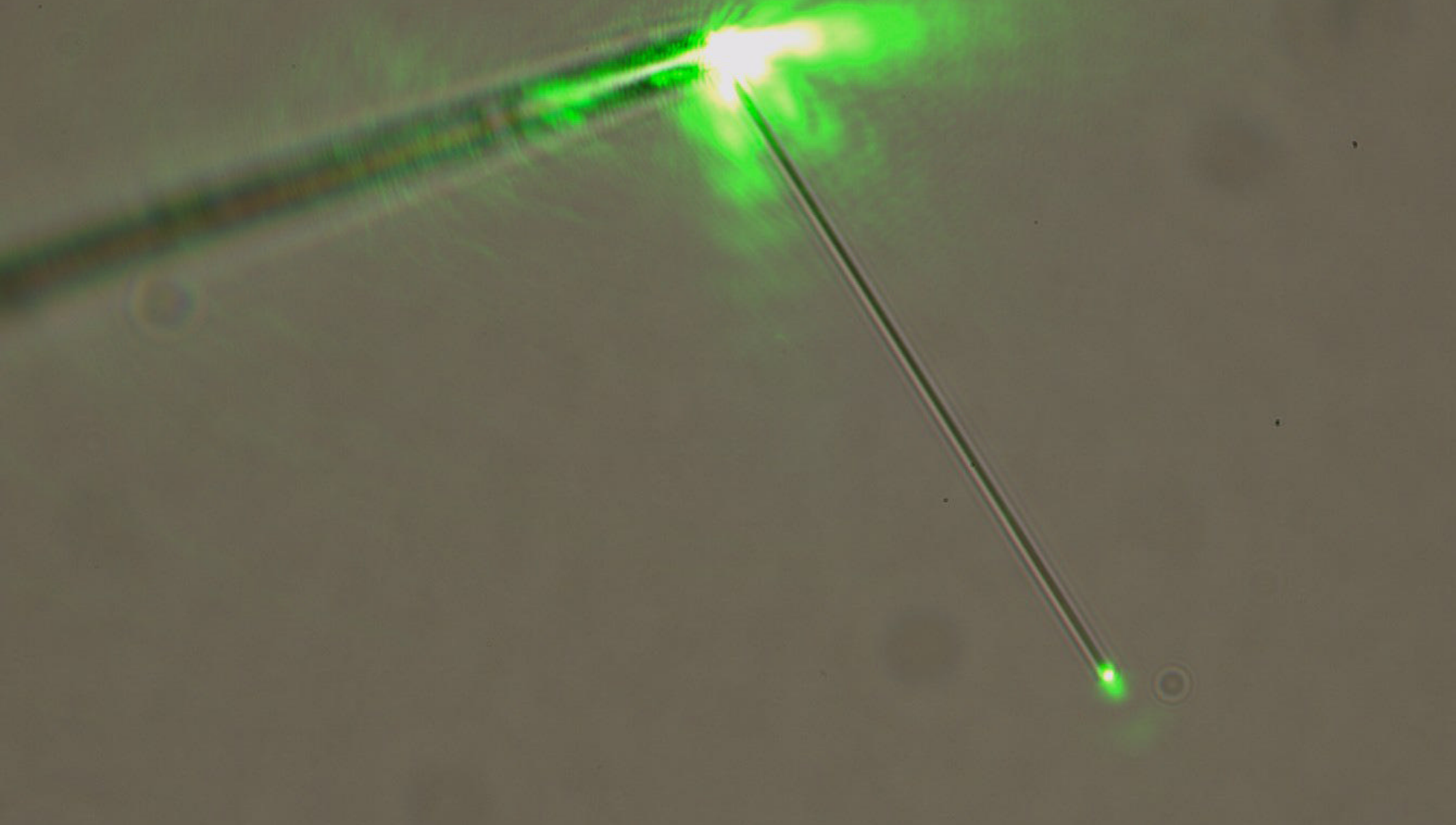
Manipulating light at the nanoscale



20 μm

Nanoletters, 7, 3675 (2007)

Manipulating light at the nanoscale



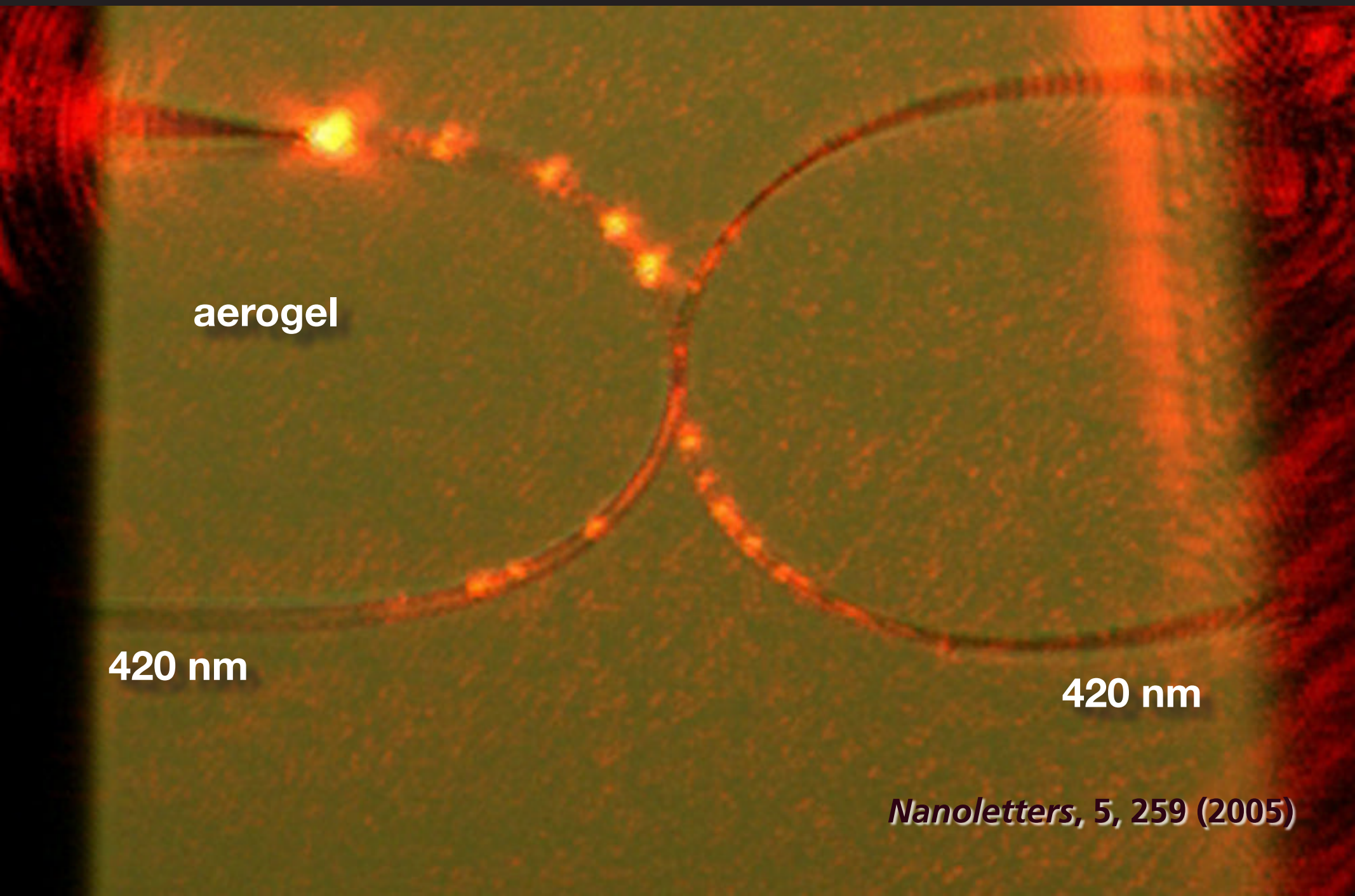
20 μm

Nanoletters, 7, 3675 (2007)

Manipulating light at the nanoscale



Manipulating light at the nanoscale



aerogel

420 nm

420 nm

Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale

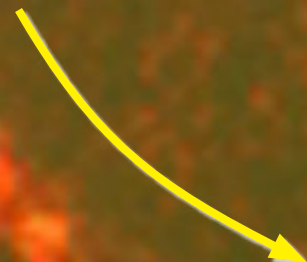
in



out

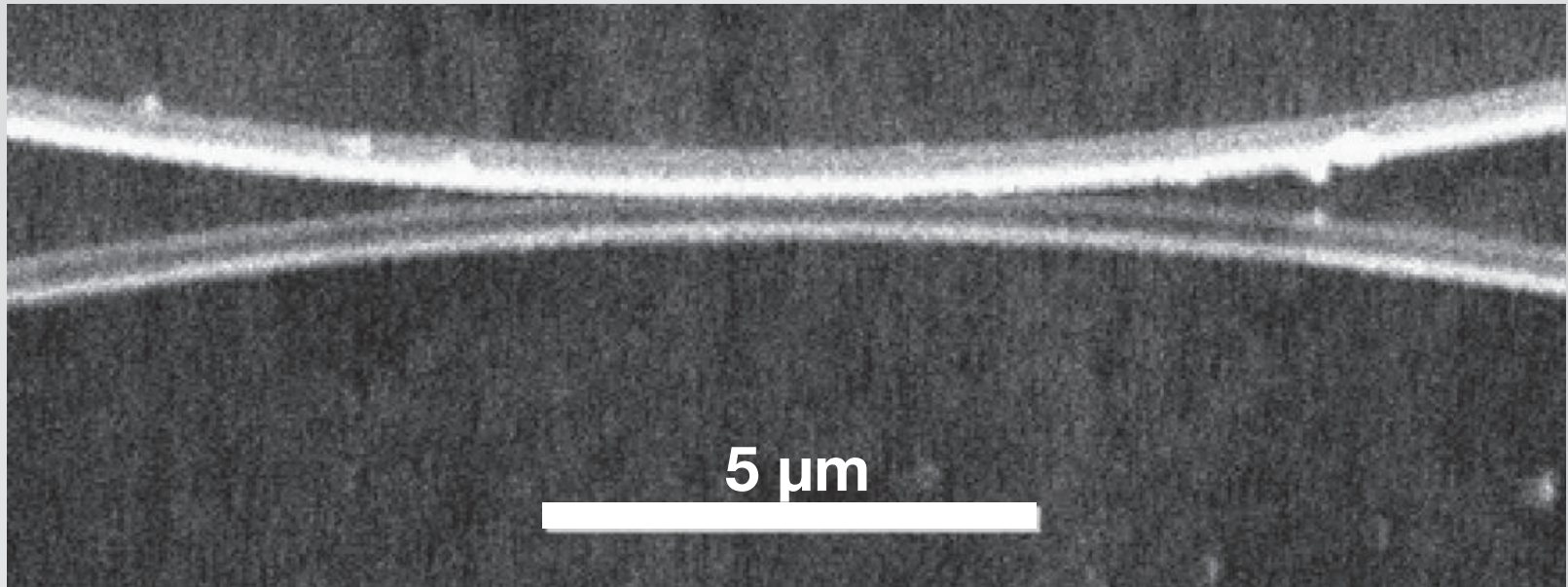


out



Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



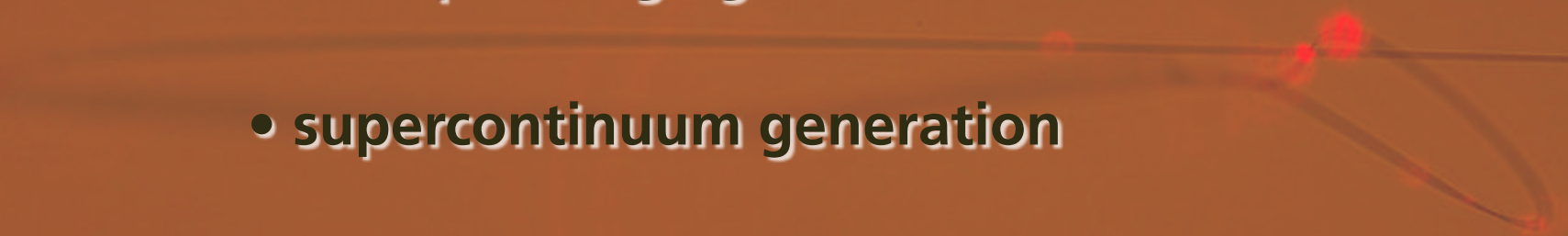
Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale

Points to keep in mind:

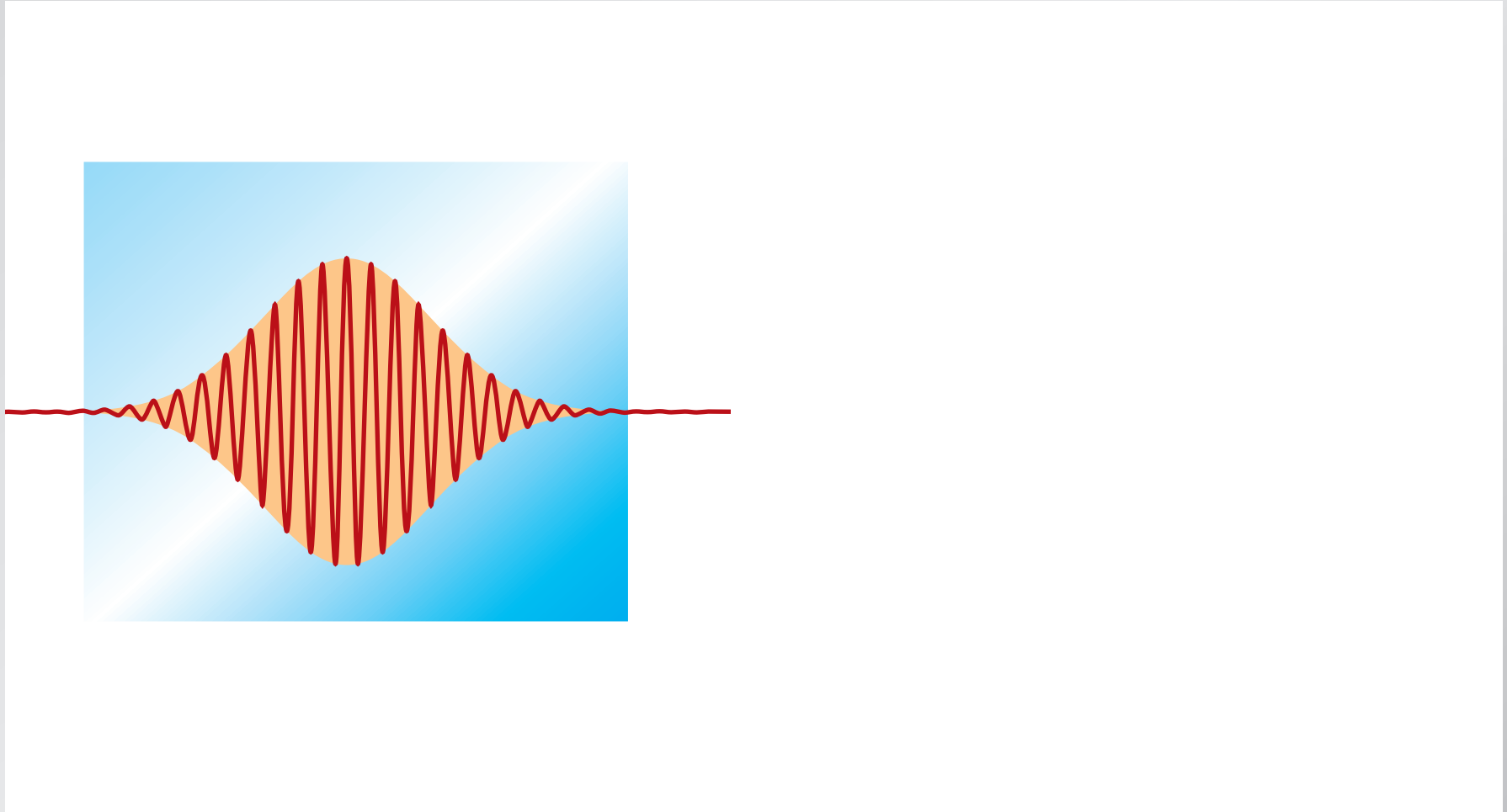
- **low-loss guiding**
- **convenient evanescent coupling**
- **attached to ordinary fiber**

Outline

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

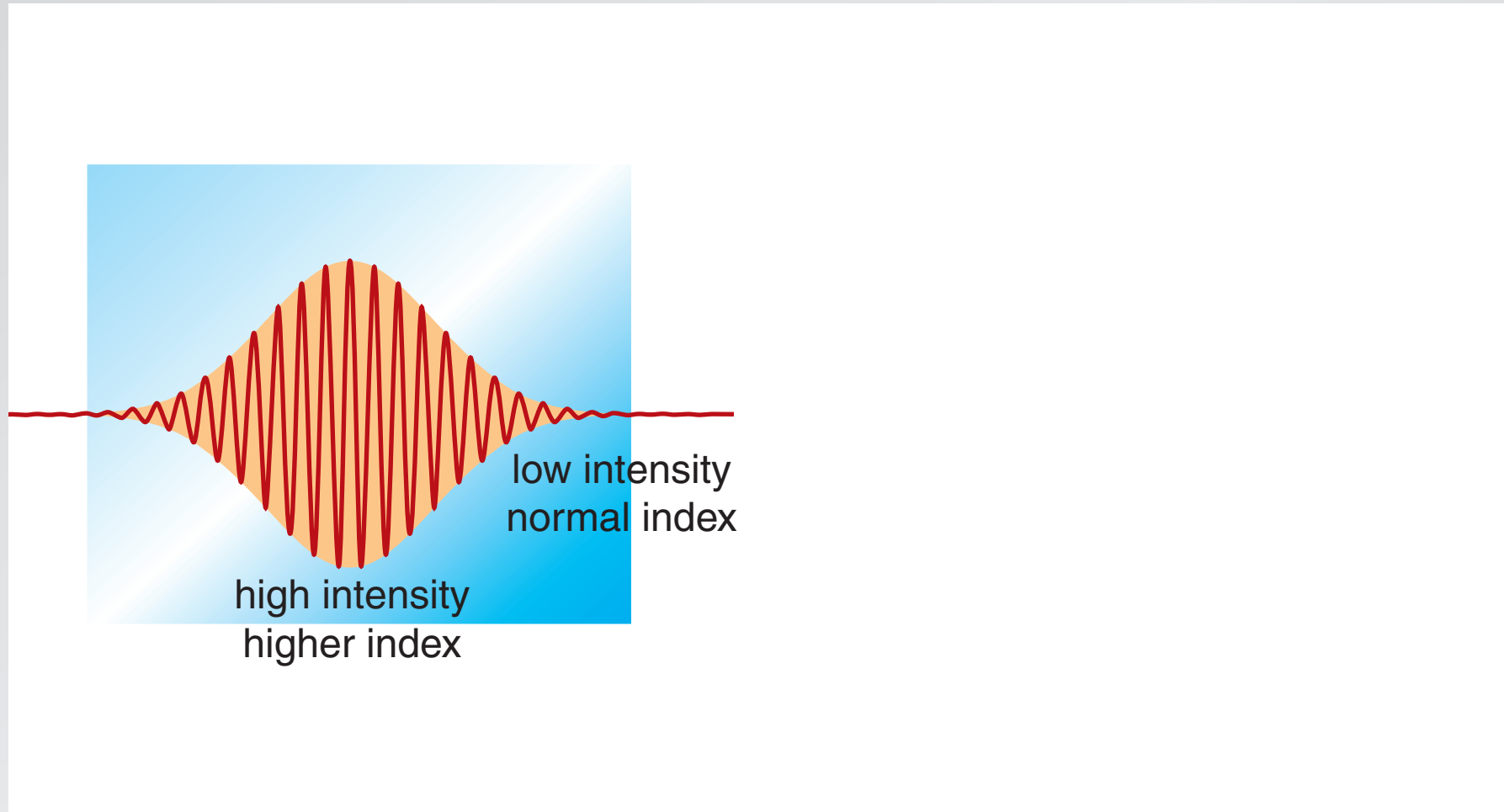
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



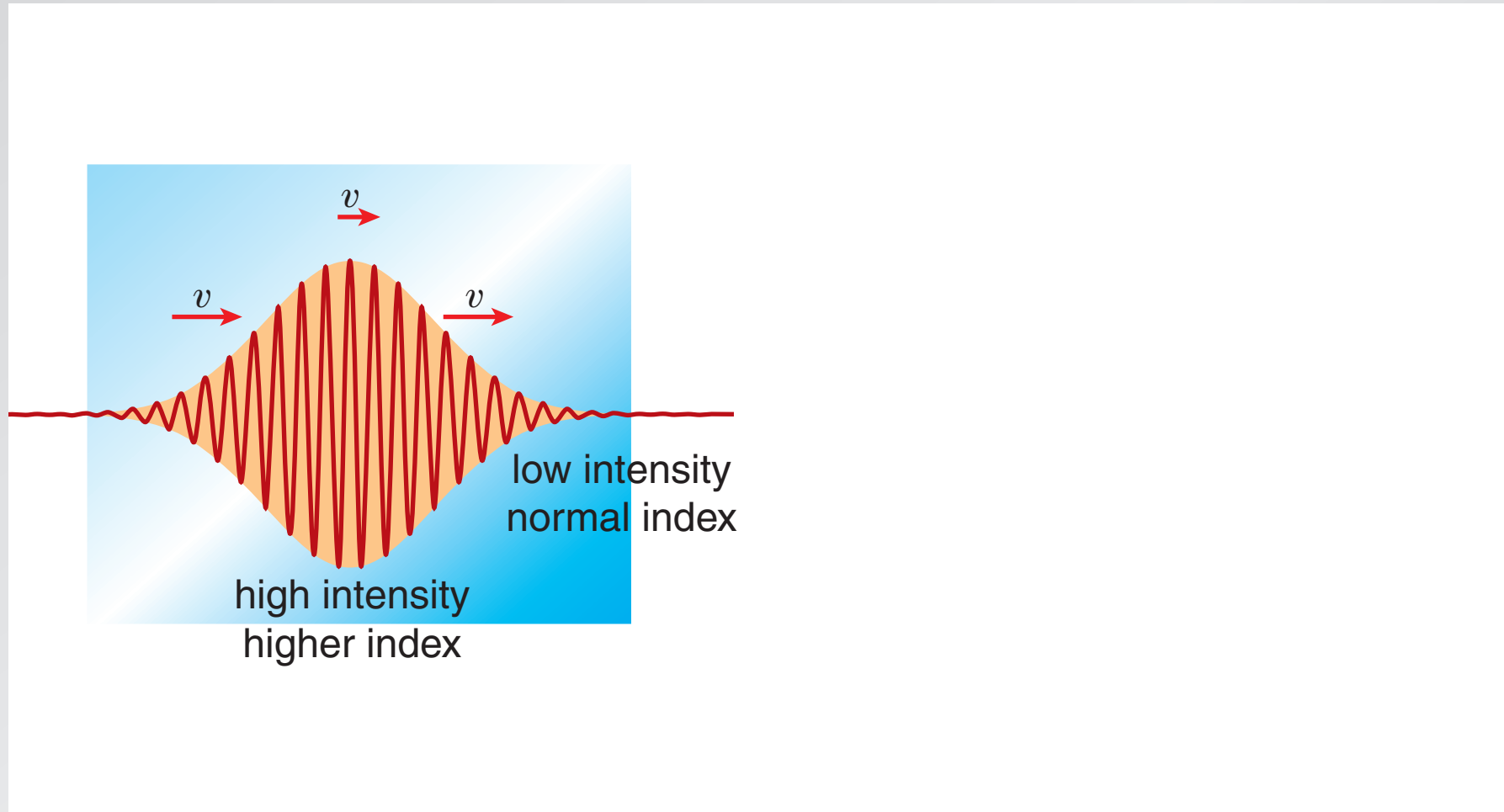
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



