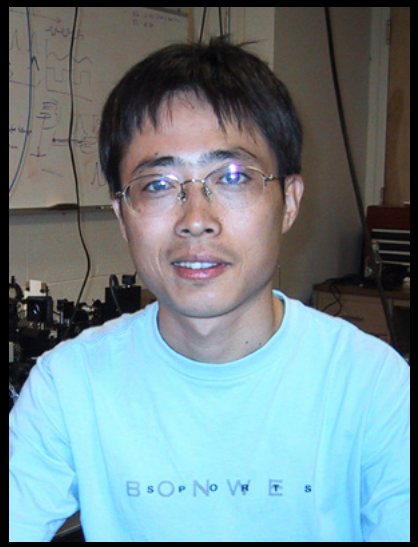
Nonlinear optics at the nanoscale

Louisiana State University
Baton Rouge, LA, 28 April 2014

Geoff Svacha

Rafael Gattass

Tobias Voss



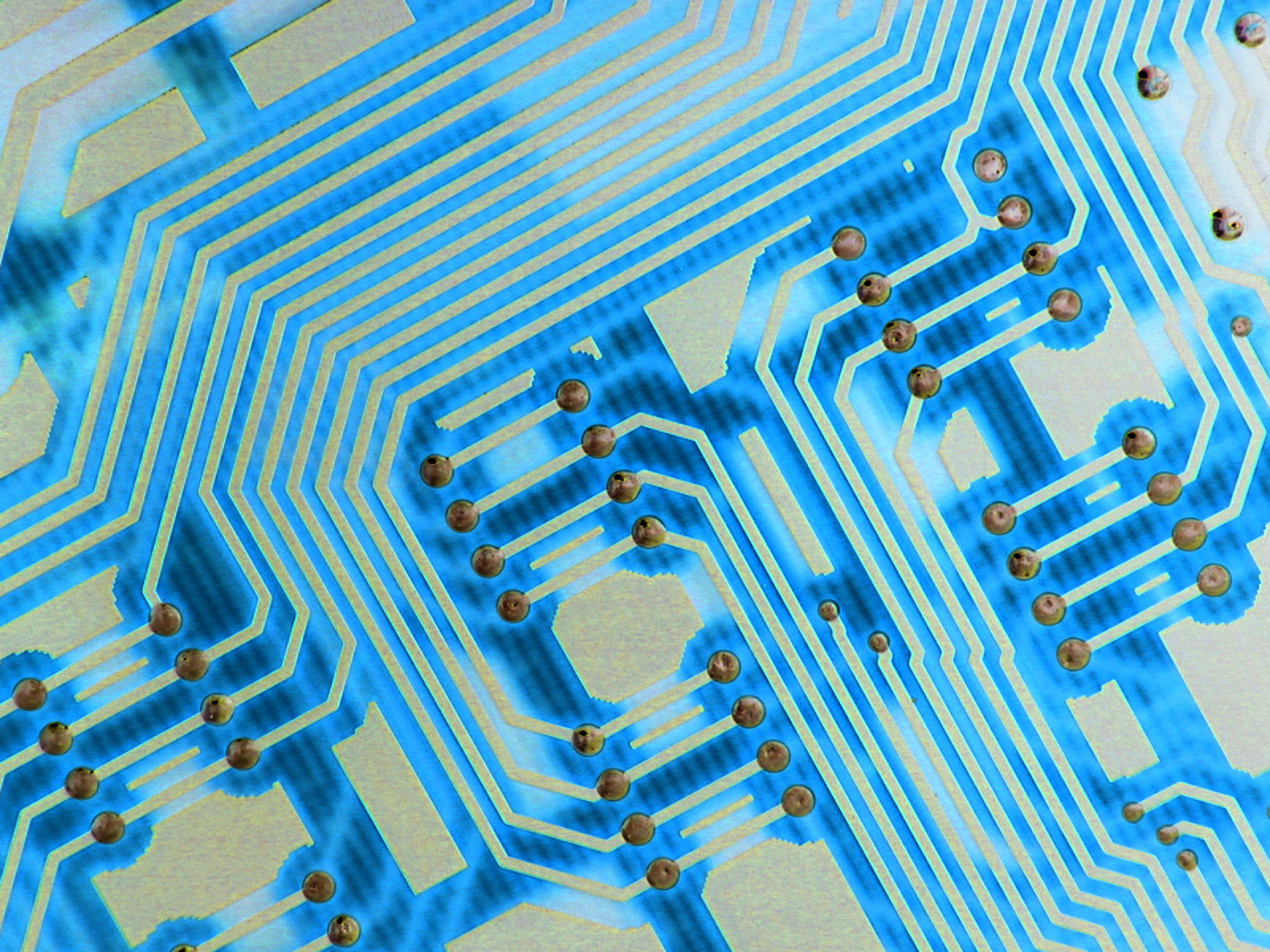
Limin Tong

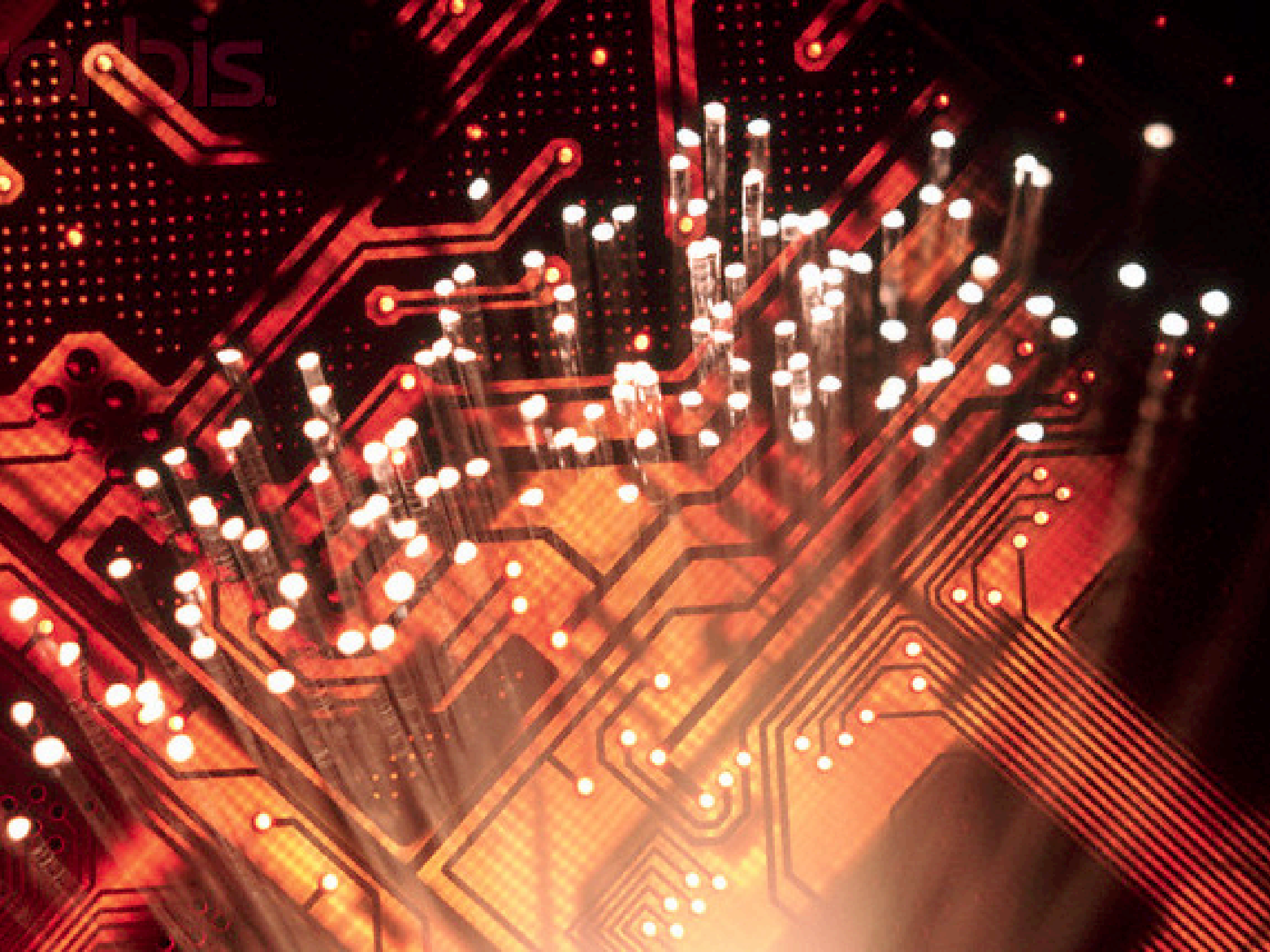
eric_mazur

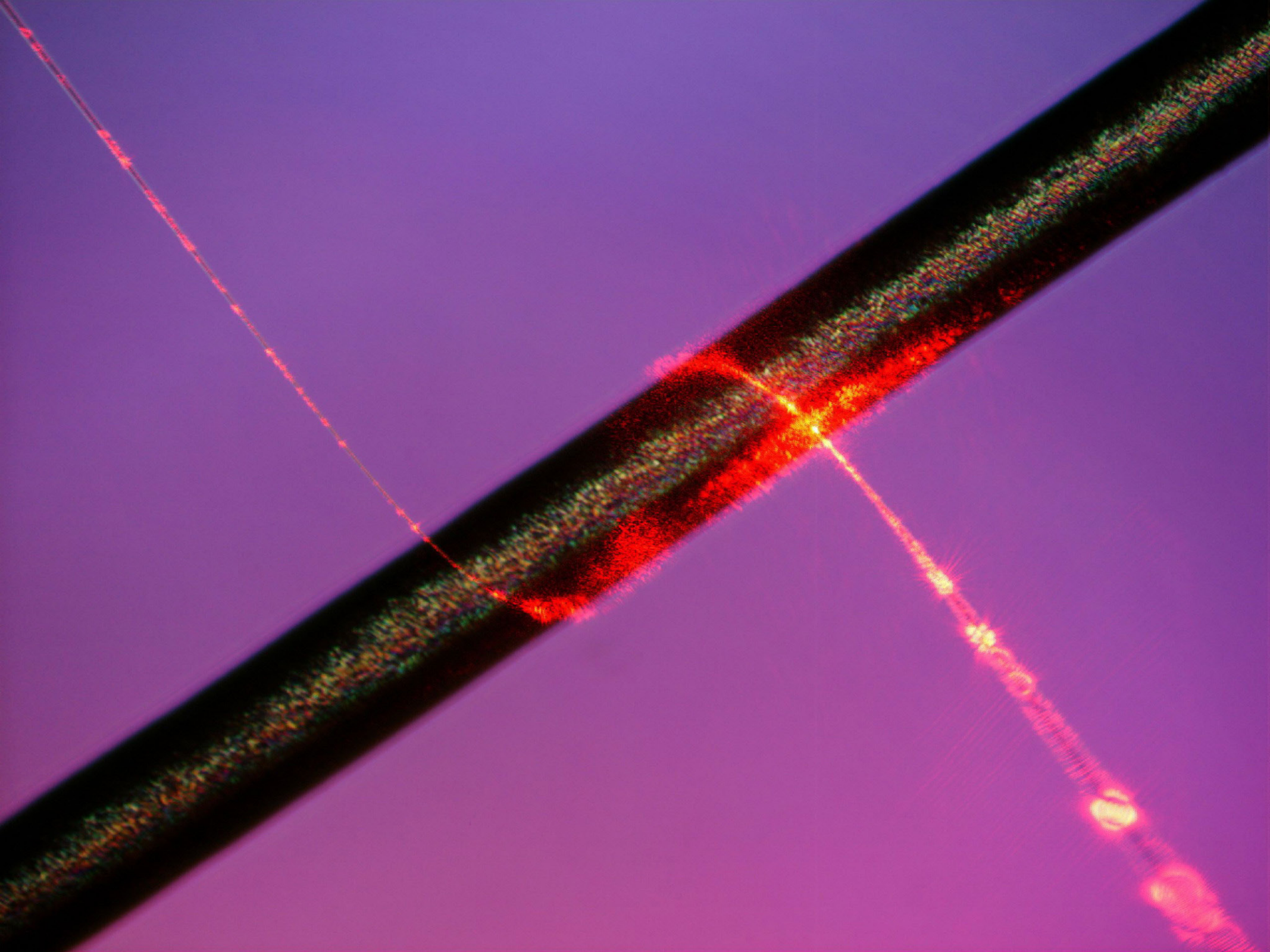
and also....

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)




corbis



Outline

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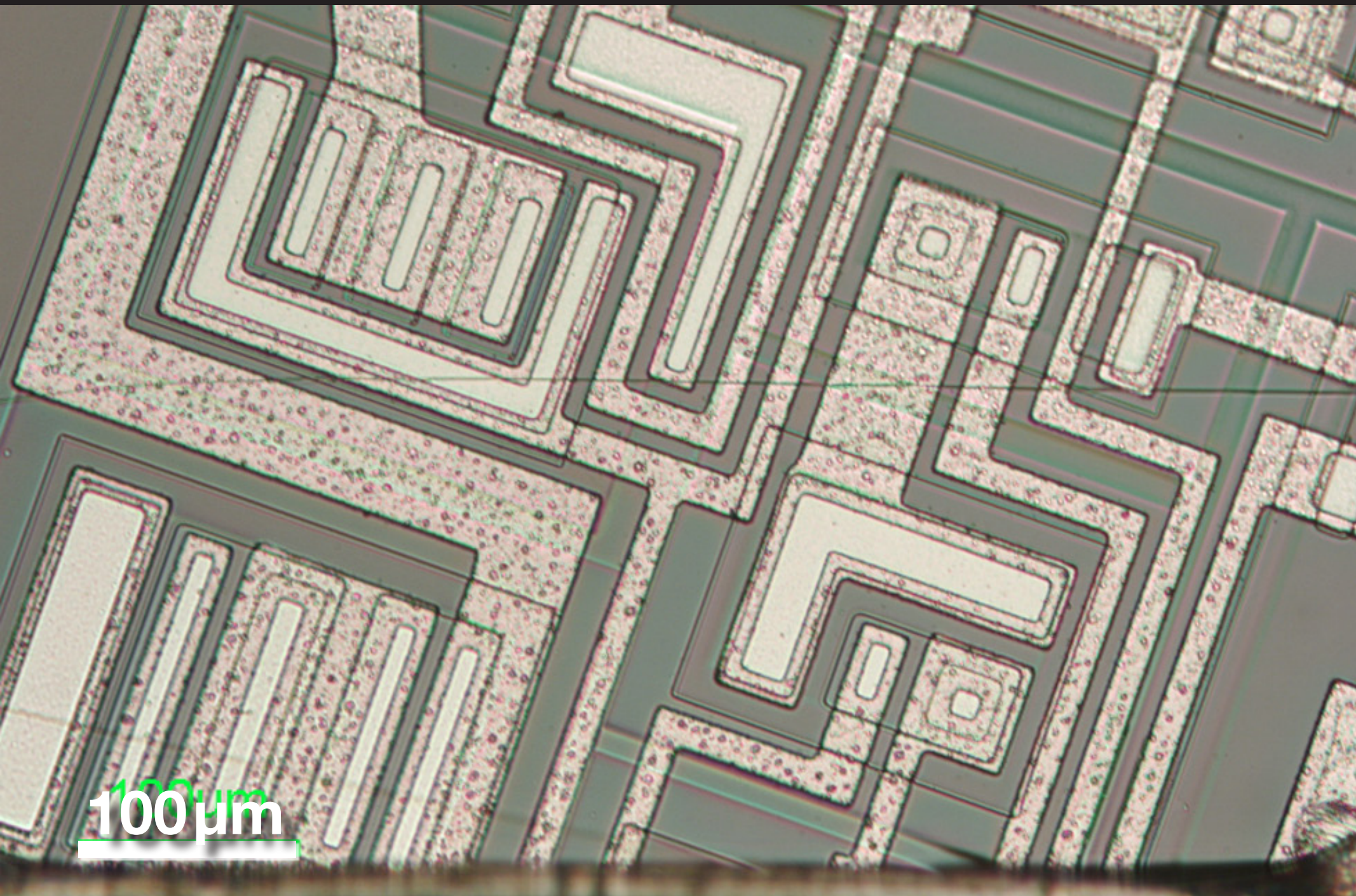
- manipulating light at the nanoscale
- supercontinuum generation
- optical logic gates

Manipulating light at the nanoscale

Nature, 426, 816 (2003)

Manipulating light at the nanoscale



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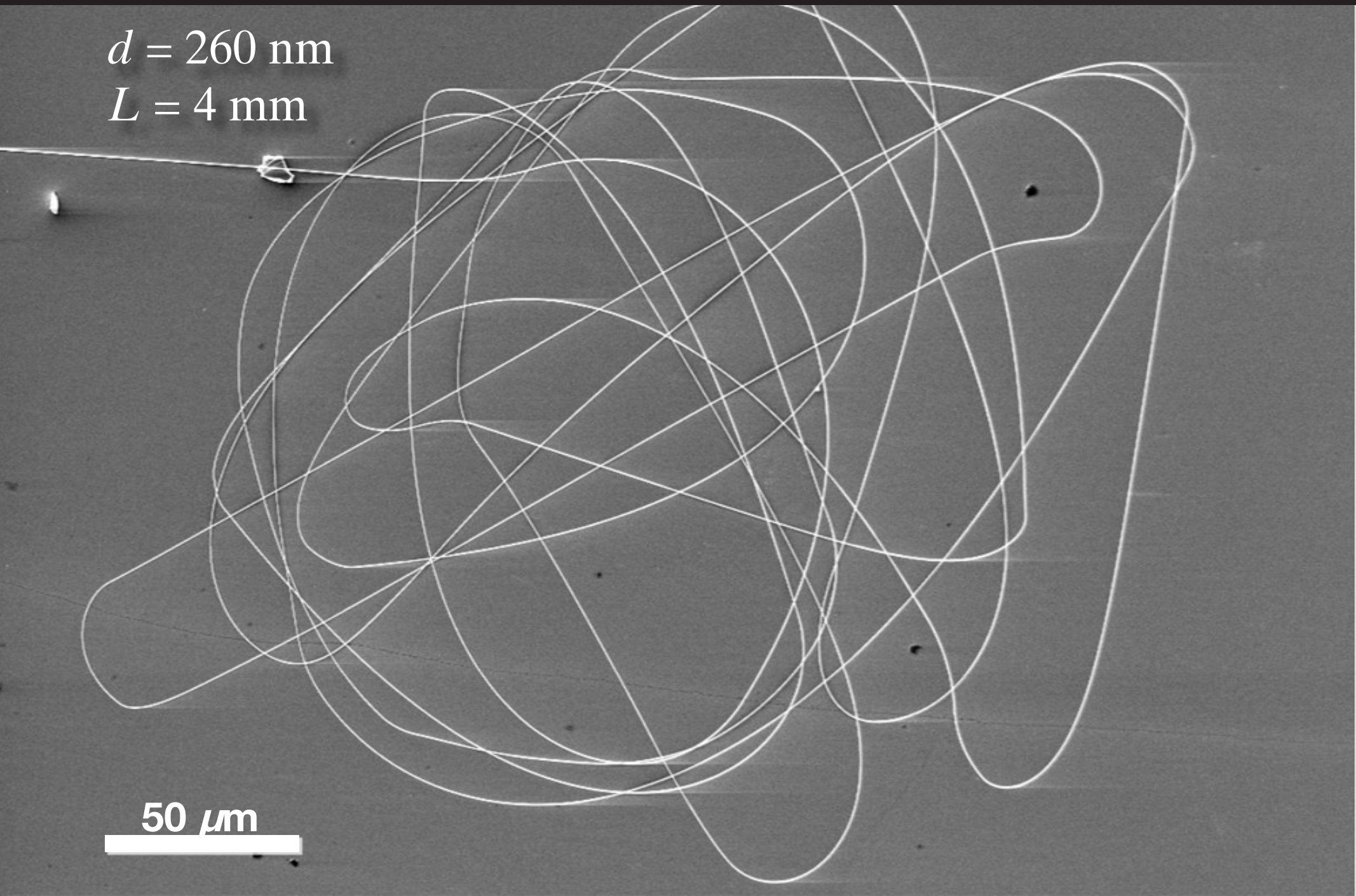

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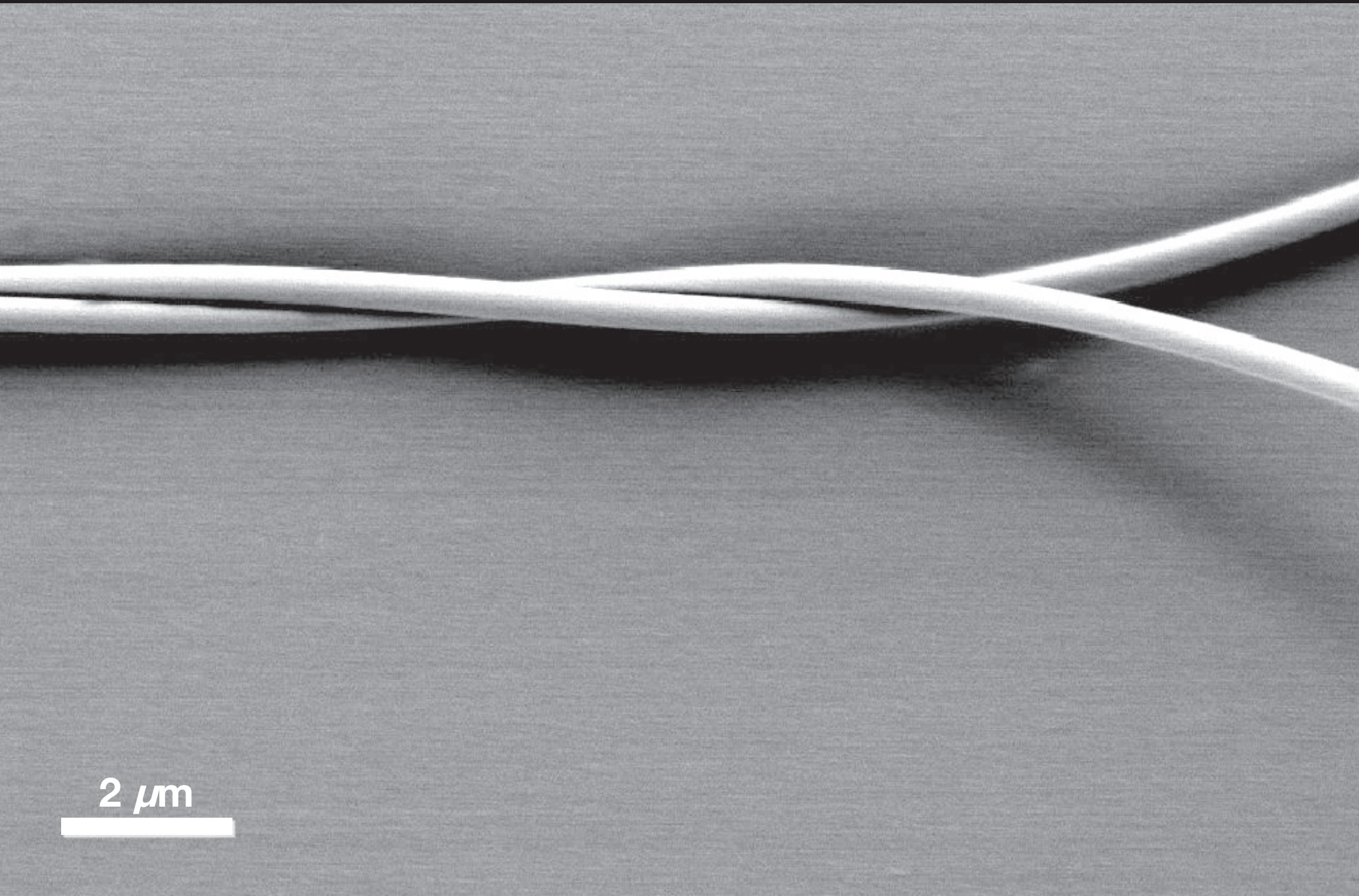

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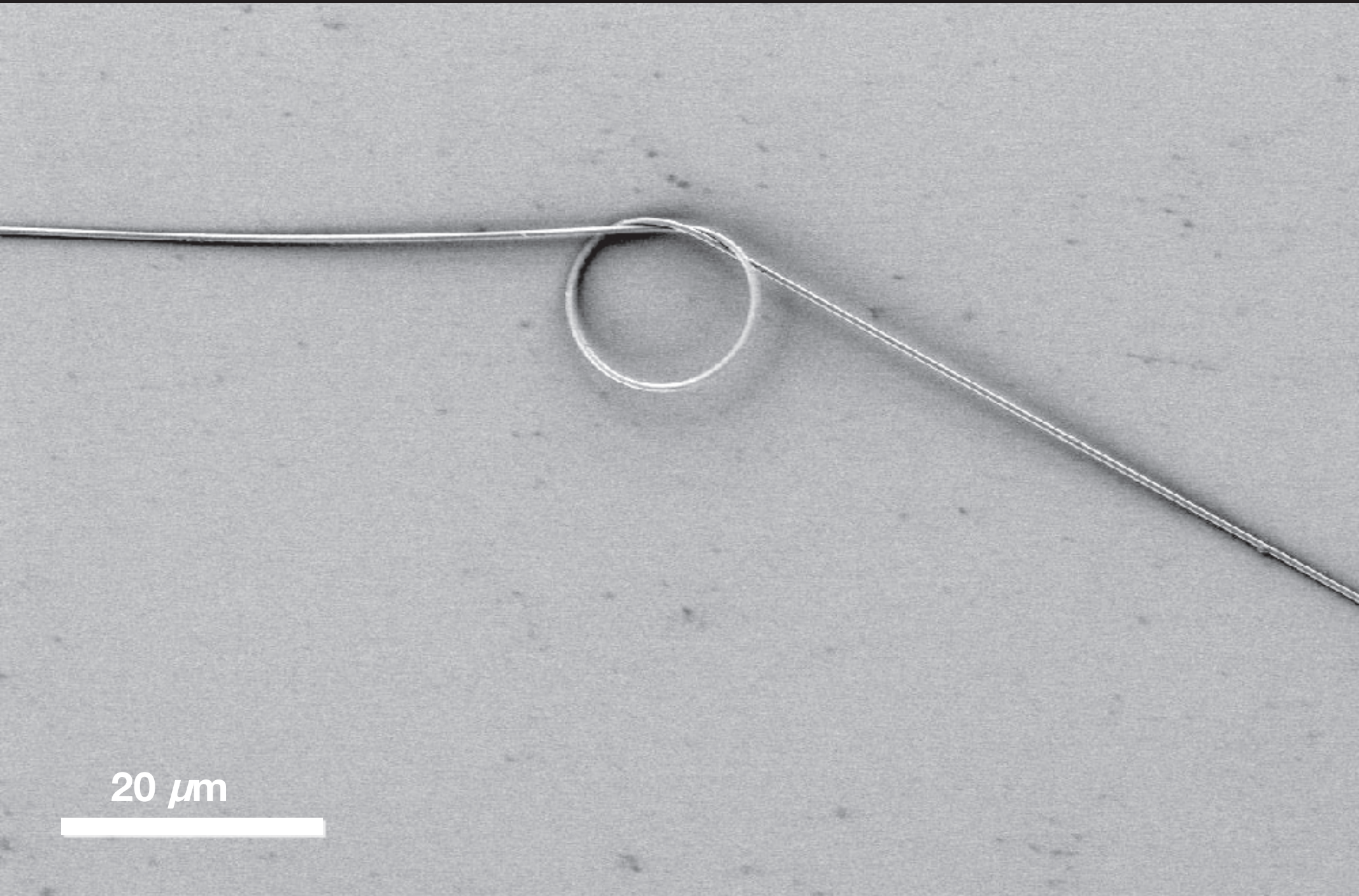

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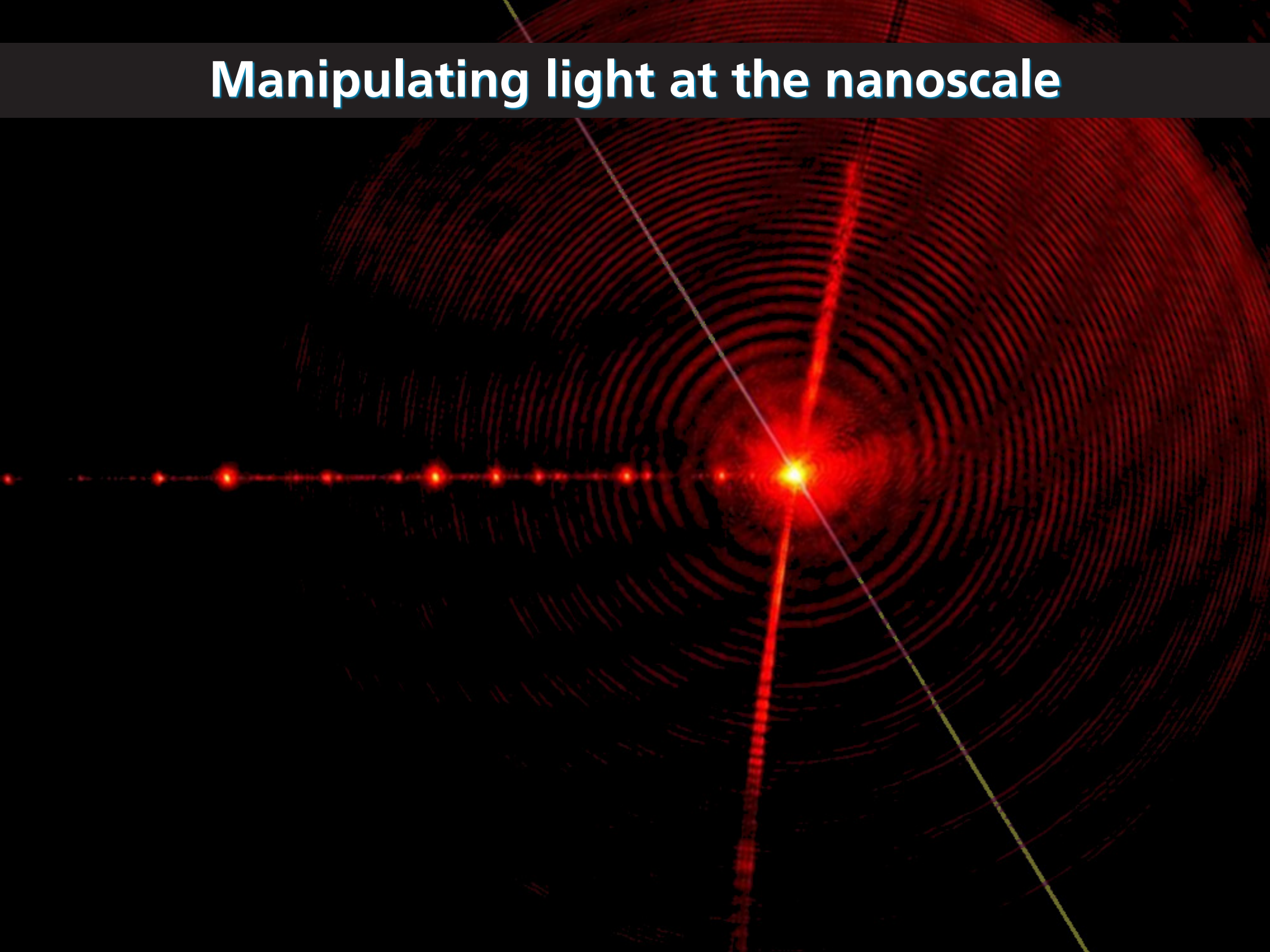
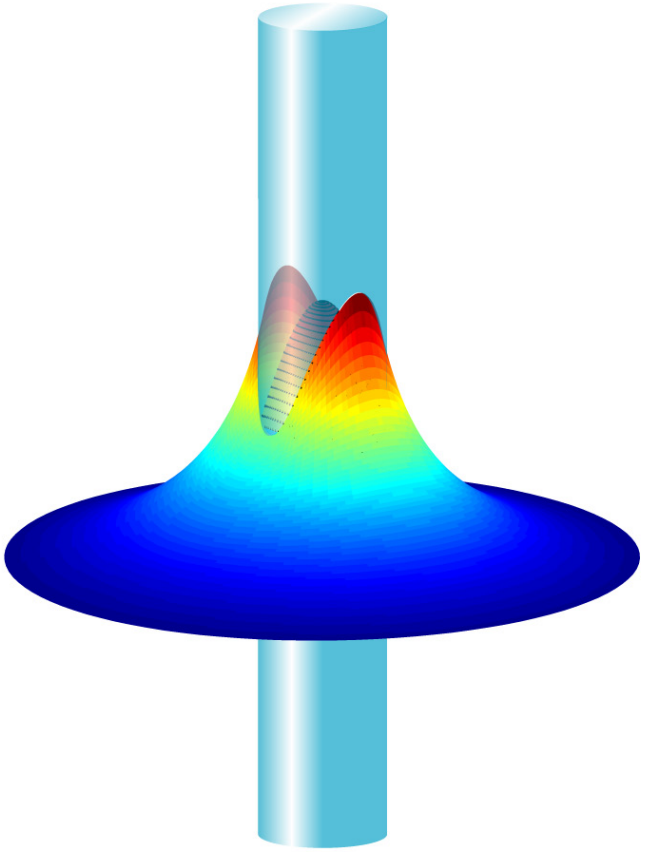


Manipulating light at the nanoscale

Poynting vector profile for 200-nm nanowire



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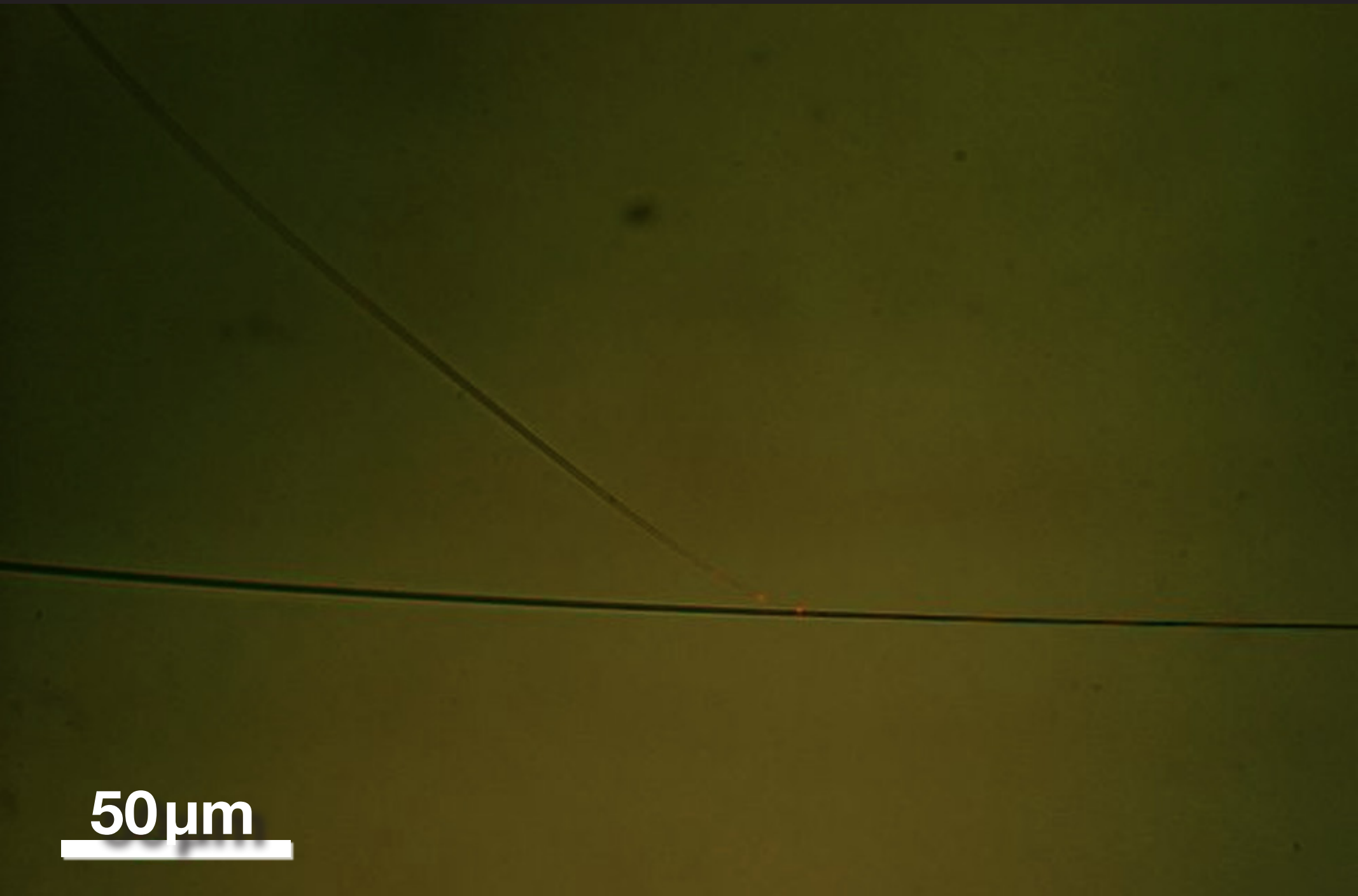

