# Nonlinear optics at the nanoscale

Fysikermøtet 2013
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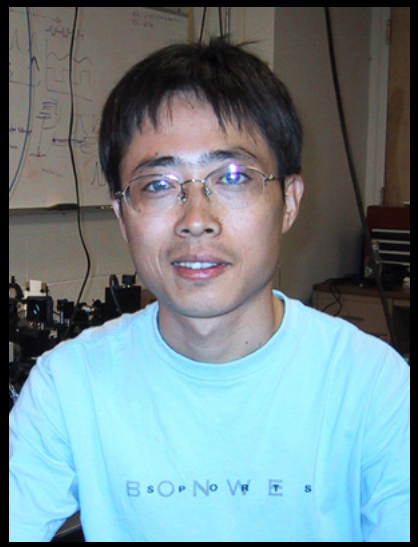
Geoff Svacha

Rafael Gattass

Tobias Voss



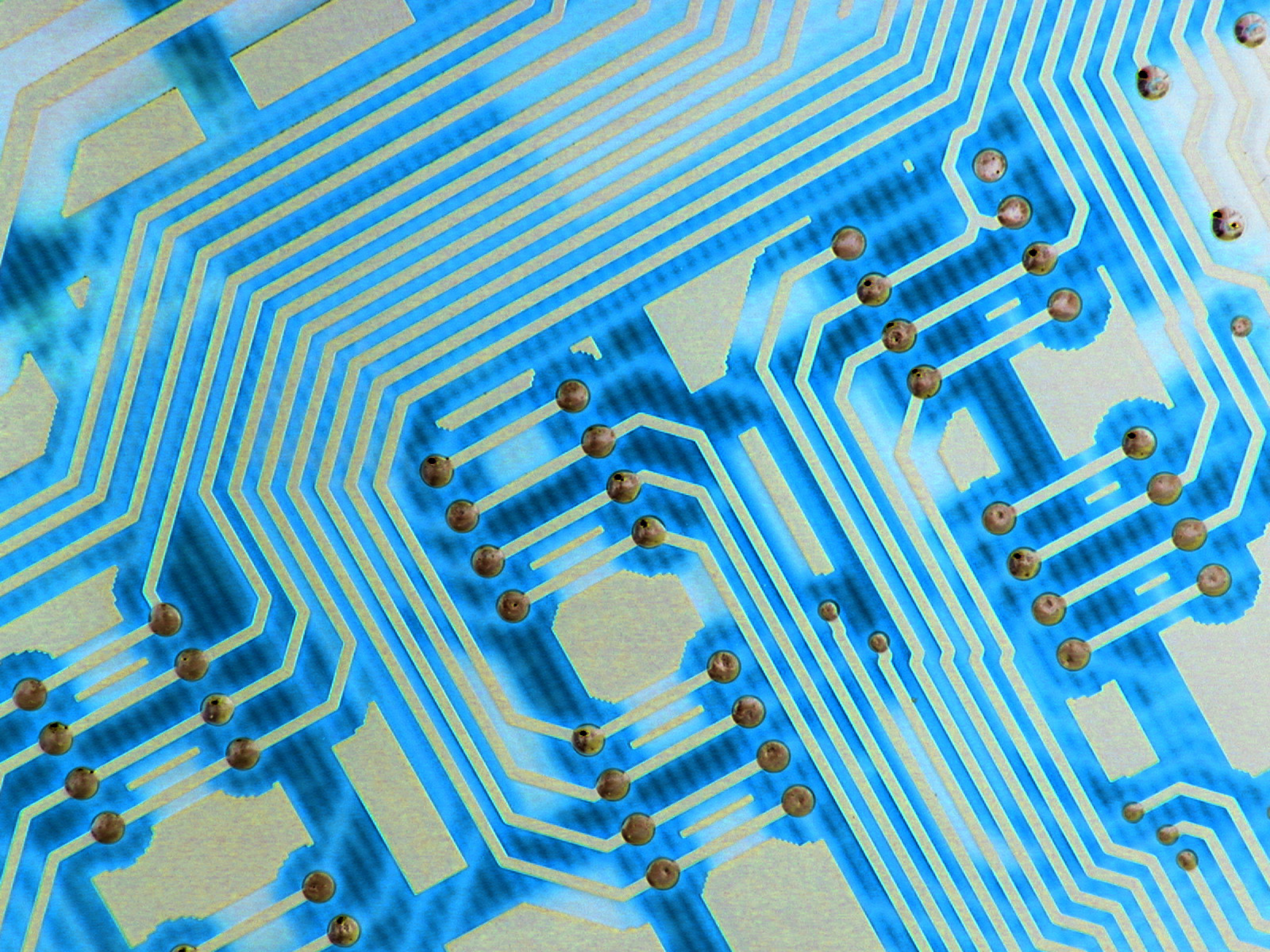
Limin Tong

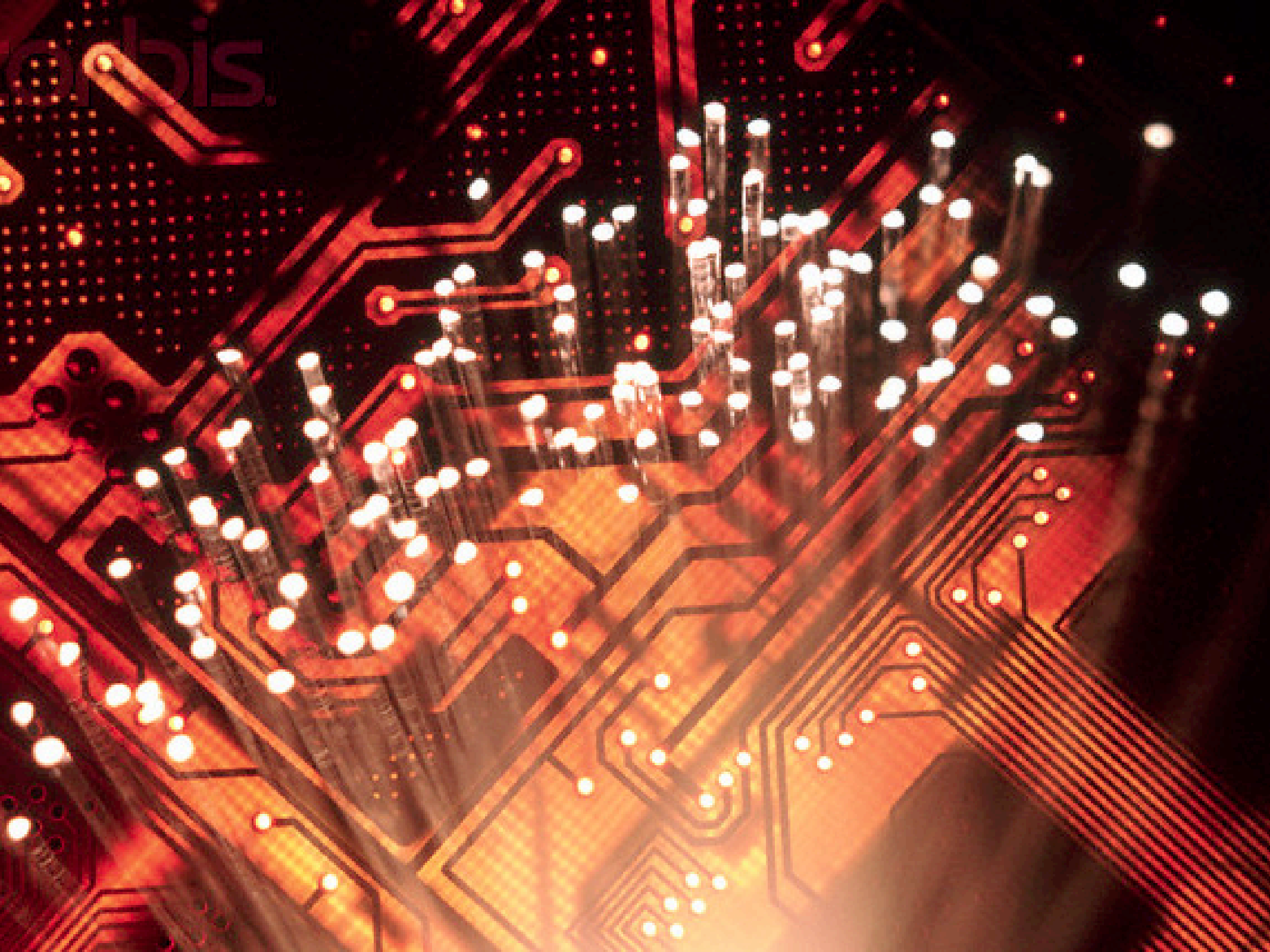