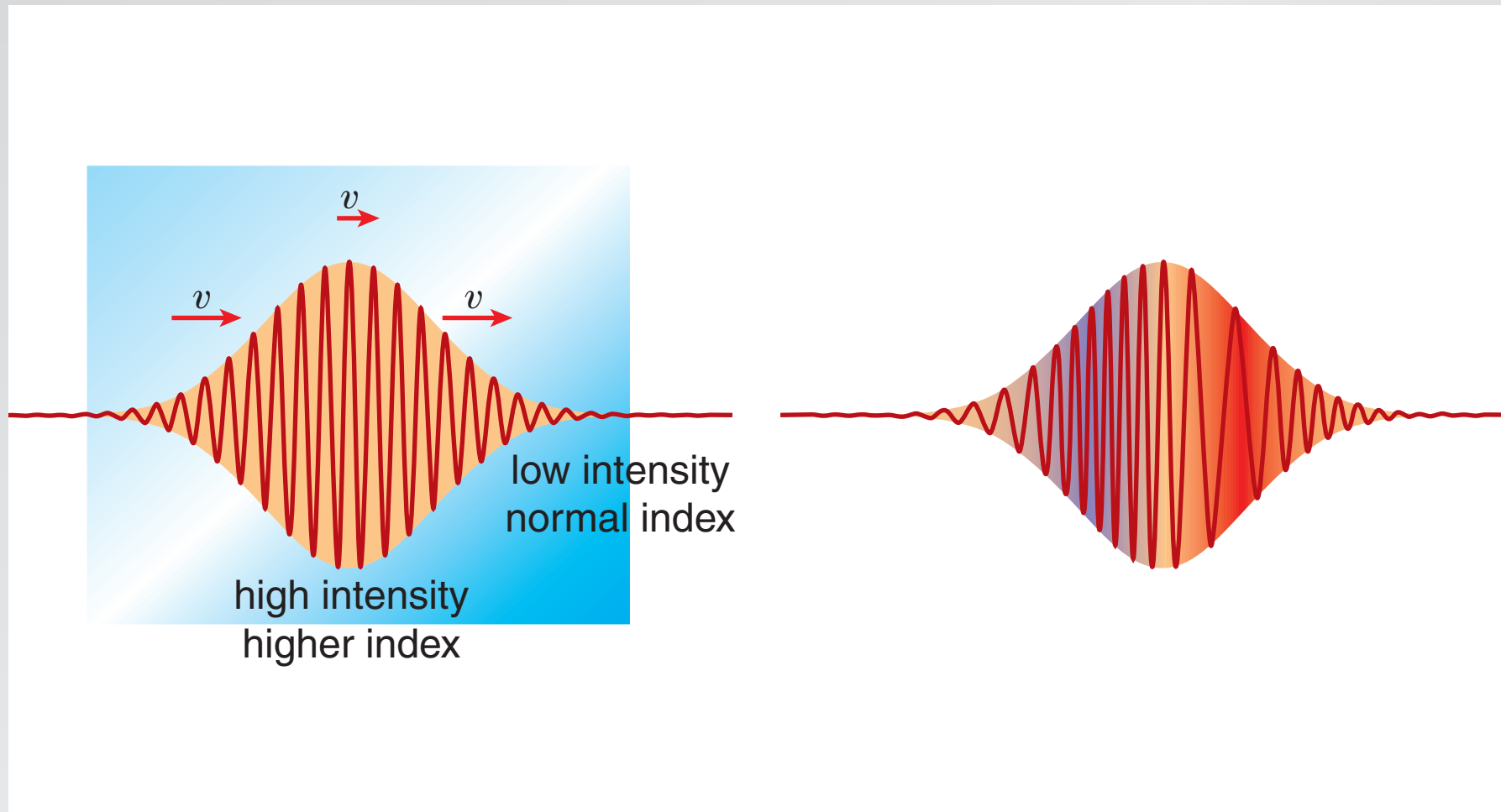
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



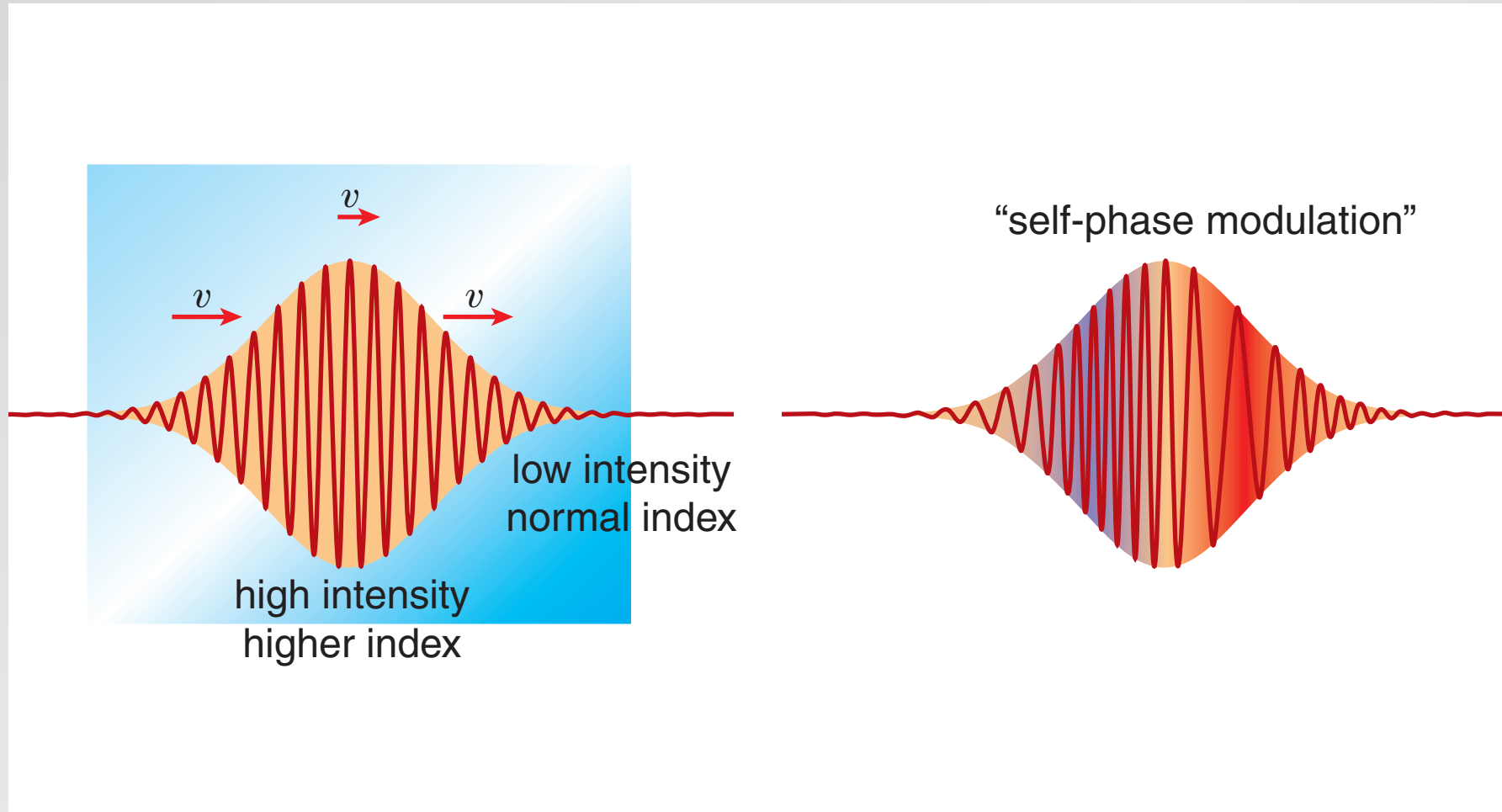
Supercontinuum generation

nonlinear dispersion: $n = n_0 + n_2 I$



Supercontinuum generation

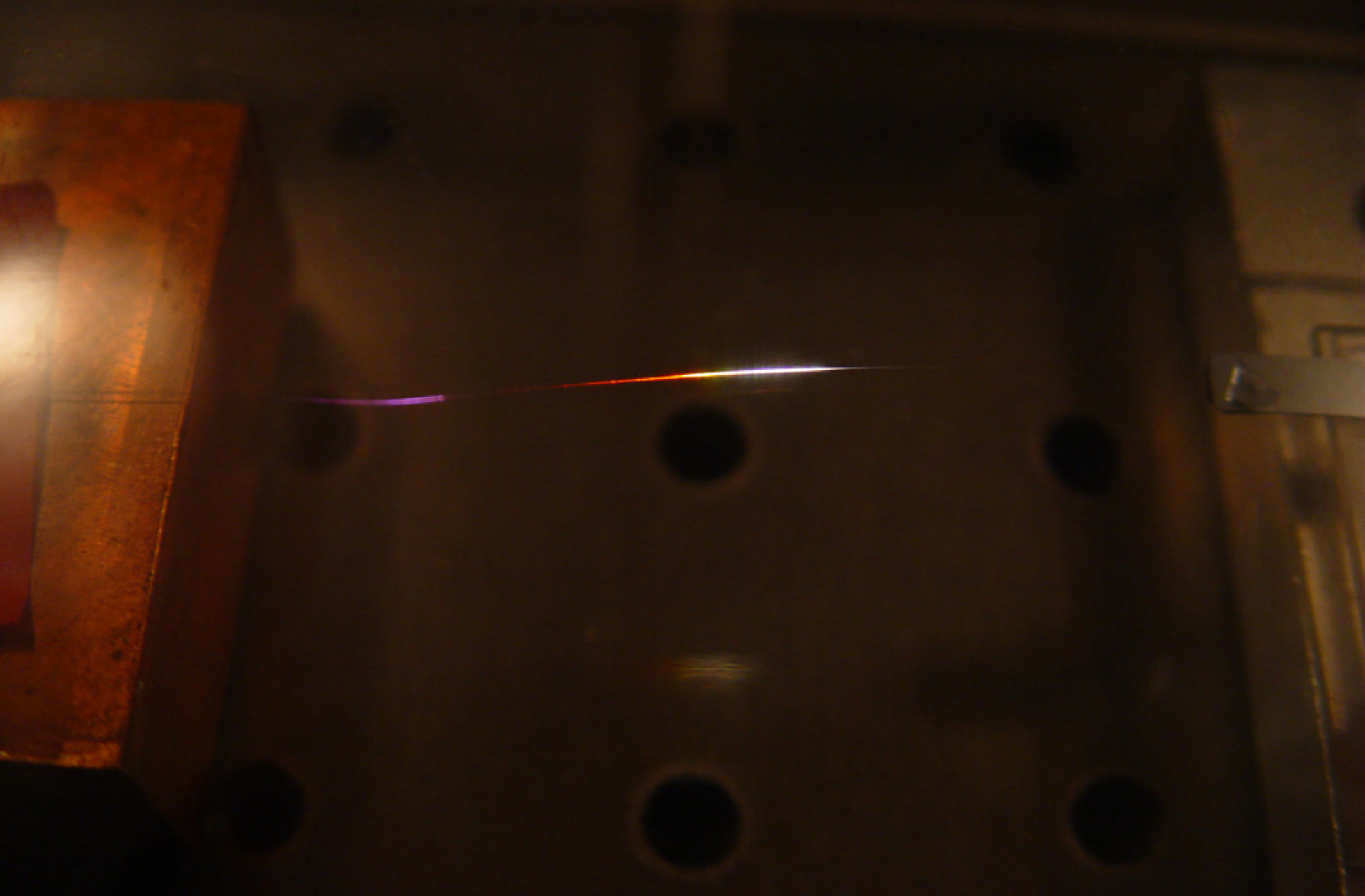
nonlinear dispersion: $n = n_0 + n_2 I$



Supercontinuum generation

strong confinement \longrightarrow **high intensity**

Supercontinuum generation

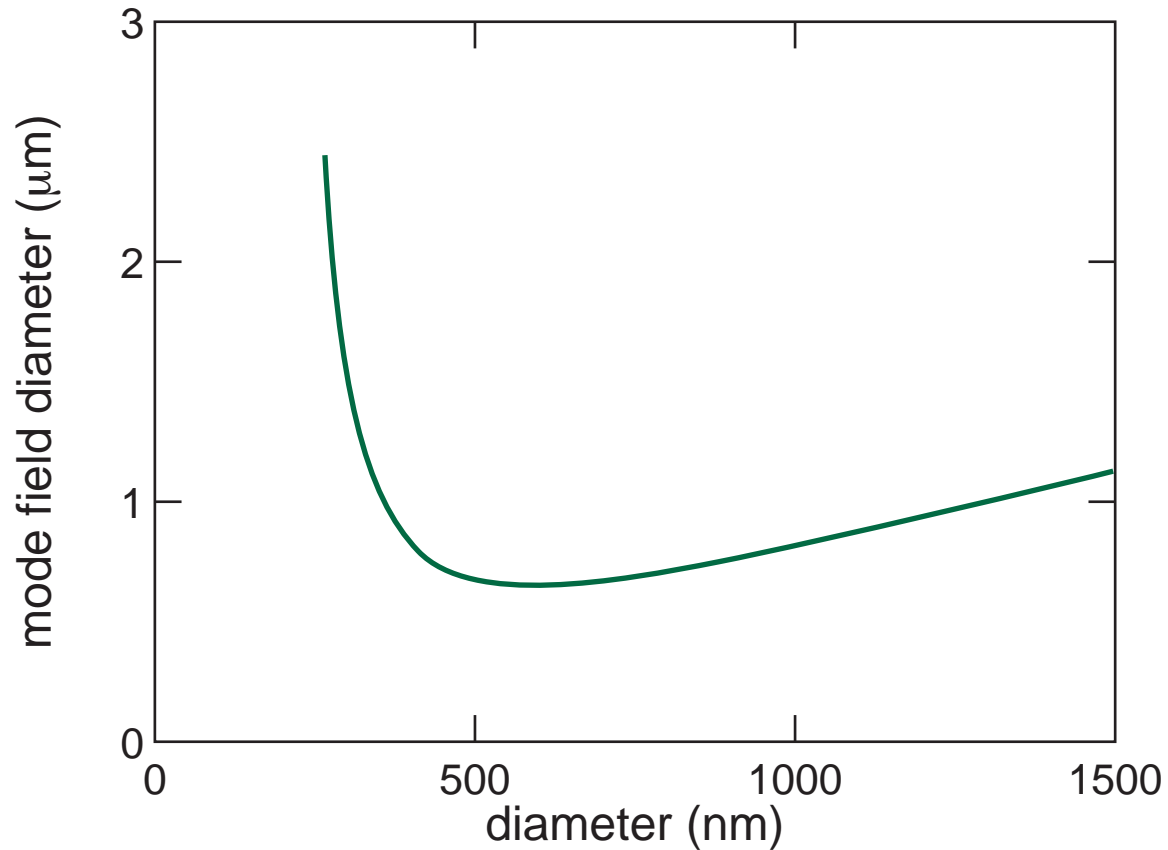


Supercontinuum generation



Supercontinuum generation

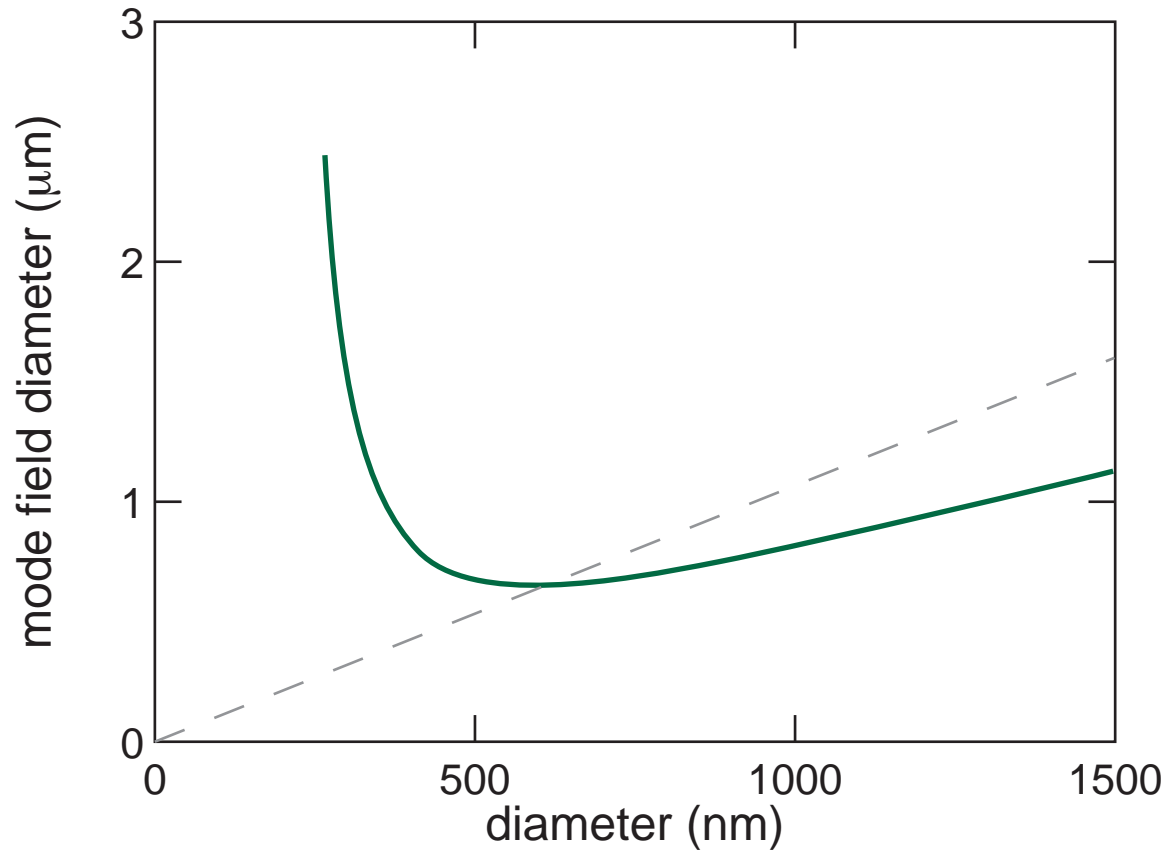
mode field diameter ($\lambda = 800$ nm)



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

Supercontinuum generation

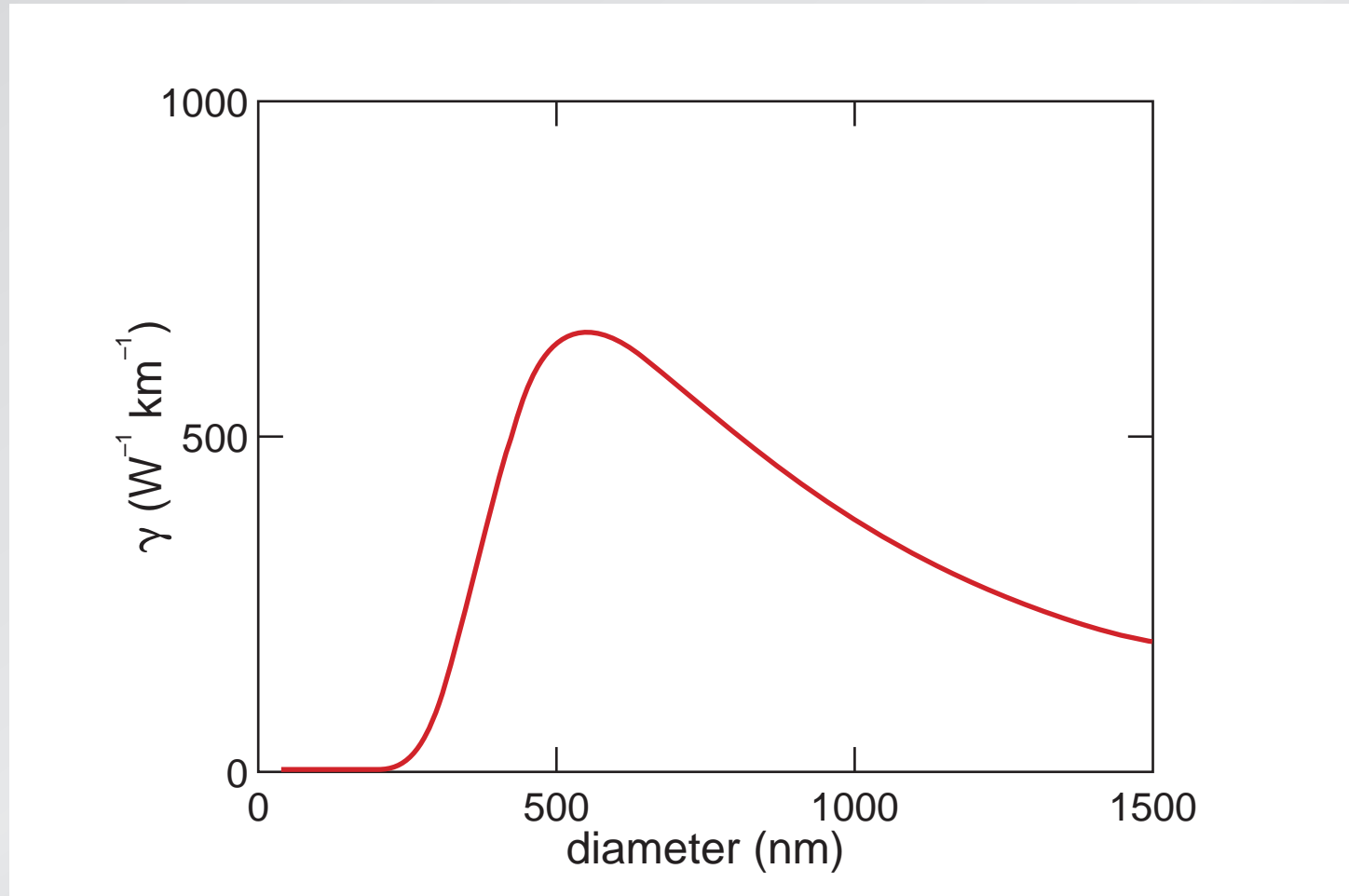
mode field diameter ($\lambda = 800$ nm)