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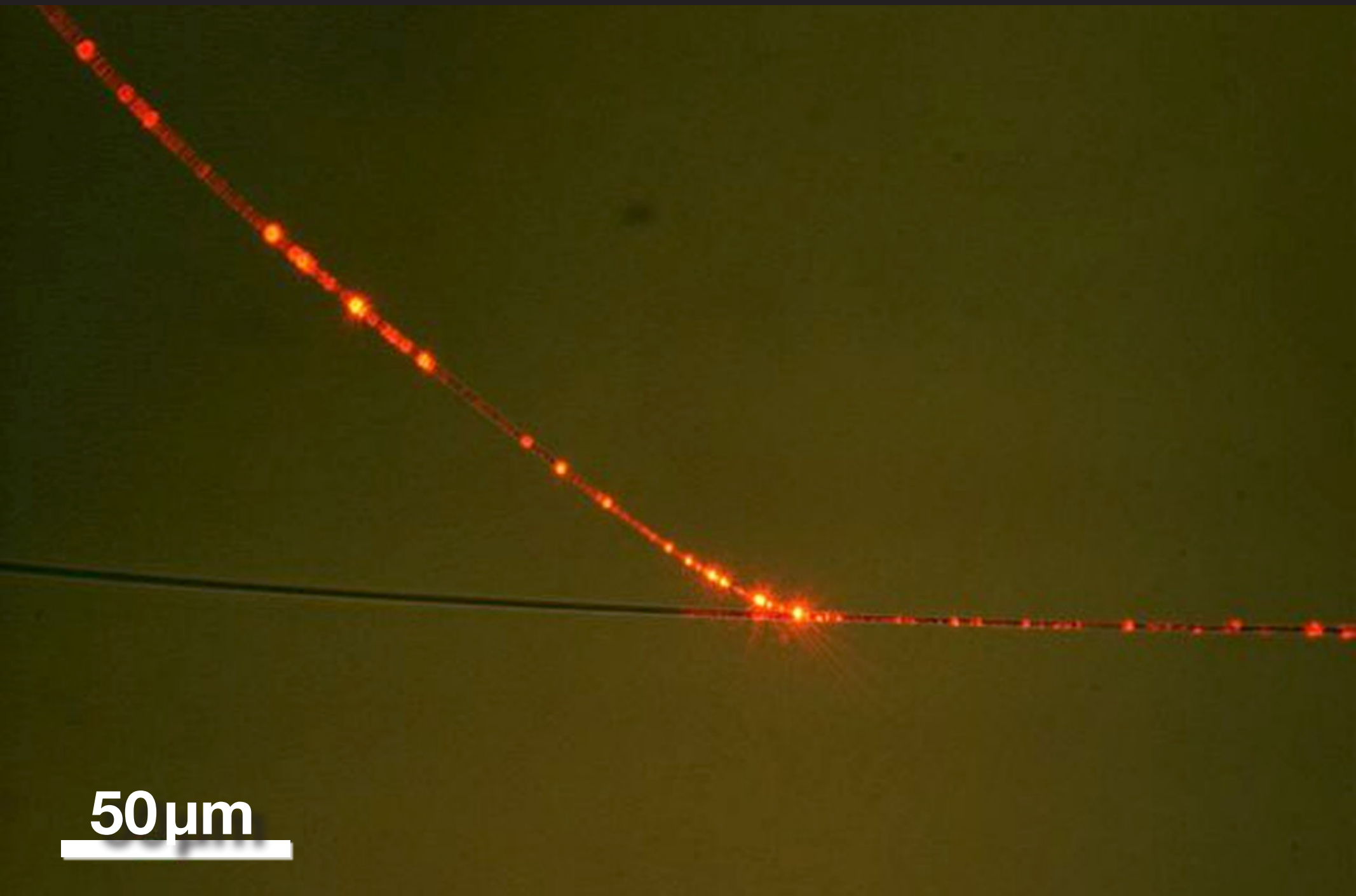

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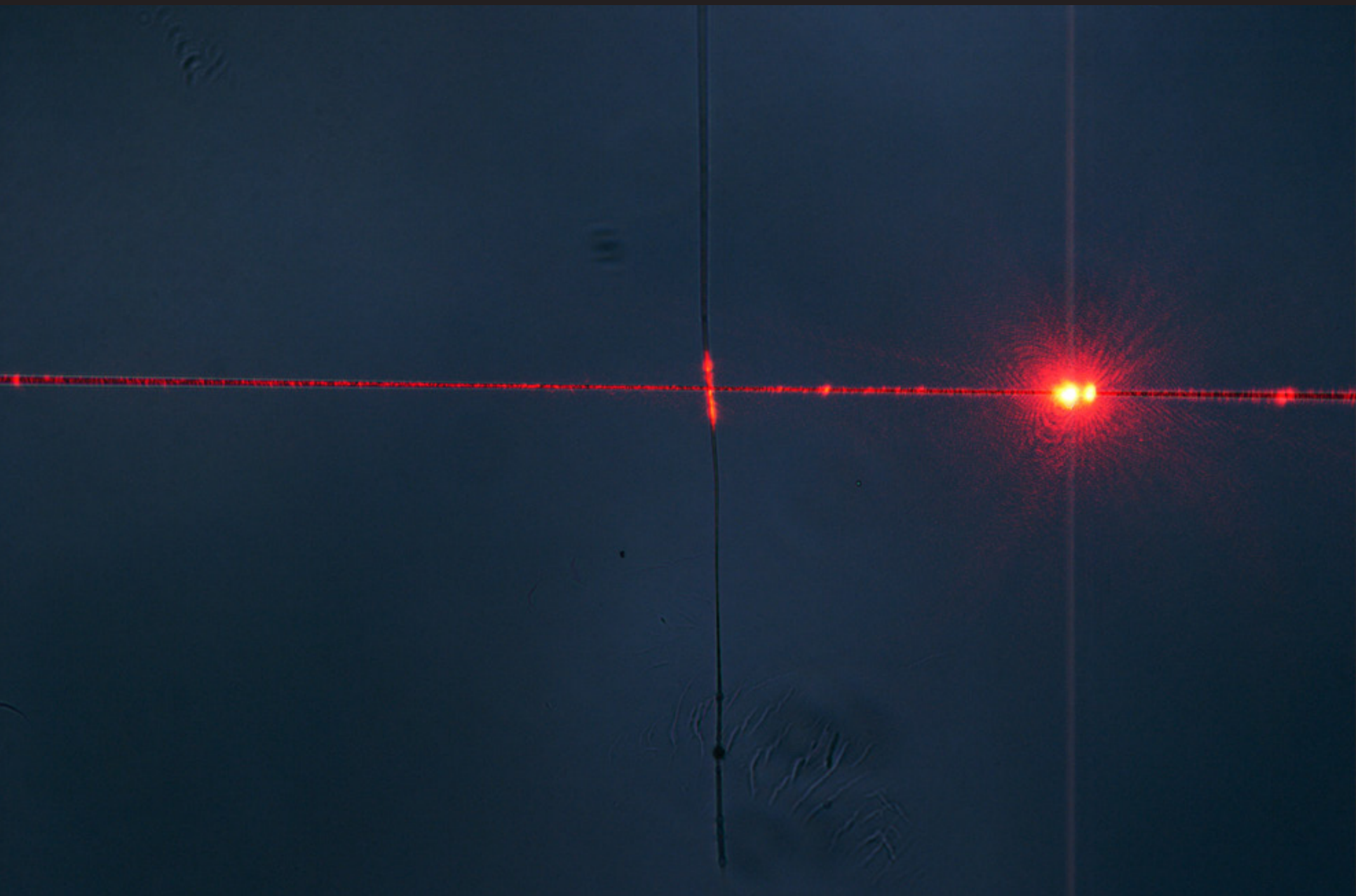

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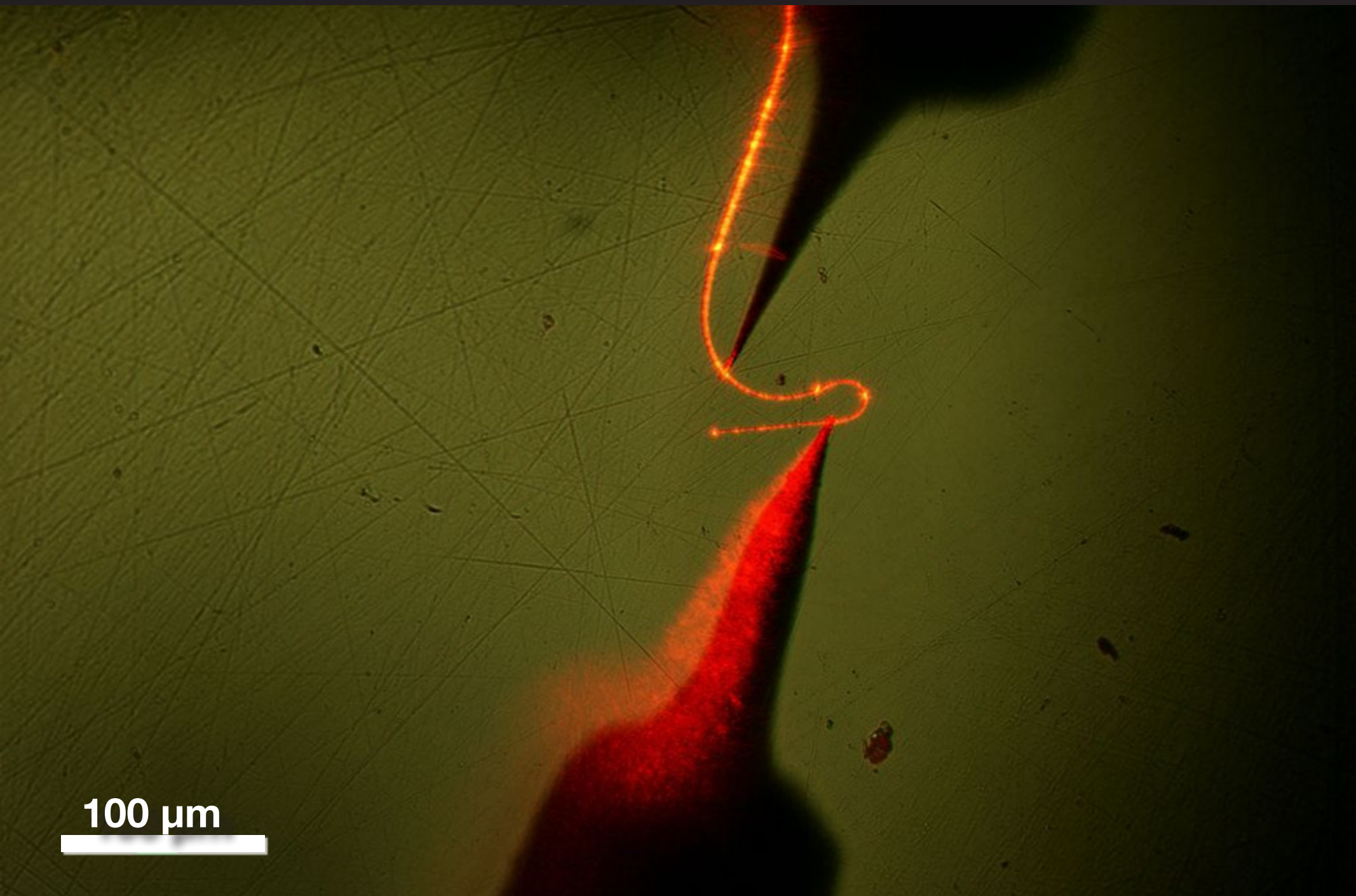

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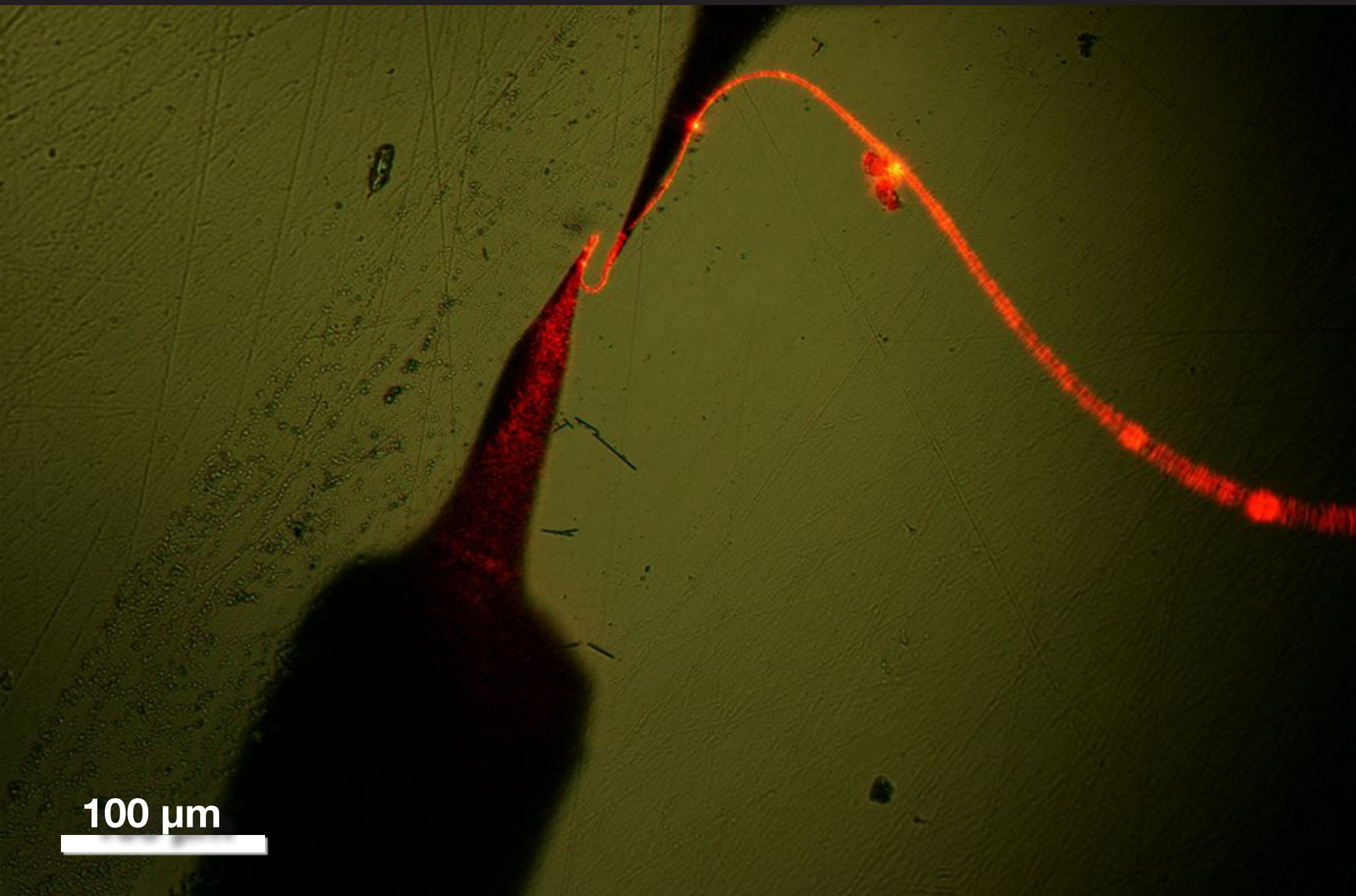

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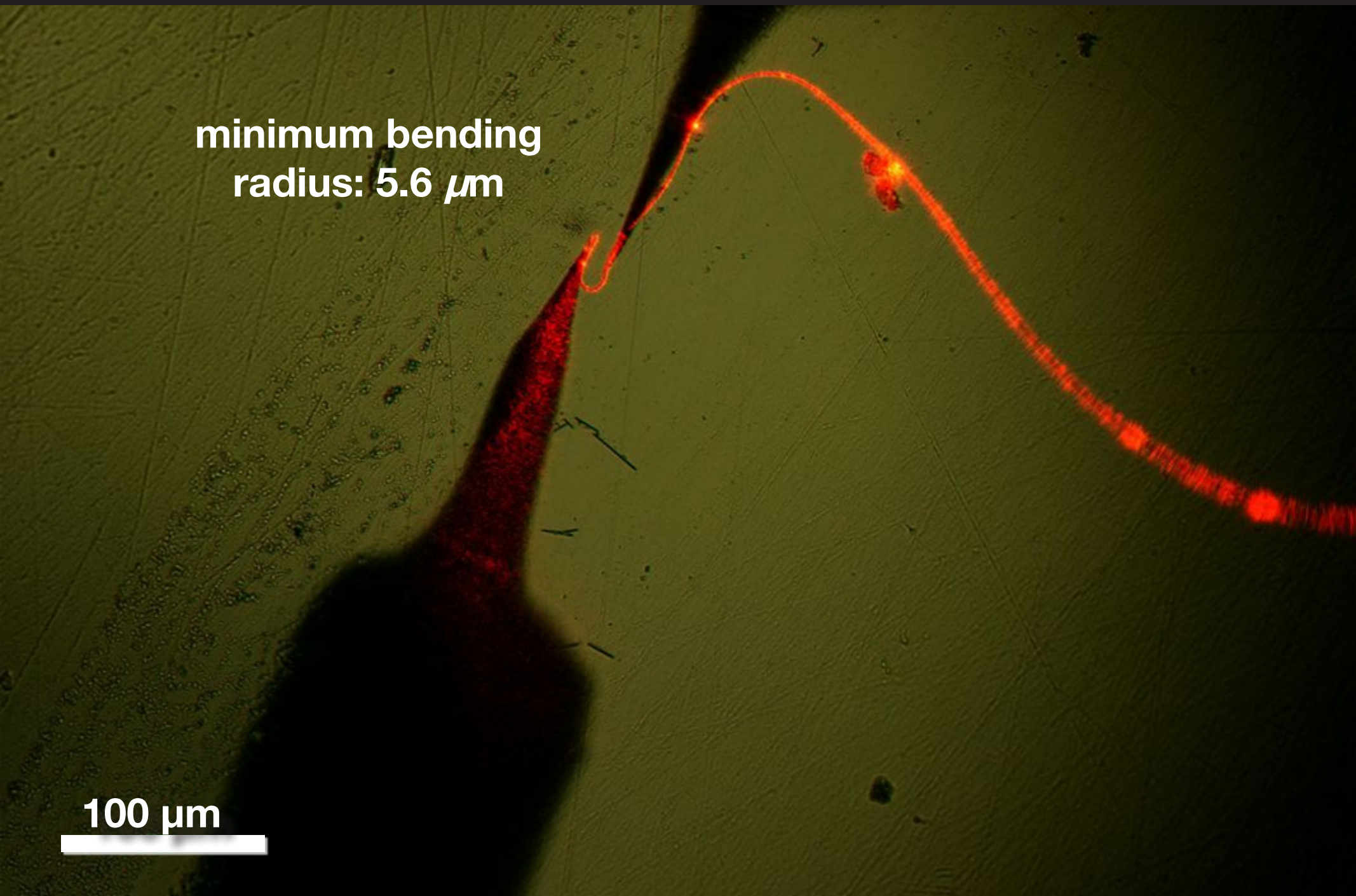

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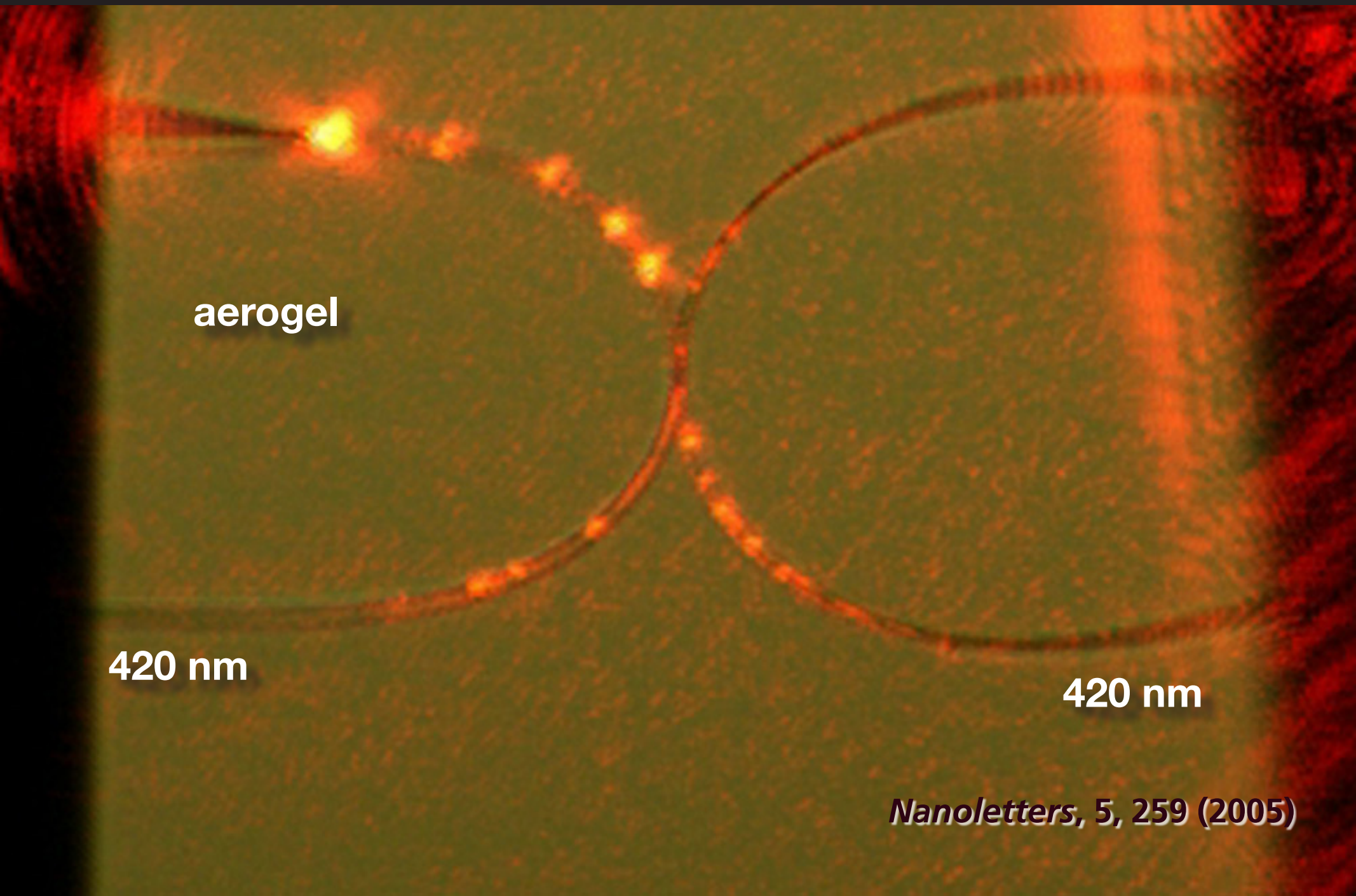
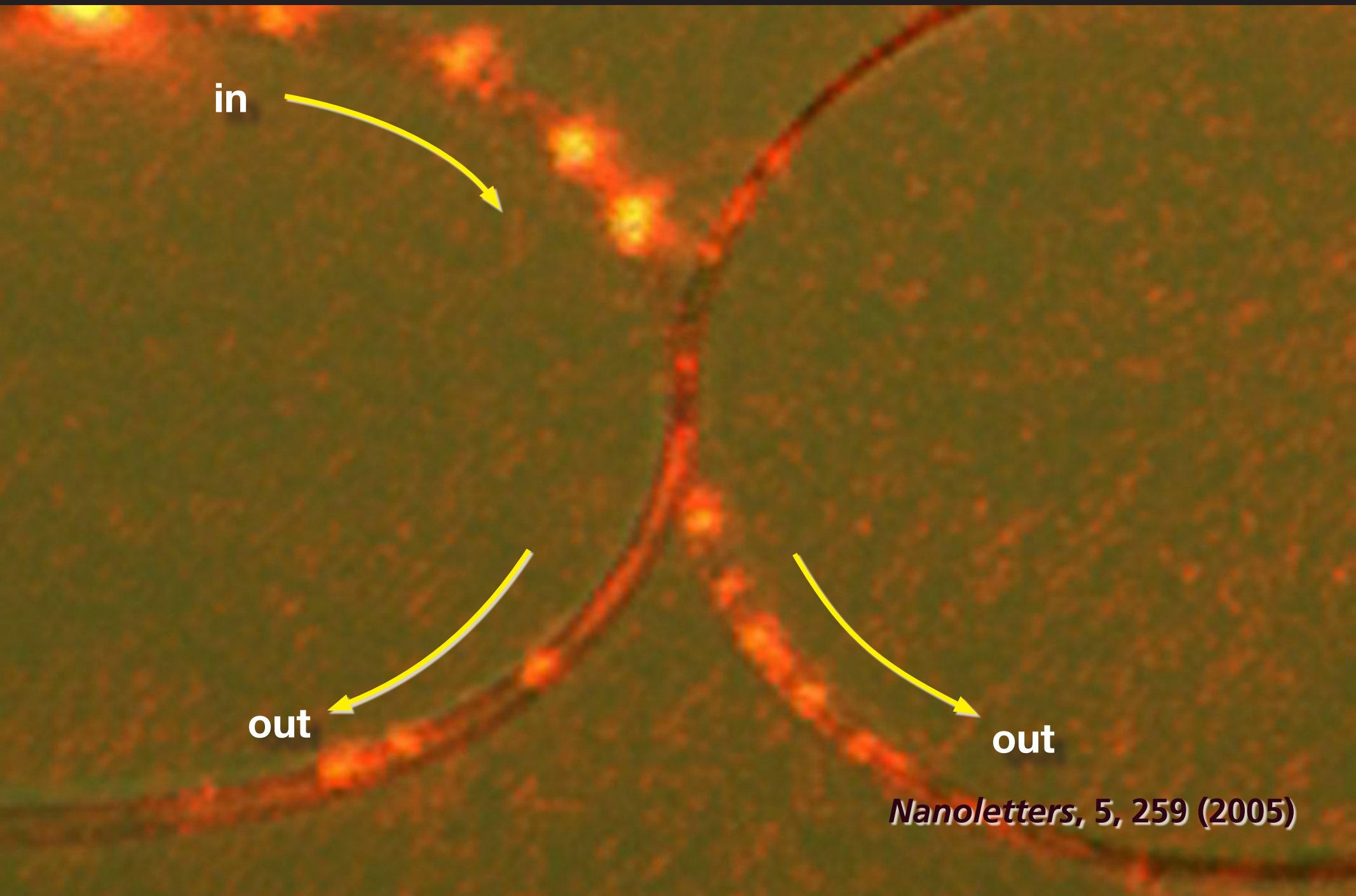


Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale



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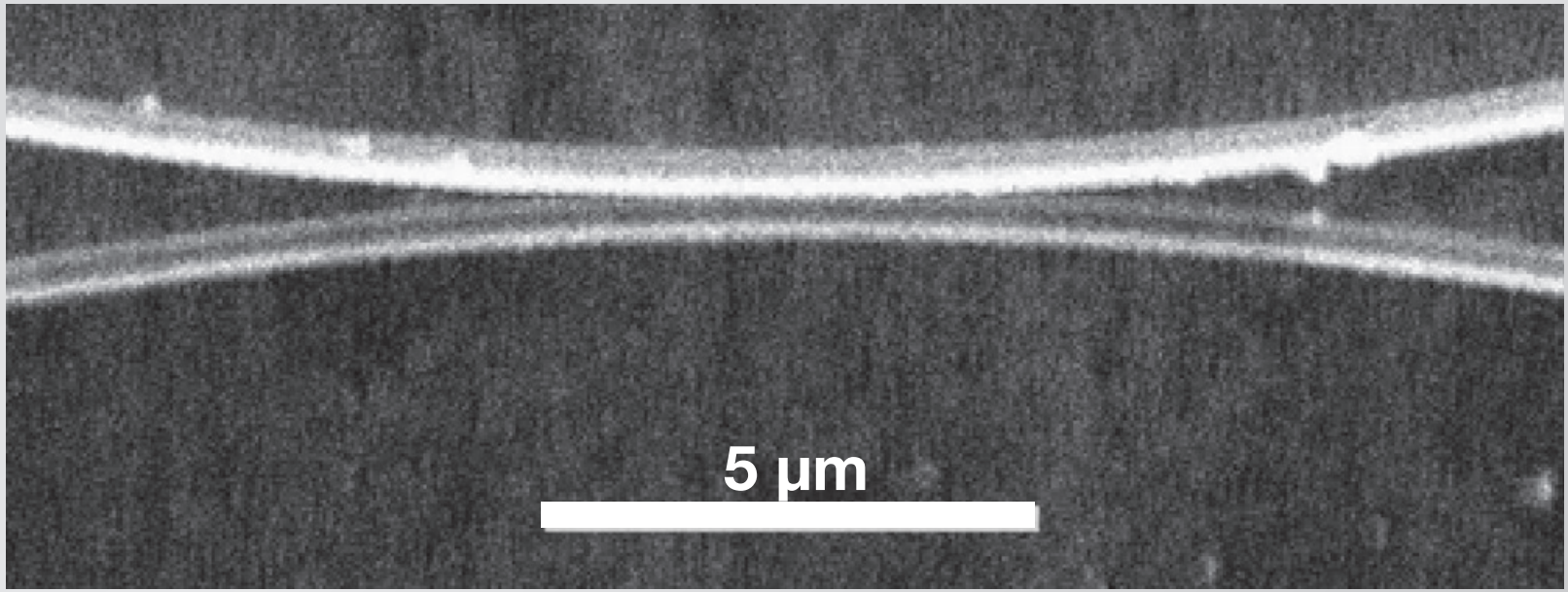


Nanoletters, 5, 259 (2005)

Manipulating light at the nanoscale

Points to keep in mind:

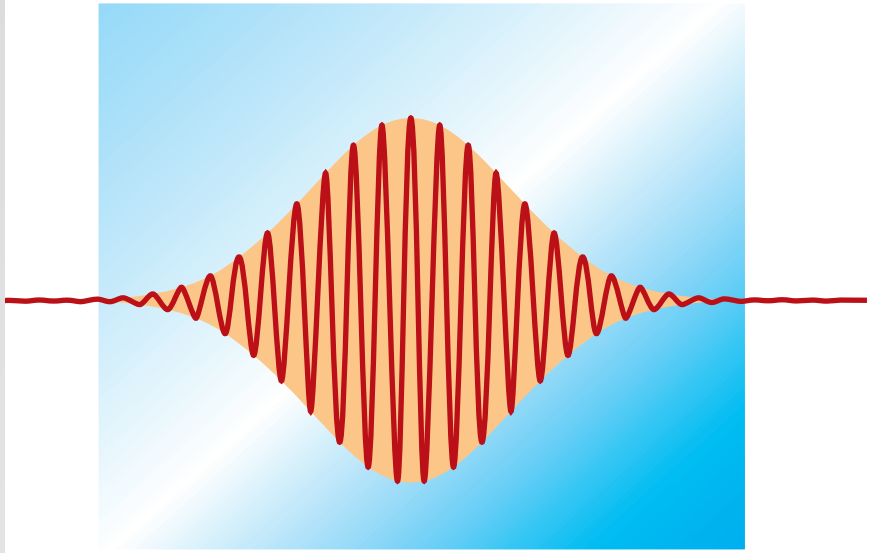
- low-loss guiding
- convenient evanescent coupling
- attached to ordinary fiber

Outline

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

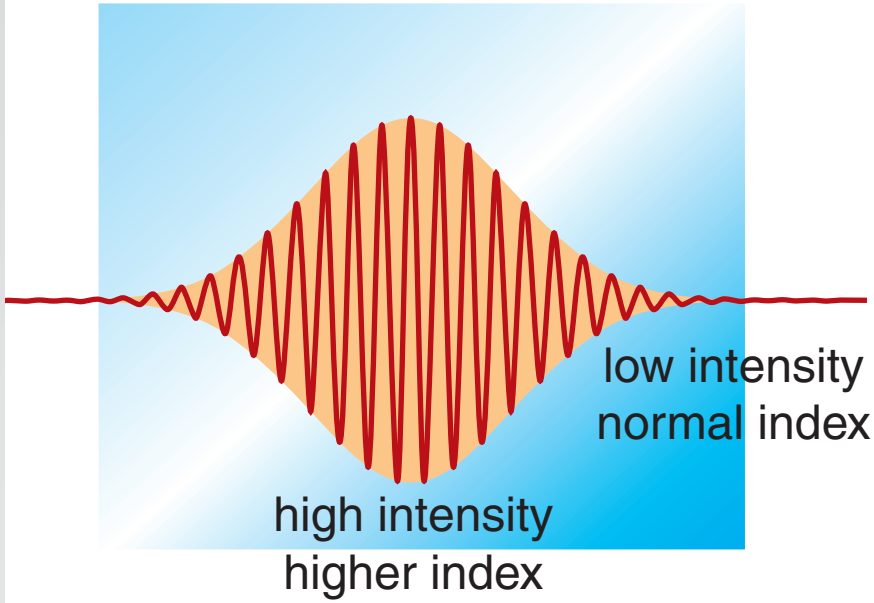
Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



Supercontinuum generation

nonlinear dispersion: $n = n_o + n_2 I$



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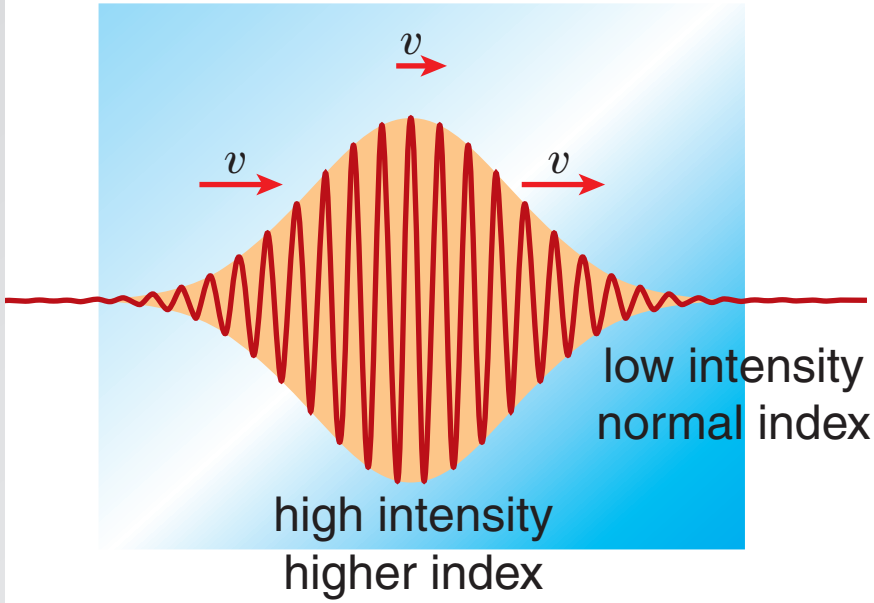

Supercontinuum generation

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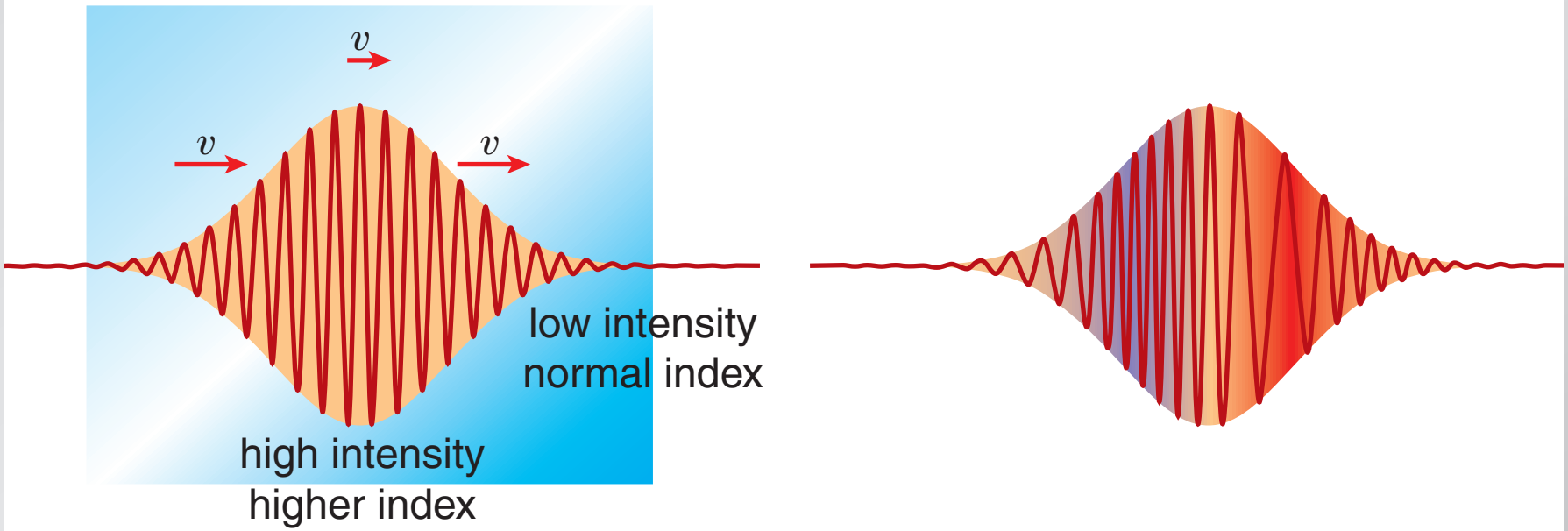