eric_mazur

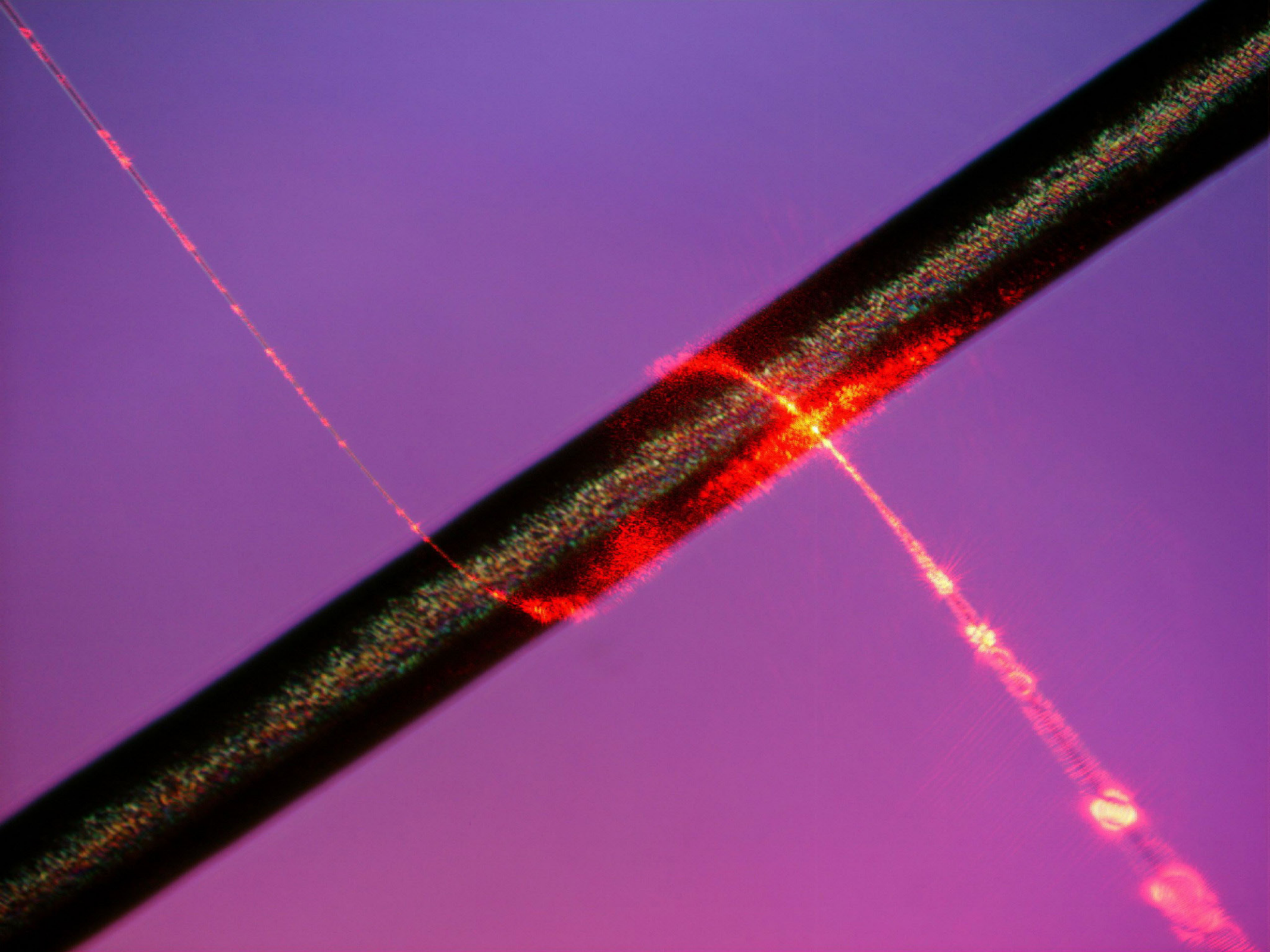
and also....

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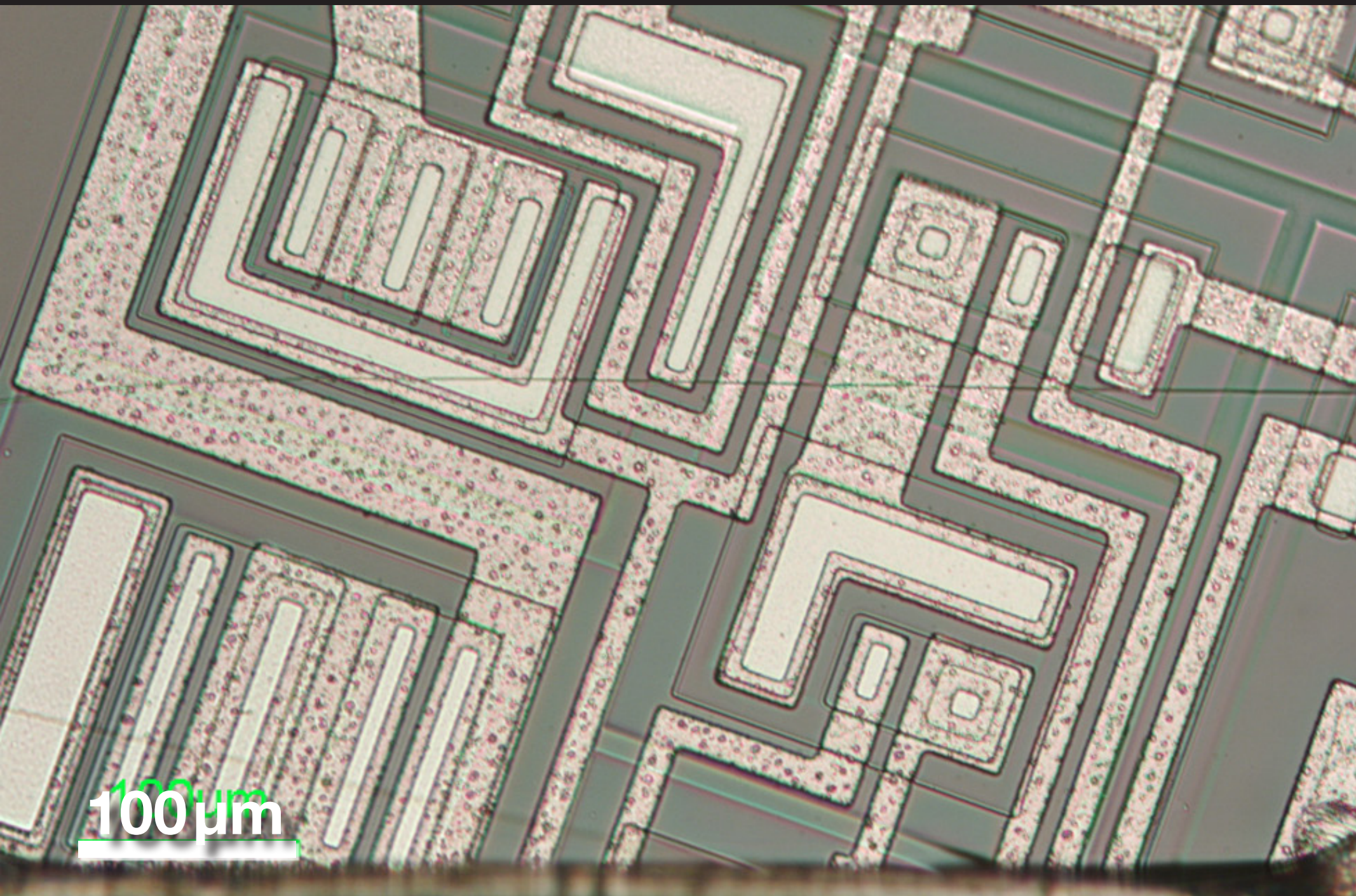
- manipulating light at the nanoscale
- supercontinuum generation
- optical logic gates