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

Supercontinuum generation

nonlinear parameter



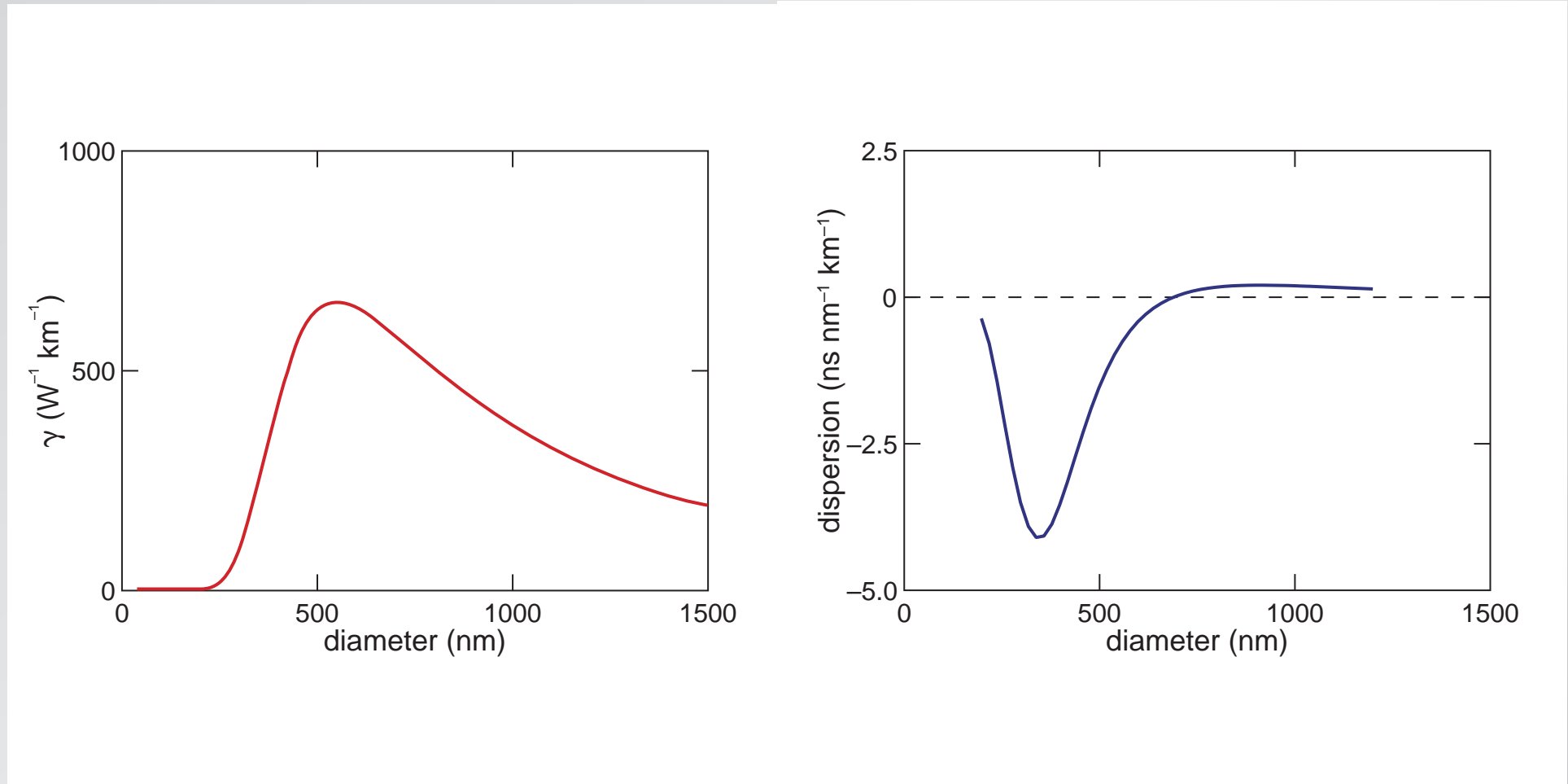
M.A. Foster, et al., *Optics Express*, 12, 2880 (2004)

Supercontinuum generation

dispersion important!

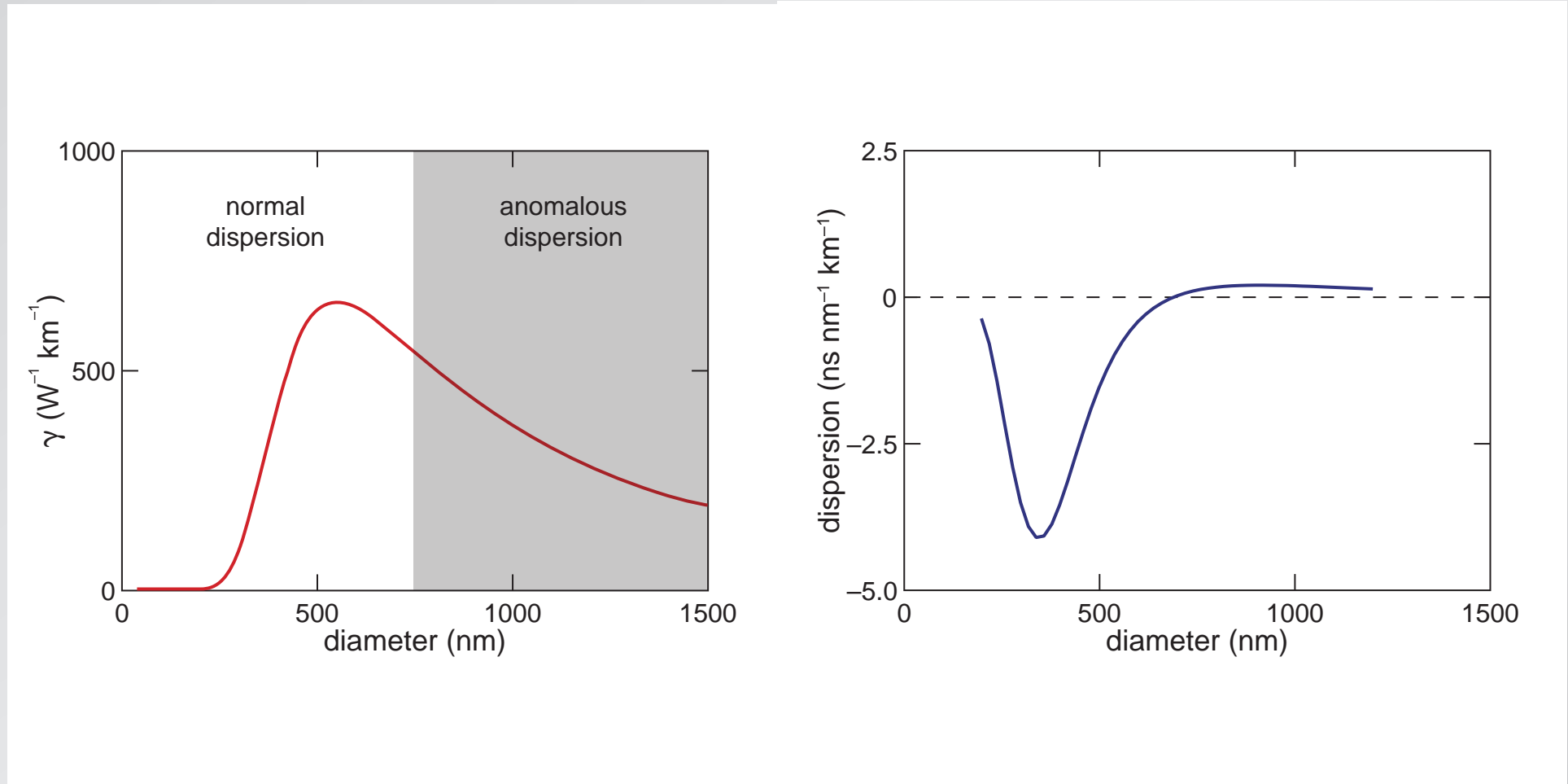
Supercontinuum generation

waveguide dispersion



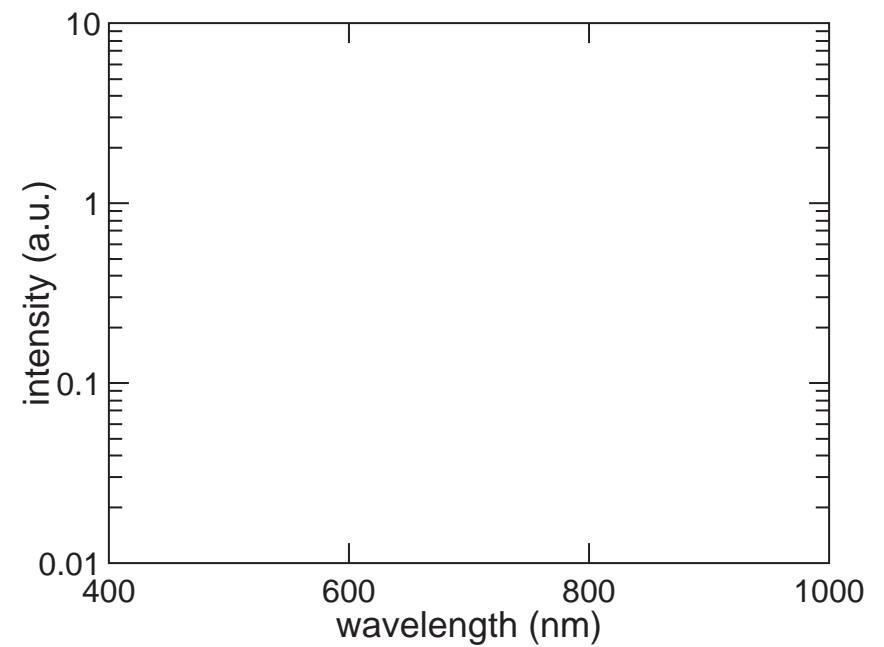
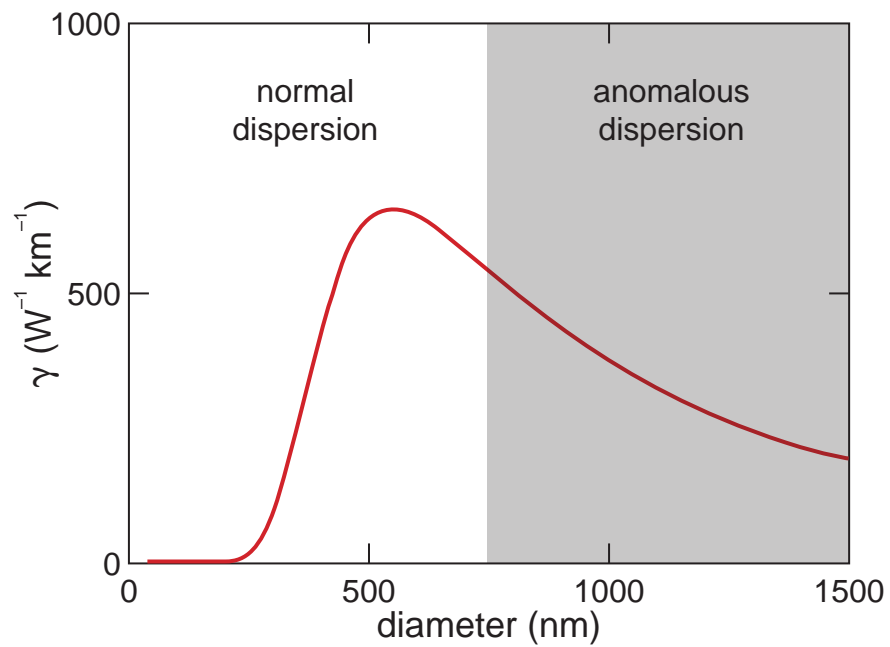
Supercontinuum generation

