

# Nonlinear optics at the nanoscale



Temple University  
Philadelphia, PA, 21 September 2009





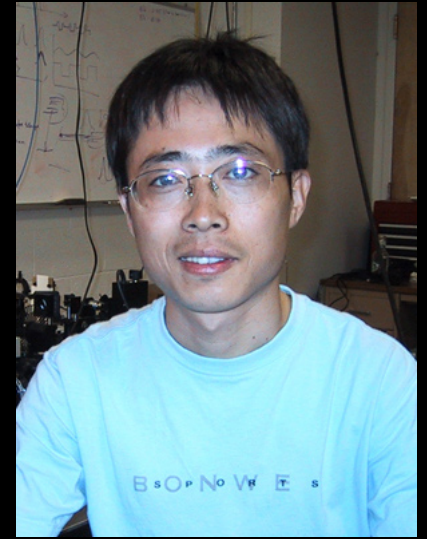
**Geoff Svacha**



**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)**

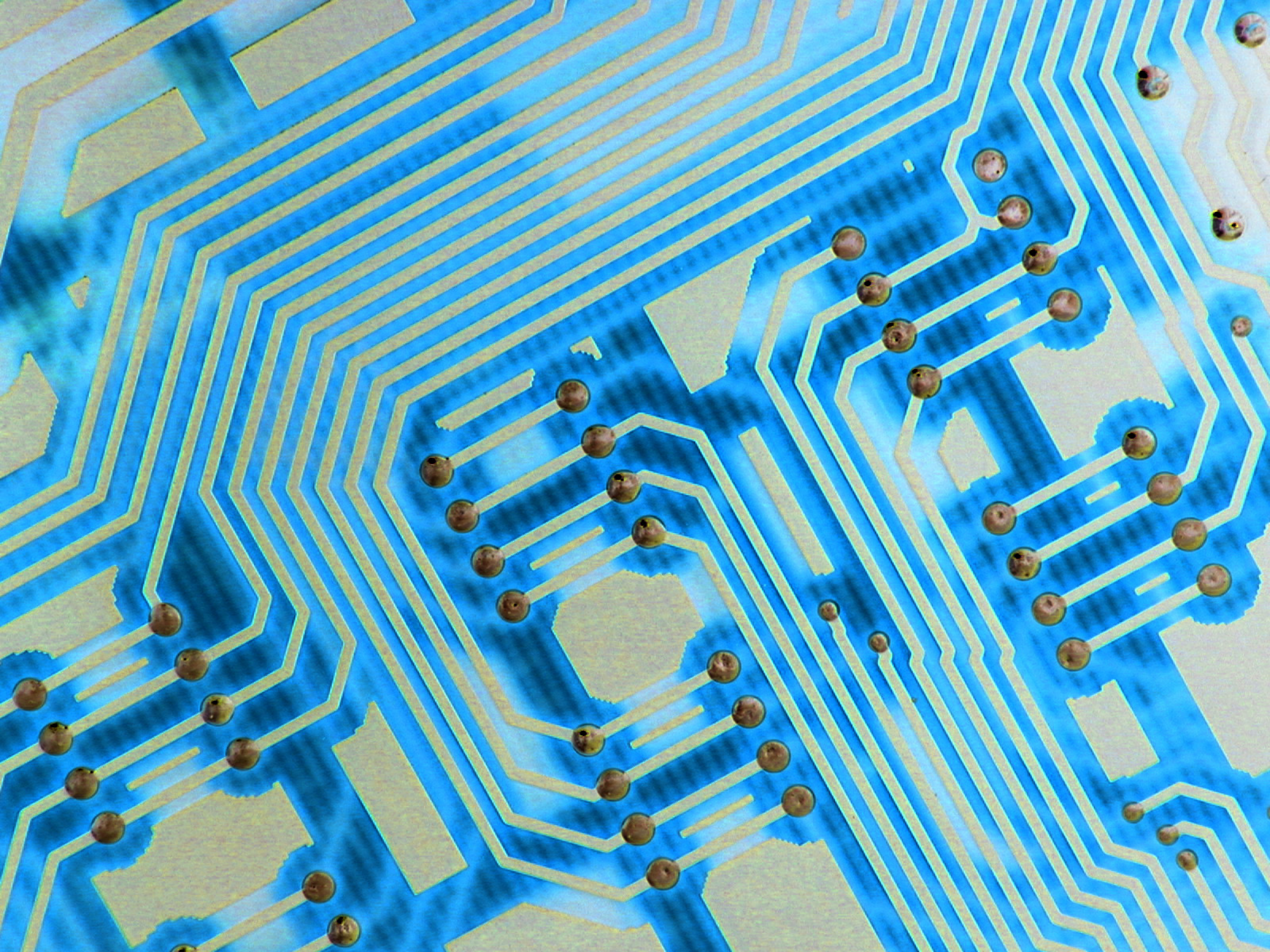
**Dr. Jingyi Lou (Zhejiang)**

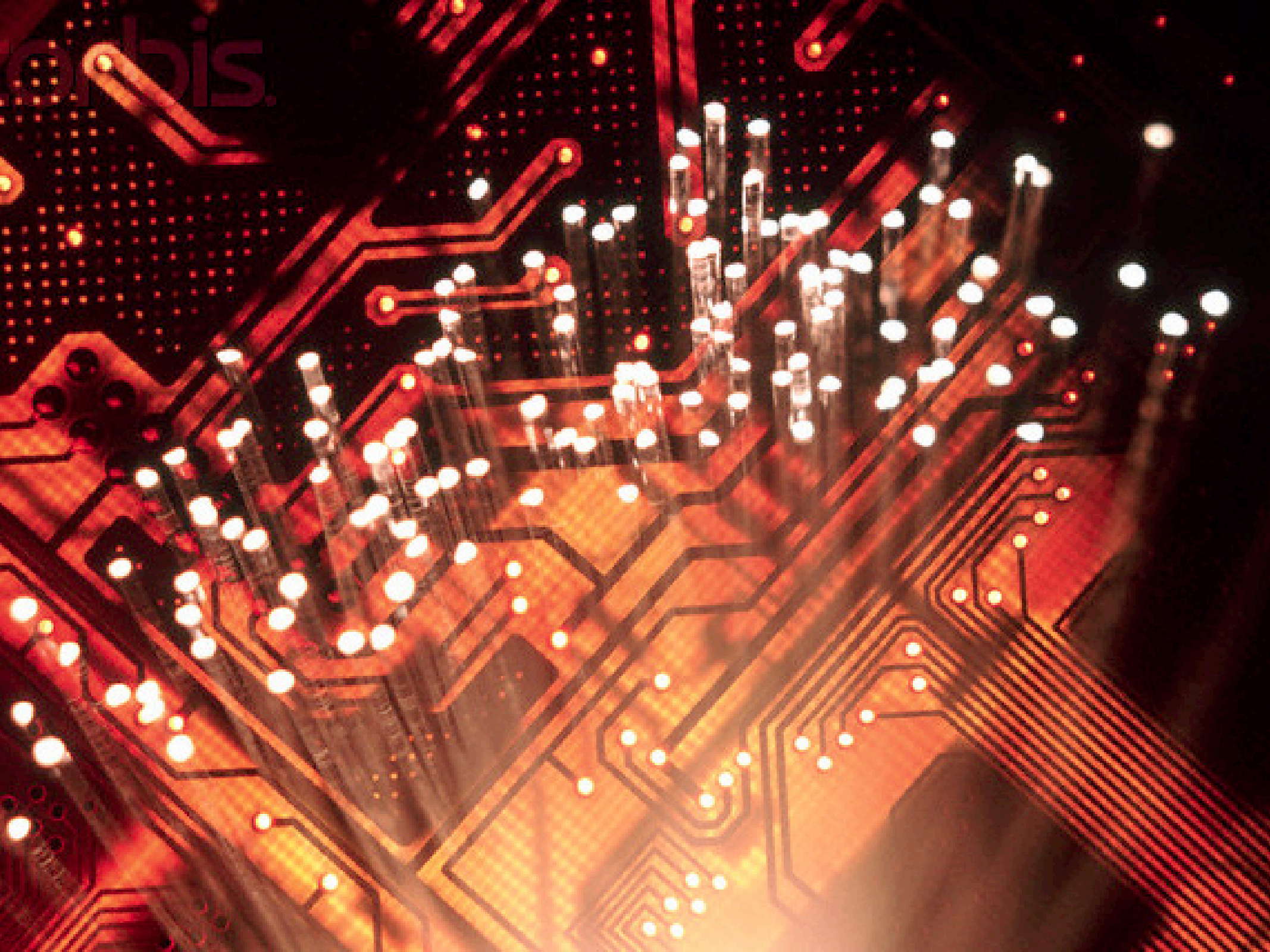
**Dr. Ray Mariella (LLNL)**

**Prof. Frank Marlow (MPI Mülheim)**

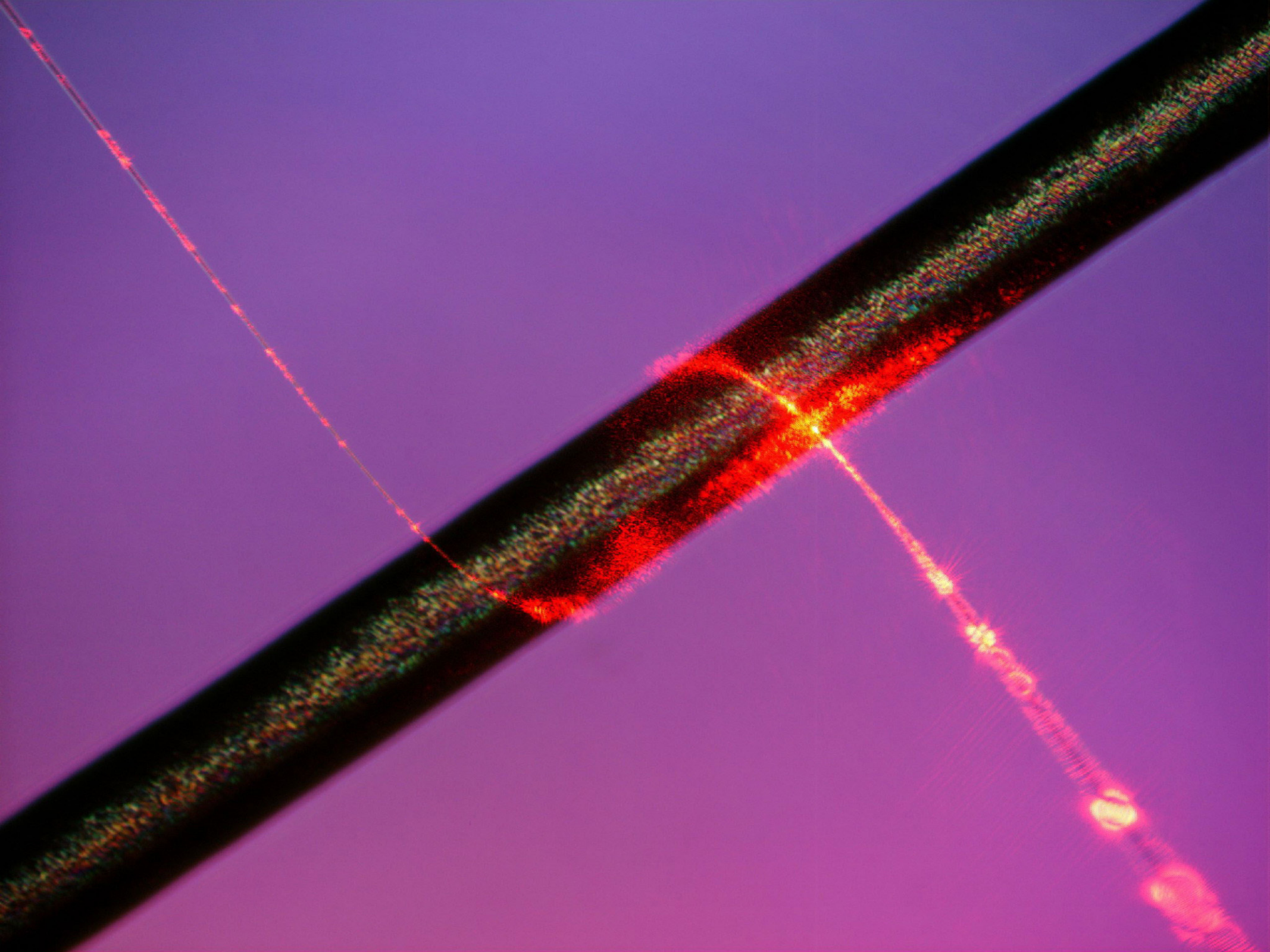
**Prof. Sven Müller (Göttingen)**

**Prof. Carsten Ronning (Göttingen)**





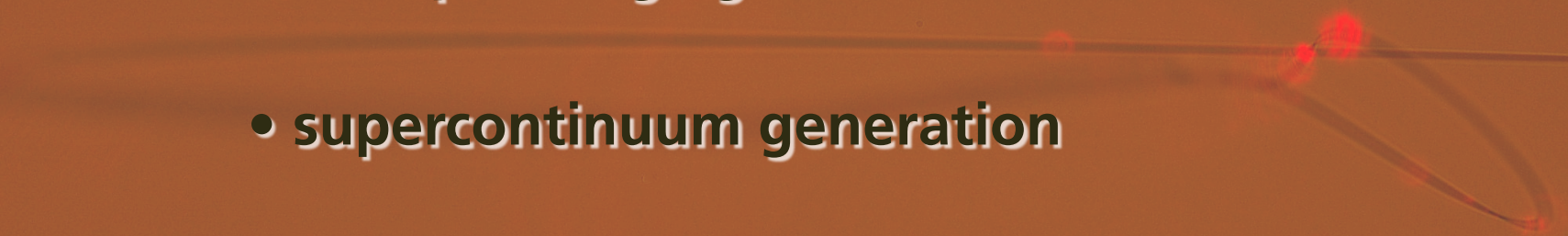
orbis.



# Outline



# Outline

- **manipulating light at the nanoscale**
  - **supercontinuum generation**
  - **optical logic gates**
- 
- A decorative graphic on the right side of the slide shows a thin, dark line representing a light path. It starts from the left, moves horizontally to the right, then curves downwards and loops back to the left. Several bright red spots are placed along this path, suggesting points of interest or interaction.



# Manipulating light at the nanoscale



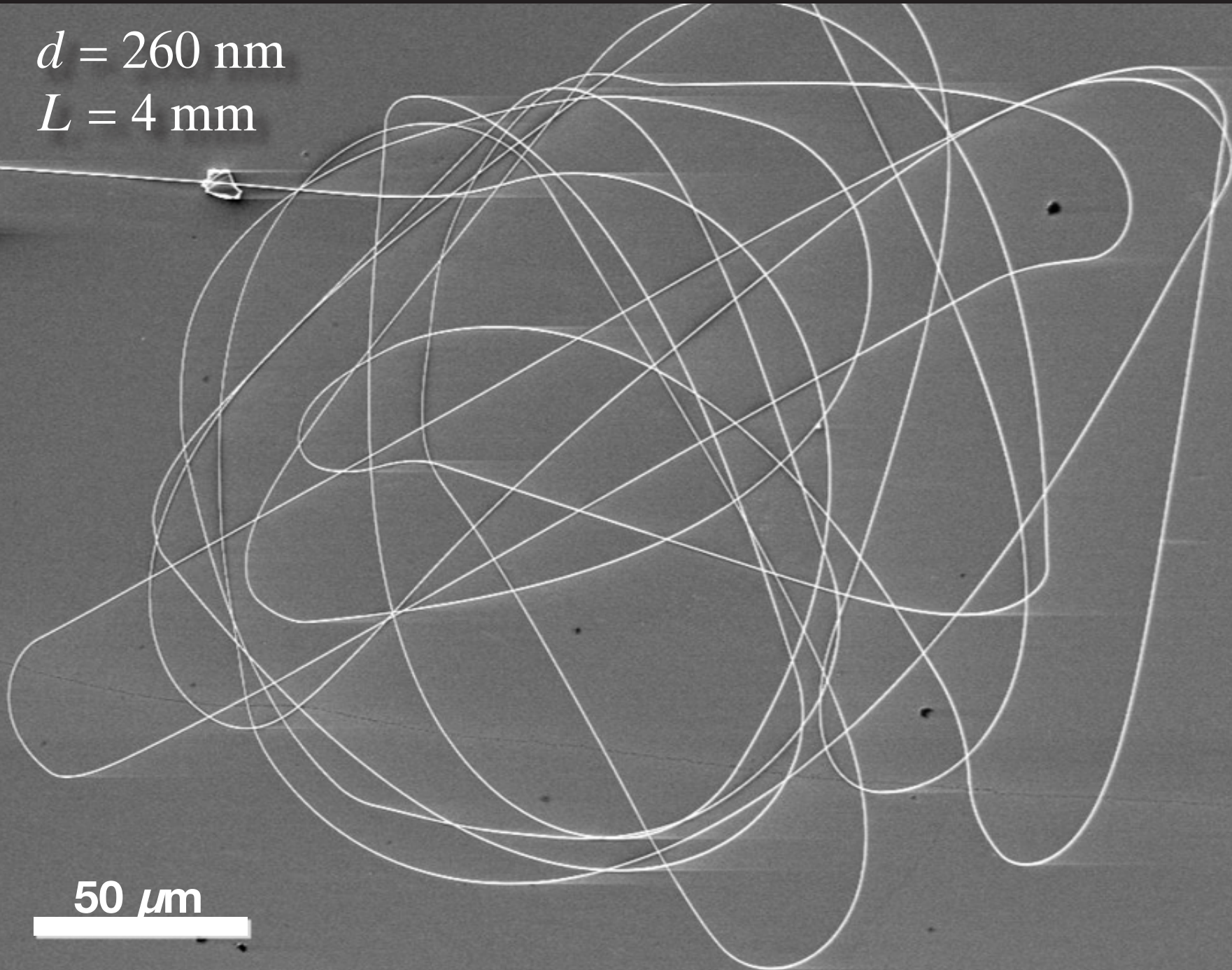
***Nature*, 426, 816 (2003)**



# Manipulating light at the nanoscale

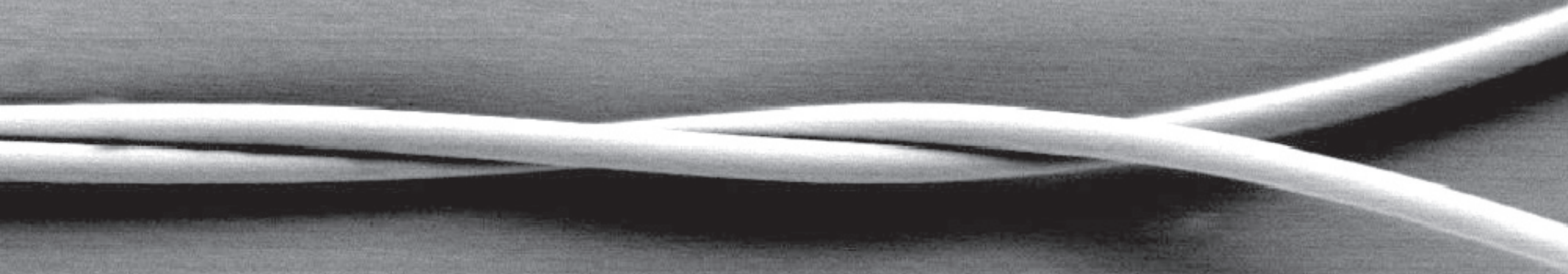
$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50  $\mu\text{m}$

