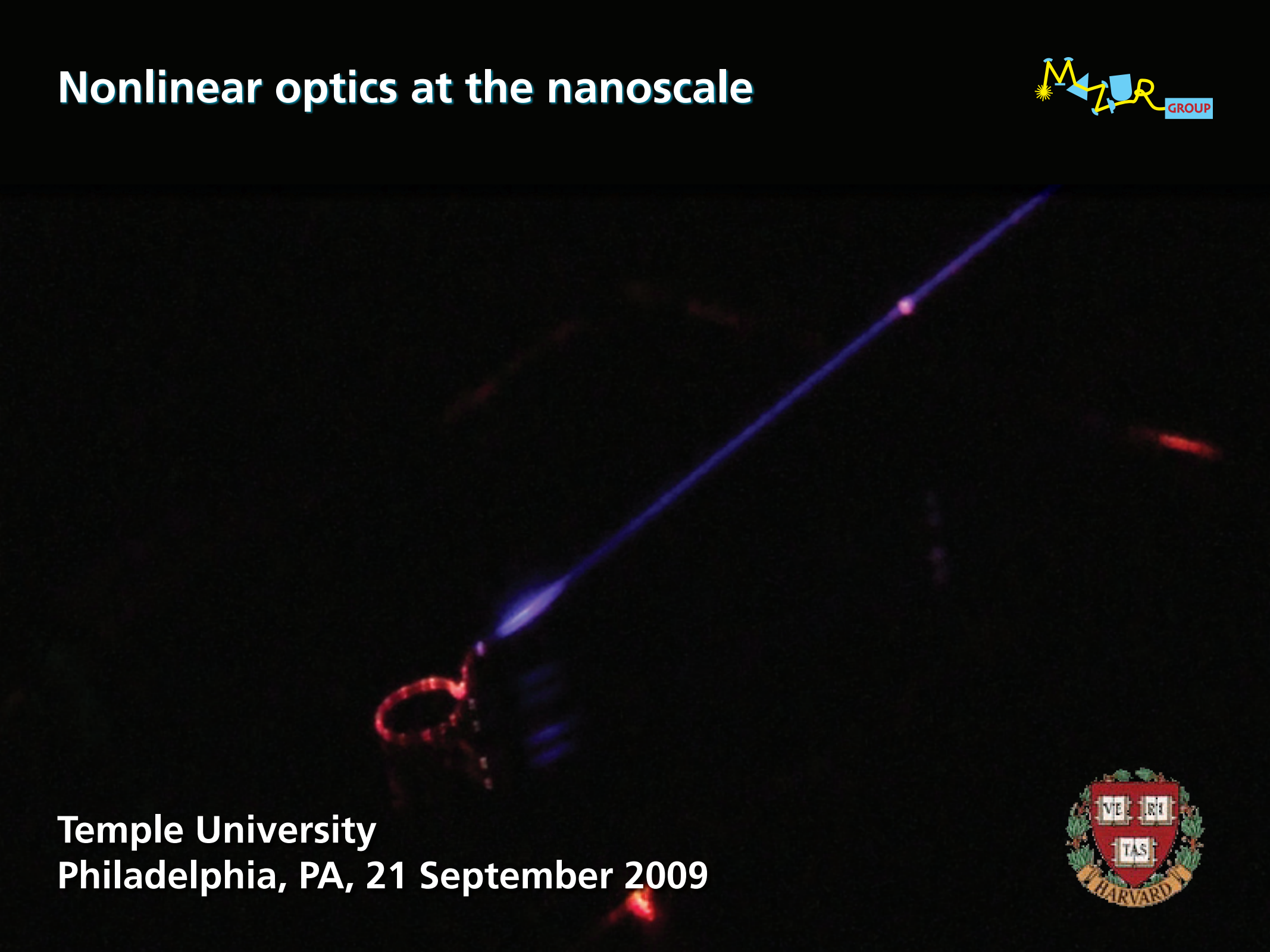
Nonlinear optics at the nanoscale

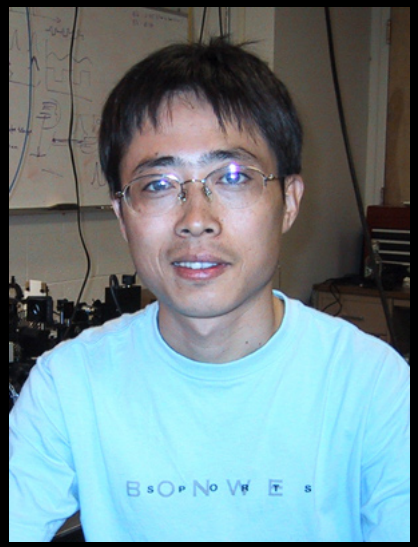


Temple University
Philadelphia, PA, 21 September 2009

Geoff Svacha

Rafael Gattass

Tobias Voss

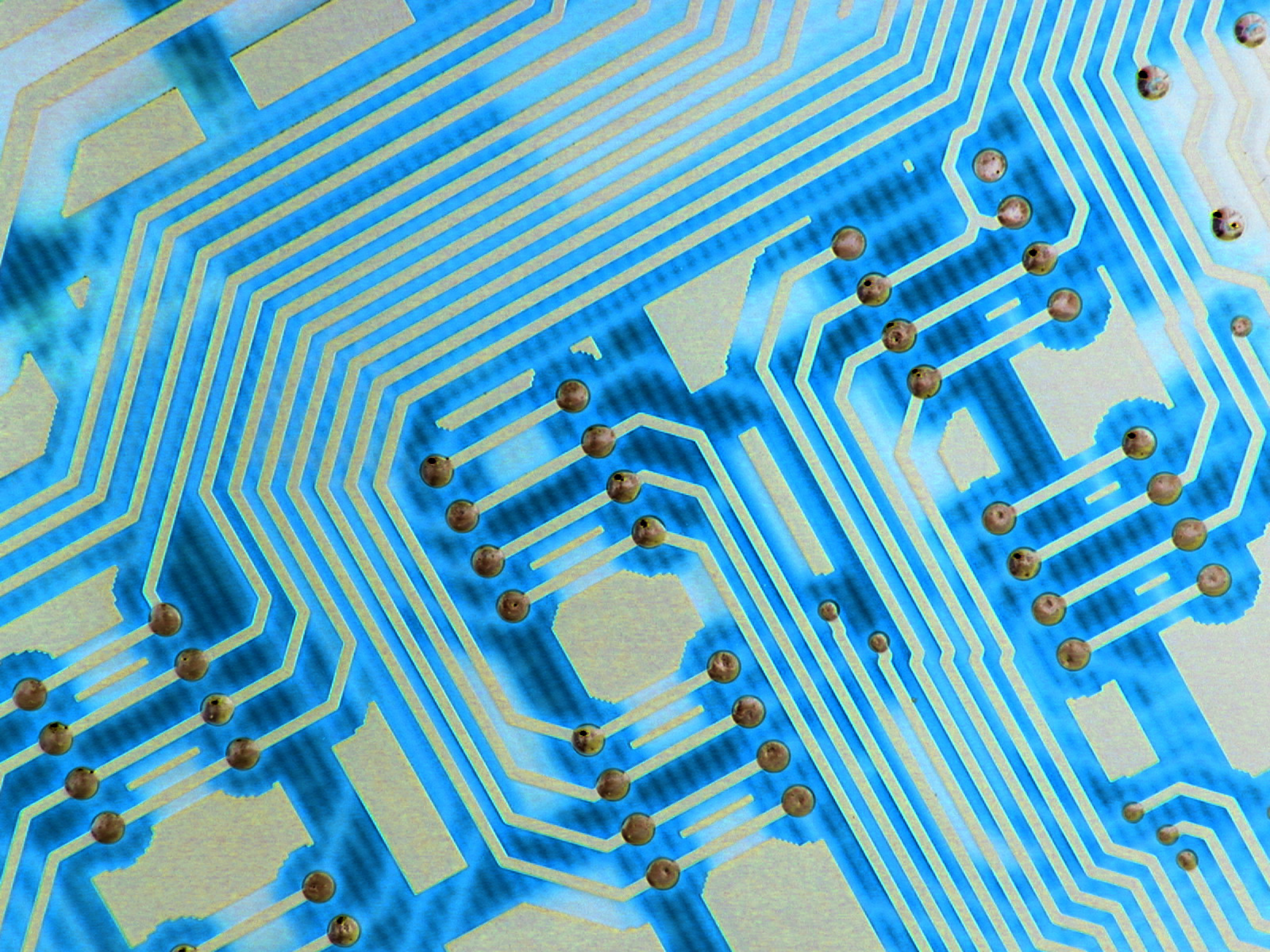


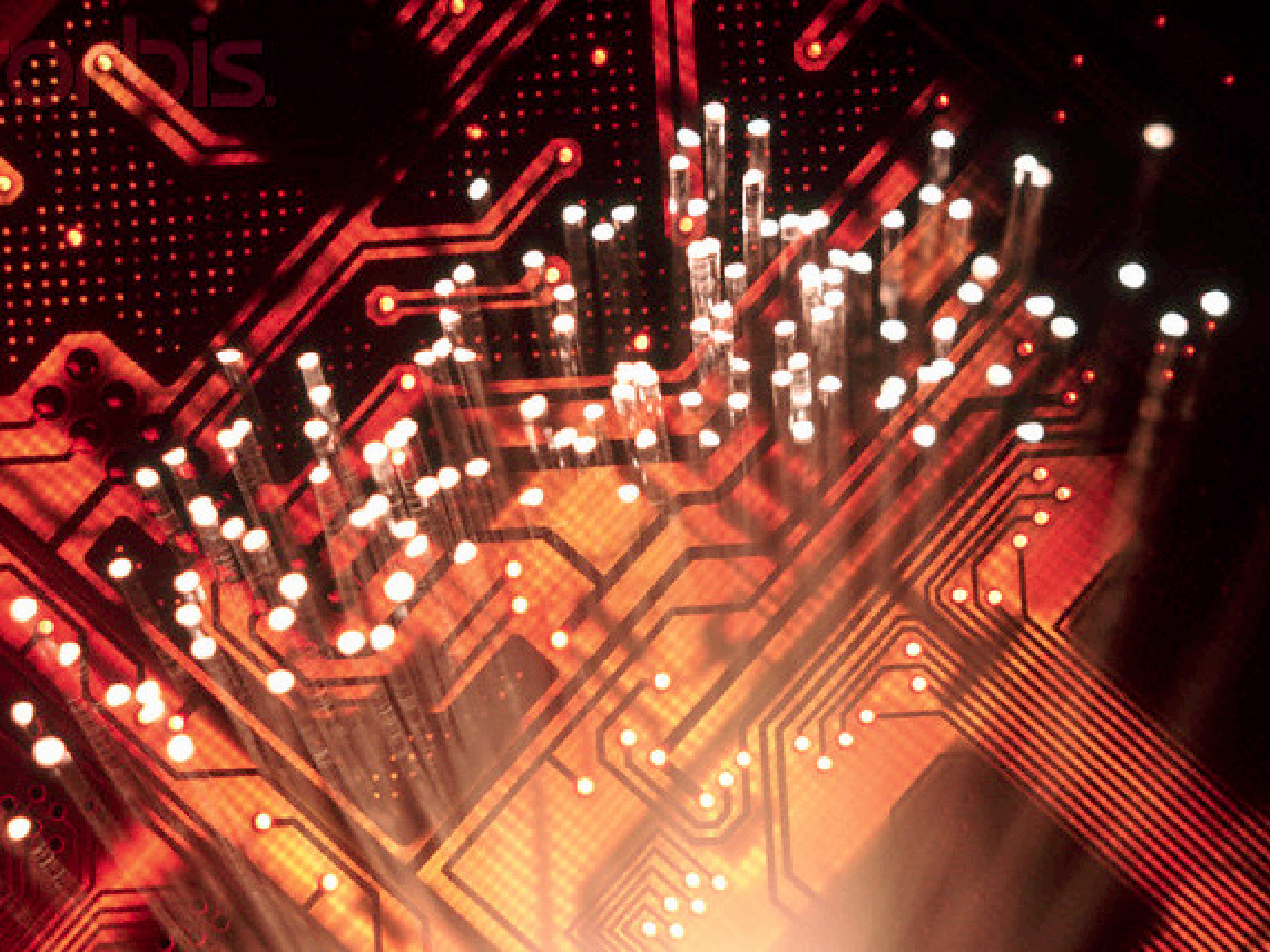
Limin Tong

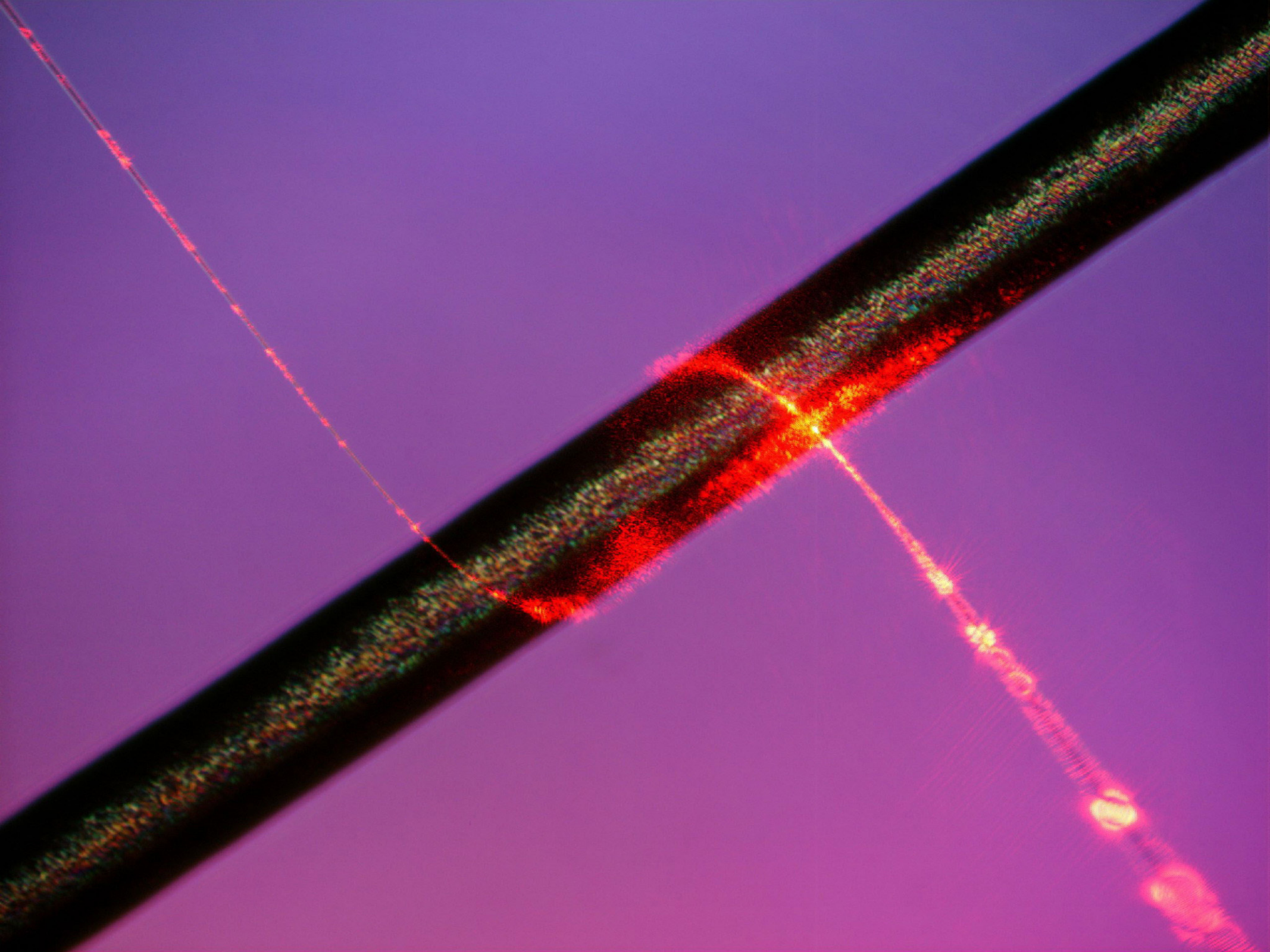
and also....

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)
Xuewen Chen (Zhejiang)
Zhanghua Han (Zhejiang)
Dr. Sailing He (Zhejiang)
Liu Liu (Zhejiang)
Dr. Jingyi Lou (Zhejiang)
Dr. Ray Mariella (LLNL)
Prof. Frank Marlow (MPI Mühlheim)
Prof. Sven Müller (Göttingen)
Prof. Carsten Ronning (Göttingen)







Outline

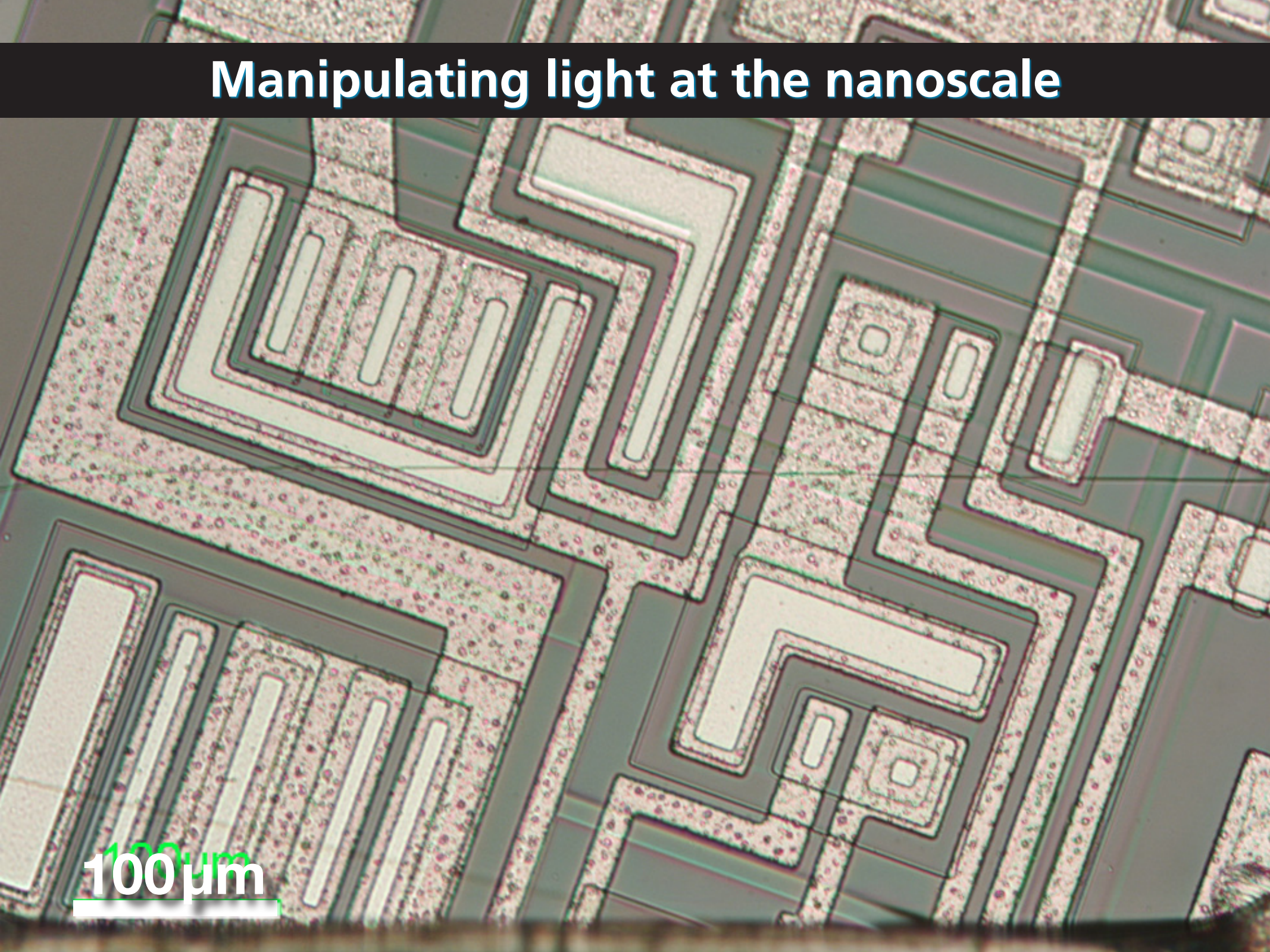
Outline

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

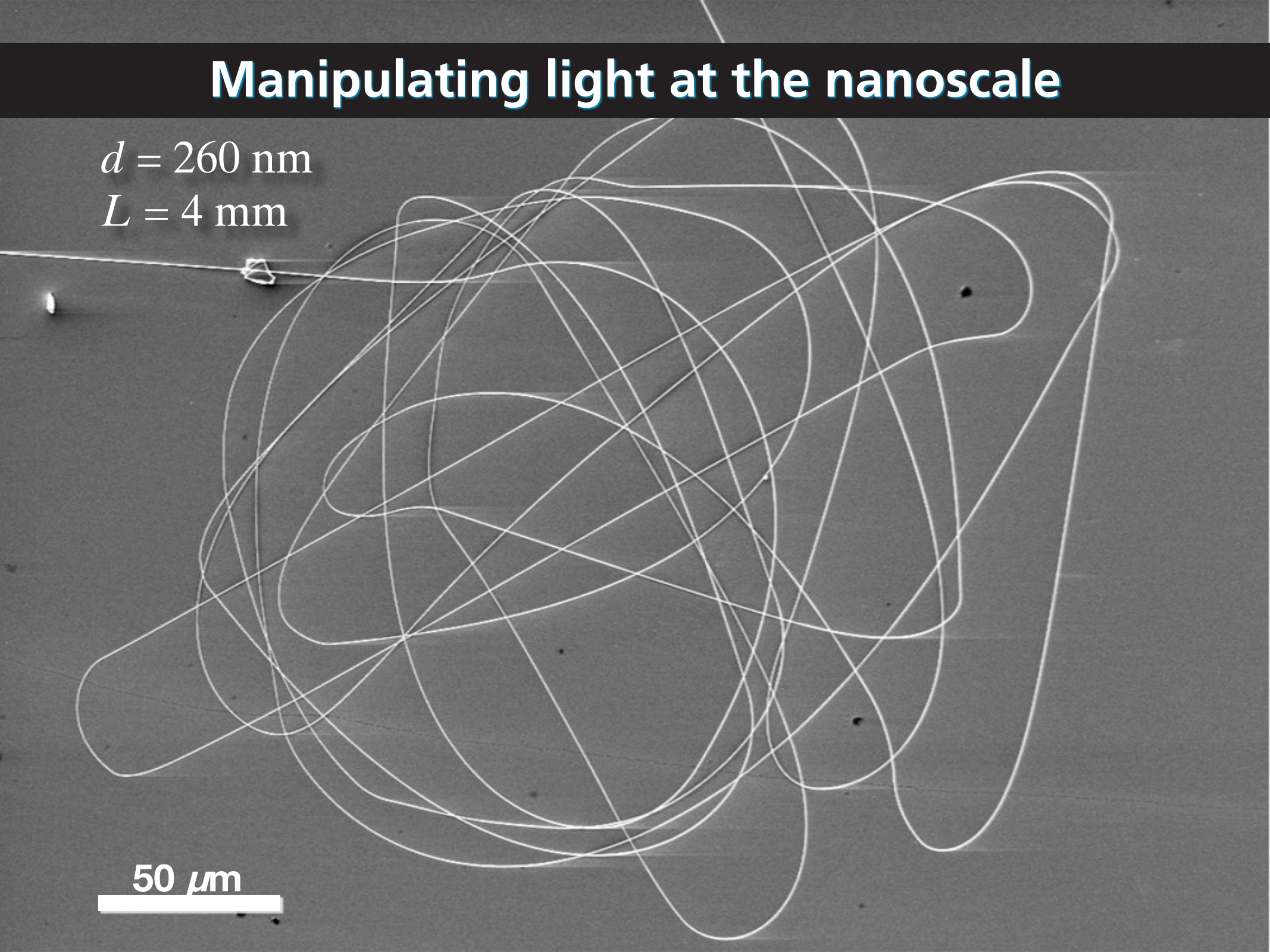
Manipulating light at the nanoscale

Nature, 426, 816 (2003)

