Reinventing the light switch: logic with photons

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University of Massachusetts, Lowell
Lowell, MA, 25 April 2012

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Orad Reshef

Jon Bradley

Eric Mazur

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and also....

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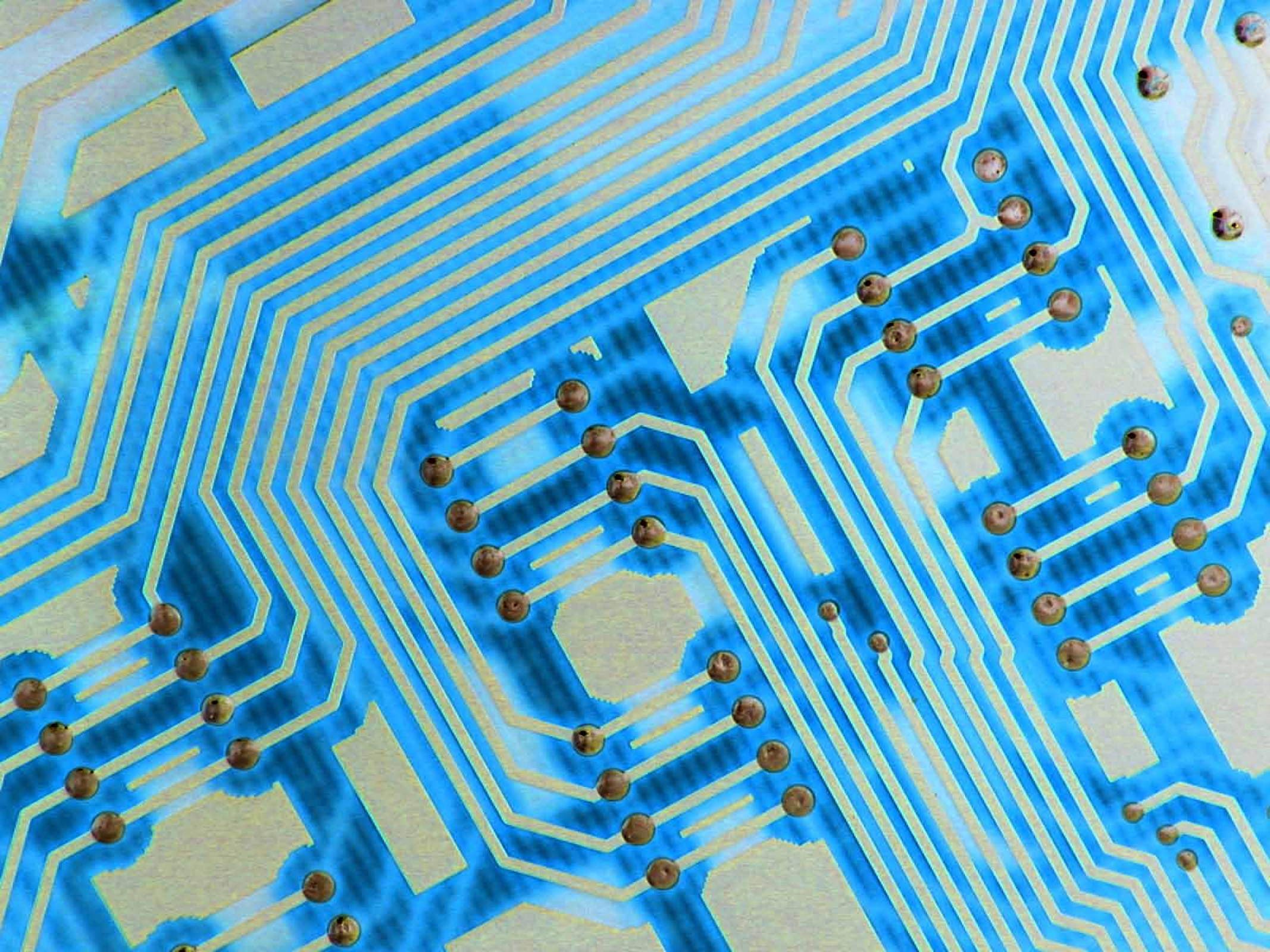
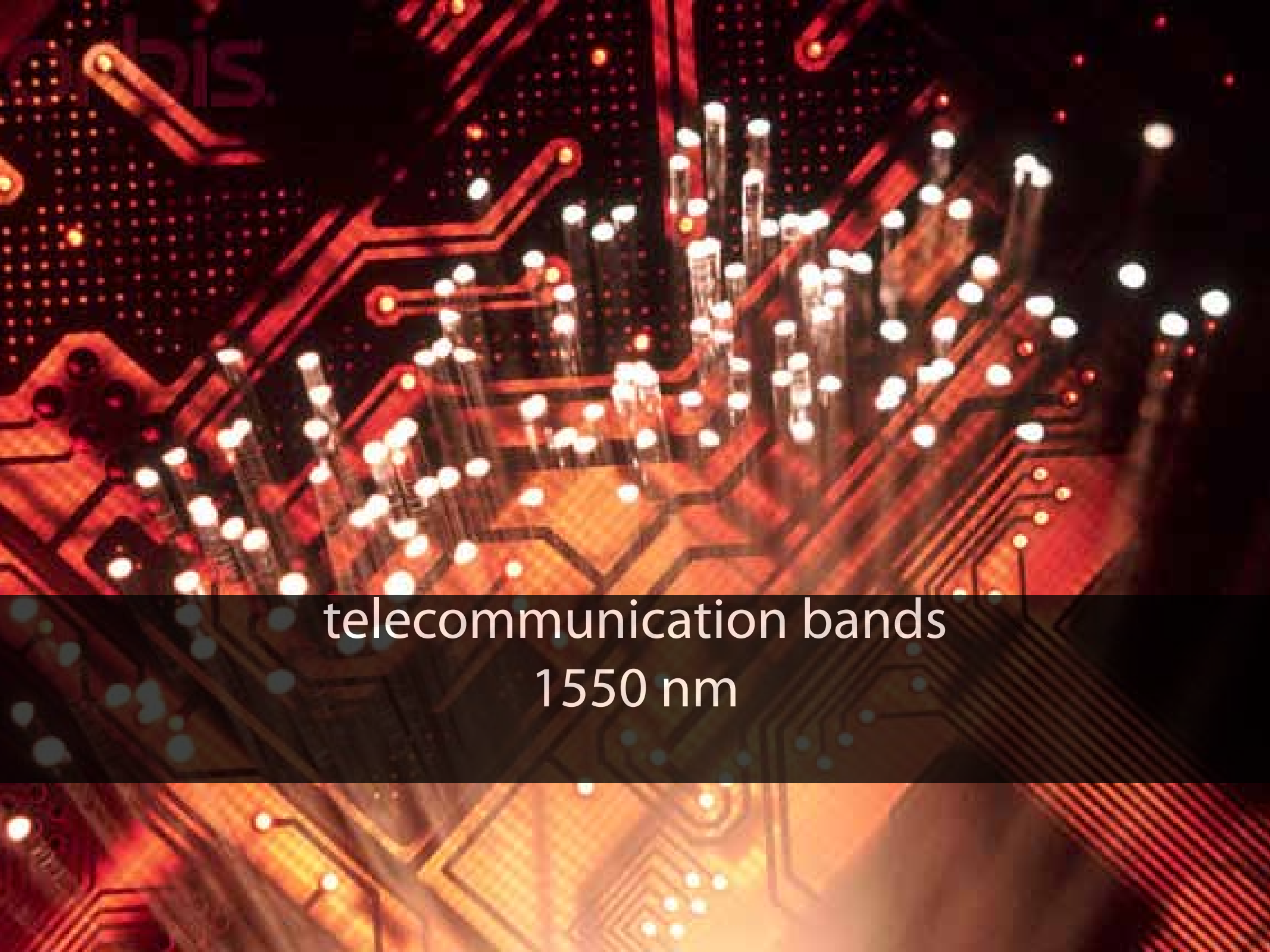
Kasey Phillips
Ruwan Senaratne
Francois Parsy
Grisel Rivera Batista
Stephanie Scwartz

Prof. Erwin Martí-Panameño (BUAP)
Prof. Marco Loncar (Harvard)
Prof. Markus Pollnau (Twente)
Prof. Erich Ippen (MIT)

Prof. Limin Tong (Zhejiang)

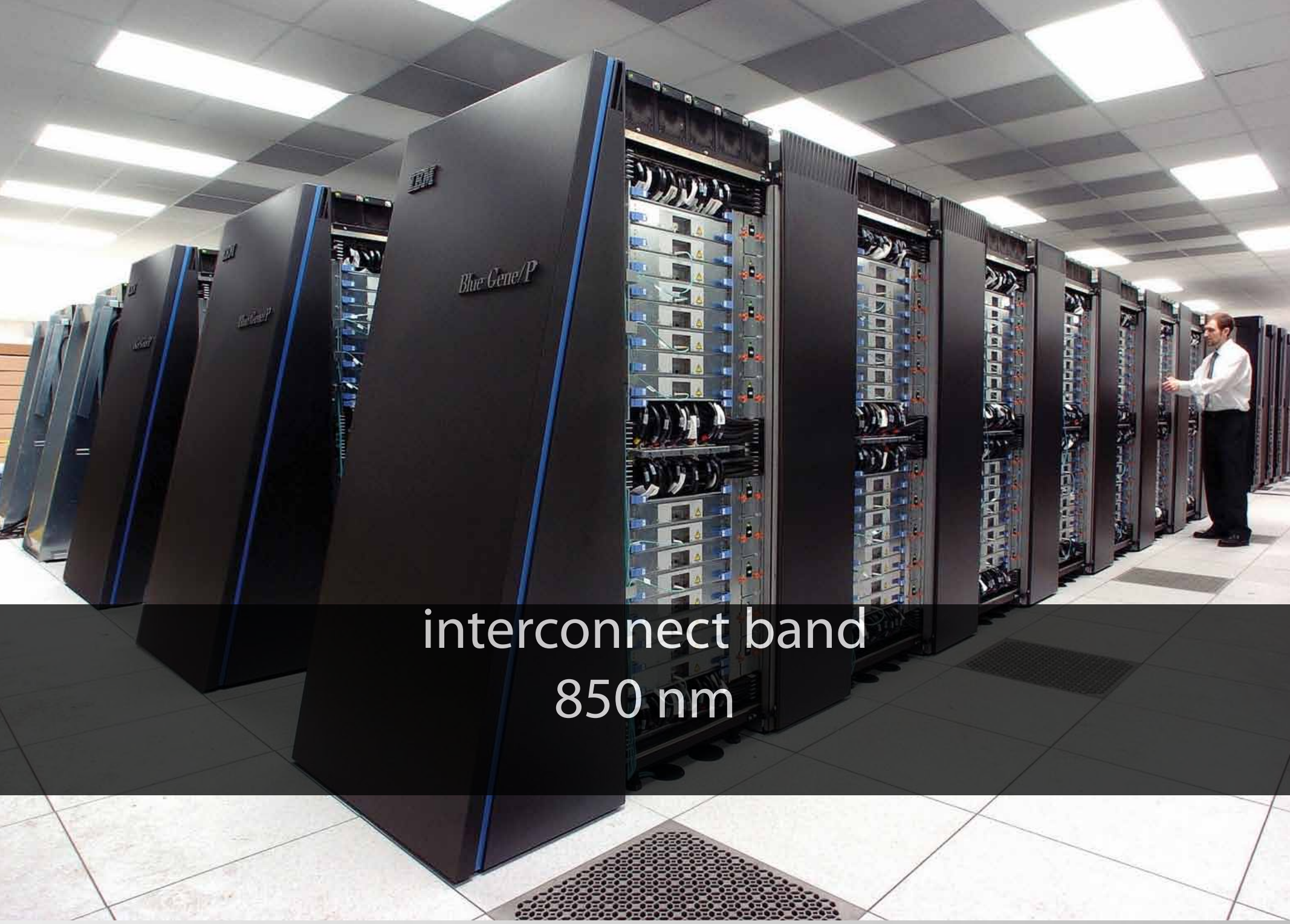
Dr. Geoff Svacha
Dr. Rafael Gattass
Prof. Tobias Voss



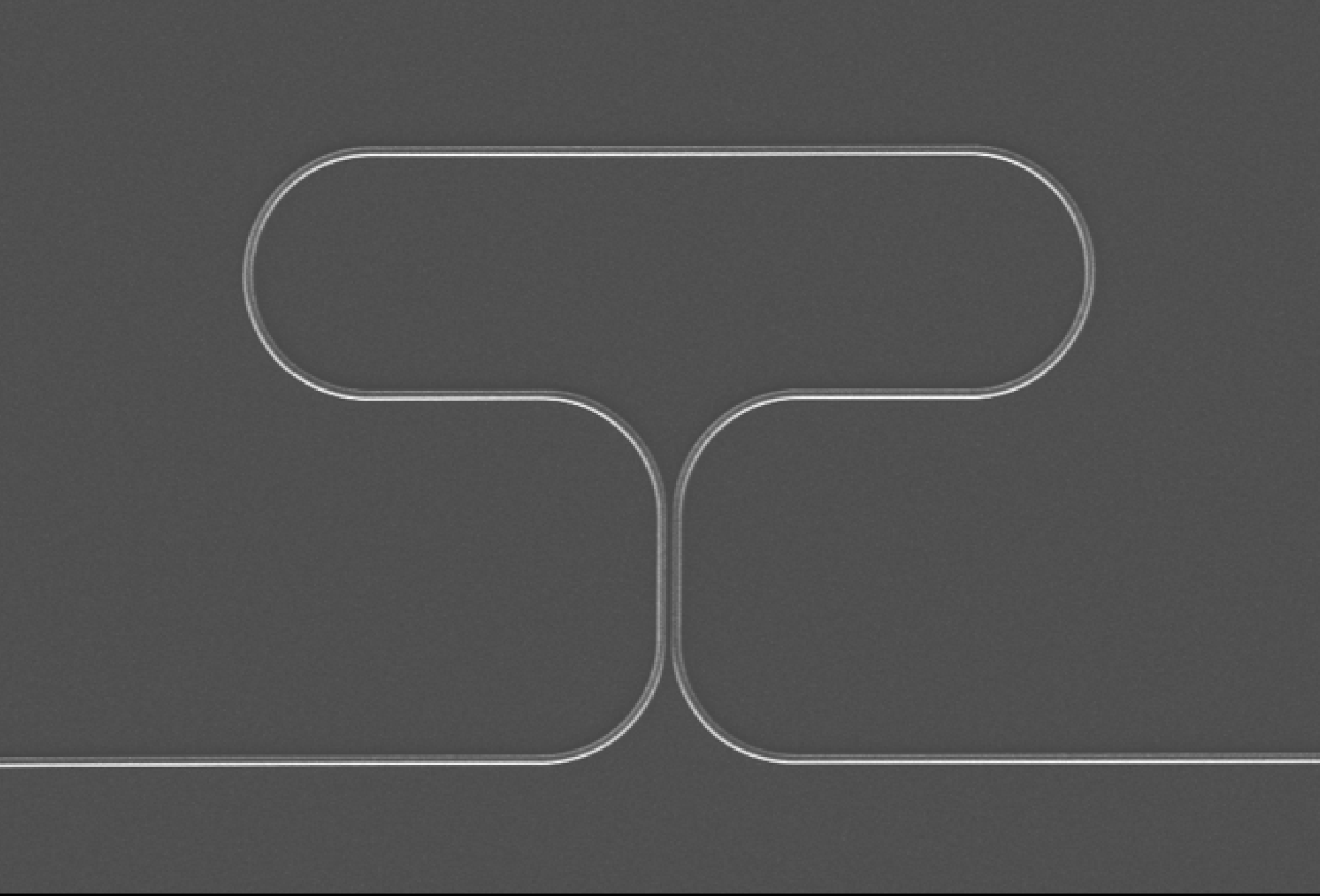


telecommunication bands
1550 nm

telecommunication bands
1300 and 1550 nm



interconnect band
850 nm

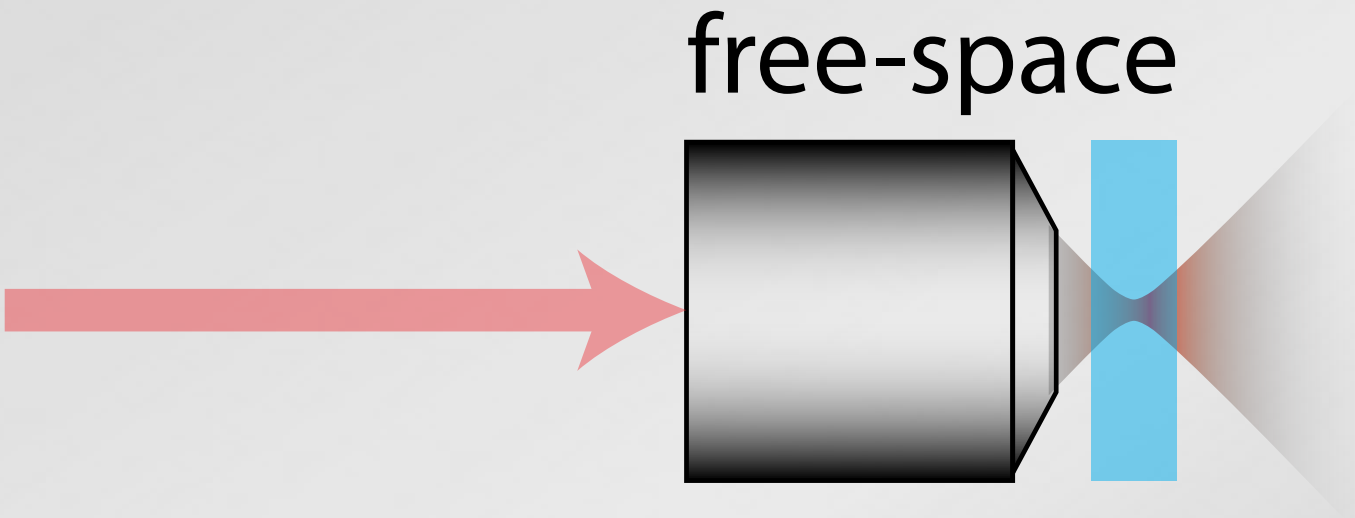


1 all-optical logic

2 NL materials

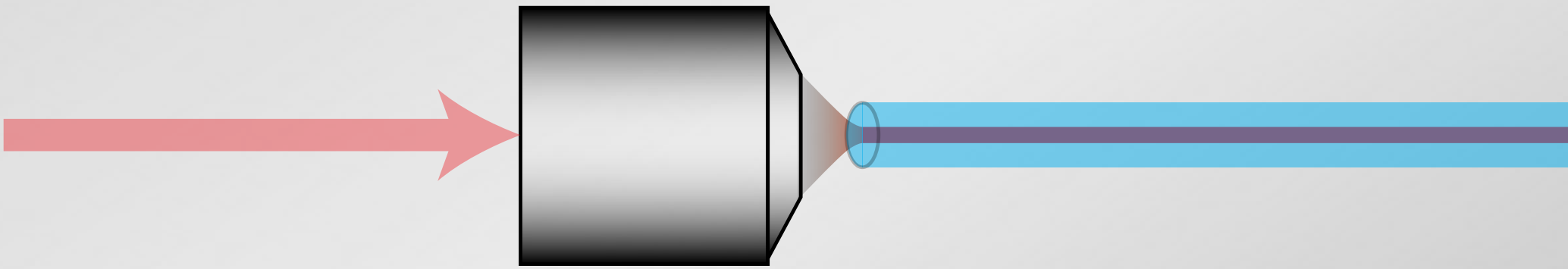
3 TiO_2 photonics

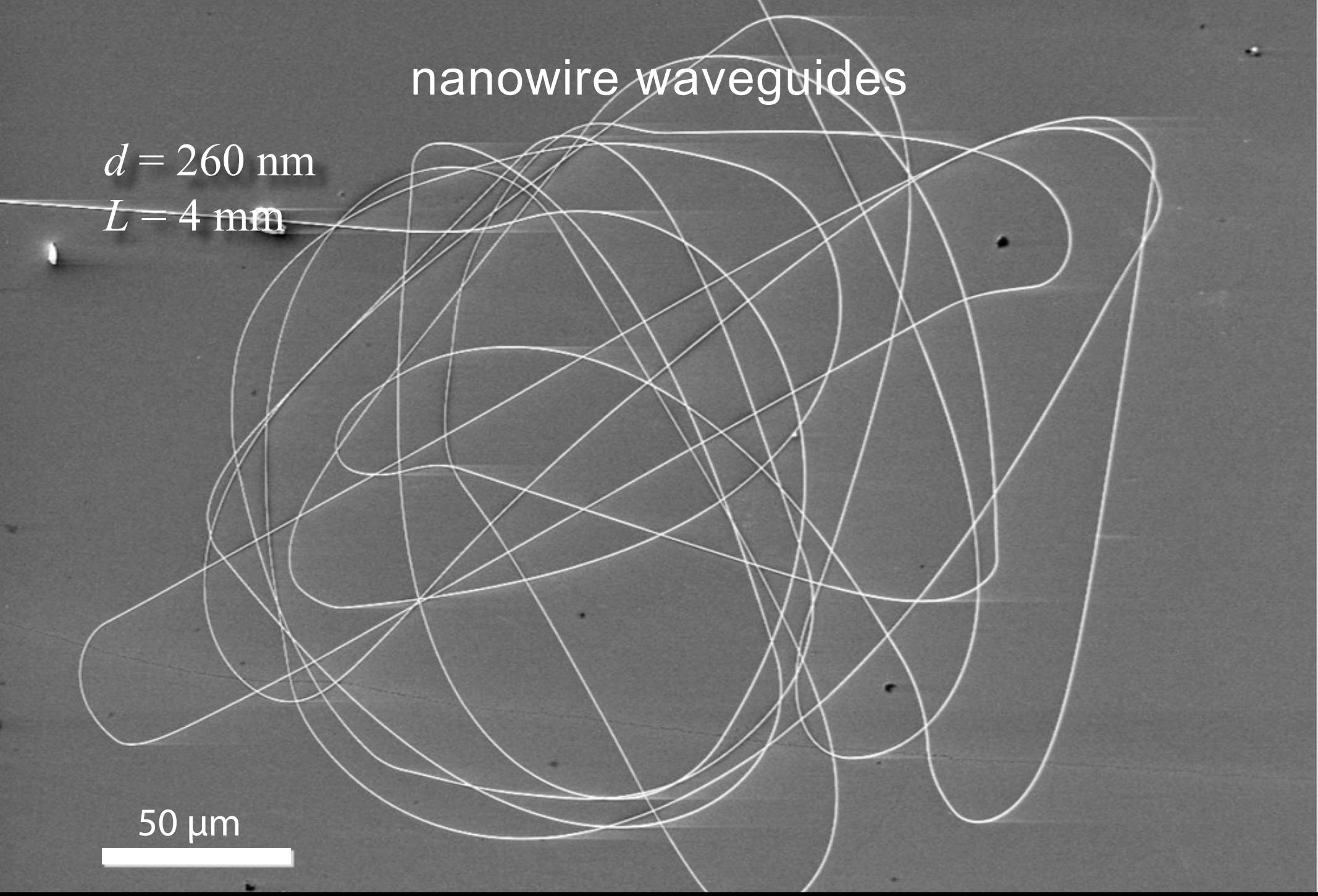
large divergence, small NL interactions



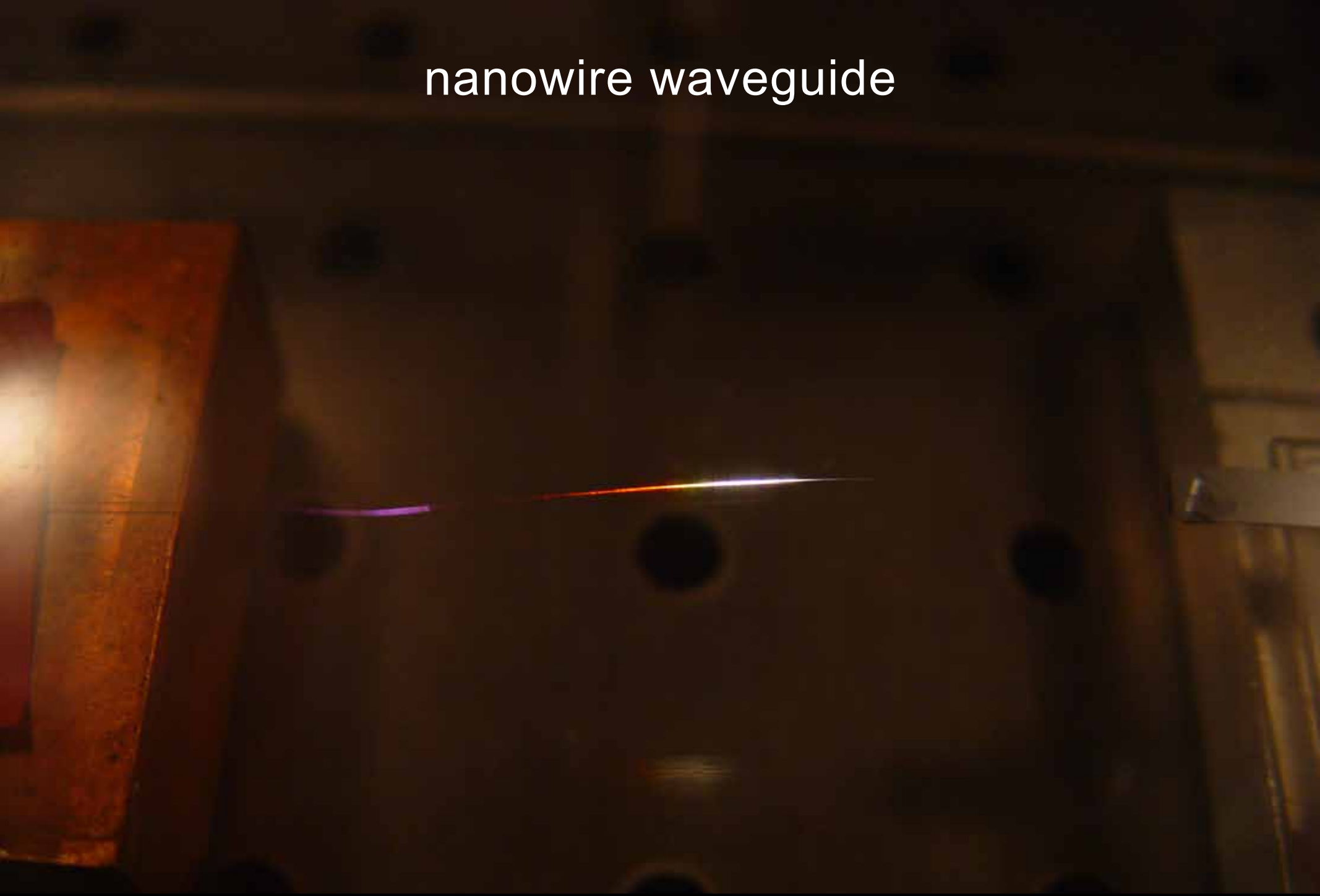
strong confinement, sustained NL interactions

waveguides





1 all-optical logic



1 all-optical logic

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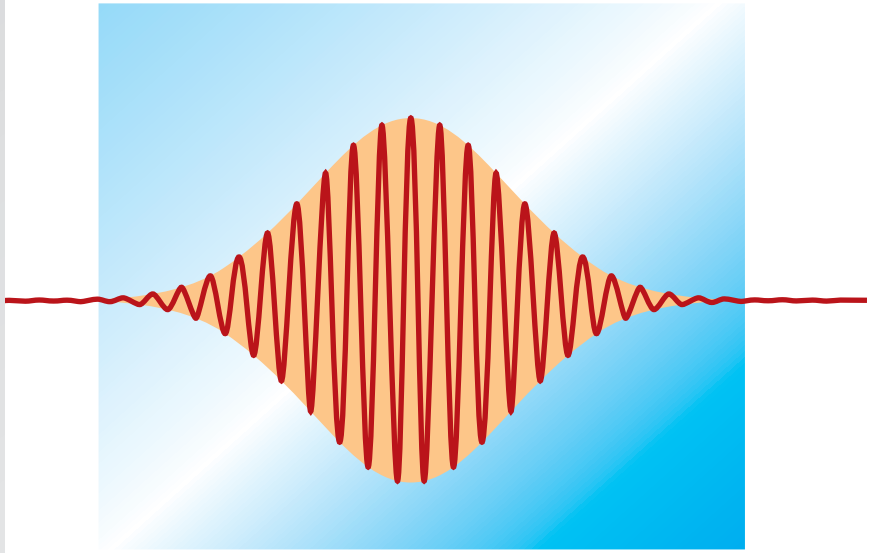
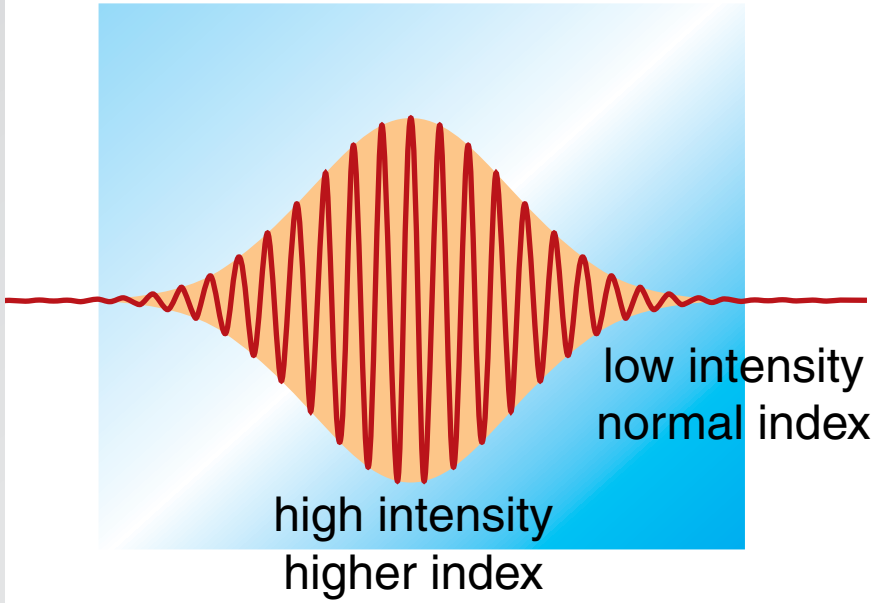
spectral broadening

self-phase modulation: $n = n_o + n_2 I$



spectral broadening

self-phase modulation: $n = n_o + n_2 I$



spectral broadening

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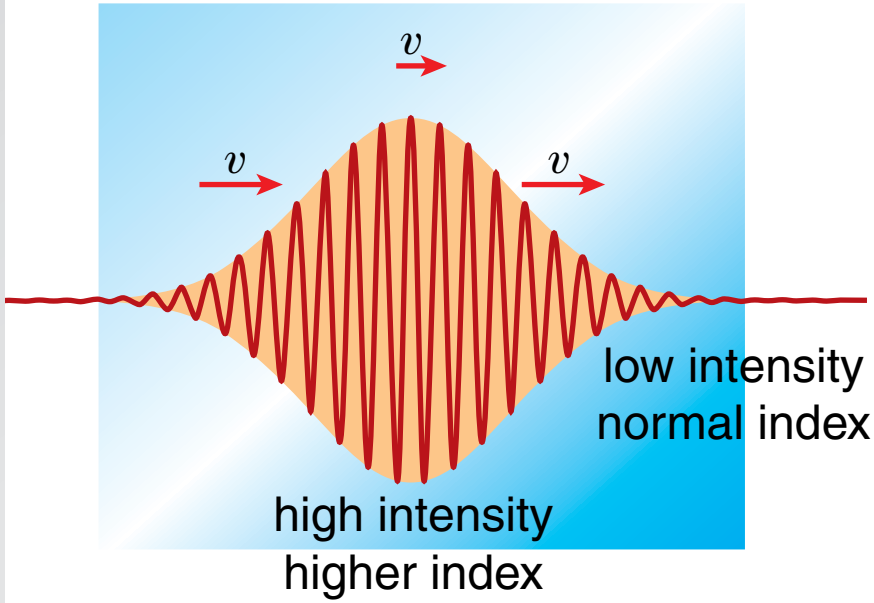

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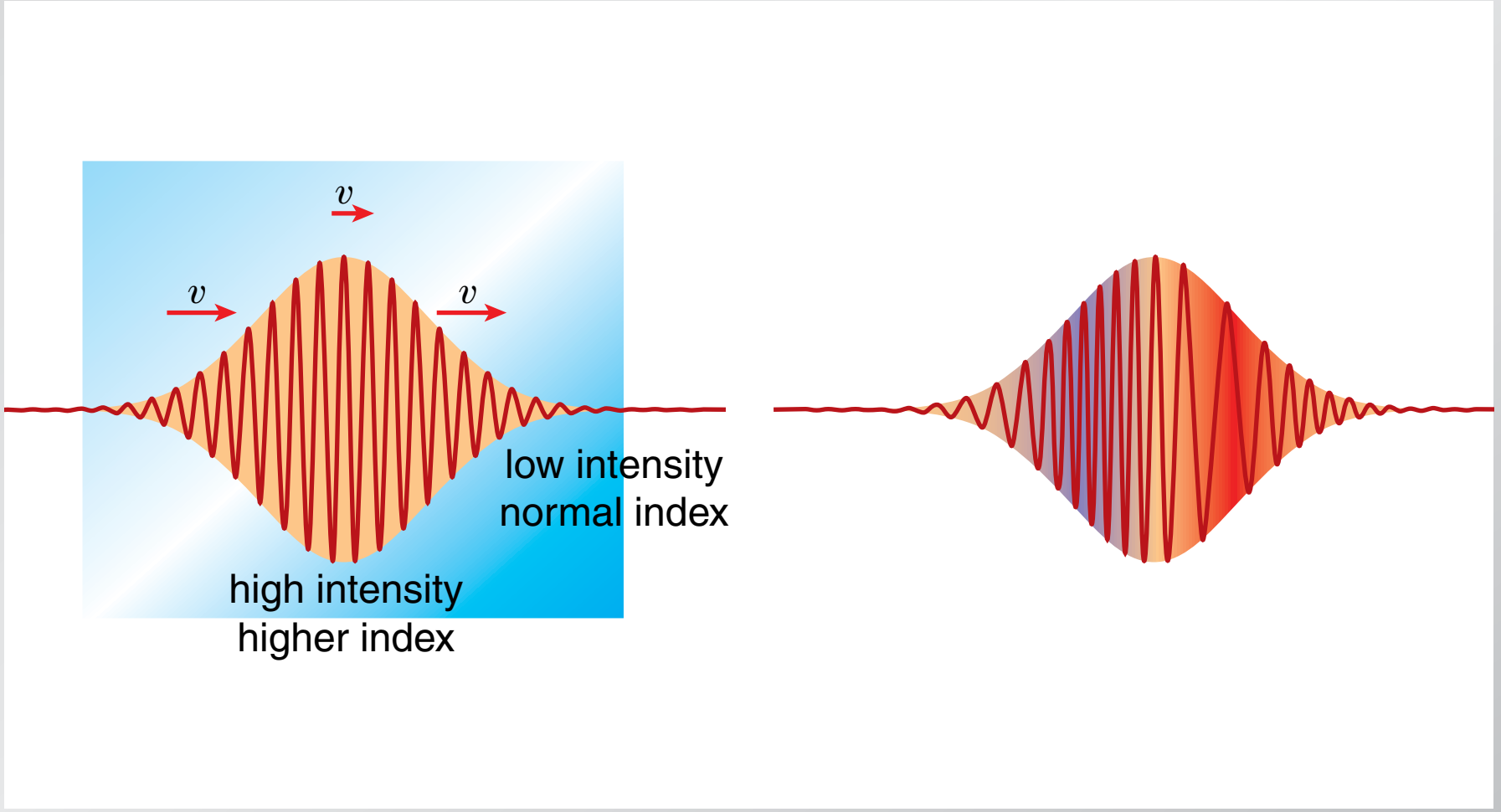

spectral broadening

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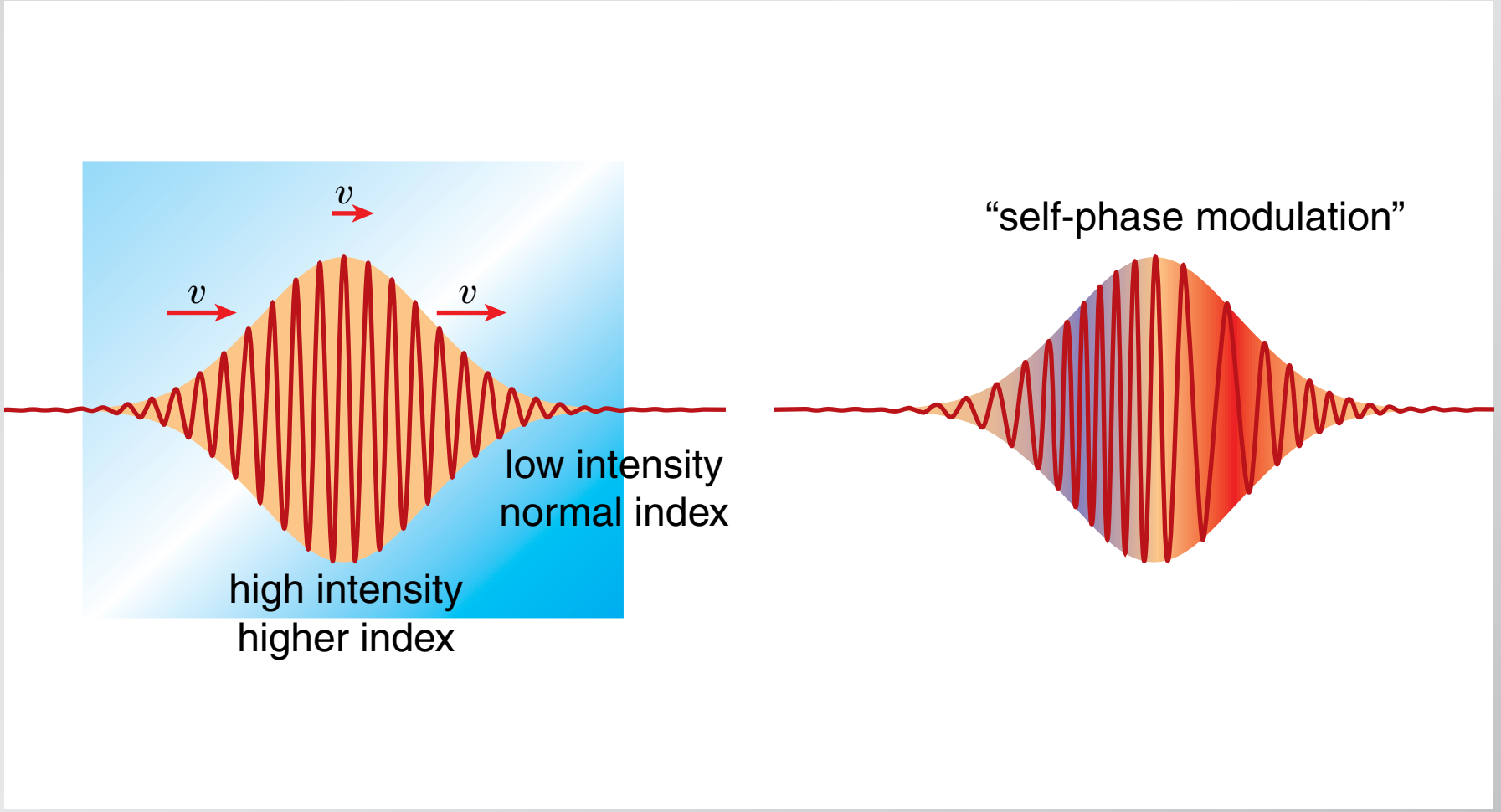
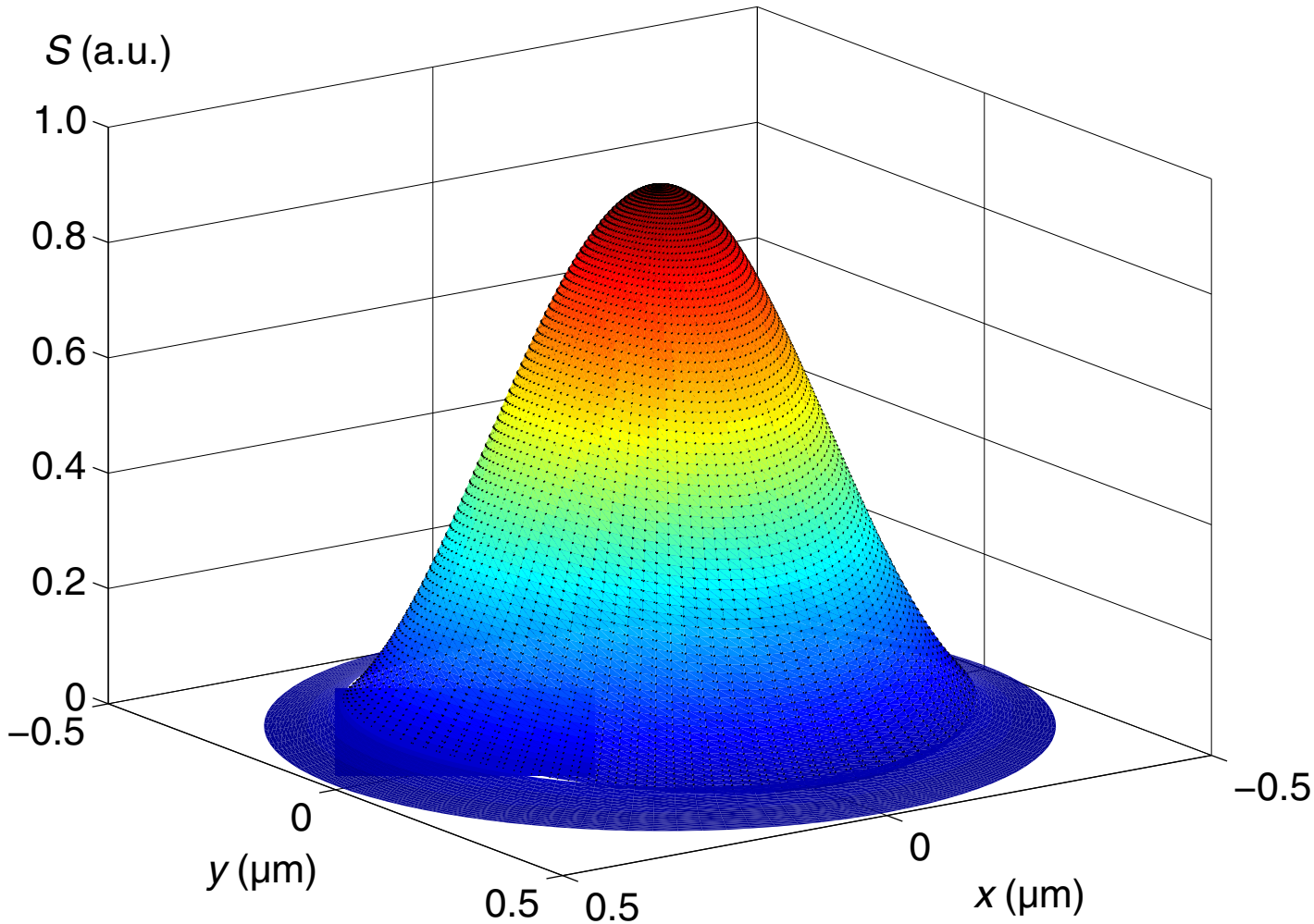