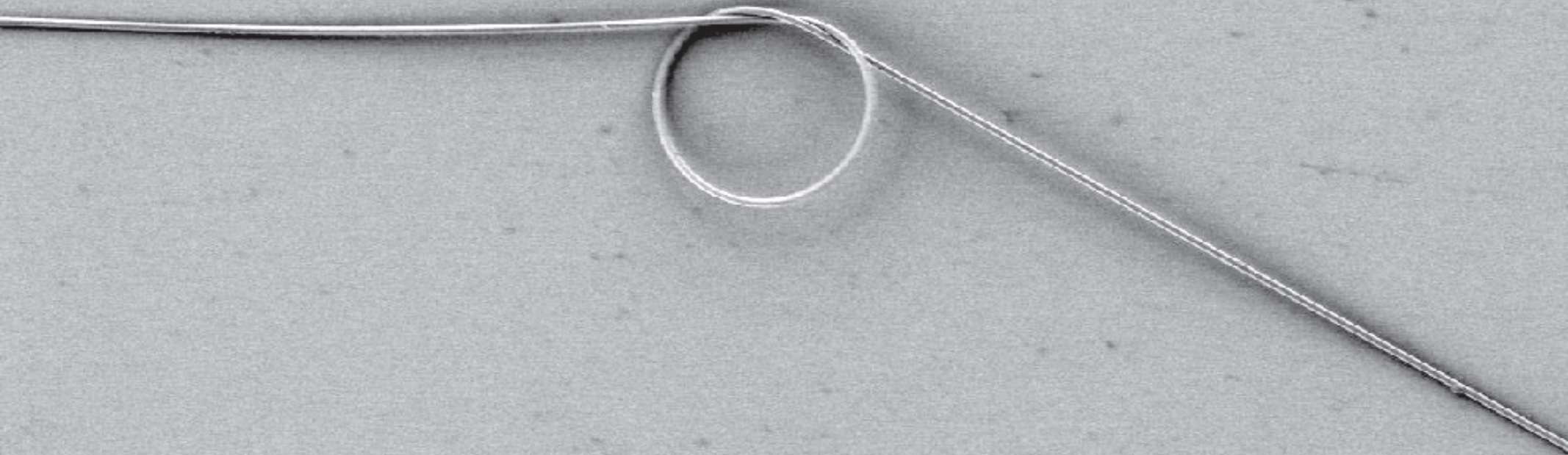
# Manipulating light at the nanoscale



2  $\mu\text{m}$



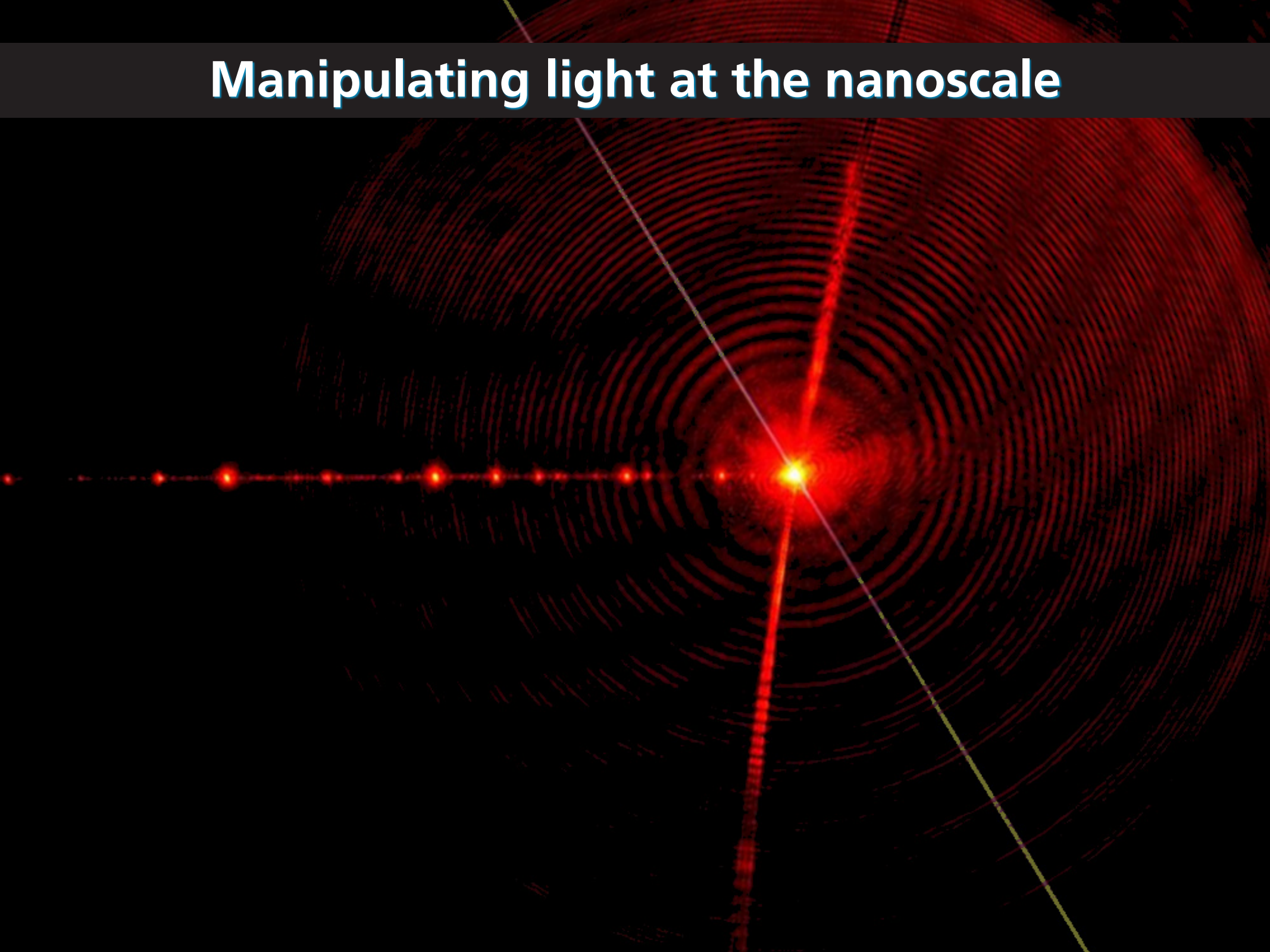
# Manipulating light at the nanoscale



20  $\mu\text{m}$

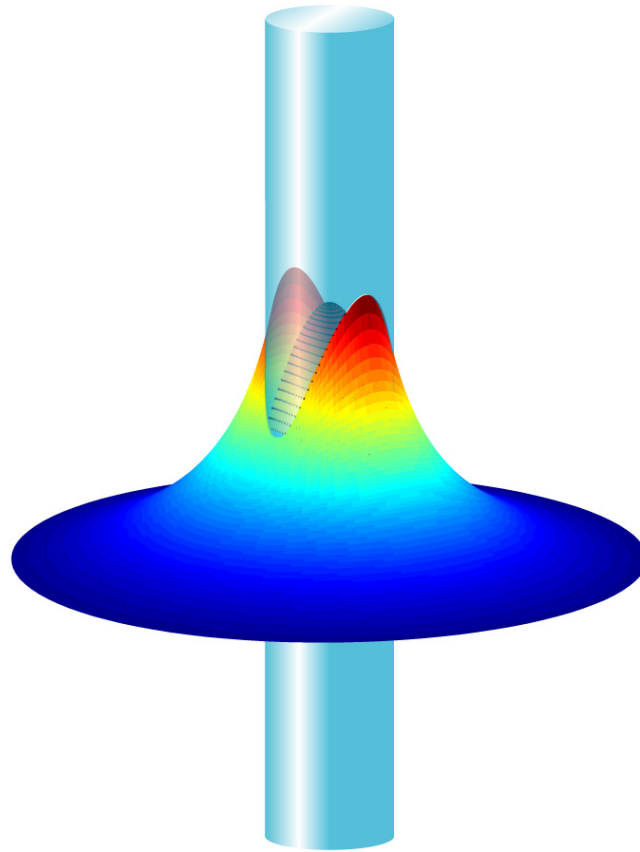


# Manipulating light at the nanoscale

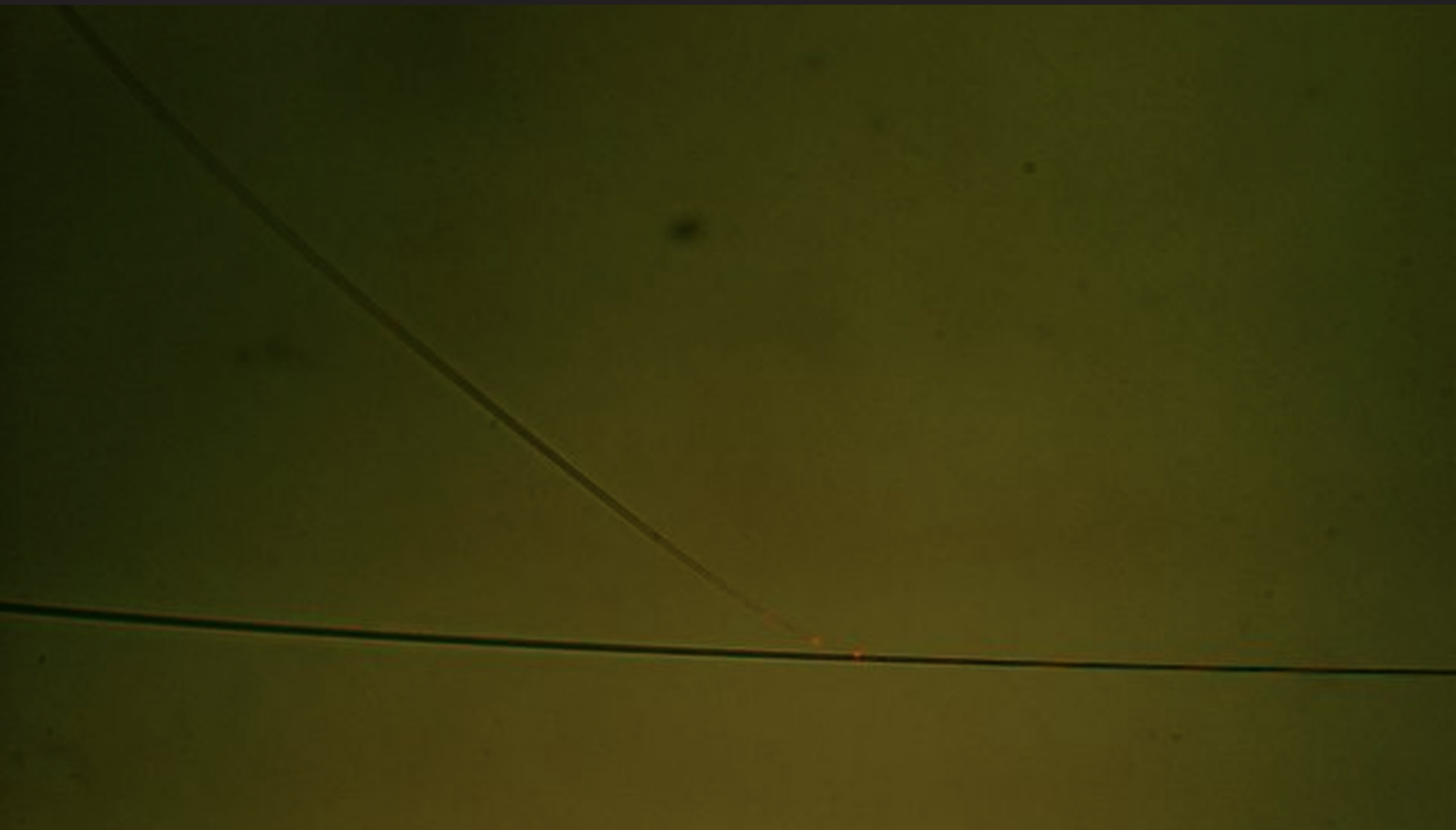


# Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



# Manipulating light at the nanoscale



**50  $\mu\text{m}$**

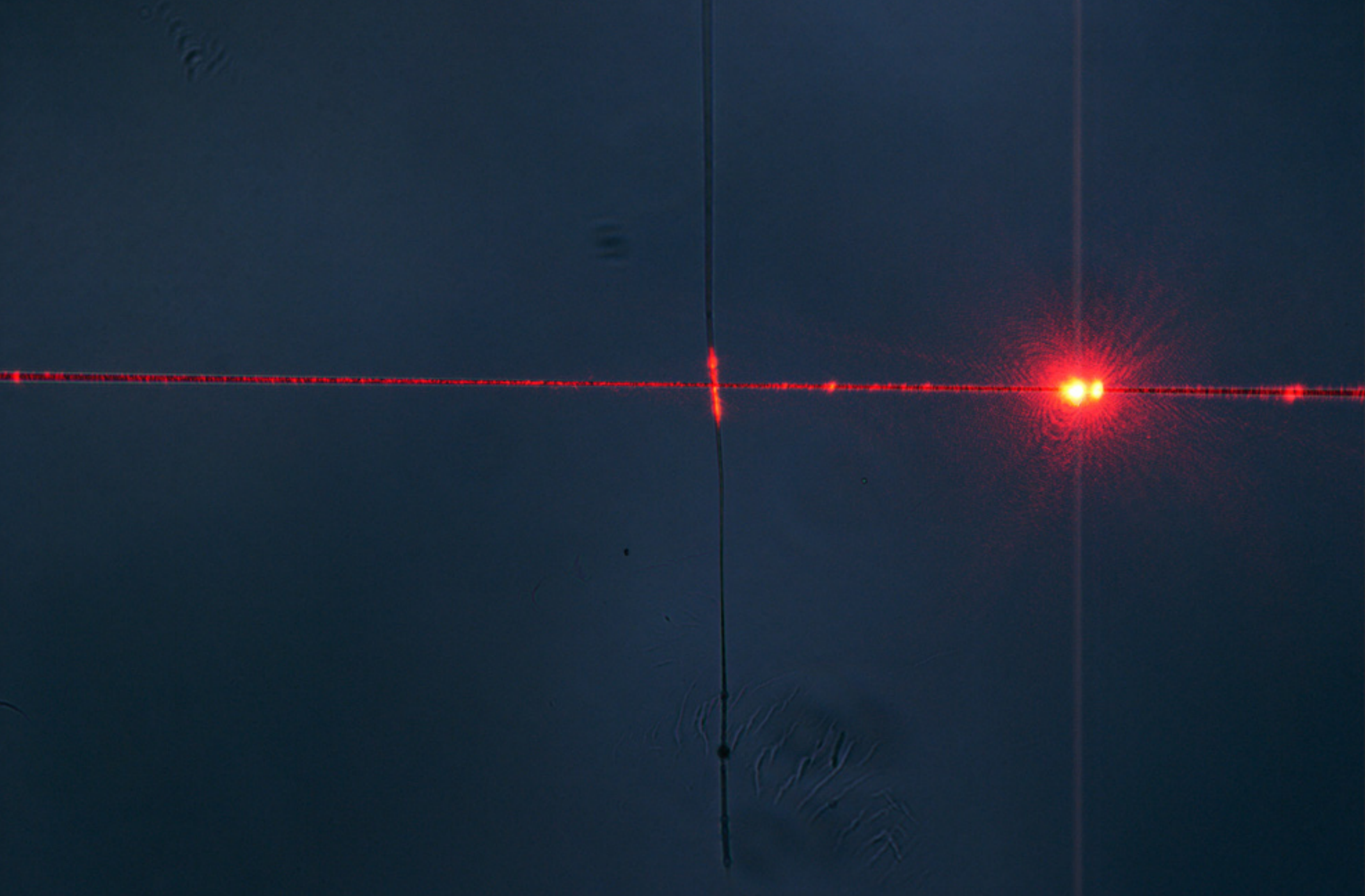


# Manipulating light at the nanoscale

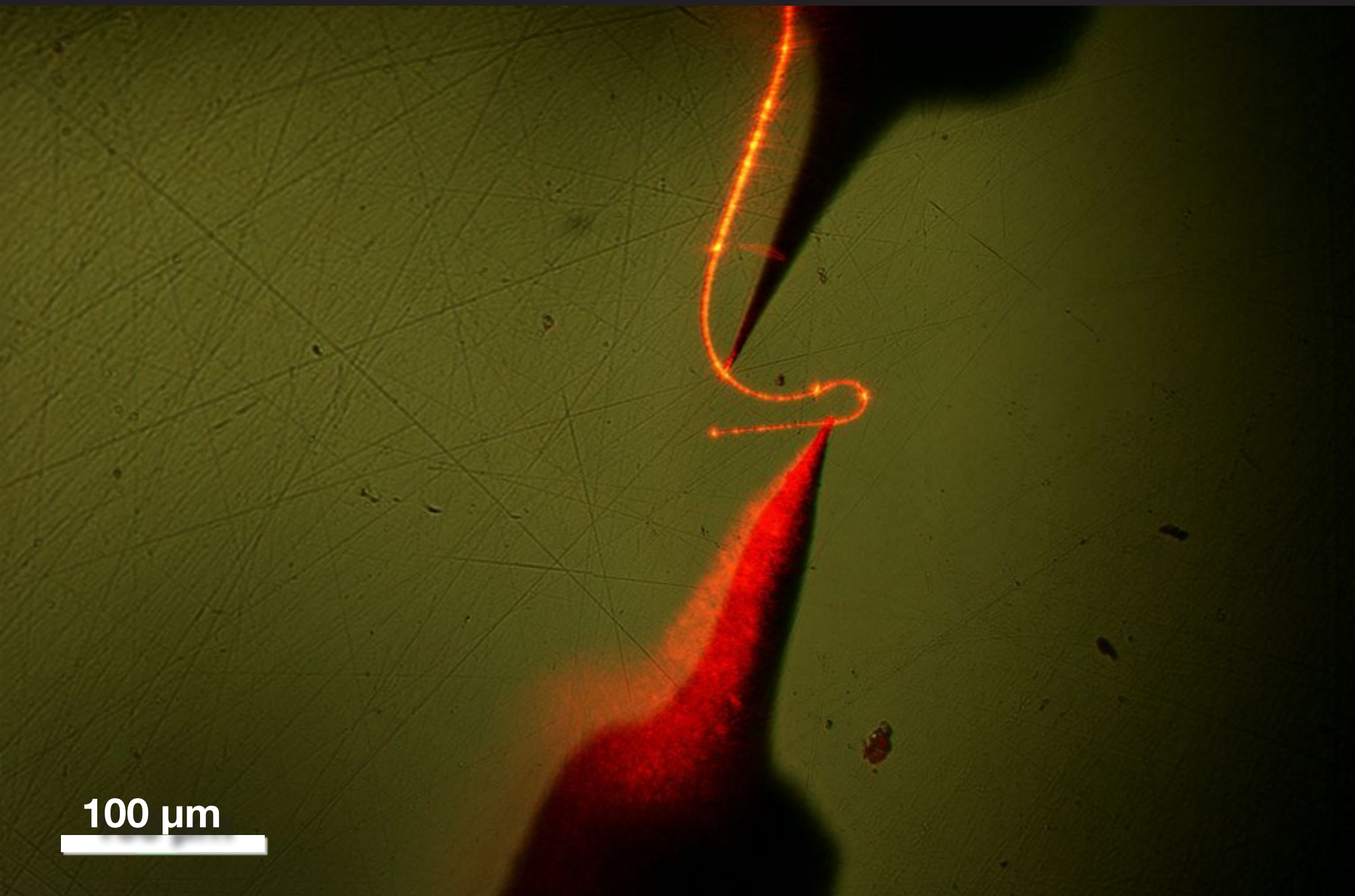


**50  $\mu\text{m}$**

# Manipulating light at the nanoscale

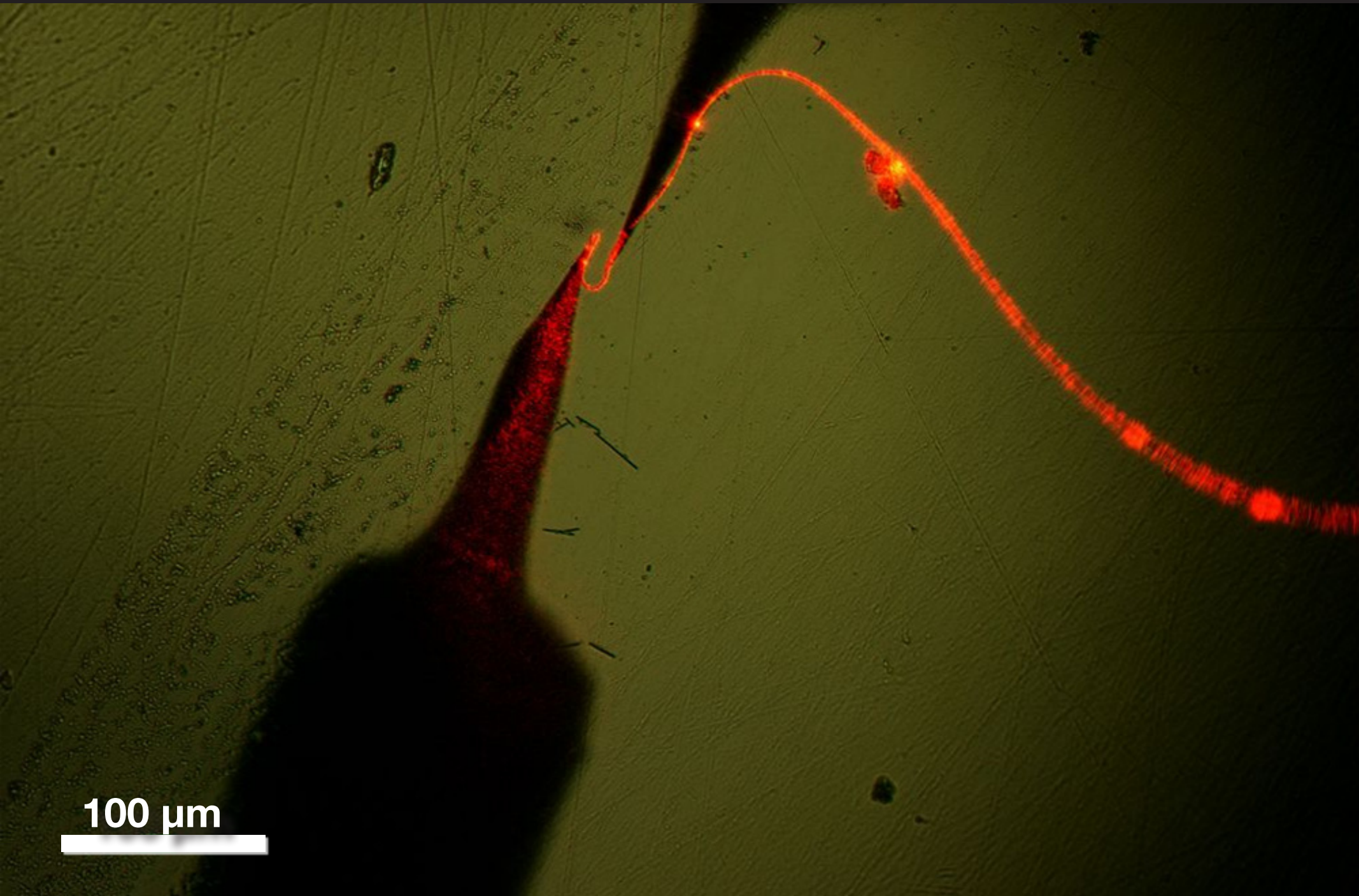


# Manipulating light at the nanoscale



100  $\mu\text{m}$

# Manipulating light at the nanoscale

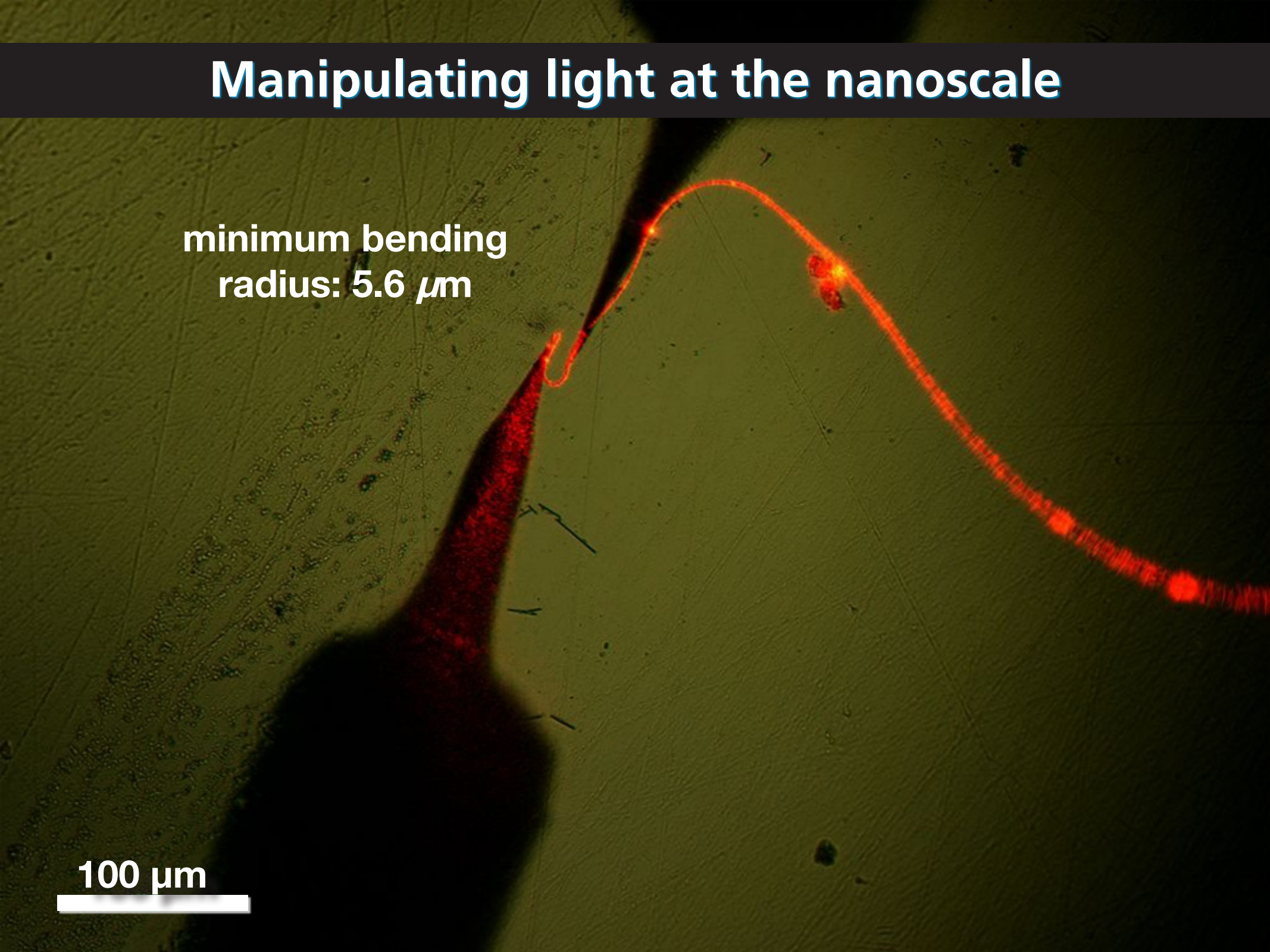


100  $\mu\text{m}$

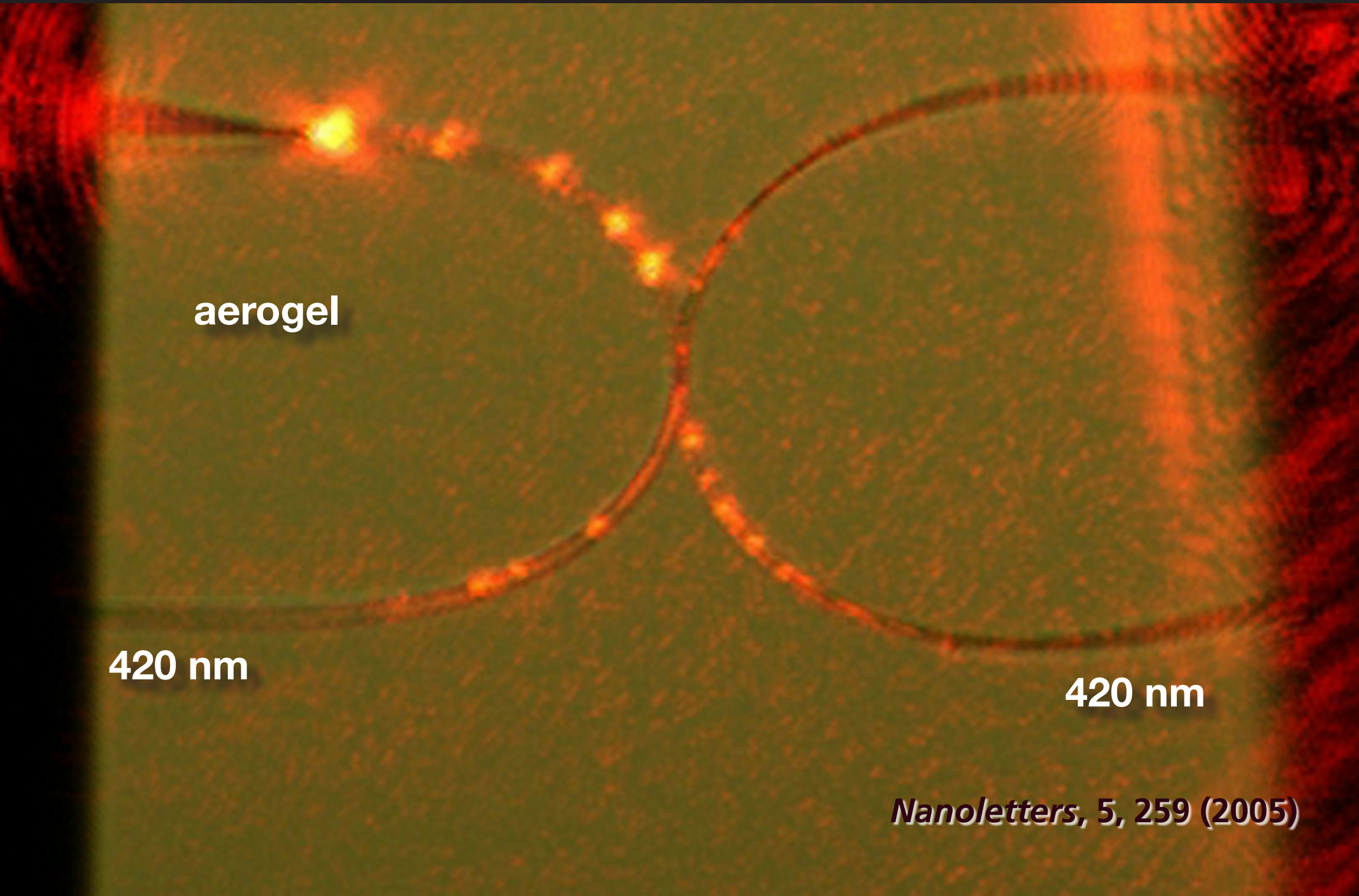
# Manipulating light at the nanoscale

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

100  $\mu\text{m}$

A micrograph showing a fiber optic cable with a sharp bend. The fiber is illuminated from the left, creating a bright red glow. The bend is very tight, and the light is visible as a bright red line following the curve of the fiber. The background is dark green with some faint scratches and dust. 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

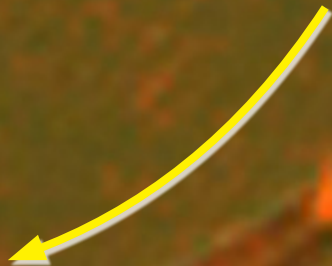
*Nanoletters*, 5, 259 (2005)

# Manipulating light at the nanoscale

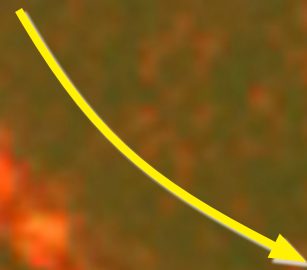
in



out

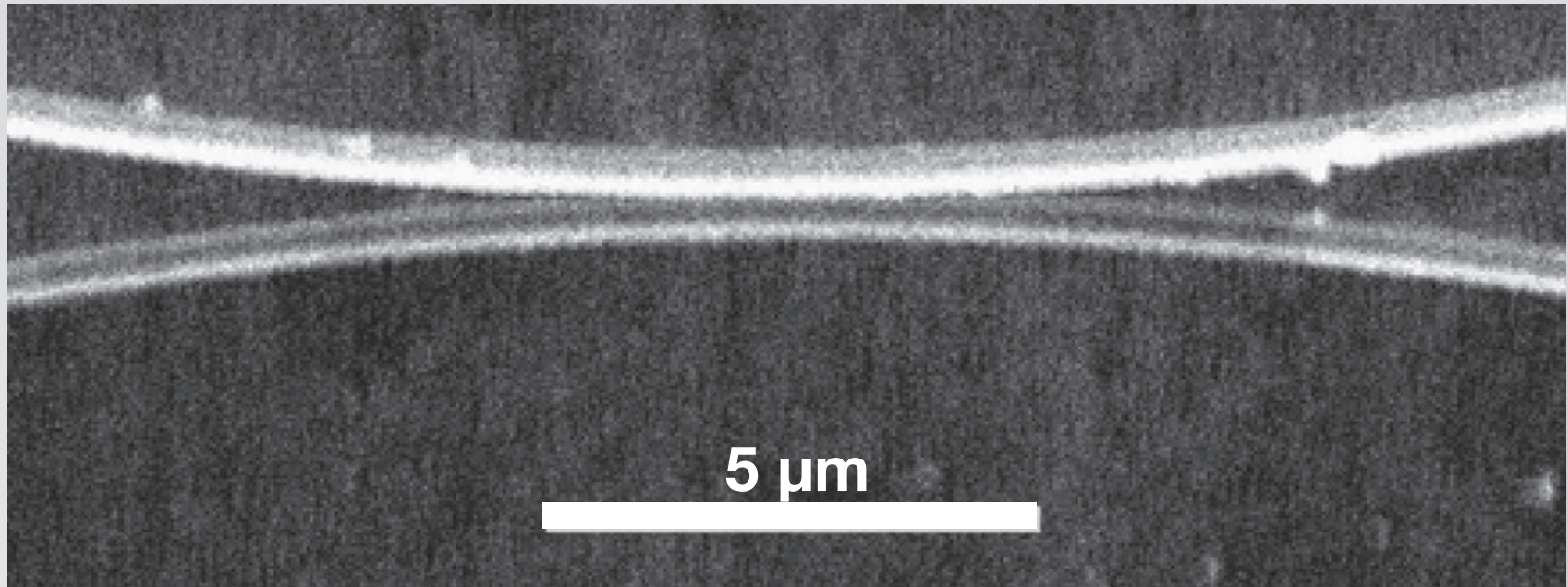


out



*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**

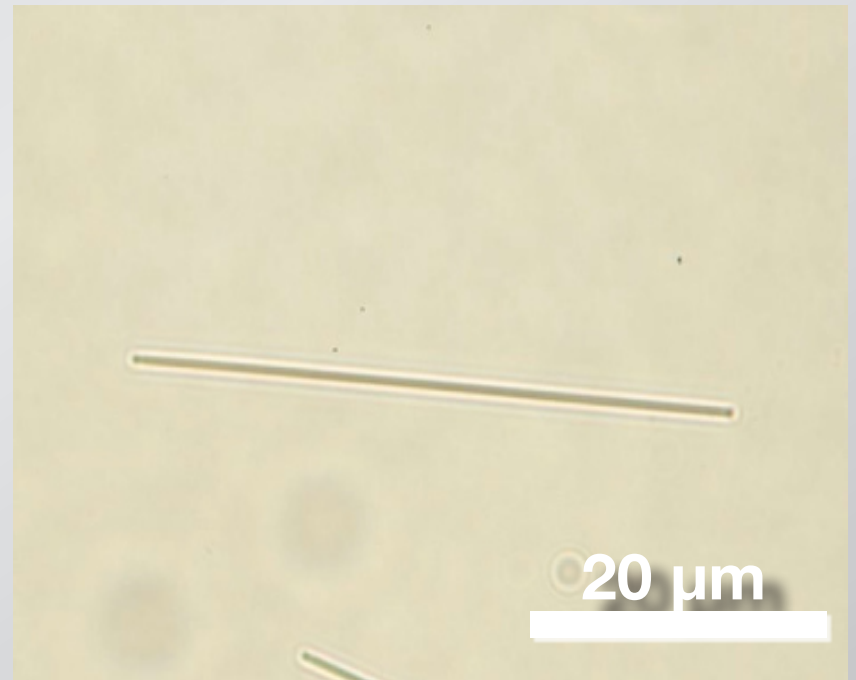
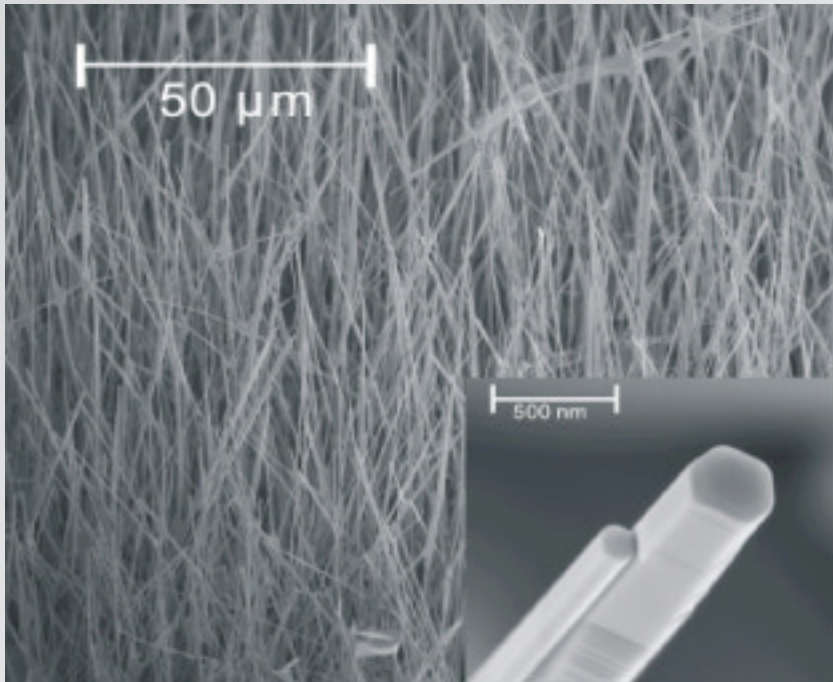
# Manipulating light at the nanoscale

**ZnO: non-toxic, wide bandgap semiconductor**

A petri dish containing a white, powdery substance, likely ZnO nanoparticles, used for light manipulation at the nanoscale.

# 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

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ZnO

silica

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bottom-up

top-down

semiconductor

glass

active photonic devices

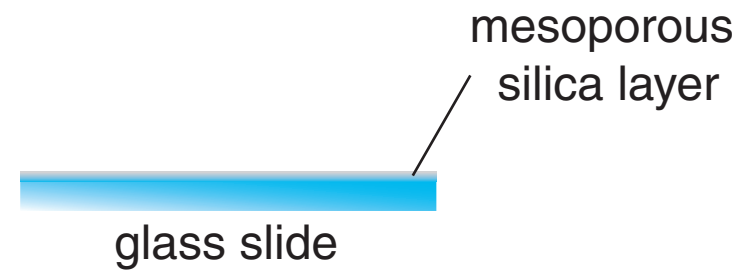
passive waveguides

electrical operation

link to macroworld

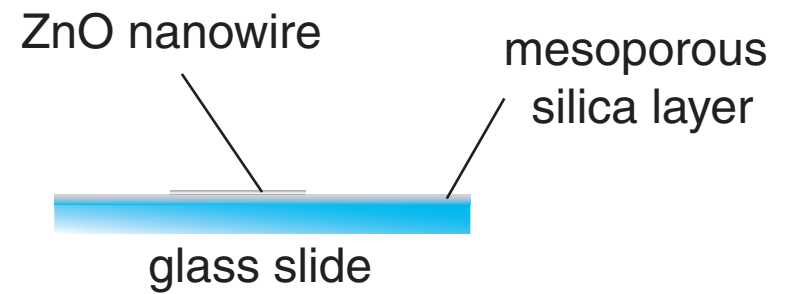
# Manipulating light at the nanoscale

coupling to ZnO nanowires



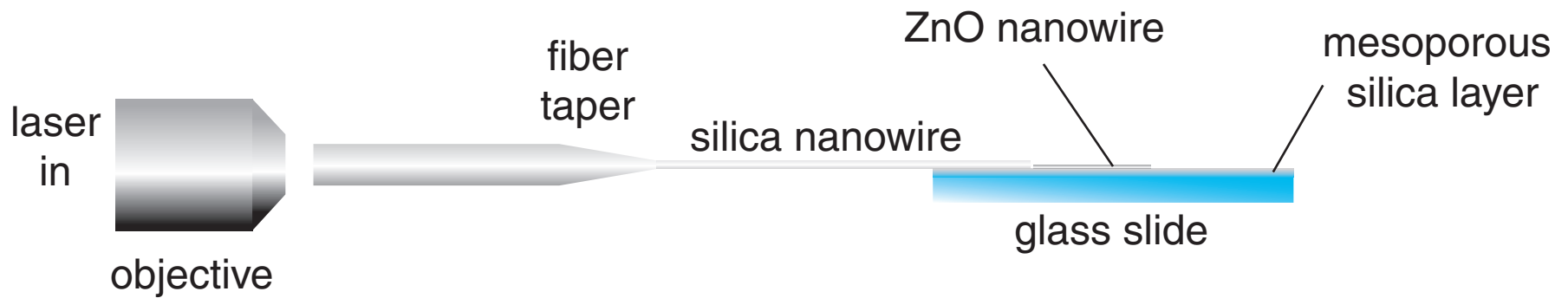
# Manipulating light at the nanoscale

coupling to ZnO nanowires



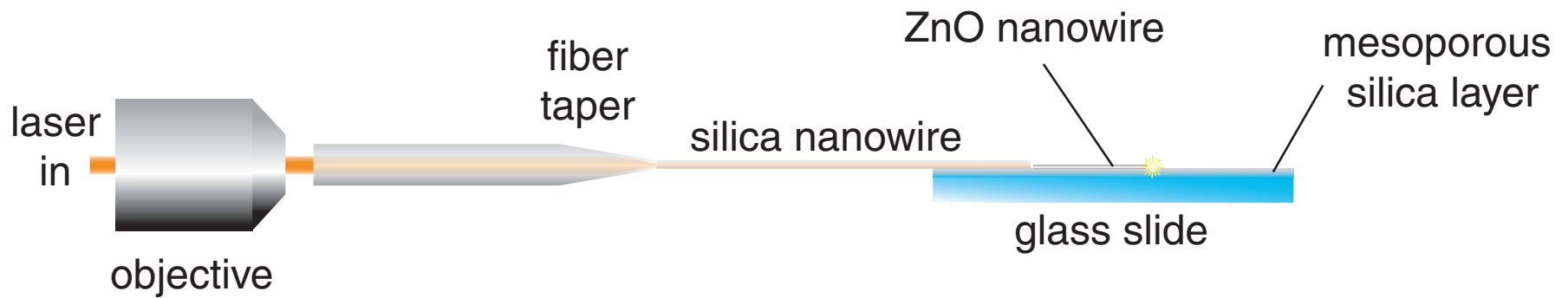
# Manipulating light at the nanoscale

## coupling to ZnO nanowires



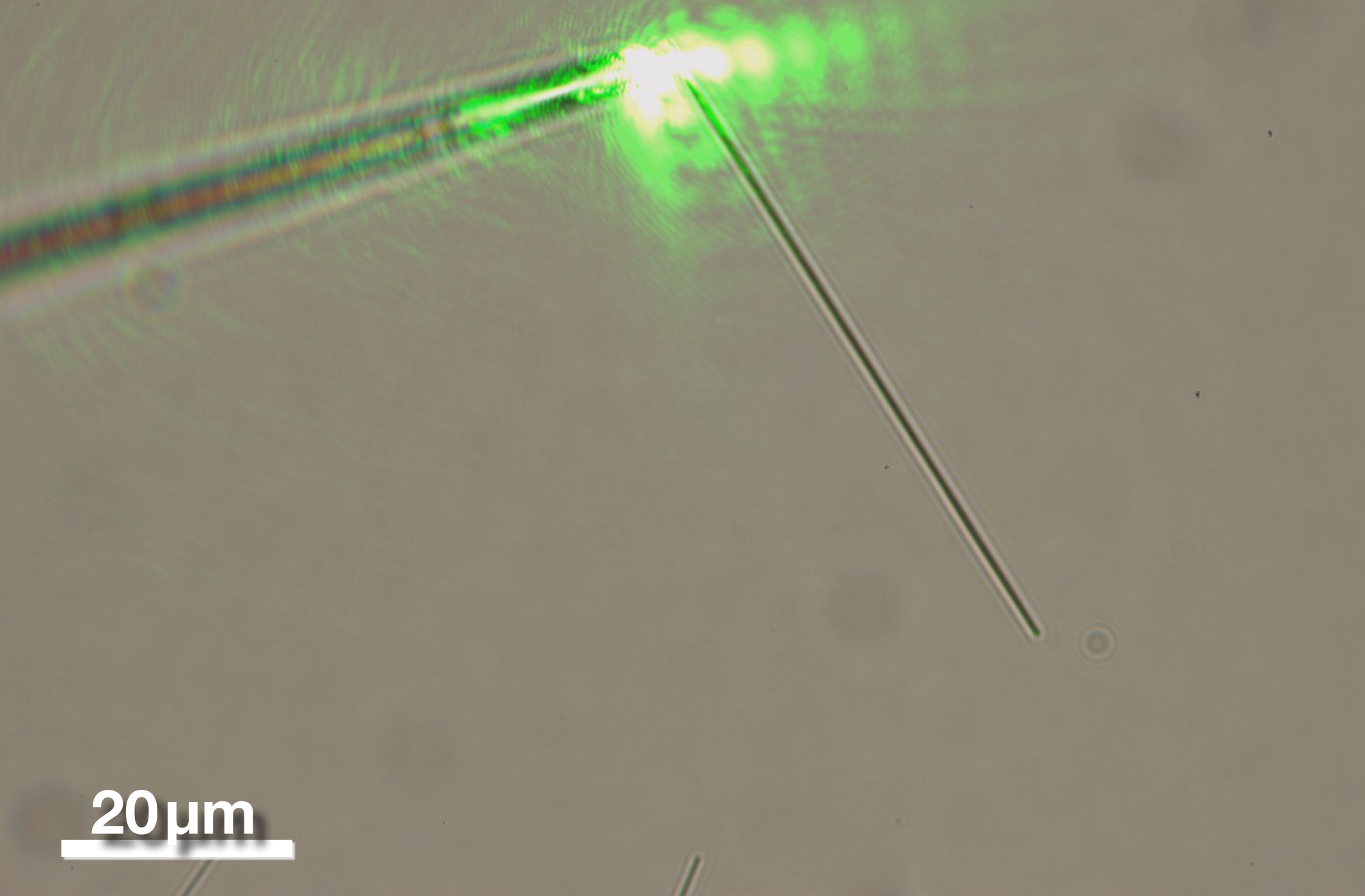
# Manipulating light at the nanoscale

## coupling to ZnO nanowires



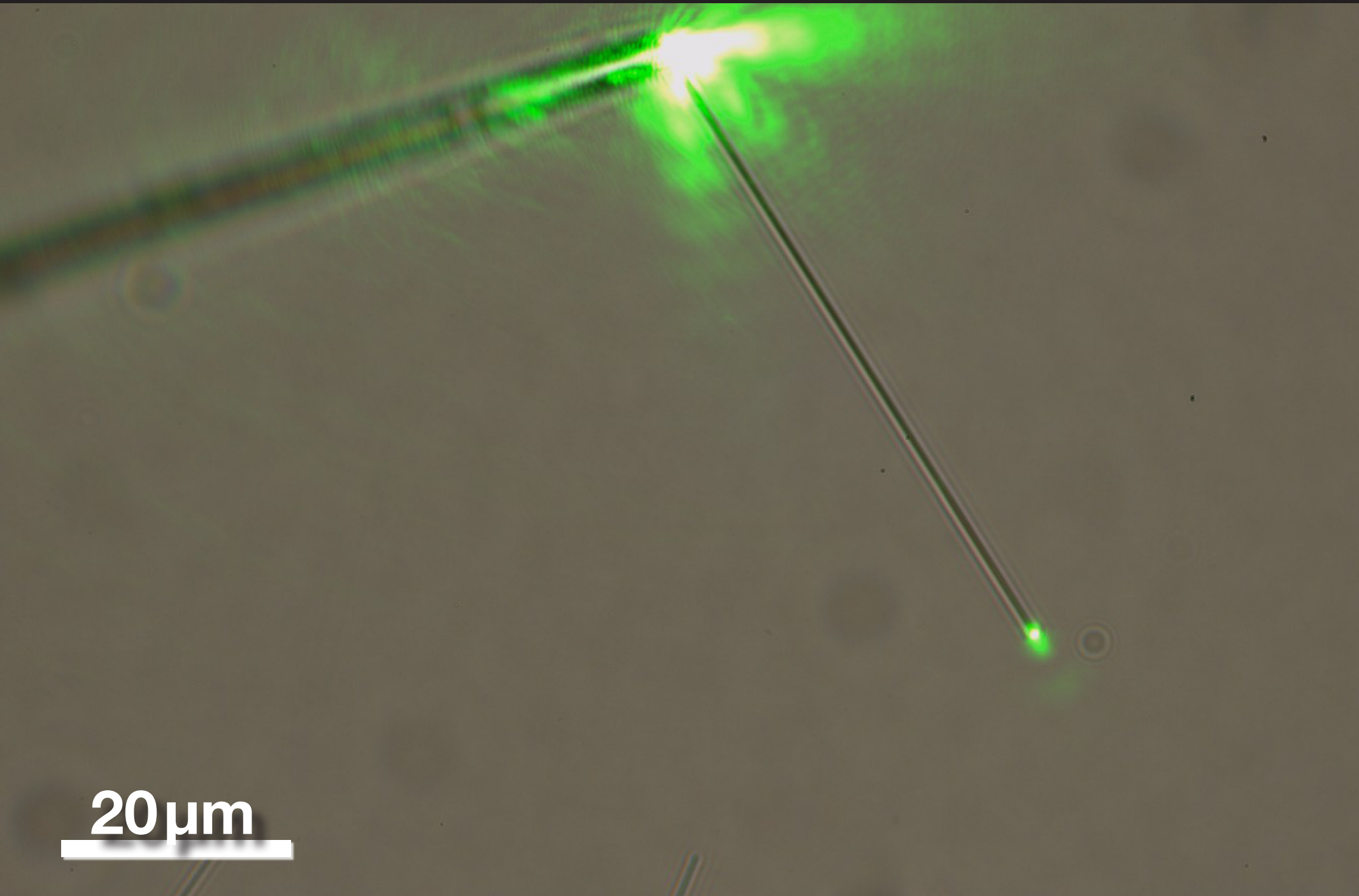


# Manipulating light at the nanoscale



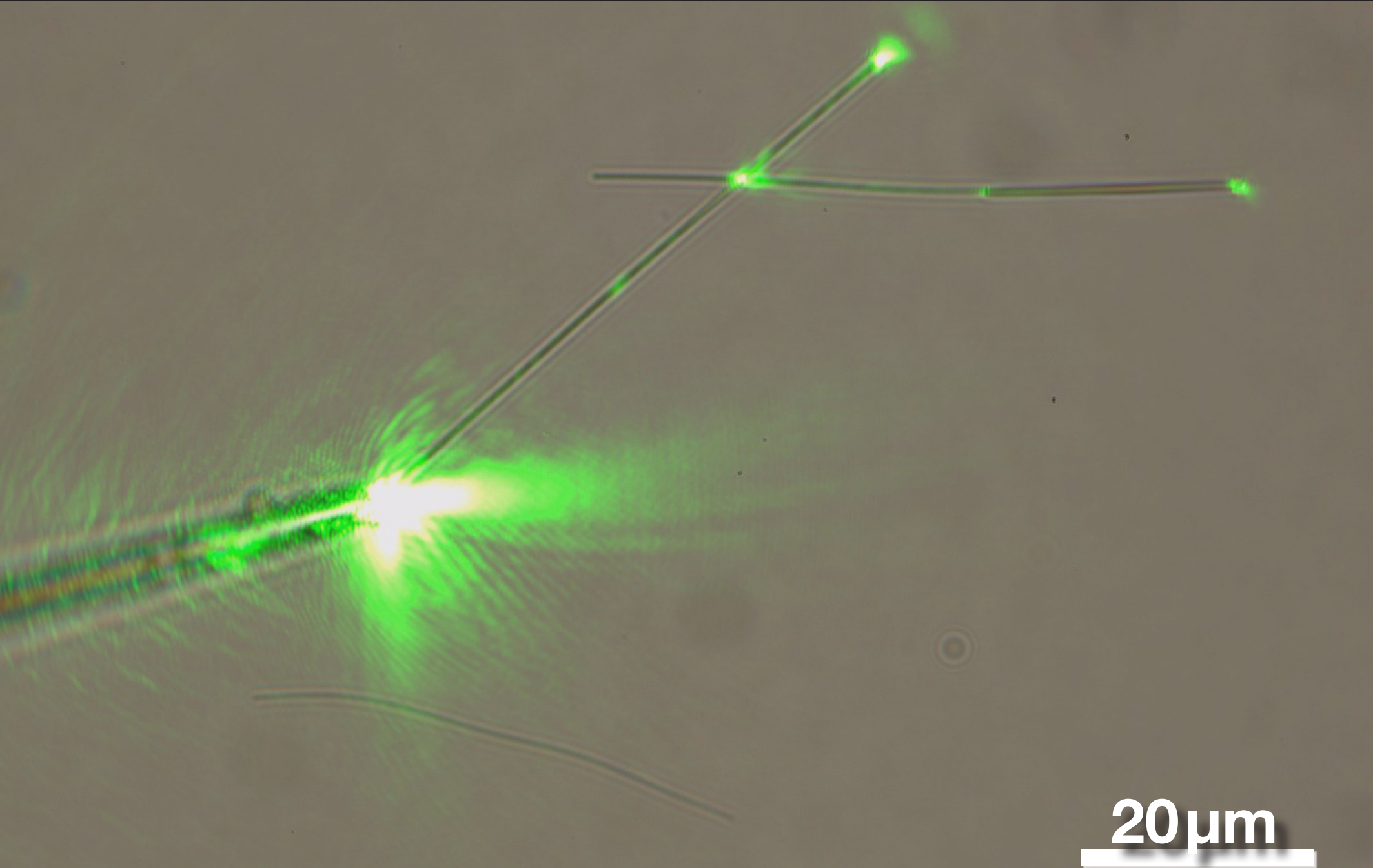
20  $\mu\text{m}$

# Manipulating light at the nanoscale

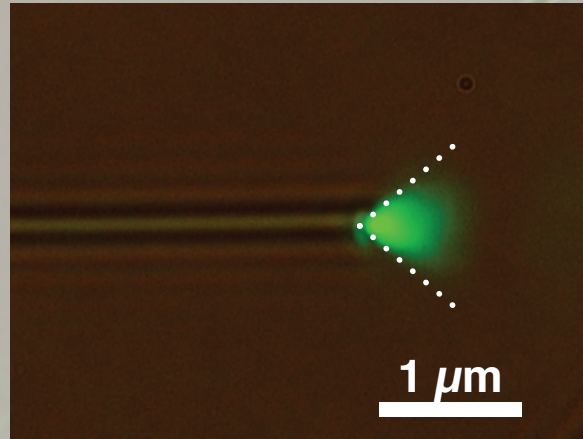


20  $\mu\text{m}$

# Manipulating light at the nanoscale

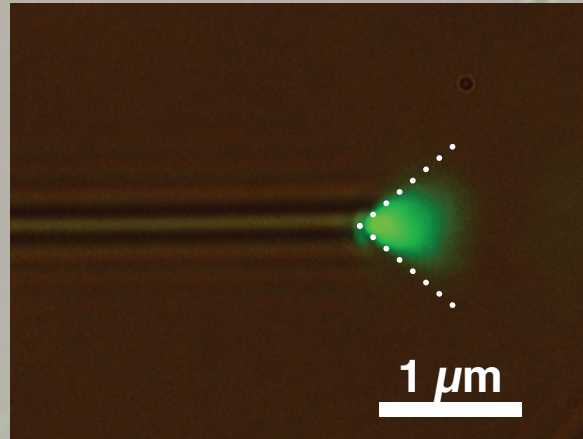


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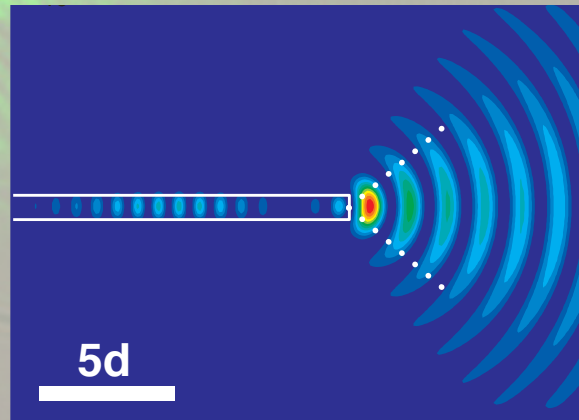


*Nano Lett.*, 7, 3675 (2007)