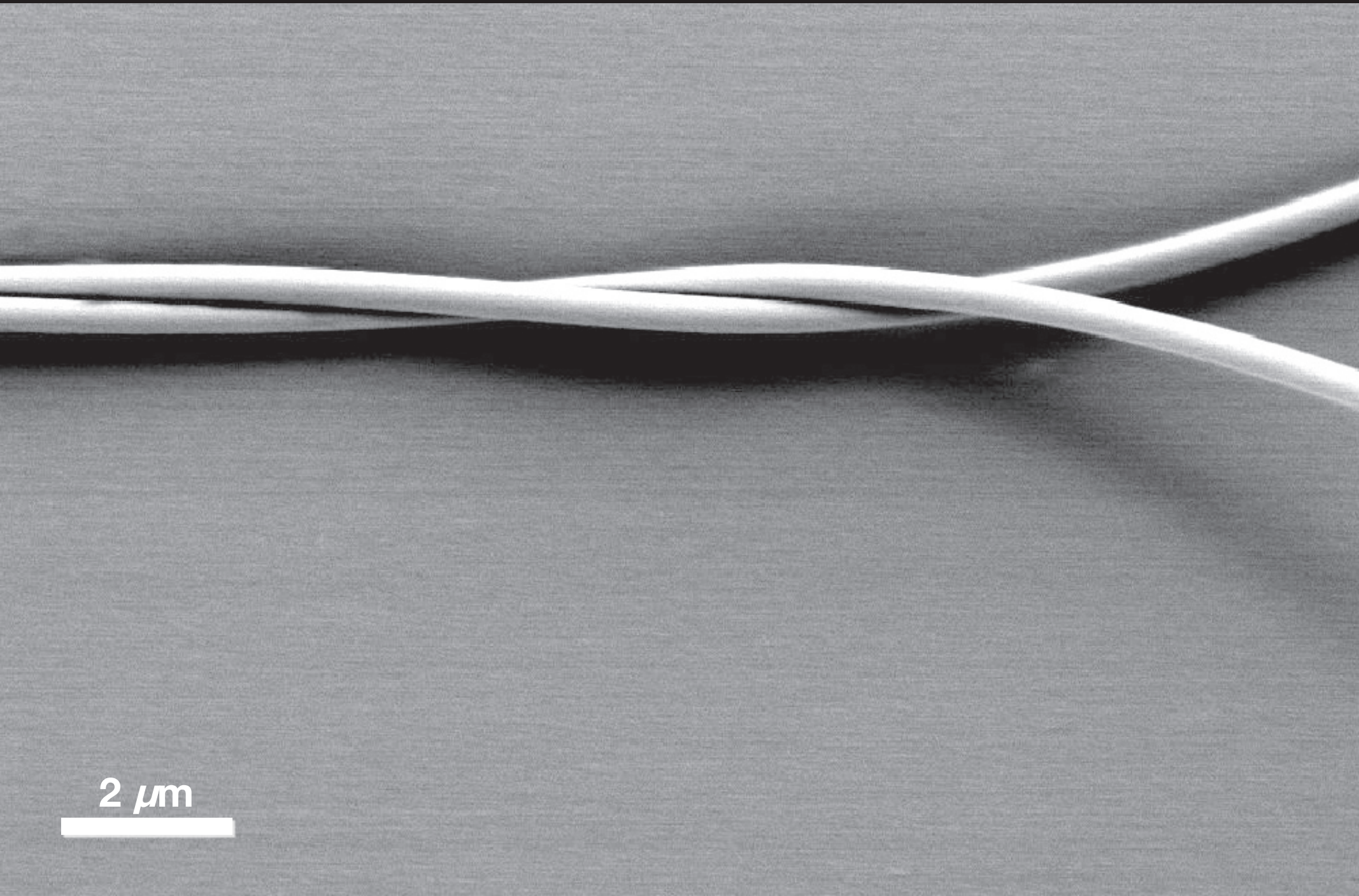
Manipulating light at the nanoscale



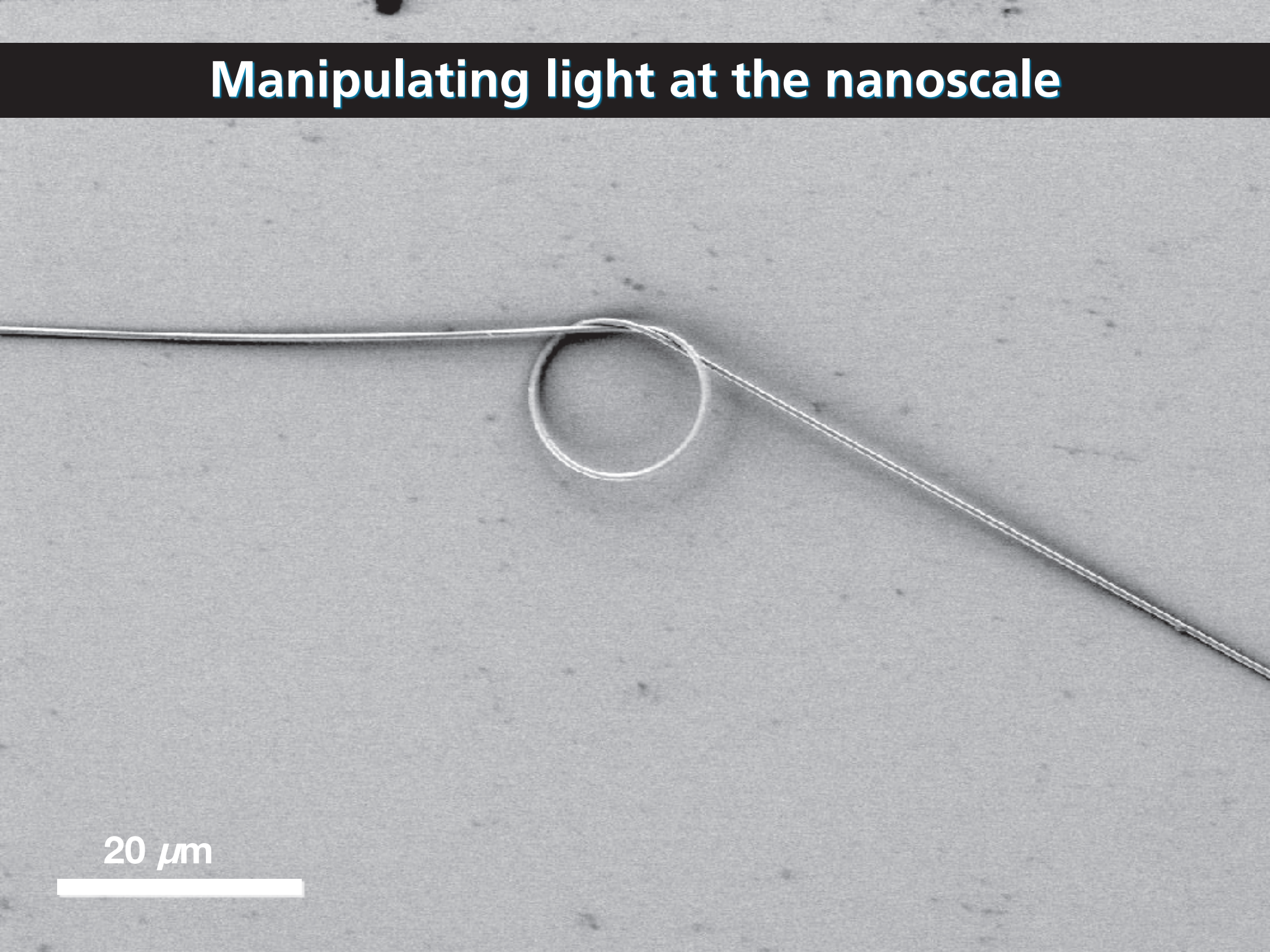
Manipulating light at the nanoscale



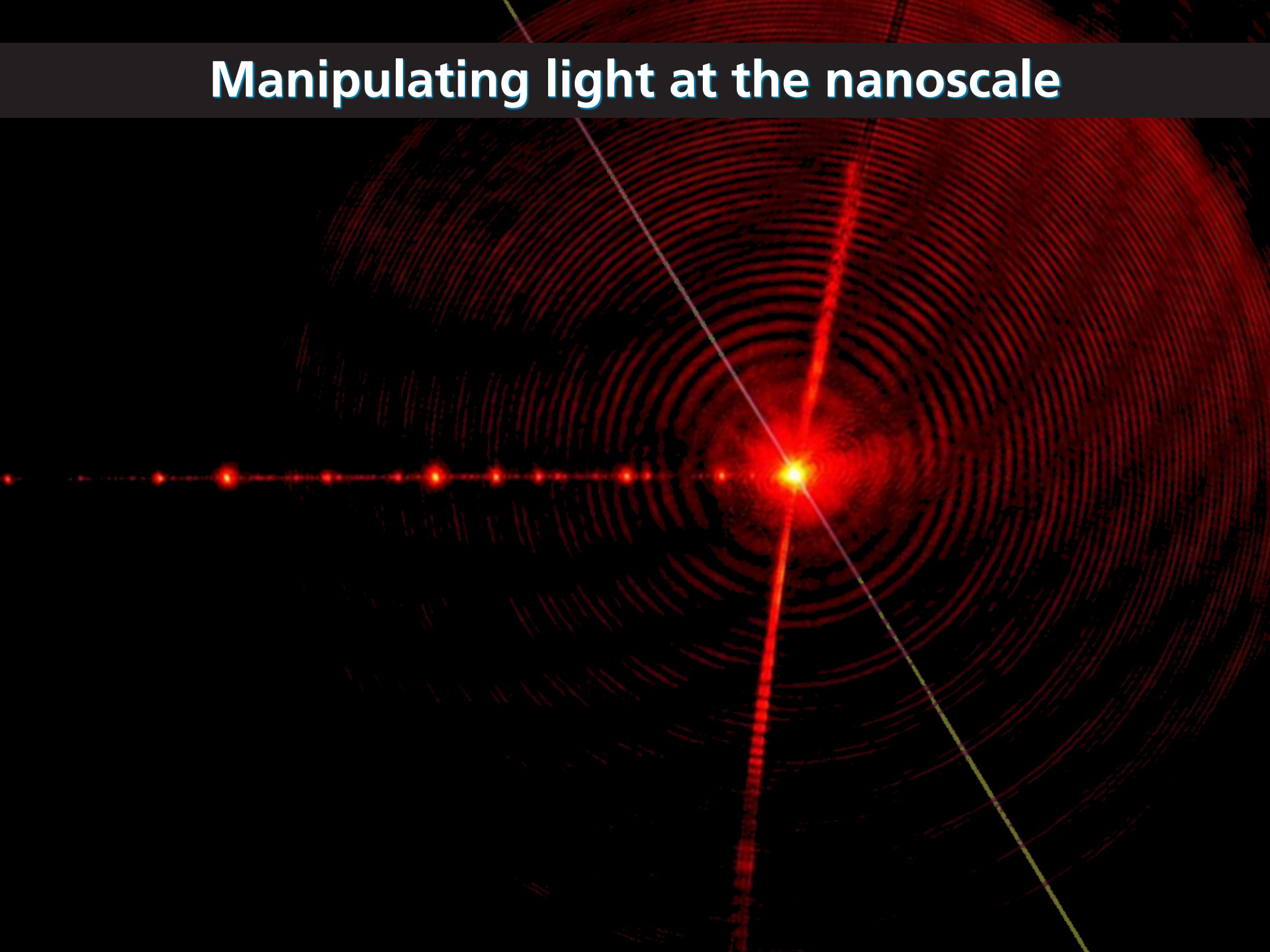
Manipulating light at the nanoscale



Manipulating light at the nanoscale

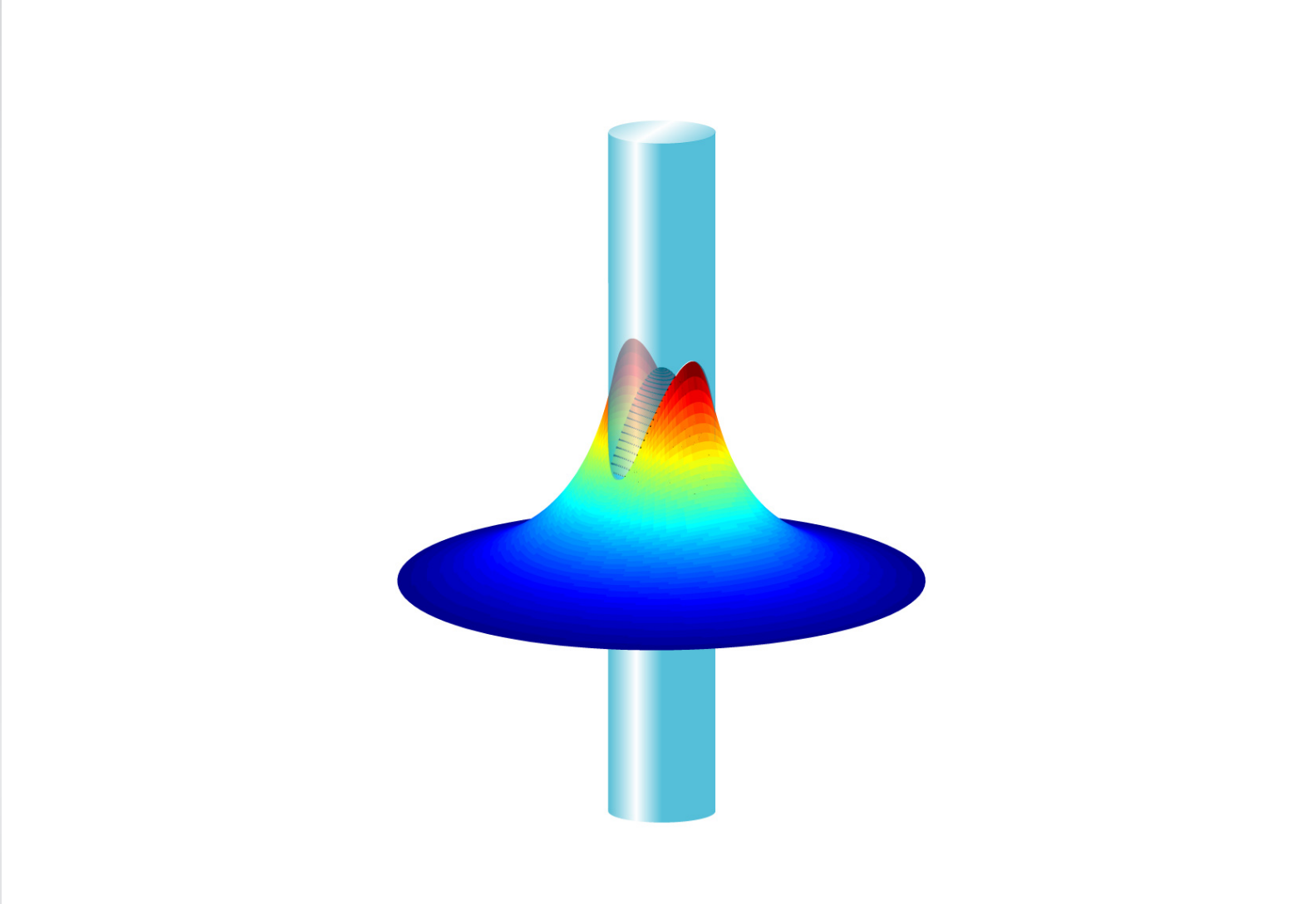


Manipulating light at the nanoscale

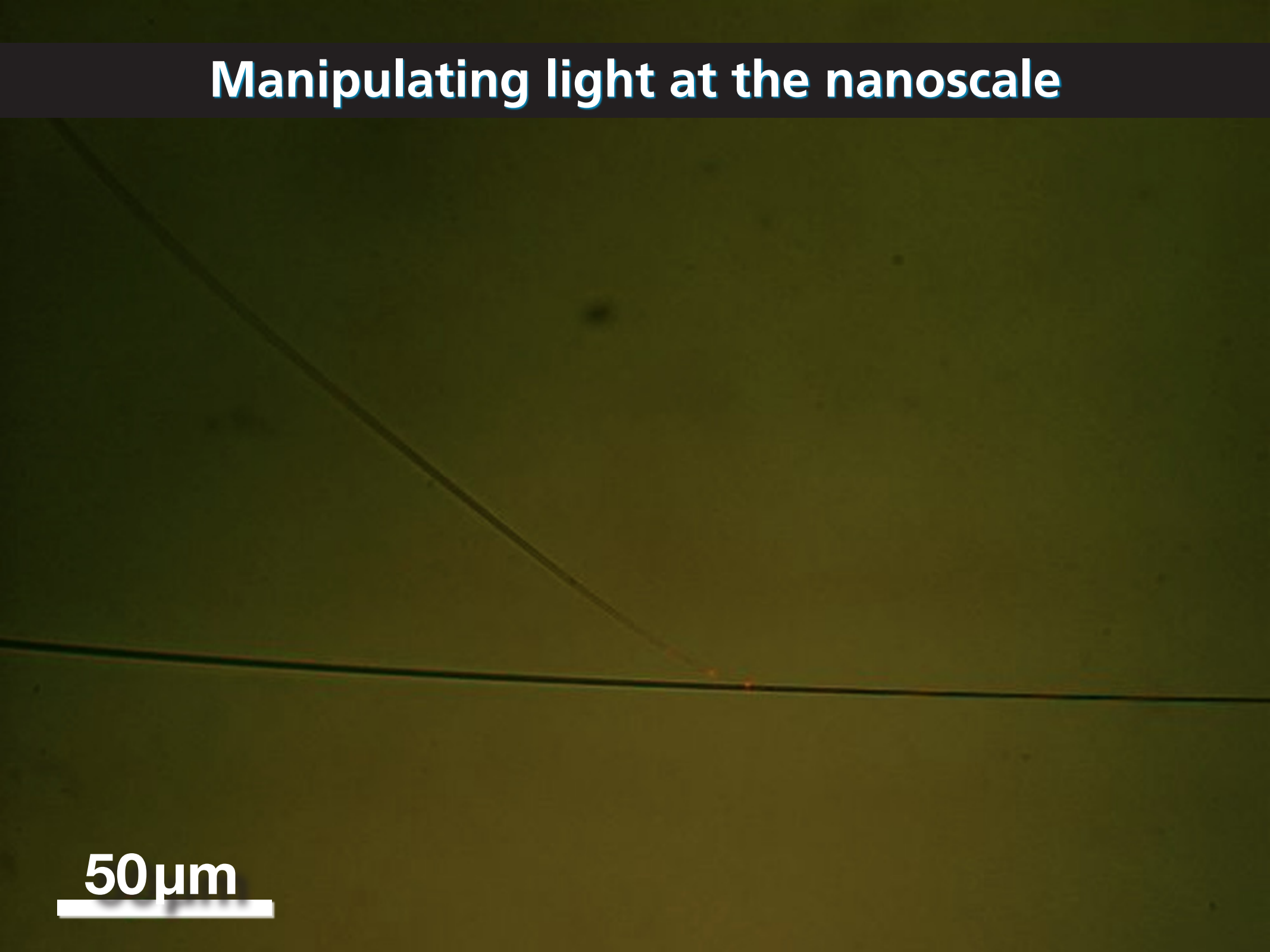


Manipulating light at the nanoscale

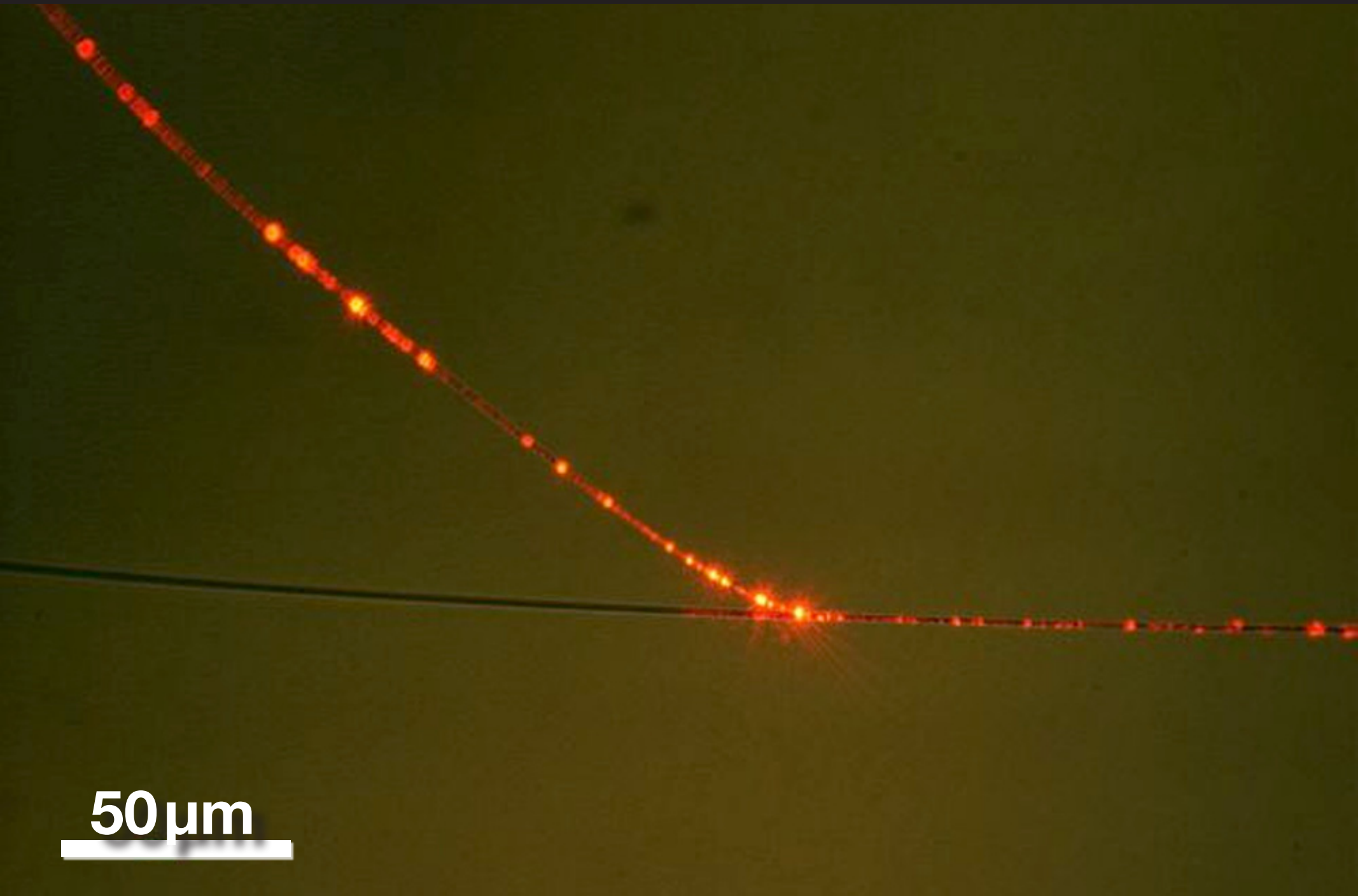
Poynting vector profile for 200-nm nanowire



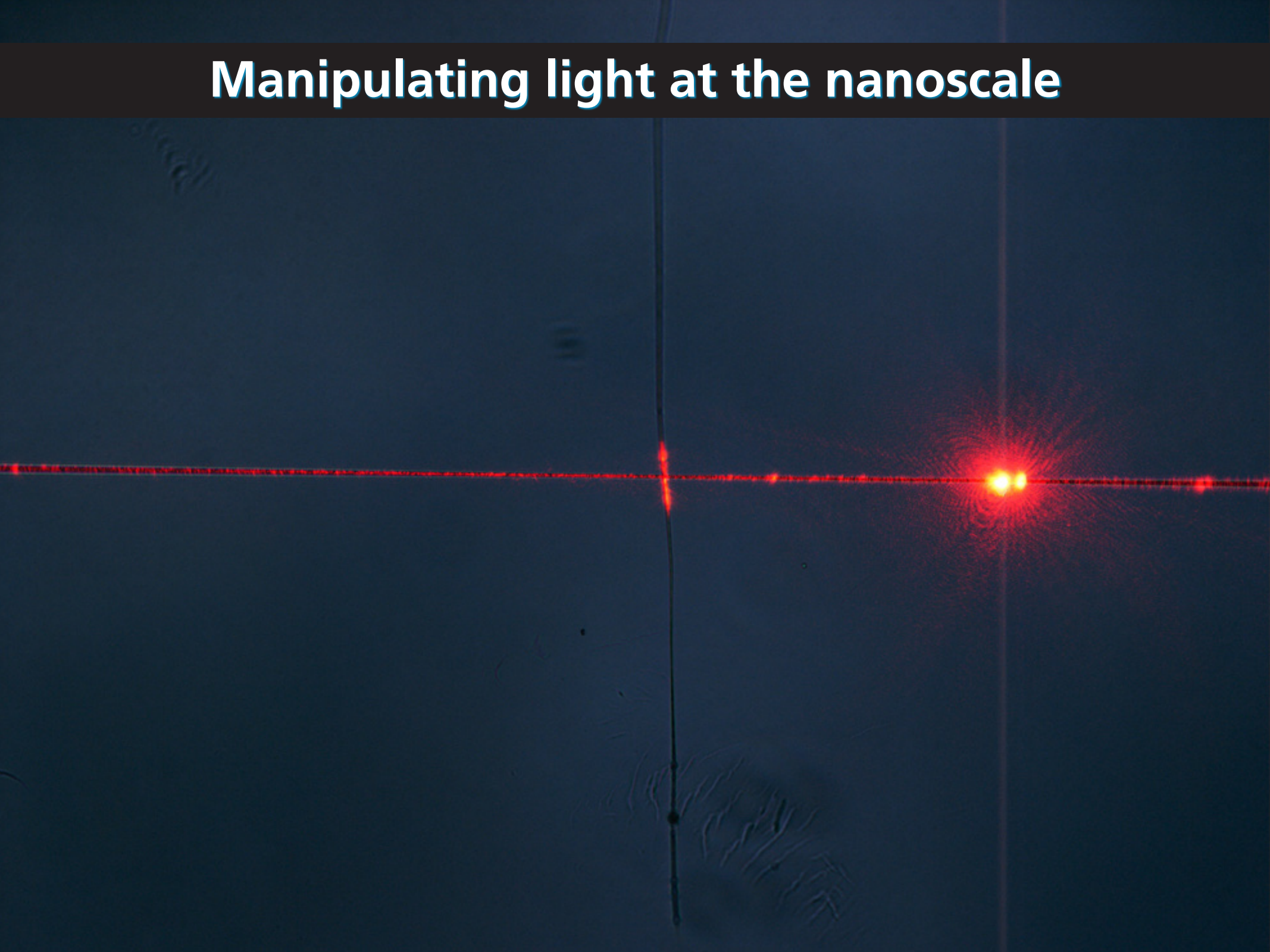
Manipulating light at the nanoscale



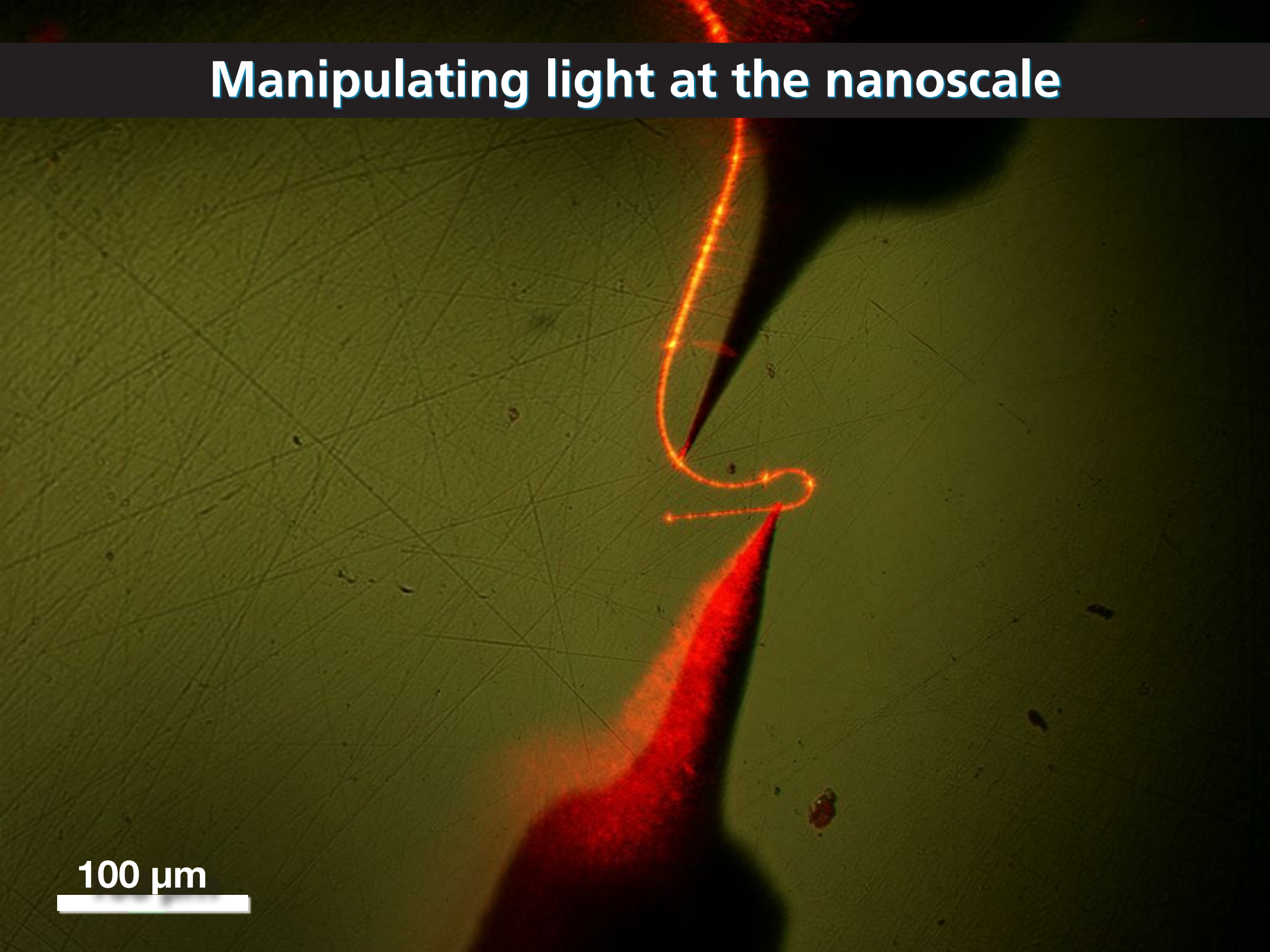
Manipulating light at the nanoscale



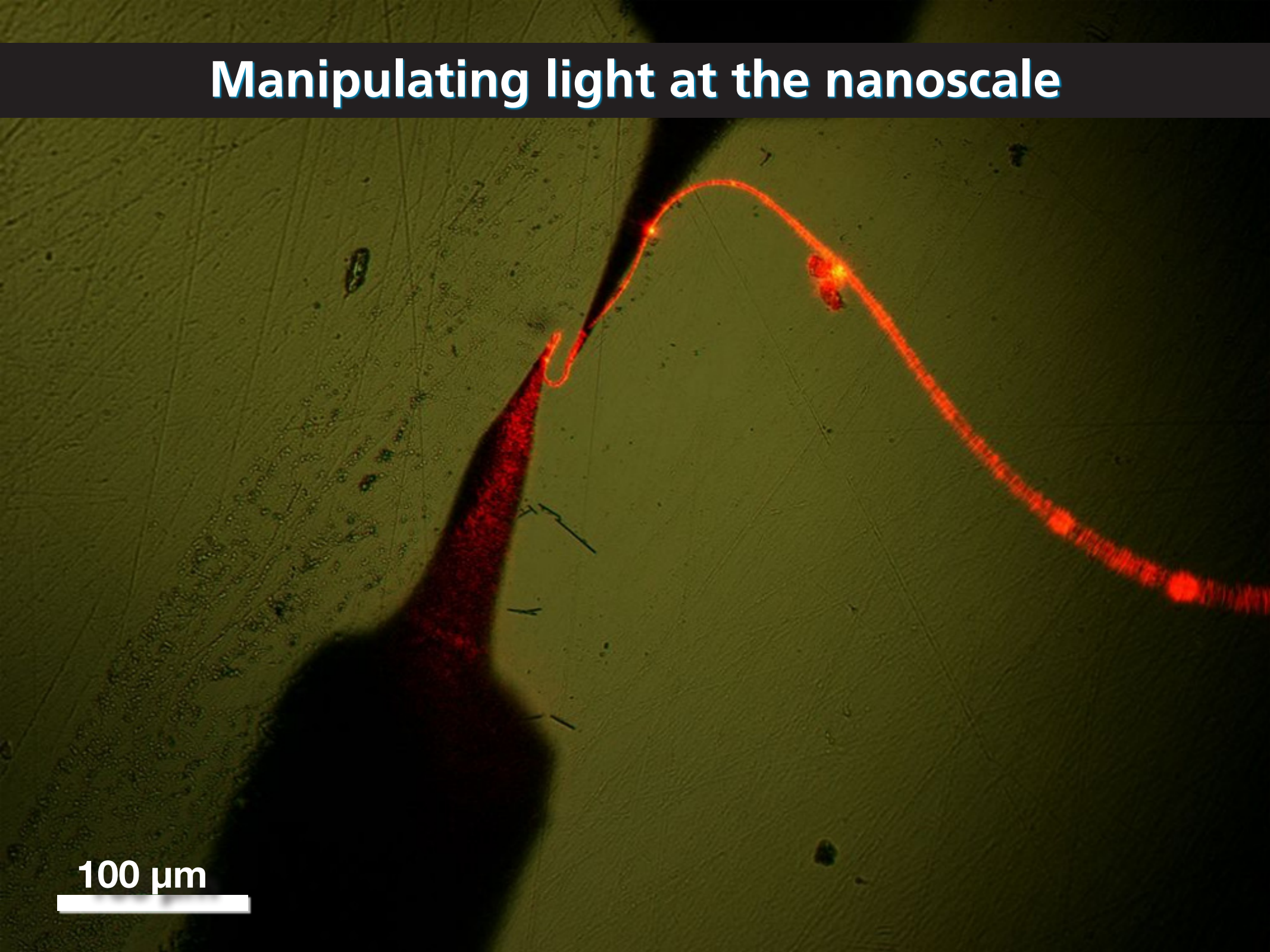
Manipulating light at the nanoscale



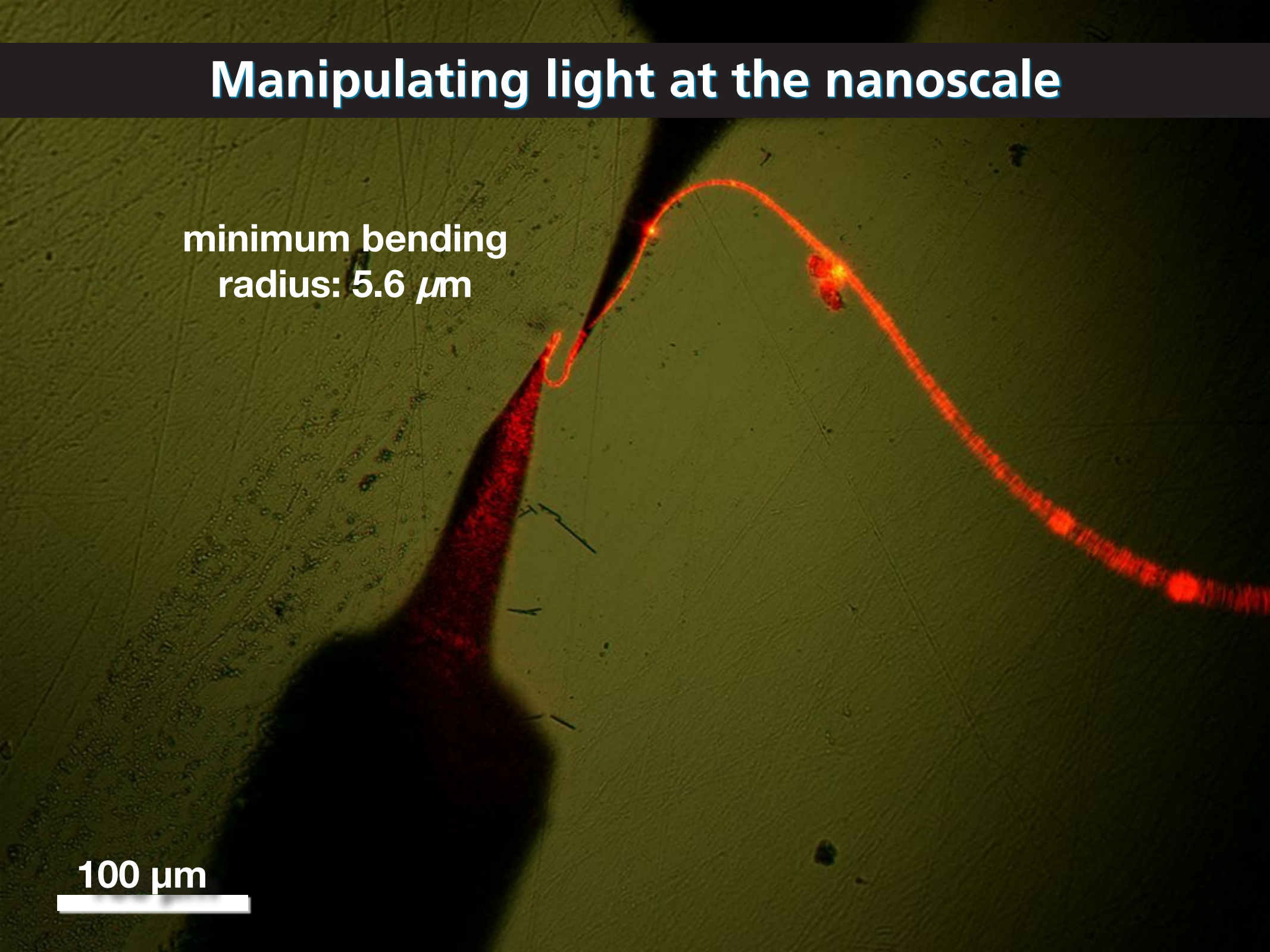
Manipulating light at the nanoscale



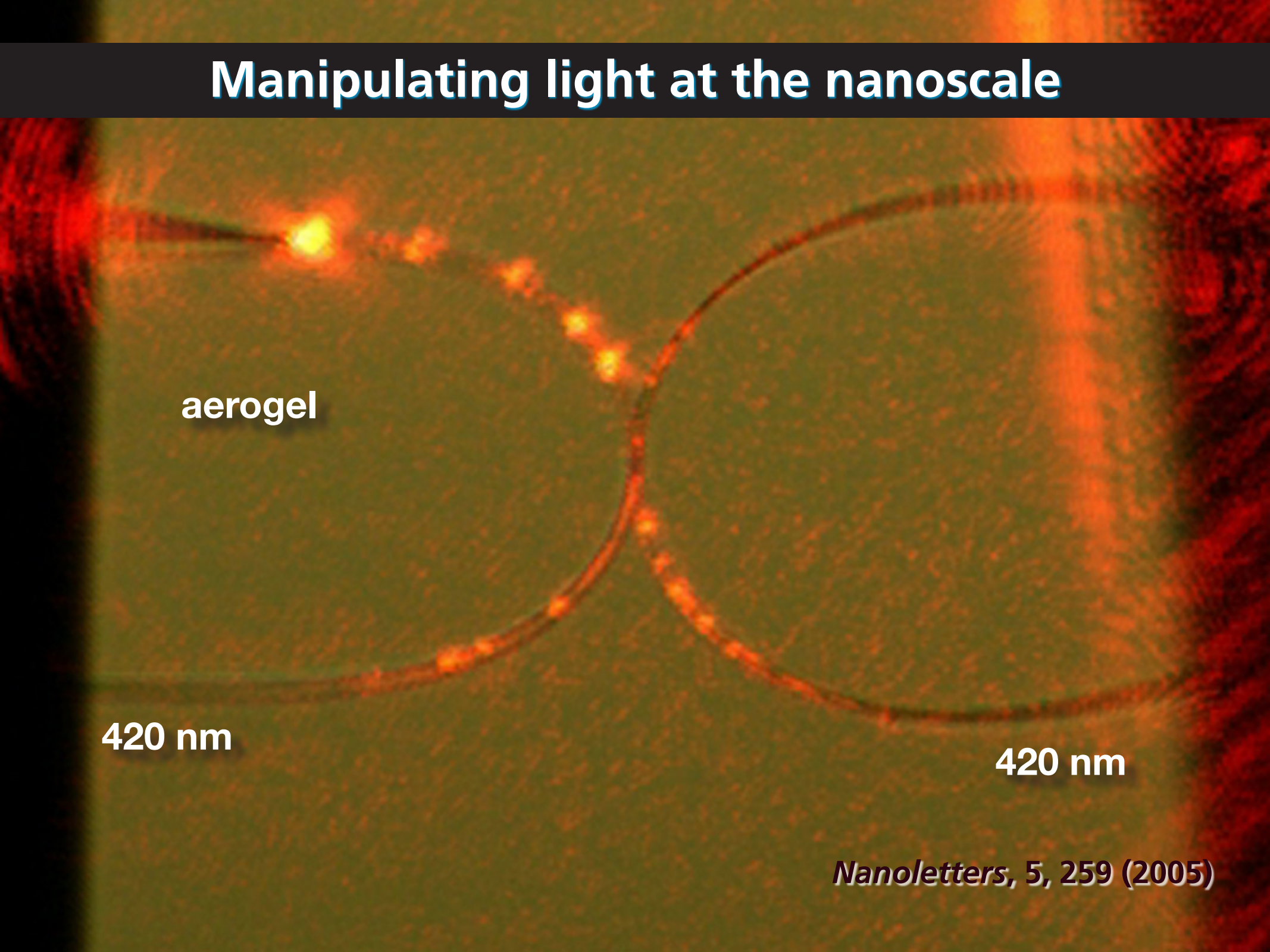
Manipulating light at the nanoscale



Manipulating light at the nanoscale

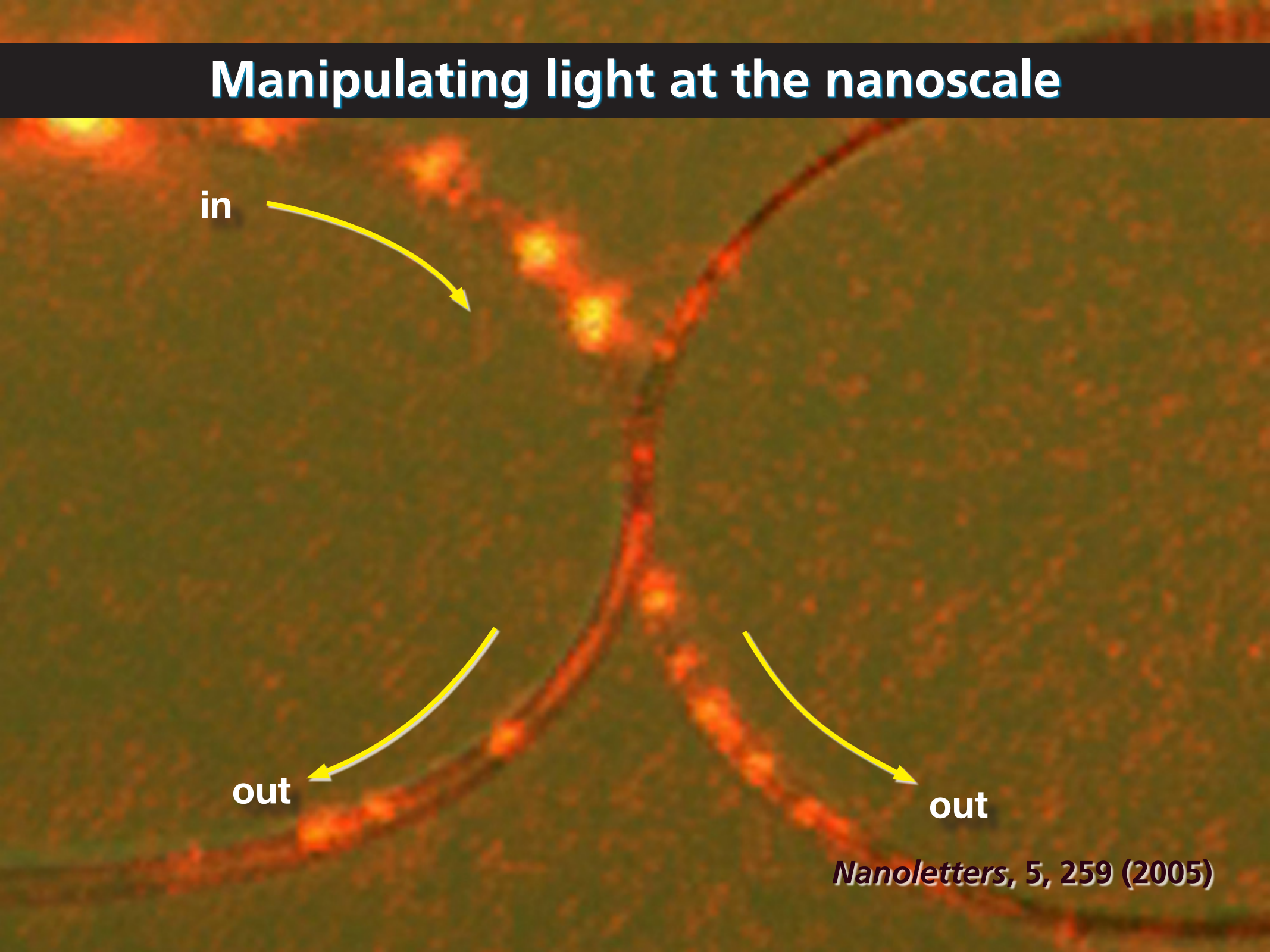


Manipulating light at the nanoscale



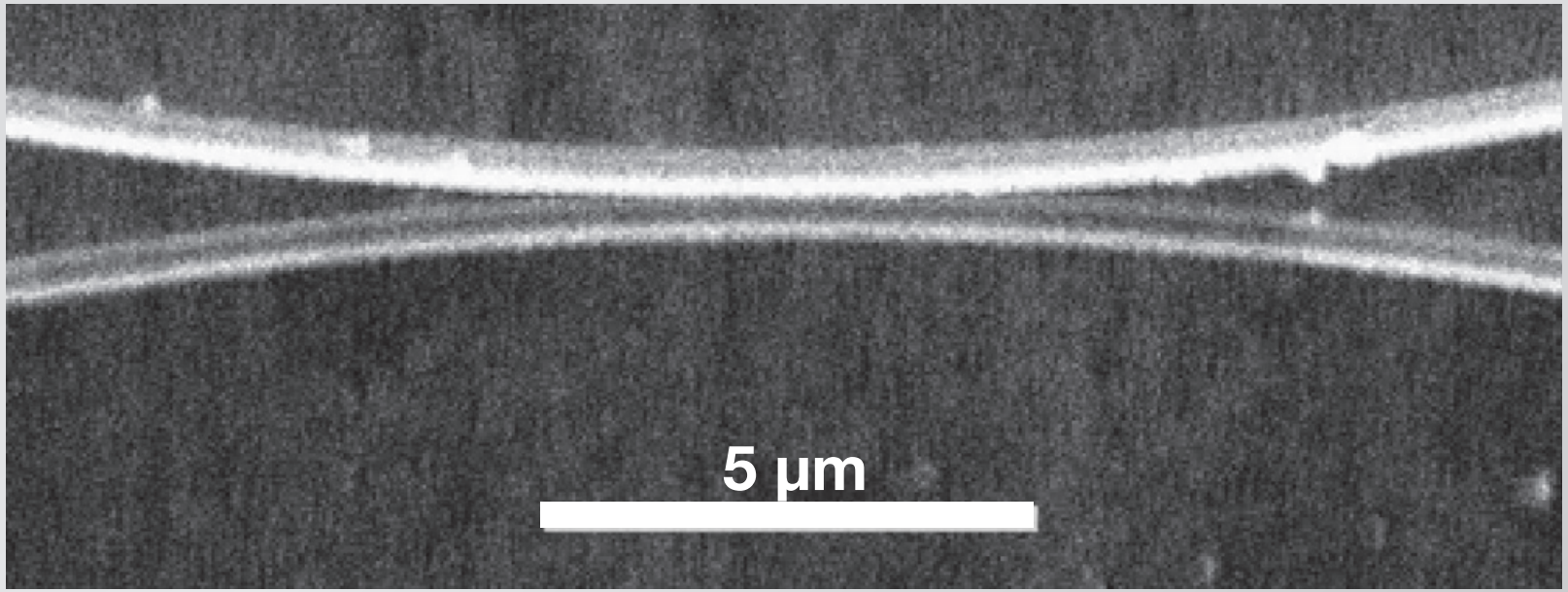
Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



Nanoletters, 5, 259 (2005)

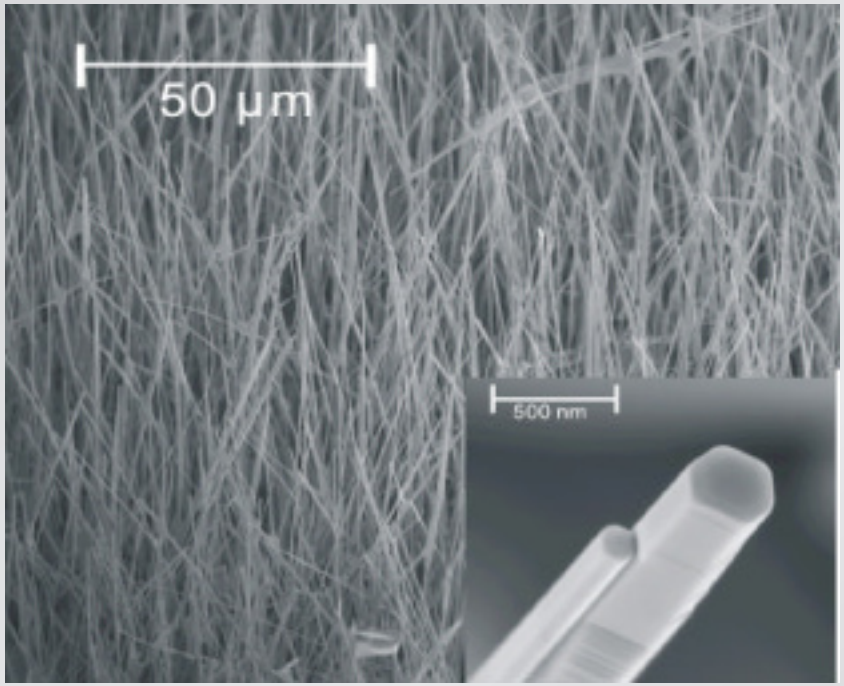
Manipulating light at the nanoscale

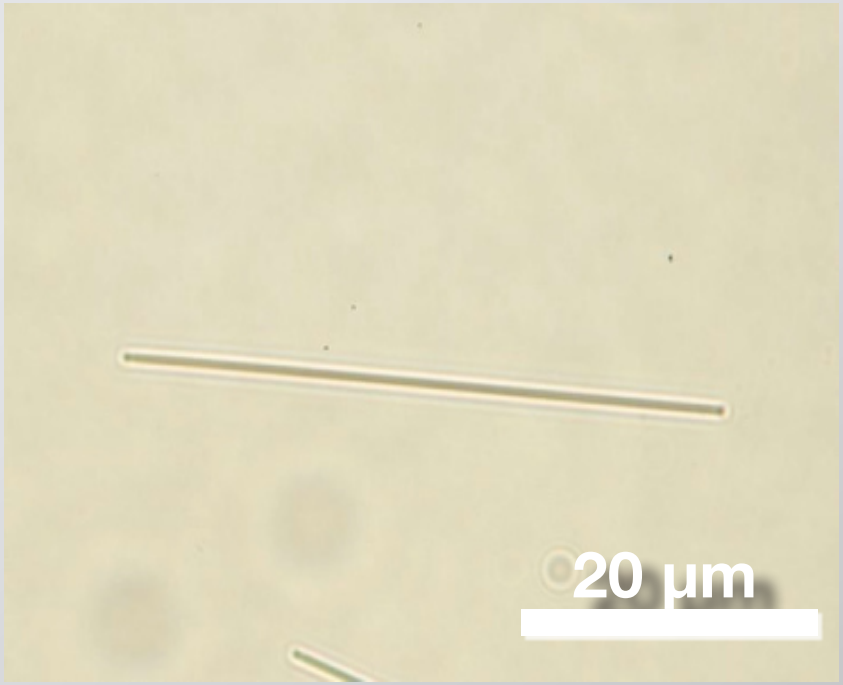
use tapered fibers to couple light to nanoscale objects

Manipulating light at the nanoscale

Manipulating light at the nanoscale

vapor transport grown ZnO nanowires





80–400 nm diameter, up to 80 µm long

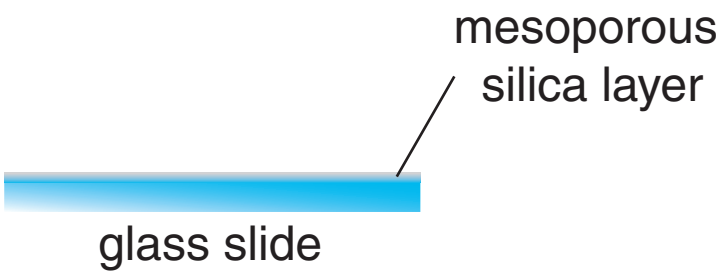
Manipulating light at the nanoscale

best of both worlds

ZnO	silica
bottom-up	top-down
semiconductor	glass
active photonic devices	passive waveguides
electrical operation	link to macroworld