strong confinement



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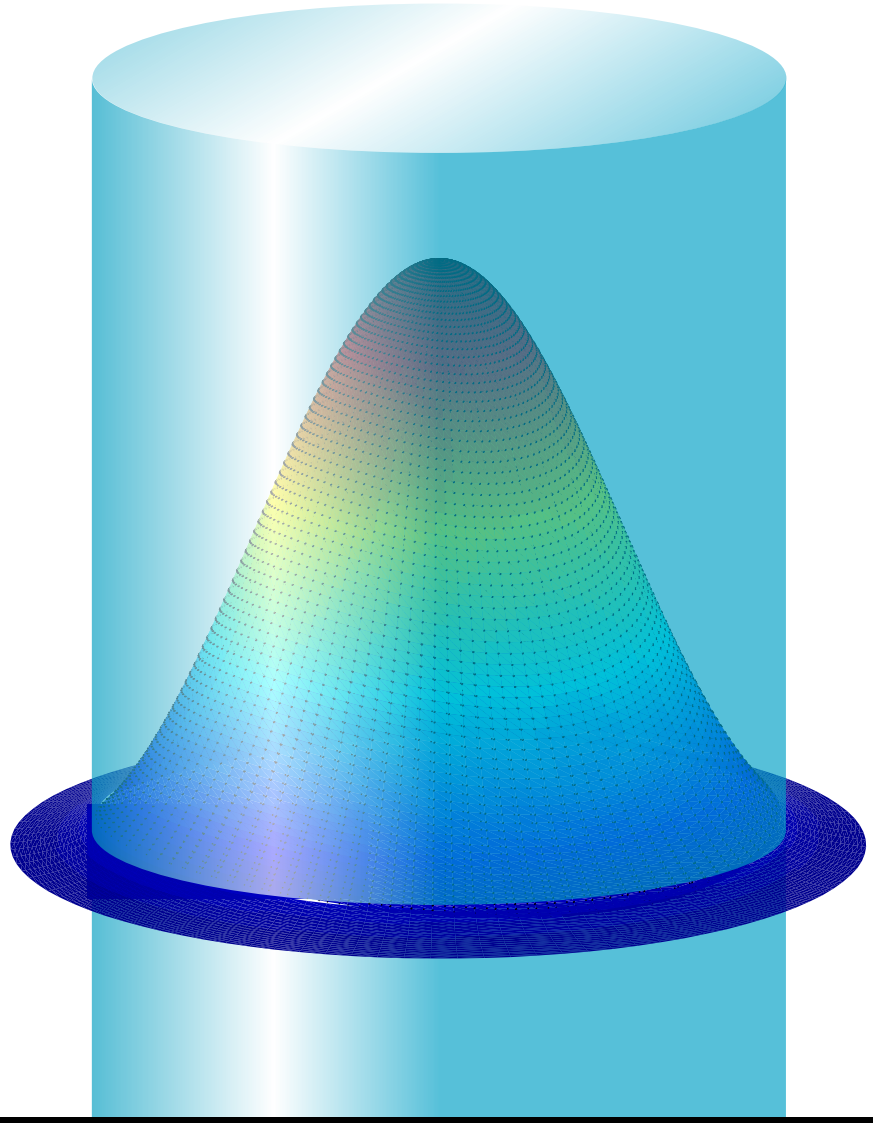
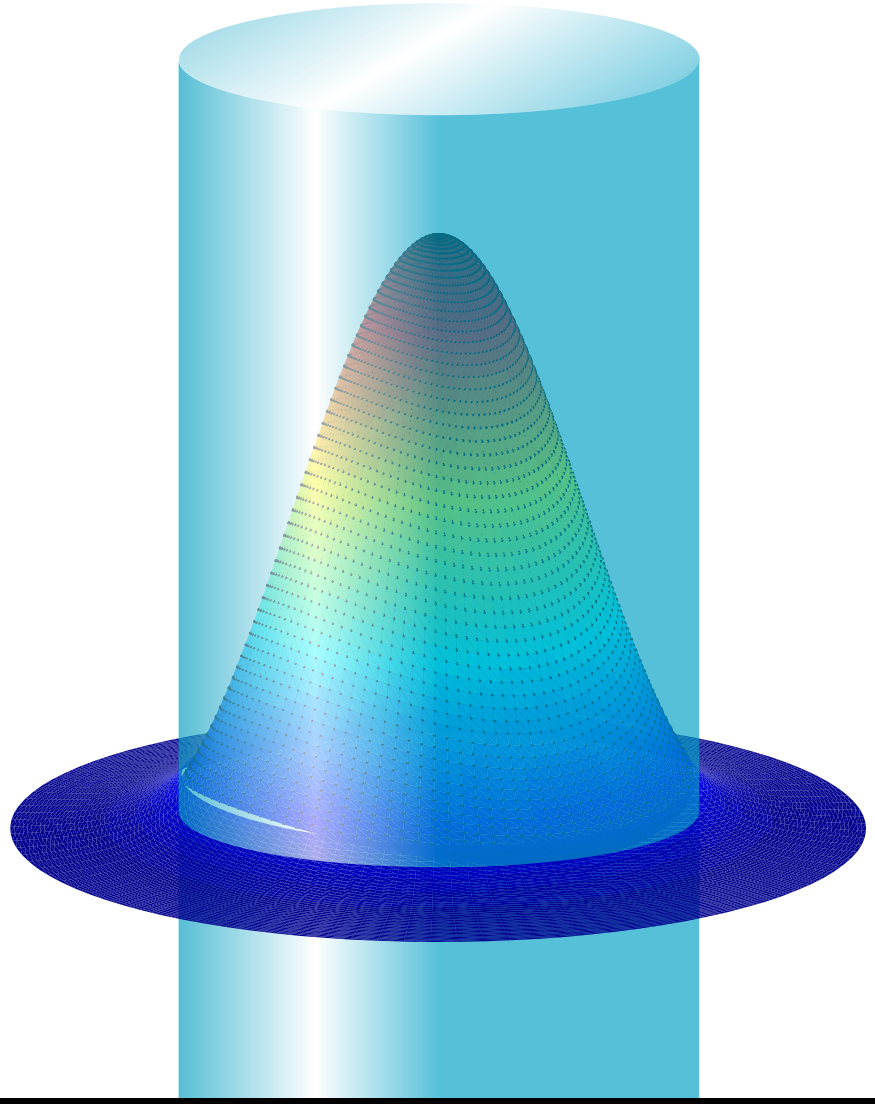


strong confinement



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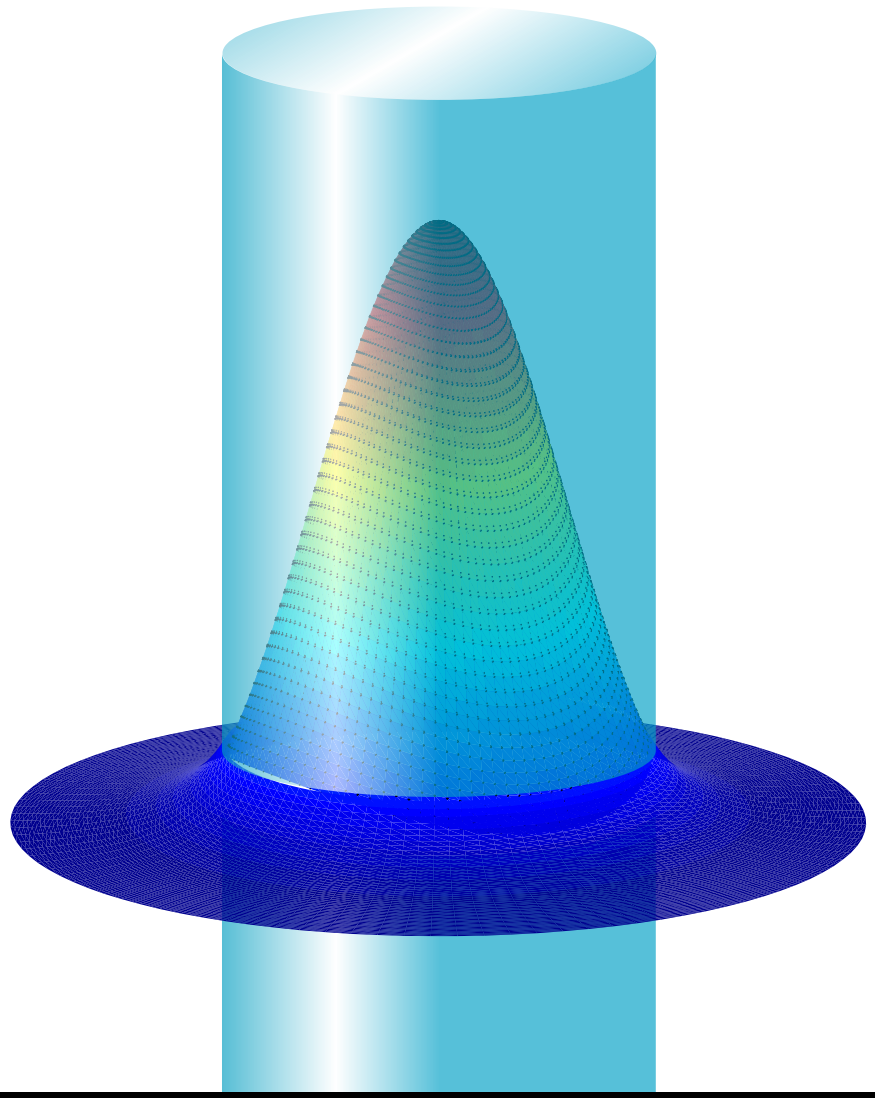

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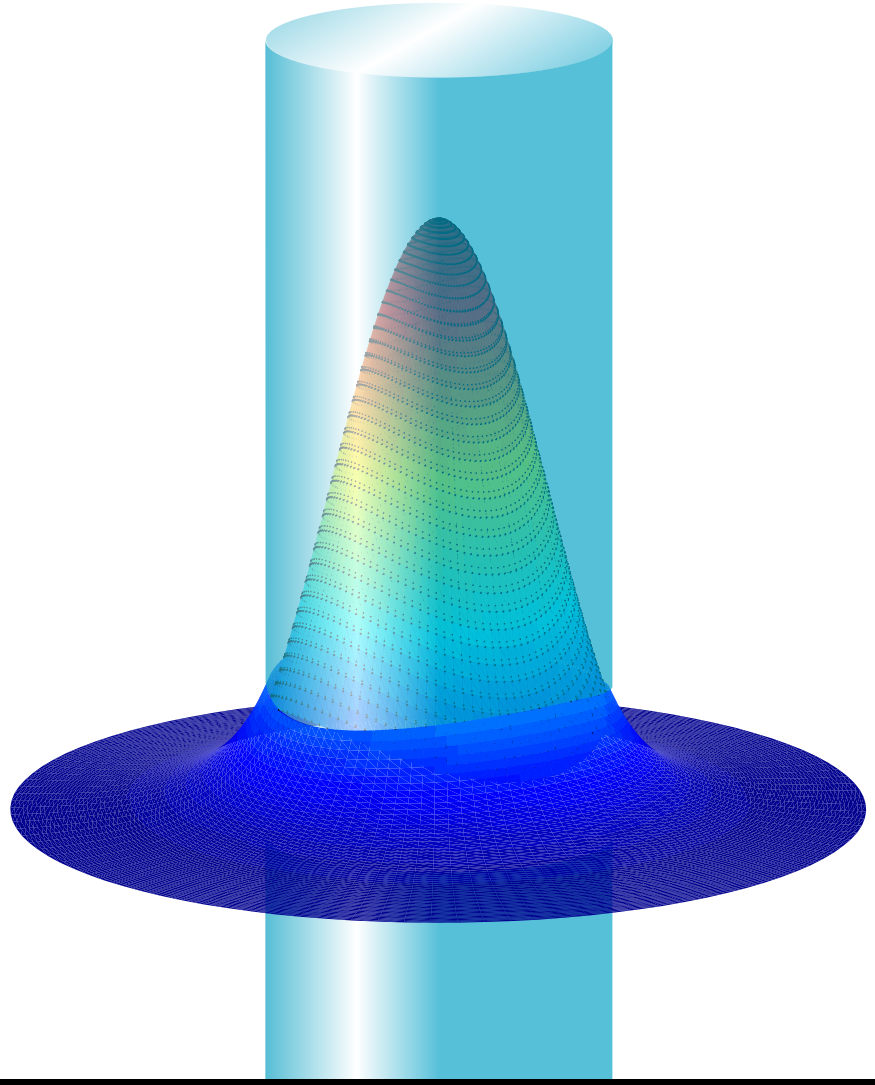

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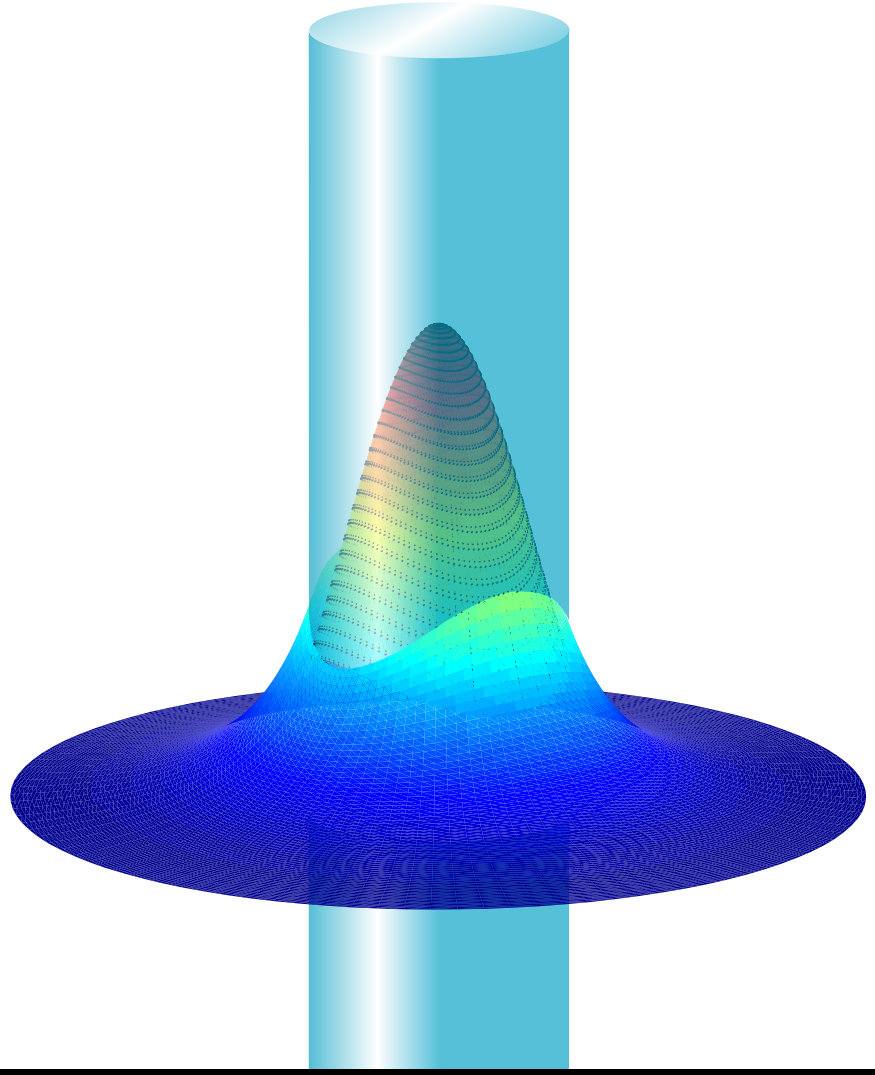
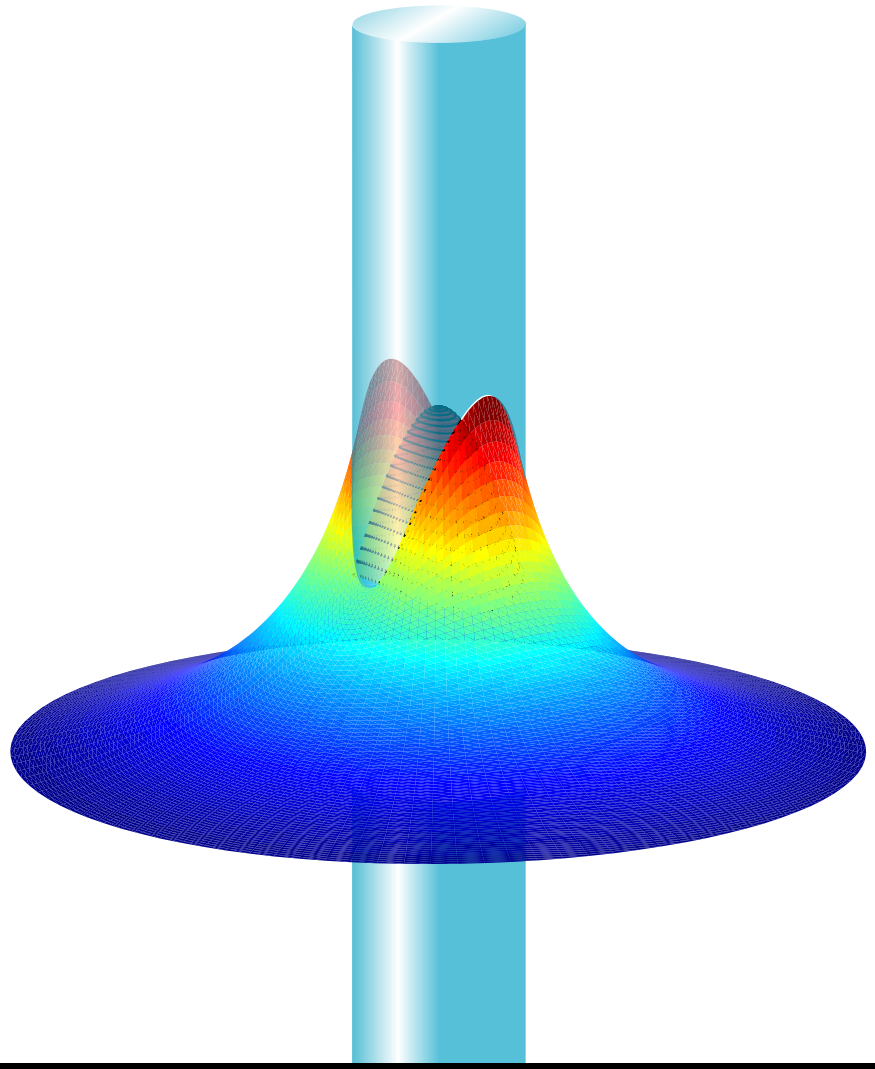
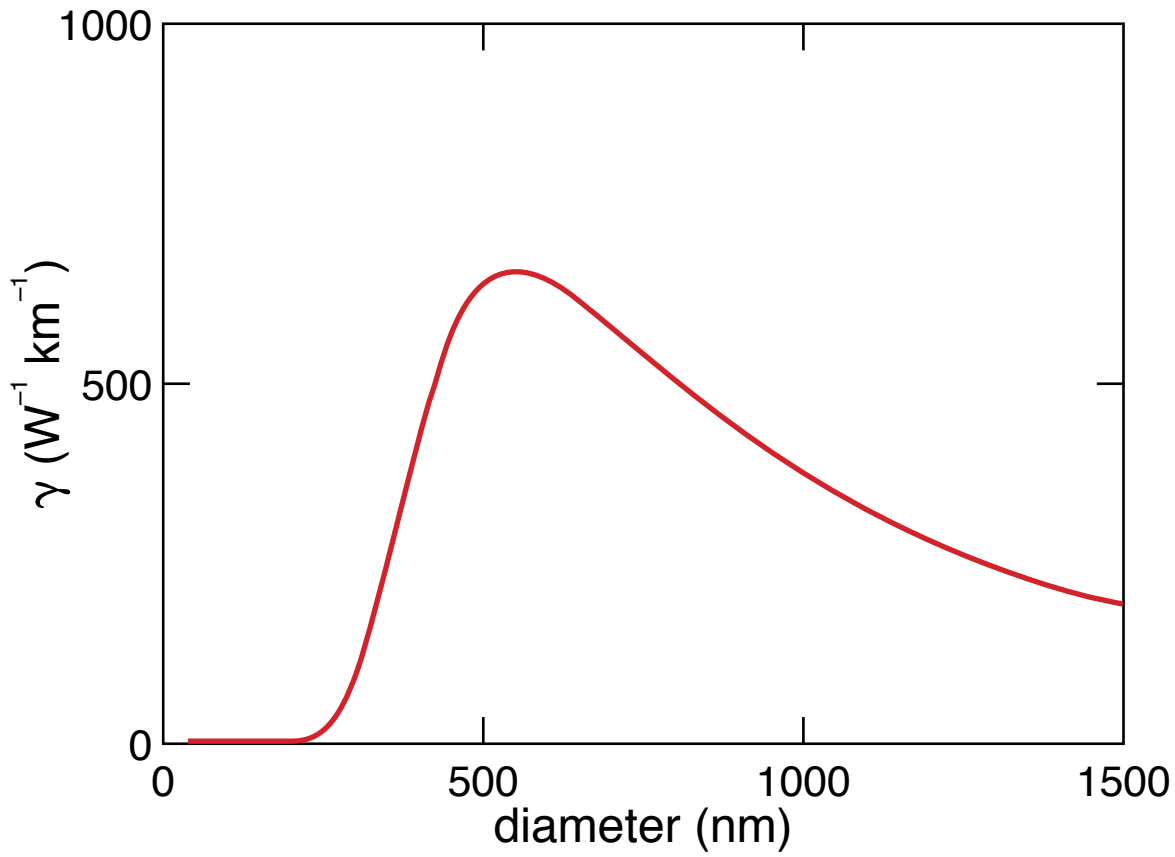


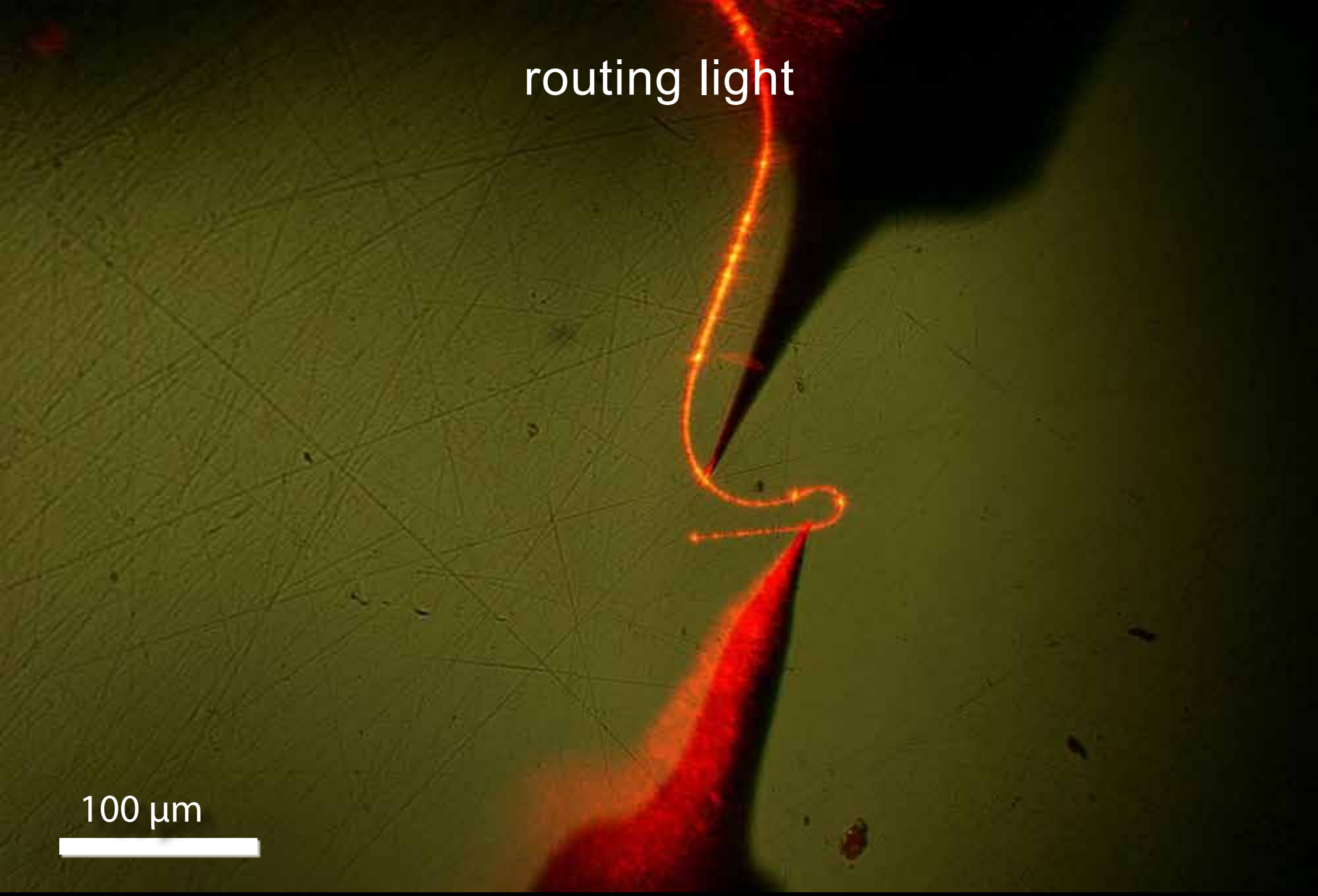
large evanescent field



high effective nonlinearity

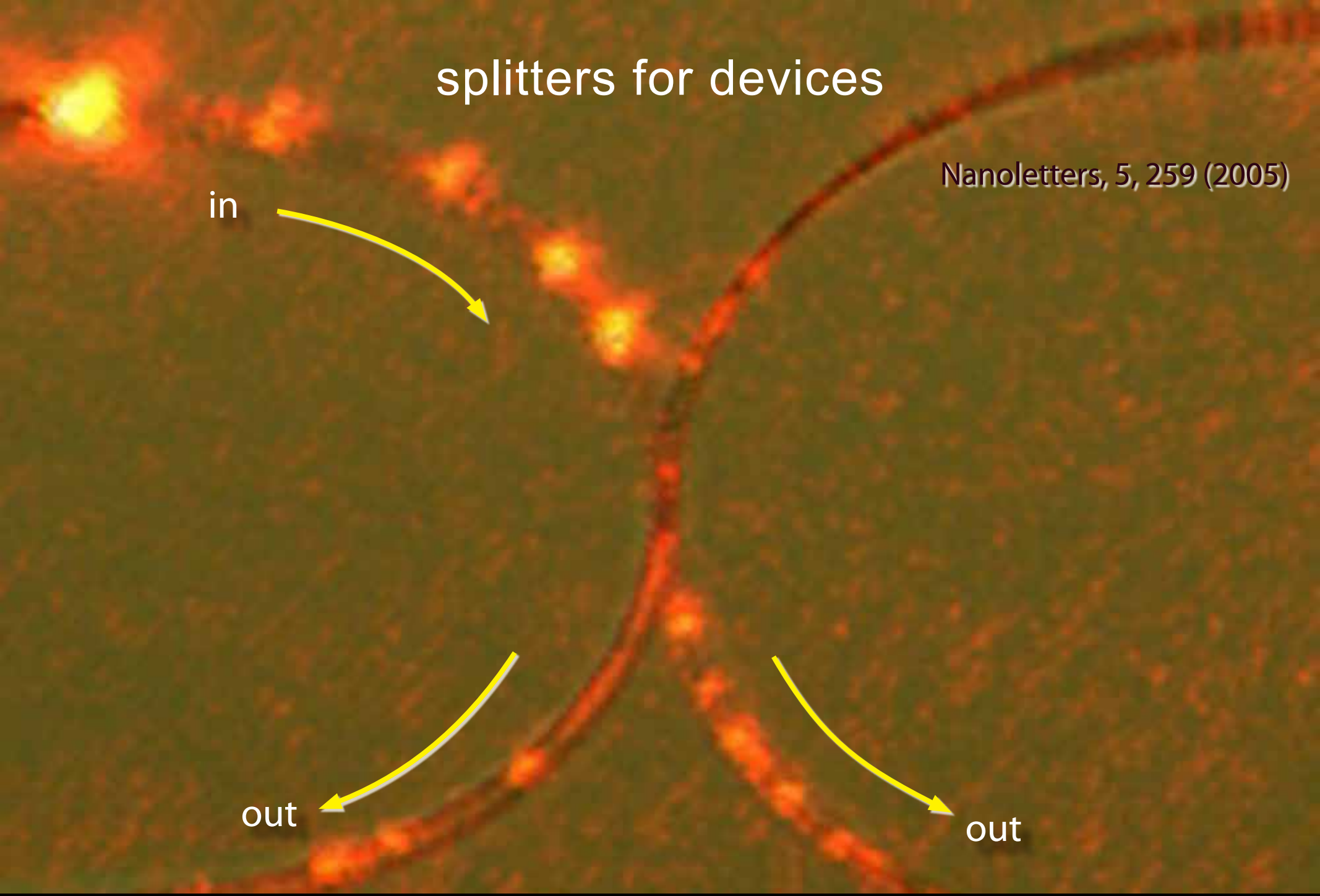
silica fiber at 800 nm





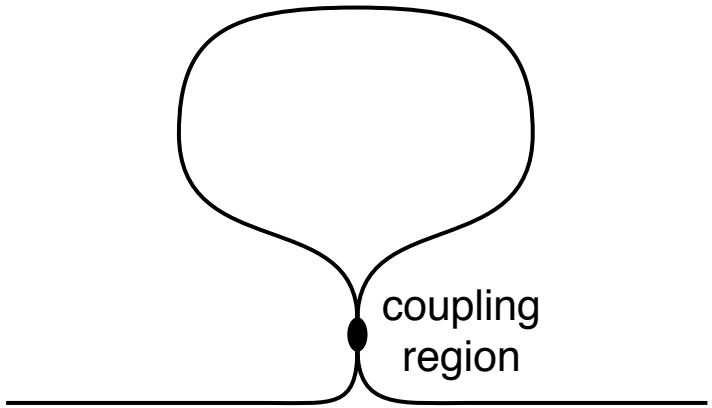
1 all-optical logic

splitters for devices



all-optical modulation

nanowire Sagnac interferometer



all-optical modulation

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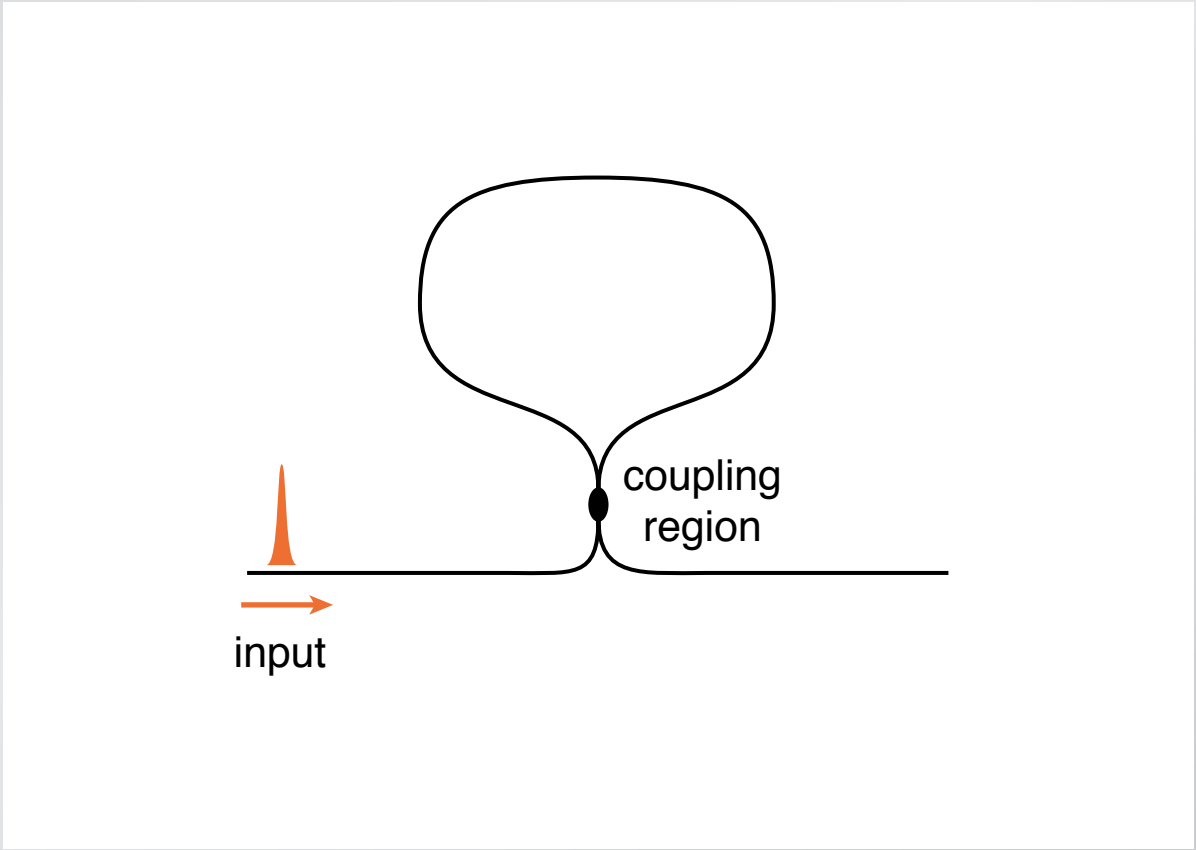