# Manipulating light at the nanoscale




*Nature*, 426, 816 (2003)

# Manipulating light at the nanoscale



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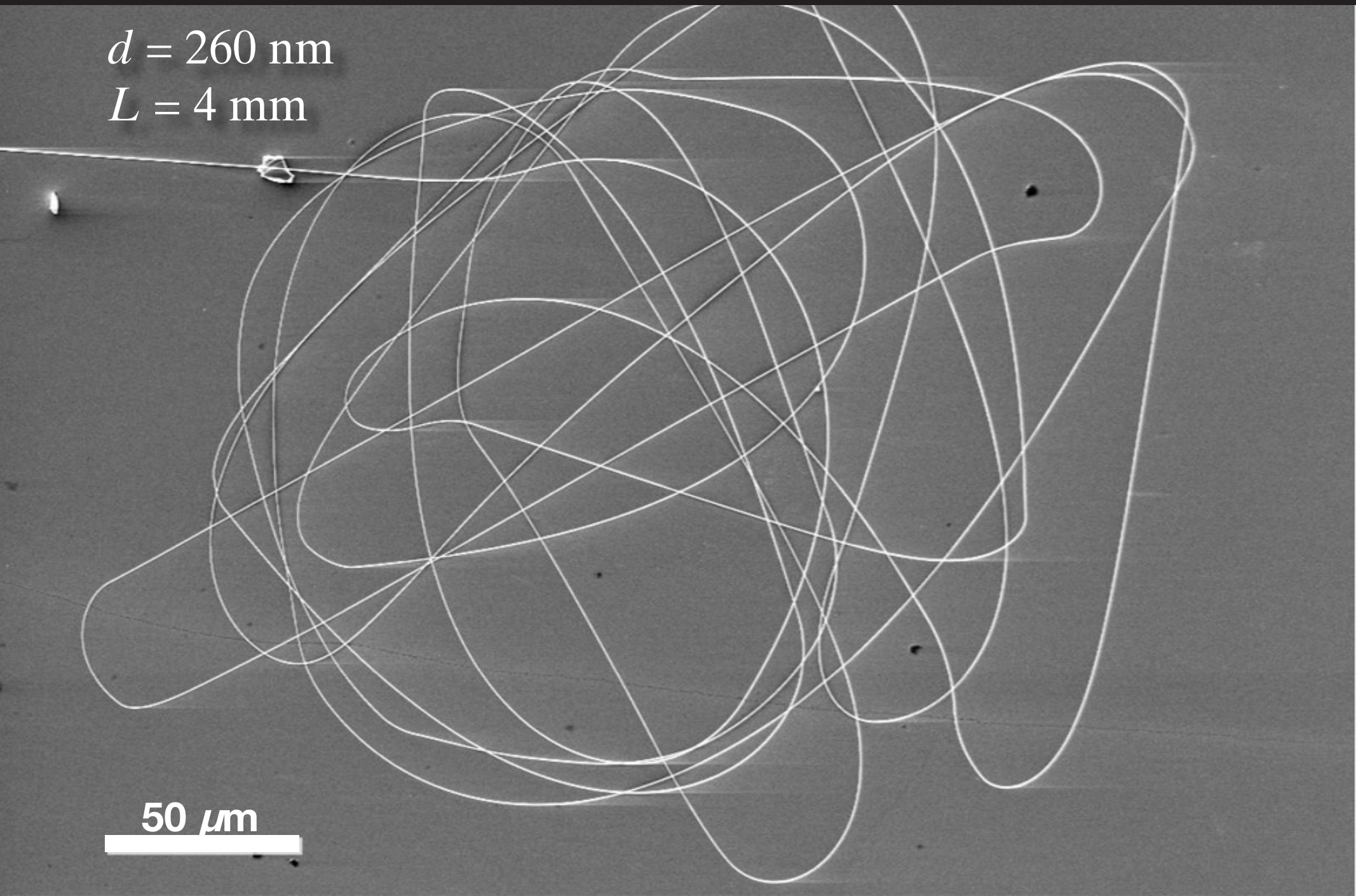

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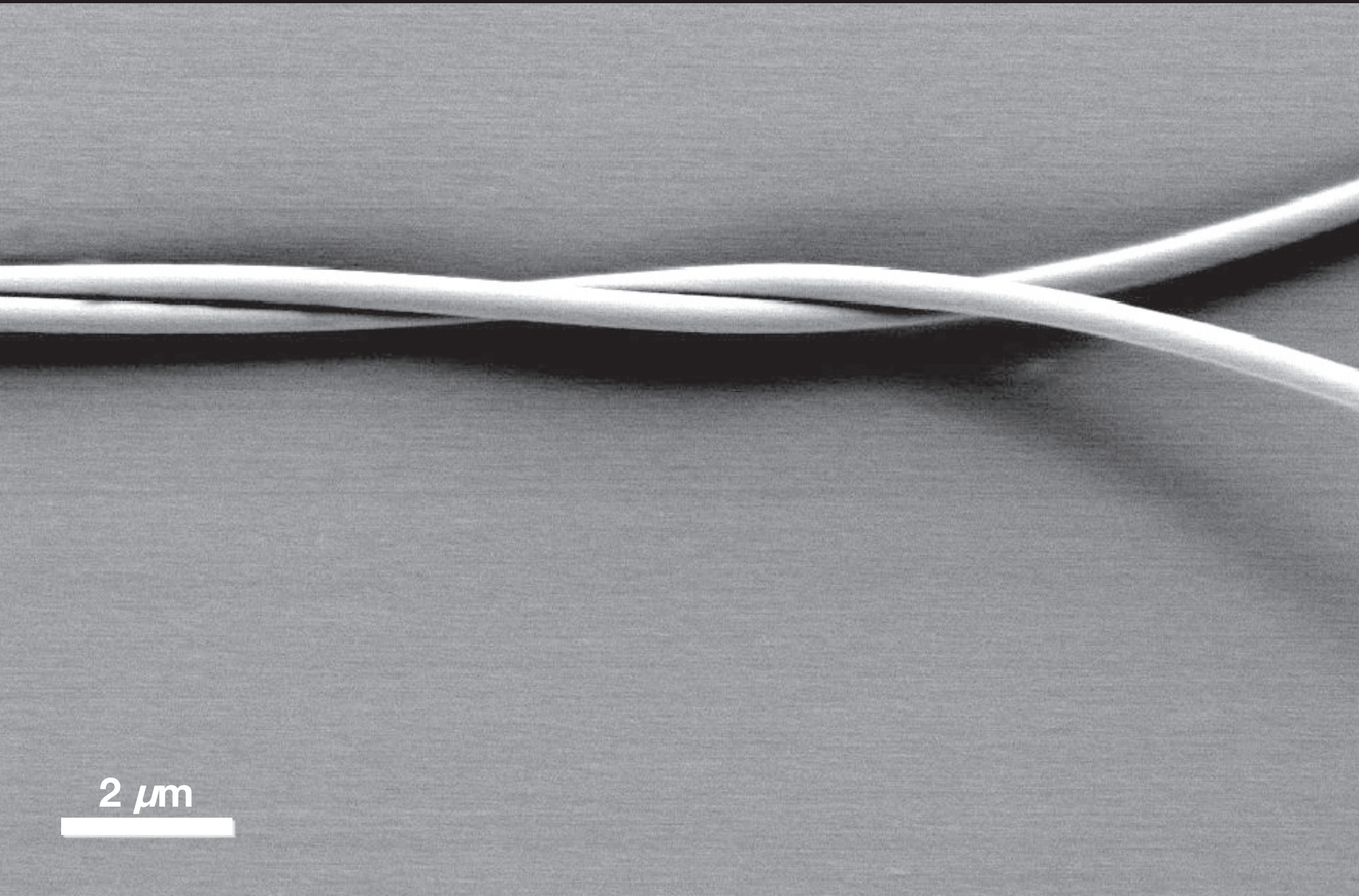

