

# Nonlinear optics at the nanoscale



Benemérita Universidad Autónoma de Puebla  
Puebla, Mexico, 28 May 2009

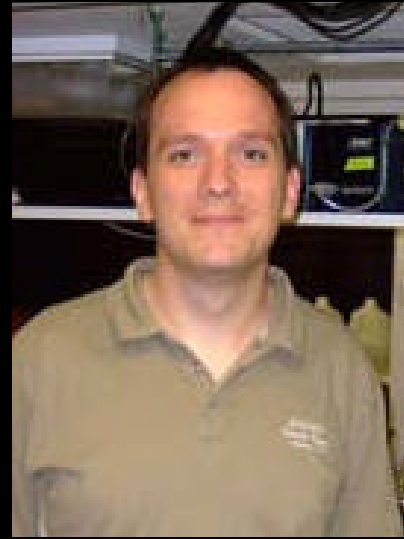




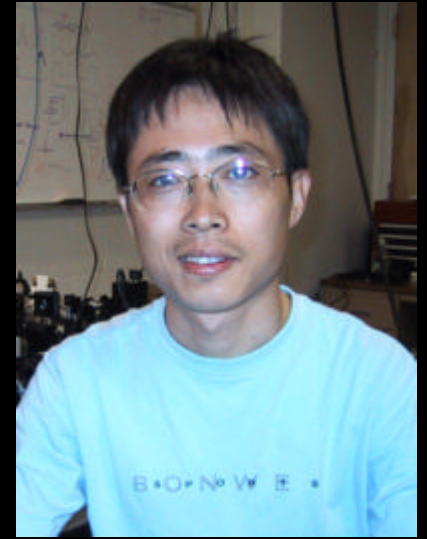
**Geoff Svacha**



**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)**

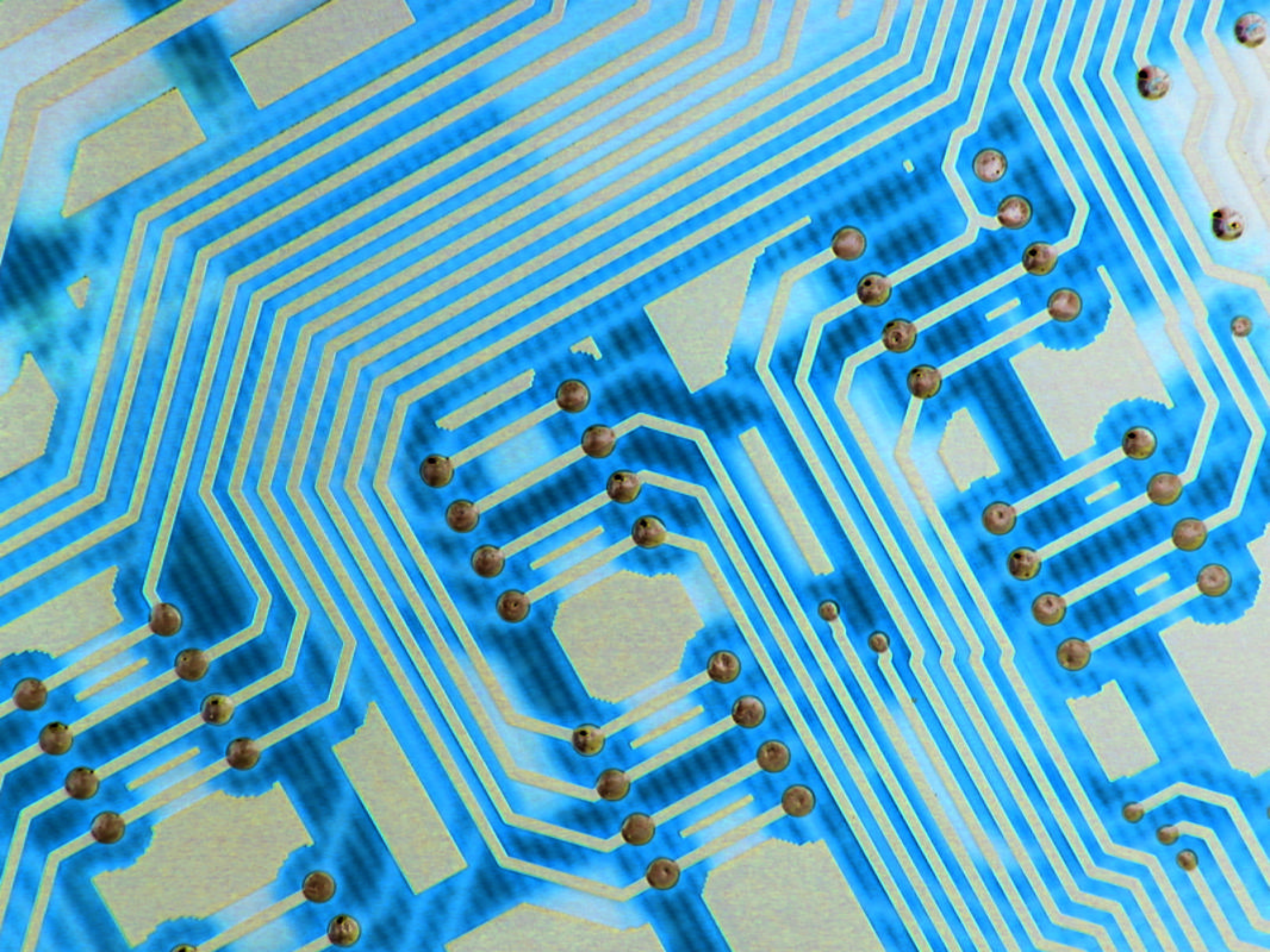
**Dr. Jingyi Lou (Zhejiang)**

**Dr. Ray Mariella (LLNL)**

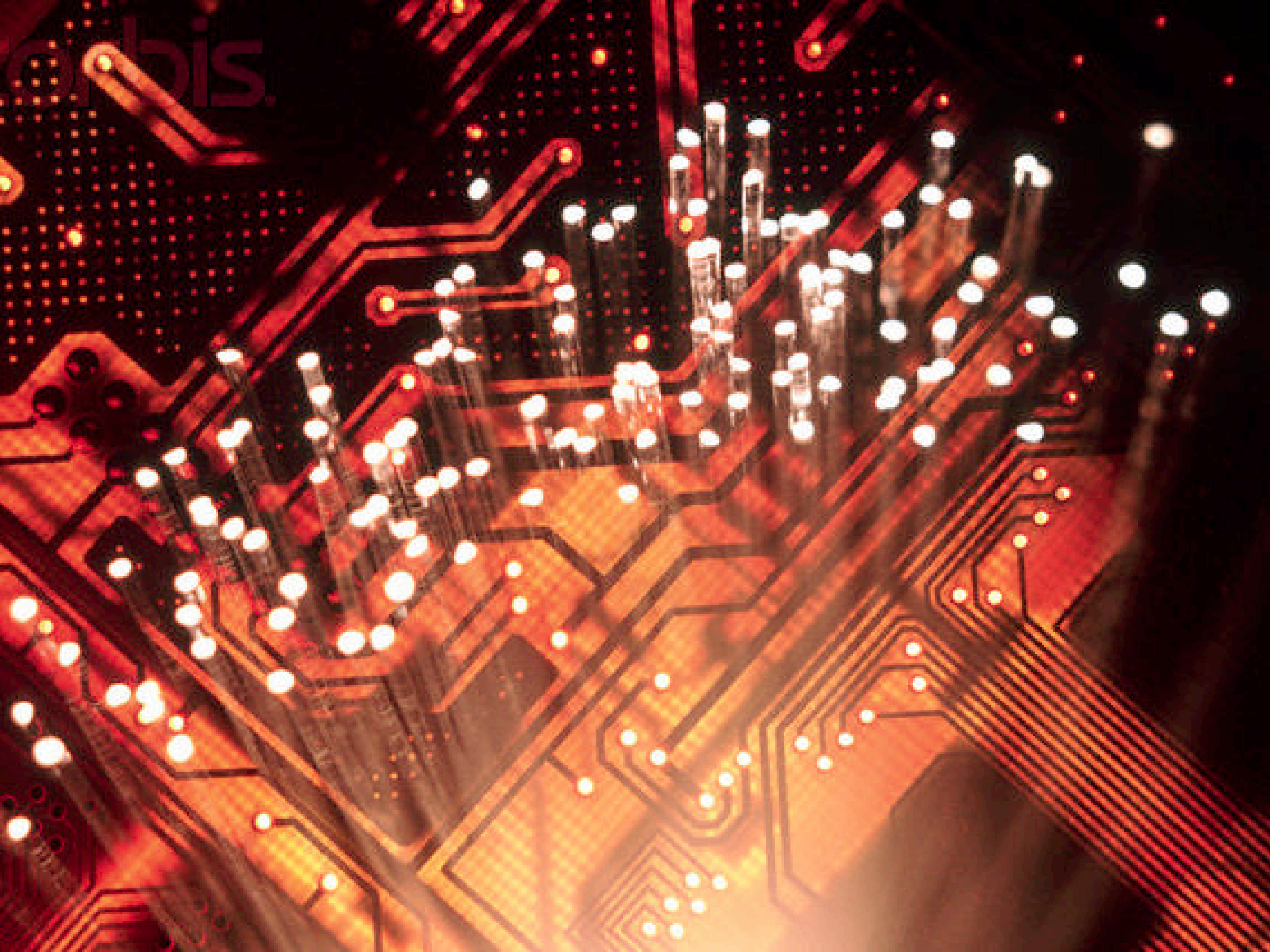
**Prof. Frank Marlow (MPI Mülheim)**

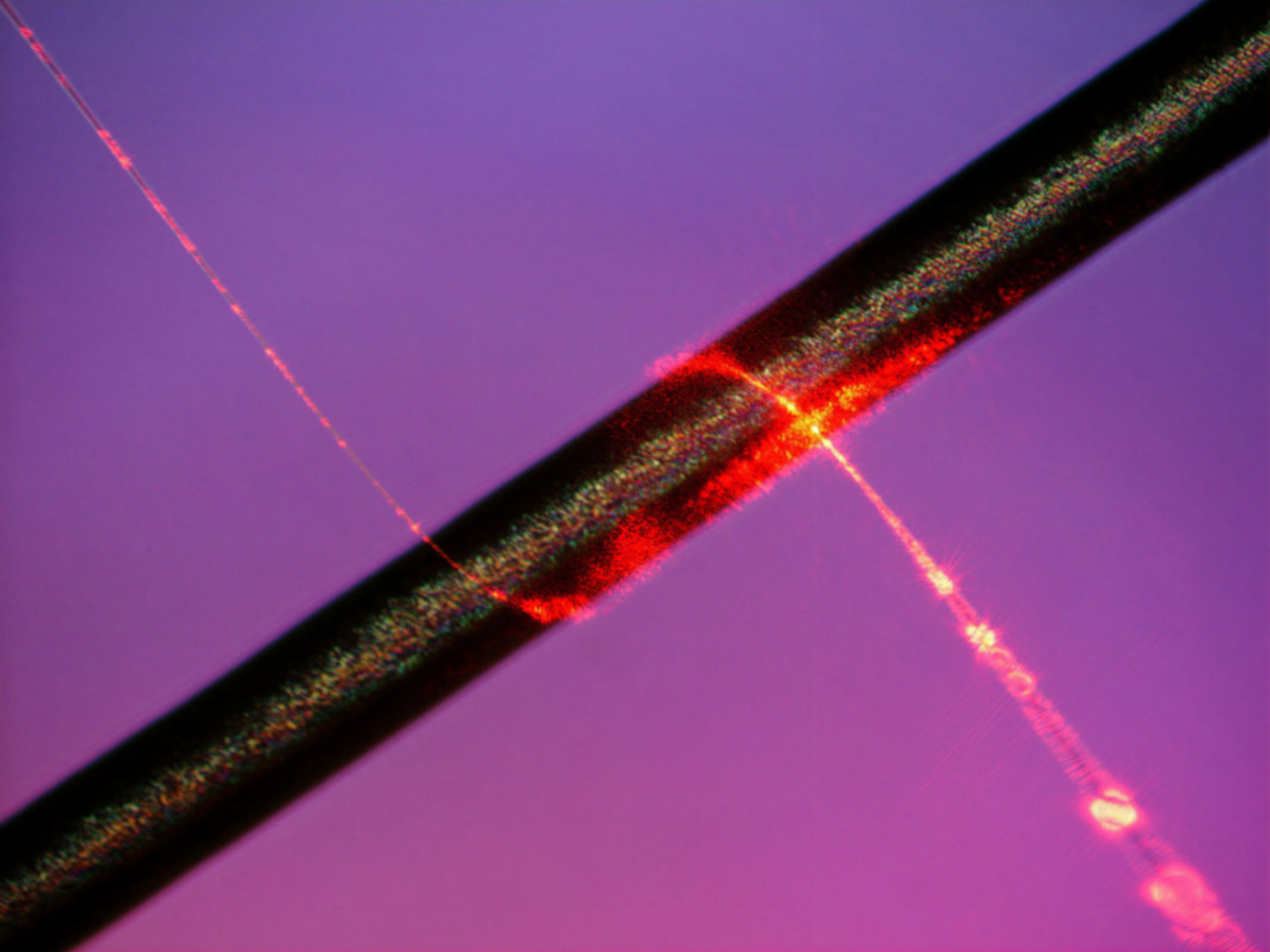
**Prof. Sven Müller (Göttingen)**

**Prof. Carsten Ronning (Göttingen)**



orbis

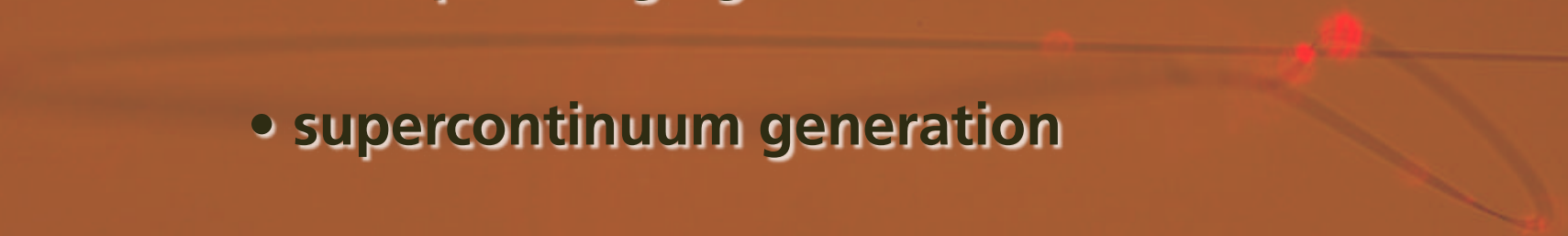




# Outline



# Outline

- **manipulating light at the nanoscale**
  - **supercontinuum generation**
  - **optical logic gates**
- 
- A decorative graphic on the right side of the slide shows a horizontal fiber optic cable with several red light spots. A curved line branches off from the cable, ending in a red light spot, suggesting a signal or light path.

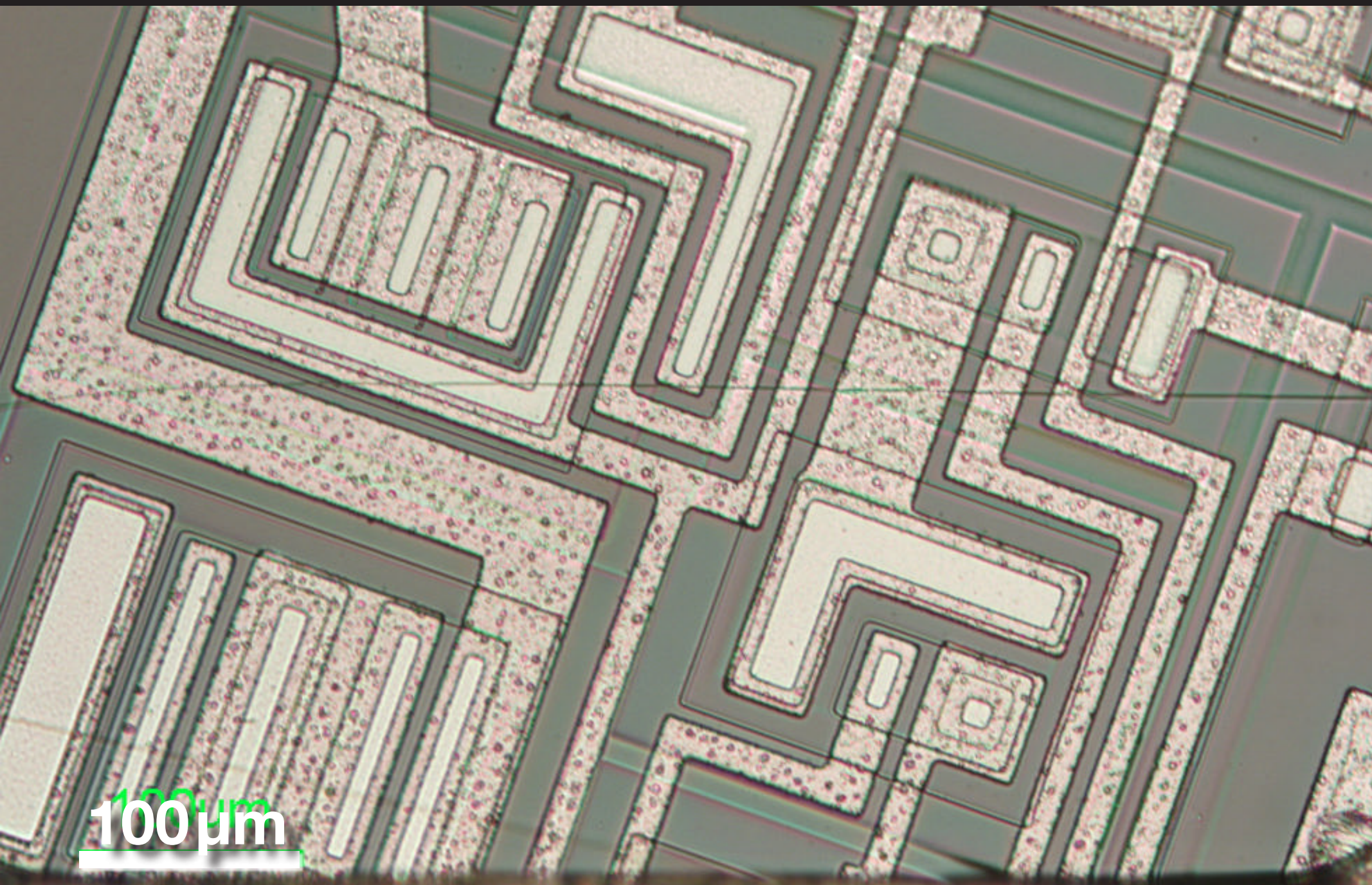


# Manipulating light at the nanoscale



*Nature*, 426, 816 (2003)