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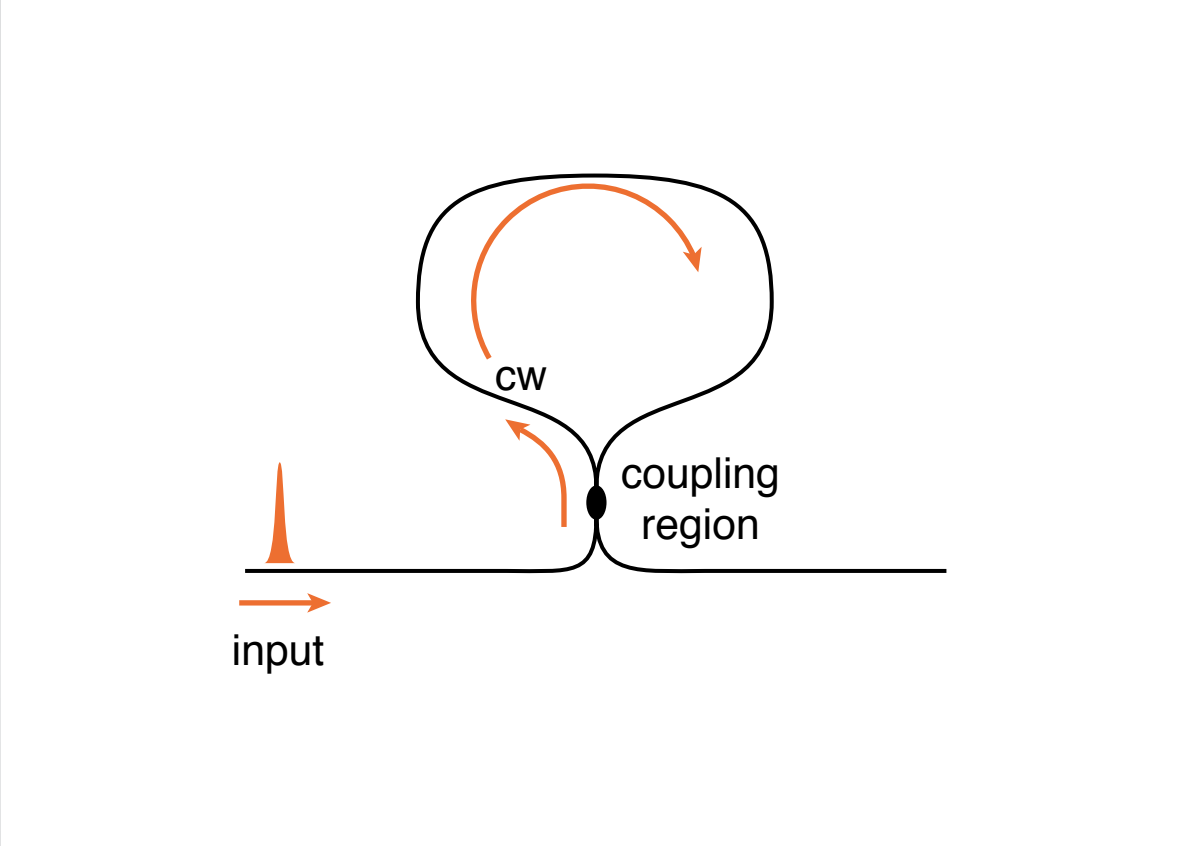
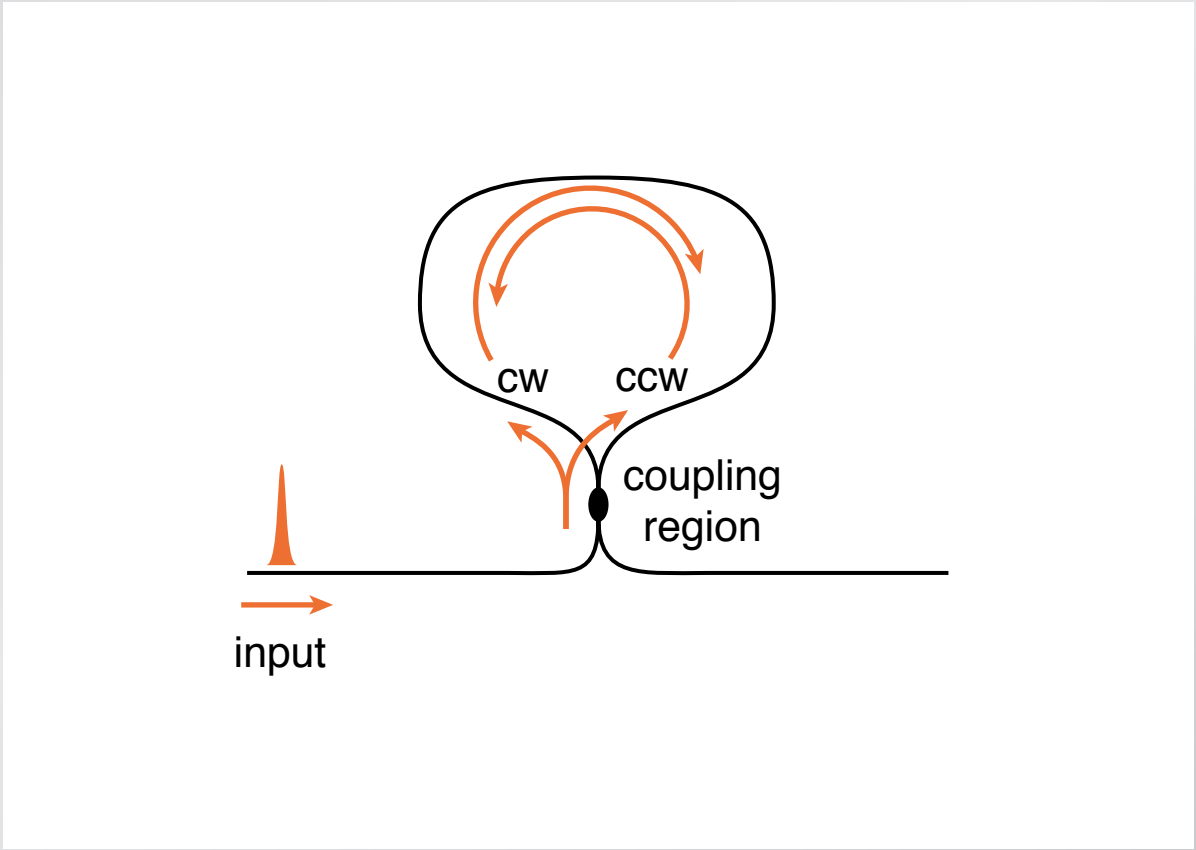
nanowire Sagnac interferometer



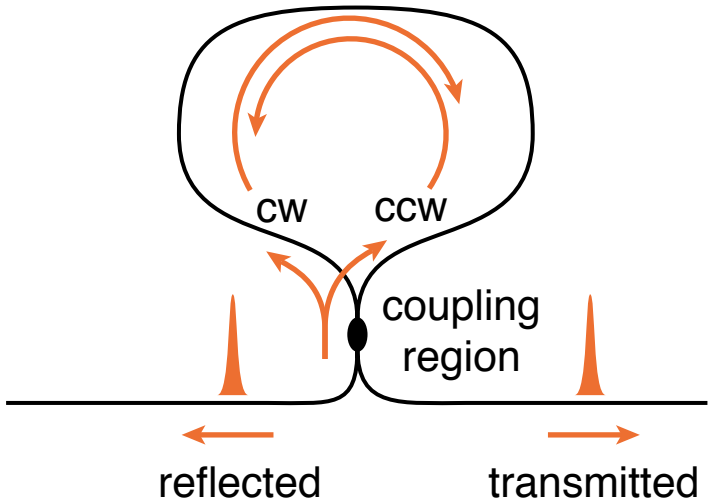
all-optical modulation

nanowire Sagnac interferometer



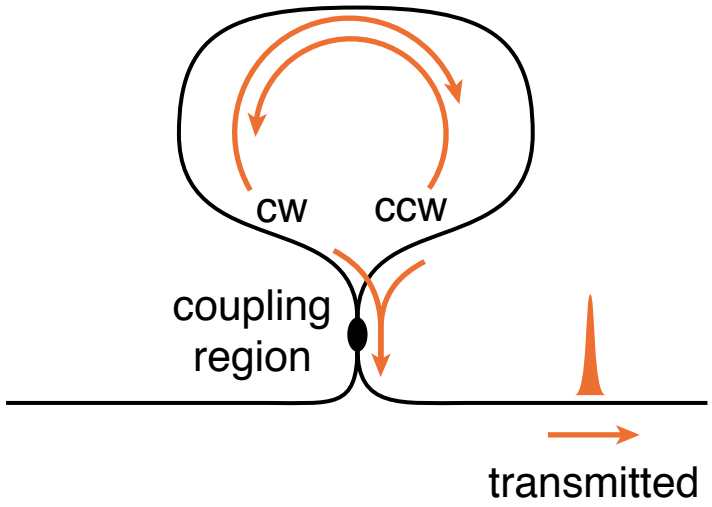
all-optical modulation

nanowire Sagnac interferometer



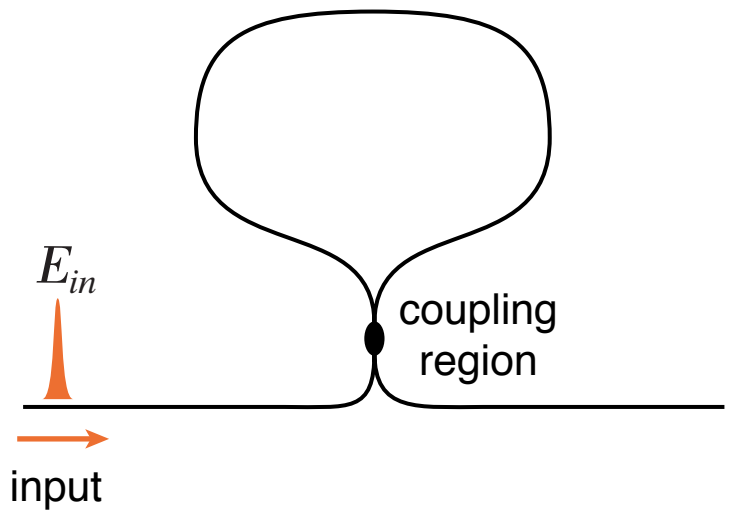
all-optical modulation

output = transmitted cw + ccw power



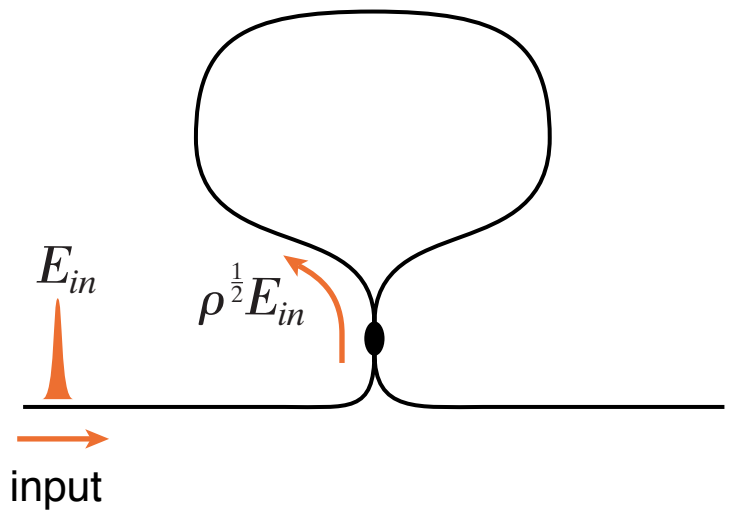
all-optical modulation

input electric field amplitude E_{in}



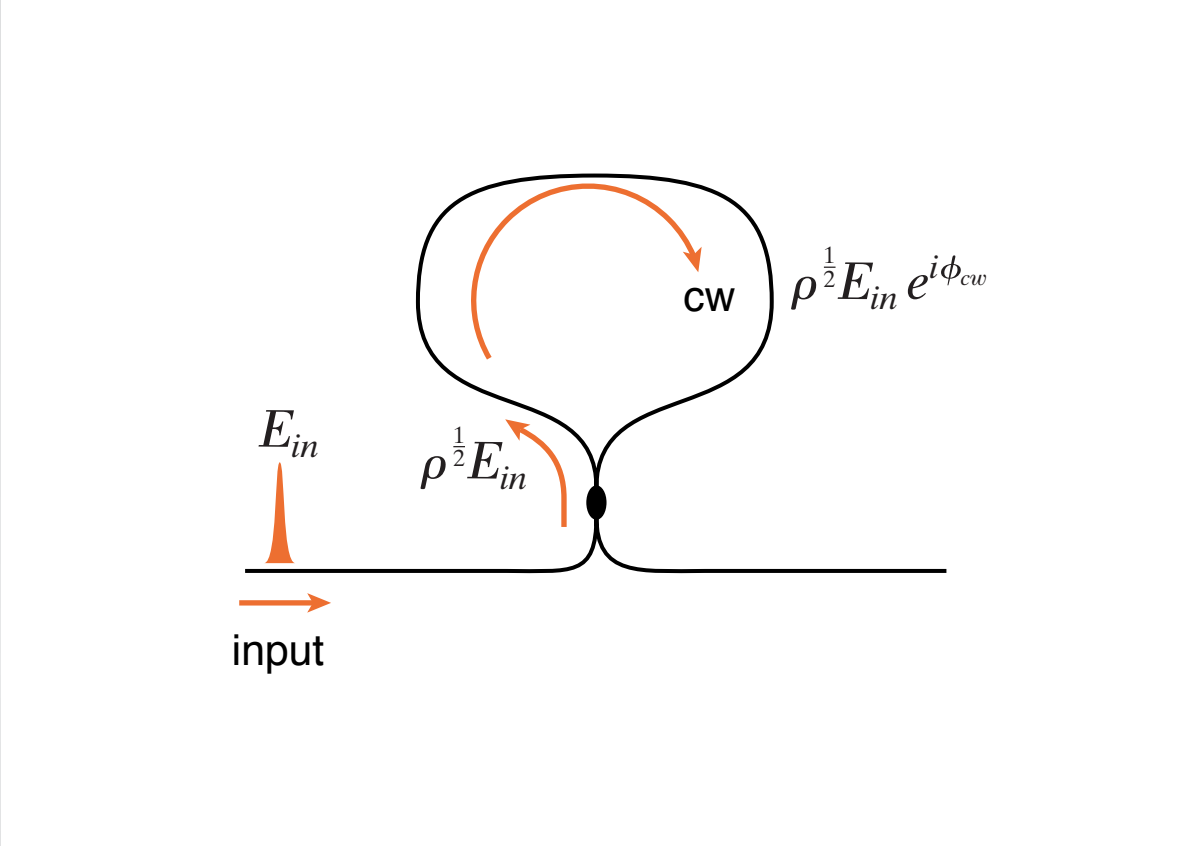
all-optical modulation

coupling parameter: ρ



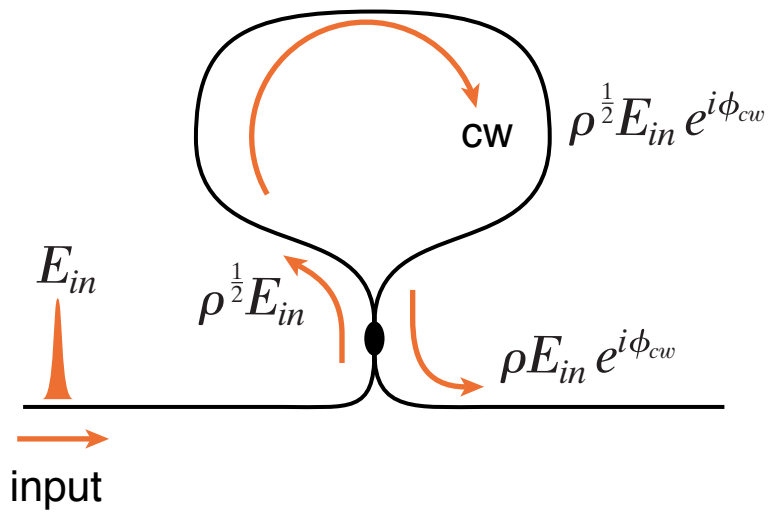
all-optical modulation

phase accumulation over path length of loop



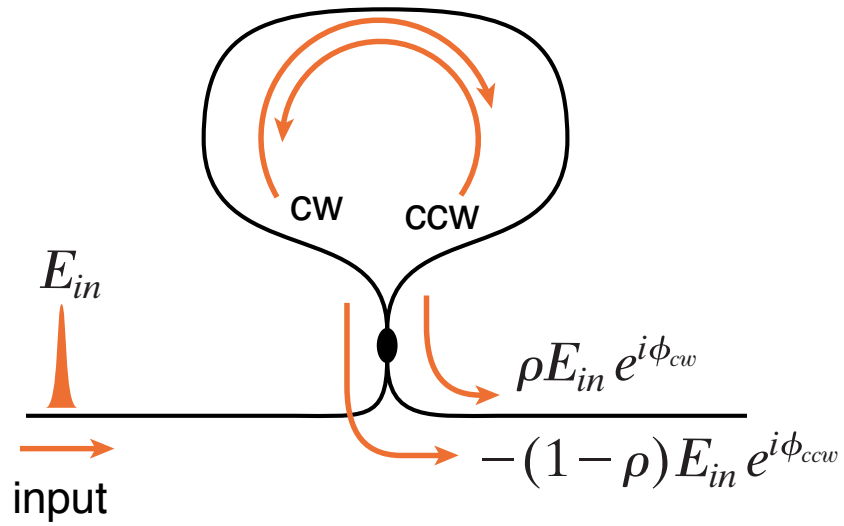
all-optical modulation

coupling parameter: ρ



all-optical modulation

output is sum of transmitted cw and ccw



all-optical modulation

accumulated phase:

$$\phi = k_o n$$

all-optical modulation

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nonlinear index:

$$n = n_o + n_2 I = n_o + n_2 \frac{P_i}{A_{eff}}$$

all-optical modulation

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:

$$\gamma = n_2 \frac{k_o}{A_{eff}}$$

all-optical modulation

power-dependent output:

$$\frac{E_{out}^2}{E_{in}^2} = 1 - 2\rho(1 - \rho)\{1 + \cos[(1 - 2\rho)\gamma P_o L]\}$$

all-optical modulation

power-dependent output:

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for 50-50 coupler:

$$\rho = 0.5$$

all-optical modulation

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:

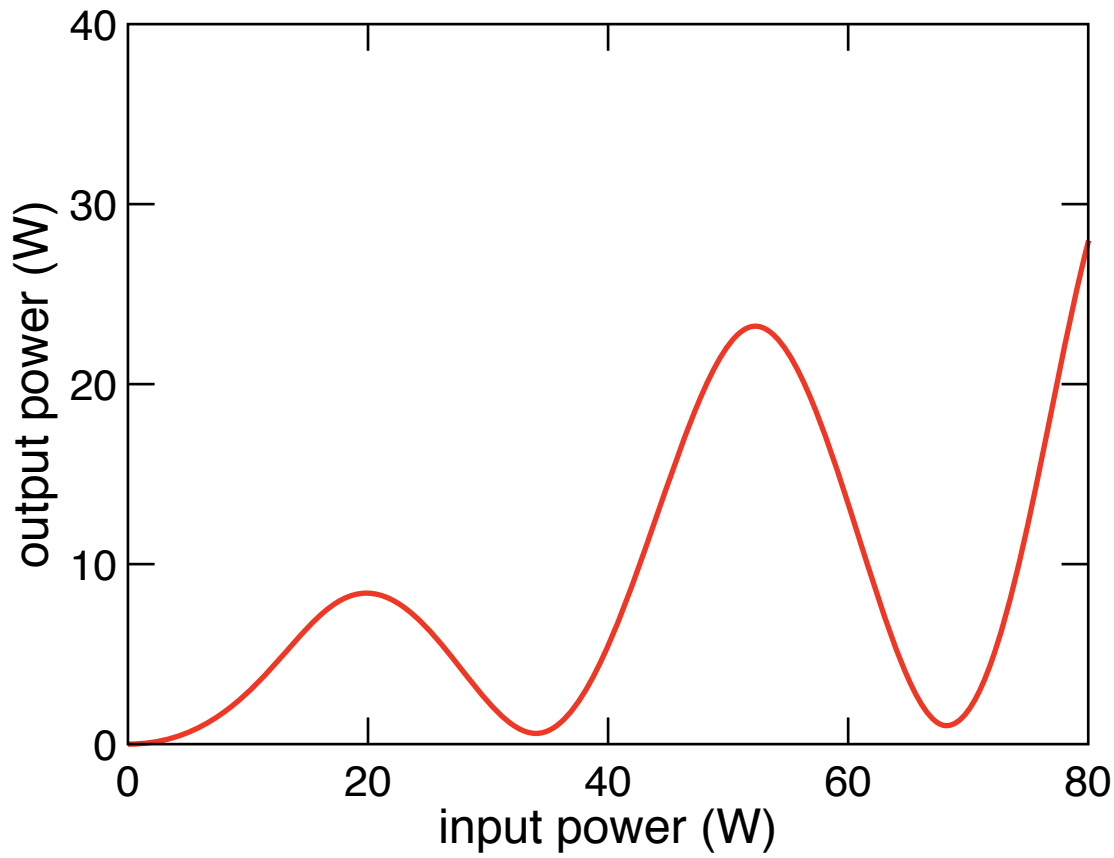
$$\rho = 0.5$$

no transmission:

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

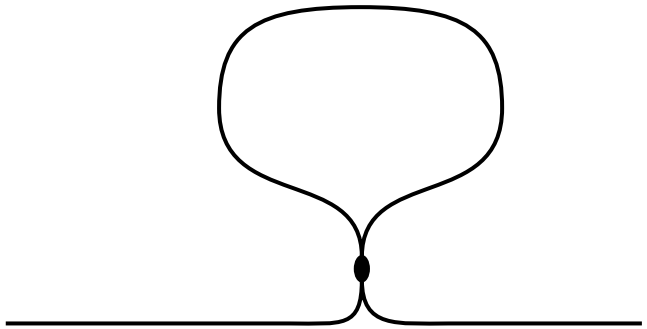
Sagnac interferometer transmission

when $\rho \neq 0.5$:



logic gates

nonlinear nanogate



logic gates

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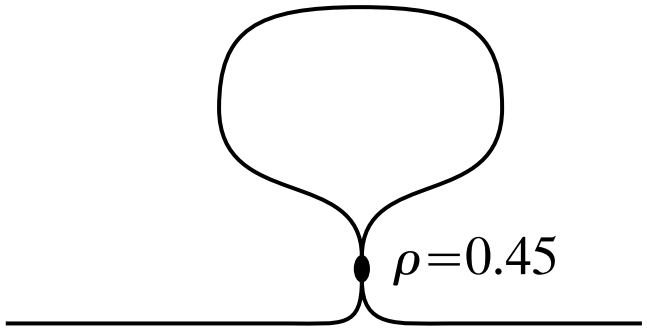

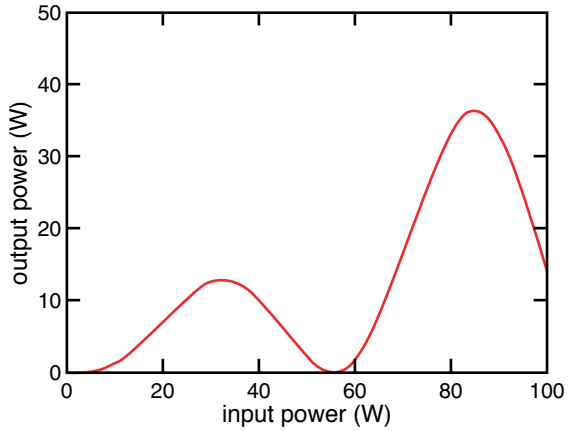

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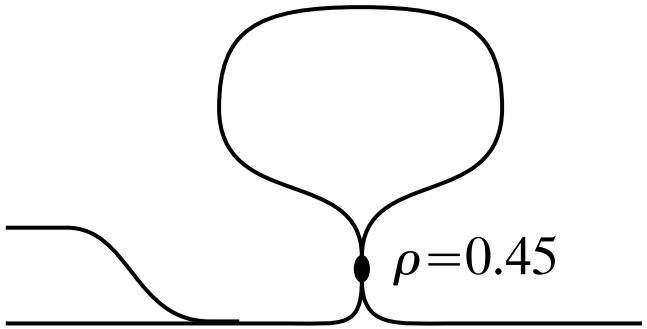

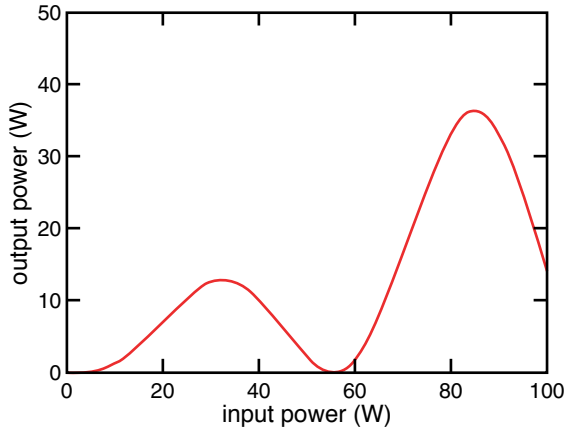

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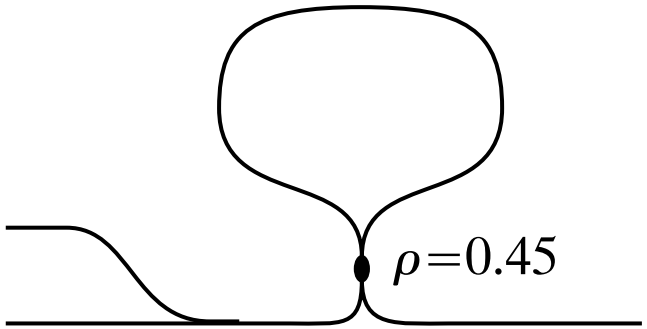

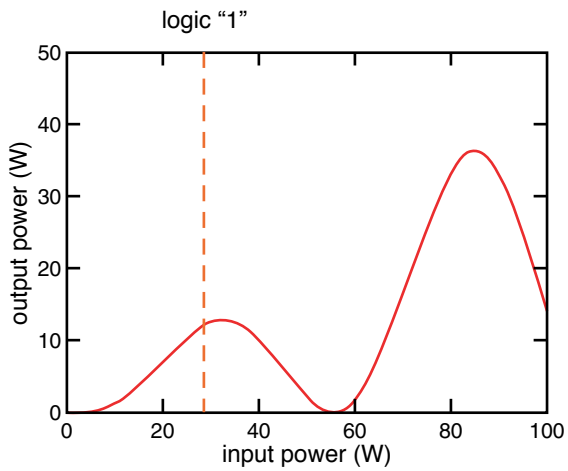

logic gates

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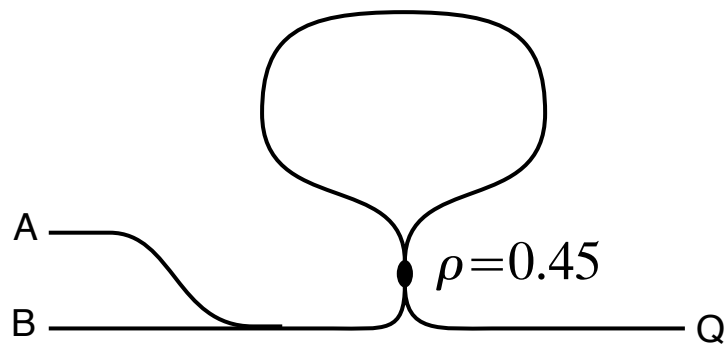
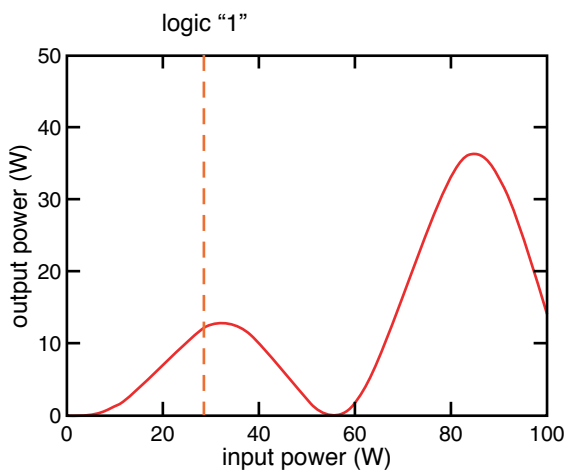
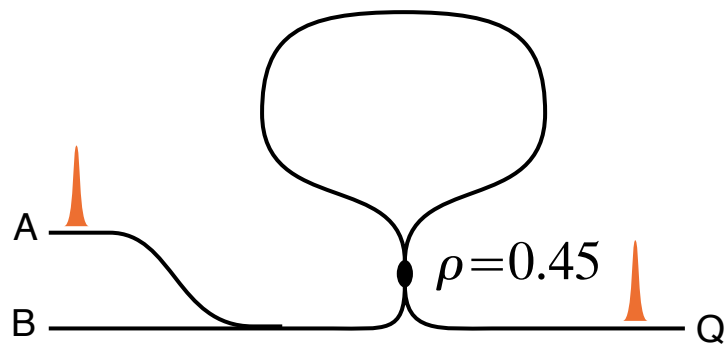


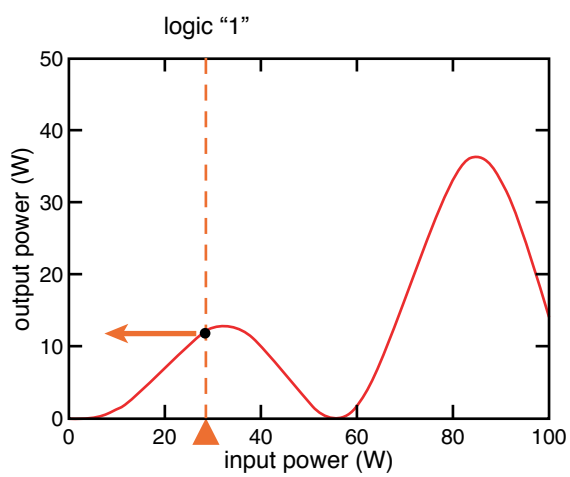


A	B	Q
0	0	0

logic gates

nonlinear nanogate

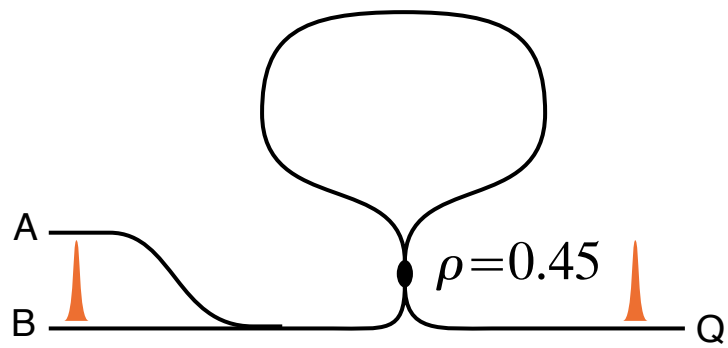


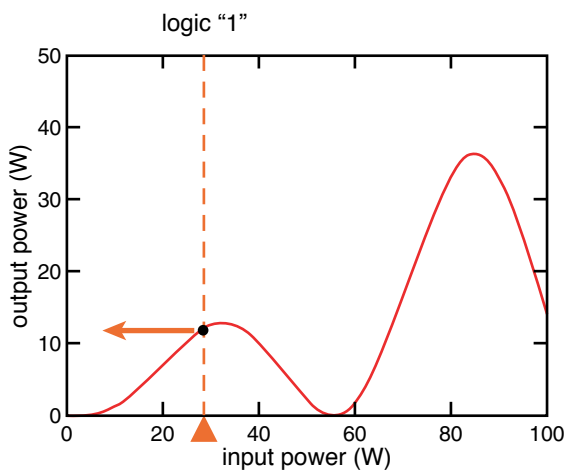


A	B	Q
0	0	0
1	0	1

logic gates

nonlinear nanogate

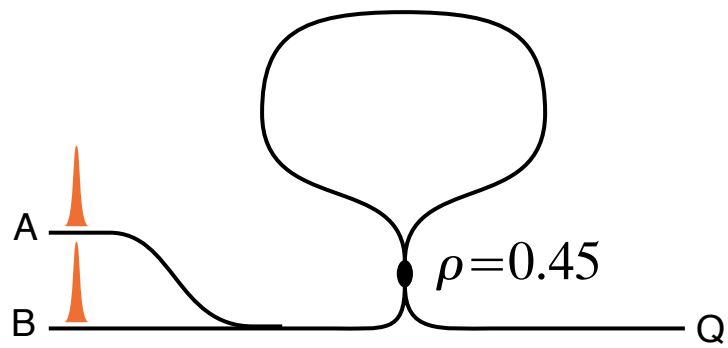


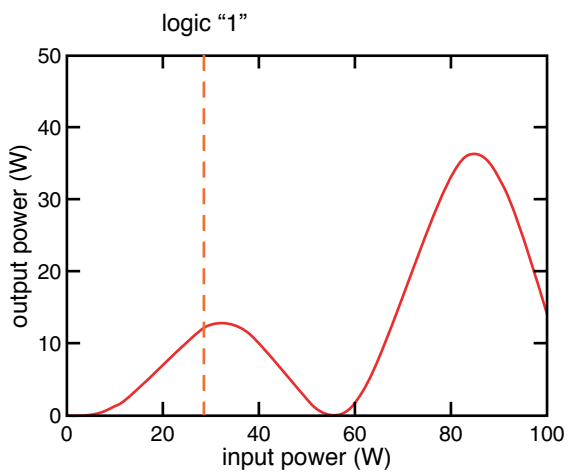


A	B	Q
0	0	0
1	0	1
0	1	1

logic gates

nonlinear nanogate





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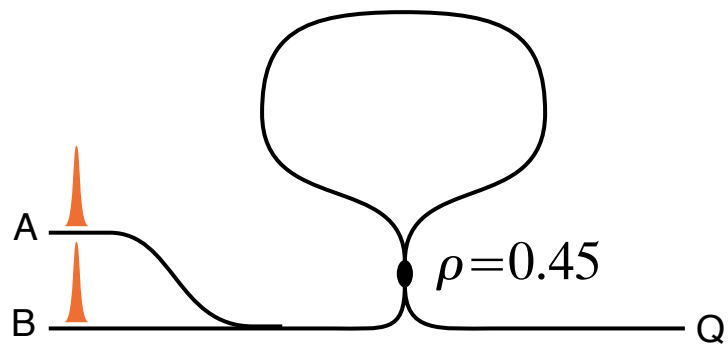

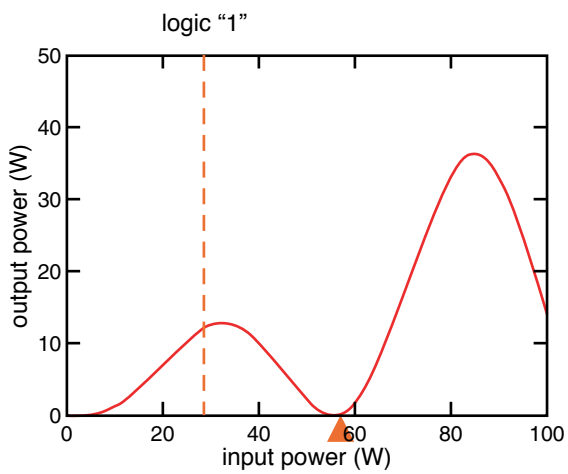

A	B	Q
0	0	0
1	0	1
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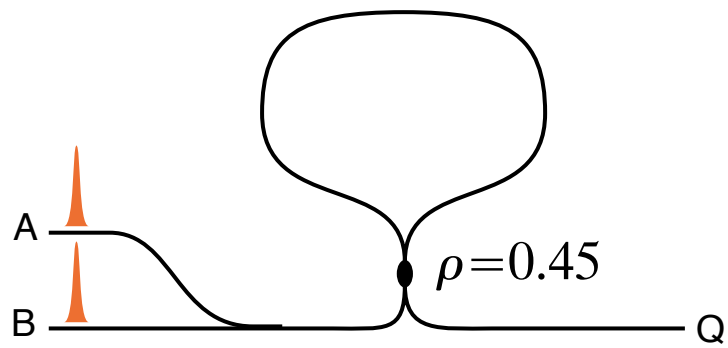
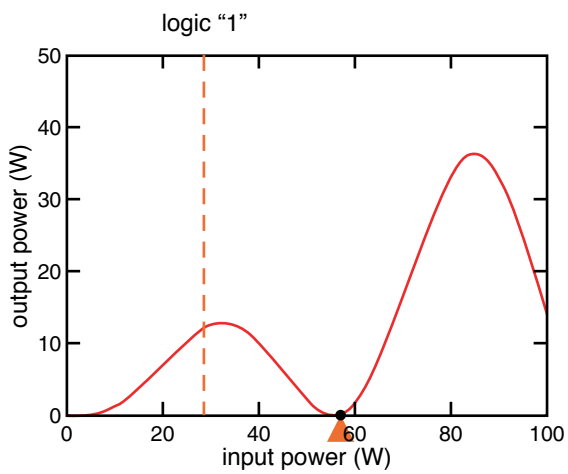
nonlinear nanogate