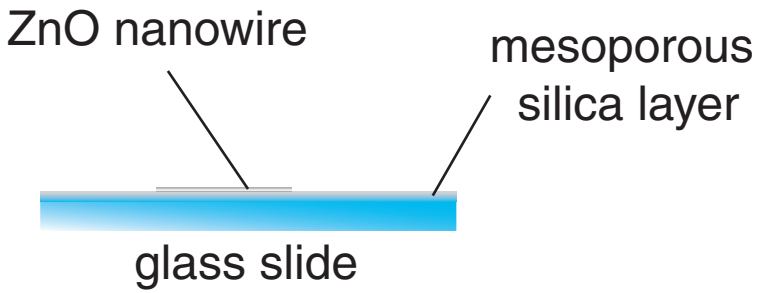
Manipulating light at the nanoscale

coupling to ZnO nanowires



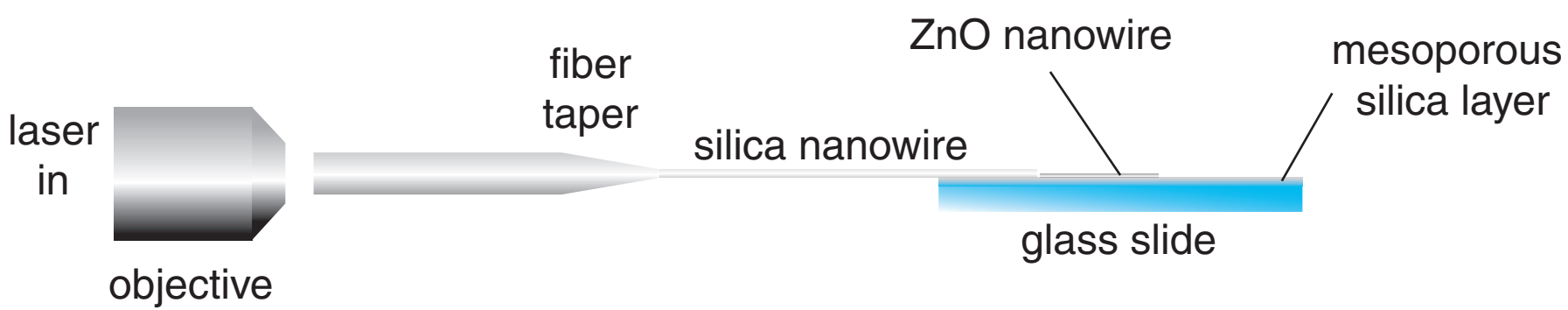
Manipulating light at the nanoscale

coupling to ZnO nanowires



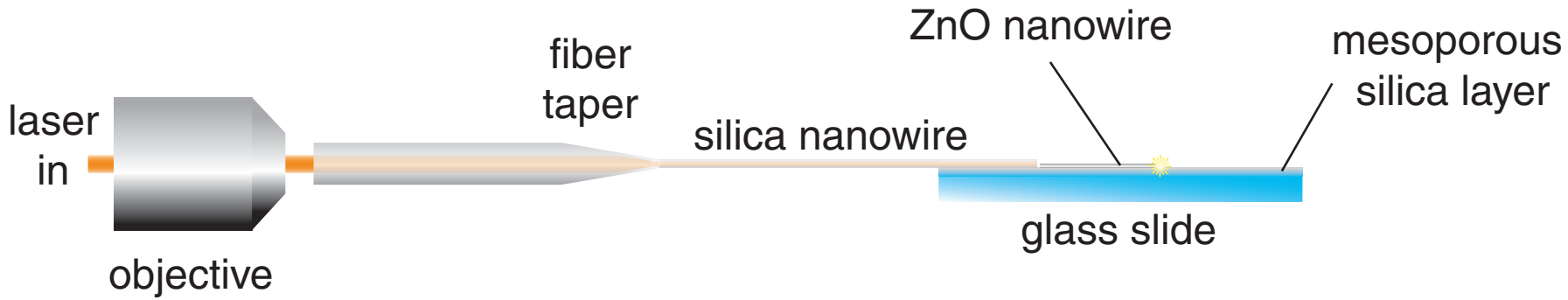
Manipulating light at the nanoscale

coupling to ZnO nanowires

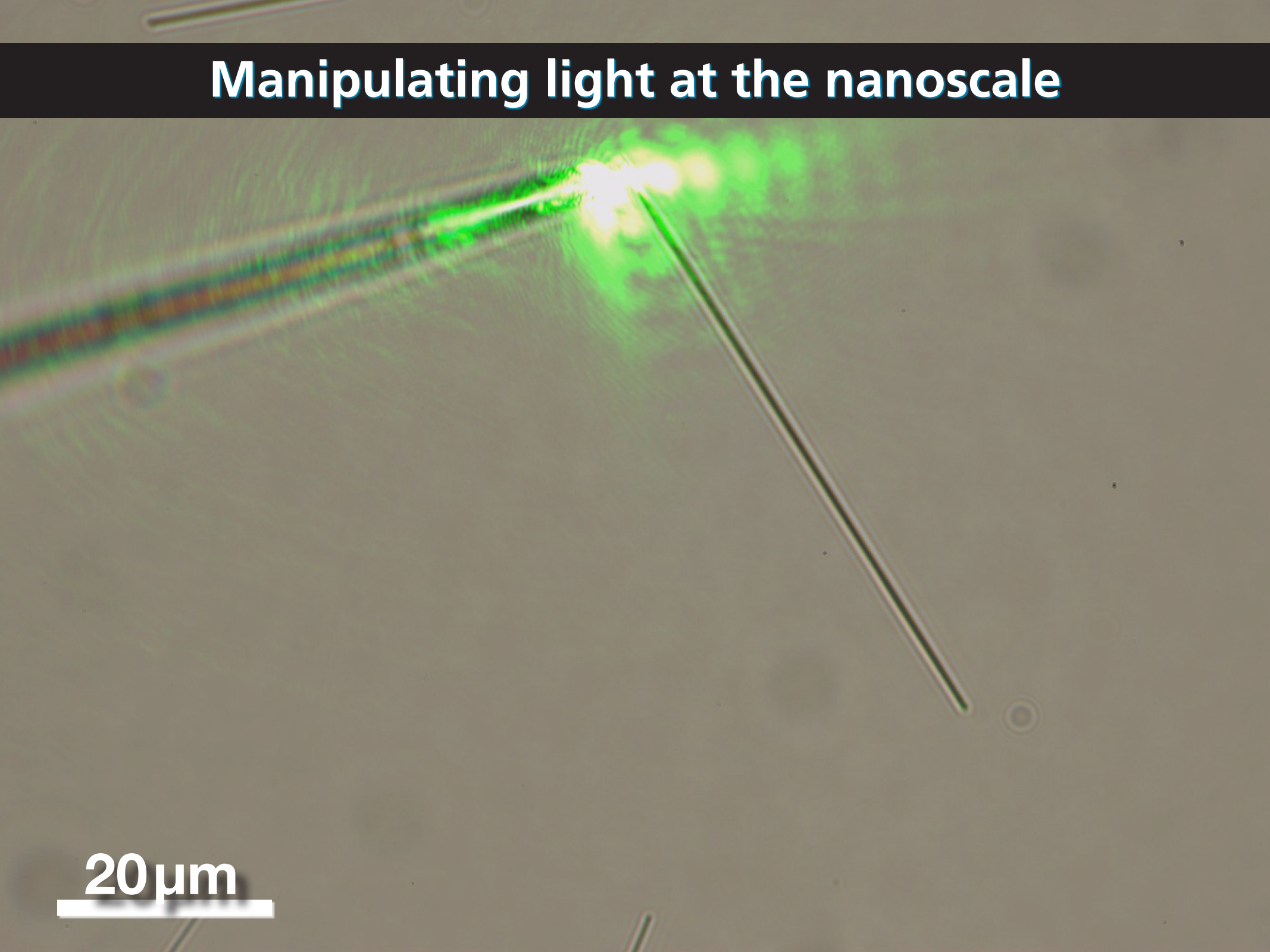


Manipulating light at the nanoscale

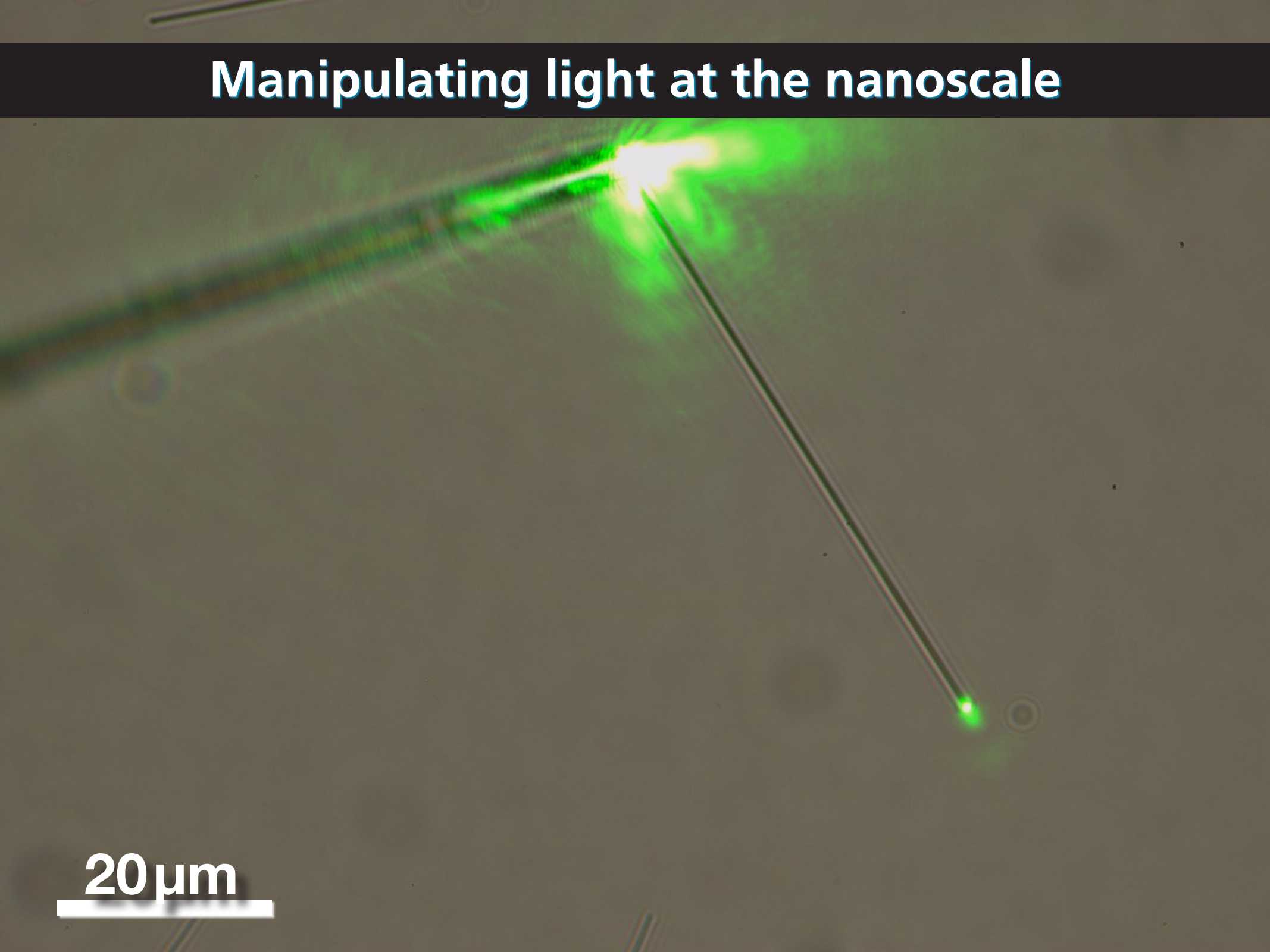
coupling to ZnO nanowires



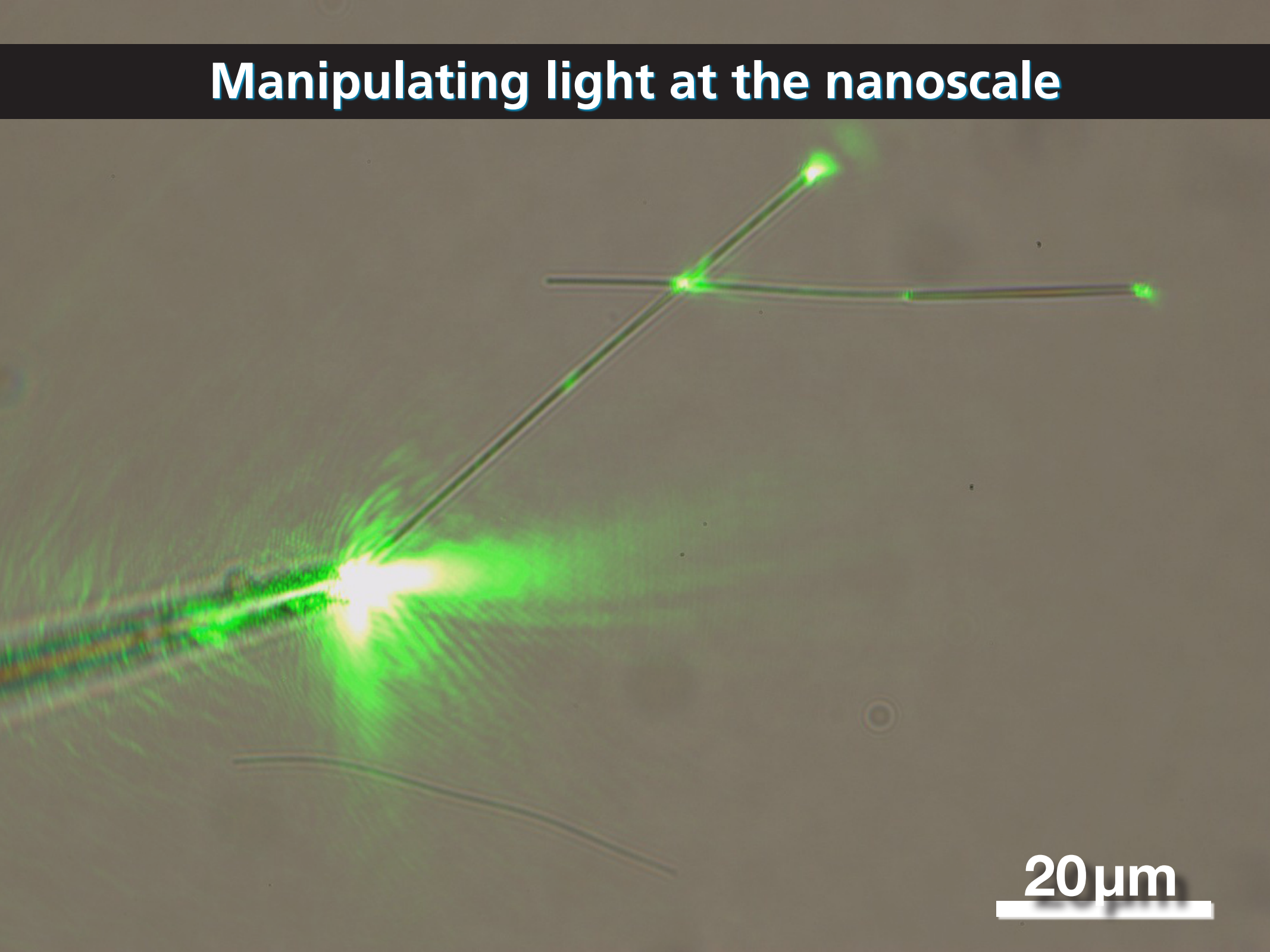
Manipulating light at the nanoscale



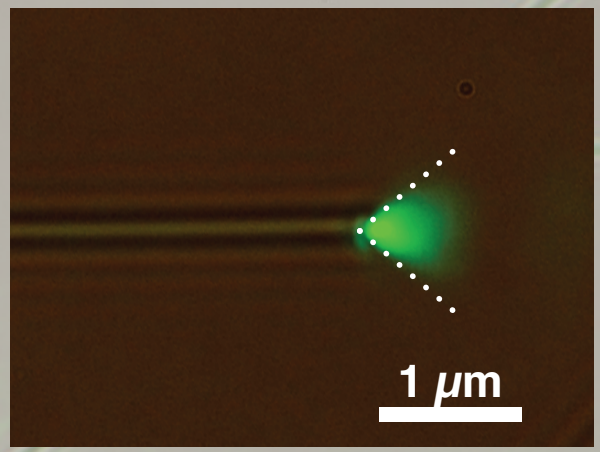
Manipulating light at the nanoscale



Manipulating light at the nanoscale

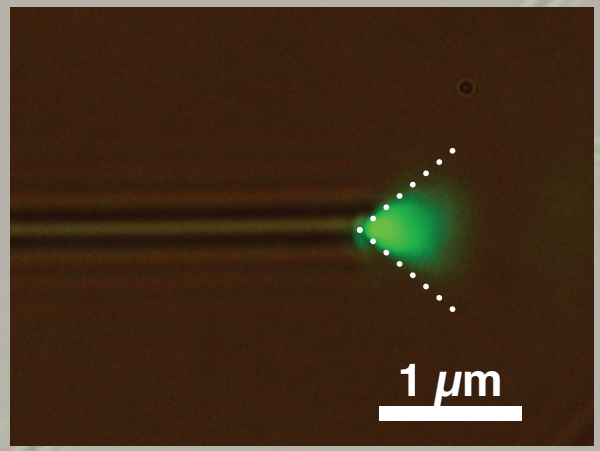


Manipulating light at the nanoscale

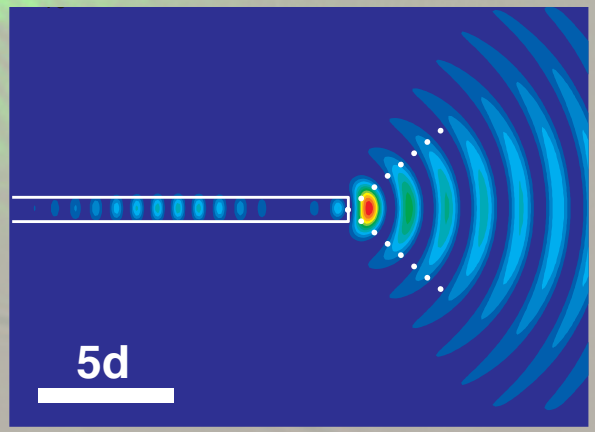


Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



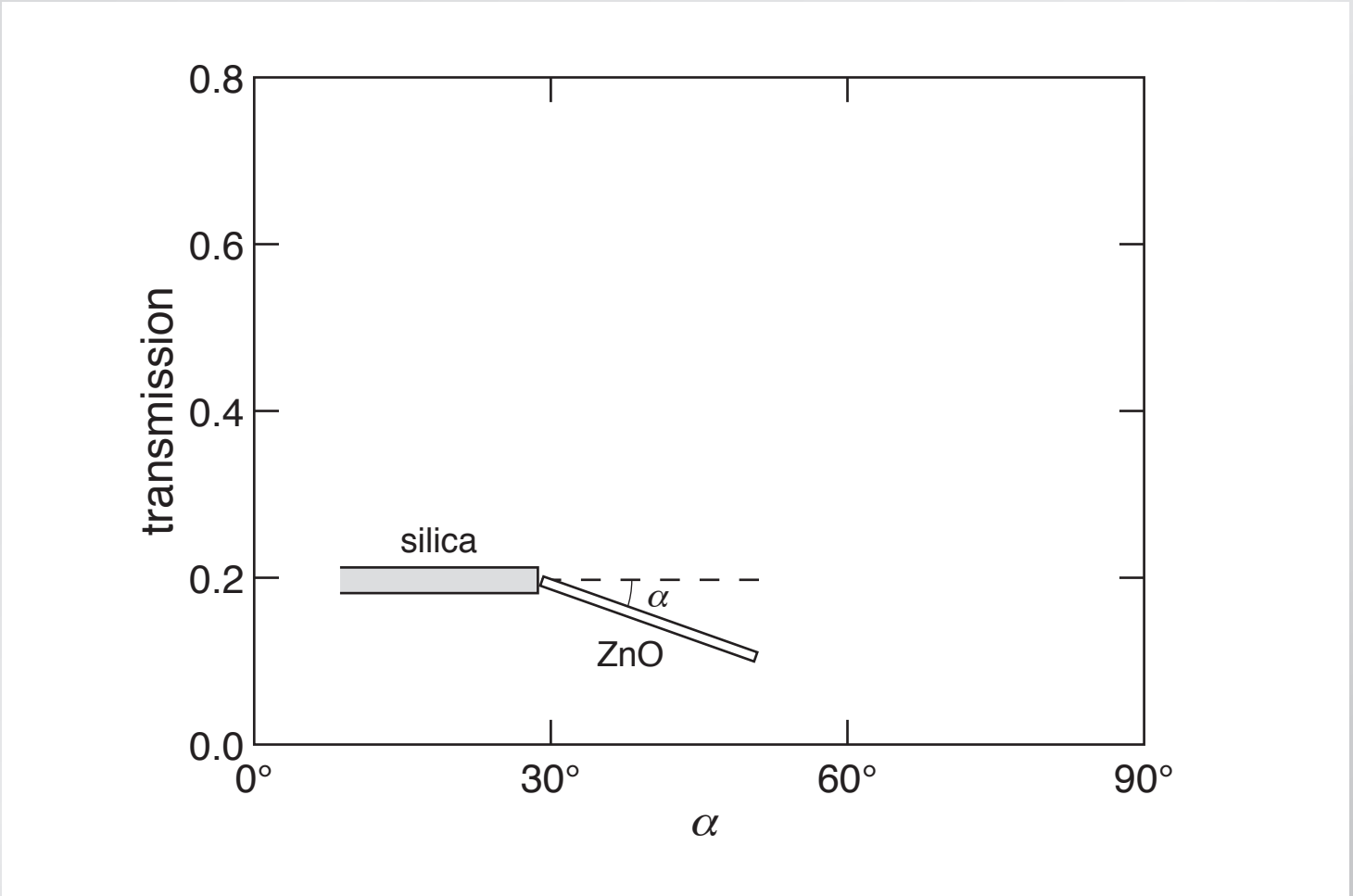
FDTD simulation



ab-initio.mit.edu/wiki/index/Meep

Manipulating light at the nanoscale

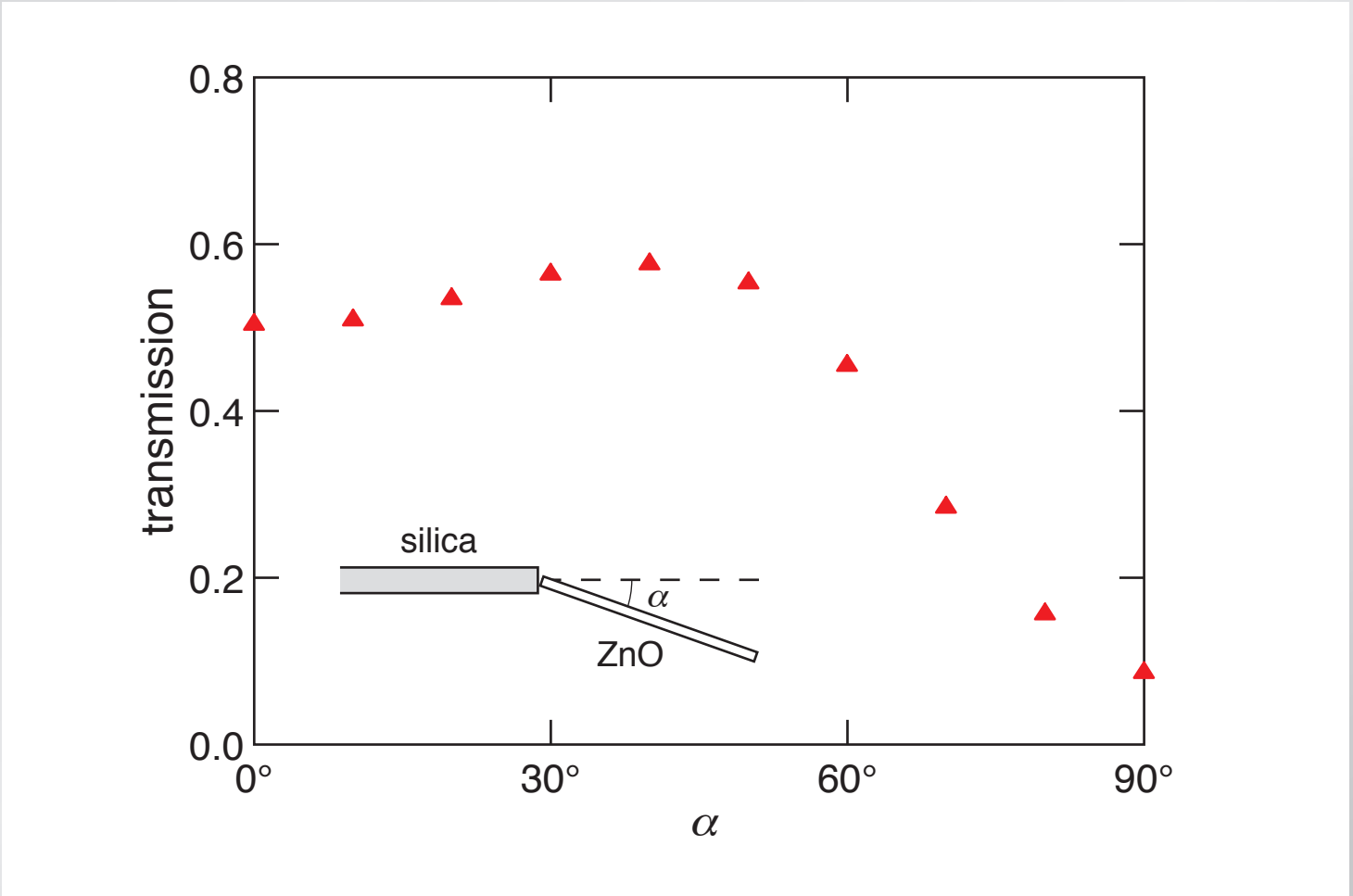
coupling efficiency



Nano Lett., 7, 3675 (2007)

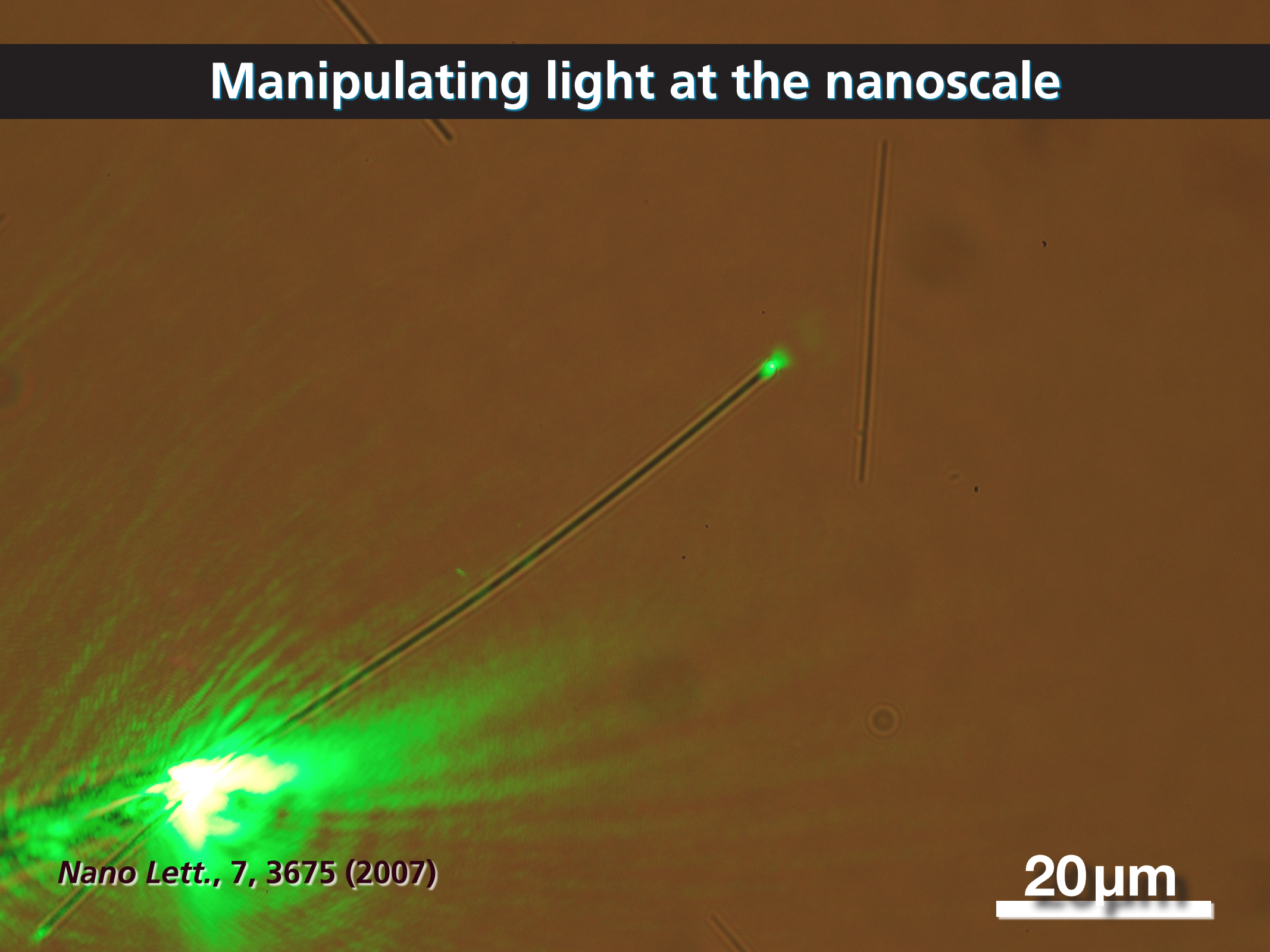
Manipulating light at the nanoscale

coupling efficiency



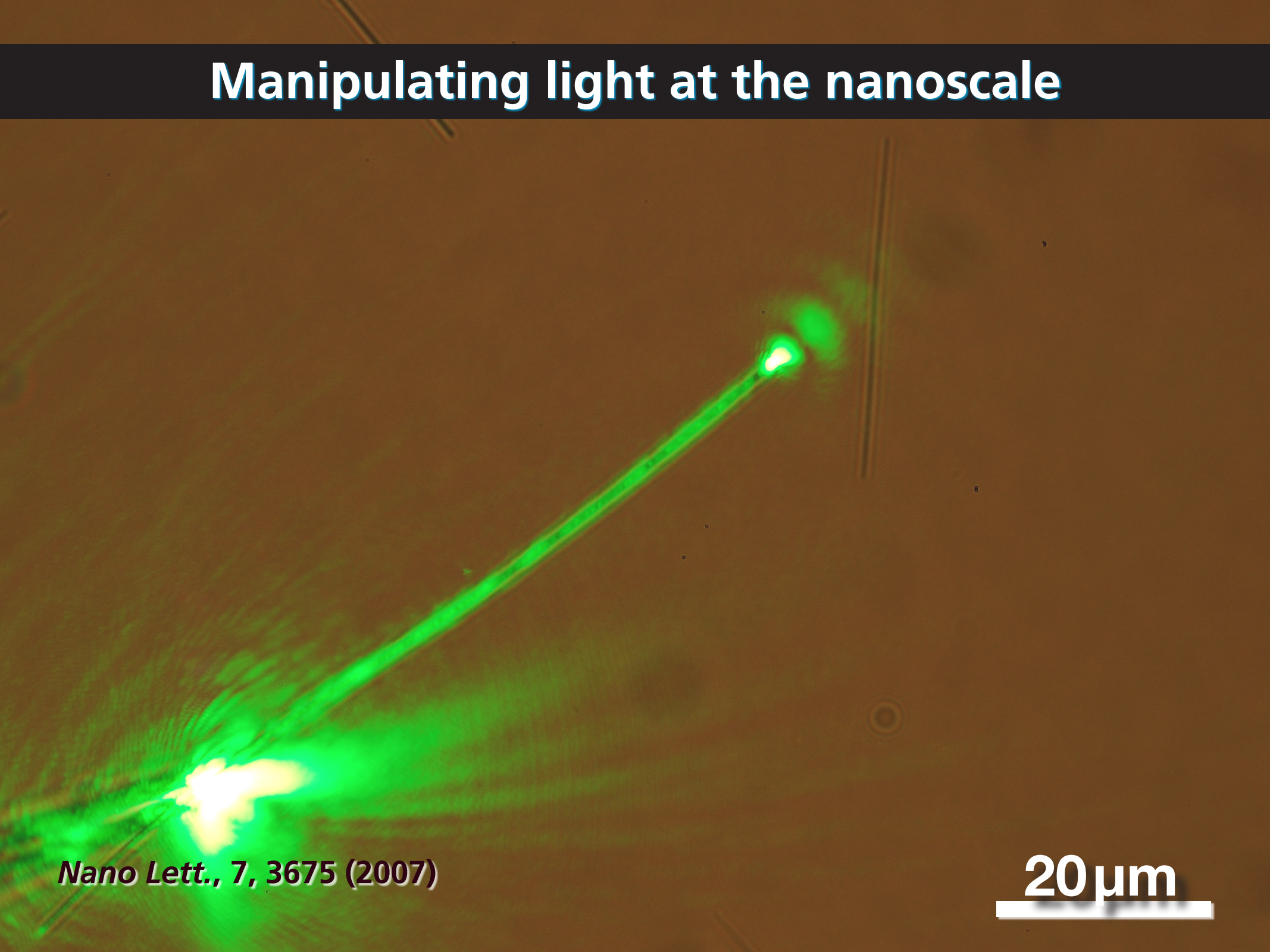
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

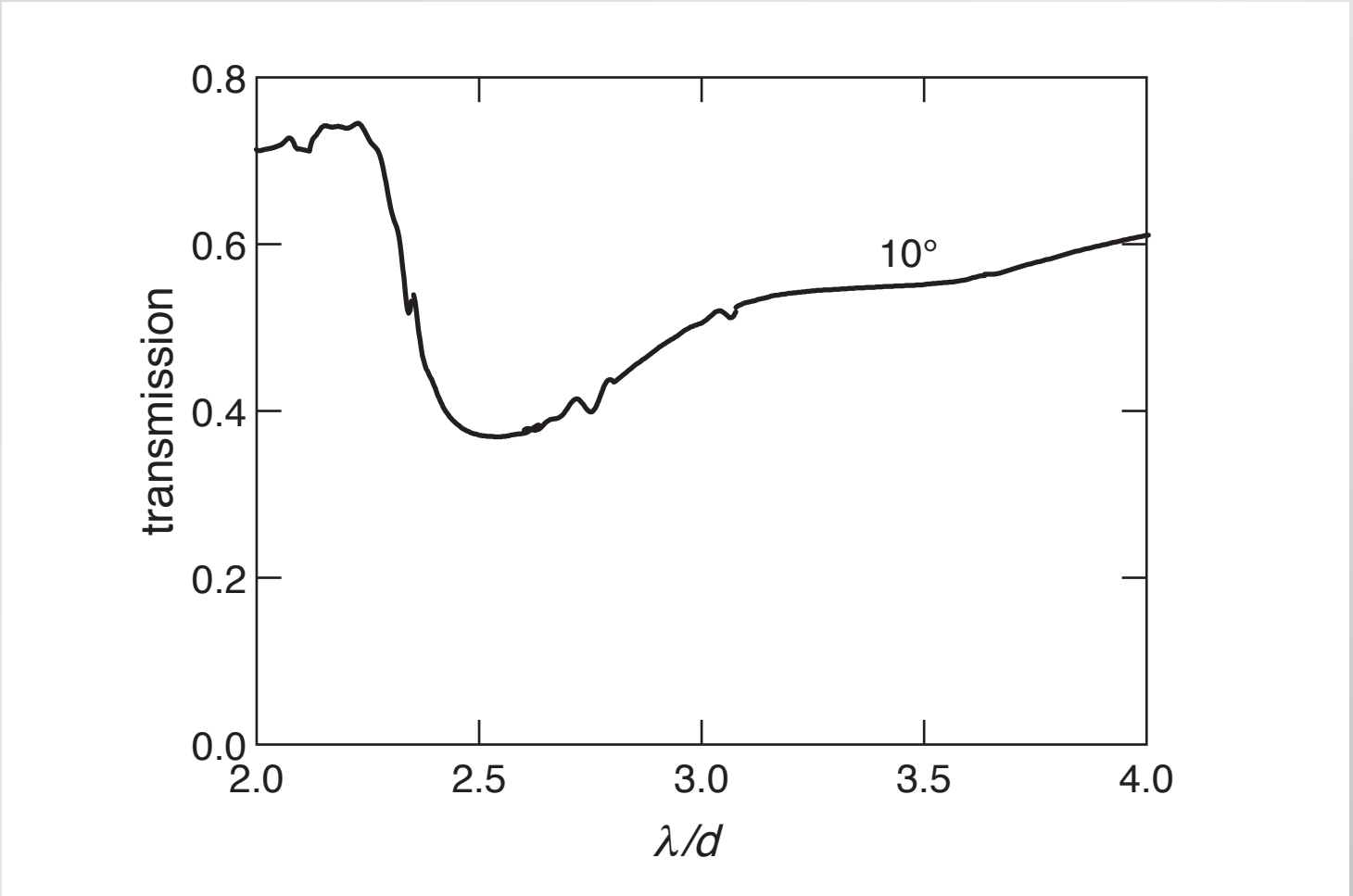
Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