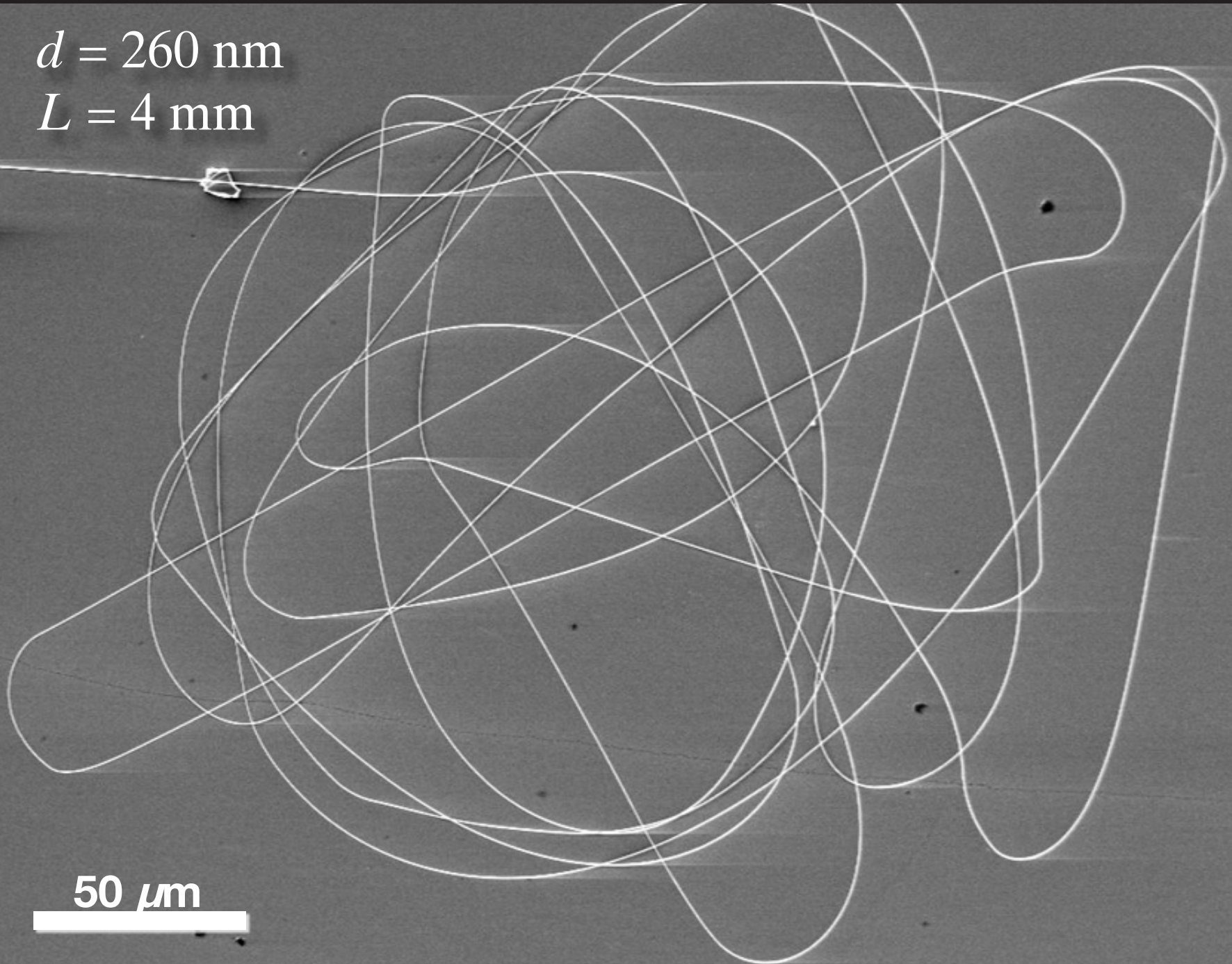
# Manipulating light at the nanoscale



# Manipulating light at the nanoscale

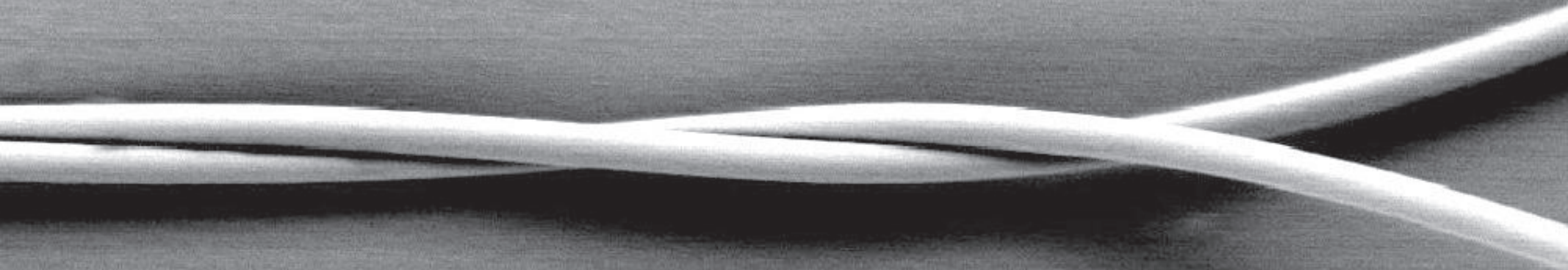
$d = 260 \text{ nm}$

$L = 4 \text{ mm}$



50  $\mu\text{m}$

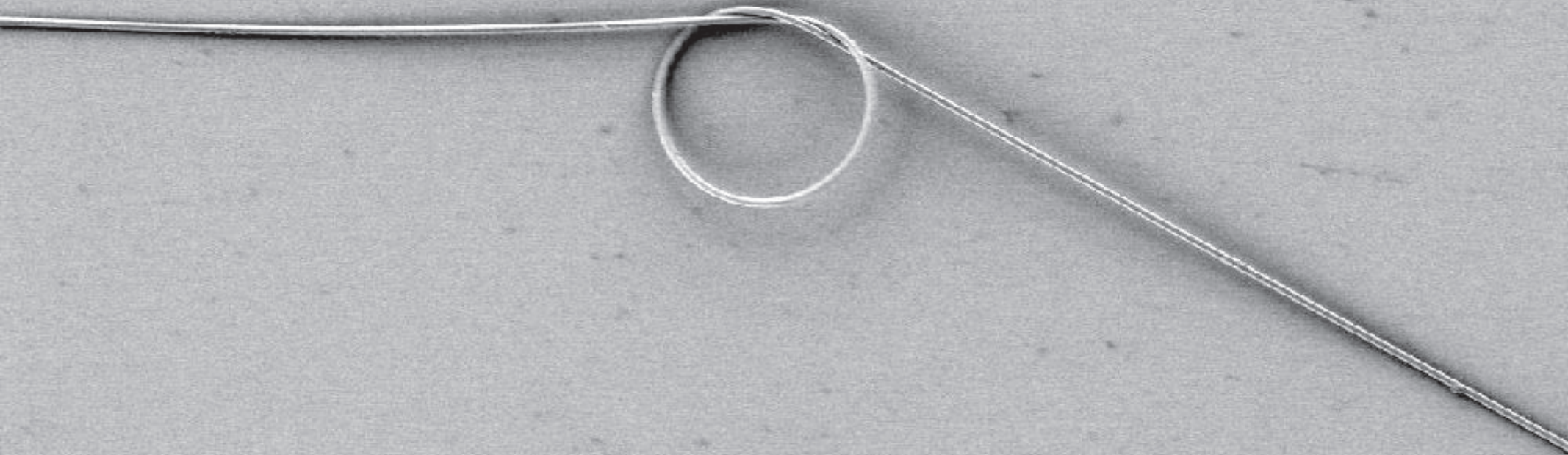
# Manipulating light at the nanoscale



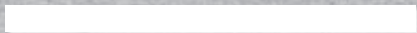
2  $\mu\text{m}$



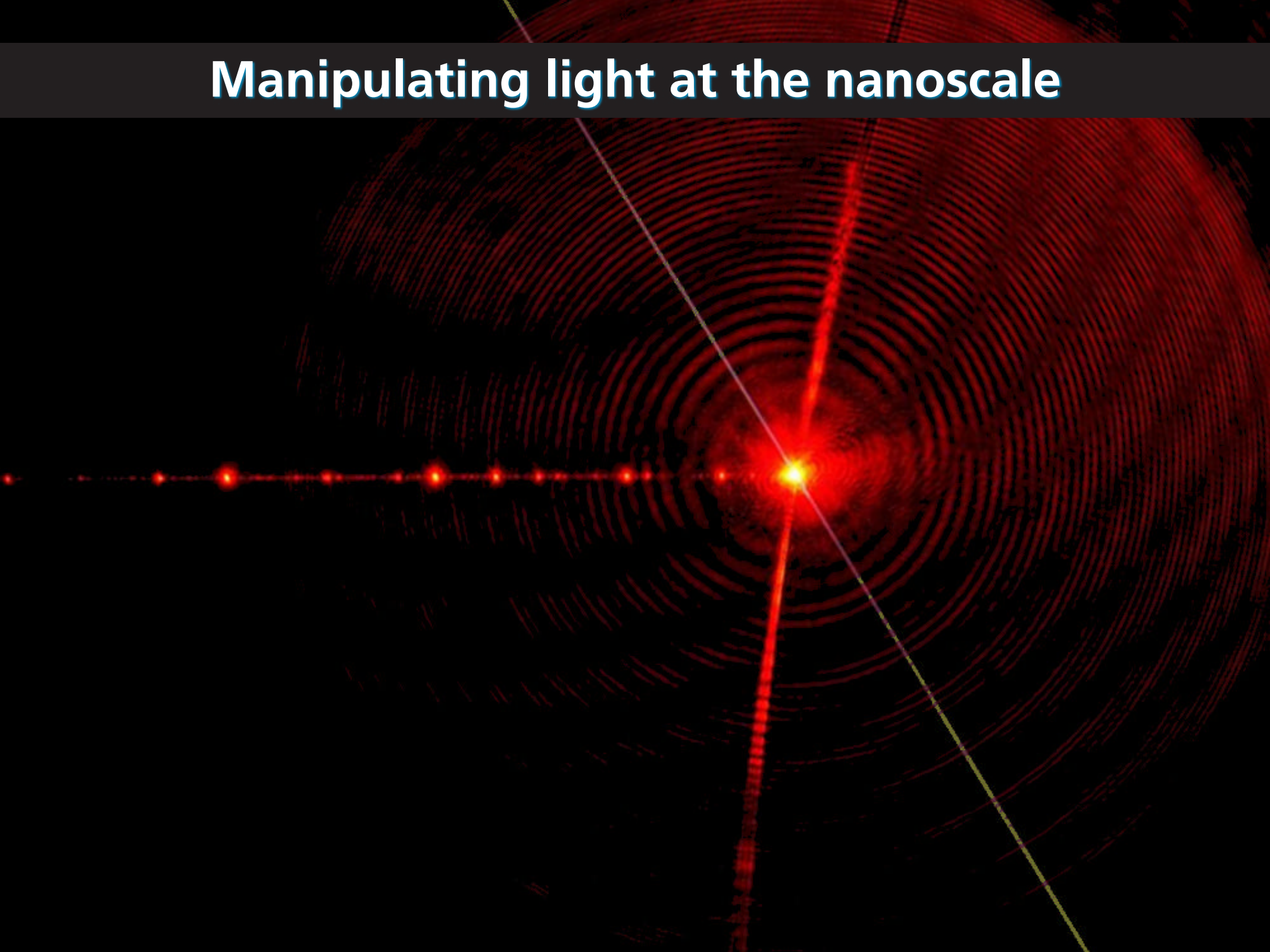
# Manipulating light at the nanoscale



20  $\mu\text{m}$

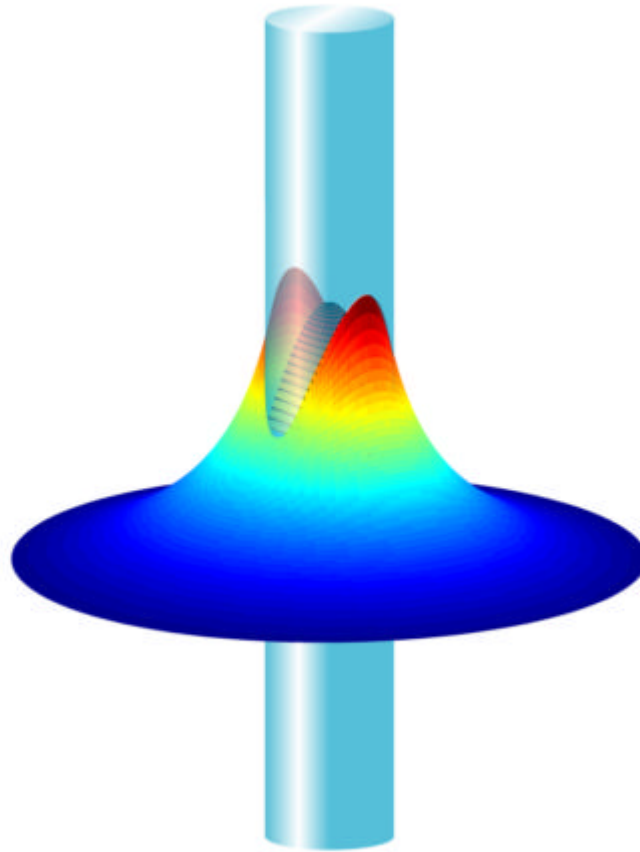


# Manipulating light at the nanoscale

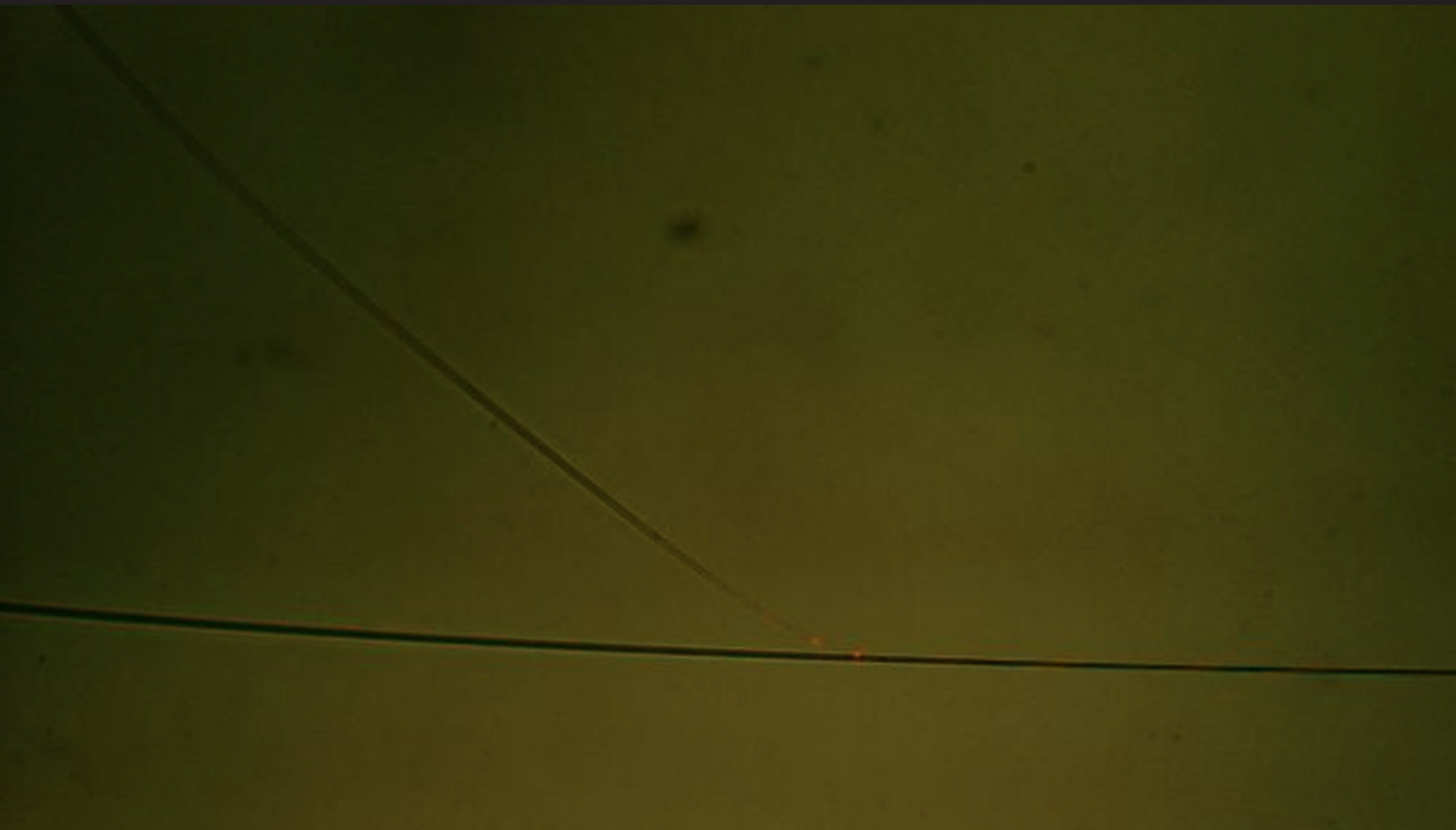


# Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



# Manipulating light at the nanoscale



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

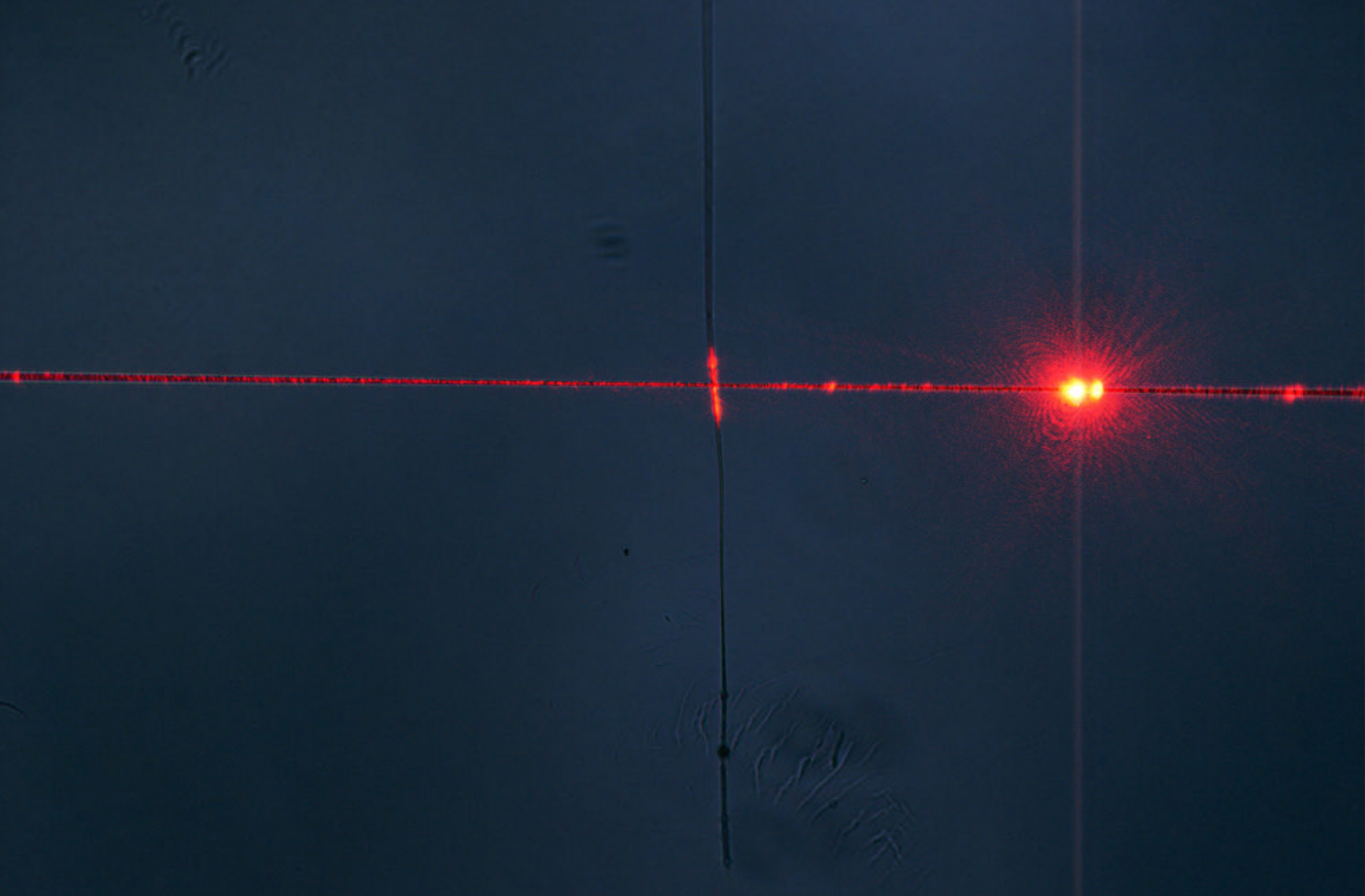


# Manipulating light at the nanoscale

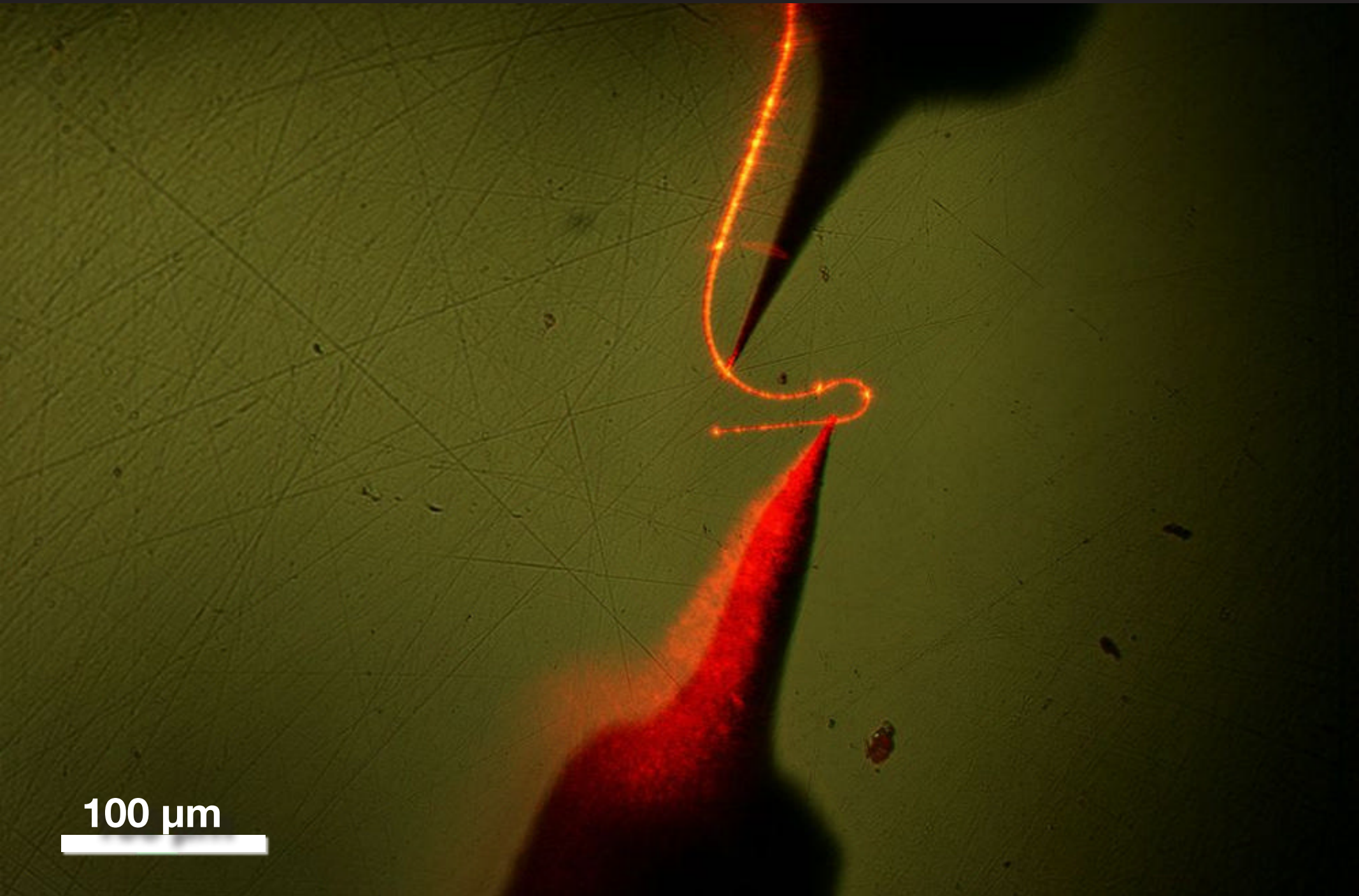


**50  $\mu\text{m}$**

# Manipulating light at the nanoscale

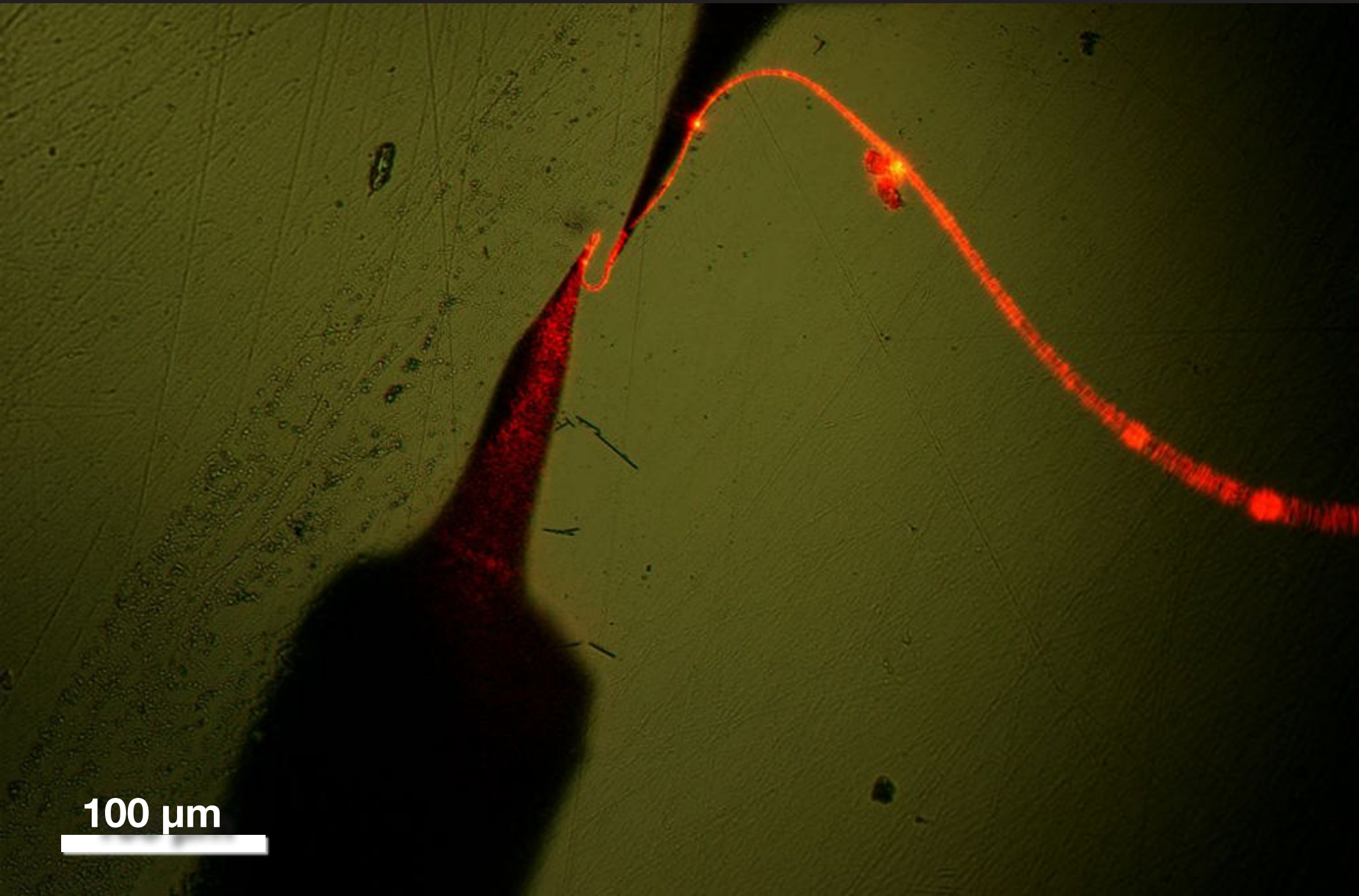


# Manipulating light at the nanoscale



100  $\mu\text{m}$

# Manipulating light at the nanoscale

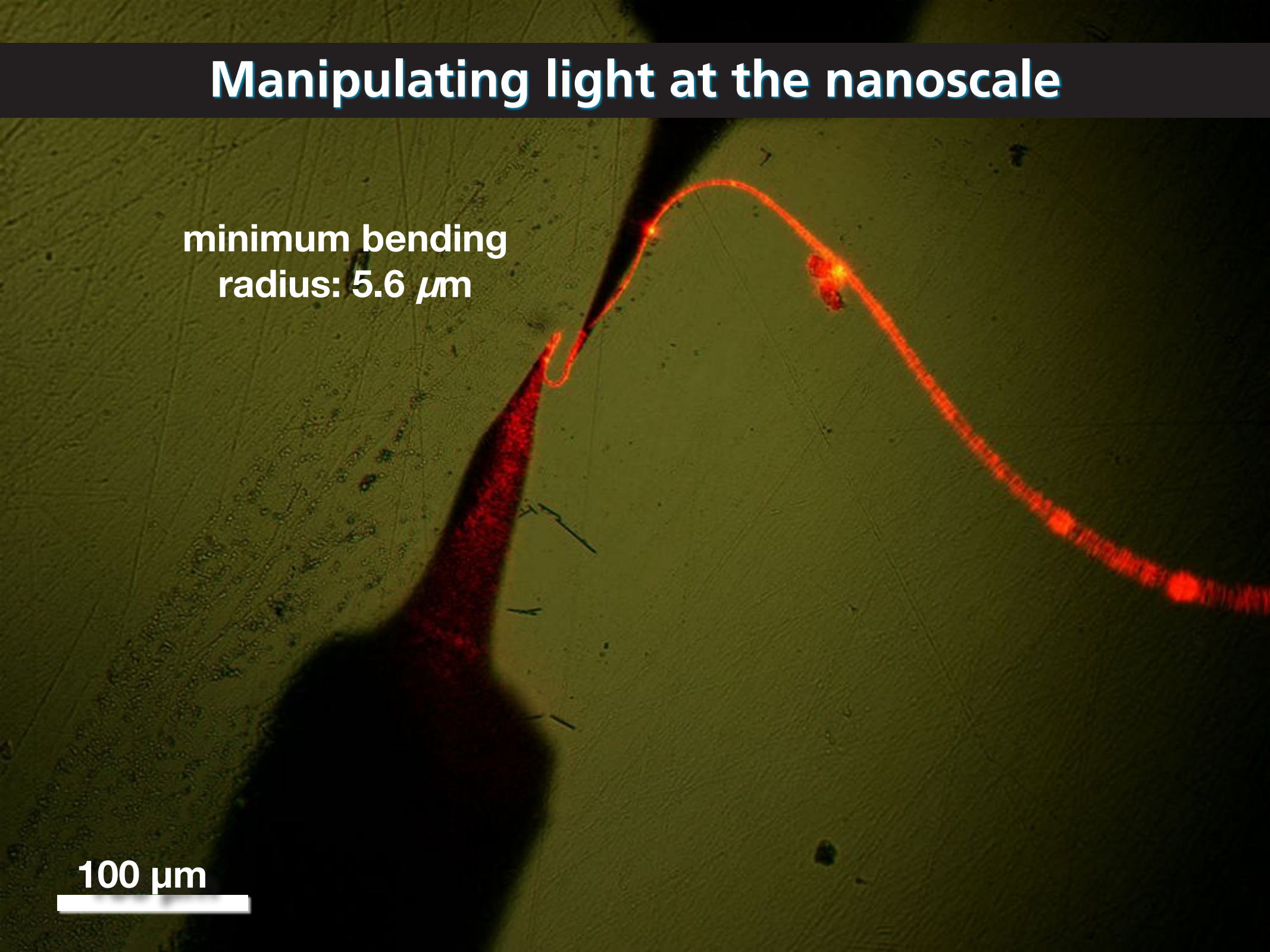


100  $\mu\text{m}$

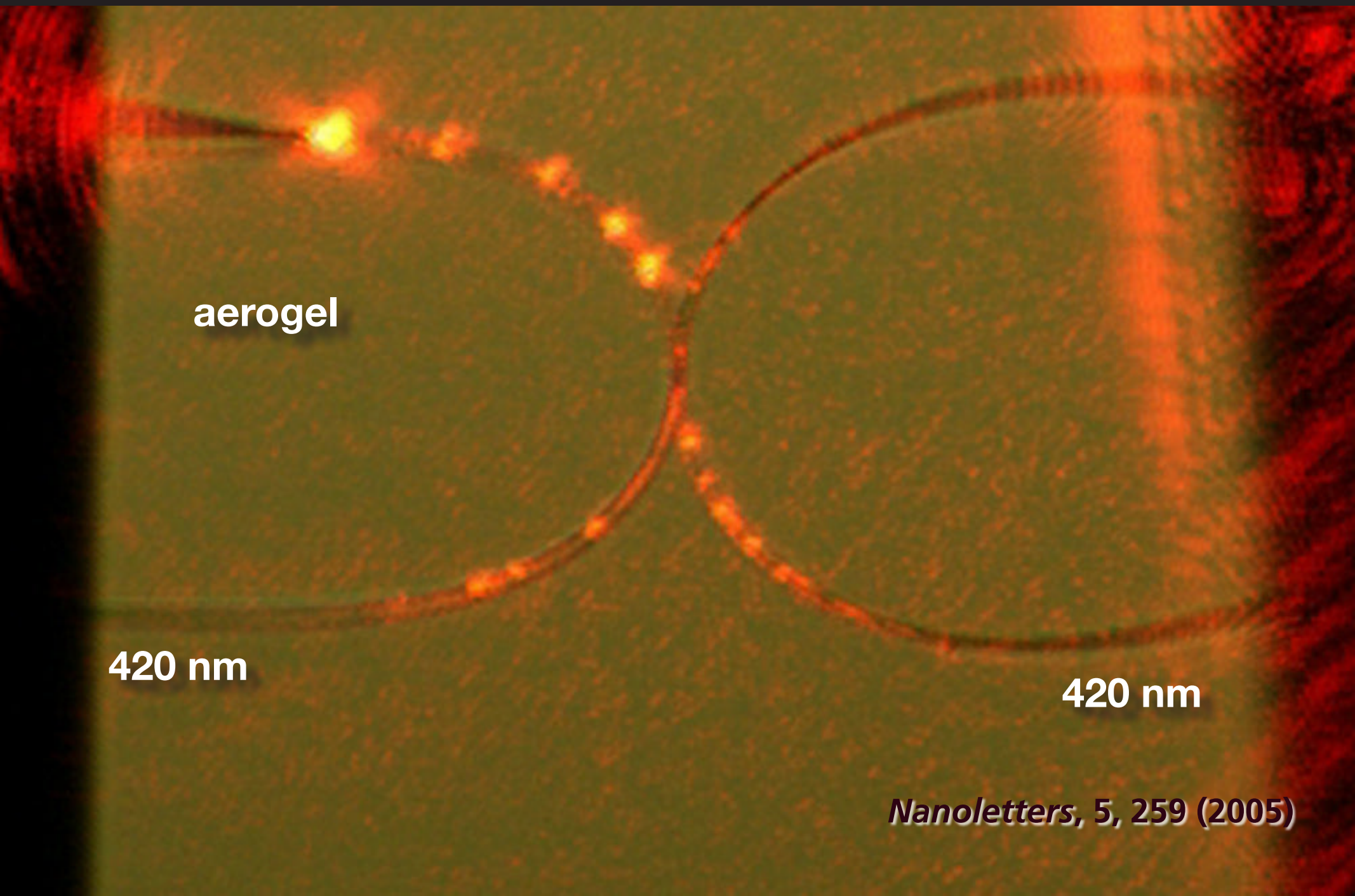
# Manipulating light at the nanoscale

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

100  $\mu\text{m}$

A micrograph showing a fiber optic cable with a sharp bend. The 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

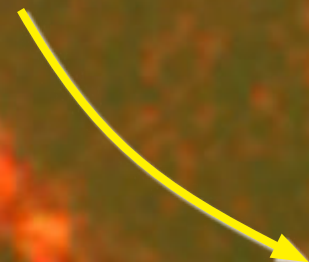
in



out

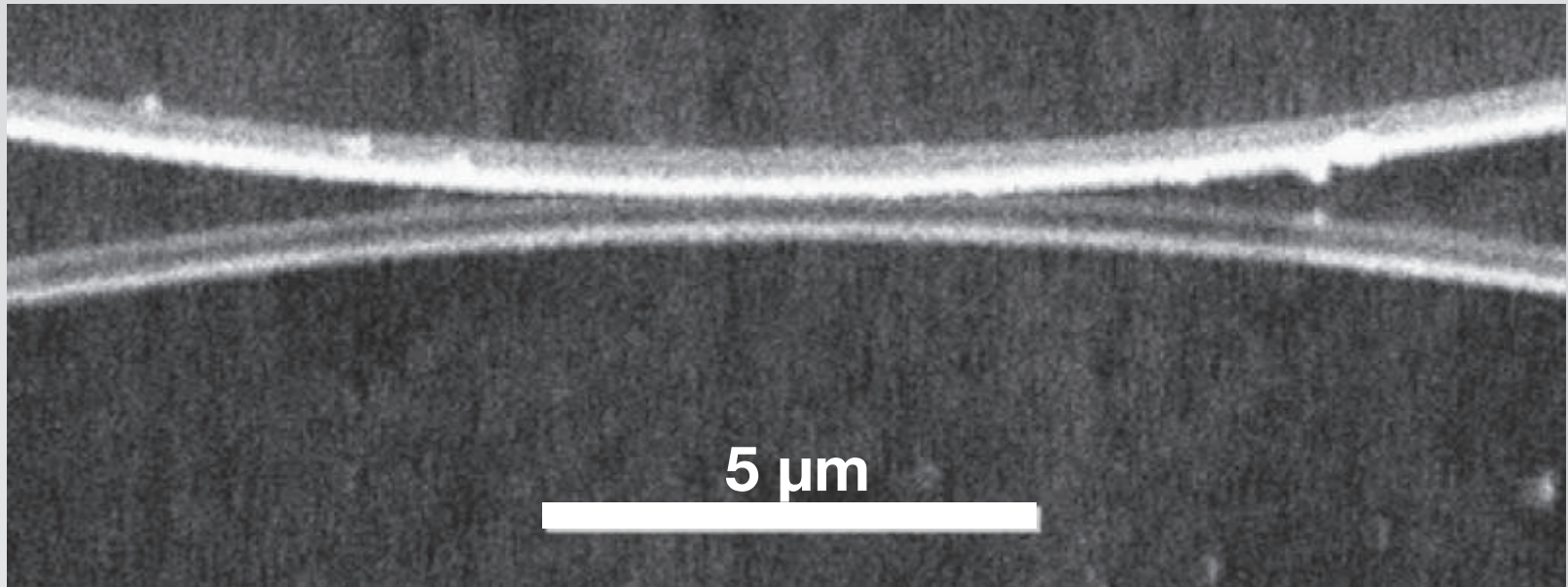


out



*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**

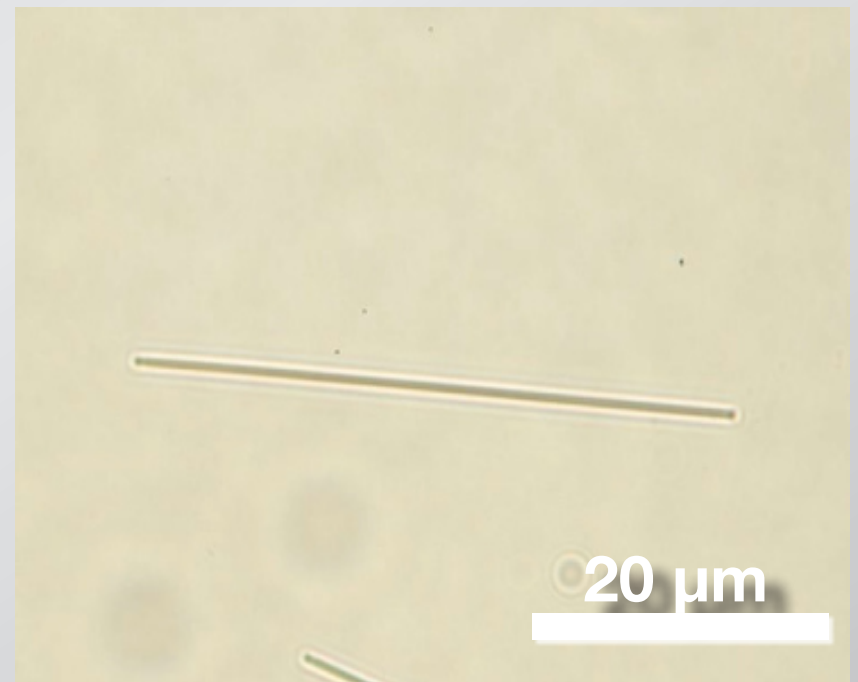
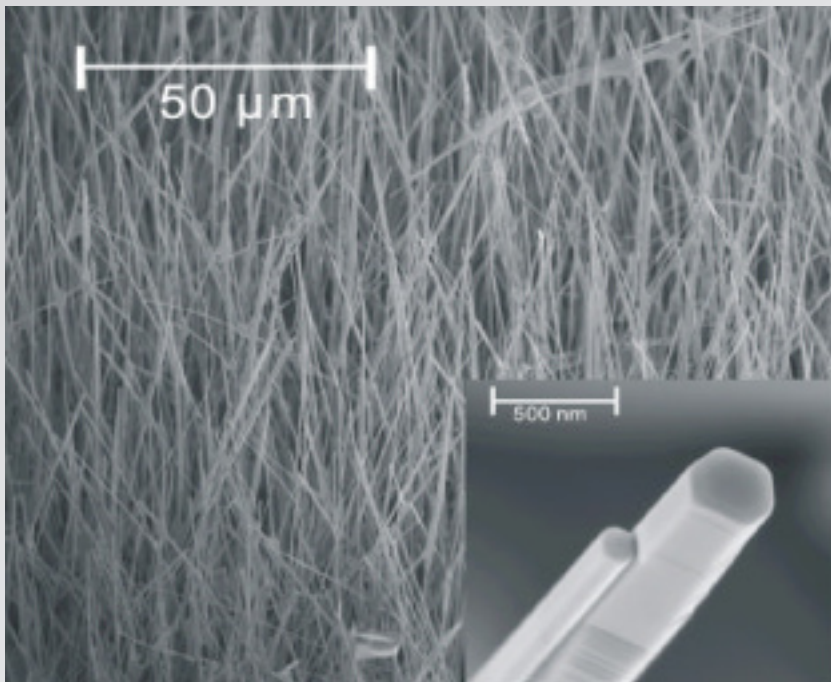
# Manipulating light at the nanoscale

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

A petri dish containing a white, granular powder, likely ZnO, with a dark cylindrical object resting on the right side.

# 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

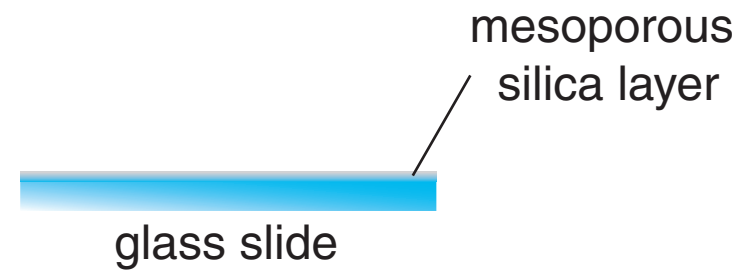
passive waveguides

electrical operation

link to macroworld

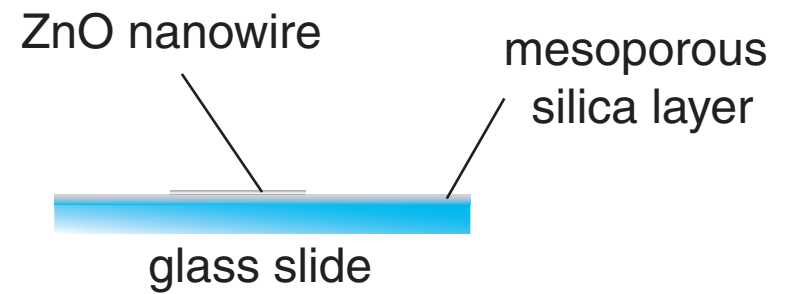
# Manipulating light at the nanoscale

coupling to ZnO nanowires



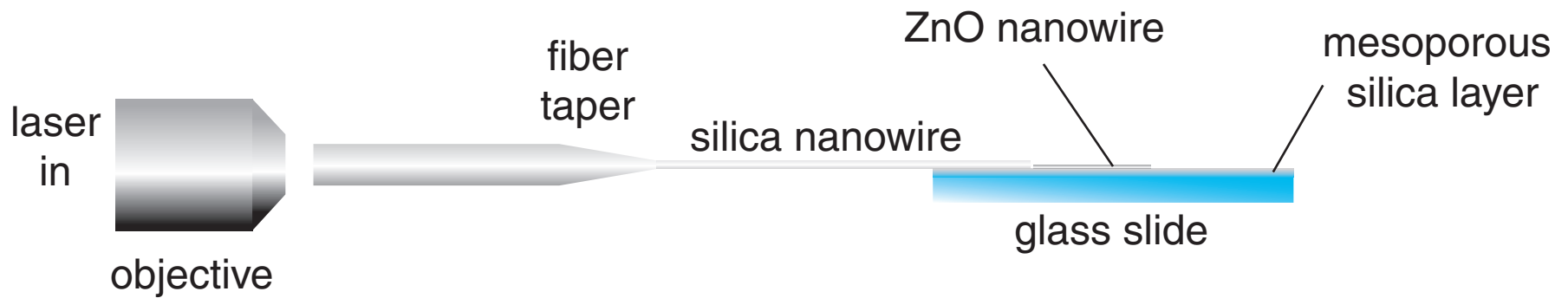
# Manipulating light at the nanoscale

coupling to ZnO nanowires



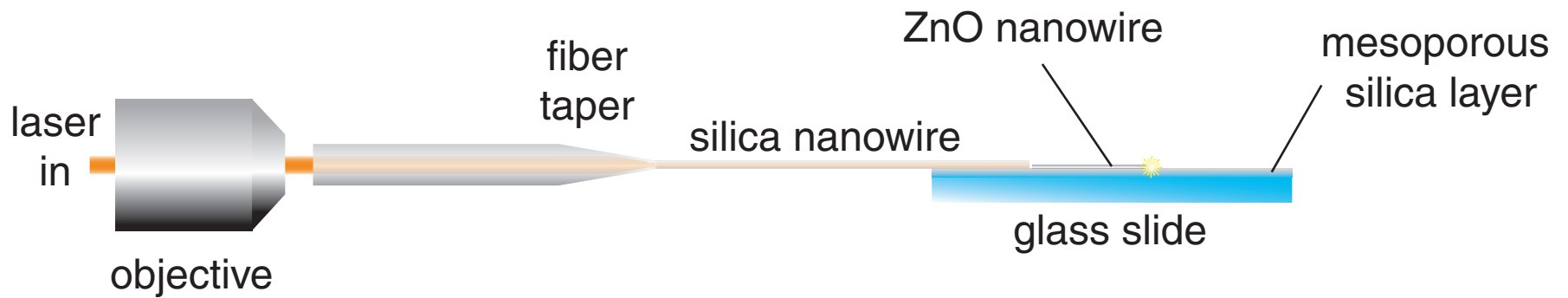
# Manipulating light at the nanoscale

## coupling to ZnO nanowires



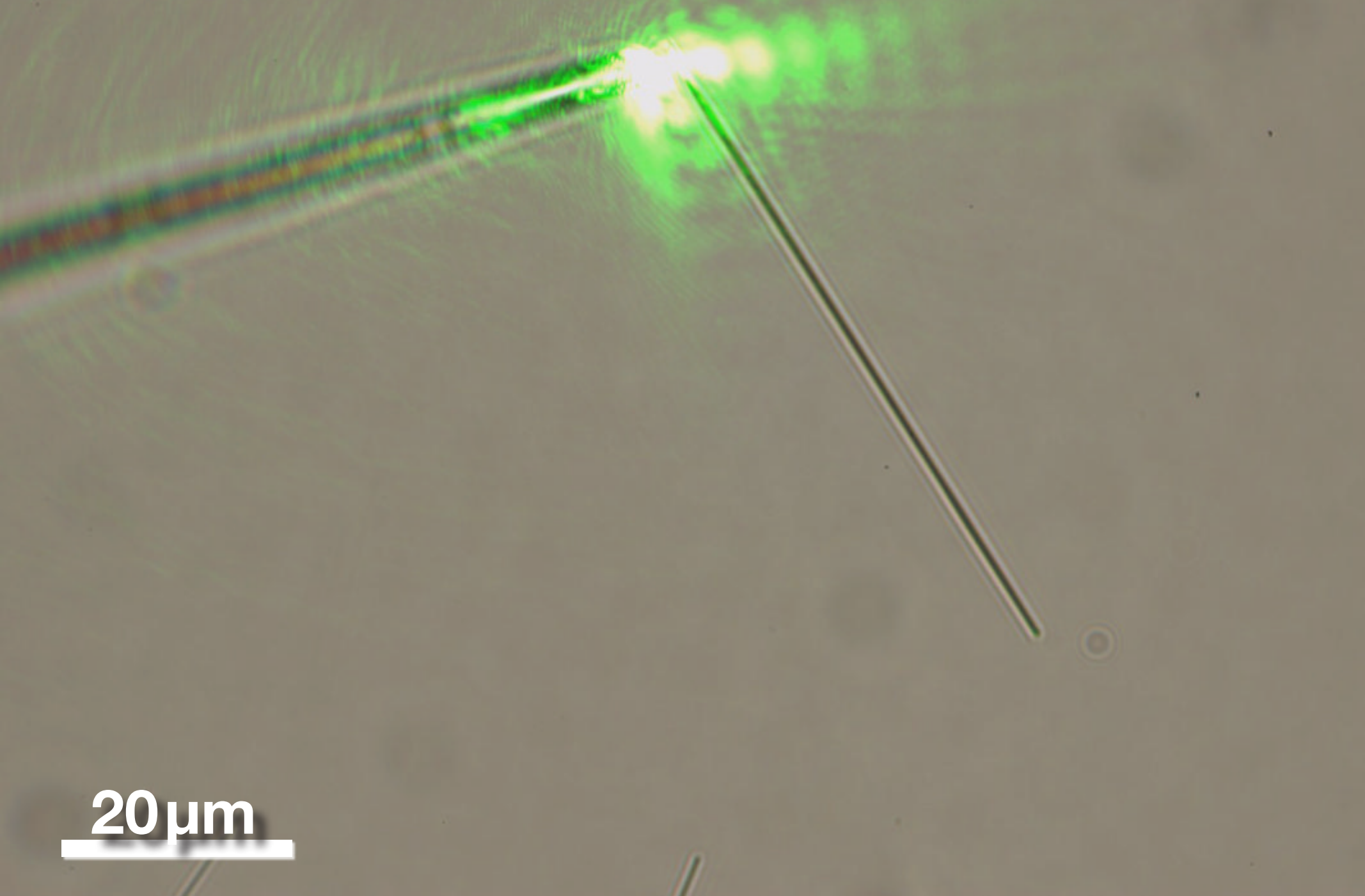
# Manipulating light at the nanoscale

coupling to ZnO nanowires



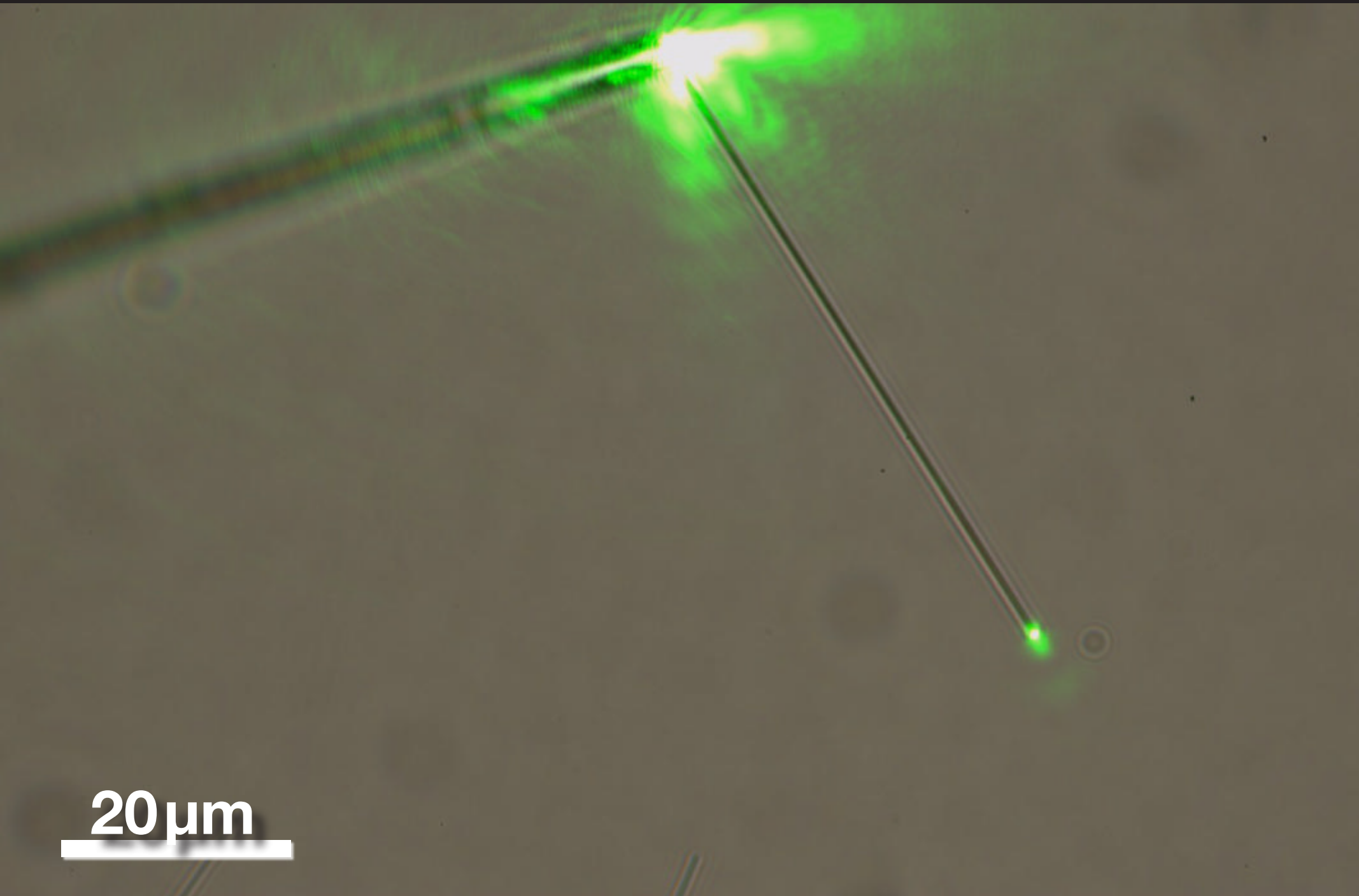


# Manipulating light at the nanoscale



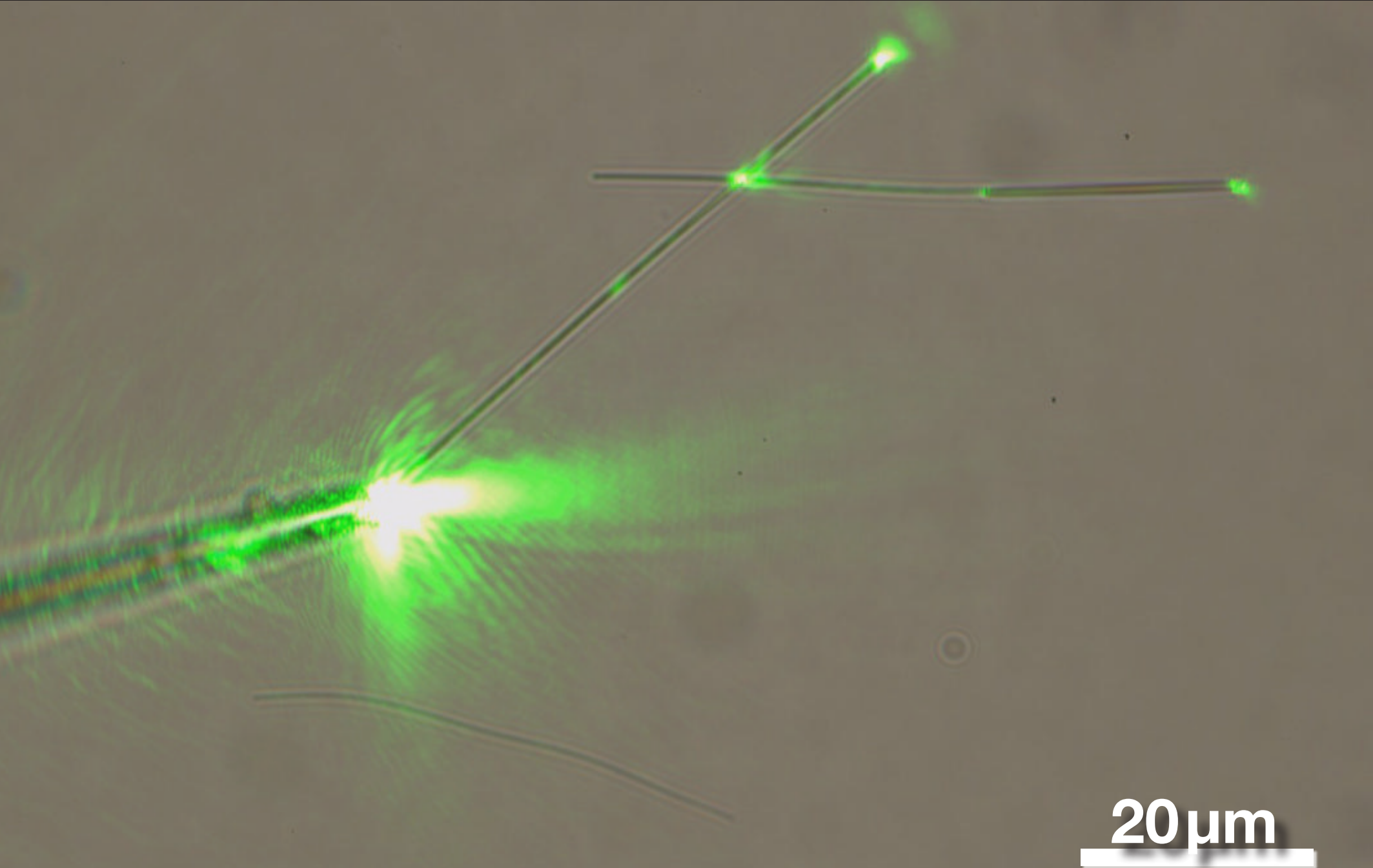
20  $\mu\text{m}$

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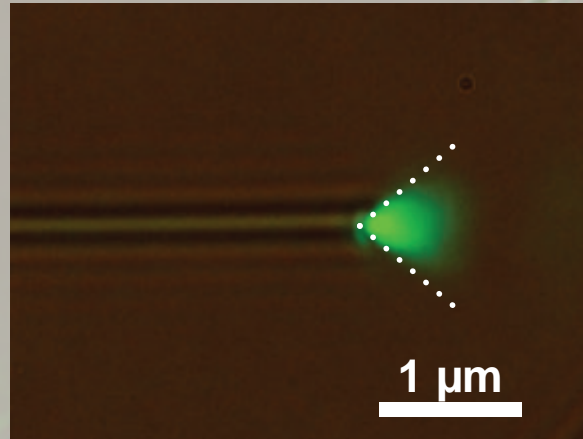


20  $\mu\text{m}$

# Manipulating light at the nanoscale

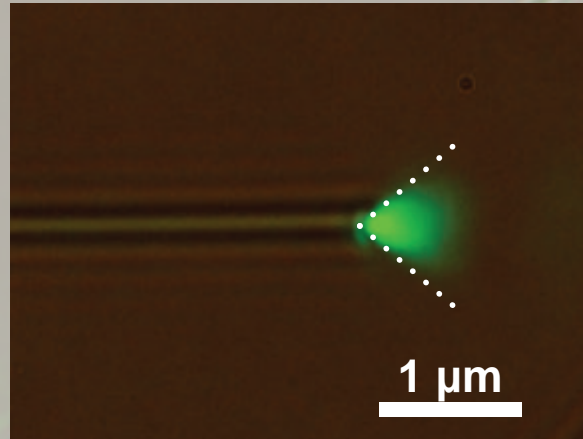


# Manipulating light at the nanoscale

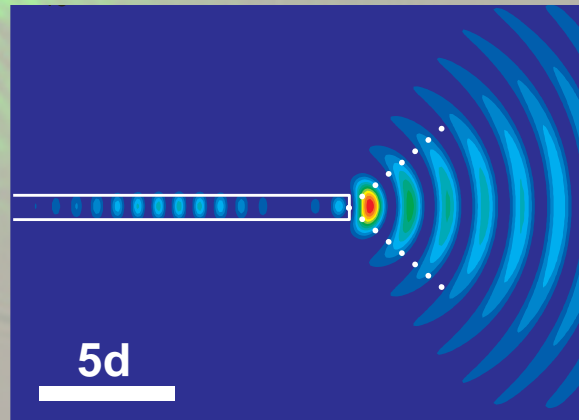


*Nano Lett.*, 7, 3675 (2007)