# Manipulating light at the nanoscale

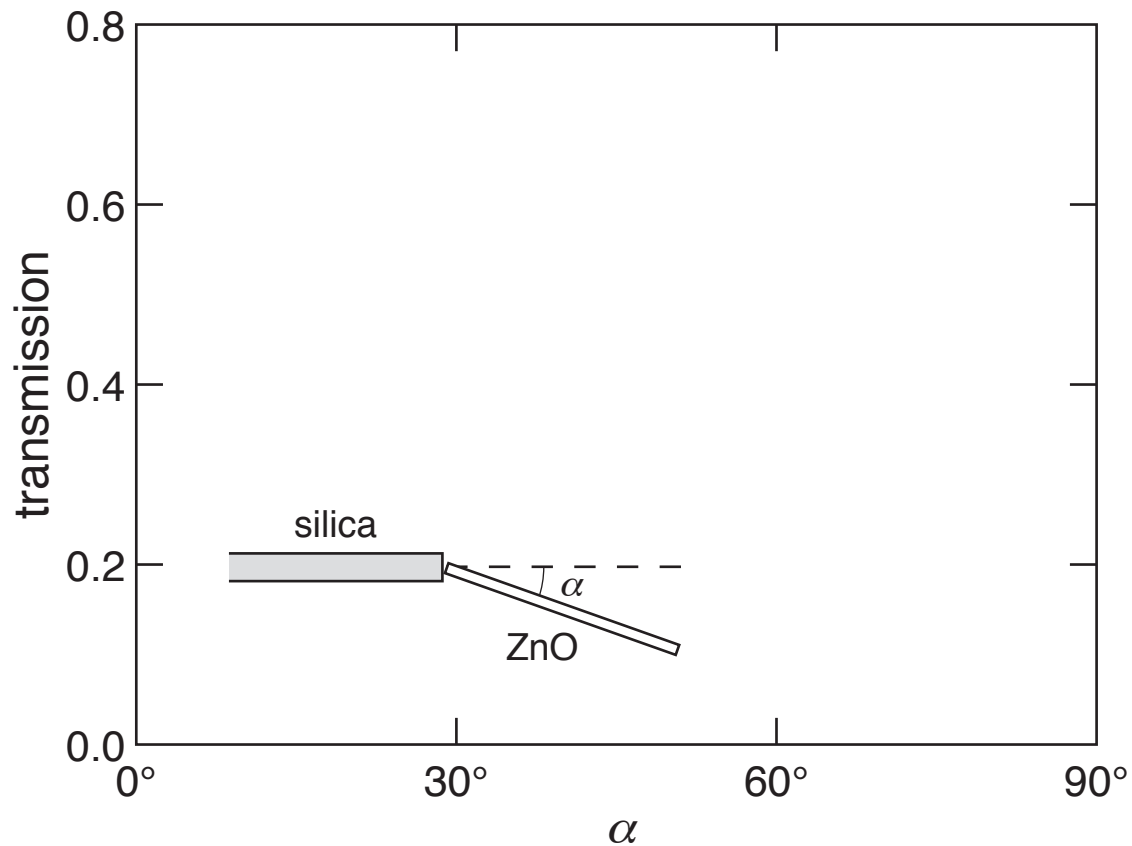


FDTD simulation



# Manipulating light at the nanoscale

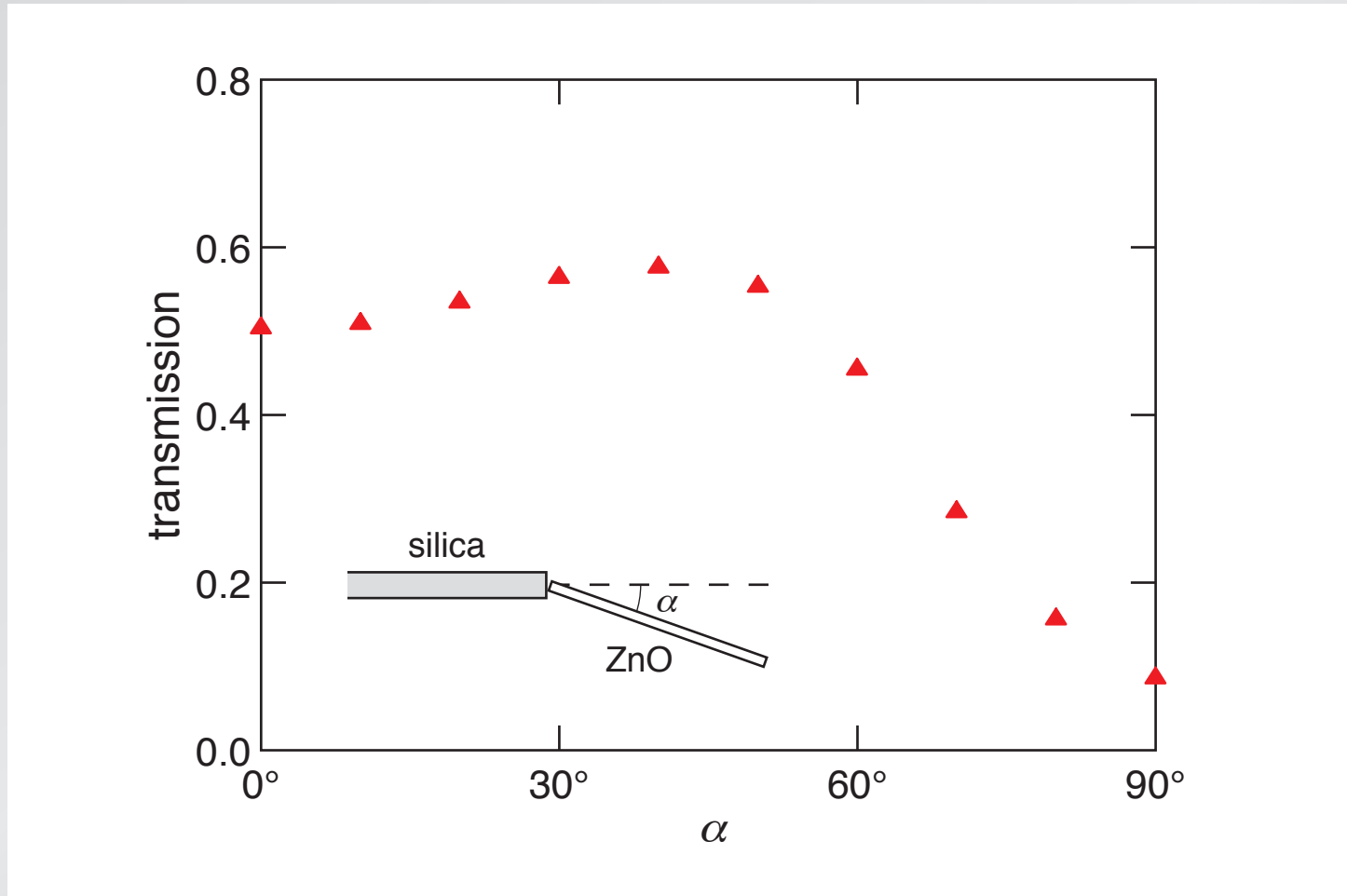
coupling efficiency



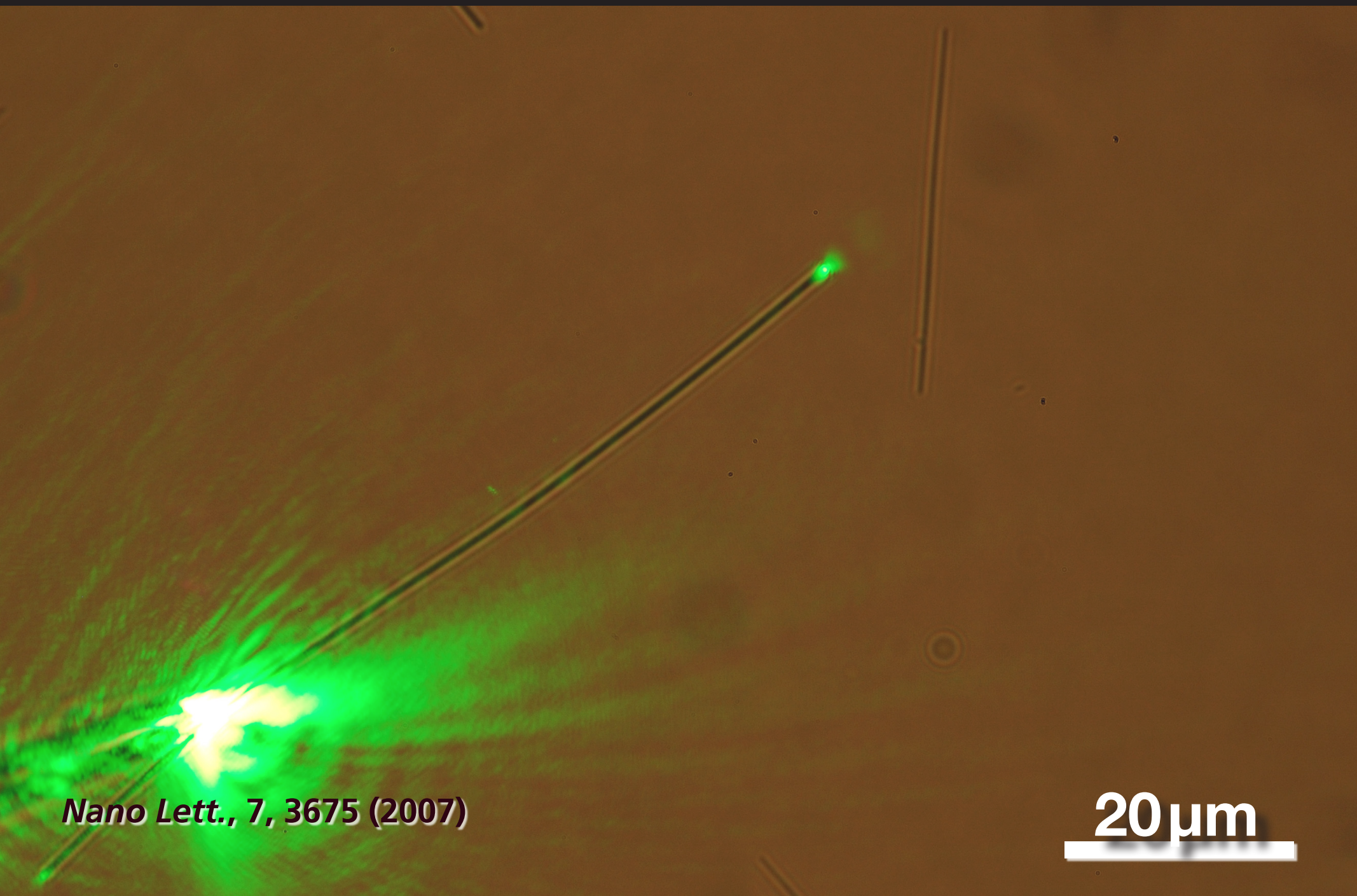
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# Manipulating light at the nanoscale

## coupling efficiency



# Manipulating light at the nanoscale

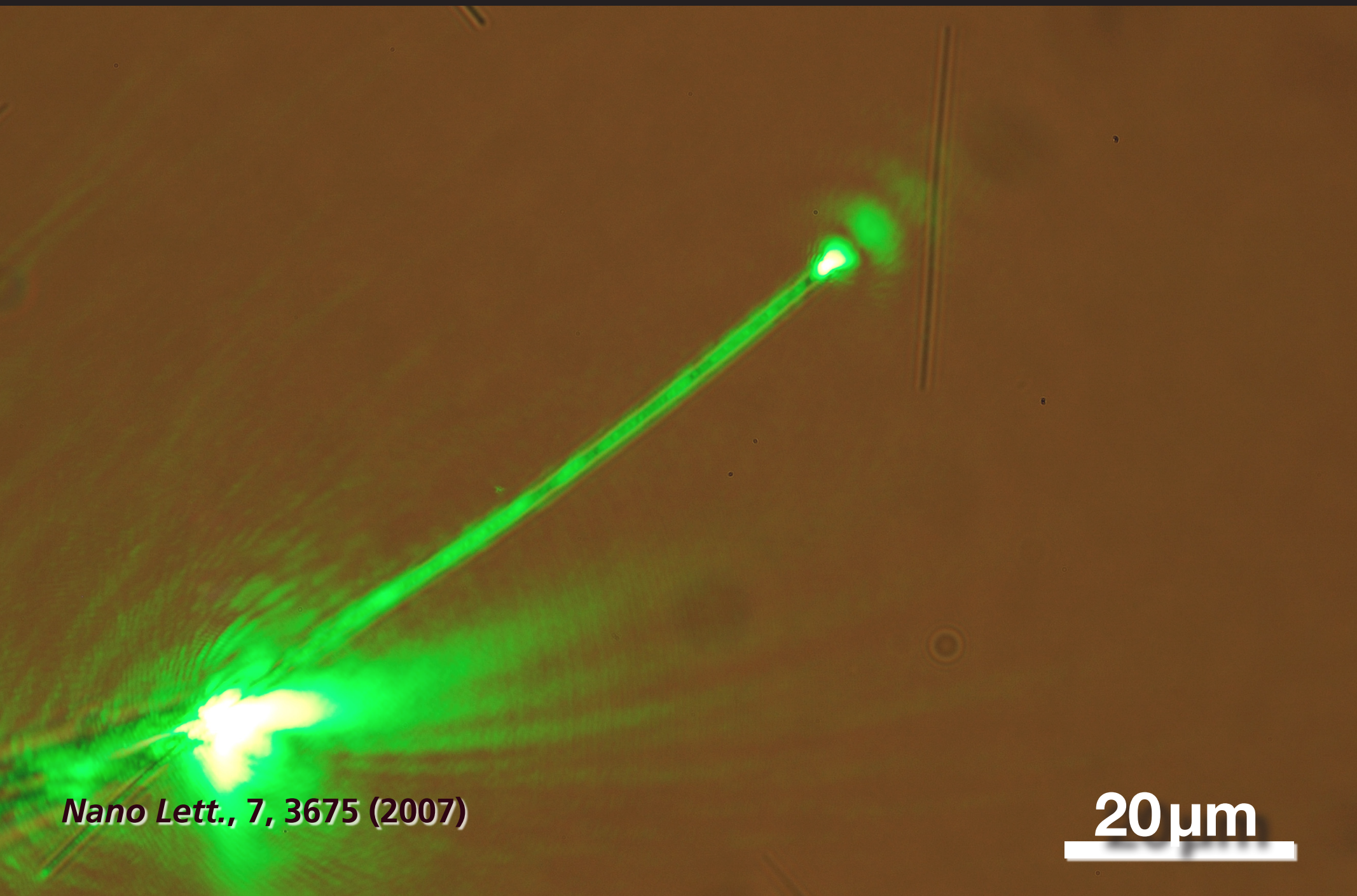


*Nano Lett.*, 7, 3675 (2007)

20  $\mu\text{m}$



# Manipulating light at the nanoscale

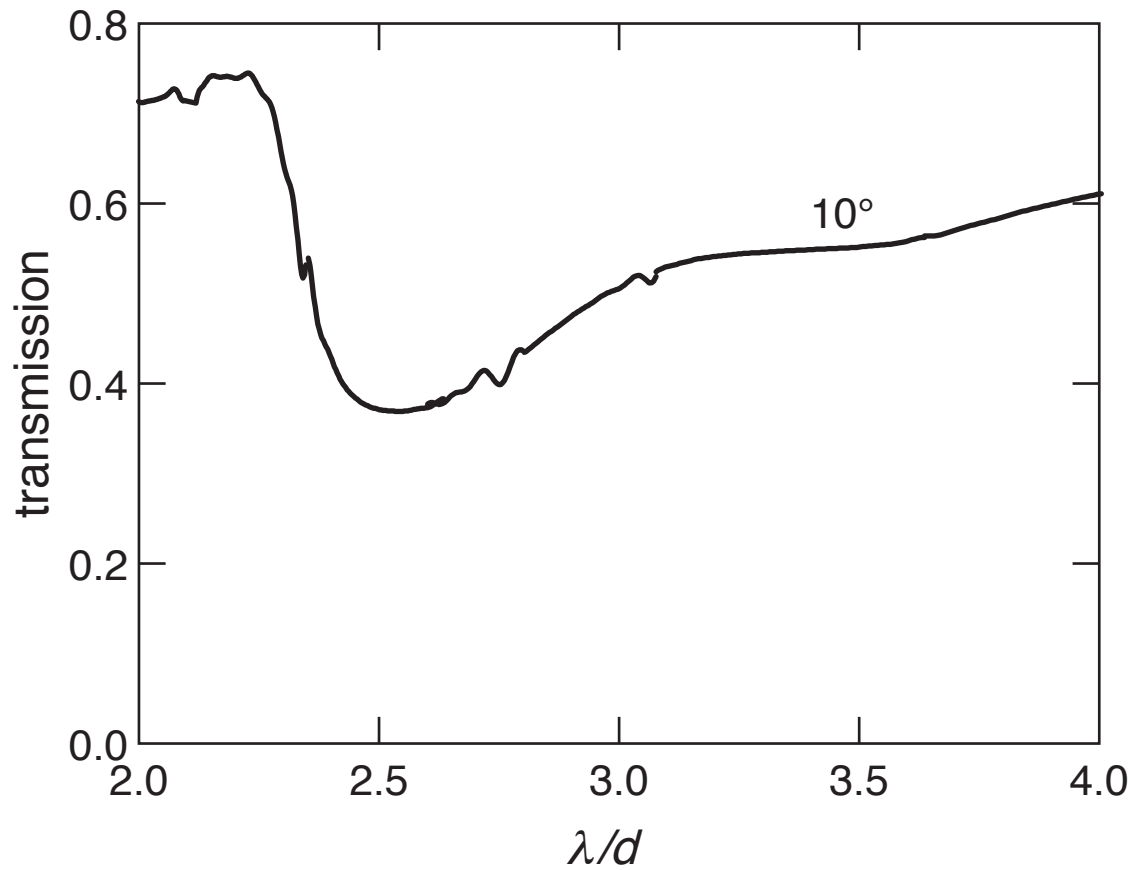


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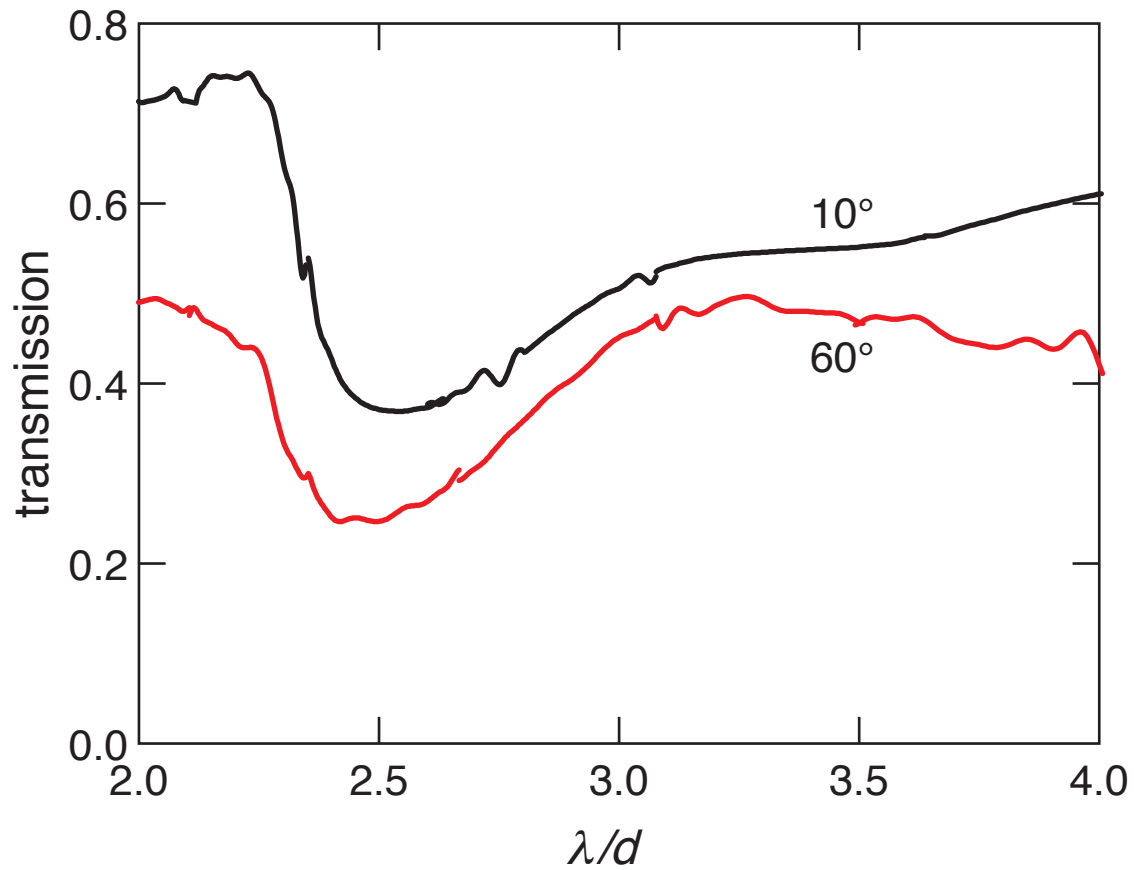
# Manipulating light at the nanoscale

## transmission spectrum



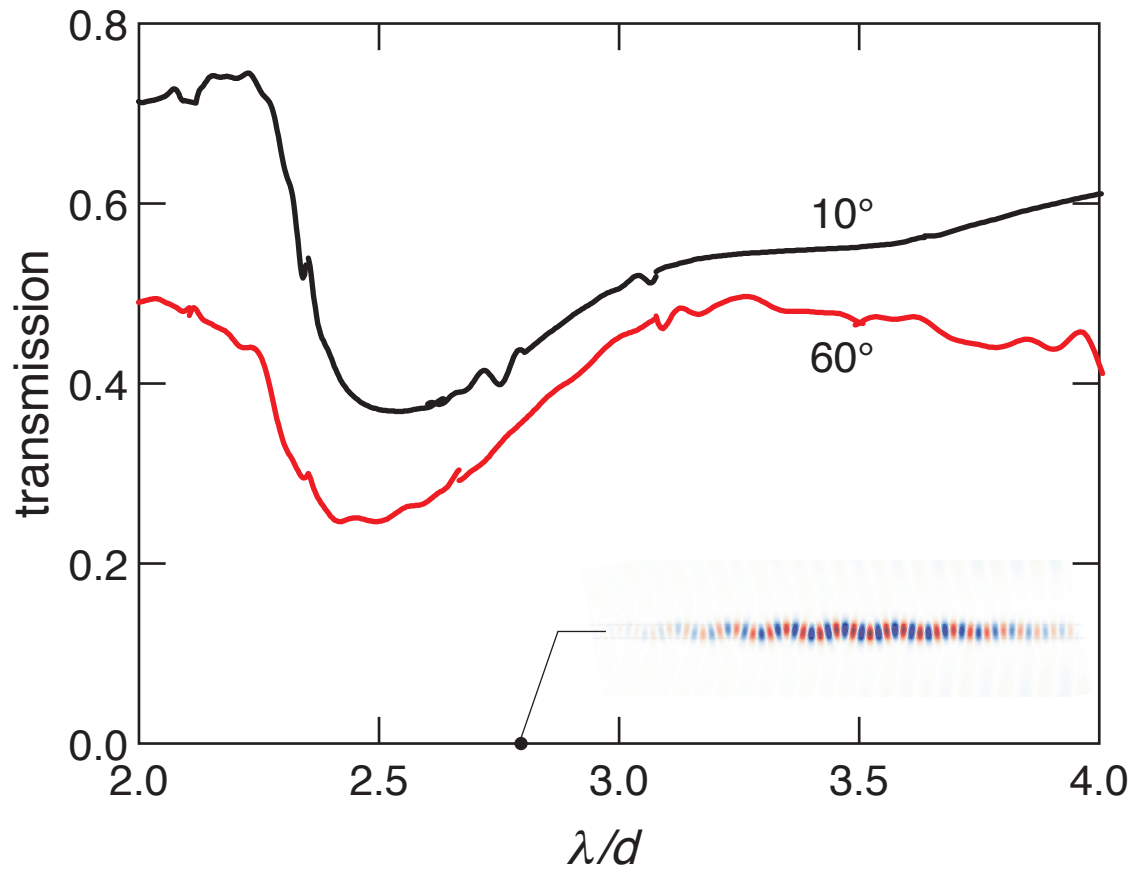
# Manipulating light at the nanoscale

## transmission spectrum



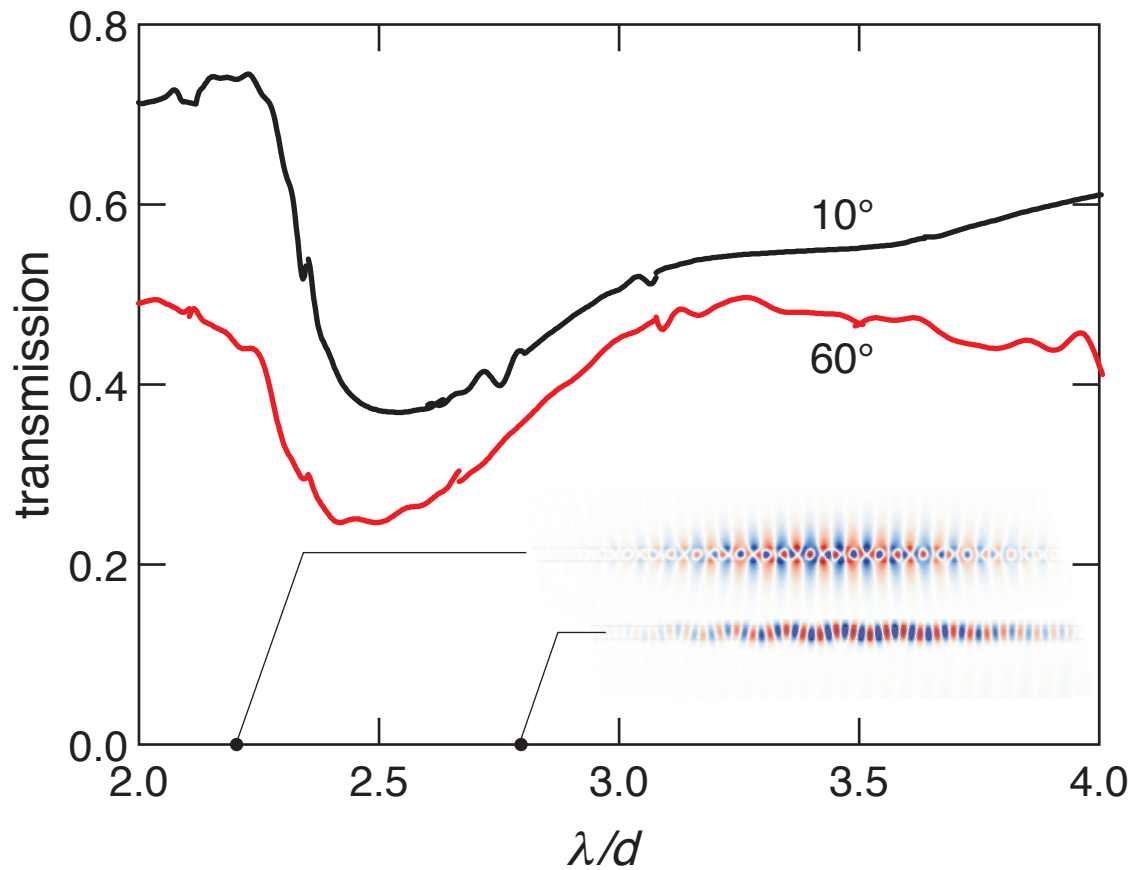
# Manipulating light at the nanoscale

## transmission spectrum

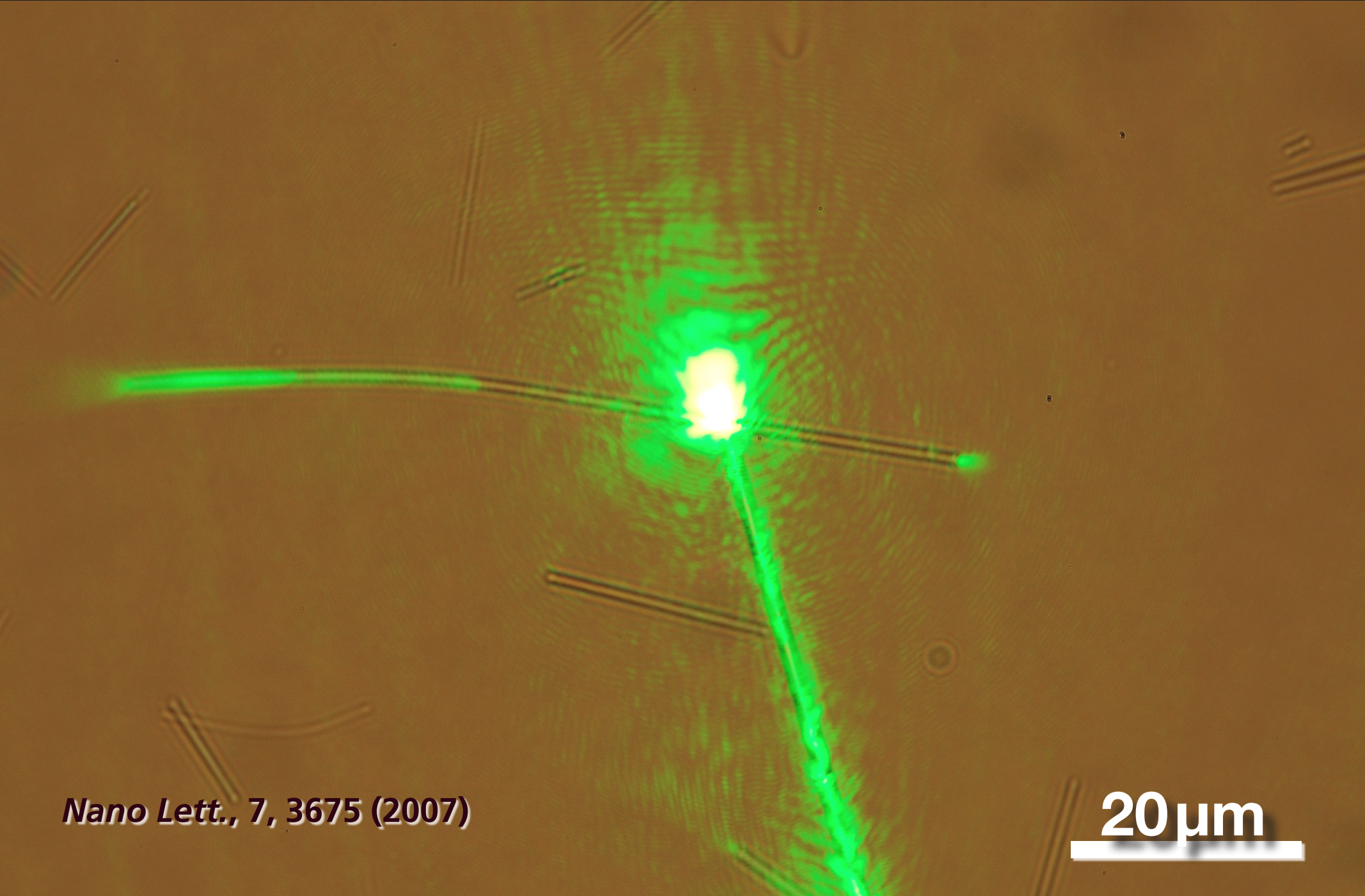


# Manipulating light at the nanoscale

## transmission spectrum



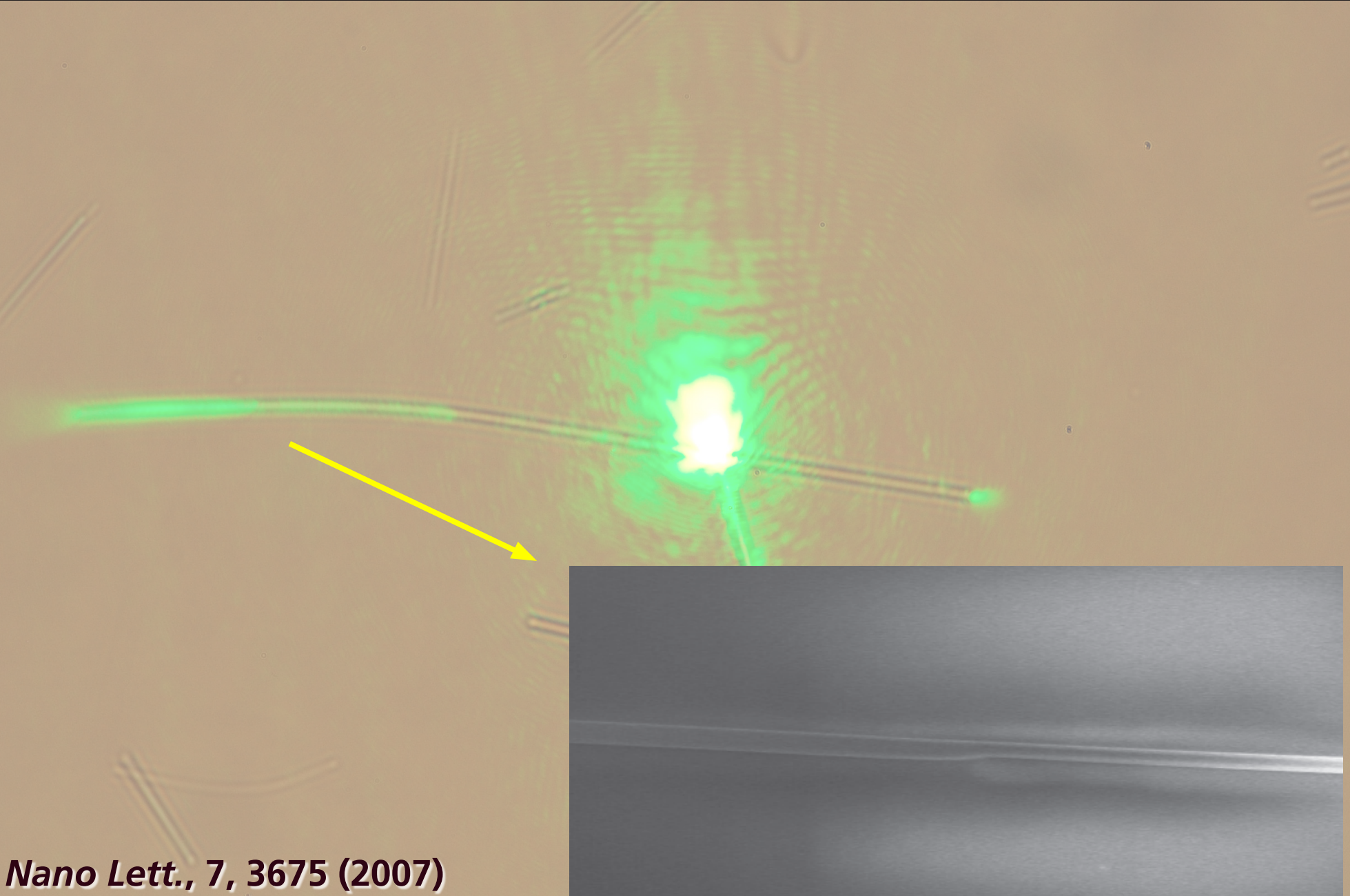
# Manipulating light at the nanoscale



*Nano Lett.*, 7, 3675 (2007)

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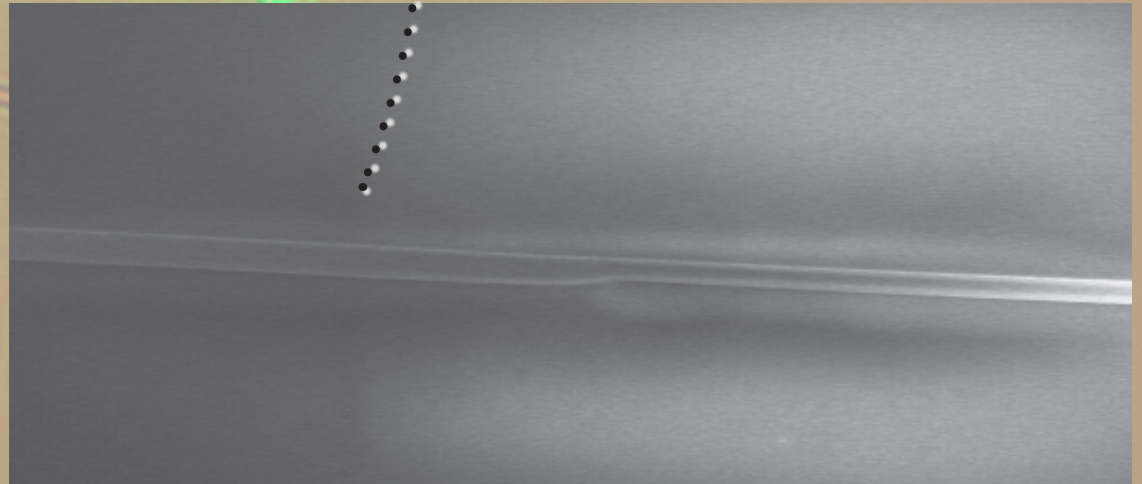
# Manipulating light at the nanoscale



*Nano Lett.*, 7, 3675 (2007)

# Manipulating light at the nanoscale

large diameter:  
multimode

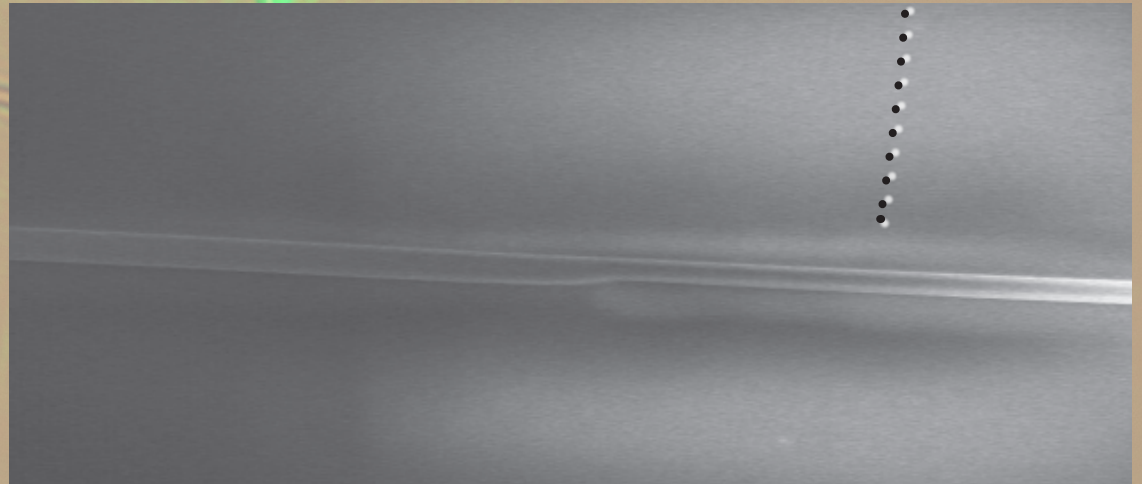


*Nano Lett.*, 7, 3675 (2007)



# Manipulating light at the nanoscale

small diameter:  
single mode



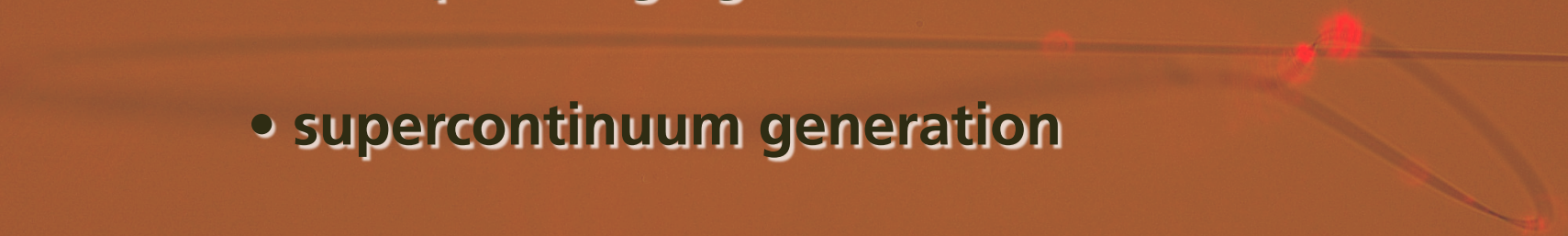
*Nano Lett.*, 7, 3675 (2007)

# Manipulating light at the nanoscale

**Points to keep in mind:**

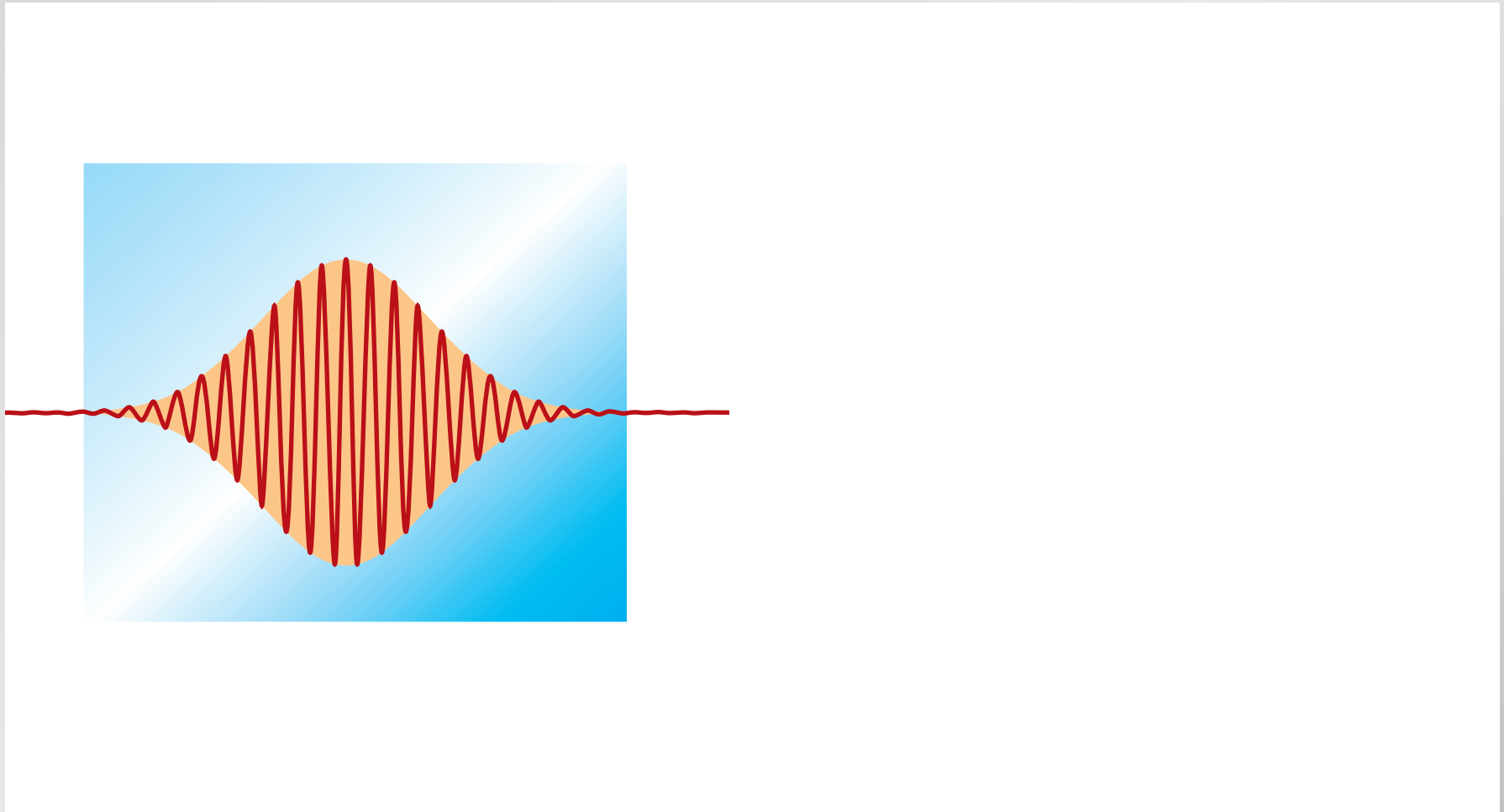
- **low-loss guiding**
- **convenient evanescent coupling**
- **attached to ordinary fiber**

# Outline

- **manipulating light at the nanoscale**
  - **supercontinuum generation**
  - **optical logic gates**
- 
- A decorative graphic on the right side of the slide shows a thin, dark line representing a light path. It starts from the left, moves horizontally to the right, then curves downwards and loops back to the left. Several bright red spots are placed along this path, suggesting points of interaction or emission.