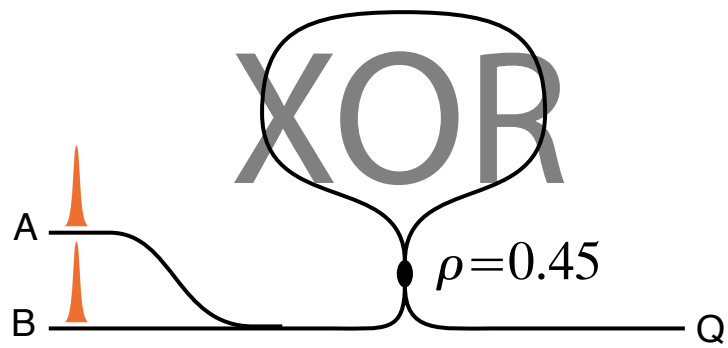


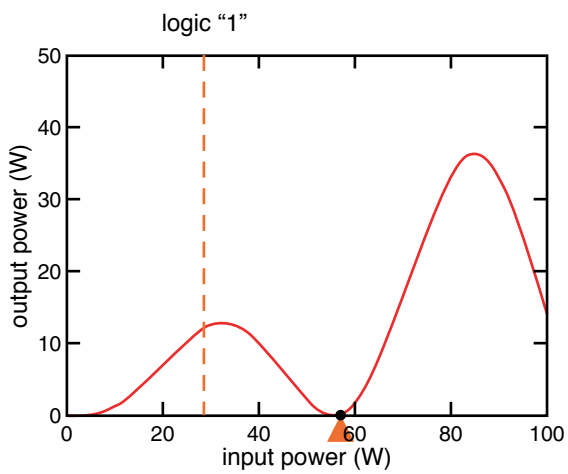


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

logic gates

nonlinear nanogate

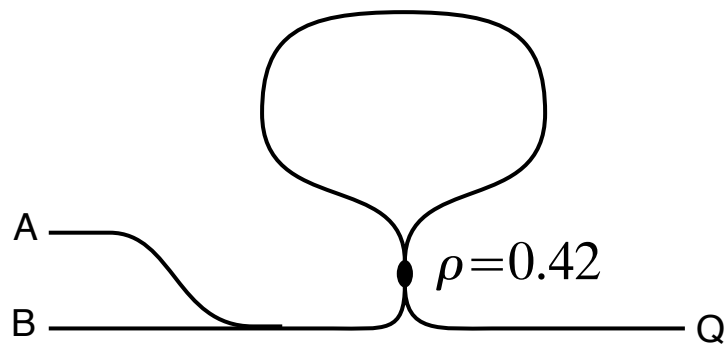


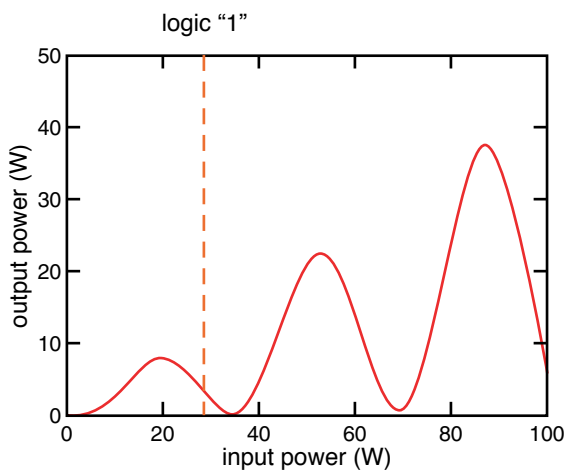


A	B	Q
0	0	0
1	0	1
0	1	1
1	1	0

logic gates

nonlinear nanogate

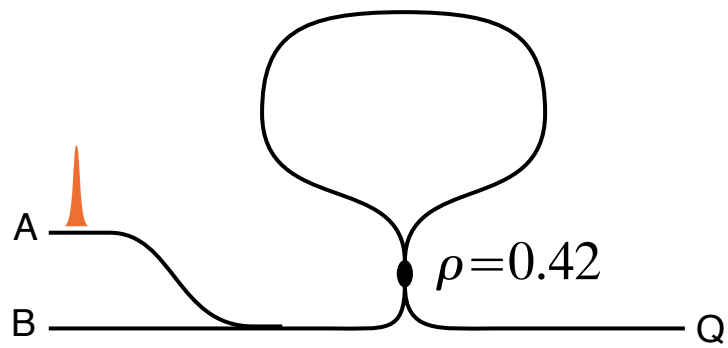


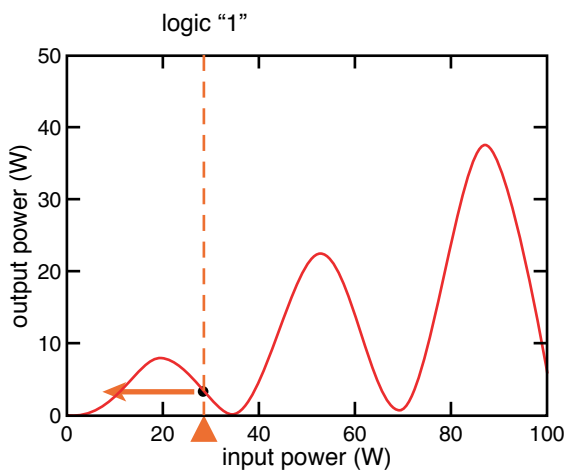


A	B	Q
0	0	0

logic gates

nonlinear nanogate

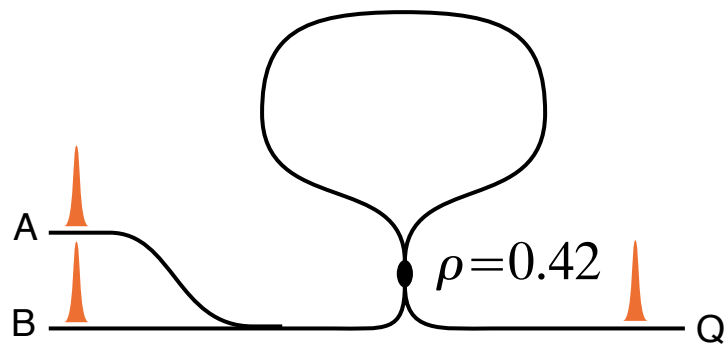


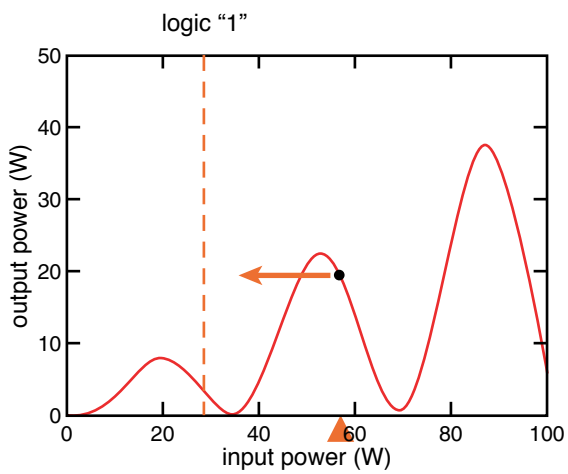


A	B	Q
0	0	0
1	0	0
0	1	0

logic gates

nonlinear nanogate

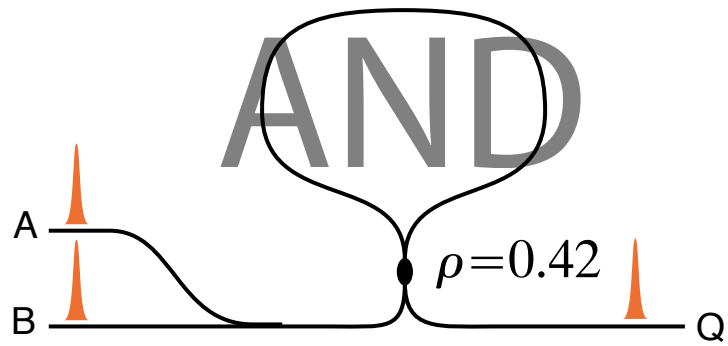


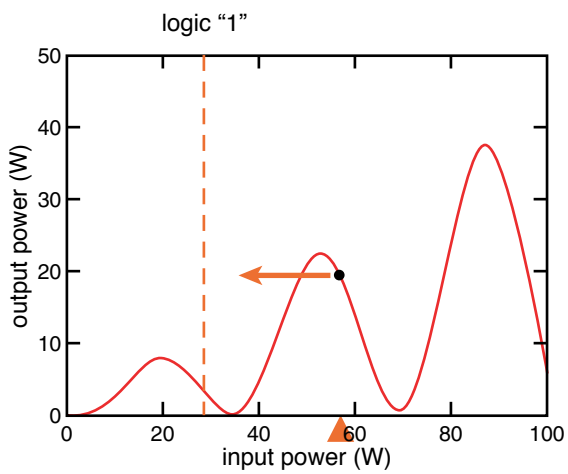


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

logic gates

nonlinear nanogate

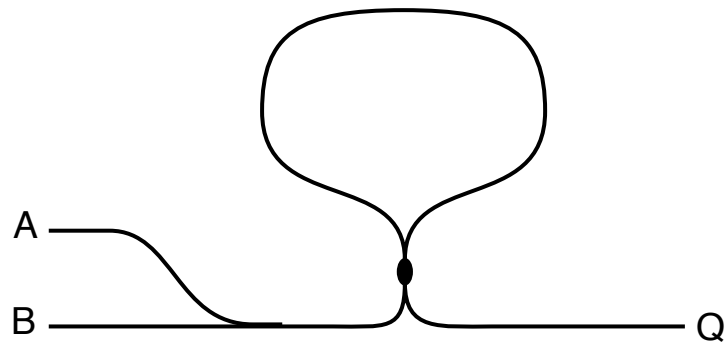


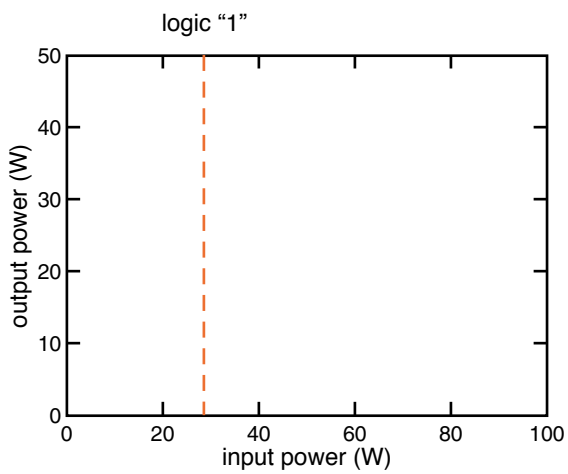


A	B	Q
0	0	0
1	0	0
0	1	0
1	1	1

logic gates

for NAND gate need ouput with no input

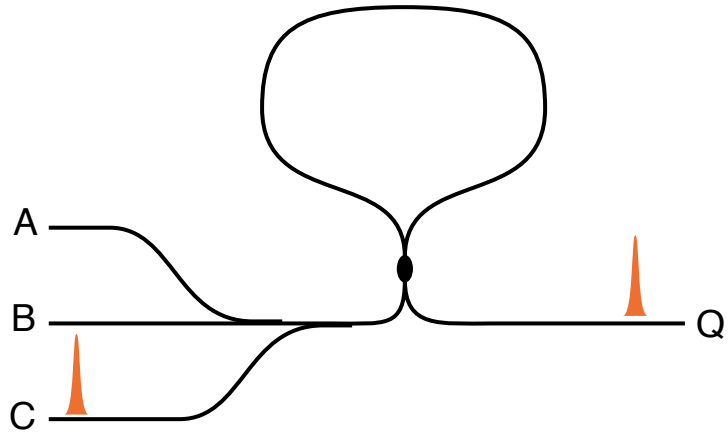


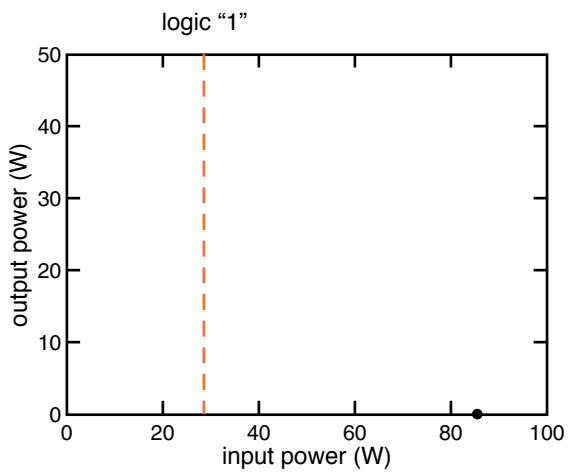


A	B	Q
0	0	1

logic gates

for NAND gate need ouput with no input

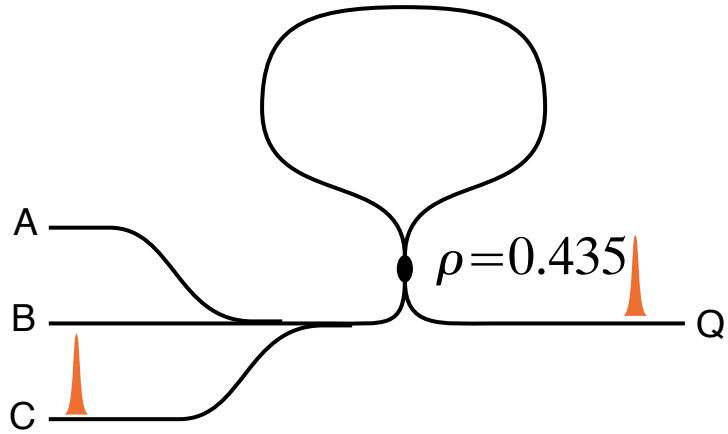


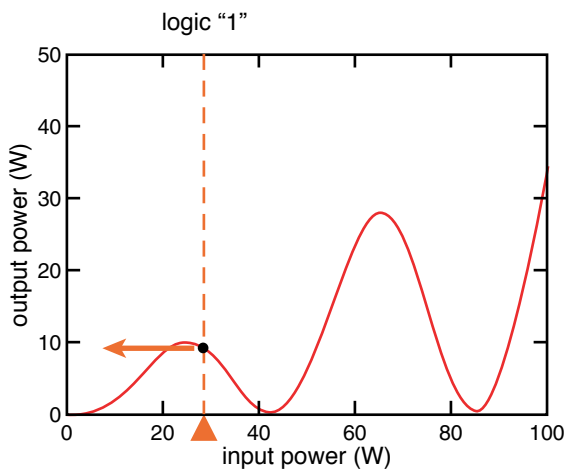


A	B	Q
0	0	1

logic gates

for NAND gate need ouput with no input

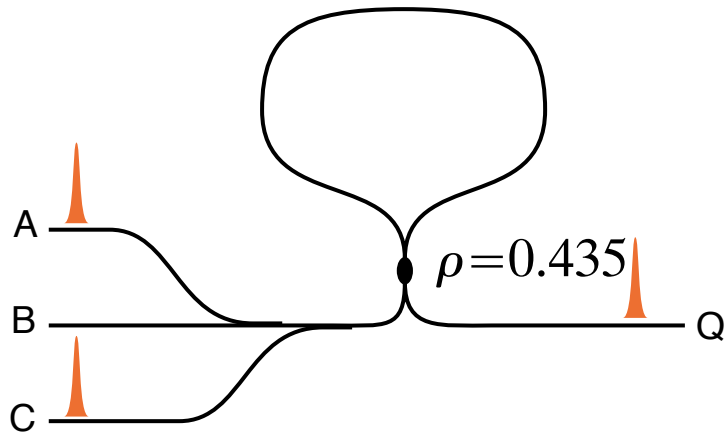


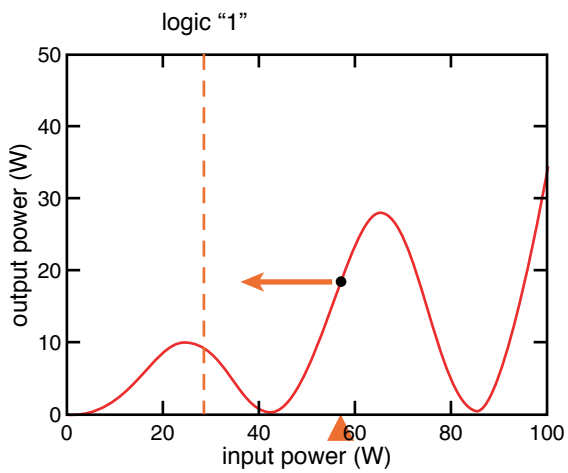


A	B	Q
0	0	1

logic gates

universal NAND gate

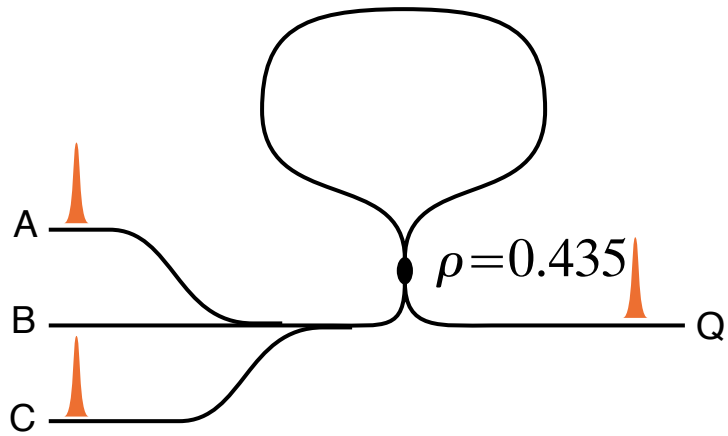


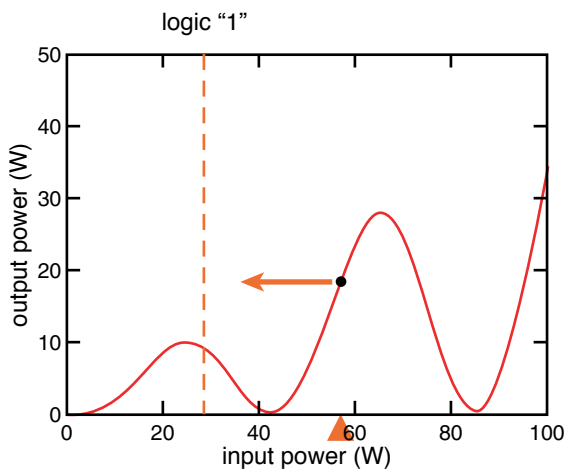


A	B	Q
0	0	1
1	0	1
0	1	1

logic gates

universal NAND gate

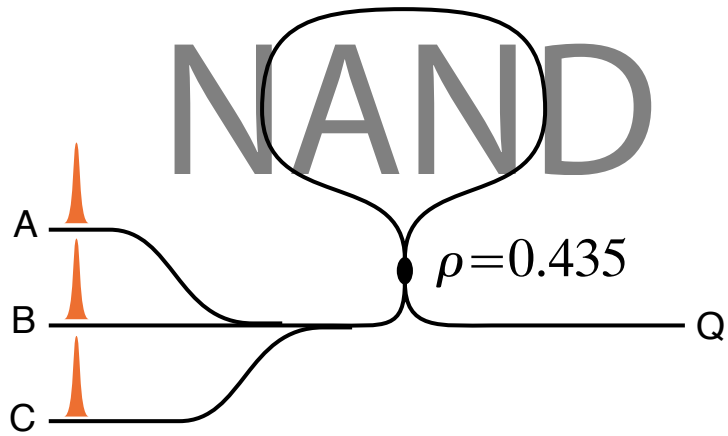


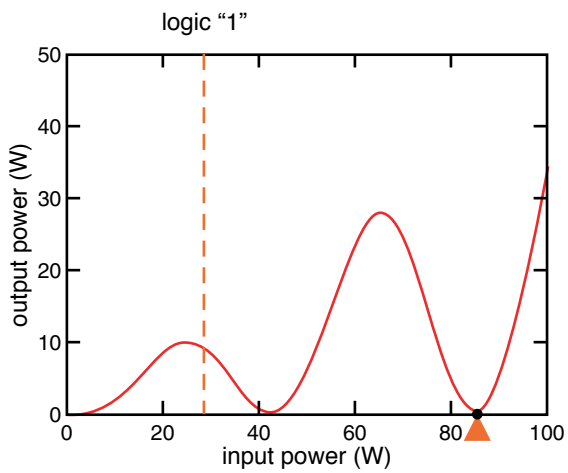


A	B	Q
0	0	1
1	0	1
0	1	1

logic gates

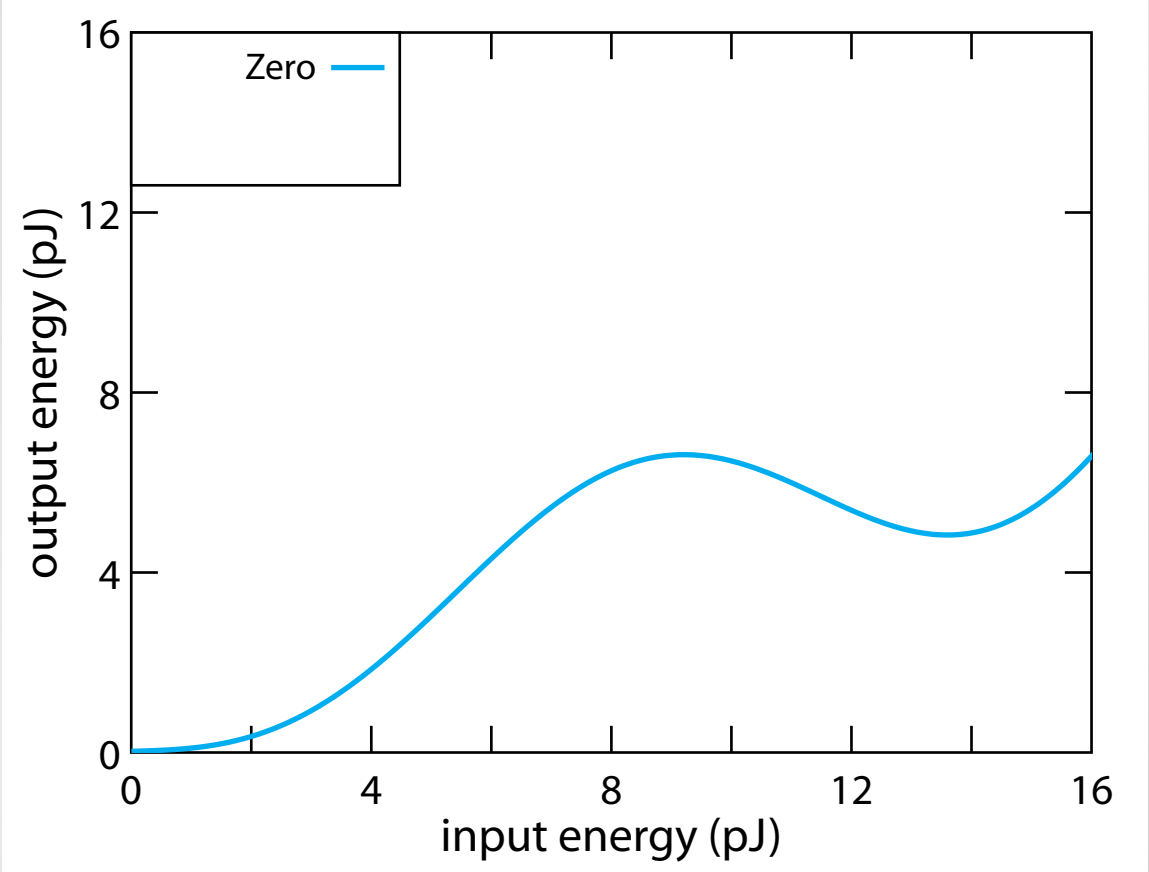
universal NAND gate





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

what about a Gaussian pulse?

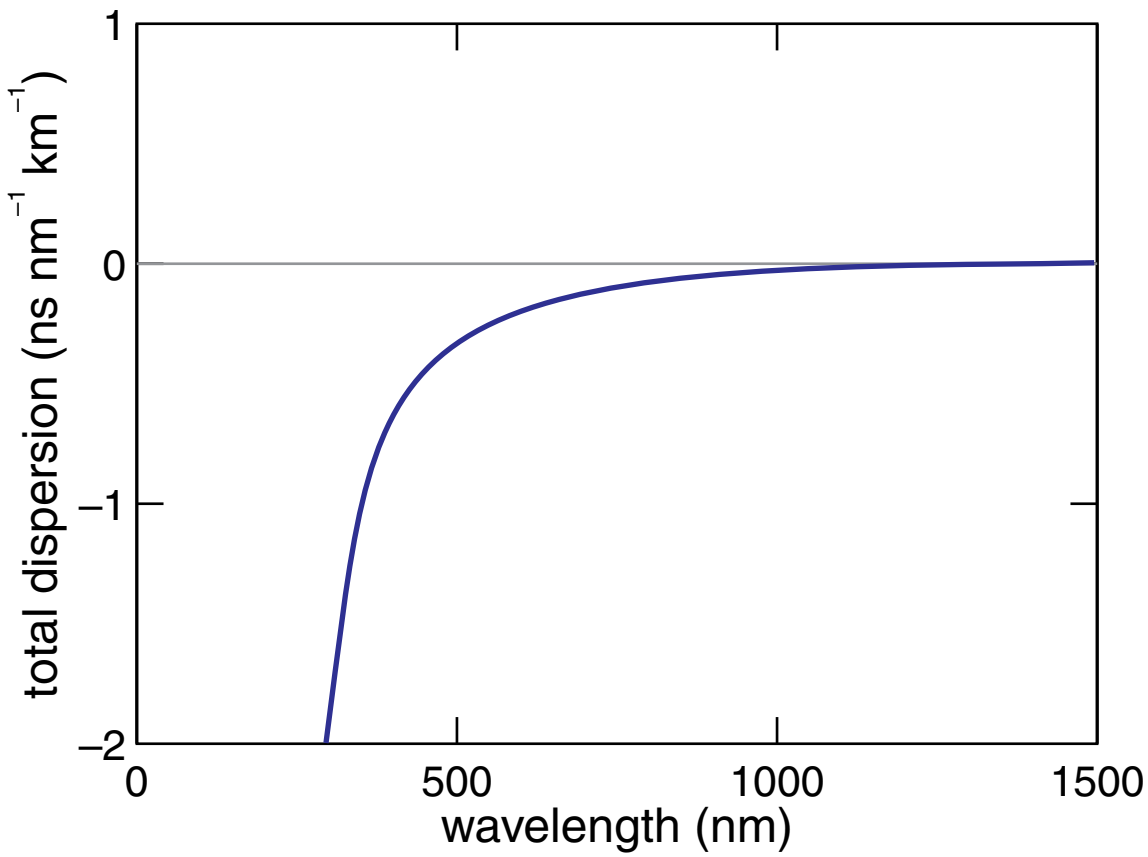


dispersion can change the intensity

- modal dispersion
- material dispersion
- waveguide dispersion

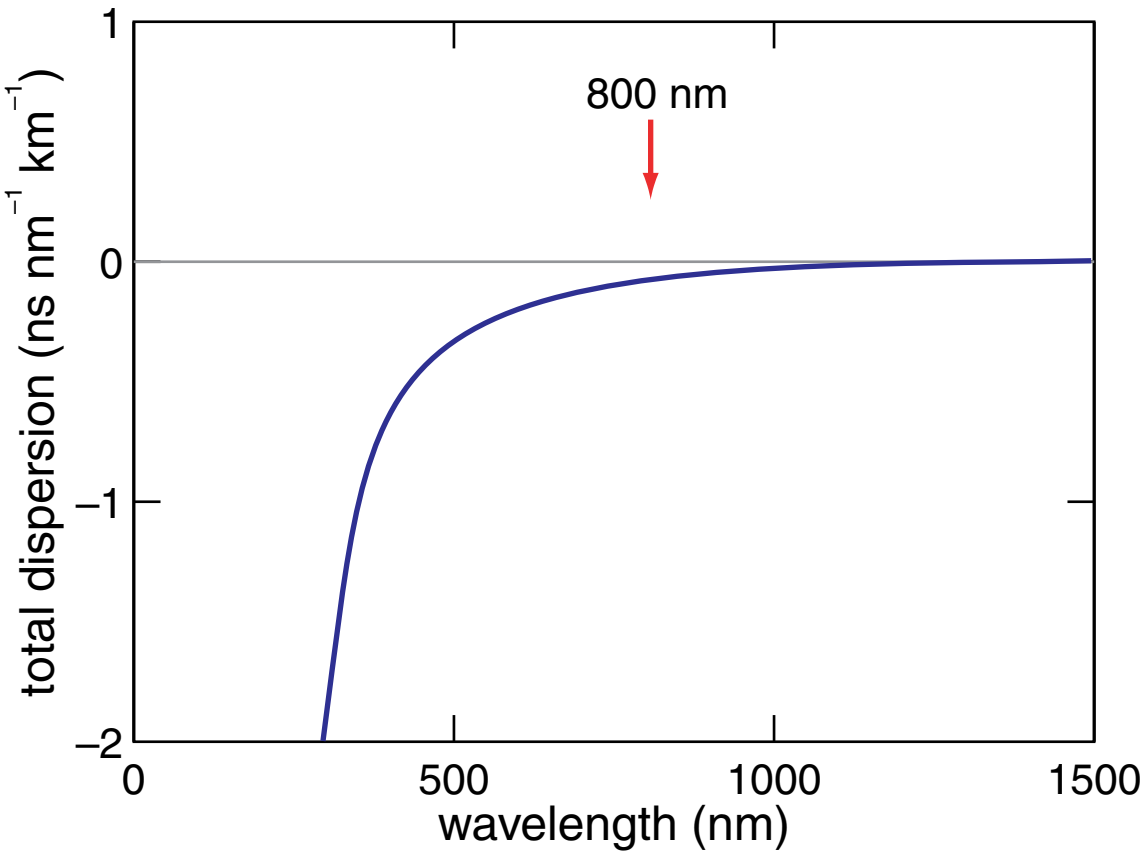
engineering dispersion

waveguide dispersion

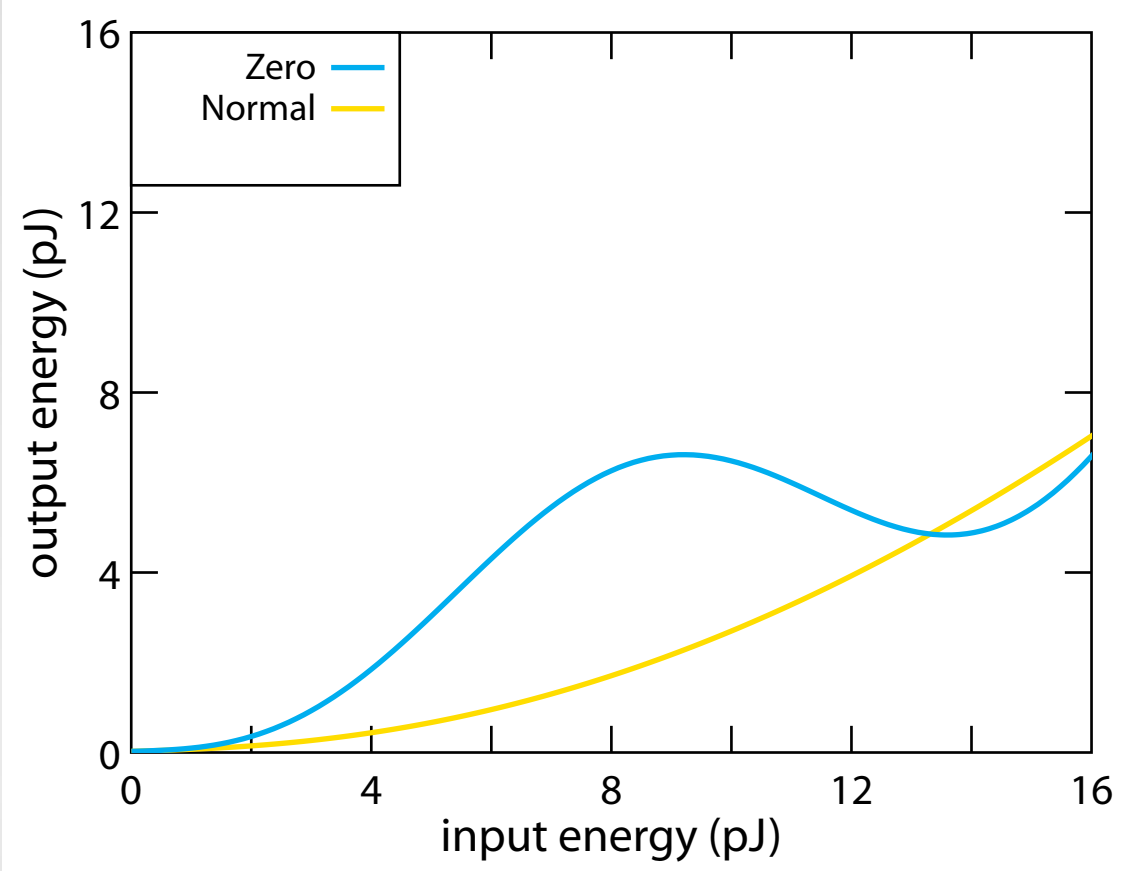


engineering dispersion

waveguide dispersion

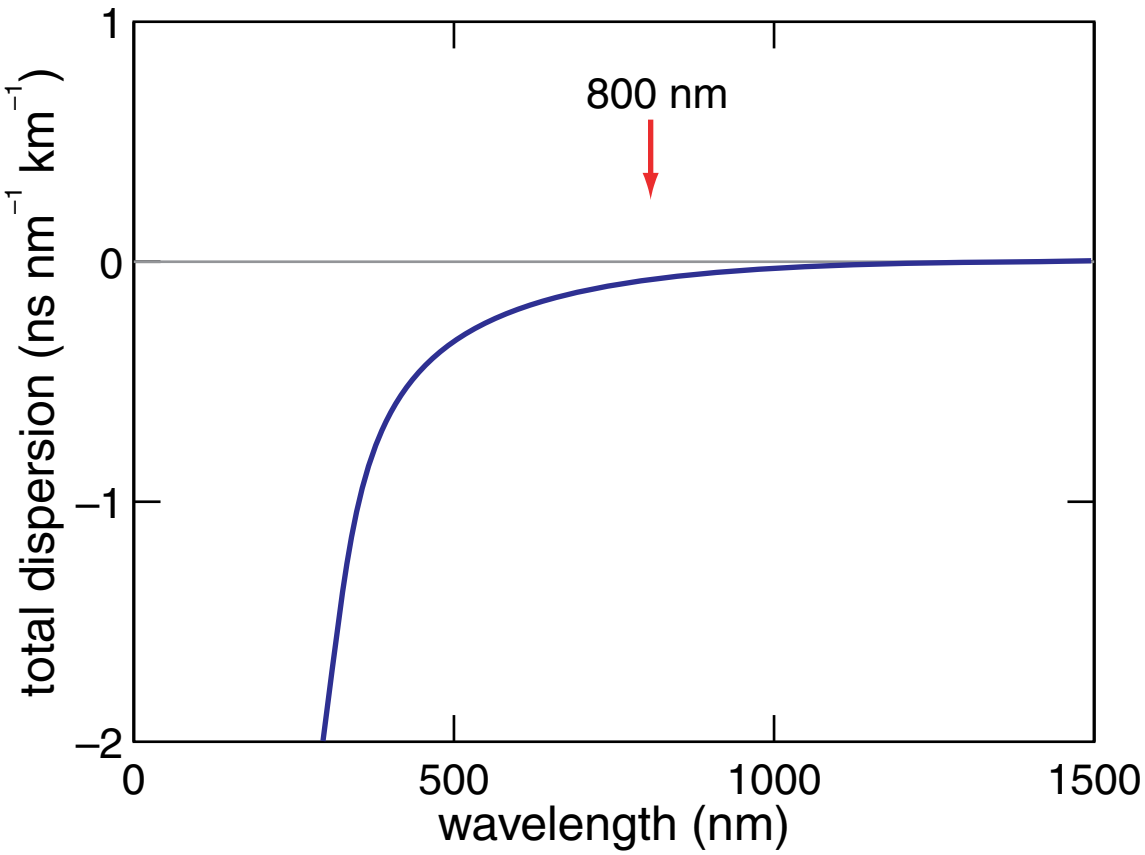


pulses in a Sagnac



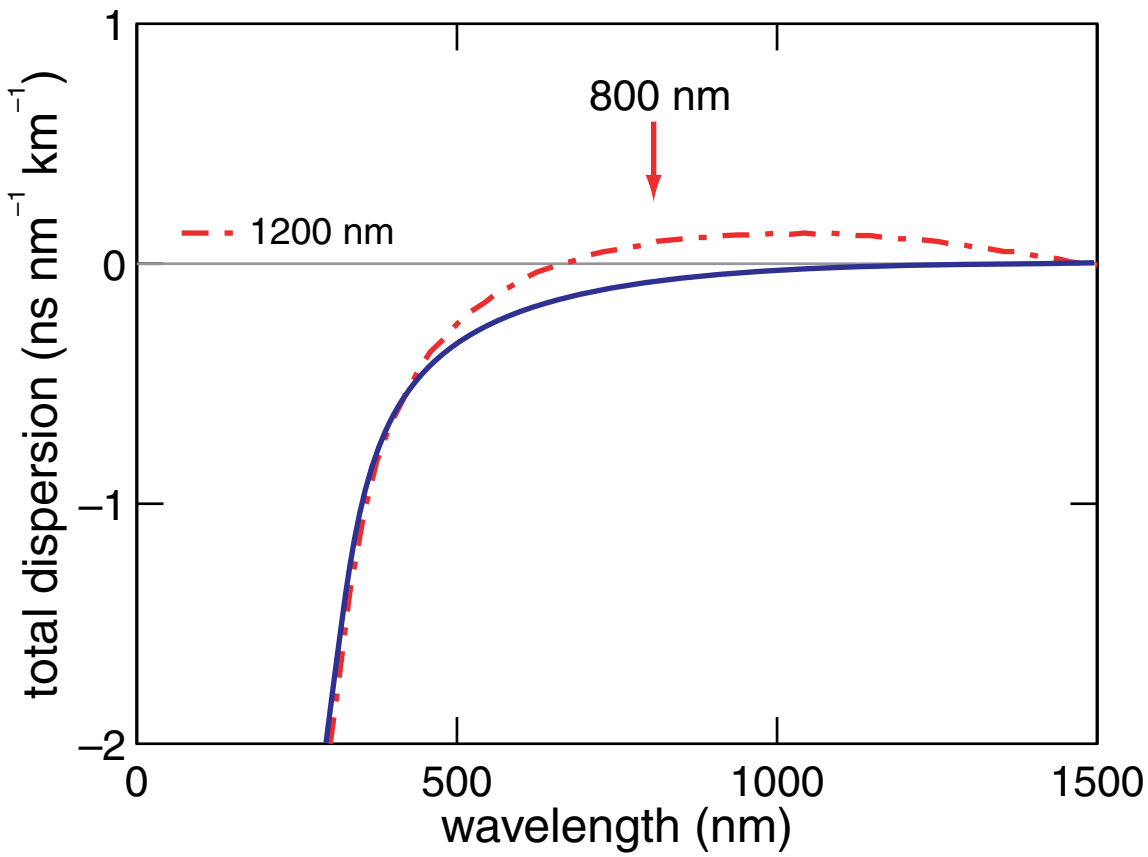
engineering dispersion

waveguide dispersion



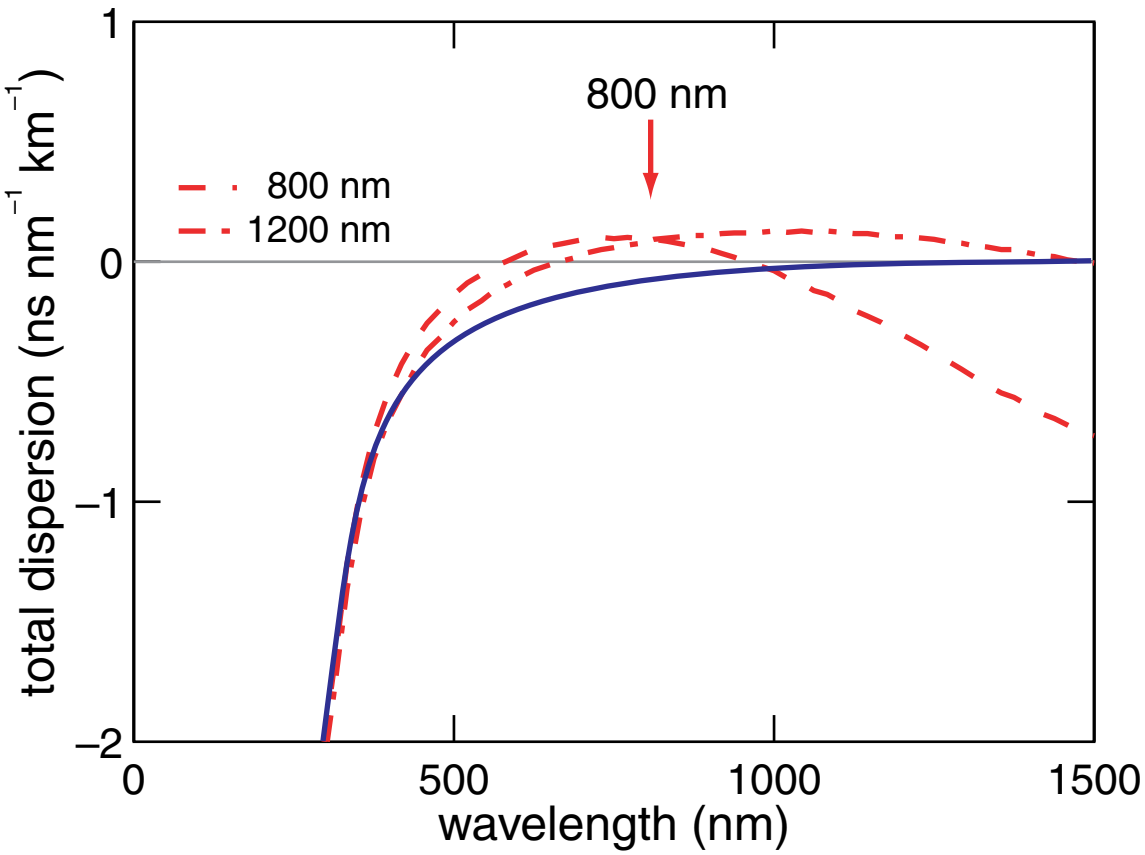
solitons: “light bullets”!