Supercontinuum generation

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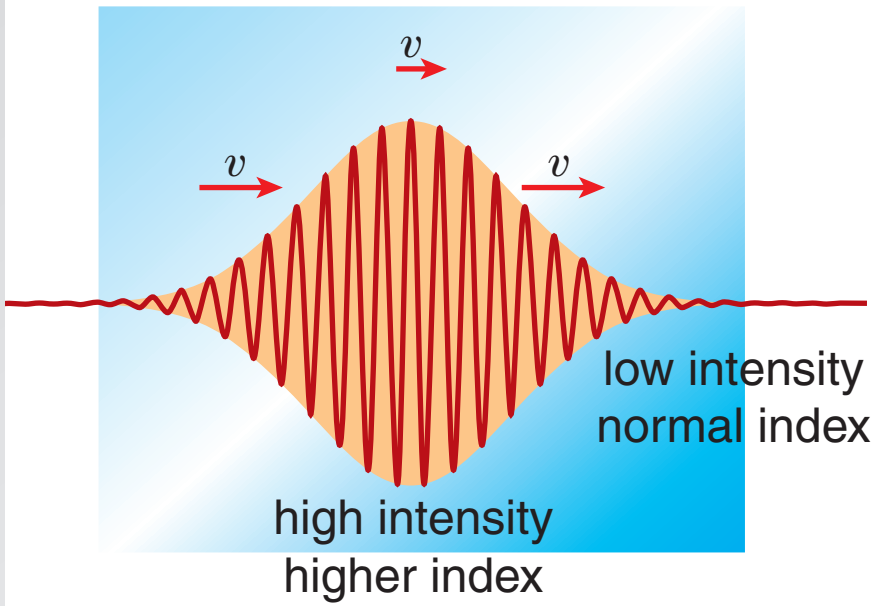
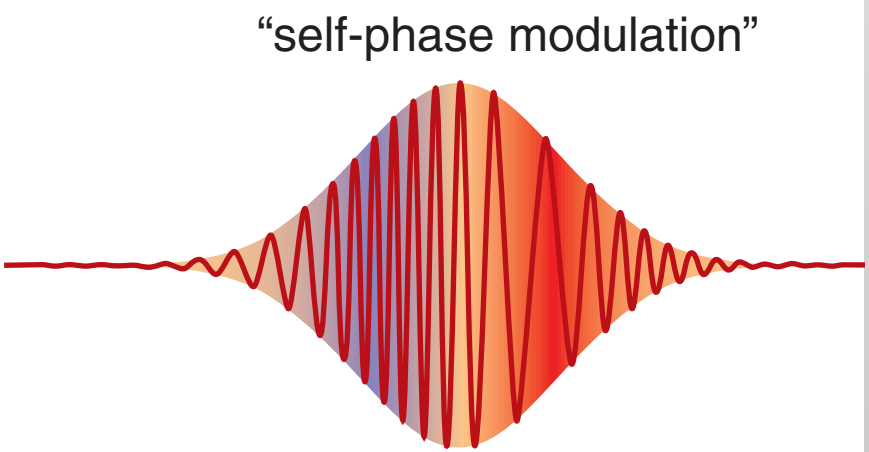
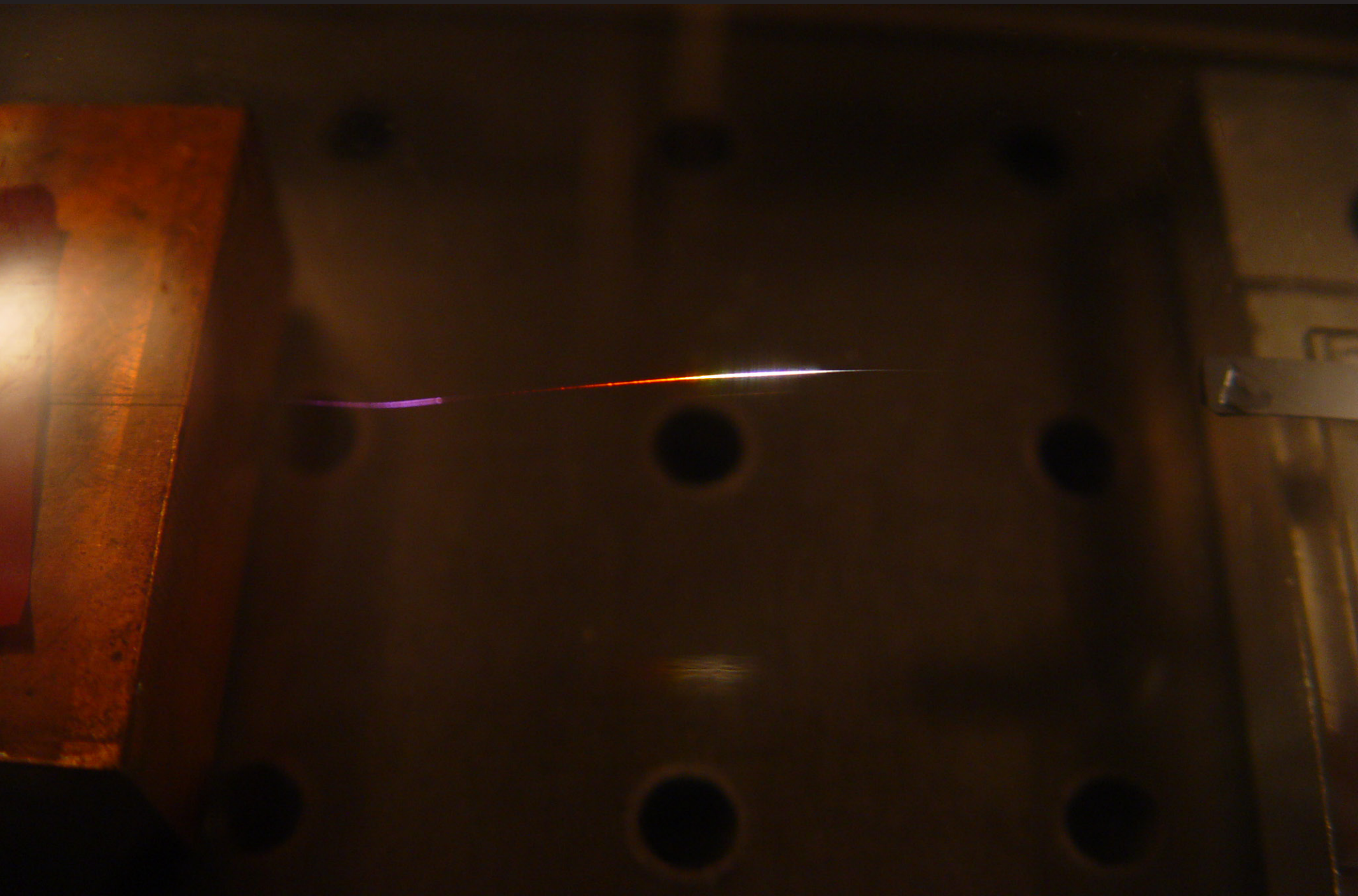




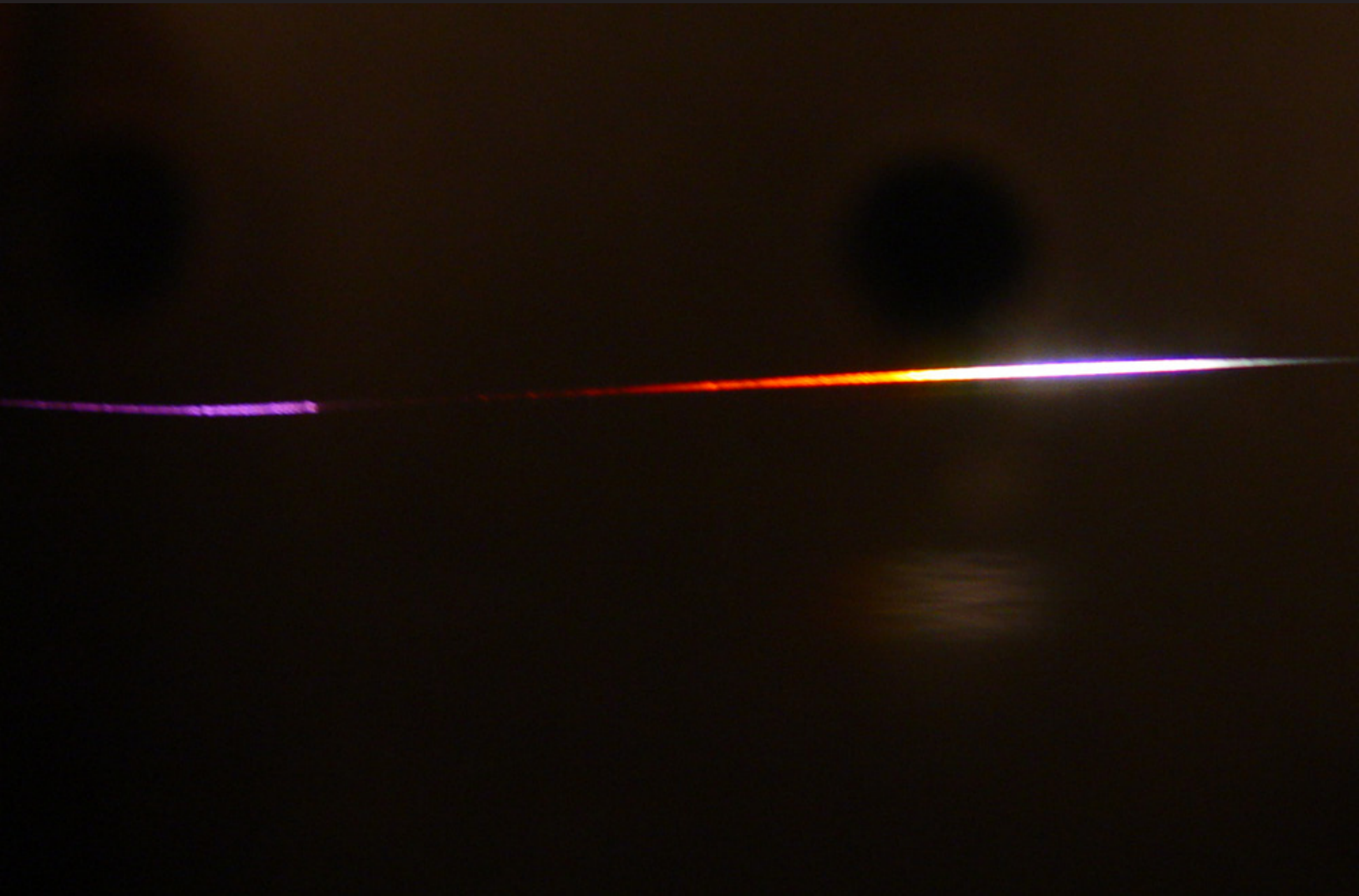
Supercontinuum generation

strong confinement $\longrightarrow$ high intensity

Supercontinuum generation

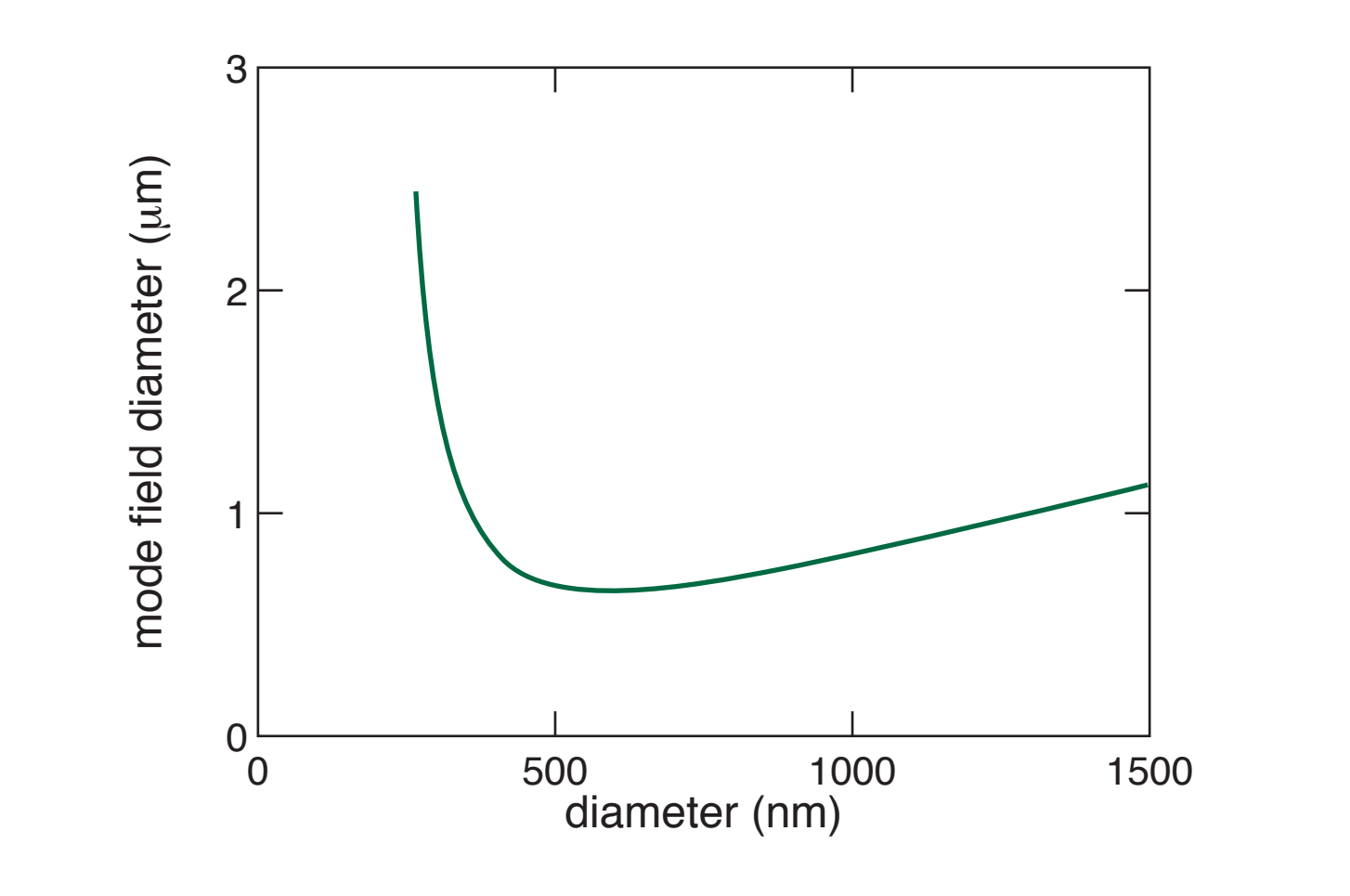


Supercontinuum generation



Supercontinuum generation

mode field diameter (λ = 800 nm)



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

Supercontinuum generation

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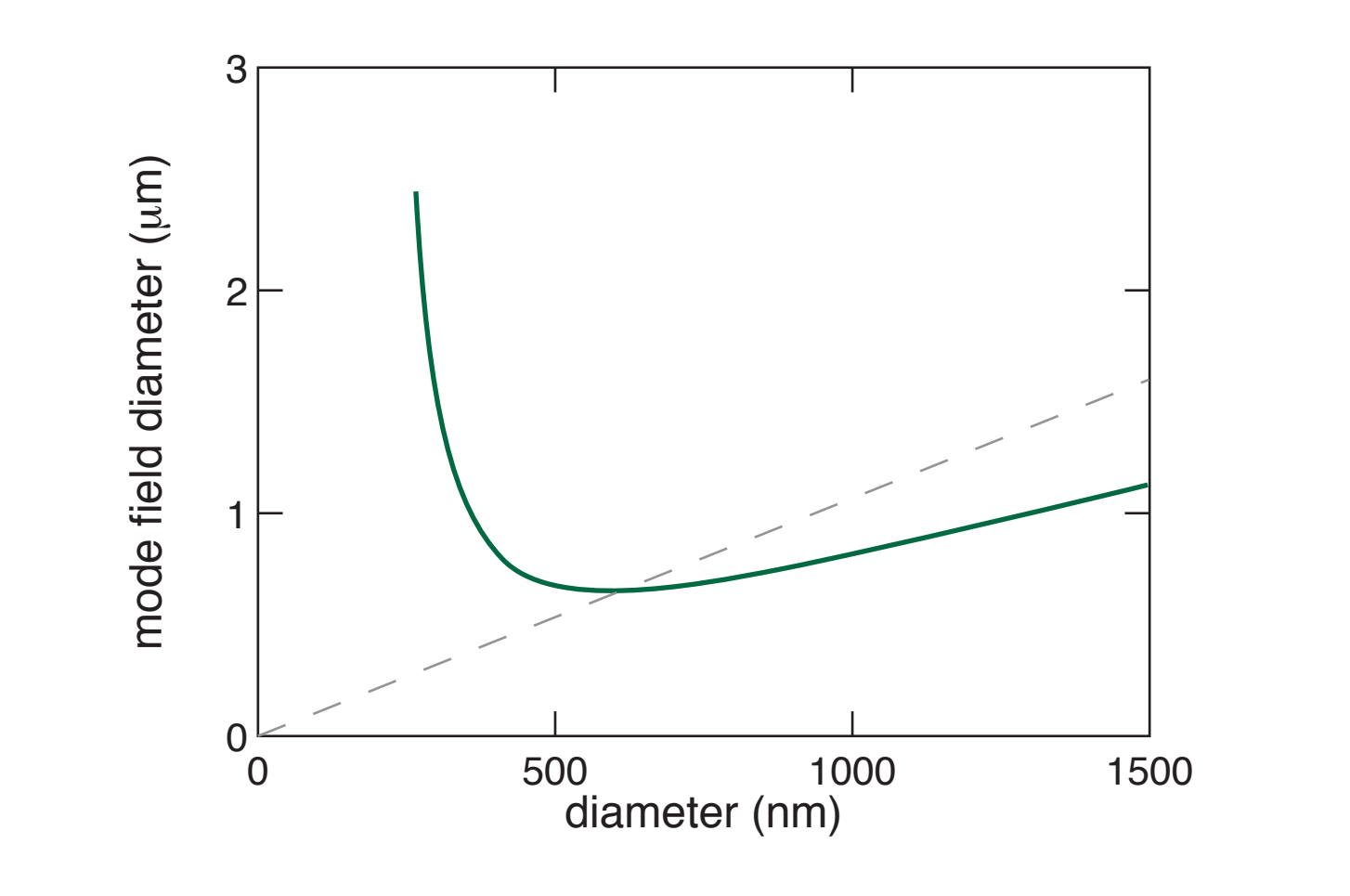

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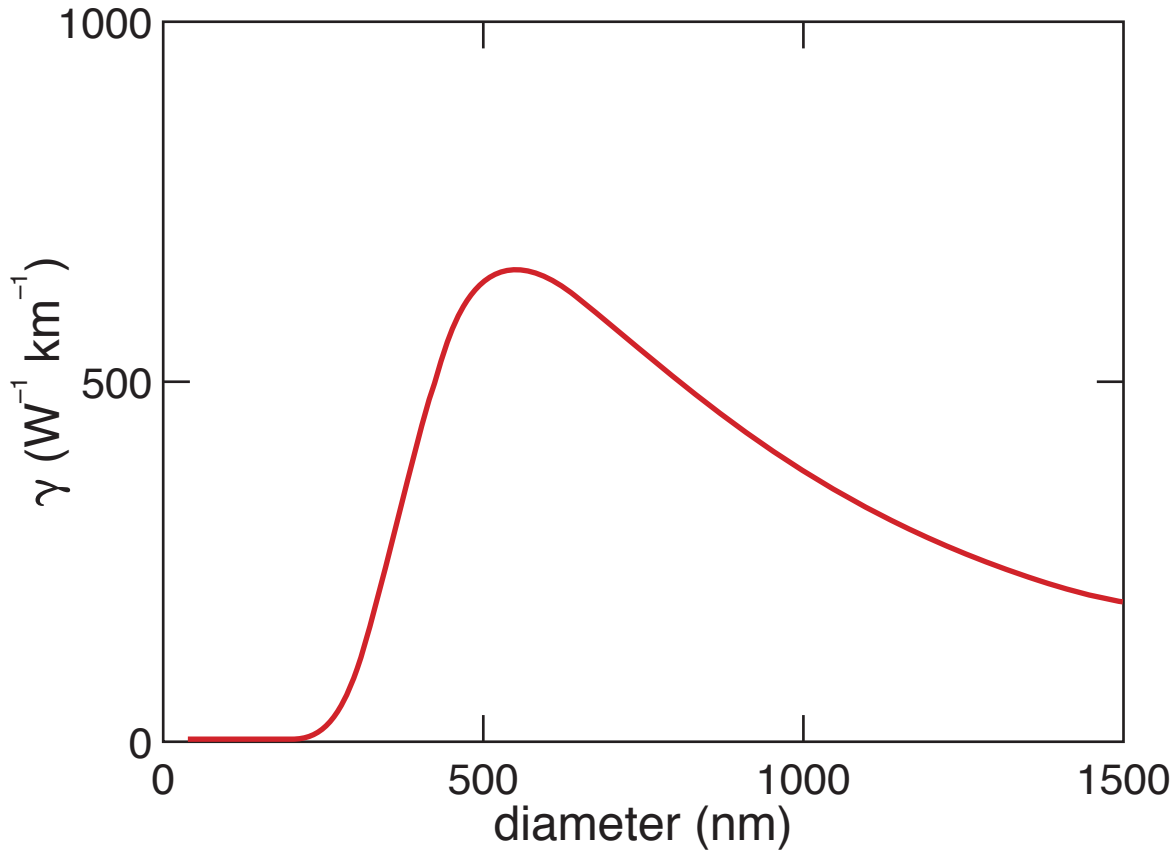
Supercontinuum generation

nonlinear parameter



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

Supercontinuum generation

dispersion important!

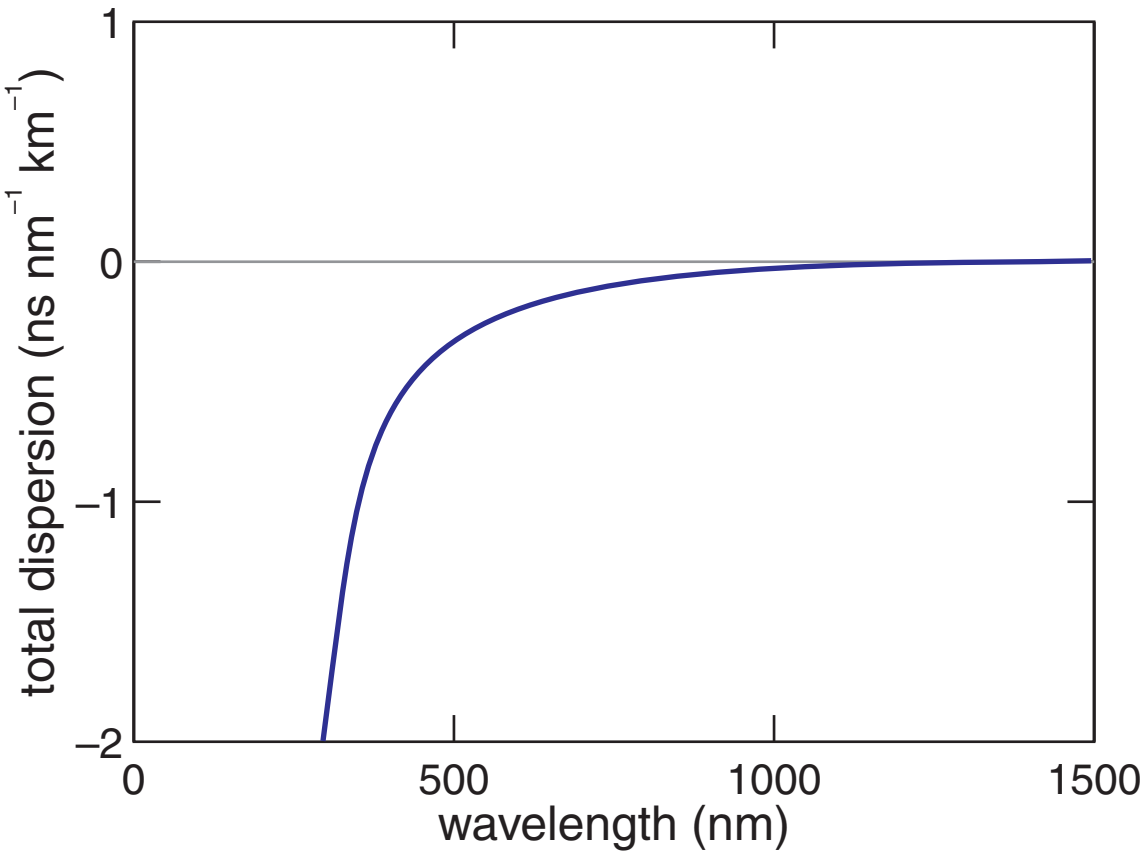
Supercontinuum generation

dispersion:

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

Supercontinuum generation

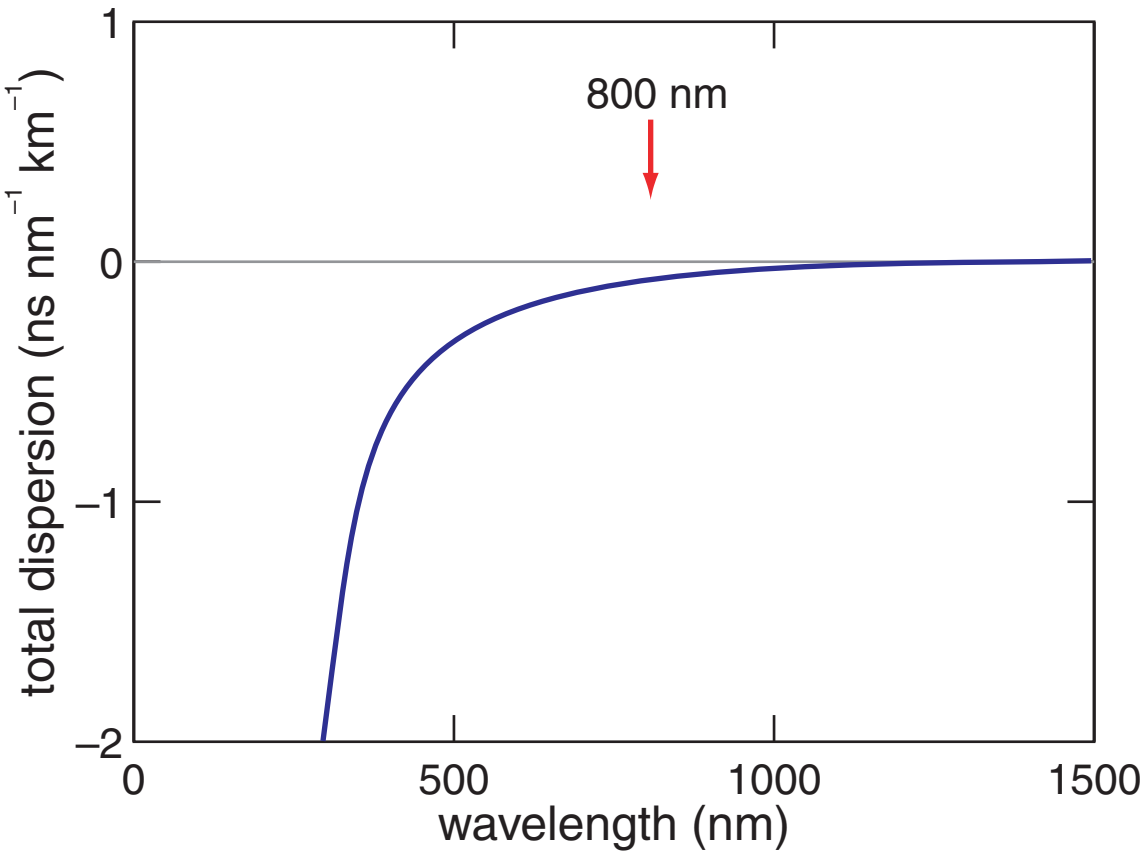
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

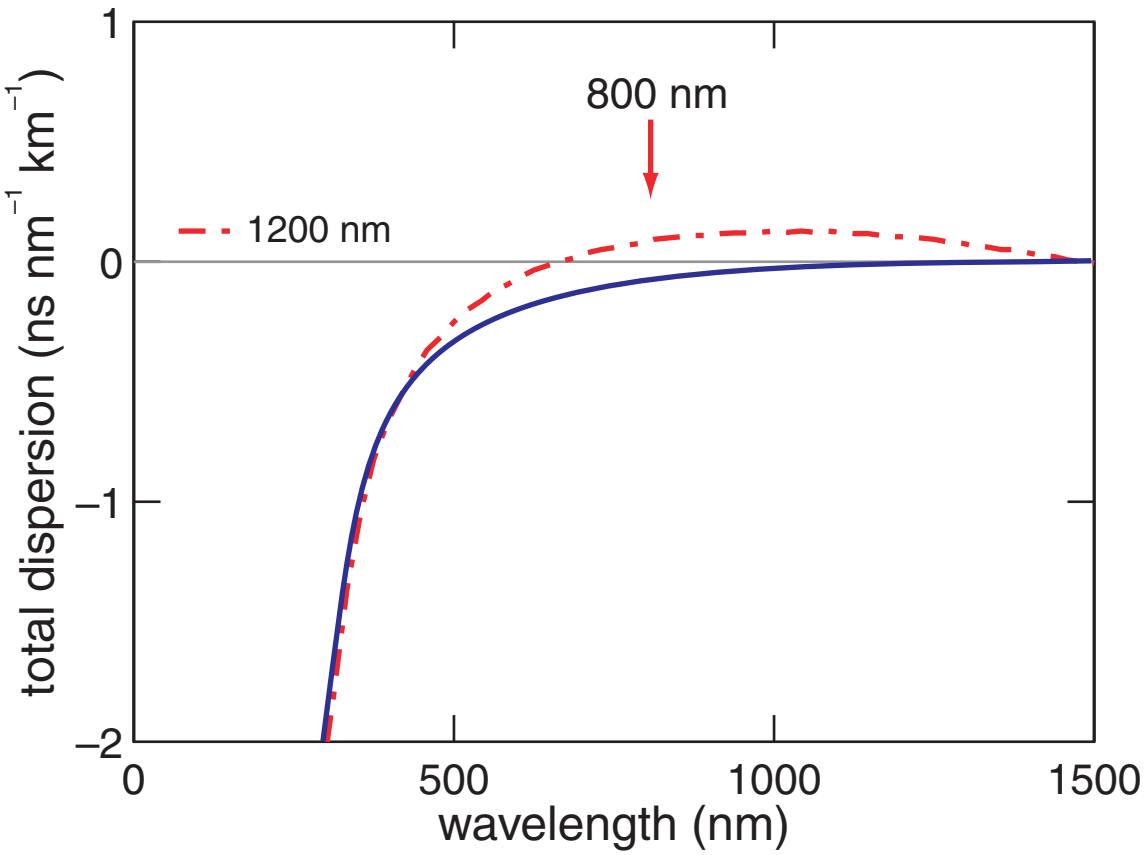
waveguide dispersion



Optics Express, 12, 1025 (2004)

Supercontinuum generation

waveguide dispersion



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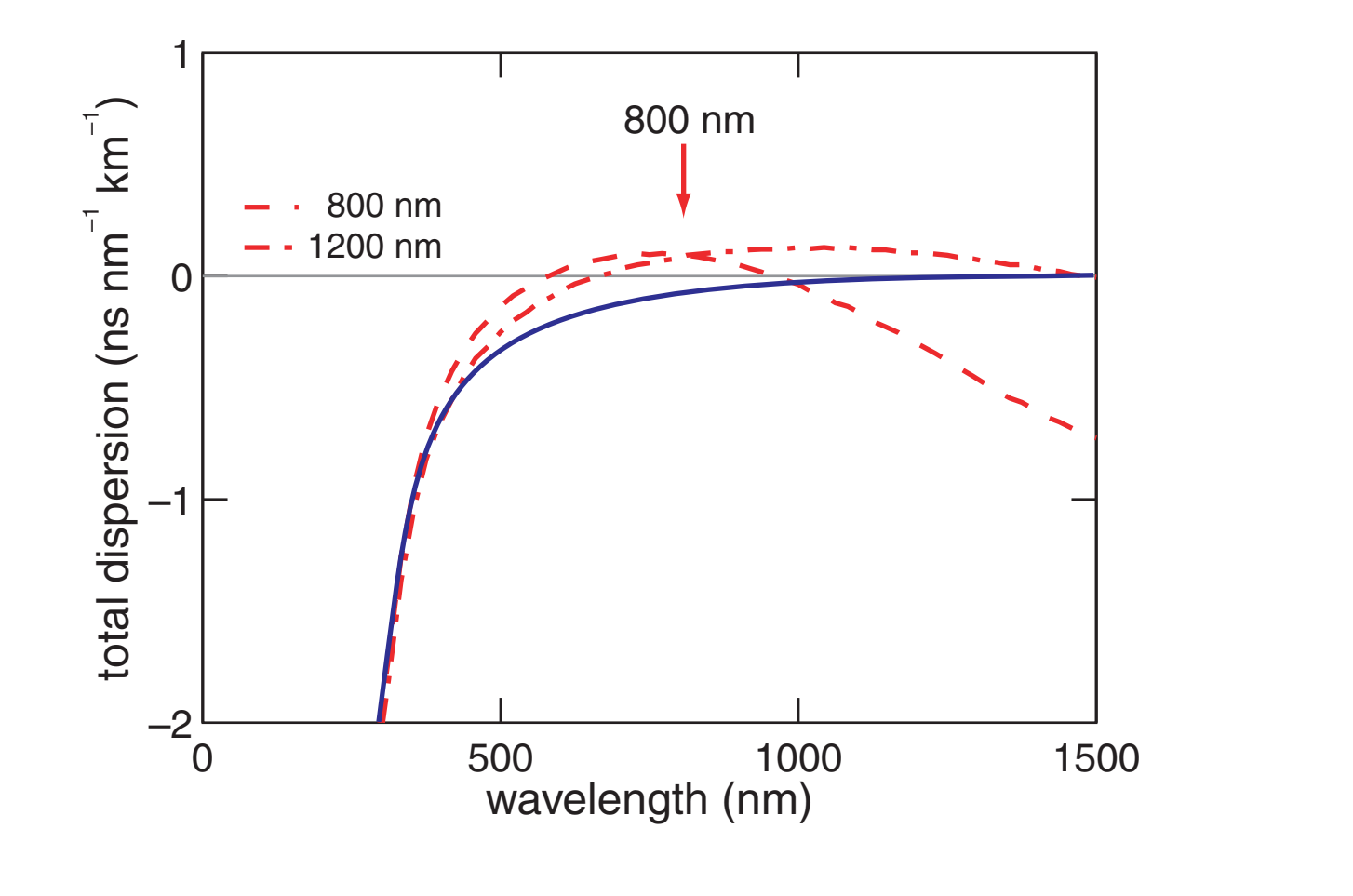
Supercontinuum generation

waveguide dispersion



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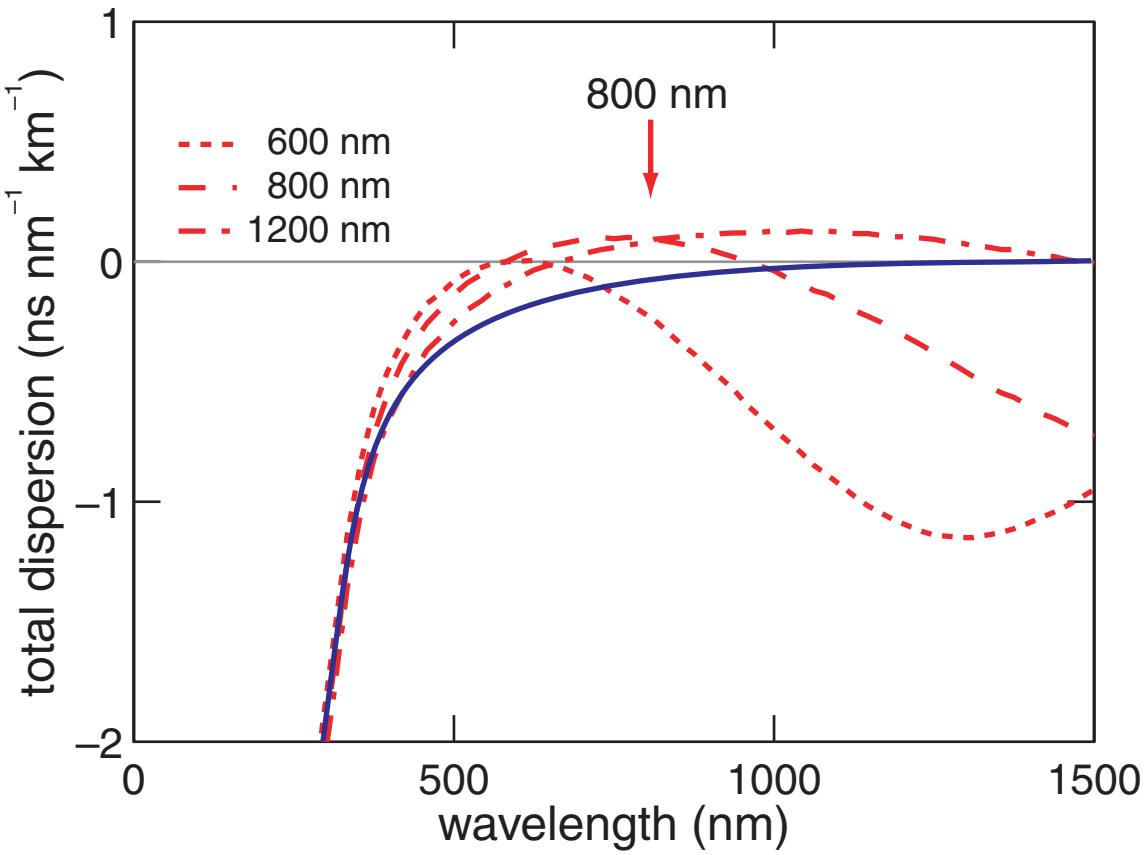
Supercontinuum generation

waveguide dispersion



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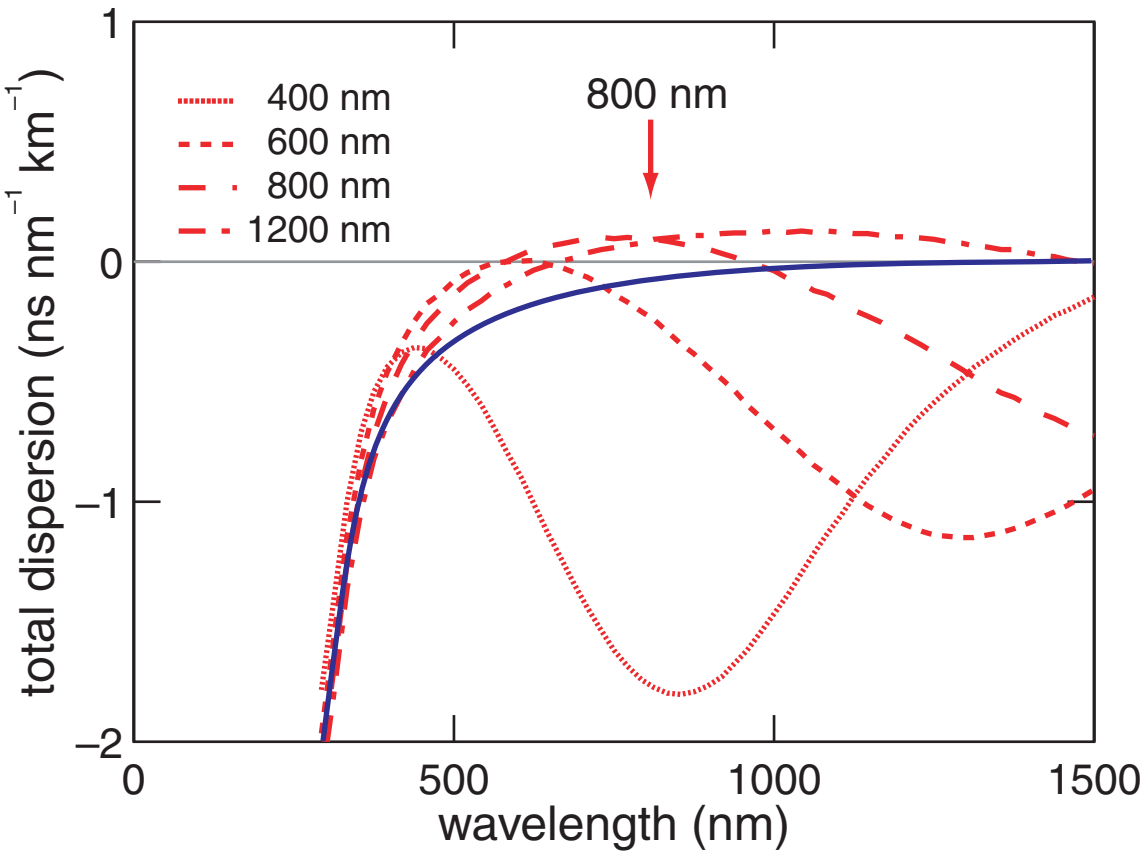
Supercontinuum generation