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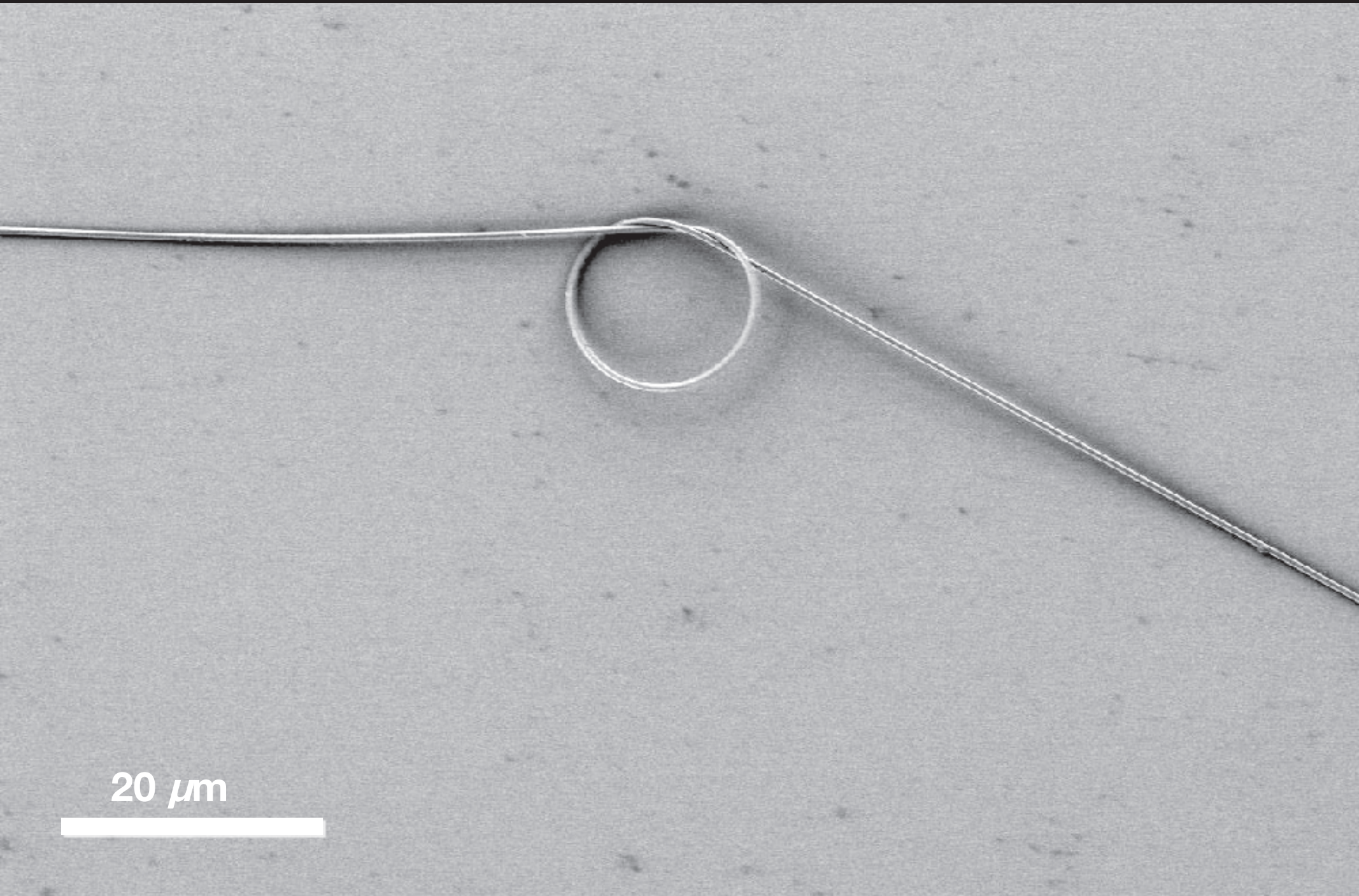

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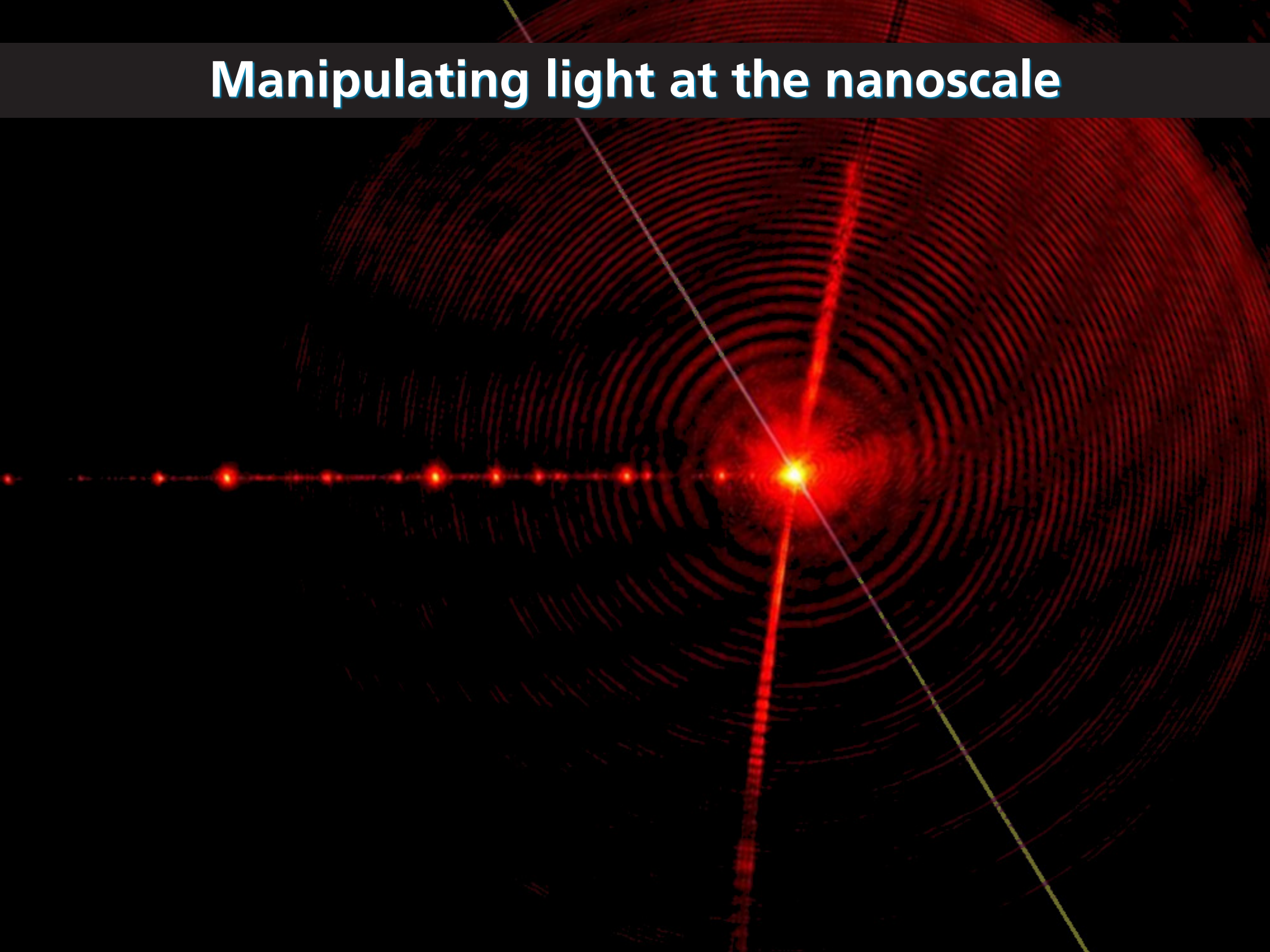
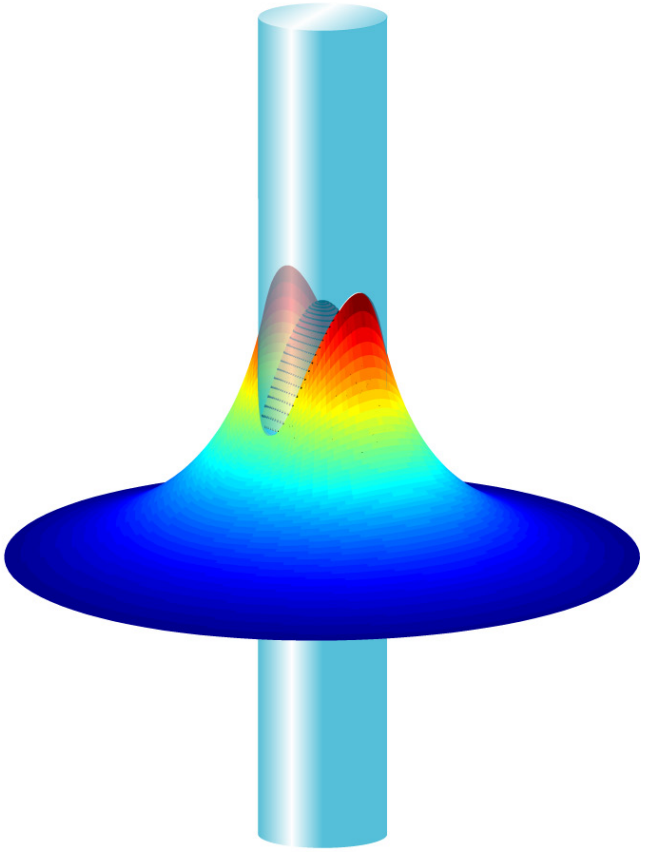