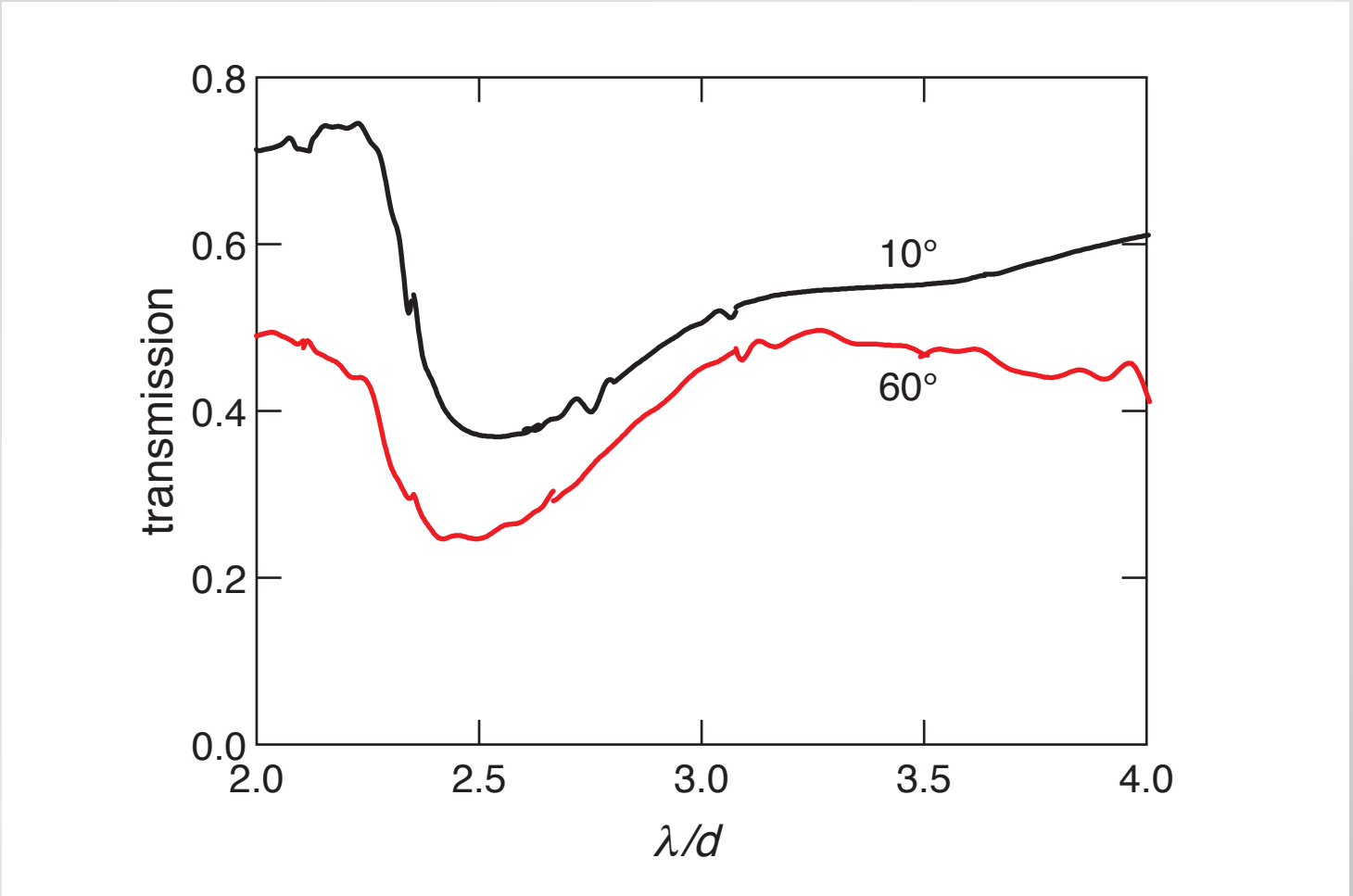
transmission spectrum



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

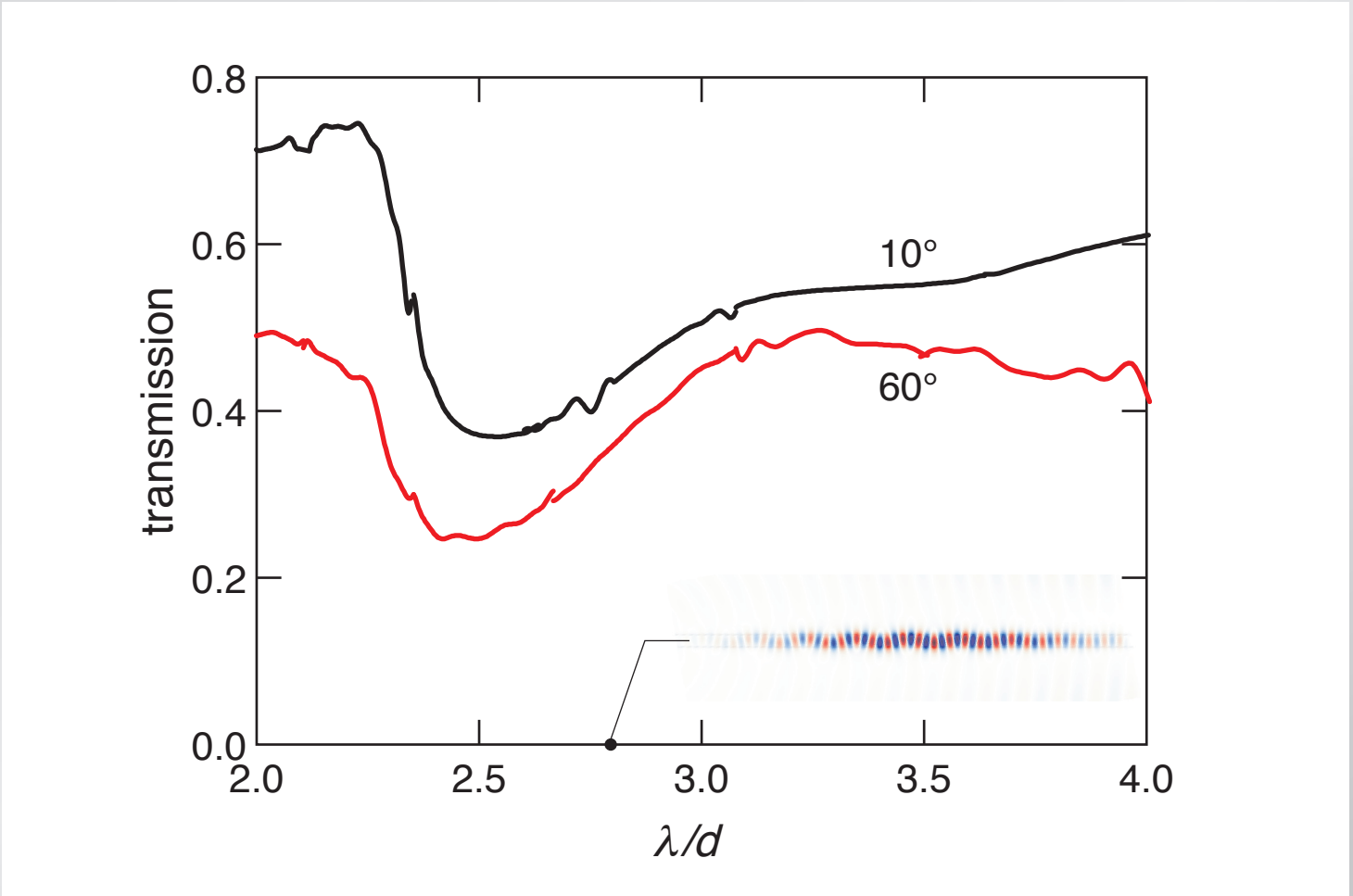
transmission spectrum



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

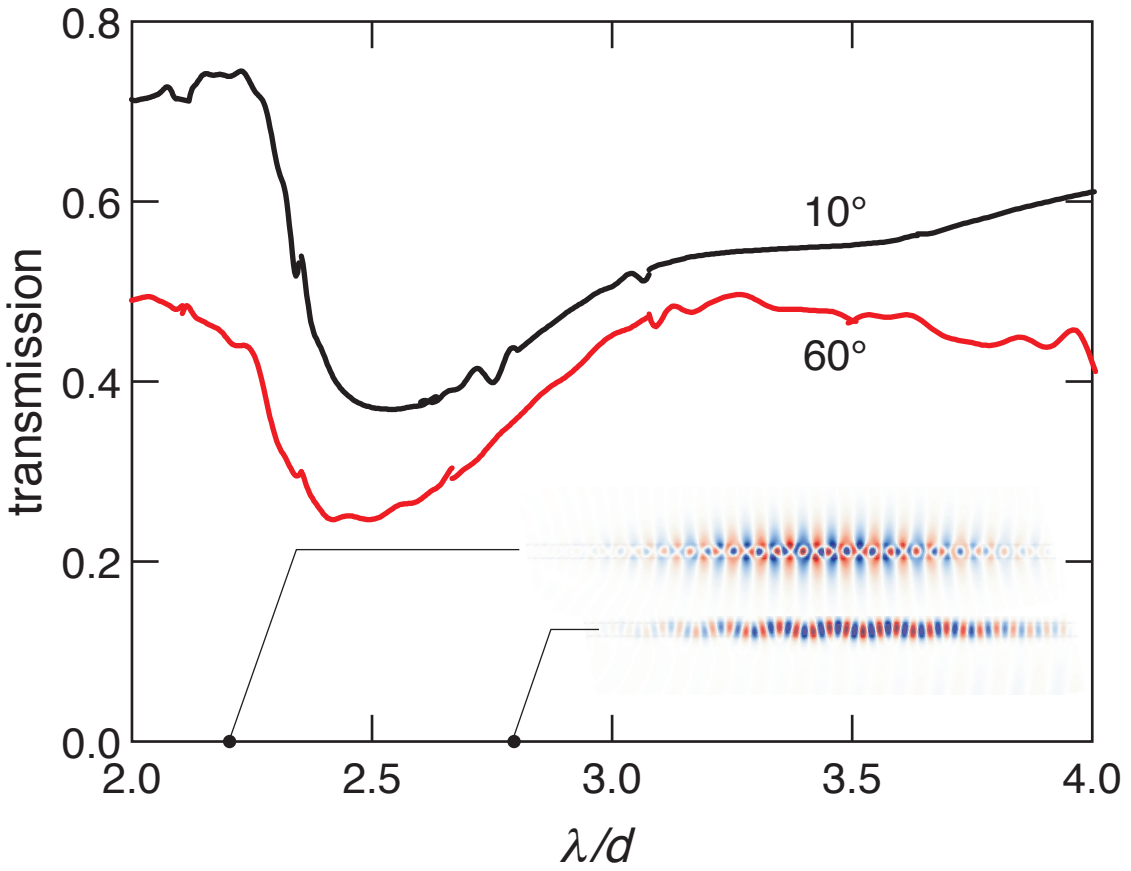
transmission spectrum



Nano Lett., 7, 3675 (2007)

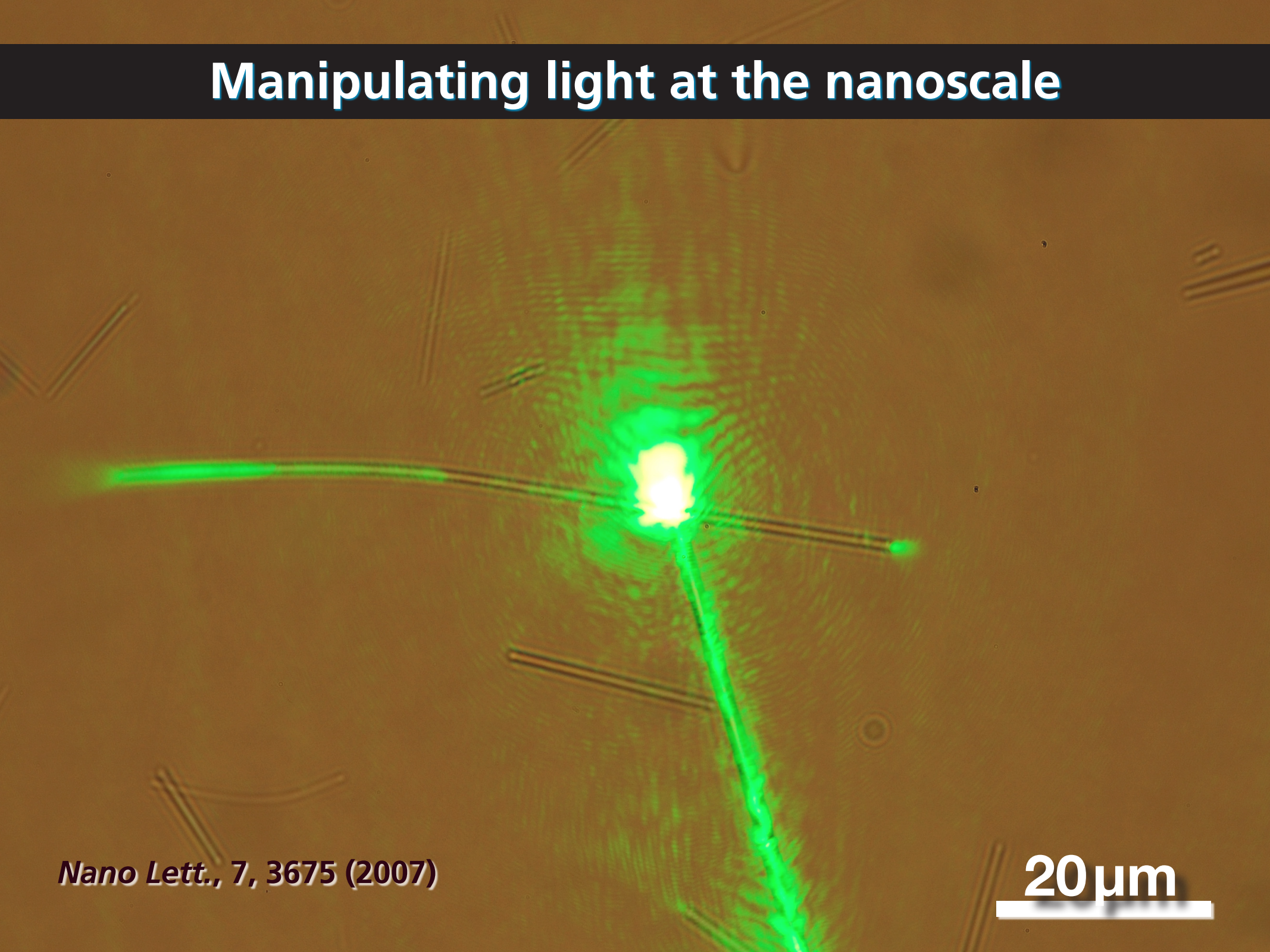
Manipulating light at the nanoscale

transmission spectrum



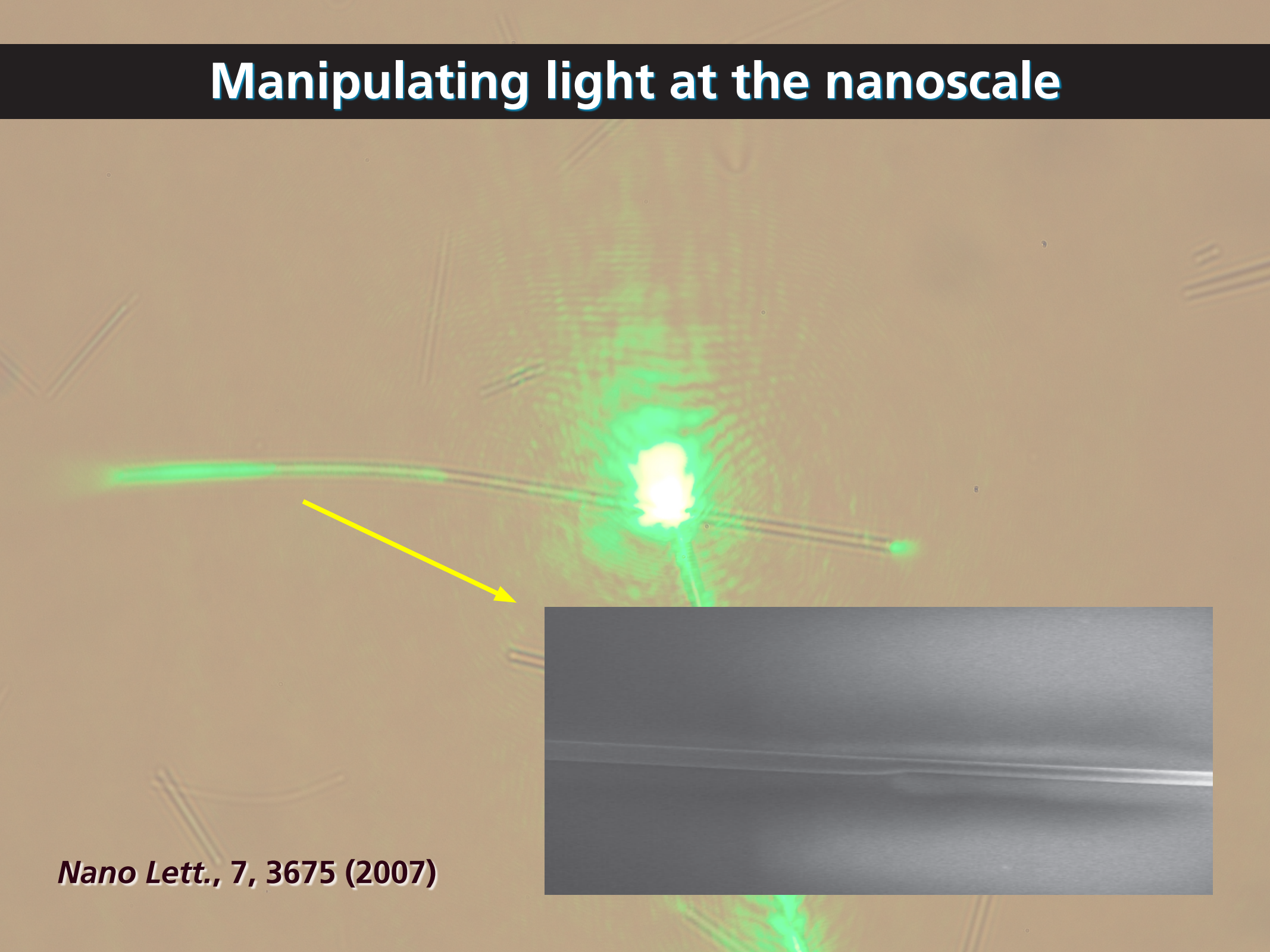
Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

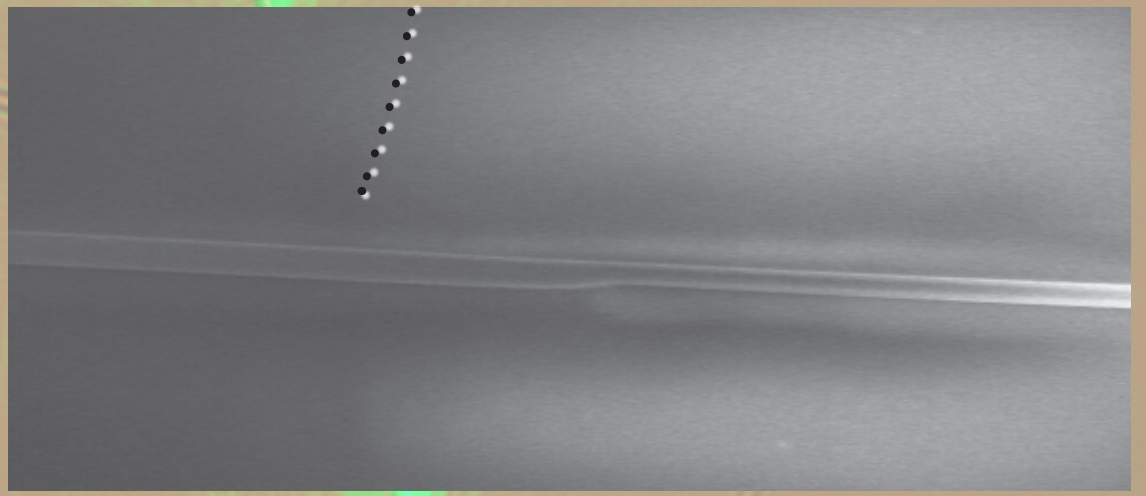
Manipulating light at the nanoscale



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

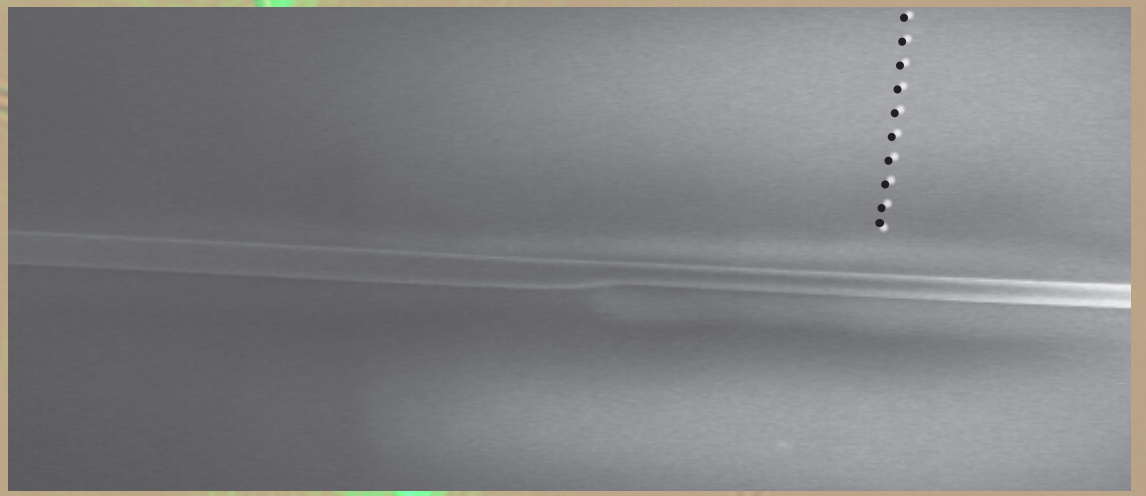
large diameter:
multimode



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

small diameter:
single mode



Nano Lett., 7, 3675 (2007)

Manipulating light at the nanoscale

Points to keep in mind:

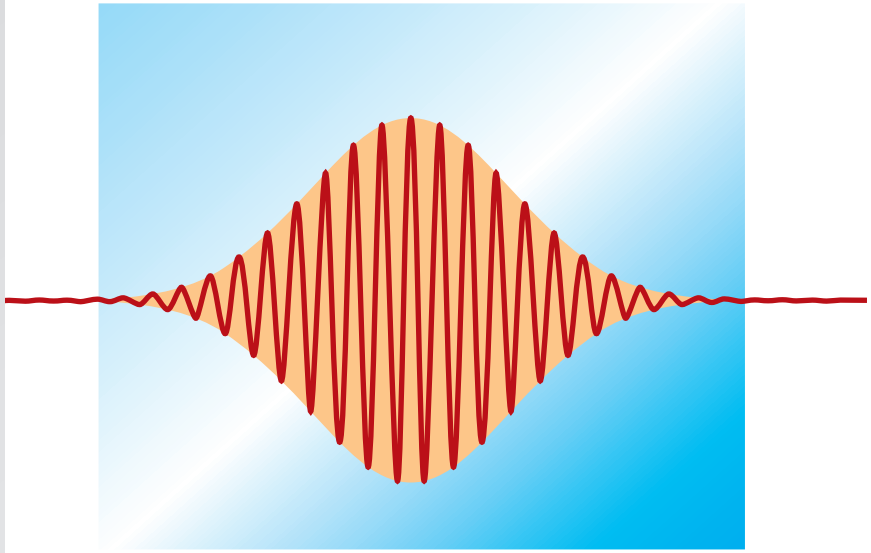
- low-loss guiding
- convenient evanescent coupling
- attached to ordinary fiber

Outline

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

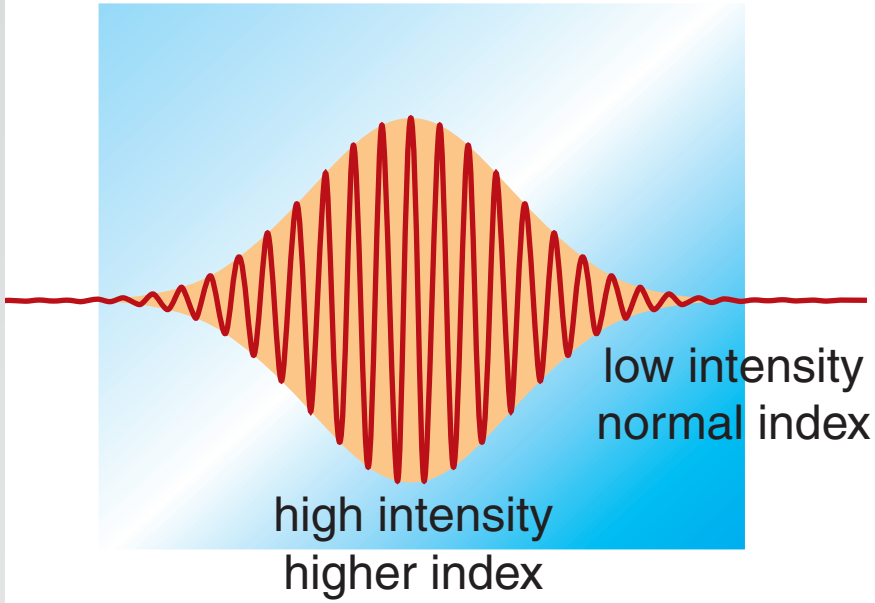
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



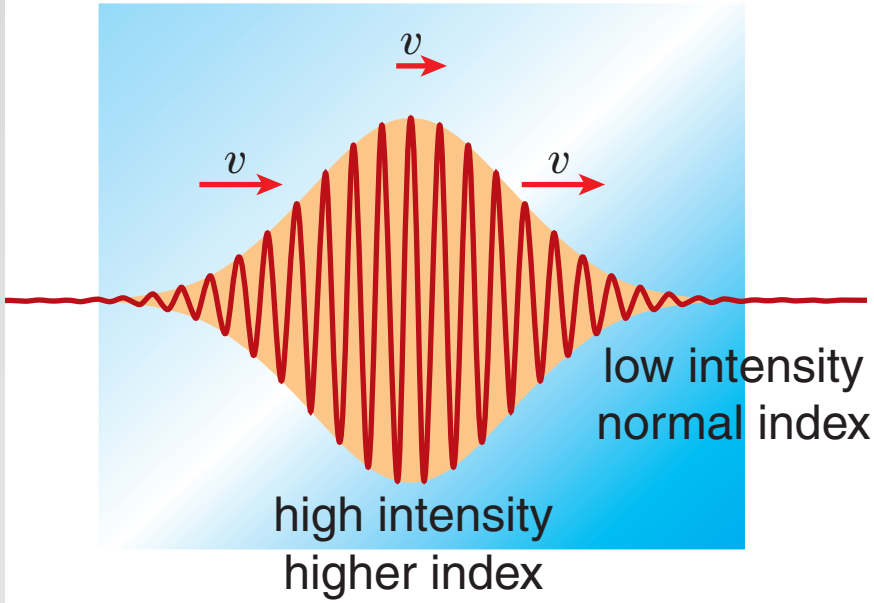
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



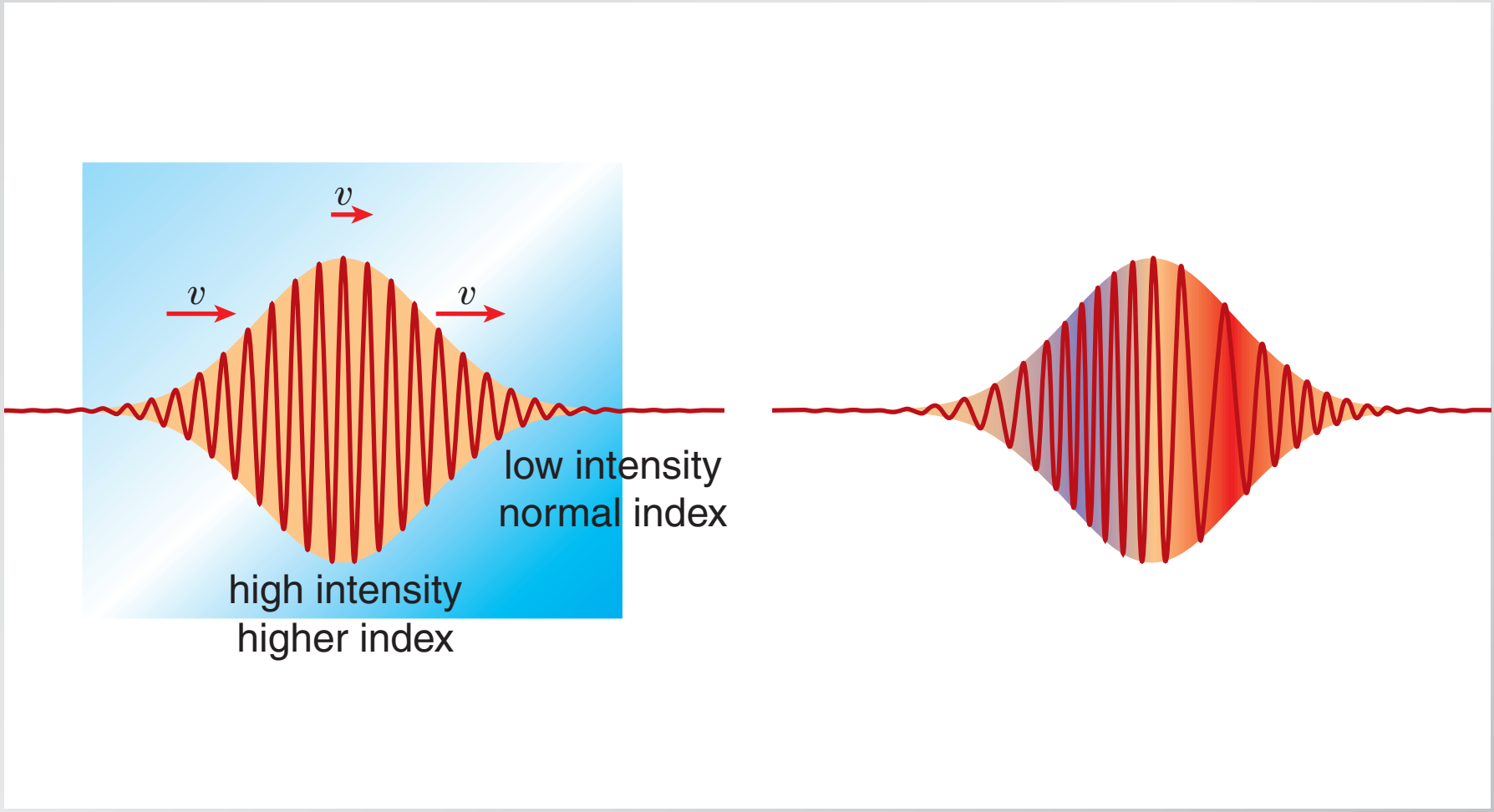
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



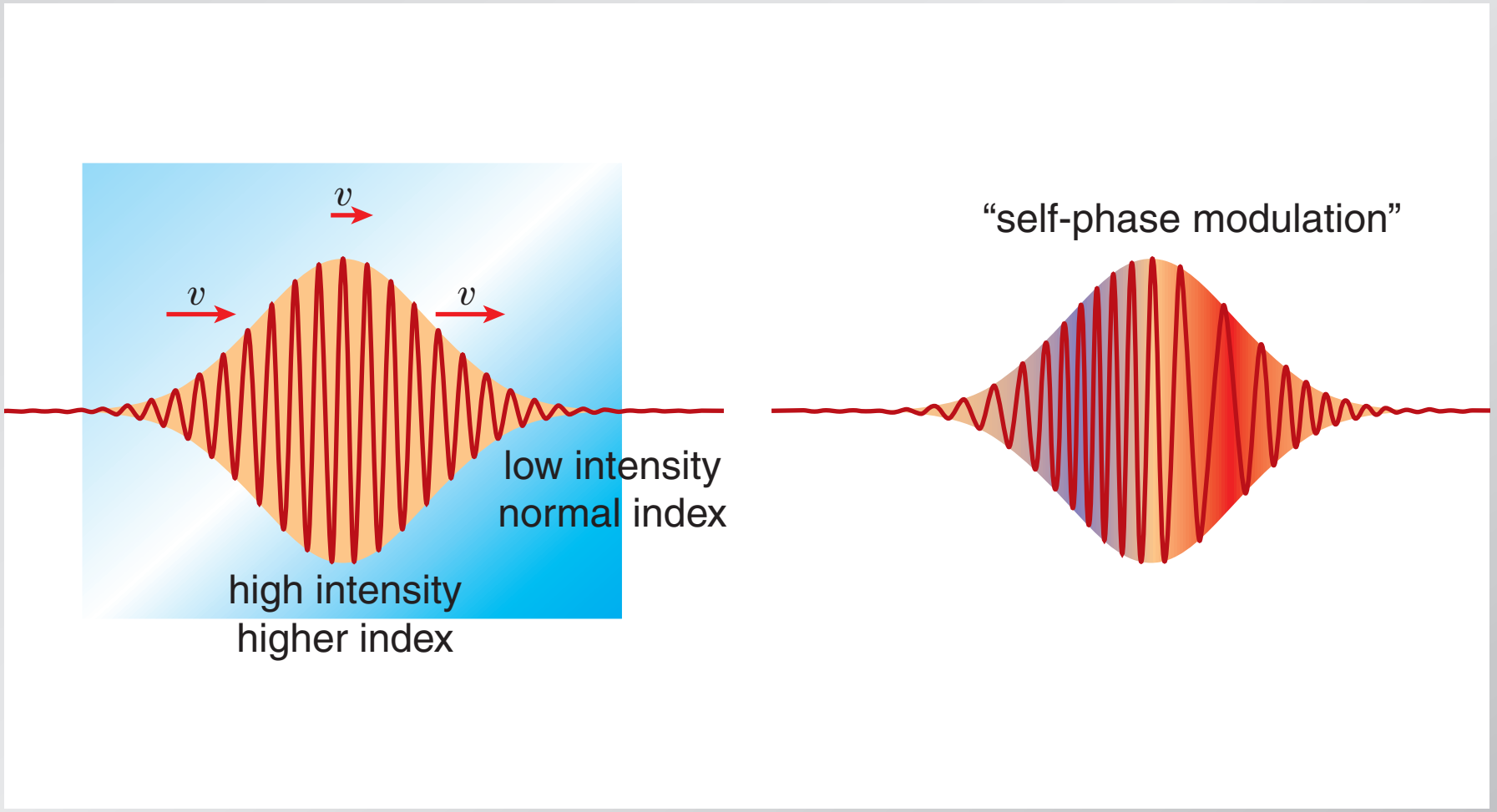
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



Supercontinuum generation

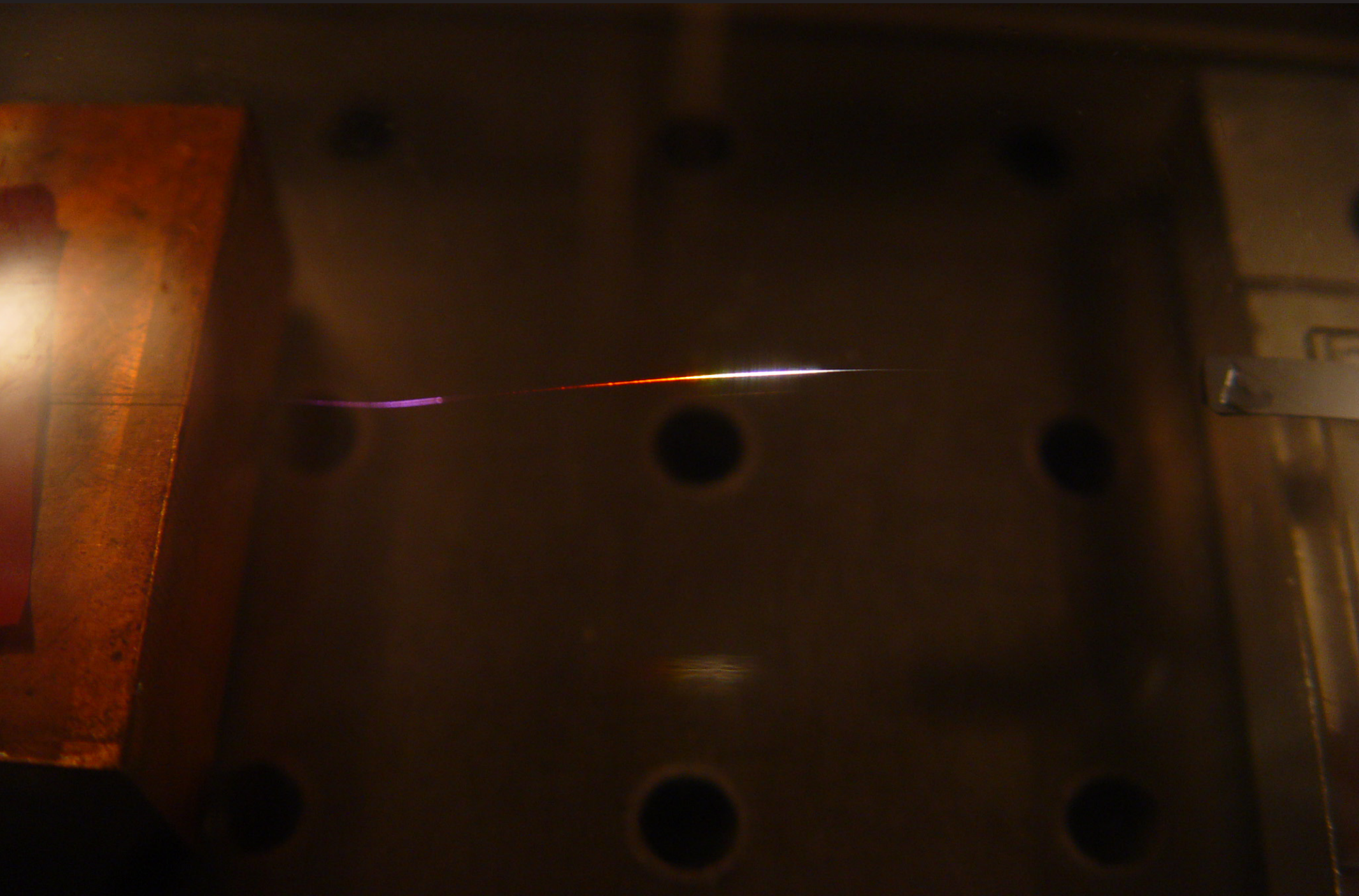
nonlinear dispersion: $n = n_o + n_2 I$



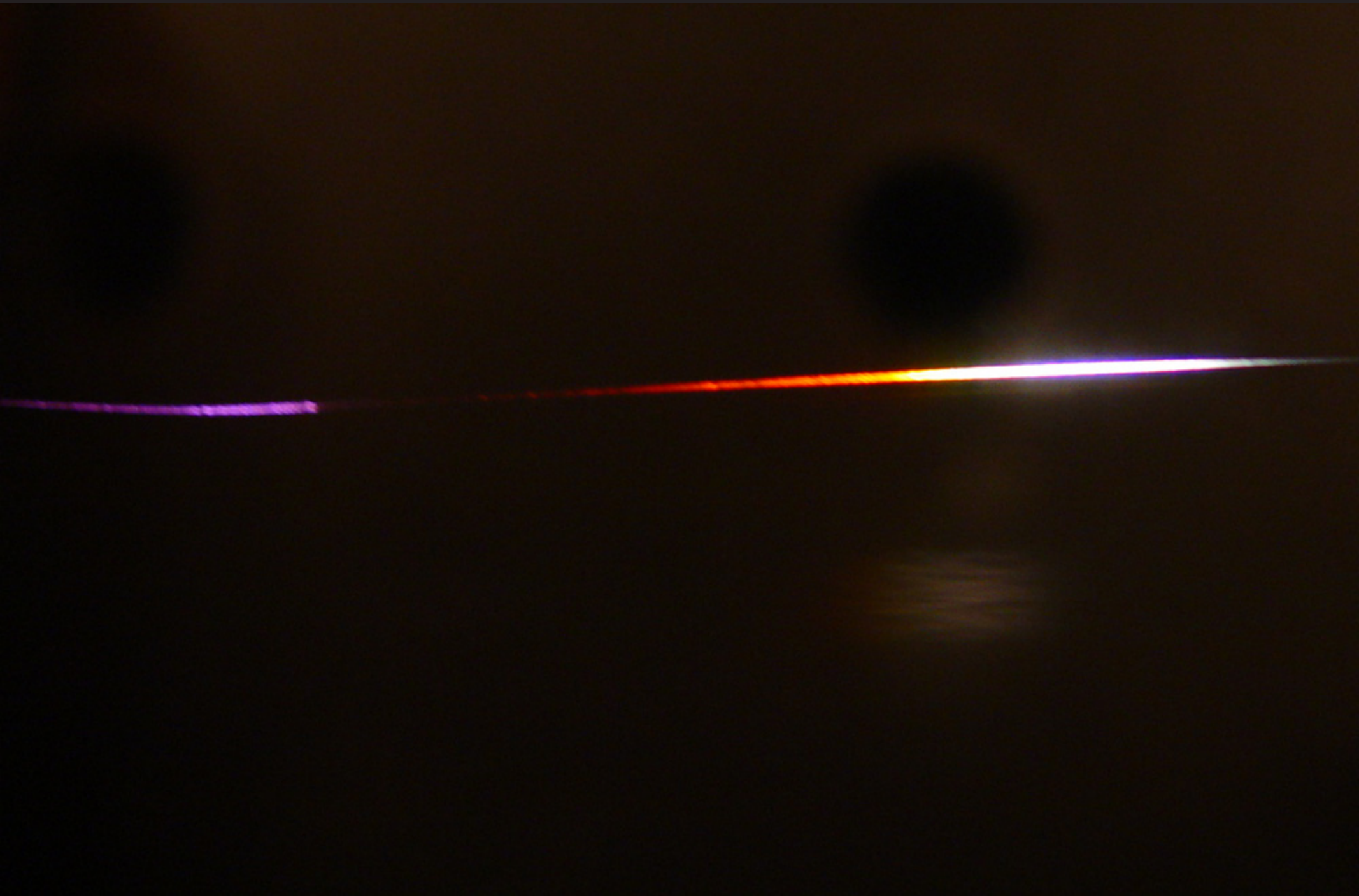
Supercontinuum generation

strong confinement $\longrightarrow$ high intensity

Supercontinuum generation

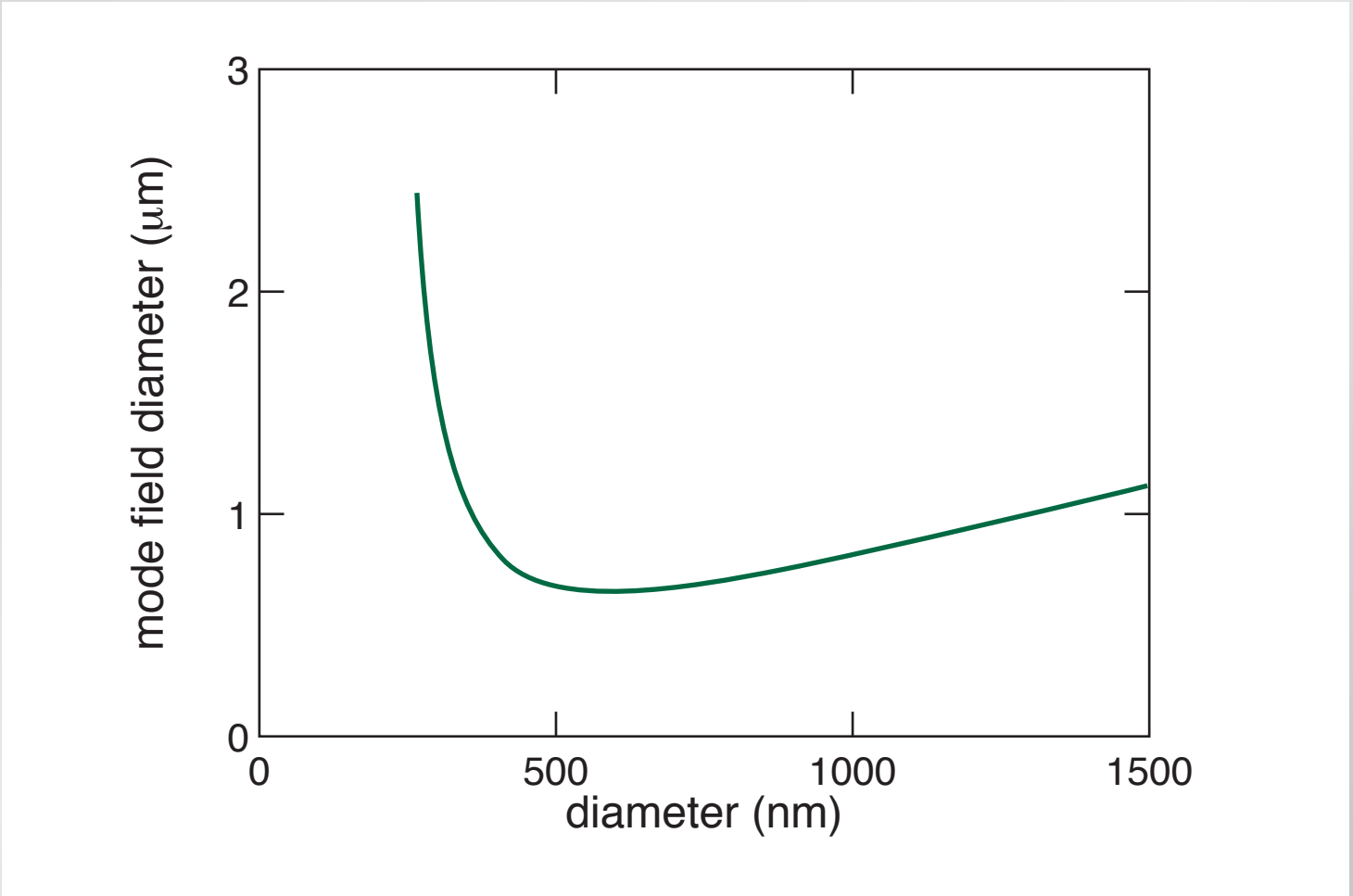


Supercontinuum generation



Supercontinuum generation

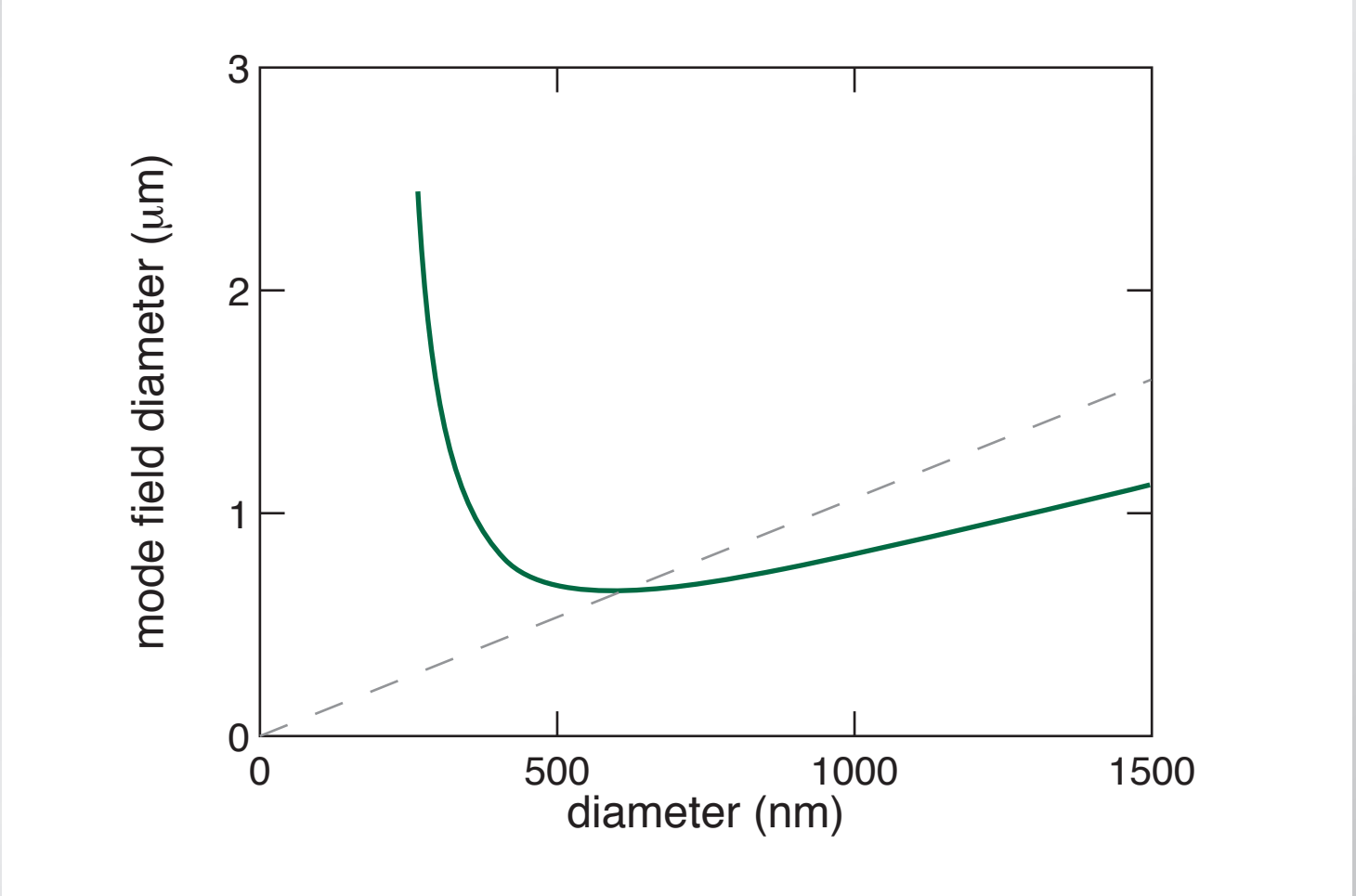
mode field diameter (λ = 800 nm)