waveguide dispersion



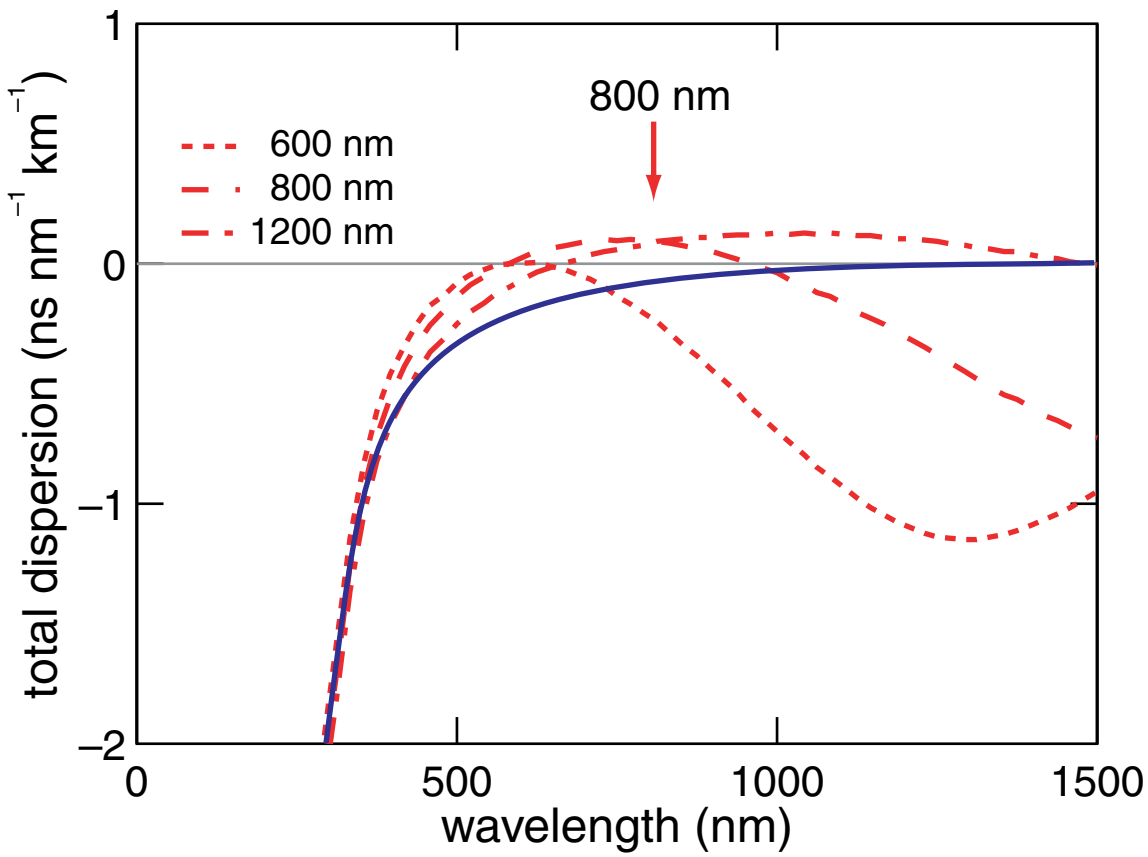
engineering dispersion

waveguide dispersion



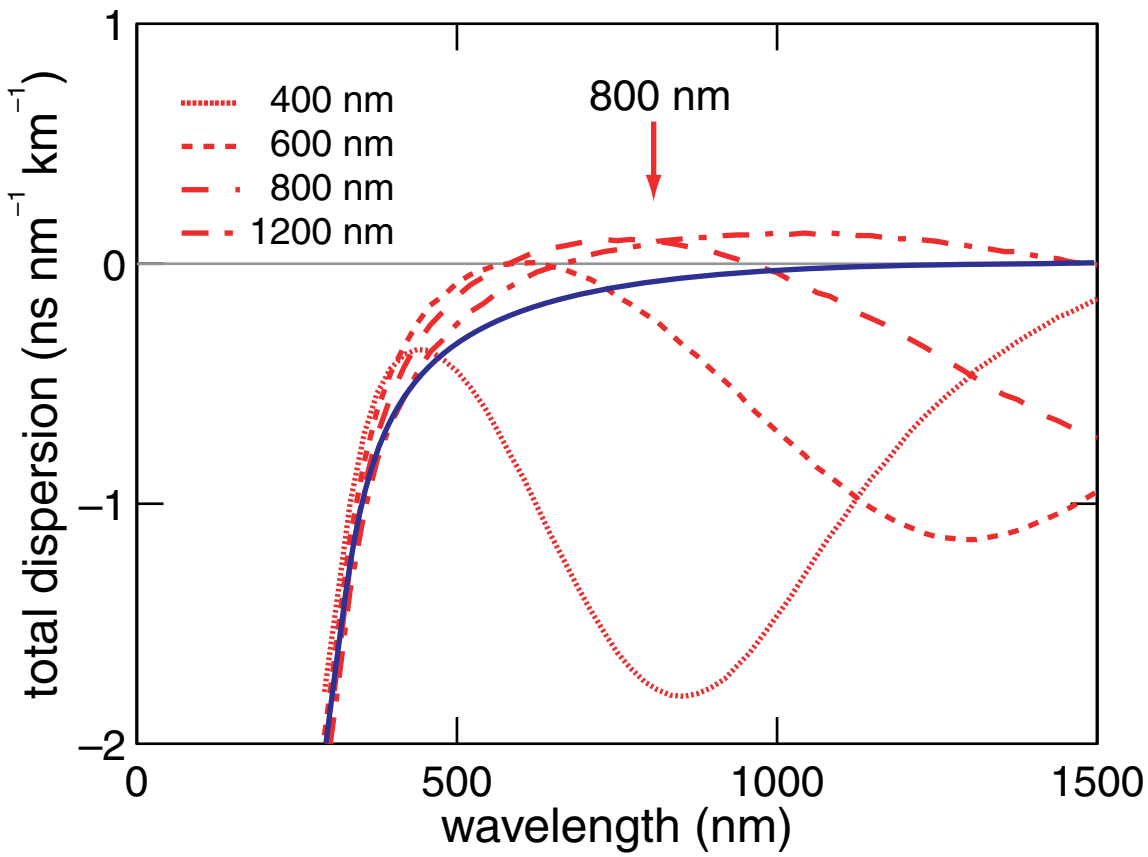
engineering dispersion

waveguide dispersion



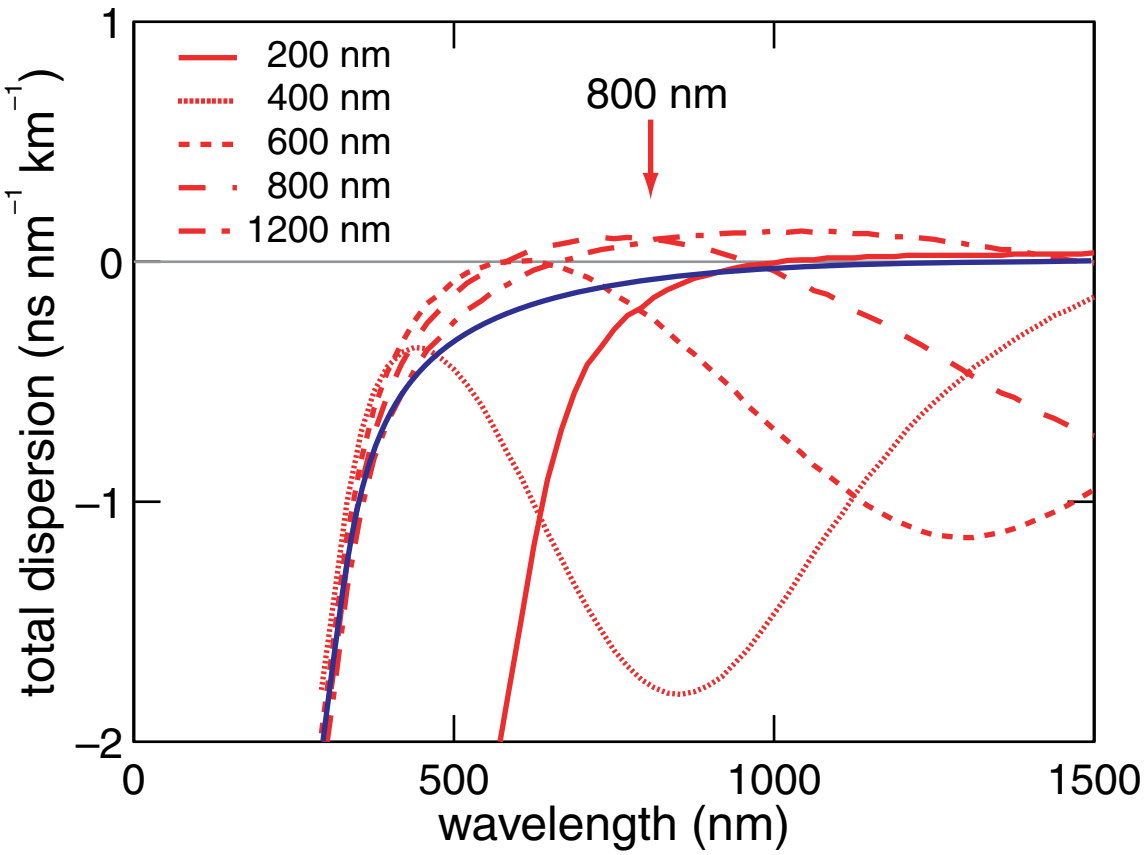
engineering dispersion

waveguide dispersion

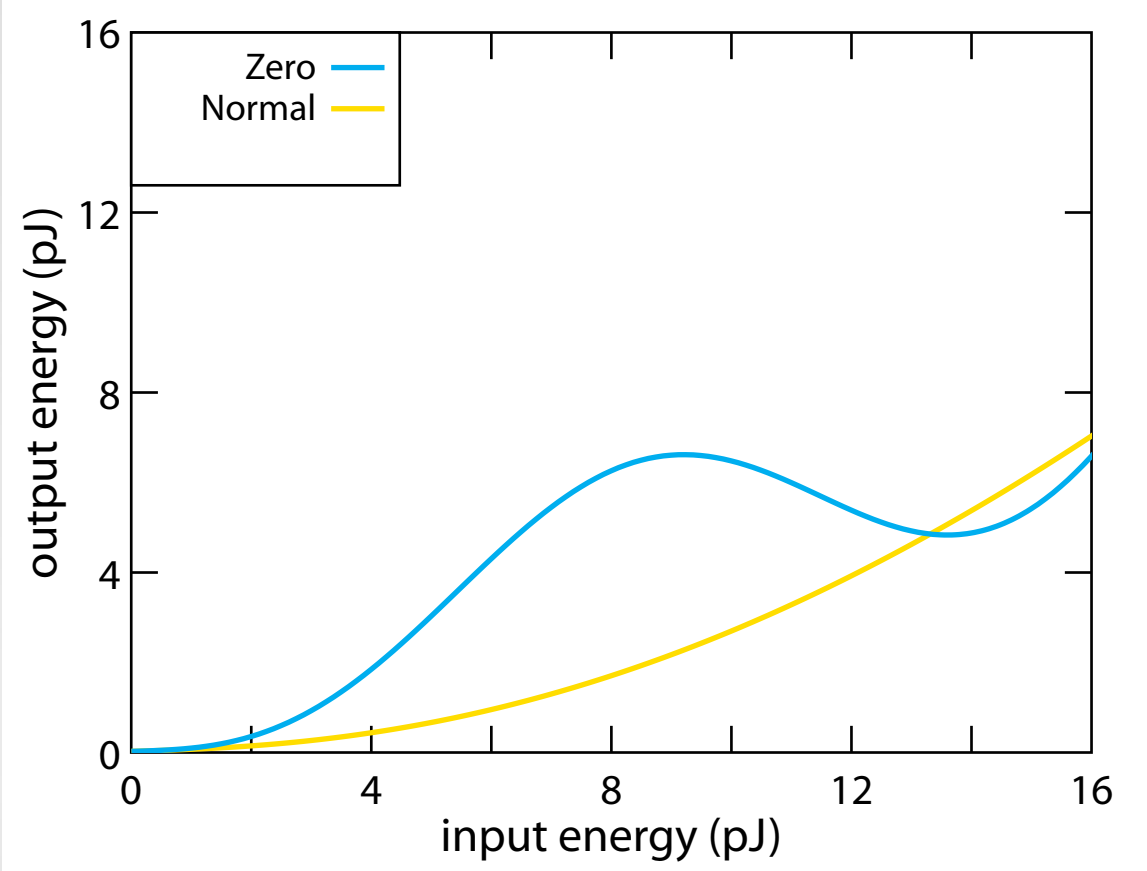


engineering dispersion

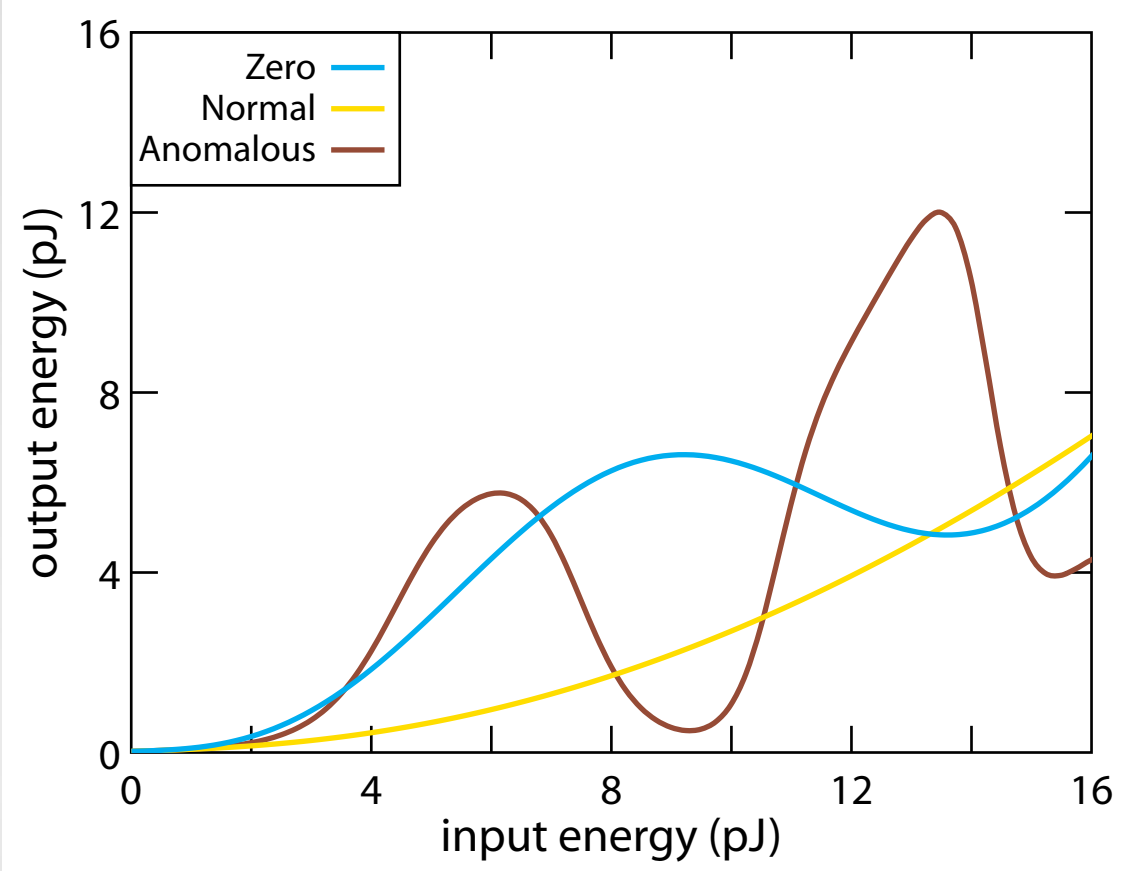
waveguide dispersion



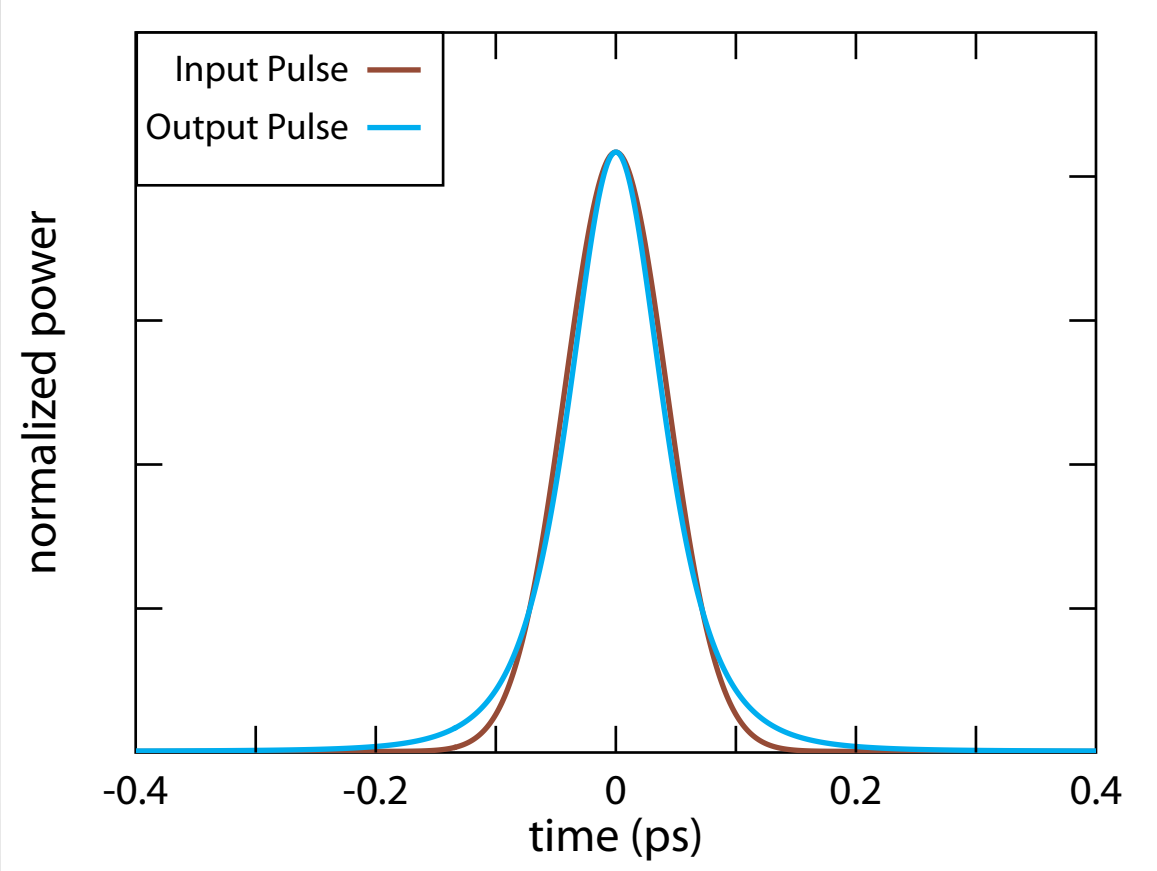
soliton pulses in a Sagnac

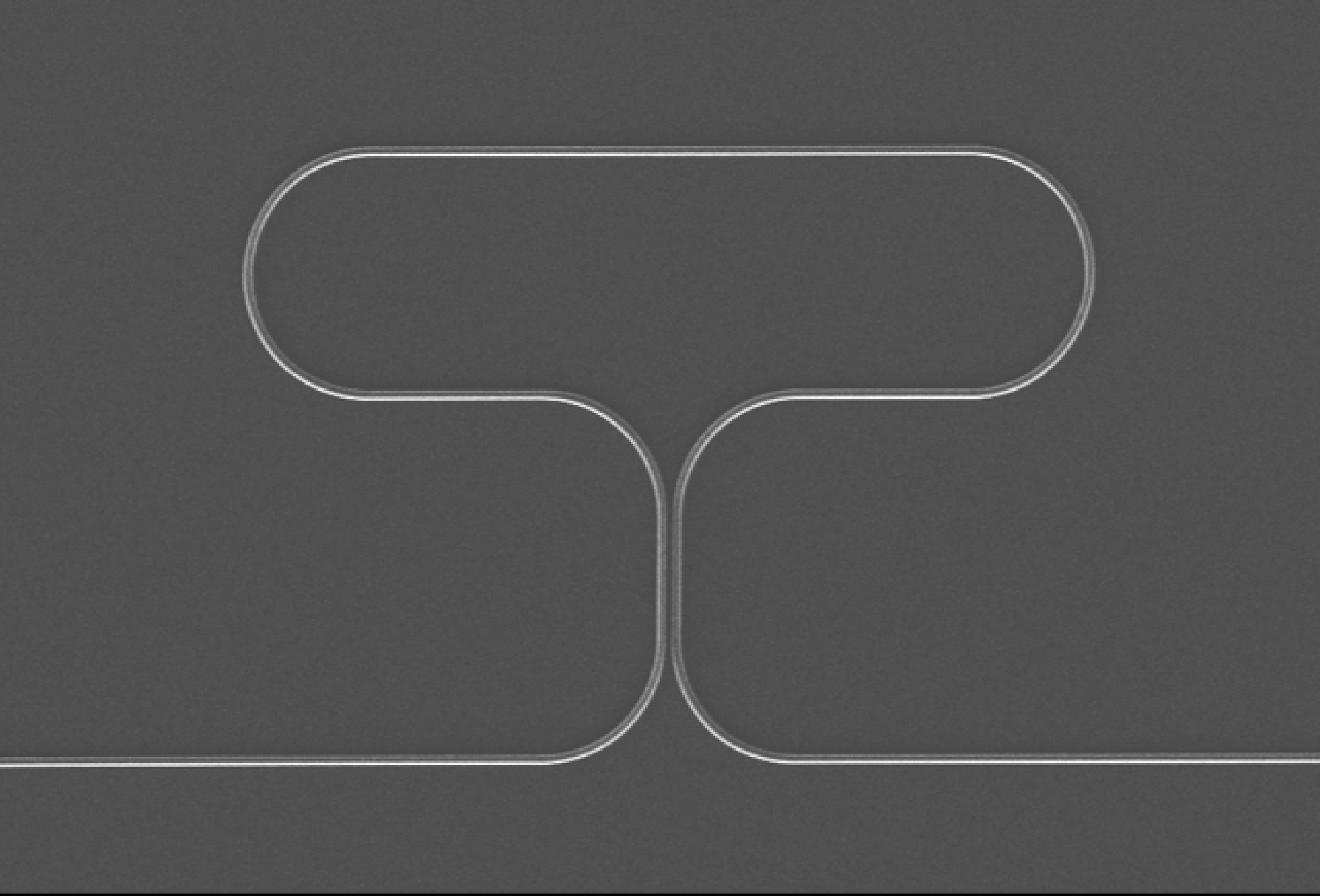


soliton pulses in a Sagnac



soliton pulses in a Sagnac



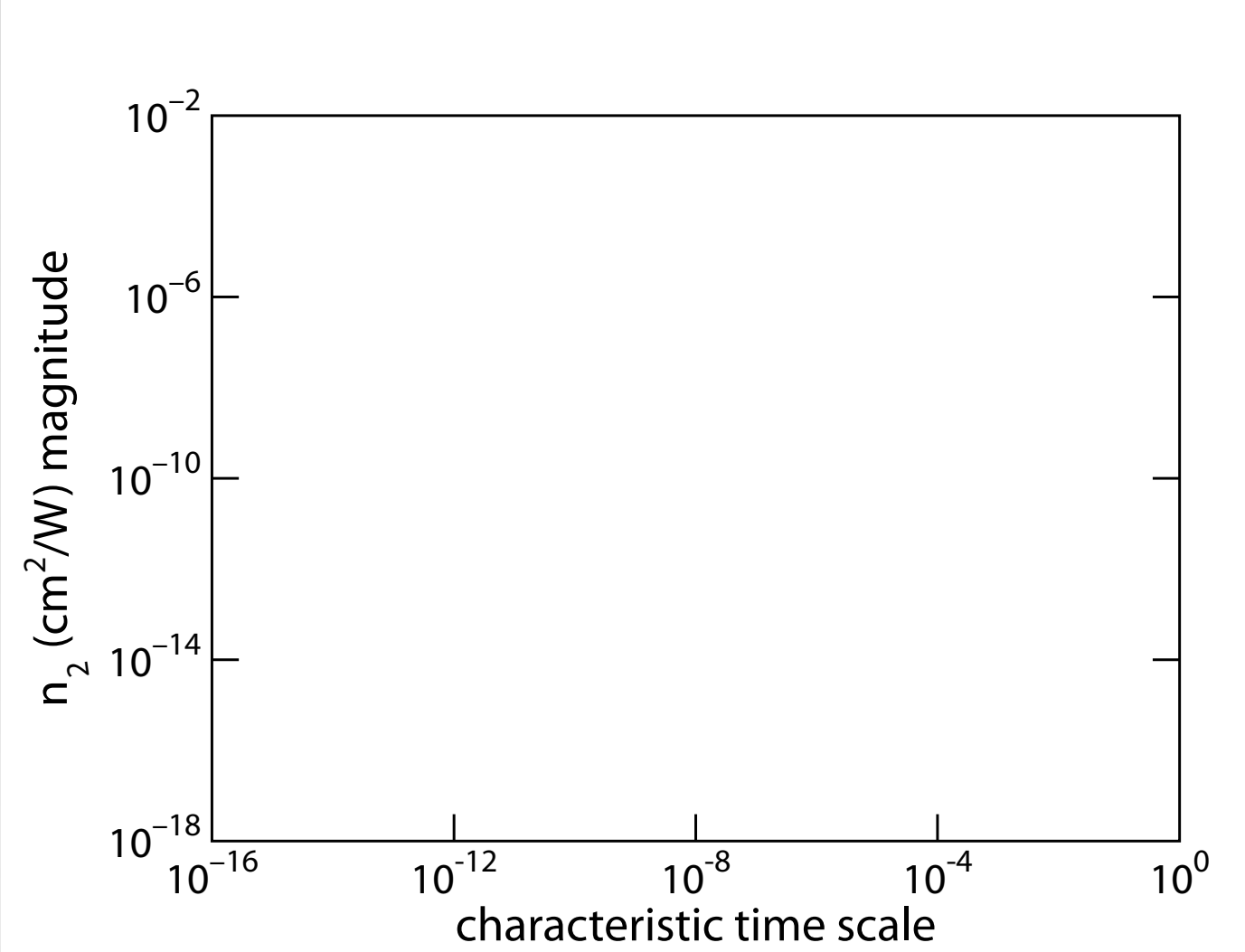


1 all-optical logic

2 NL materials

3 TiO_2 photonics

fast nonlinearities

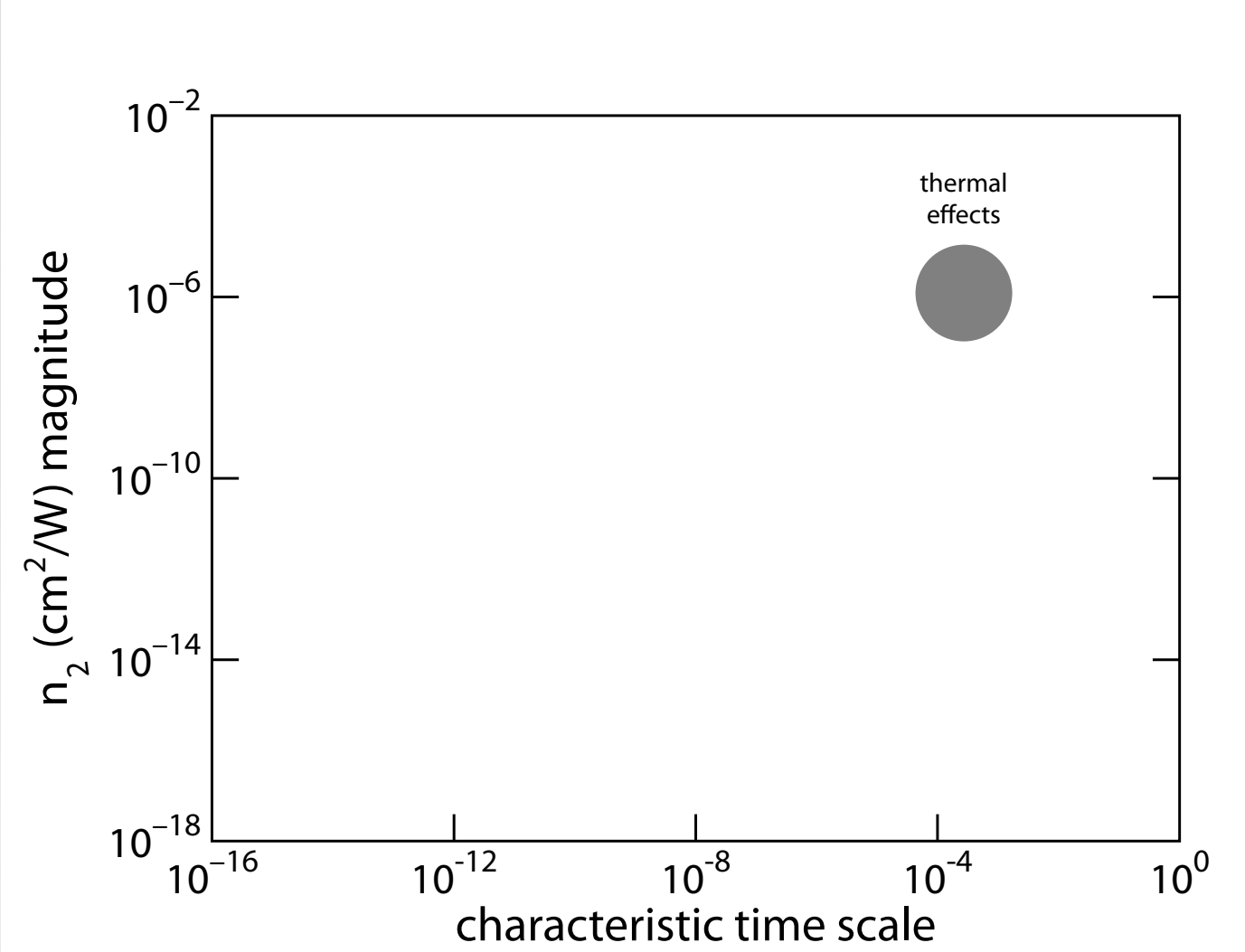


Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic

2 NL materials

fast nonlinearities



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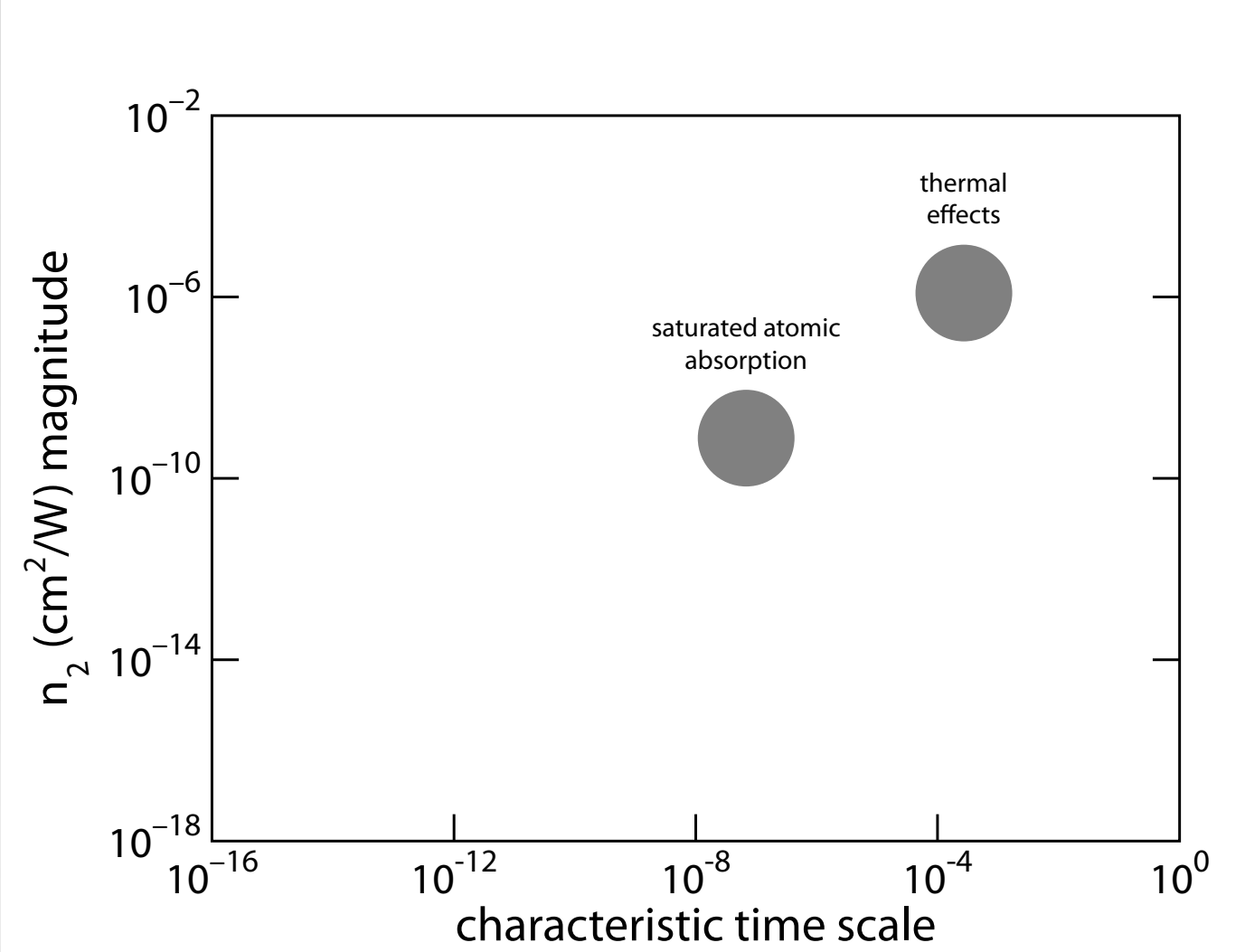
2 NL materials

fast nonlinearities



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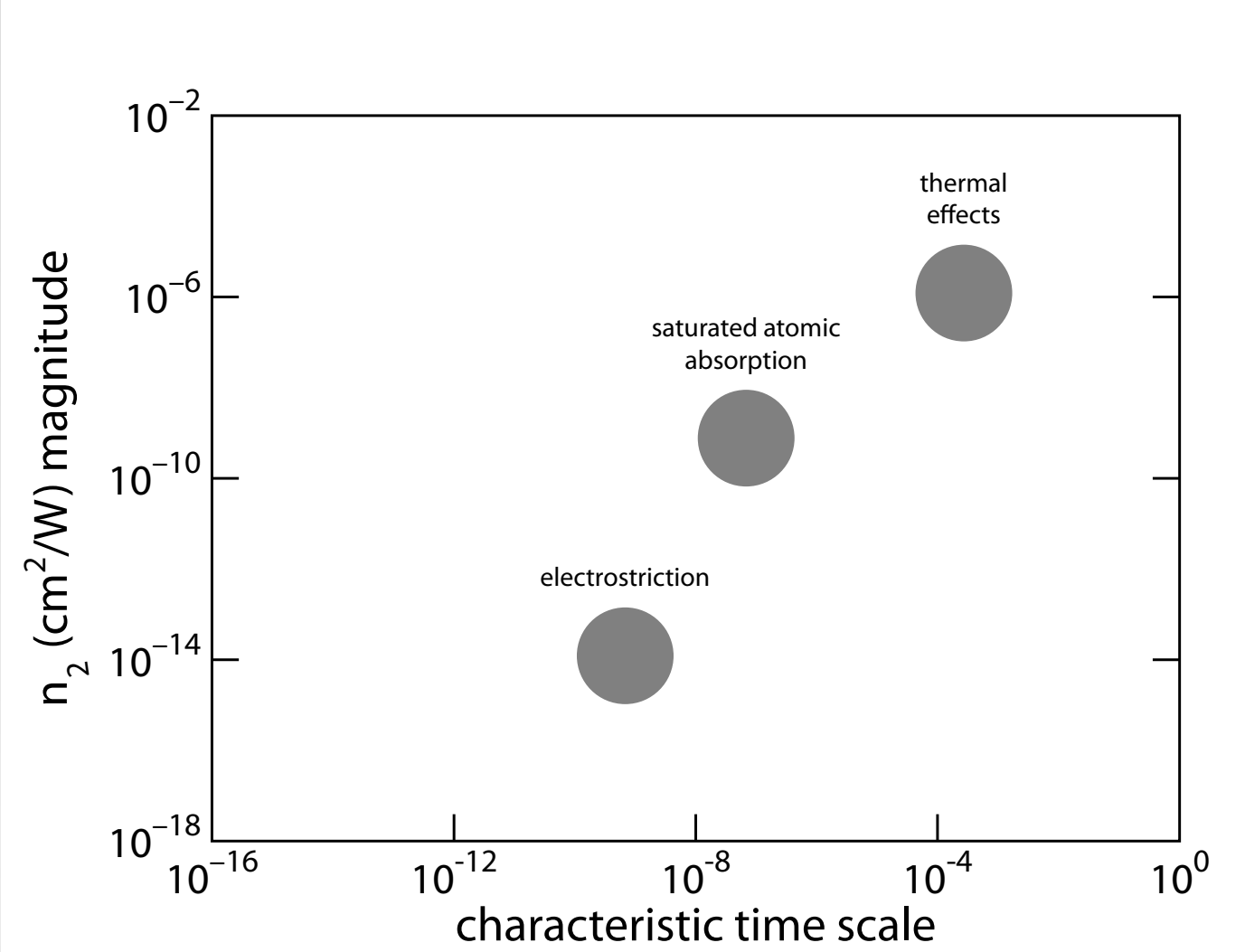
2 NL materials

fast nonlinearities



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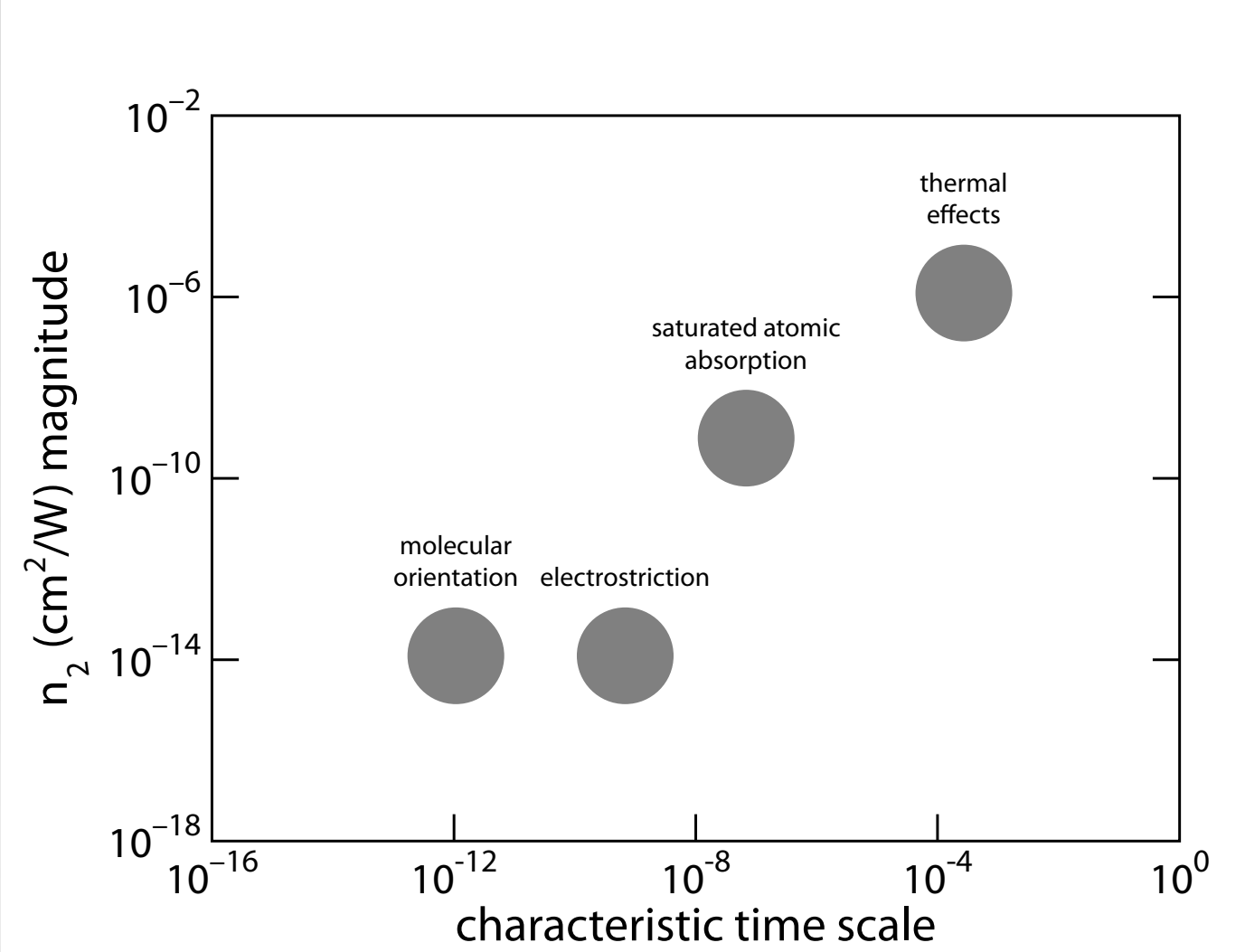
fast nonlinearities