# Manipulating light at the nanoscale

## Poynting vector profile for 200-nm nanowire



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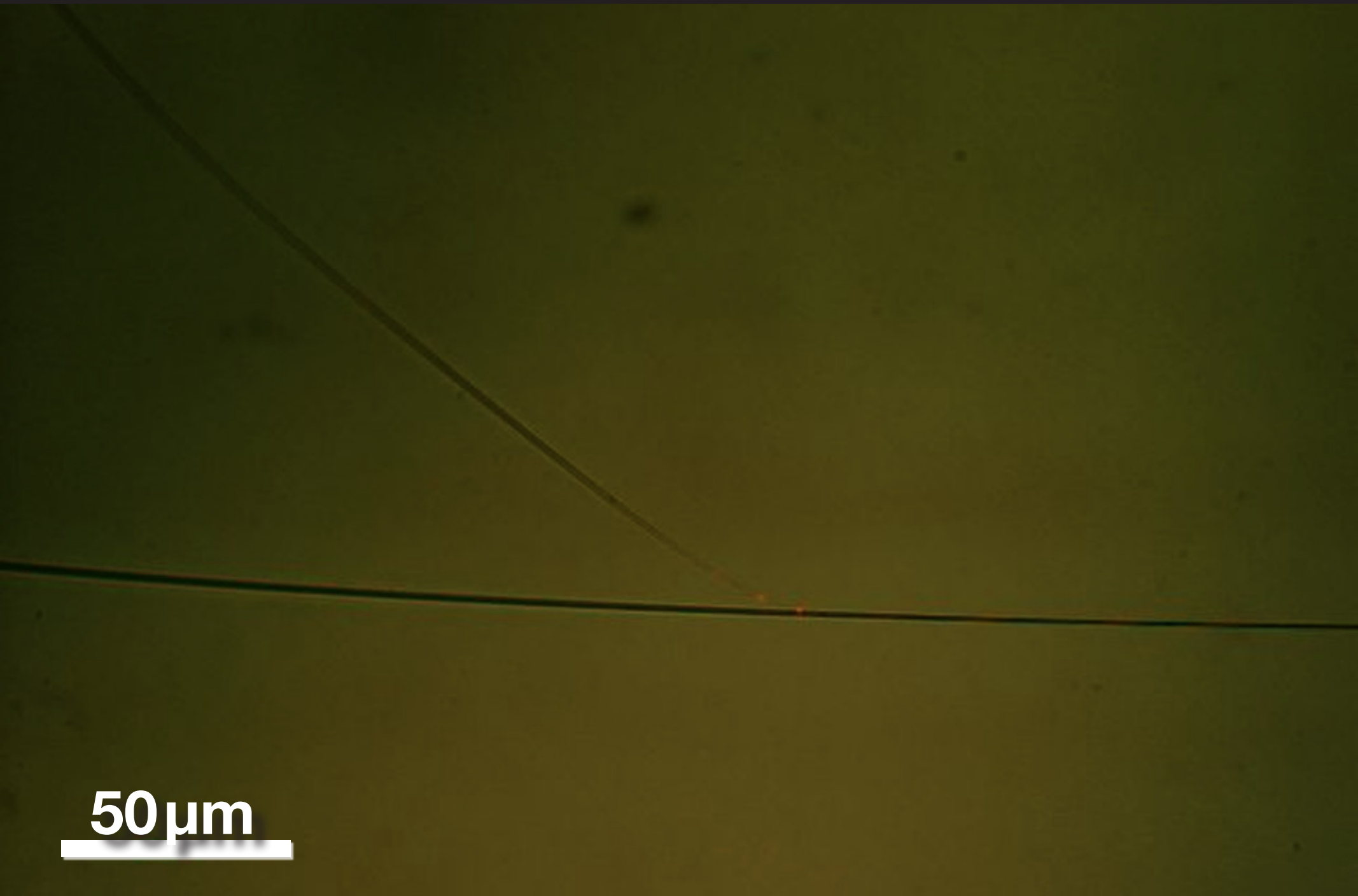

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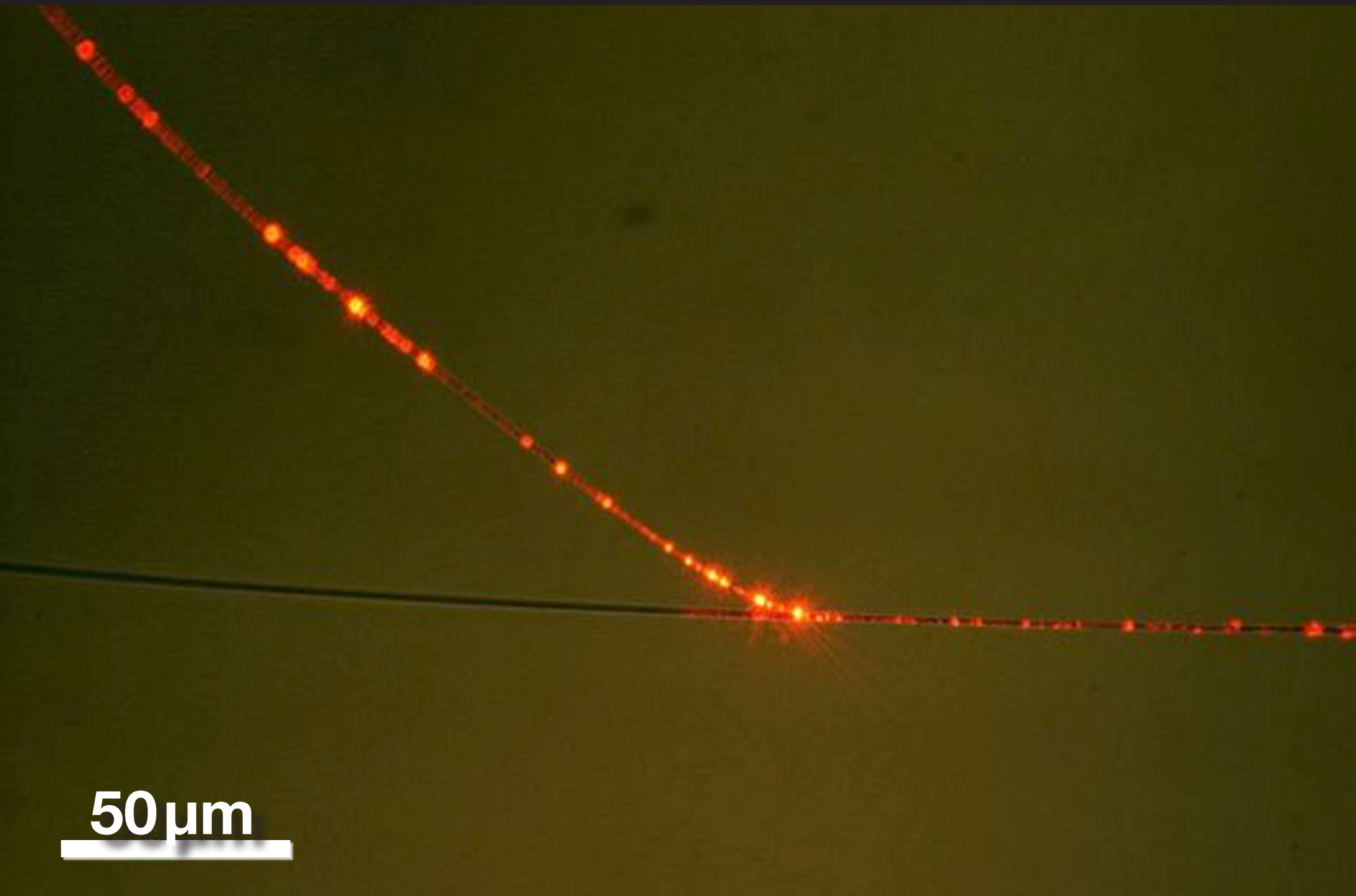