waveguide dispersion



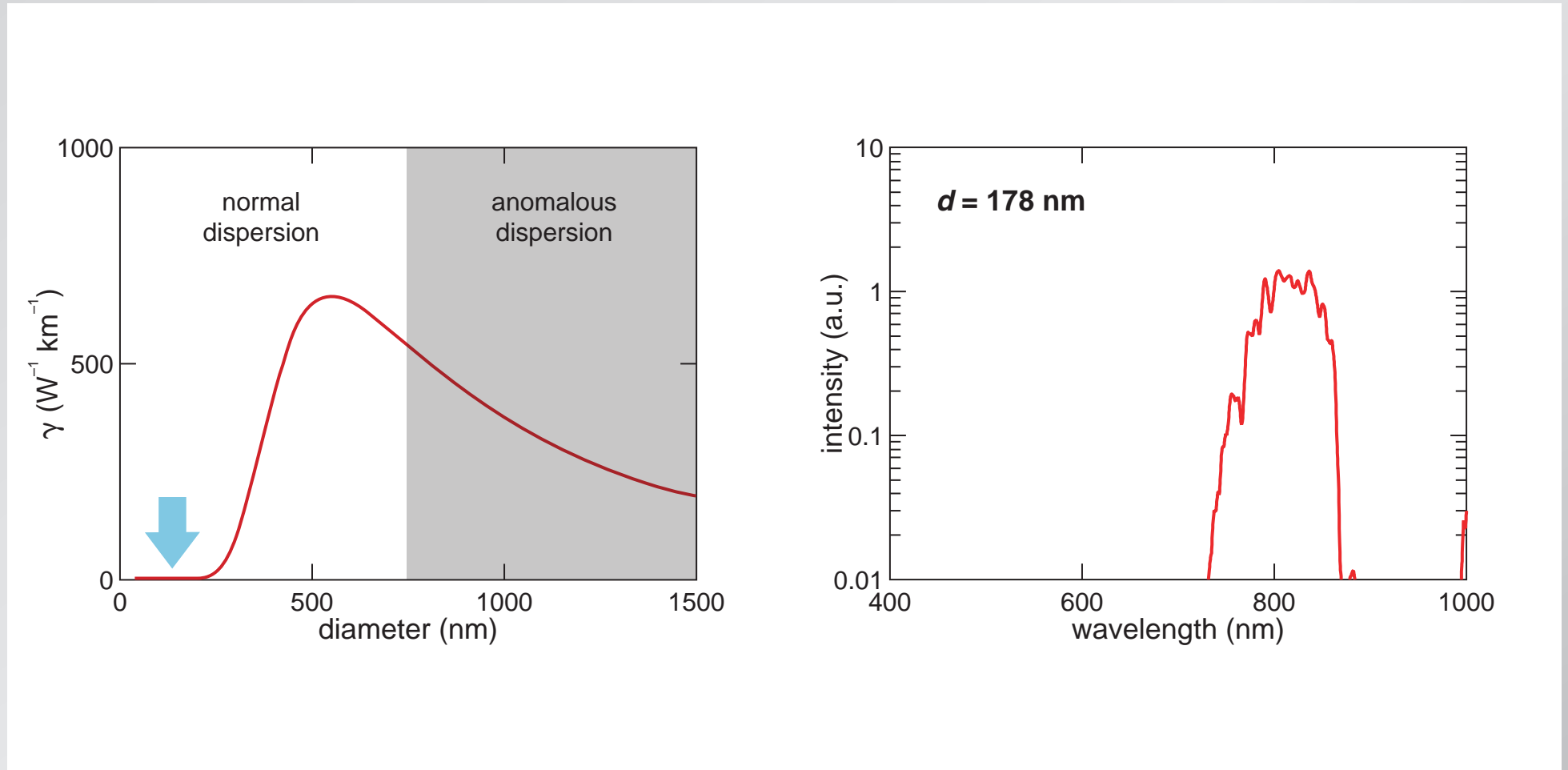
Supercontinuum generation

nanowire continuum generation



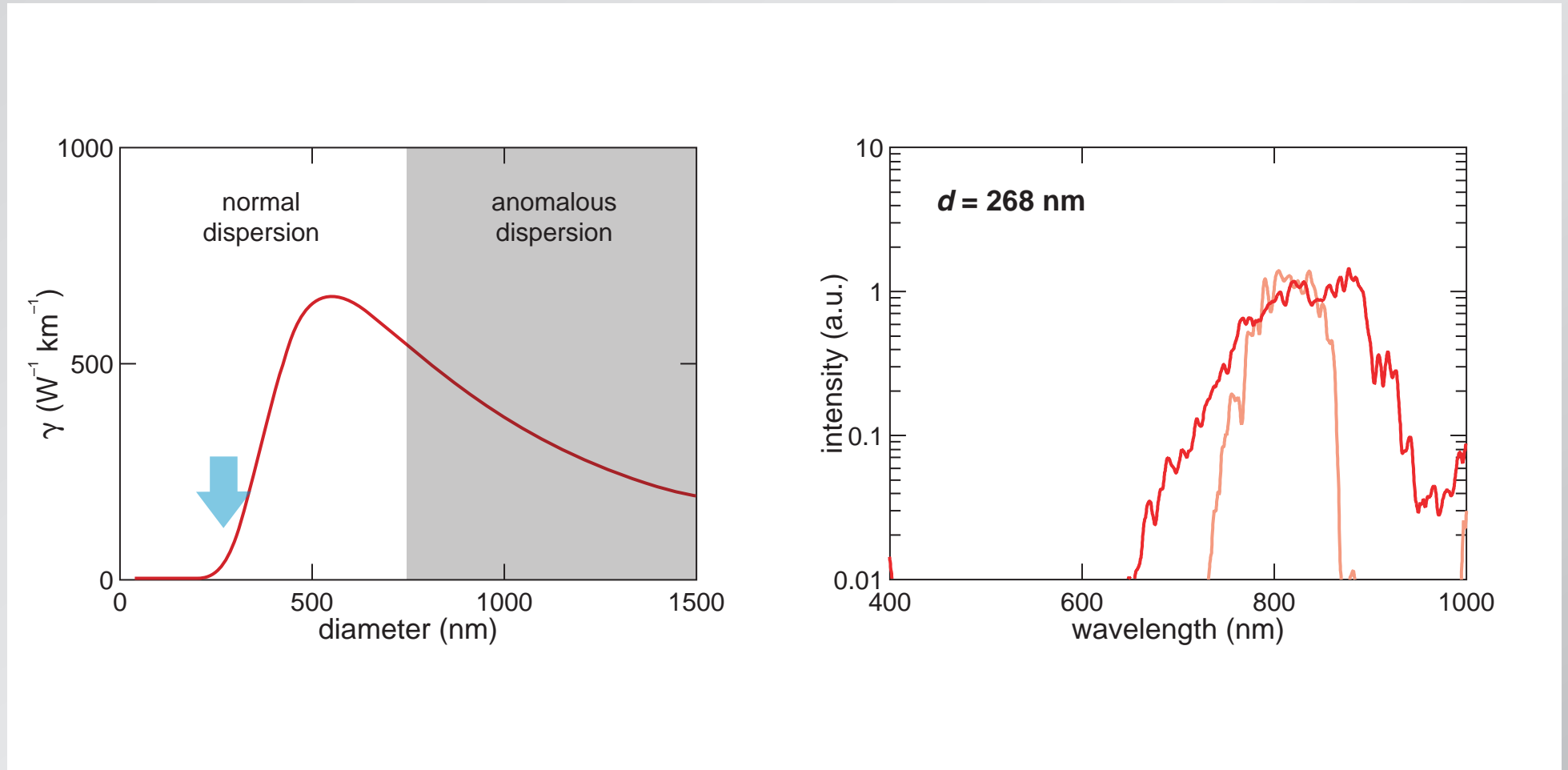
Supercontinuum generation

nanowire continuum generation



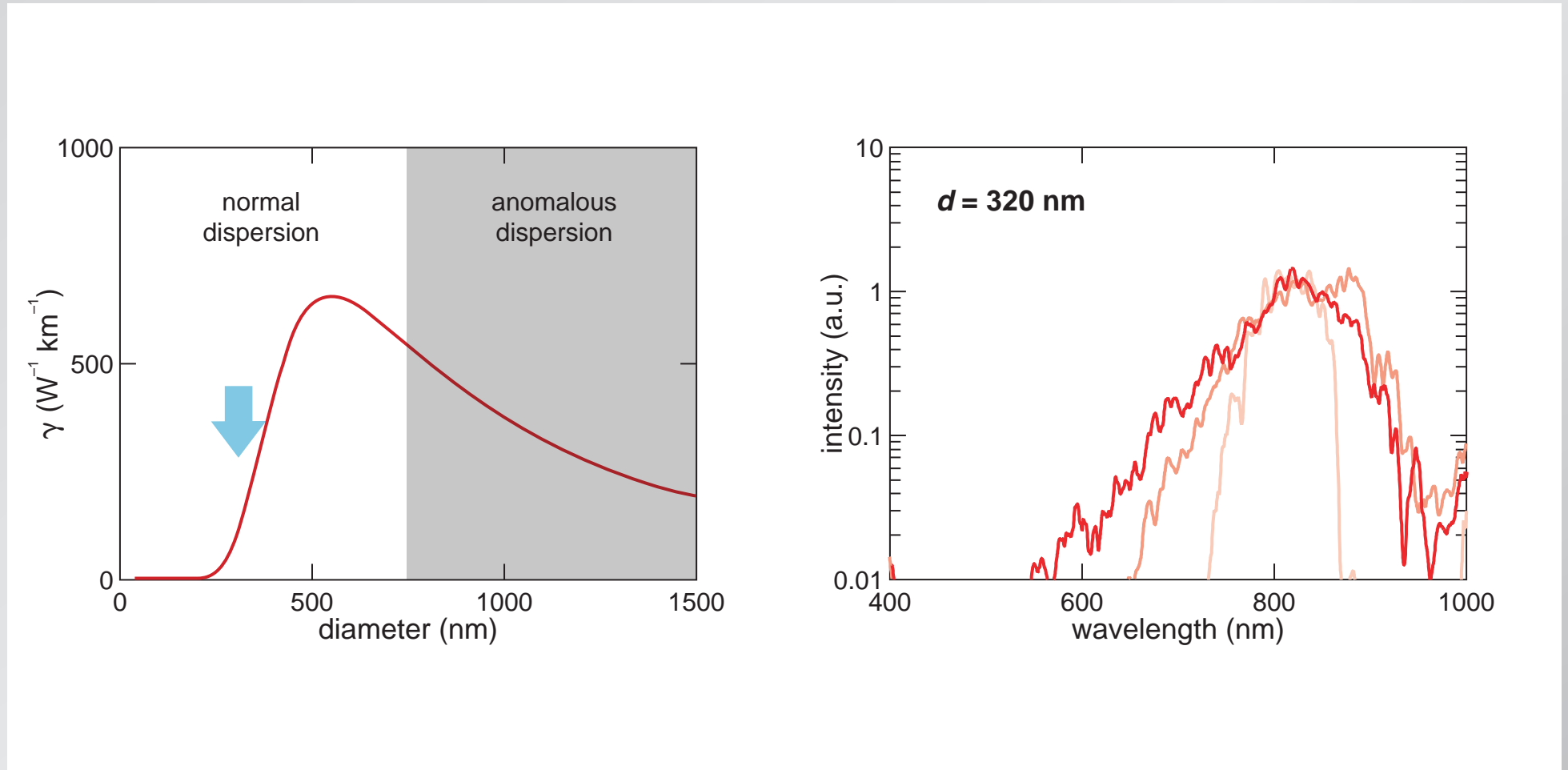
Supercontinuum generation

nanowire continuum generation



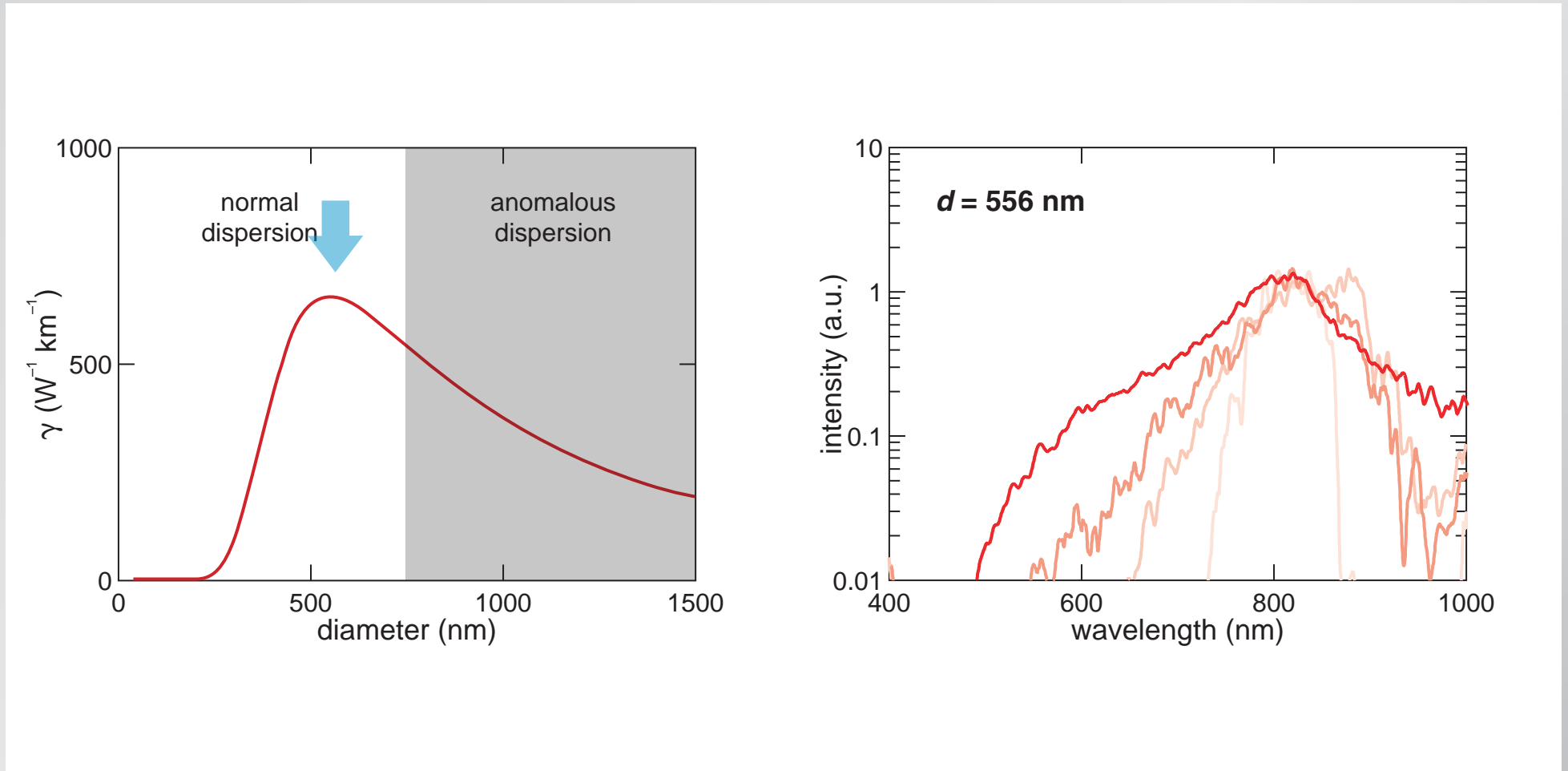
Supercontinuum generation

nanowire continuum generation



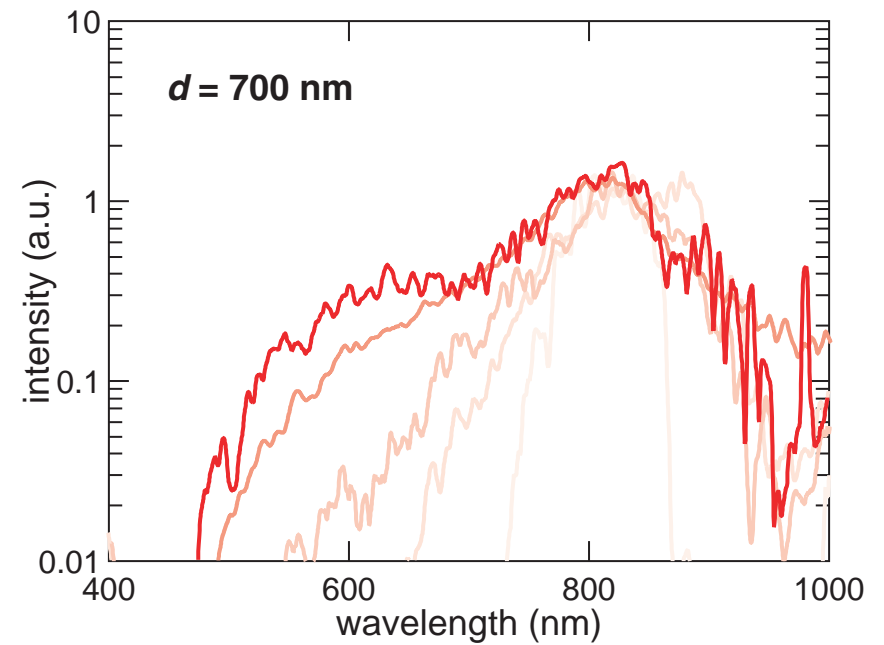
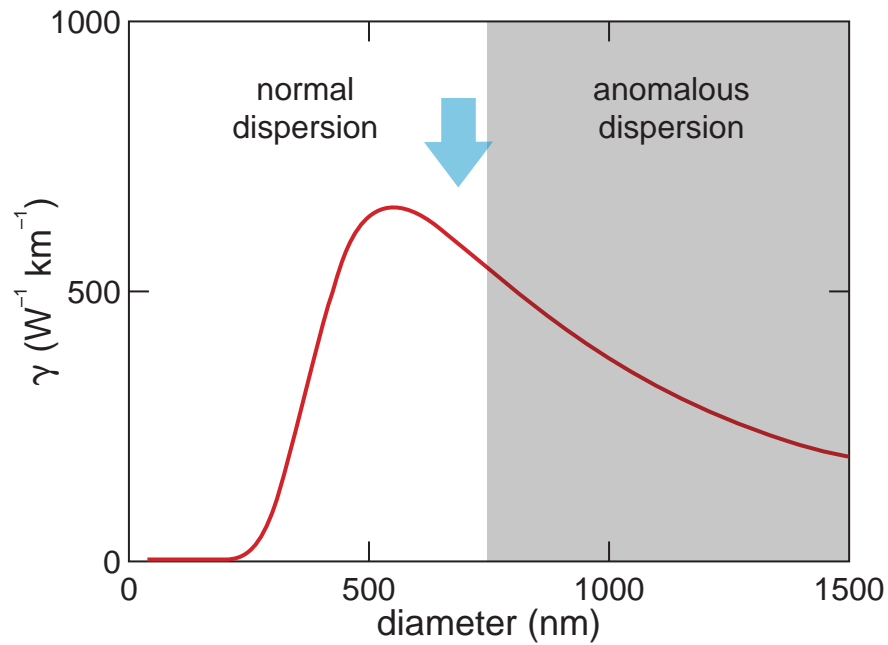
Supercontinuum generation

nanowire continuum generation



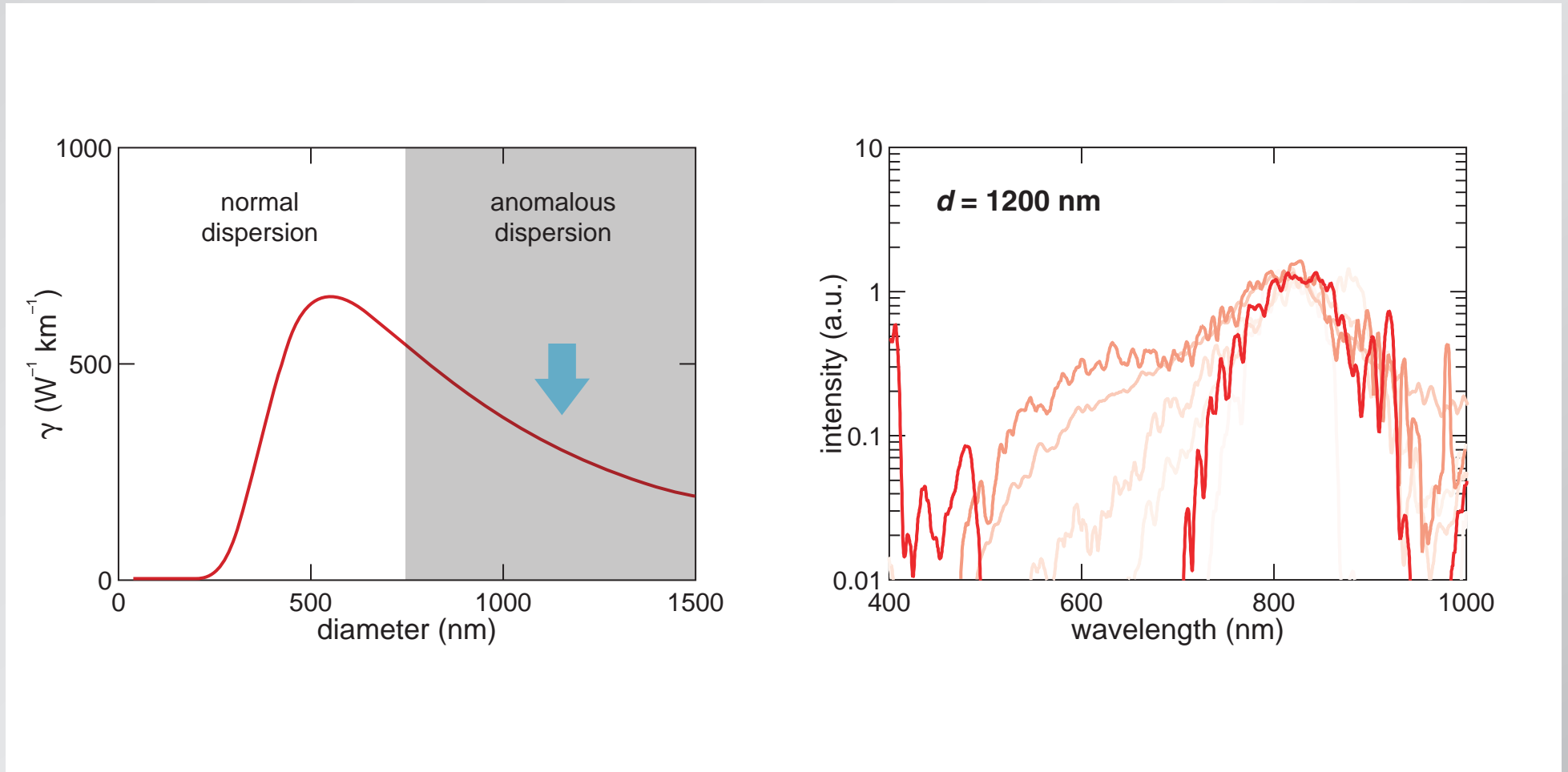
Supercontinuum generation

nanowire continuum generation



Supercontinuum generation

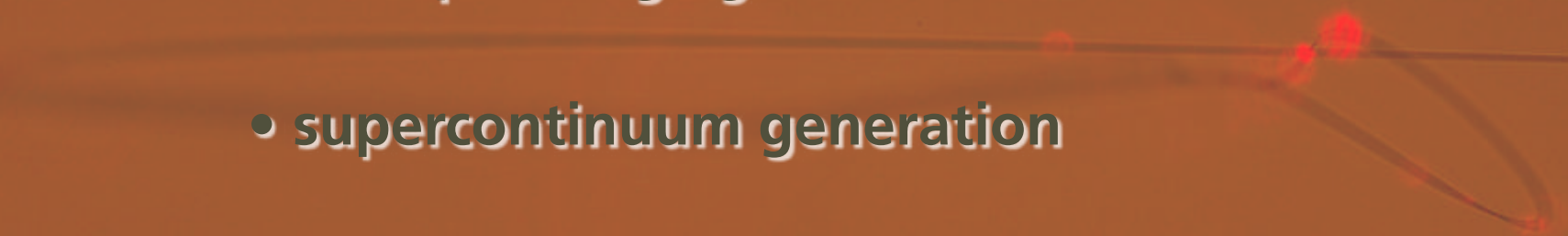
nanowire continuum generation



Supercontinuum generation

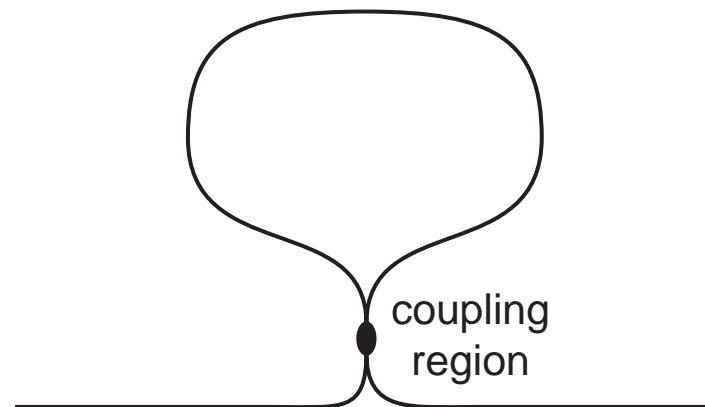
energy in nanowire < 100 pJ!