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

Supercontinuum generation

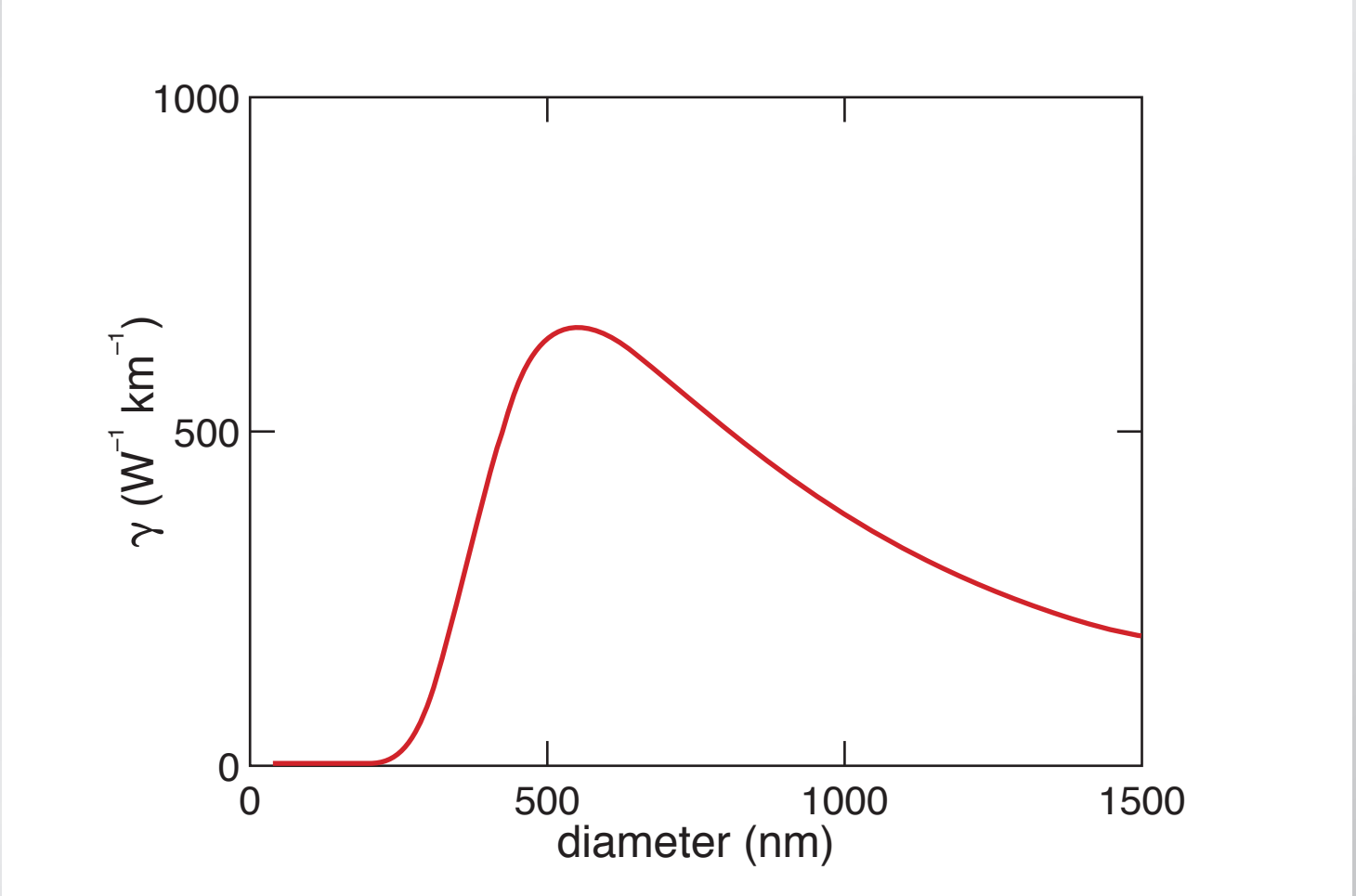
mode field diameter (λ = 800 nm)



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!

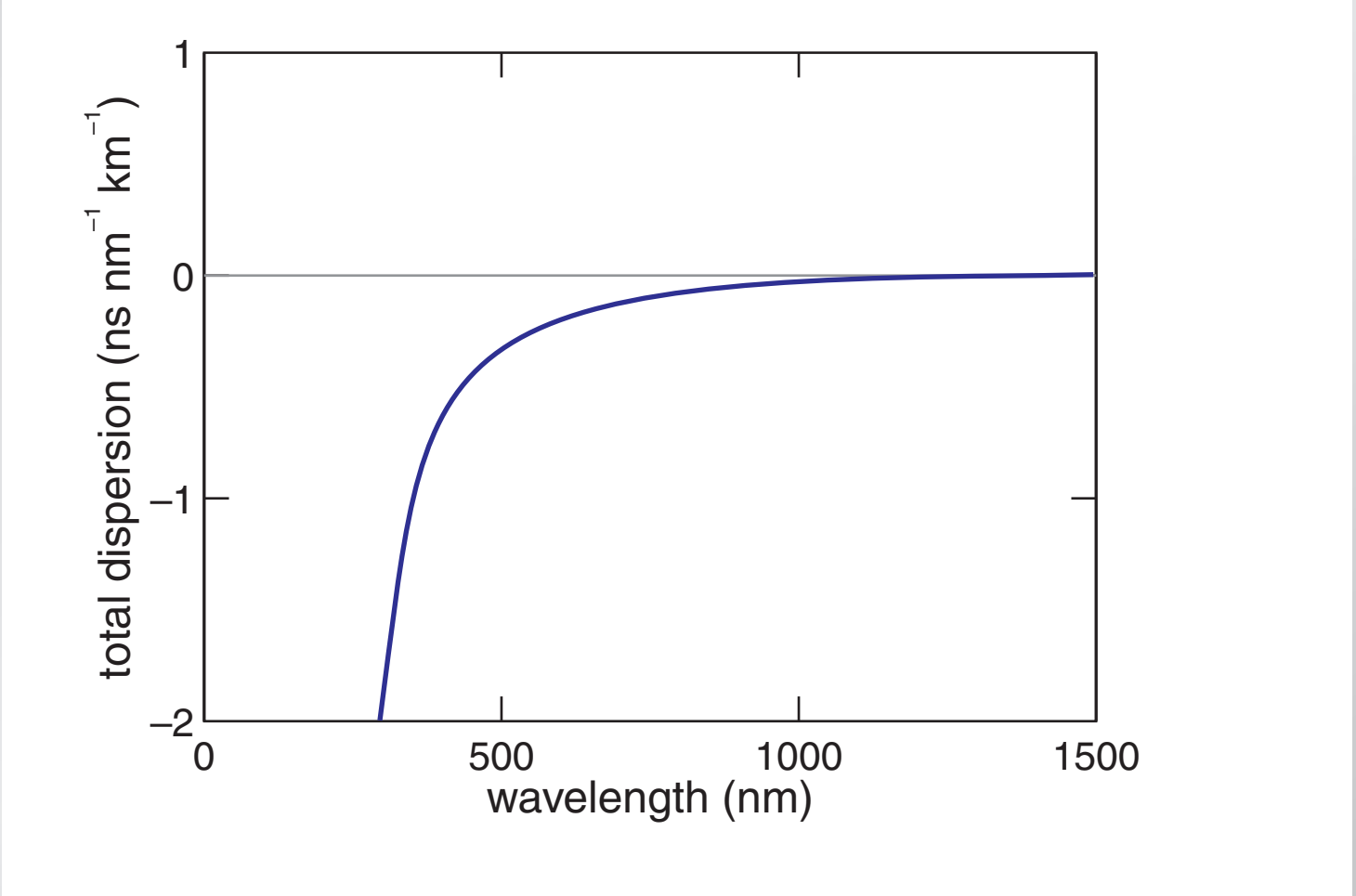
Supercontinuum generation

dispersion:

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

Supercontinuum generation

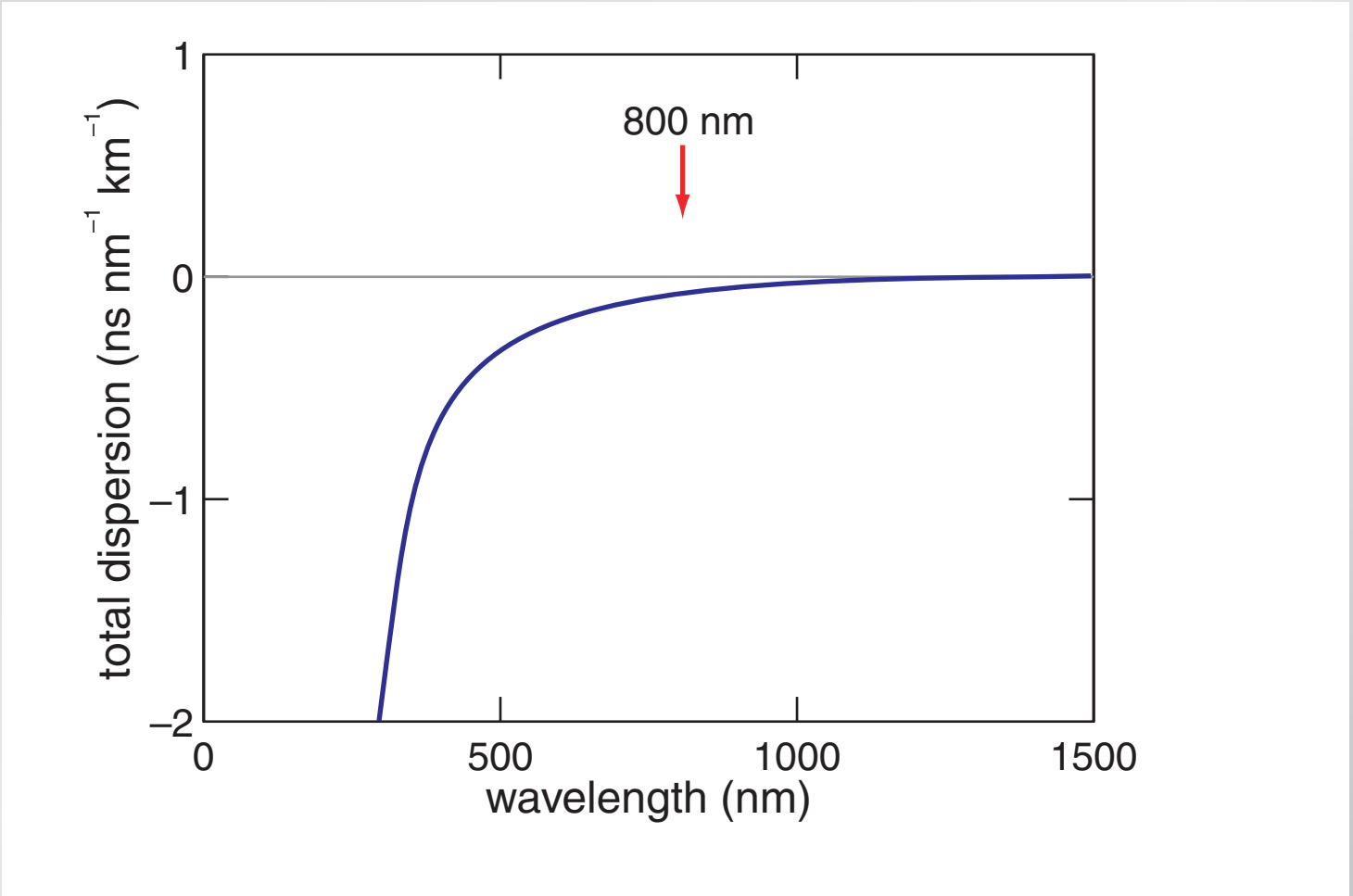
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

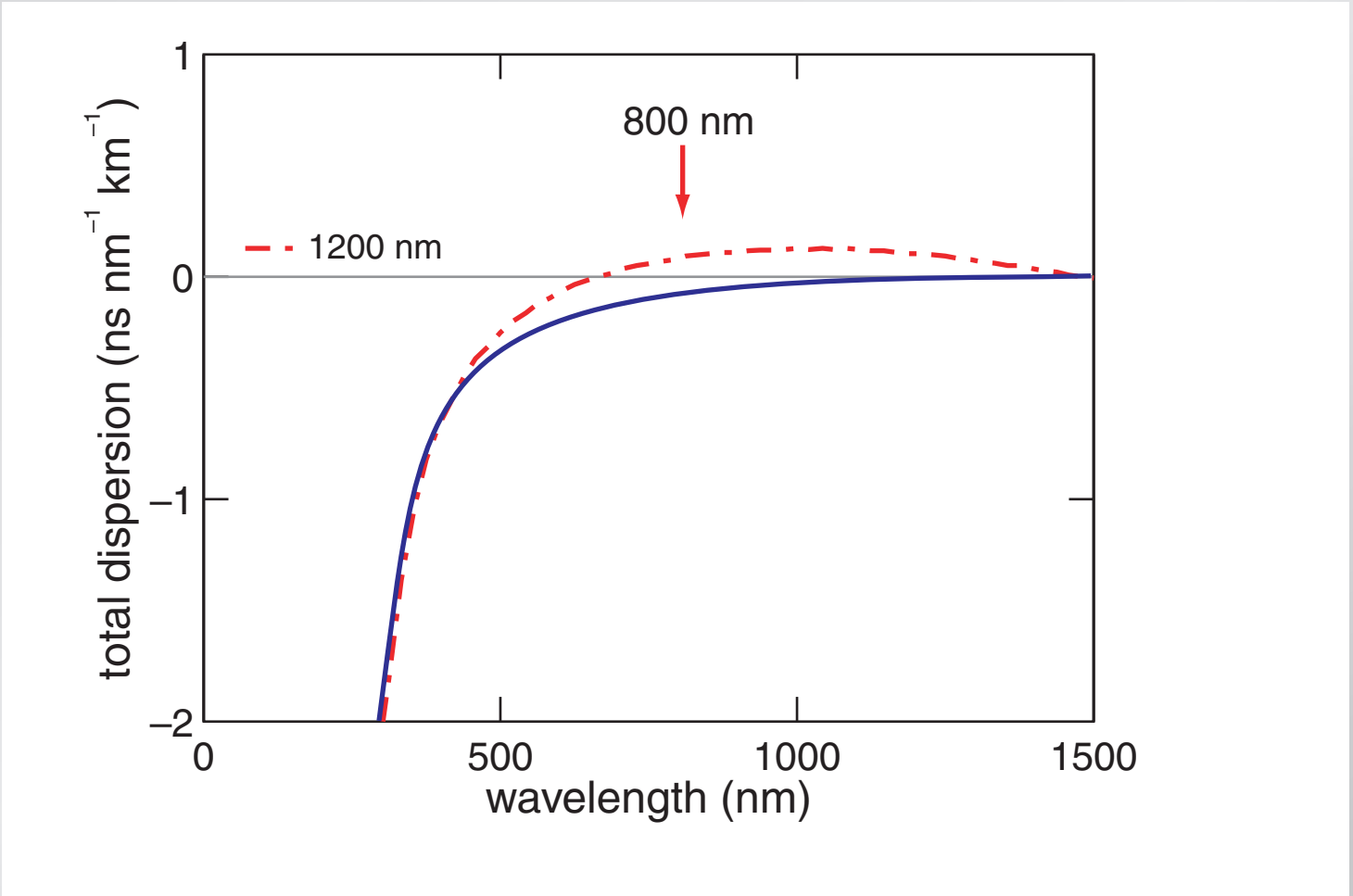
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

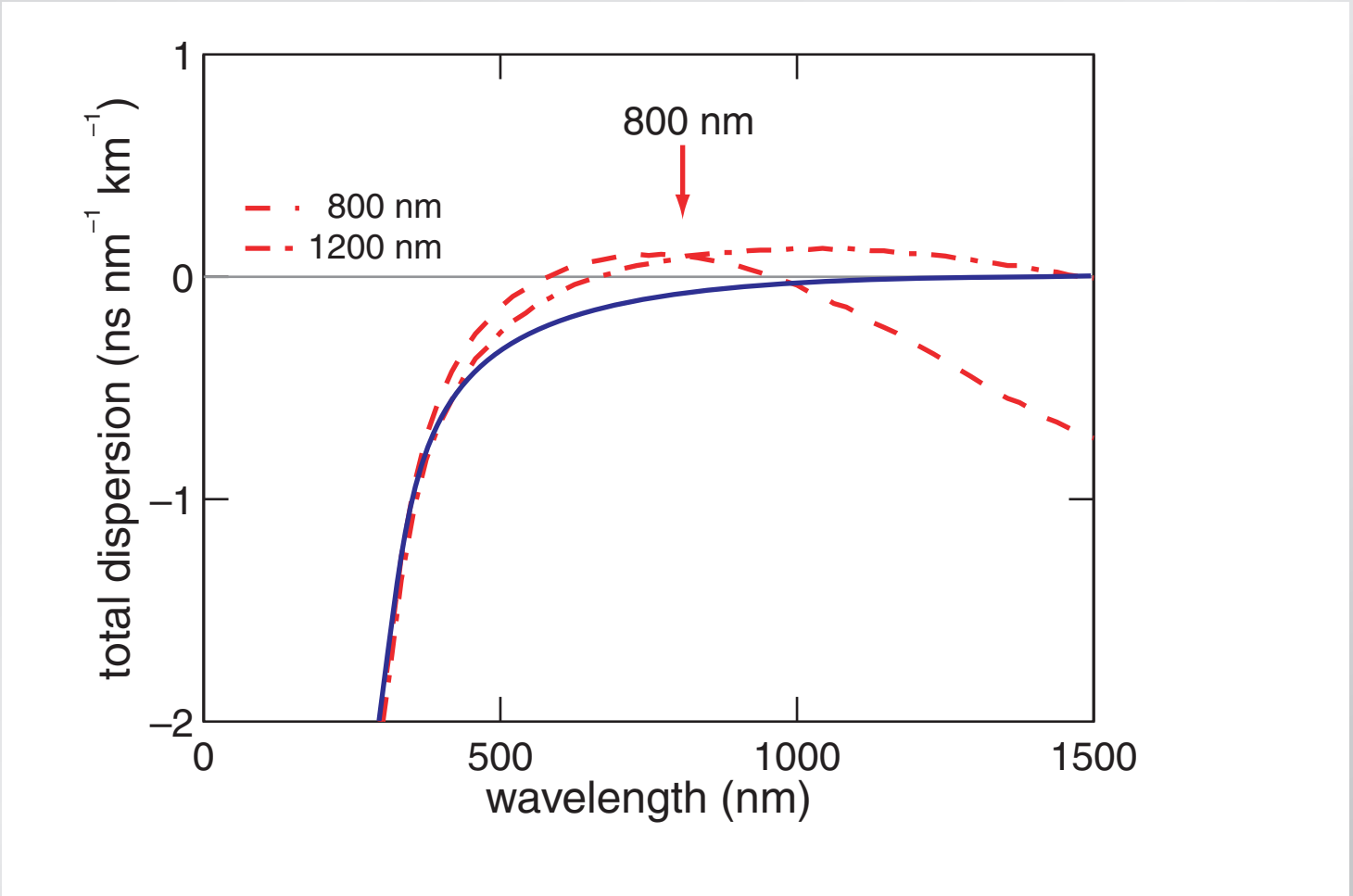
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

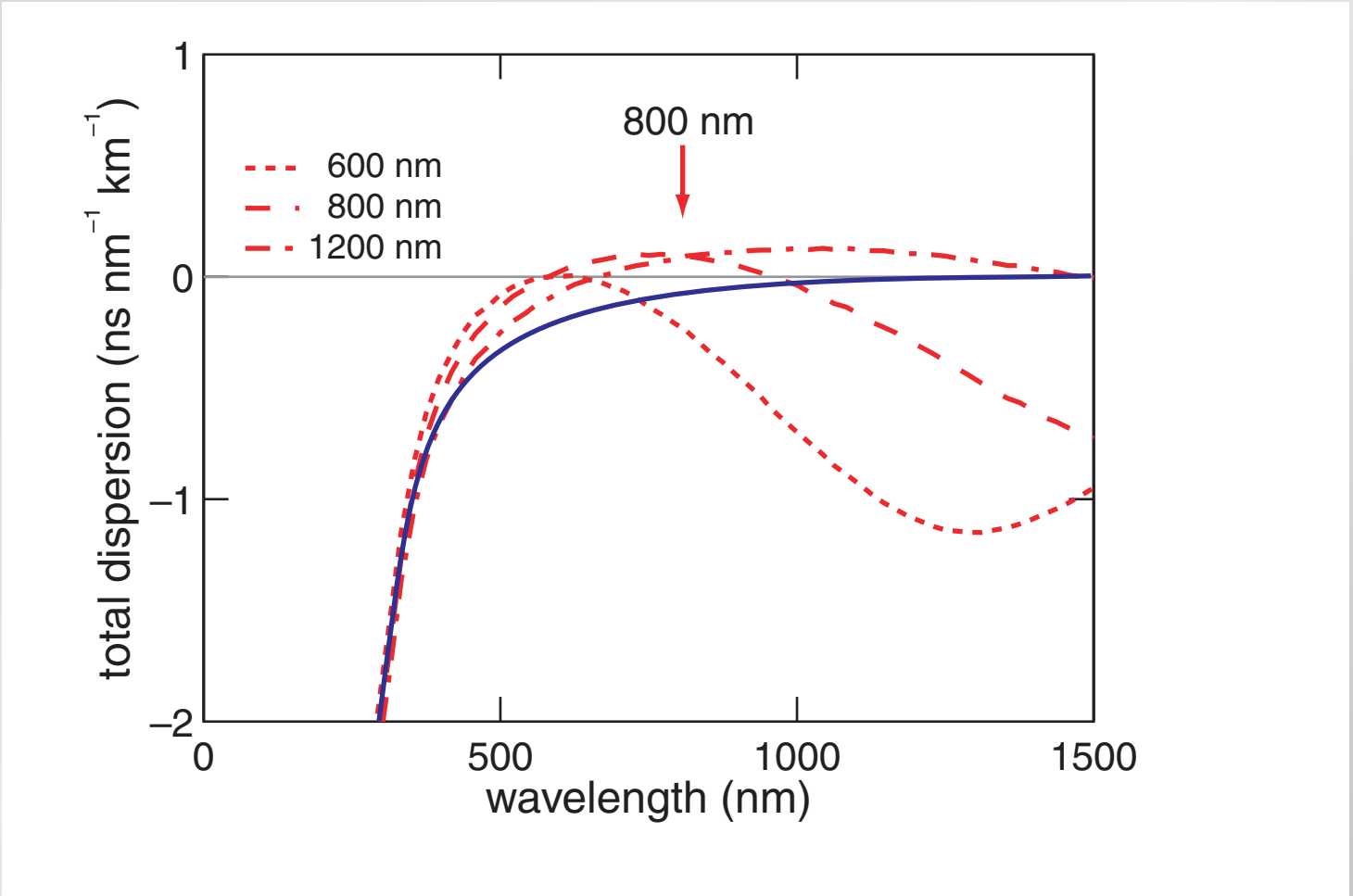
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

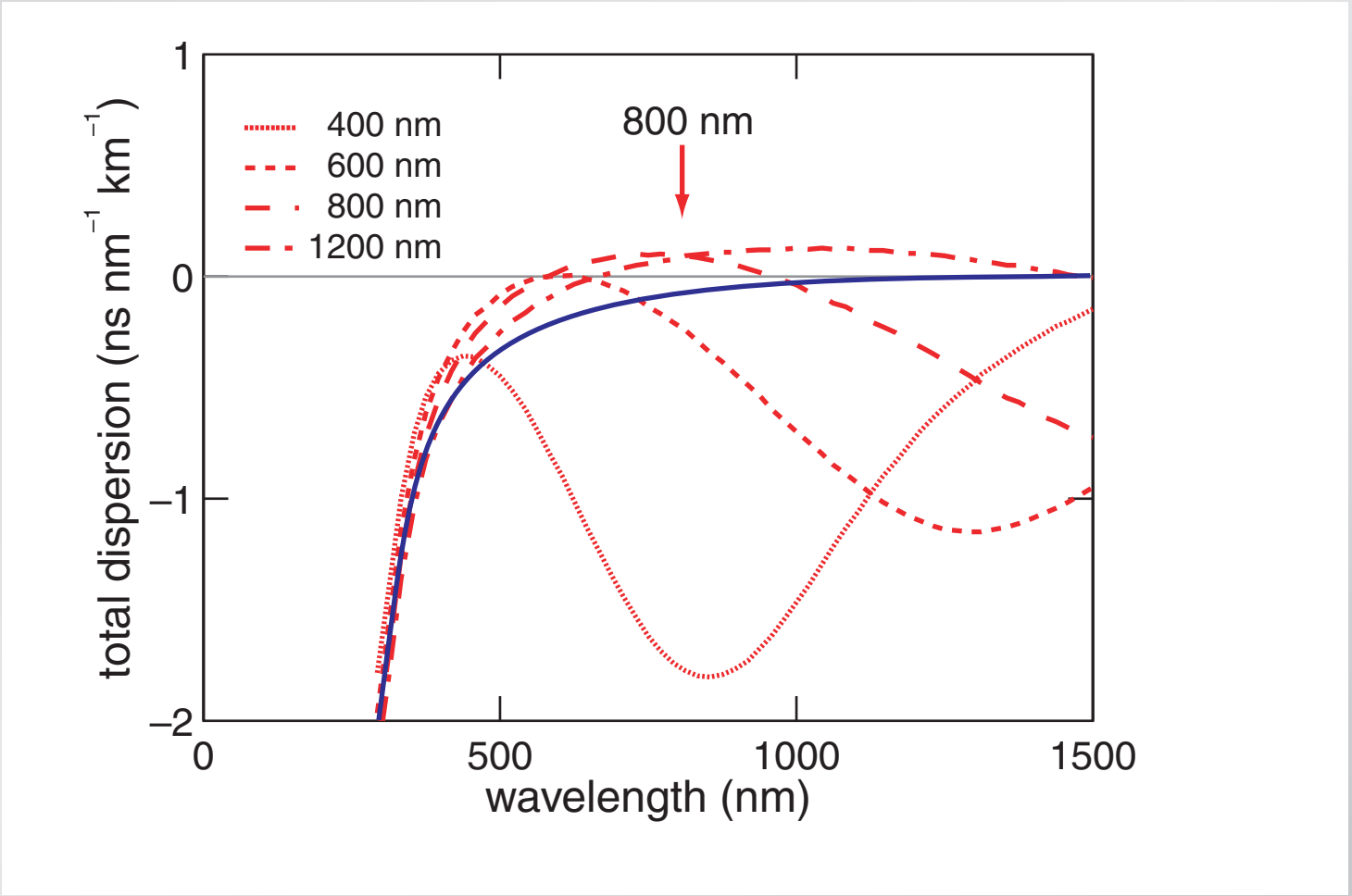
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

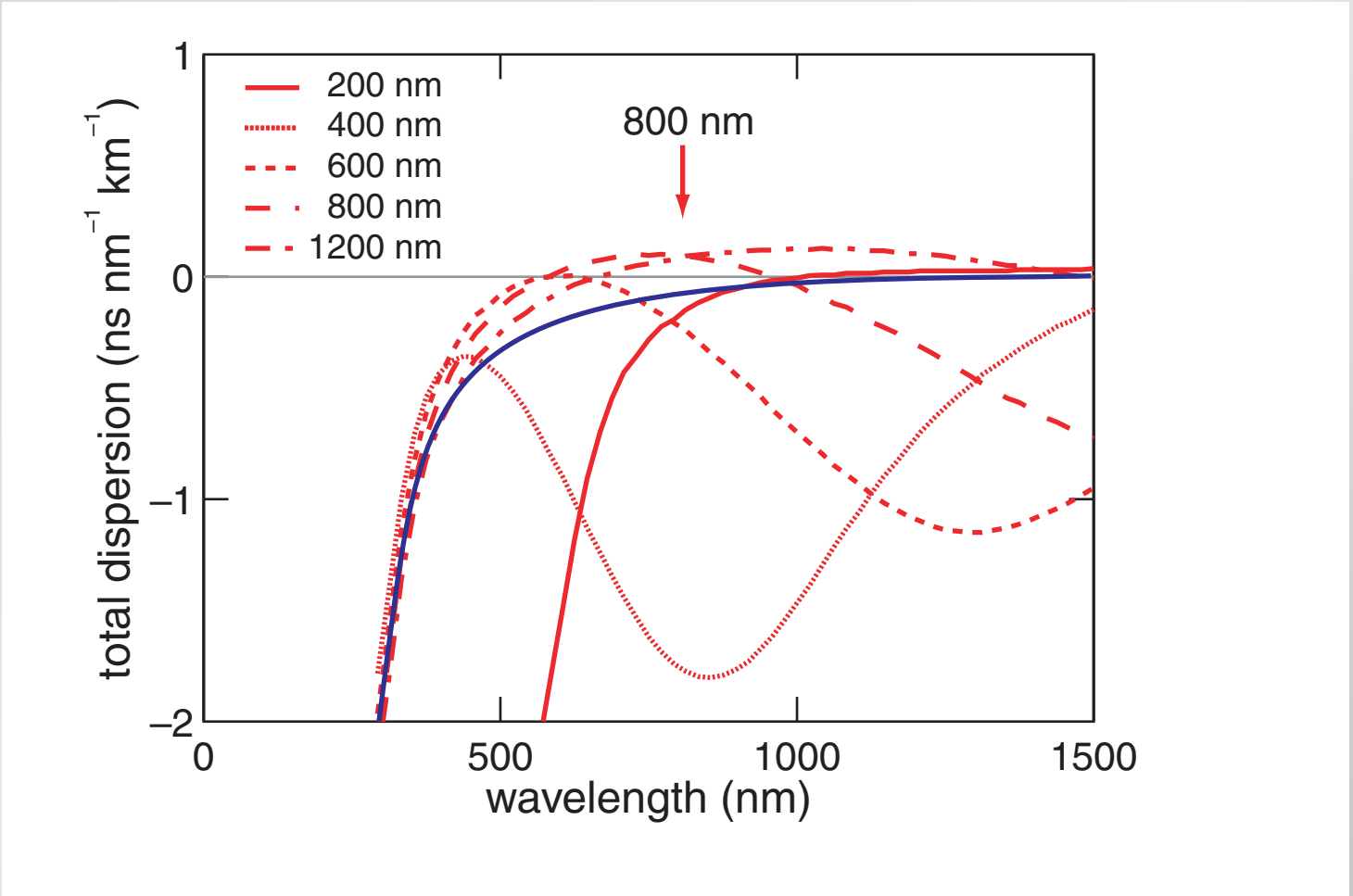
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

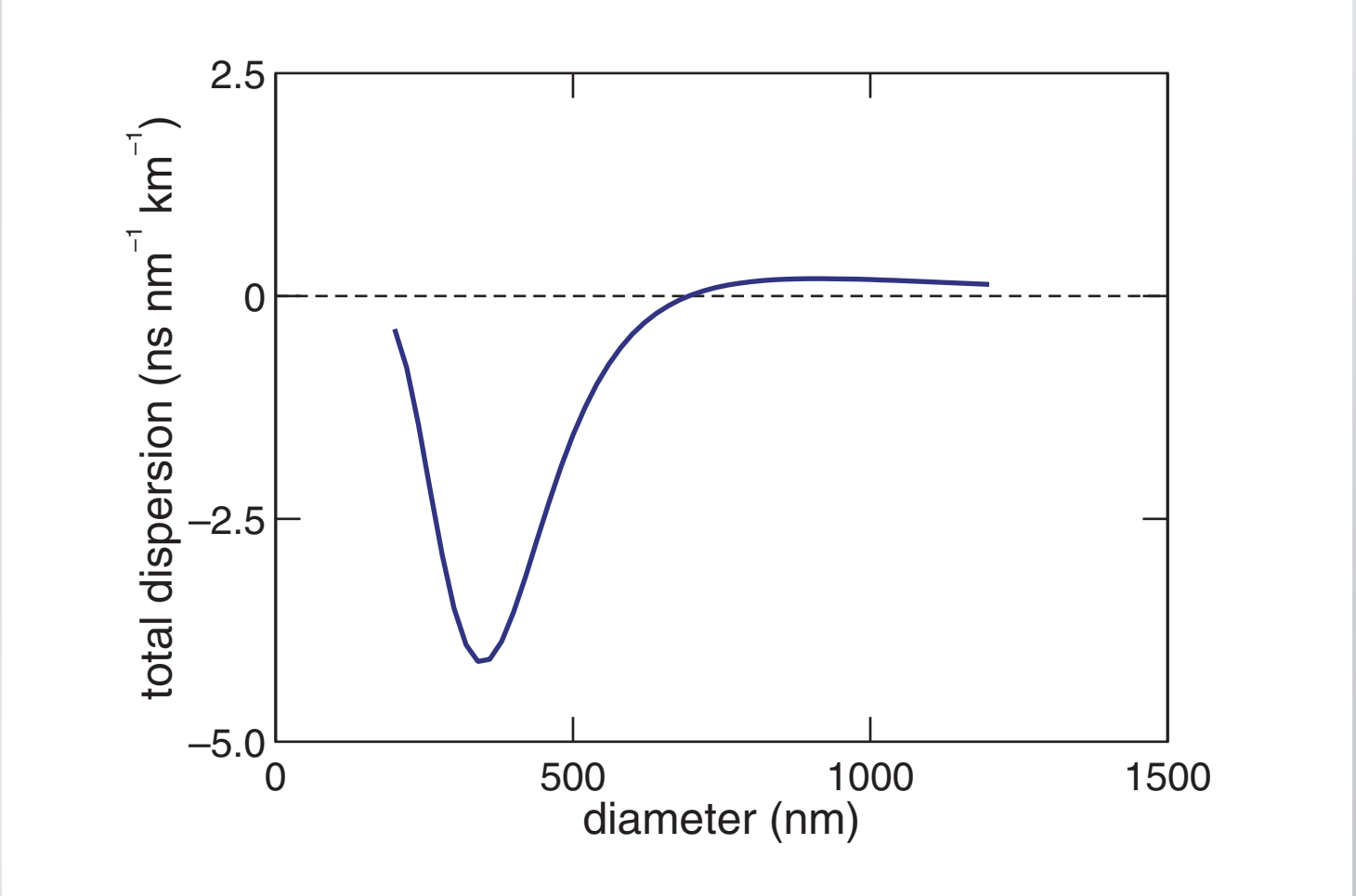
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