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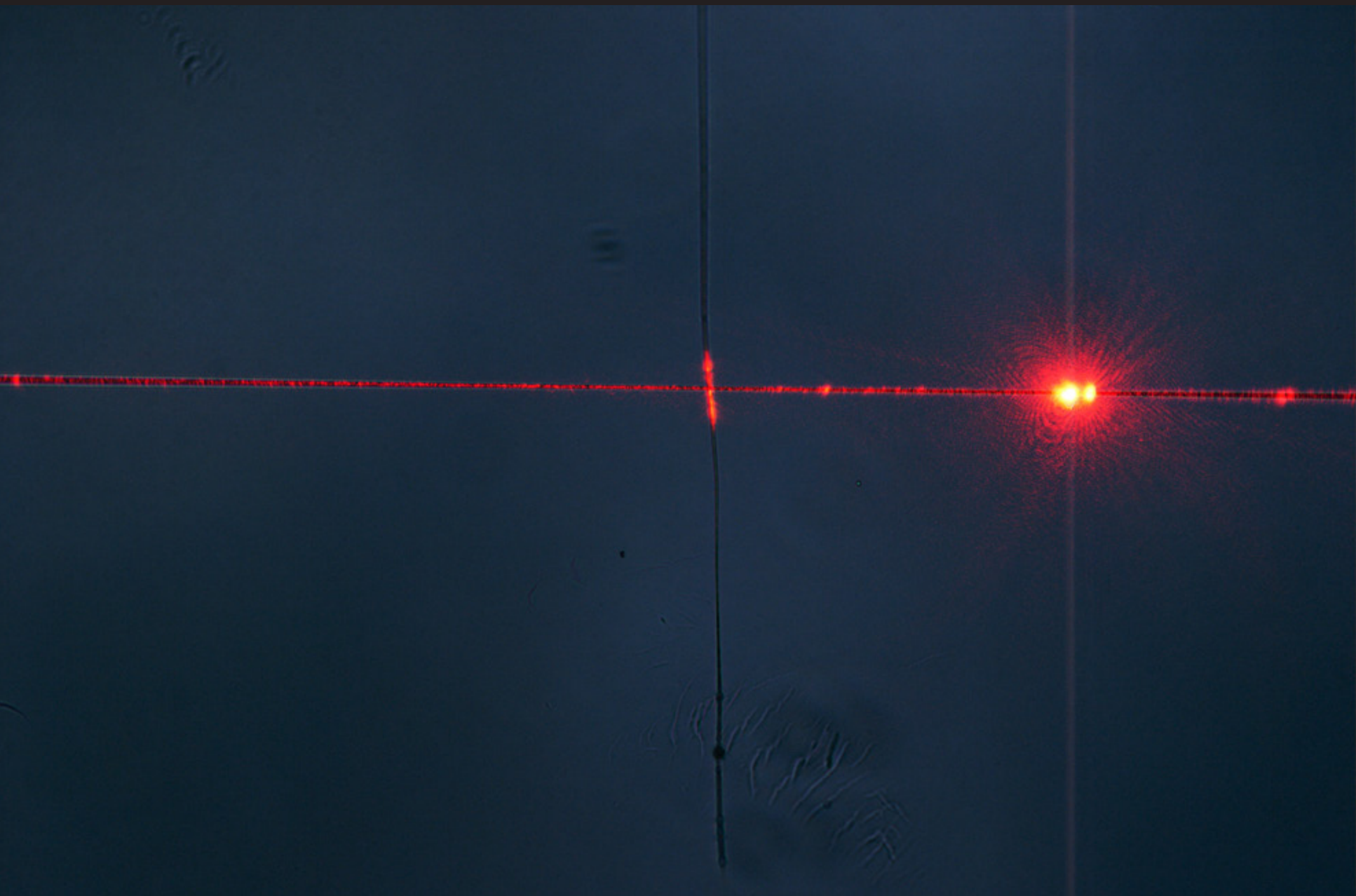

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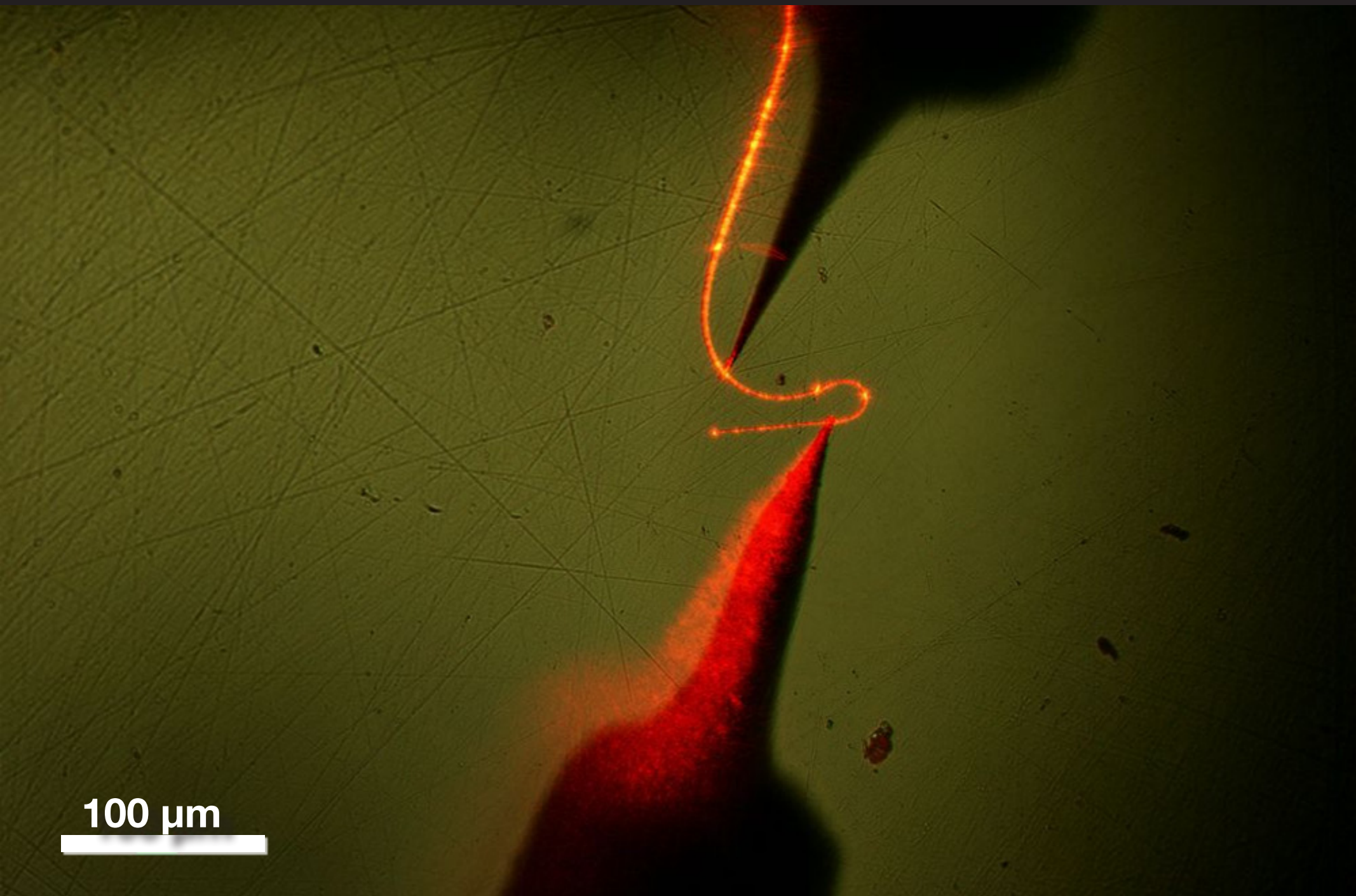