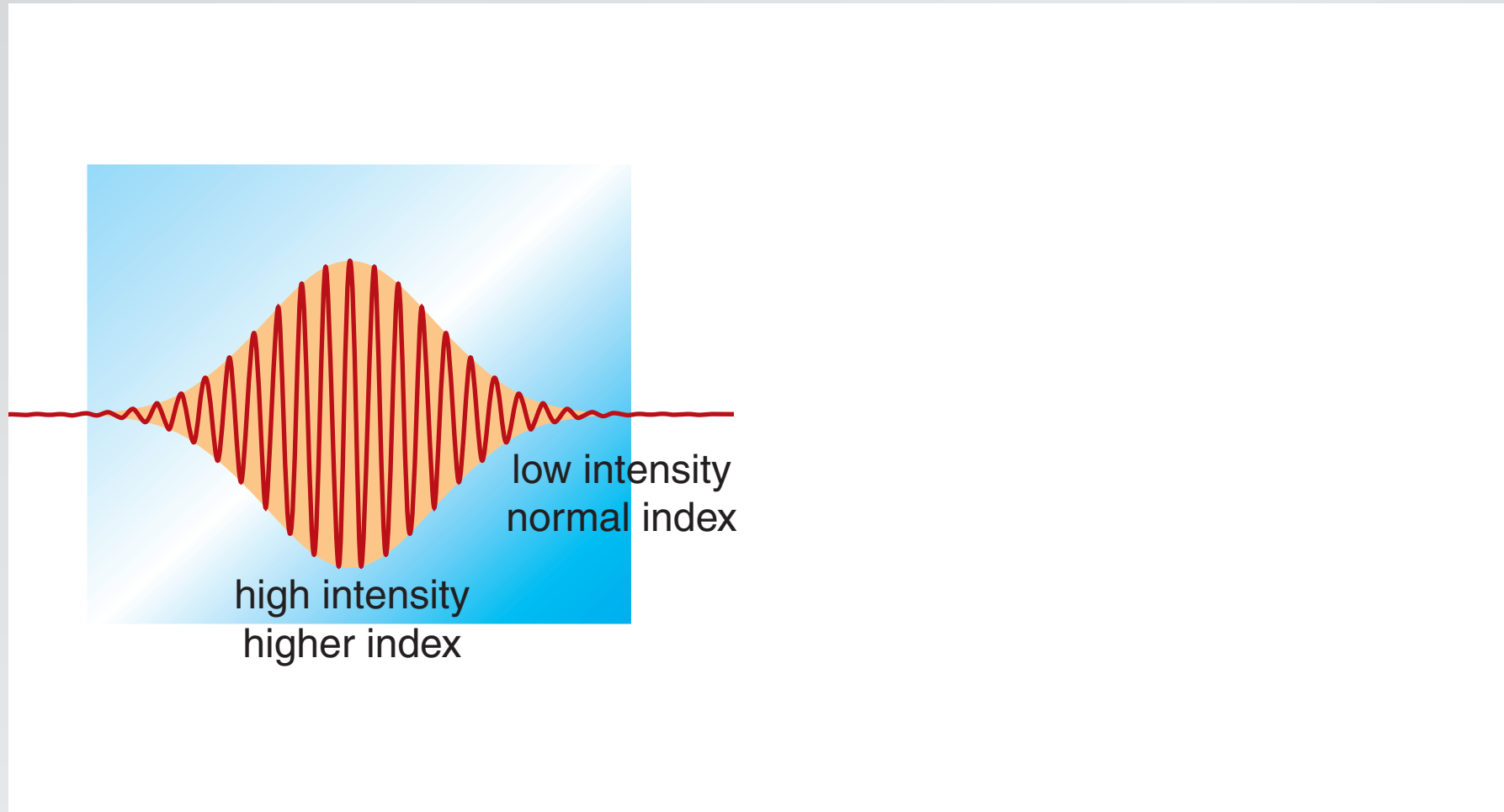
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



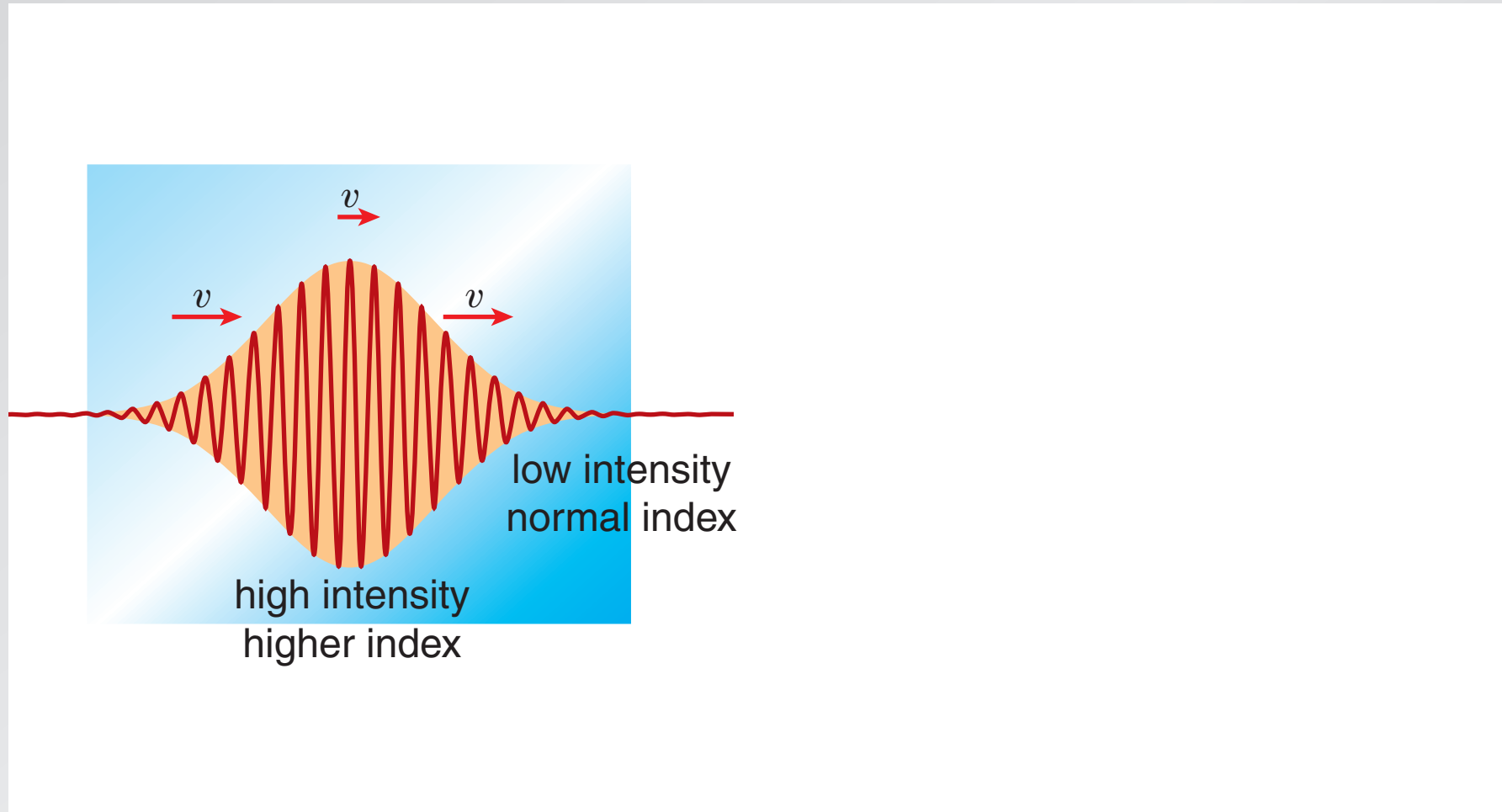
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



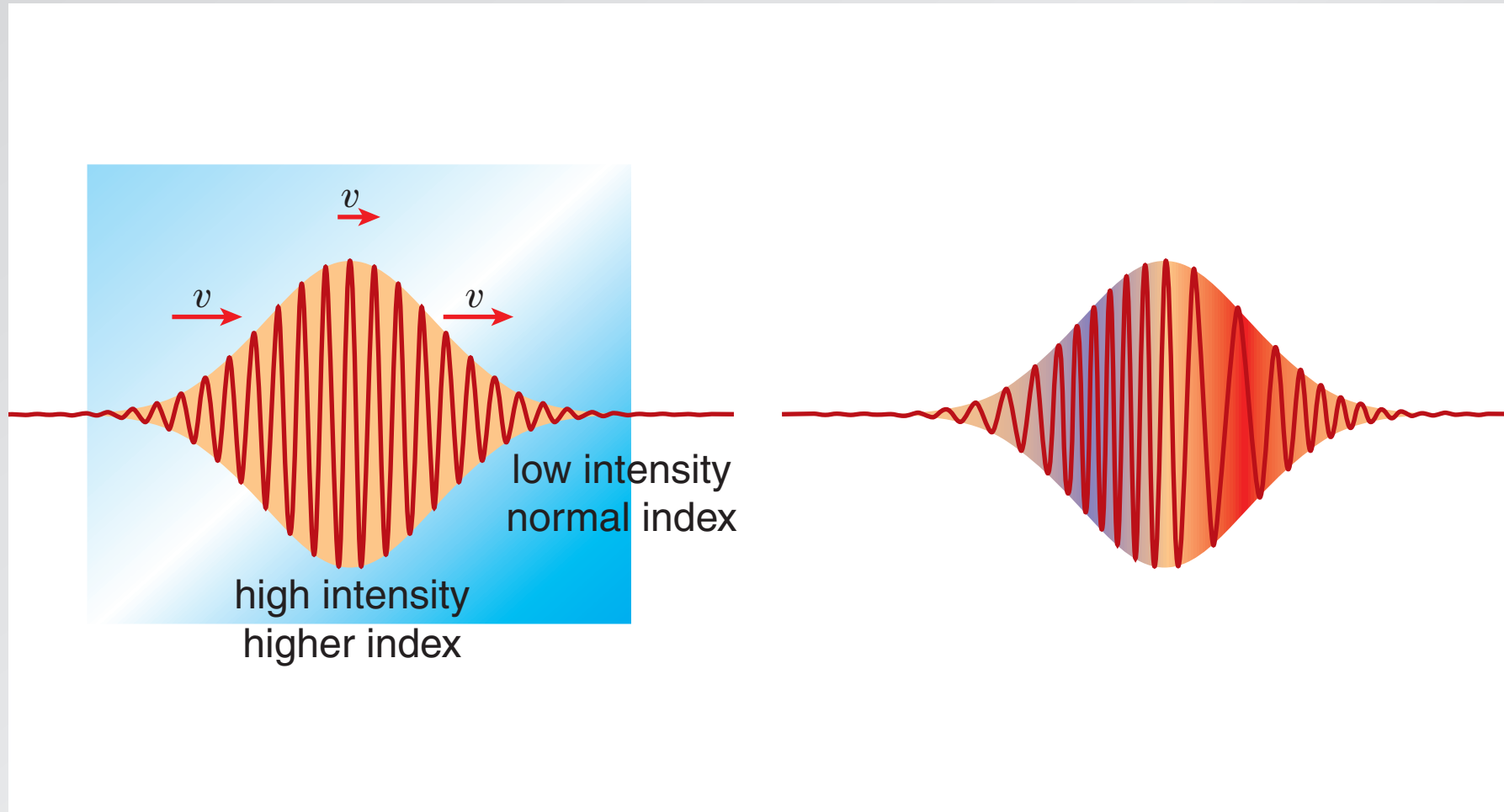
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



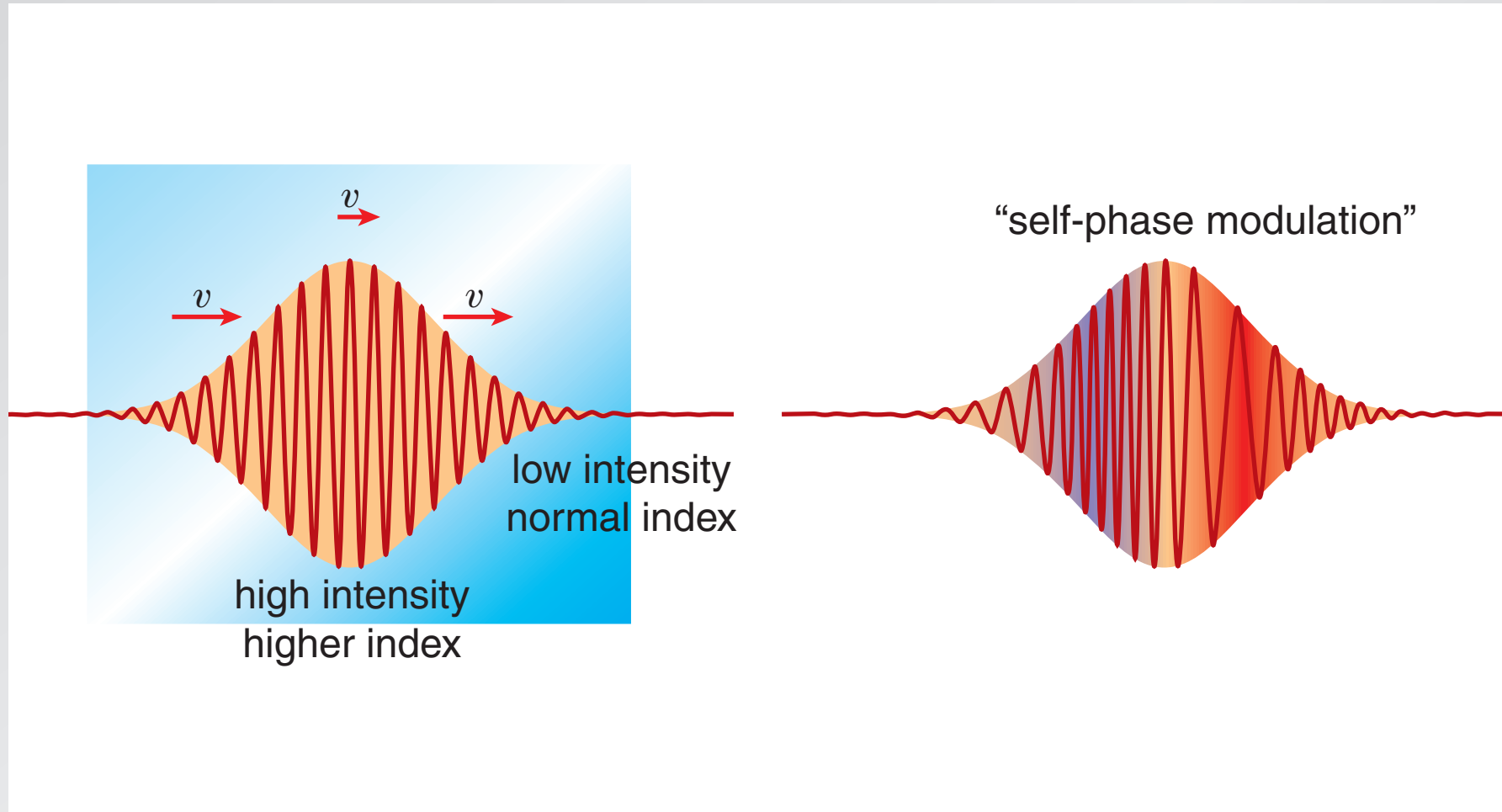
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$

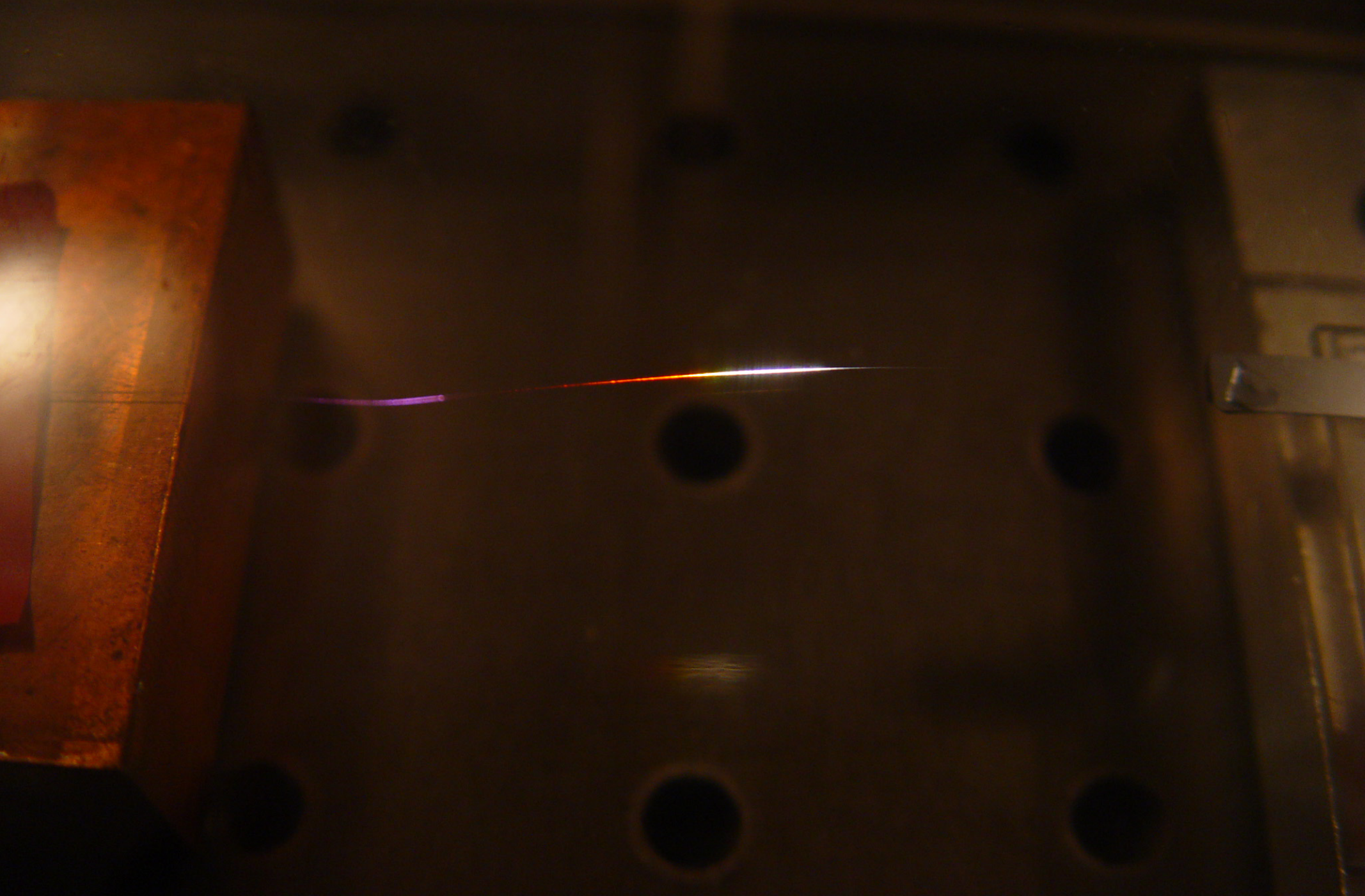




# Supercontinuum generation

**strong confinement**  $\longrightarrow$  **high intensity**

# Supercontinuum generation

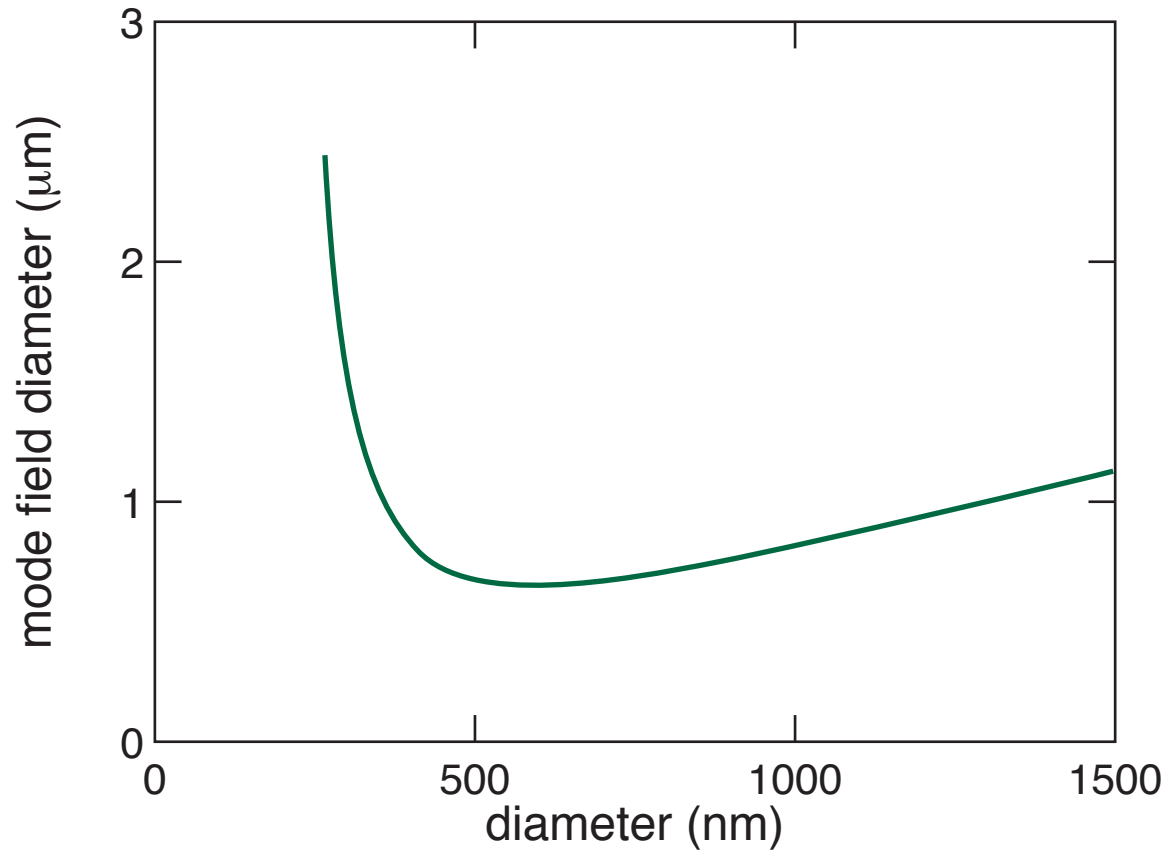


# Supercontinuum generation



# Supercontinuum generation

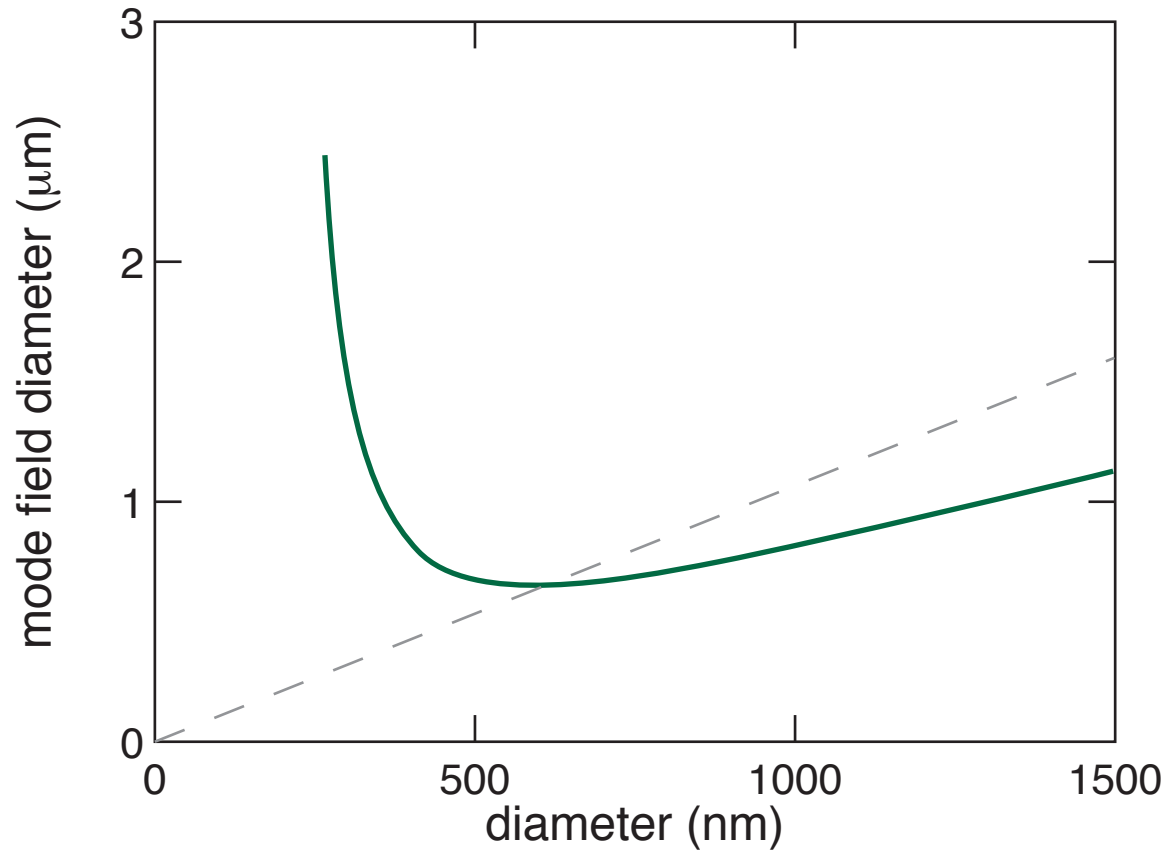
mode field diameter ( $\lambda = 800$  nm)



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

# Supercontinuum generation

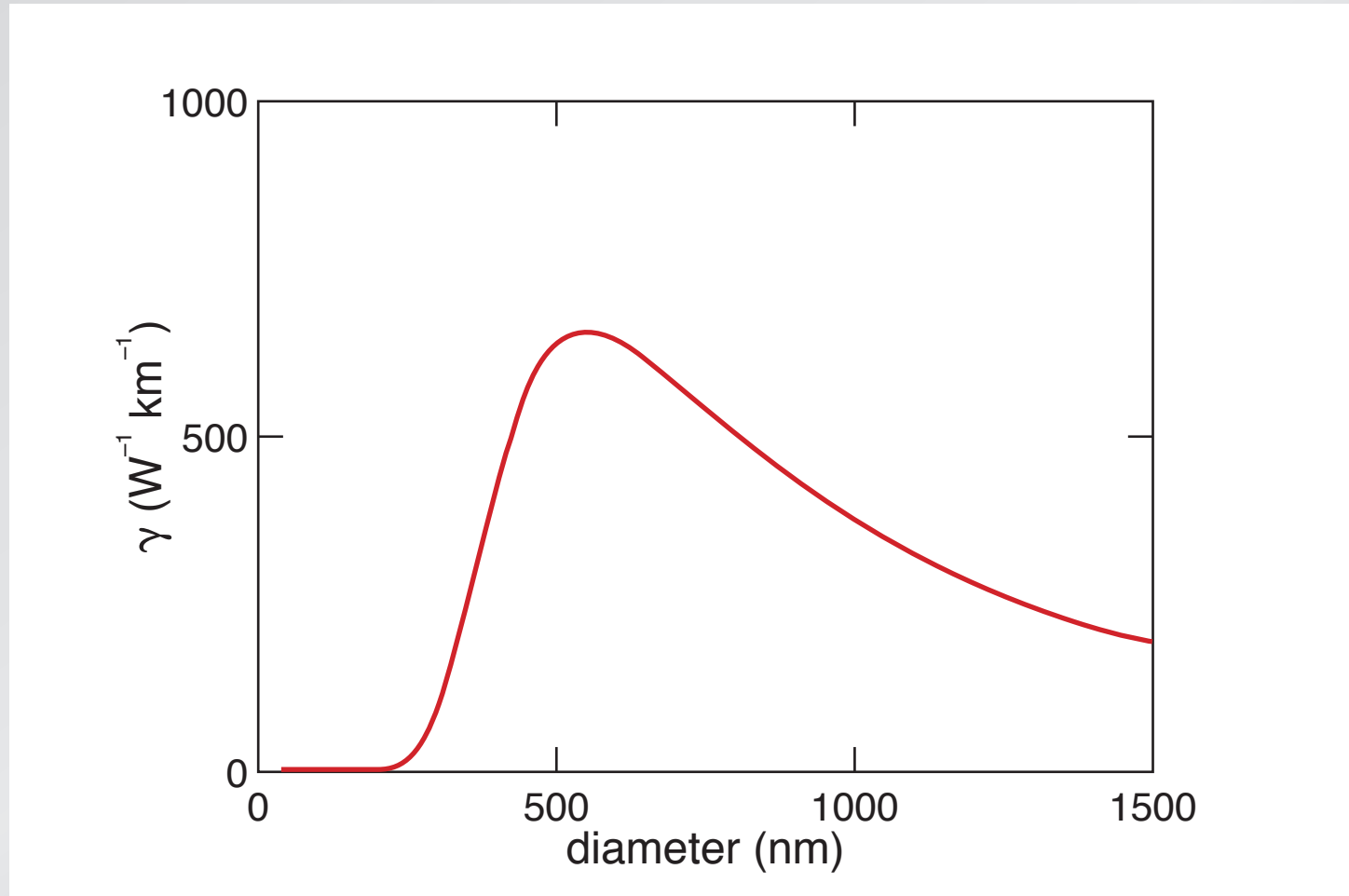
mode field diameter ( $\lambda = 800$  nm)



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

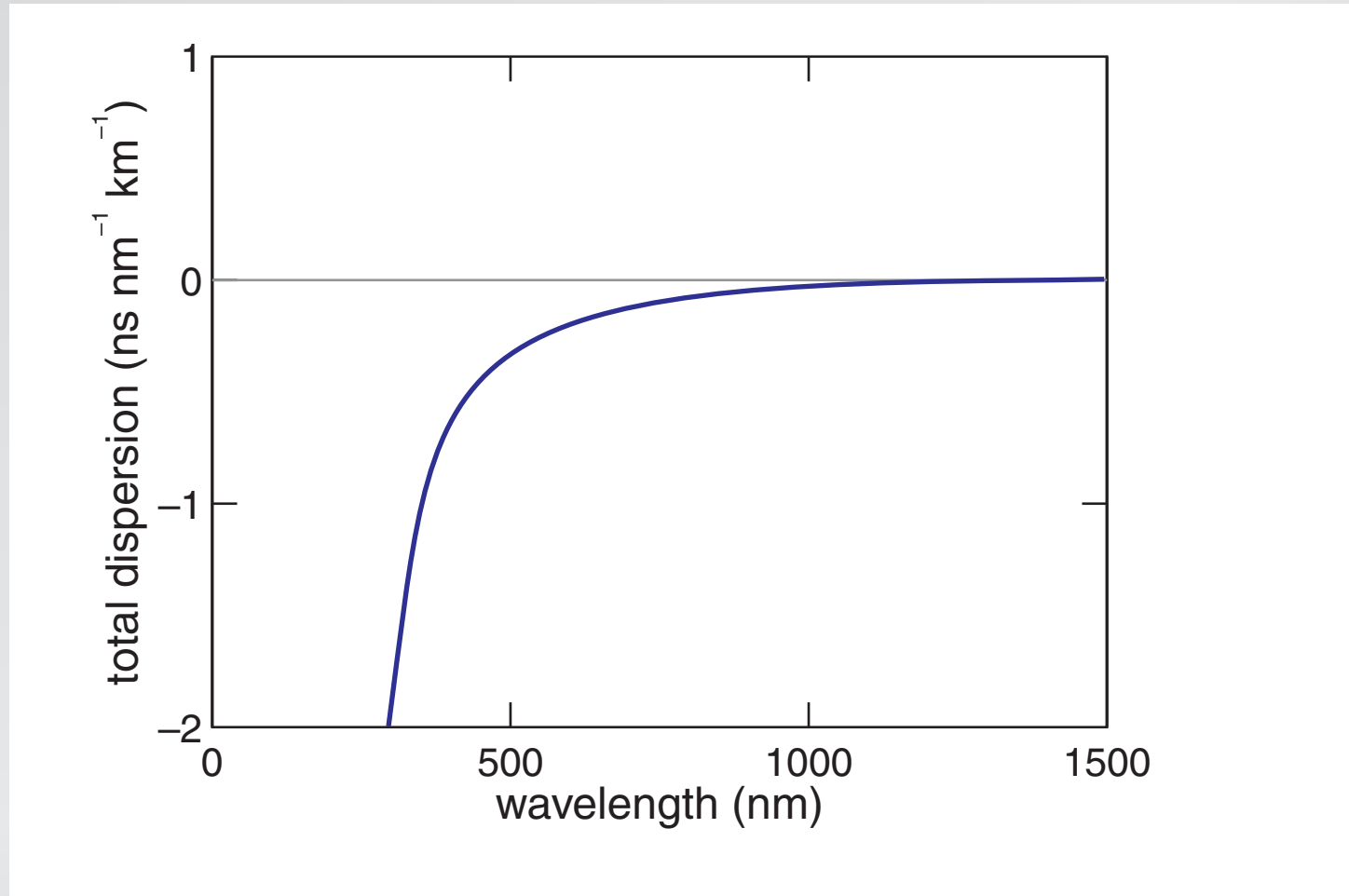
dispersion:

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



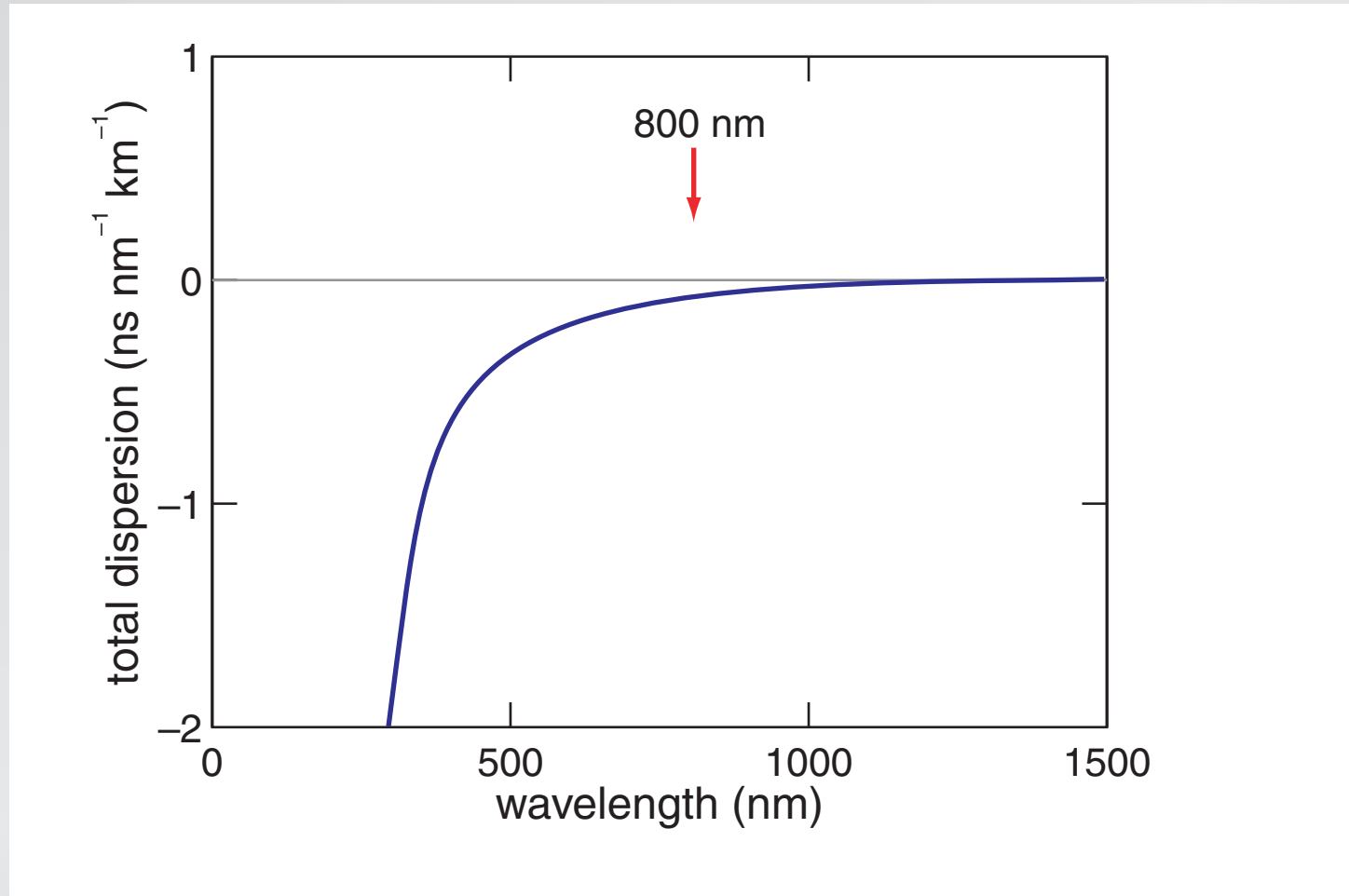
# Supercontinuum generation

## waveguide dispersion



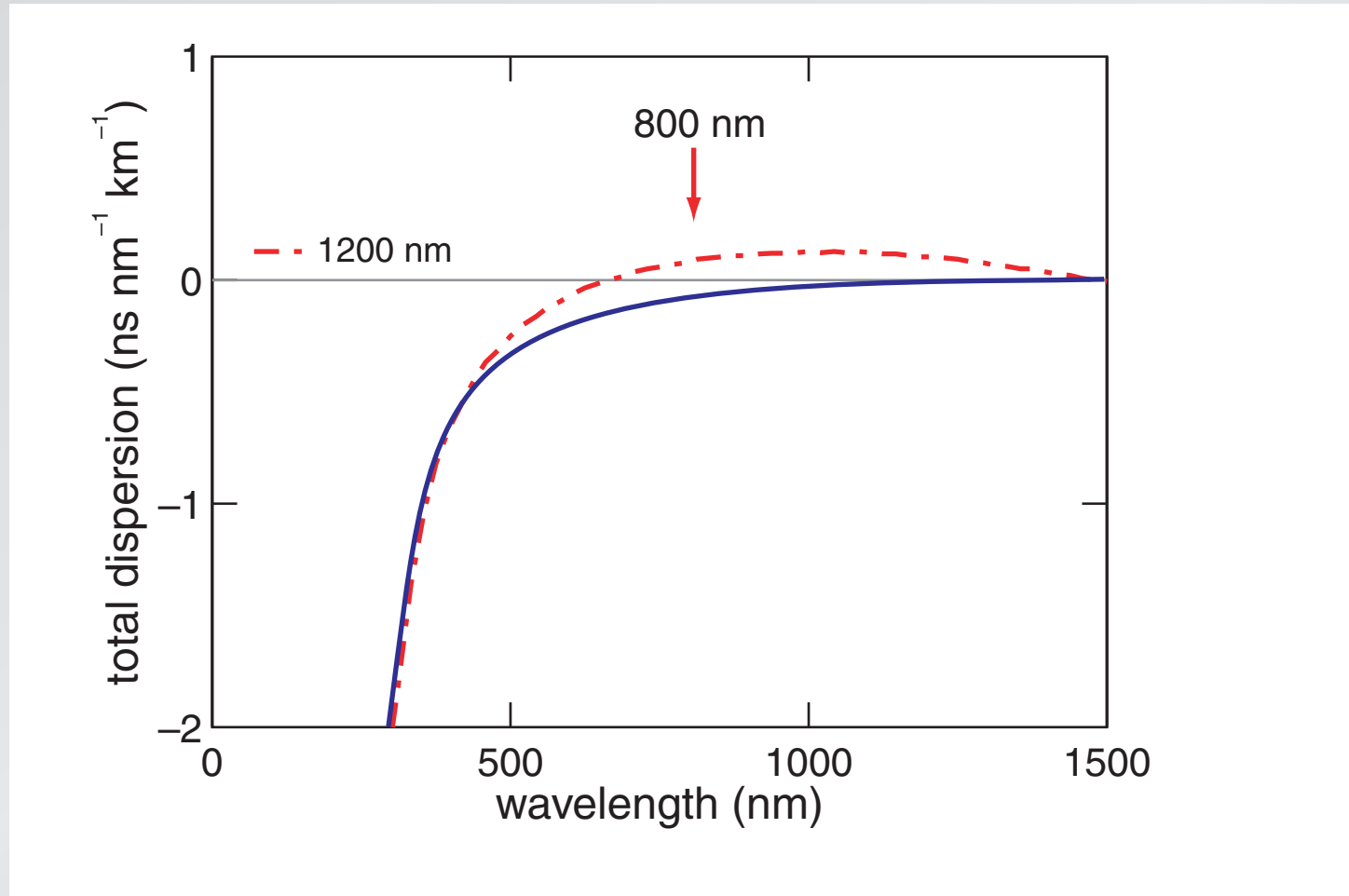
# Supercontinuum generation

## waveguide dispersion



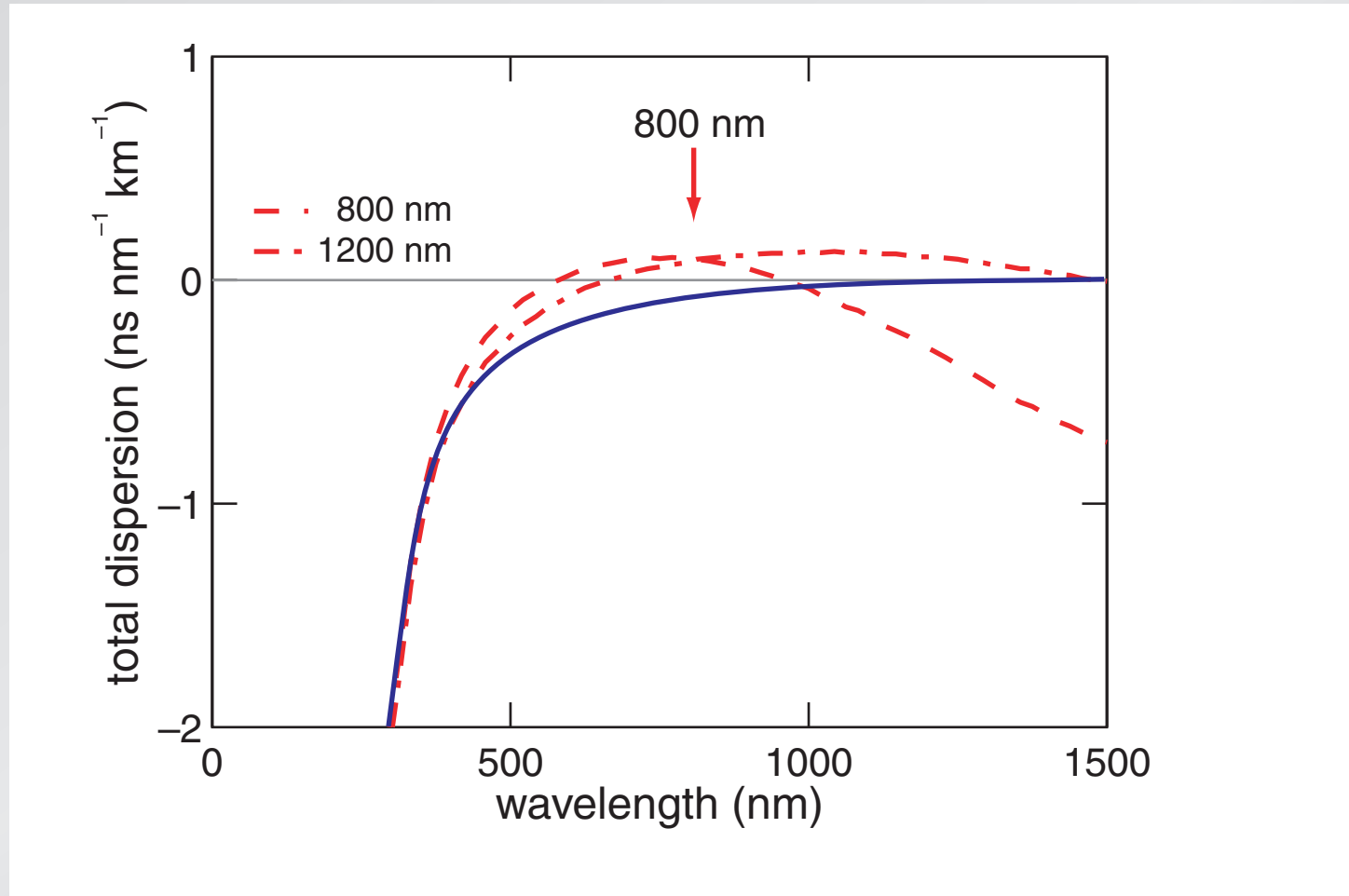
# Supercontinuum generation

## waveguide dispersion



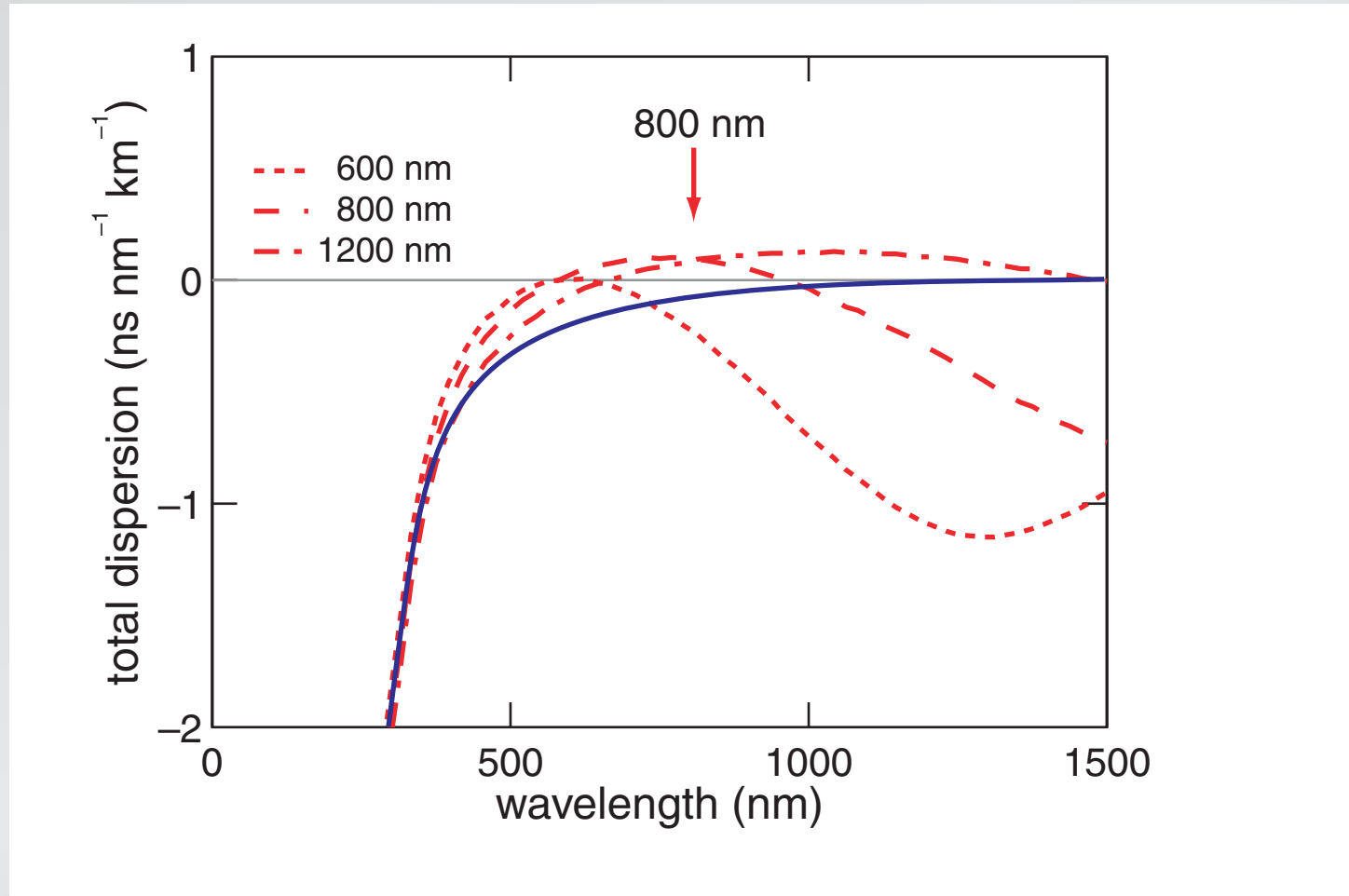
# Supercontinuum generation

## waveguide dispersion



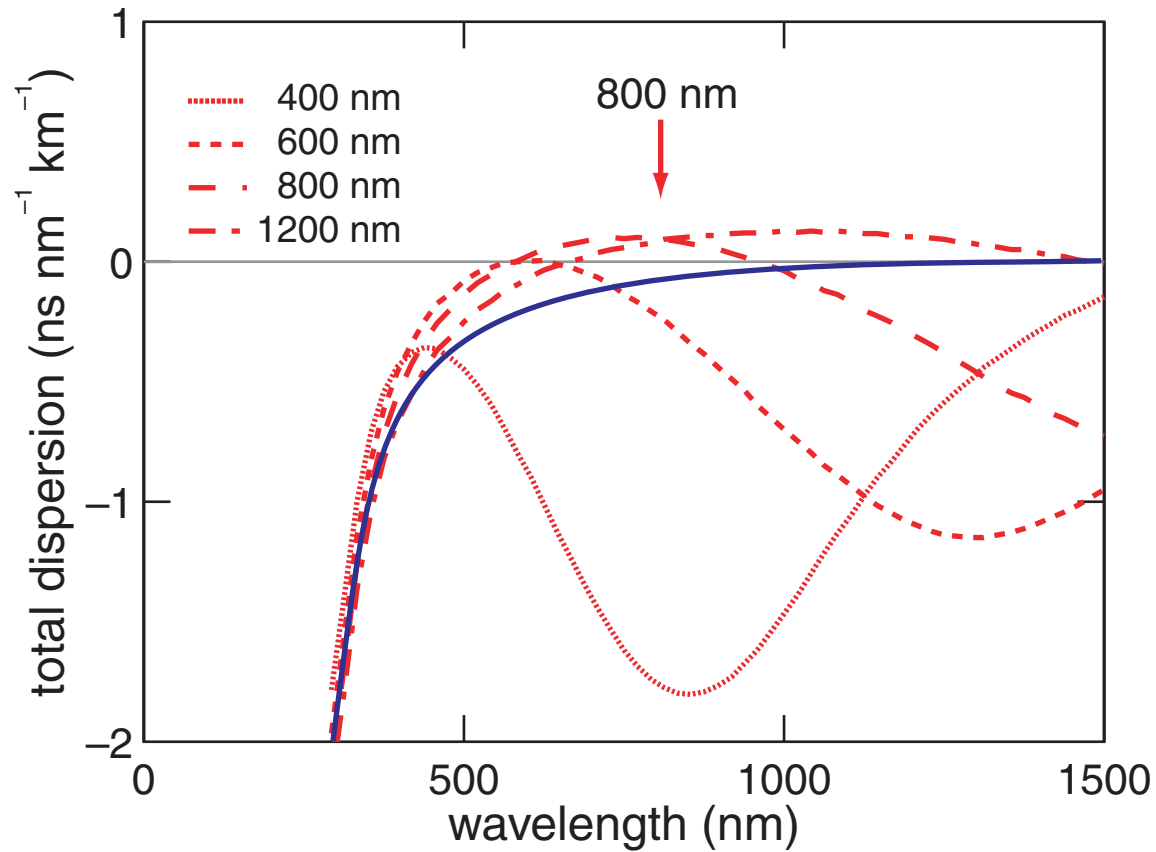
# Supercontinuum generation

## waveguide dispersion



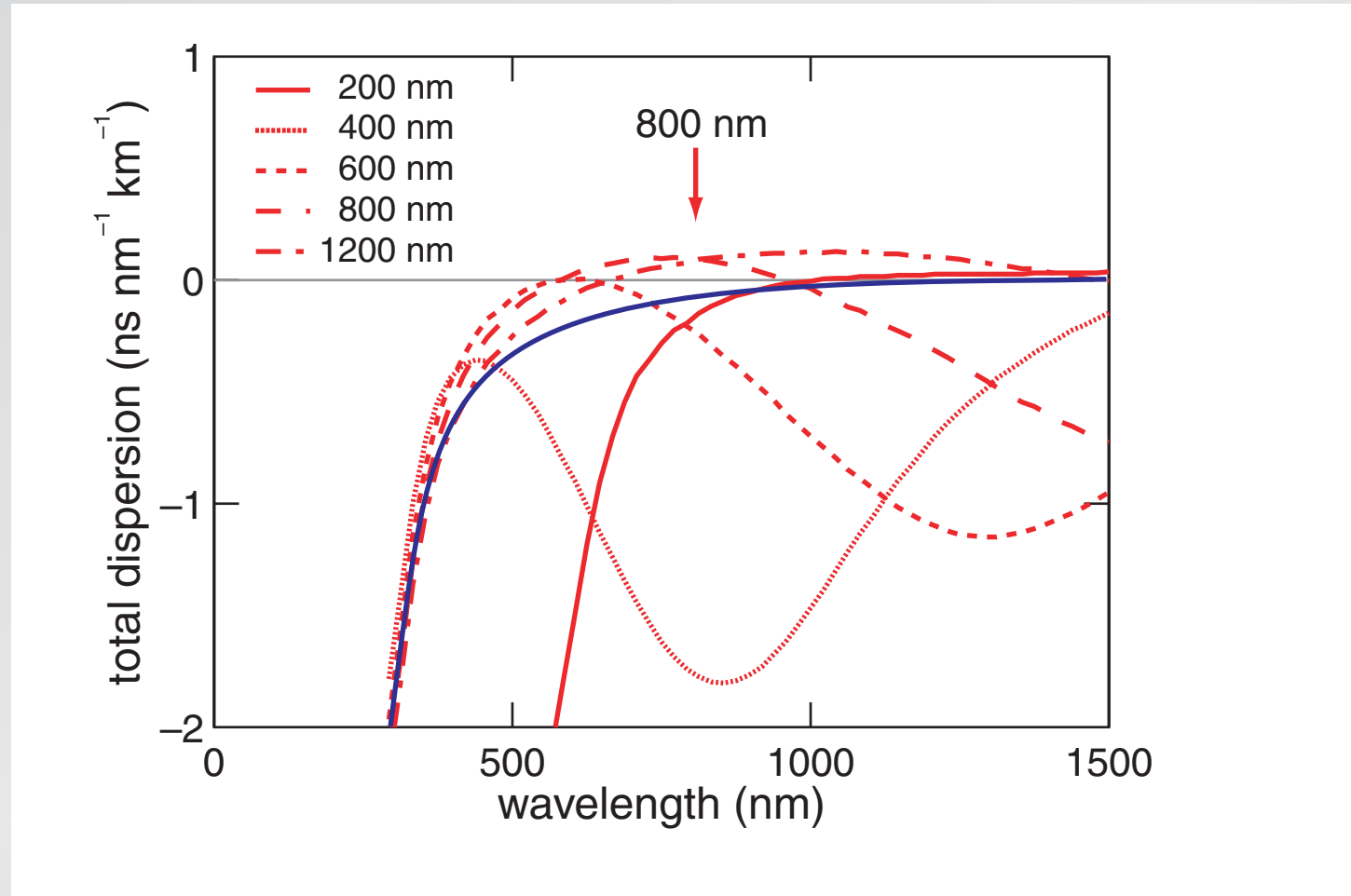
# Supercontinuum generation

## waveguide dispersion



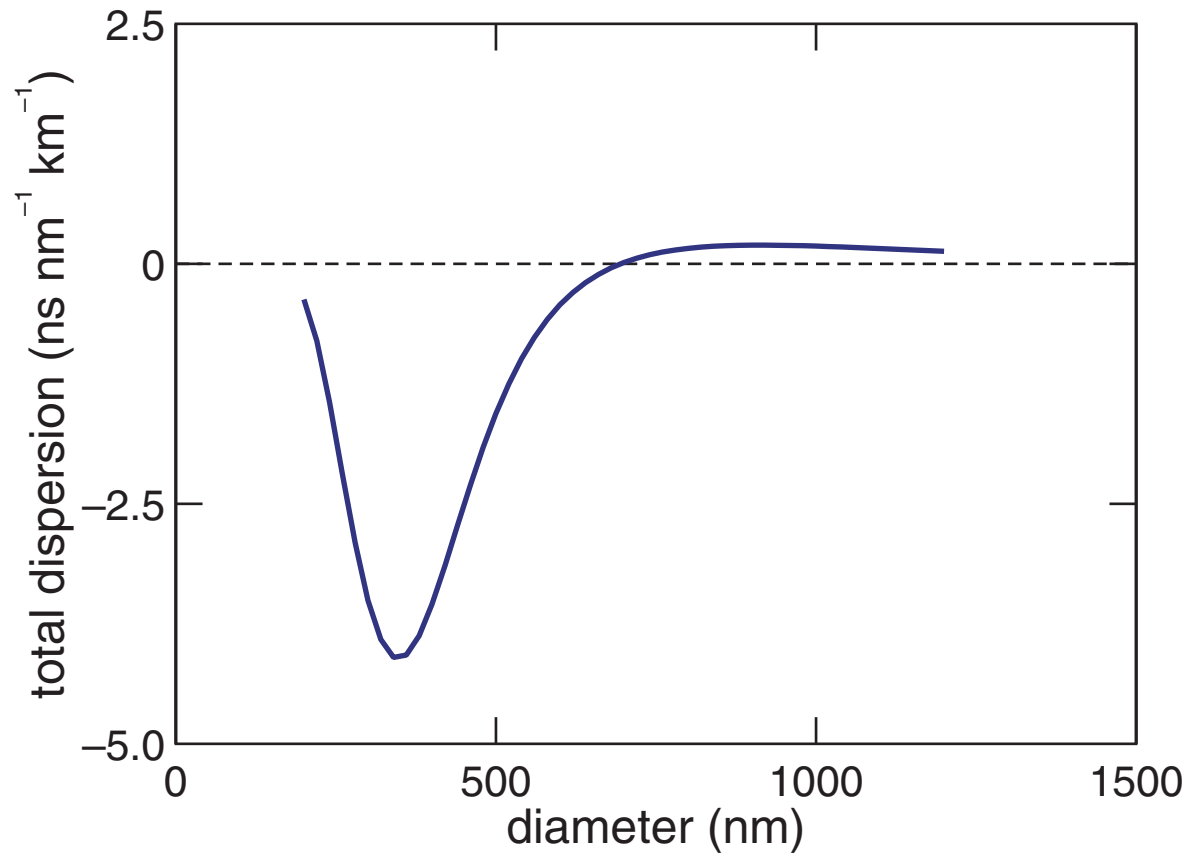
# Supercontinuum generation

## waveguide dispersion



# Supercontinuum generation

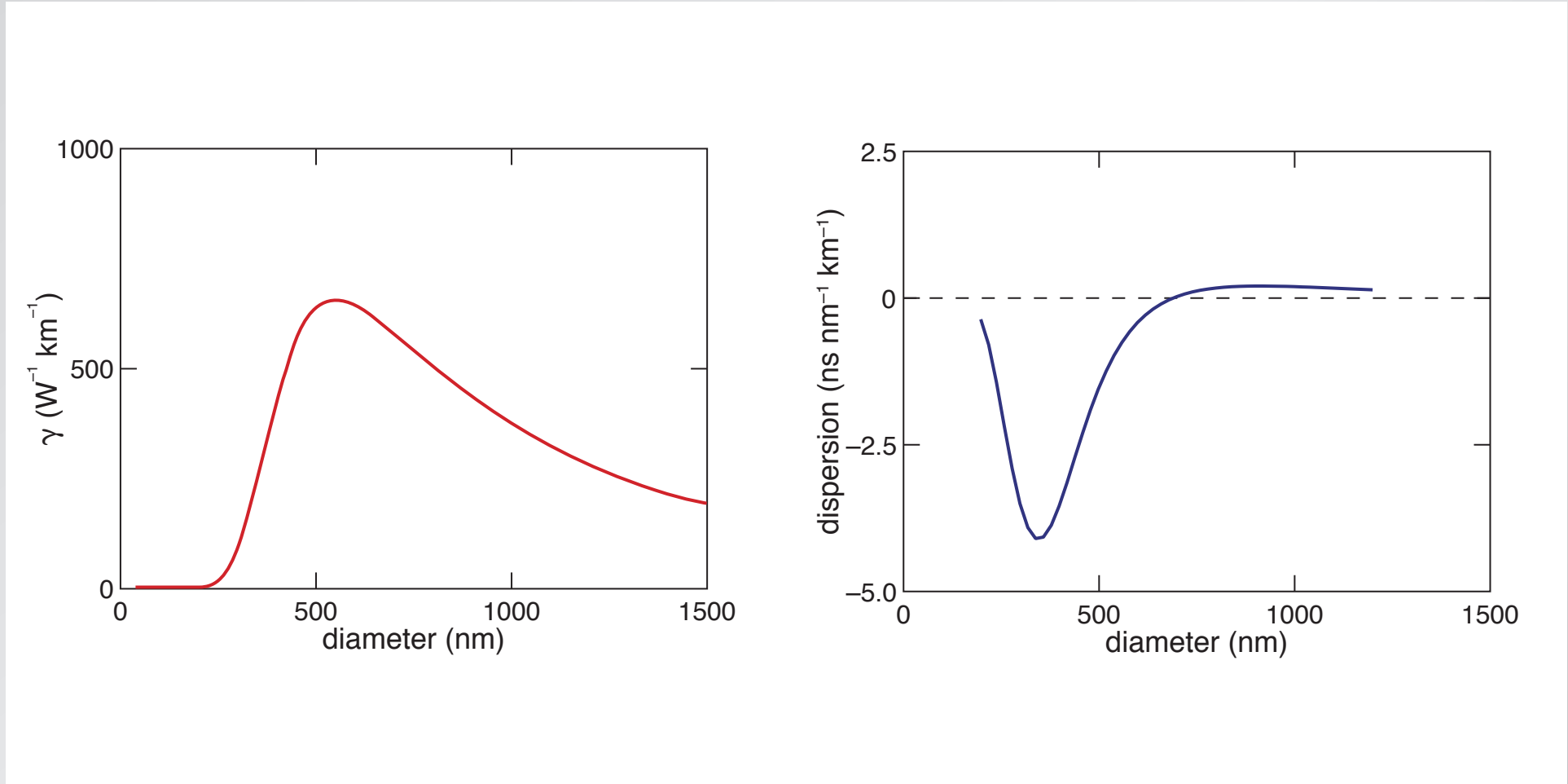
## waveguide dispersion





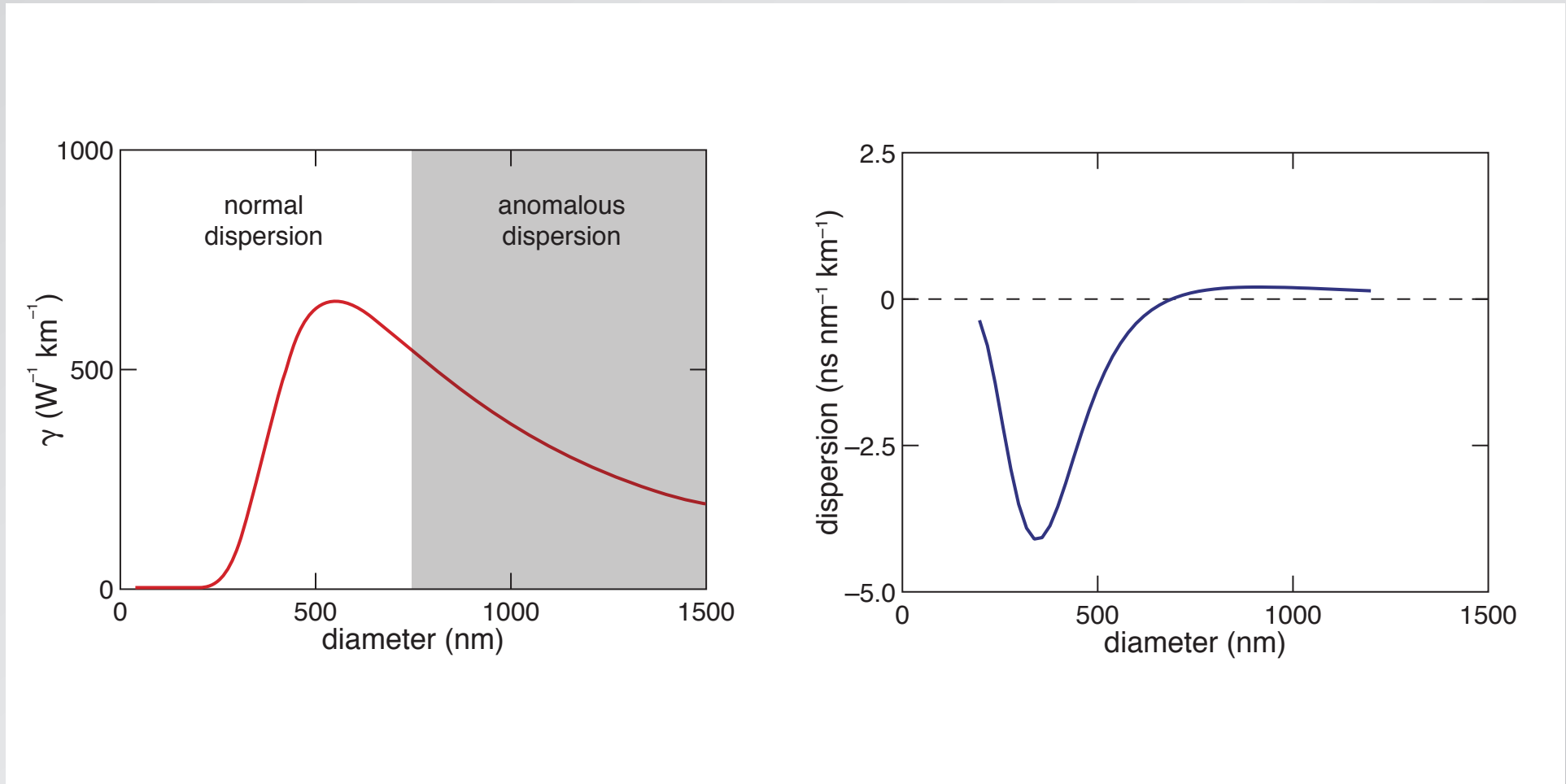
# Supercontinuum generation

## waveguide dispersion



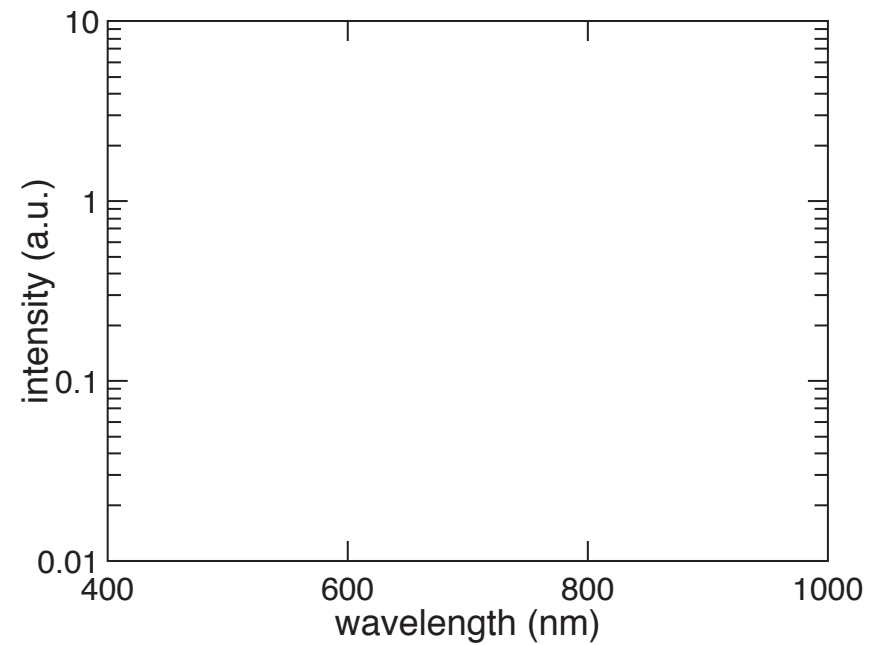
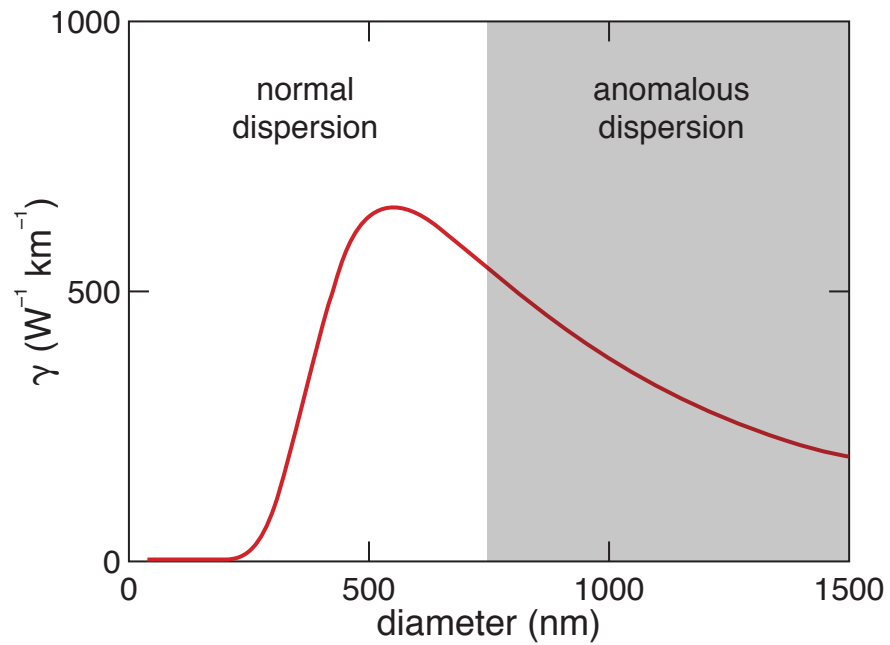
# Supercontinuum generation