Outline

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

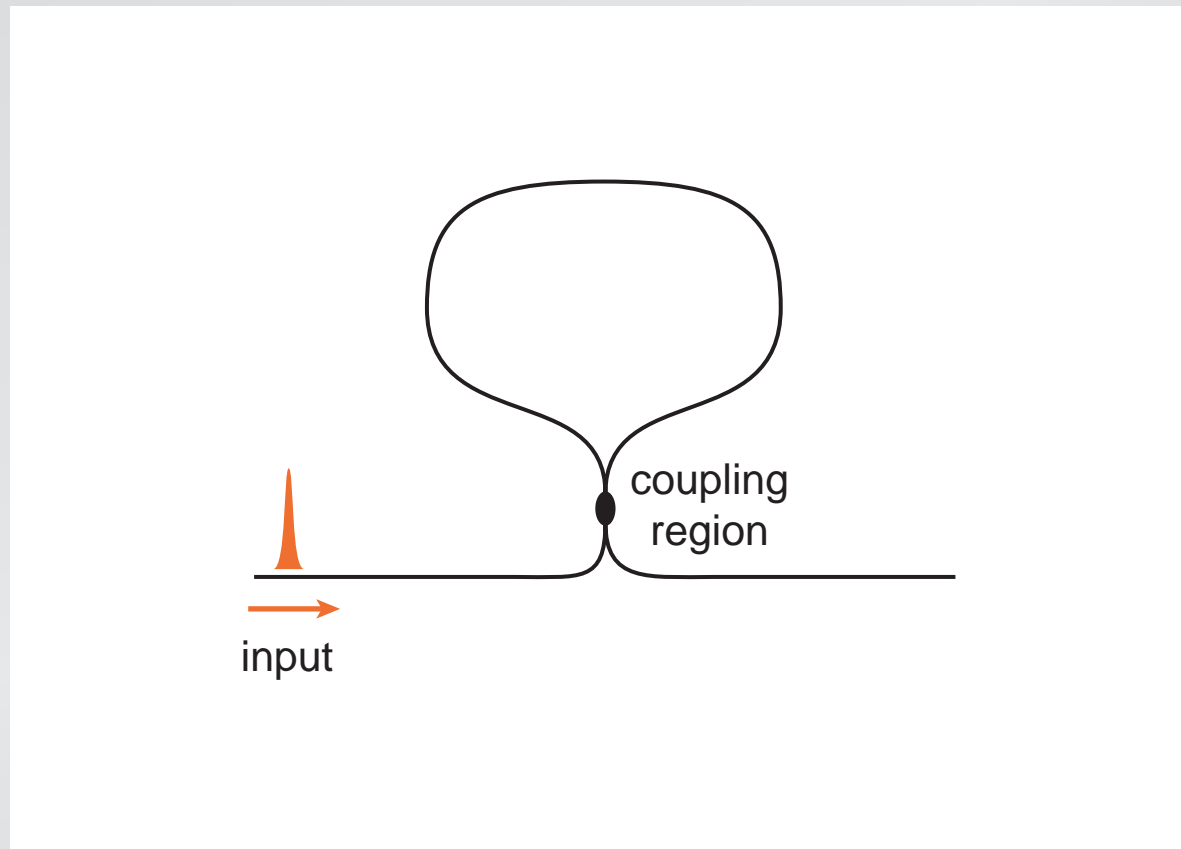
Optical logic gates

nanowire Sagnac interferometer



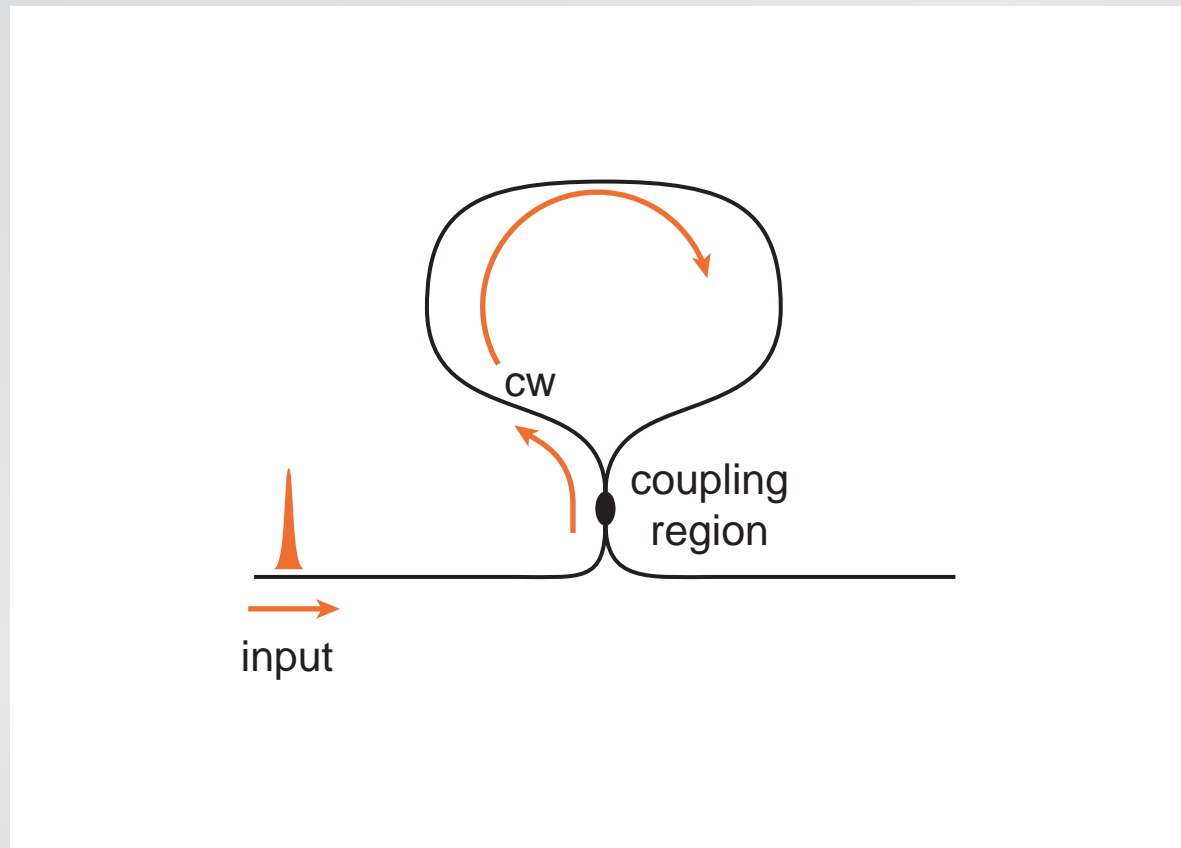
Optical logic gates

nanowire Sagnac interferometer



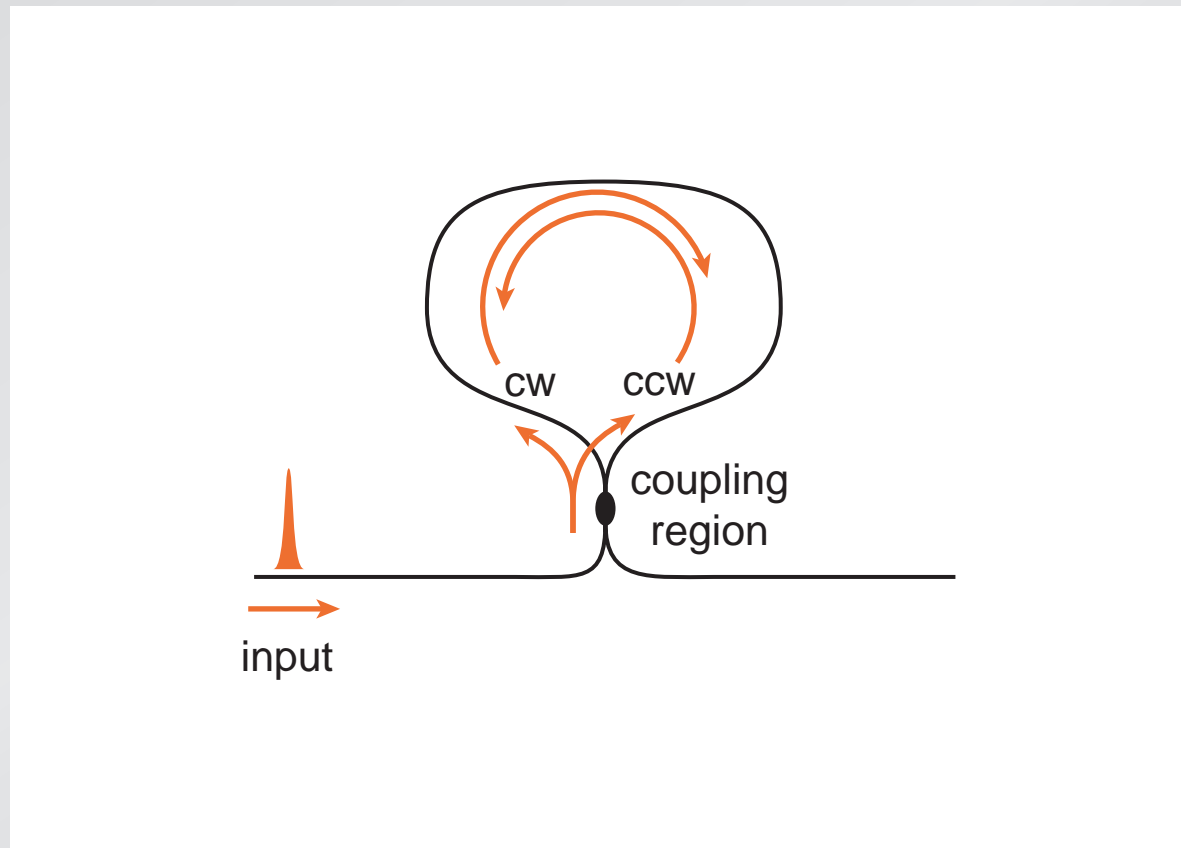
Optical logic gates

nanowire Sagnac interferometer



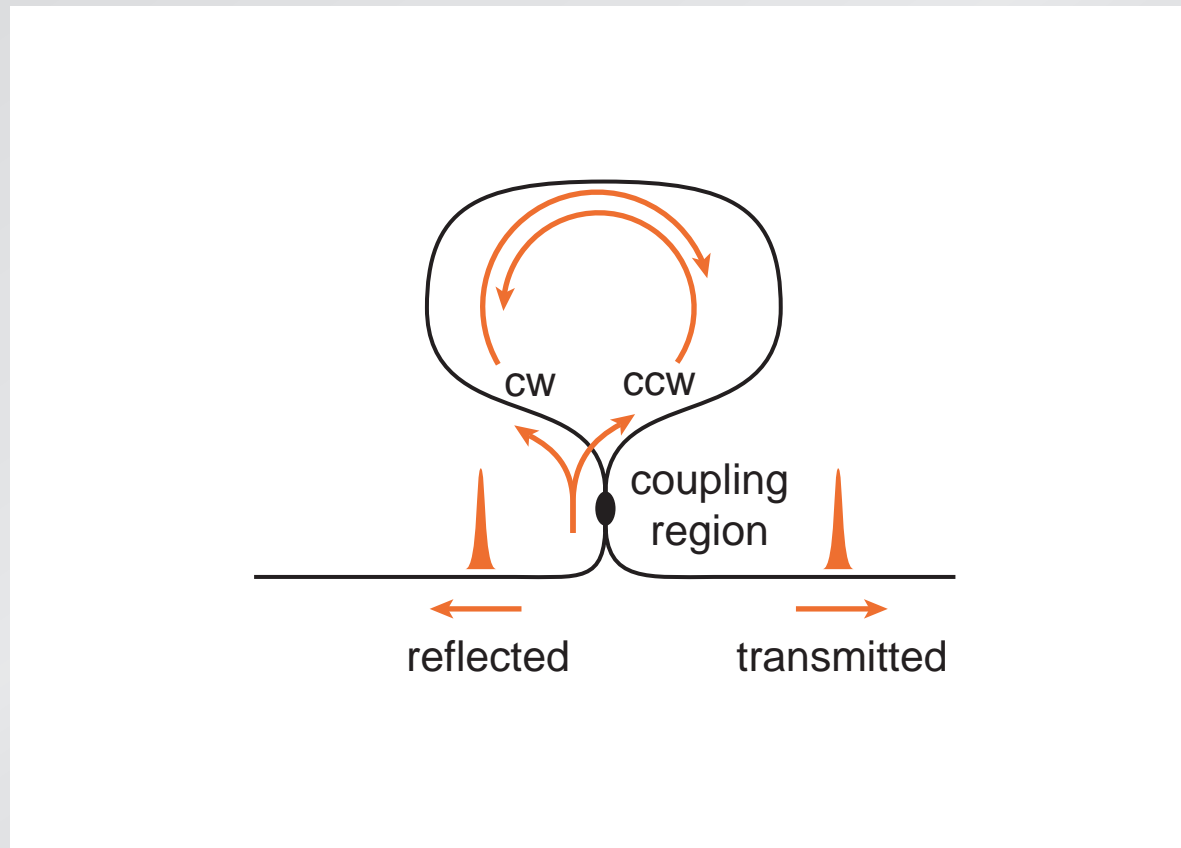
Optical logic gates

nanowire Sagnac interferometer



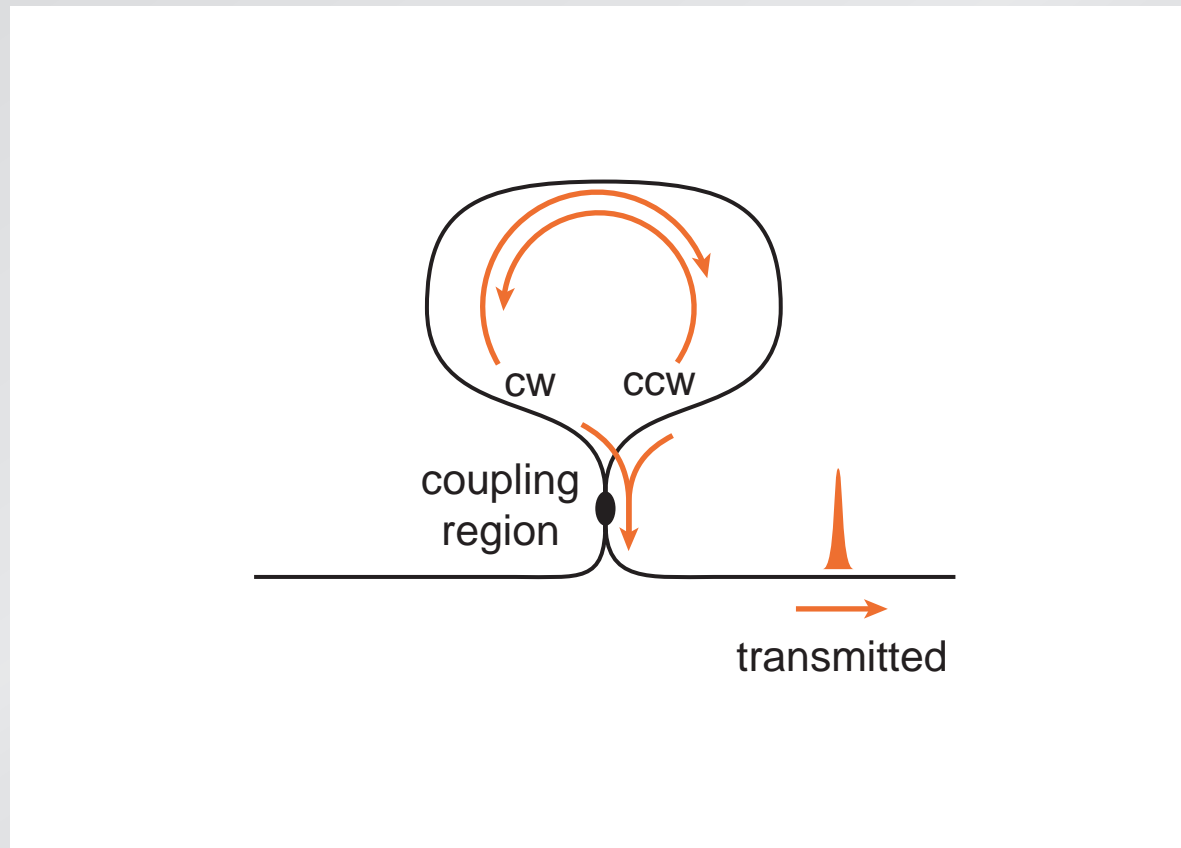
Optical logic gates

nanowire Sagnac interferometer



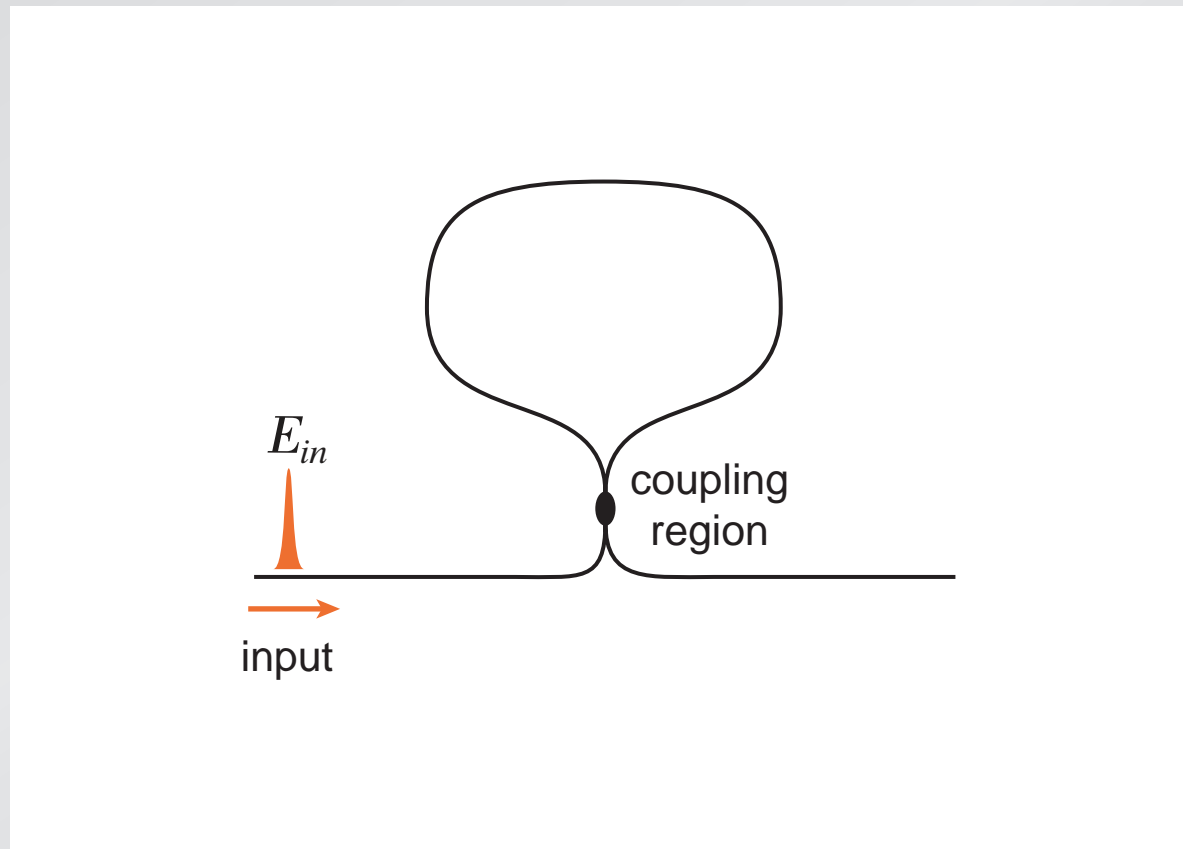
Optical logic gates

output = transmitted cw + ccw power



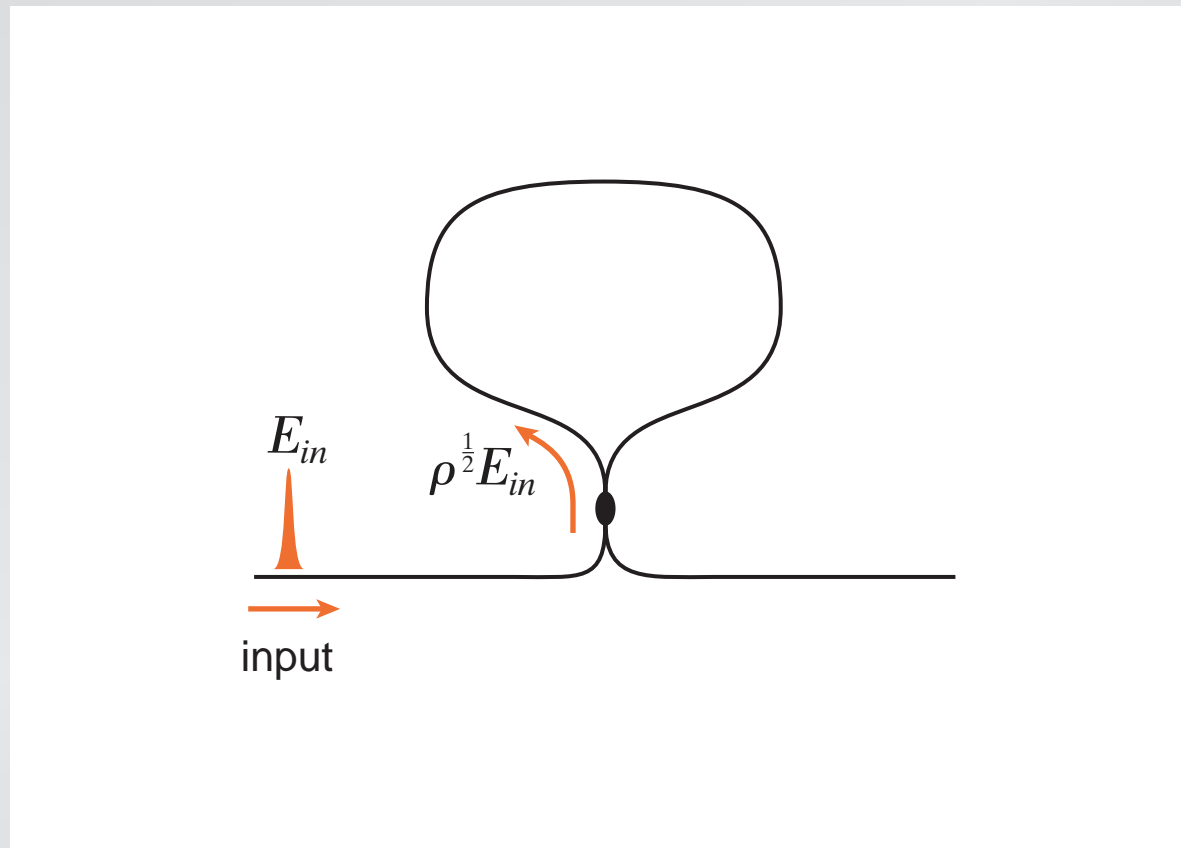
Optical logic gates

input electric field amplitude E_{in}



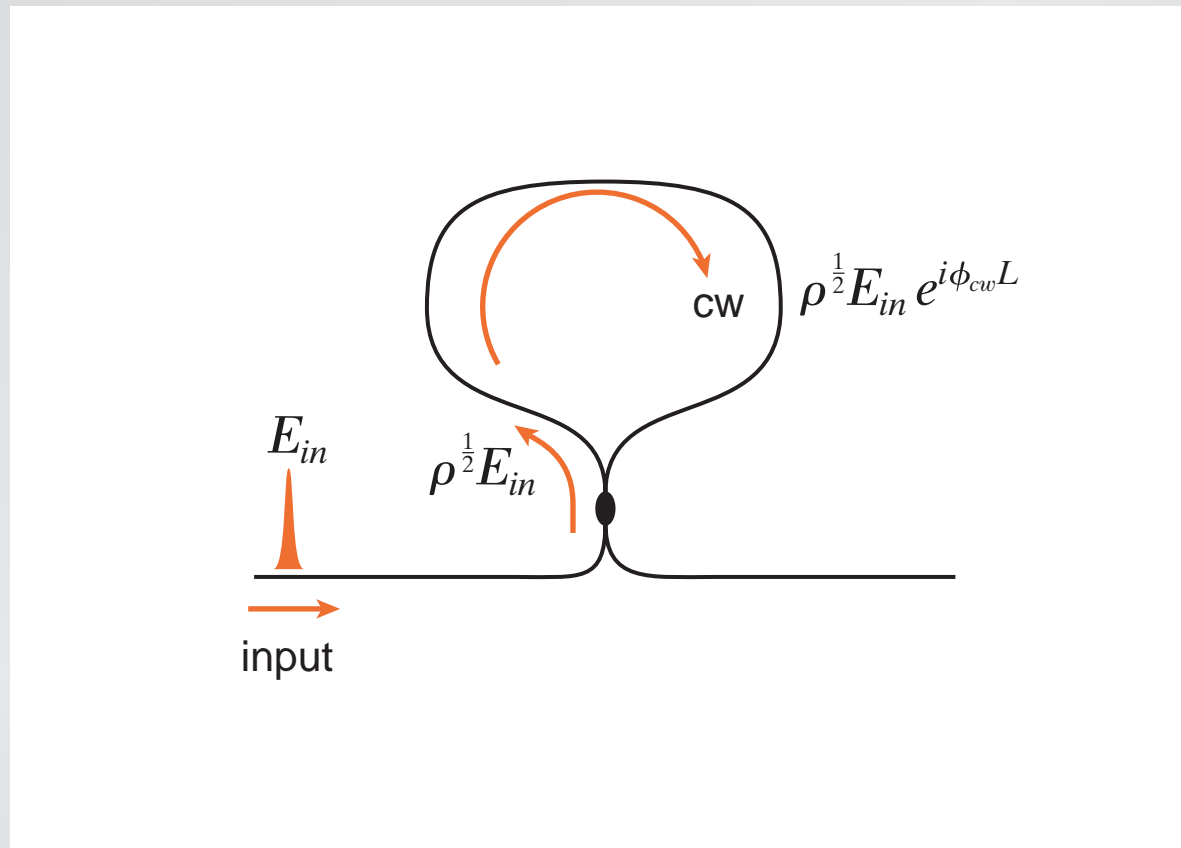
Optical logic gates

coupling parameter: ρ



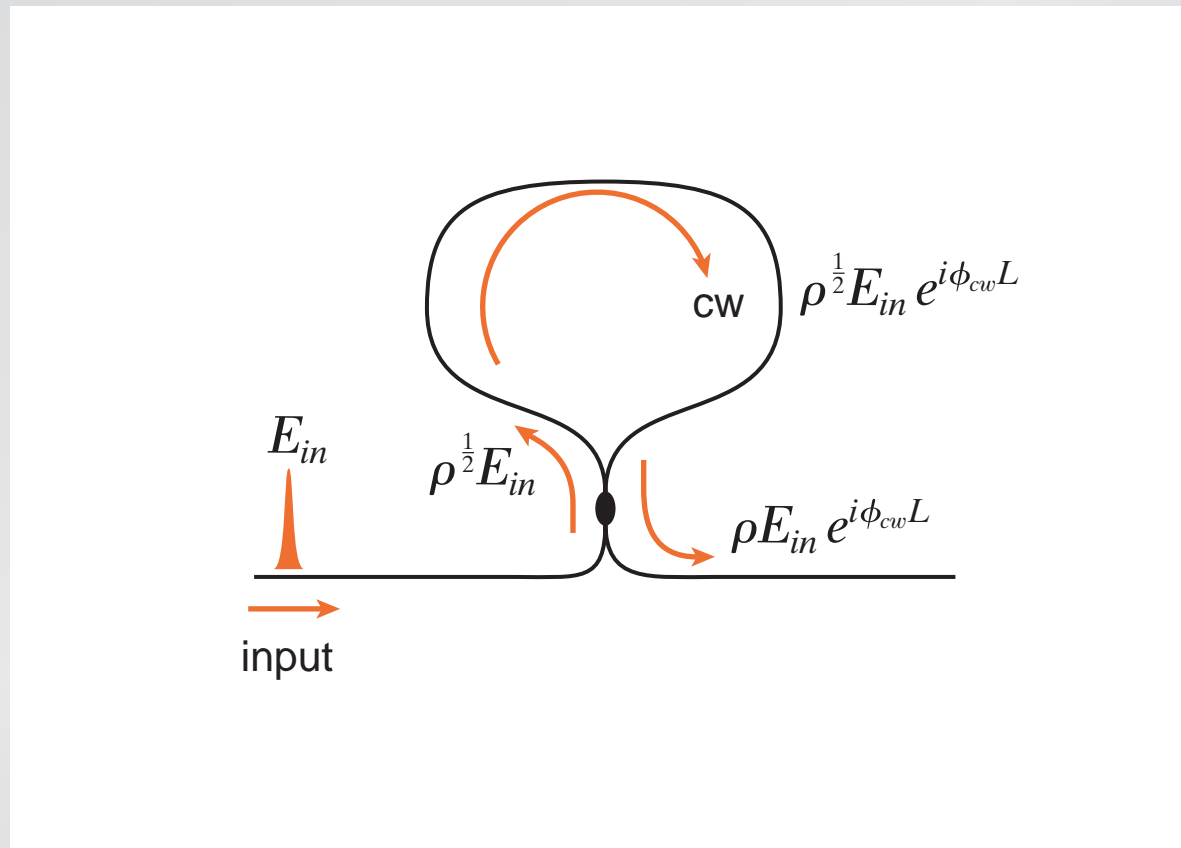
Optical logic gates

phase accumulation over path length of loop L



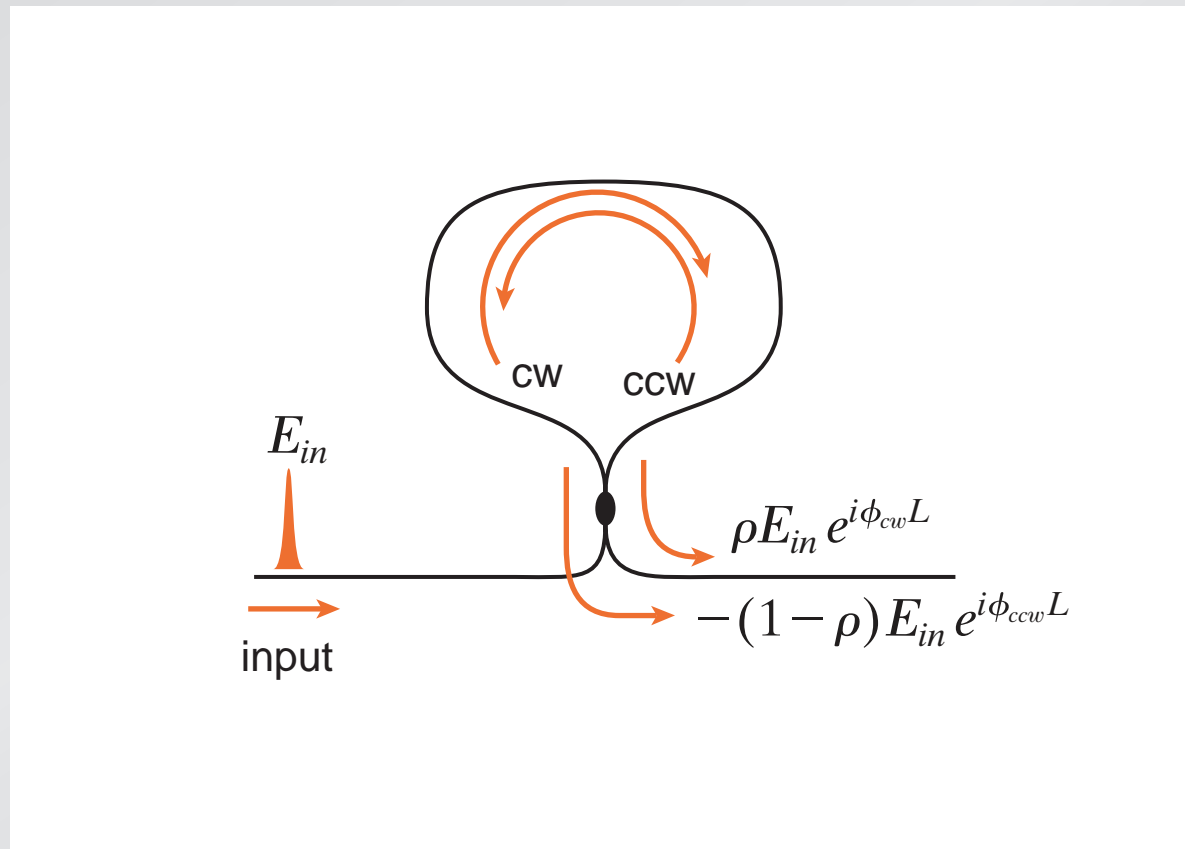
Optical logic gates

coupling parameter: ρ



Optical logic gates

output is sum of transmitted cw and ccw



Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n$$

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:

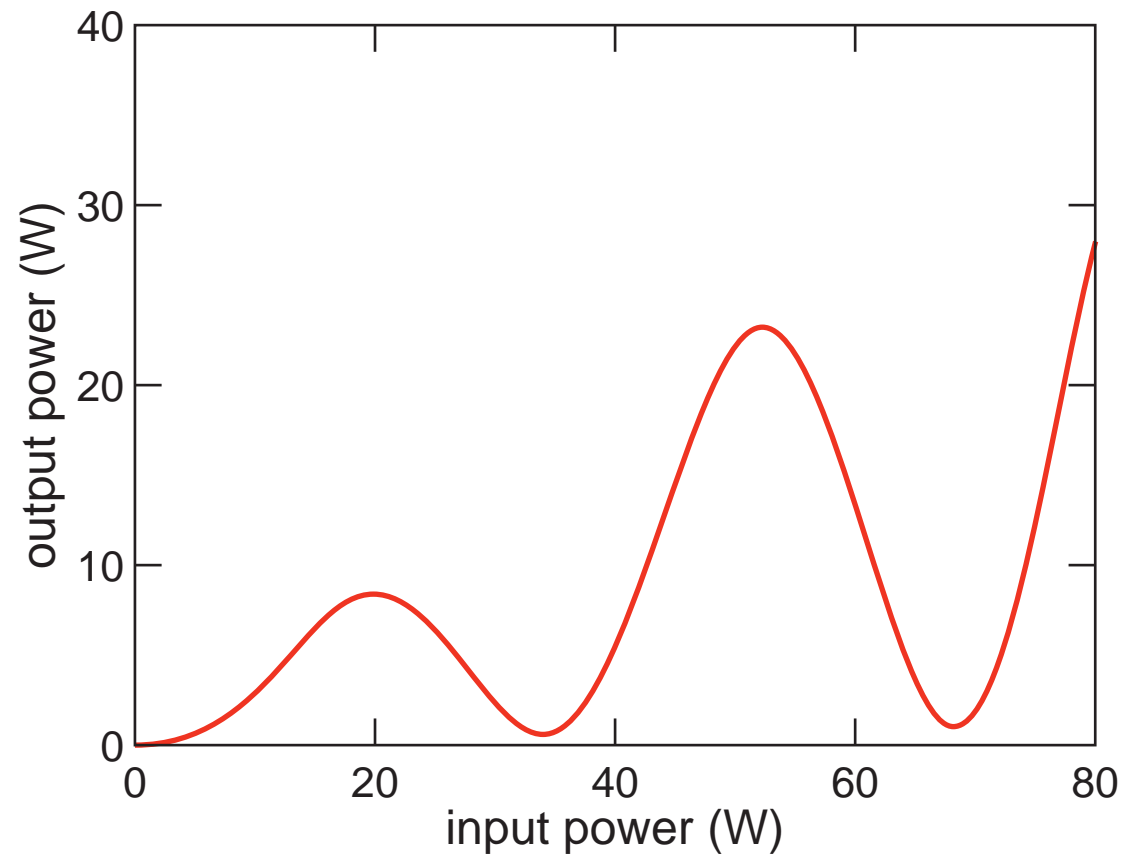