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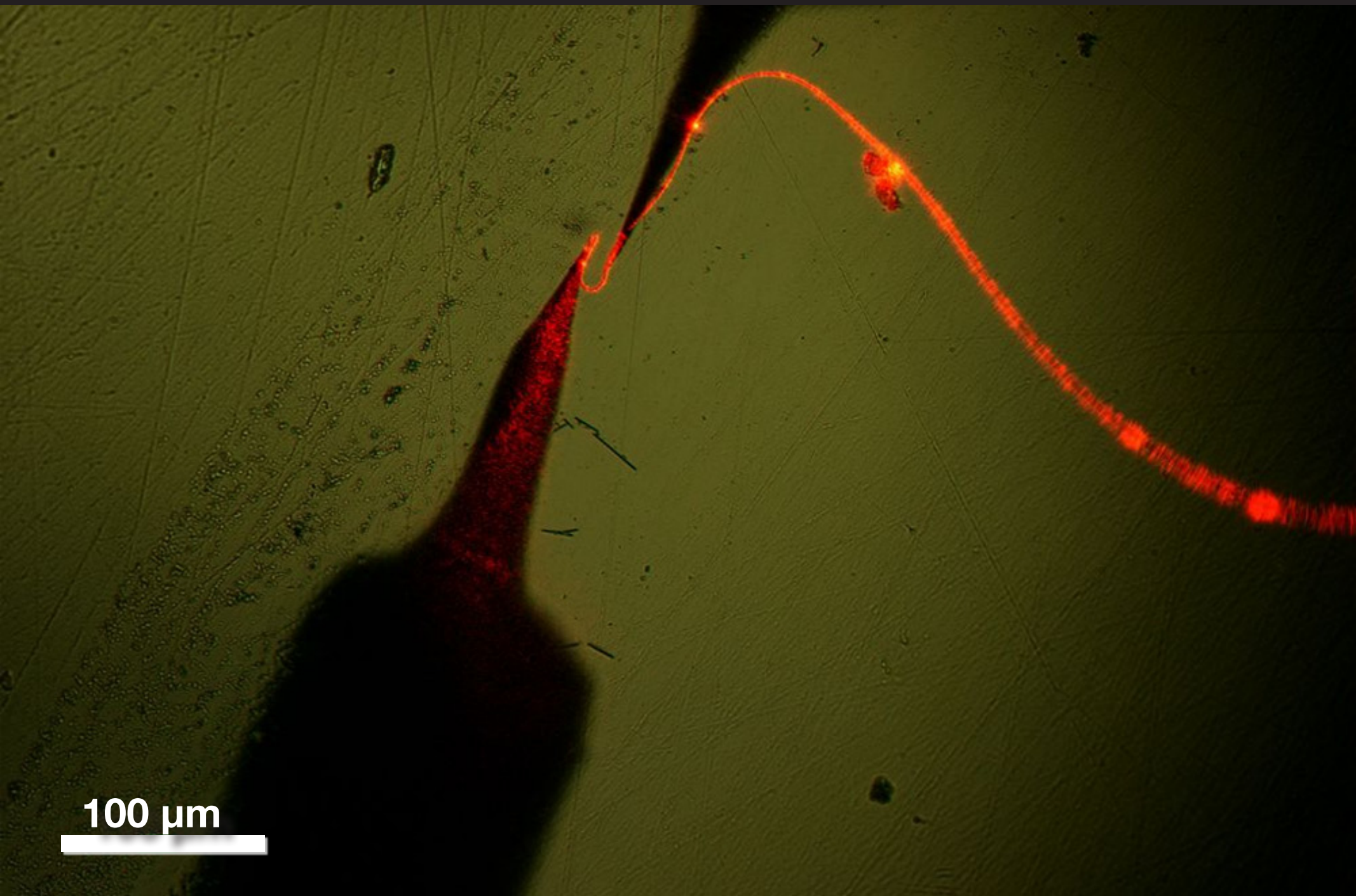

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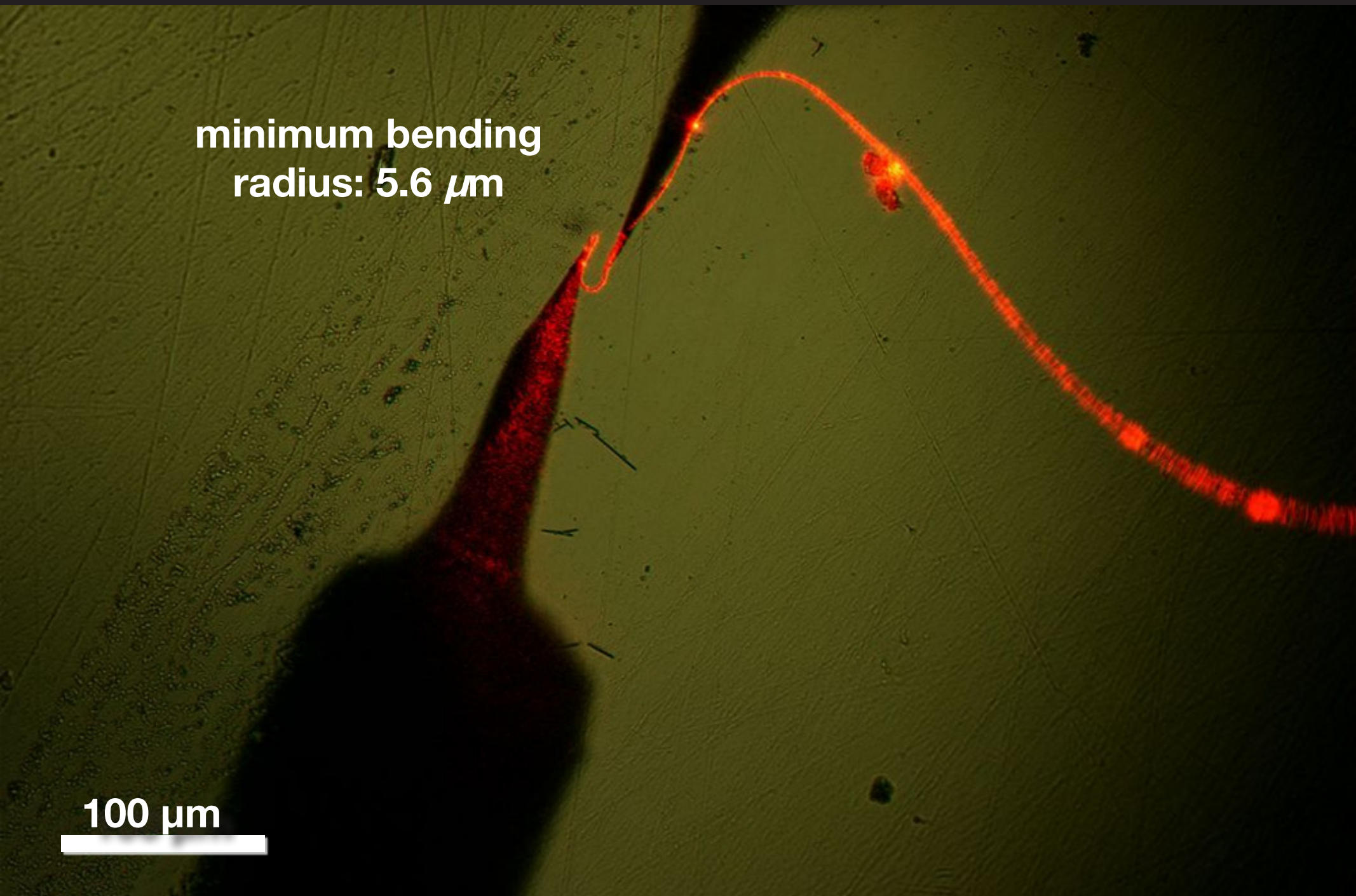