## waveguide dispersion



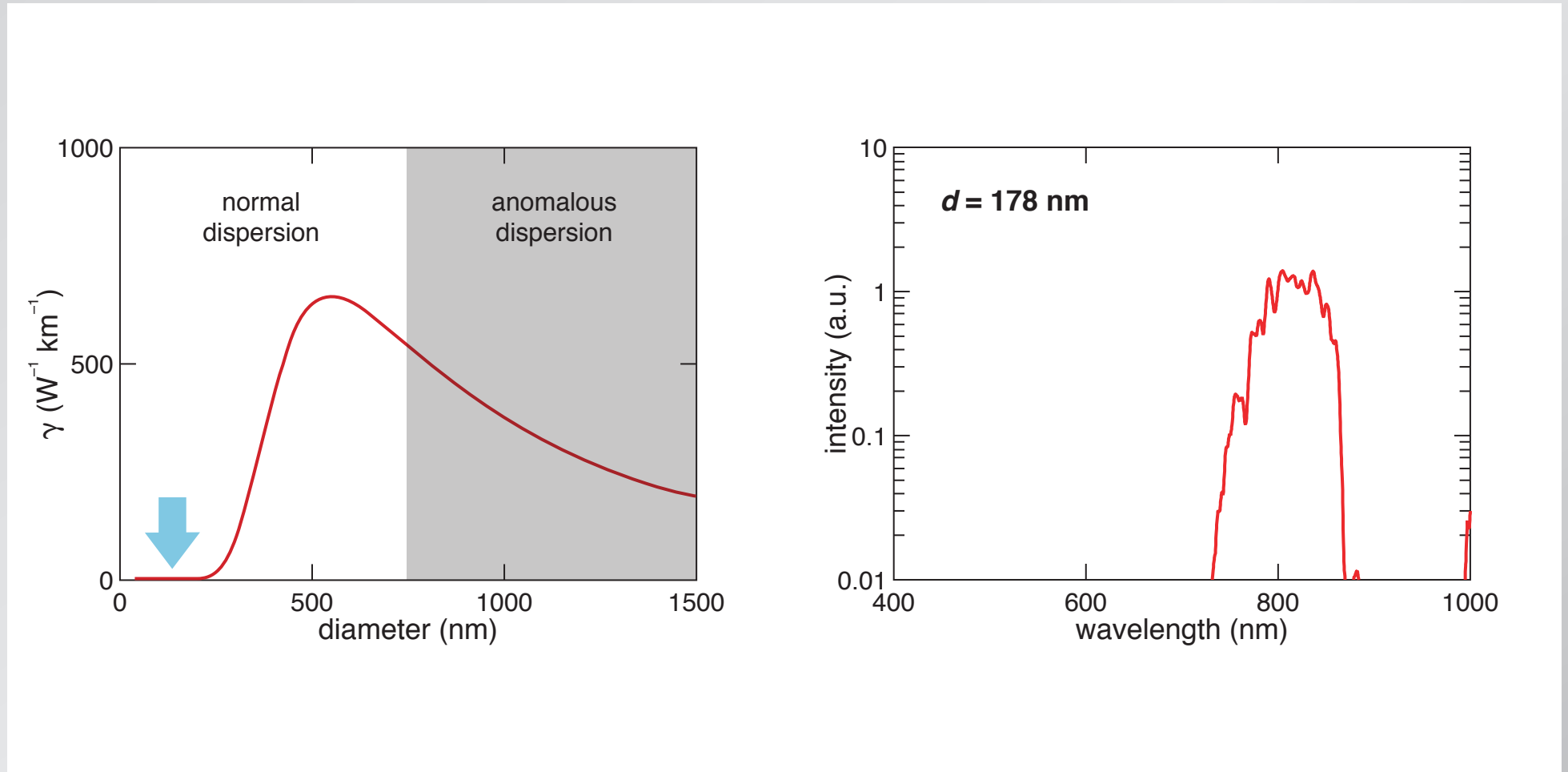
# Supercontinuum generation

## nanowire continuum generation



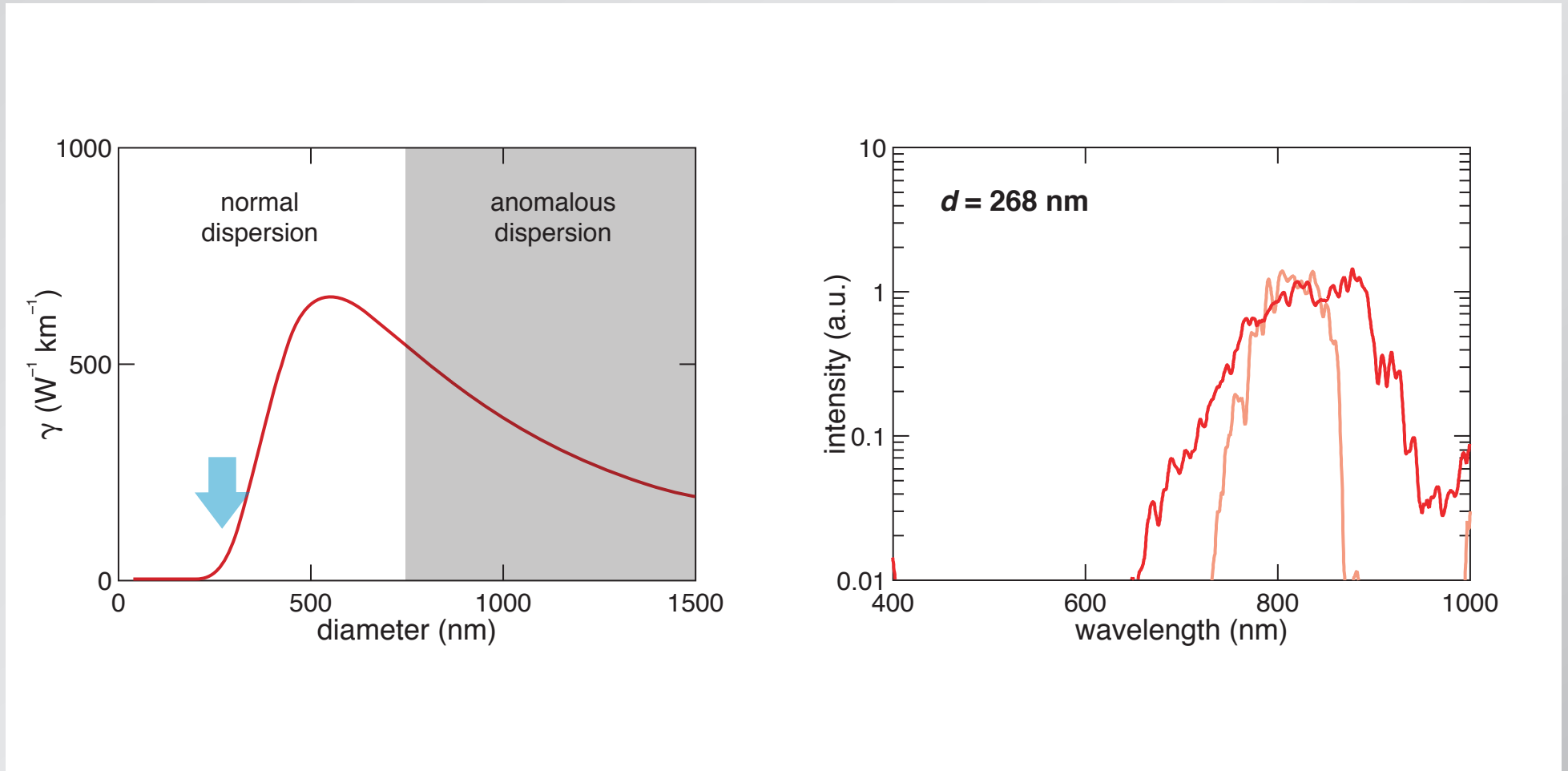
# Supercontinuum generation

## nanowire continuum generation



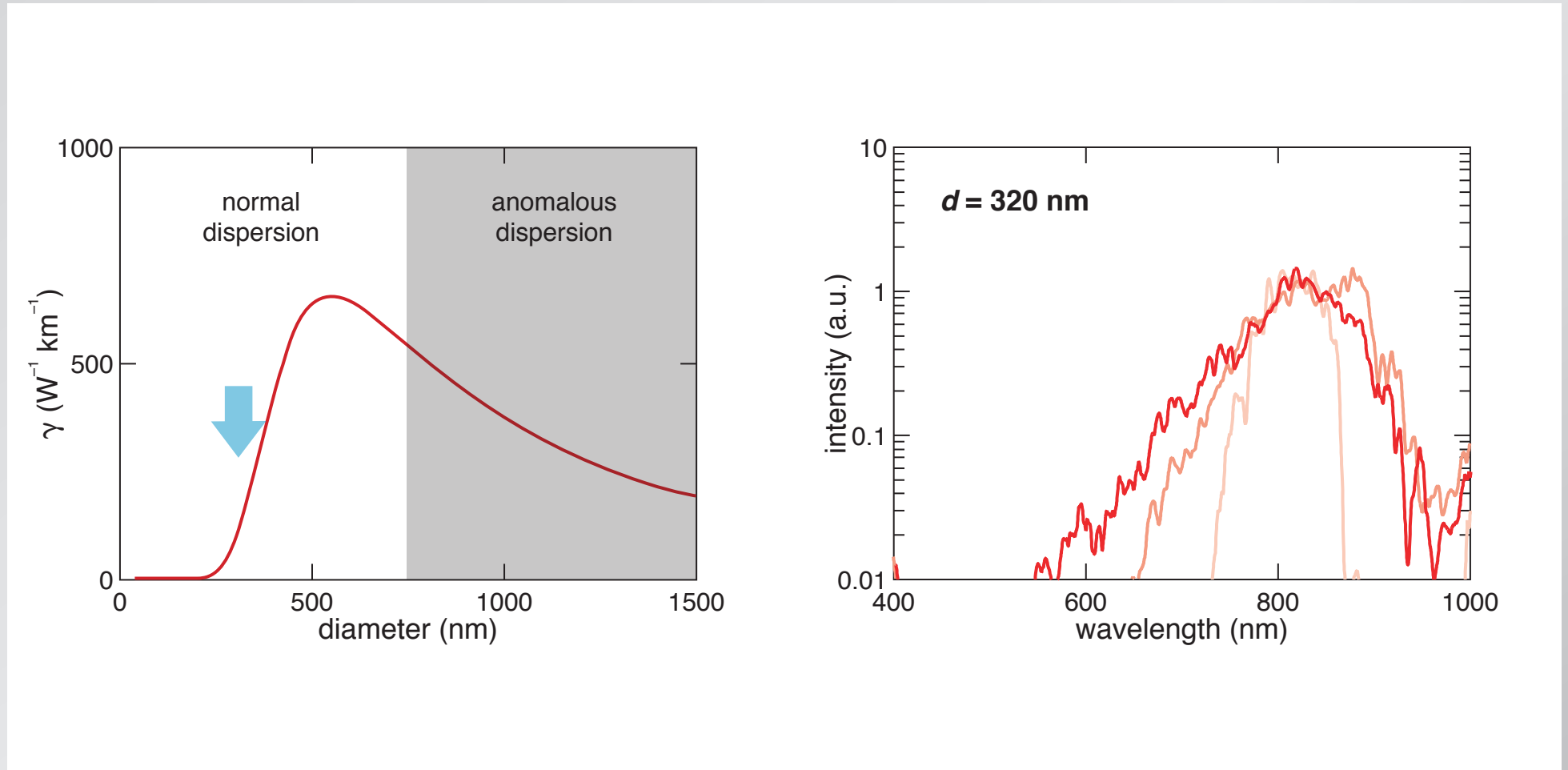
# Supercontinuum generation

## nanowire continuum generation



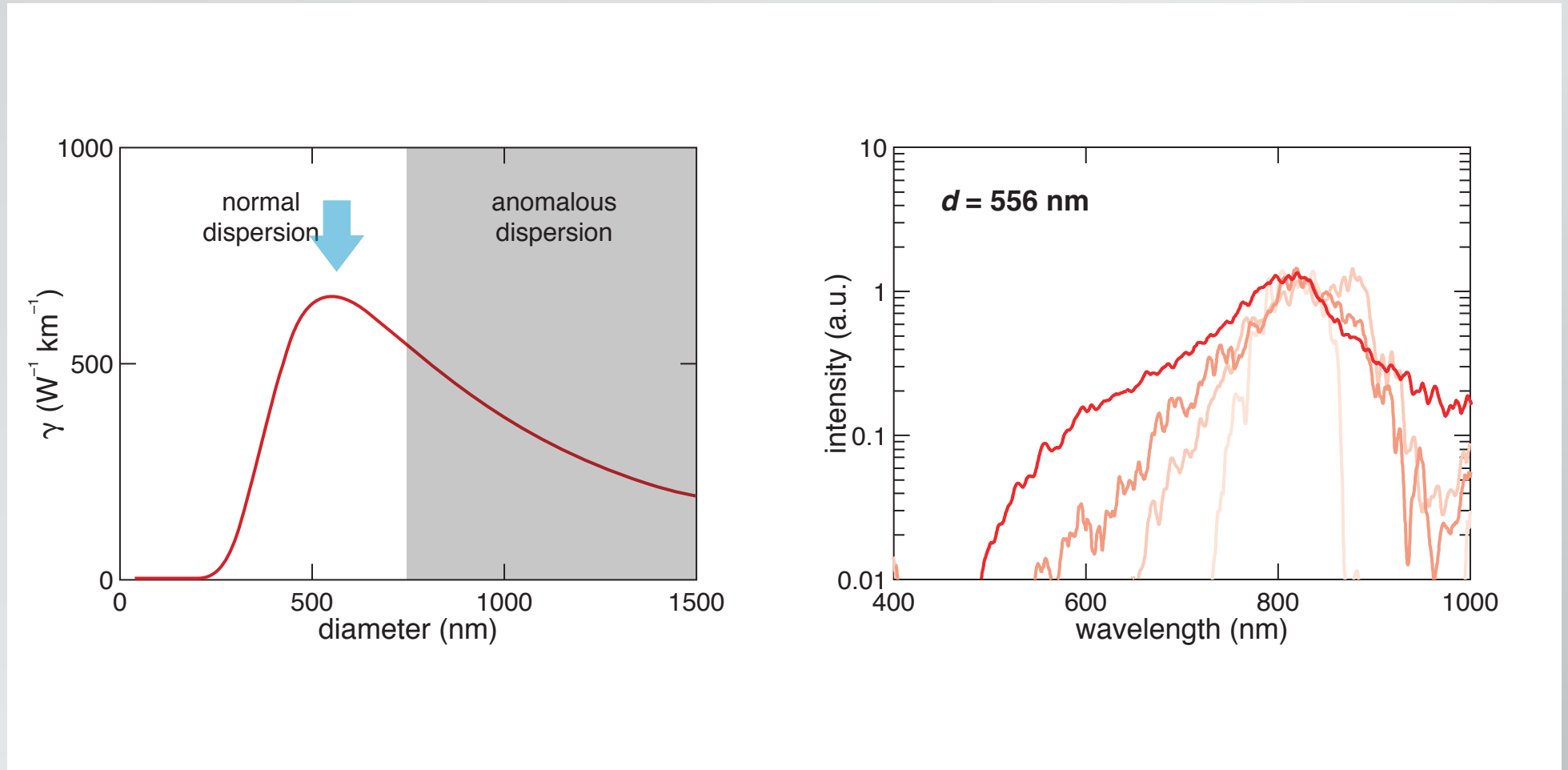
# Supercontinuum generation

## nanowire continuum generation



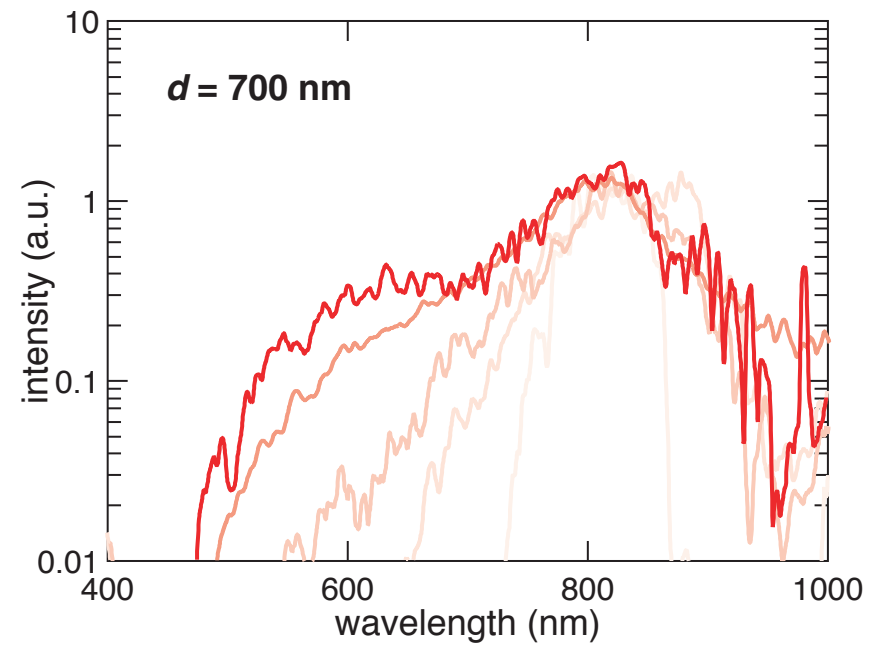
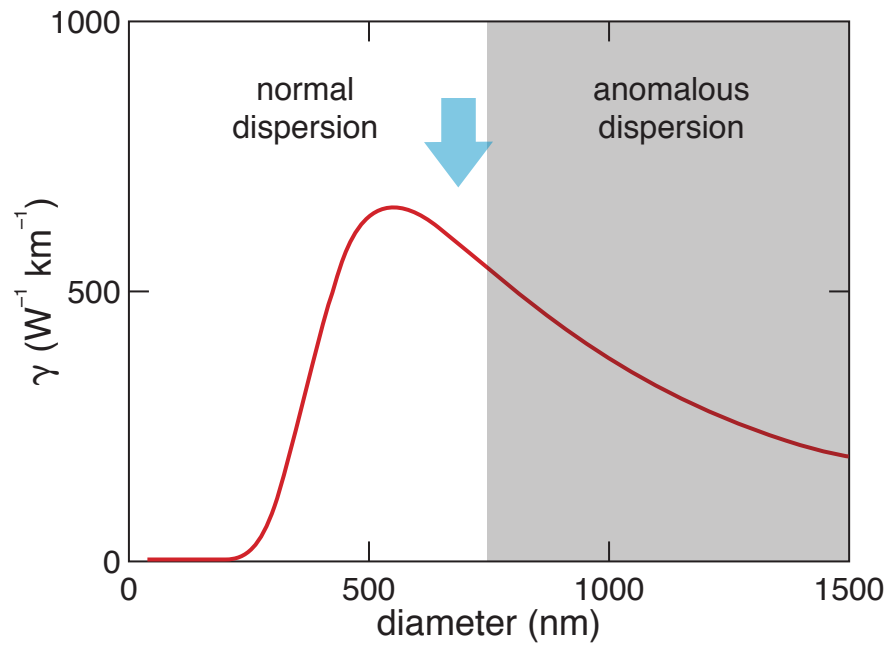
# Supercontinuum generation

## nanowire continuum generation



# Supercontinuum generation

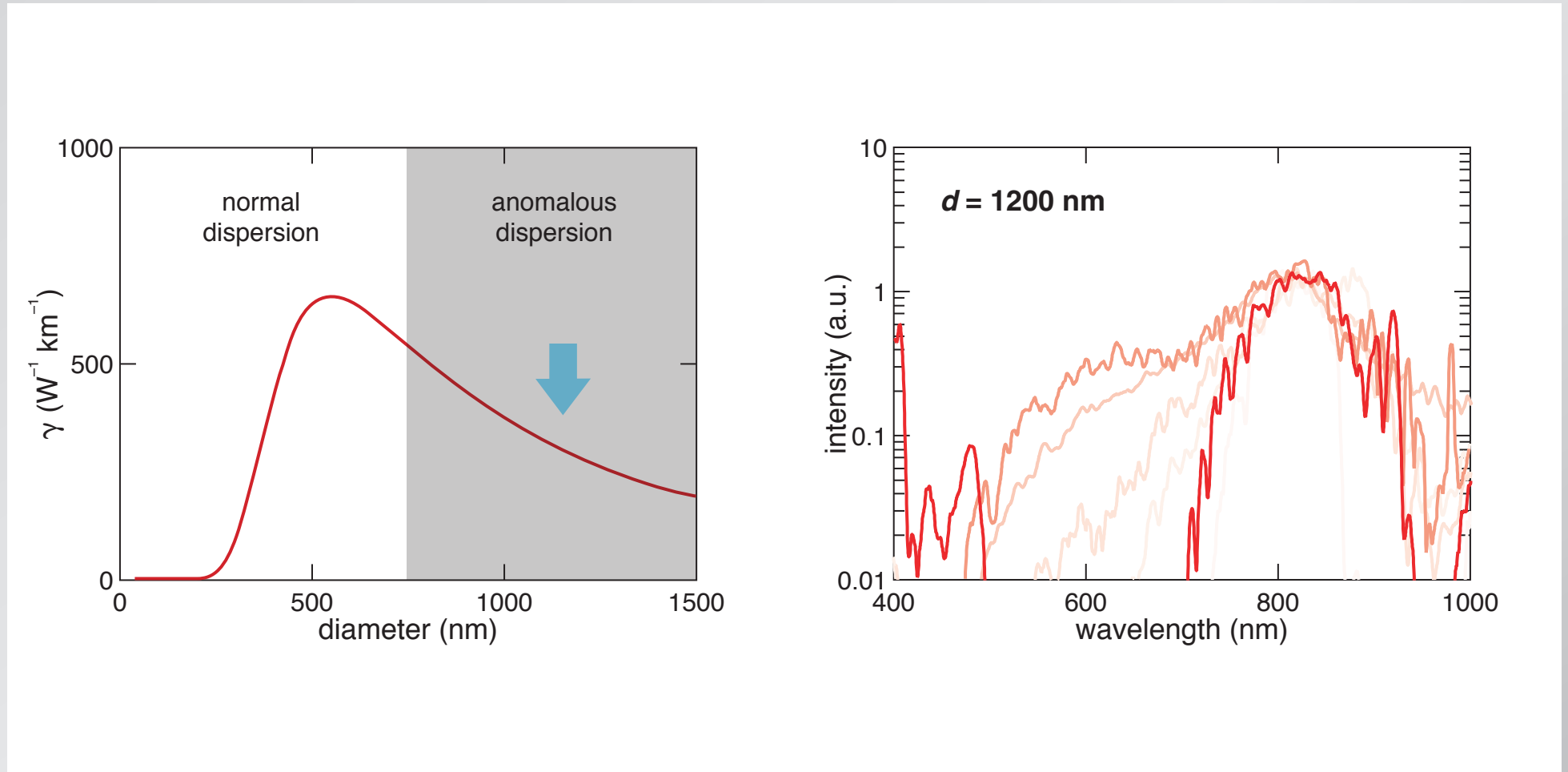
## nanowire continuum generation





# Supercontinuum generation

## nanowire continuum generation



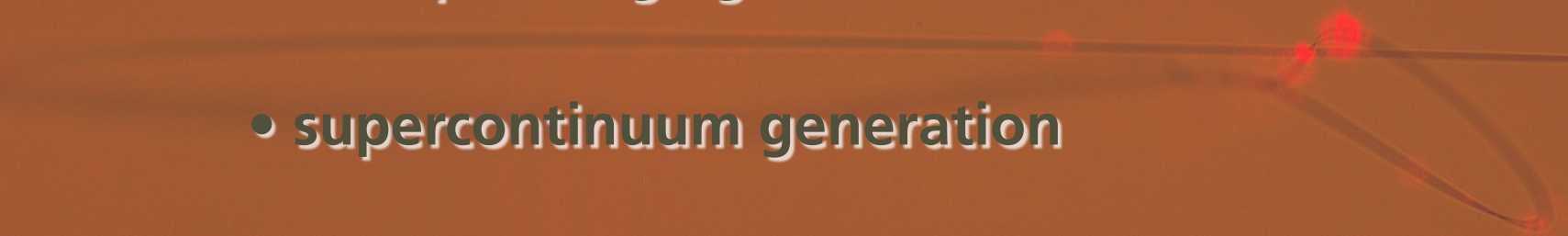
# Supercontinuum generation

energy in nanowire  $< 100$  pJ!

# Supercontinuum generation

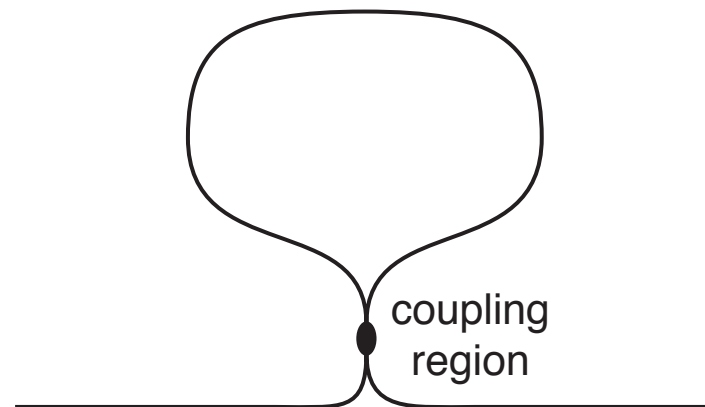
- **picojoule nonlinear optics**
- **optimum diameter for silica 500–600 nm**
- **low dispersion**

# Outline

- **manipulating light at the nanoscale**
  - **supercontinuum generation**
  - **optical logic gates**
- 
- A decorative graphic on the right side of the slide shows a thin, dark line representing a light path. It starts from the left, moves horizontally to the right, then curves downwards and loops back to the left, ending in a small red dot. There are several other red dots of varying sizes along the path, suggesting points of interaction or emission.