$$\rho = 0.5$$

no transmission:

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

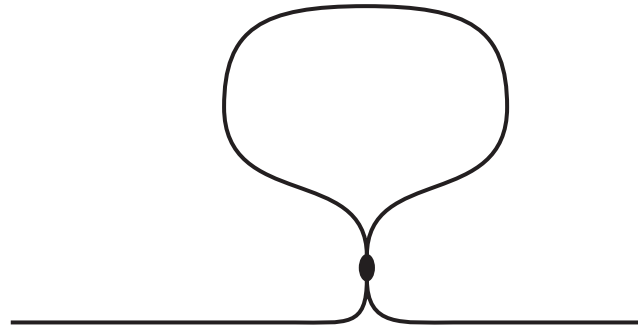
Optical logic gates

when $\rho \neq 0.5$:



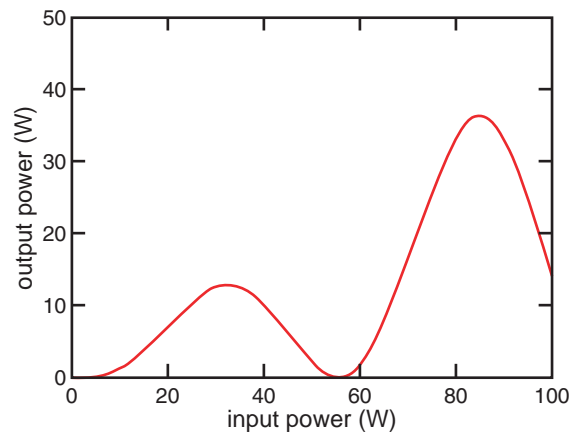
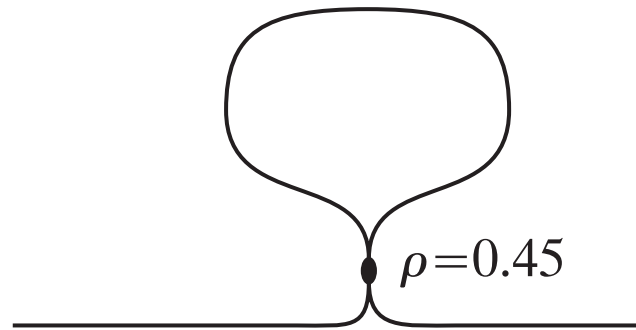
Optical logic gates

nonlinear nanogate



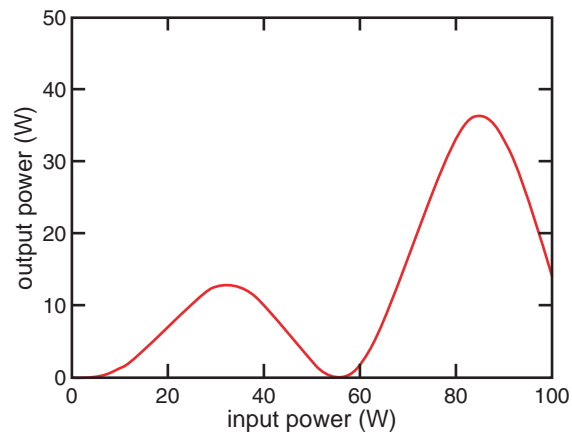
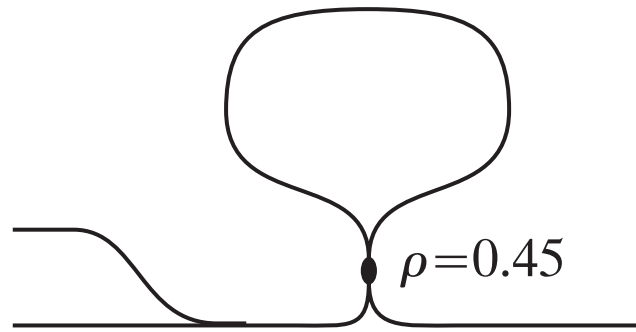
Optical logic gates

nonlinear nanogate



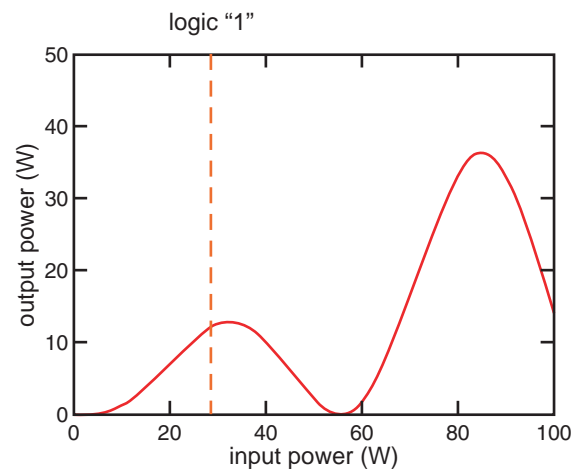
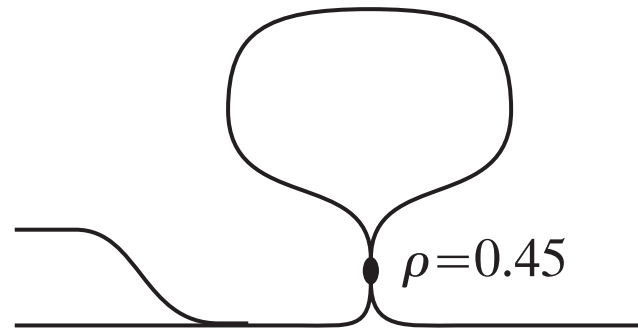
Optical logic gates

nonlinear nanogate



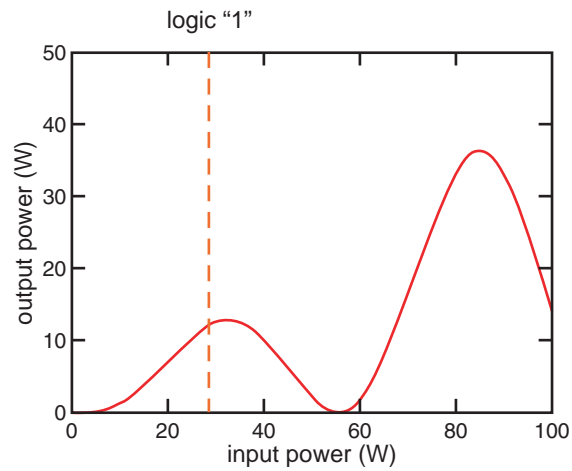
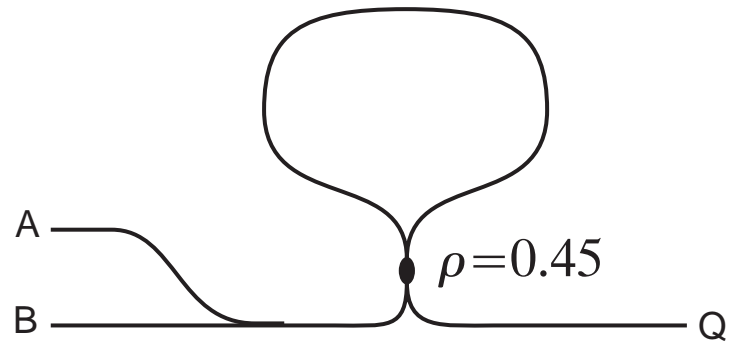
Optical logic gates

nonlinear nanogate



Optical logic gates

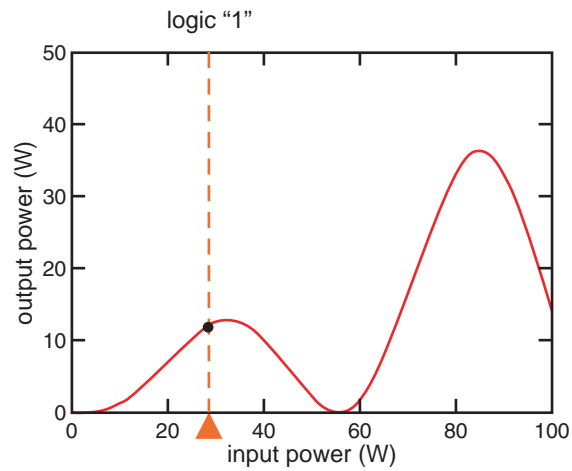
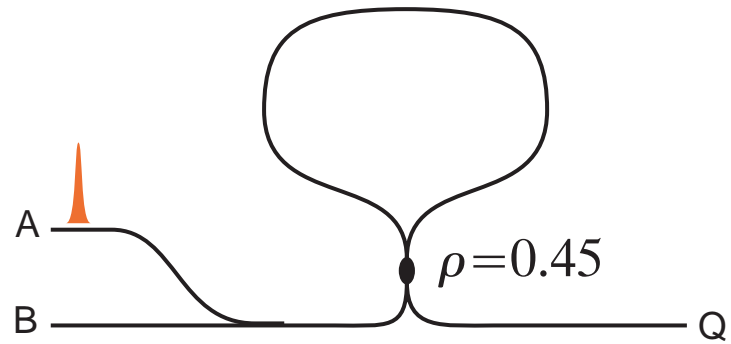
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

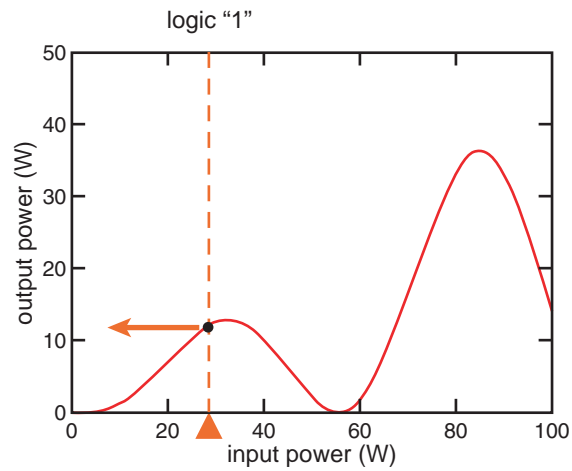
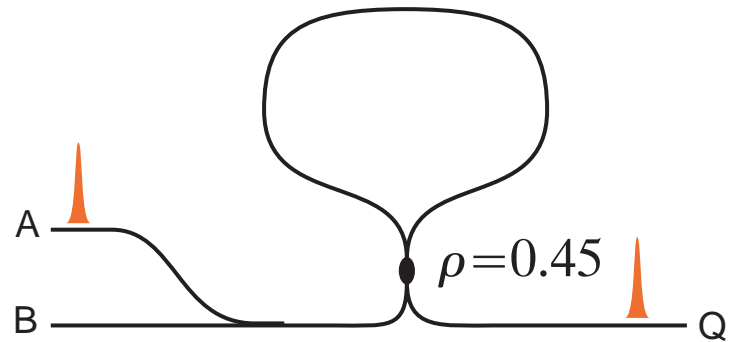
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

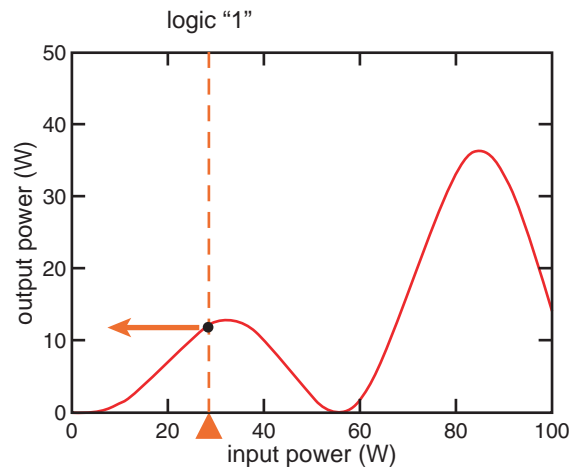
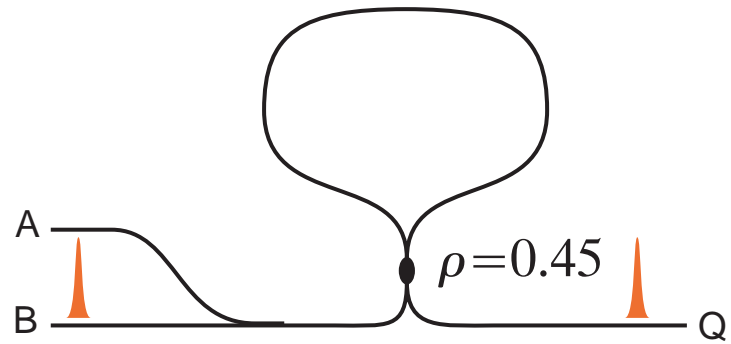
nonlinear nanogate



A	B	Q
0	0	0
1	0	1

Optical logic gates

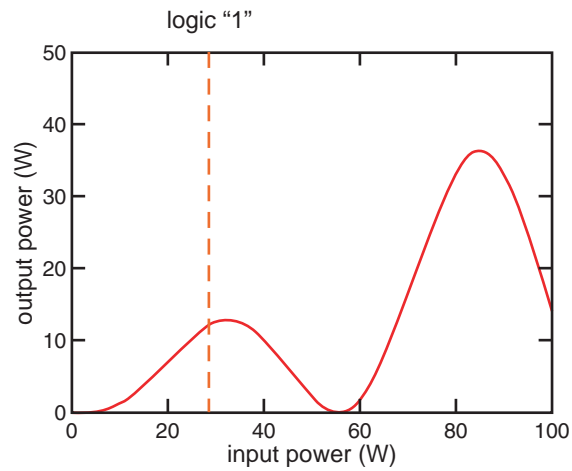
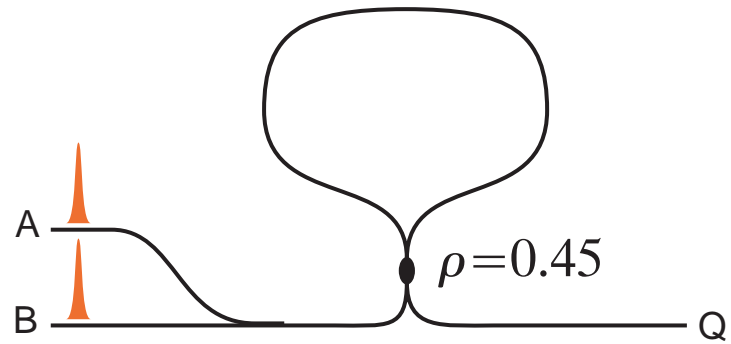
nonlinear nanogate