waveguide dispersion



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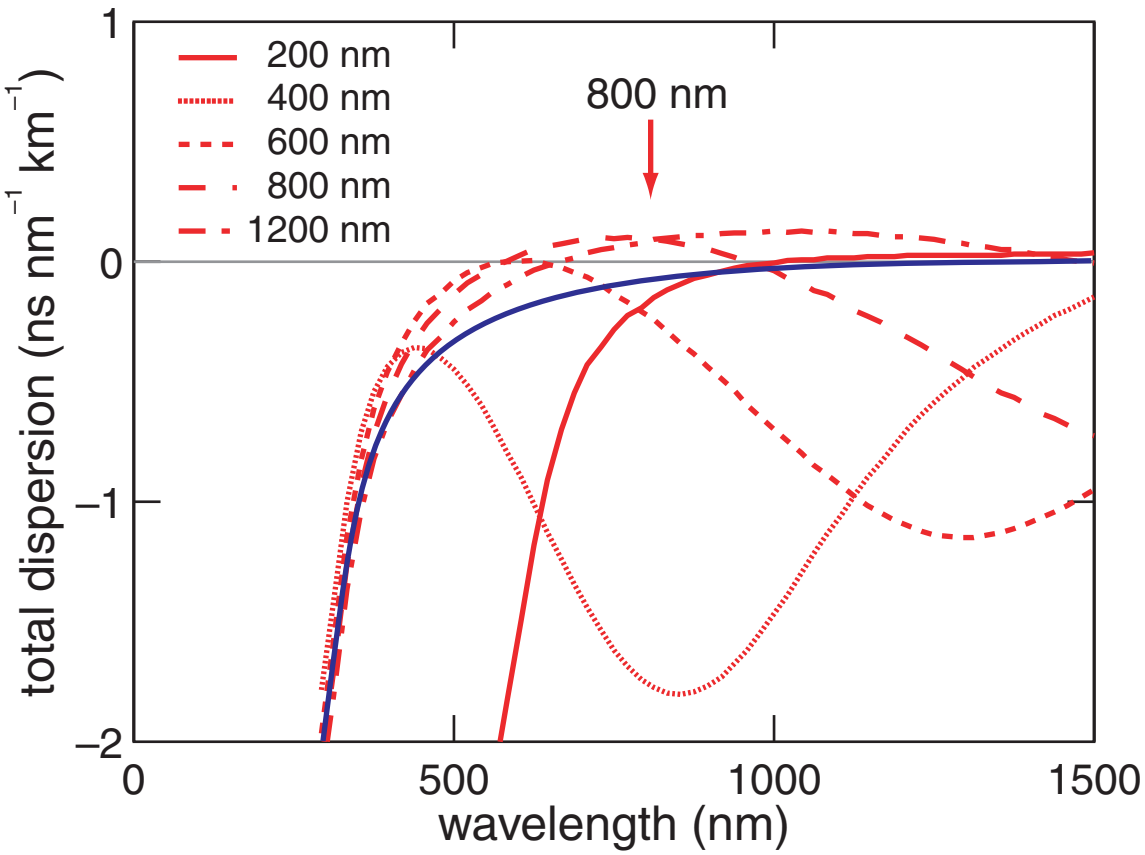
Supercontinuum generation

waveguide dispersion



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Supercontinuum generation

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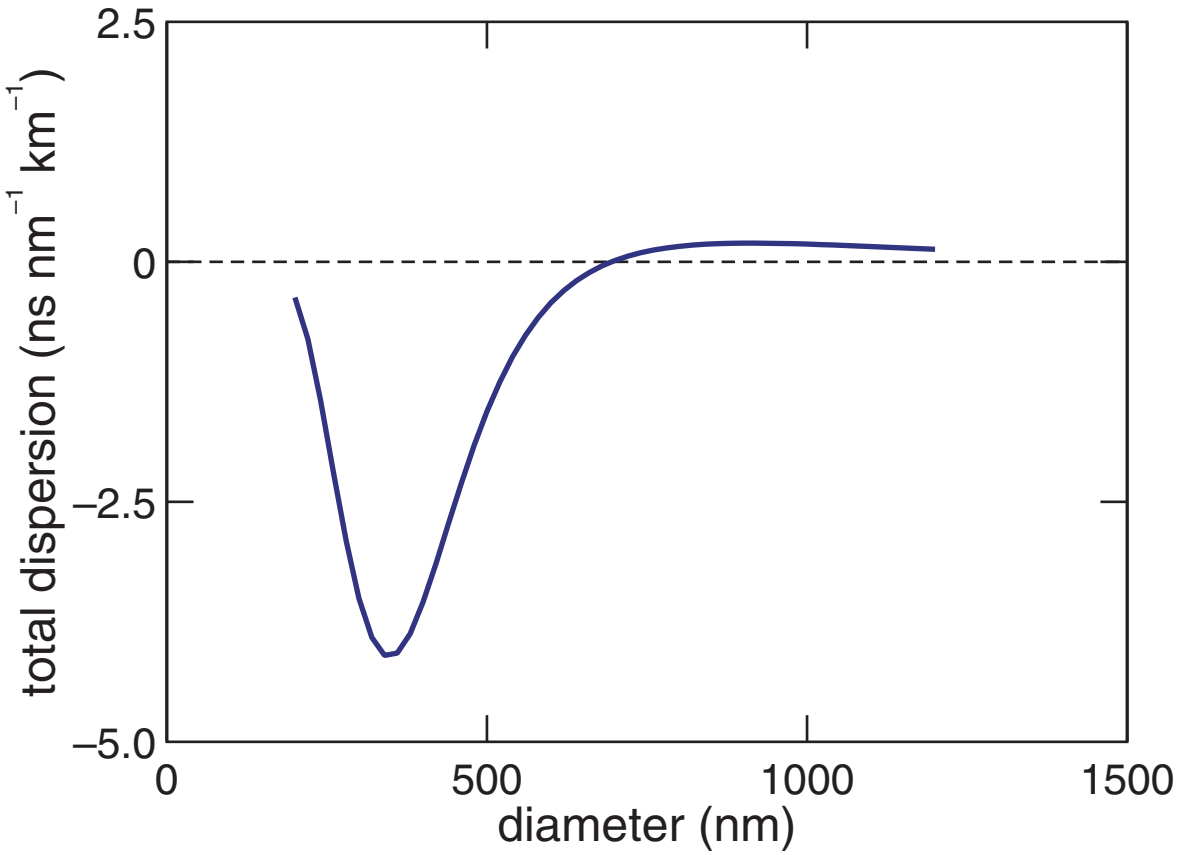

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Supercontinuum generation

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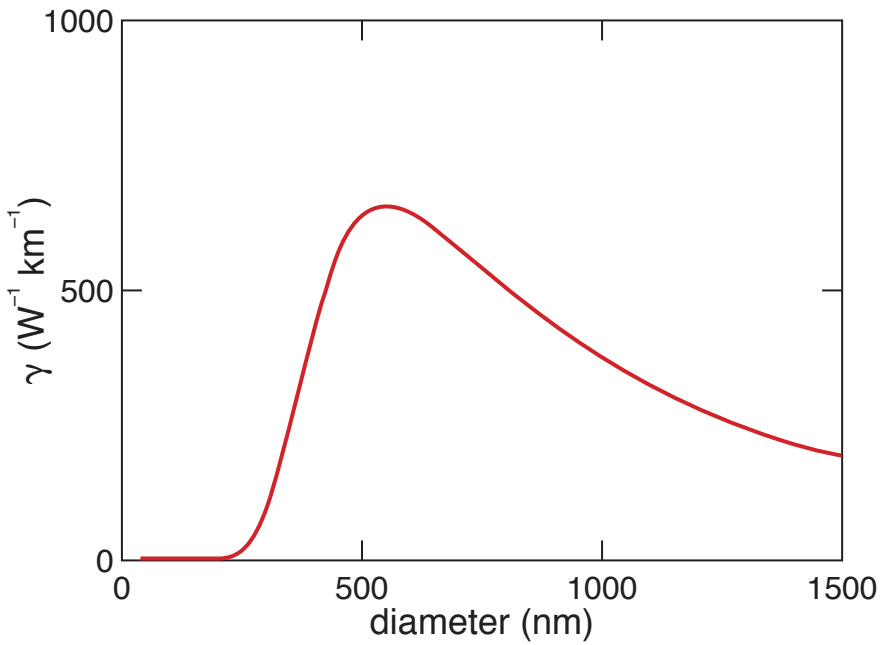

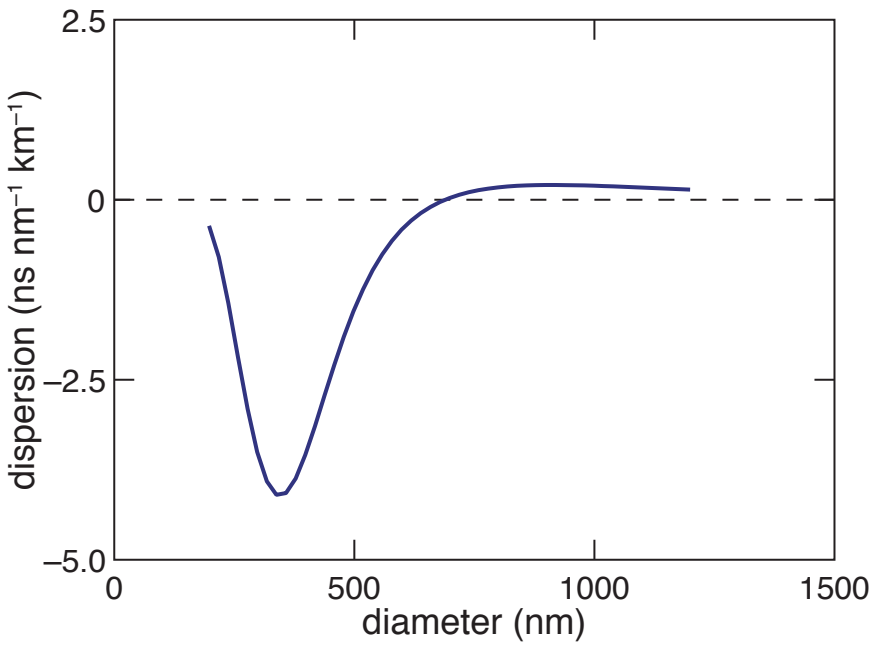

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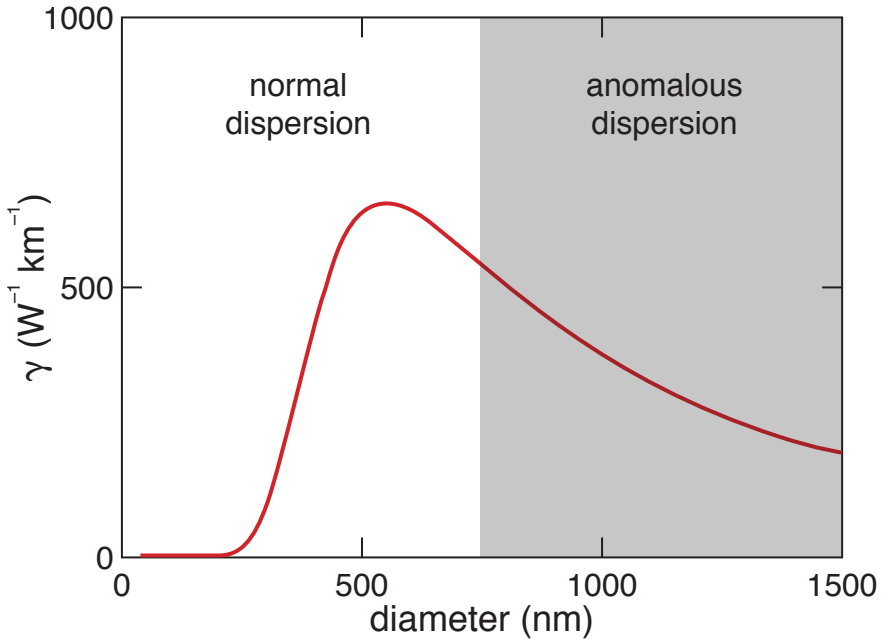

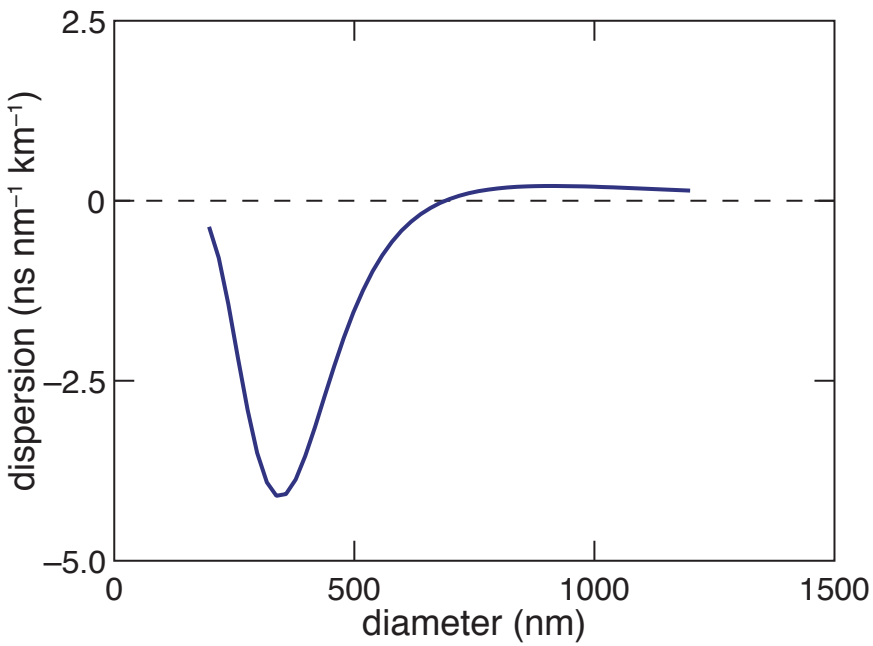

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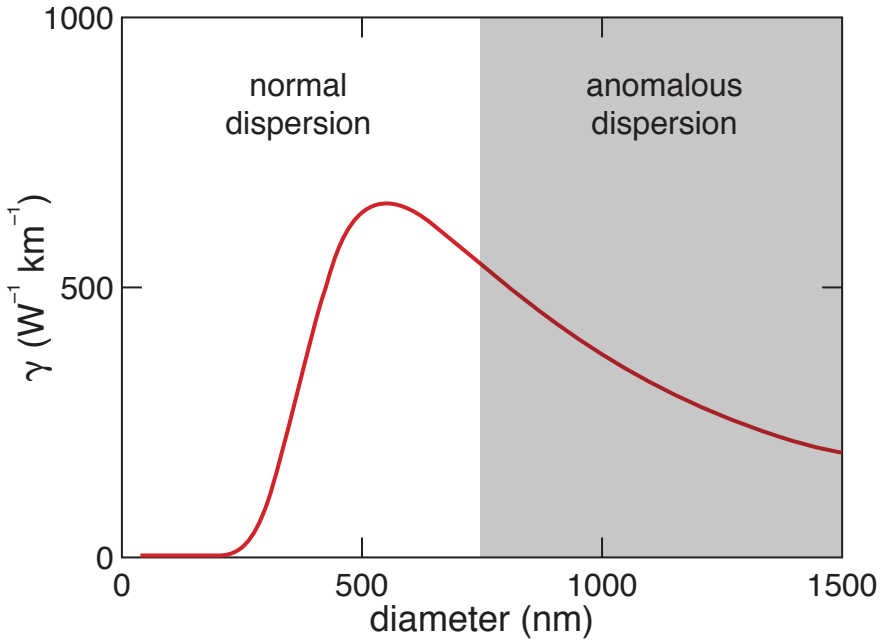
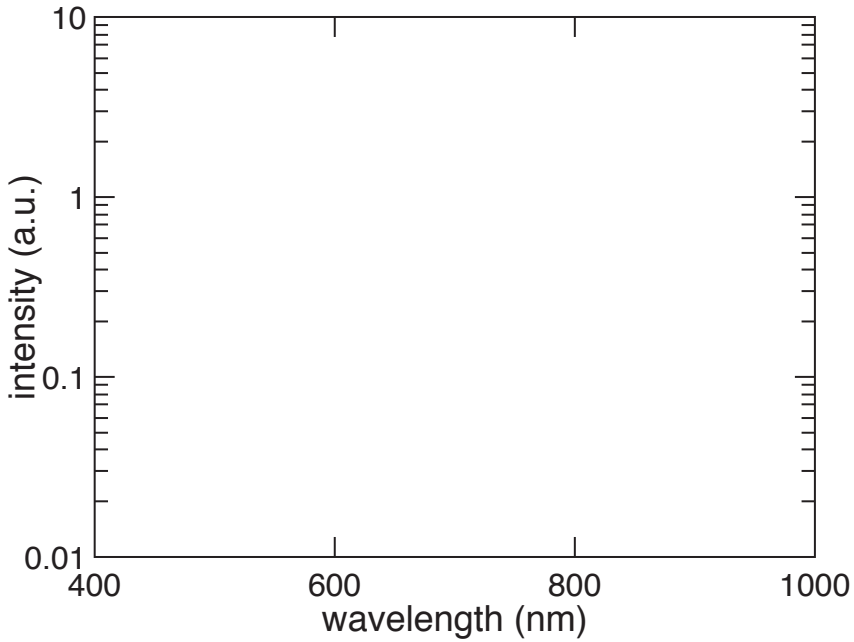
Supercontinuum generation

nanowire continuum generation





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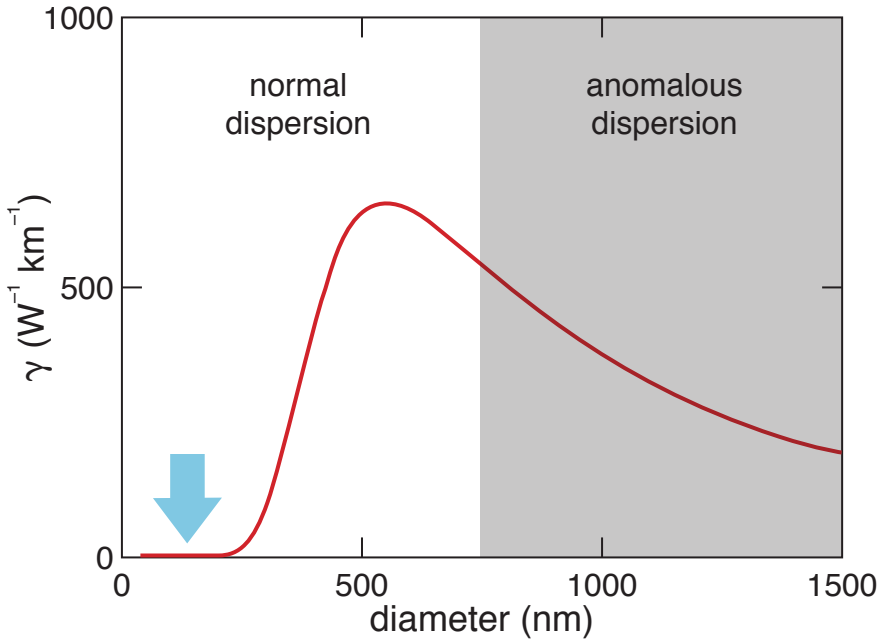

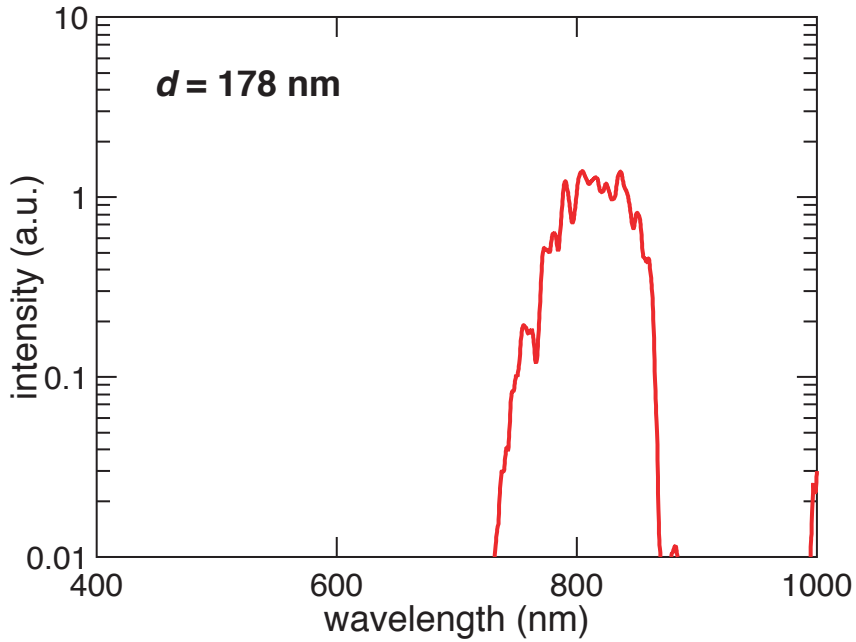

Optics Express, 14, 9408 (2006)

Supercontinuum generation

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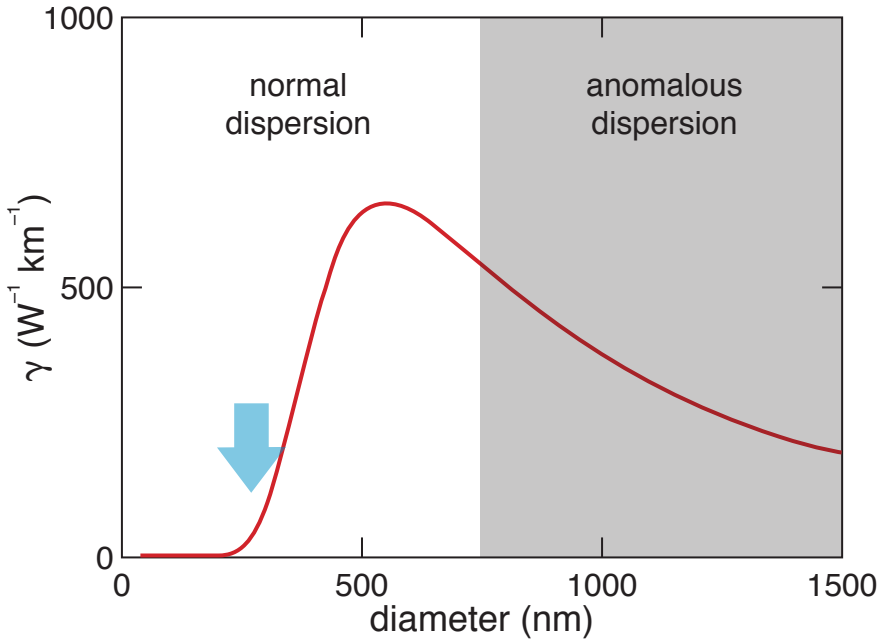

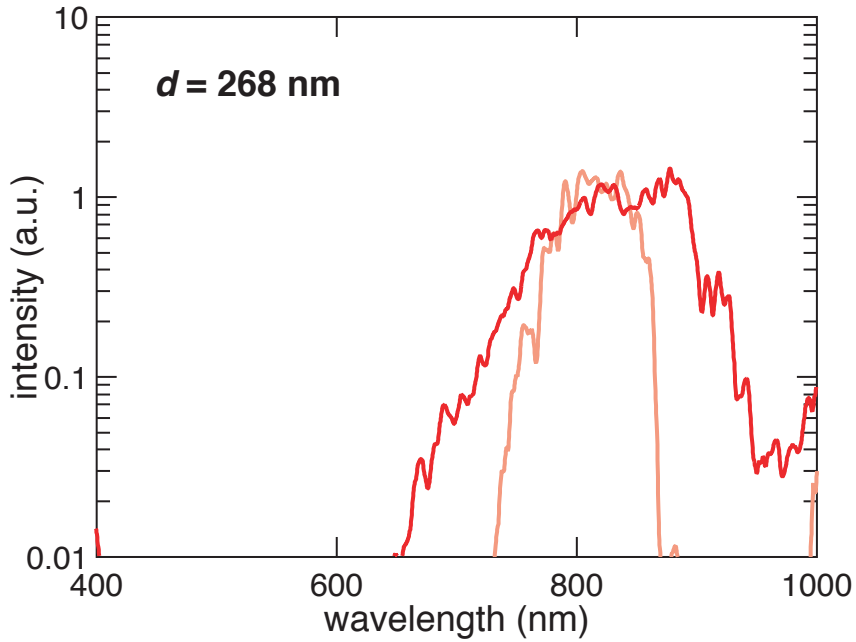

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Supercontinuum generation

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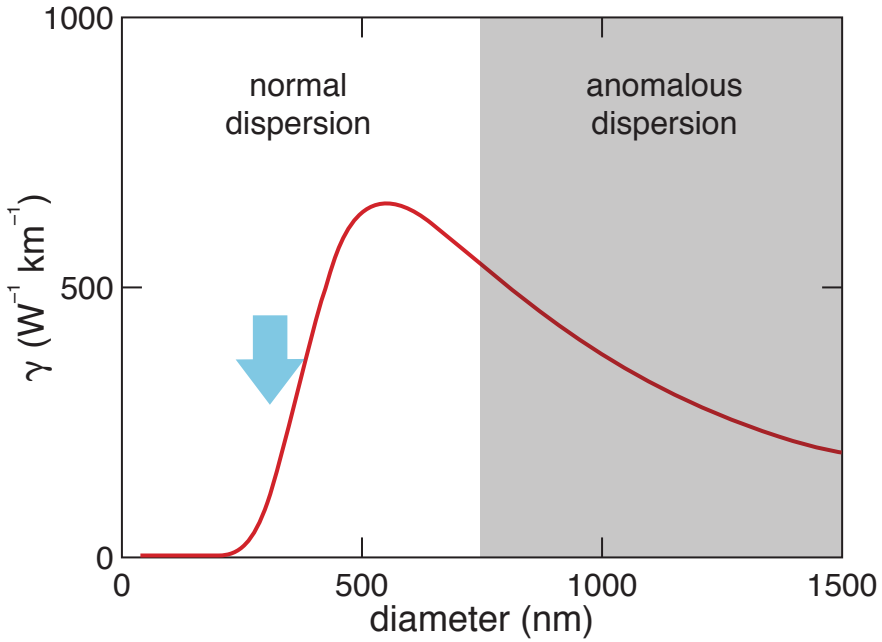

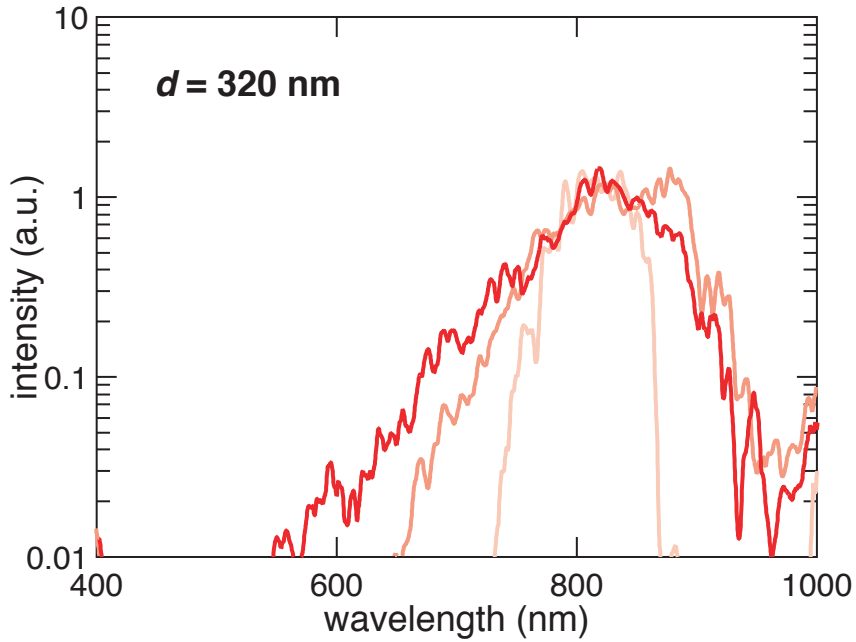

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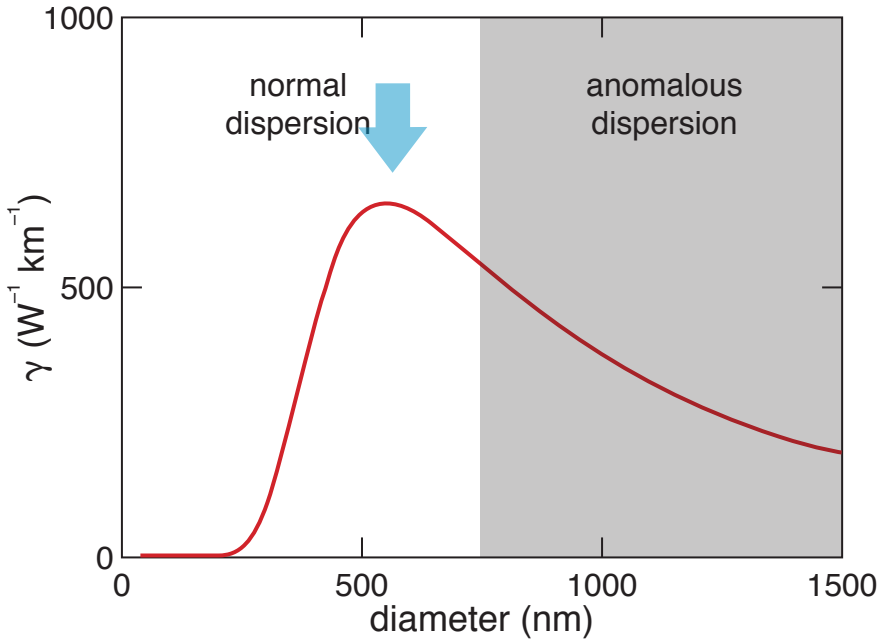

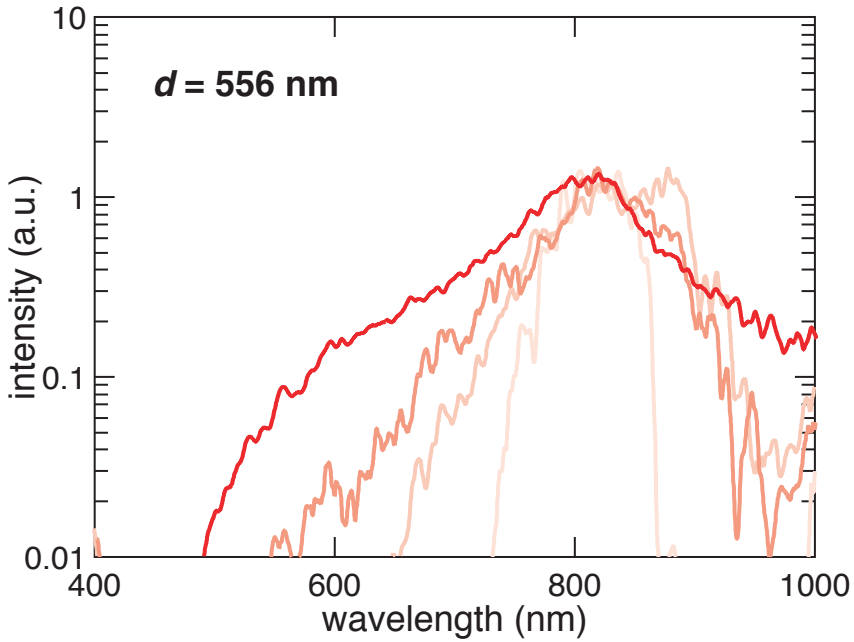

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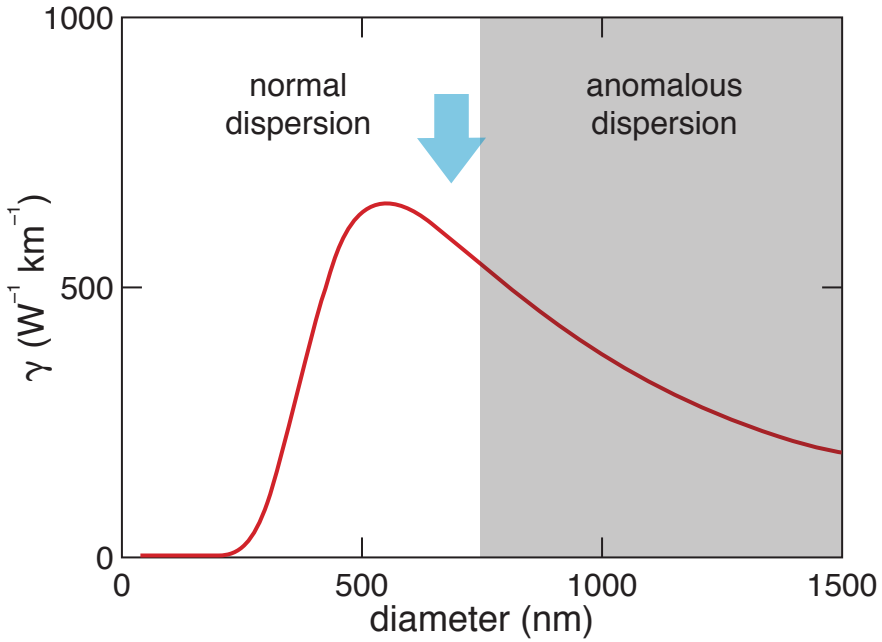
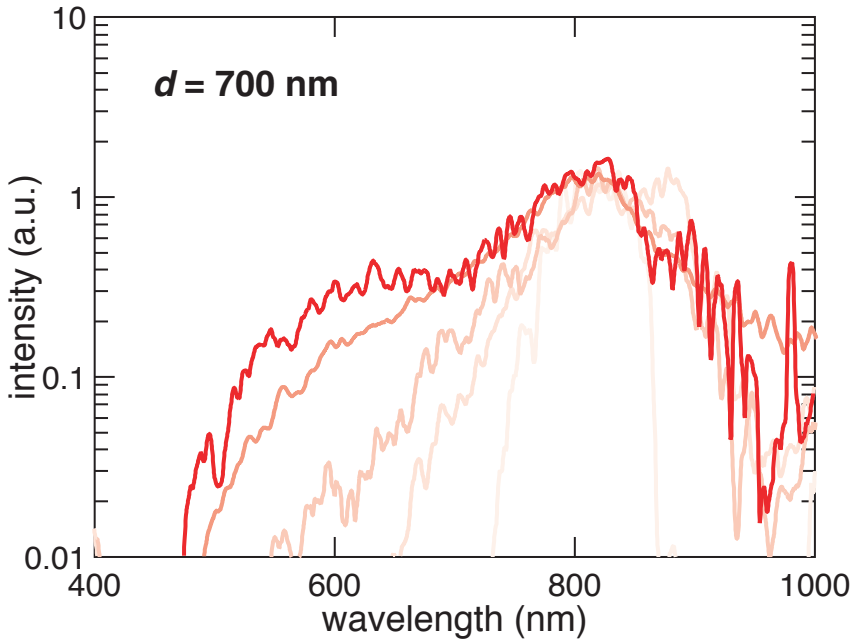
nanowire continuum generation

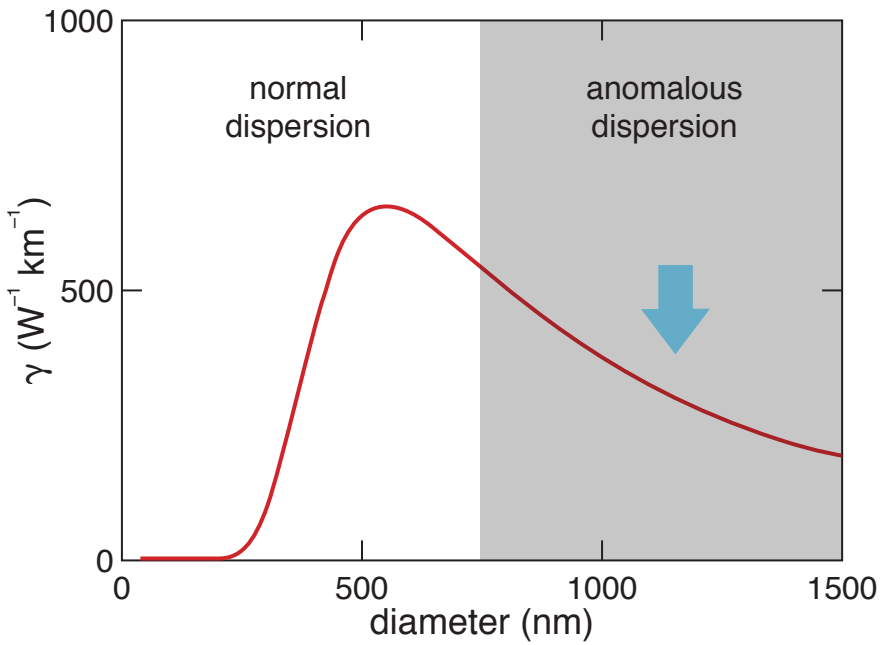


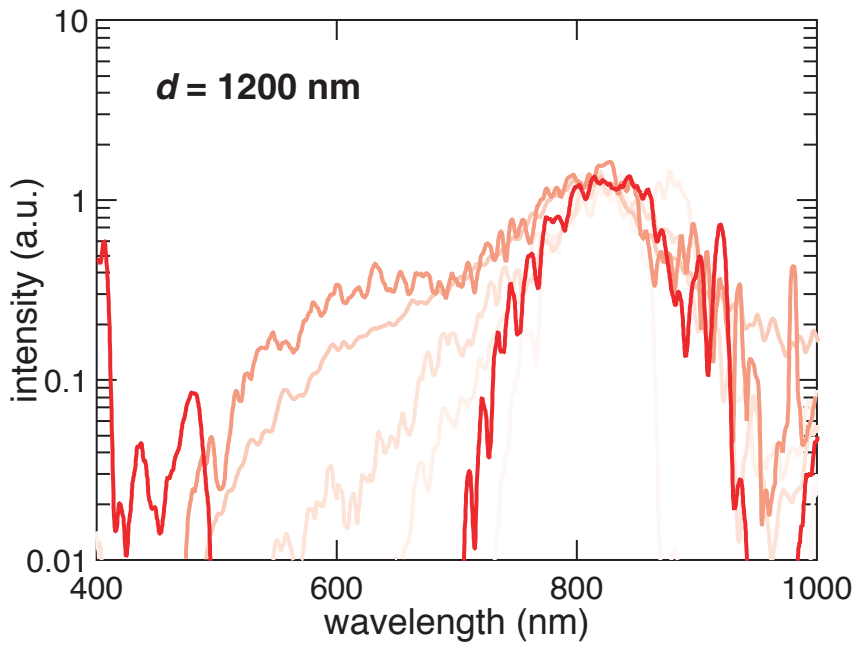


Optics Express, 14, 9408 (2006)

Supercontinuum generation

nanowire continuum generation





Optics Express, 14, 9408 (2006)

Supercontinuum generation

energy in nanowire < 100 pJ!