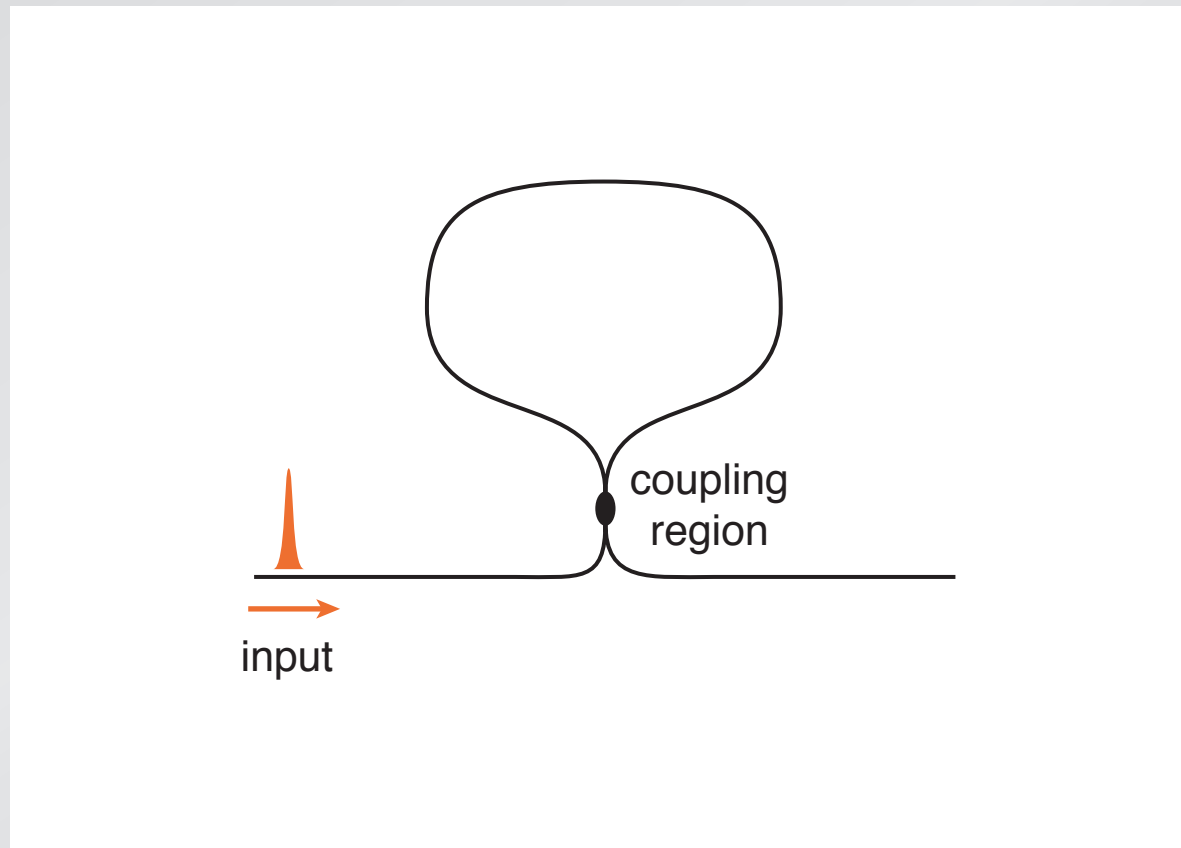
# Optical logic gates

nanowire Sagnac interferometer



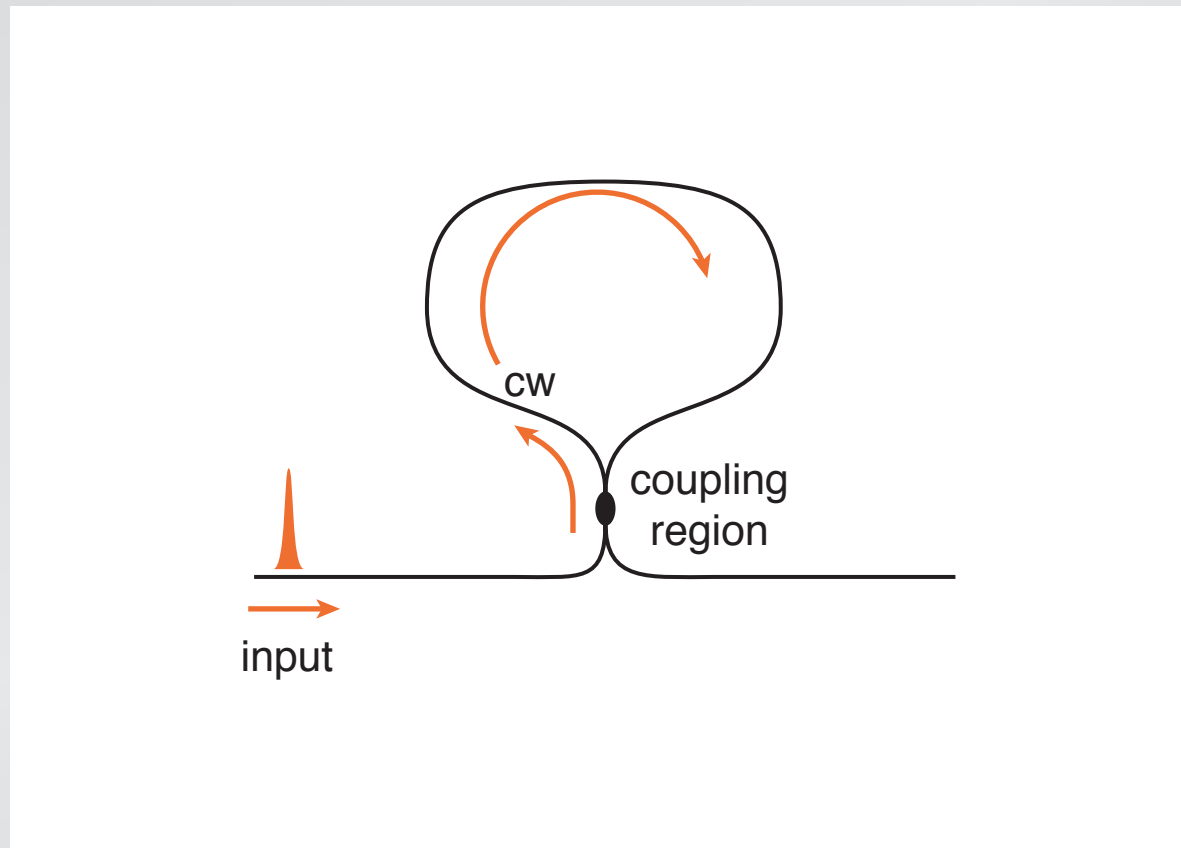
# Optical logic gates

## nanowire Sagnac interferometer



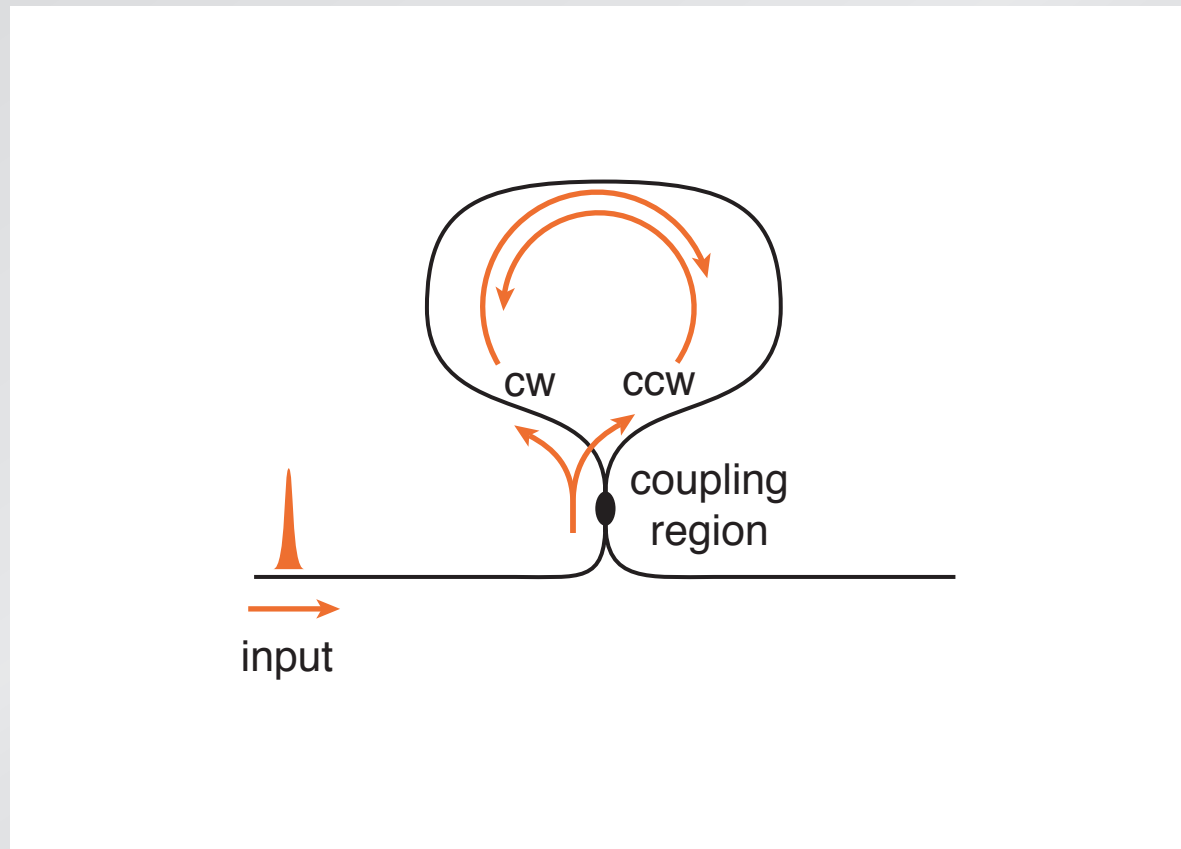
# Optical logic gates

## nanowire Sagnac interferometer



# Optical logic gates

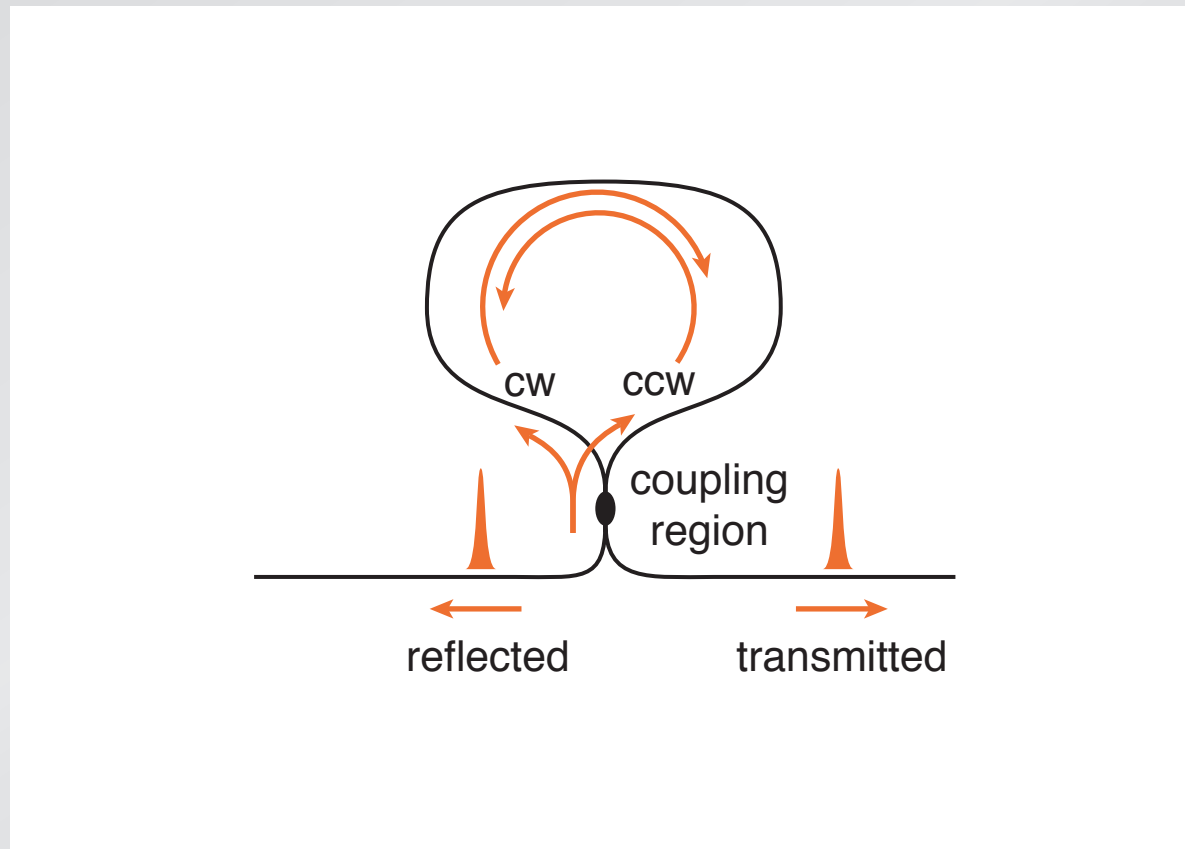
## nanowire Sagnac interferometer





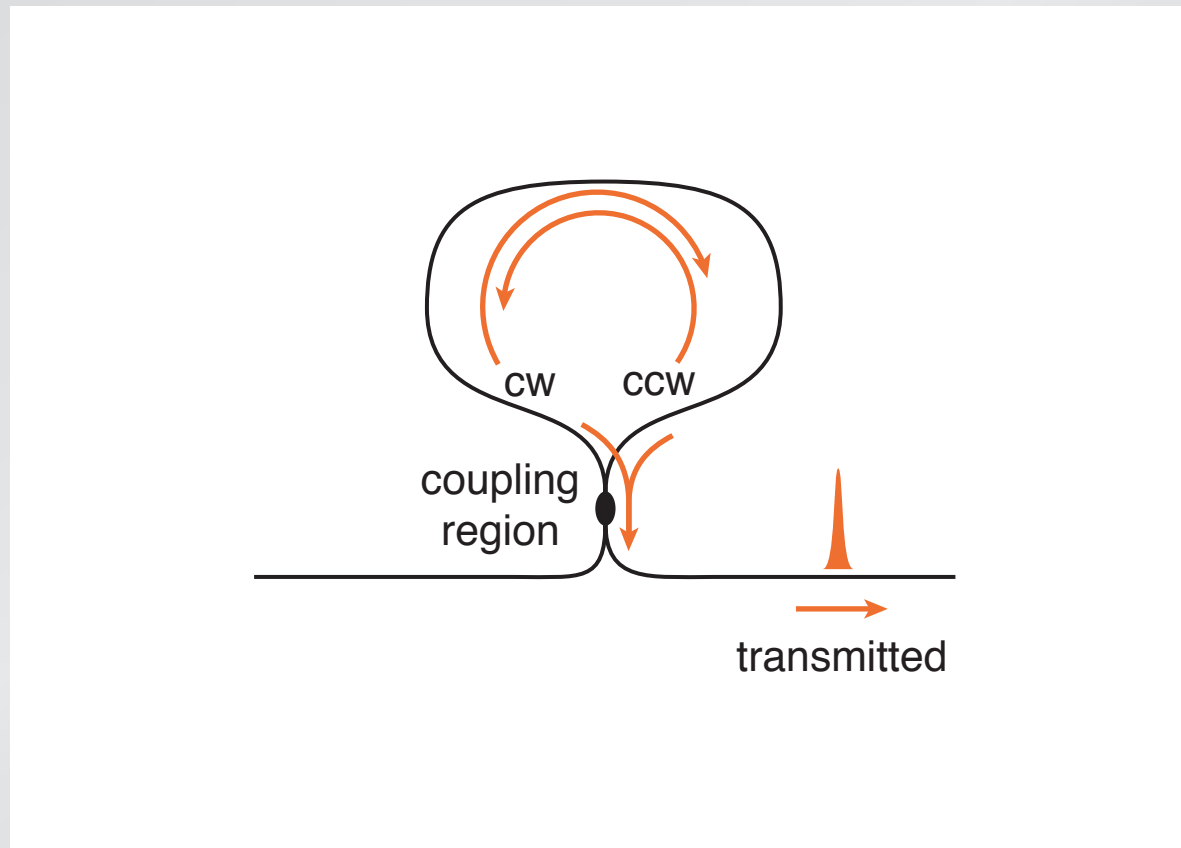
# Optical logic gates

## nanowire Sagnac interferometer



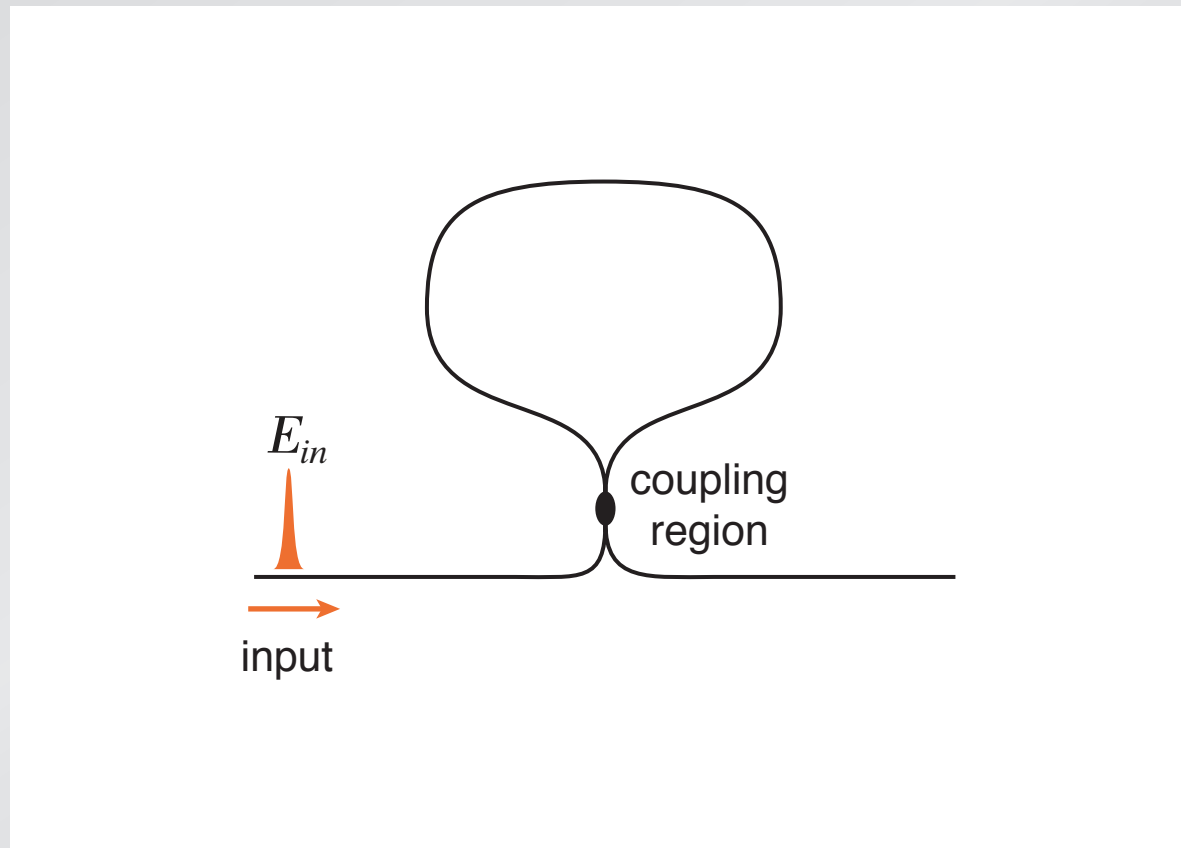
# Optical logic gates

output = transmitted cw + ccw power



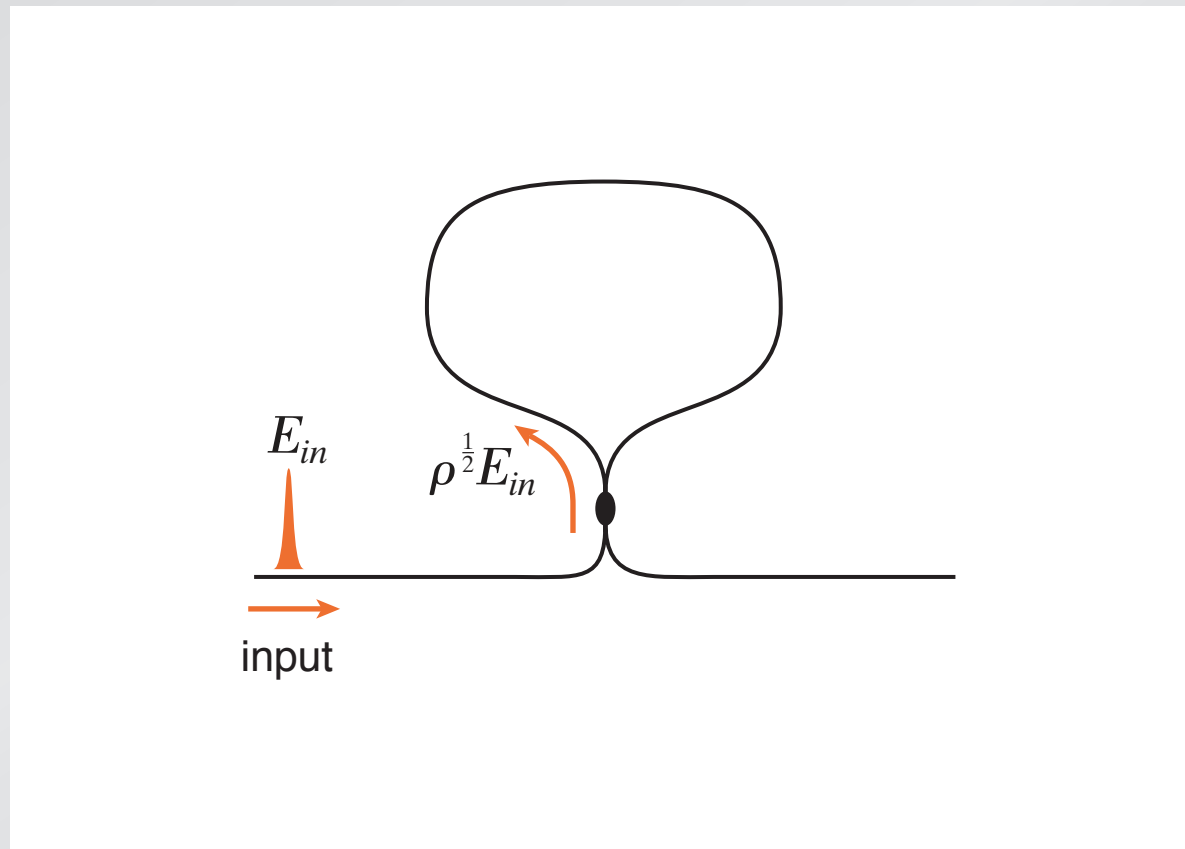
# Optical logic gates

input electric field amplitude  $E_{in}$



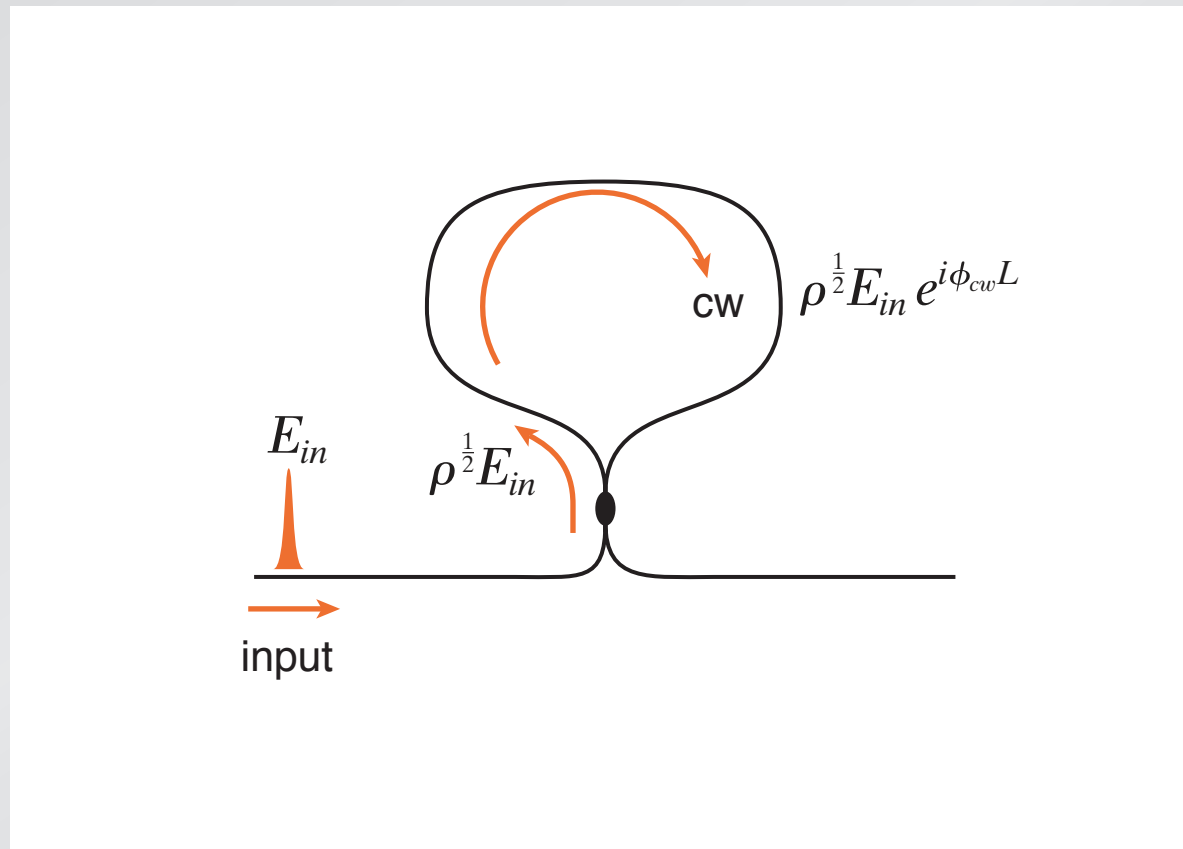
# Optical logic gates

coupling parameter:  $\rho$



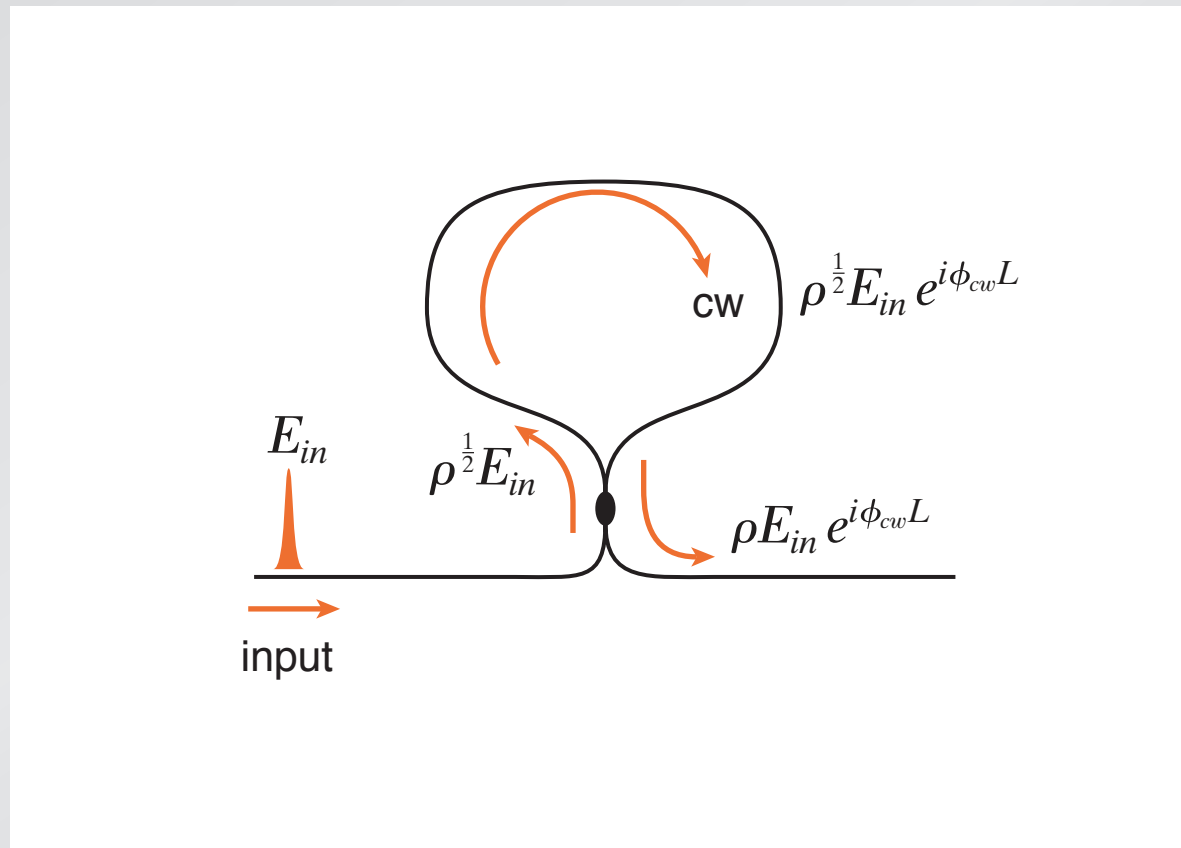
# Optical logic gates

phase accumulation over path length of loop  $L$



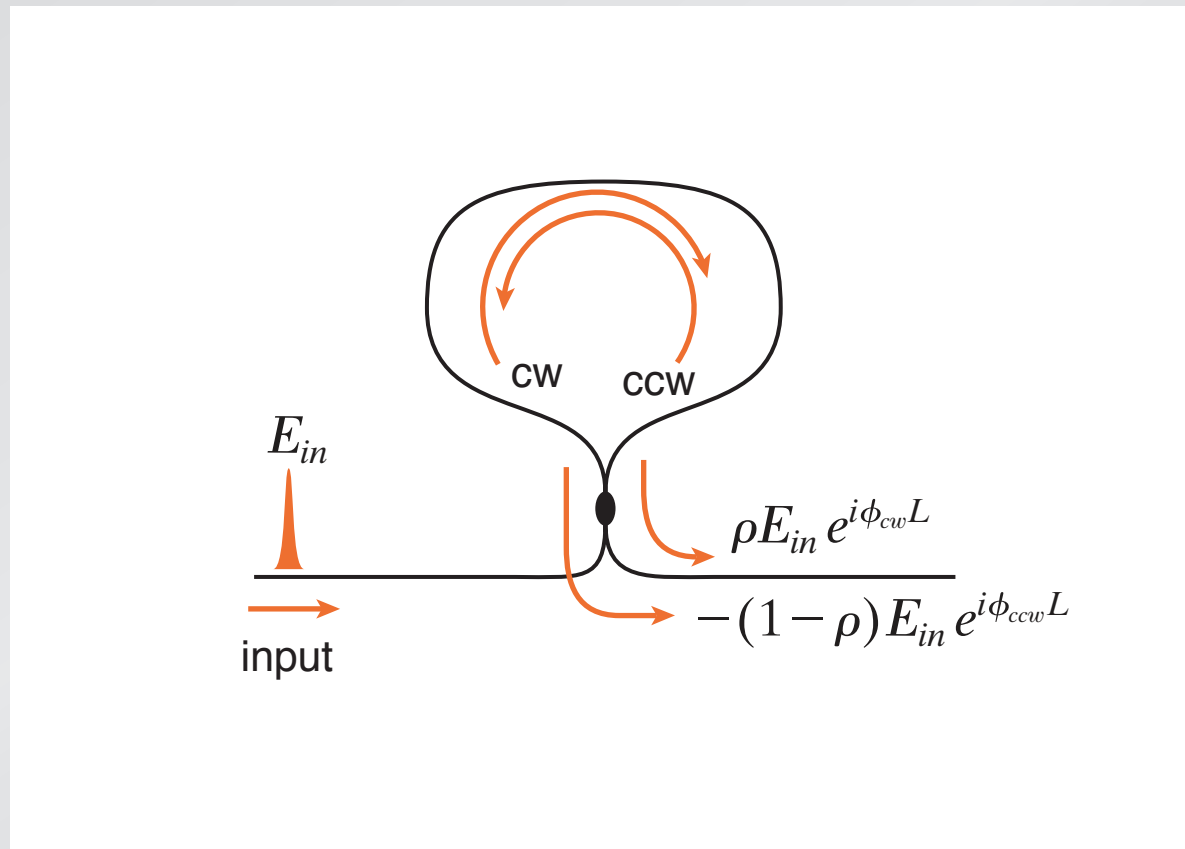
# Optical logic gates

coupling parameter:  $\rho$



# 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

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$$\phi = k_o n$$

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:**

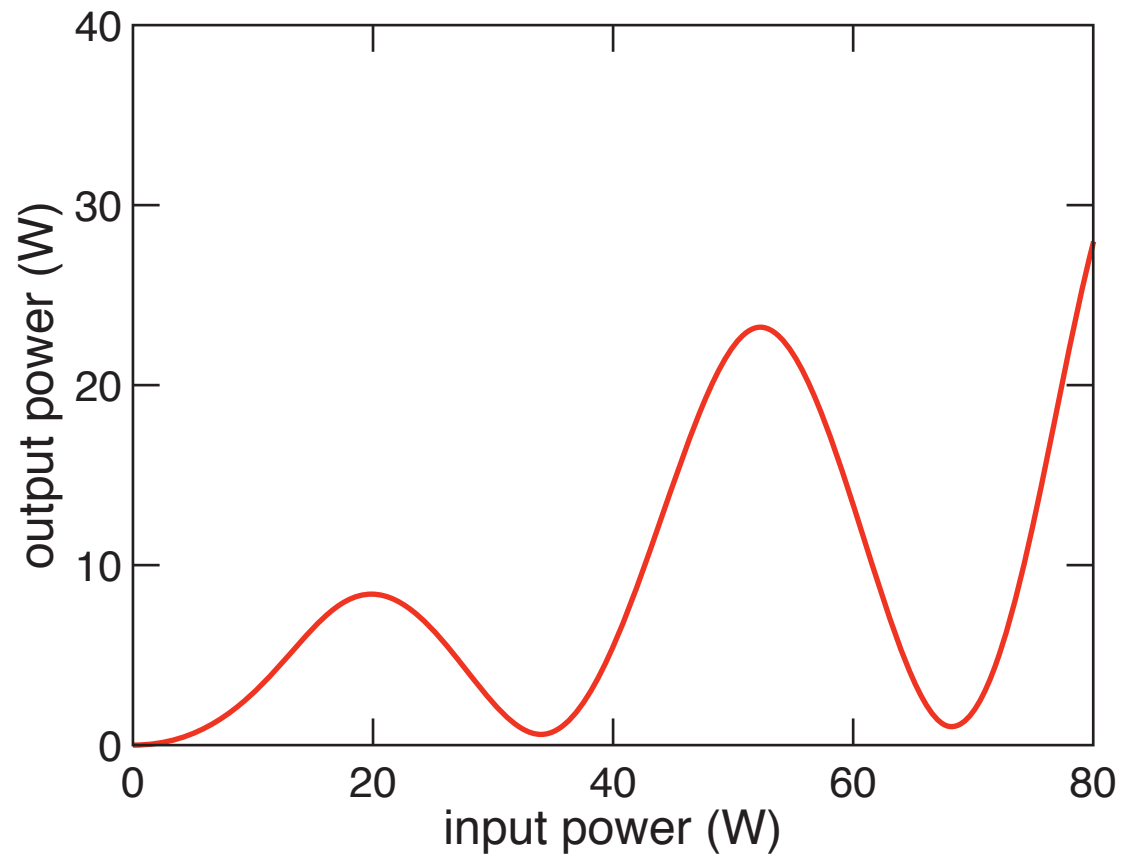
$$\rho = 0.5$$

**no transmission:**

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

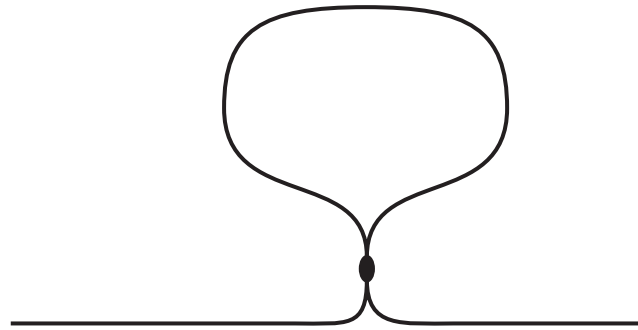
# Optical logic gates

when  $\rho \neq 0.5$ :



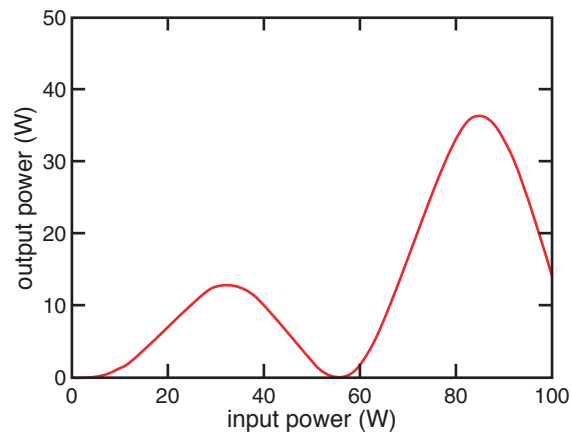
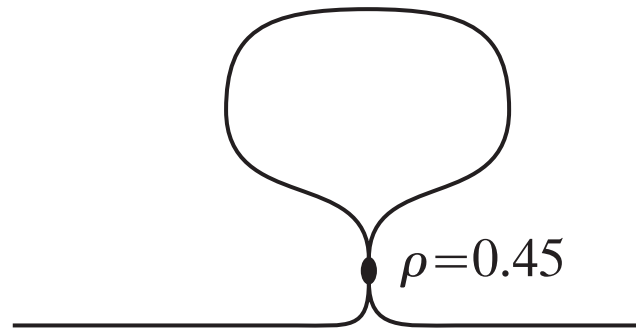
# Optical logic gates

nonlinear nanogate



# Optical logic gates

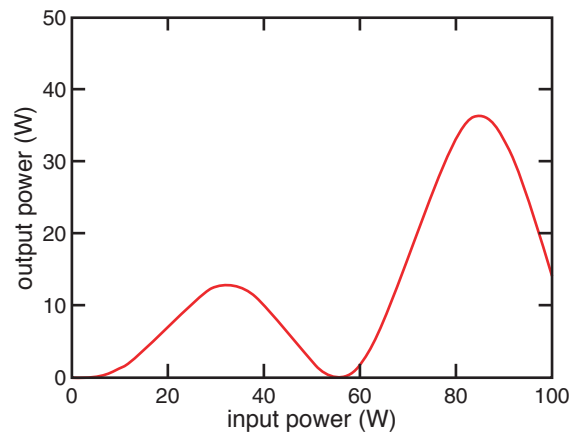
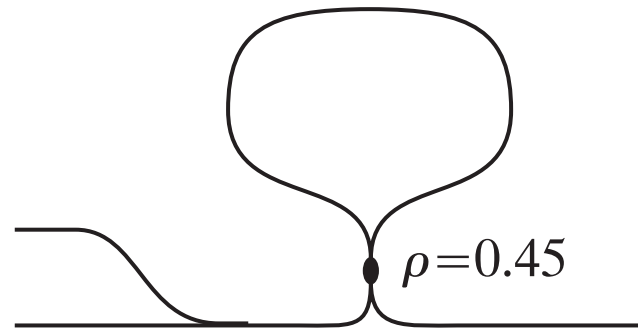
## nonlinear nanogate





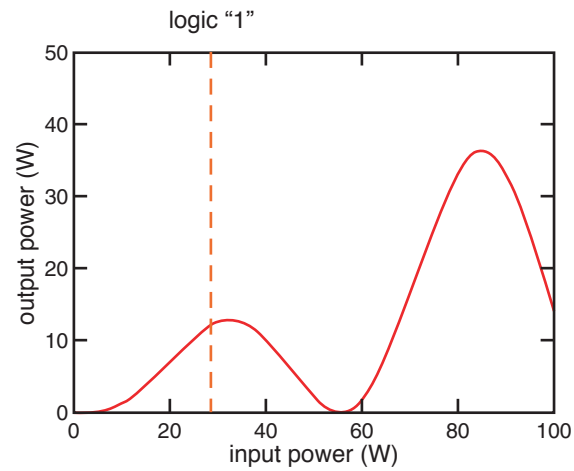
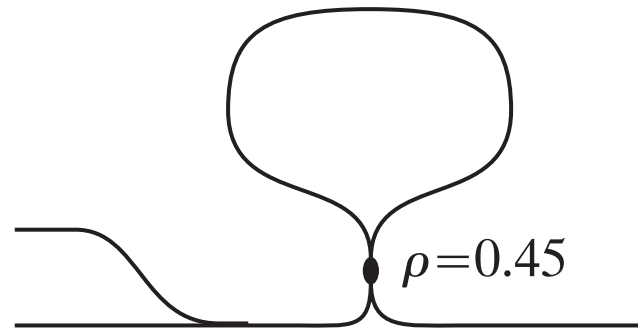
# Optical logic gates

## nonlinear nanogate



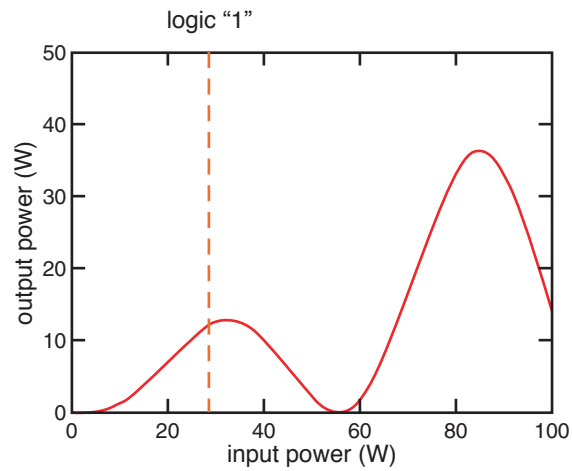
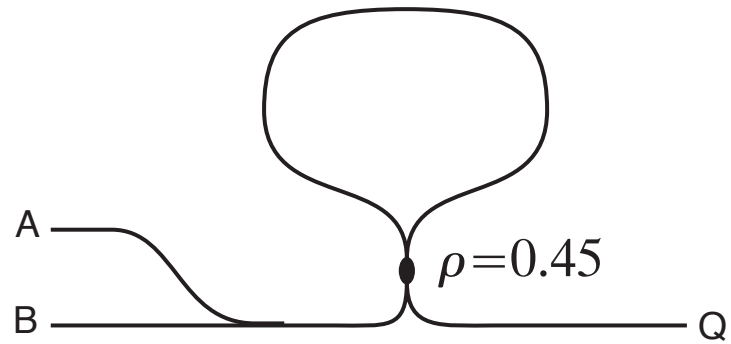
# Optical logic gates

## nonlinear nanogate



# Optical logic gates

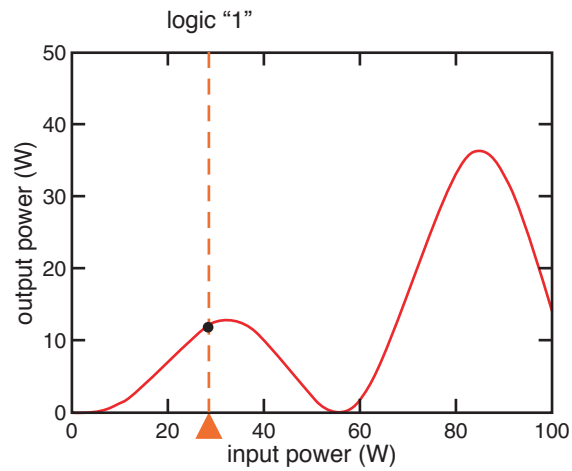
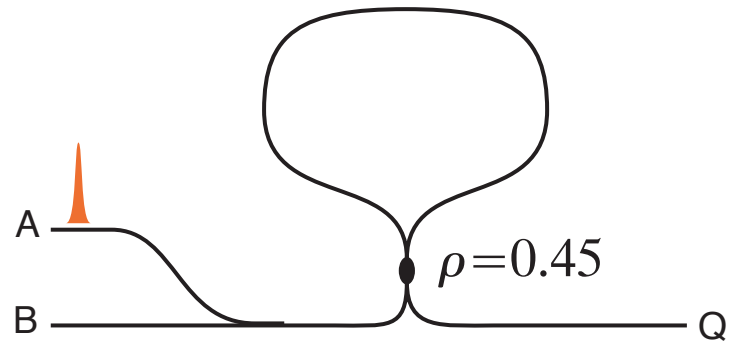
## nonlinear nanogate



A	B	Q
0	0	0

# Optical logic gates

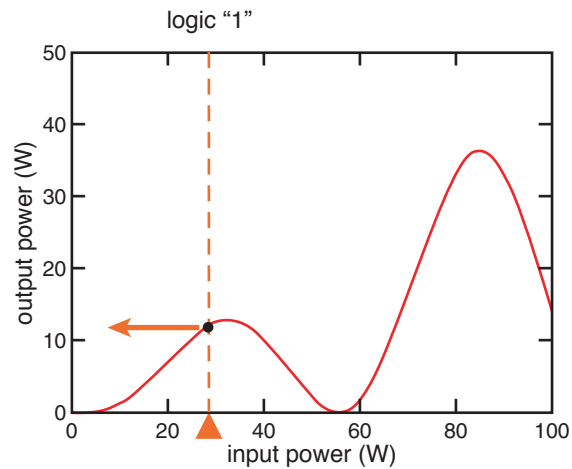
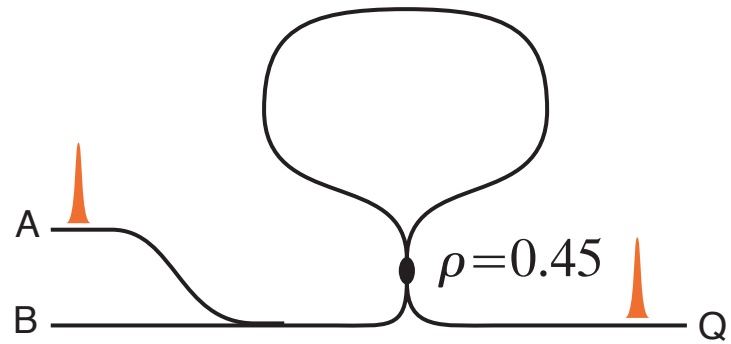
## nonlinear nanogate



A	B	Q
0	0	0

# Optical logic gates

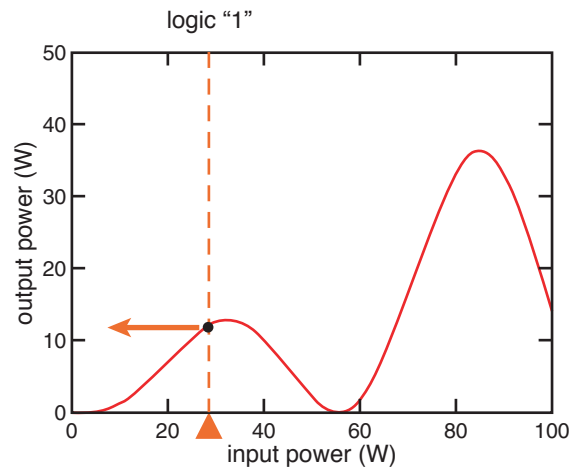
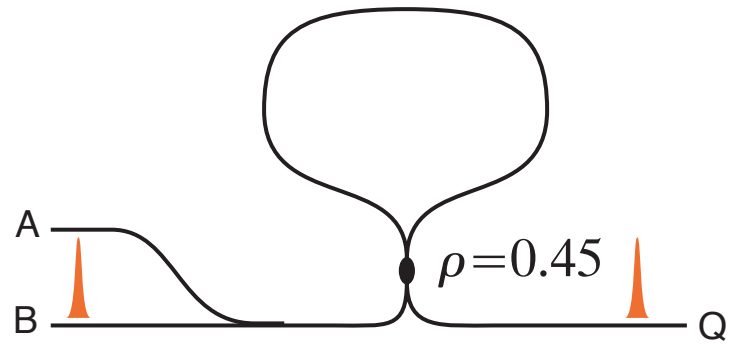
## nonlinear nanogate



A	B	Q
0	0	0
1	0	1

# Optical logic gates

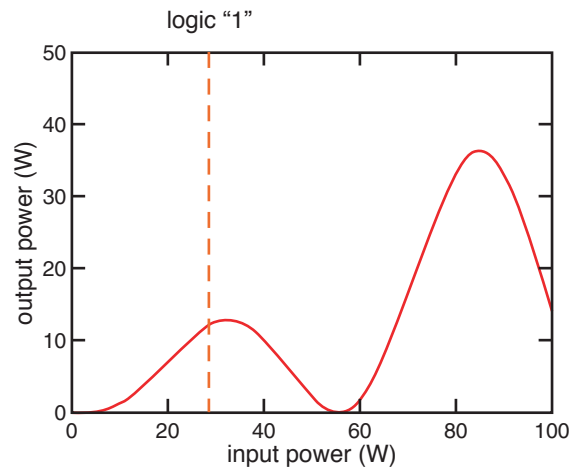
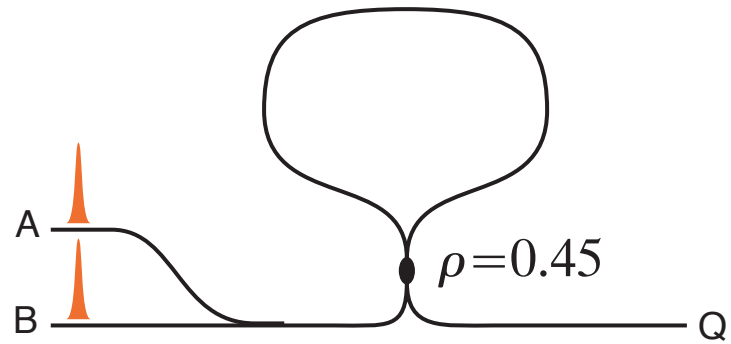
## nonlinear nanogate



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

# Optical logic gates

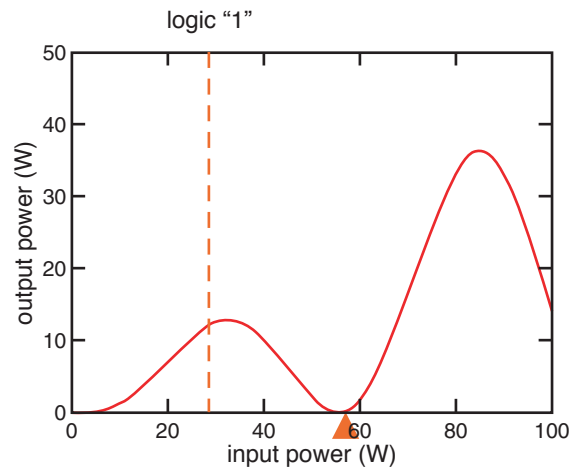
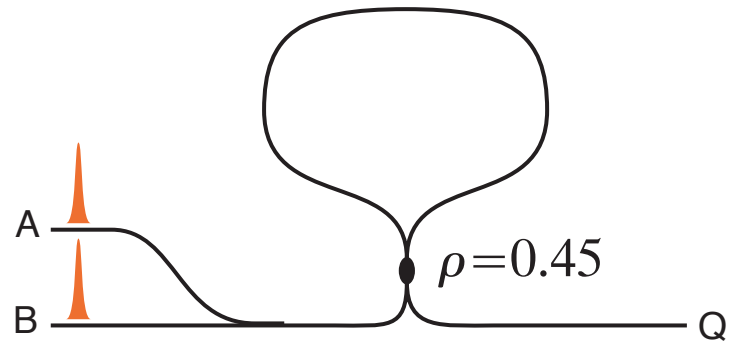
## nonlinear nanogate



A	B	Q
0	0	0
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# Optical logic gates

## nonlinear nanogate

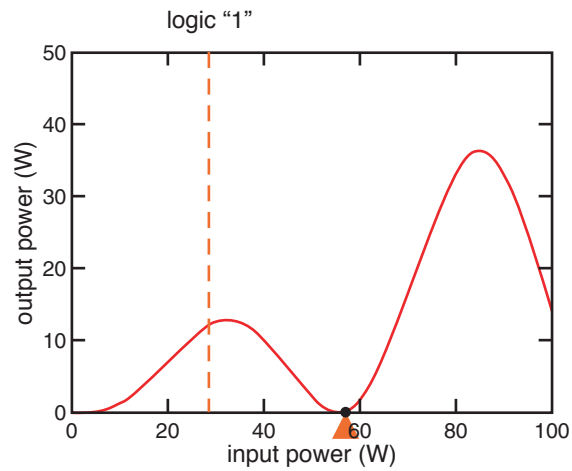
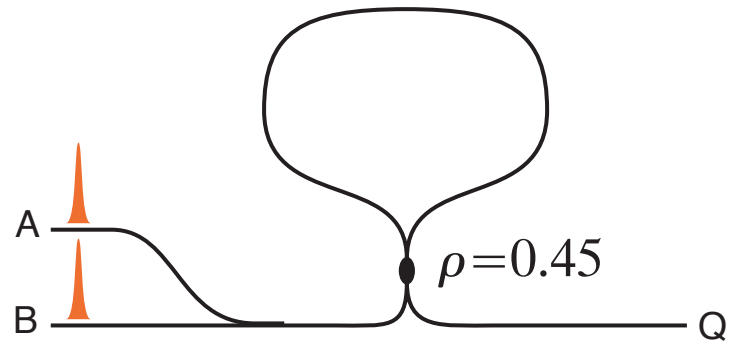


A	B	Q
0	0	0
1	0	1
0	1	1



# Optical logic gates

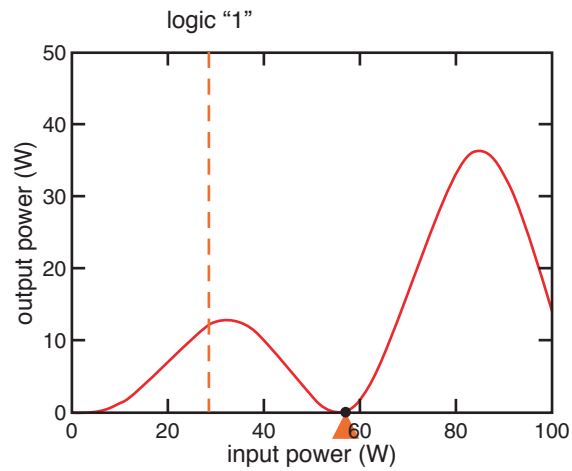
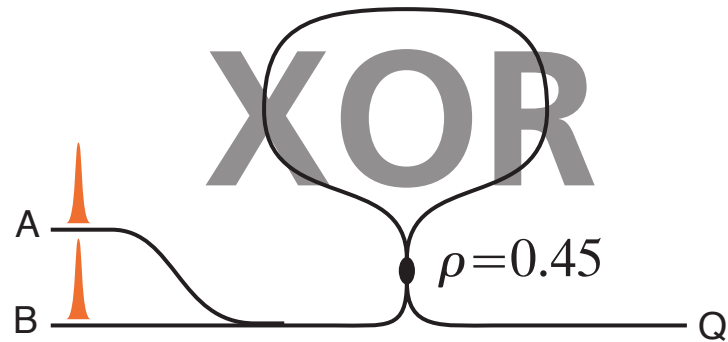
## nonlinear nanogate



A	B	Q
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1	1	0

# Optical logic gates

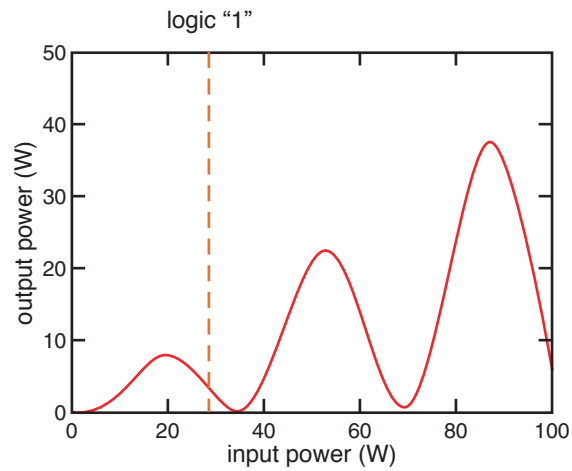
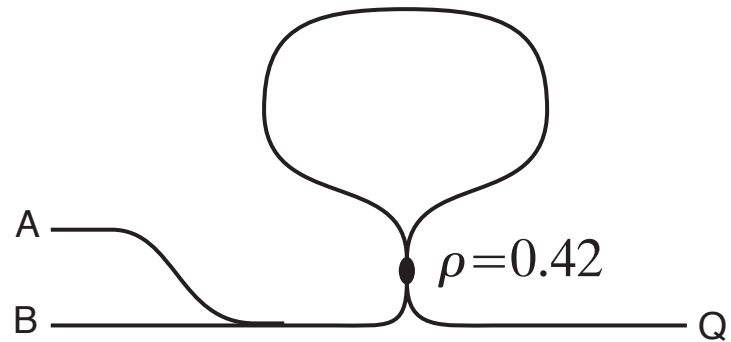
## nonlinear nanogate



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

# Optical logic gates

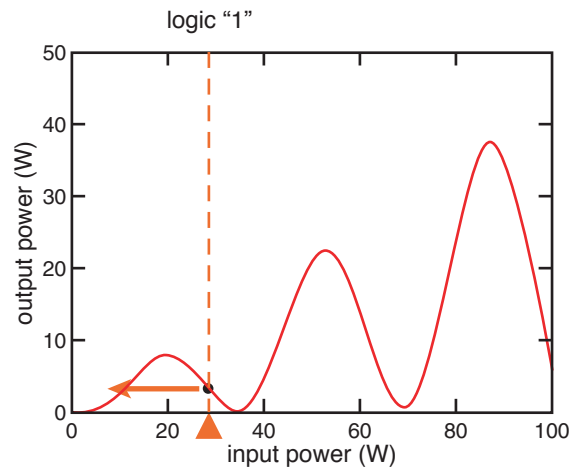
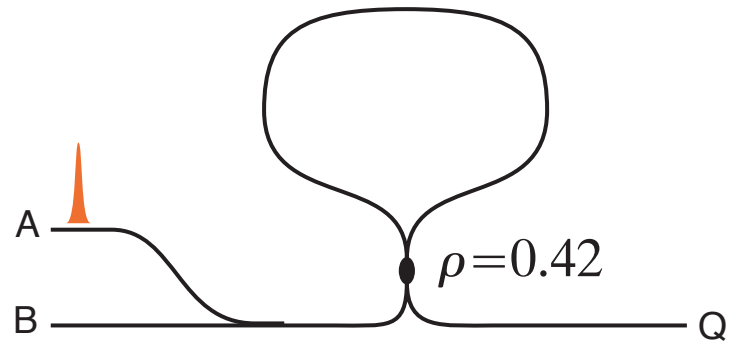
## nonlinear nanogate