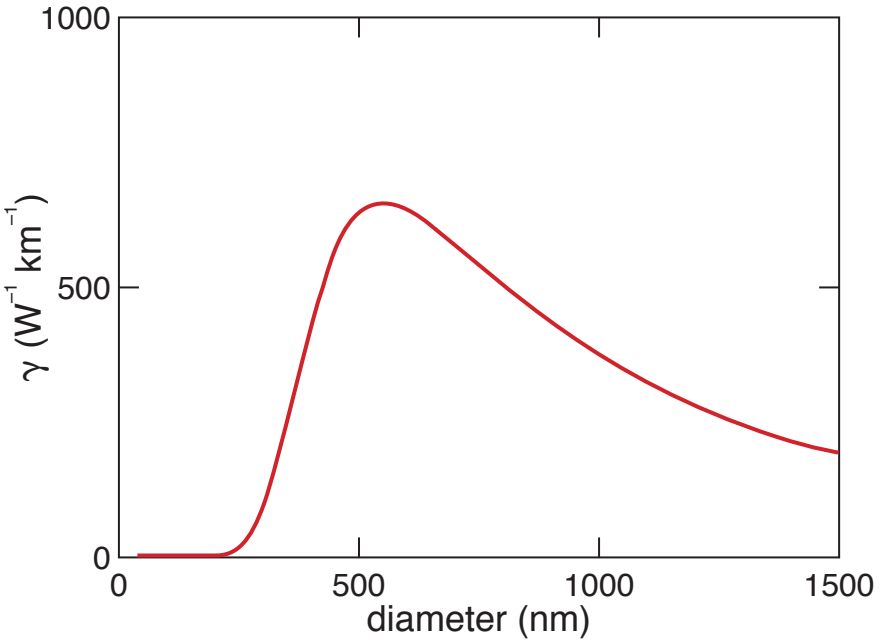
waveguide dispersion

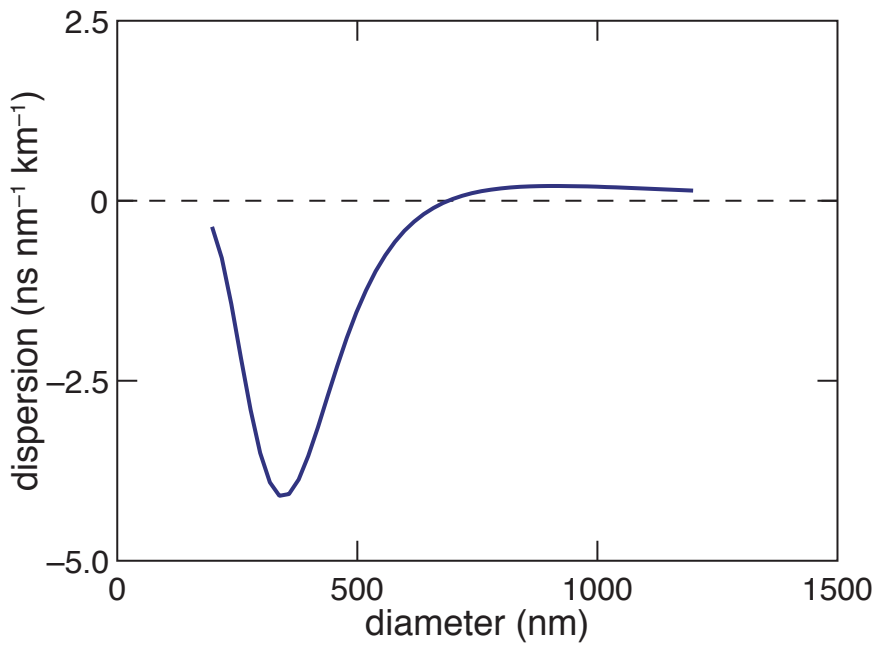


Optics Express, 12, 1025 (2004)

Supercontinuum generation

waveguide dispersion

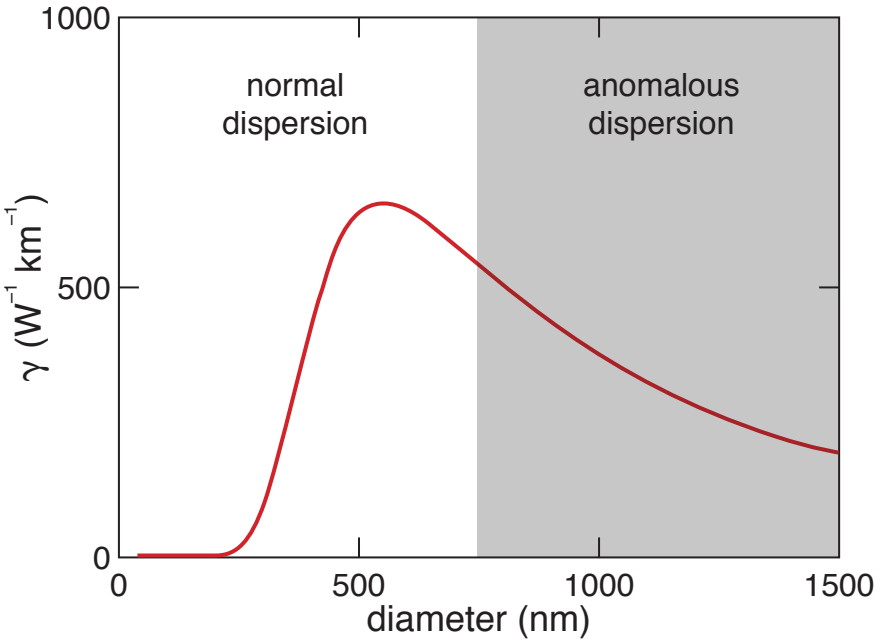


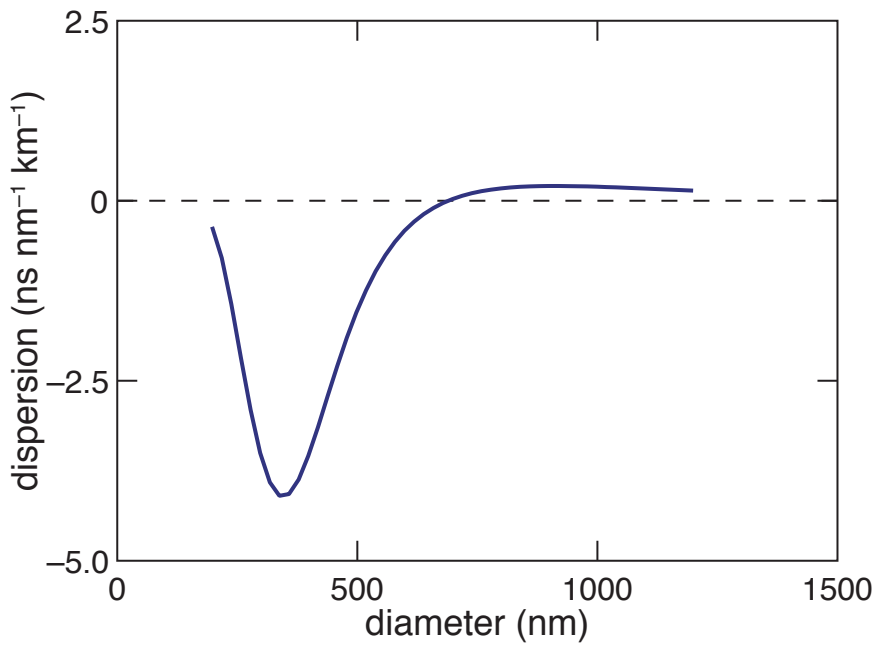


Optics Express, 12, 1025 (2004)

Supercontinuum generation

waveguide dispersion

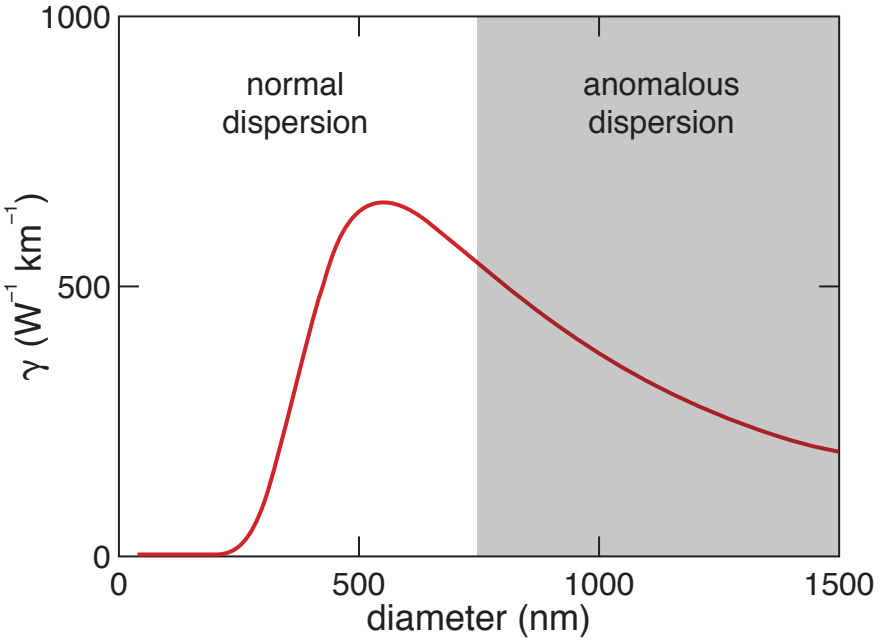


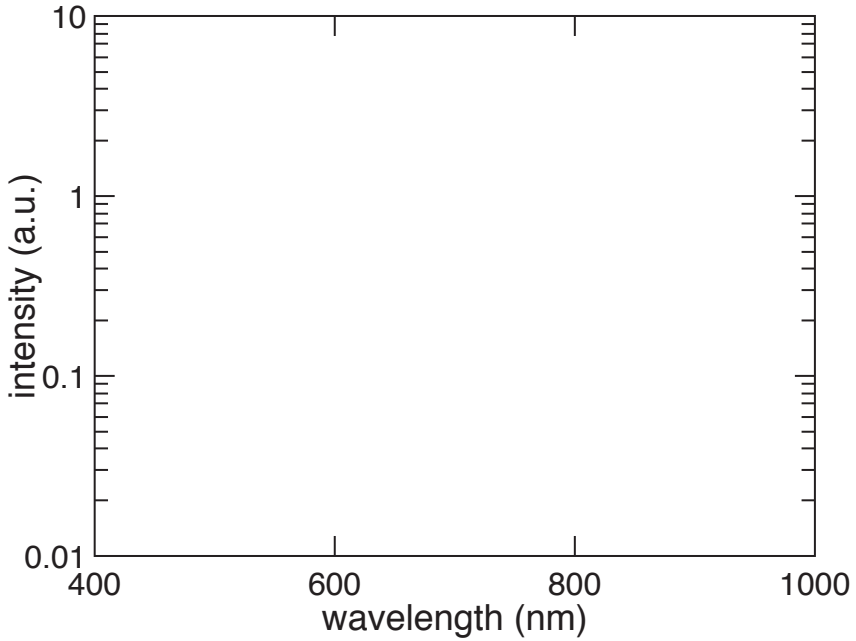


Optics Express, 12, 1025 (2004)

Supercontinuum generation

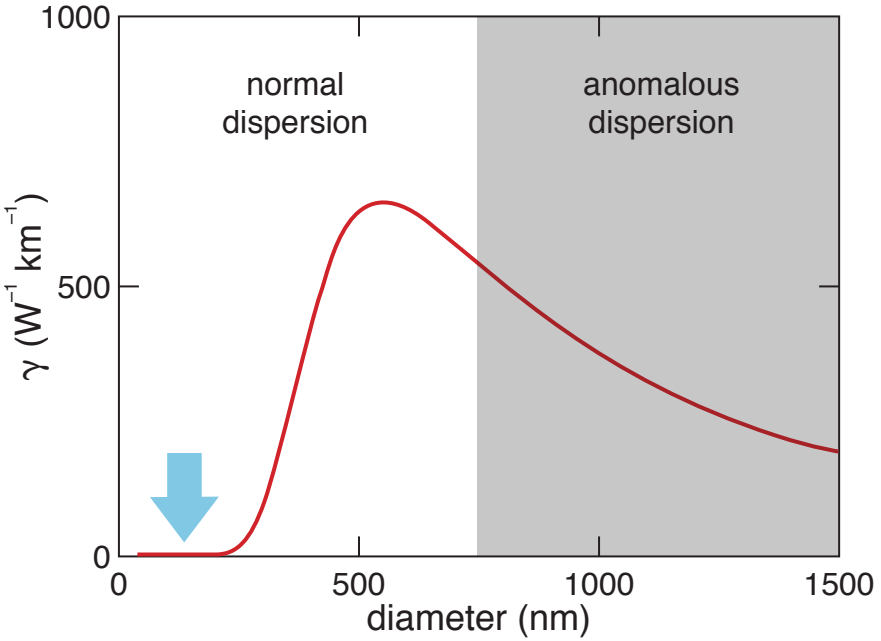
nanowire continuum generation

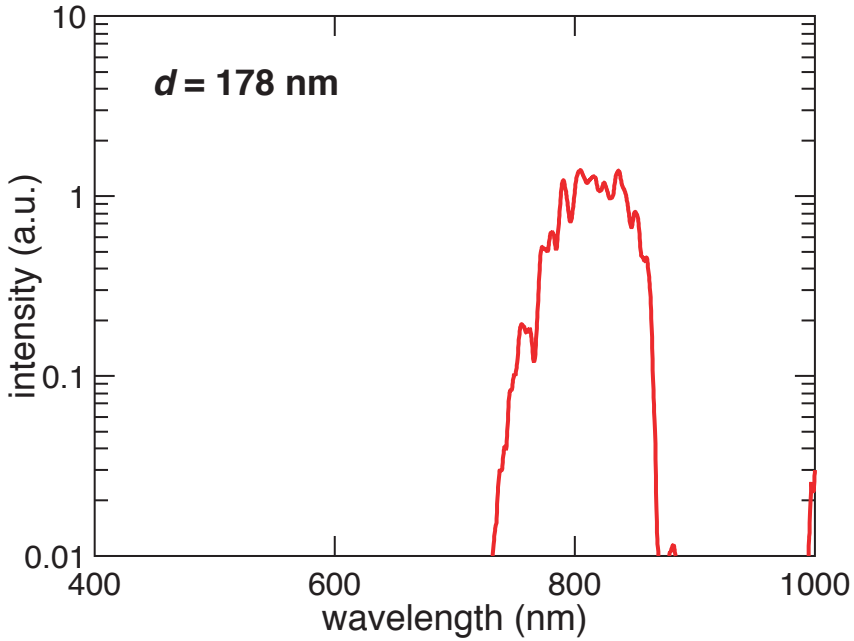




Supercontinuum generation

nanowire continuum generation

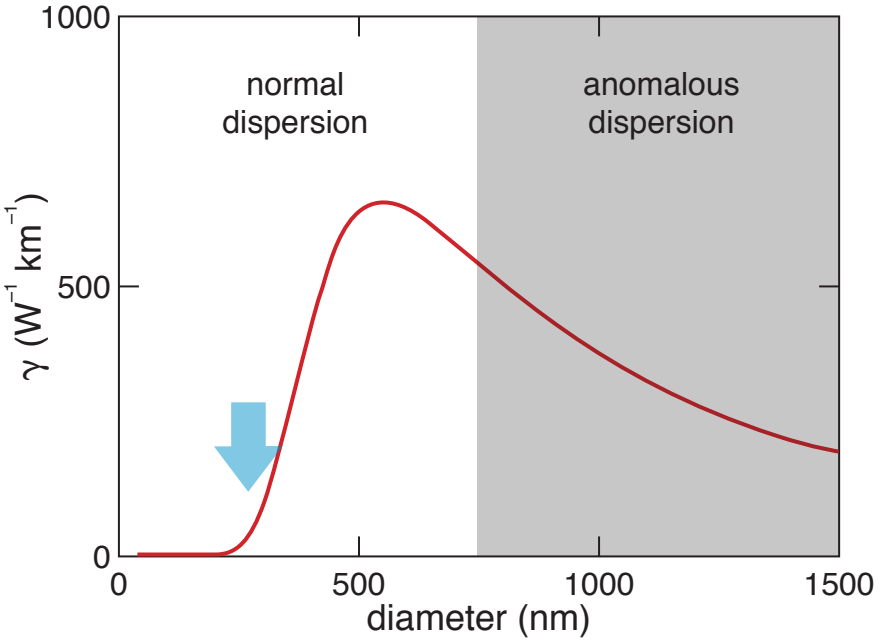


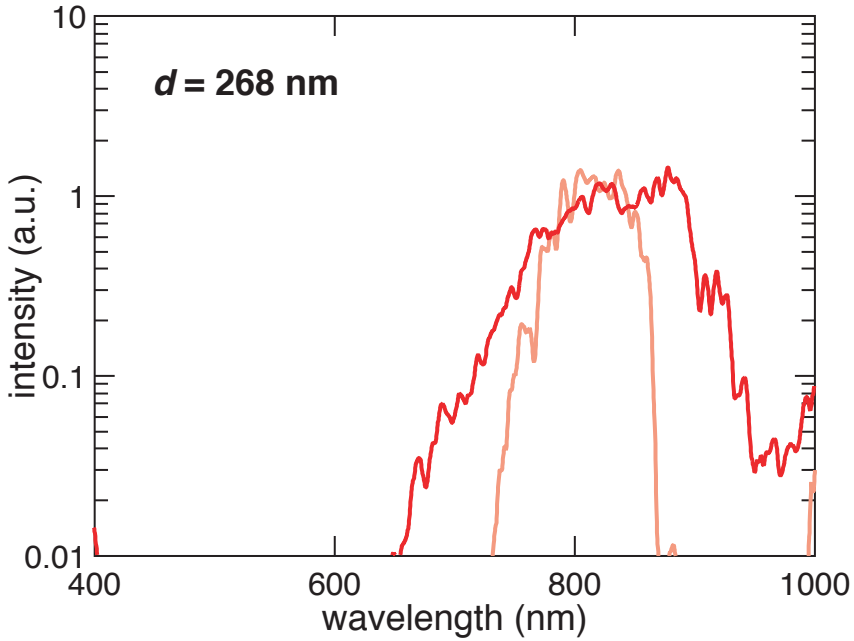


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation

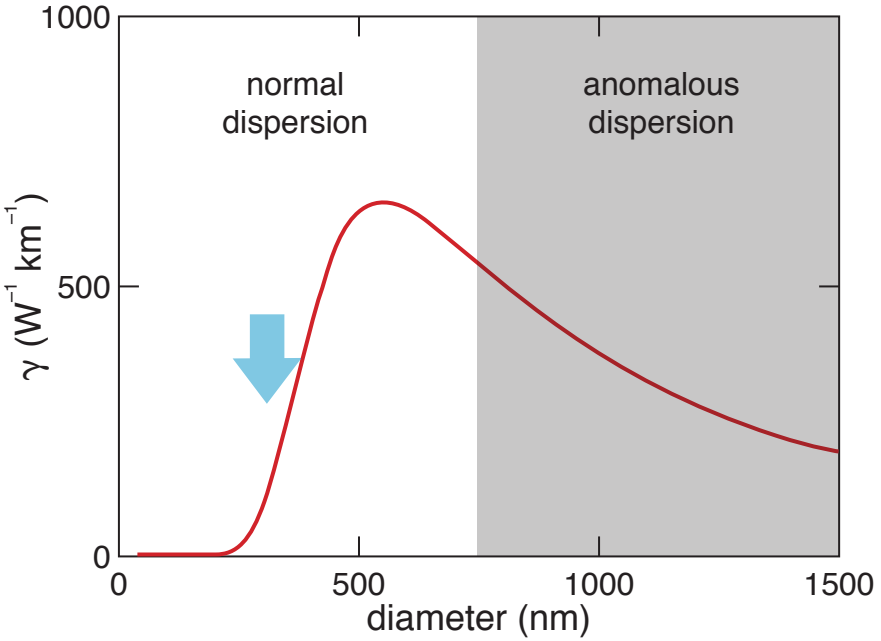


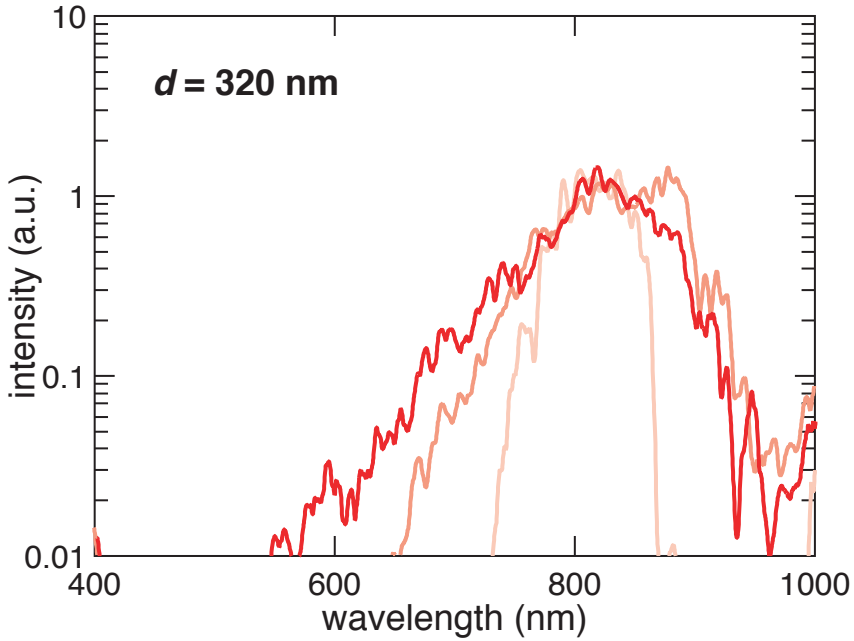


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation

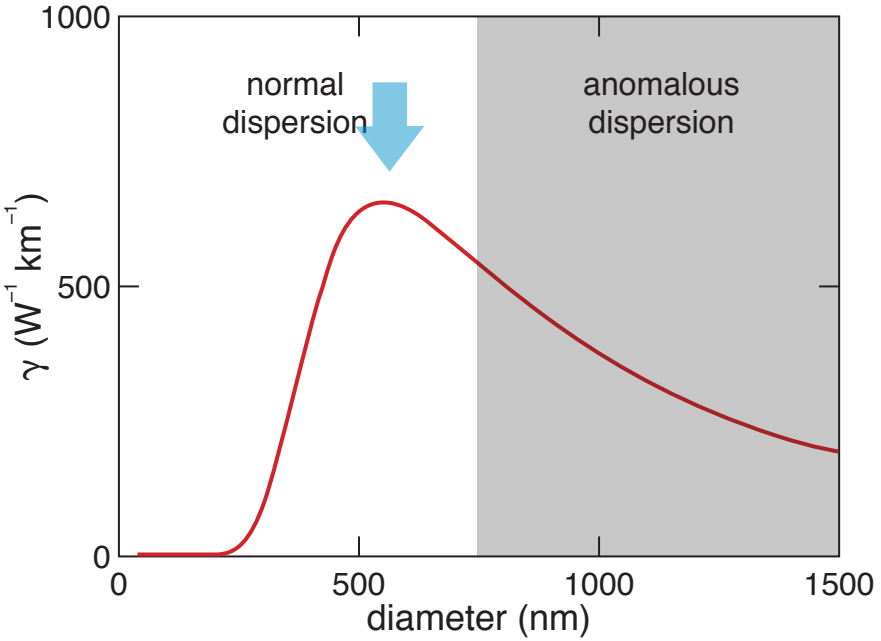


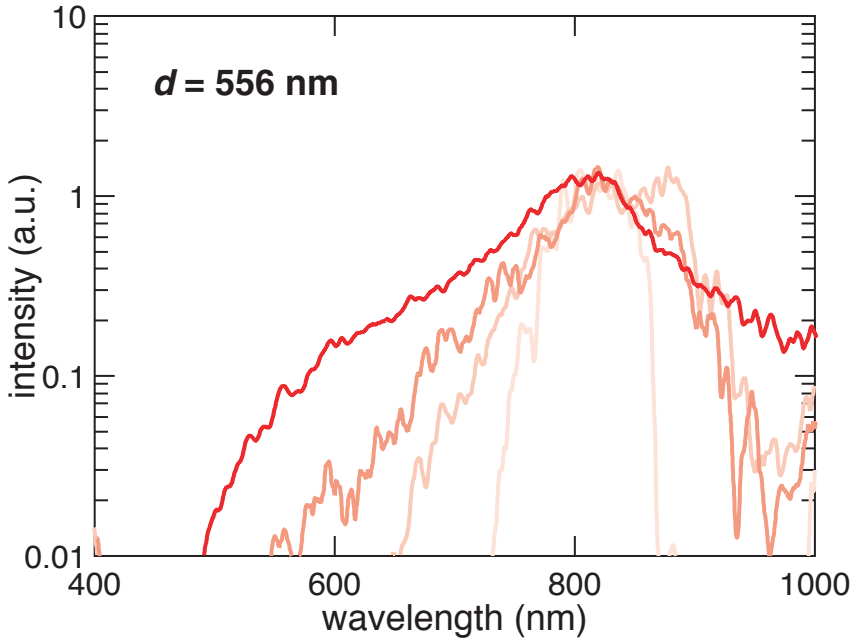


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation

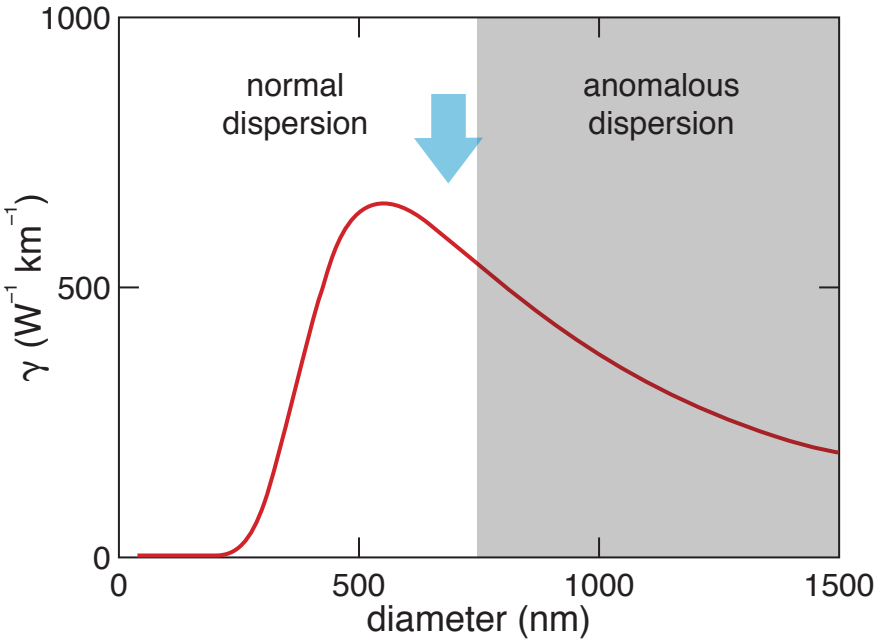


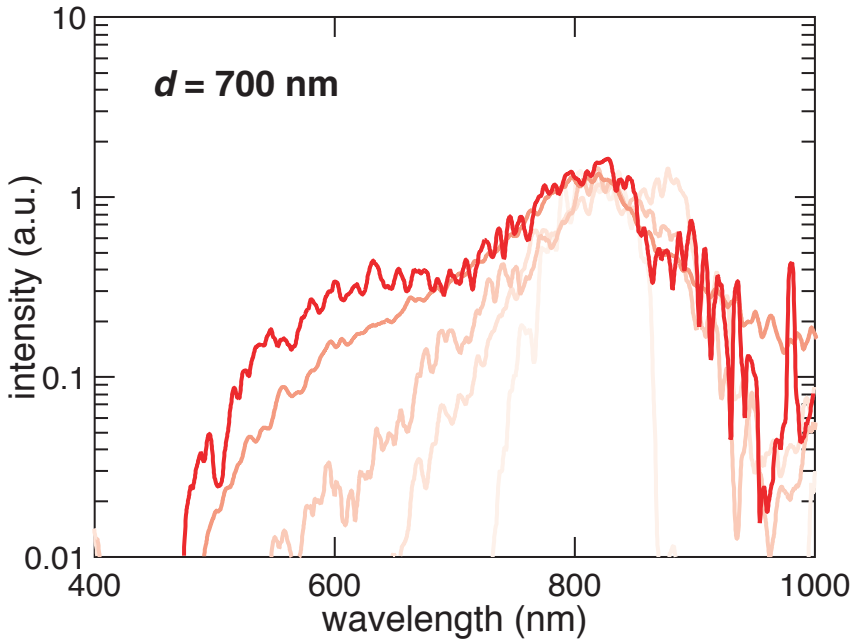


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation

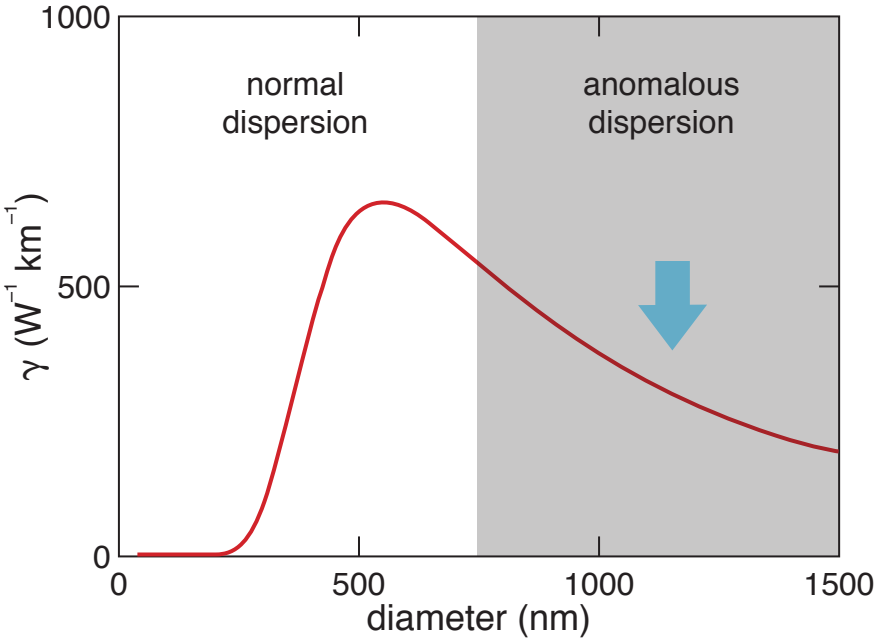


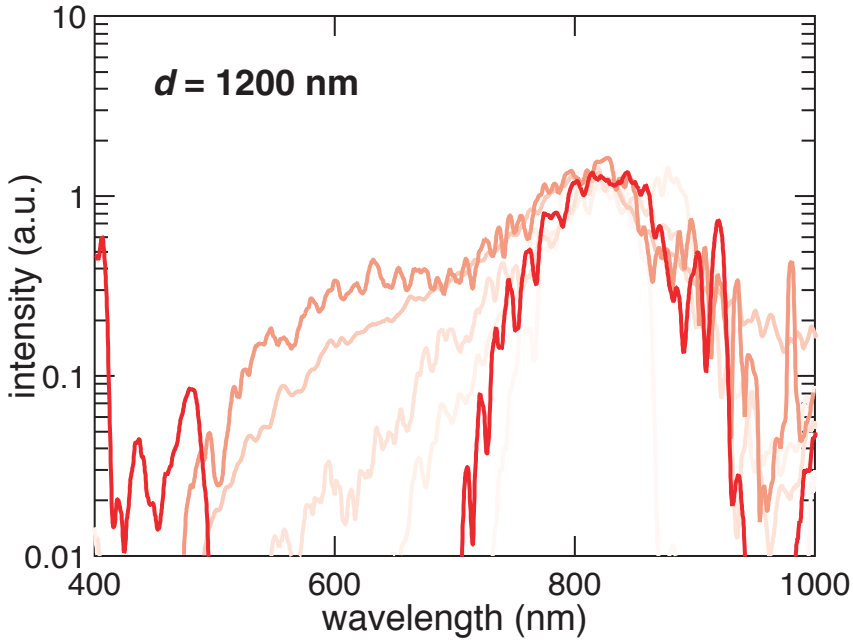


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation





Optics Express, 14, 9408 (2006)

Supercontinuum generation

energy in nanowire < 100 pJ!

Supercontinuum generation

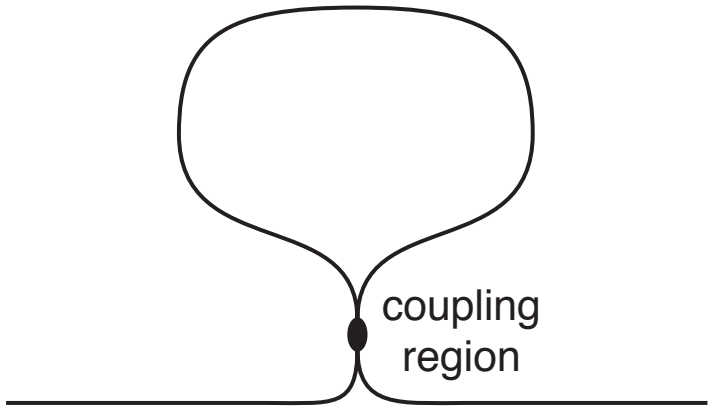
- picojoule nonlinear optics
- optimum diameter for silica 500–600 nm
- low dispersion