Supercontinuum generation

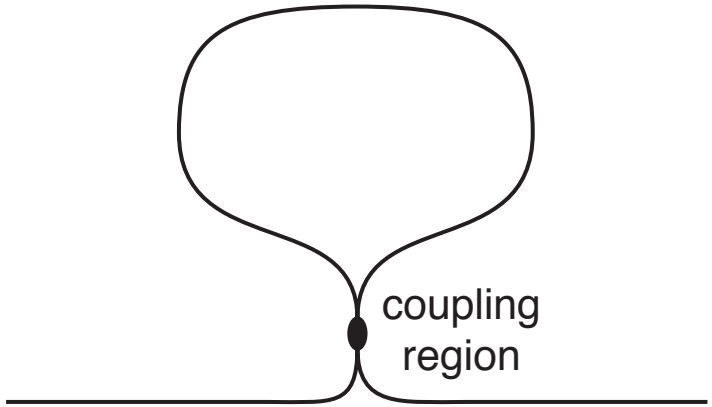
- picojoule nonlinear optics
- optimum diameter for silica 500–600 nm
- low dispersion

Outline

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

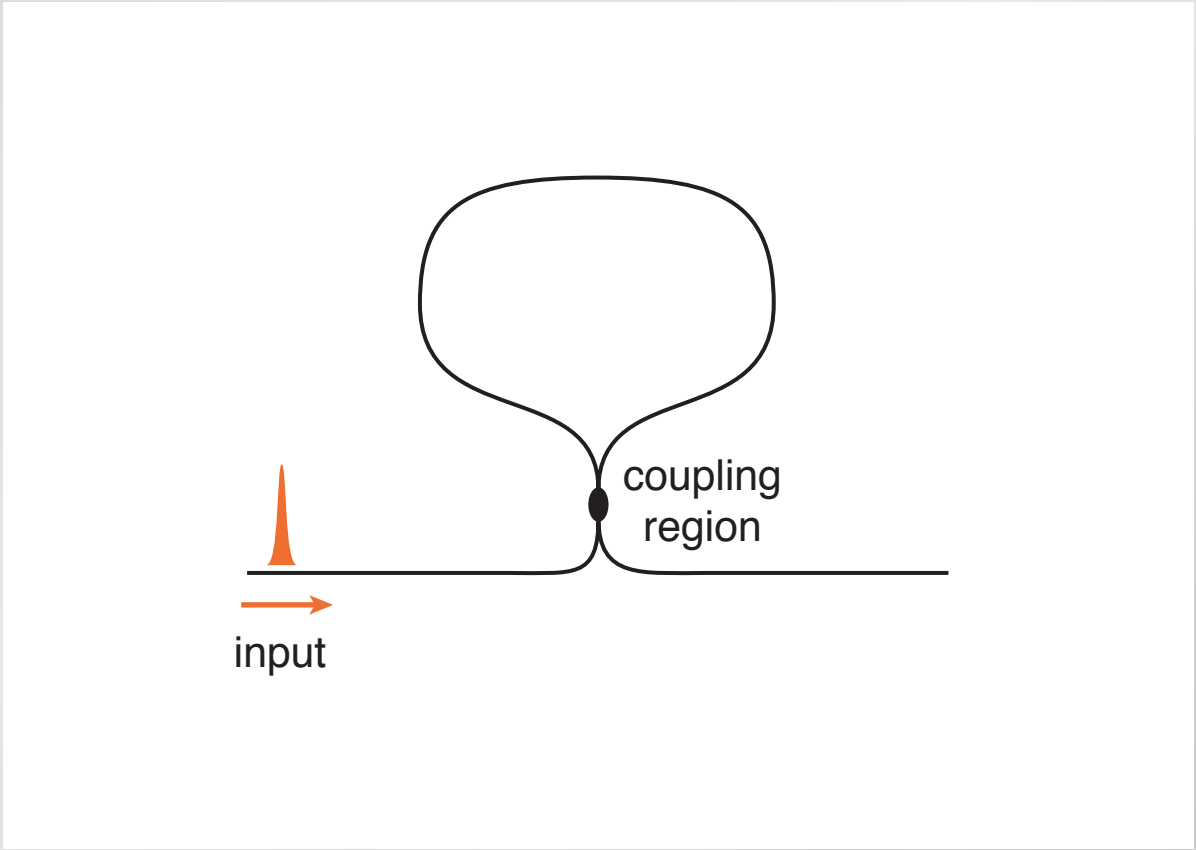
Optical logic gates

nanowire Sagnac interferometer



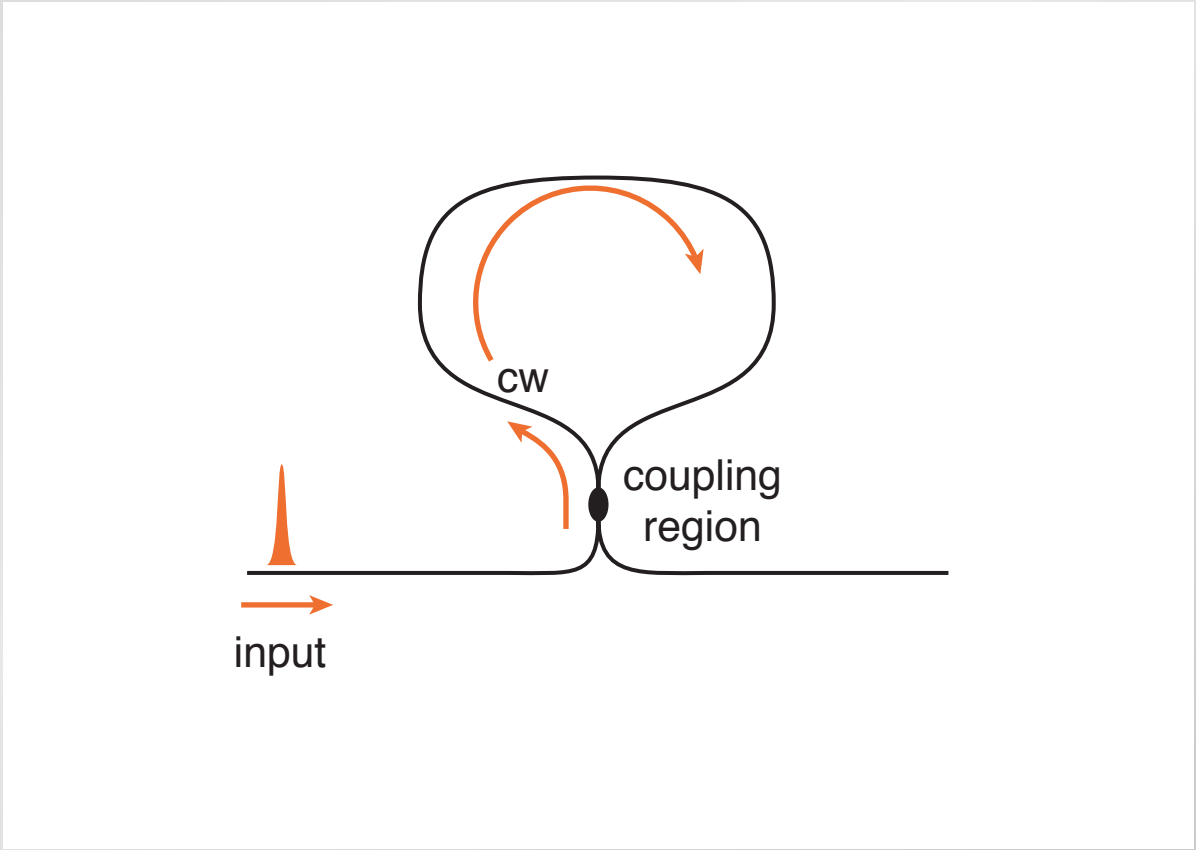
Optical logic gates

nanowire Sagnac interferometer



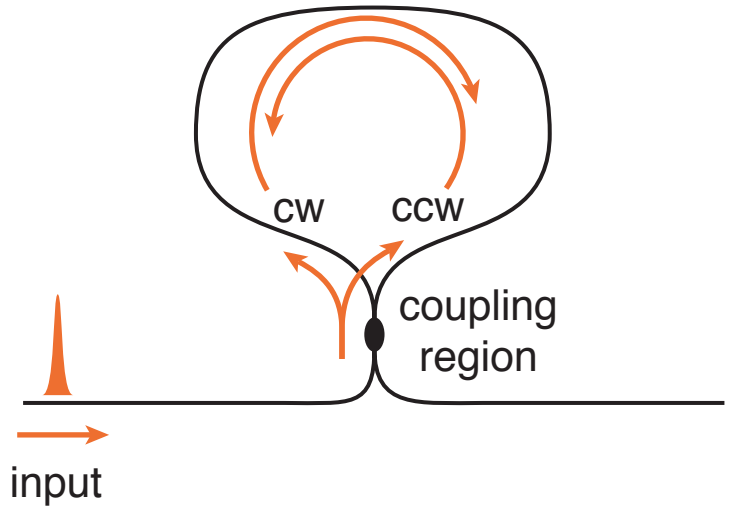
Optical logic gates

nanowire Sagnac interferometer



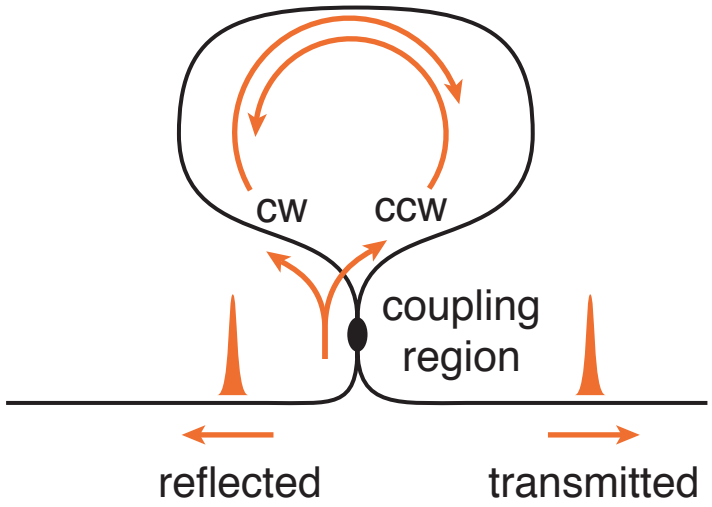
Optical logic gates

nanowire Sagnac interferometer



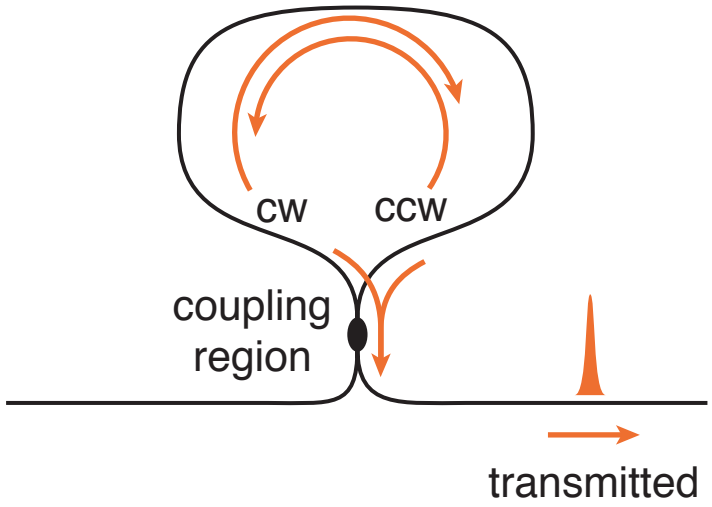
Optical logic gates

nanowire Sagnac interferometer



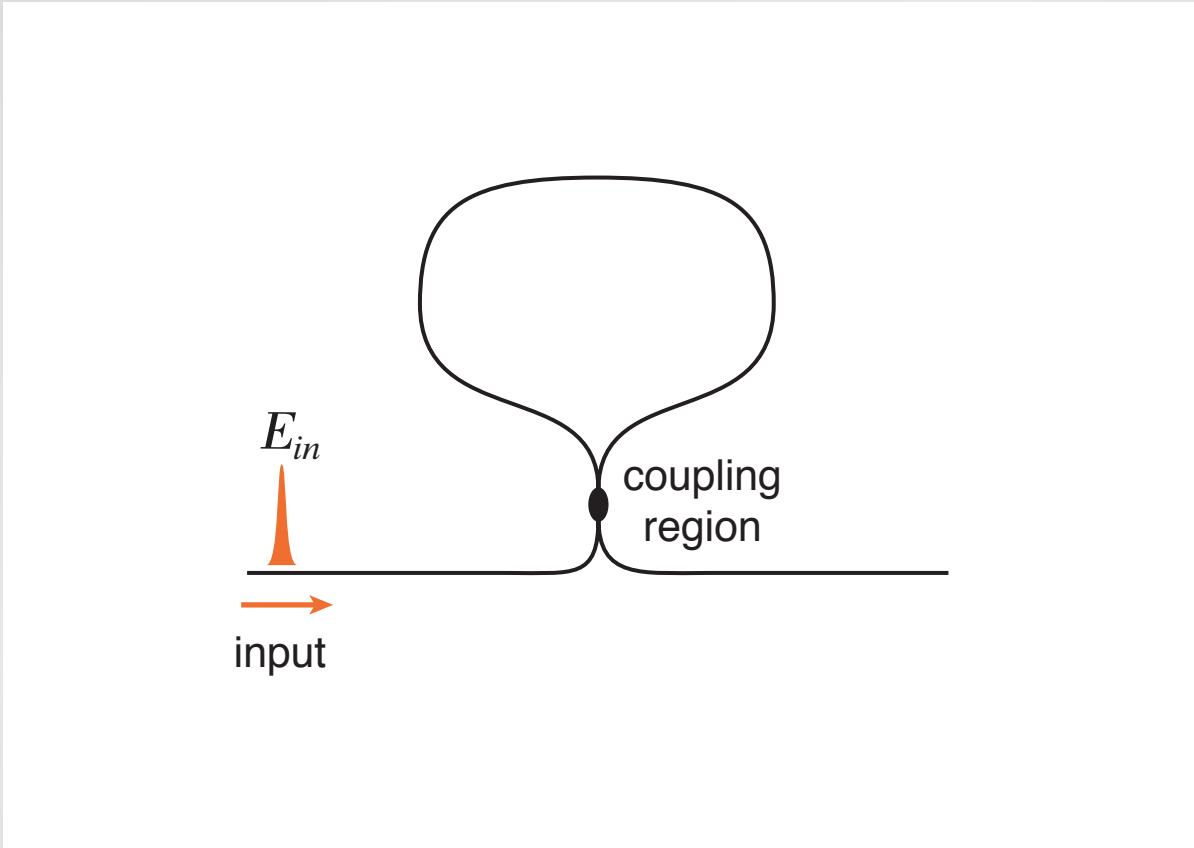
Optical logic gates

output = transmitted cw + ccw power



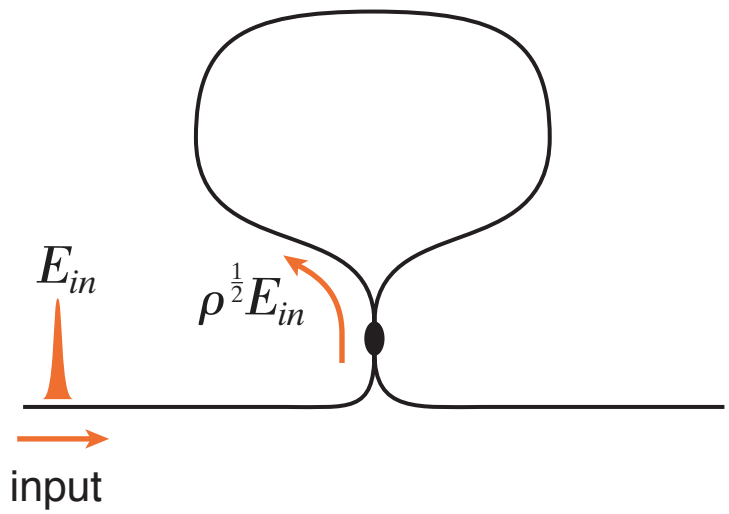
Optical logic gates

input electric field amplitude E_{in}



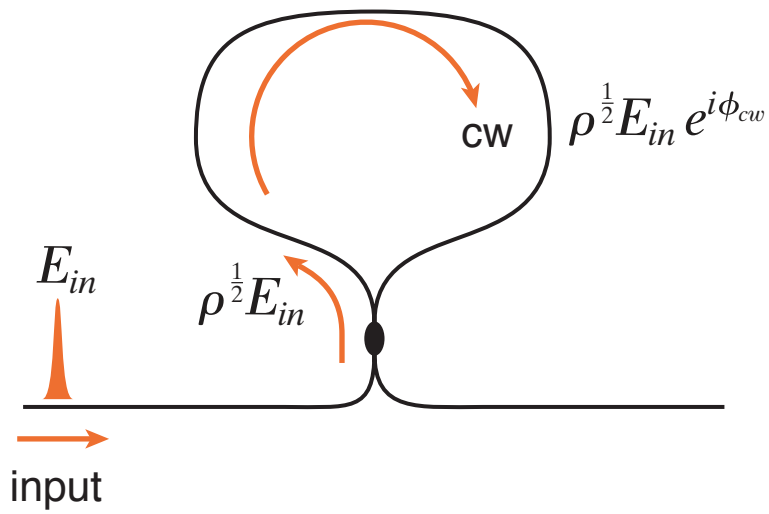
Optical logic gates

coupling parameter: ρ



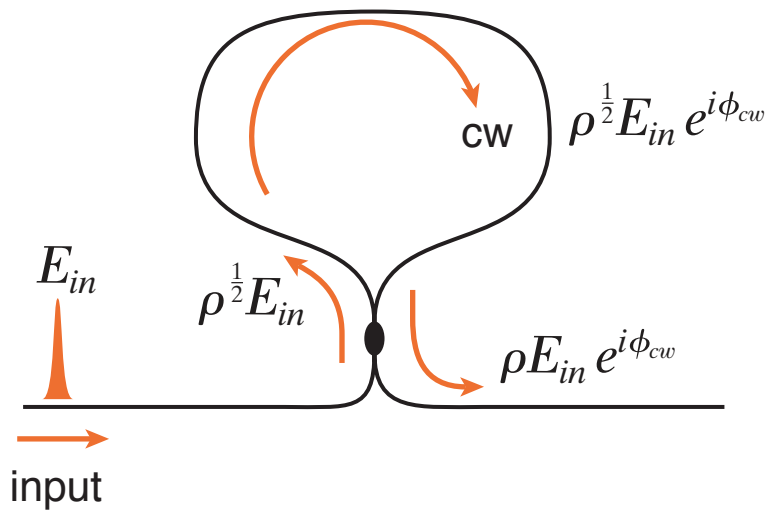
Optical logic gates

phase accumulation over path length of loop L



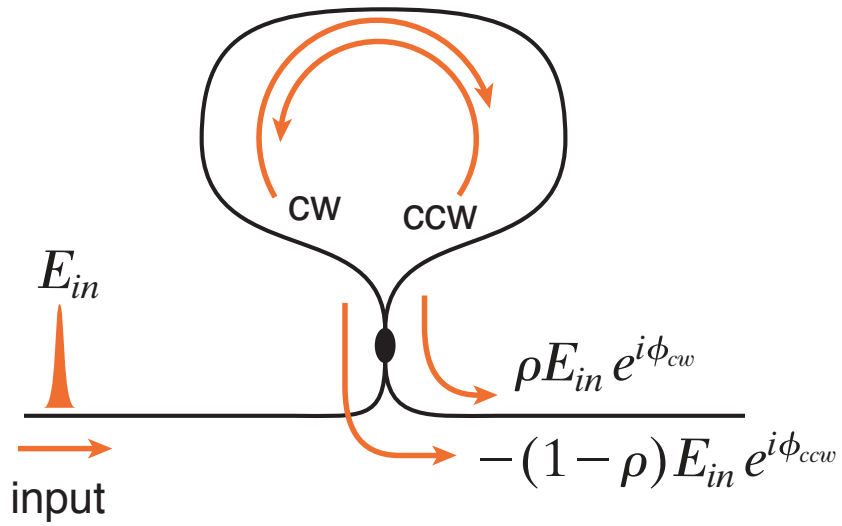
Optical logic gates

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:

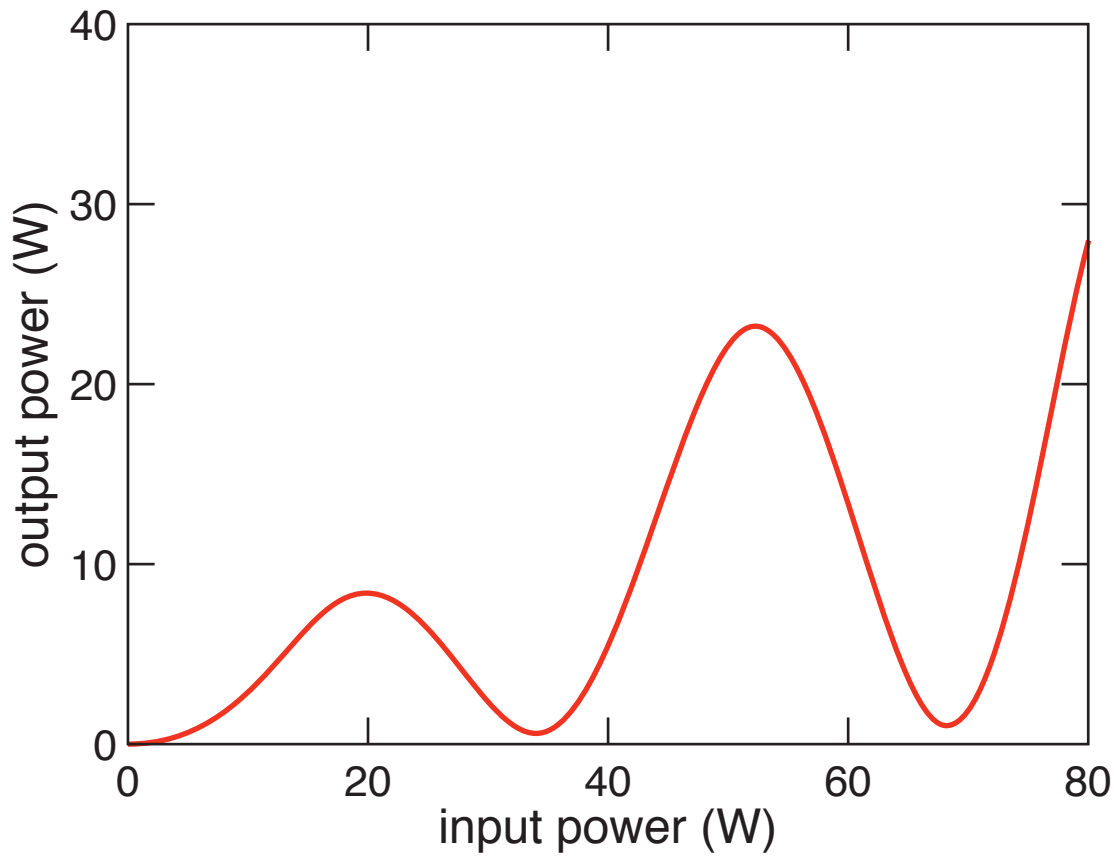
$$\rho = 0.5$$

no transmission:

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

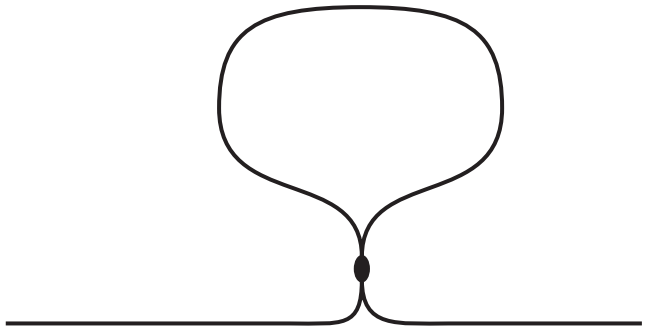
Optical logic gates

when $\rho \neq 0.5$:



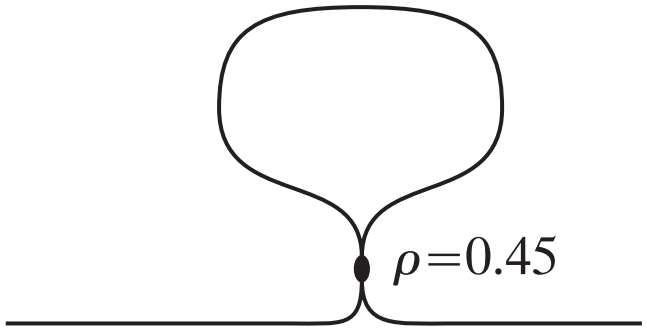
Optical logic gates

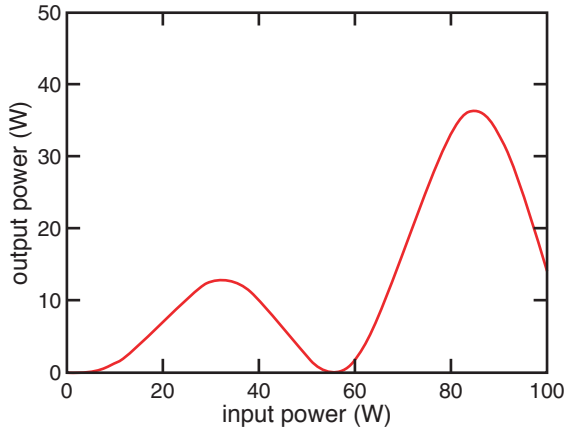
nonlinear nanogate



Optical logic gates

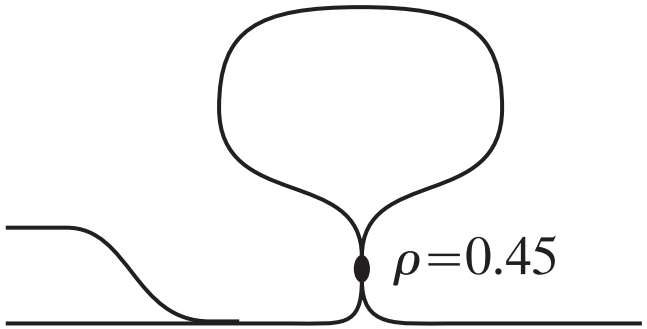
nonlinear nanogate

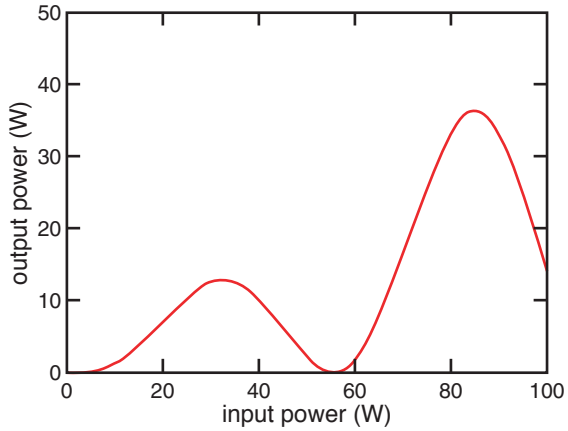




Optical logic gates

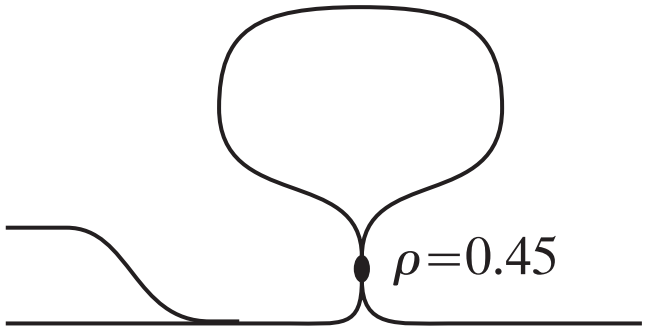
nonlinear nanogate

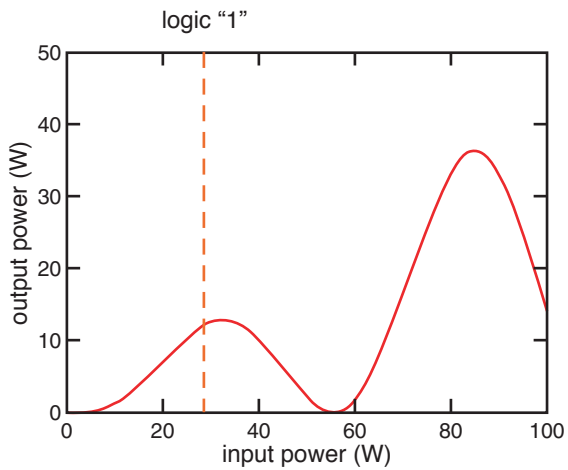




Optical logic gates

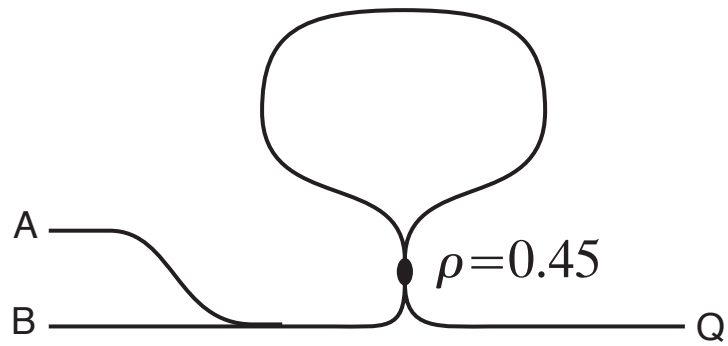
nonlinear nanogate

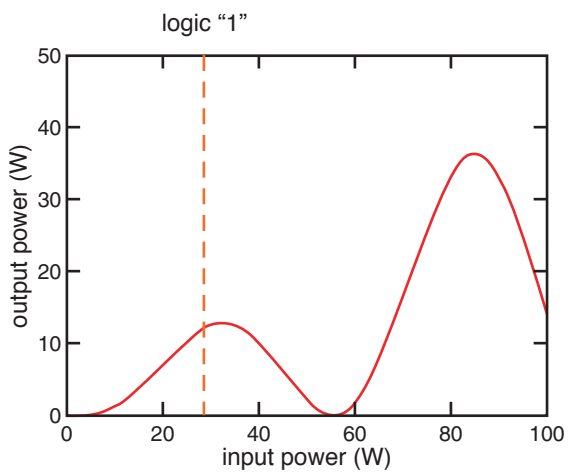




Optical logic gates

nonlinear nanogate

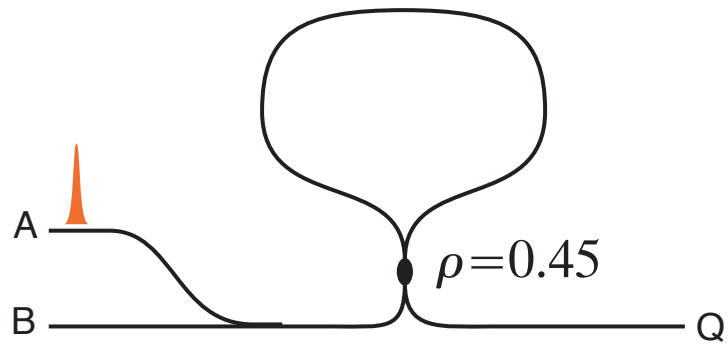


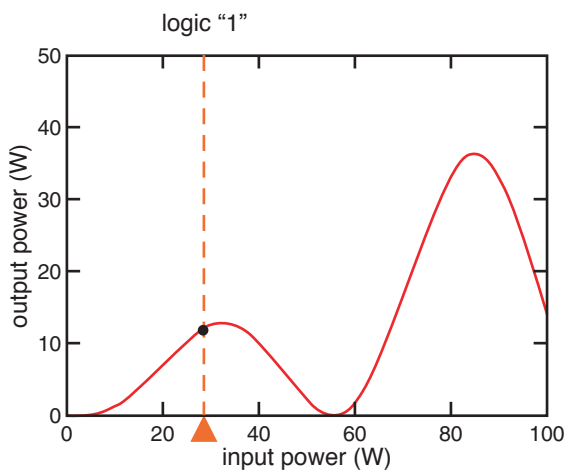


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

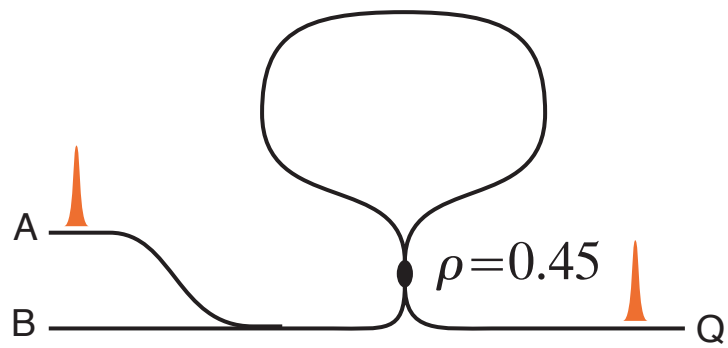


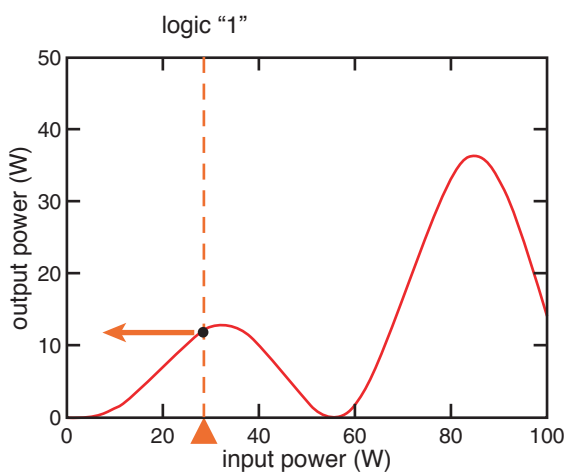


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

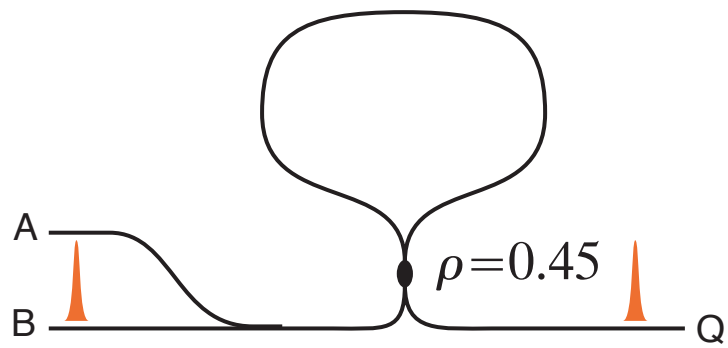


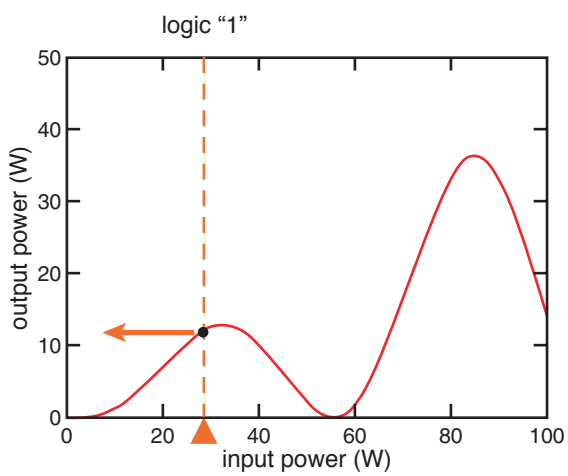


A	B	Q
0	0	0
1	0	1

Optical logic gates

nonlinear nanogate

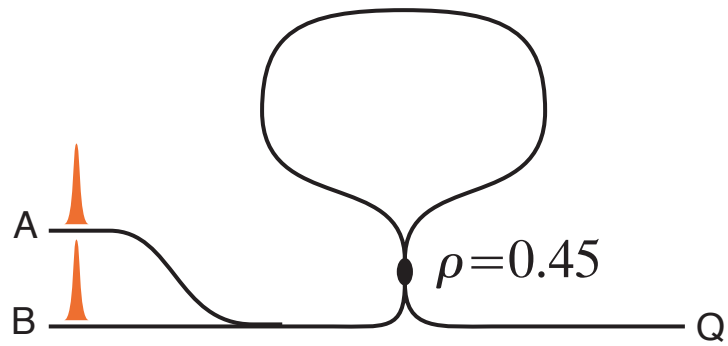


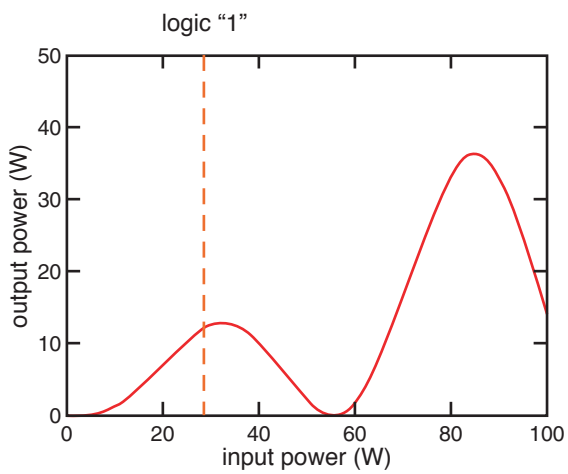


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

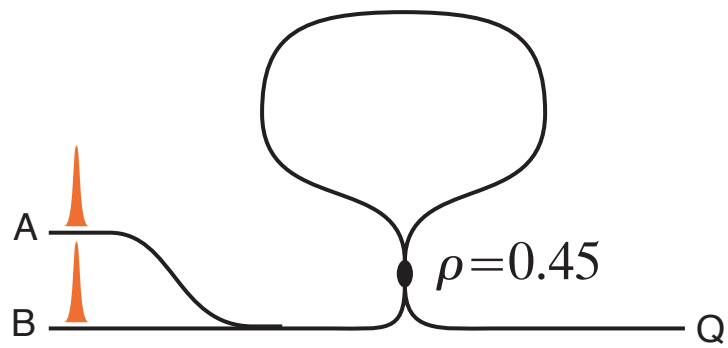


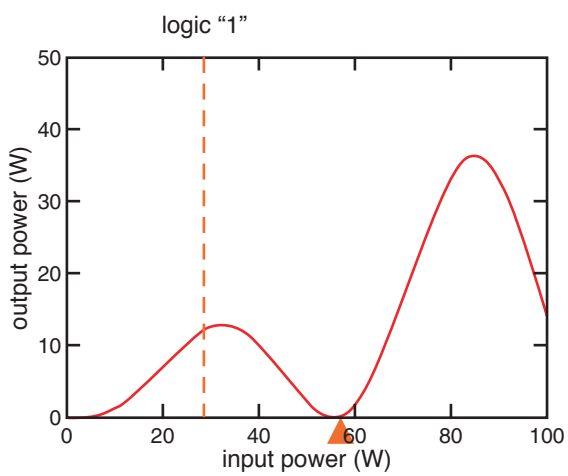


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

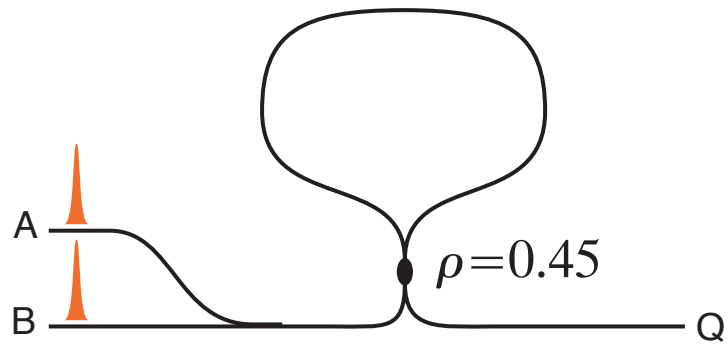


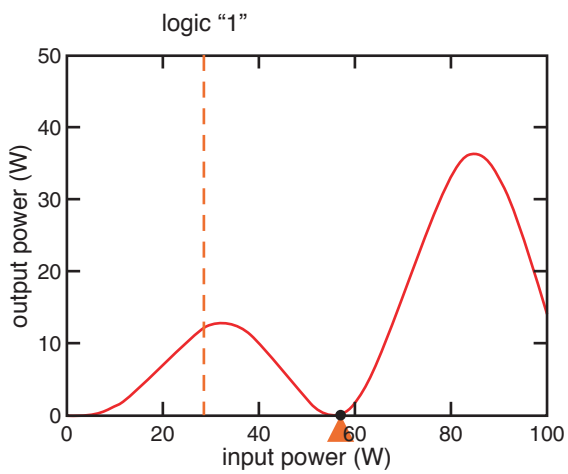


A	B	Q
0	0	0
1	0	1
0	1	1

Optical logic gates

nonlinear nanogate

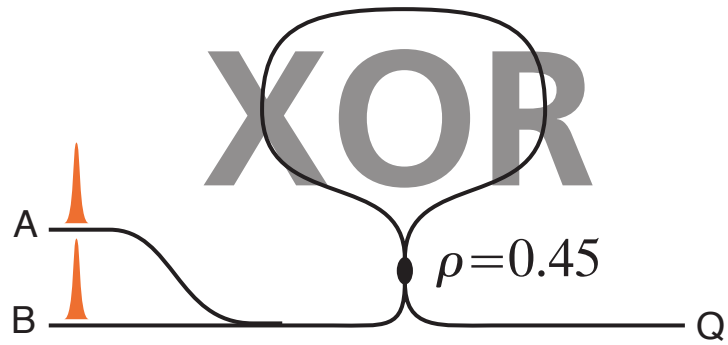


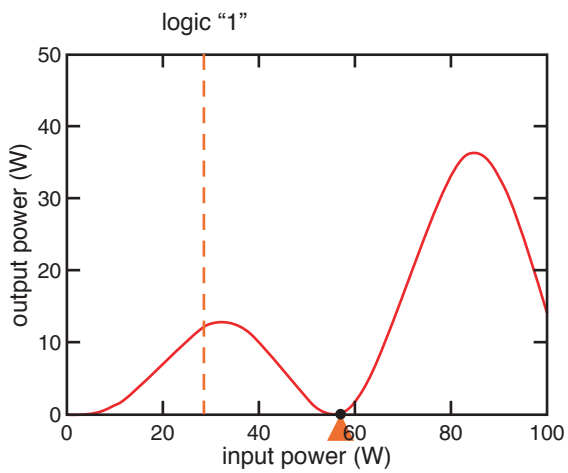


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

nonlinear nanogate

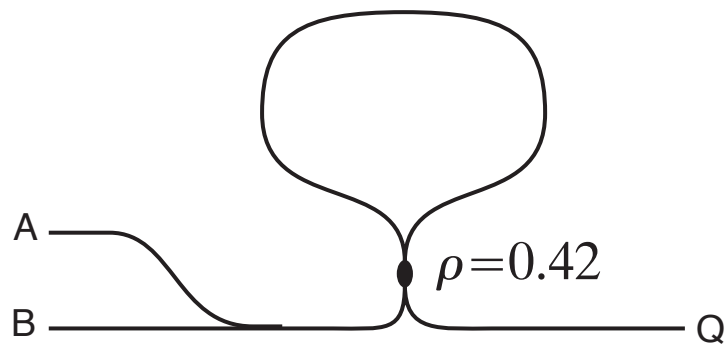


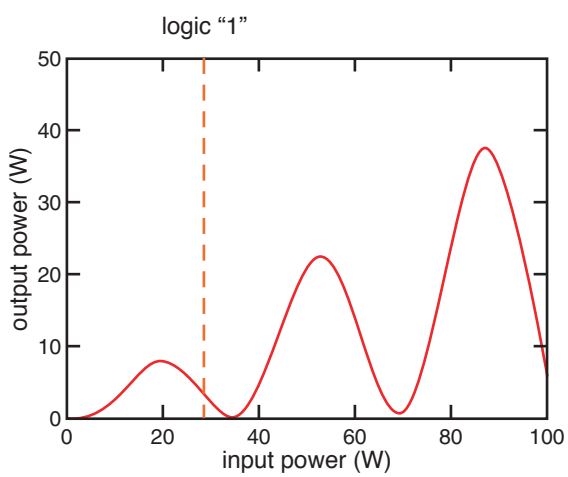


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

Optical logic gates

nonlinear nanogate

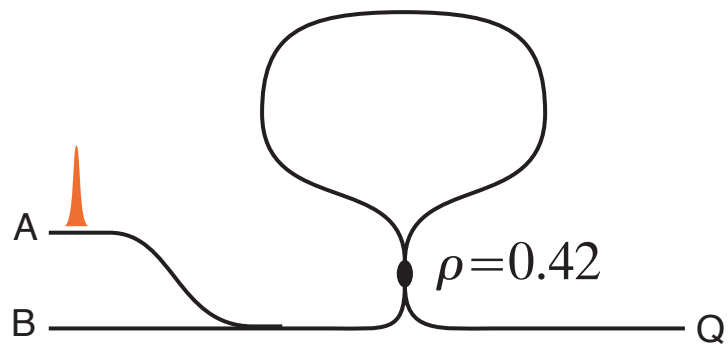


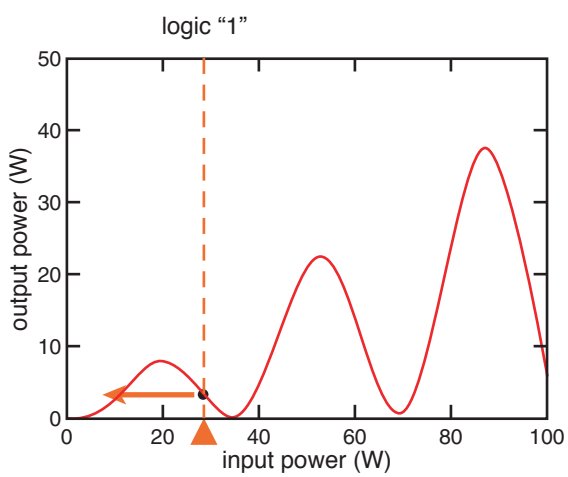


A	B	Q
0	0	0

Optical logic gates

nonlinear nanogate

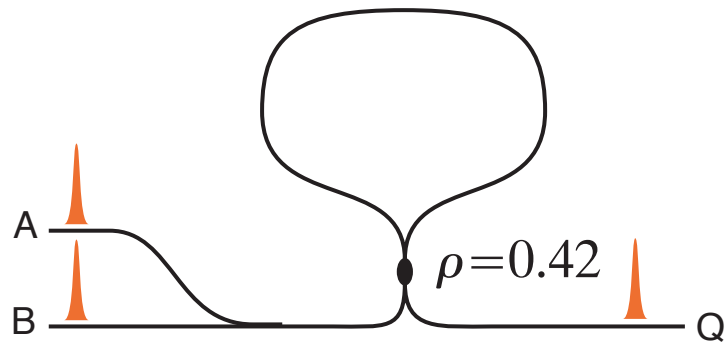


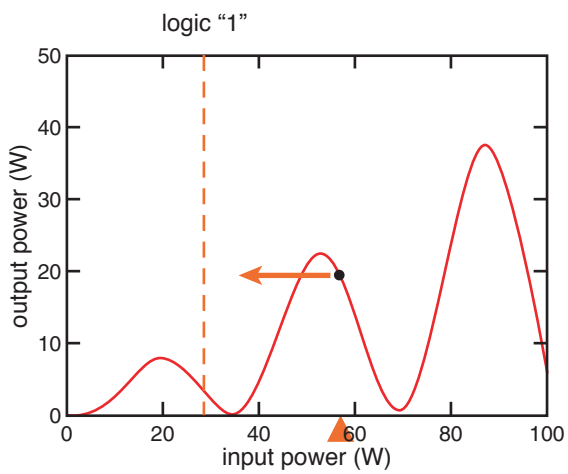


A	B	Q
0	0	0
1	0	0
0	1	0

Optical logic gates

nonlinear nanogate

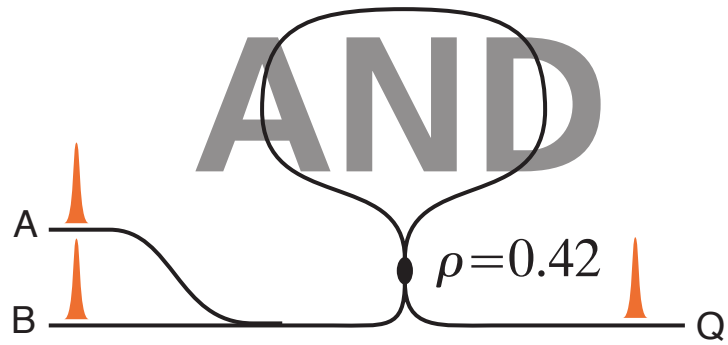


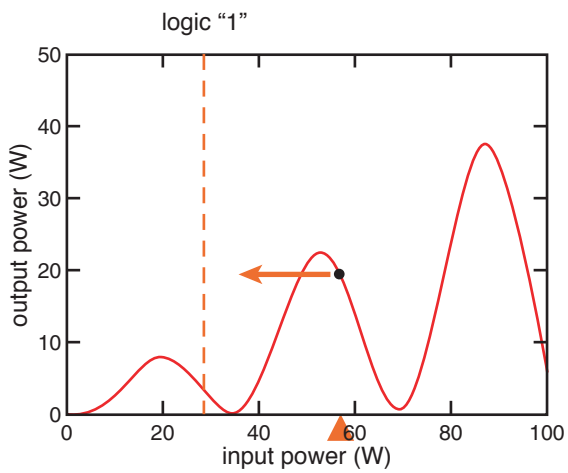


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

nonlinear nanogate

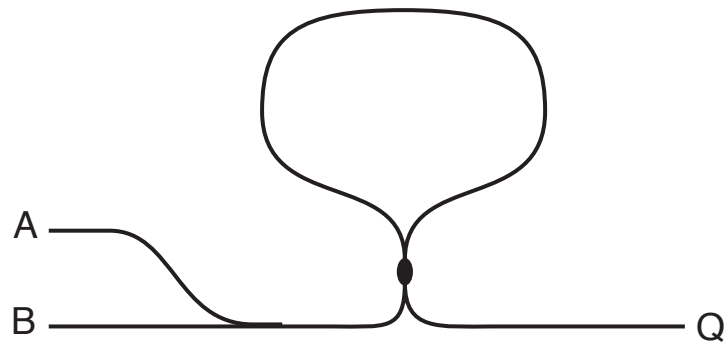


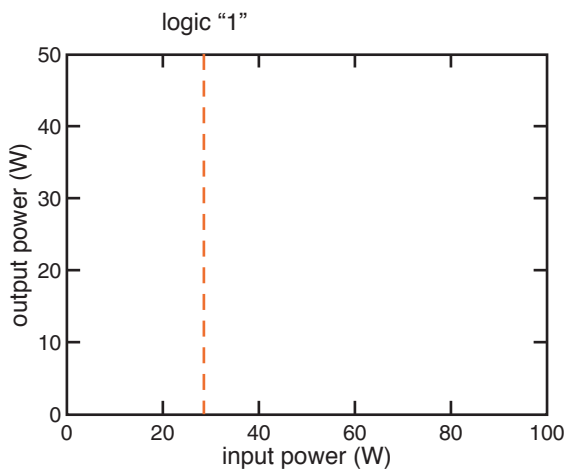


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

Optical logic gates

for NAND gate need ouput with no input

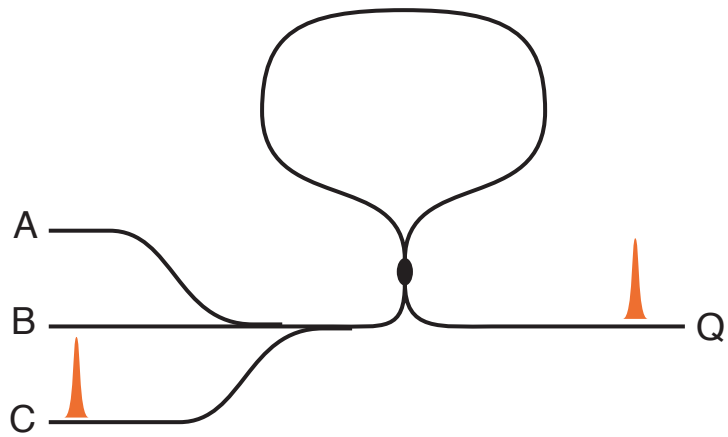


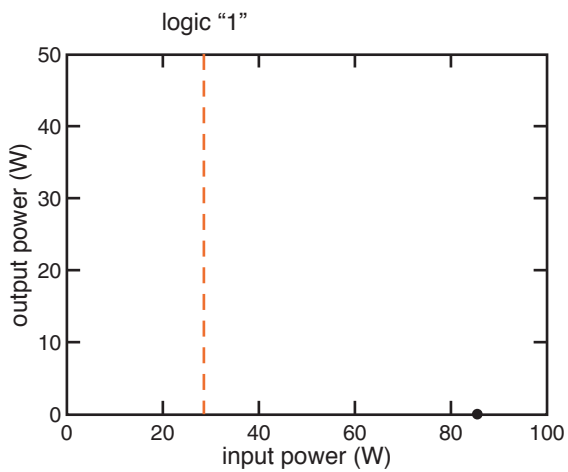


A	B	Q
0	0	1

Optical logic gates

for NAND gate need ouput with no input

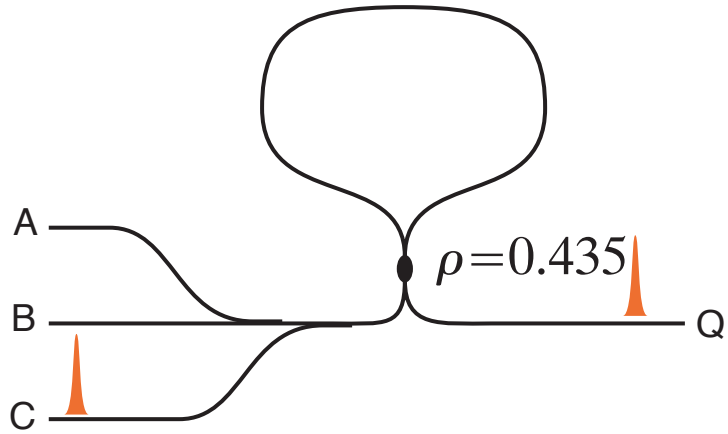


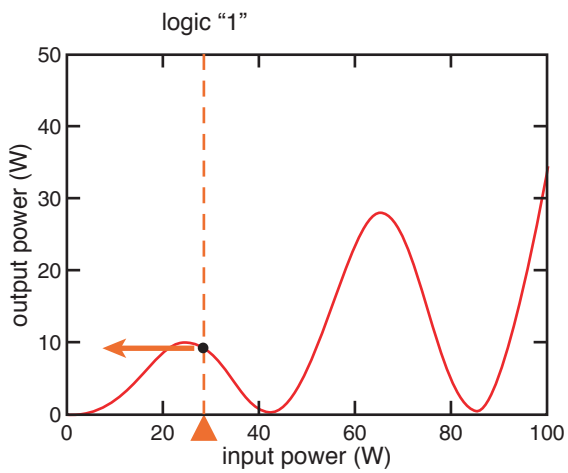


A	B	Q
0	0	1

Optical logic gates

for NAND gate need ouput with no input

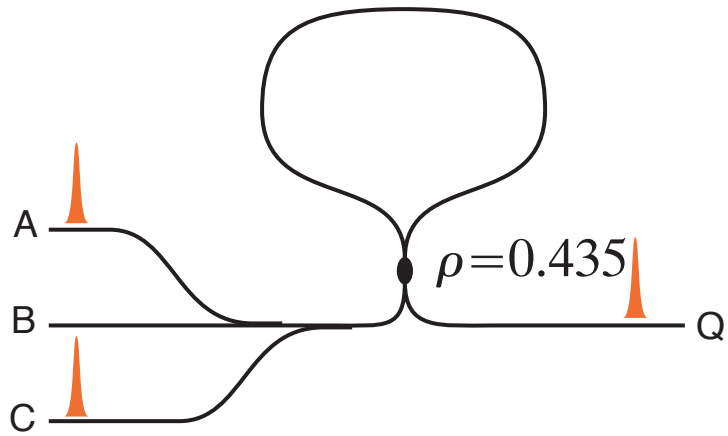


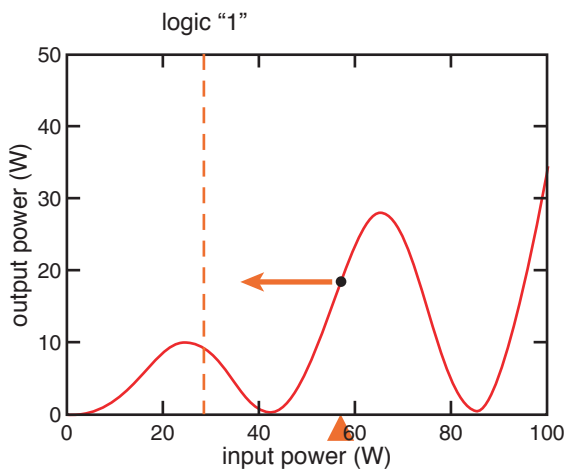


A	B	Q
0	0	1

Optical logic gates

universal NAND gate

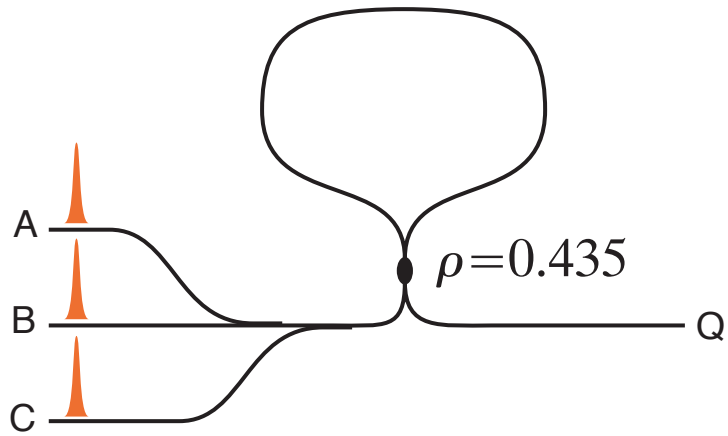


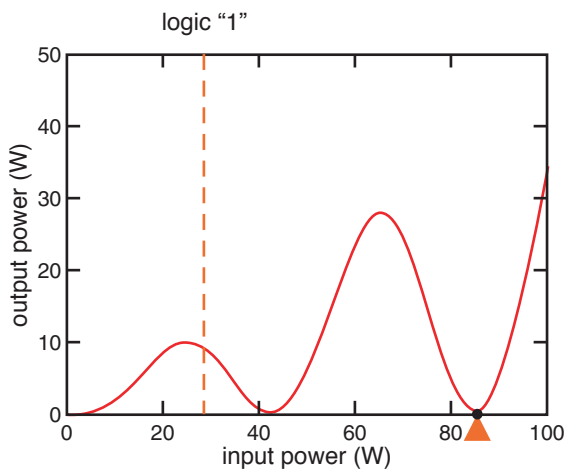


A	B	Q
0	0	1
1	0	1
0	1	1

Optical logic gates

universal NAND gate

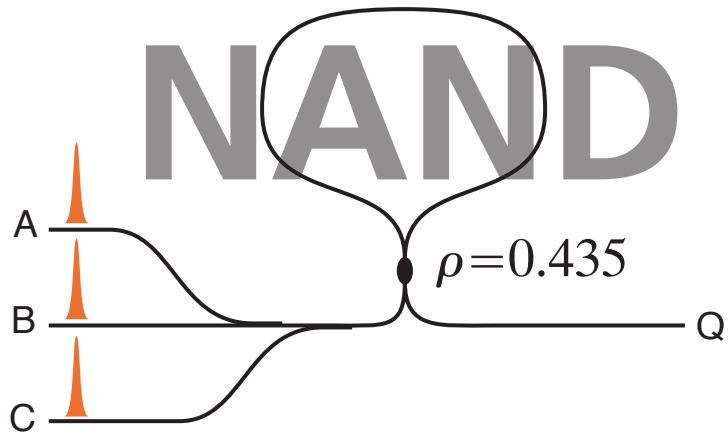


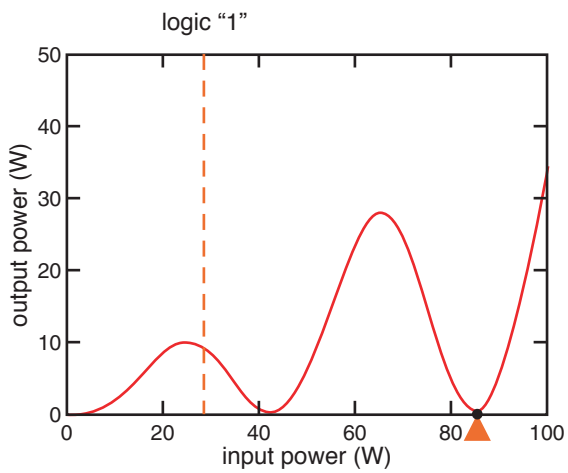


A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates

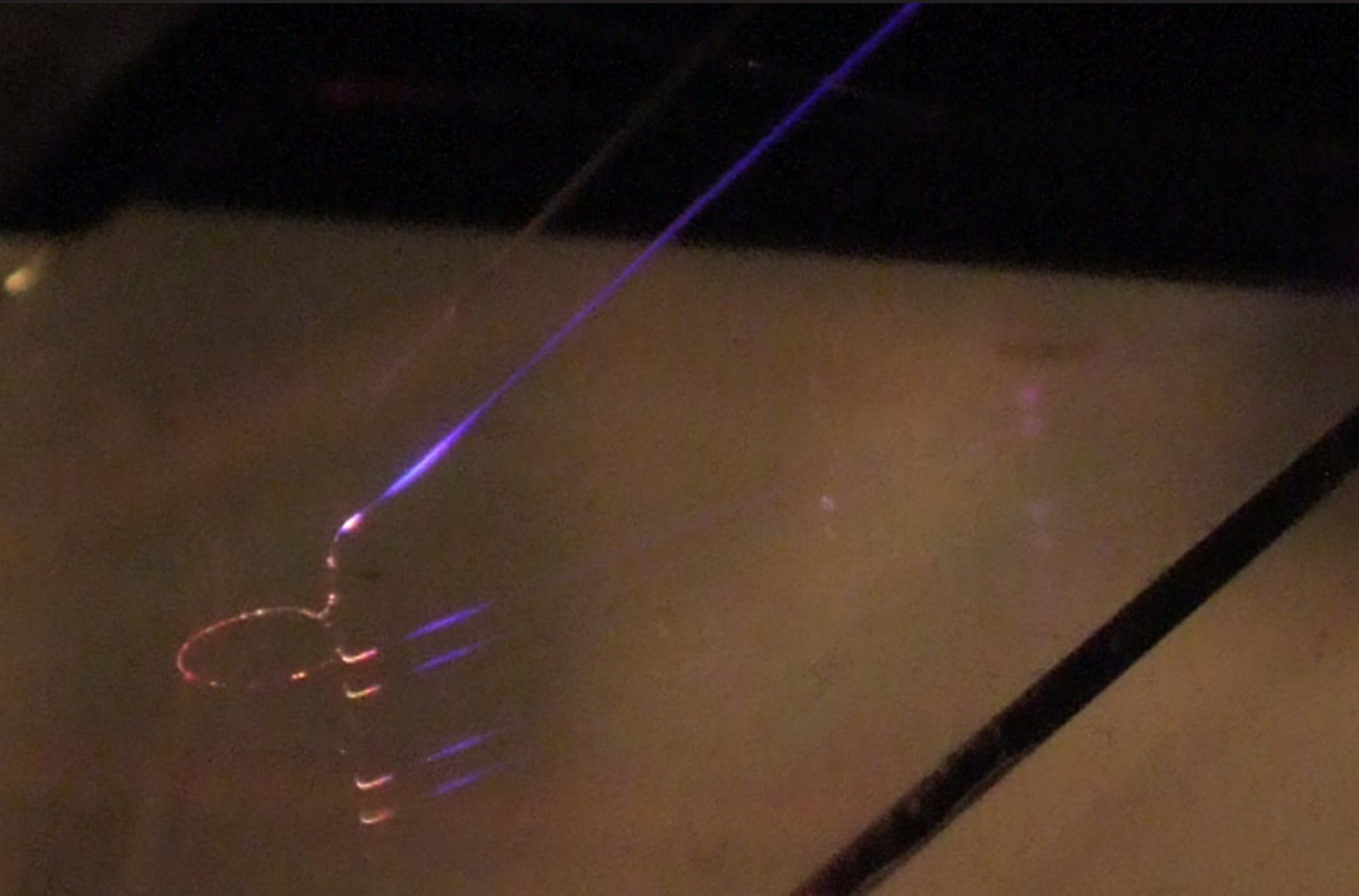
universal NAND gate





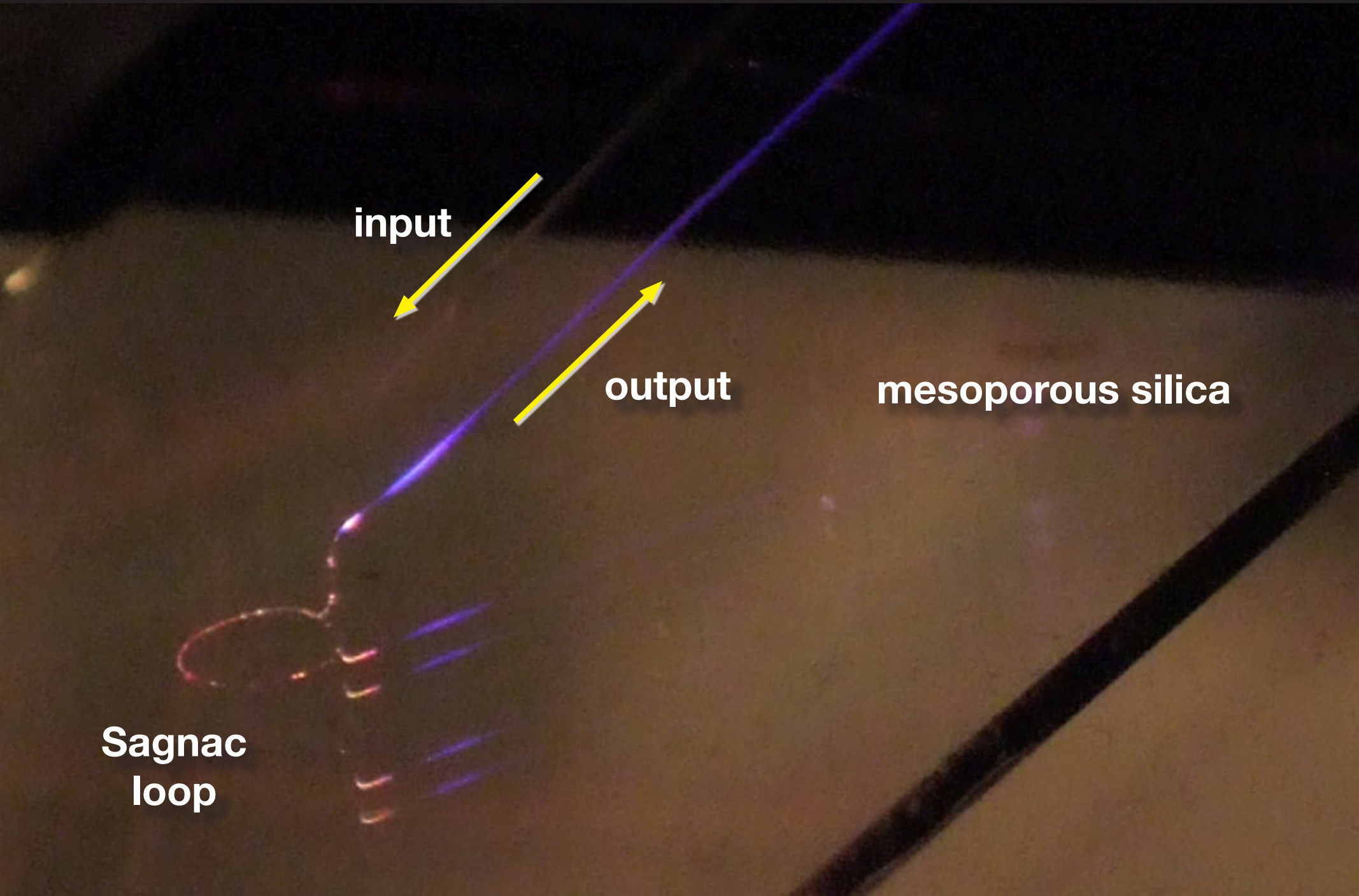
A	B	Q
0	0	1
1	0	1
0	1	1
1	1	0

Optical logic gates



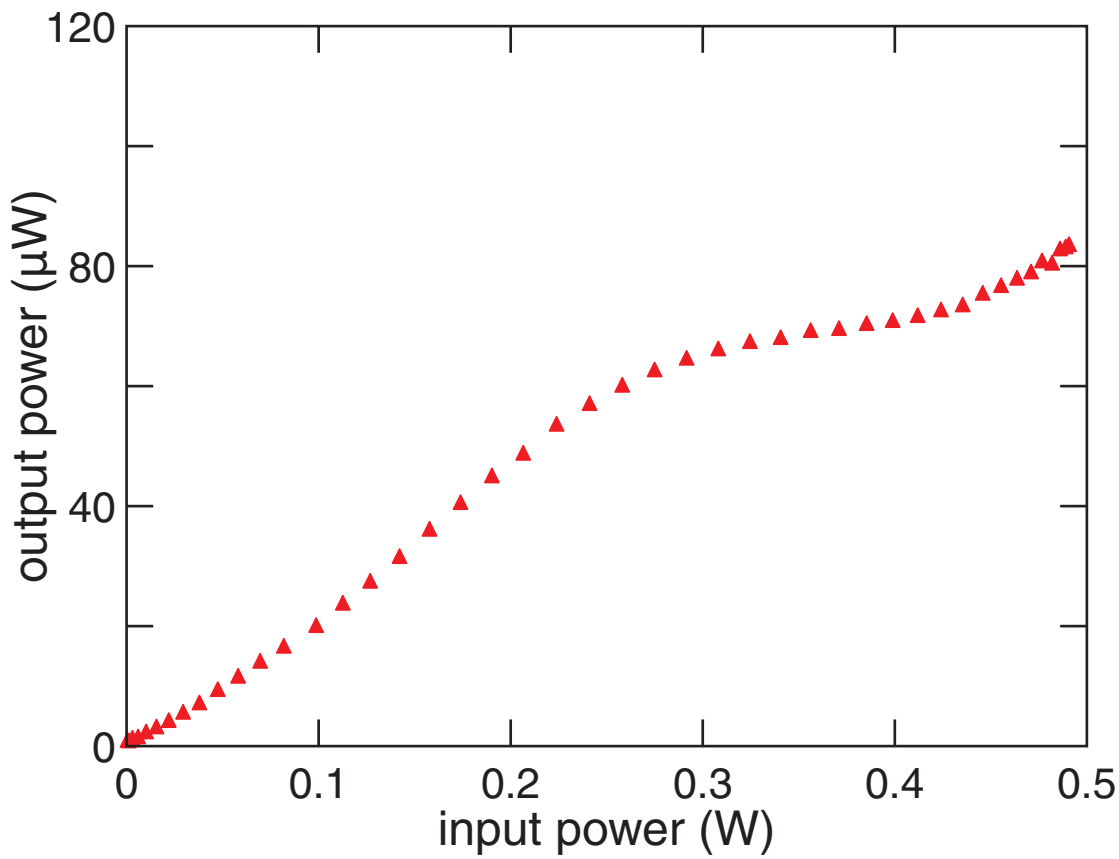
Optical logic gates

Optical logic gates



Optical logic gates

very preliminary data

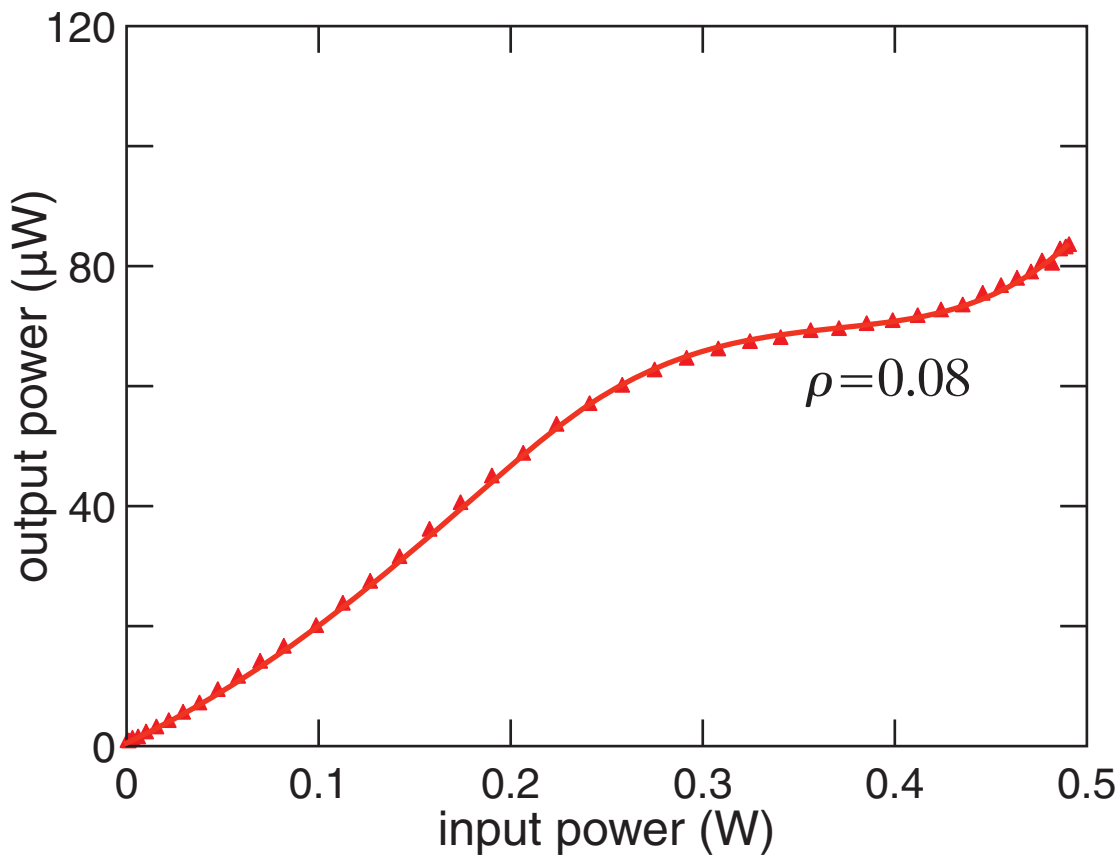


Optical logic gates

light-by-light modulation!