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

Optical logic gates

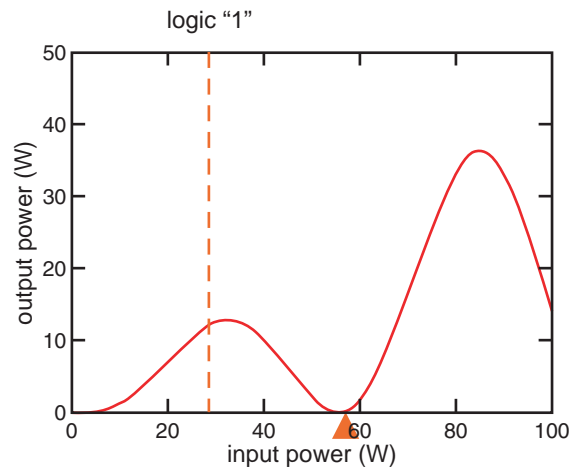
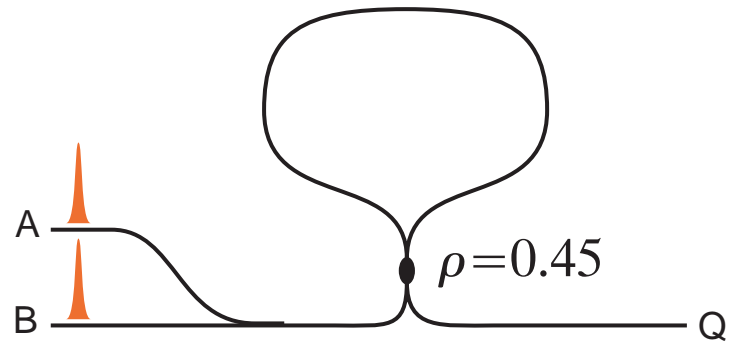
nonlinear nanogate



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

Optical logic gates

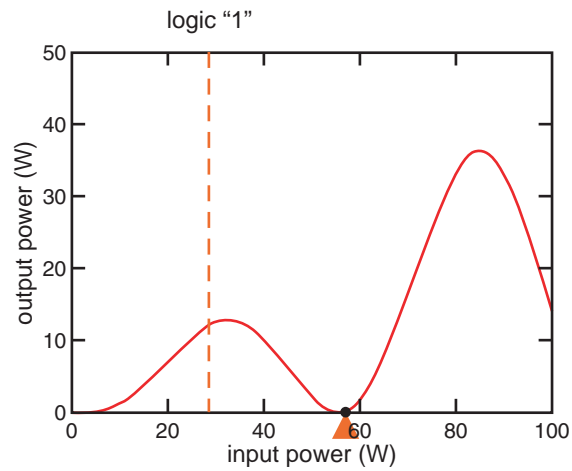
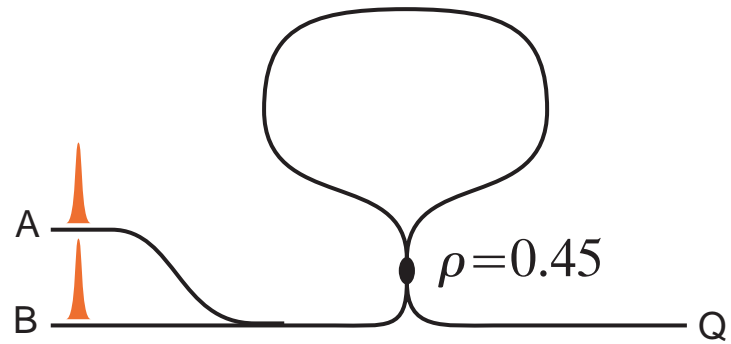
nonlinear nanogate



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

Optical logic gates

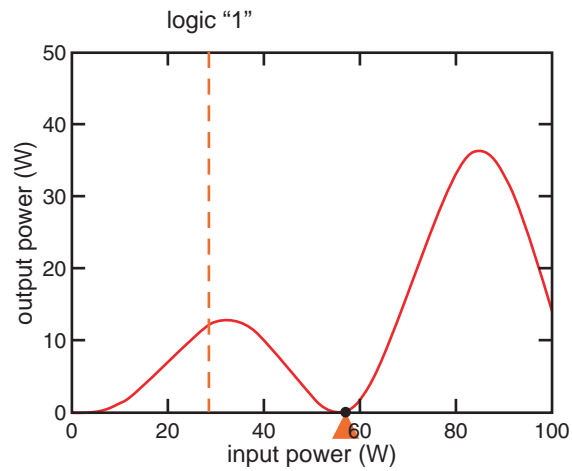
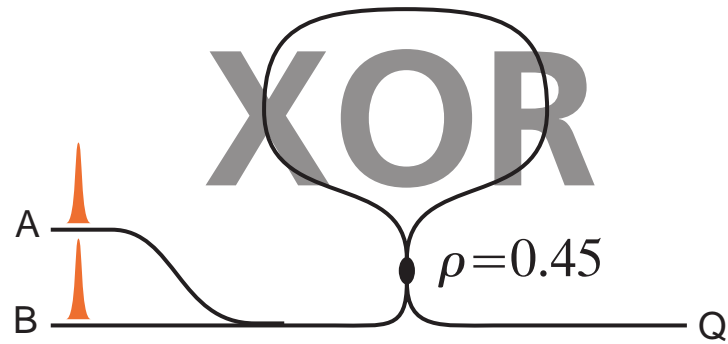
nonlinear nanogate



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

Optical logic gates

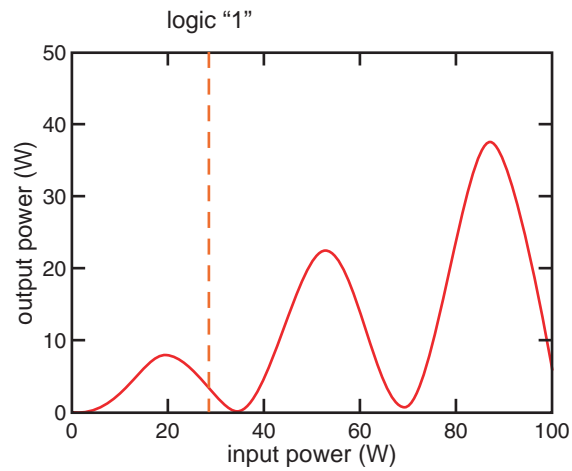
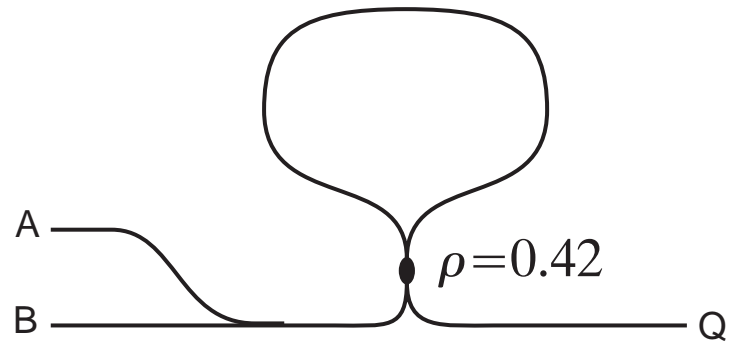
nonlinear nanogate



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

Optical logic gates

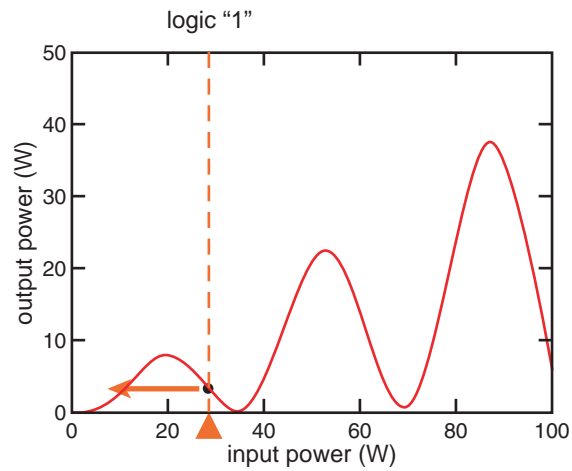
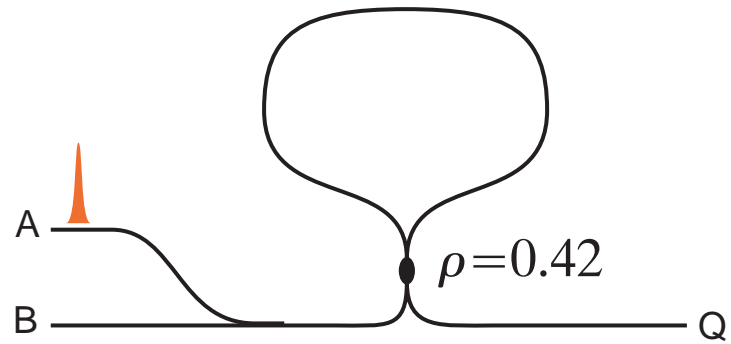
nonlinear nanogate



A	B	Q
0	0	0

Optical logic gates

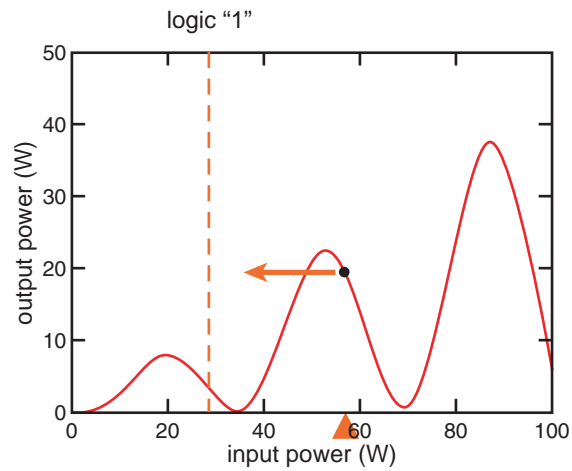
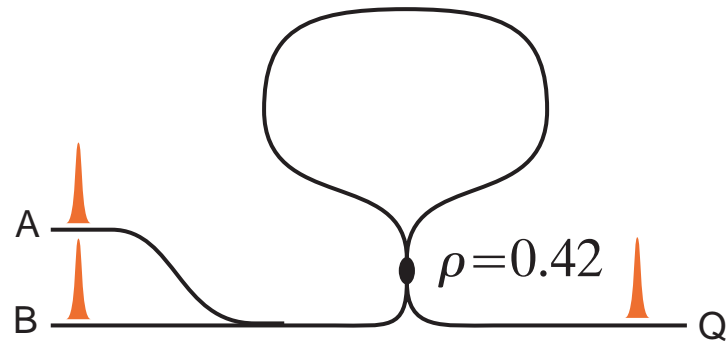
nonlinear nanogate



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

Optical logic gates

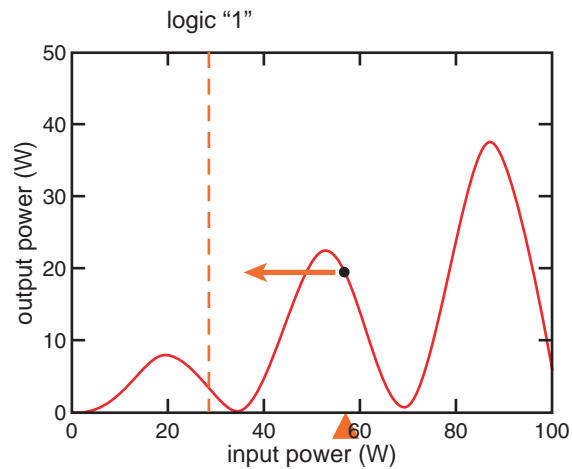
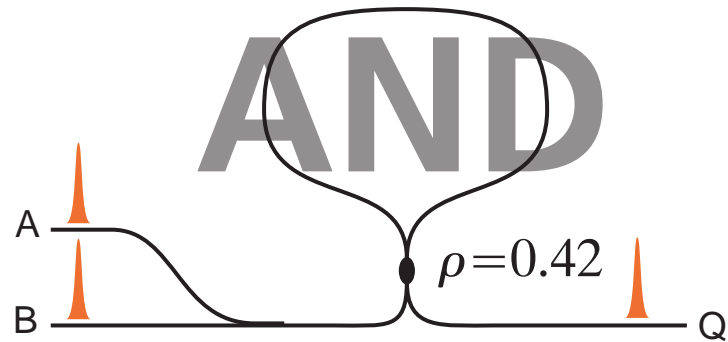
nonlinear nanogate



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

Optical logic gates

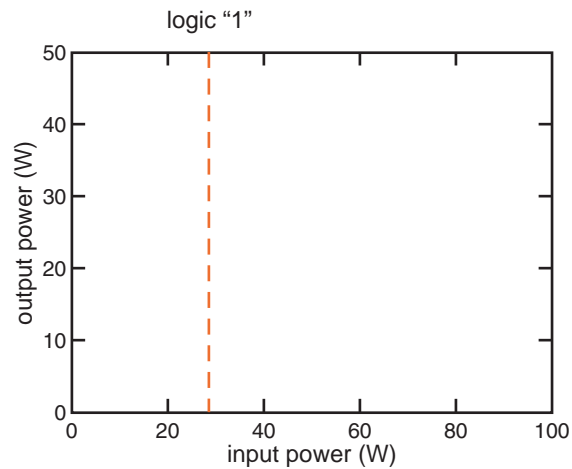
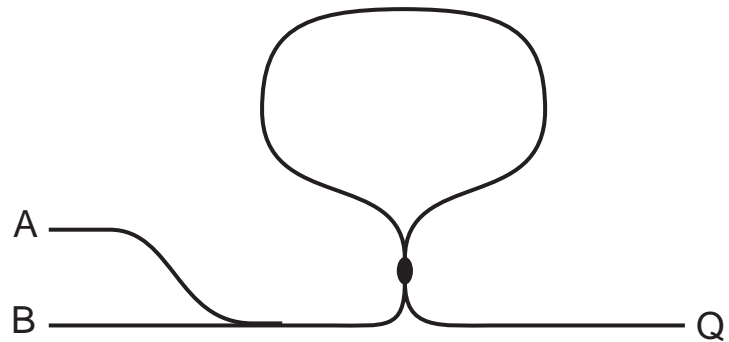
nonlinear nanogate



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

Optical logic gates

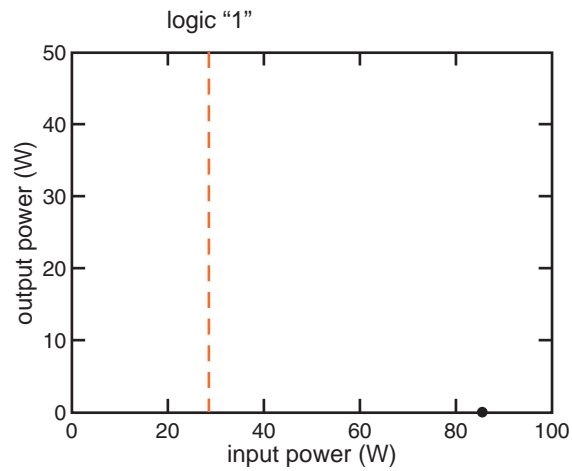
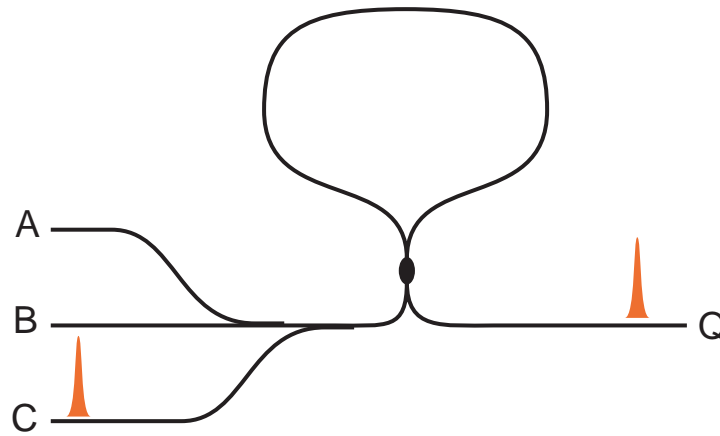
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

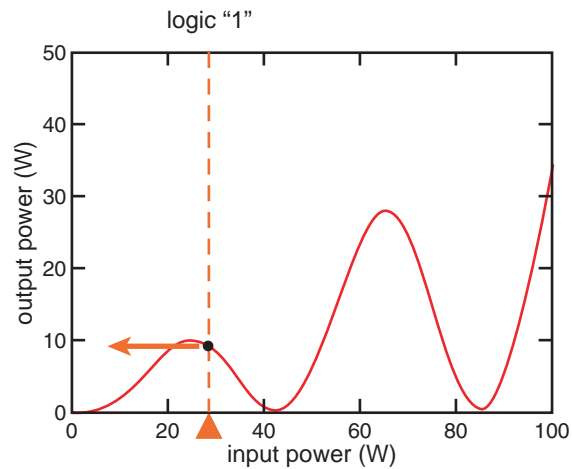
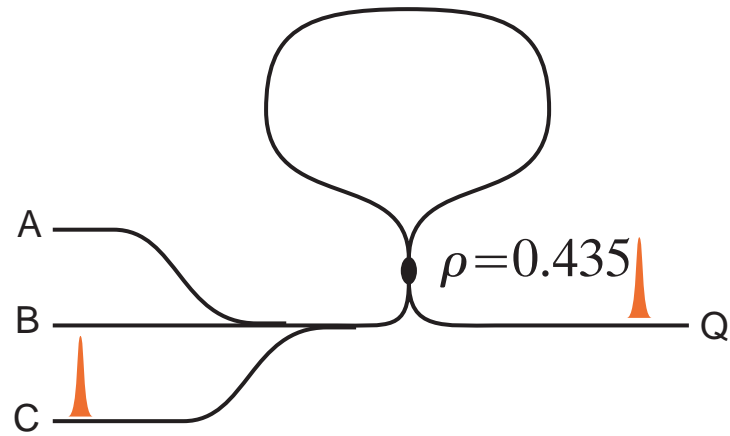
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

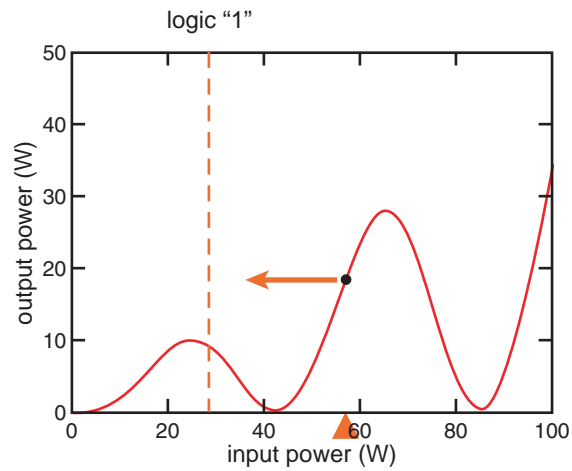
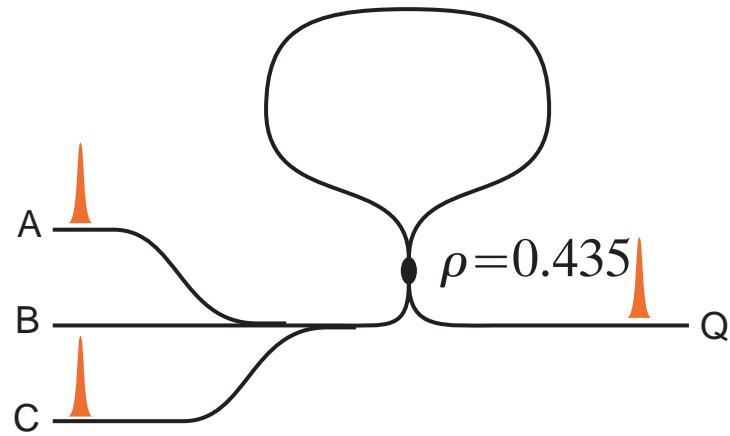
for NAND gate need output with no input



A	B	Q
0	0	1

Optical logic gates

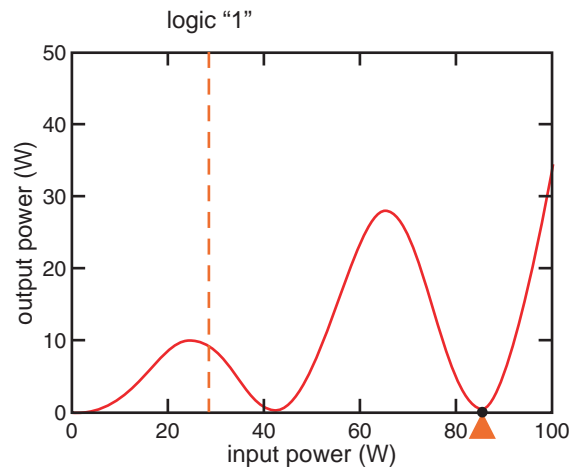
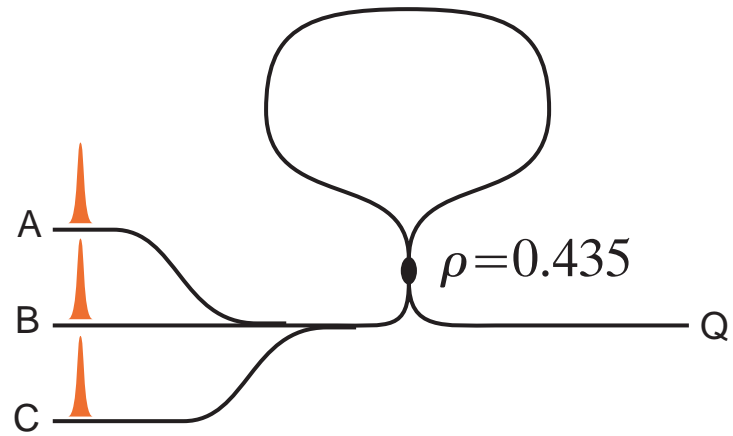
universal NAND gate