A	B	Q
0	0	0

# Optical logic gates

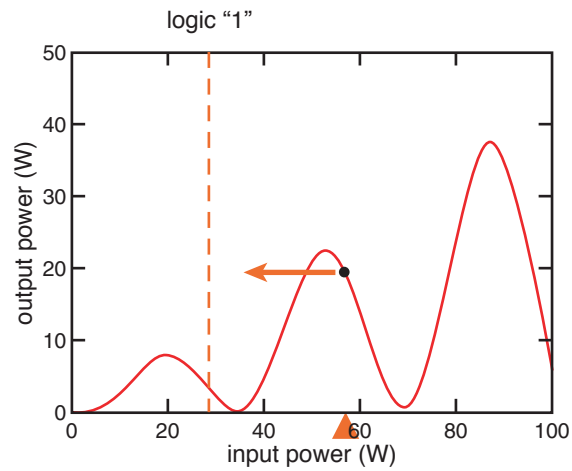
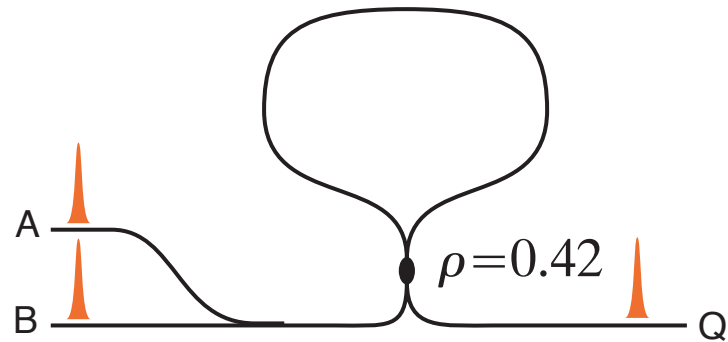
## nonlinear nanogate



A	B	Q
0	0	0
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0	1	0

# Optical logic gates

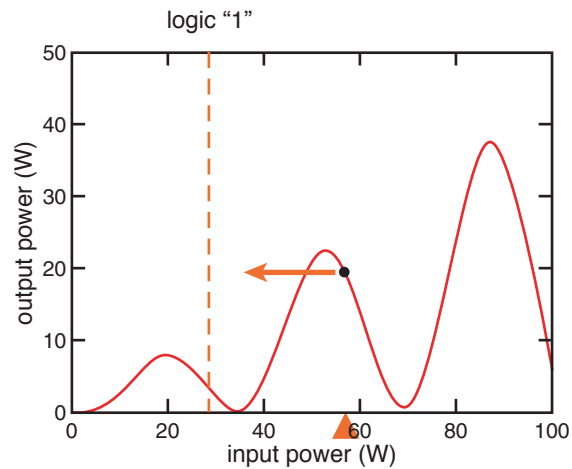
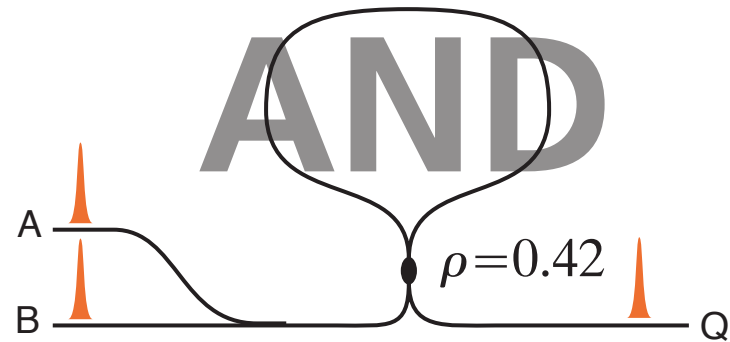
## nonlinear nanogate



A	B	Q
0	0	0
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# Optical logic gates

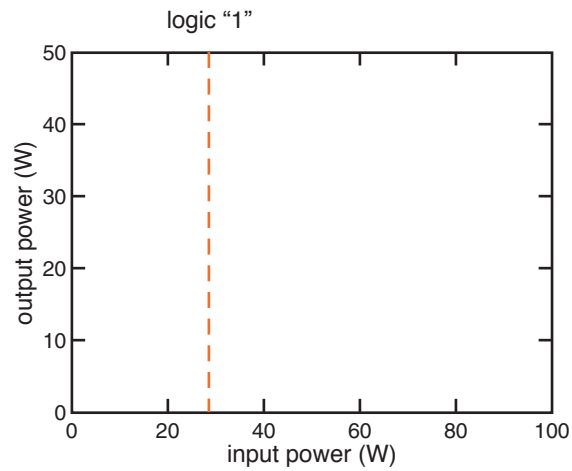
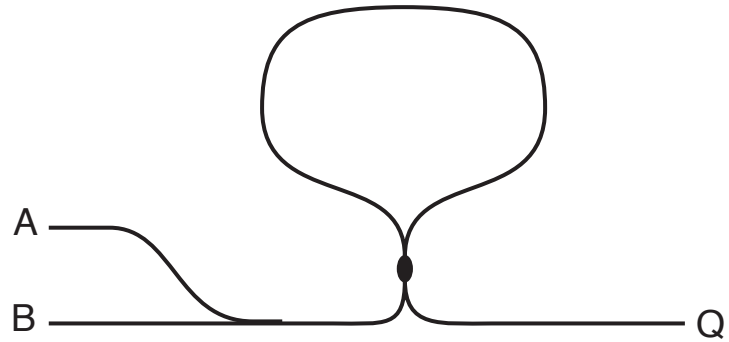
## nonlinear nanogate



A	B	Q
0	0	0
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0	1	0
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# Optical logic gates

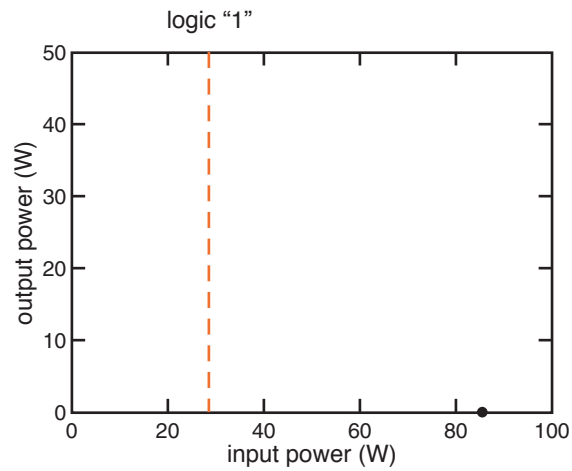
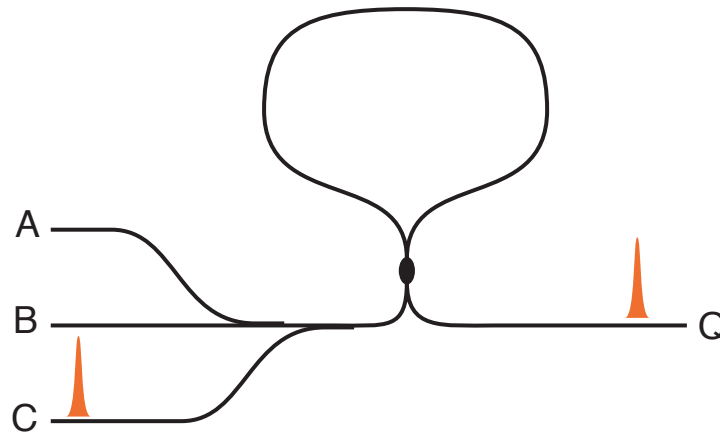
for NAND gate need output with no input



A	B	Q
0	0	1

# Optical logic gates

for NAND gate need output with no input

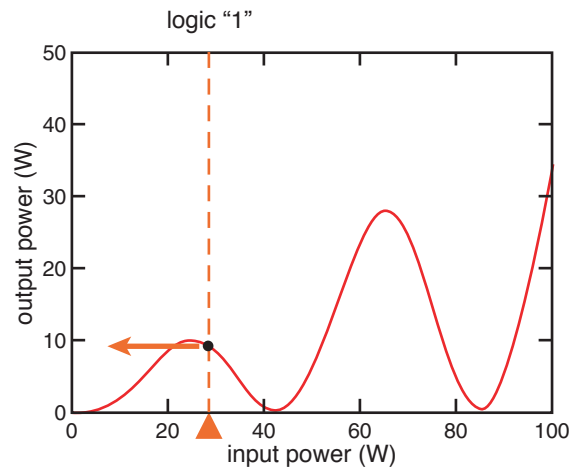
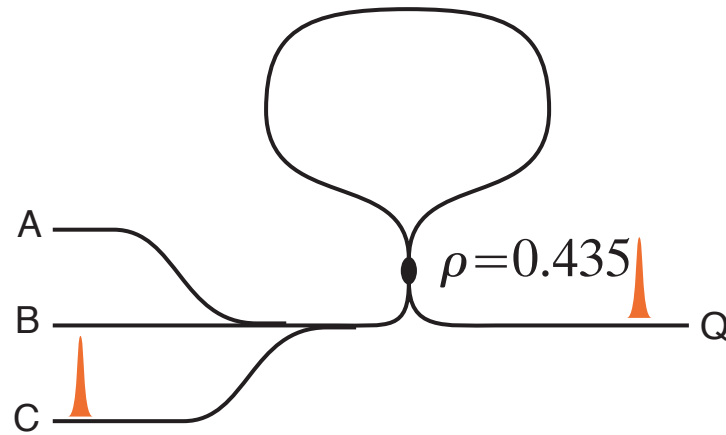


A	B	Q
0	0	1



# Optical logic gates

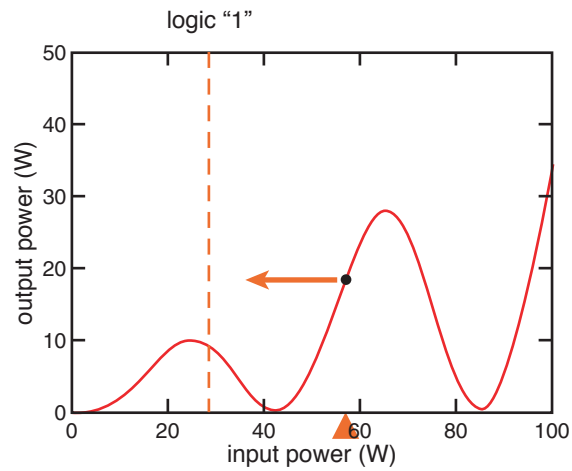
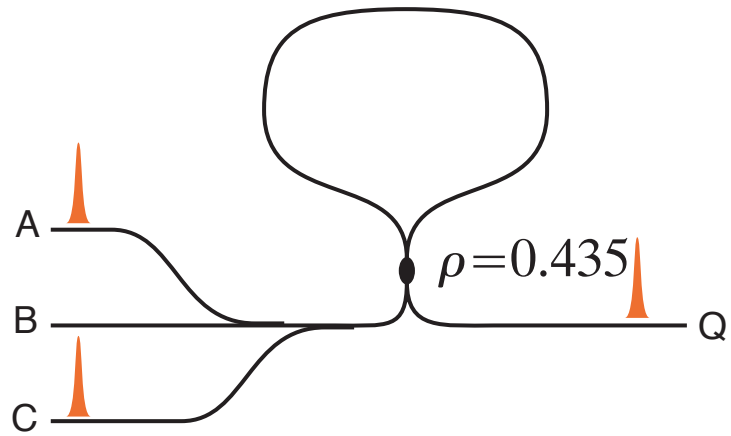
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# Optical logic gates

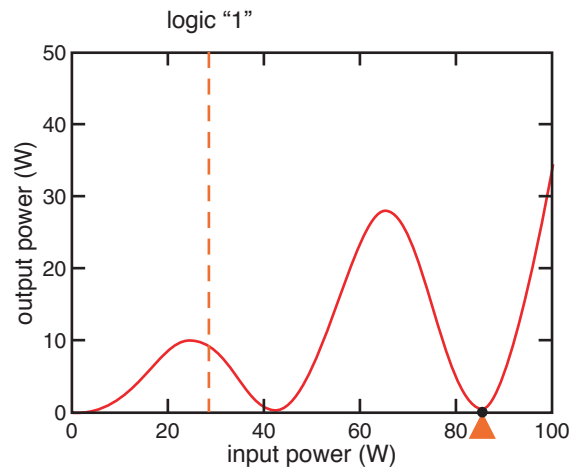
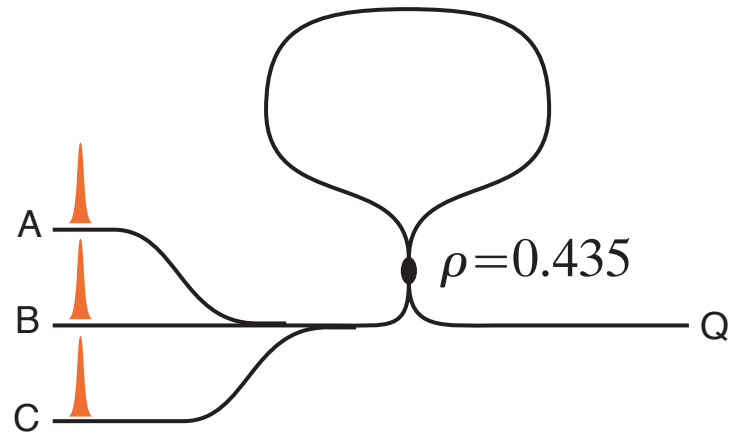
## universal NAND gate



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

# Optical logic gates

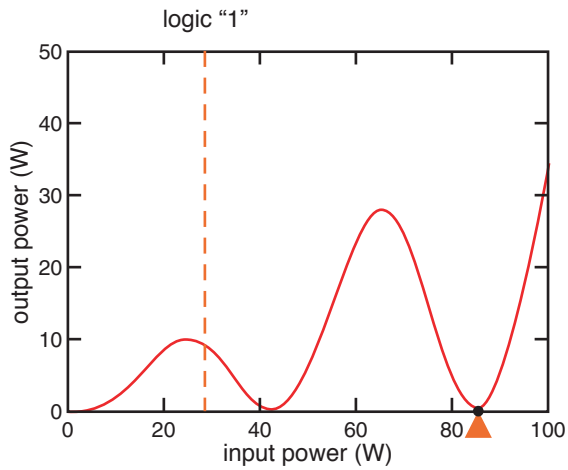
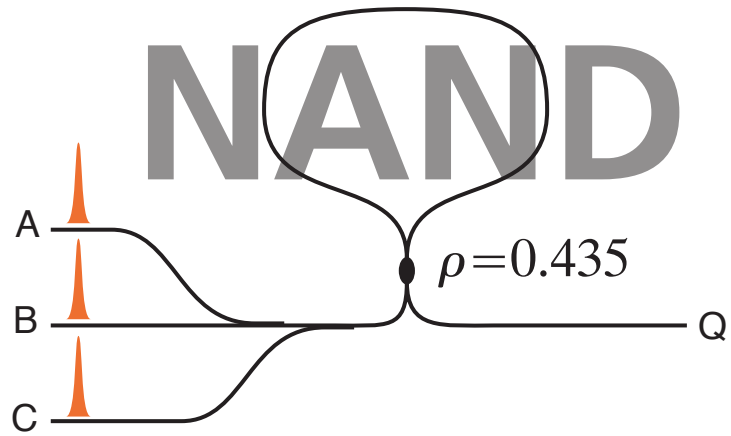
## universal NAND gate



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

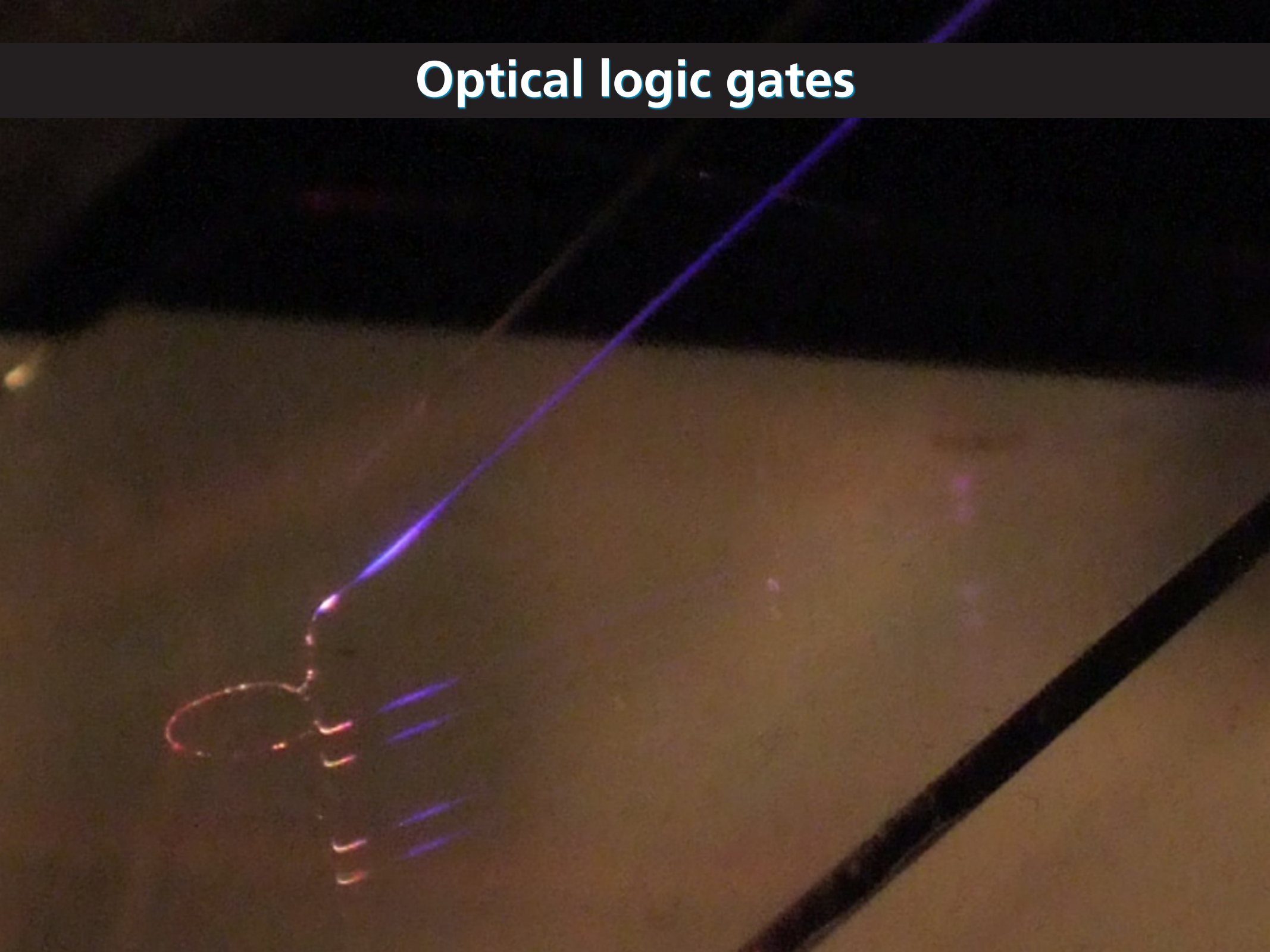
# Optical logic gates

## universal NAND gate



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

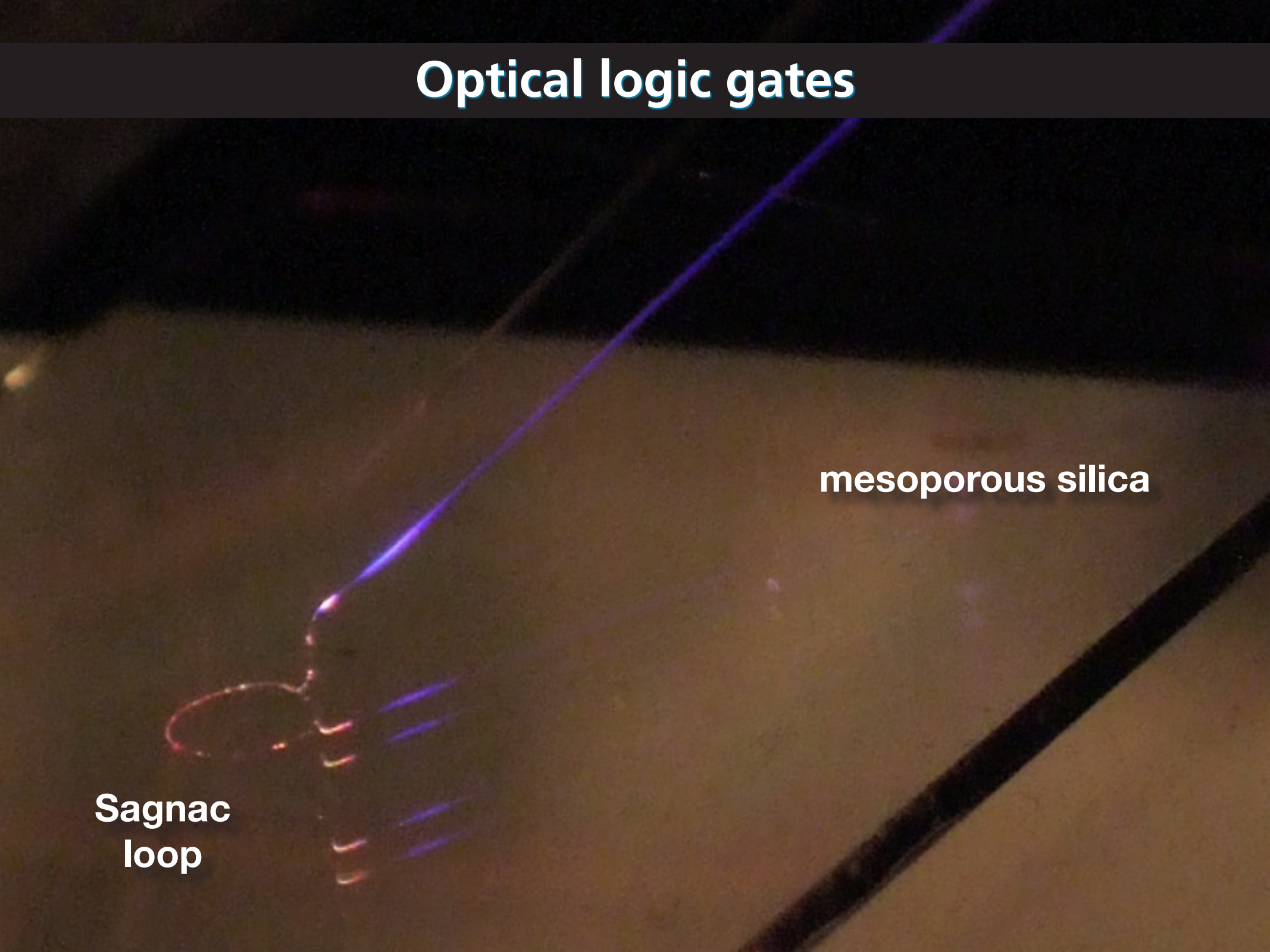
# Optical logic gates



# Optical logic gates

mesoporous silica

Sagnac  
loop



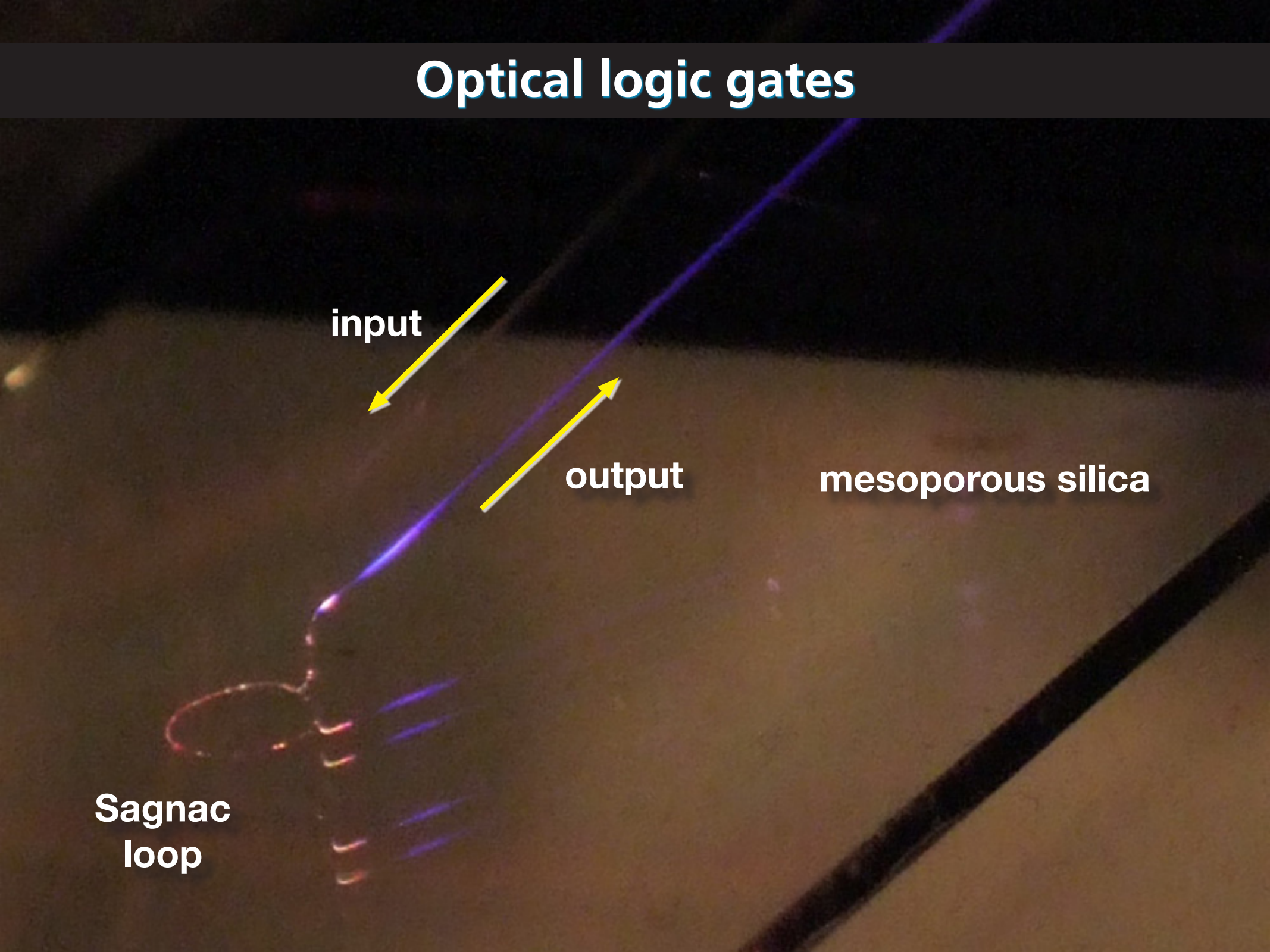
# Optical logic gates

input

output

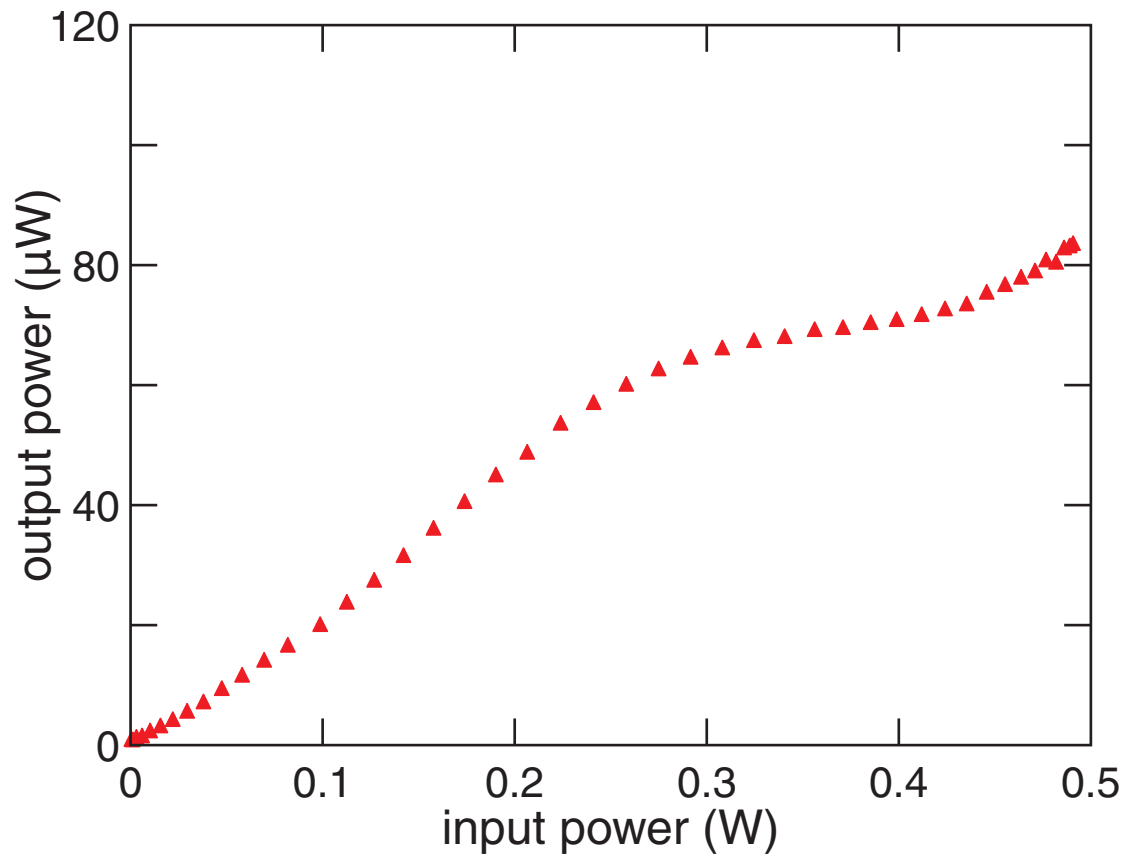
mesoporous silica

Sagnac  
loop



# Optical logic gates

very preliminary data



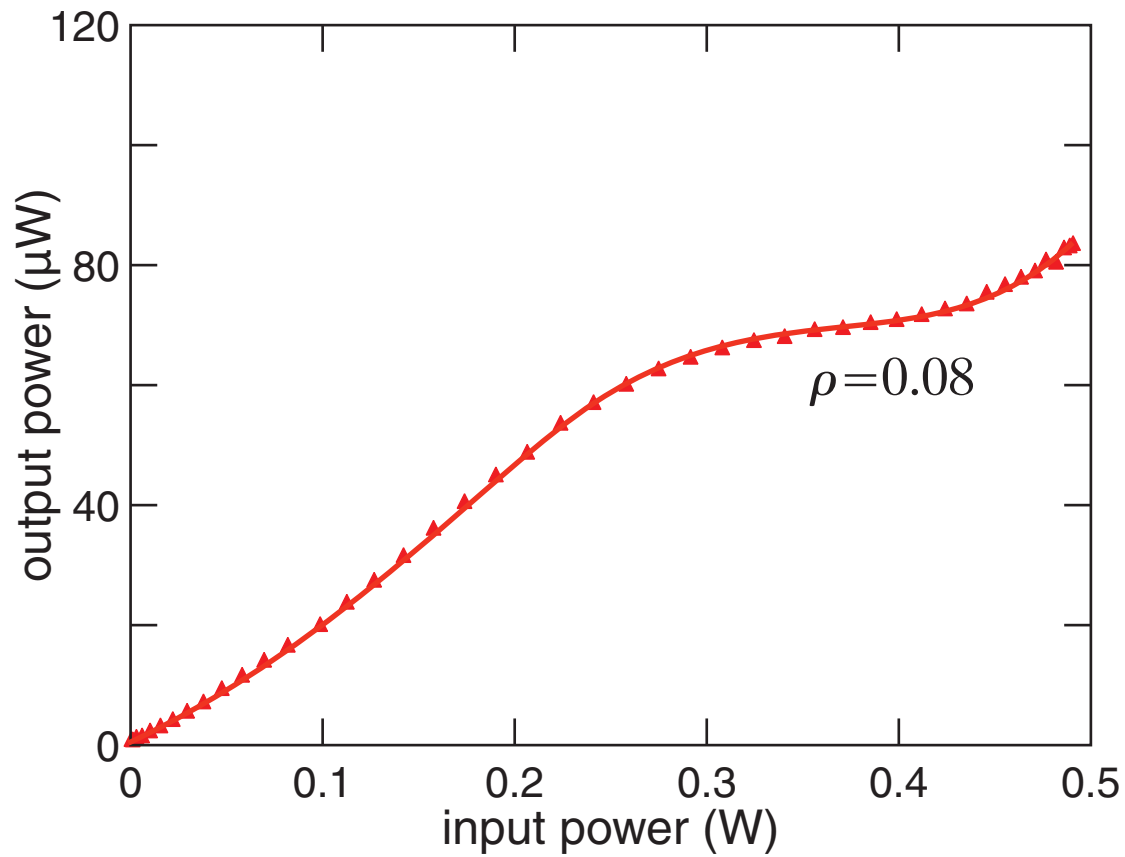


# Optical logic gates

**light-by-light modulation!**

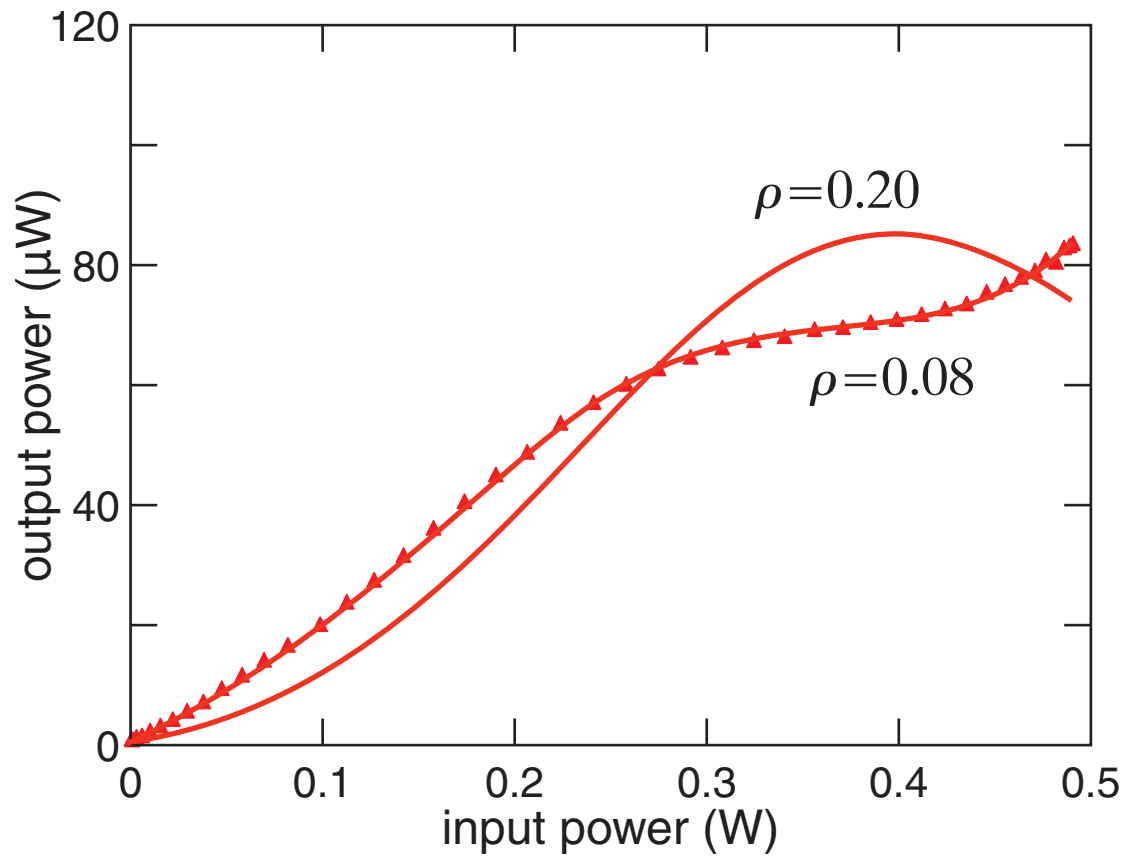
# Optical logic gates

very preliminary data

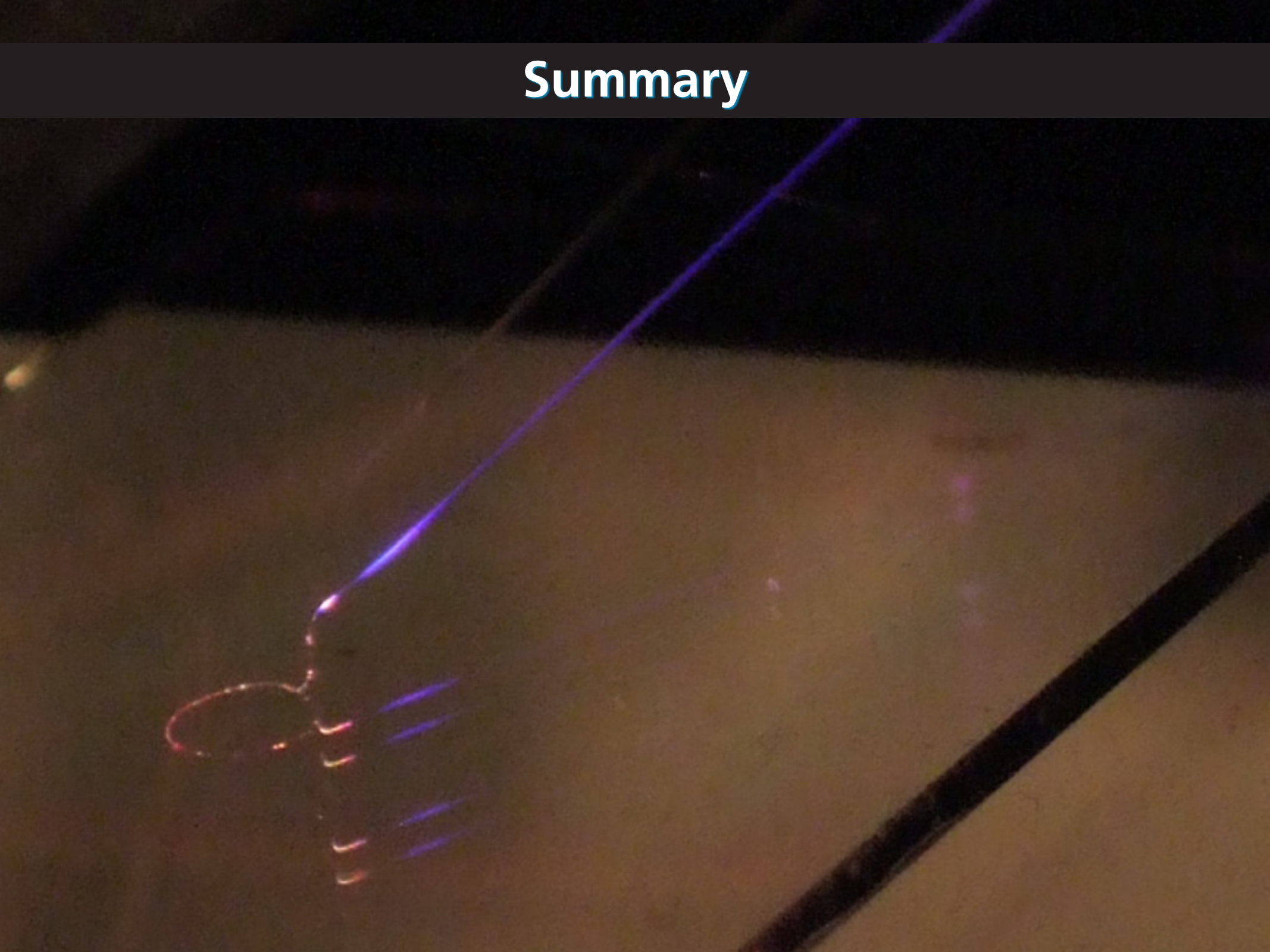


# Optical logic gates

very preliminary data



# Summary



# Summary

- several nanodevices demonstrated
- large  $\gamma$  permits miniature Sagnac loops
- switching energy  $< 10$  pJ





**Funding:**

**Harvard Center for Imaging and Mesoscopic Structures**

**National Science Foundation**

**National Natural Science Foundation of China**

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