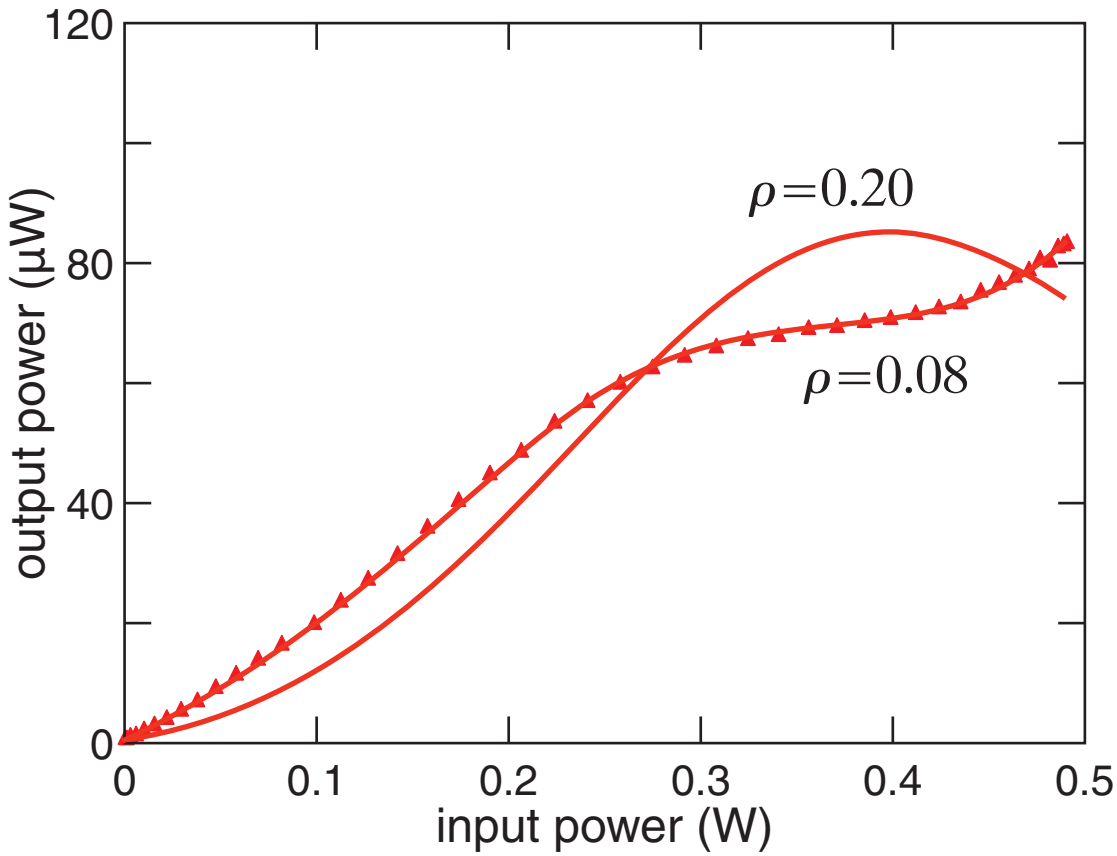
Optical logic gates

very preliminary data

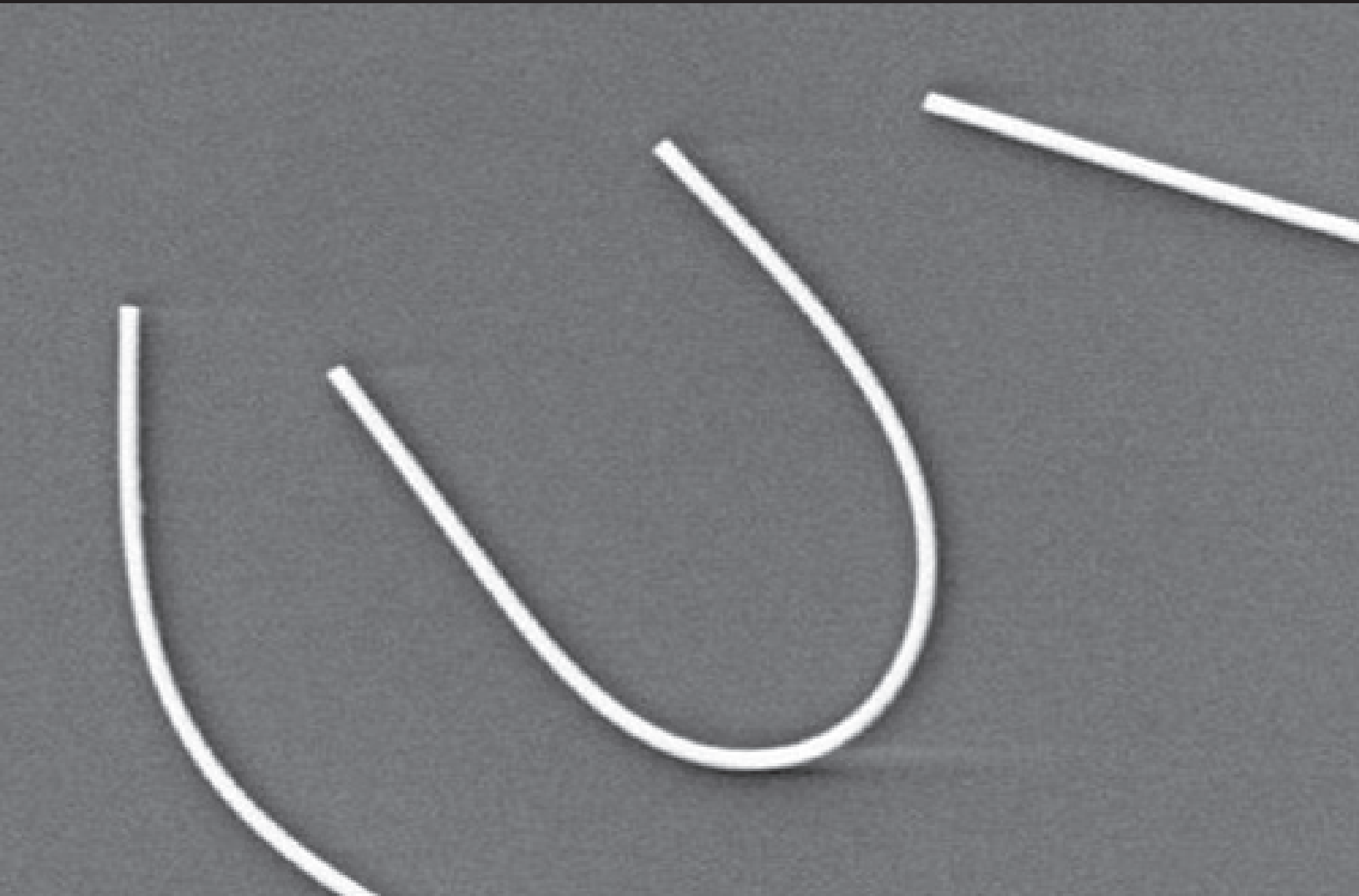


Optical logic gates

very preliminary data



Optical logic gates



Optical logic gates

need a different approach!

Optical logic gates

need a different approach!

- lithographic fabrication

Optical logic gates

need a different approach!

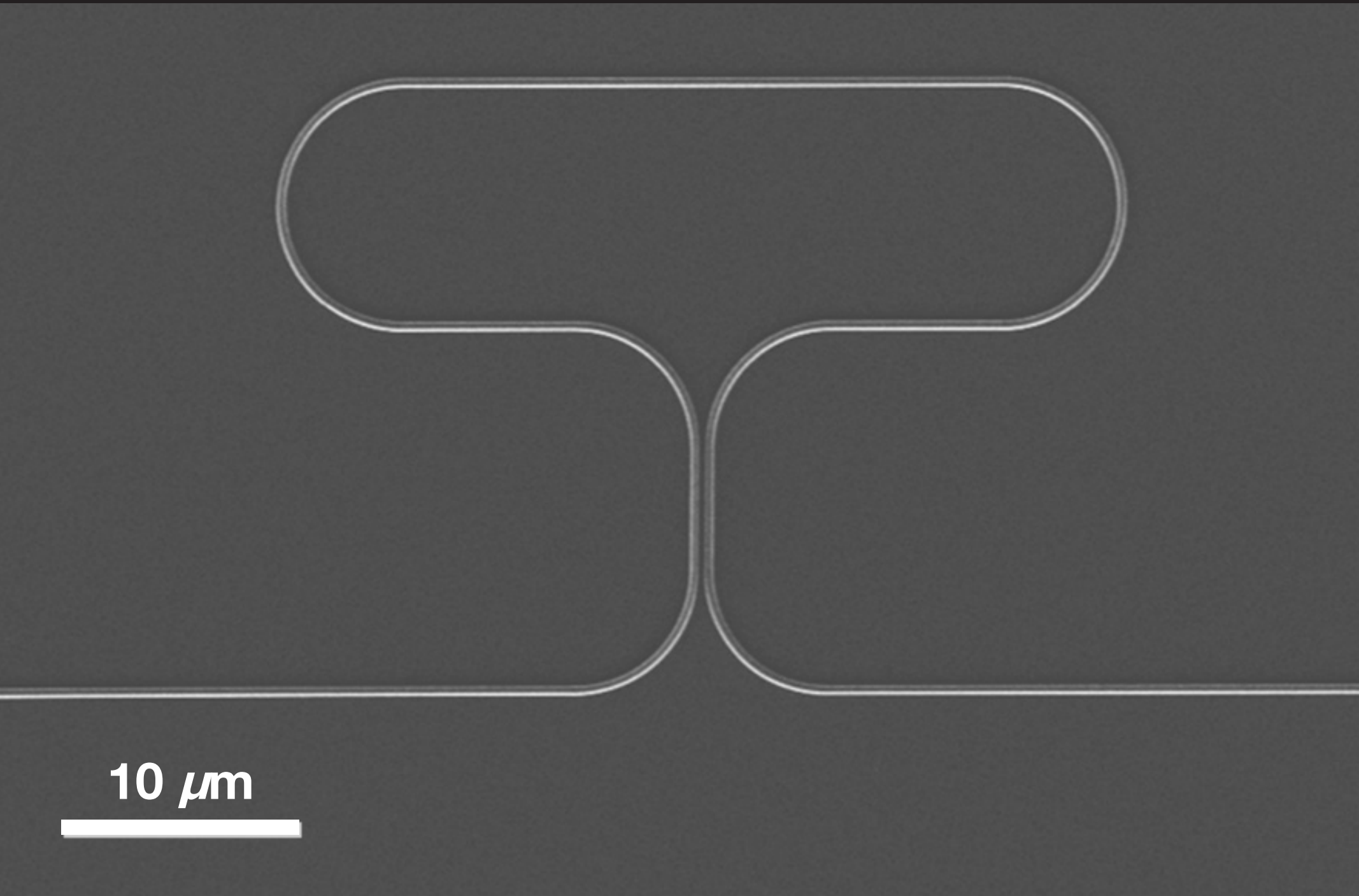
- lithographic fabrication
- greater index

Optical logic gates

need a different approach!

- lithographic fabrication
- greater index
- greater nonlinearity

Optical logic gates



Optical logic gates

TiO_2 properties

large nonlinearity	30x silica
high index of refraction	2.4
wide bandgap	3.1 eV
low two-photon absorption	> 800 nm
effective nonlinearity	50,000 W^{-1} km^{-1}

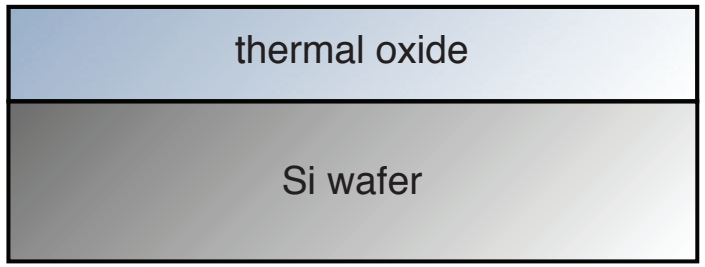
Optical logic gates

reactive sputtering of titanium with oxygen

Optics Express, 20, 23821 (2012)

Optical logic gates

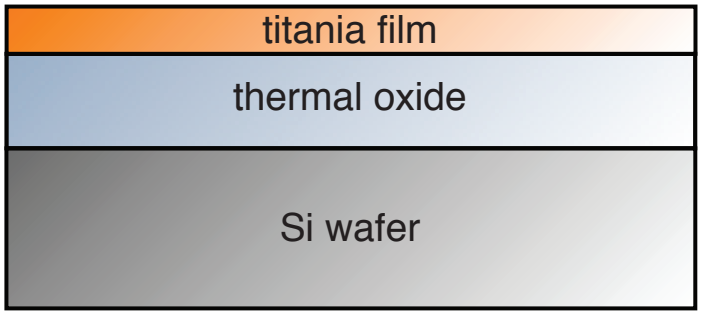
begin with silicon wafer with thermal oxide



Optics Express, 20, 23821 (2012)

Optical logic gates

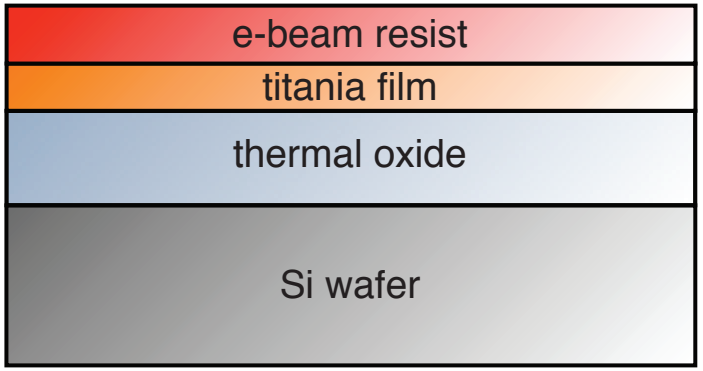
deposit titania using reactive sputtering



Optics Express, 20, 23821 (2012)

Optical logic gates

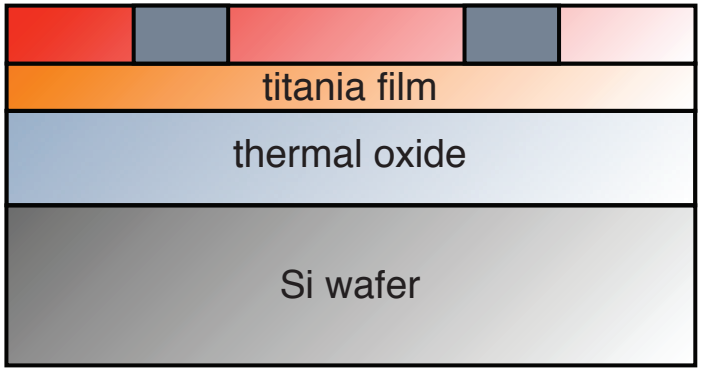
spin on e-beam resist



Optics Express, 20, 23821 (2012)

Optical logic gates

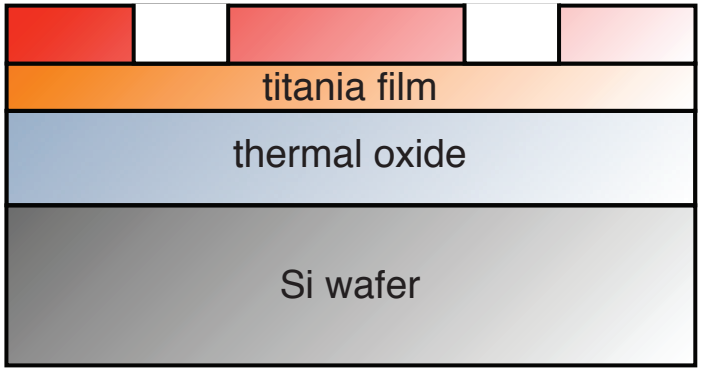
write pattern using e-beam



Optics Express, 20, 23821 (2012)

Optical logic gates

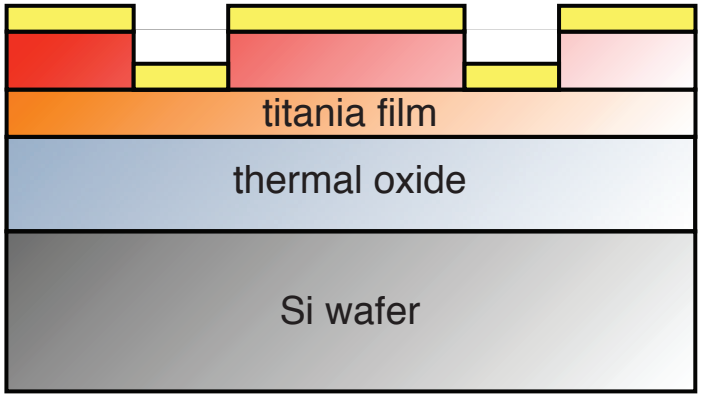
develop to remove exposed regions



Optics Express, 20, 23821 (2012)

Optical logic gates

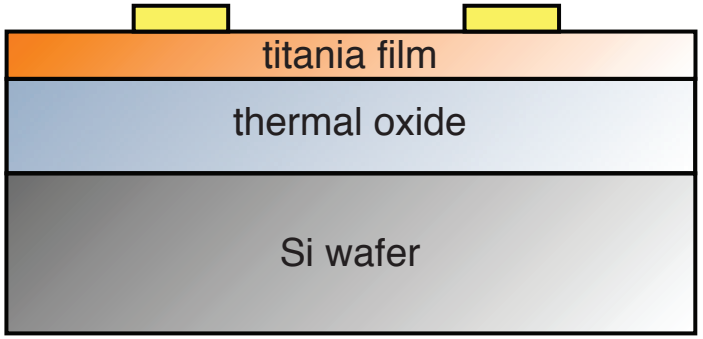
deposit thin metal film



Optics Express, 20, 23821 (2012)

Optical logic gates

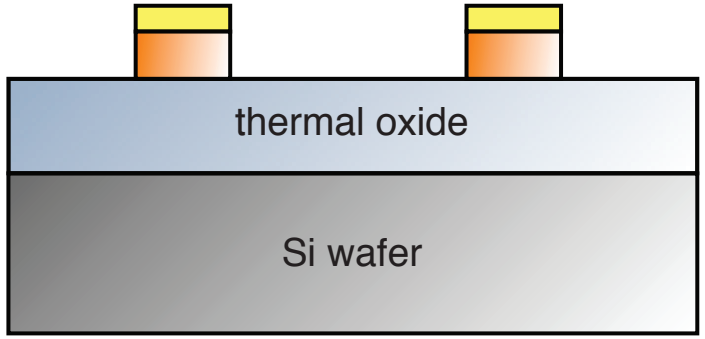
dissolve resist, lift off metal film



Optics Express, 20, 23821 (2012)

Optical logic gates

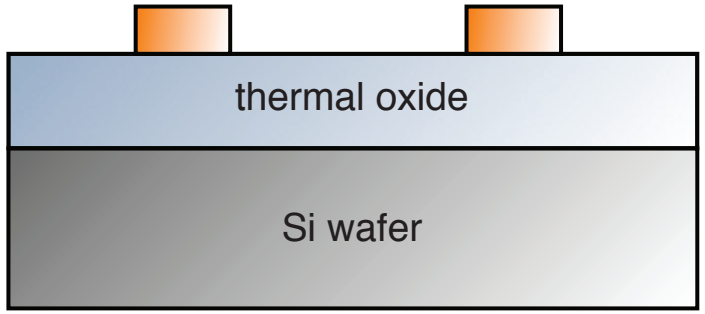
reactive ion etch through titania film



Optics Express, 20, 23821 (2012)

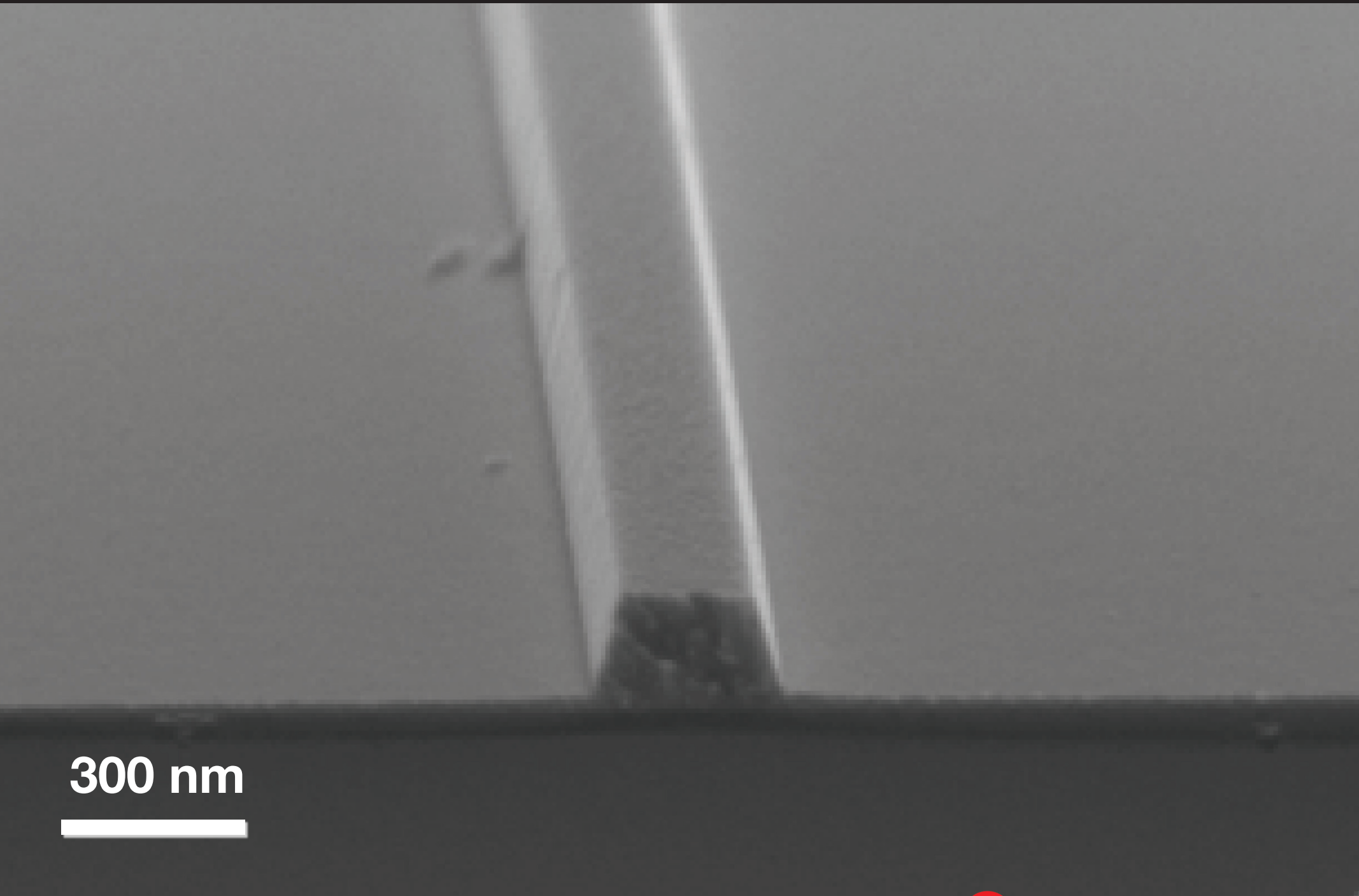
Optical logic gates

remove remaining metal

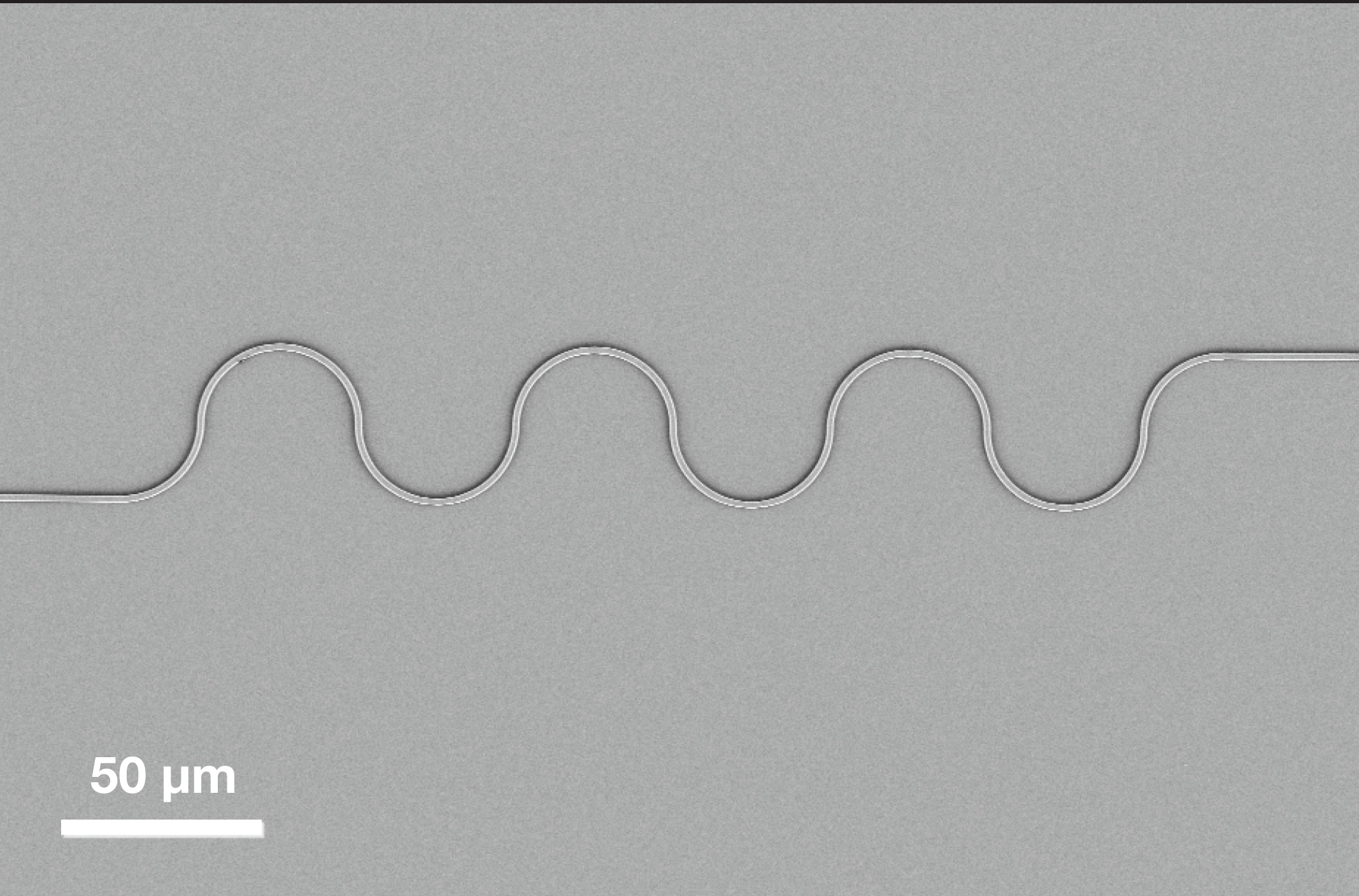


Optics Express, 20, 23821 (2012)

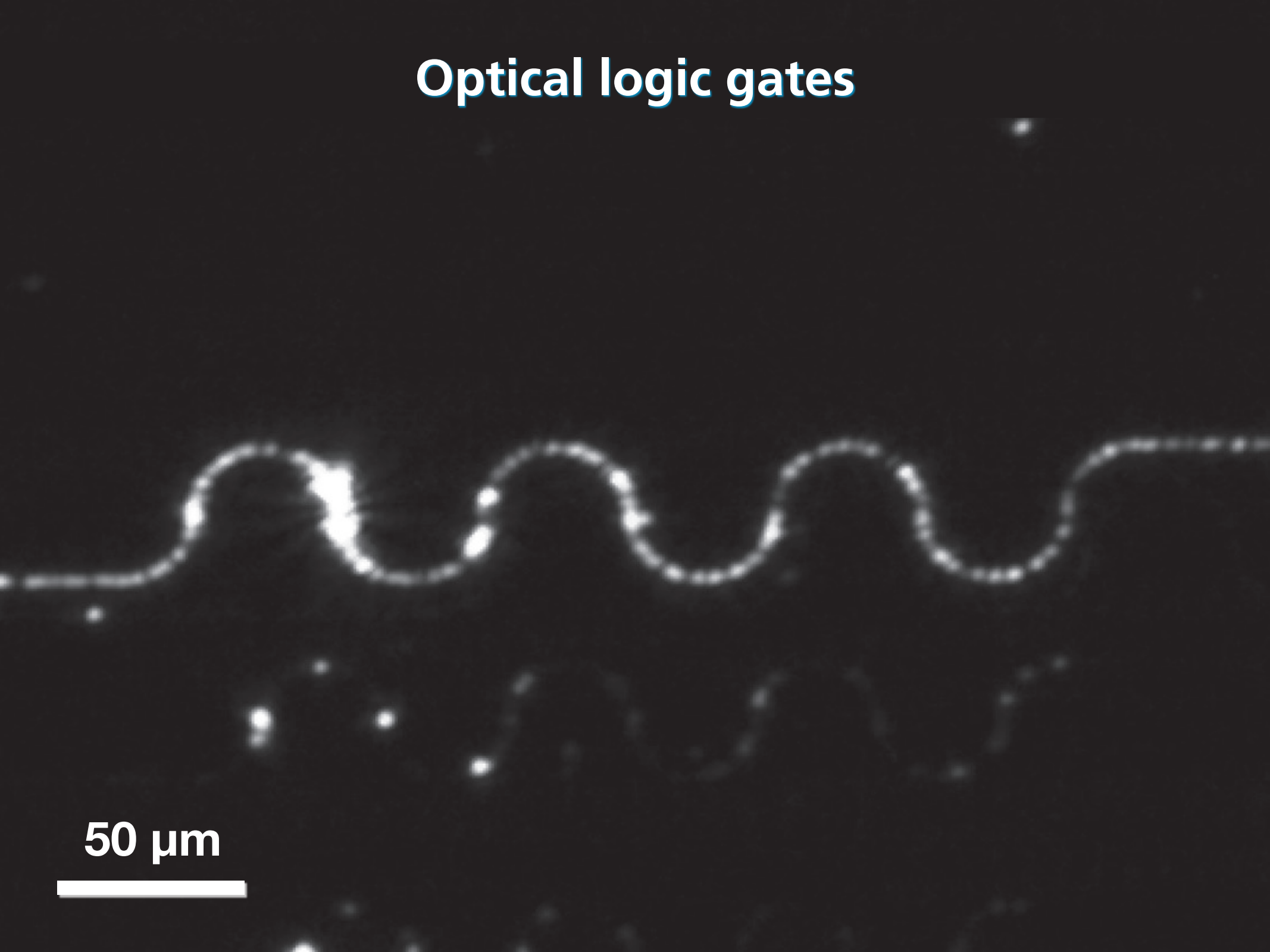
Optical logic gates



Optical logic gates



Optical logic gates



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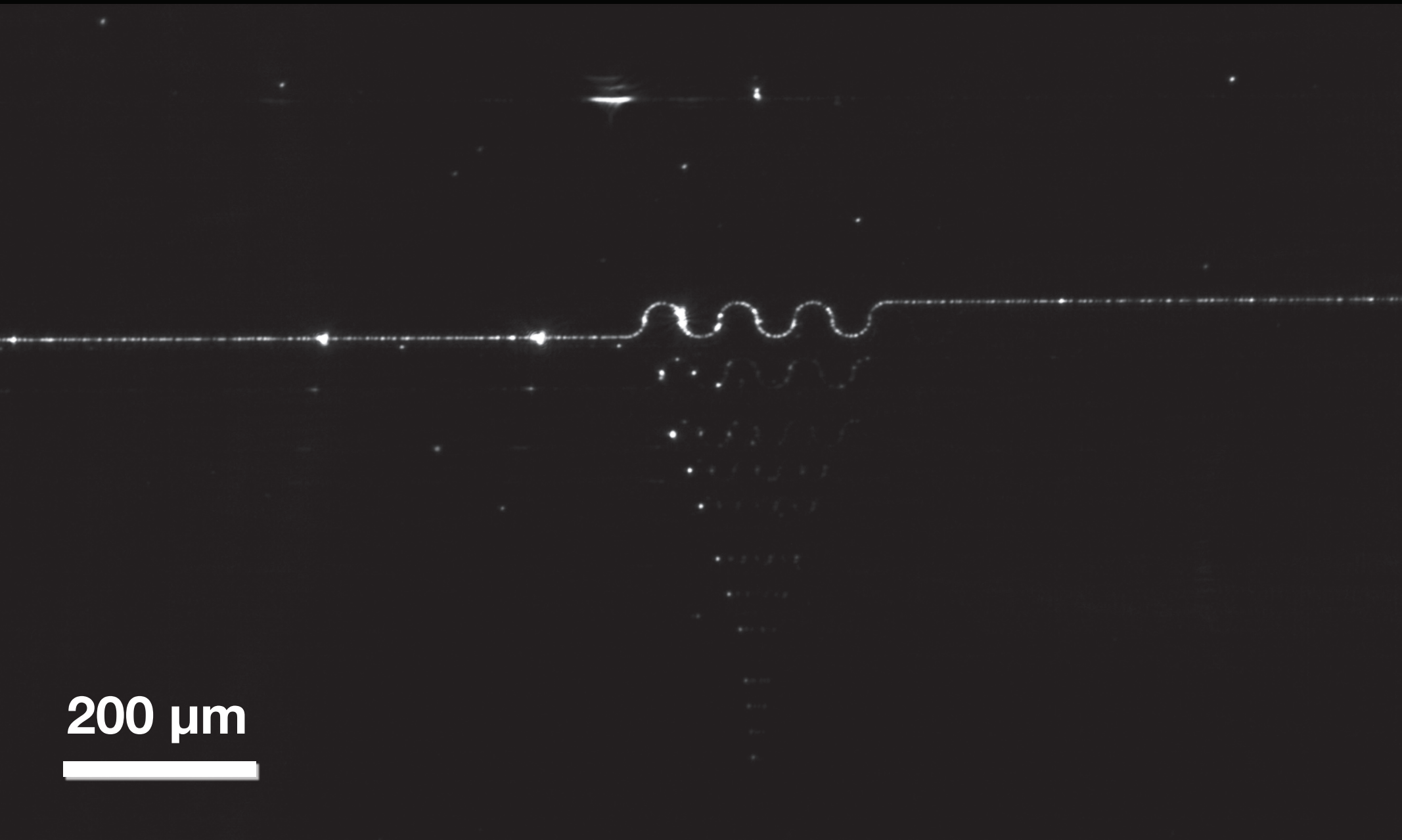
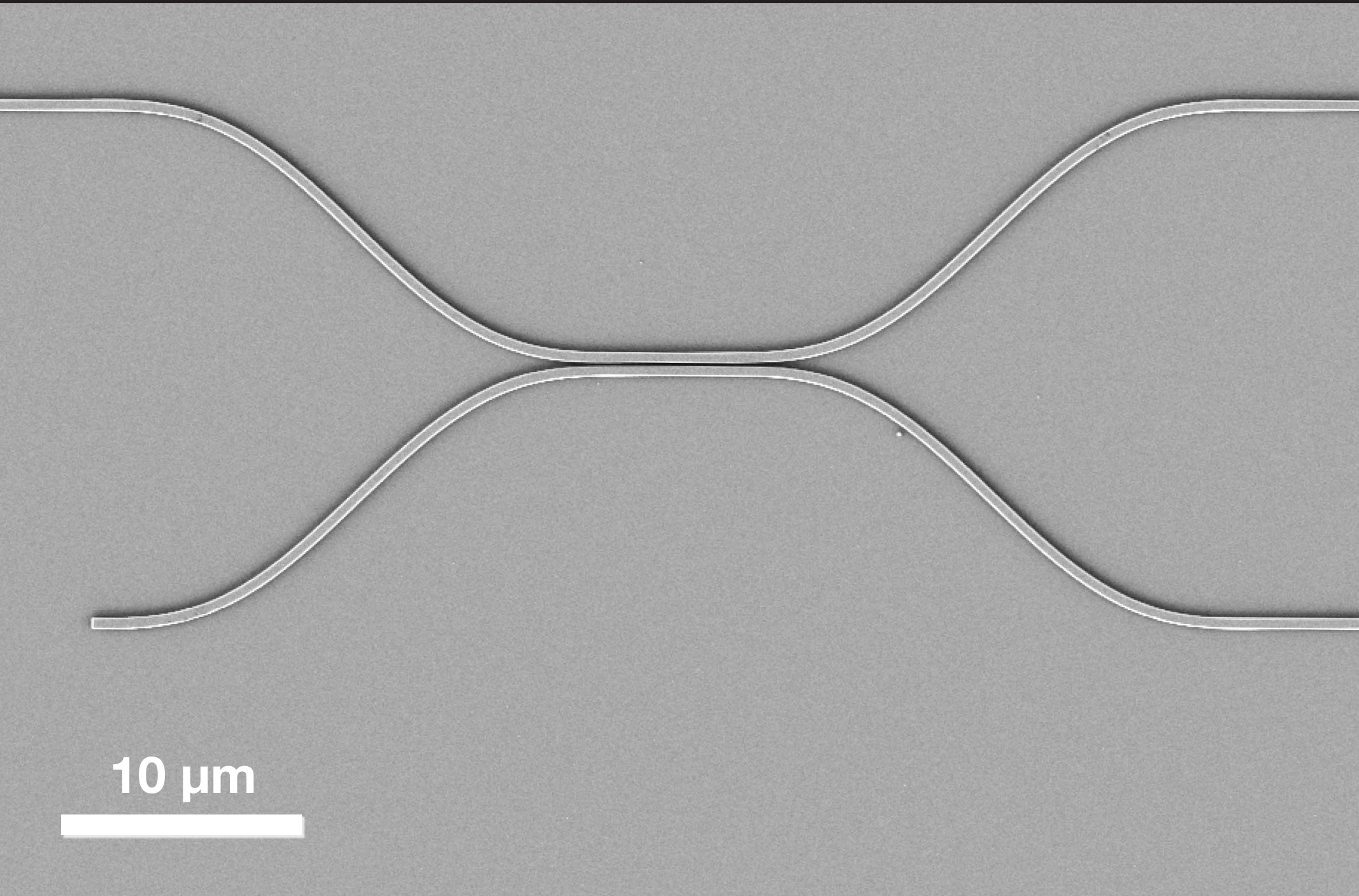
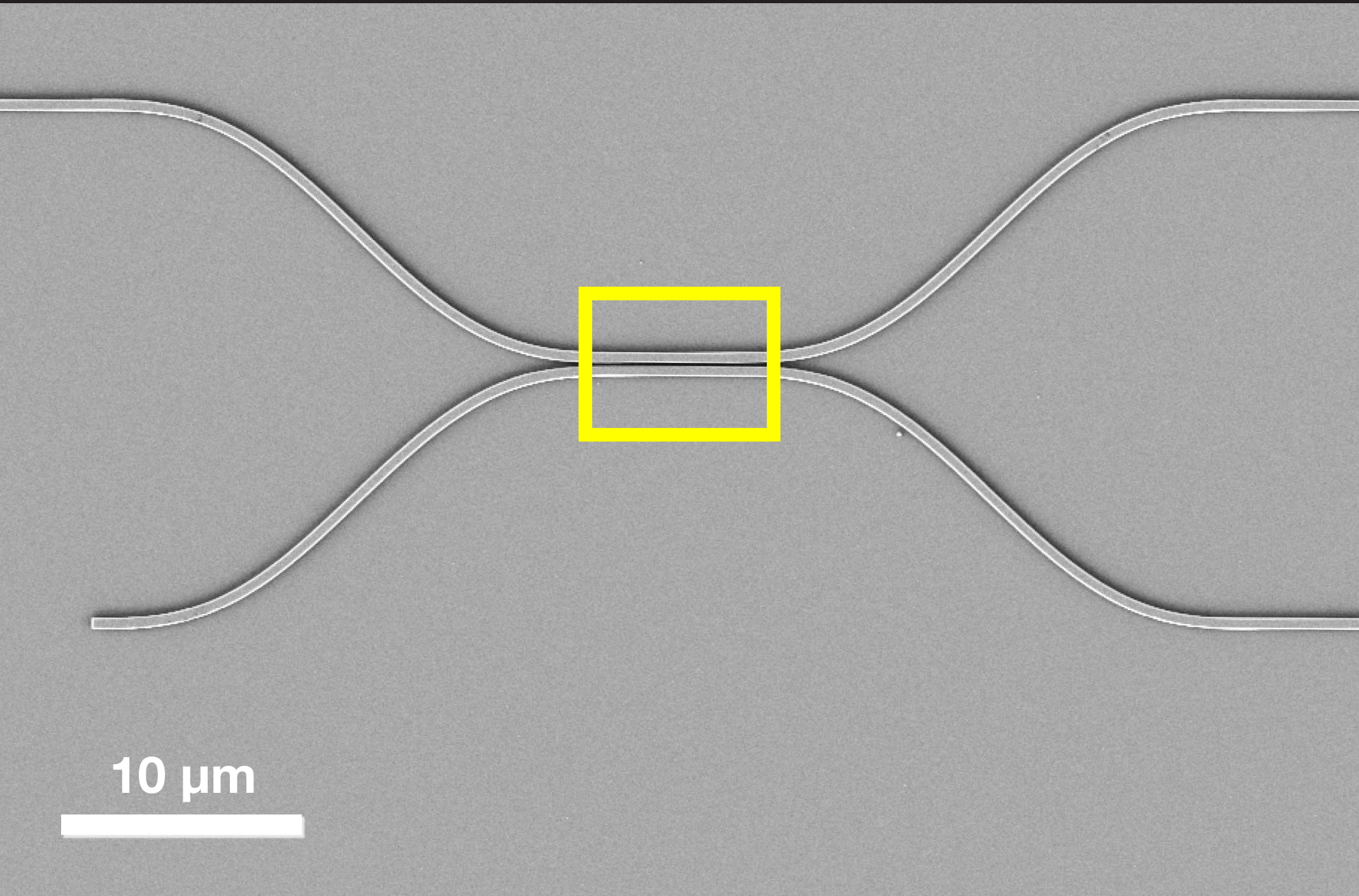