Outline

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

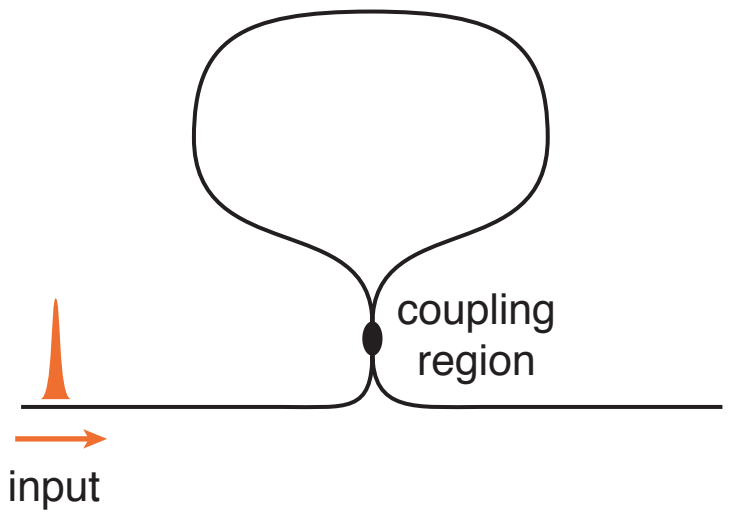
Optical logic gates

nanowire Sagnac interferometer



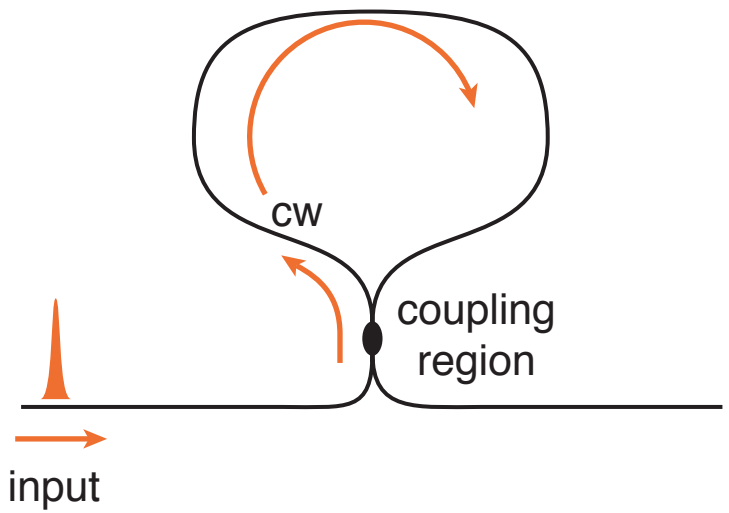
Optical logic gates

nanowire Sagnac interferometer



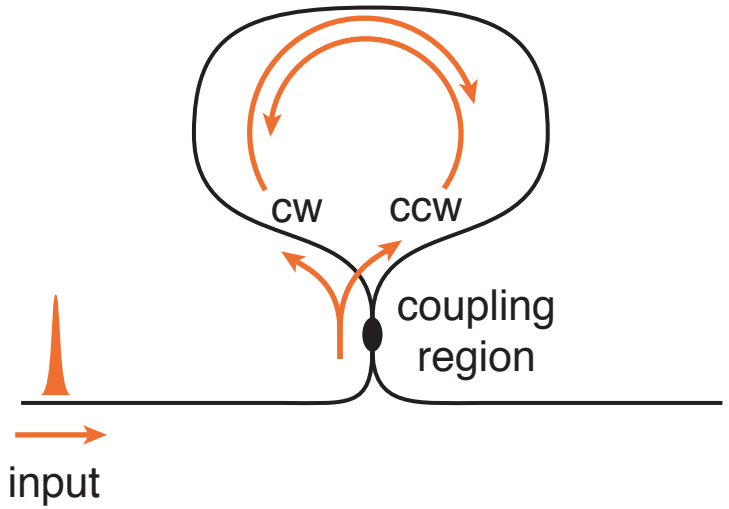
Optical logic gates

nanowire Sagnac interferometer



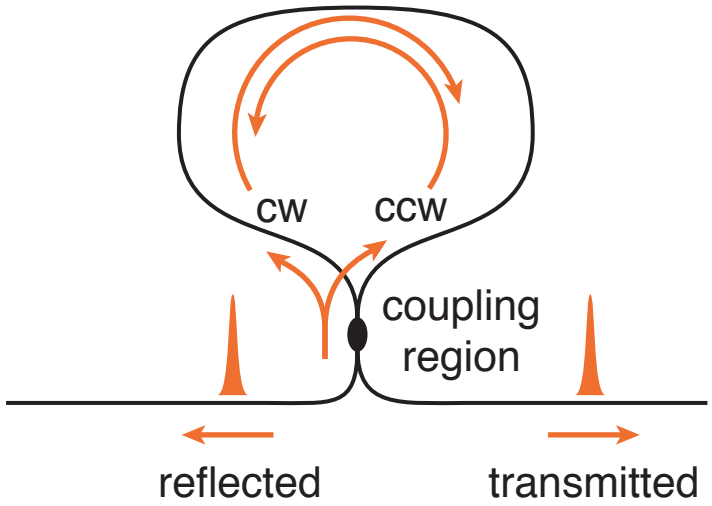
Optical logic gates

nanowire Sagnac interferometer



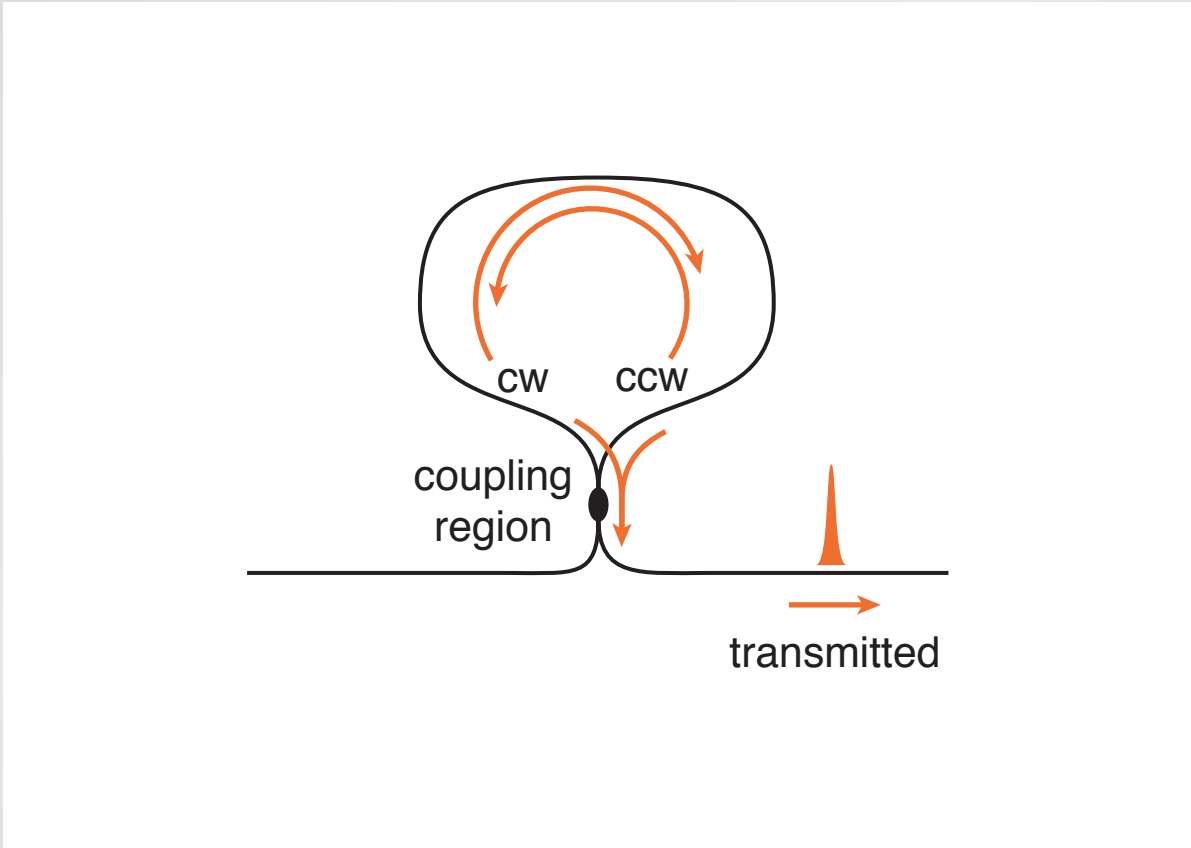
Optical logic gates

nanowire Sagnac interferometer



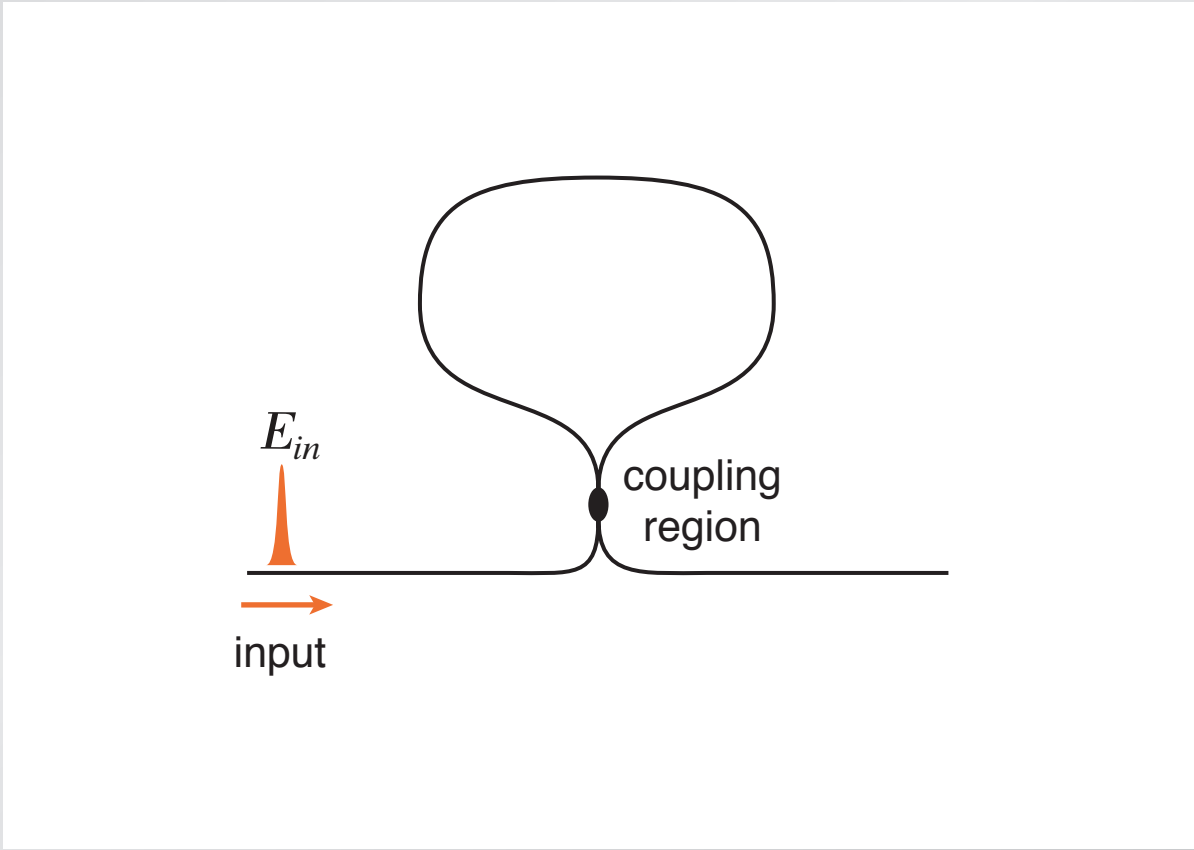
Optical logic gates

output = transmitted cw + ccw power



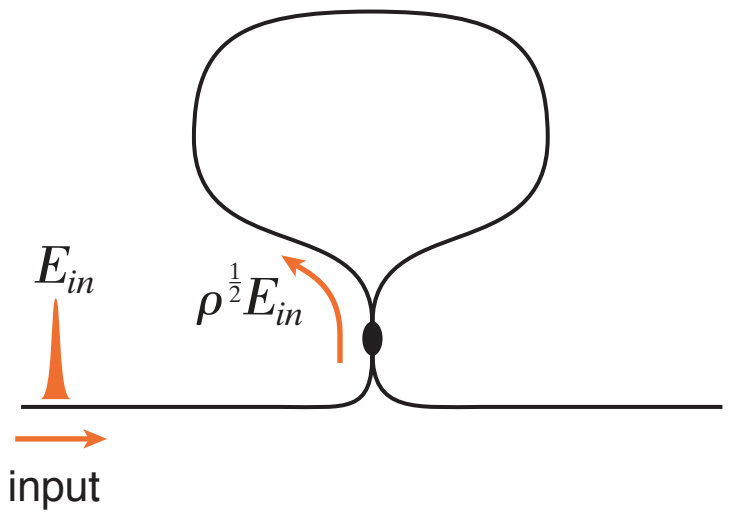
Optical logic gates

input electric field amplitude E_{in}



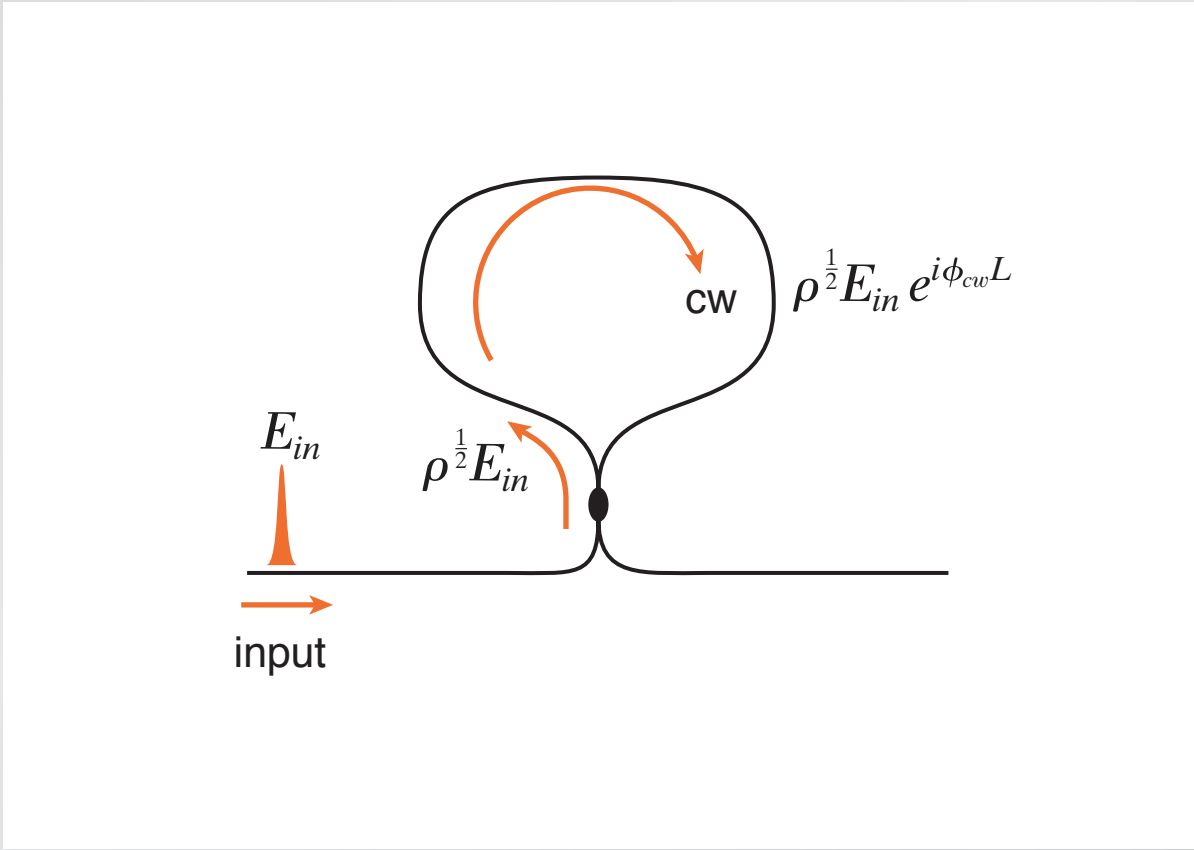
Optical logic gates

coupling parameter: ρ



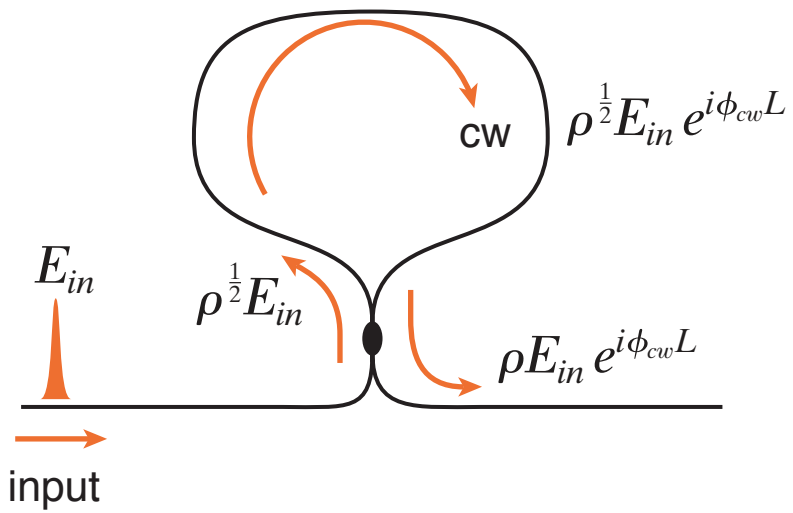
Optical logic gates

phase accumulation over path length of loop L



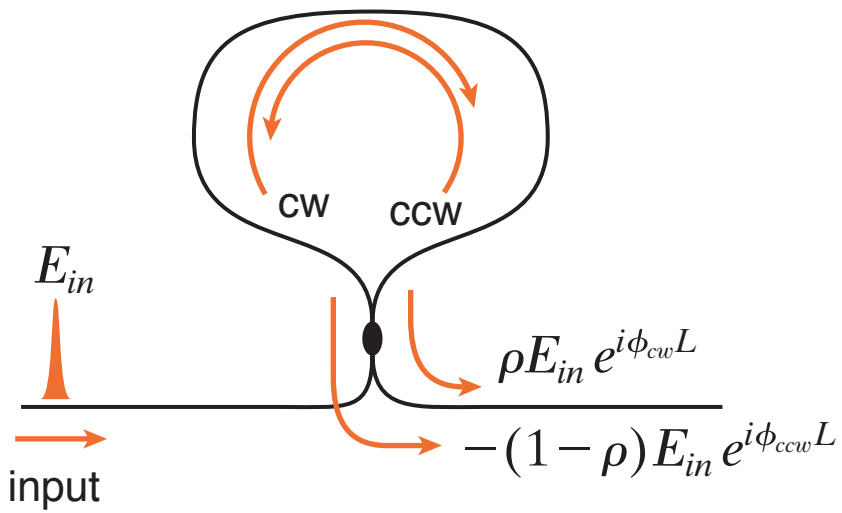
Optical logic gates

coupling parameter: ρ



Optical logic gates

output is sum of transmitted cw and ccw



Manipulating light at the nanoscale

accumulated phase:

$$\phi = k_o n$$

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:

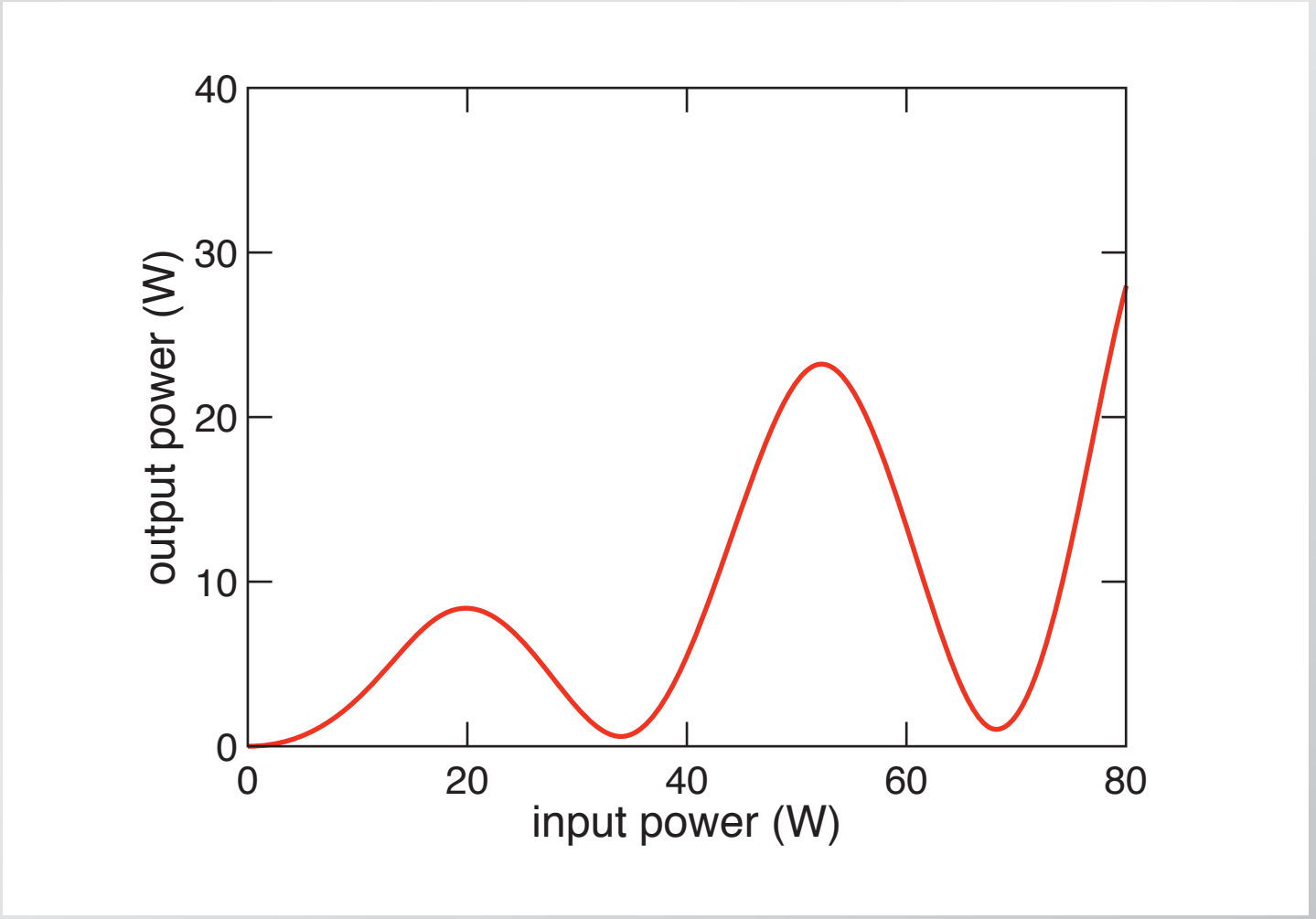
$$\rho = 0.5$$

no transmission:

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

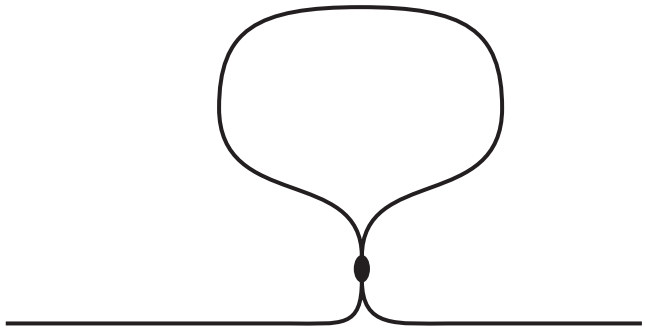
Optical logic gates

when $\rho \neq 0.5$:



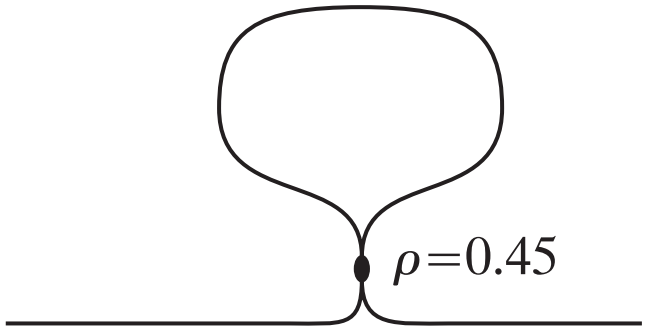
Optical logic gates

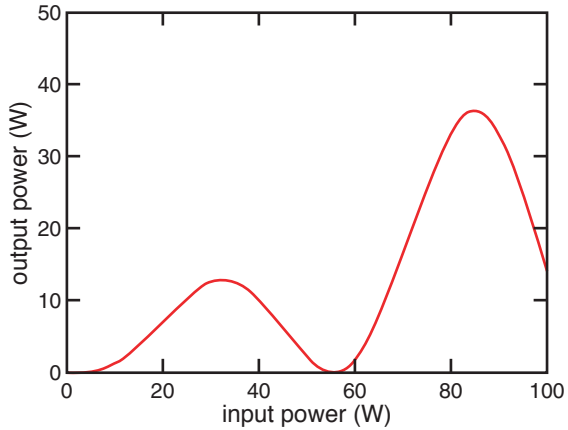
nonlinear nanogate



Optical logic gates

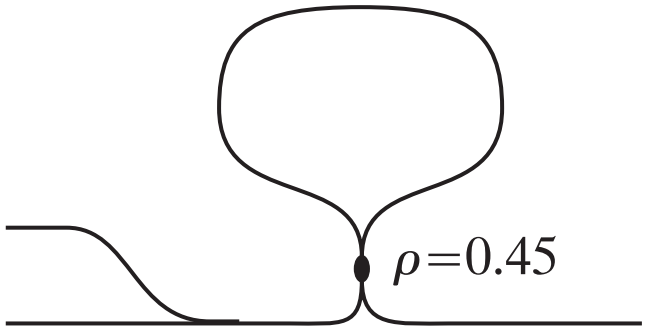
nonlinear nanogate

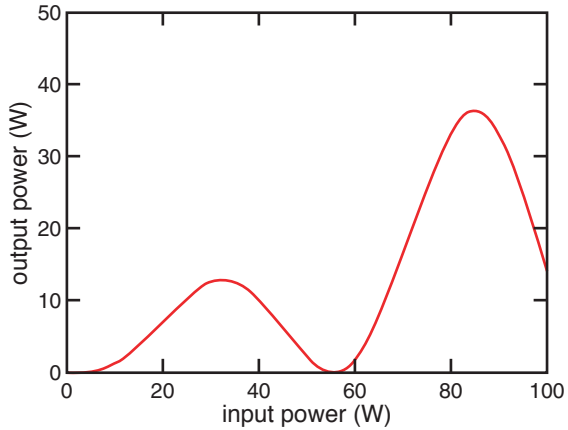




Optical logic gates

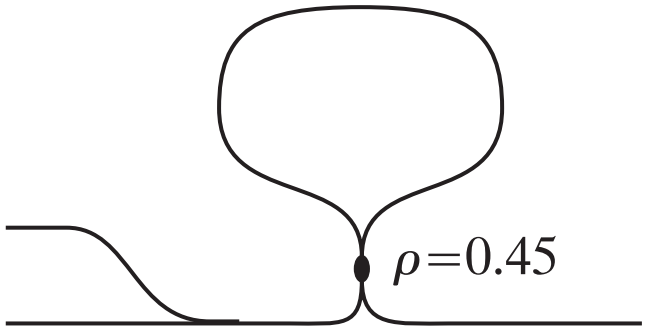
nonlinear nanogate

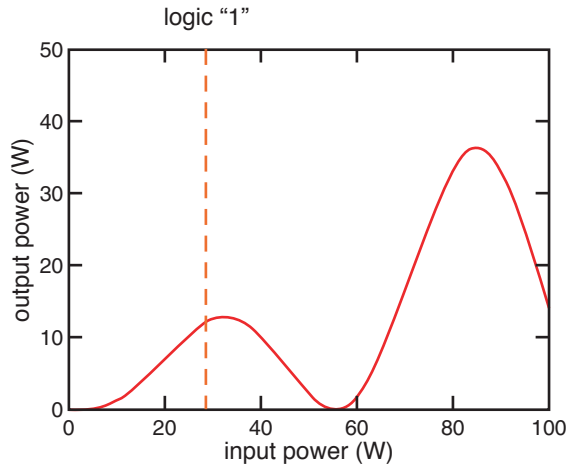




Optical logic gates

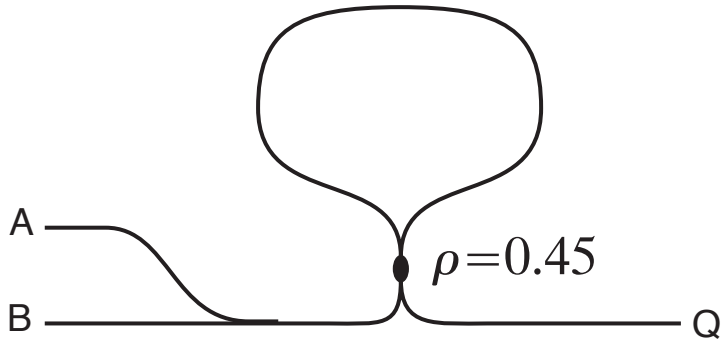
nonlinear nanogate

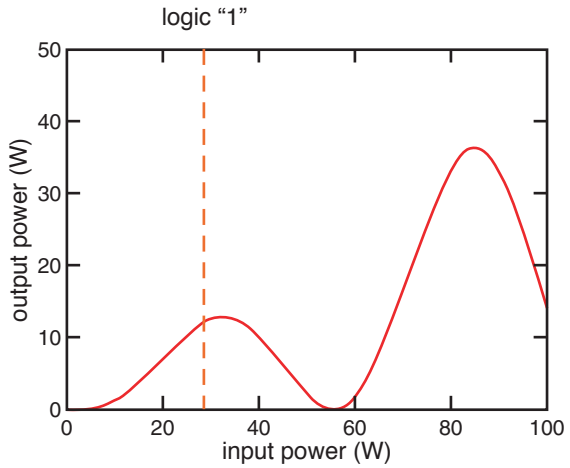




Optical logic gates

nonlinear nanogate

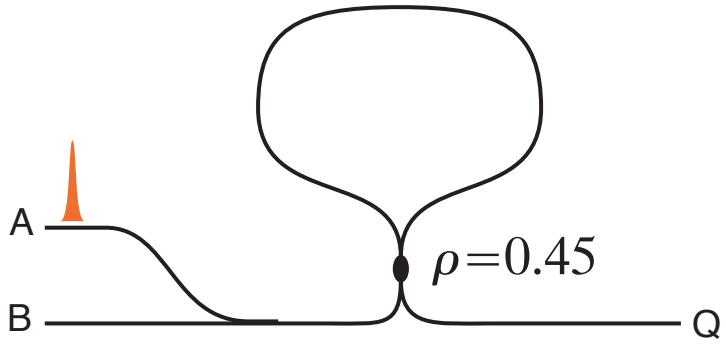


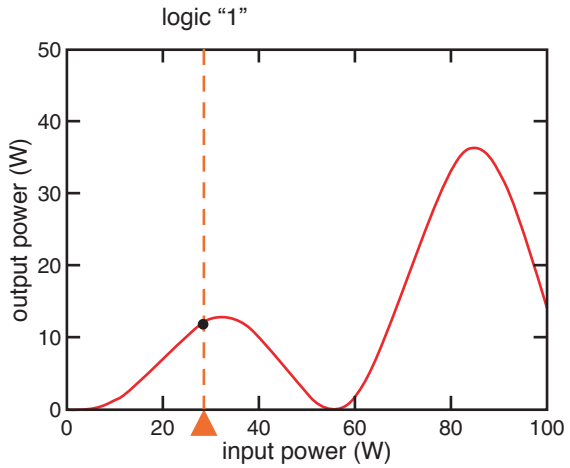


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

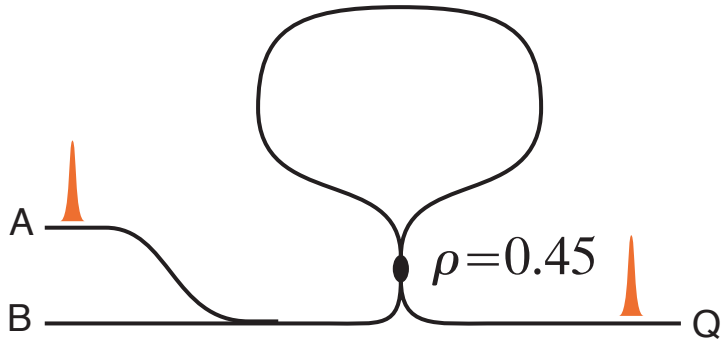


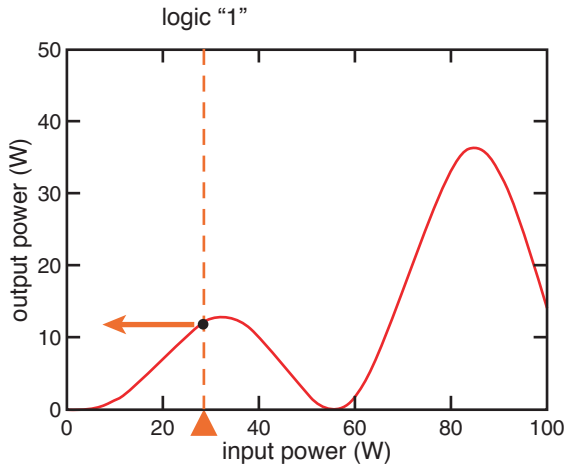


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

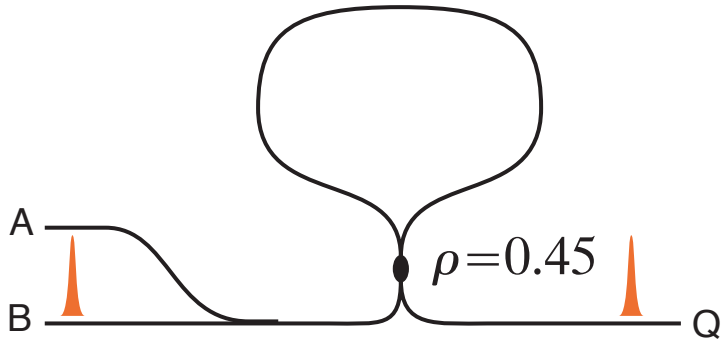


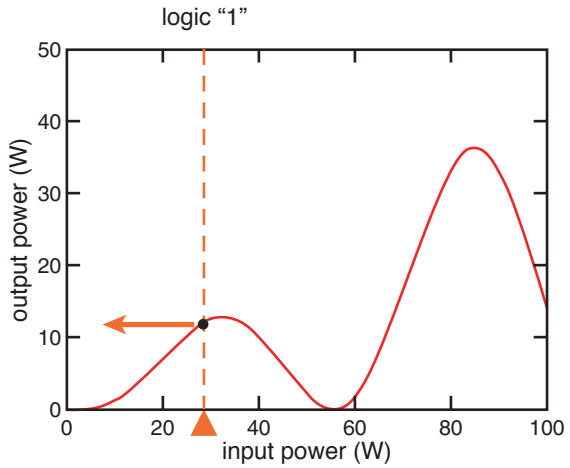


A	B	Q
0	0	0
1	0	1

Optical logic gates

nonlinear nanogate

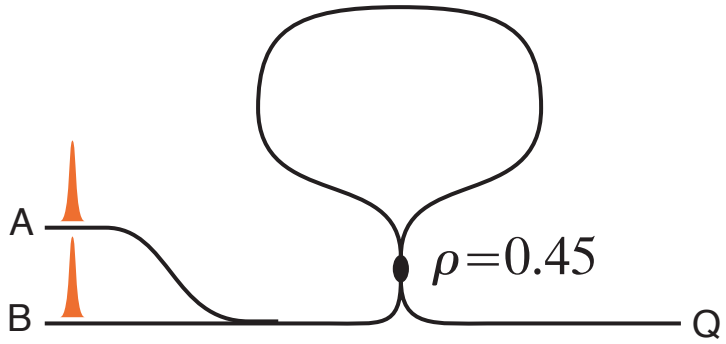


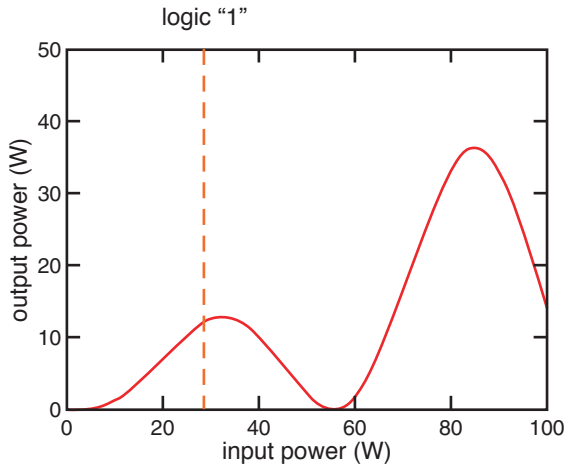


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

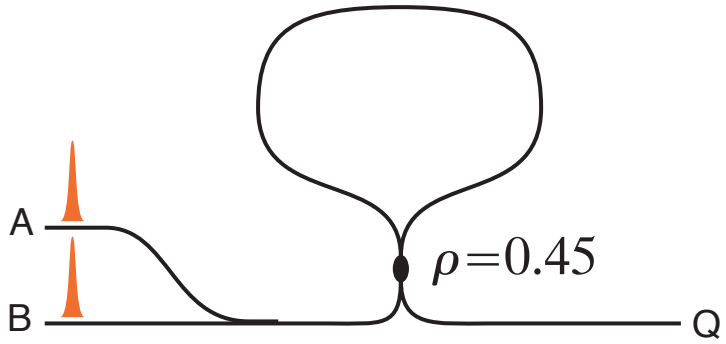


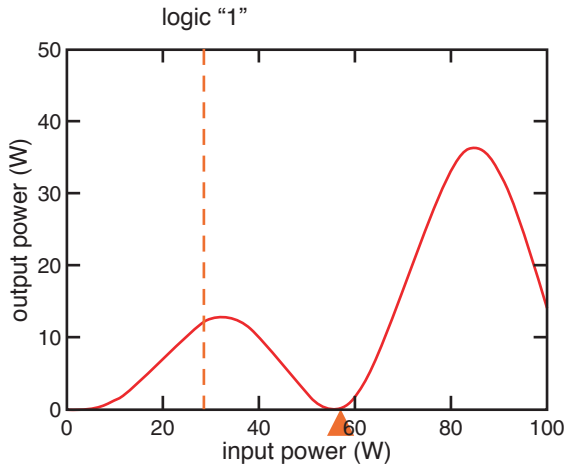


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

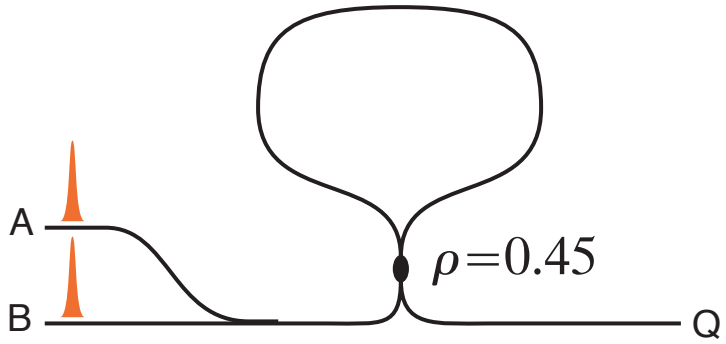


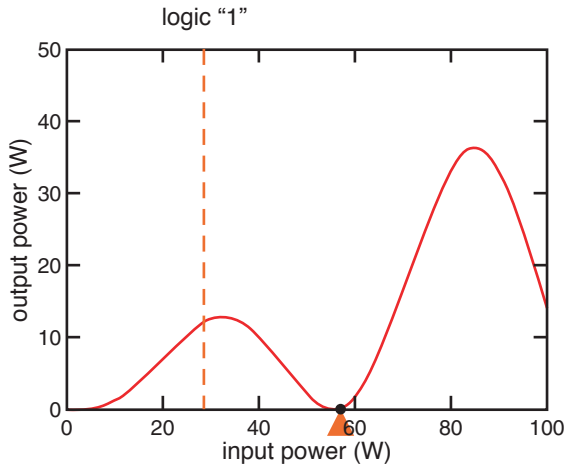


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

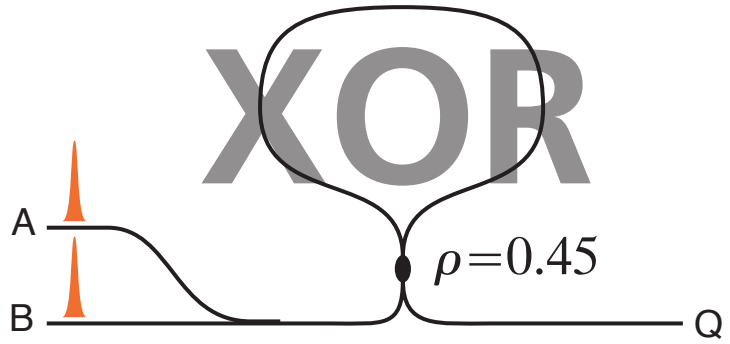


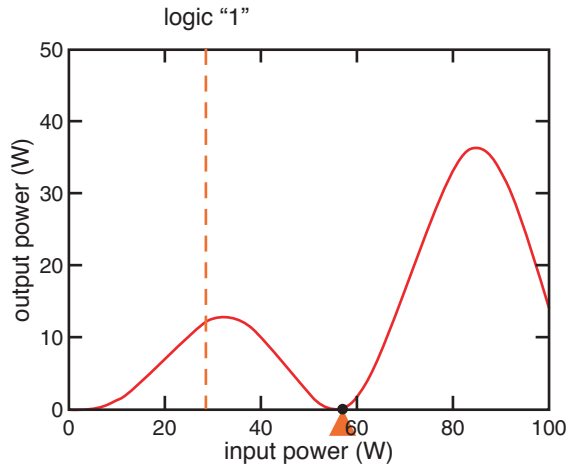


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

nonlinear nanogate

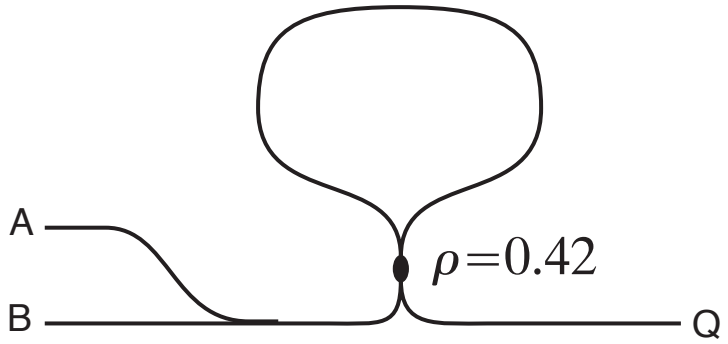


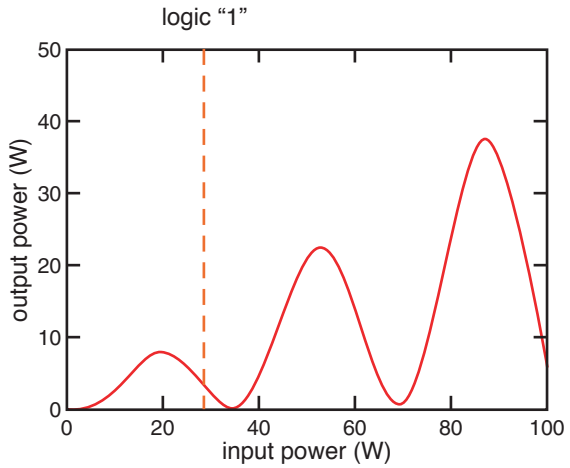


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

nonlinear nanogate

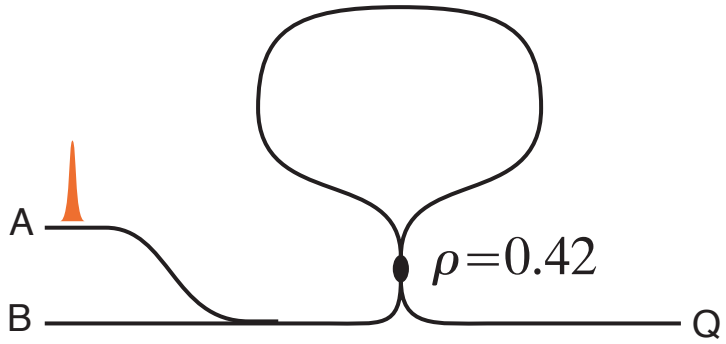


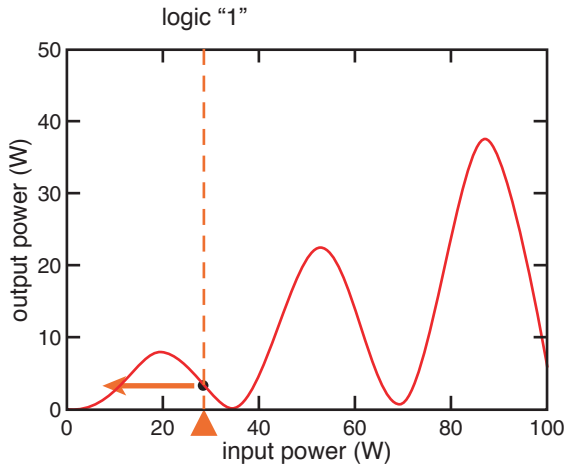


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

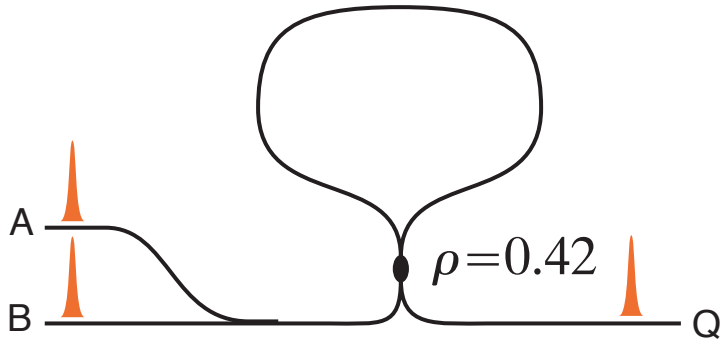


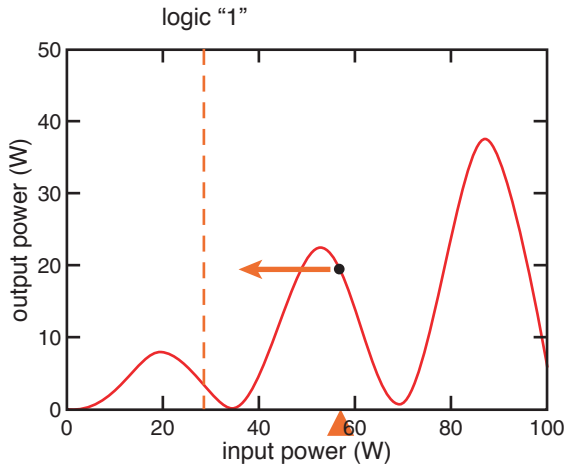


A	B	Q
0	0	0
1	0	0
0	1	0

Optical logic gates

nonlinear nanogate

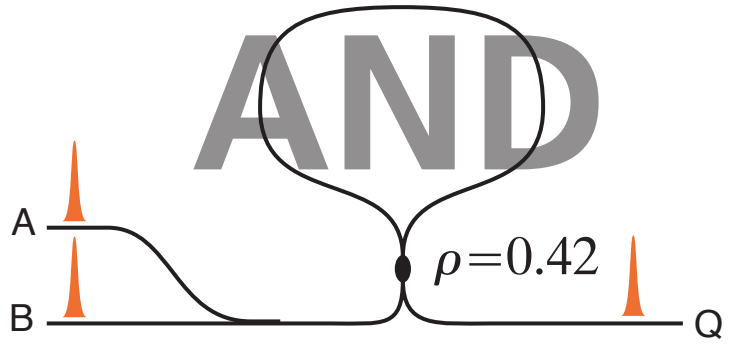


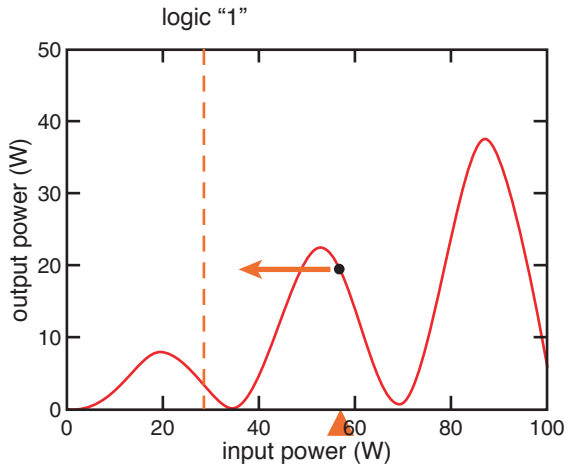


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

nonlinear nanogate

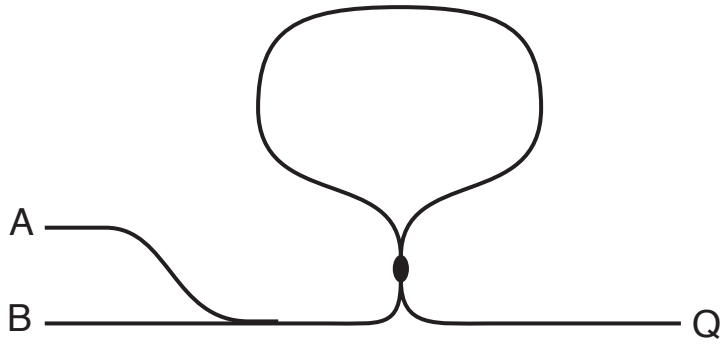


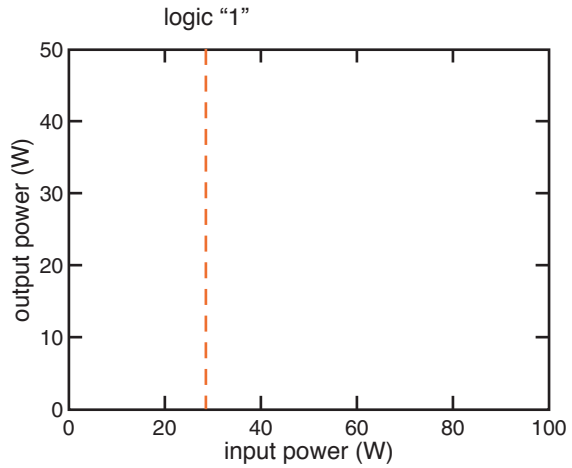


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

for NAND gate need ouput with no input

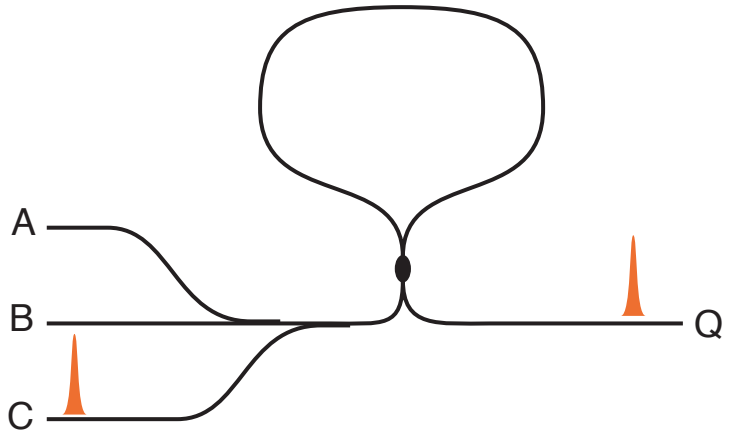


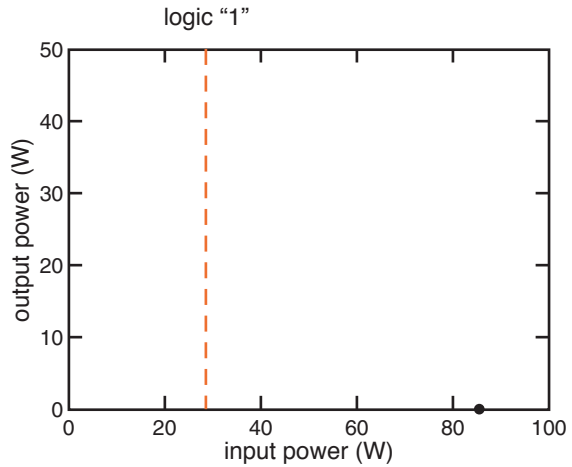


A	B	Q
0	0	1

Optical logic gates

for NAND gate need ouput with no input

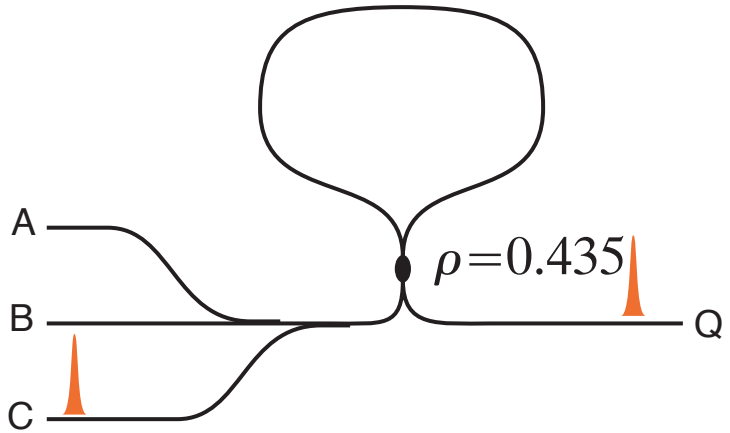


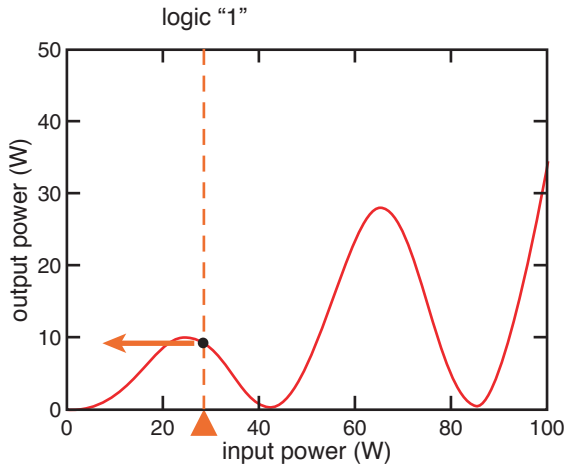


A	B	Q
0	0	1

Optical logic gates

for NAND gate need ouput with no input

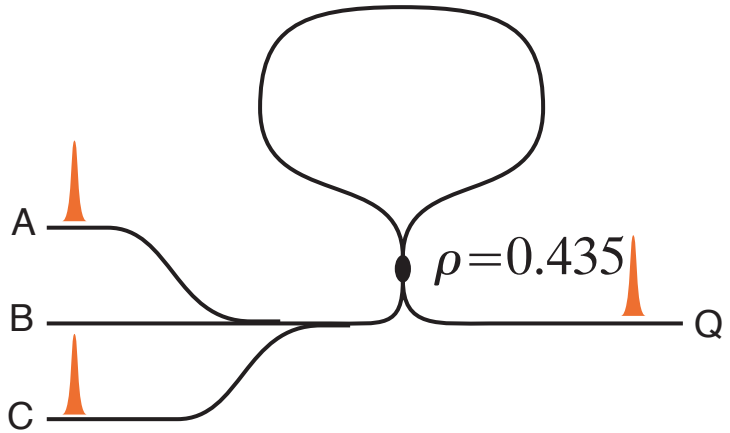


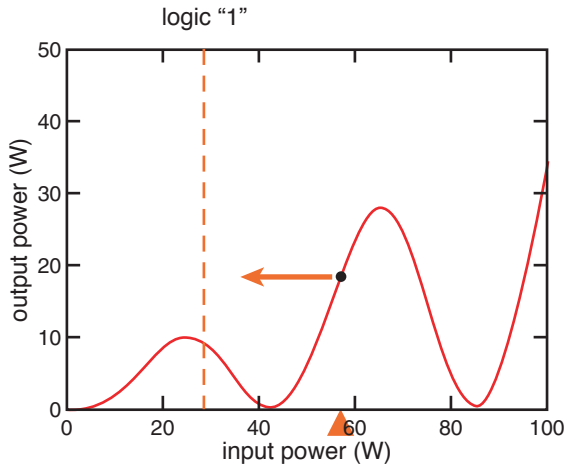


A	B	Q
0	0	1

Optical logic gates

universal NAND gate

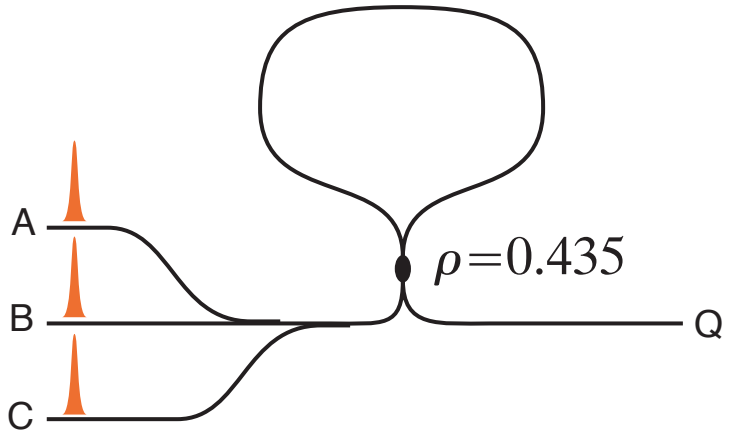


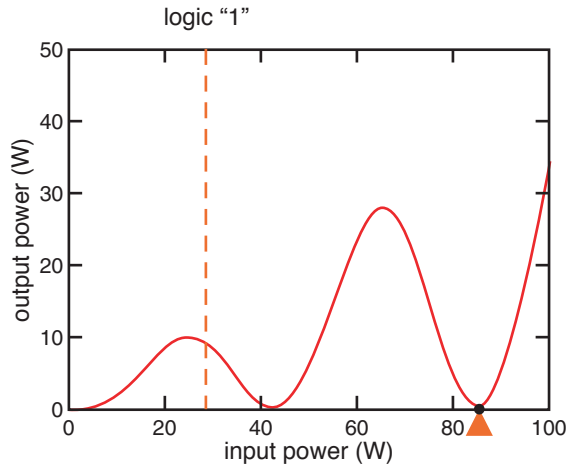


A	B	Q
0	0	1
1	0	1
0	1	1

Optical logic gates

universal NAND gate

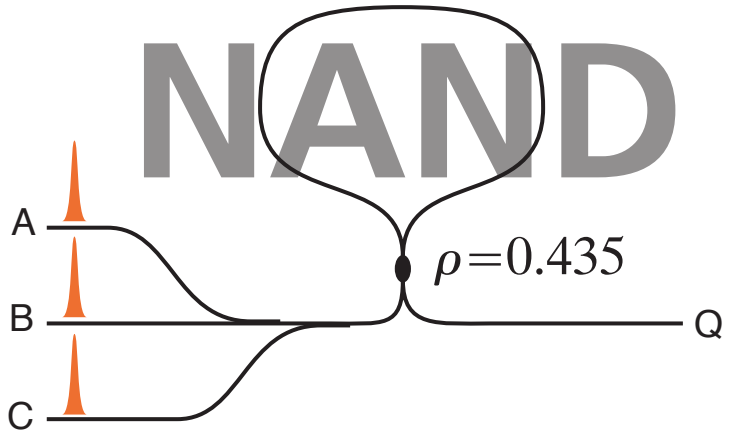


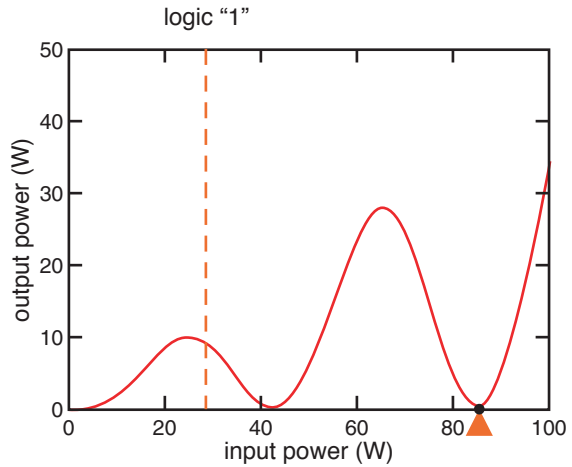


A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates

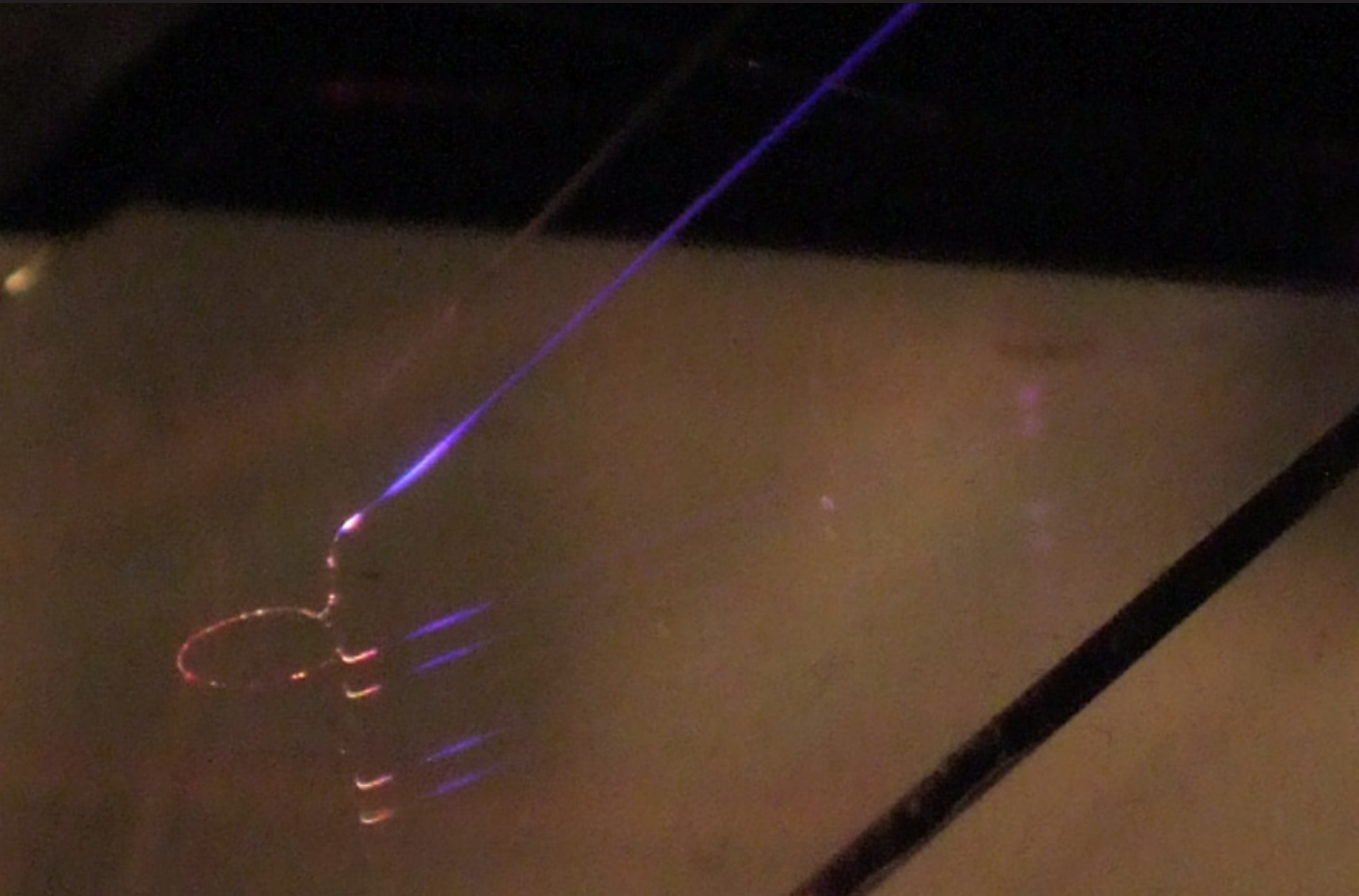
universal NAND gate



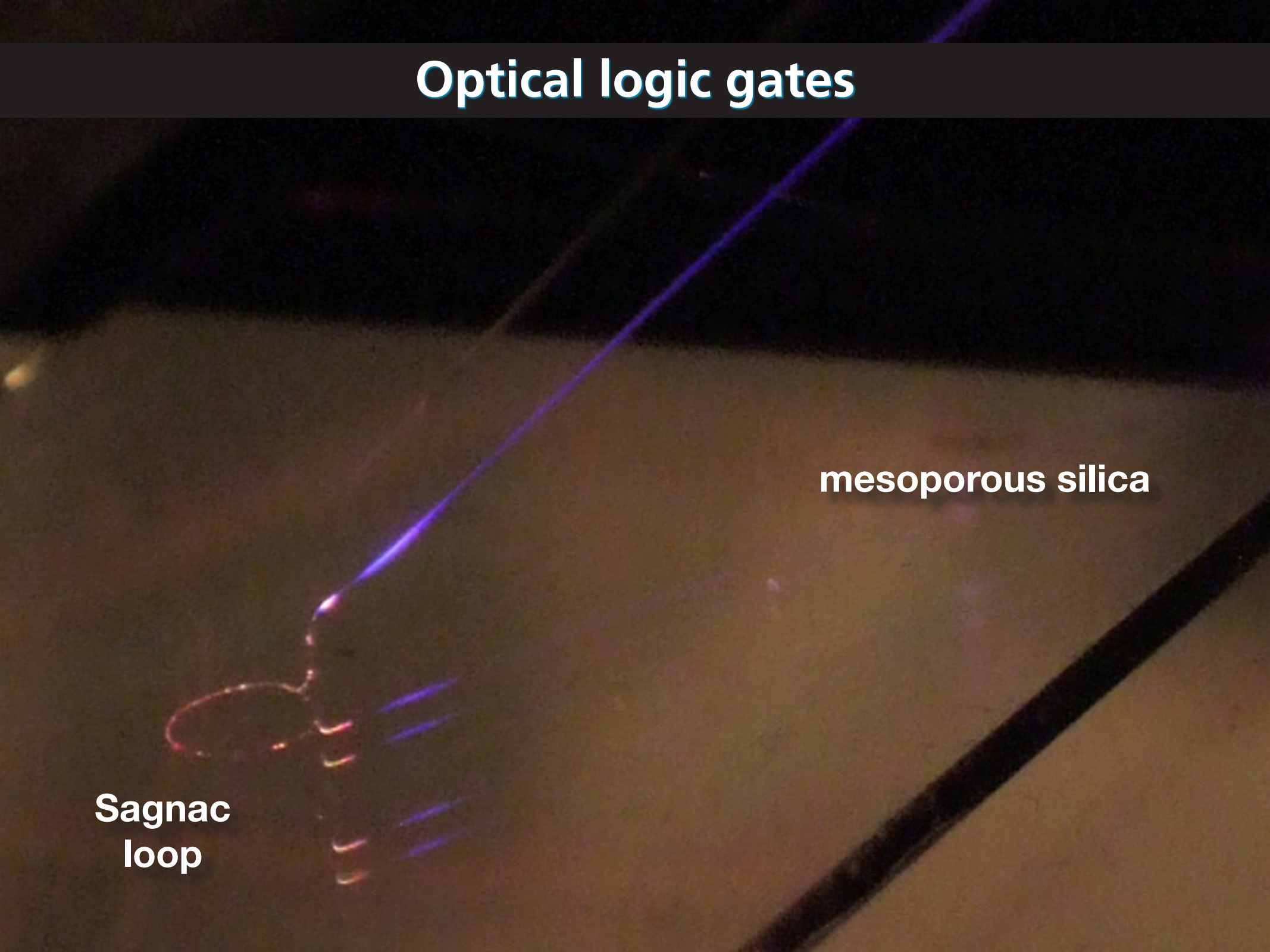


A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

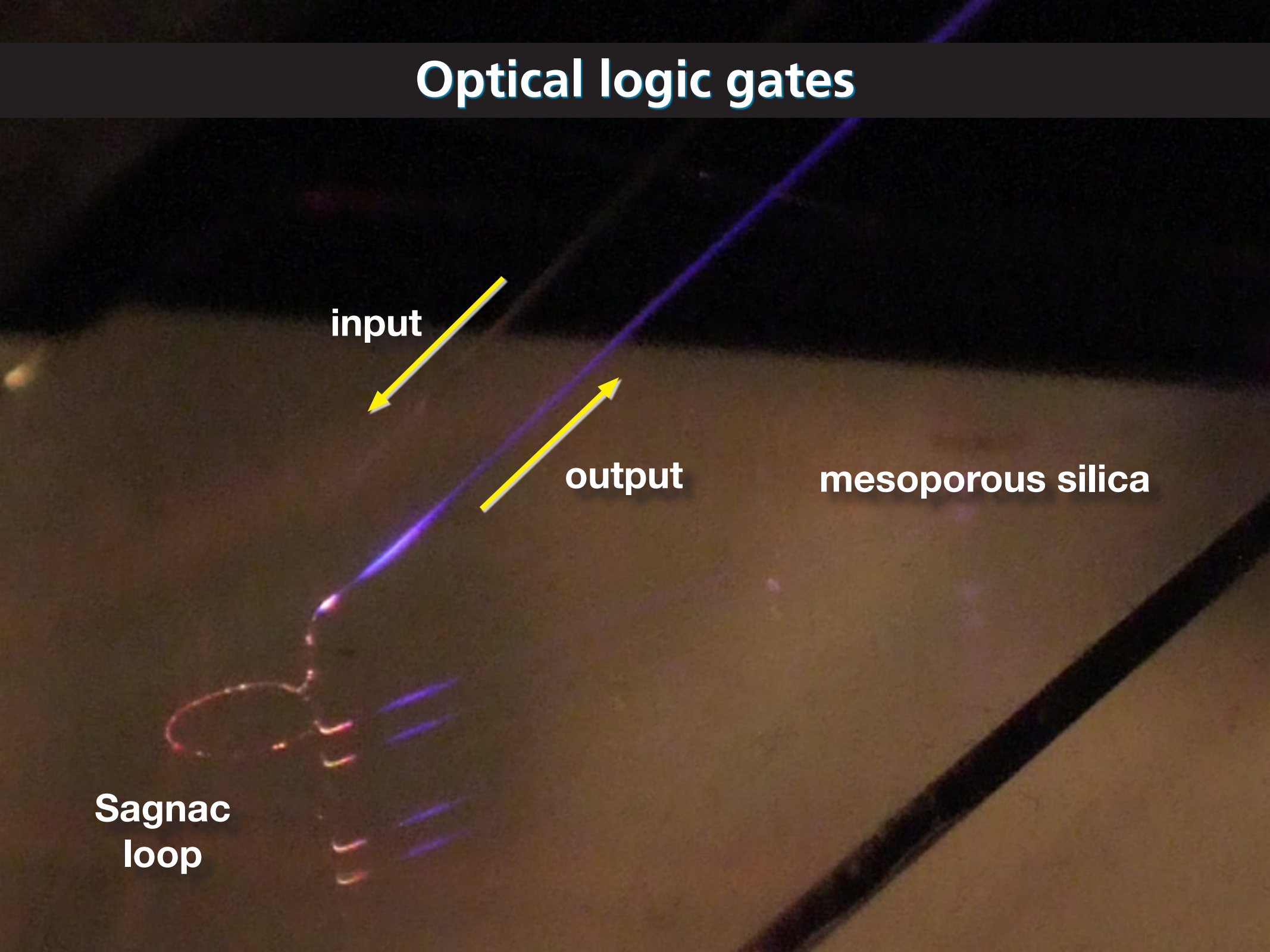
Optical logic gates



Optical logic gates

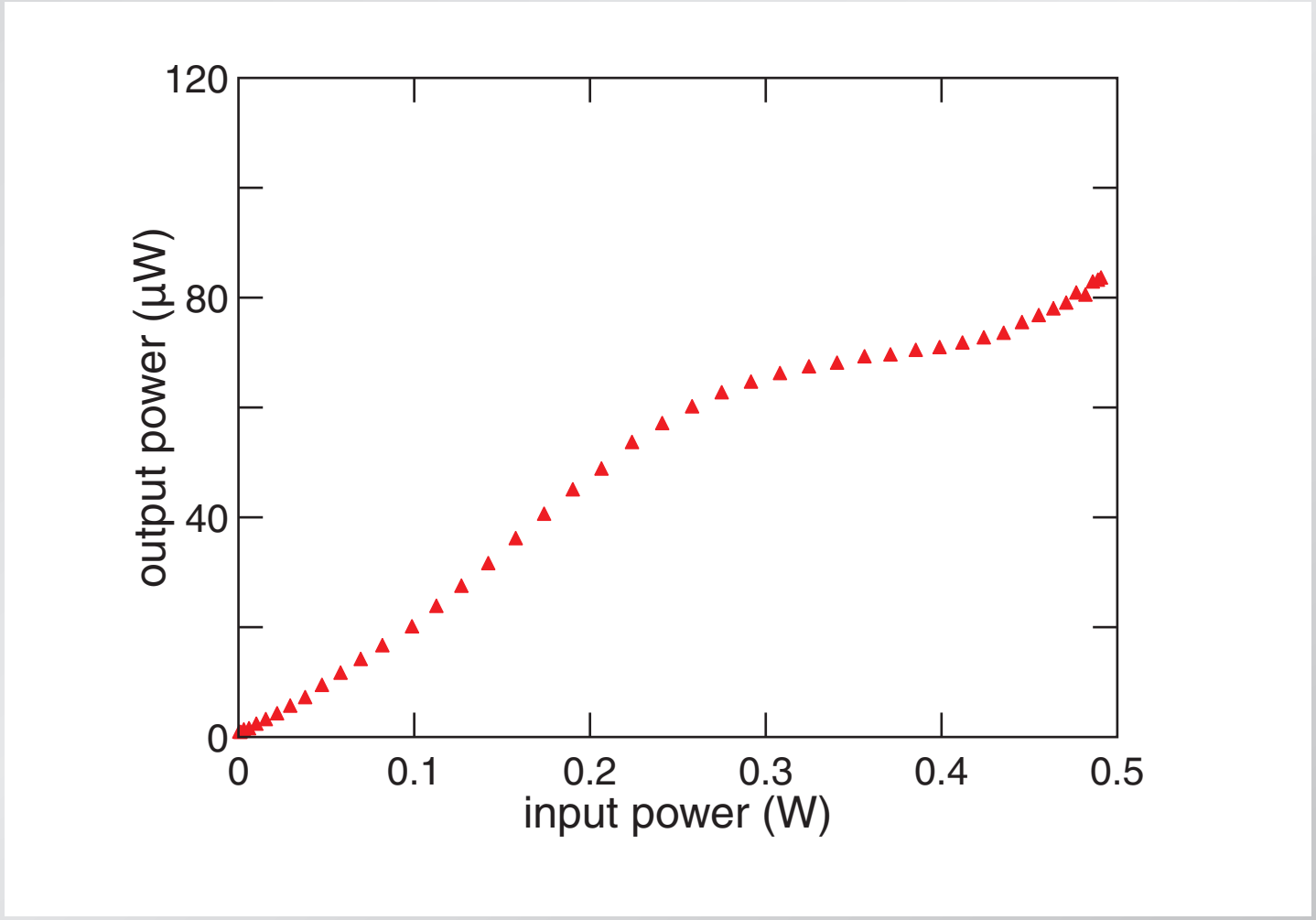


Optical logic gates



Optical logic gates

very preliminary data

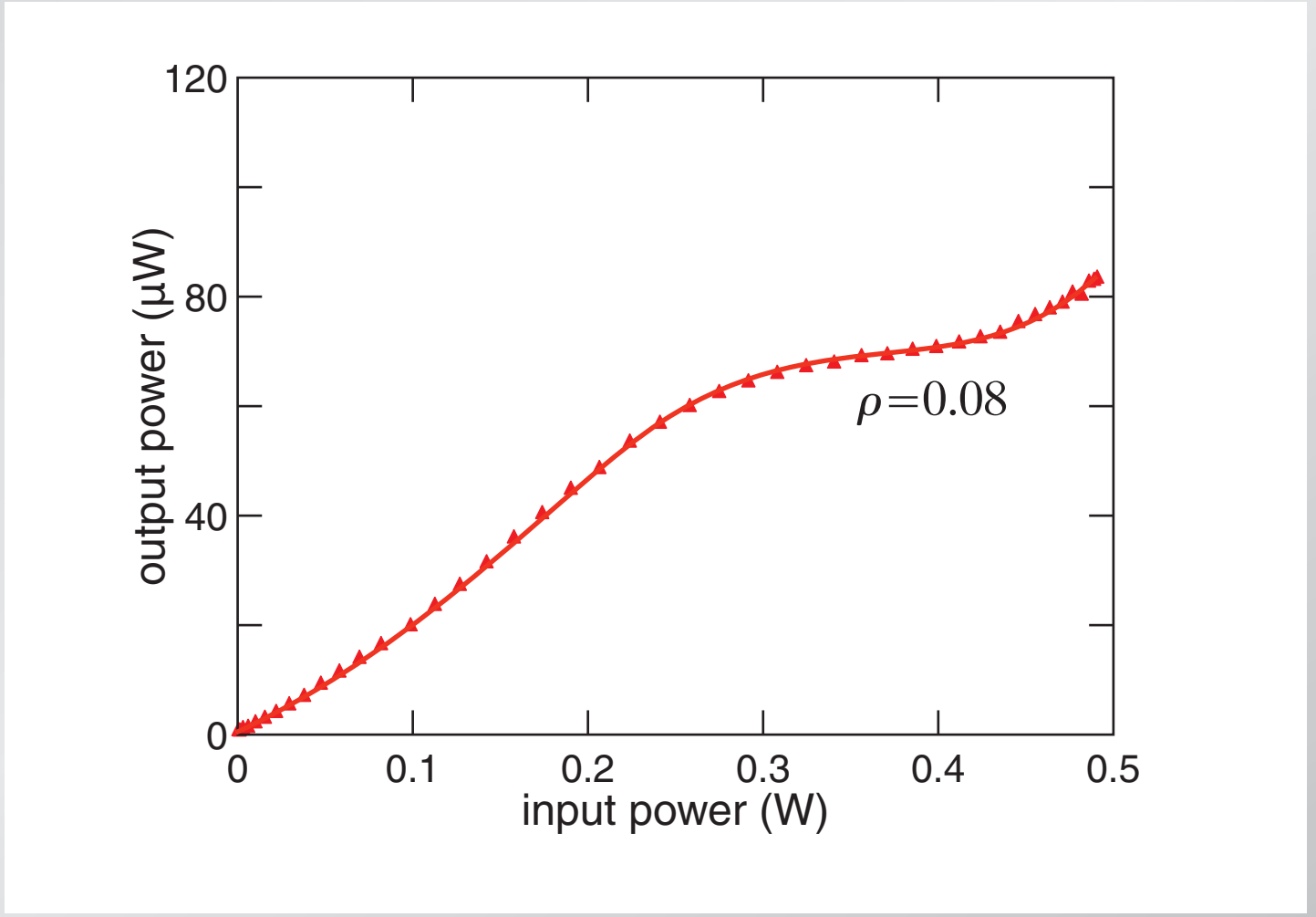


Optical logic gates

light-by-light modulation!

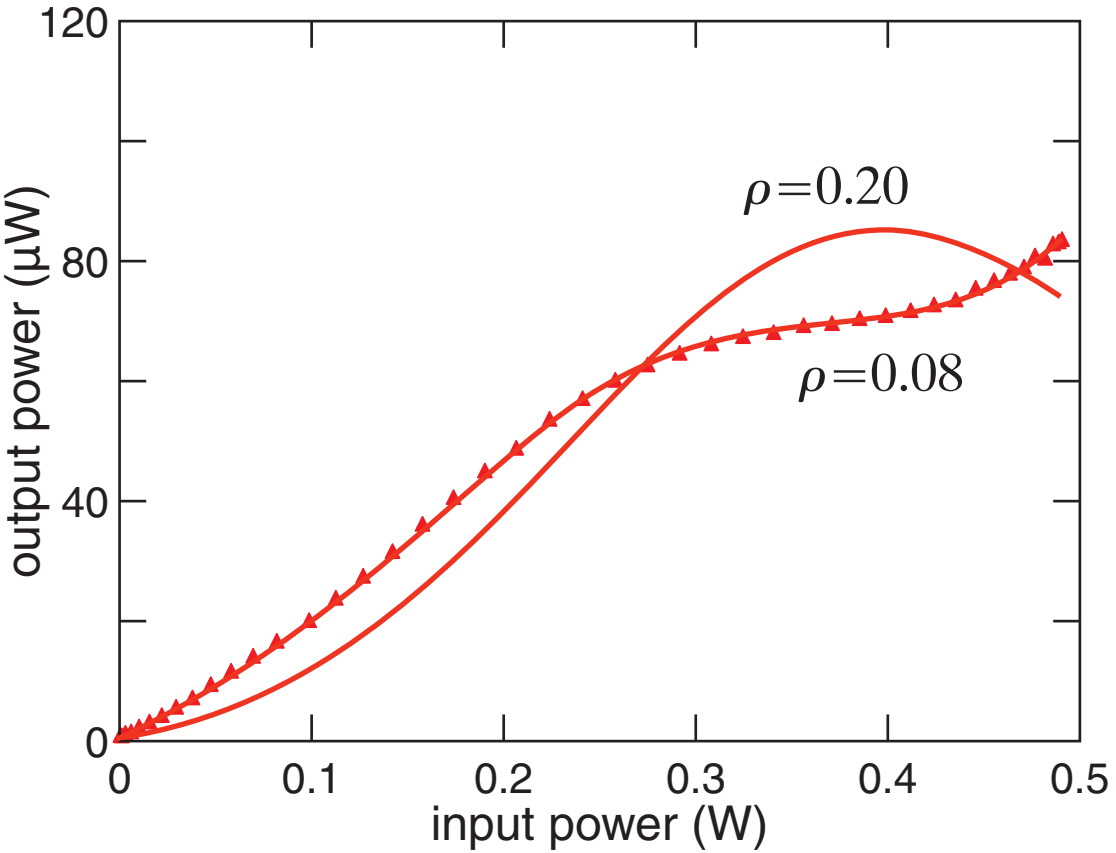
Optical logic gates

very preliminary data

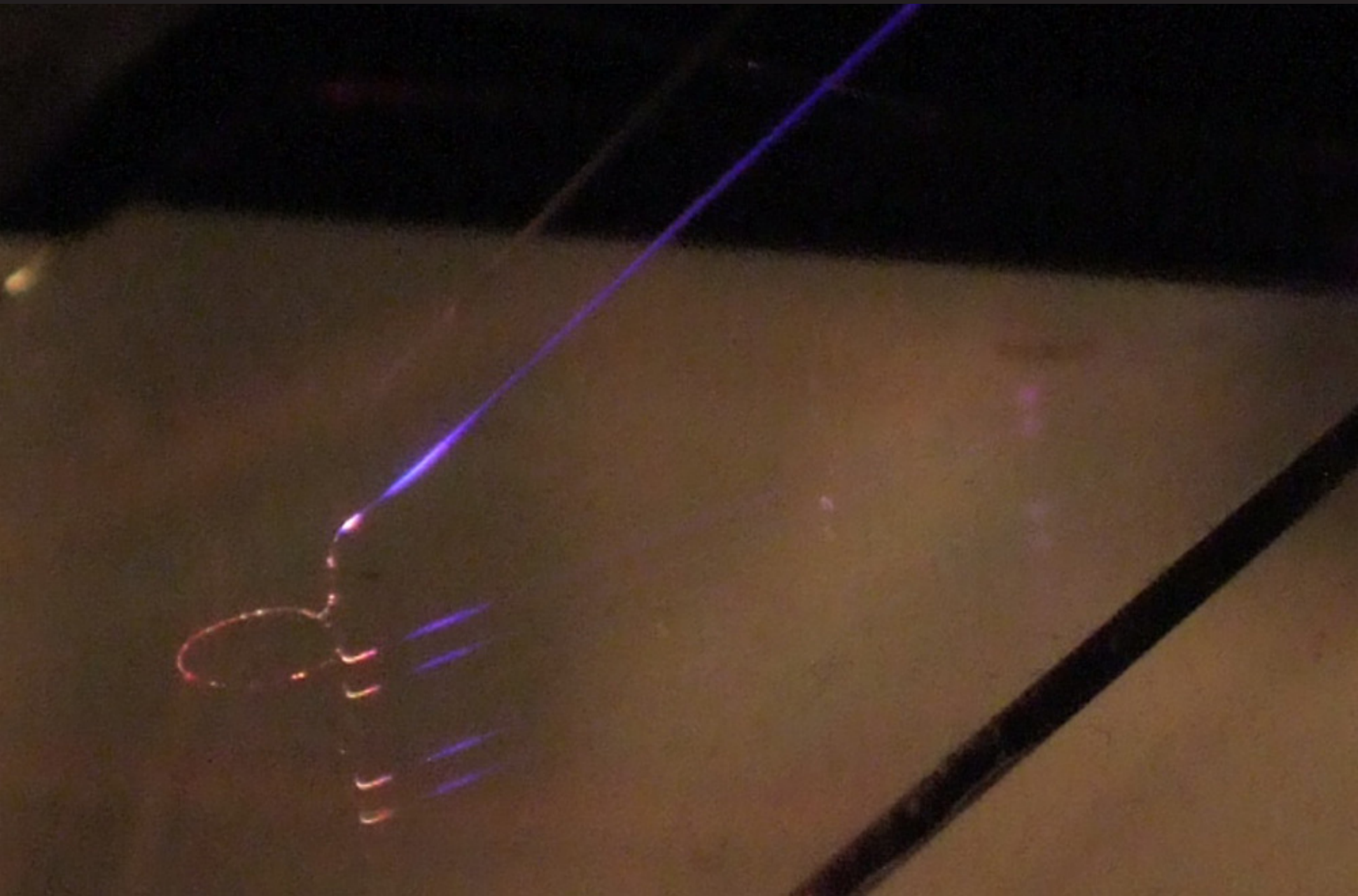


Optical logic gates

very preliminary data



Summary



Summary

- several nanodevices demonstrated
- large γ 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:

http://mazur-www.harvard.edu

http://twitter.com/eric_mazur