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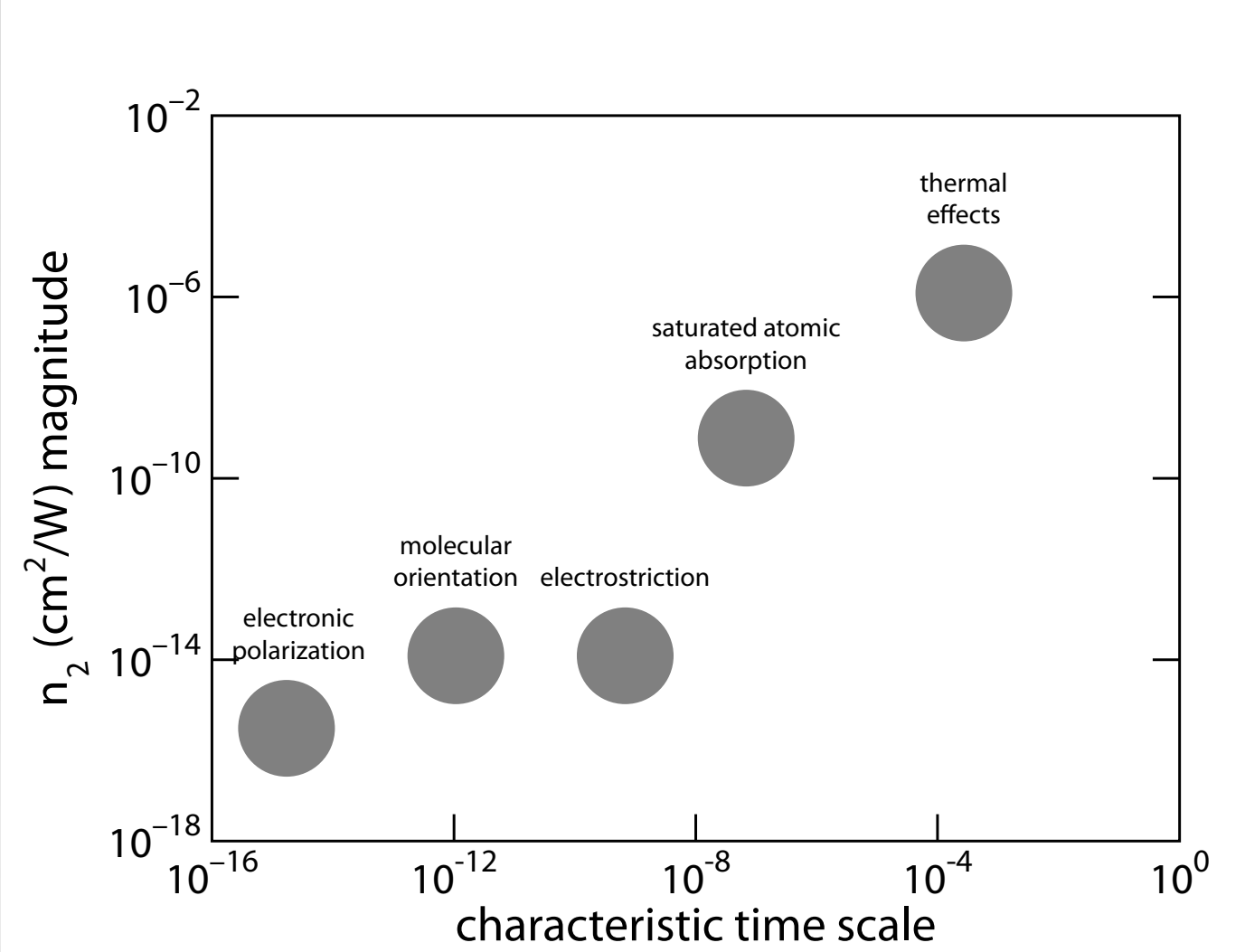
fast nonlinearities

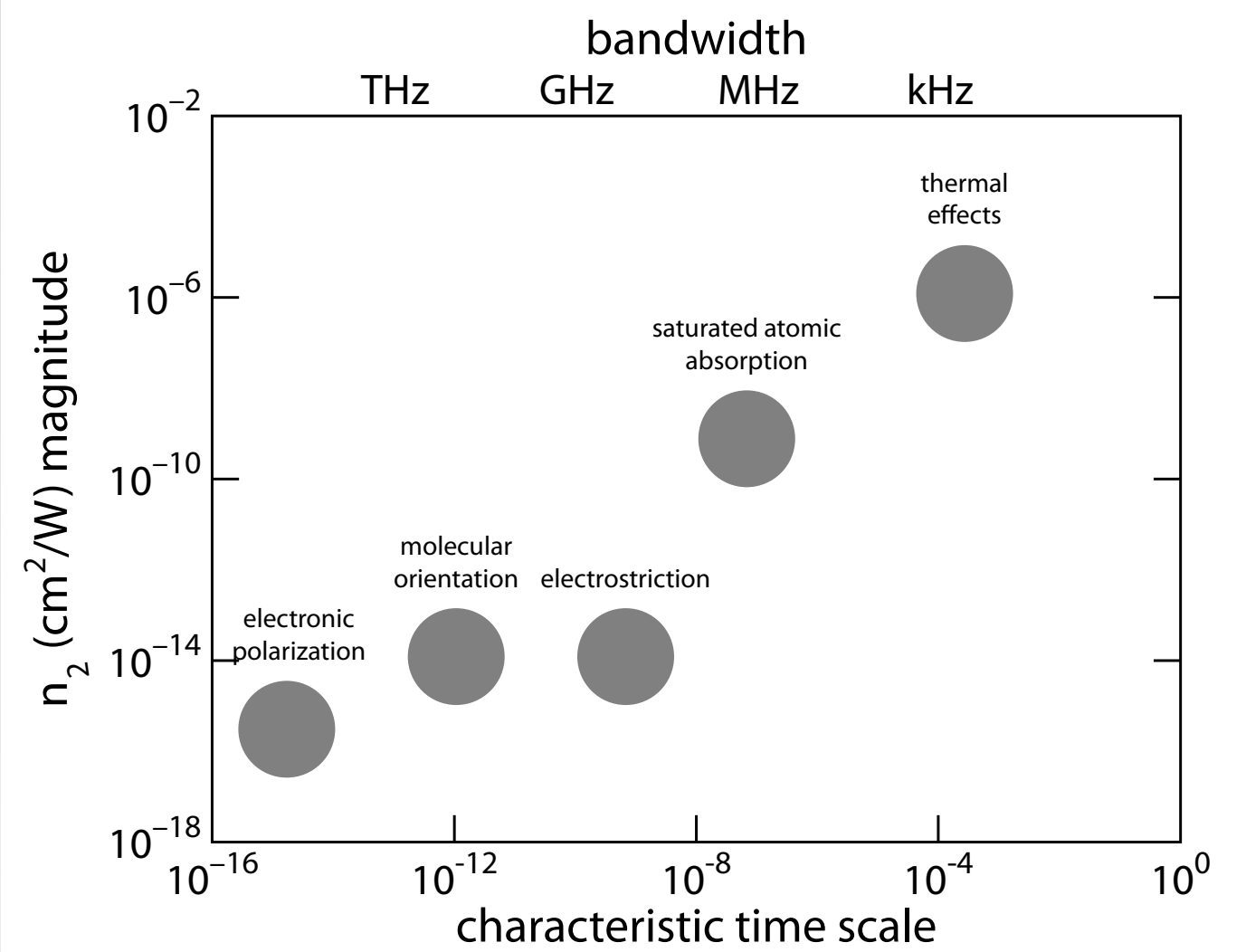


Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic

2 NL materials

fast nonlinearities

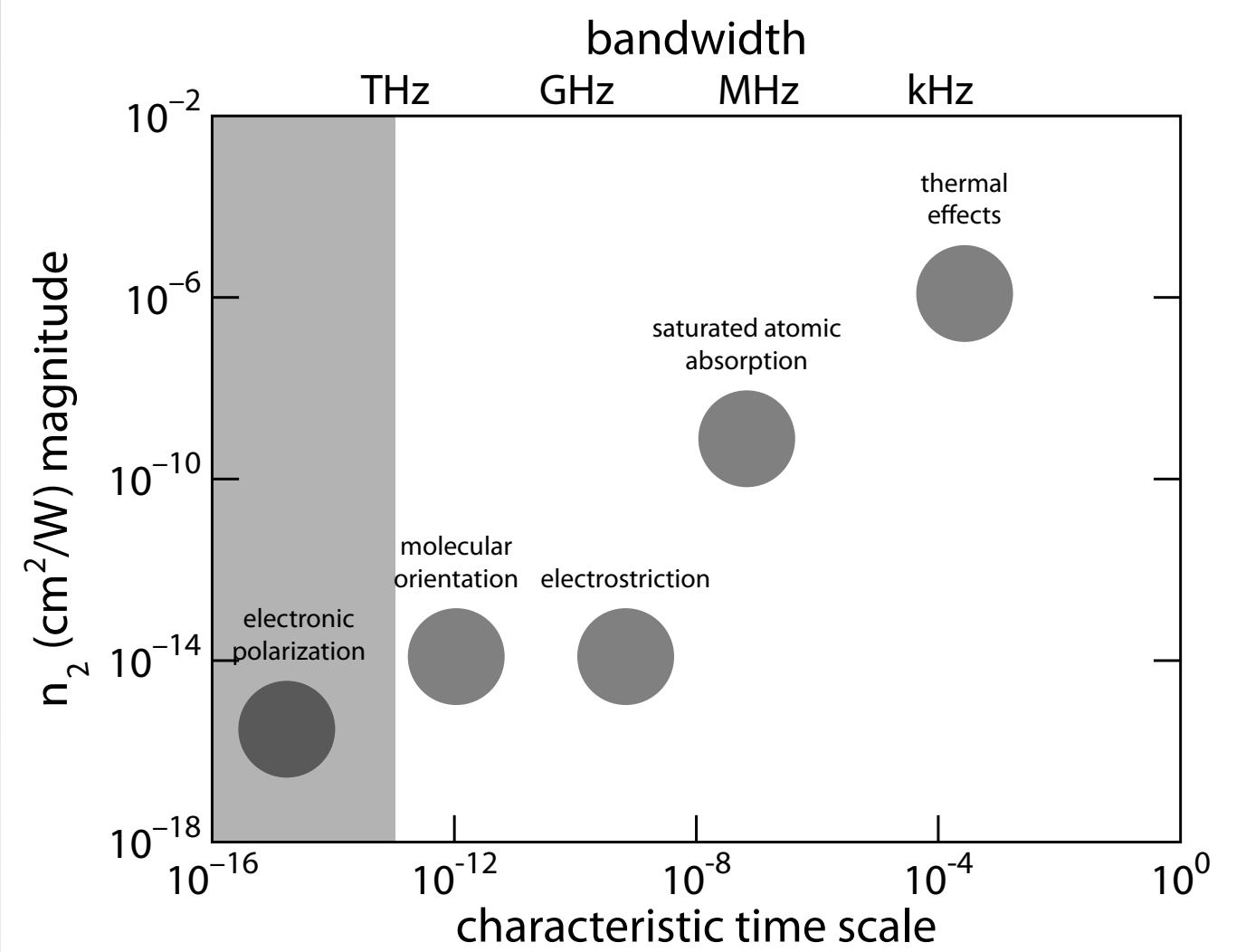


Boyd, Nonlinear optics, 3rd ed.

1 all-optical logic

2 NL materials

... comparatively small

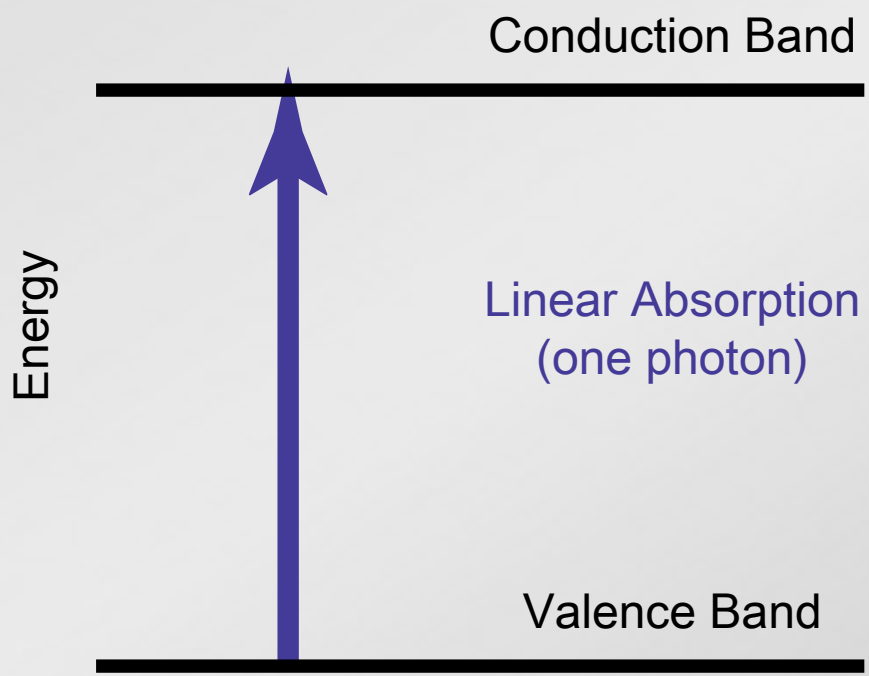


Boyd, Nonlinear optics, 3rd ed.

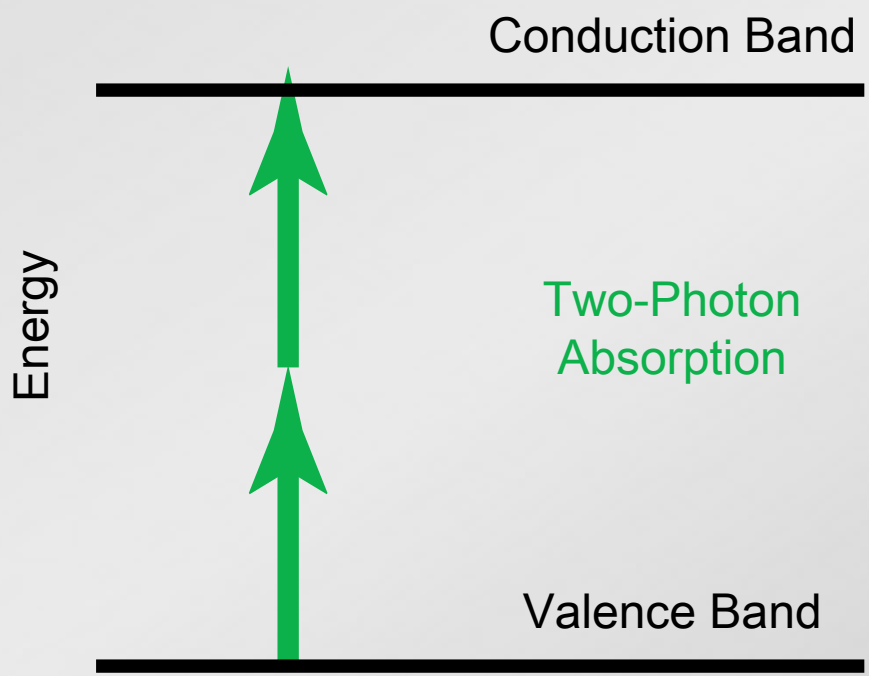
1 all-optical logic

2 NL materials

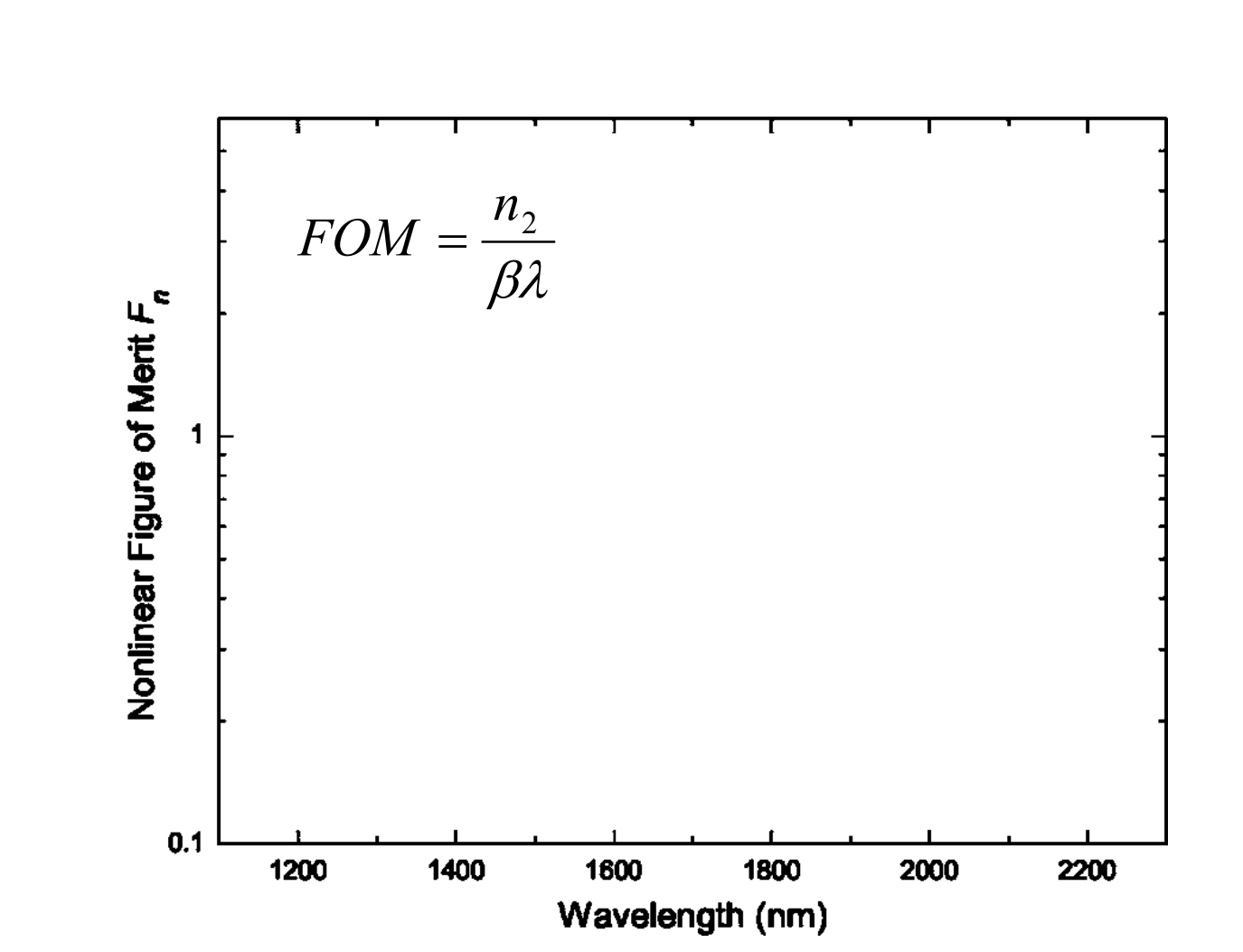
linear losses



two-photon absorption



two-photon absorption limitation

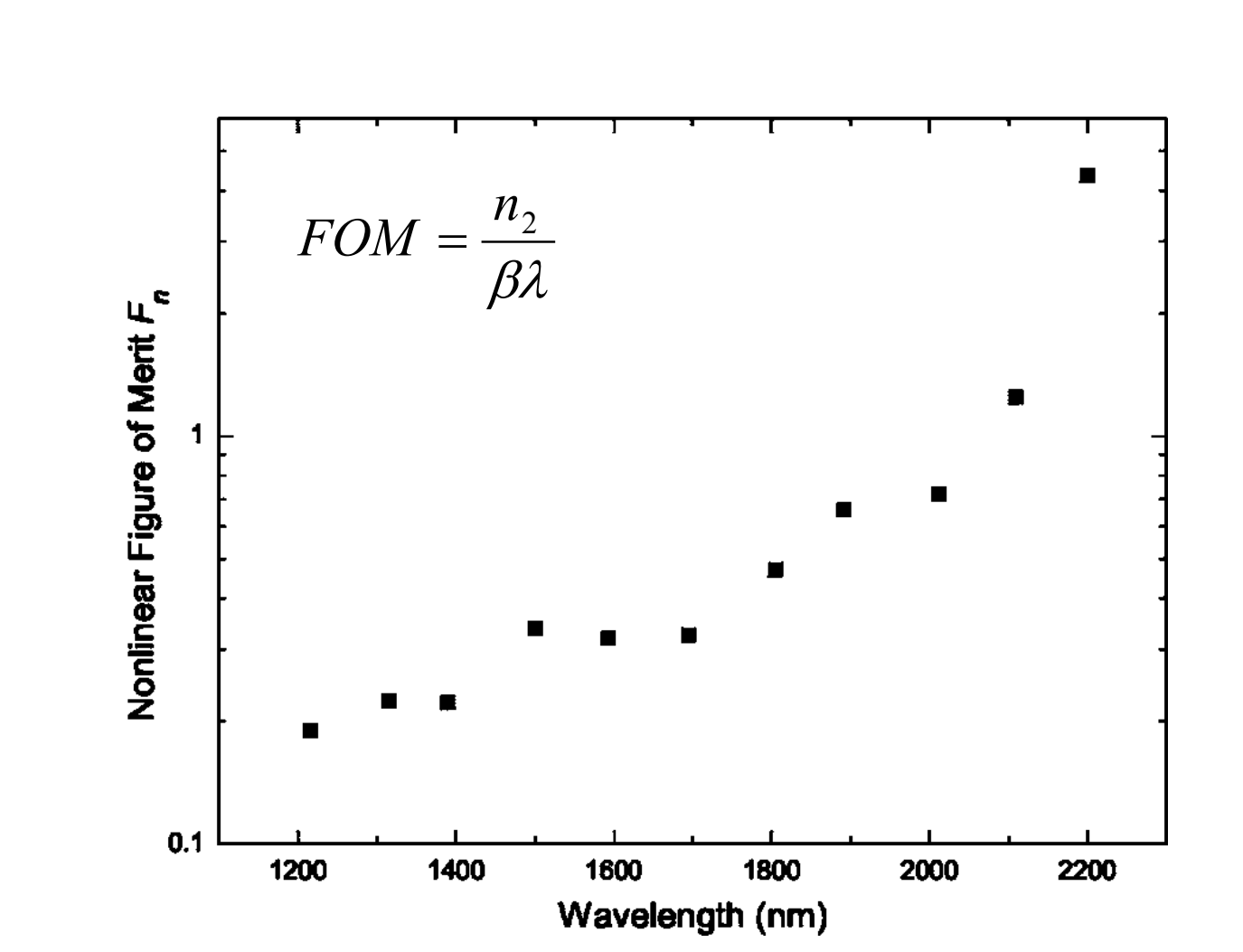


Q. Lin et. al., Appl. Phys. Lett. 91(2007).

1 all-optical logic

2 NL materials

two-photon absorption limitation in silicon



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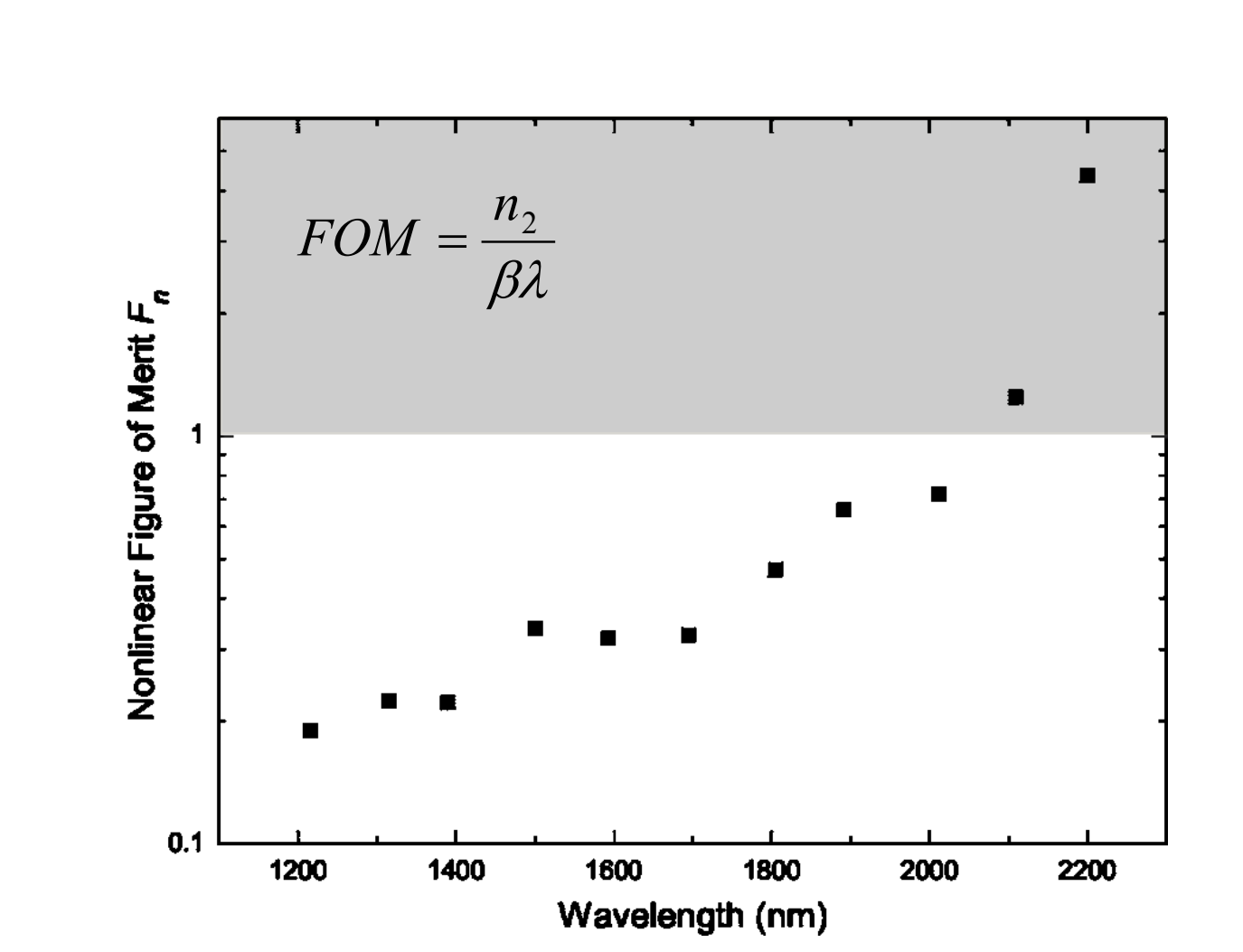
two-photon absorption limitation in silicon

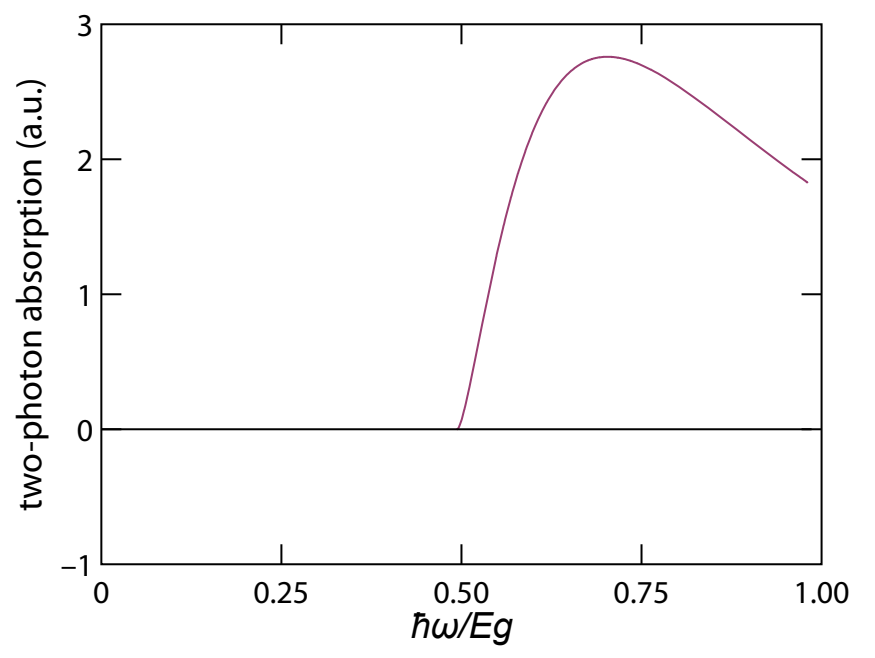


Q. Lin et. al., Appl. Phys. Lett. 91(2007).

1 all-optical logic

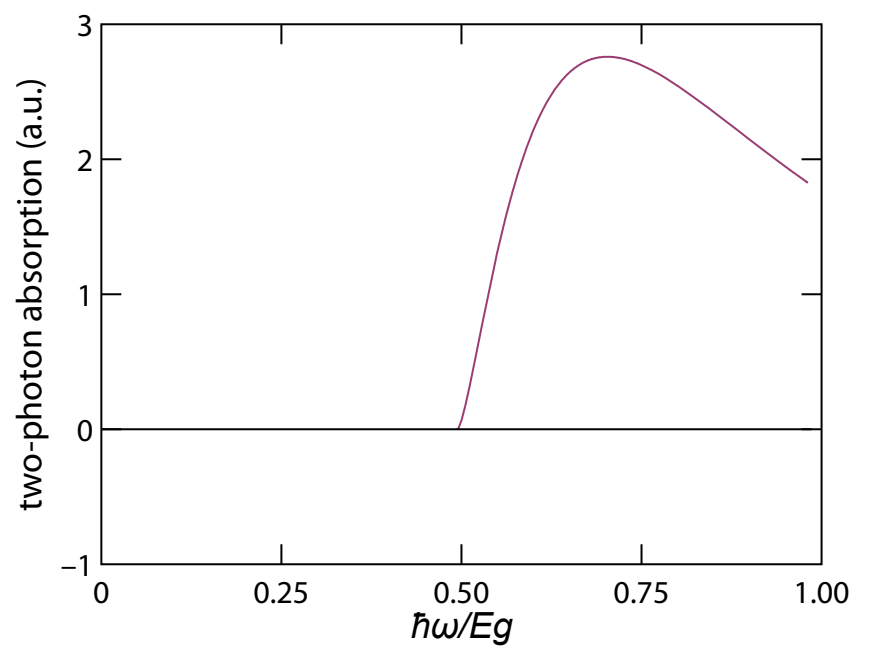
2 NL materials

modeling nonlinearities



M. Sheik-Bahae et. al., Physical Review Letters 65, 96 (1990).

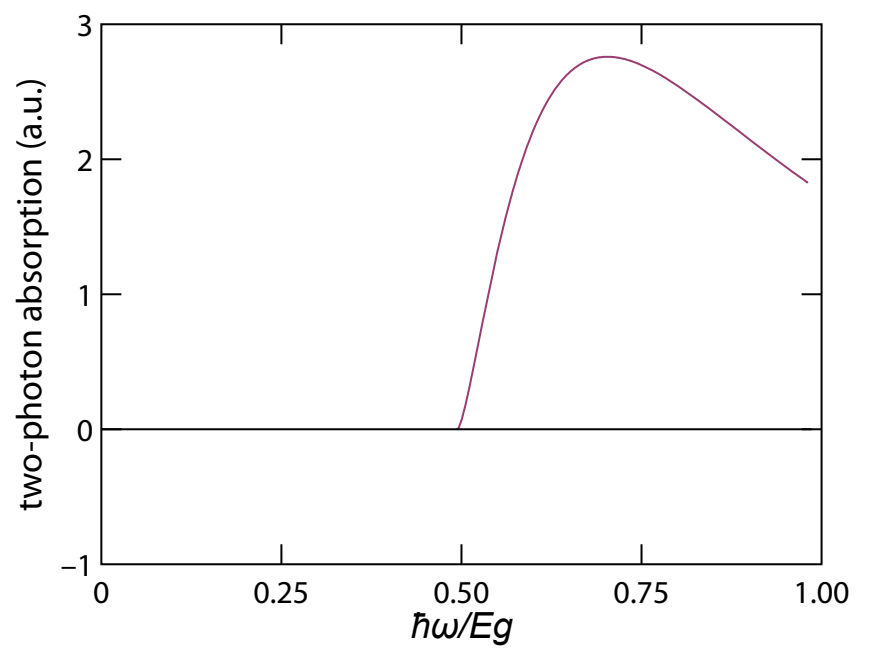
modeling nonlinearities

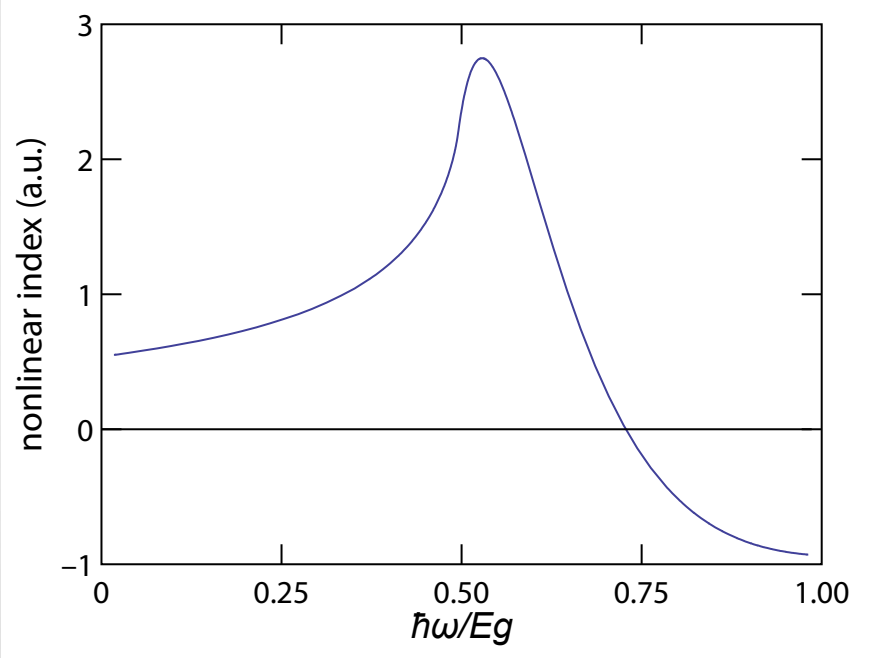


$$\frac{hc}{\lambda} < \frac{E_g}{2}$$

M. Sheik-Bahae et. al., Physical Review Letters 65, 96 (1990).

modeling nonlinearities





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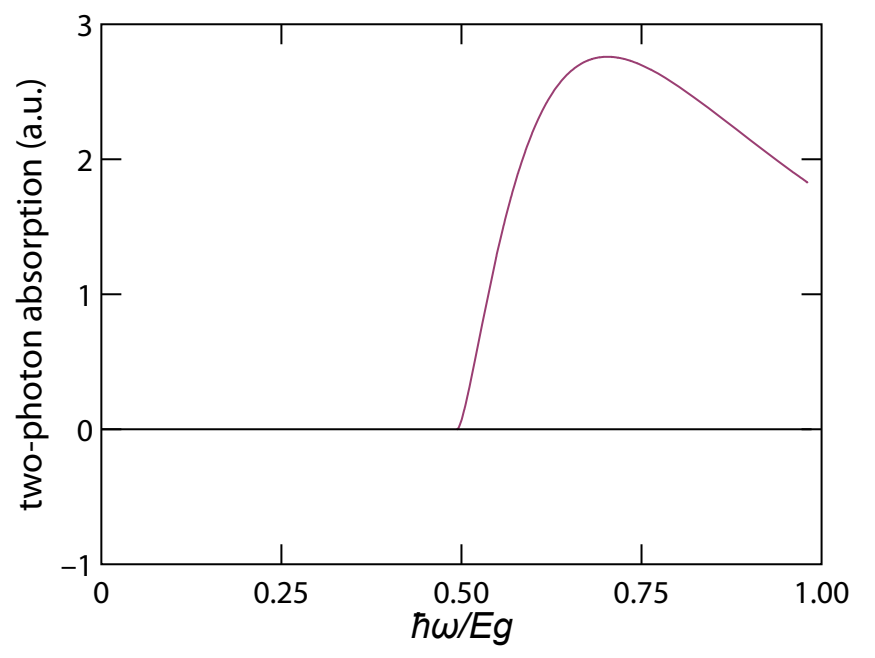
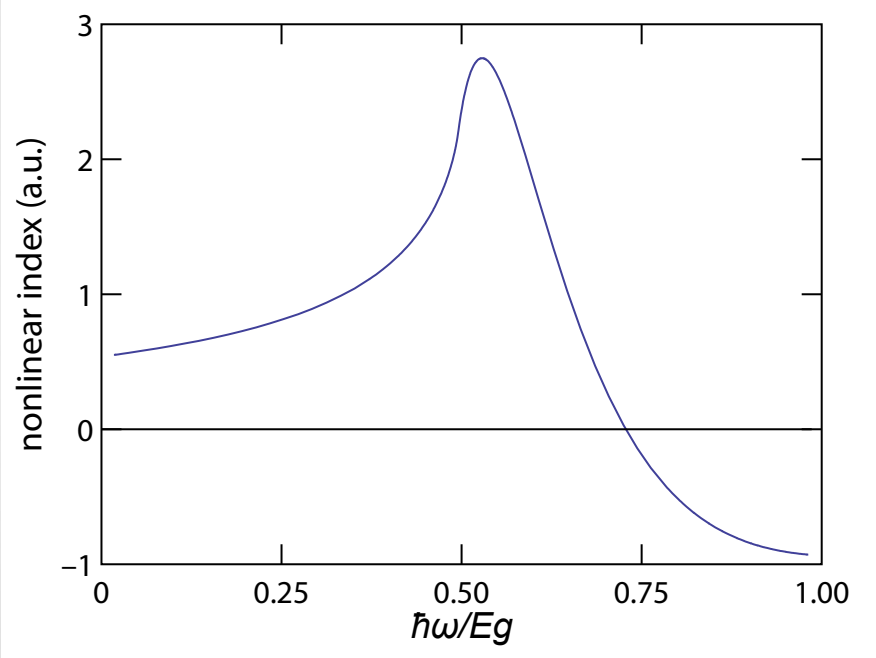
M. Sheik-Bahae et. al., Physical Review Letters 65, 96 (1990).