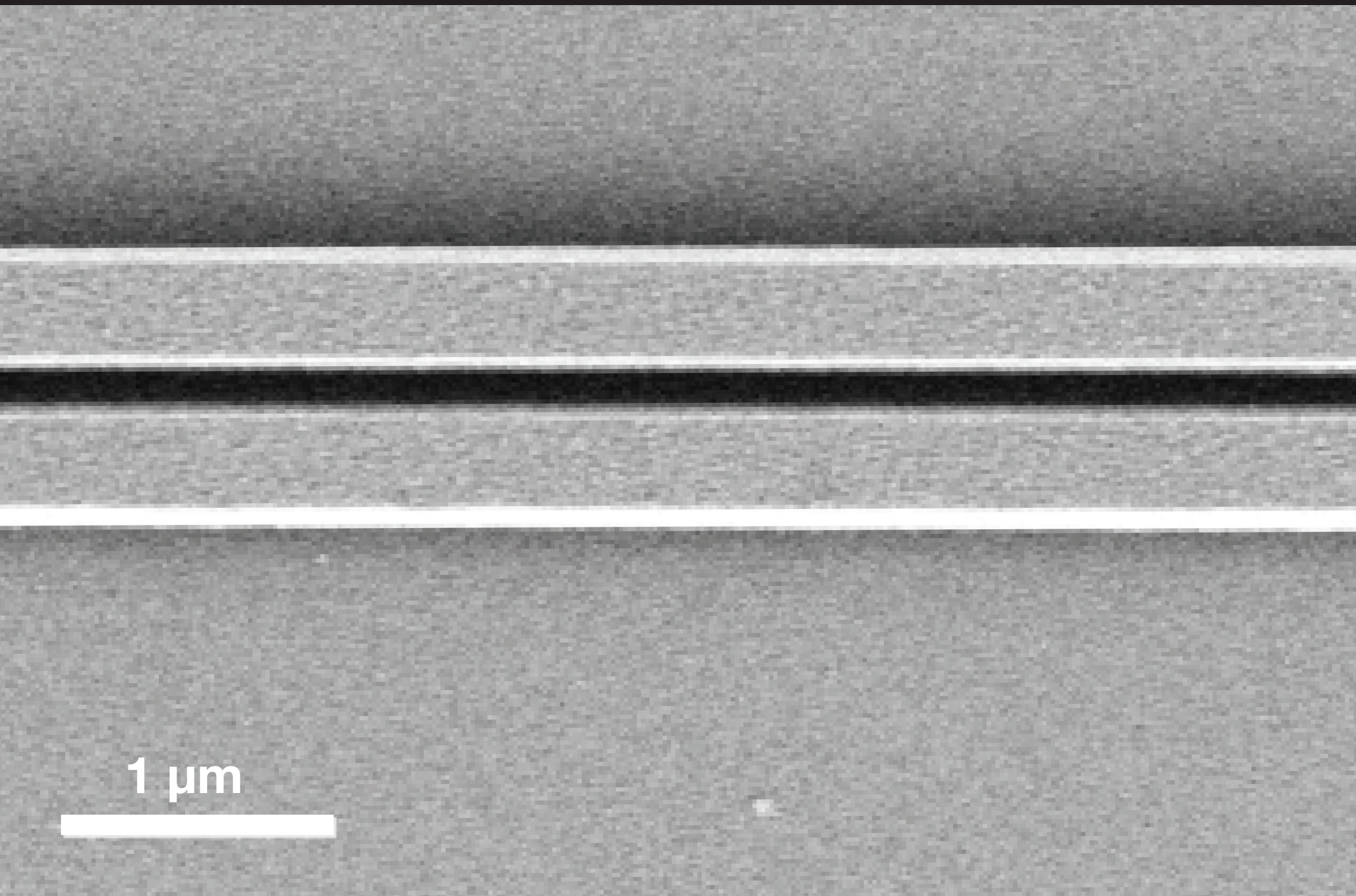
Optical logic gates



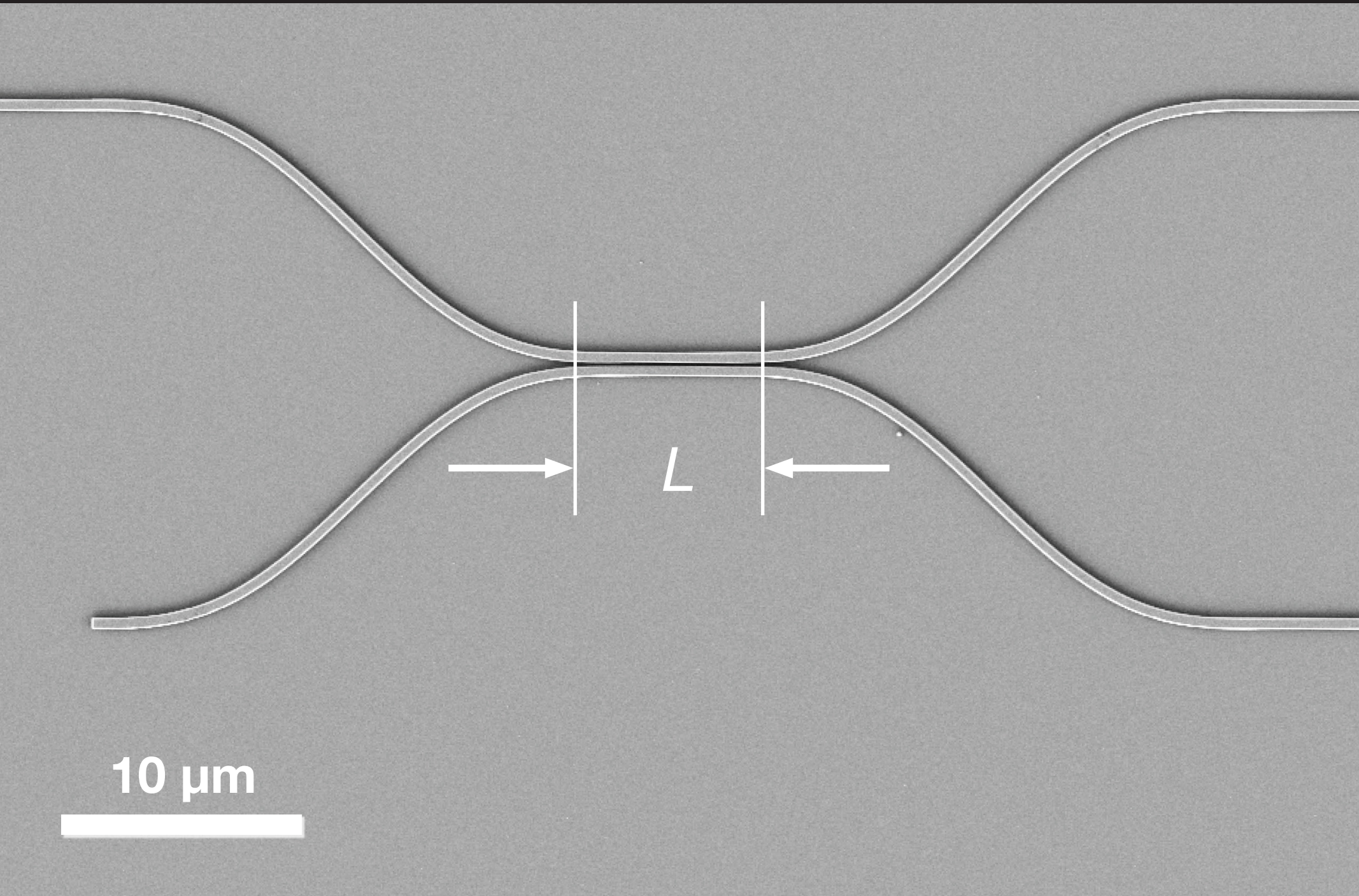
Optical logic gates



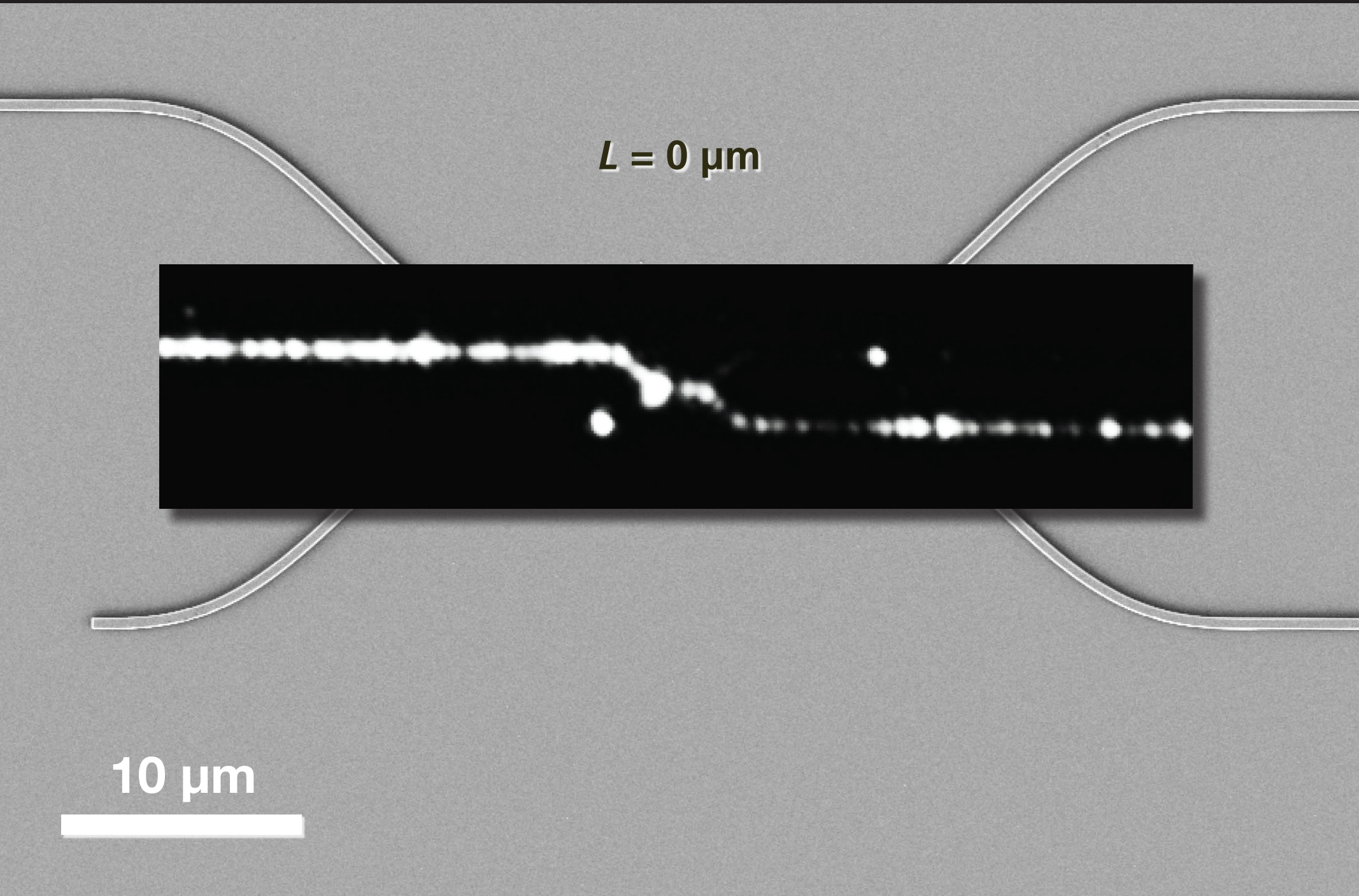
Optical logic gates



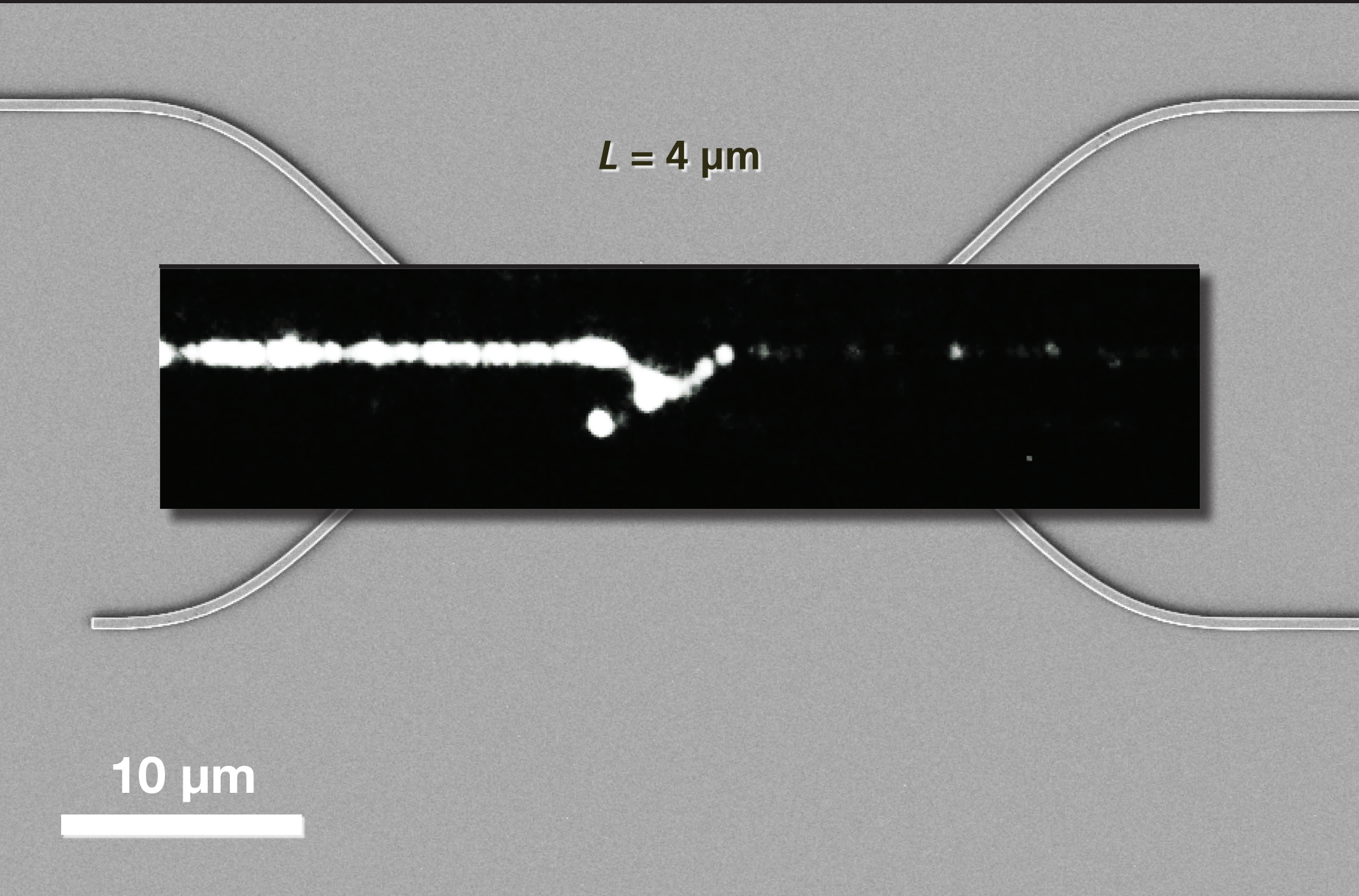
Optical logic gates



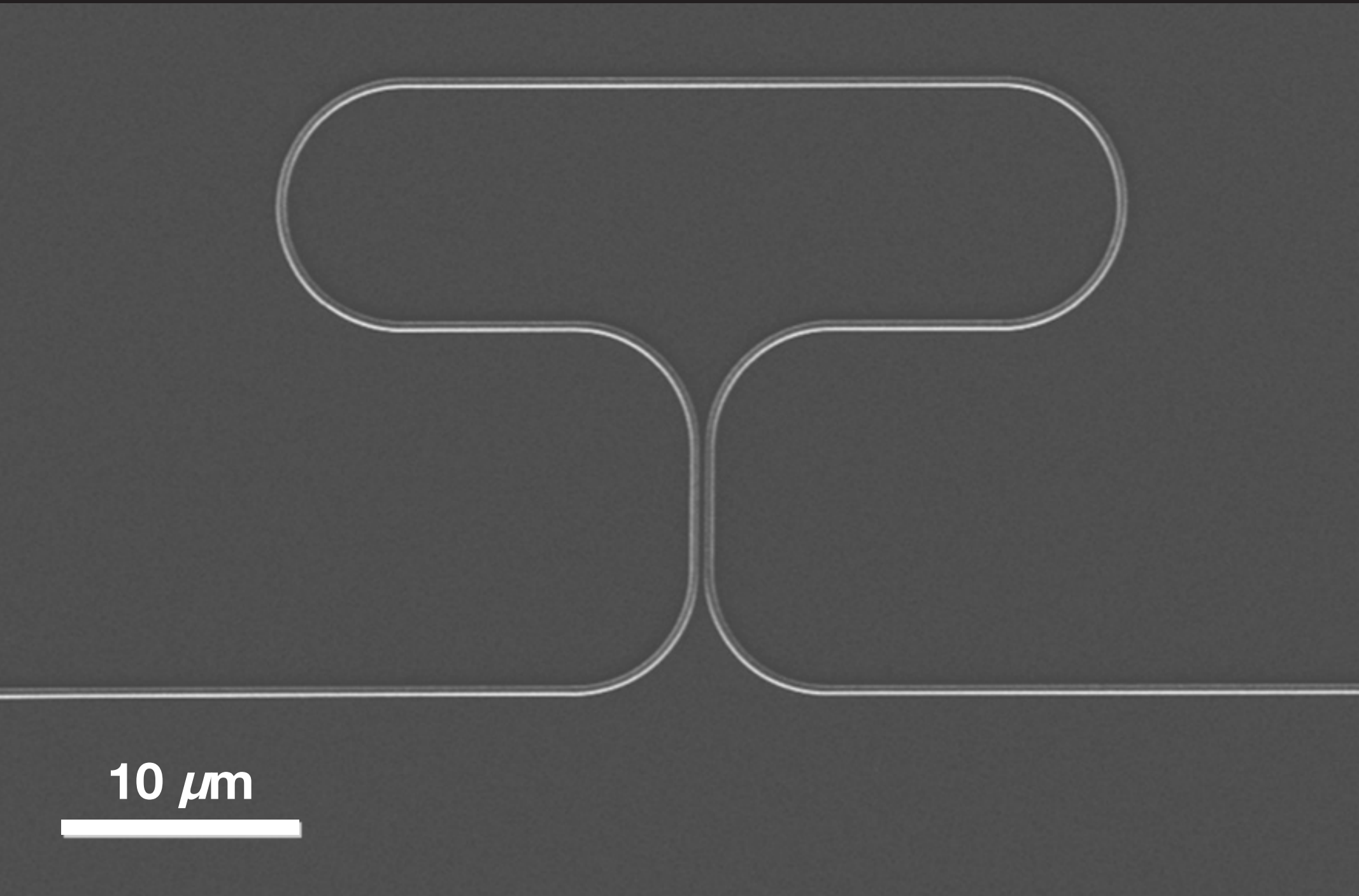
Optical logic gates



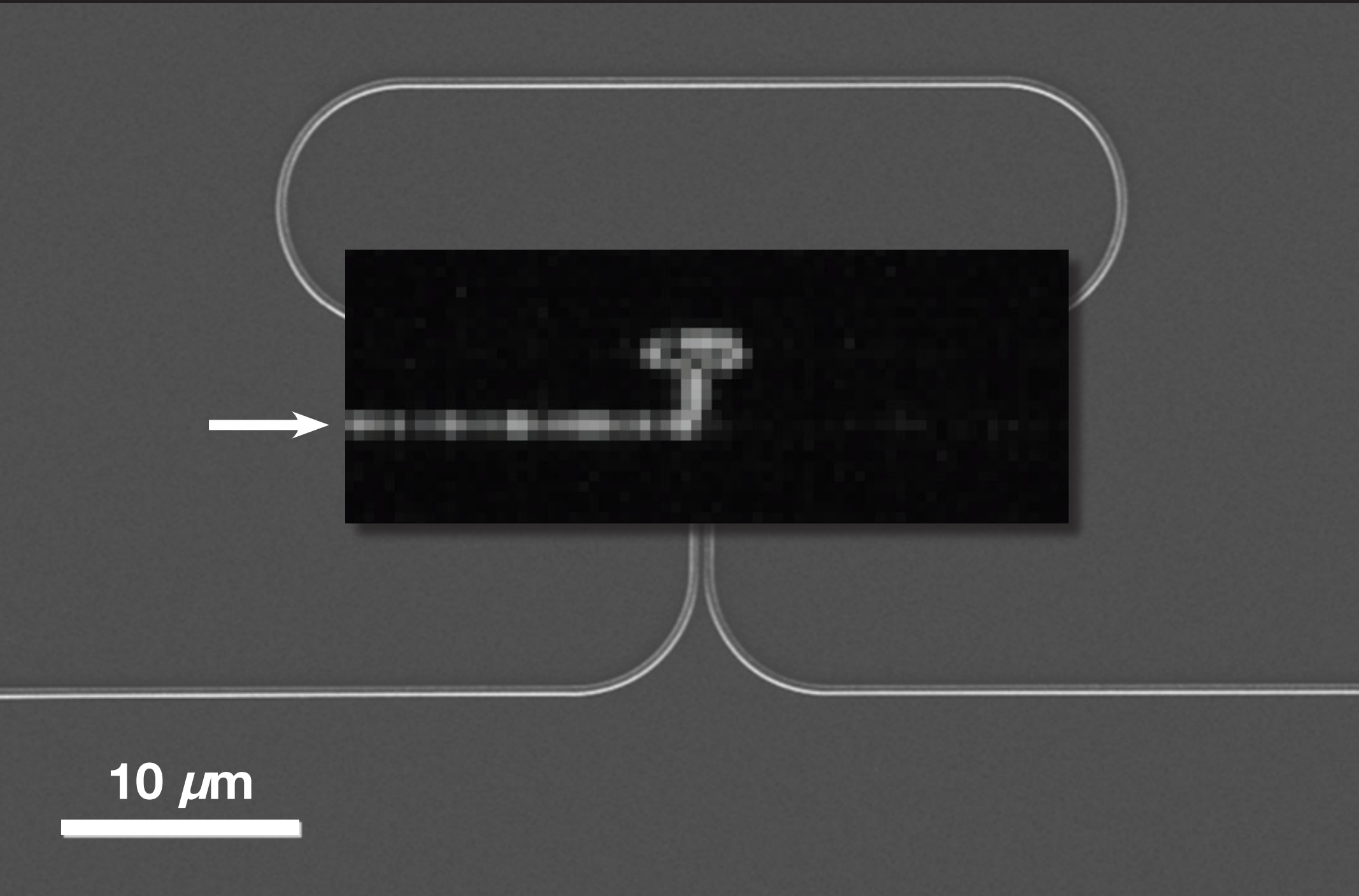
Optical logic gates



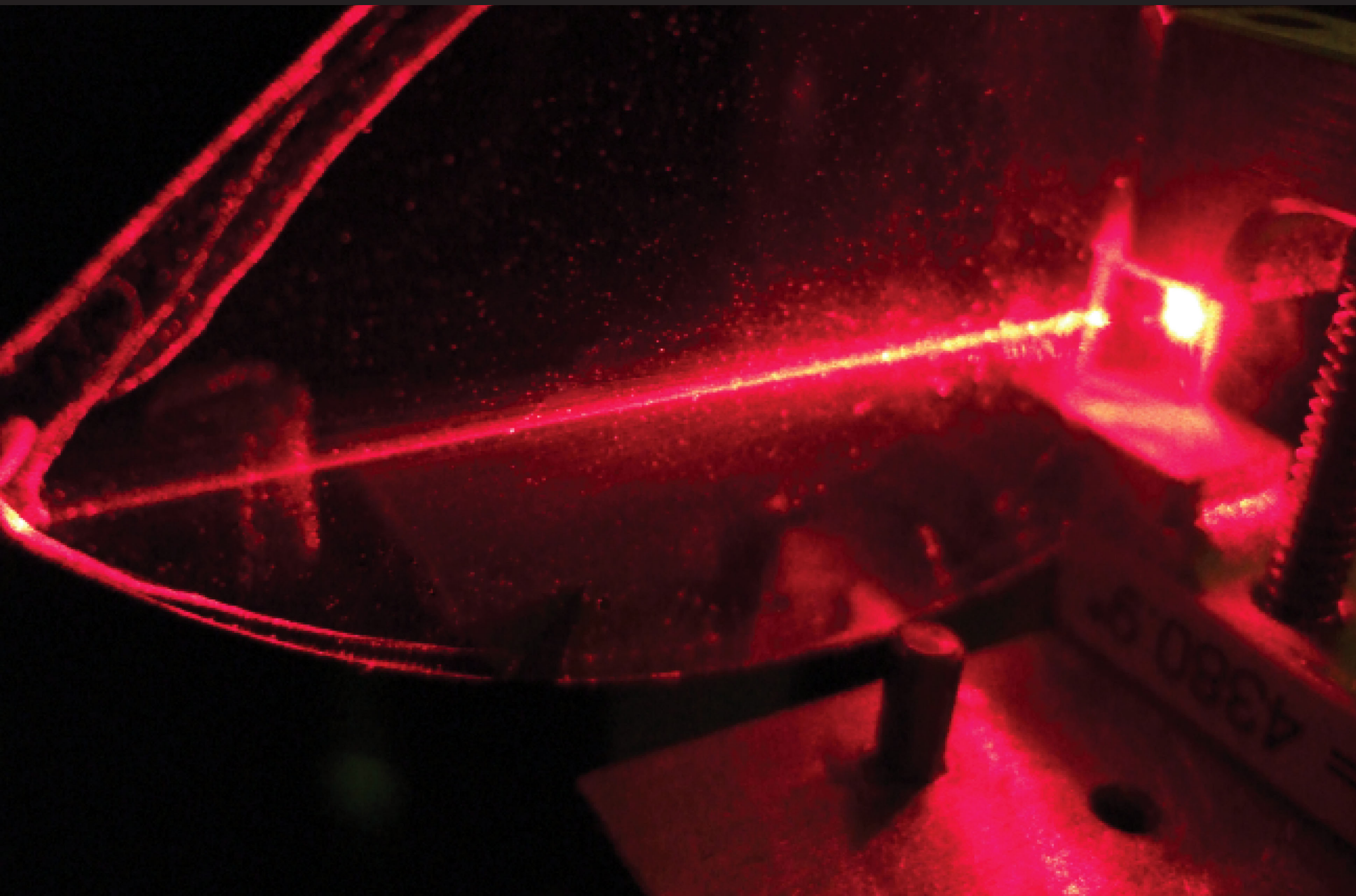
Optical logic gates



Optical logic gates



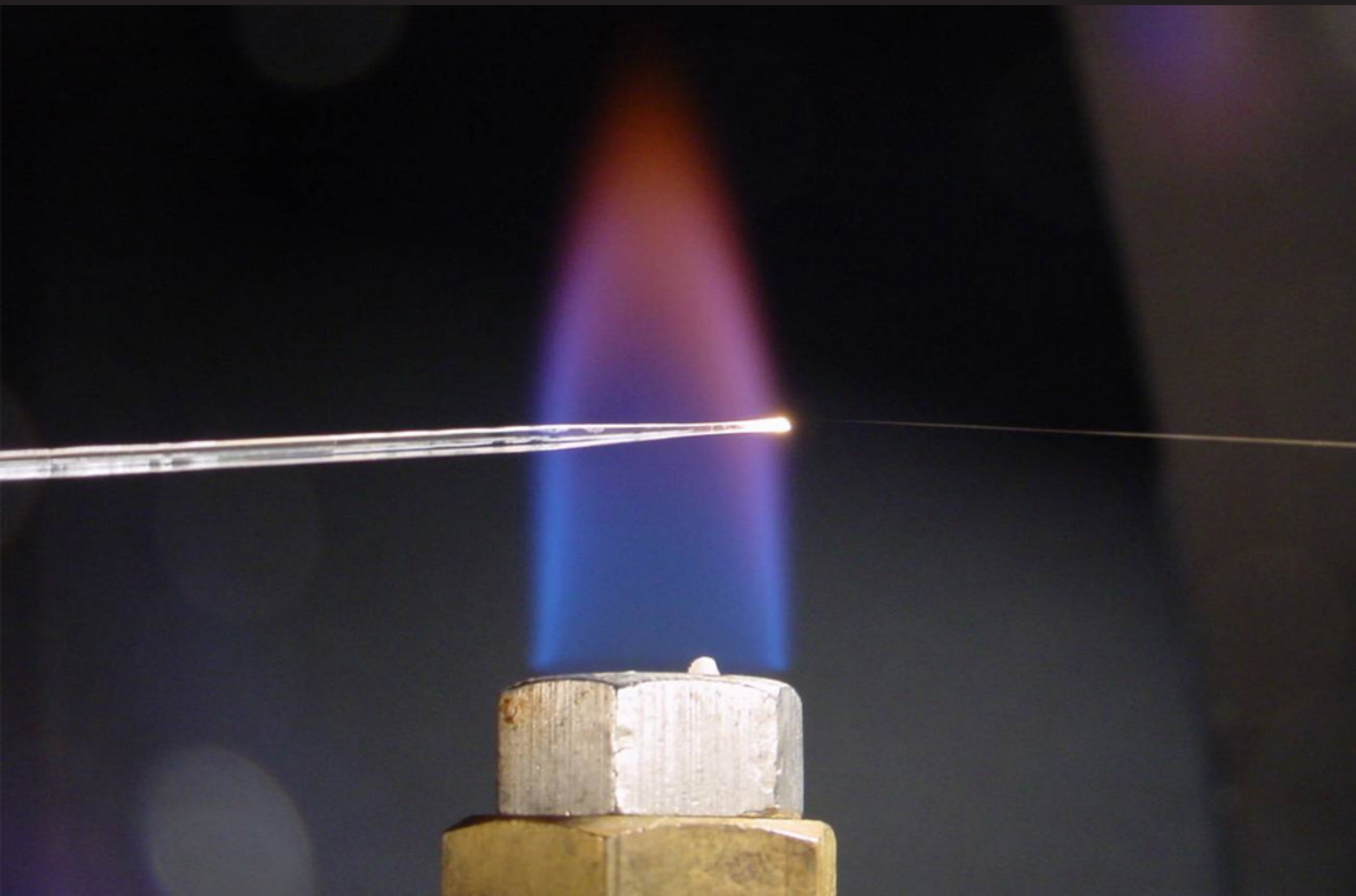
Summary



Summary

- several nanodevices demonstrated
- large γ permits miniature Sagnac loops
- switching energy $\approx$ 100 pJ

Summary



Funding:

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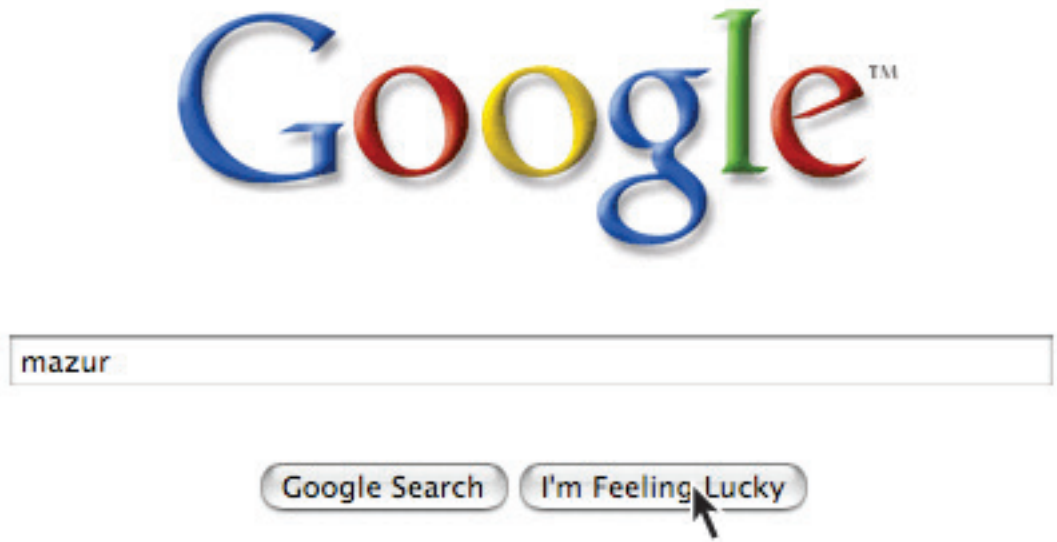
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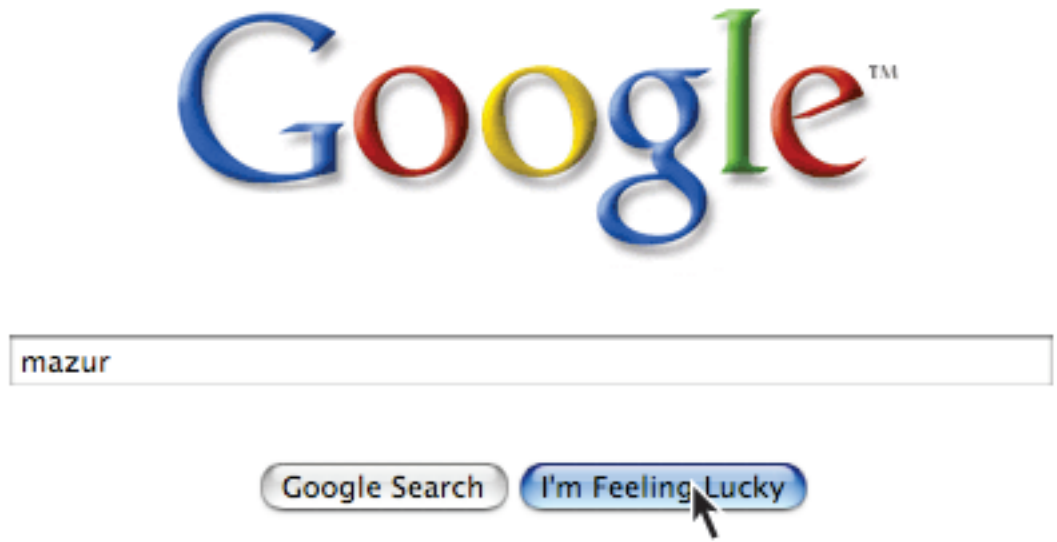
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