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

Optical logic gates

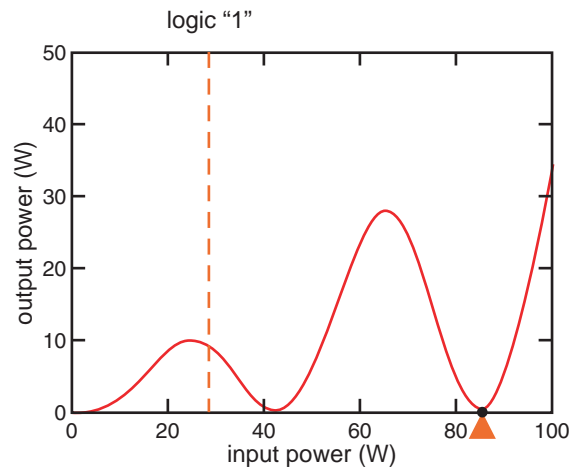
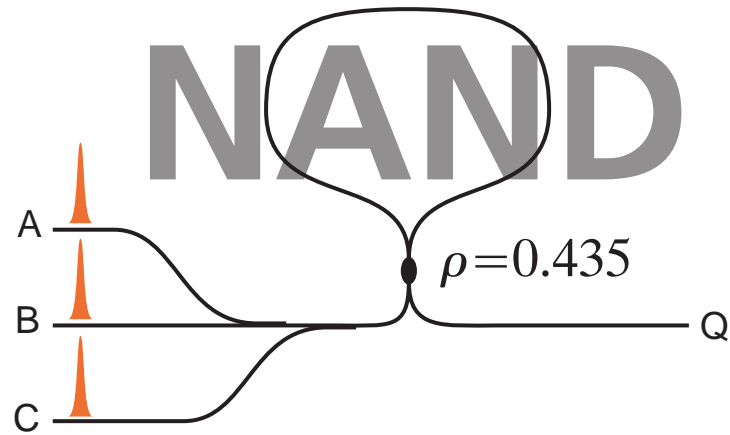
universal NAND gate



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

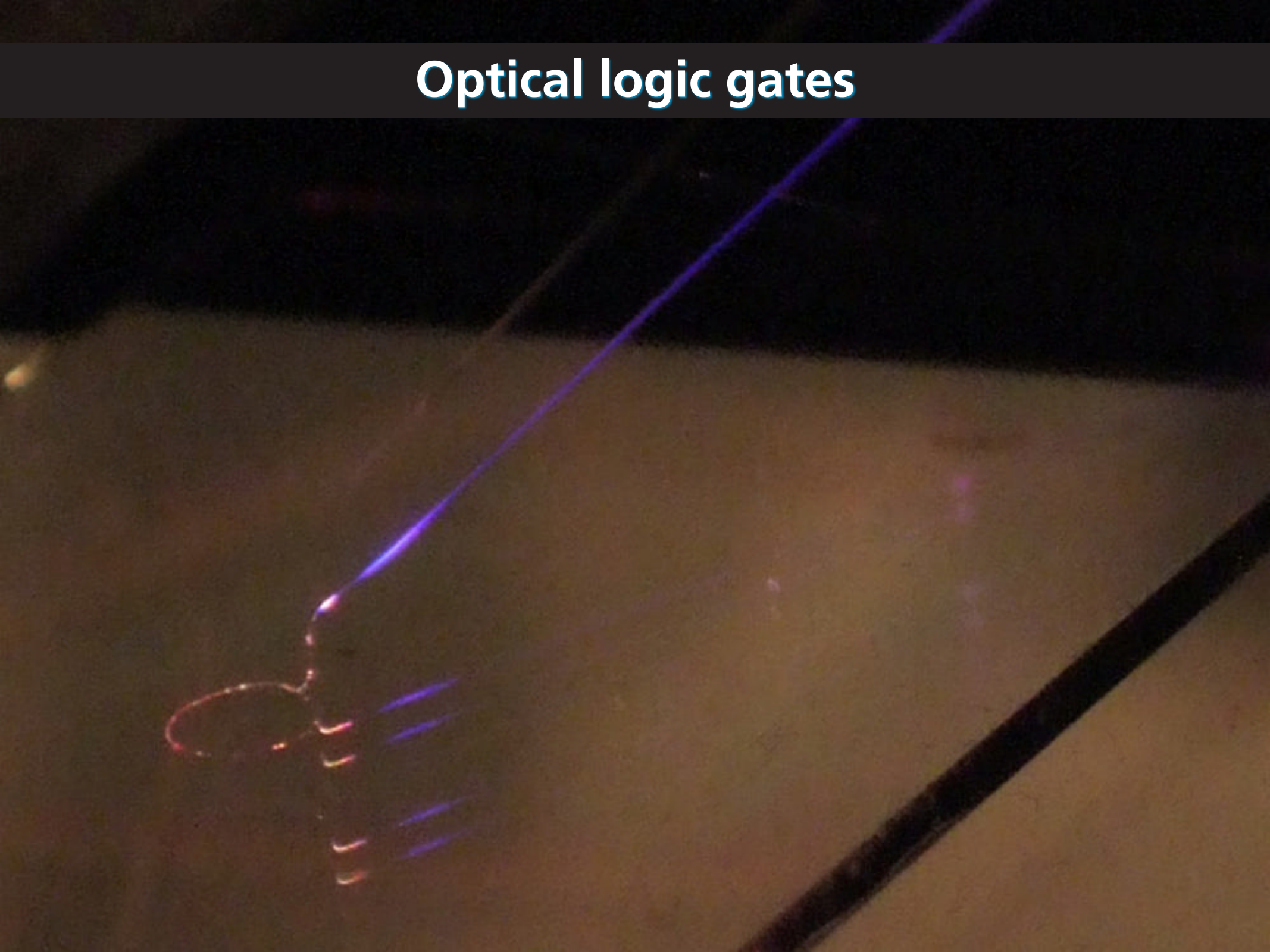
Optical logic gates

universal NAND gate



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

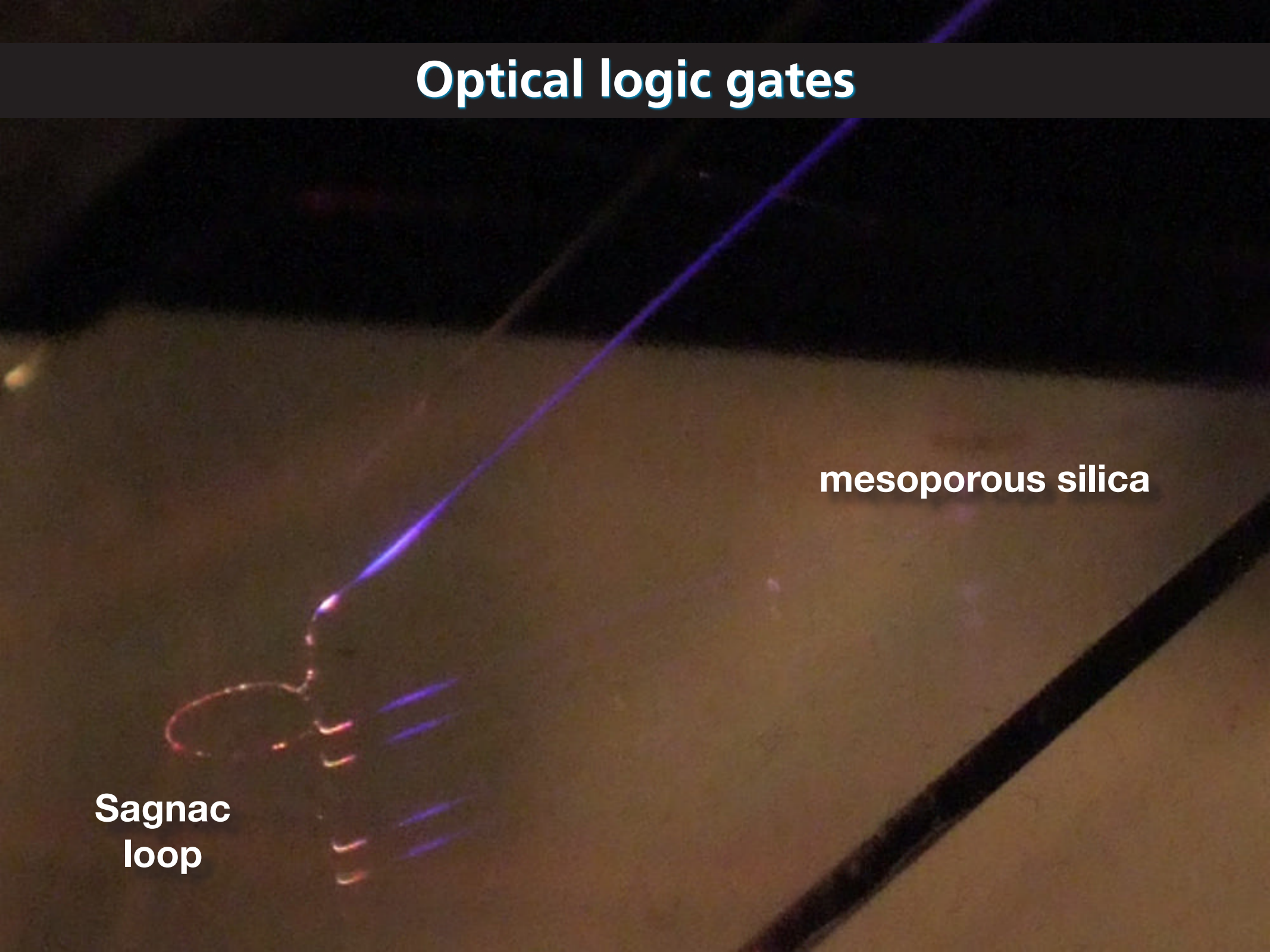
Optical logic gates



Optical logic gates

mesoporous silica

Sagnac
loop



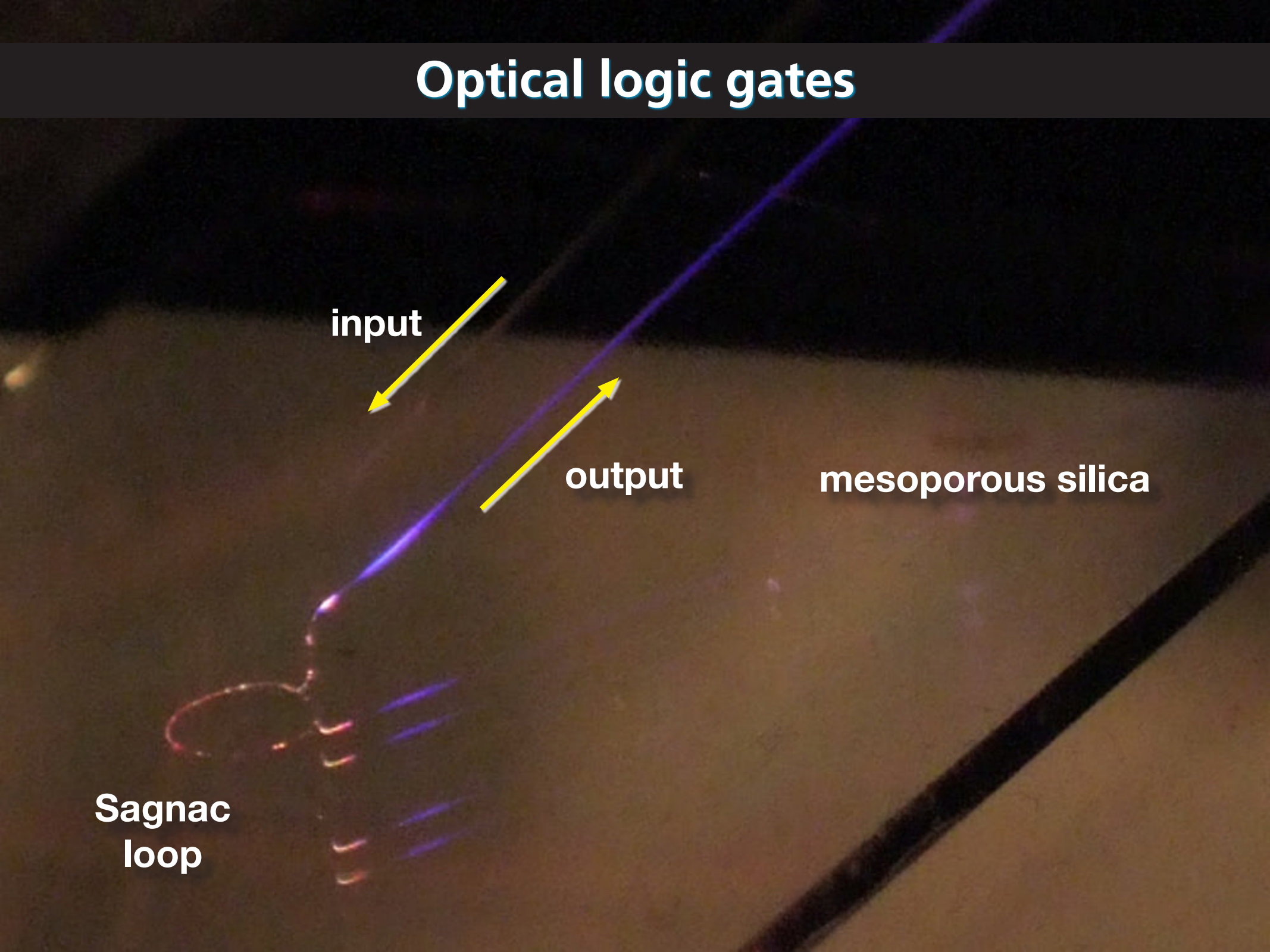
Optical logic gates

input

output

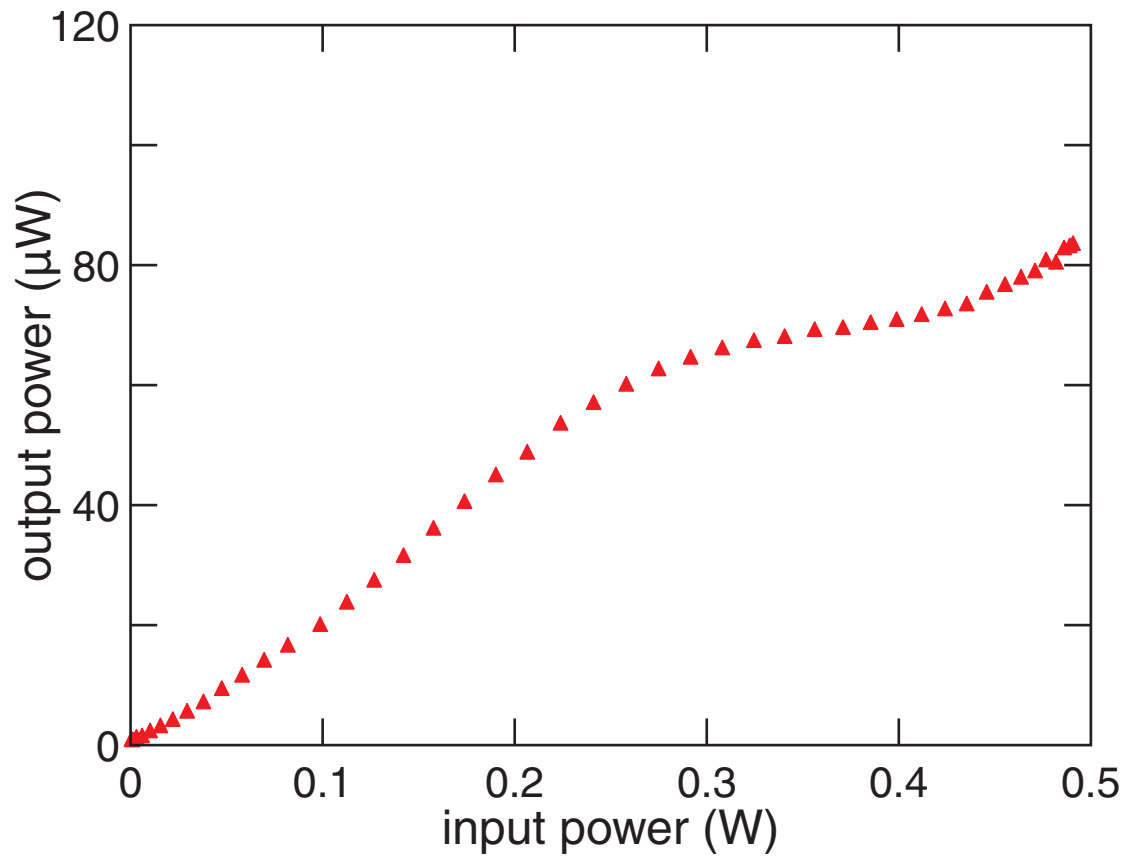
mesoporous silica

Sagnac
loop



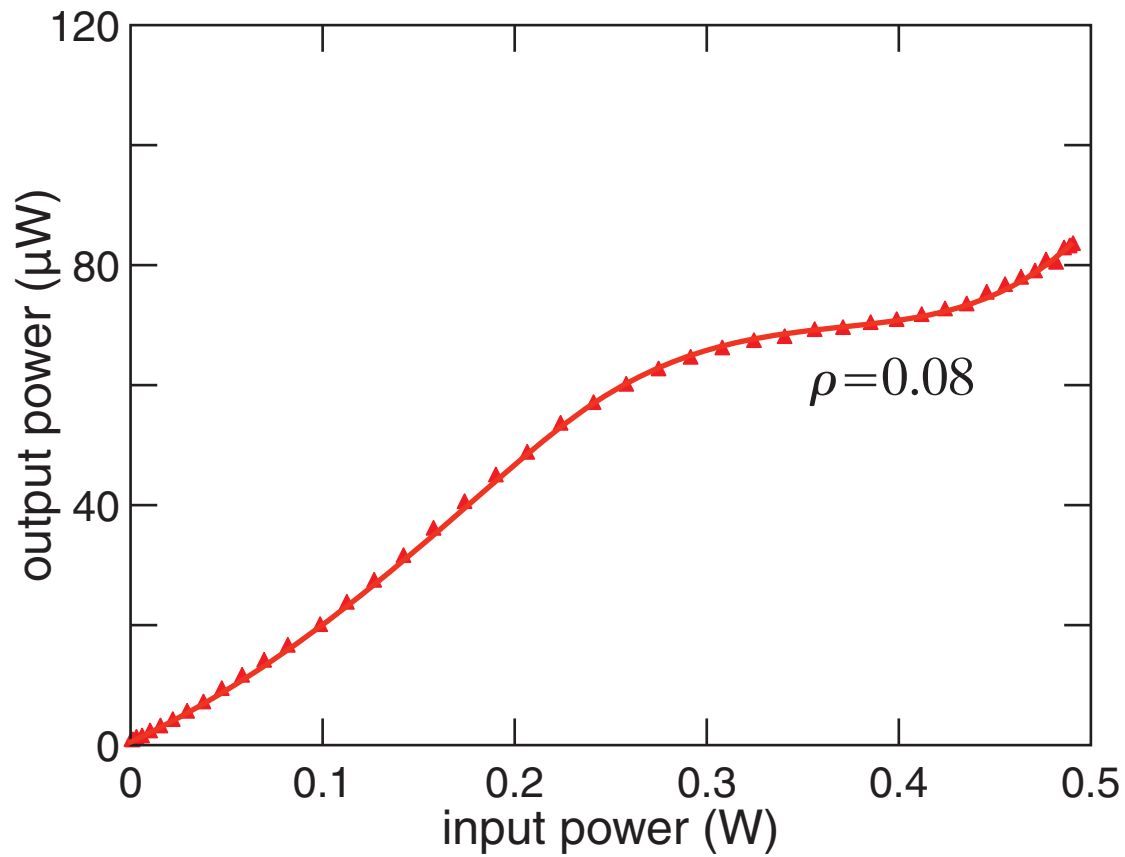
Optical logic gates

very preliminary data



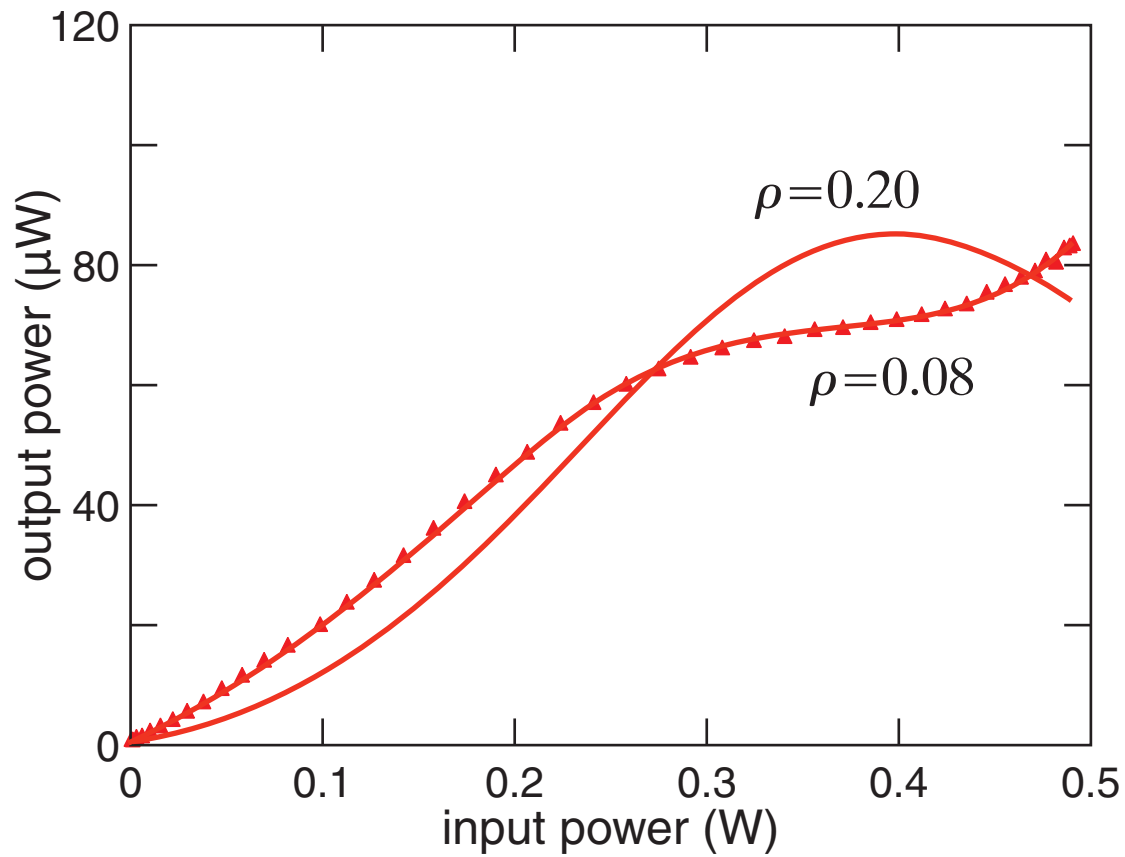
Optical logic gates

very preliminary data



Optical logic gates

very preliminary data



Optical logic gates

we're almost there!

Summary



Summary

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





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National Science Foundation

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