1 all-optical logic 2 NL materials

modeling nonlinearities





$$\frac{hc}{\lambda} < \frac{E_g}{2}$$

$$n_2 \propto \frac{1}{n_0^2 E_g^4}$$

M. Sheik-Bahae et. al., Physical Review Letters 65, 96 (1990).

1 all-optical logic

2 NL materials

Titanium dioxide (TiO_2)

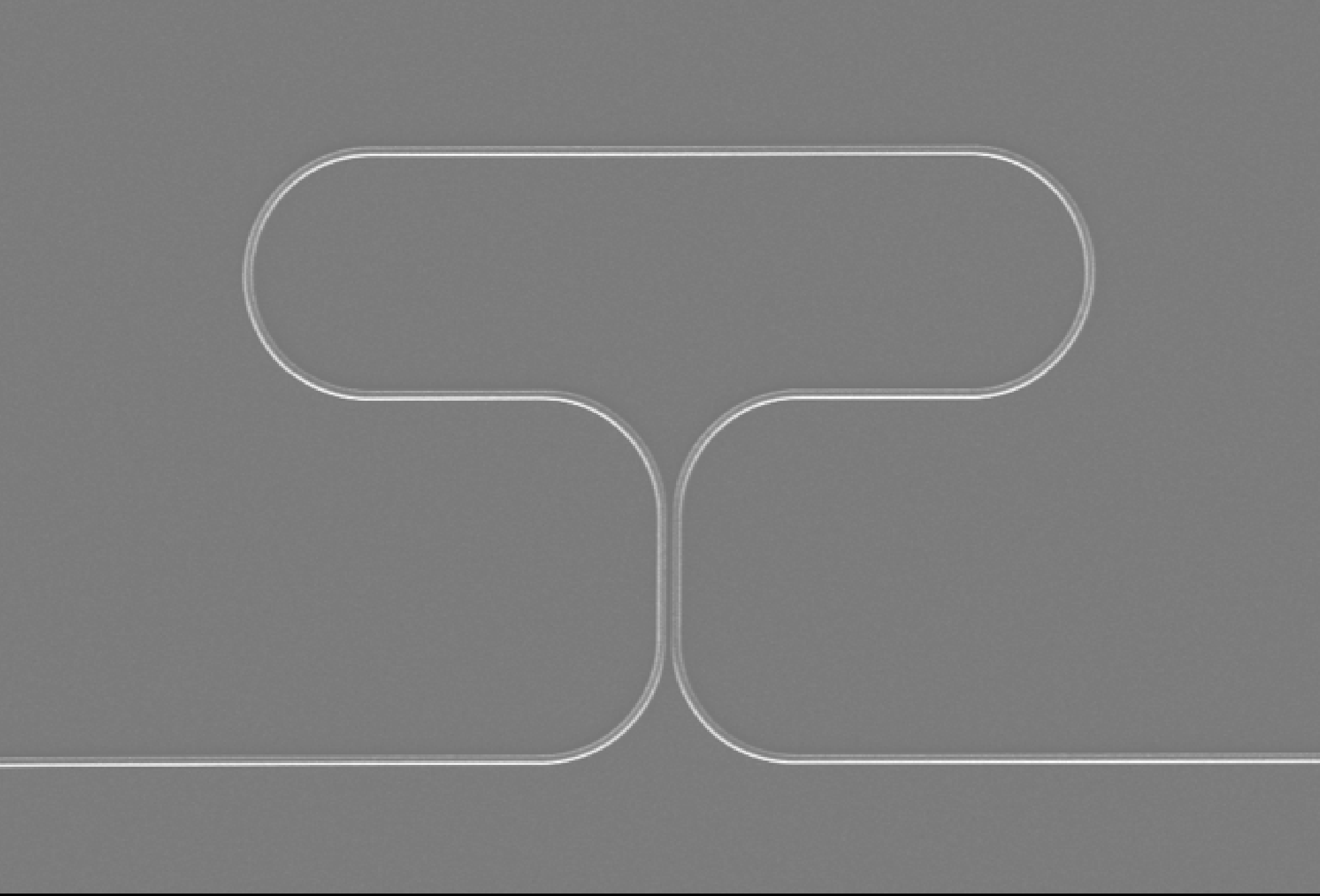
TiO_2 material properties

large nonlinearity:	30 x silica
high index of refraction:	2.5
wide bandgap:	3.1 eV
low two-photon absorption:	≥ 800 nm

several phases:

rutile, anatase, brookite and amorphous

Evans et. al., Opt. Express 20, 3118-3128 (2012).



1 all-optical logic

2 NL materials

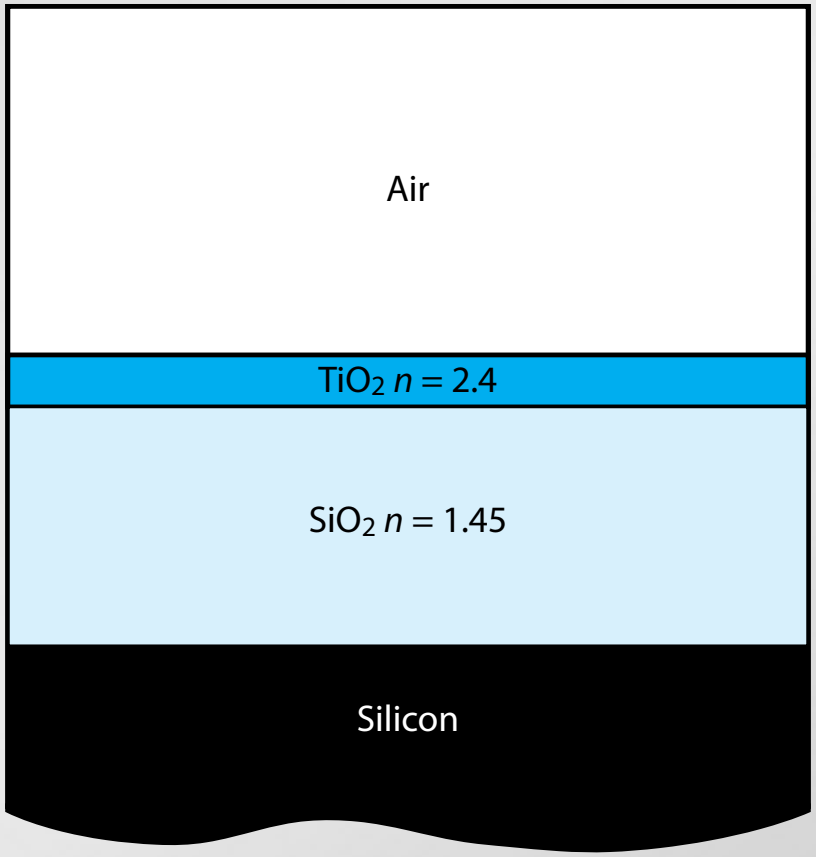
3 TiO_2 photonics

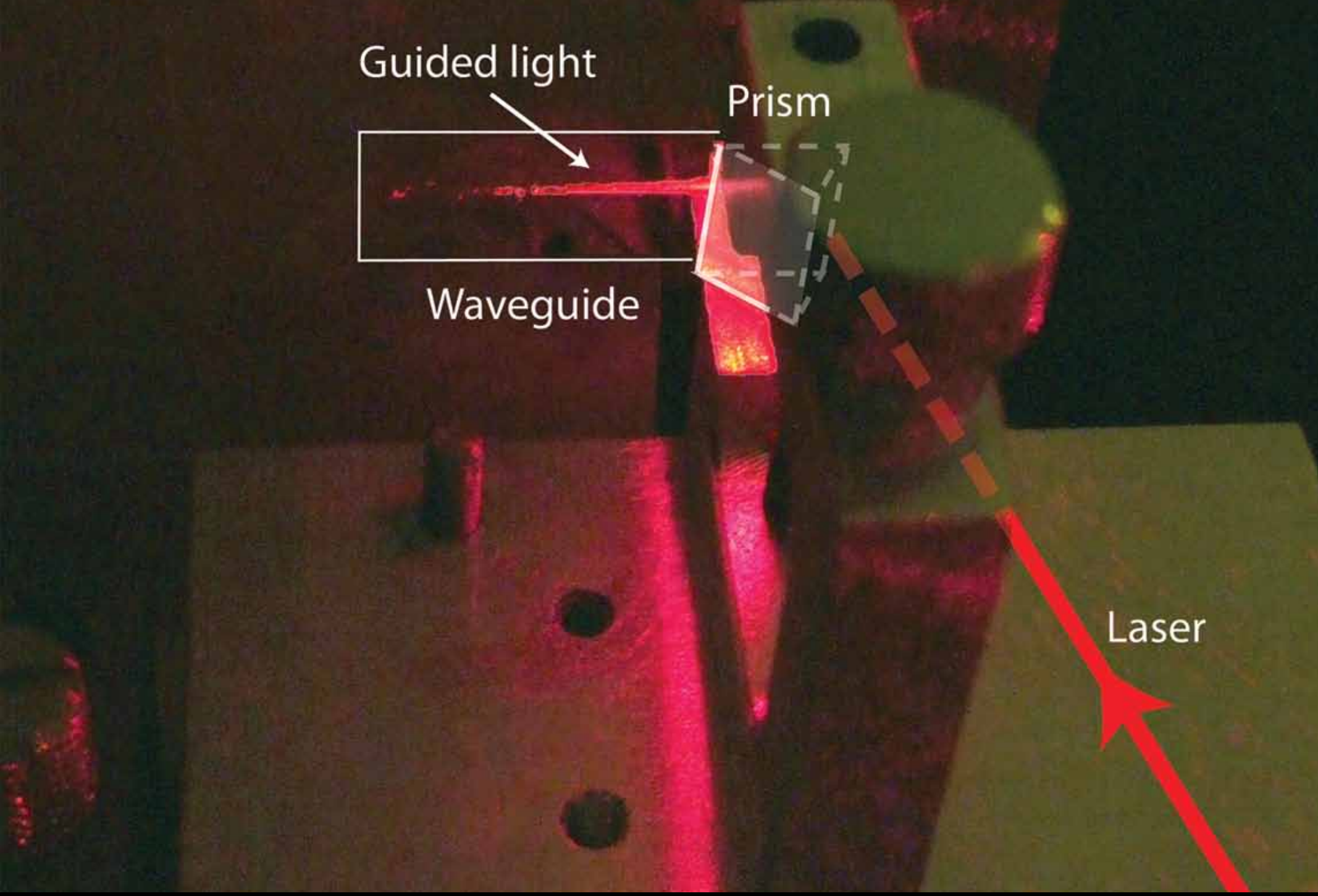
1 all-optical logic

2 NL materials

3 TiO_2 photonics

planar waveguide





1 all-optical logic

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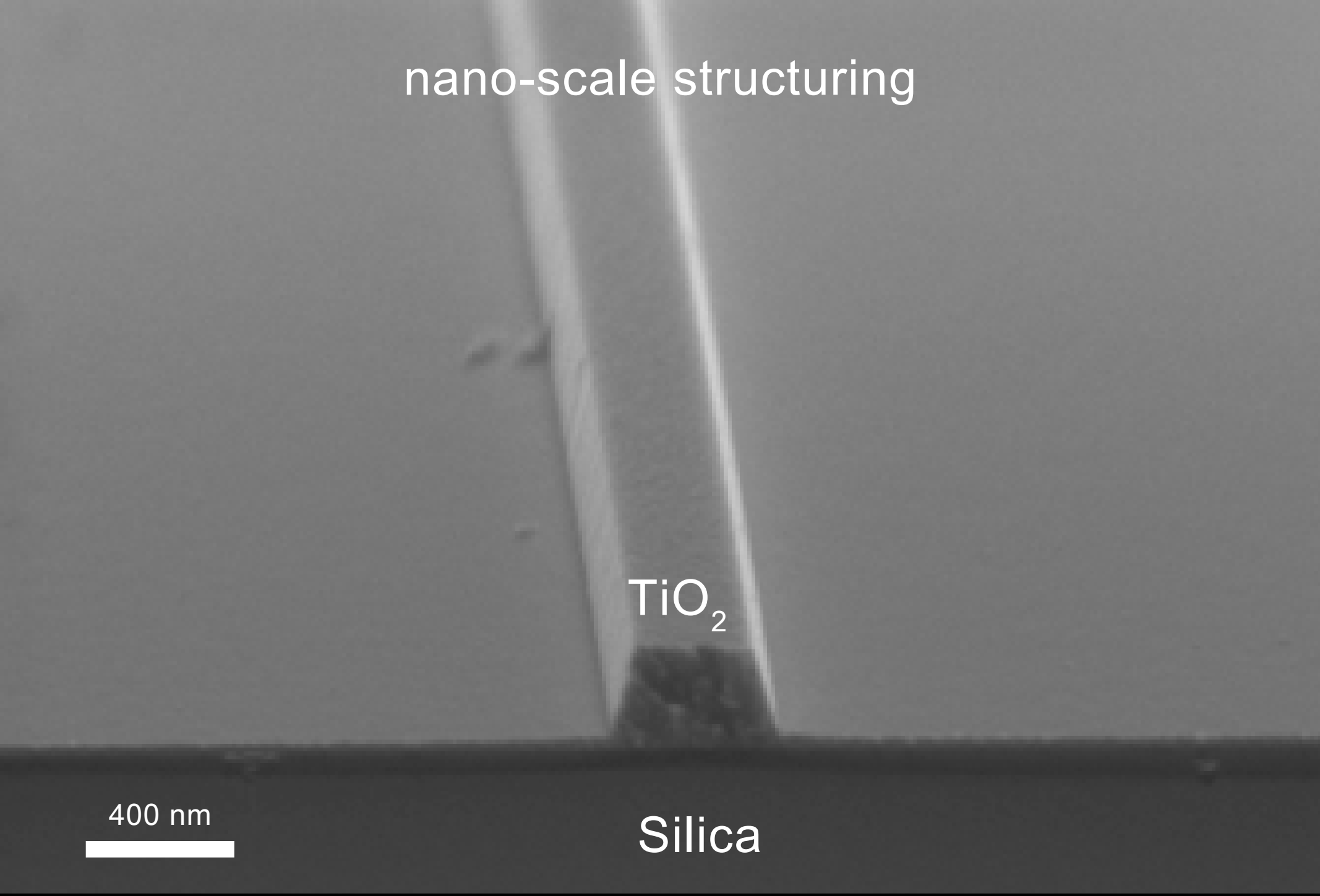

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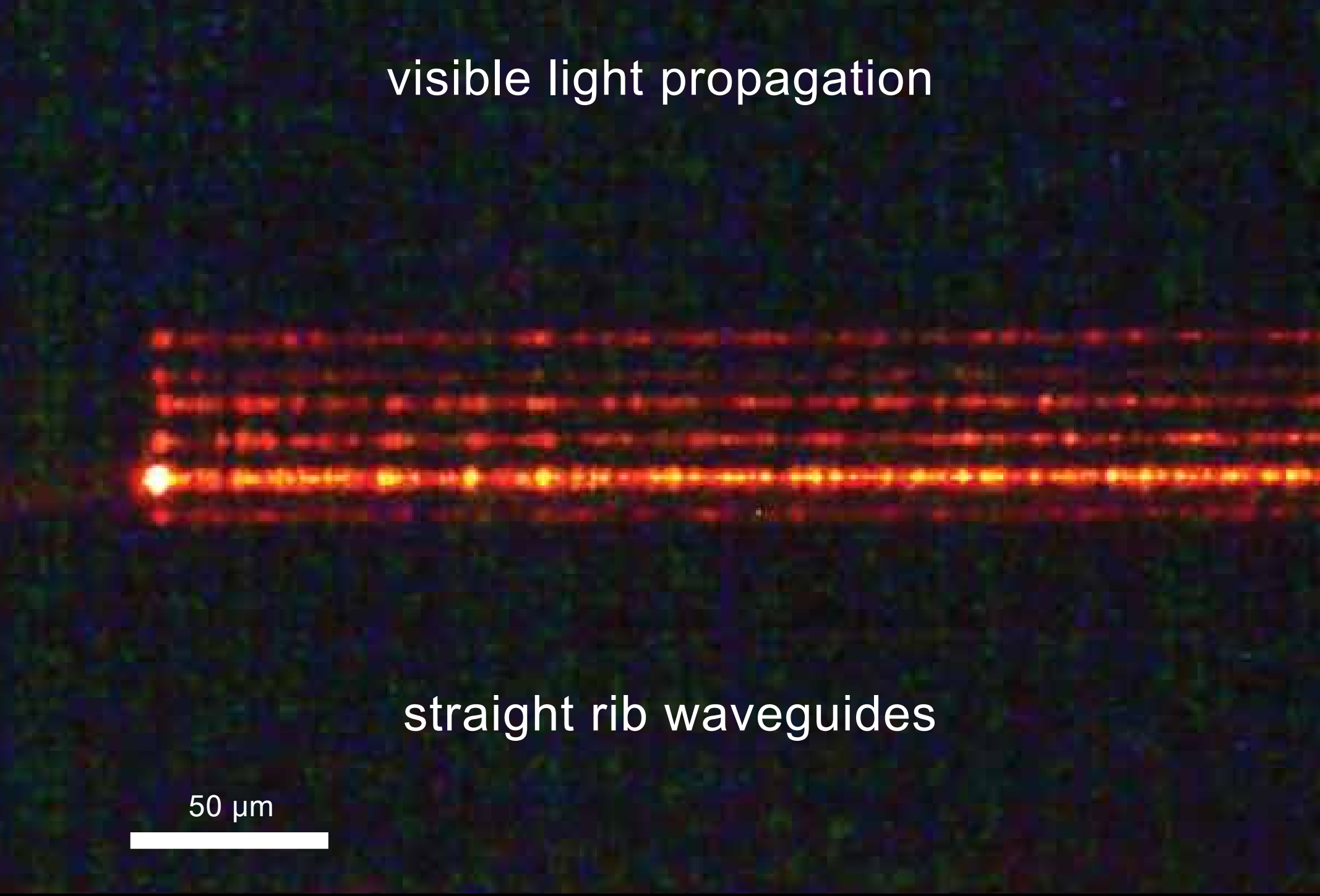

1 all-optical logic

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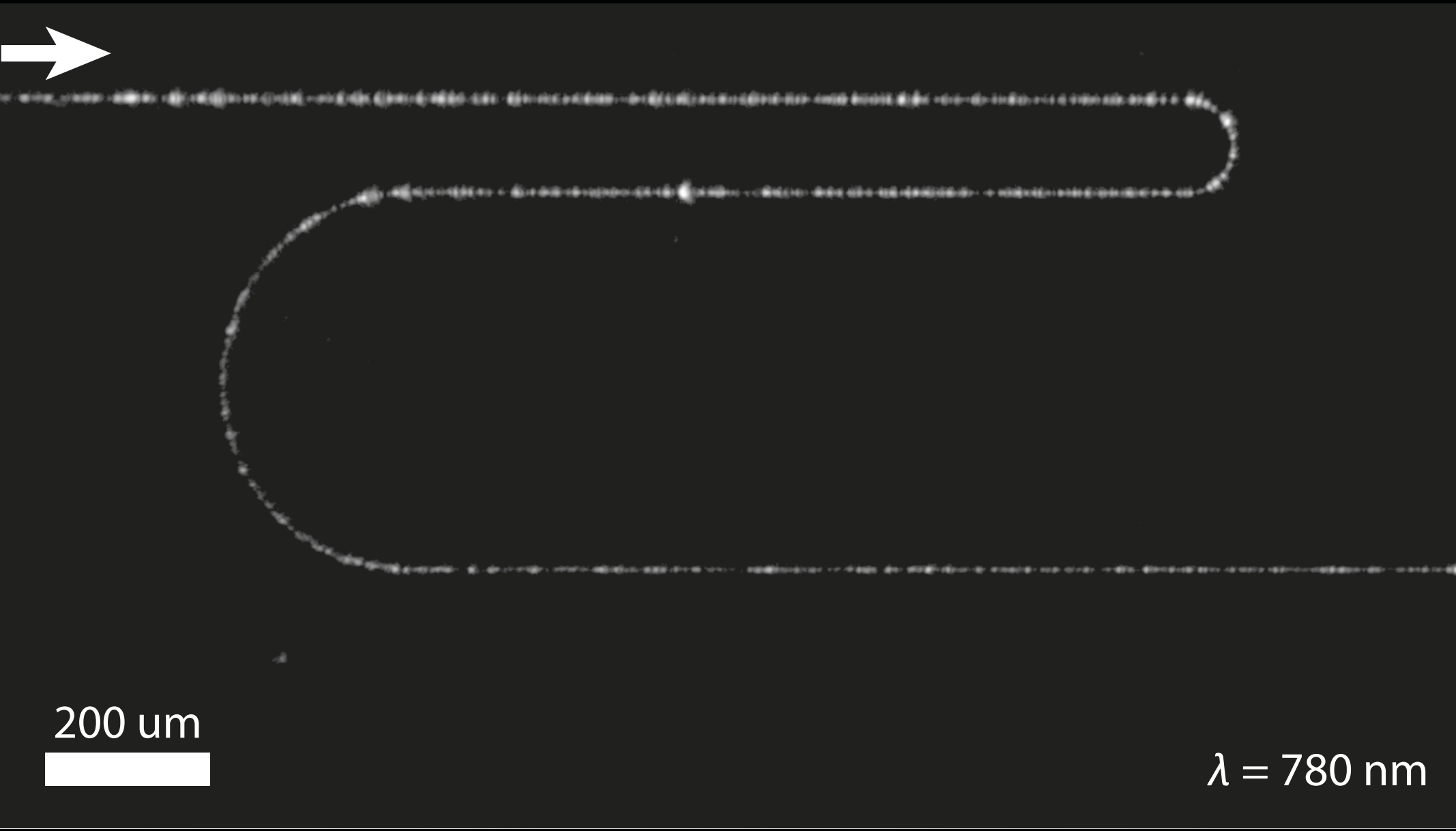
amorphous waveguides



1 all-optical logic

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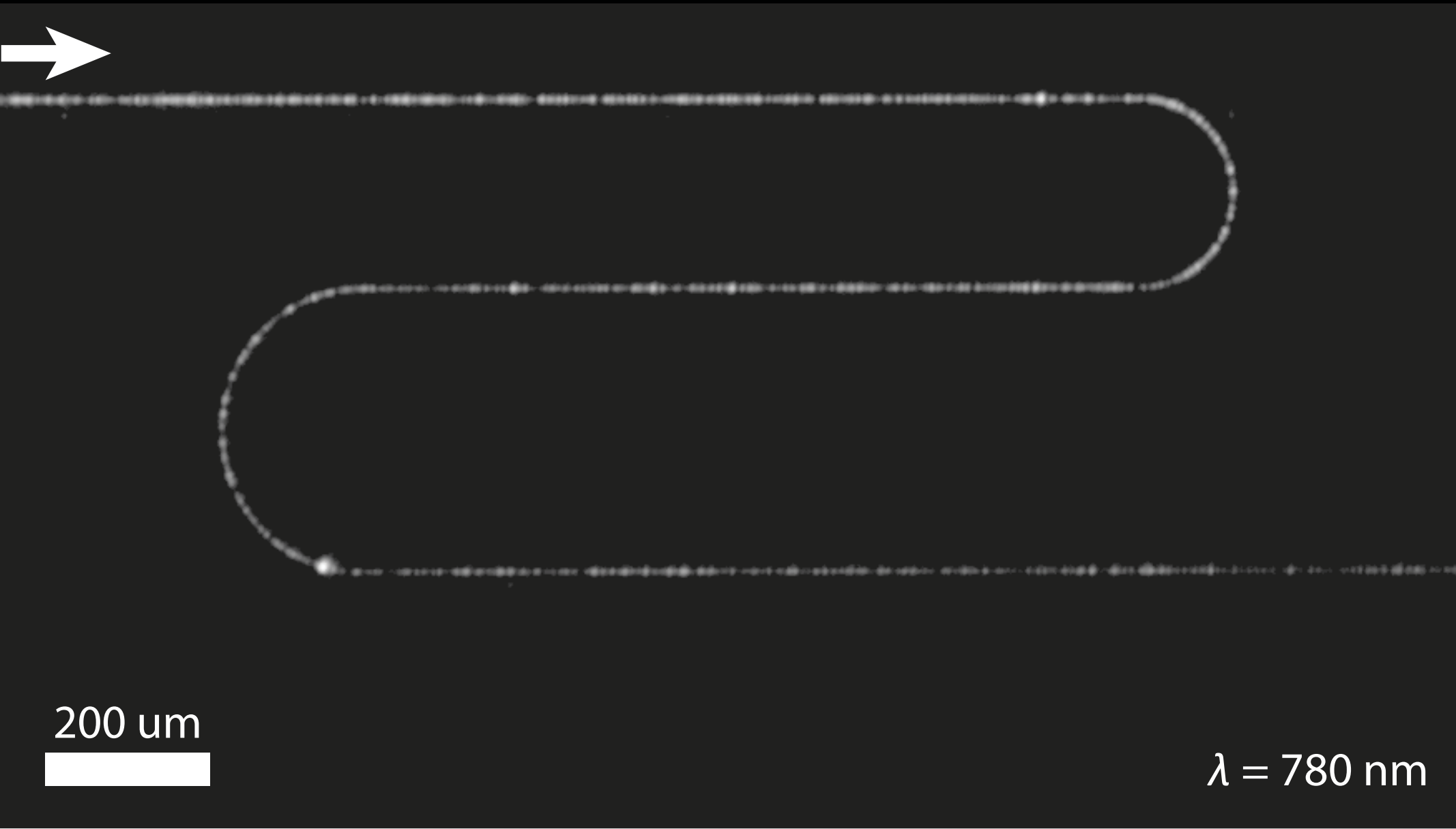
anatase waveguides



1 all-optical logic

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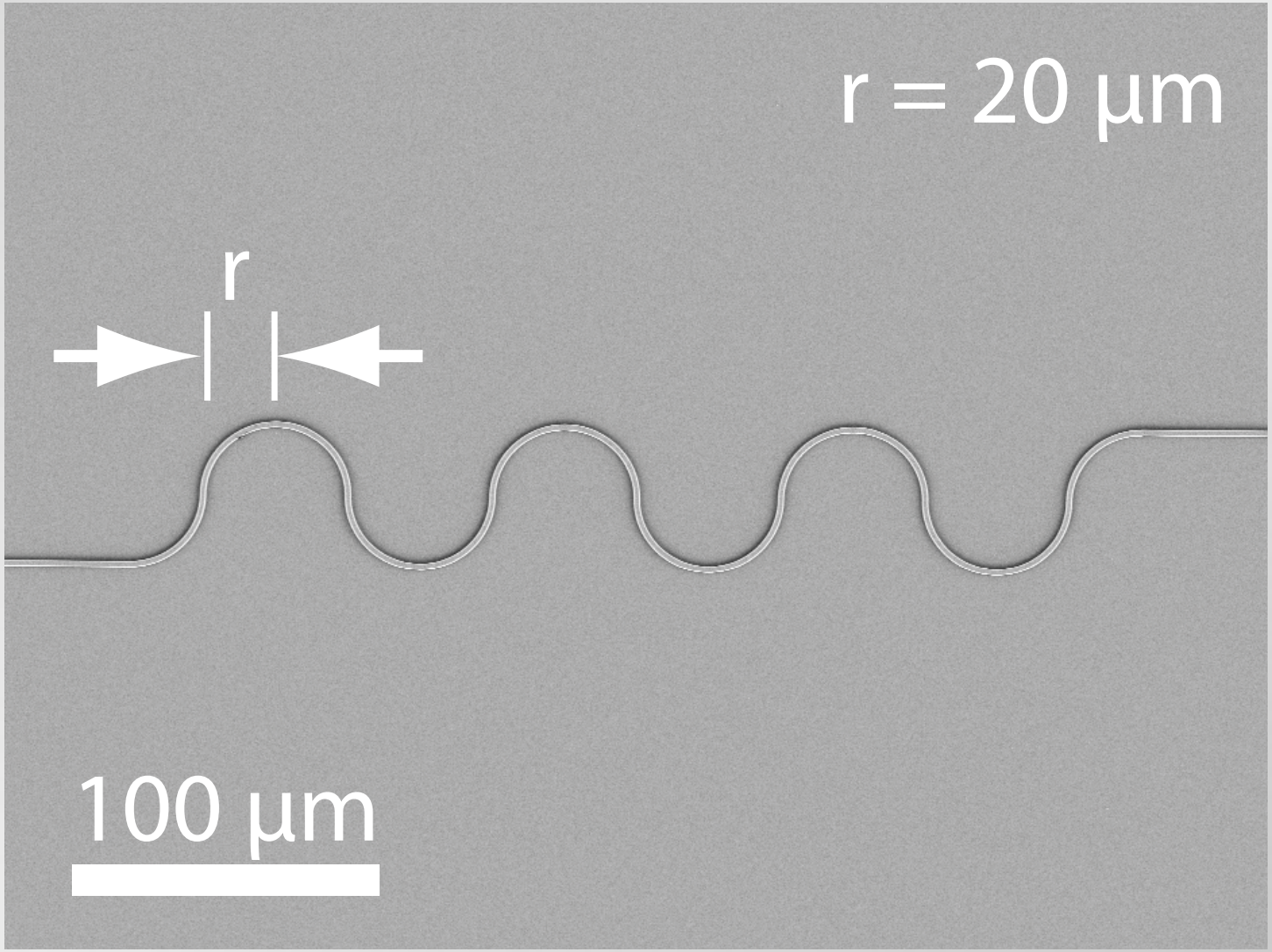
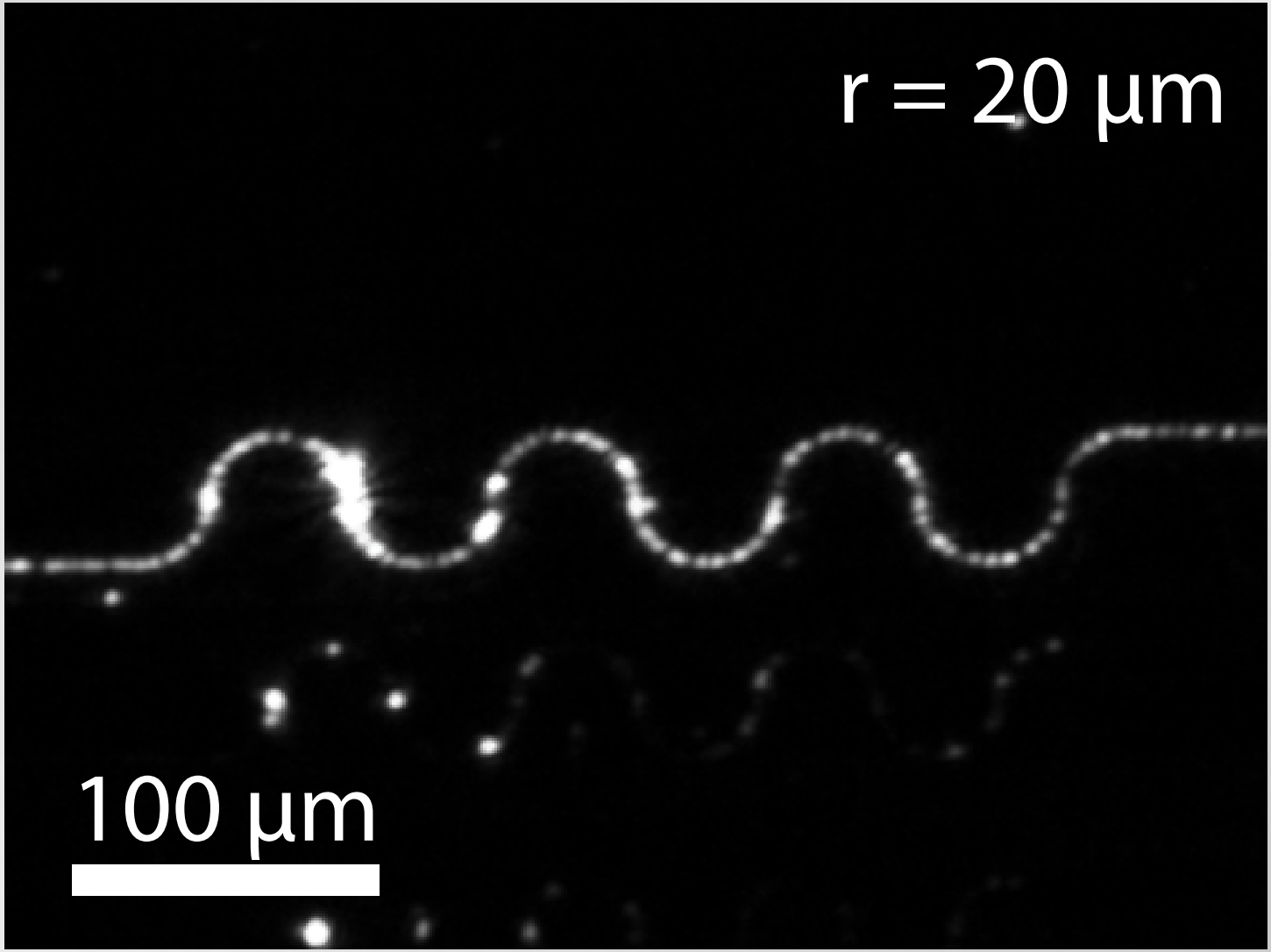
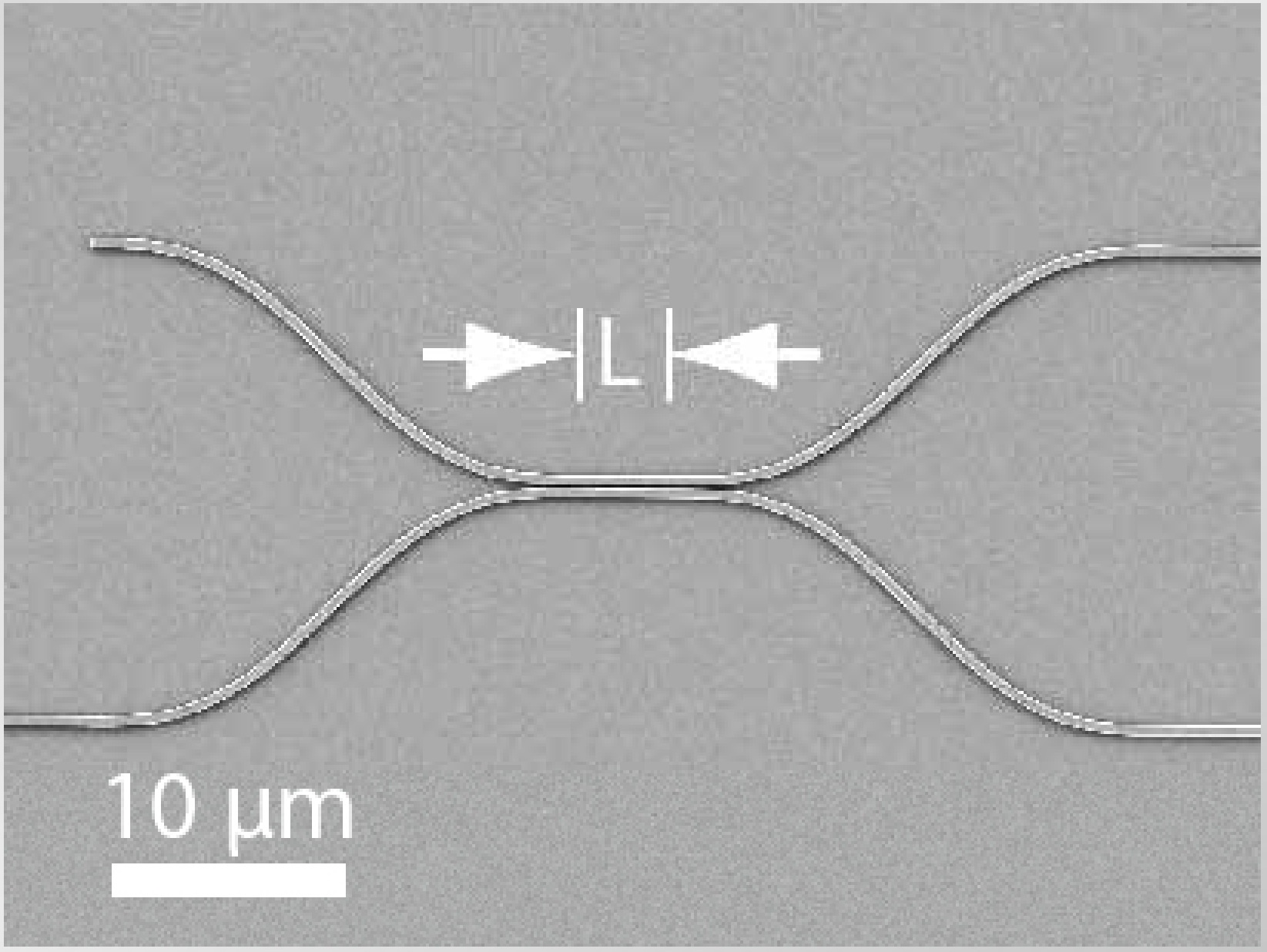
microbends



microbends



variable splitters



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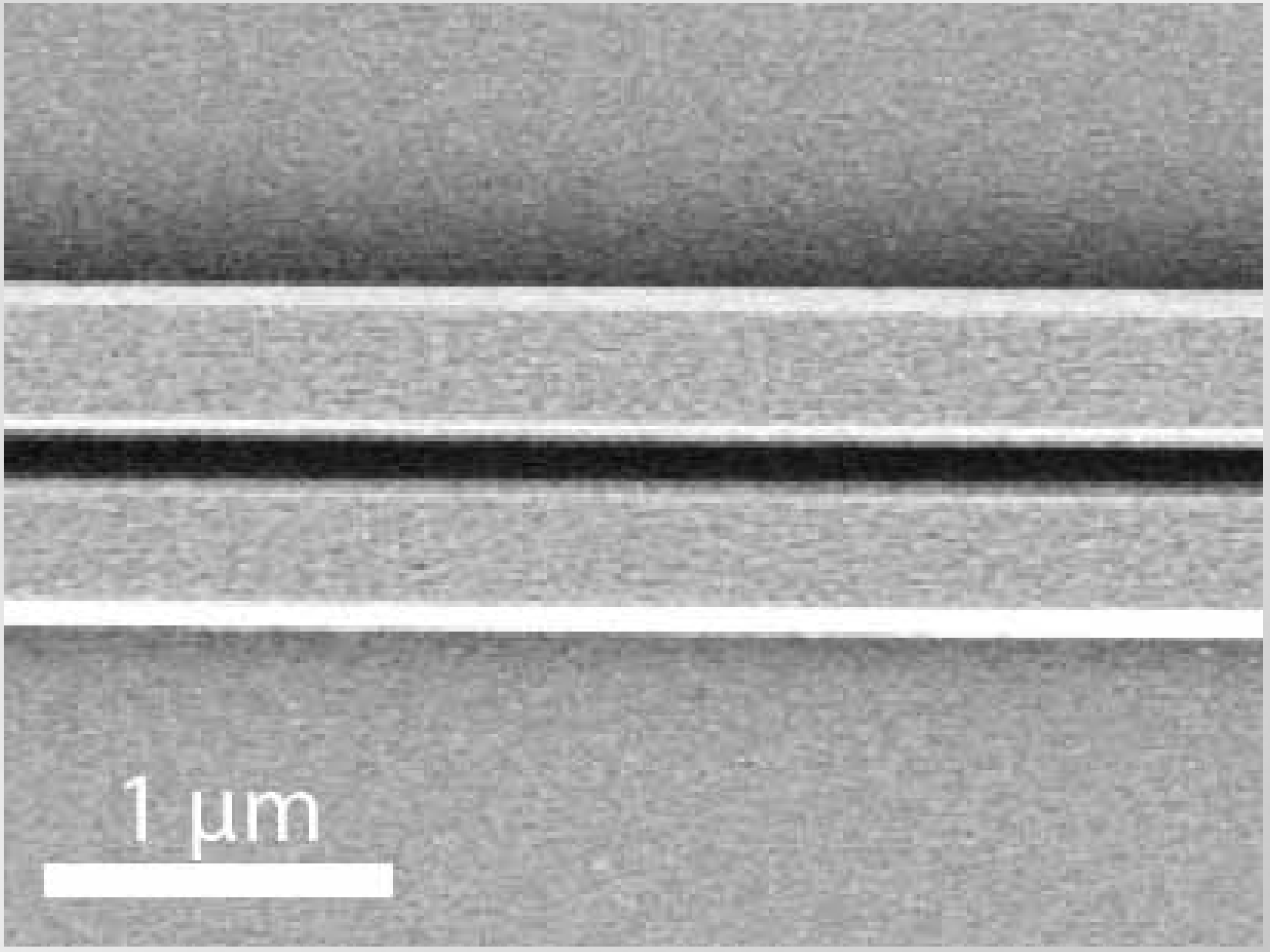
variable splitters