# Manipulating light at the nanoscale

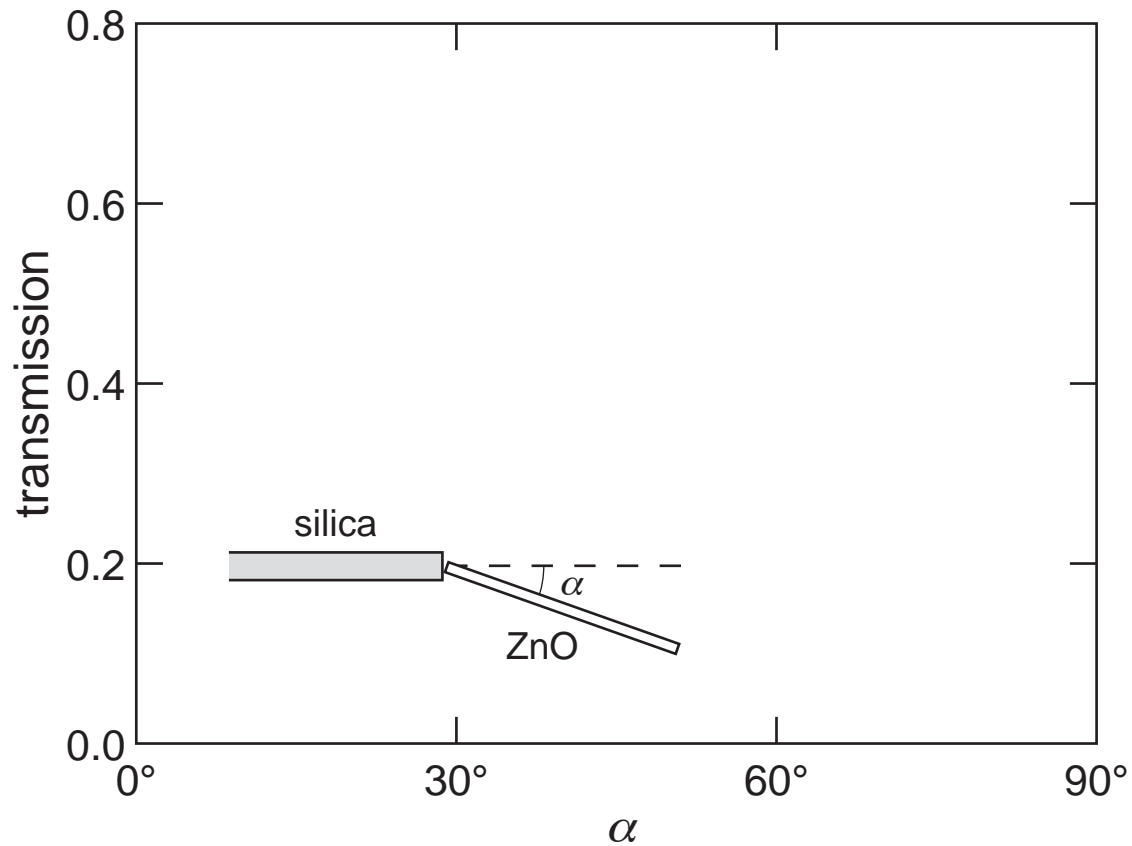


FDTD simulation



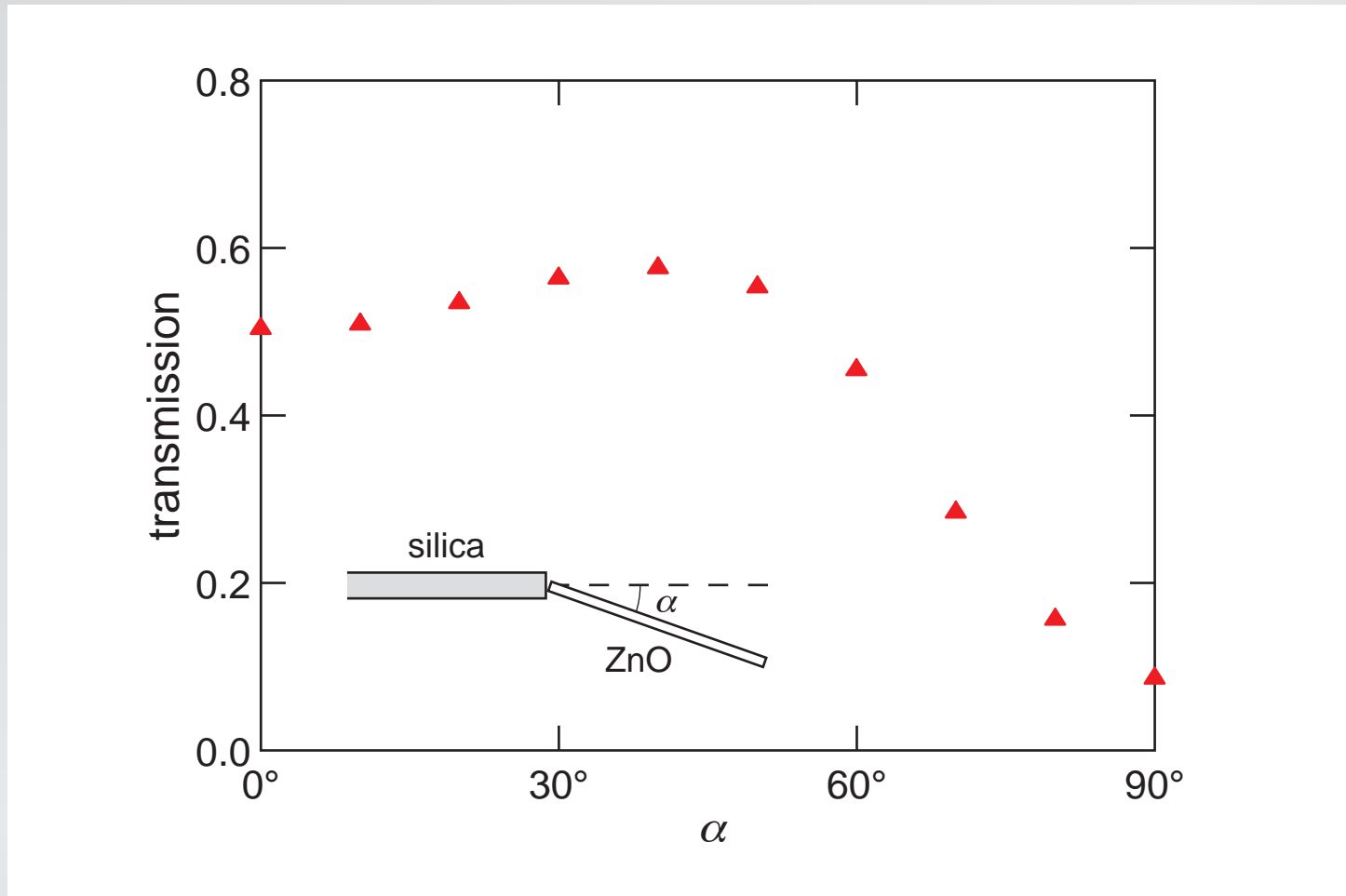
# Manipulating light at the nanoscale

coupling efficiency

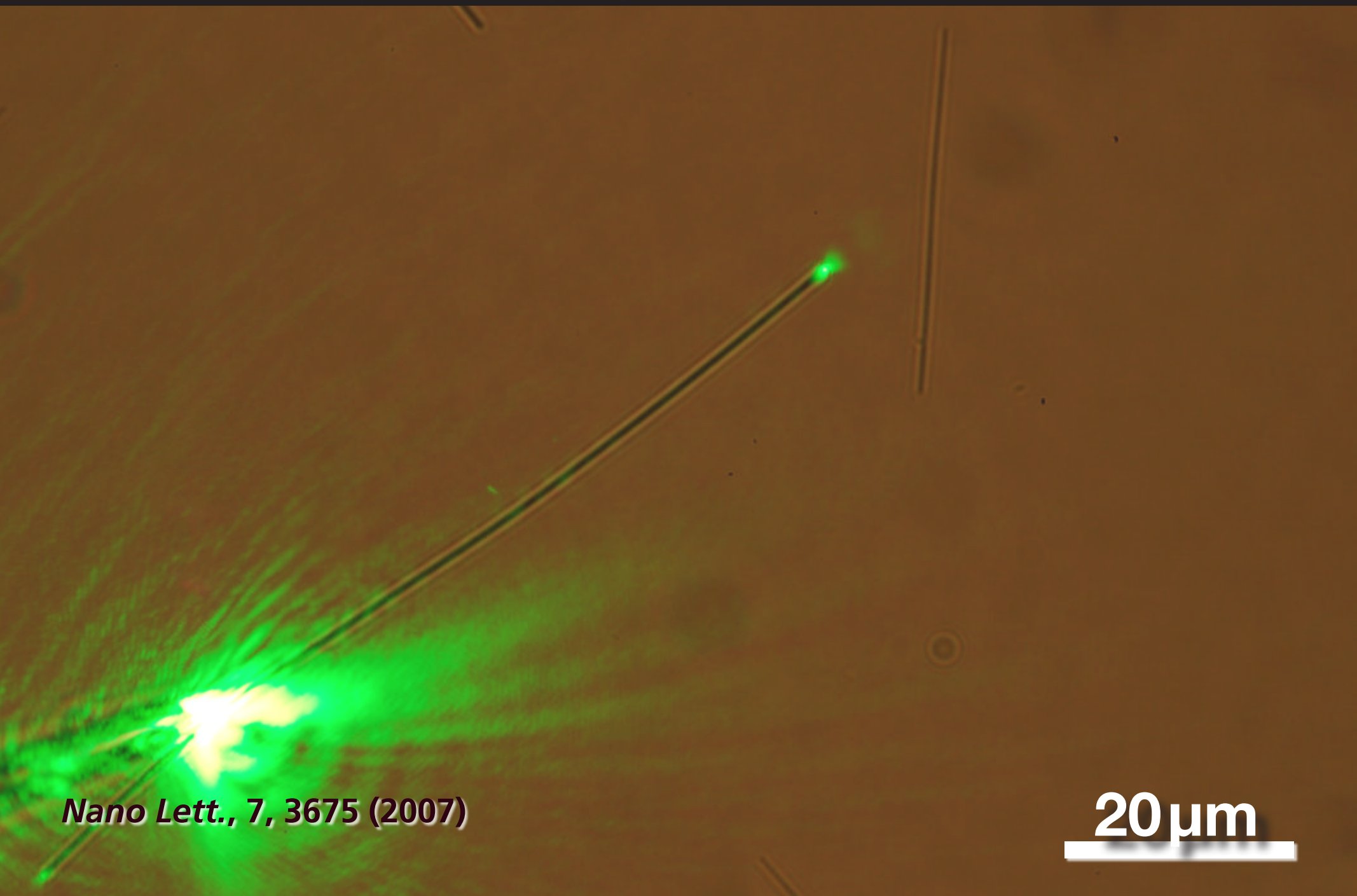


# Manipulating light at the nanoscale

## coupling efficiency



# Manipulating light at the nanoscale

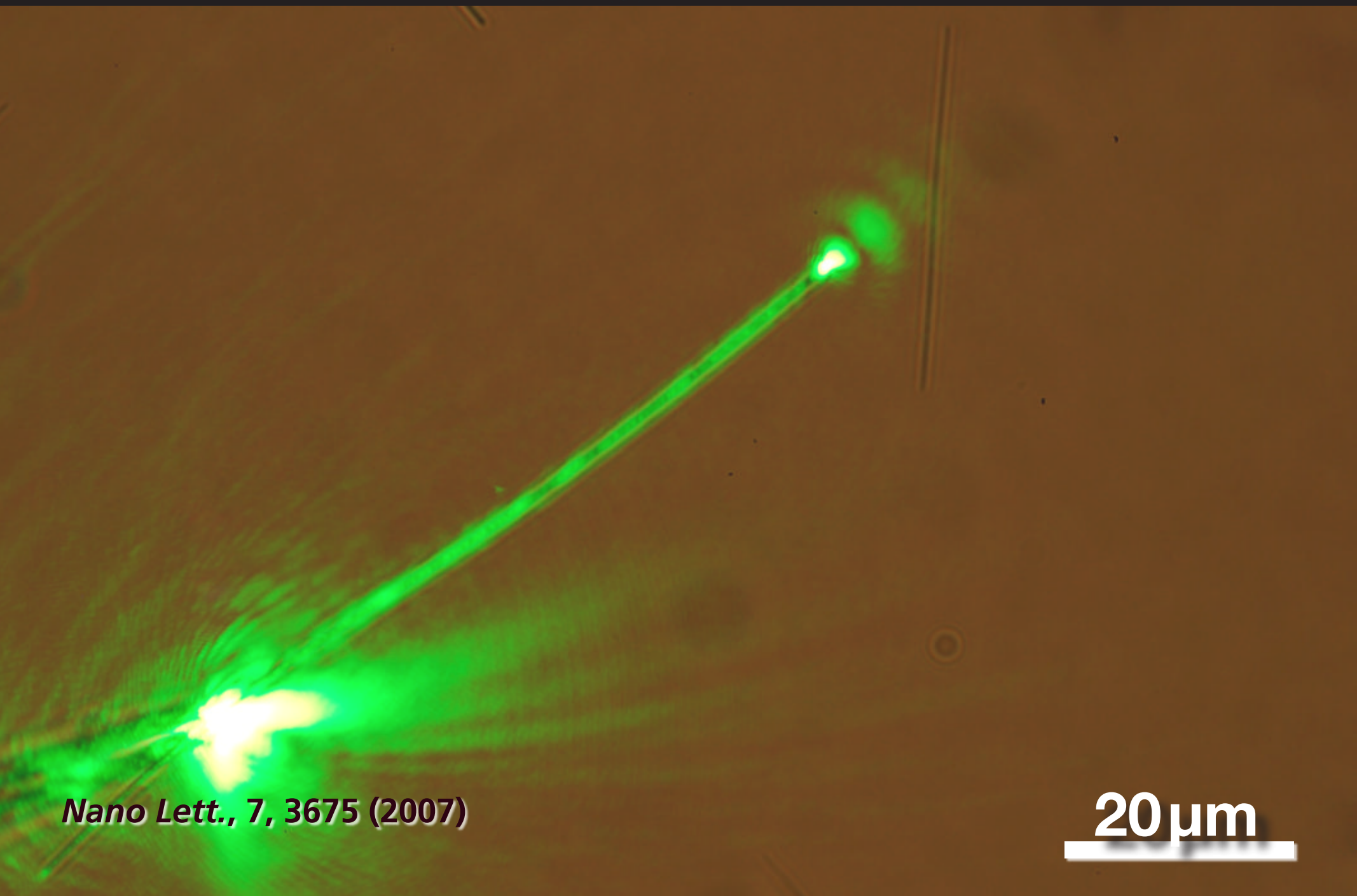


*Nano Lett.*, 7, 3675 (2007)

20  $\mu\text{m}$



# Manipulating light at the nanoscale

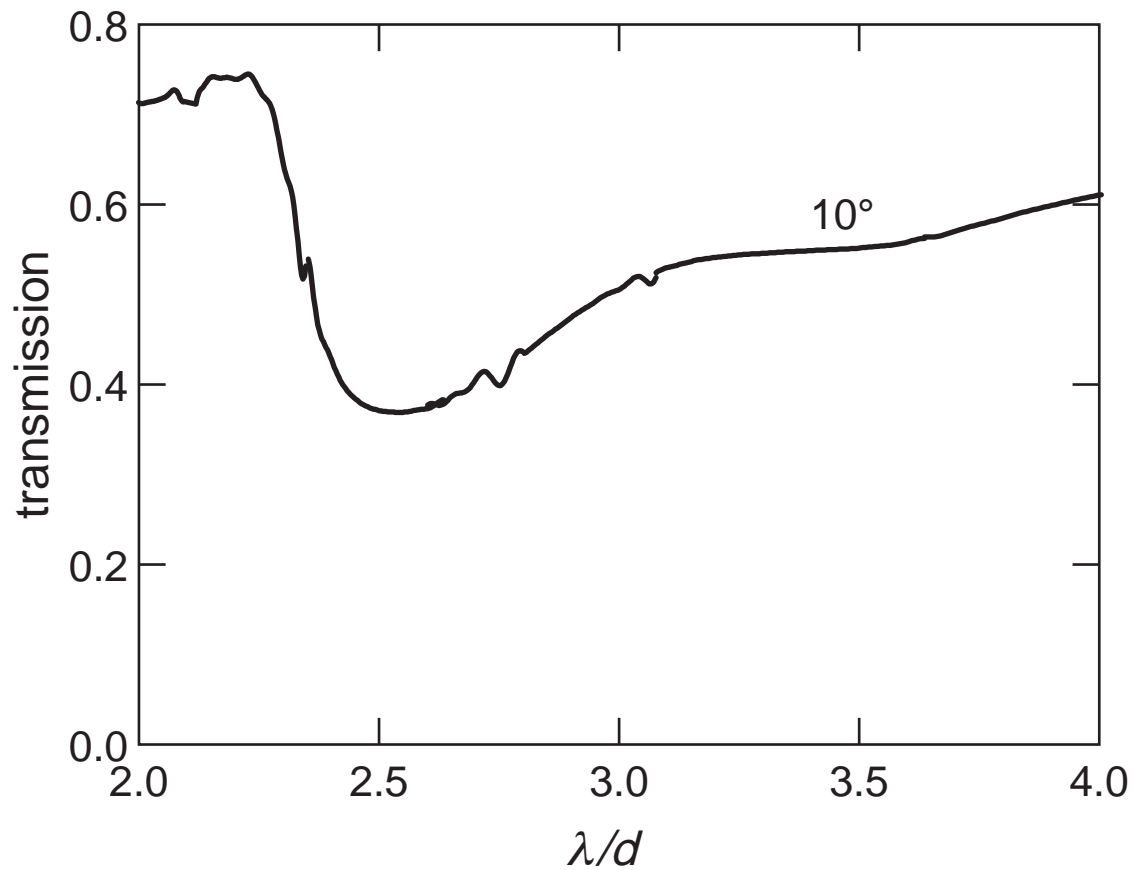


*Nano Lett.*, 7, 3675 (2007)

20  $\mu\text{m}$

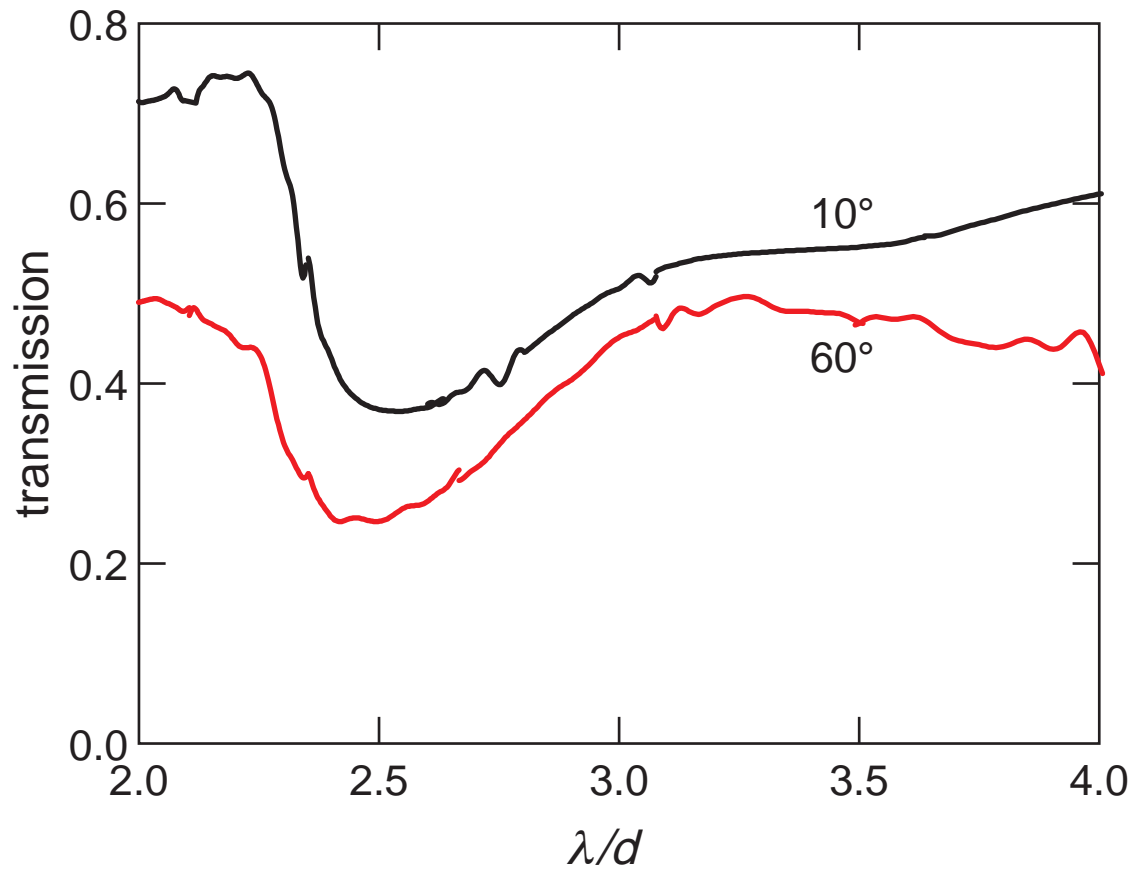
# Manipulating light at the nanoscale

## transmission spectrum



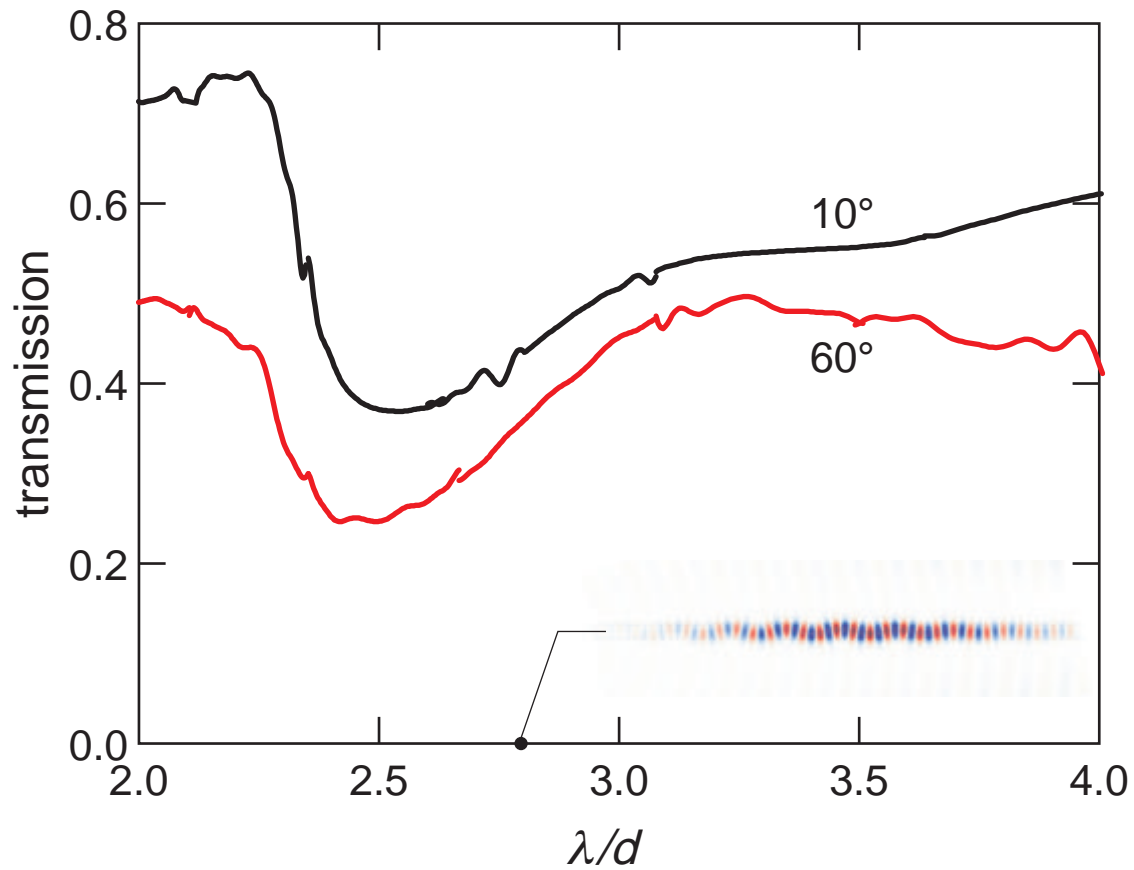
# Manipulating light at the nanoscale

## transmission spectrum



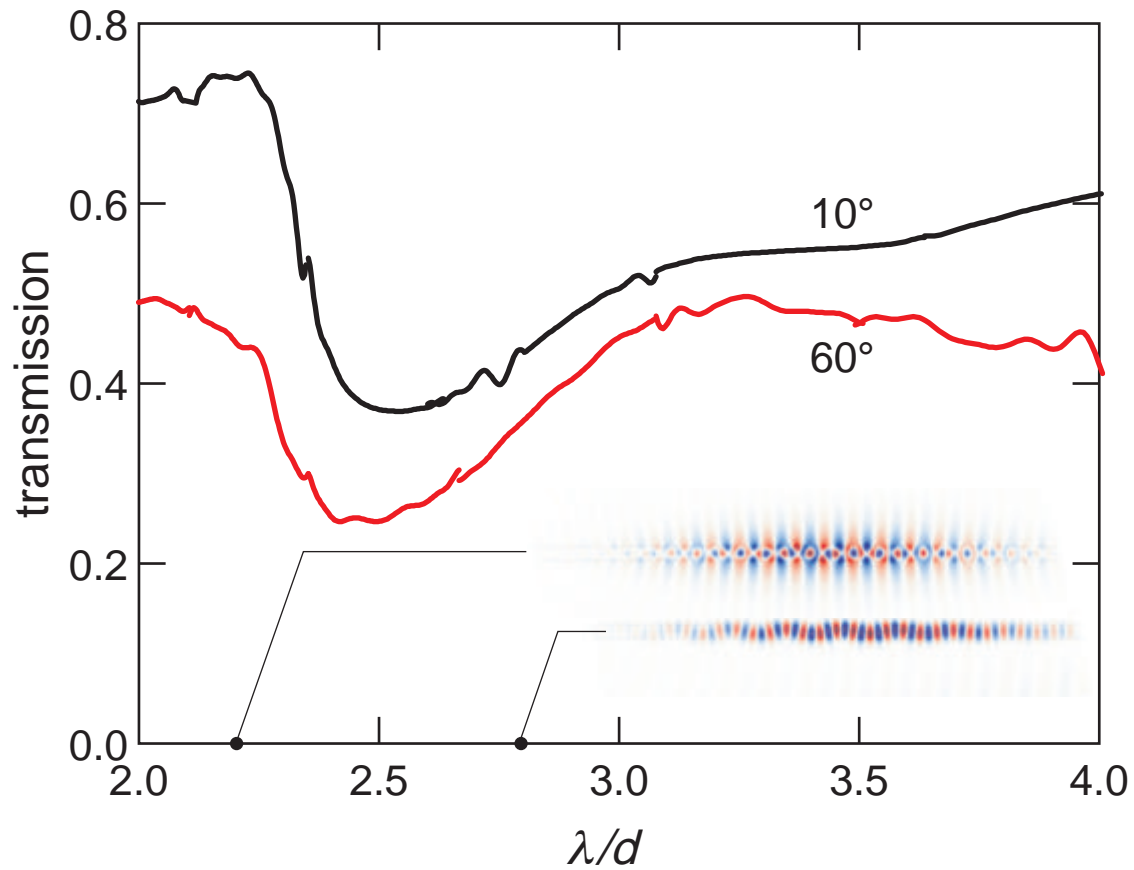
# Manipulating light at the nanoscale

## transmission spectrum

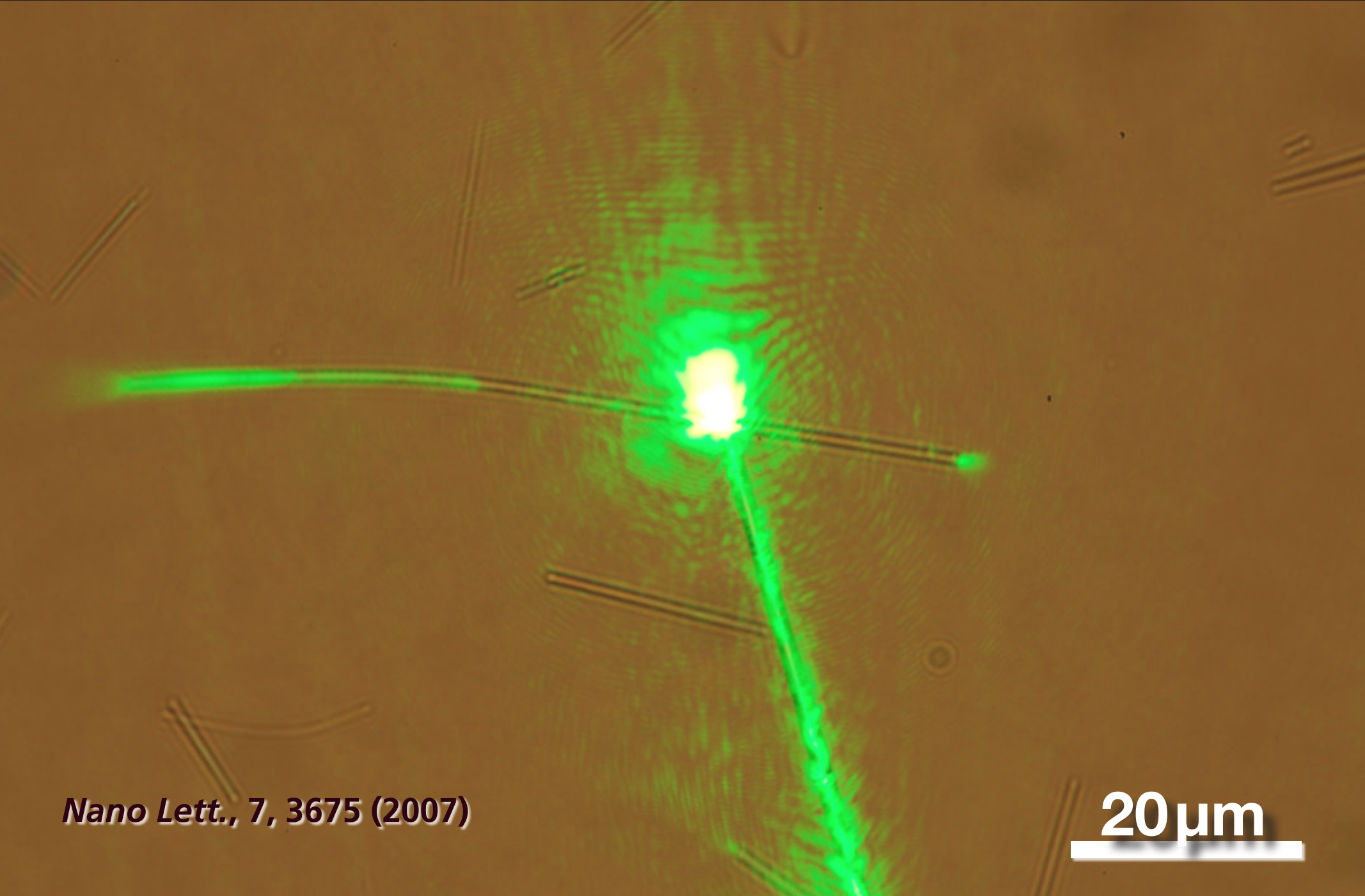


# Manipulating light at the nanoscale

## transmission spectrum



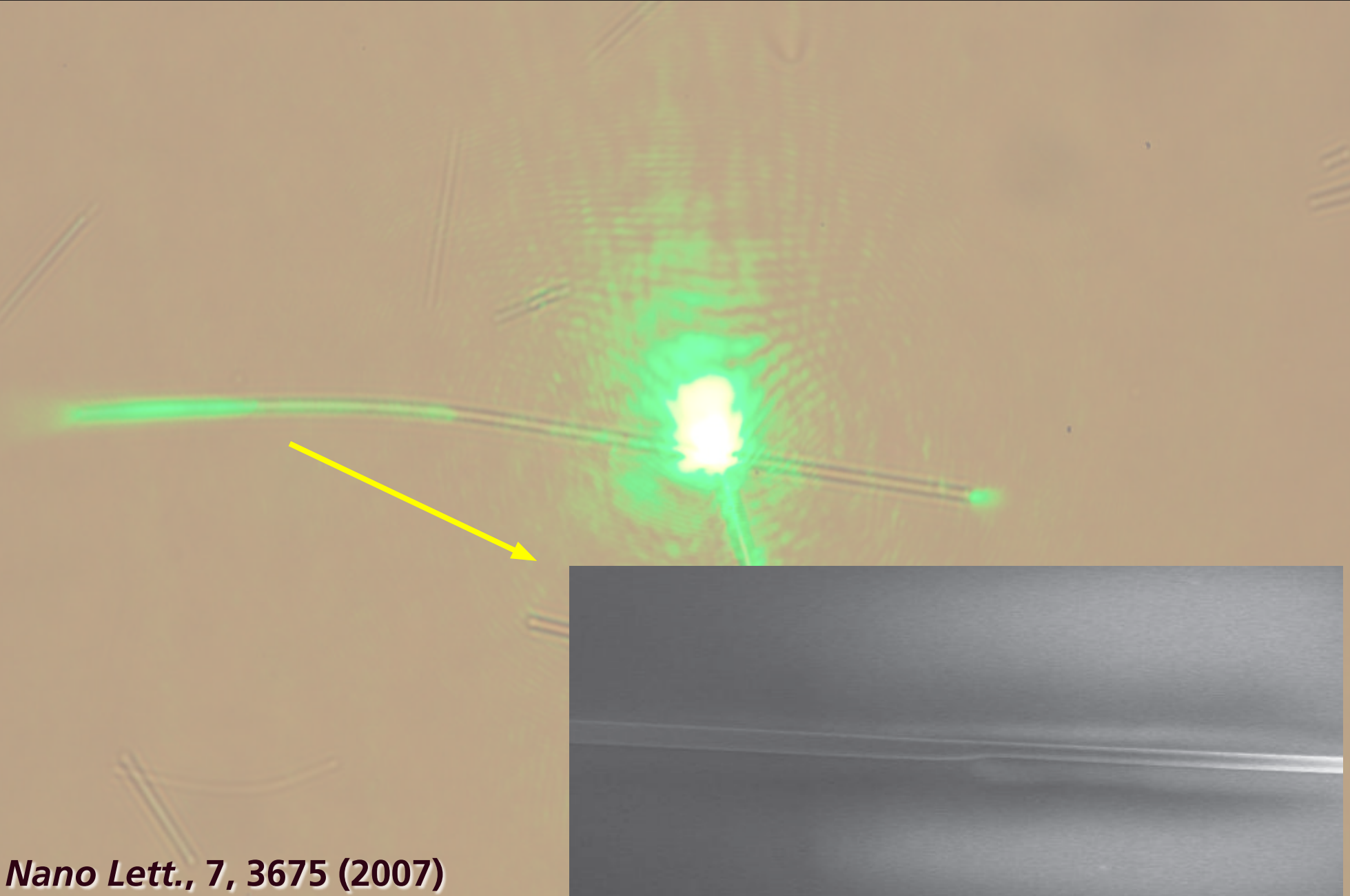
# Manipulating light at the nanoscale



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

20  $\mu\text{m}$

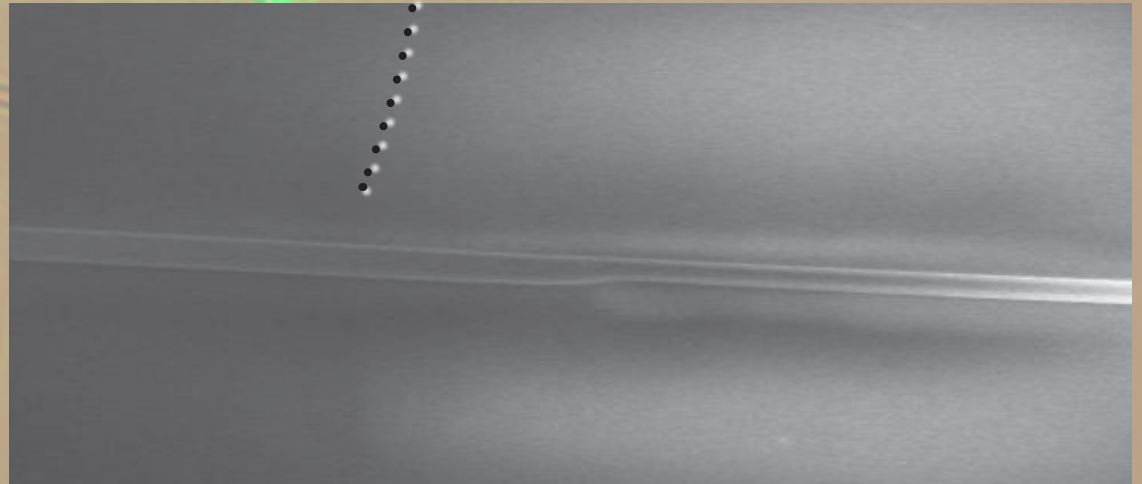
# Manipulating light at the nanoscale



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

# Manipulating light at the nanoscale

large diameter:  
multimode

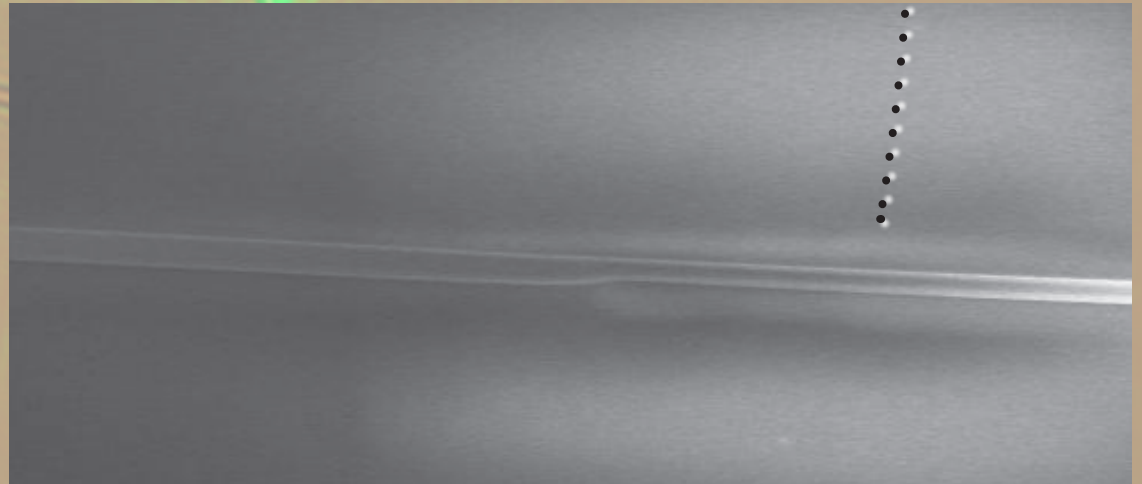


*Nano Lett.*, 7, 3675 (2007)



# Manipulating light at the nanoscale

small diameter:  
single mode



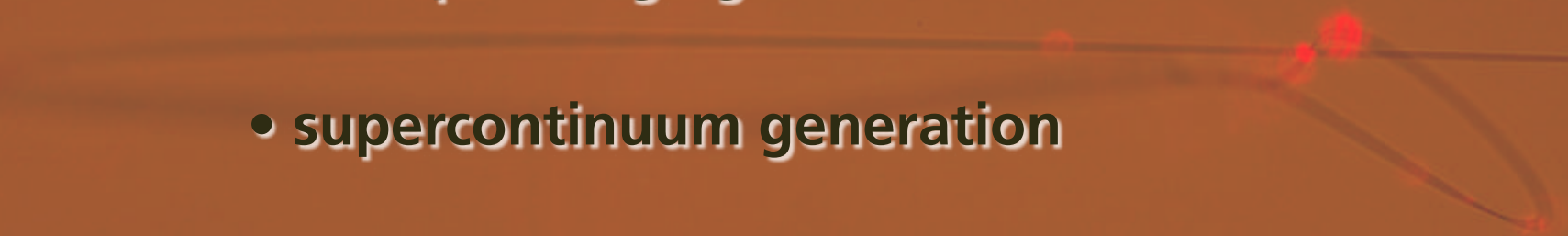
*Nano Lett.*, 7, 3675 (2007)

# Manipulating light at the nanoscale

**Points to keep in mind:**

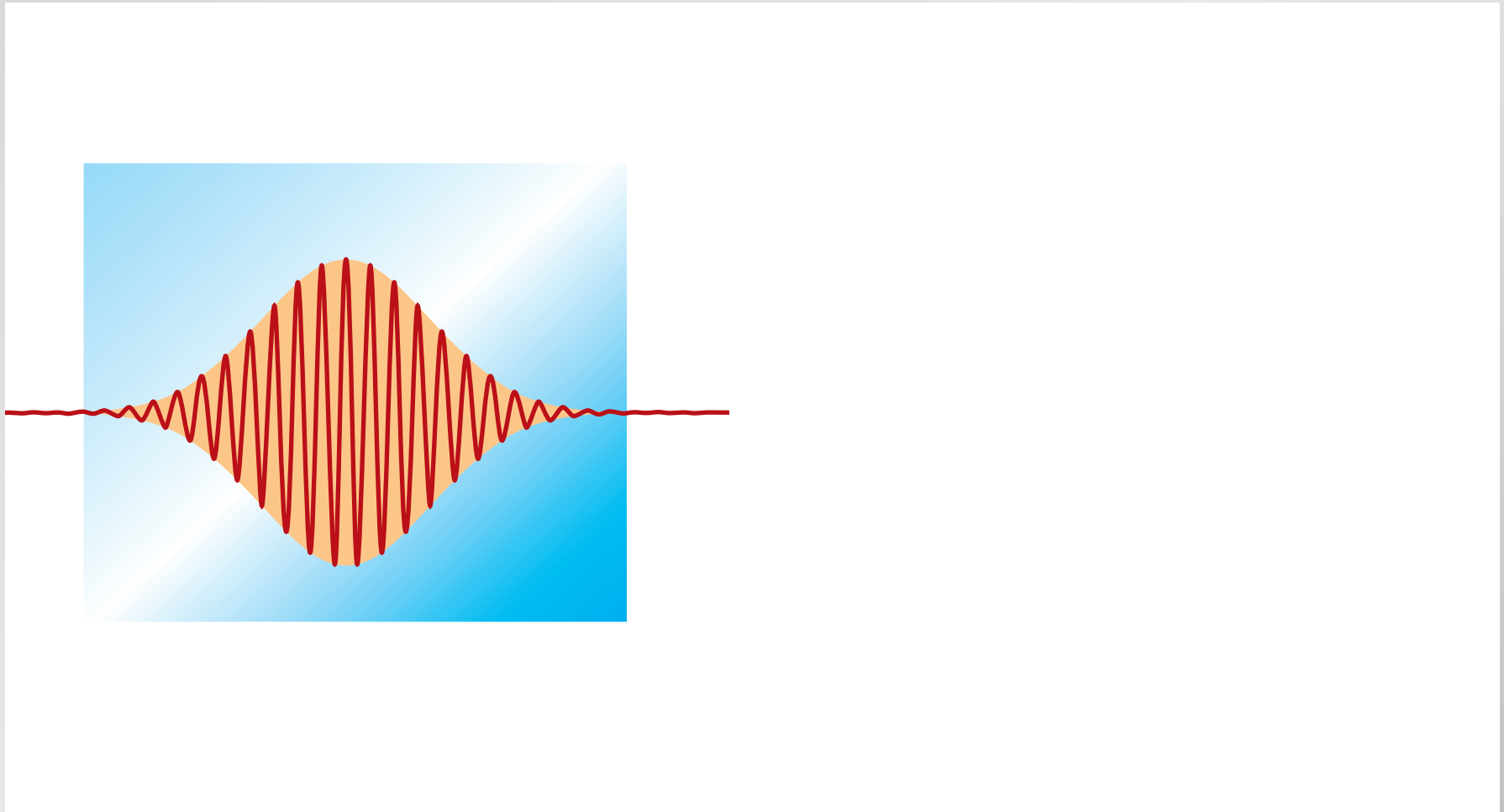
- **low-loss guiding**
- **convenient evanescent coupling**
- **attached to ordinary fiber**

# Outline

- **manipulating light at the nanoscale**
  - **supercontinuum generation**
  - **optical logic gates**
- 
- A decorative graphic on the right side of the slide shows a horizontal fiber optic cable with several red light pulses traveling along it. A curved line branches off from the main cable, also containing red light pulses, suggesting a signal path or a specific optical component.

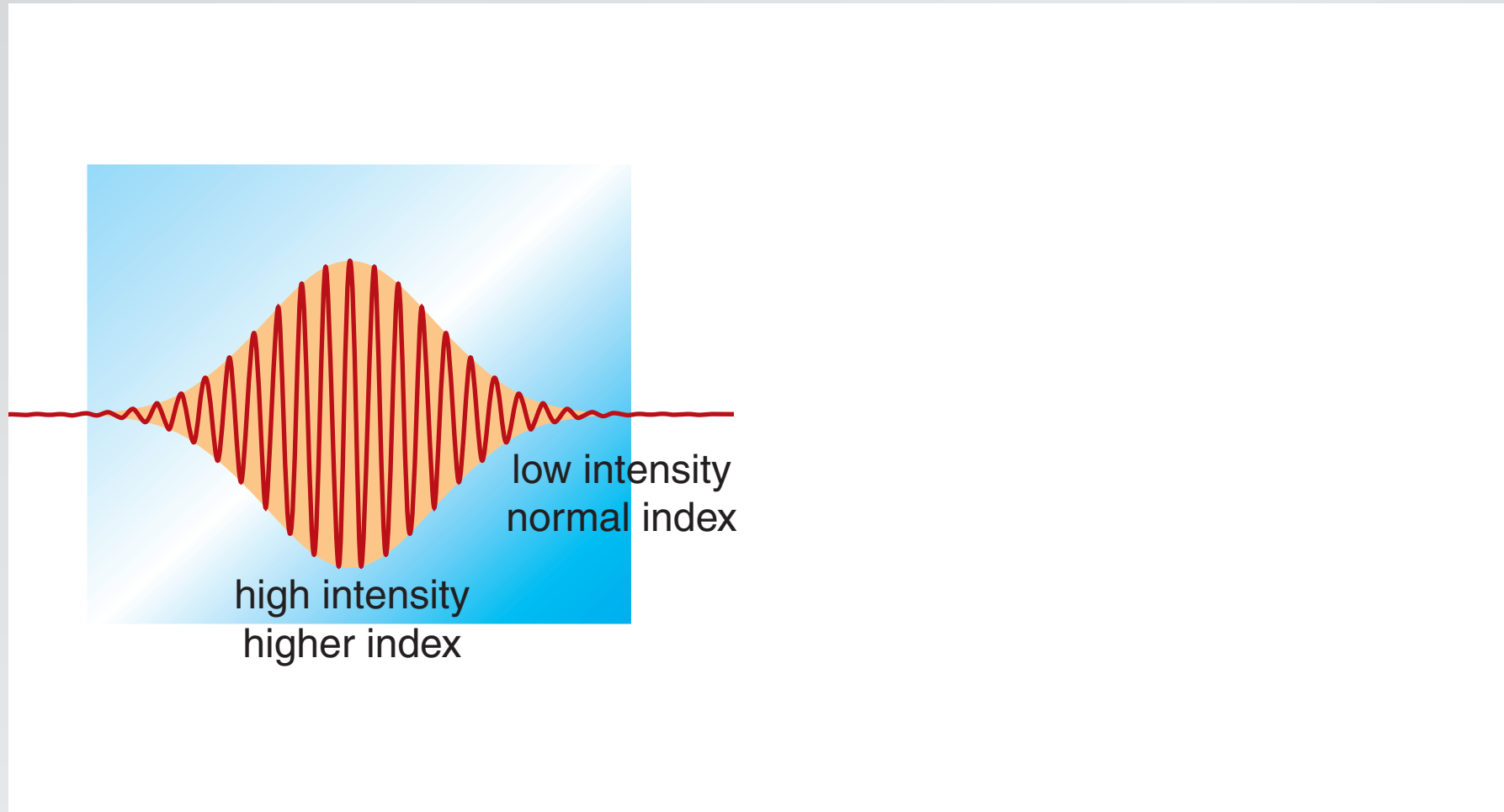
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



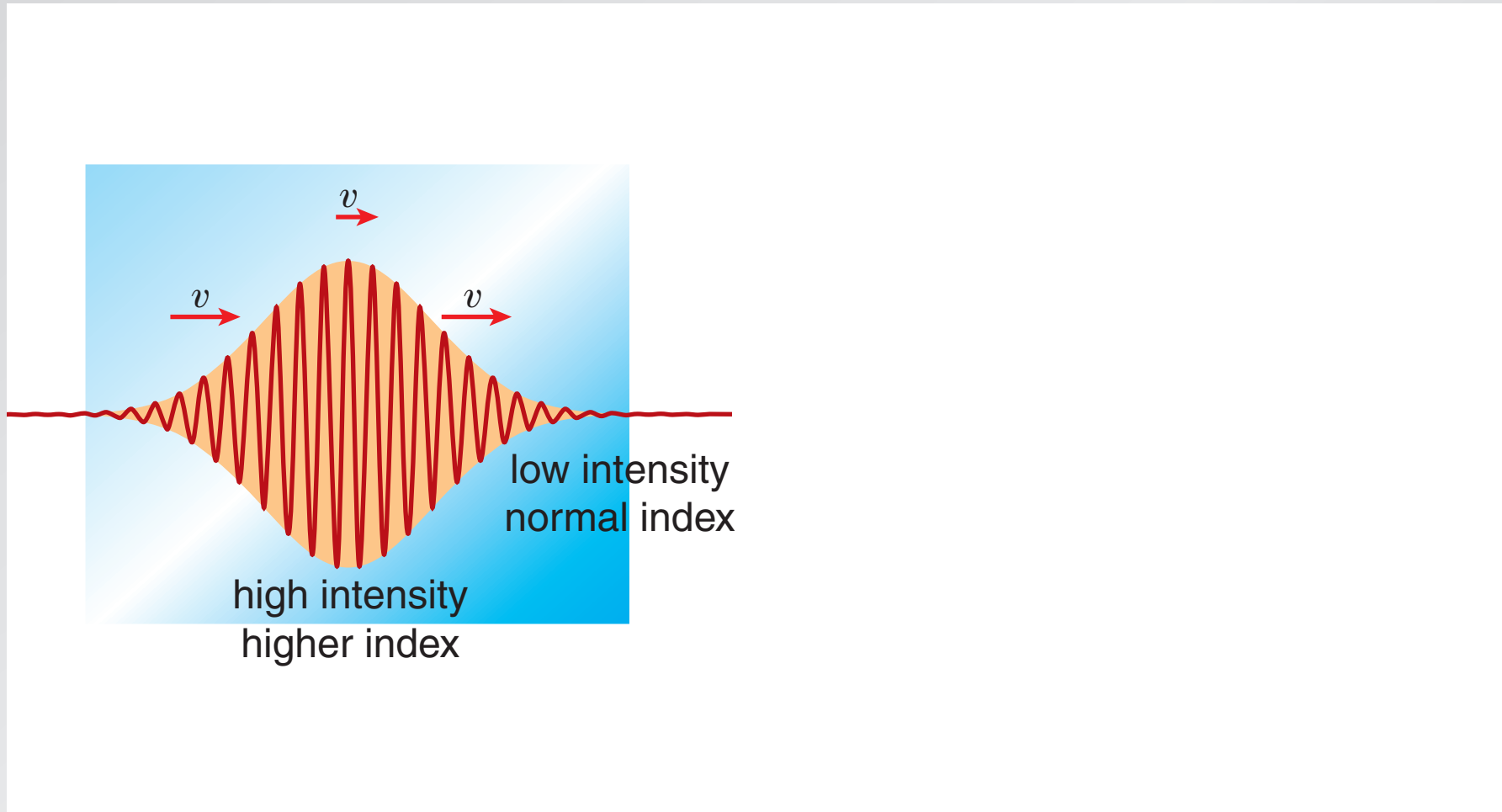
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



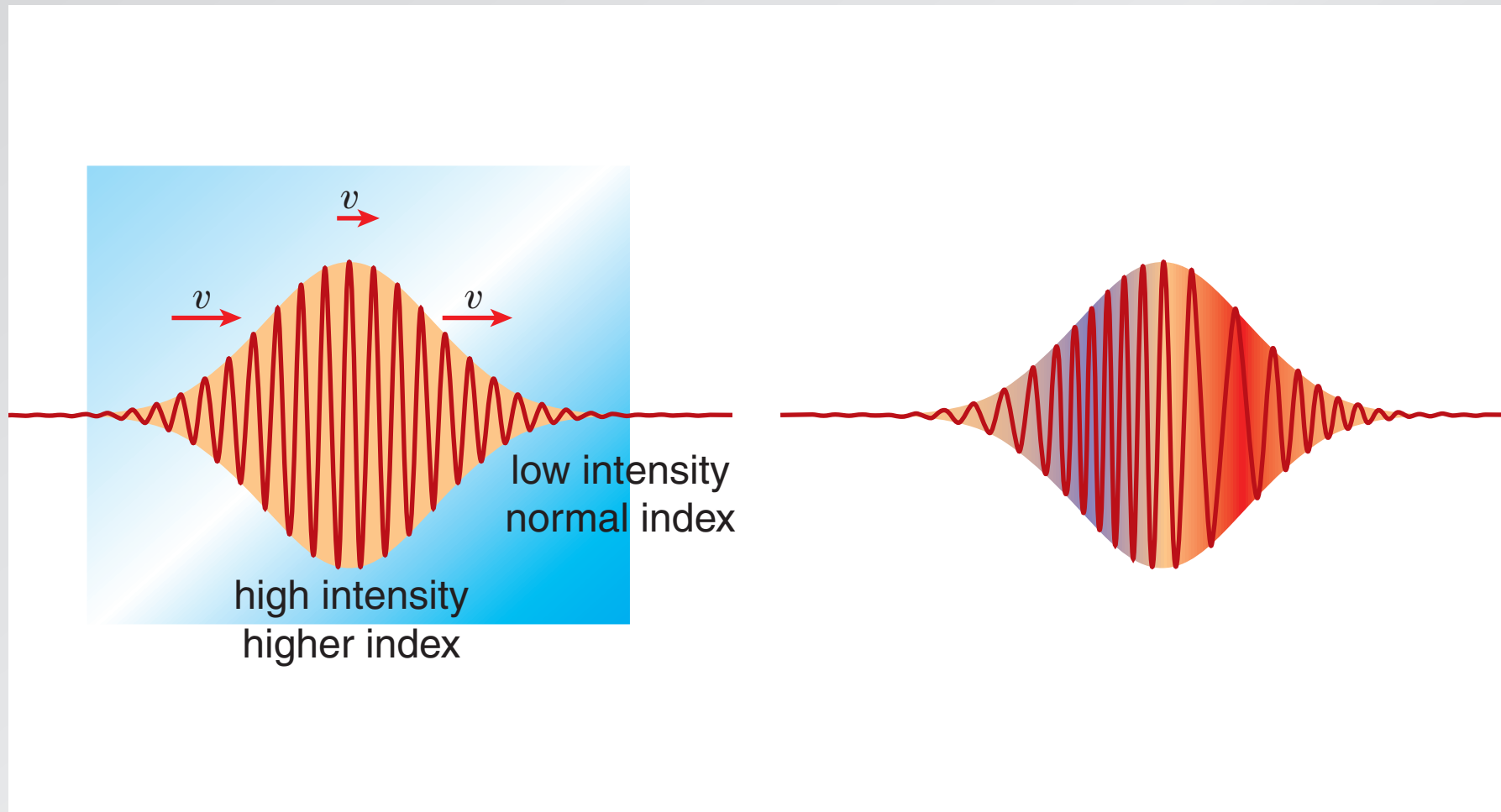
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



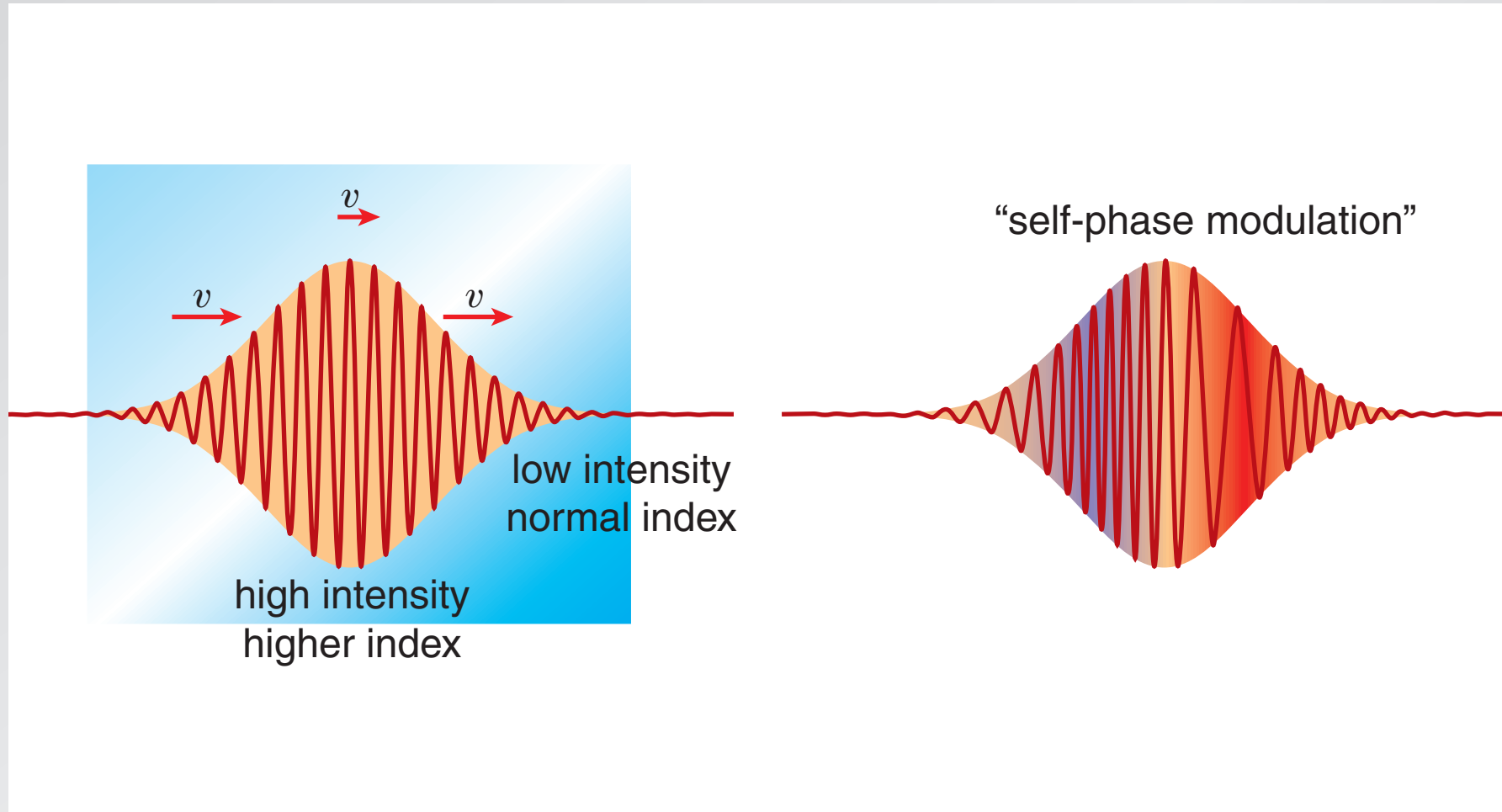
# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$



# Supercontinuum generation

nonlinear dispersion:  $n = n_0 + n_2 I$

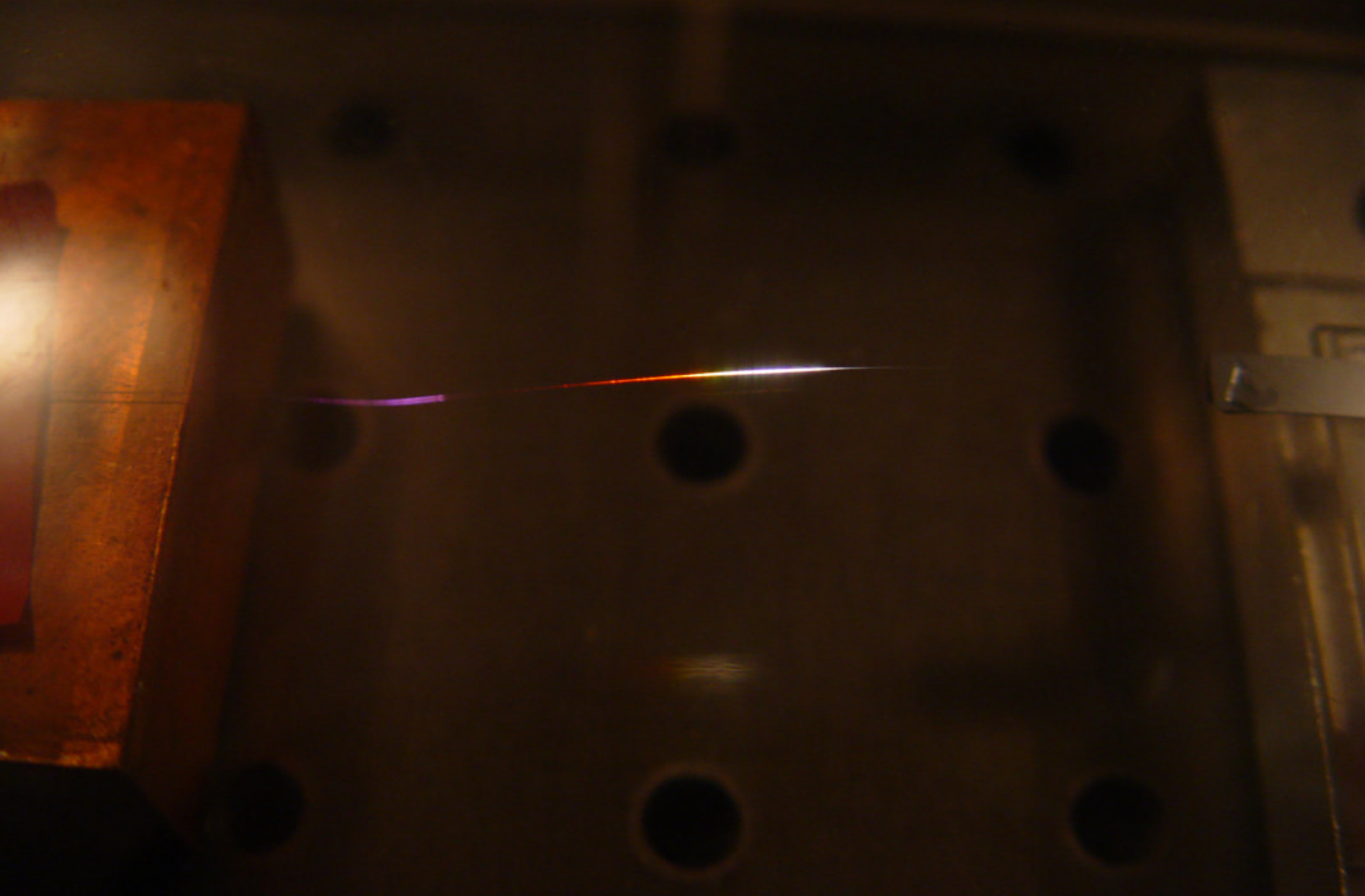




# Supercontinuum generation

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

# Supercontinuum generation

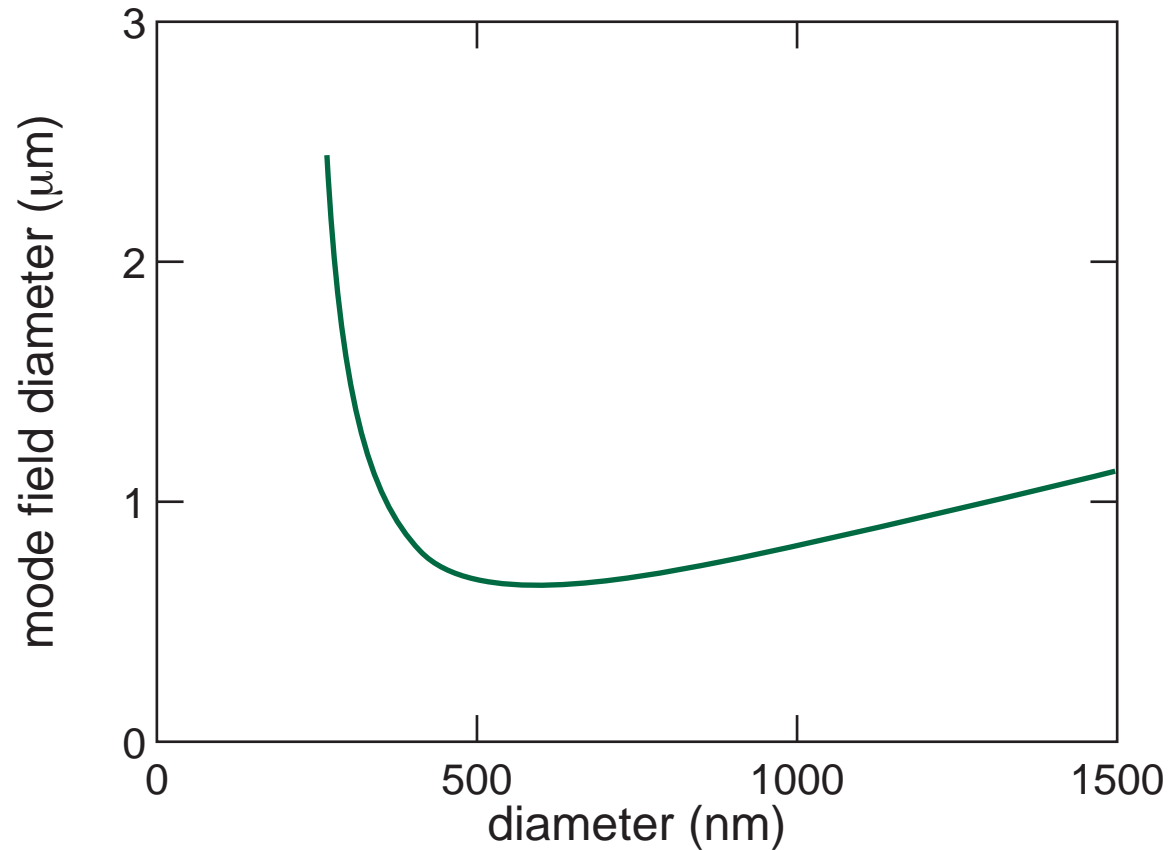


# Supercontinuum generation



# Supercontinuum generation

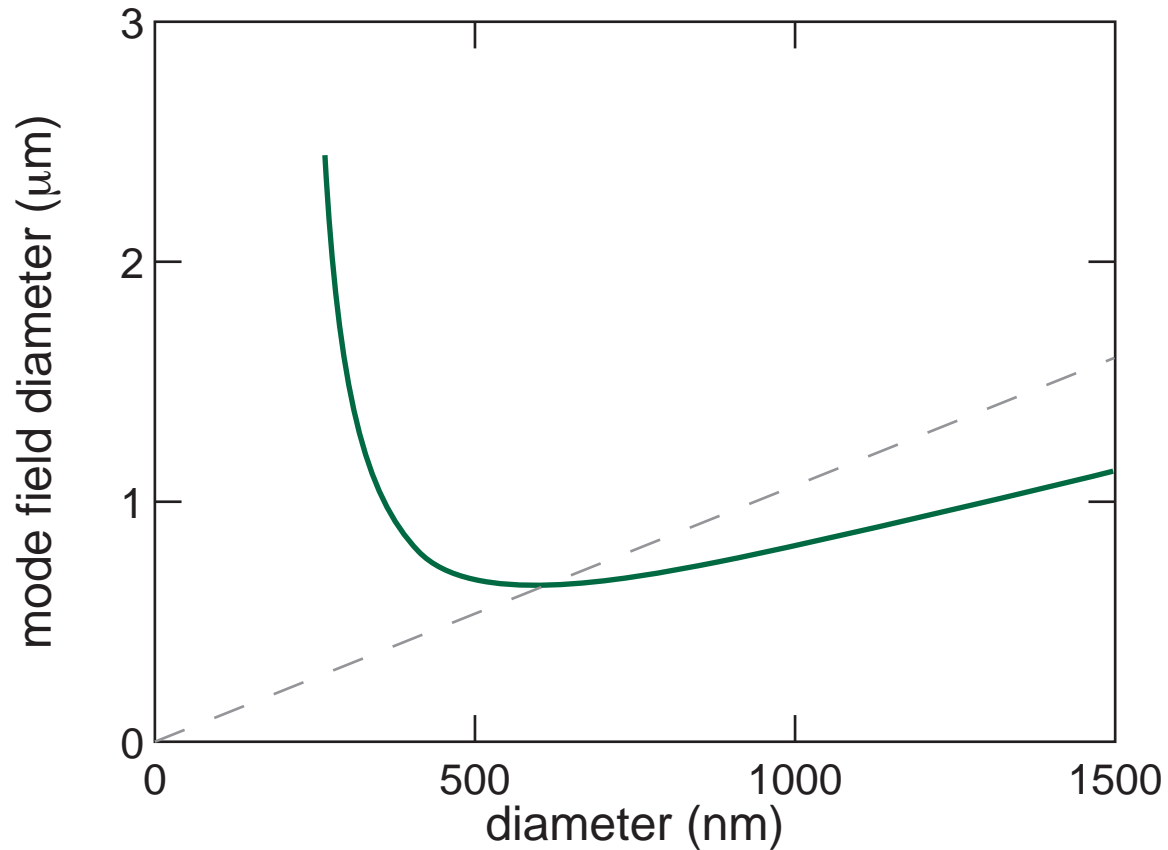
mode field diameter ( $\lambda = 800$  nm)



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

# Supercontinuum generation

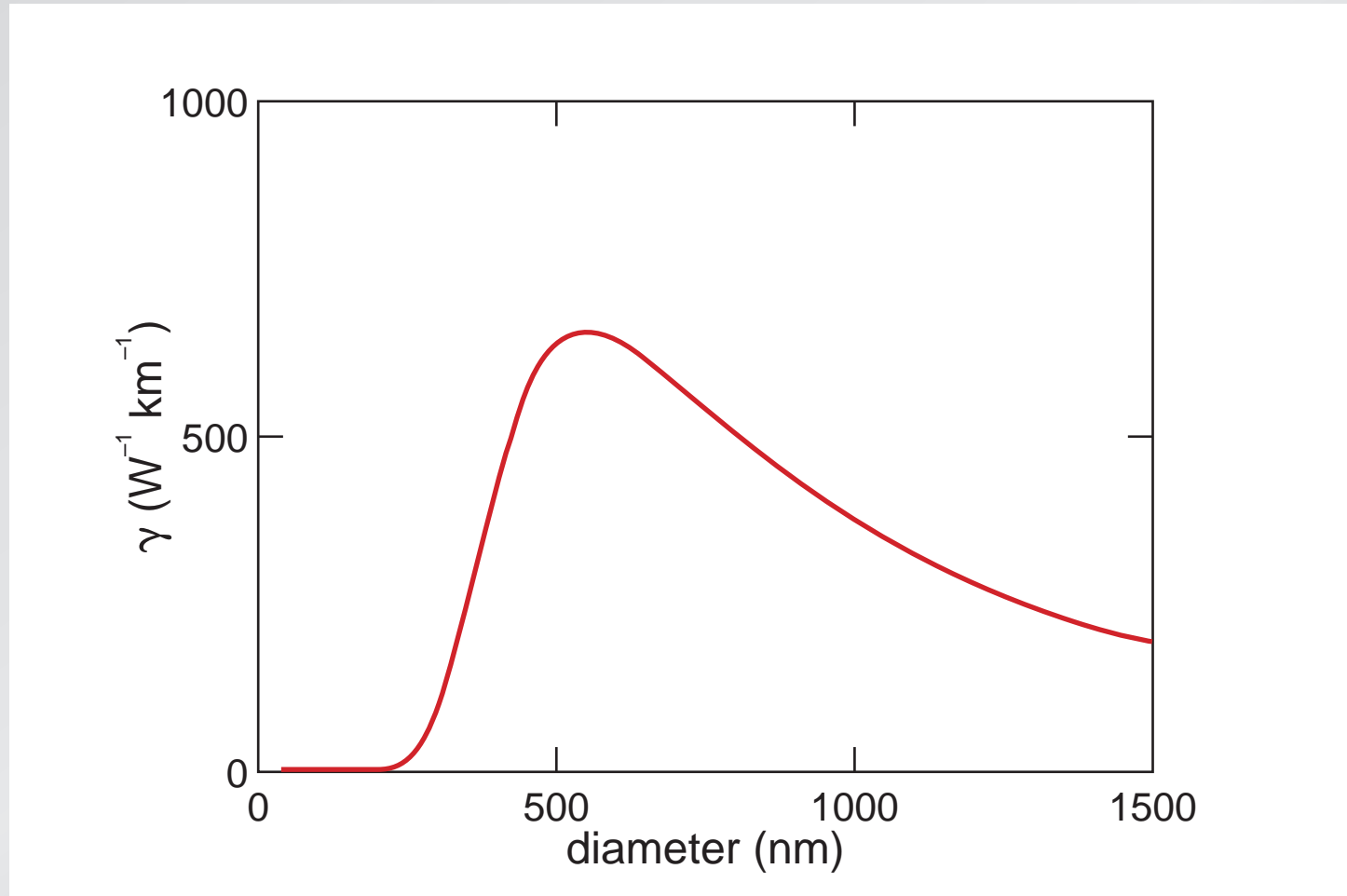
mode field diameter ( $\lambda = 800$  nm)



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

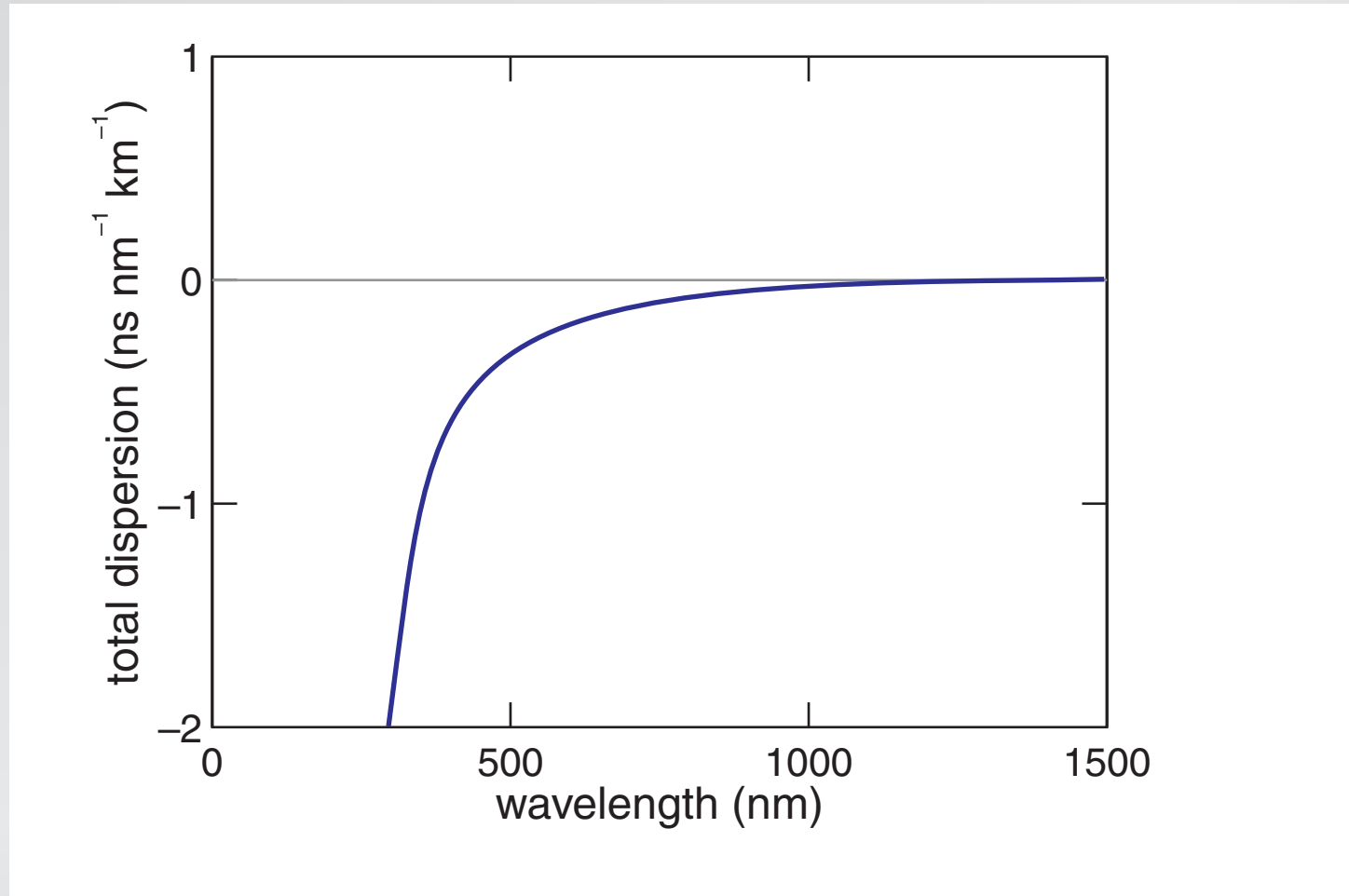
dispersion:

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



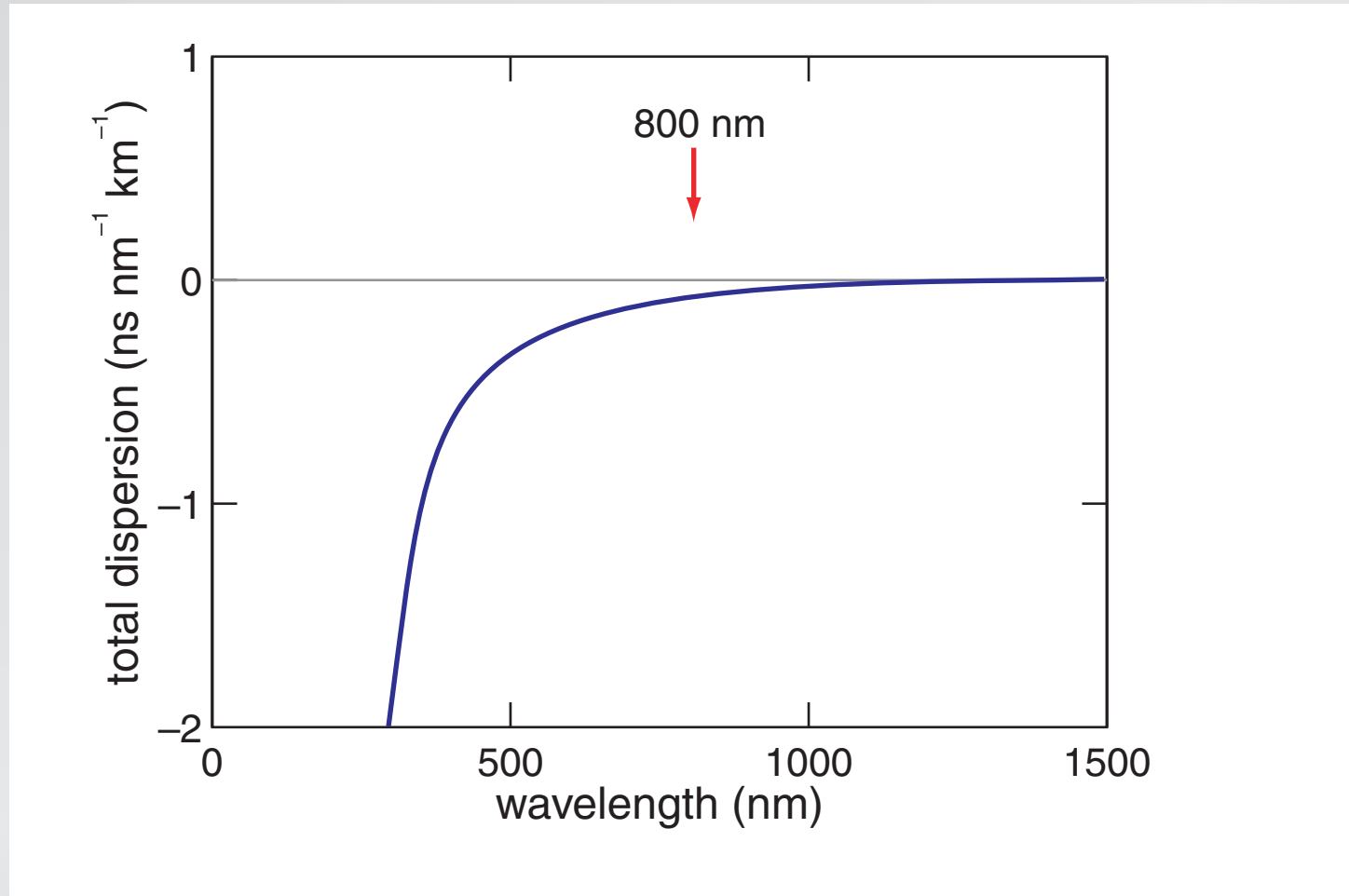
# Supercontinuum generation

## waveguide dispersion



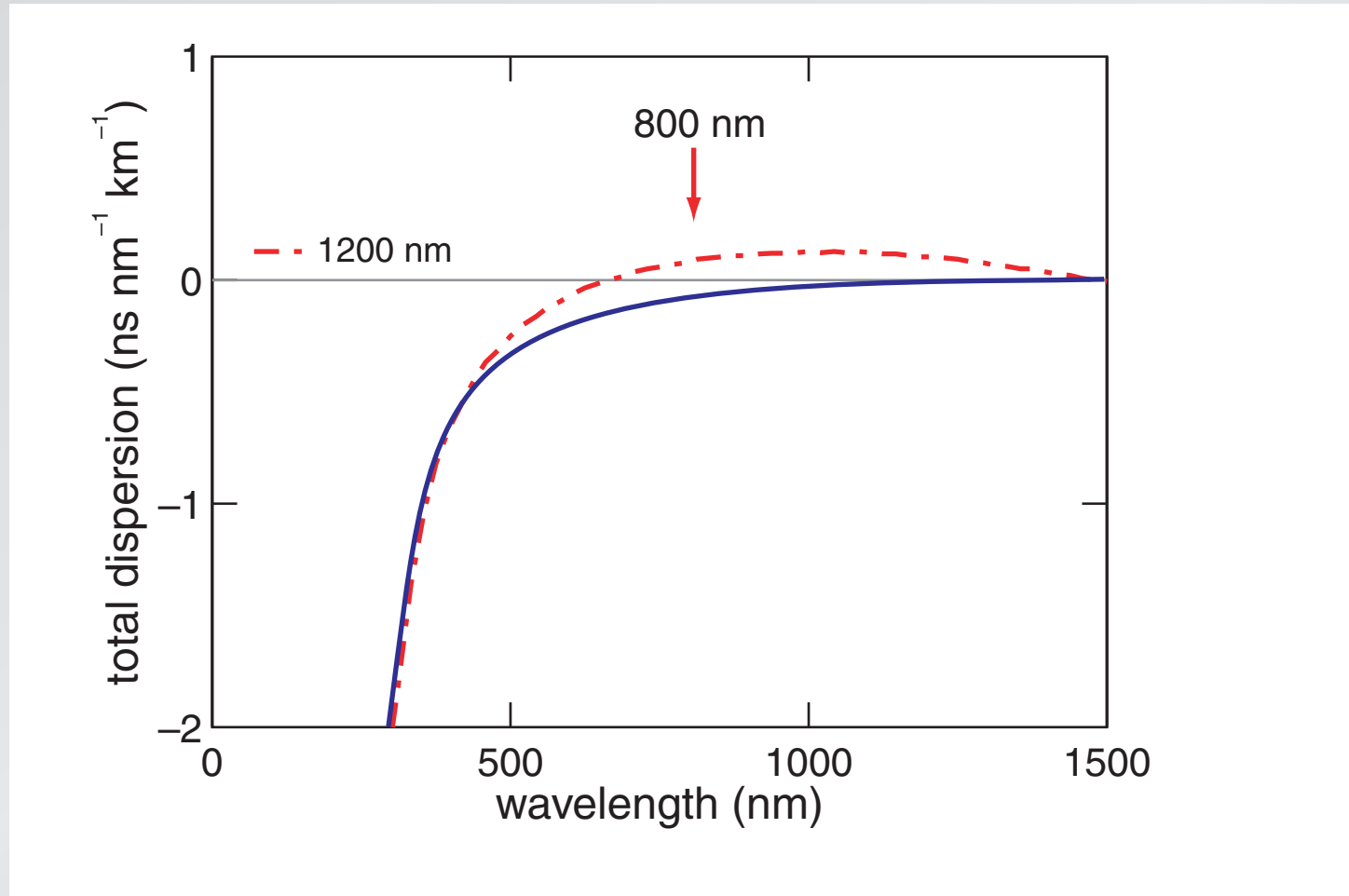
# Supercontinuum generation

## waveguide dispersion



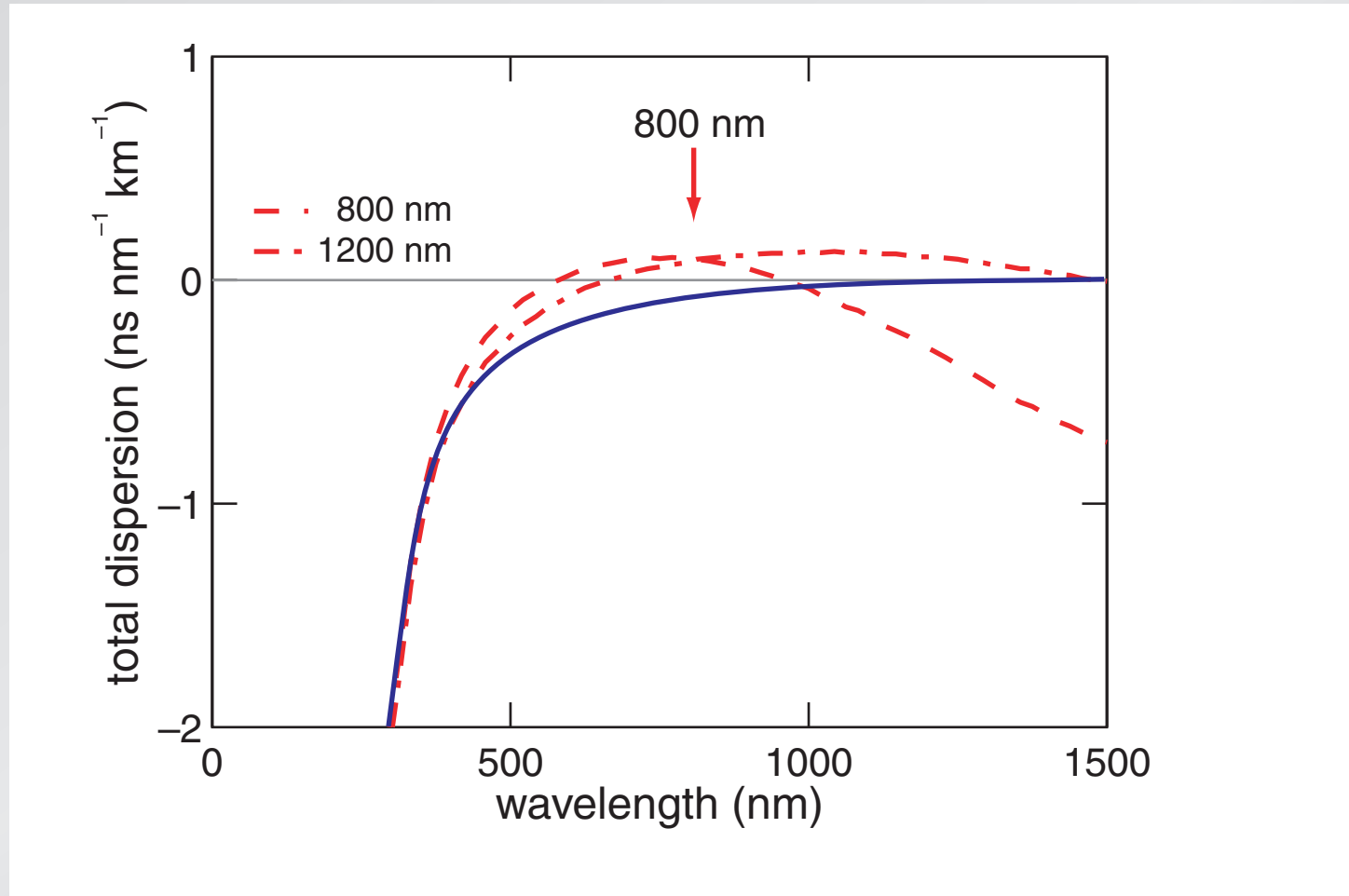
# Supercontinuum generation

## waveguide dispersion



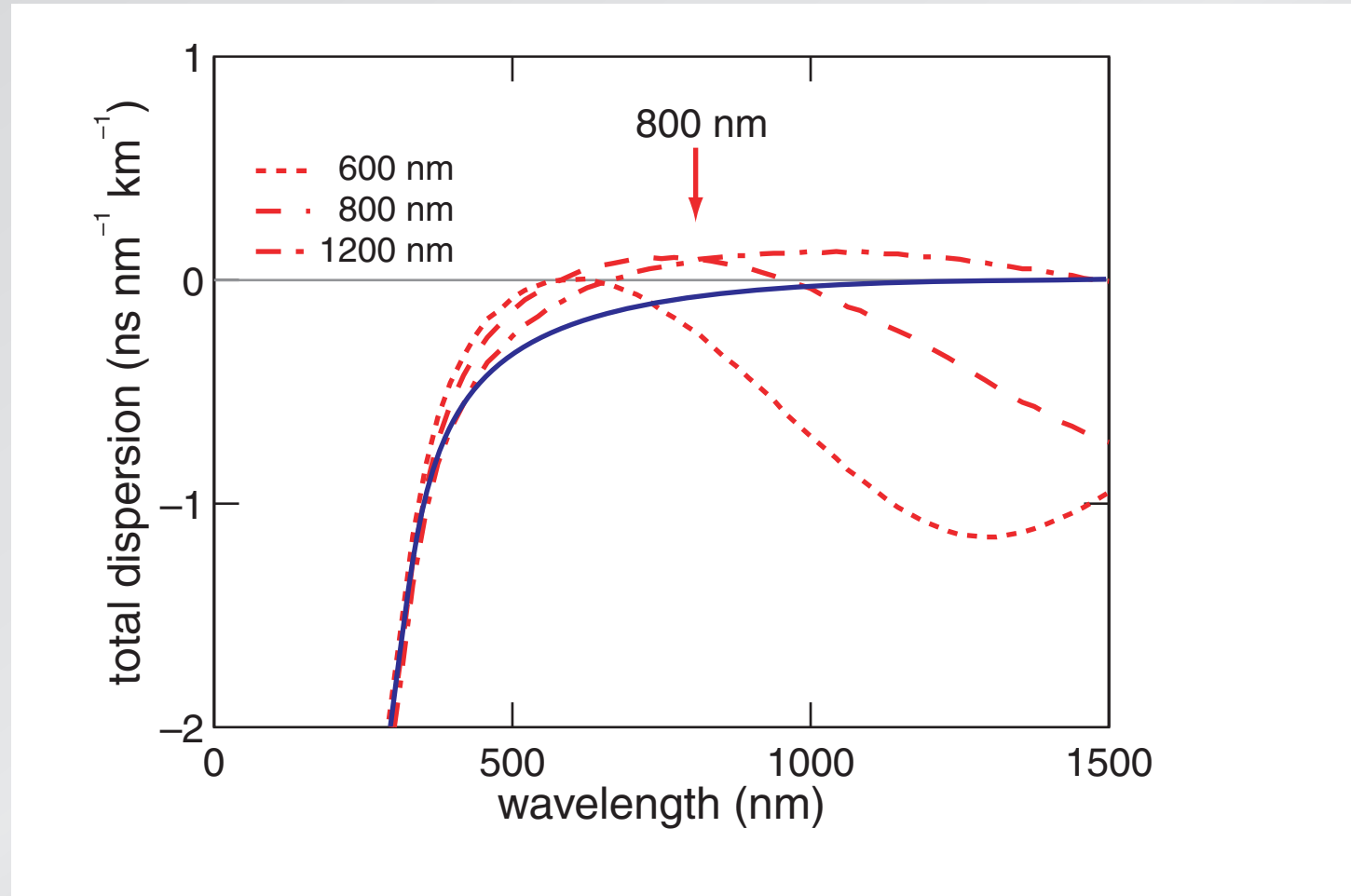
# Supercontinuum generation

## waveguide dispersion



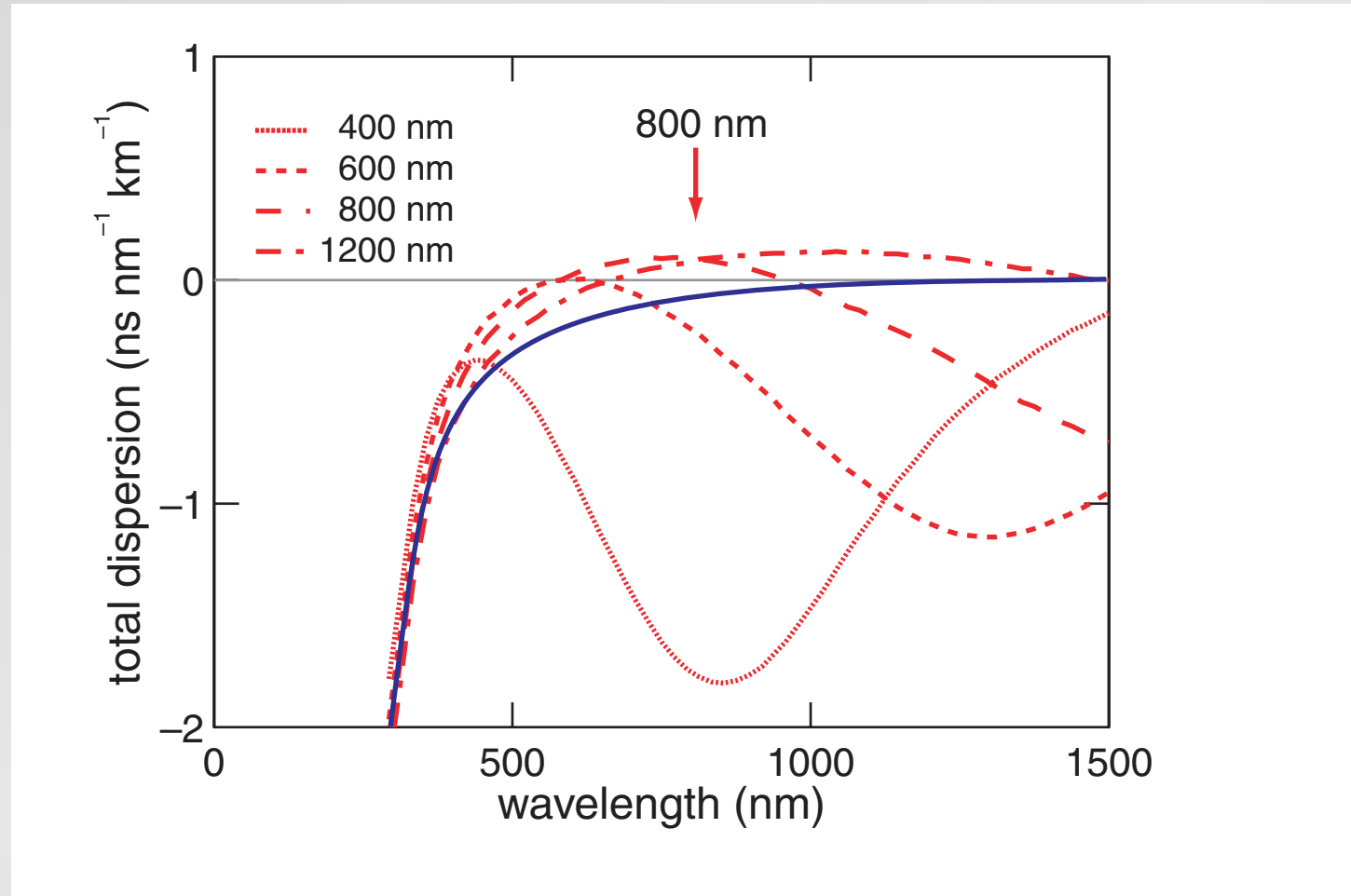
# Supercontinuum generation

## waveguide dispersion



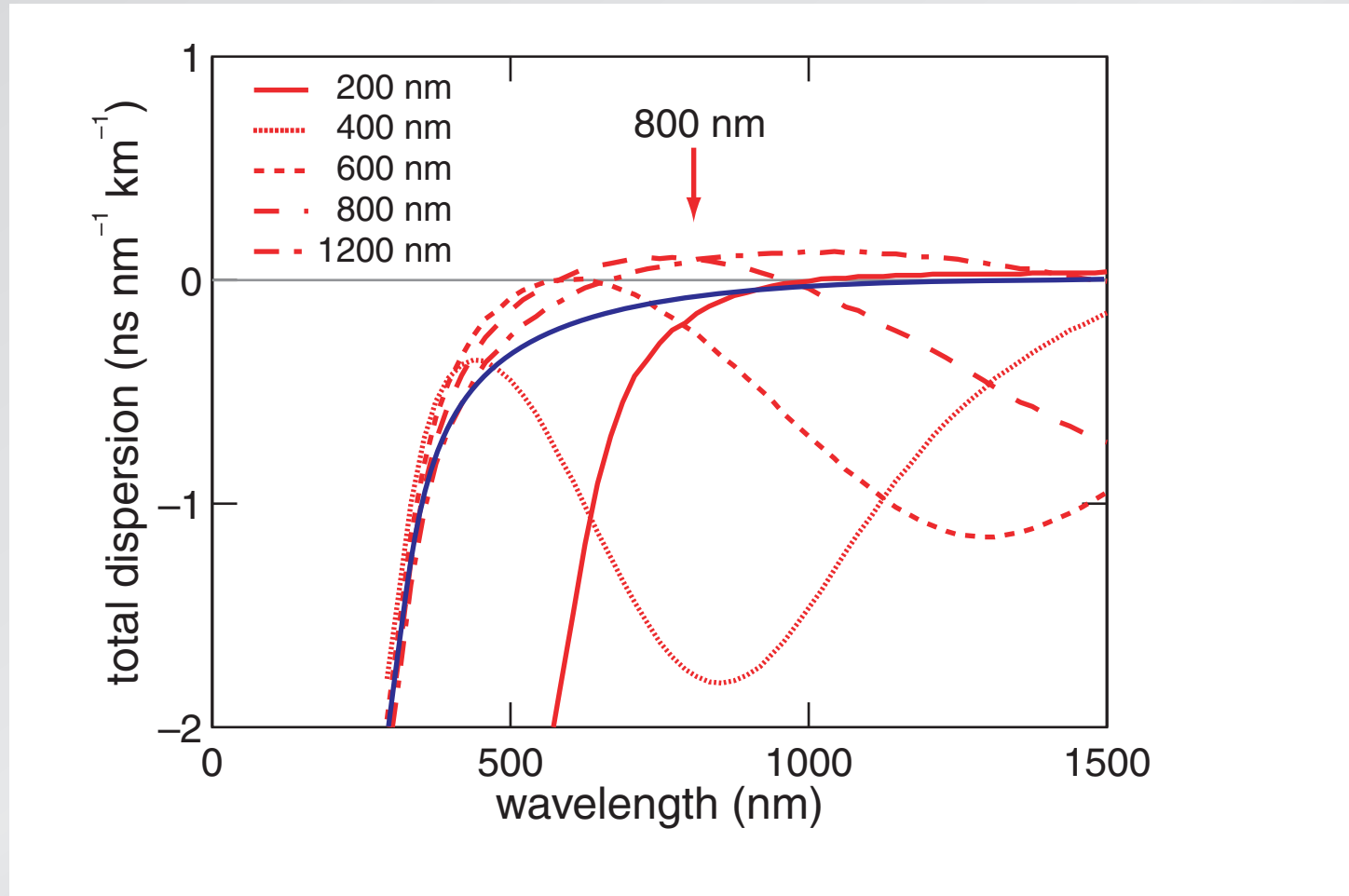
# Supercontinuum generation

## waveguide dispersion



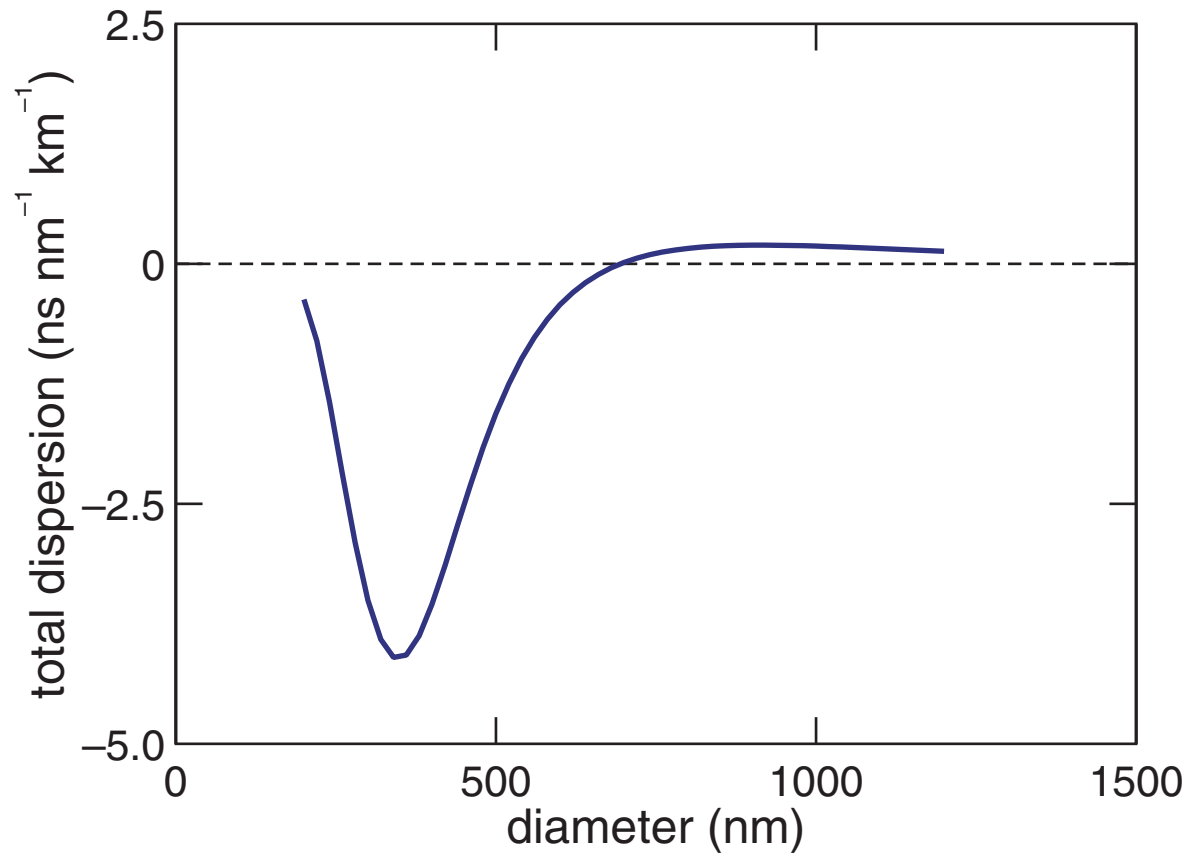
# Supercontinuum generation

## waveguide dispersion



# Supercontinuum generation

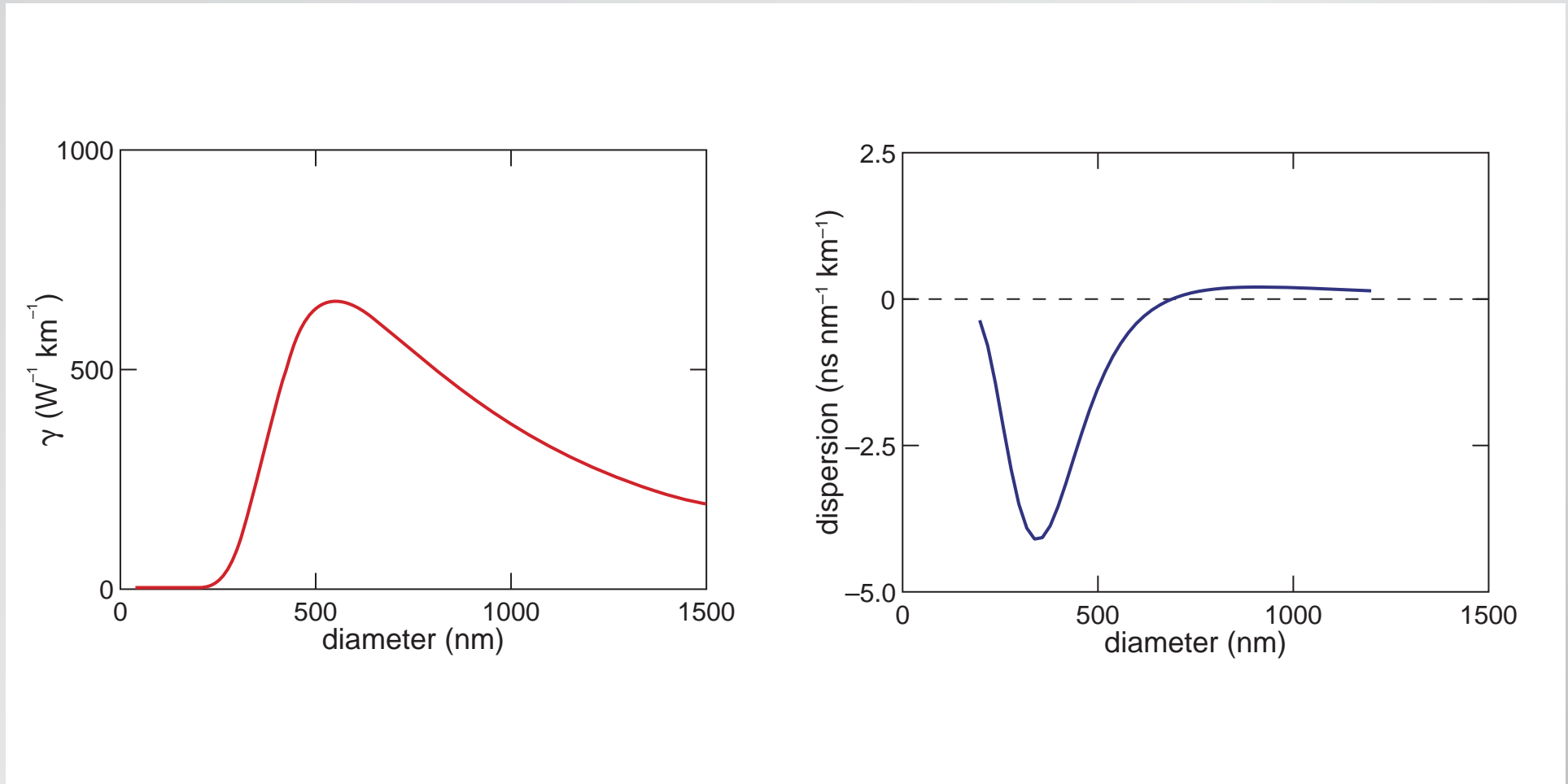
## waveguide dispersion





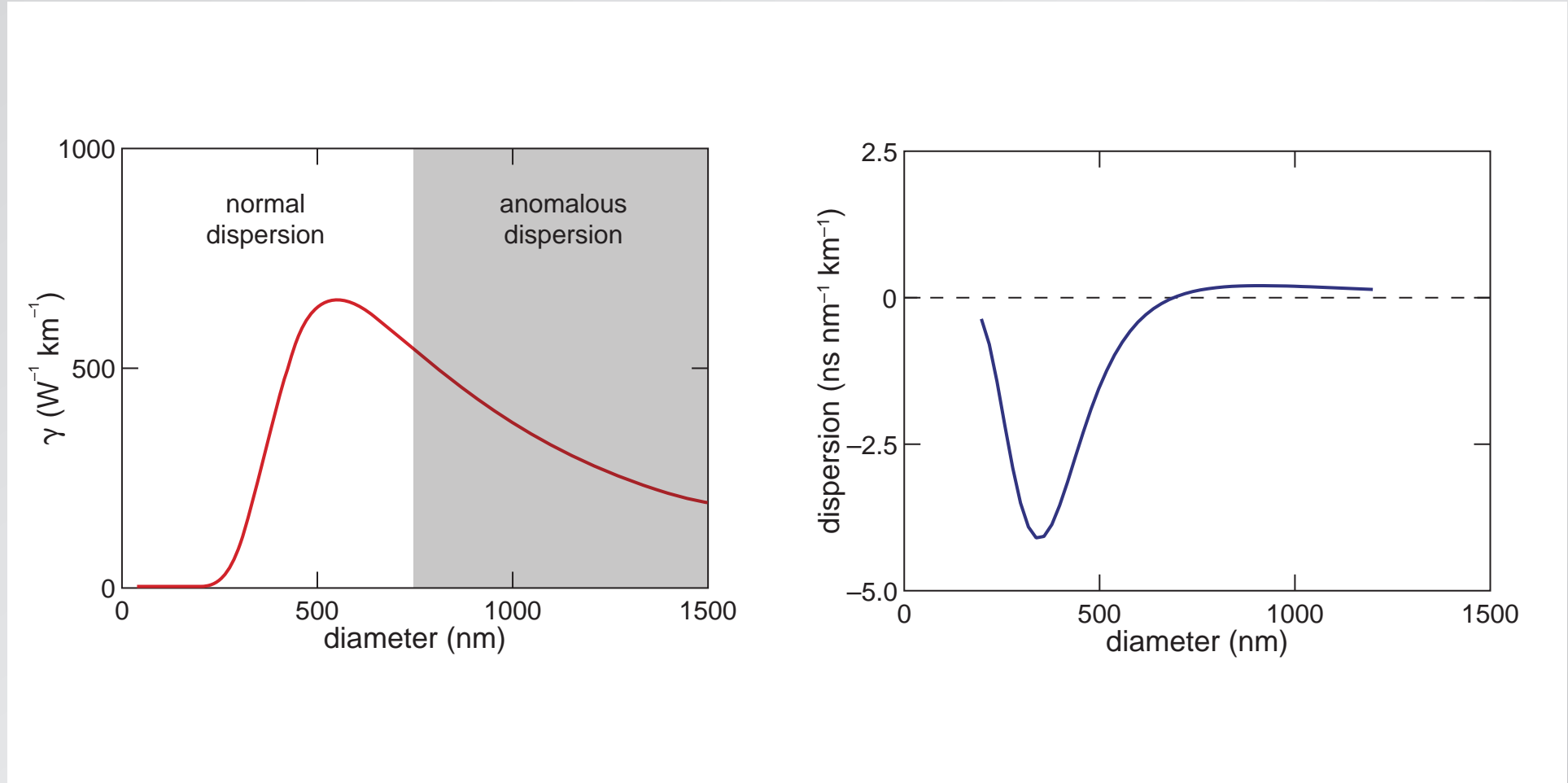
# Supercontinuum generation

## waveguide dispersion



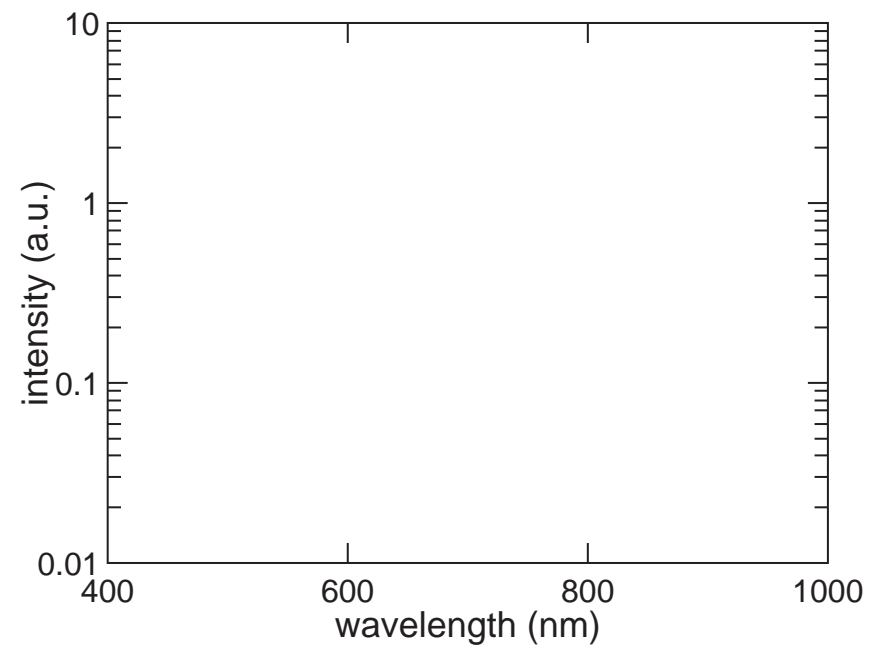
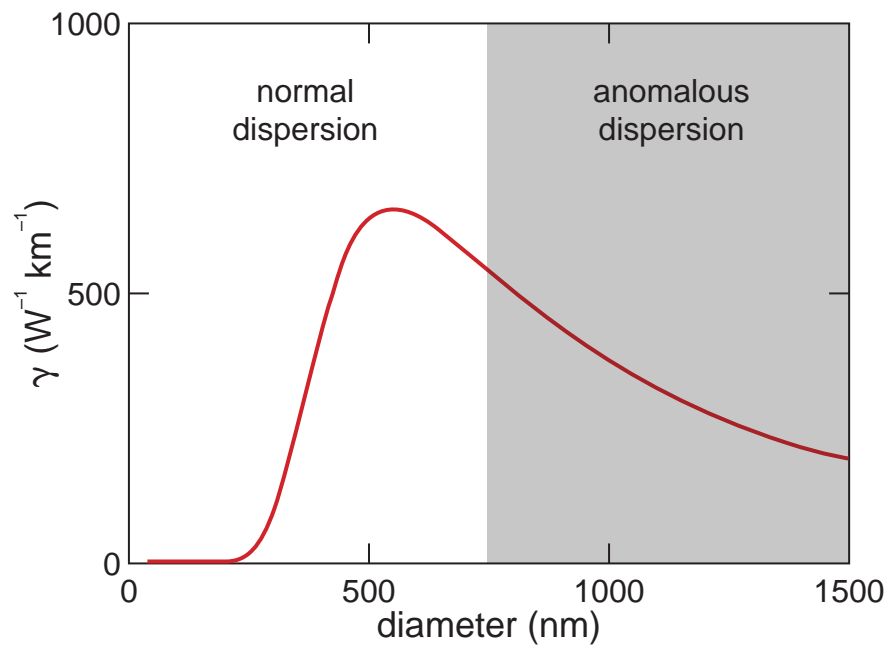
# Supercontinuum generation