1 all-optical logic

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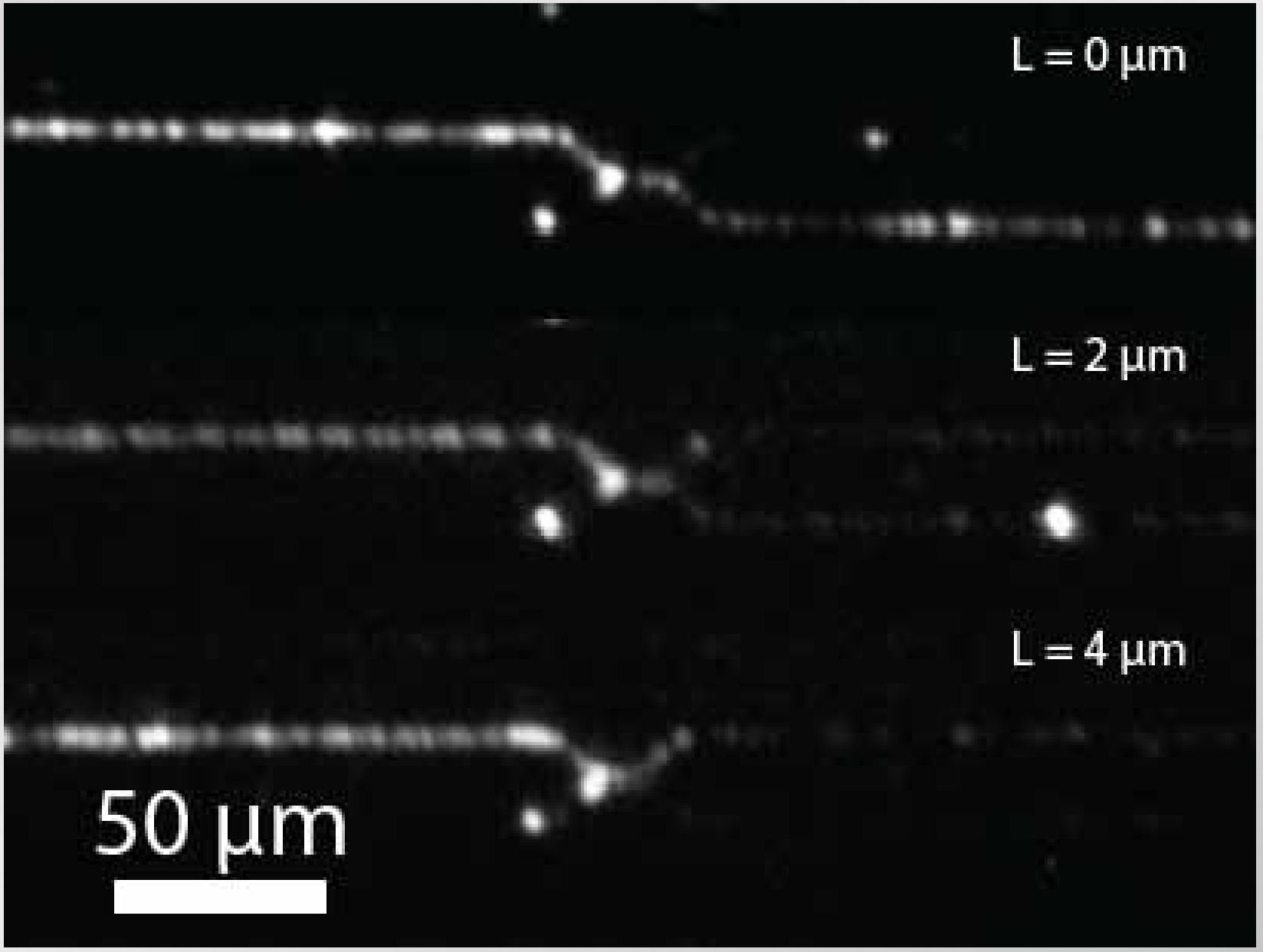
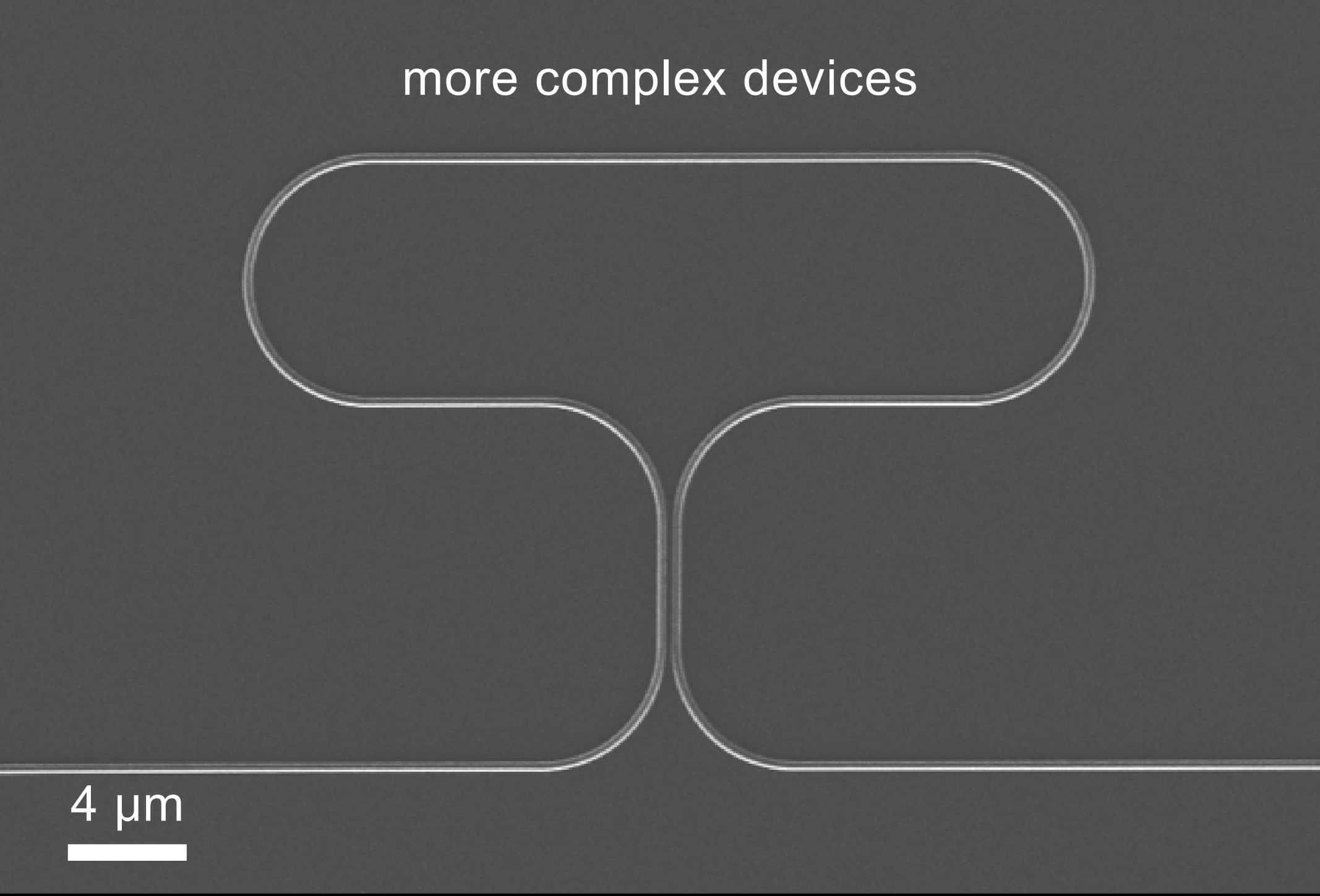
variable splitters



1 all-optical logic 2 NL materials 3 TiO_2 photonics

more complex devices



1 all-optical logic

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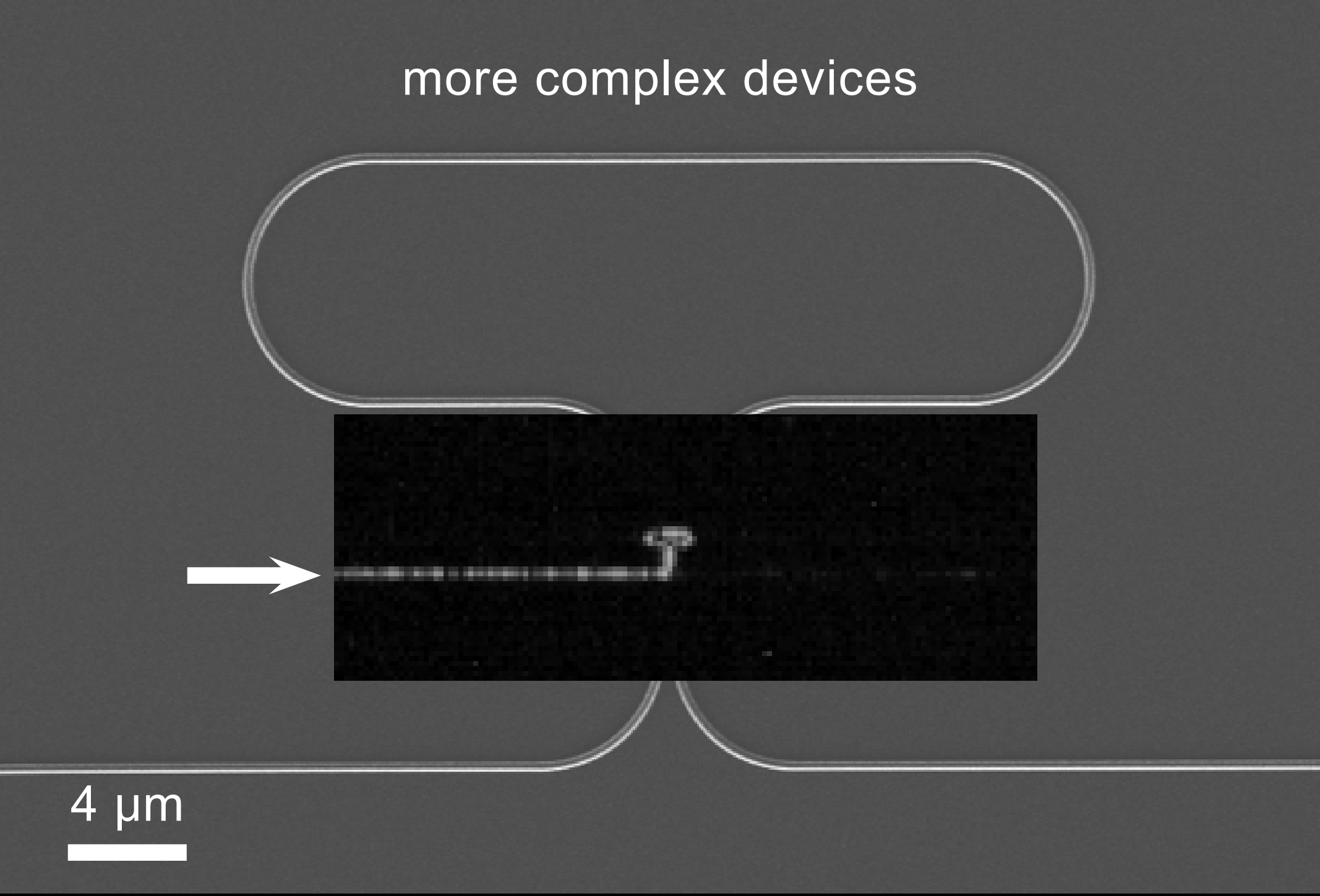
3 TiO_2 photonics

more complex devices

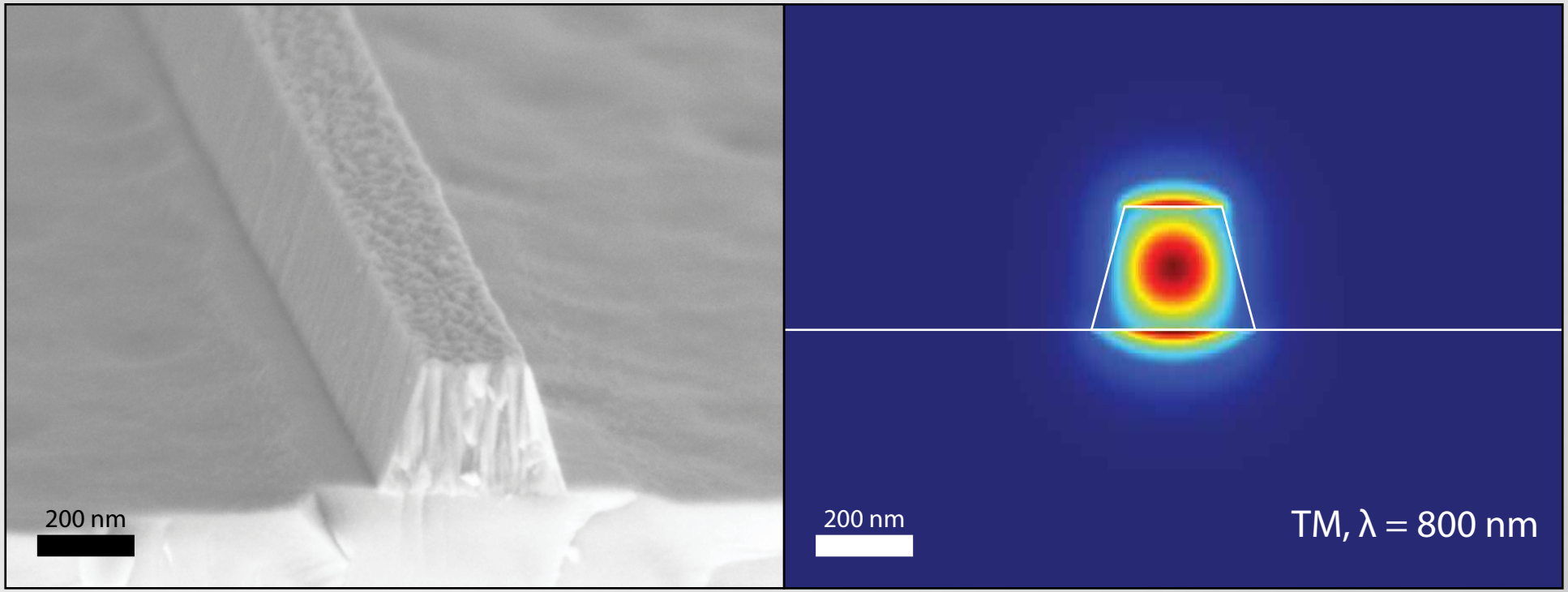


1 all-optical logic

2 NL materials

3 TiO_2 photonics

the first nonlinear optics in TiO_2



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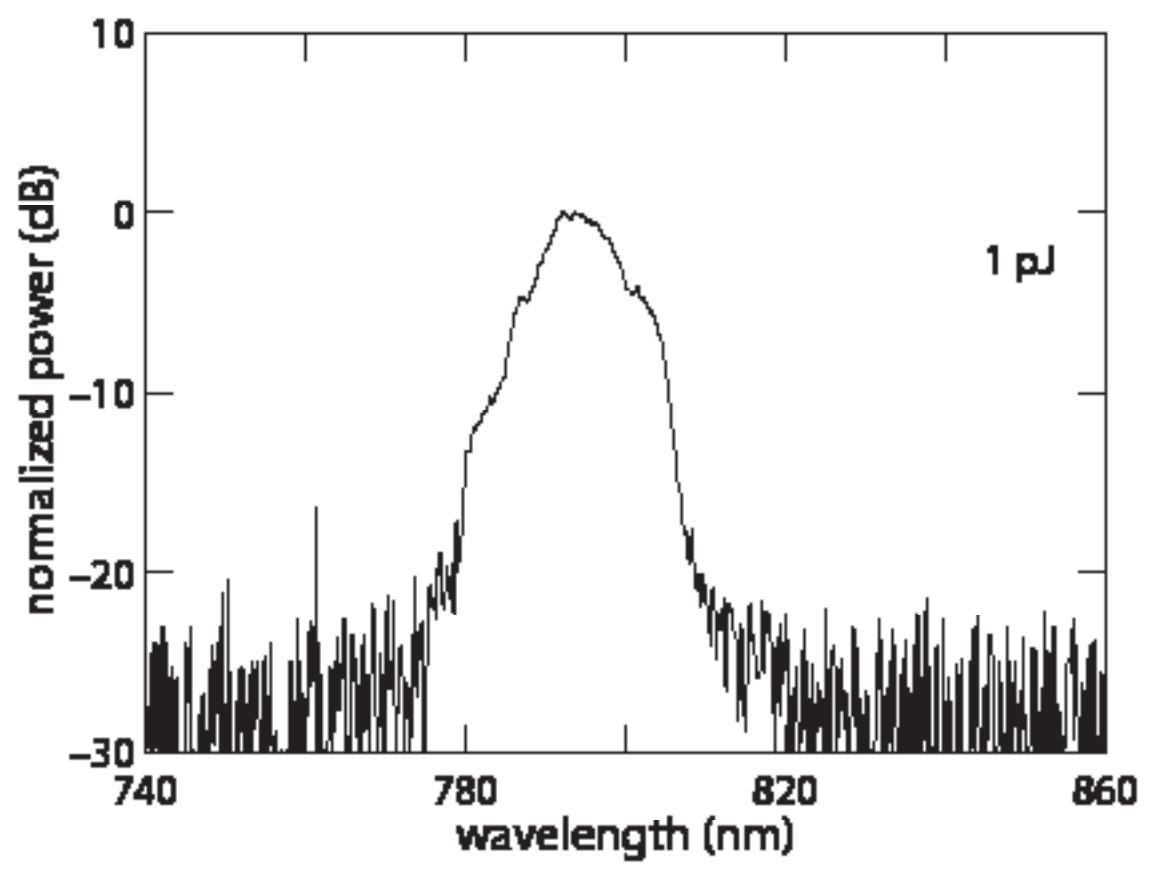

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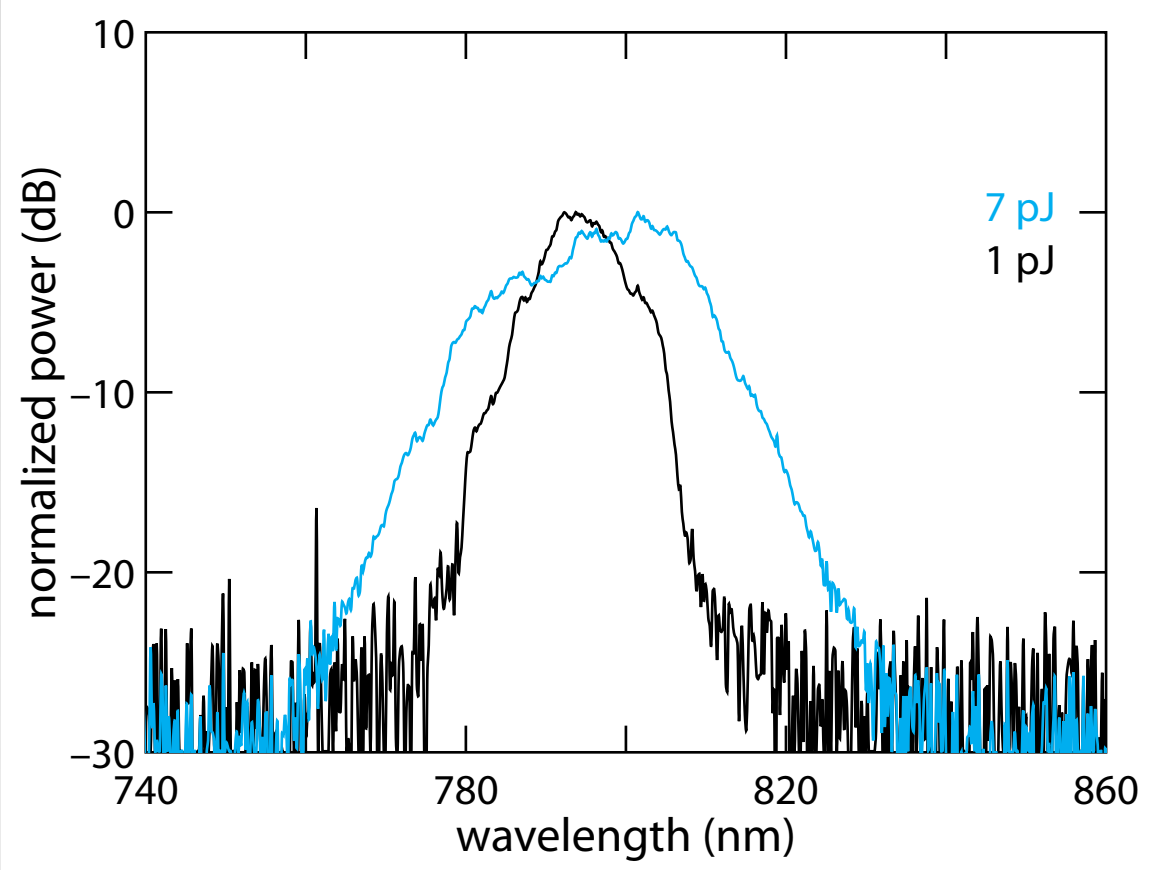

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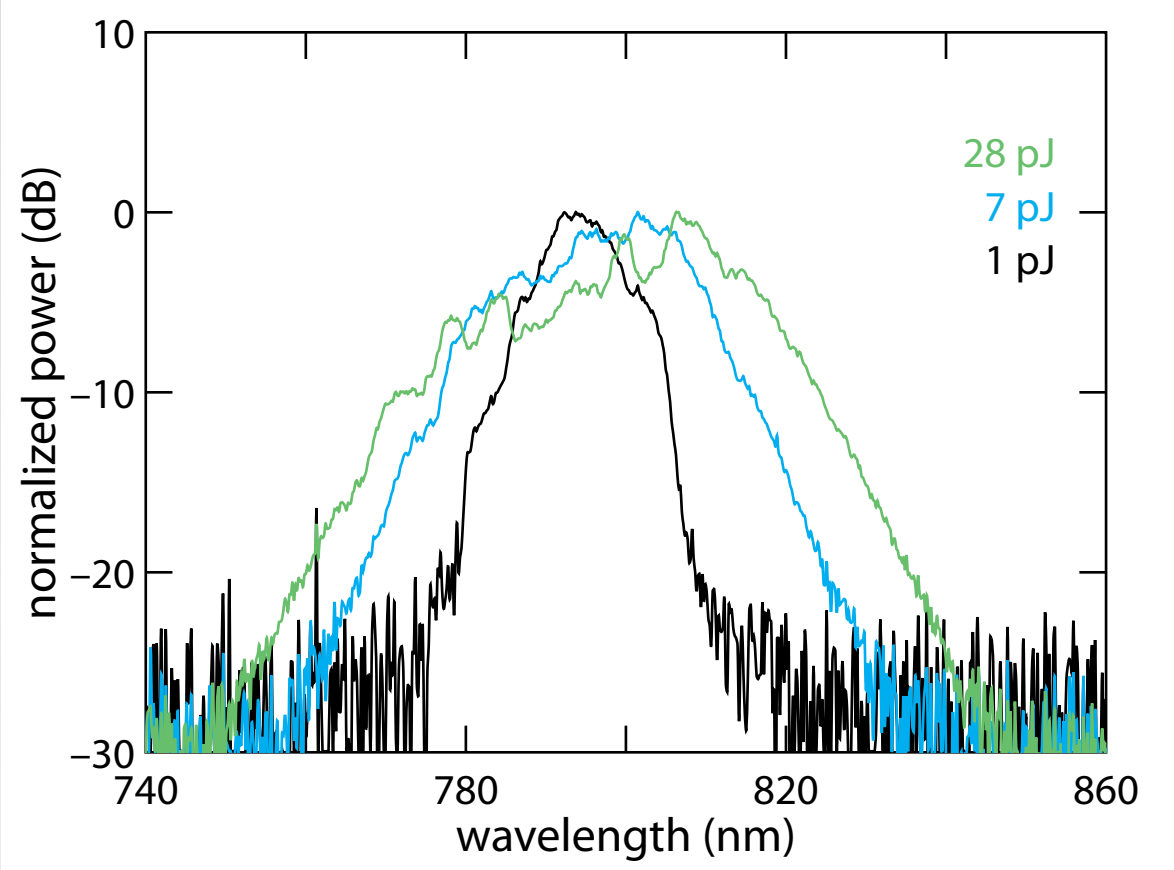

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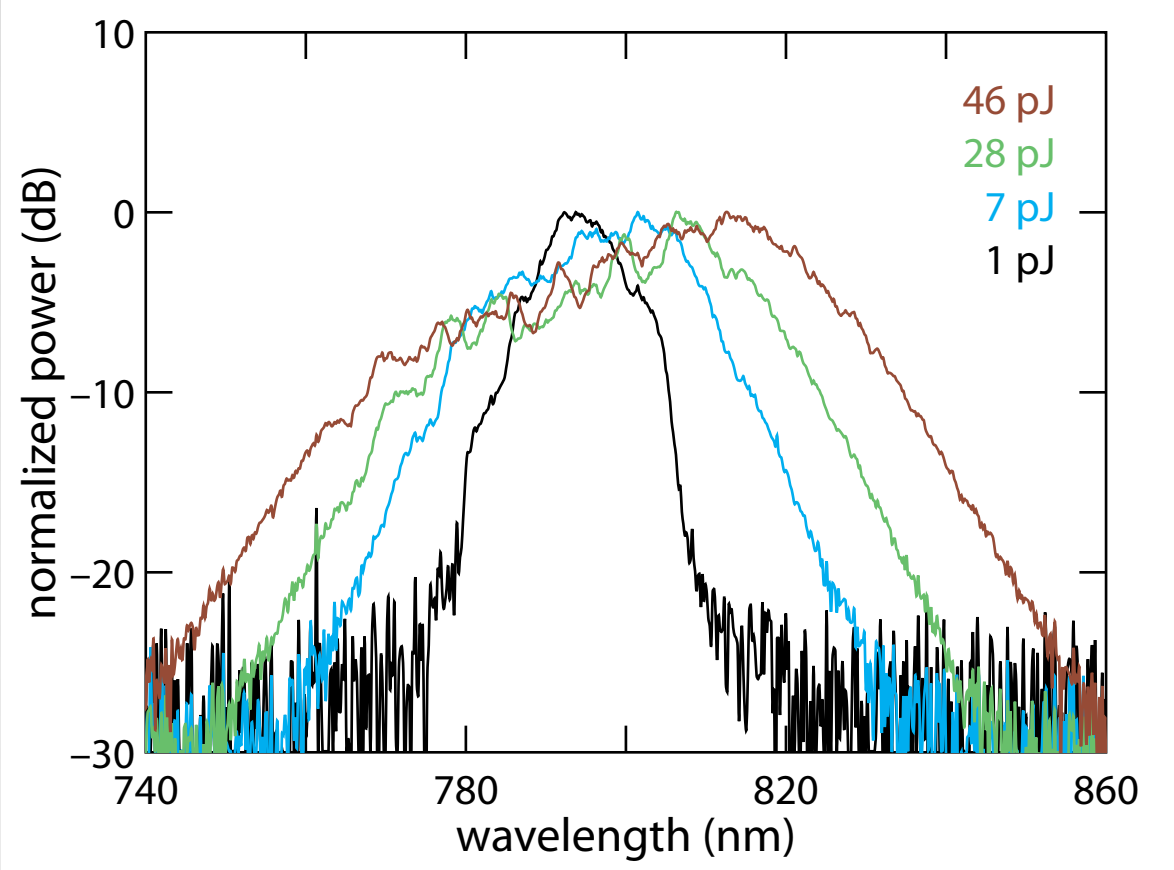

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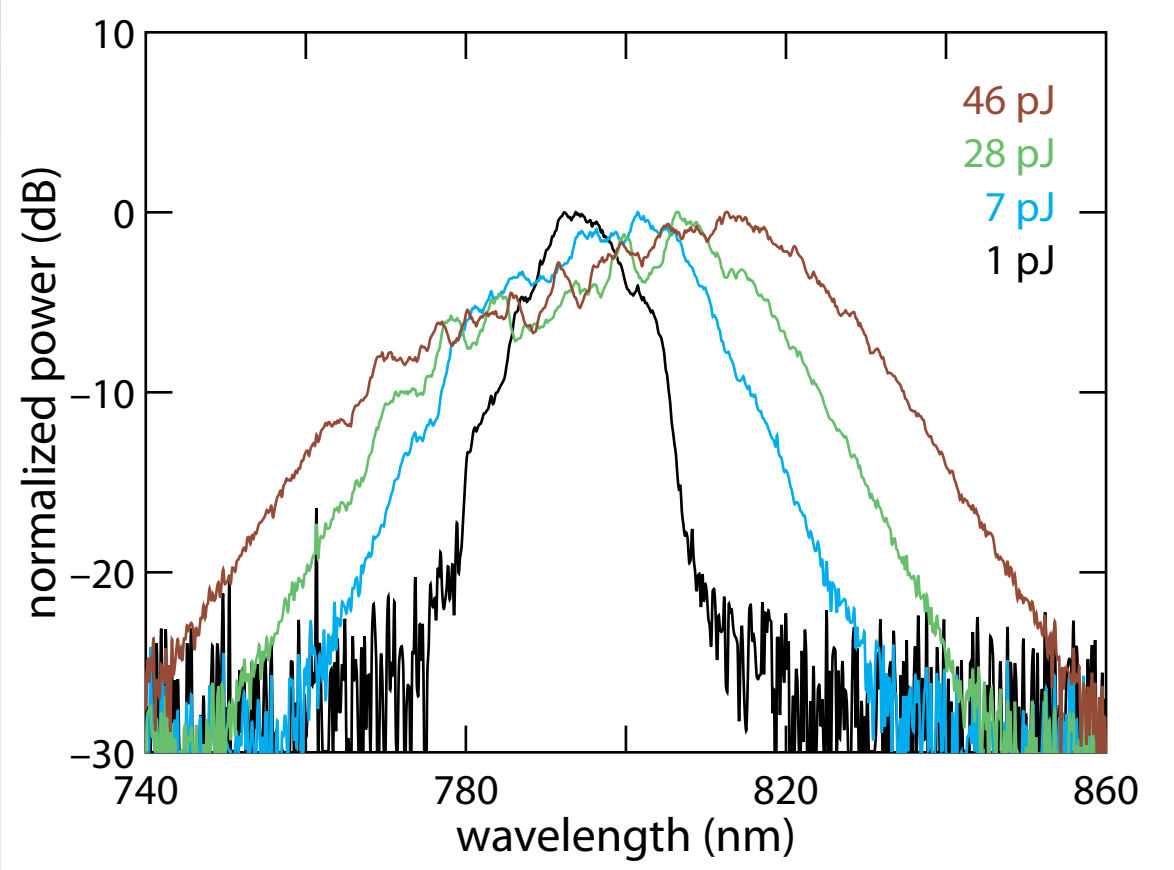

$\gamma \sim 40\ W^{-1}m^{-1}$

(~40,000 x silica fiber)

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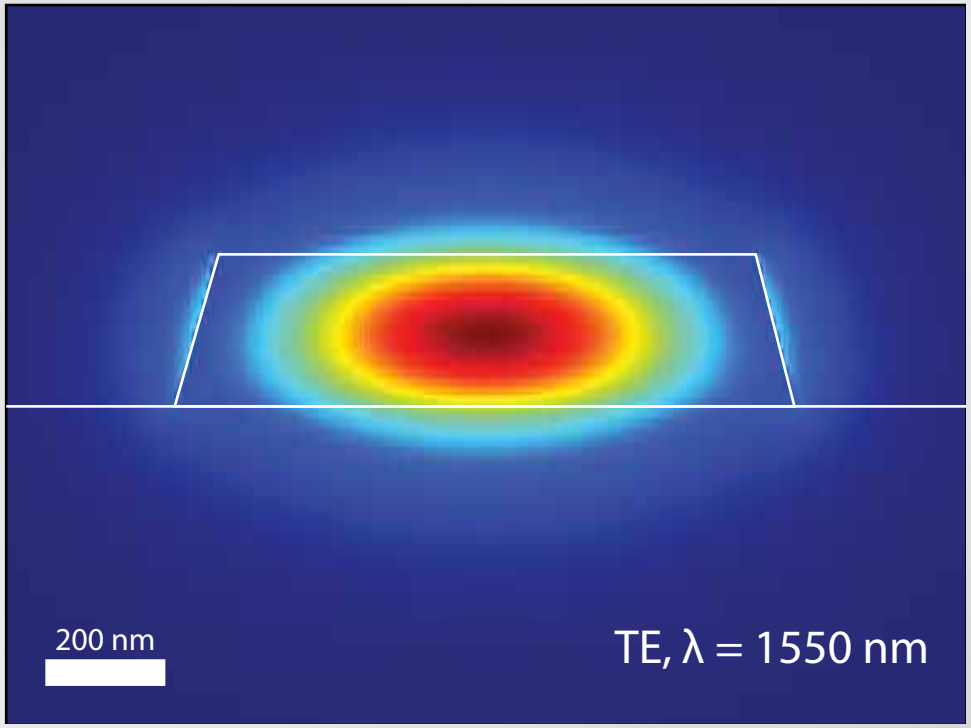
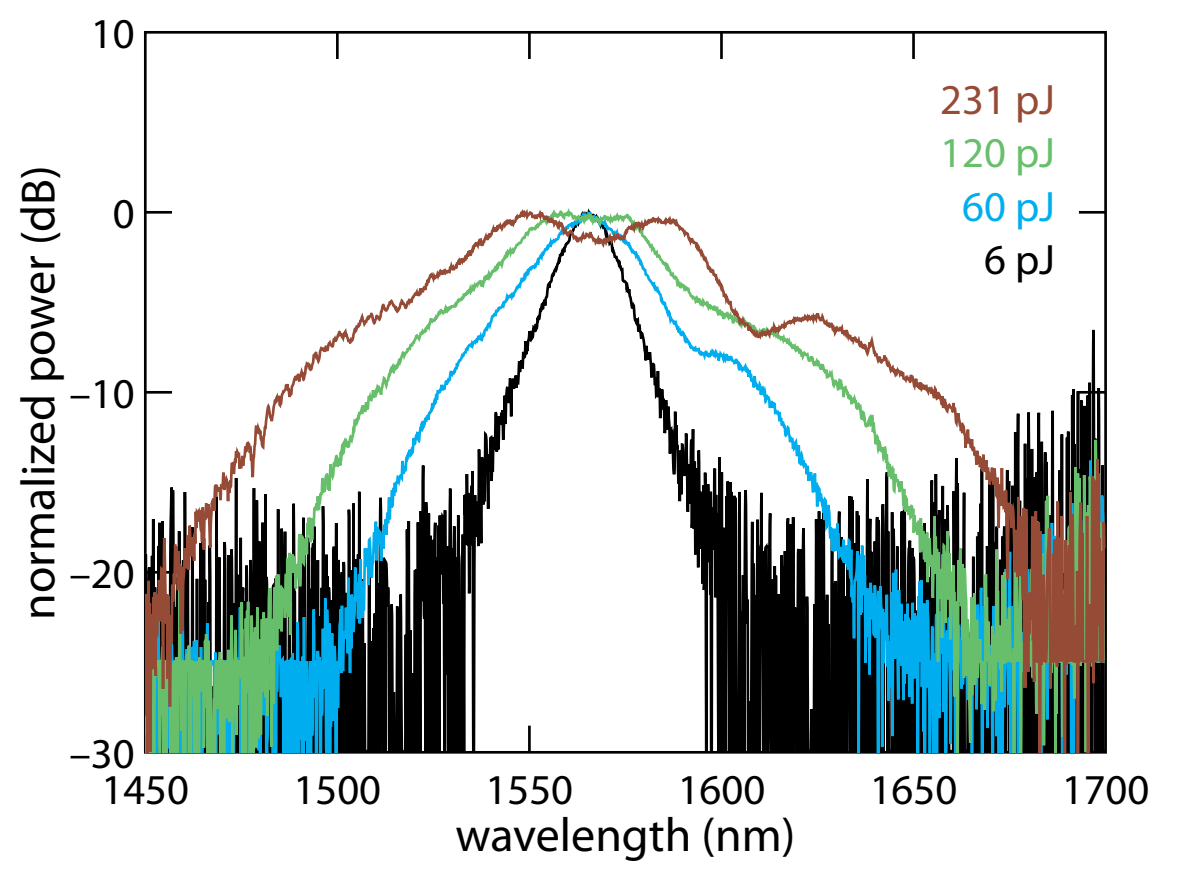
the first nonlinear optics in TiO_2



up to 4x stronger anomalous disperison than silica nanowires

... spanning the communications octave!



$\gamma \sim 10\ W^{-1}m^{-1}$

(10,000x silica fiber)

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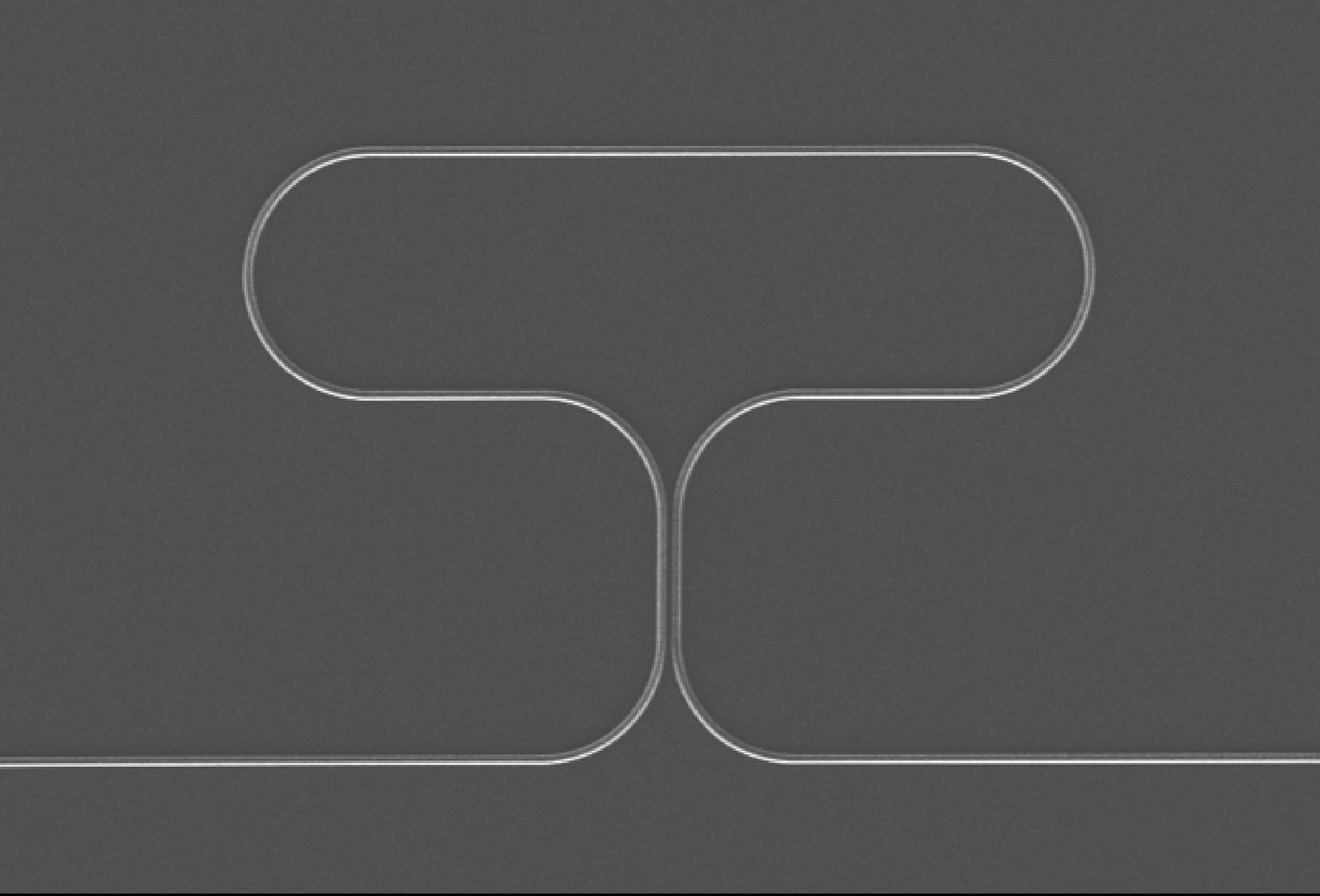

1 all-optical logic

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Summary

switching photons with photons

introduced a novel material

1 all-optical logic

2 NL materials

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Summary

switching photons with photons

introduced a novel material

... close to the first nonlinear Sagnac in TiO_2

1 all-optical logic

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Funding:

National Science Foundation

Nanoscale Science and Engineering Center
Harvard Quantum Optics Center
Department of Energy

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