## waveguide dispersion



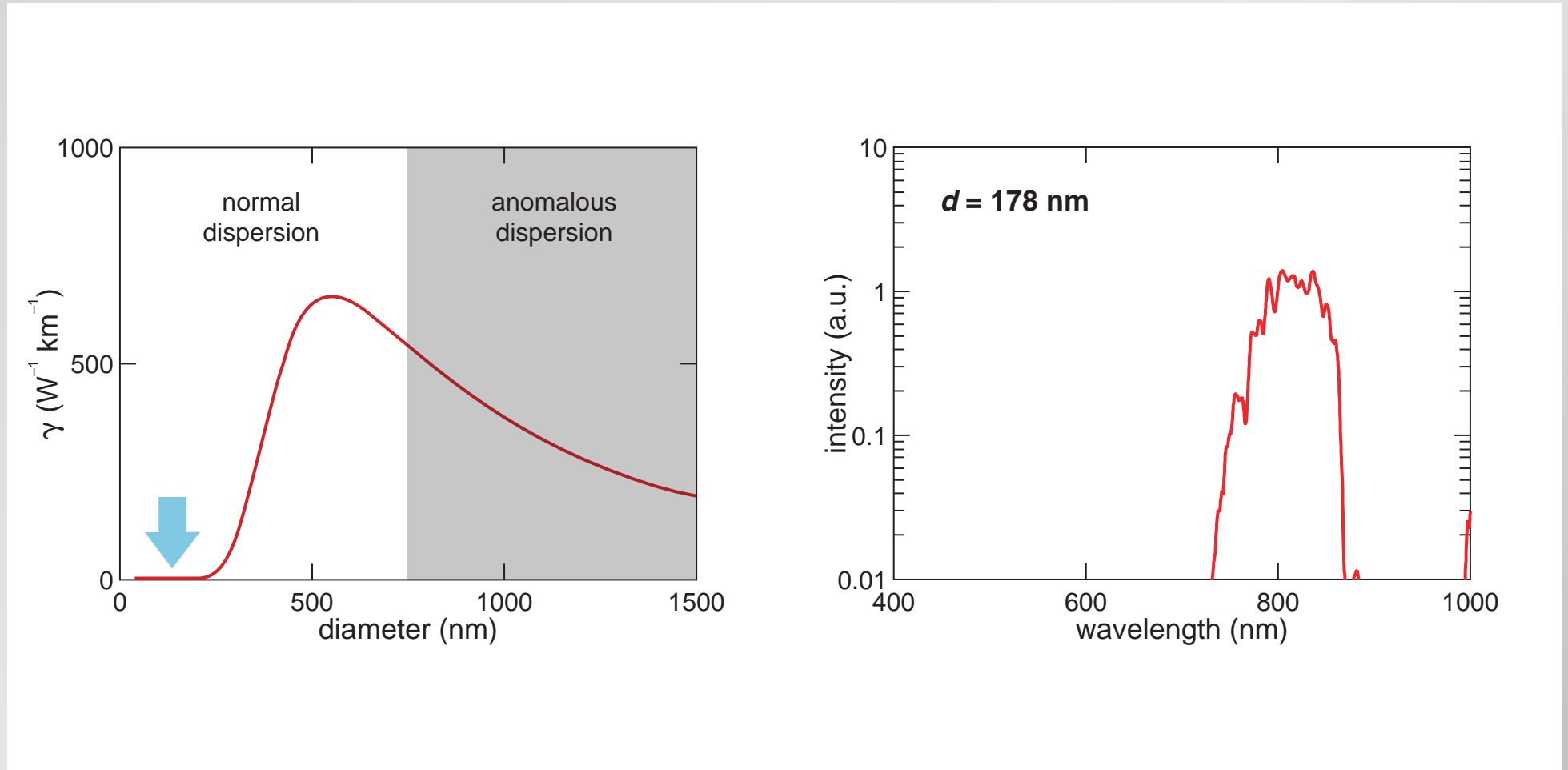
# Supercontinuum generation

## nanowire continuum generation



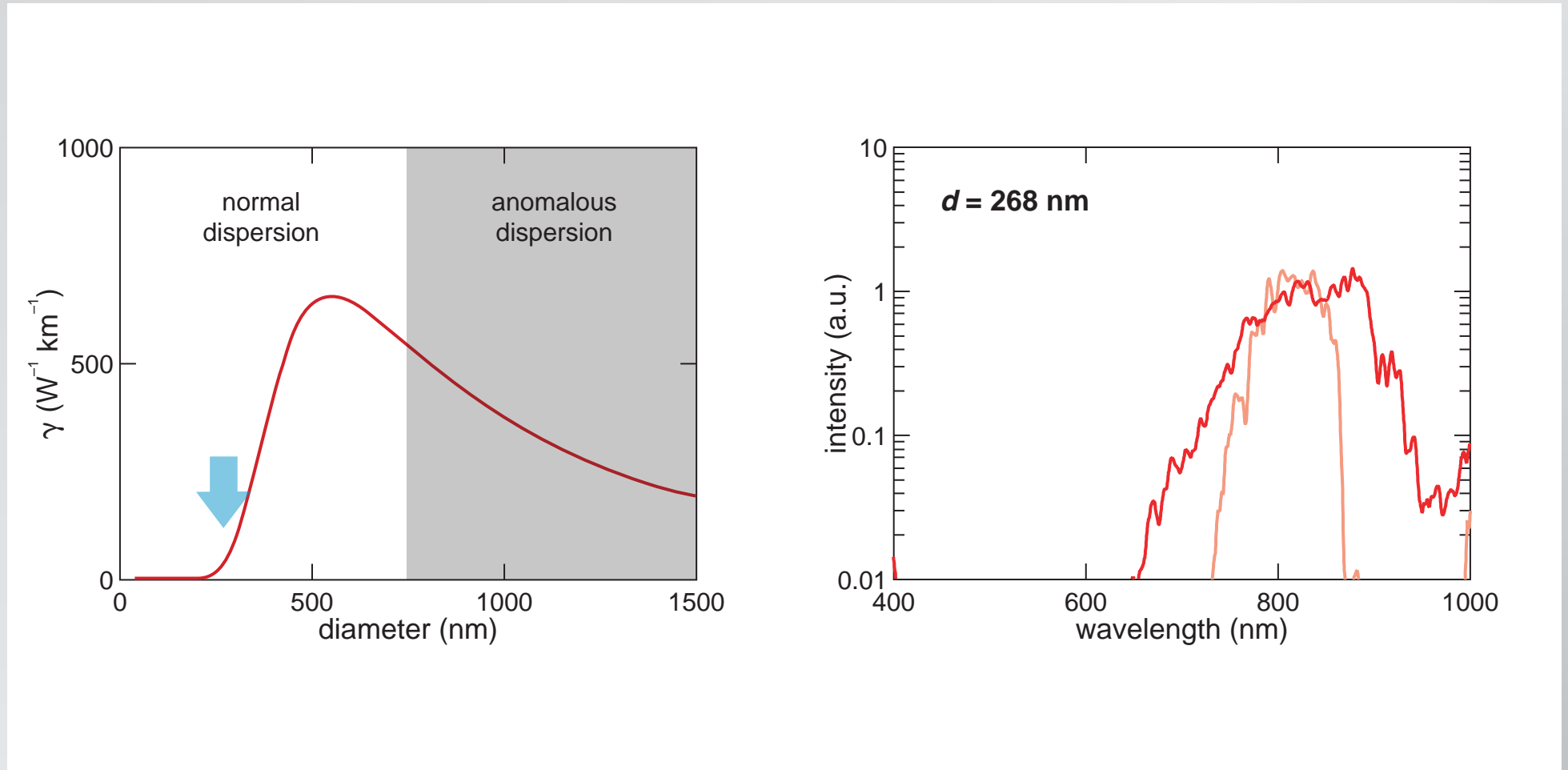
# Supercontinuum generation

## nanowire continuum generation



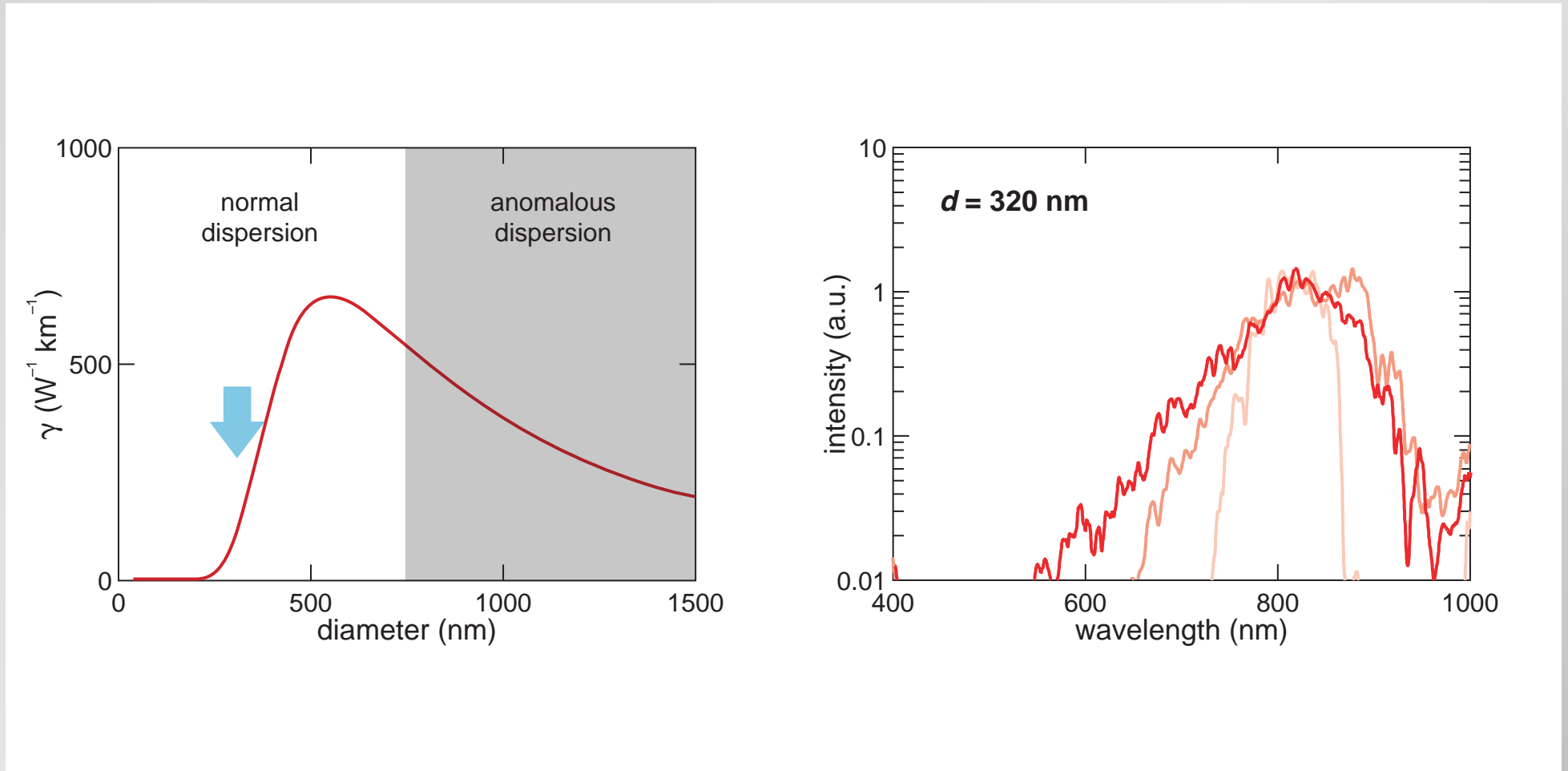
# Supercontinuum generation

## nanowire continuum generation



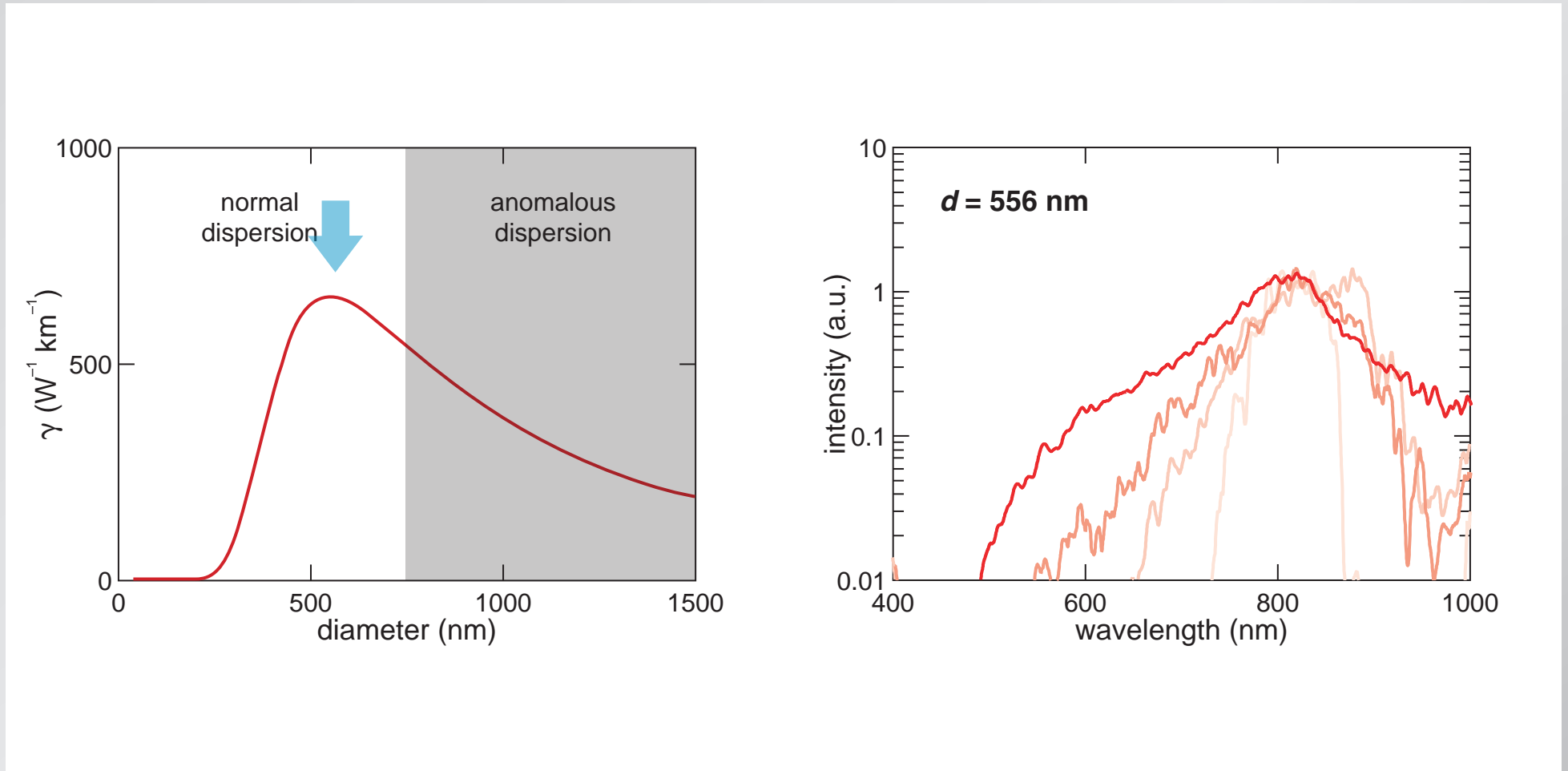
# Supercontinuum generation

## nanowire continuum generation



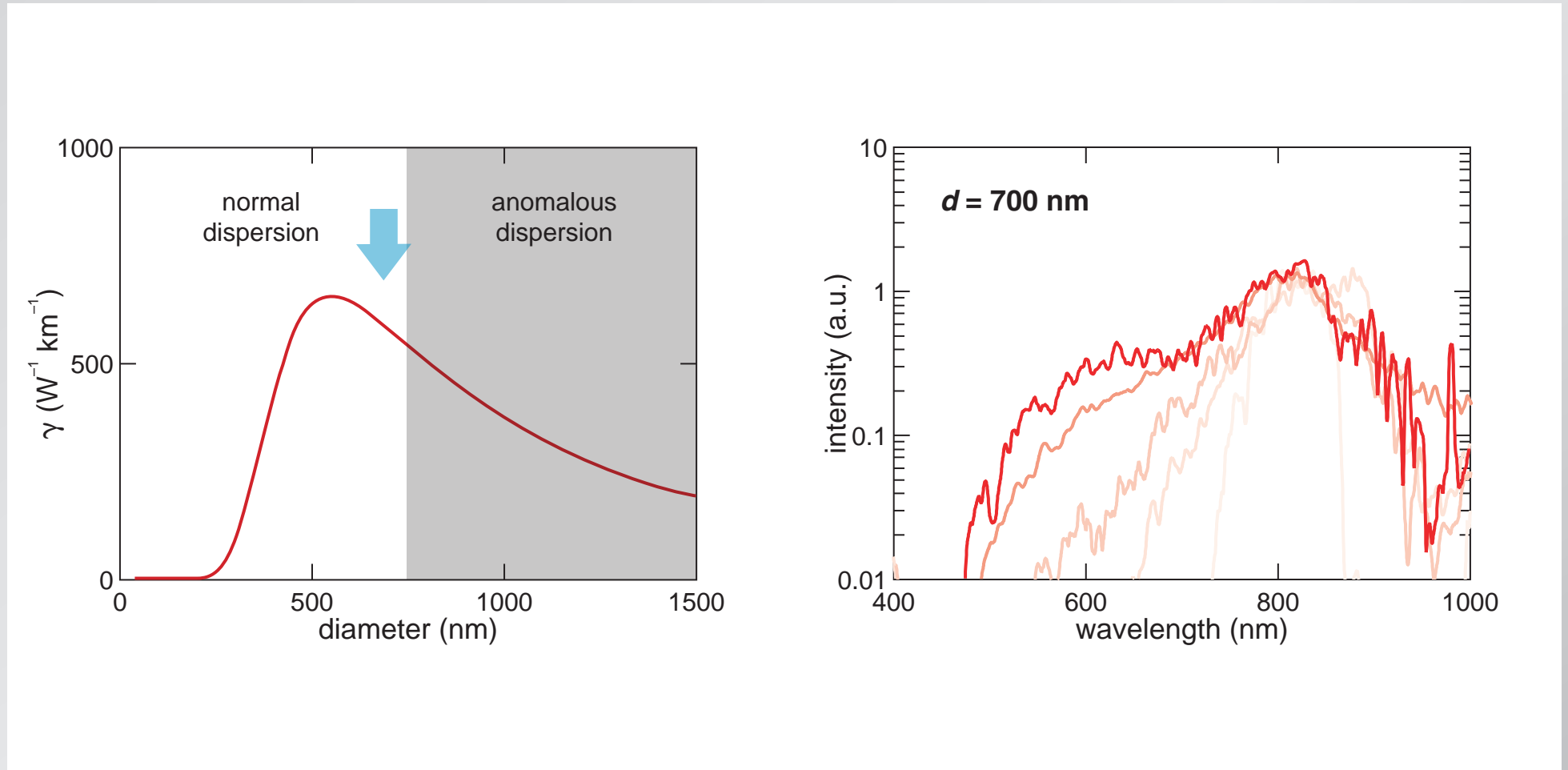
# Supercontinuum generation

## nanowire continuum generation



# Supercontinuum generation

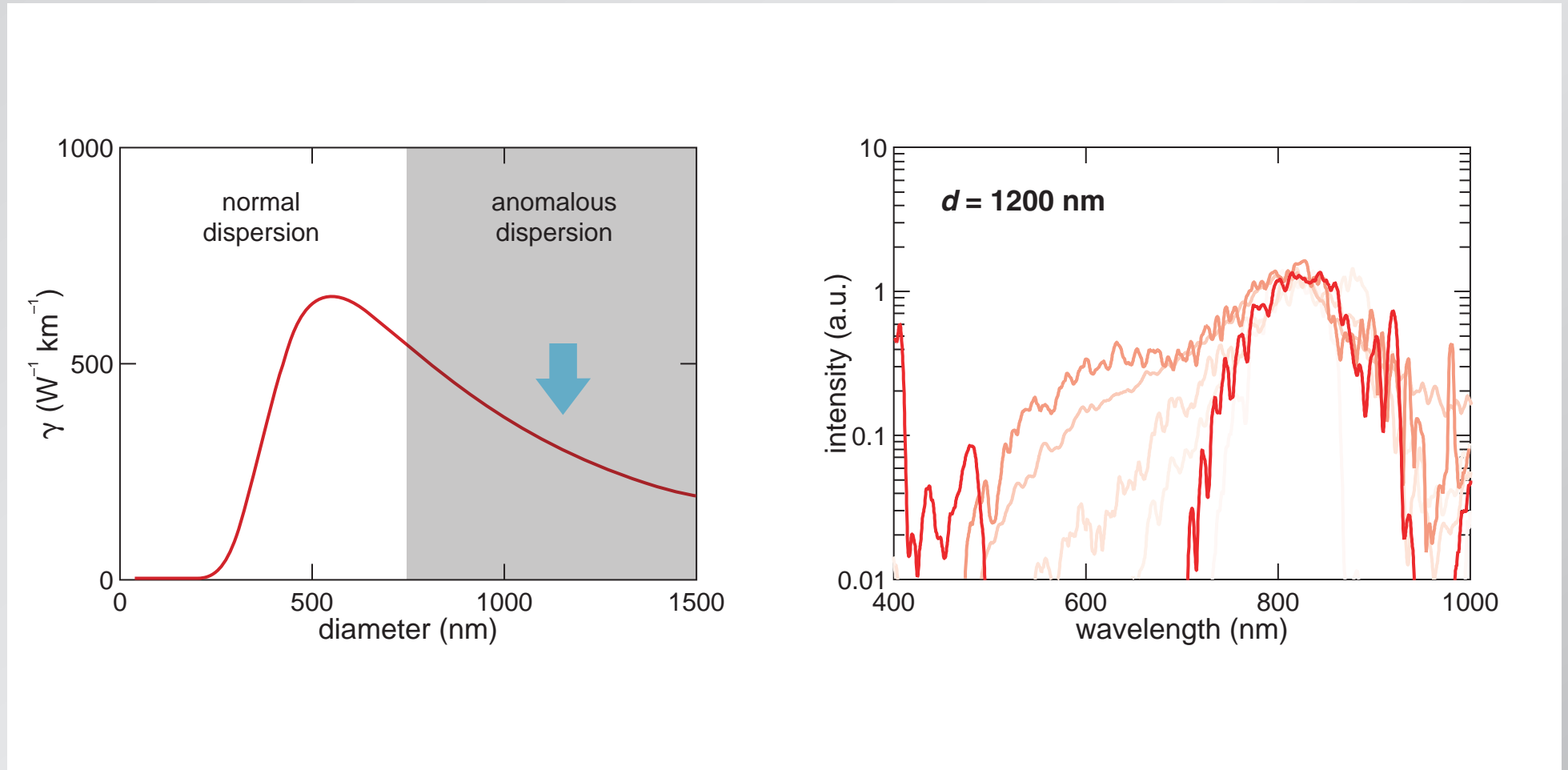
## nanowire continuum generation





# Supercontinuum generation

## nanowire continuum generation



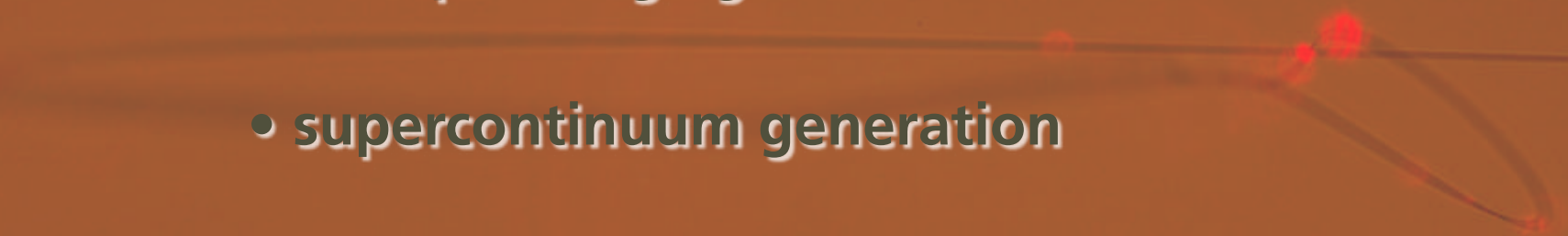
# Supercontinuum generation

energy in nanowire  $< 100$  pJ!

# Supercontinuum generation

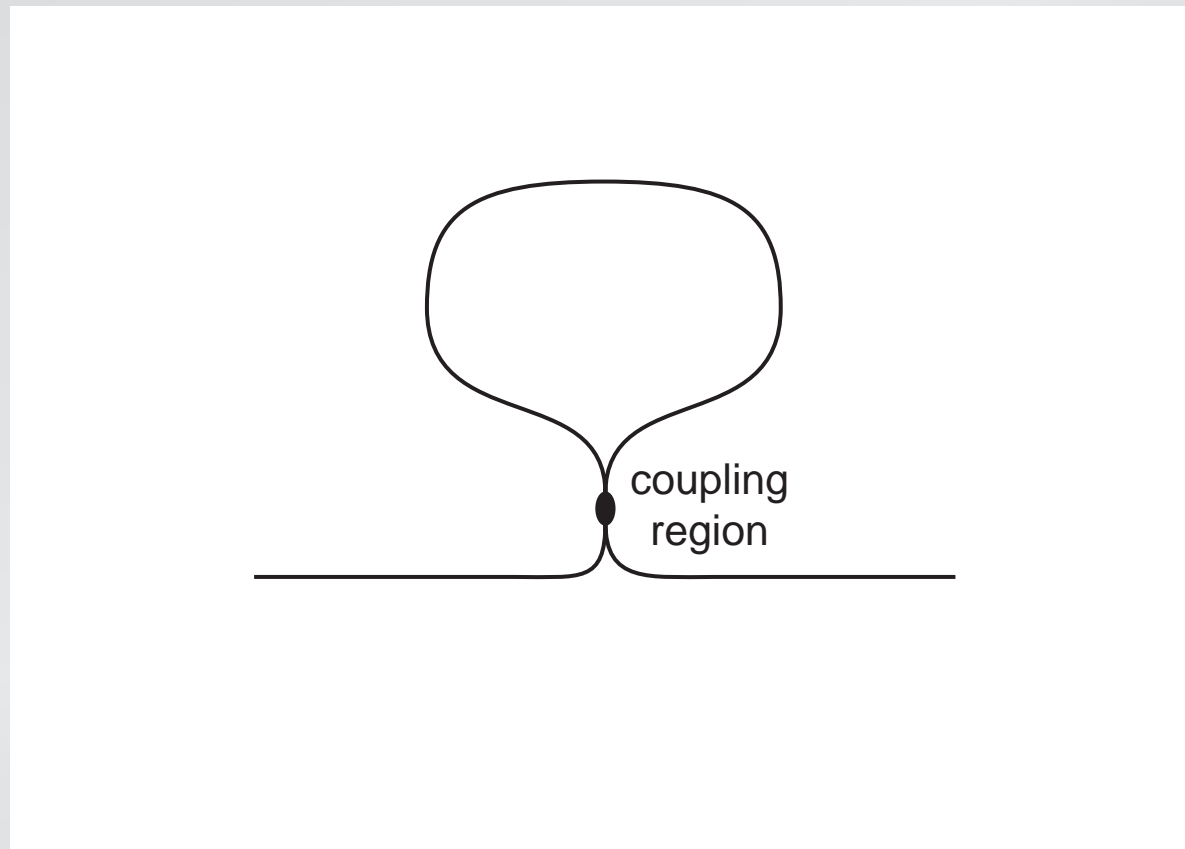
- picjoule nonlinear optics
- optimum diameter for silica 500–600 nm
- low dispersion

# Outline

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

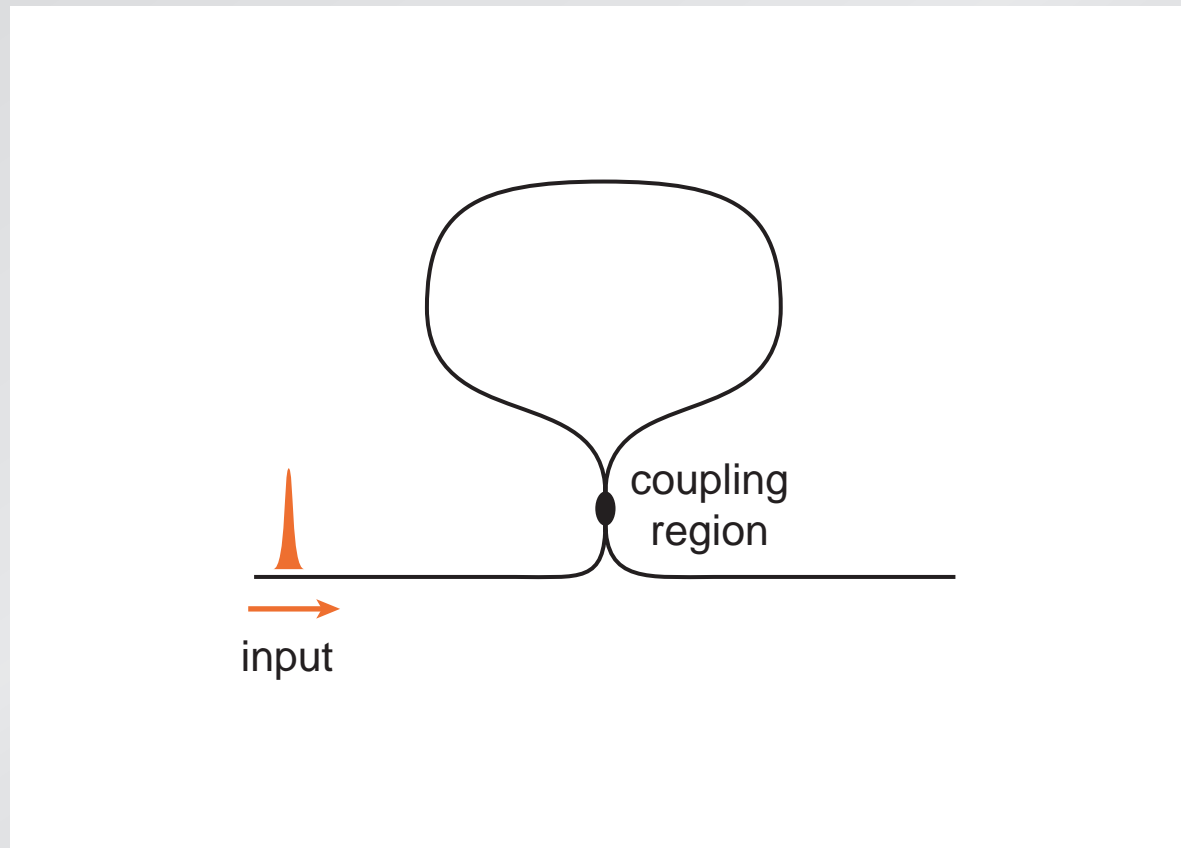
# Optical logic gates

nanowire Sagnac interferometer



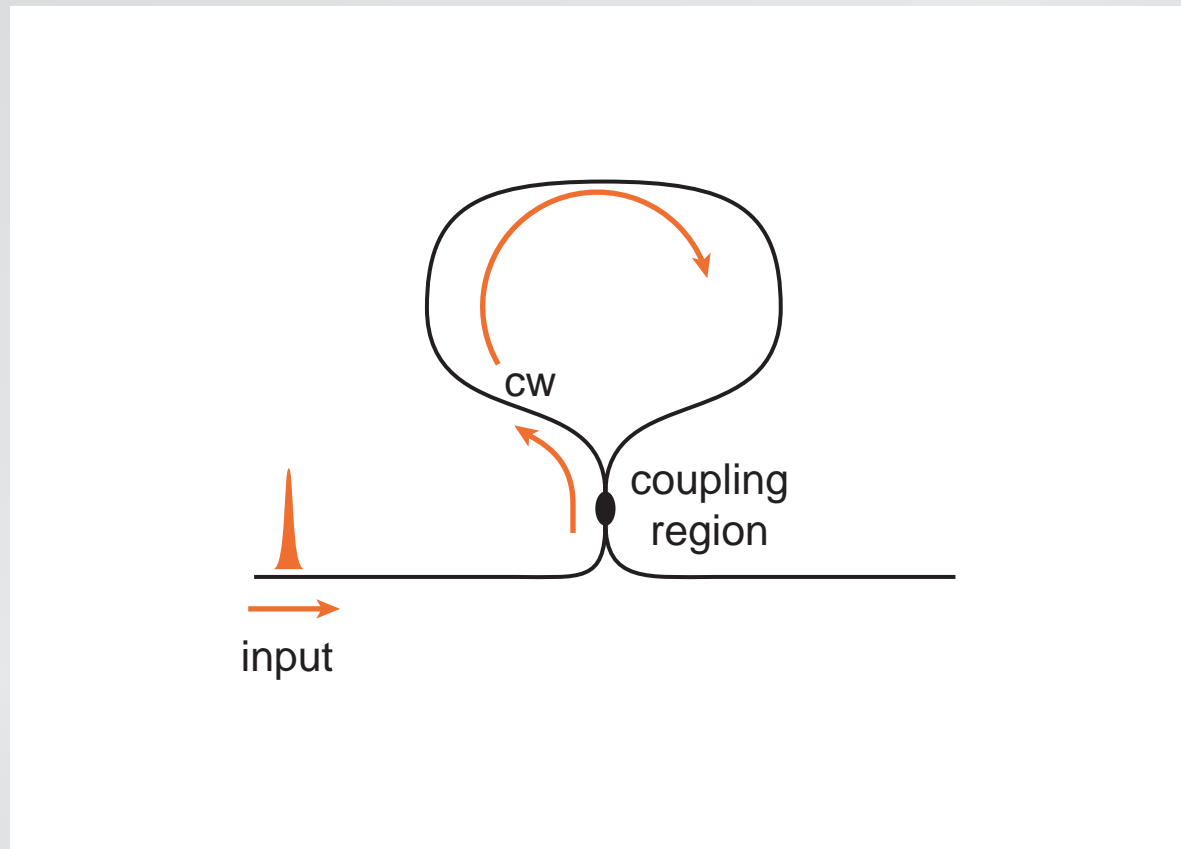
# Optical logic gates

## nanowire Sagnac interferometer



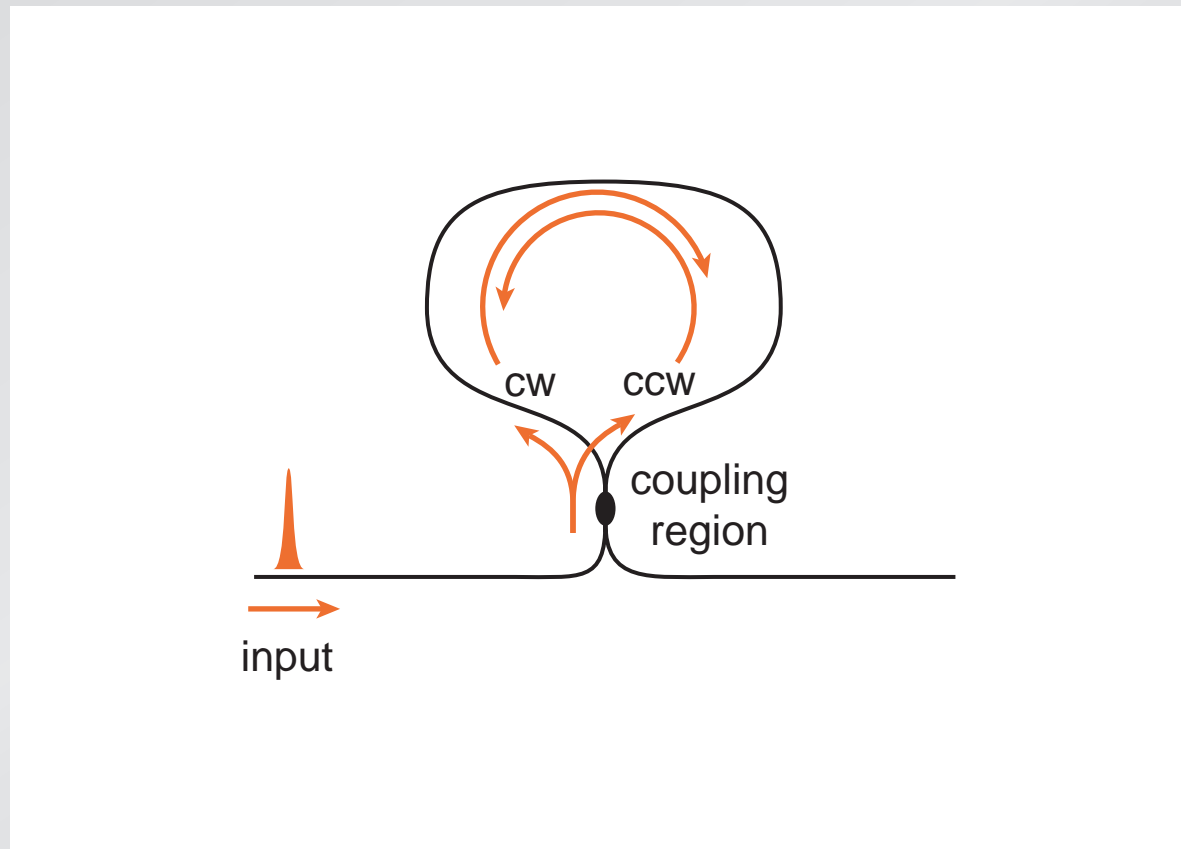
# Optical logic gates

## nanowire Sagnac interferometer



# Optical logic gates

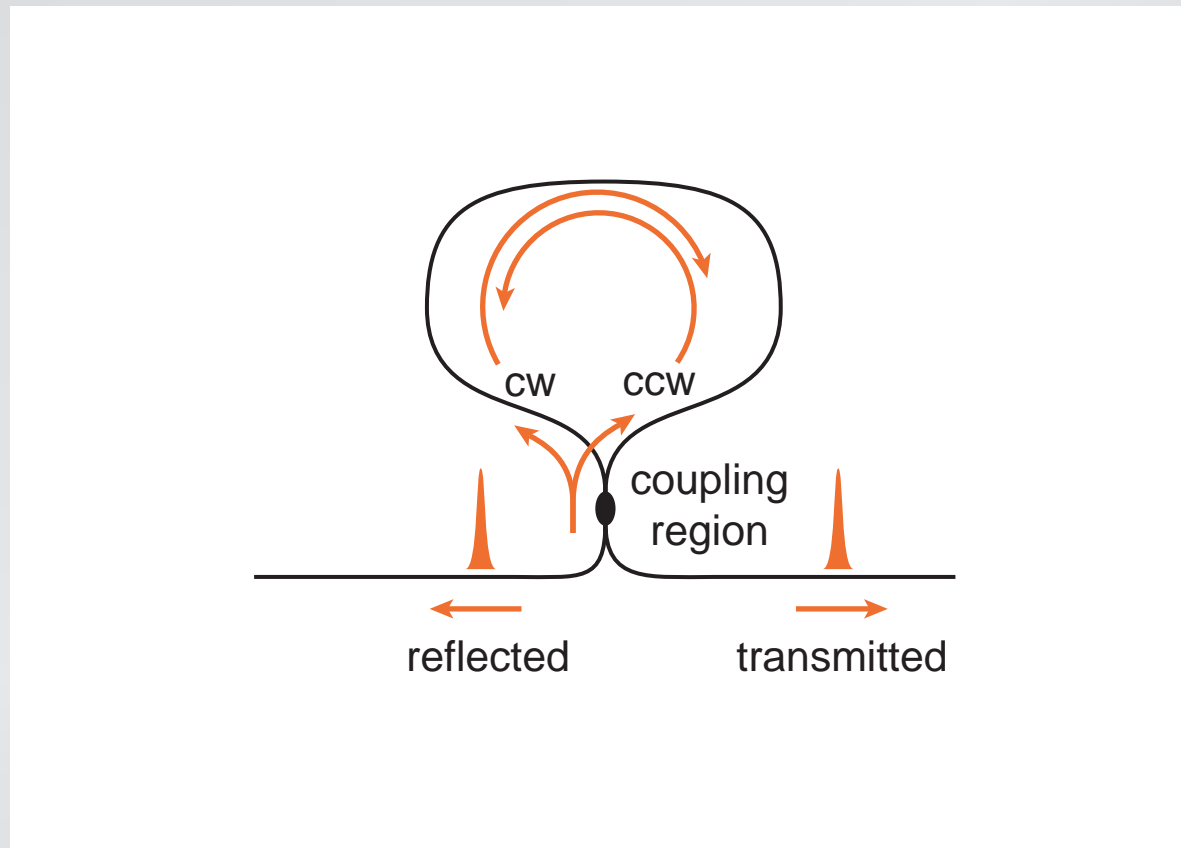
## nanowire Sagnac interferometer





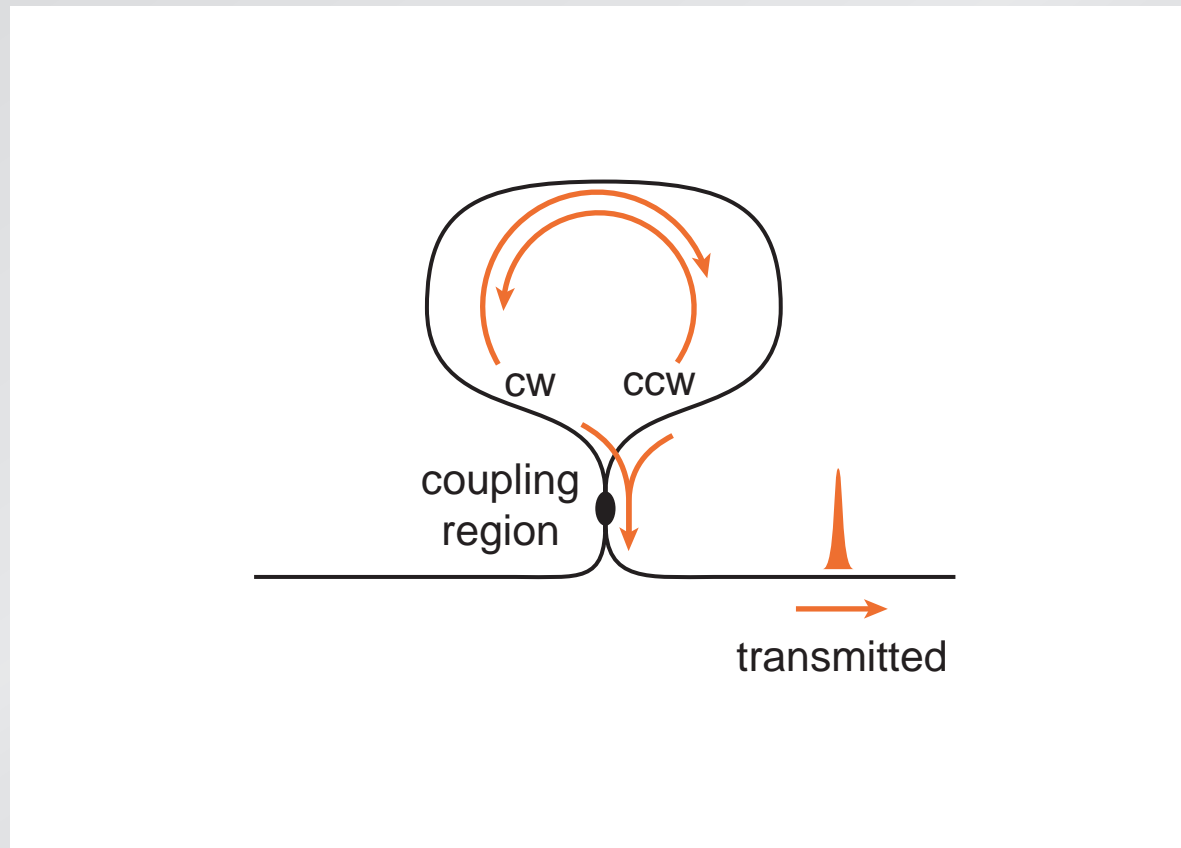
# Optical logic gates

## nanowire Sagnac interferometer



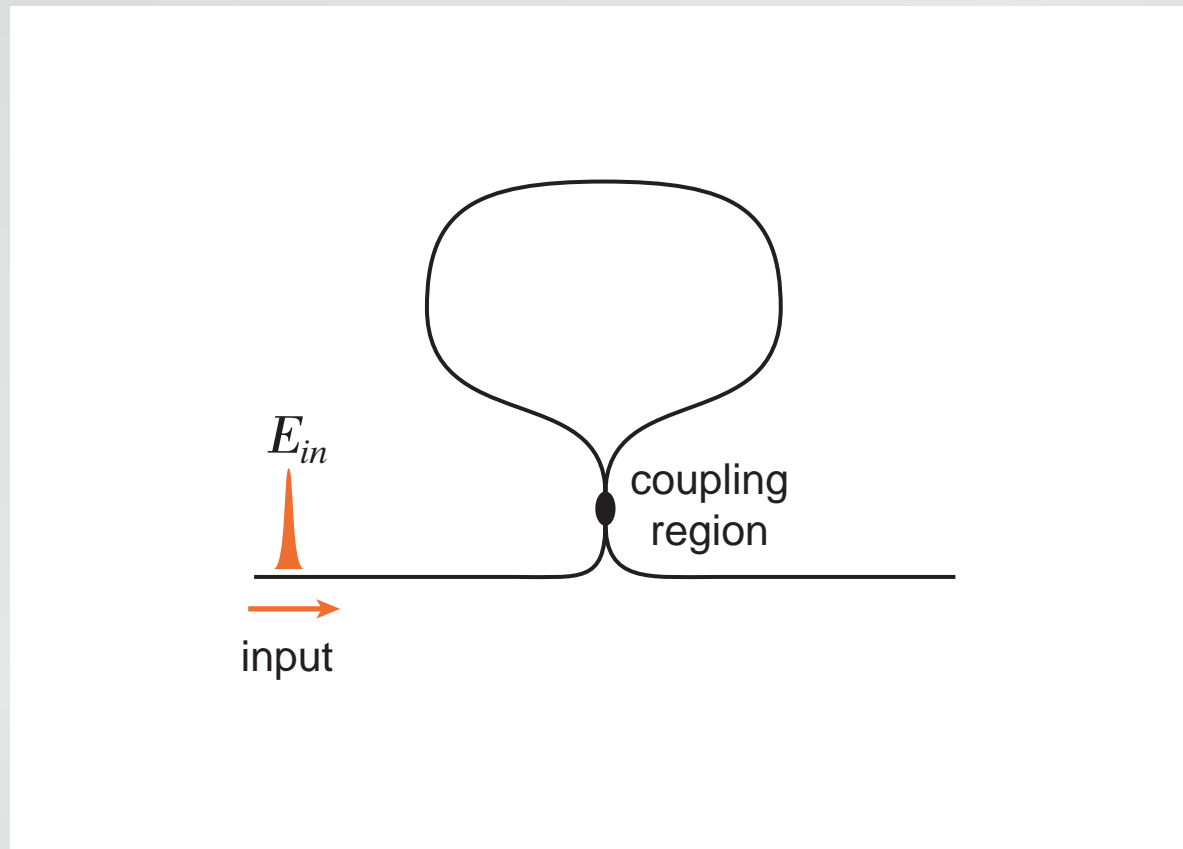
# Optical logic gates

output = transmitted cw + ccw power



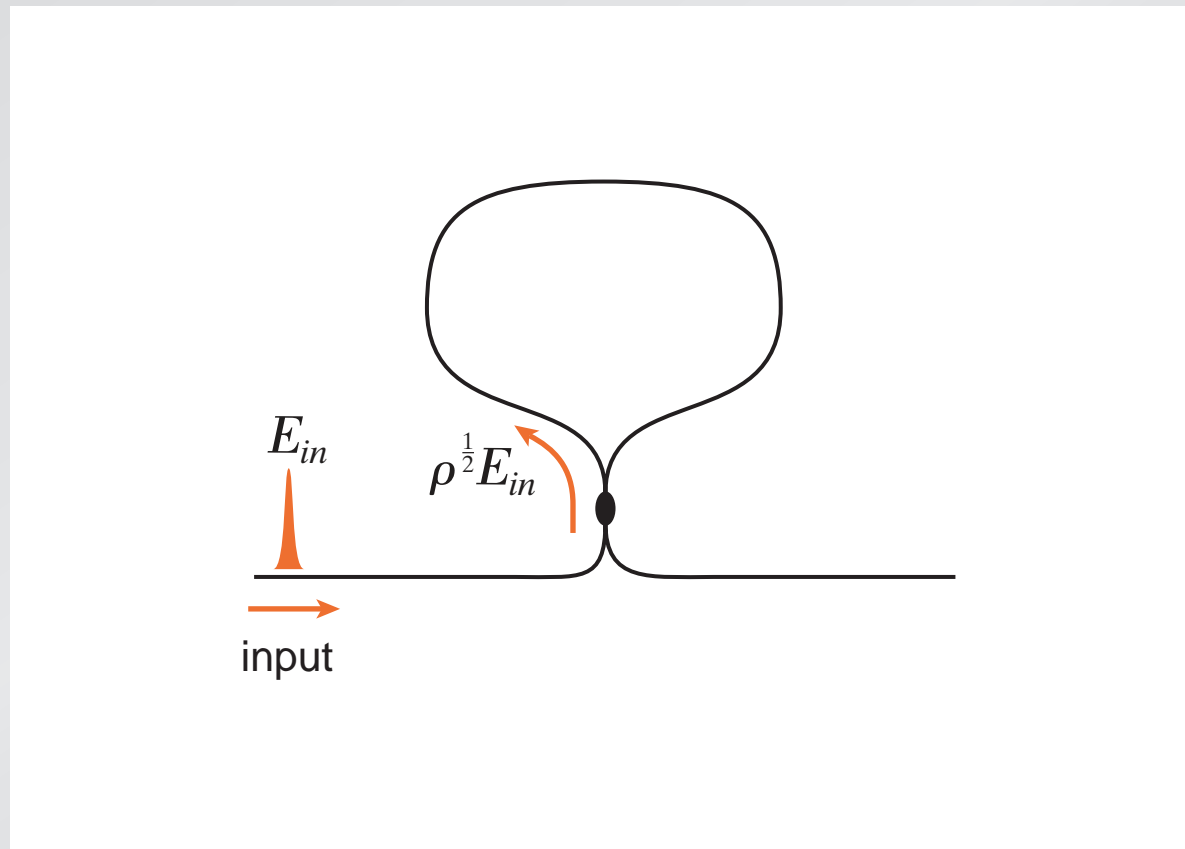
# Optical logic gates

input electric field amplitude  $E_{in}$



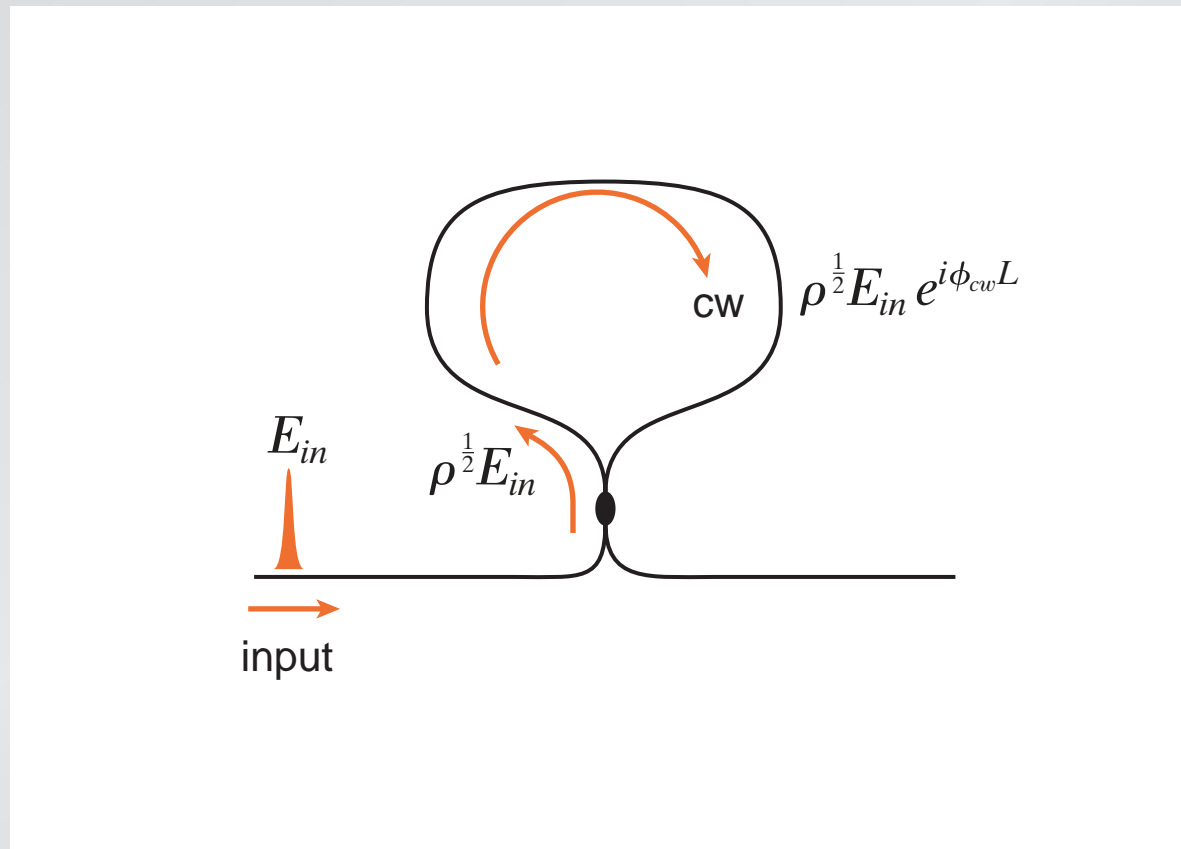
# Optical logic gates

coupling parameter:  $\rho$



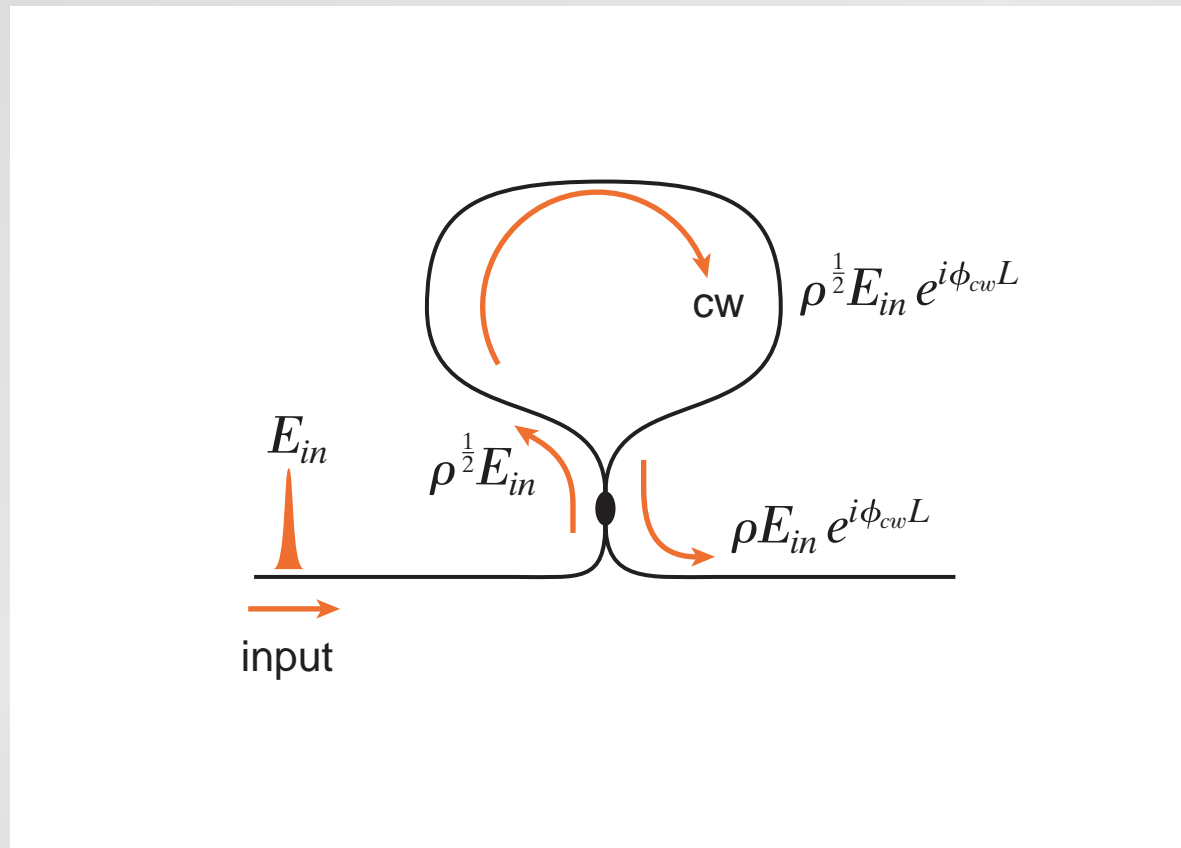
# Optical logic gates

phase accumulation over path length of loop  $L$



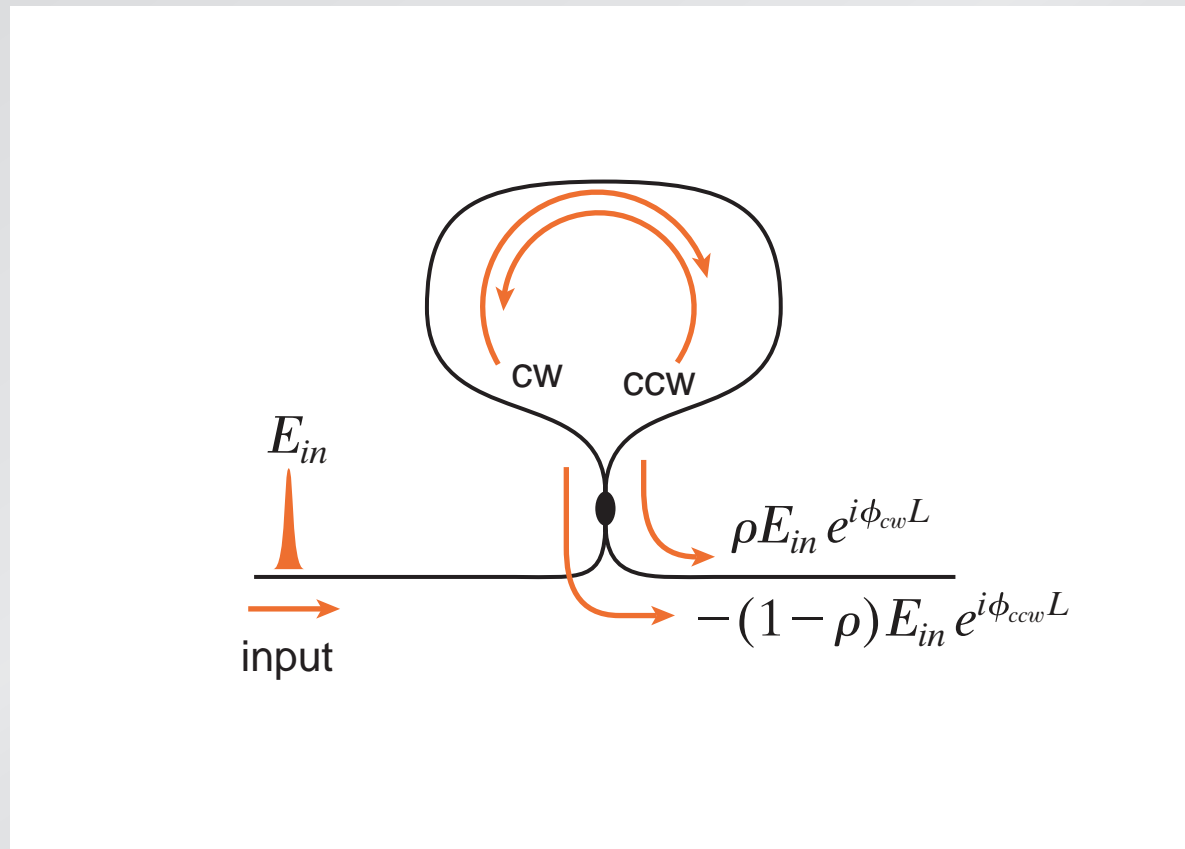
# Optical logic gates

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

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**for 50-50 coupler:**

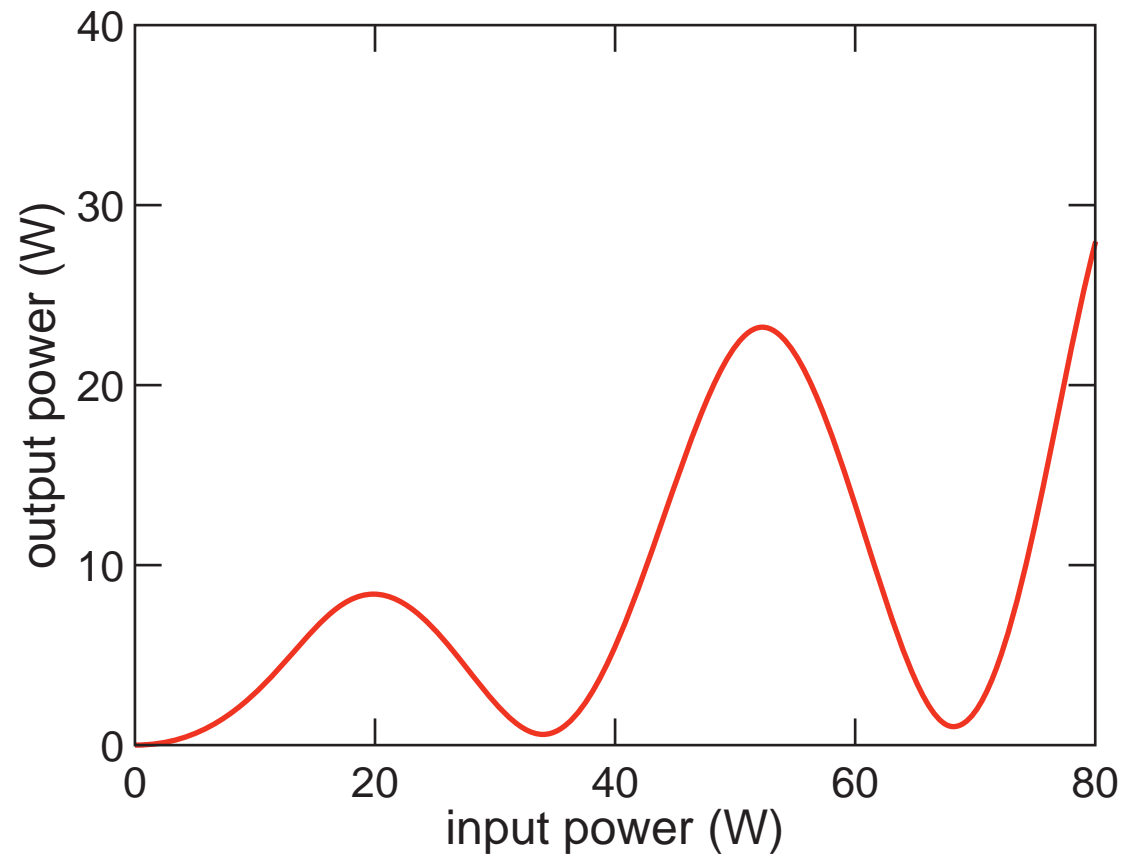
$$\rho = 0.5$$

**no transmission:**

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

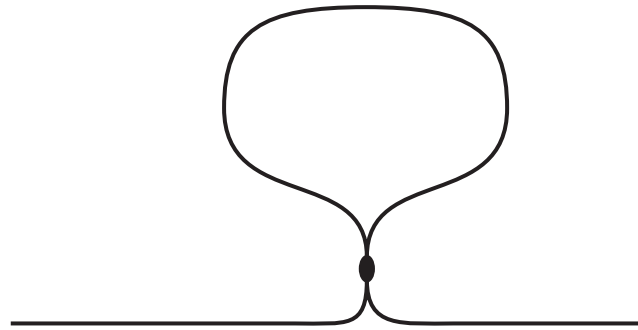
# Optical logic gates

when  $\rho \neq 0.5$ :



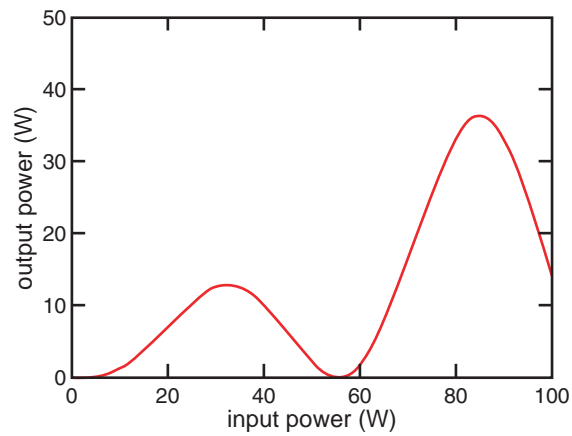
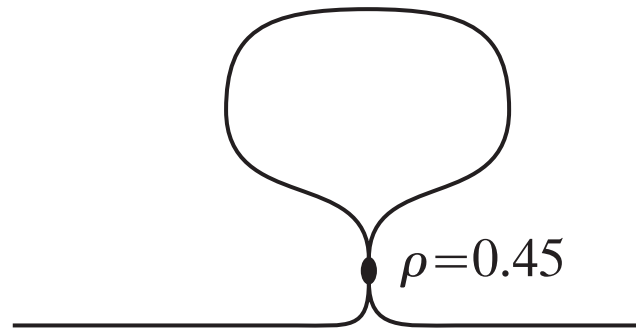
# Optical logic gates

nonlinear nanogate



# Optical logic gates

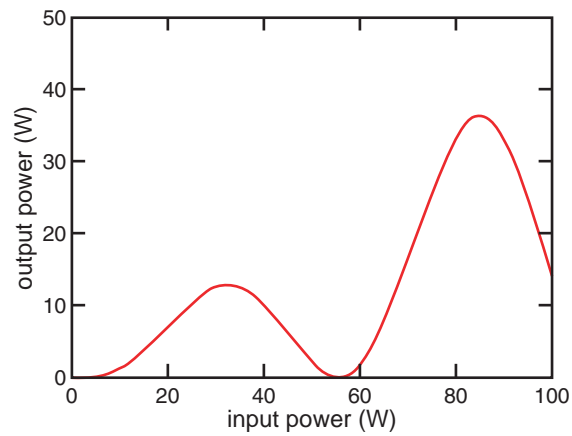
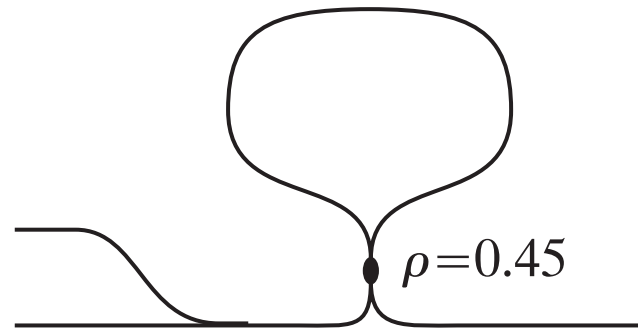
## nonlinear nanogate





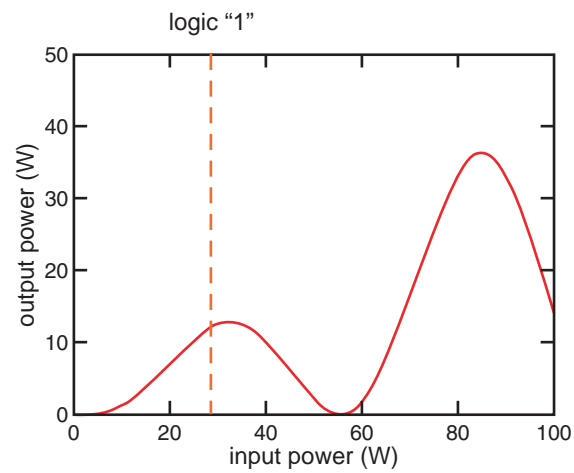
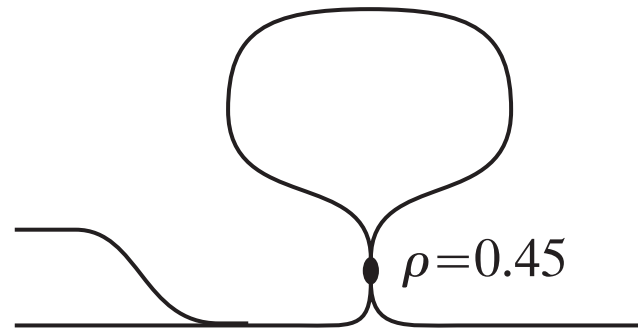
# Optical logic gates

## nonlinear nanogate



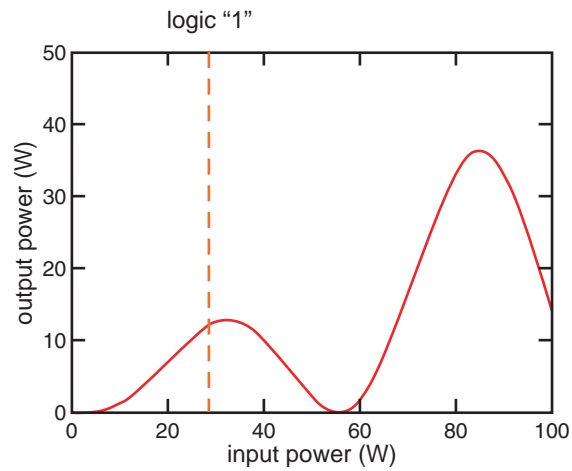
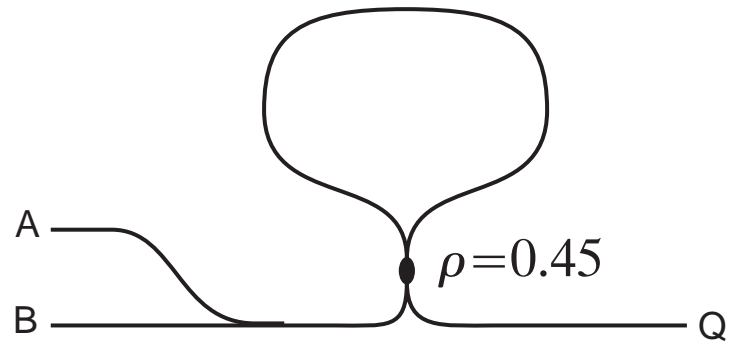
# Optical logic gates

## nonlinear nanogate



# Optical logic gates

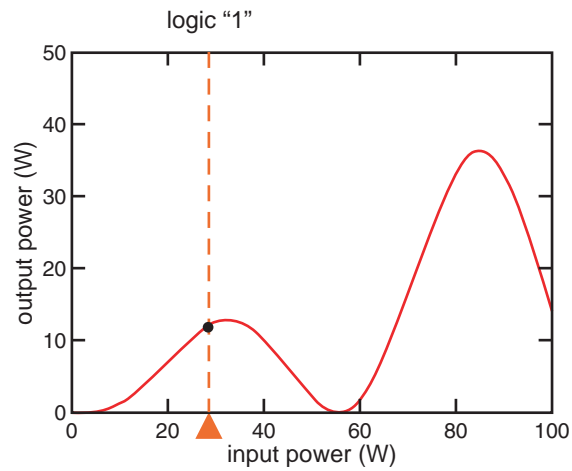
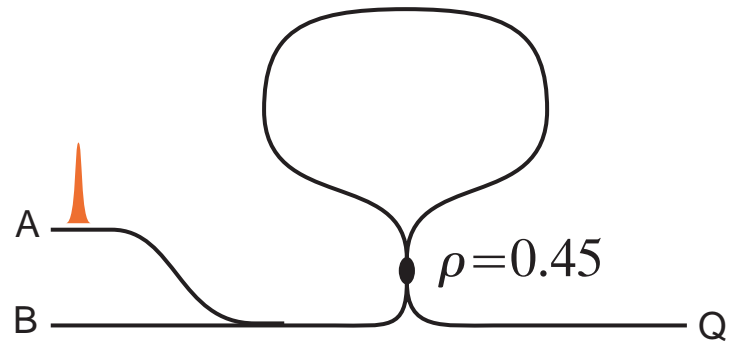
## nonlinear nanogate



A	B	Q
0	0	0

# Optical logic gates

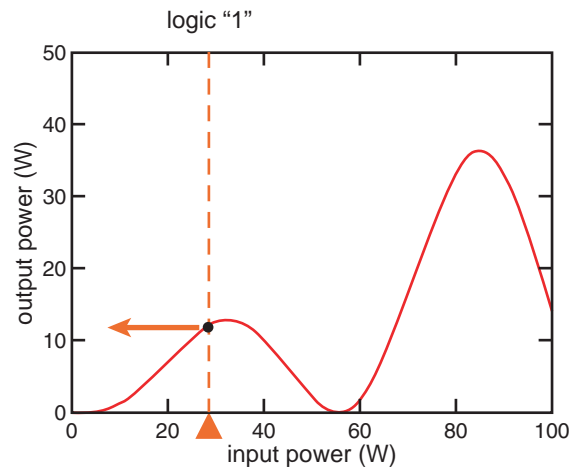
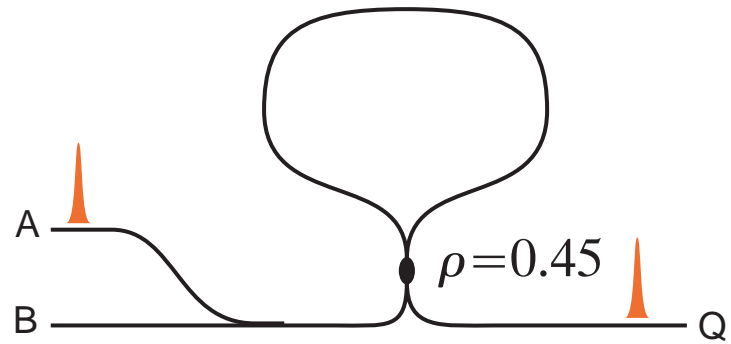
## nonlinear nanogate



A	B	Q
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# Optical logic gates

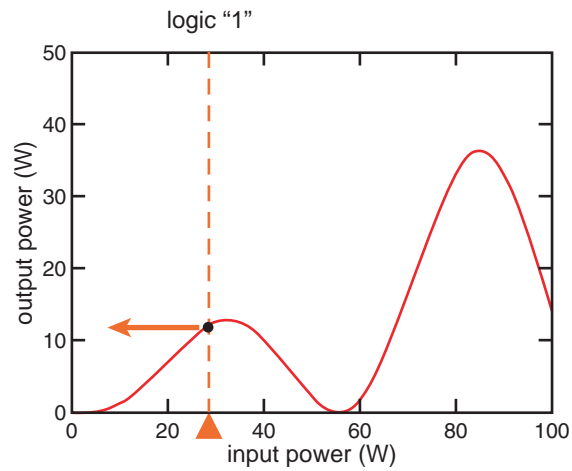
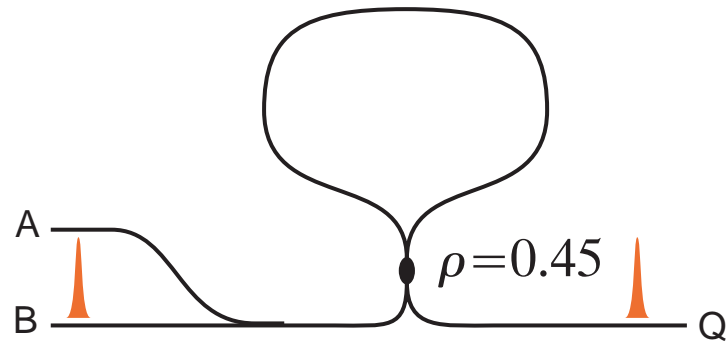
## nonlinear nanogate



A	B	Q
0	0	0
1	0	1

# Optical logic gates

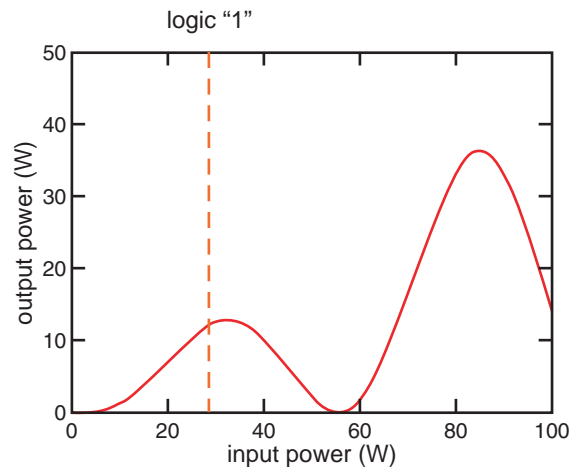
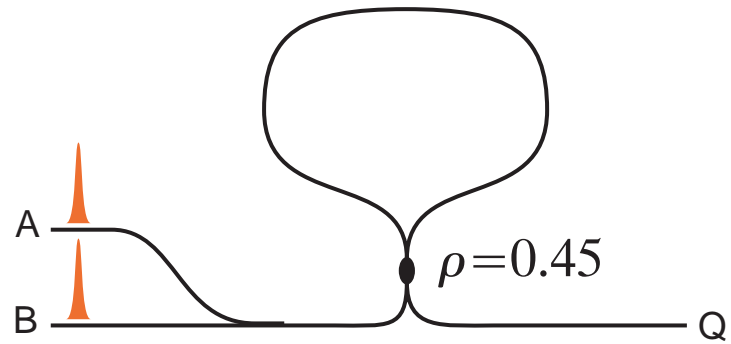
## nonlinear nanogate



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

# Optical logic gates

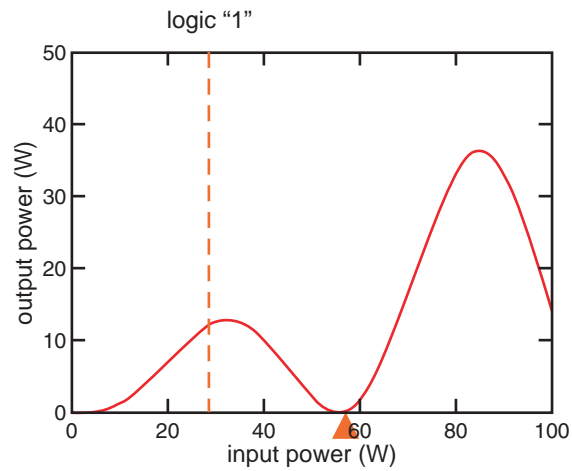
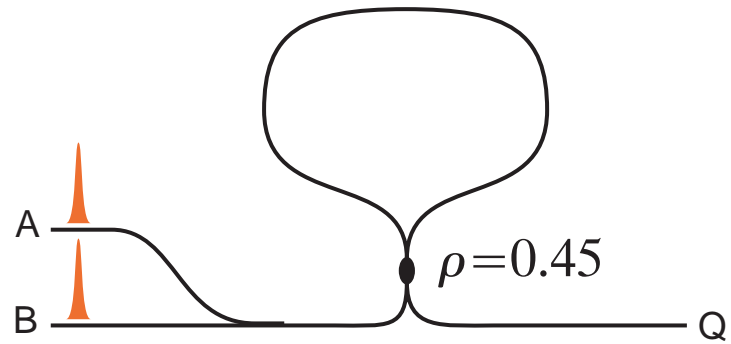
## nonlinear nanogate



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# Optical logic gates

## nonlinear nanogate

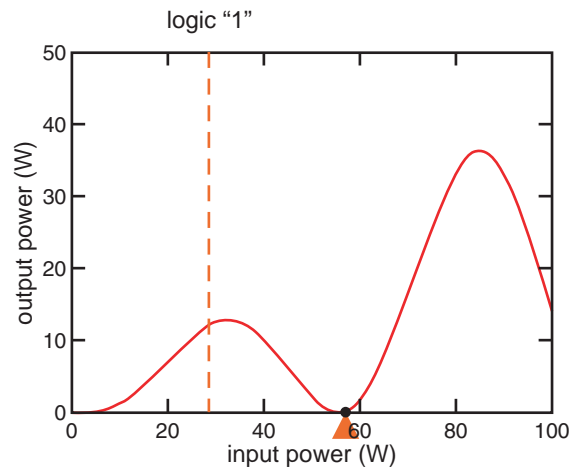
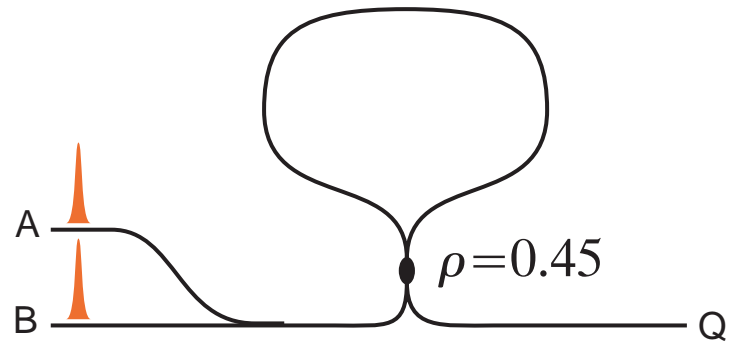


A	B	Q
0	0	0
1	0	1
0	1	1



# Optical logic gates

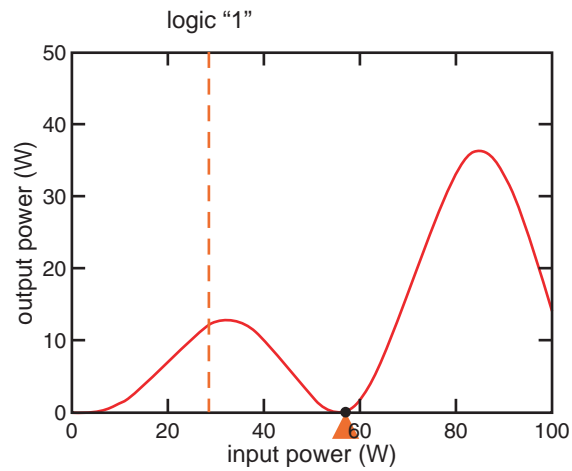
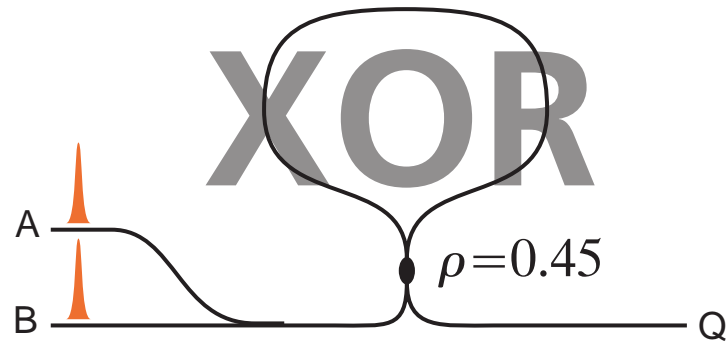
## nonlinear nanogate



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# Optical logic gates

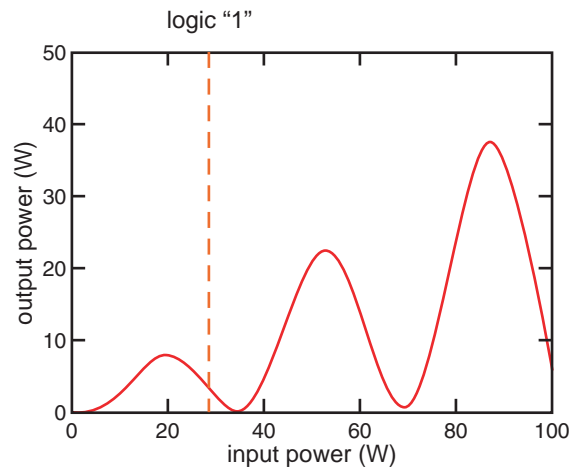
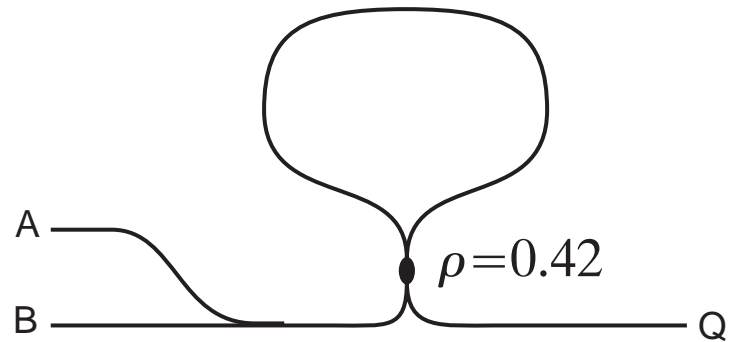
## nonlinear nanogate



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# Optical logic gates

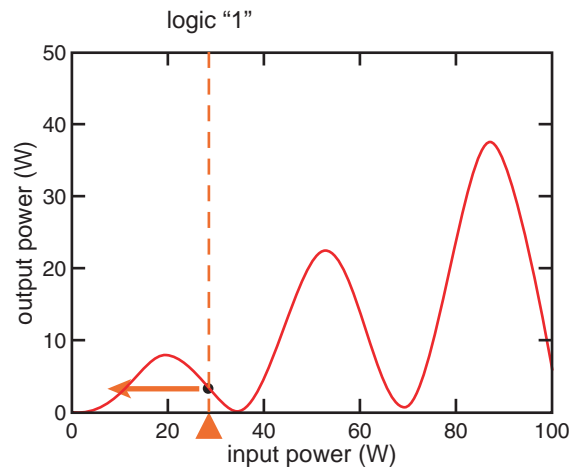
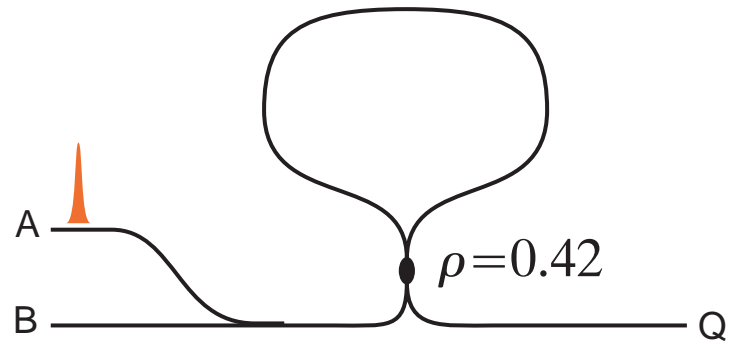
## nonlinear nanogate



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# Optical logic gates

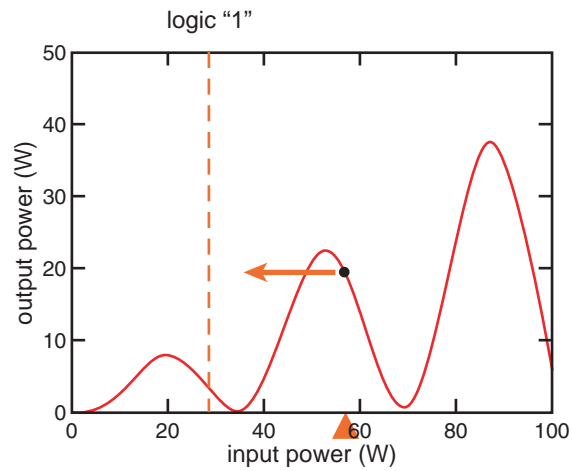
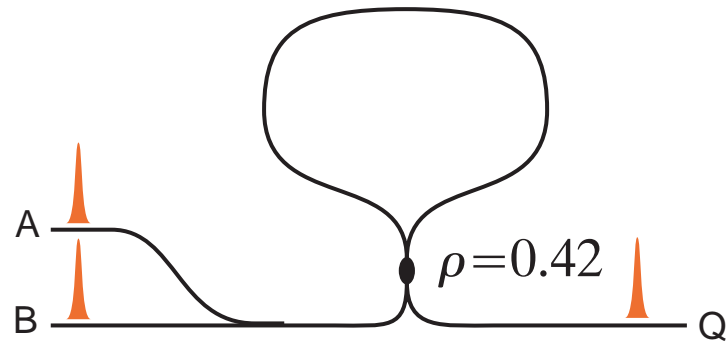
## nonlinear nanogate



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# Optical logic gates

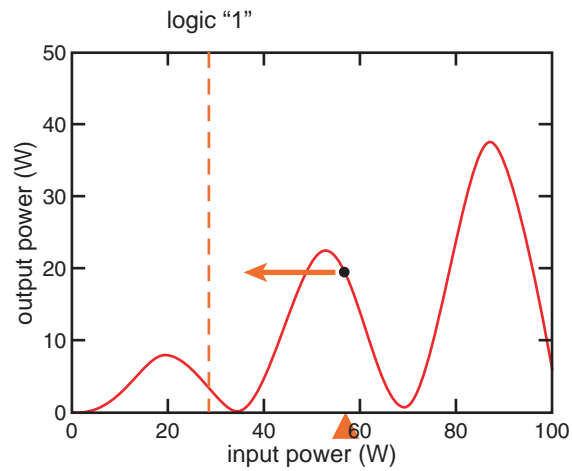
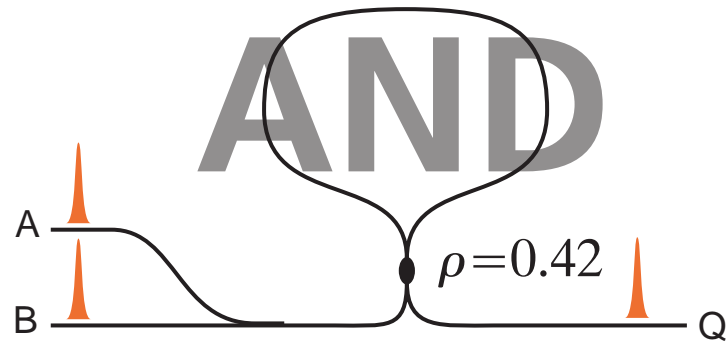
## nonlinear nanogate



A	B	Q
0	0	0
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# Optical logic gates

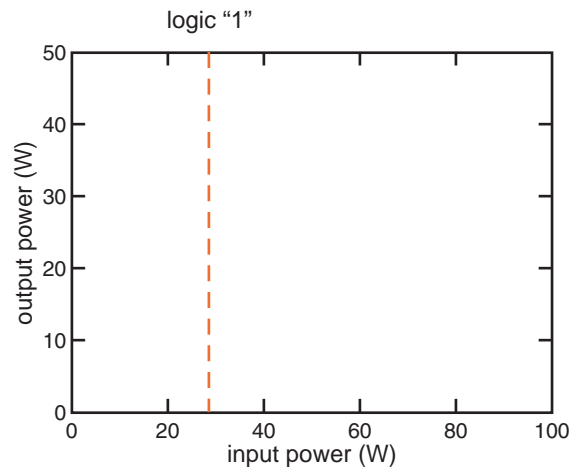
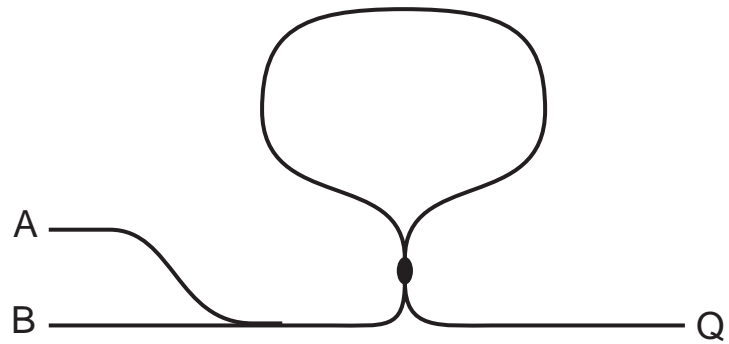
## nonlinear nanogate



A	B	Q
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# Optical logic gates

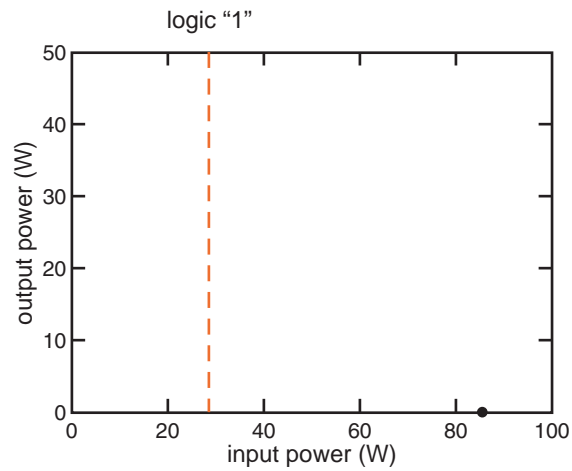
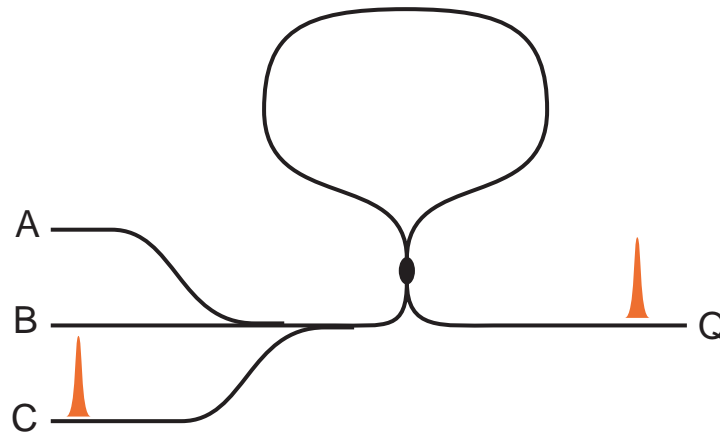
for NAND gate need output with no input



A	B	Q
0	0	1

# Optical logic gates

for NAND gate need output with no input

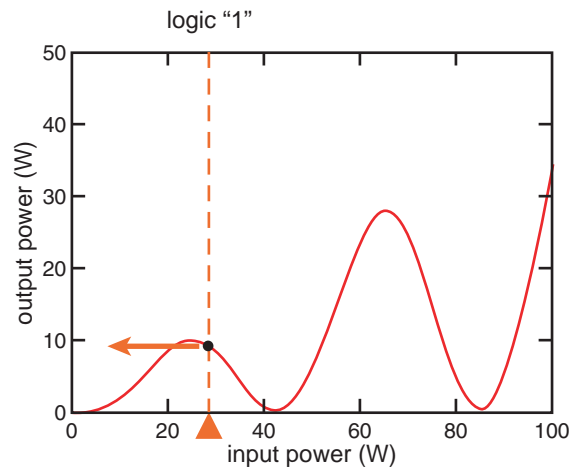
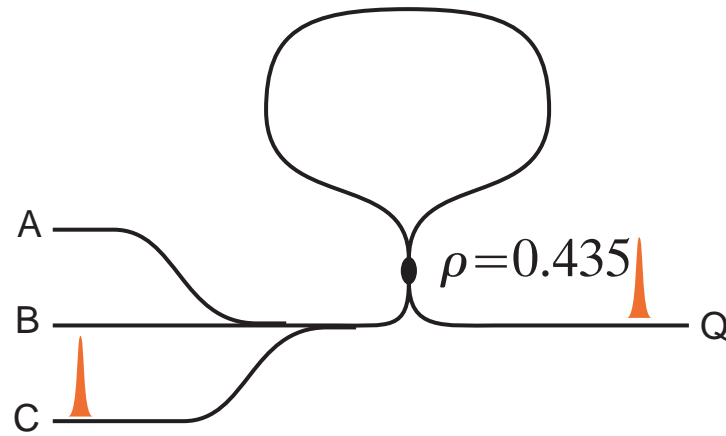


A	B	Q
0	0	1



# Optical logic gates

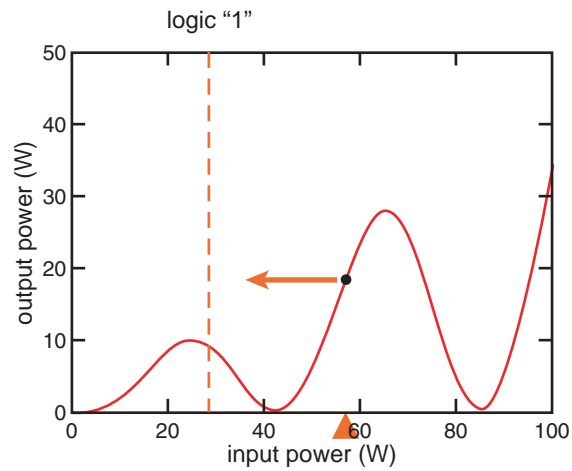
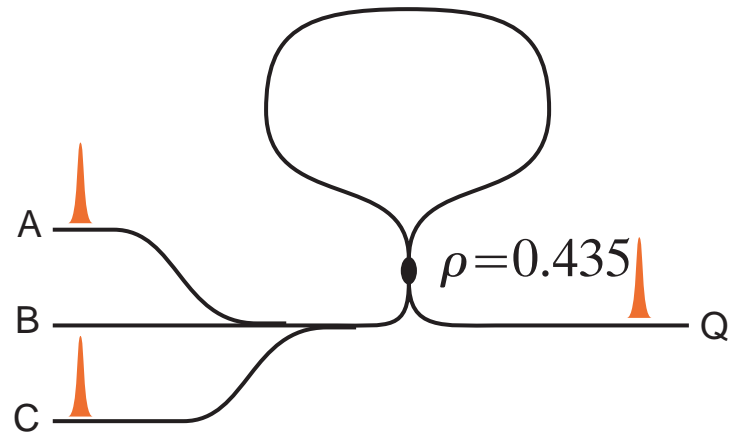
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# Optical logic gates

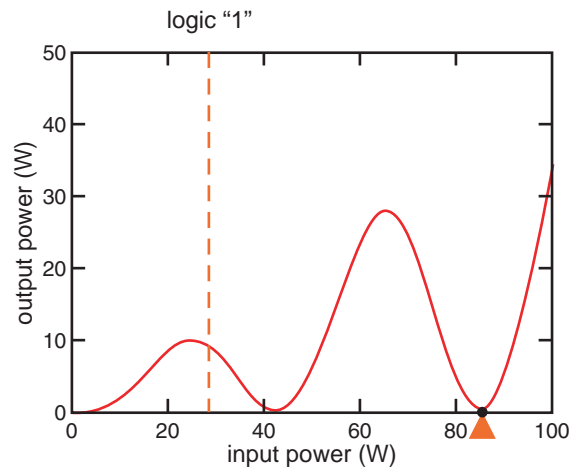
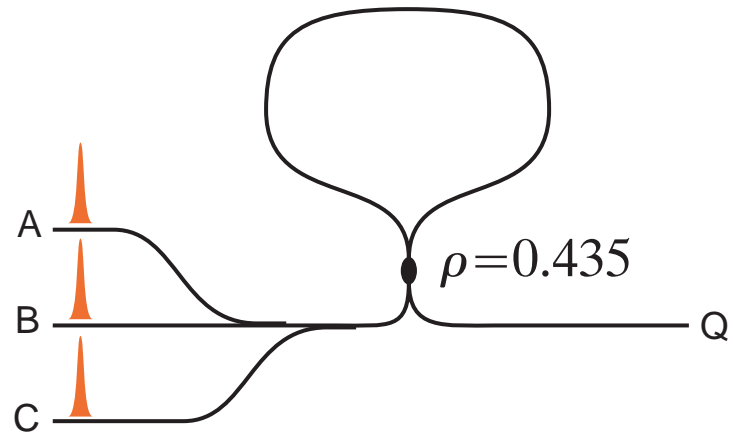
## universal NAND gate



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

# Optical logic gates

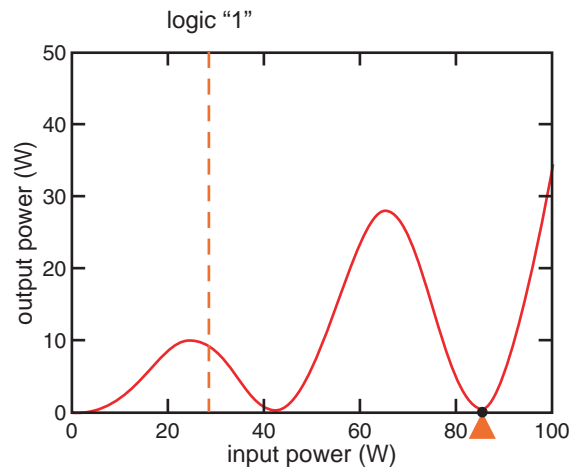
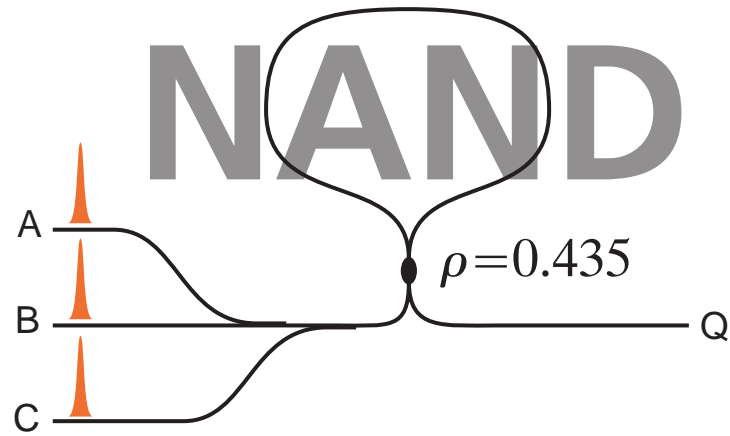
## universal NAND gate



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

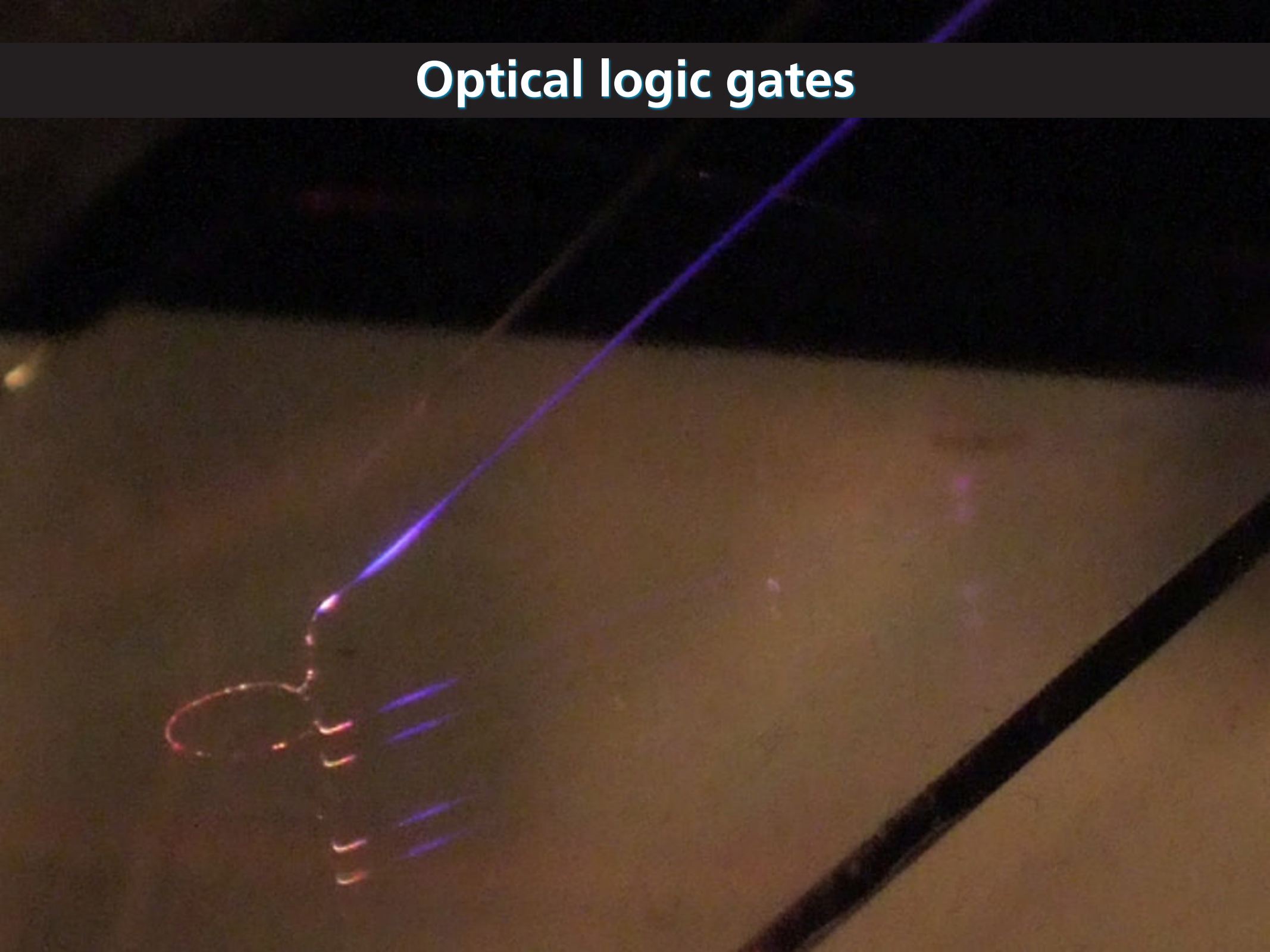
# Optical logic gates

## universal NAND gate



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

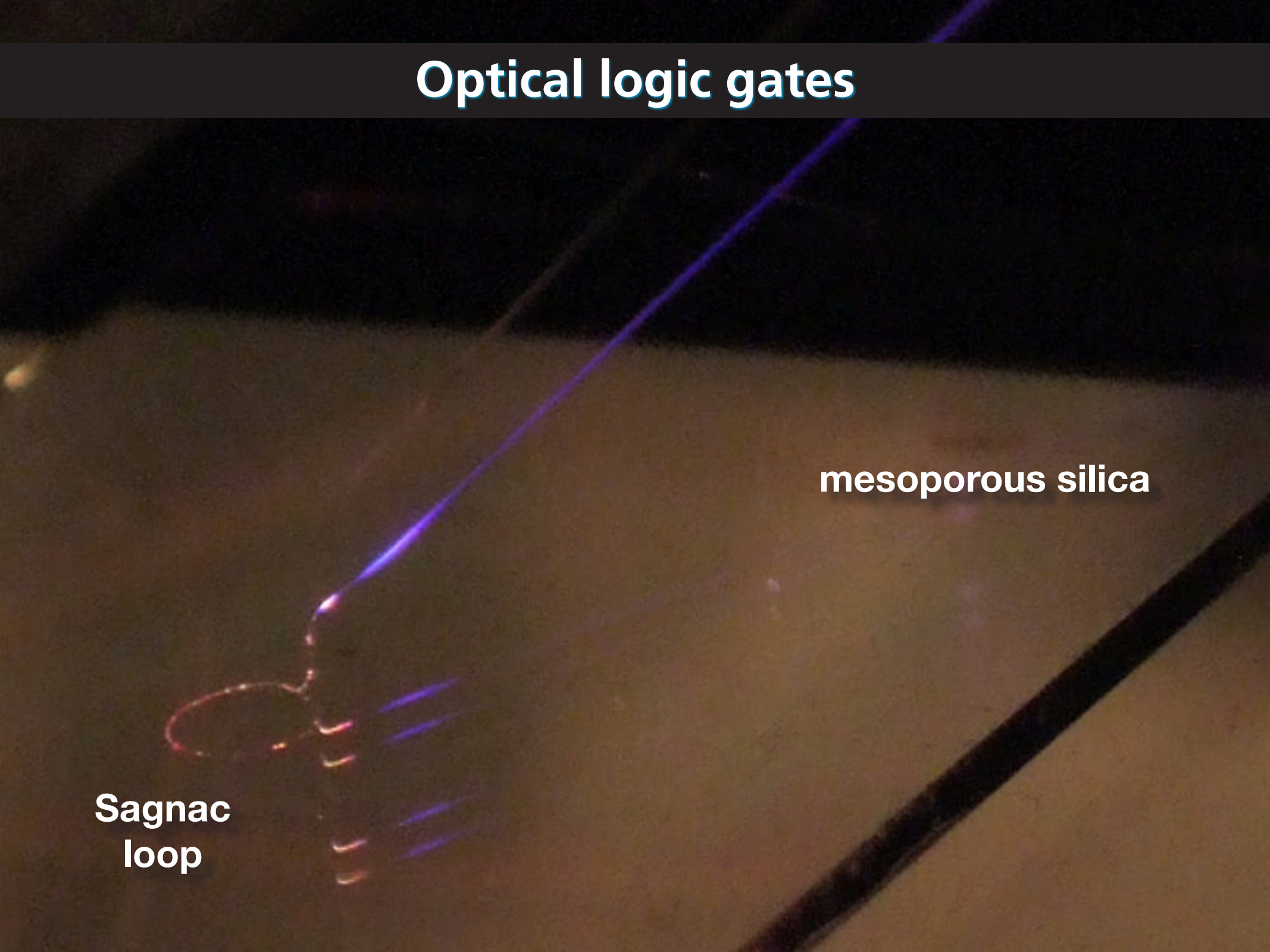
# Optical logic gates



# Optical logic gates

mesoporous silica

Sagnac  
loop



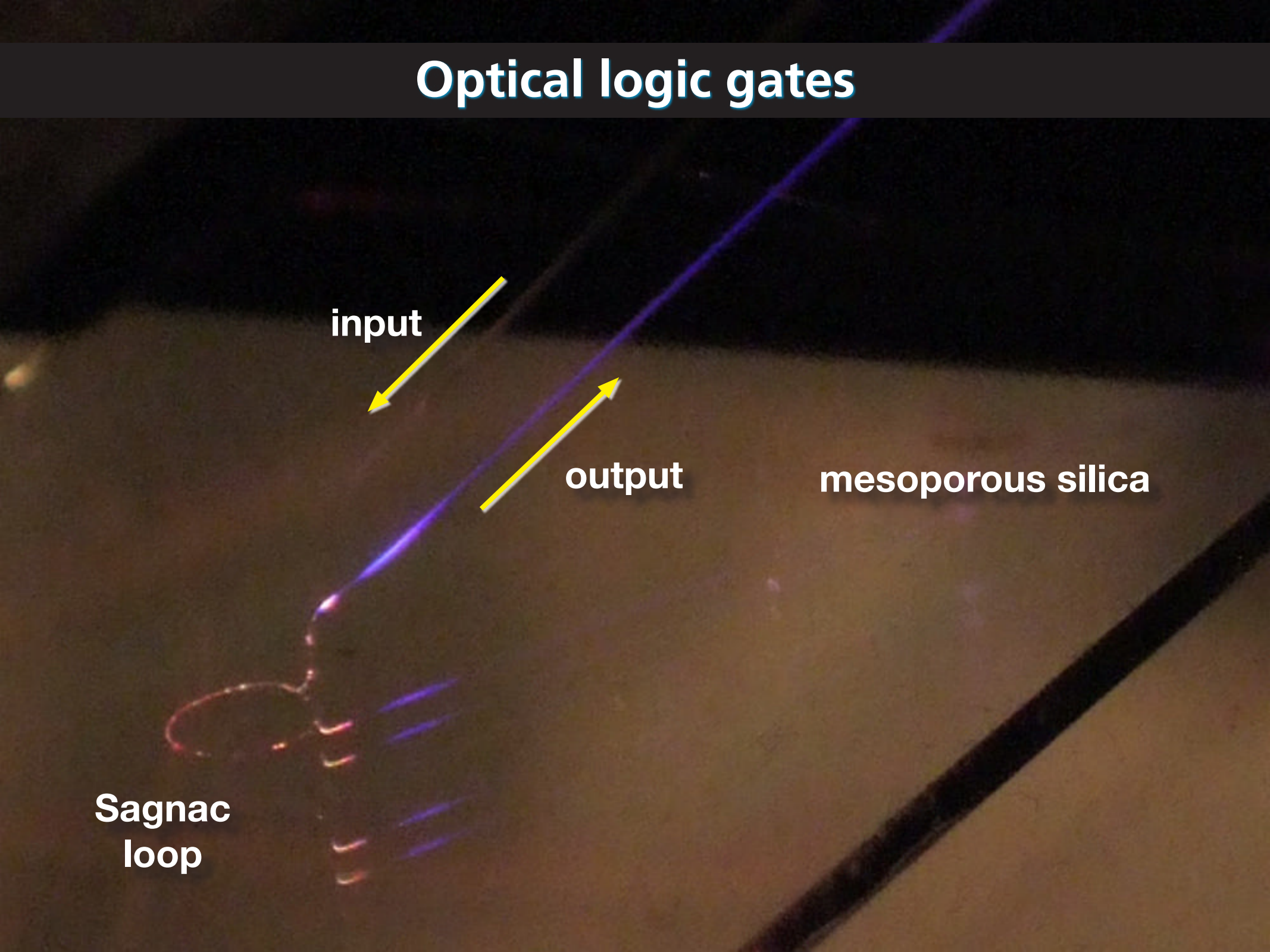
# Optical logic gates

input

output

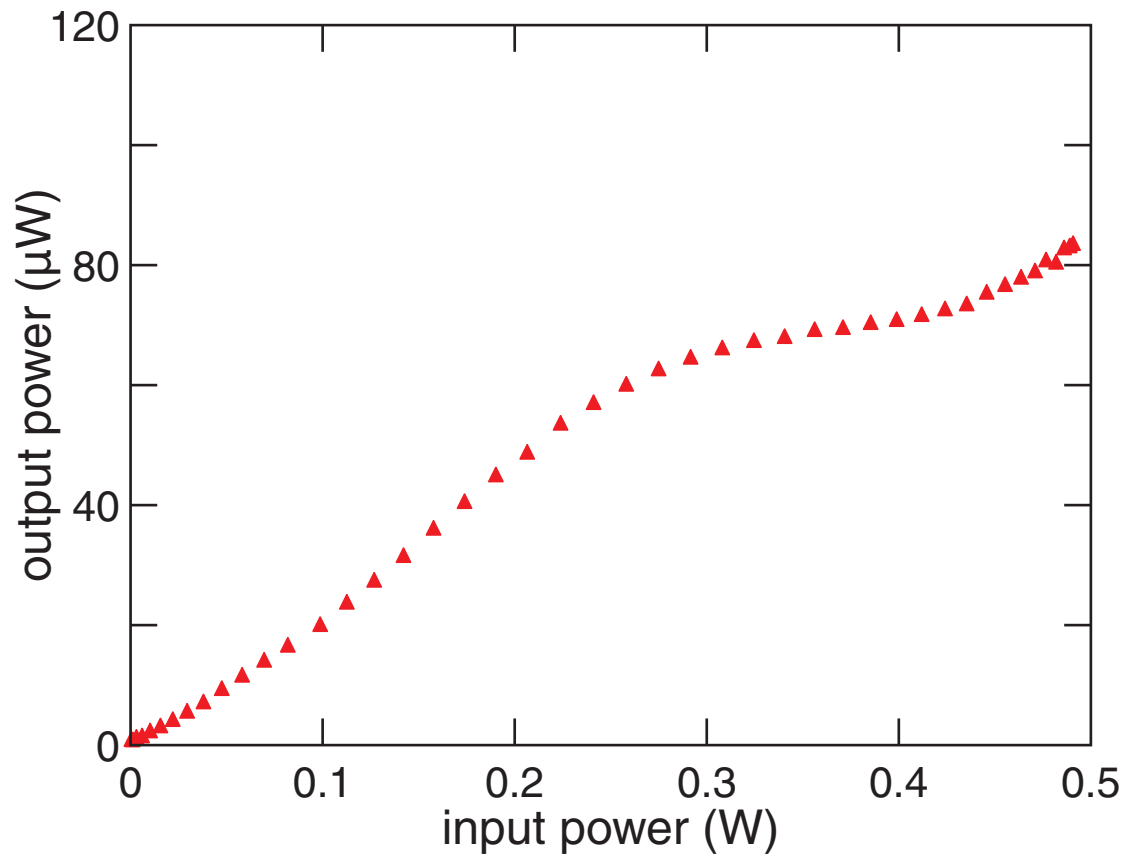
mesoporous silica

Sagnac  
loop



# Optical logic gates

very preliminary data



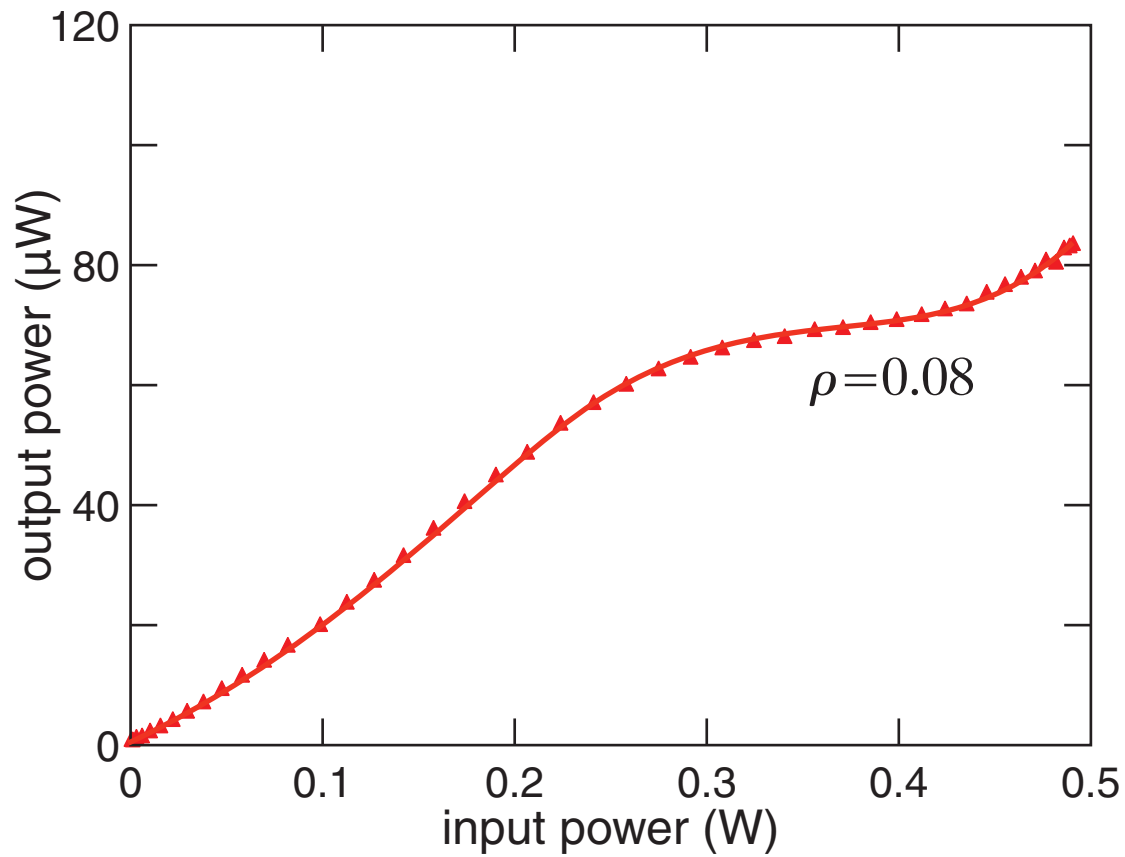


# Optical logic gates

**light-by-light modulation!**

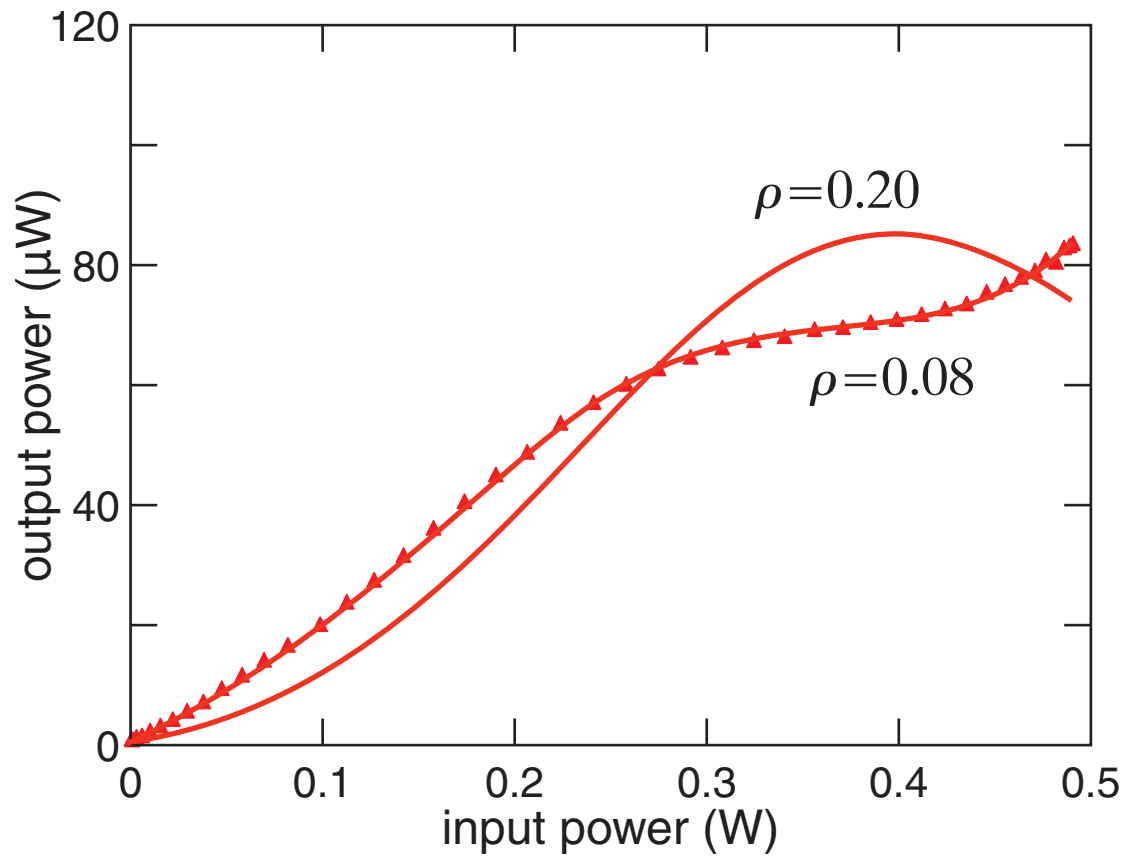
# Optical logic gates

very preliminary data

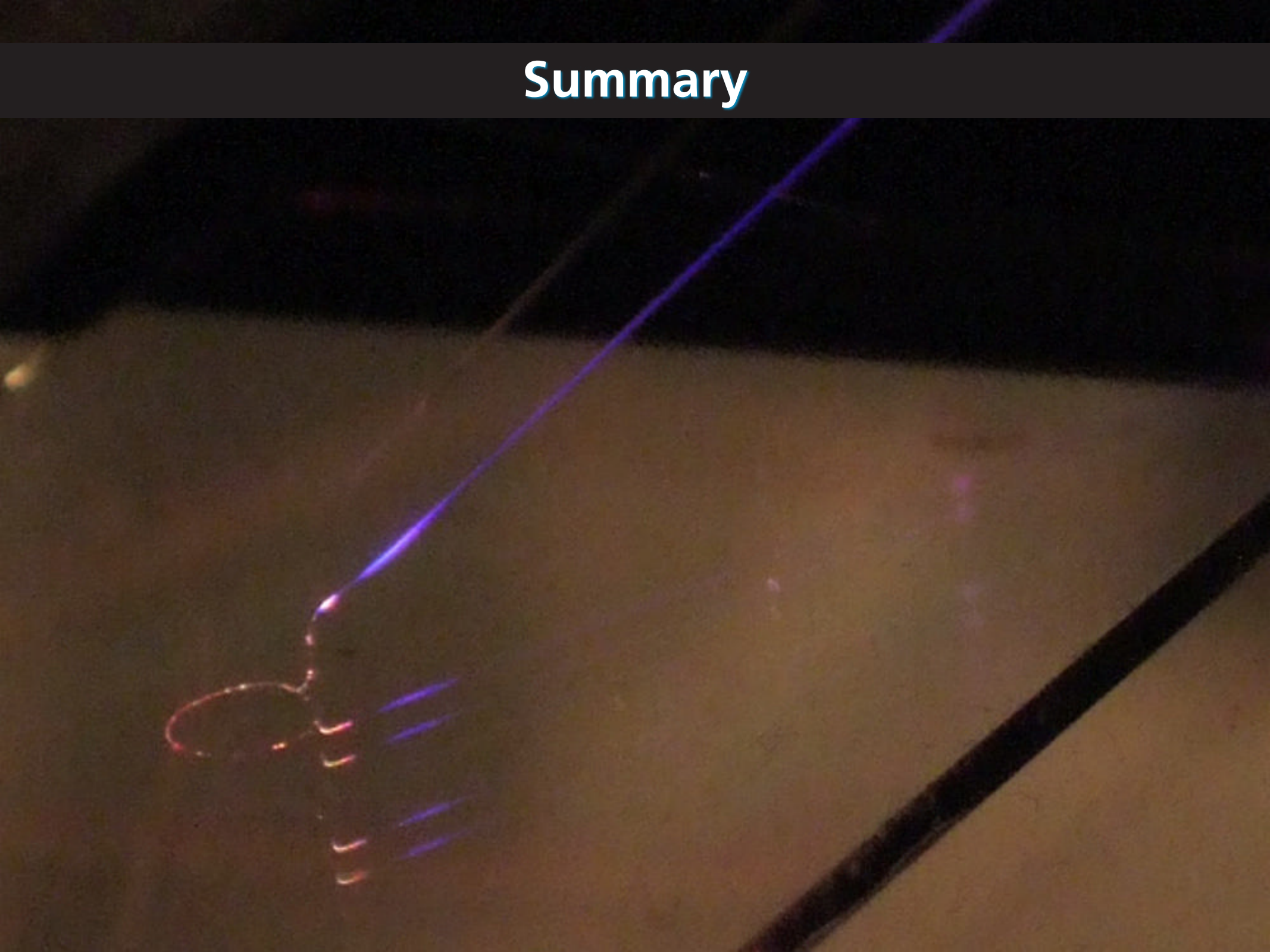


# Optical logic gates

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**

**for a copy of this presentation:**

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