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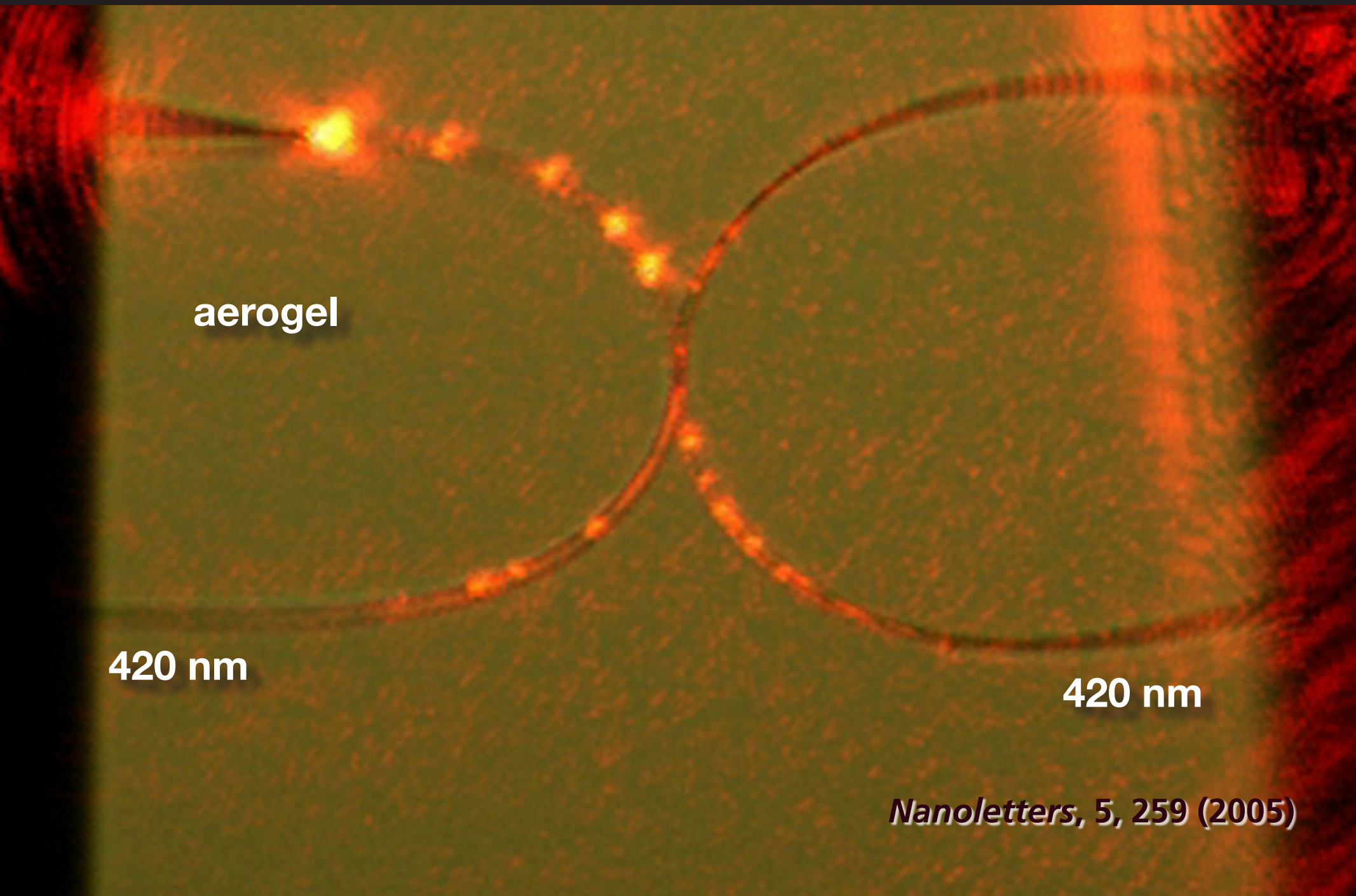


*Nanoletters*, 5, 259 (2005)

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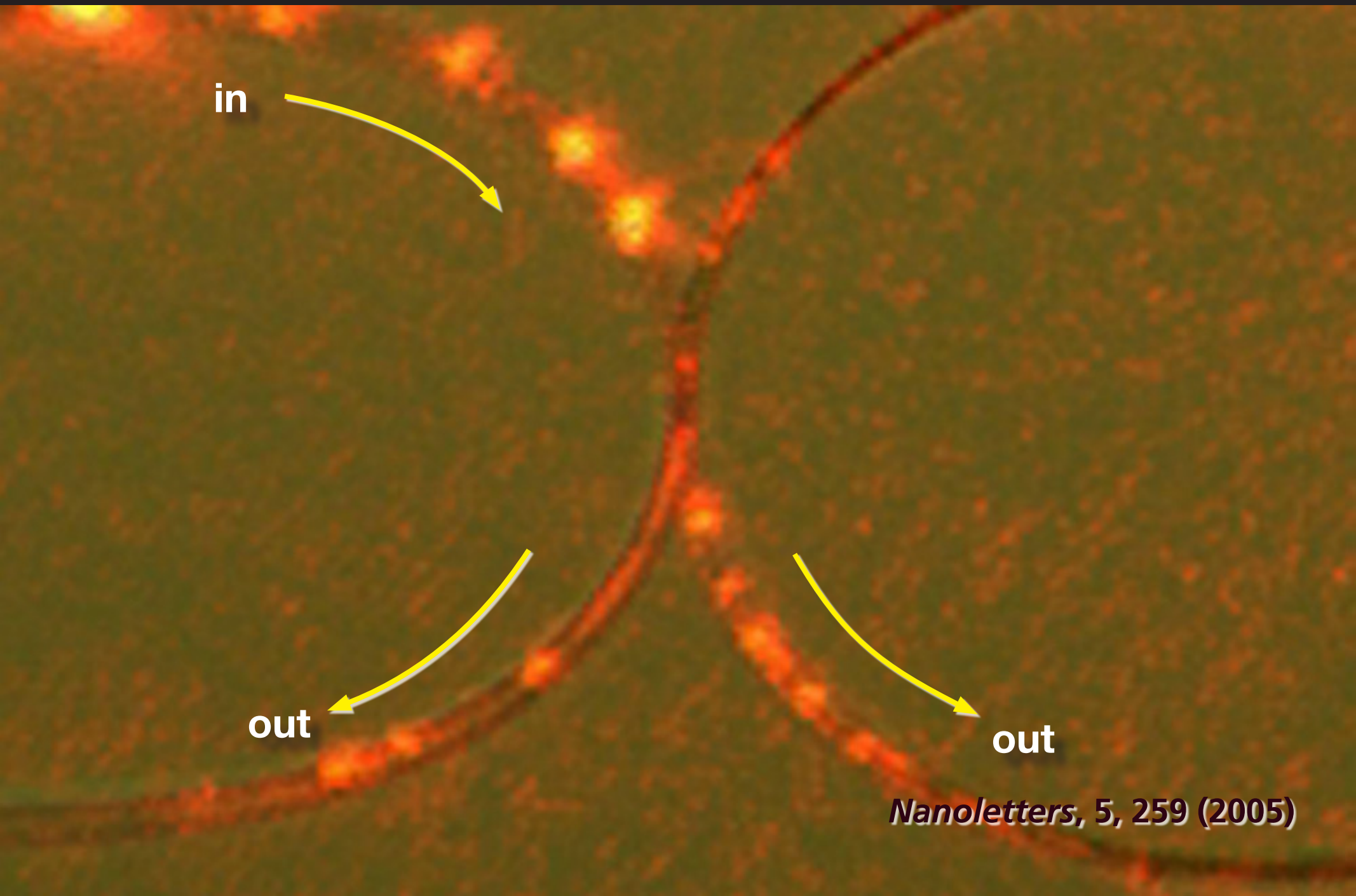


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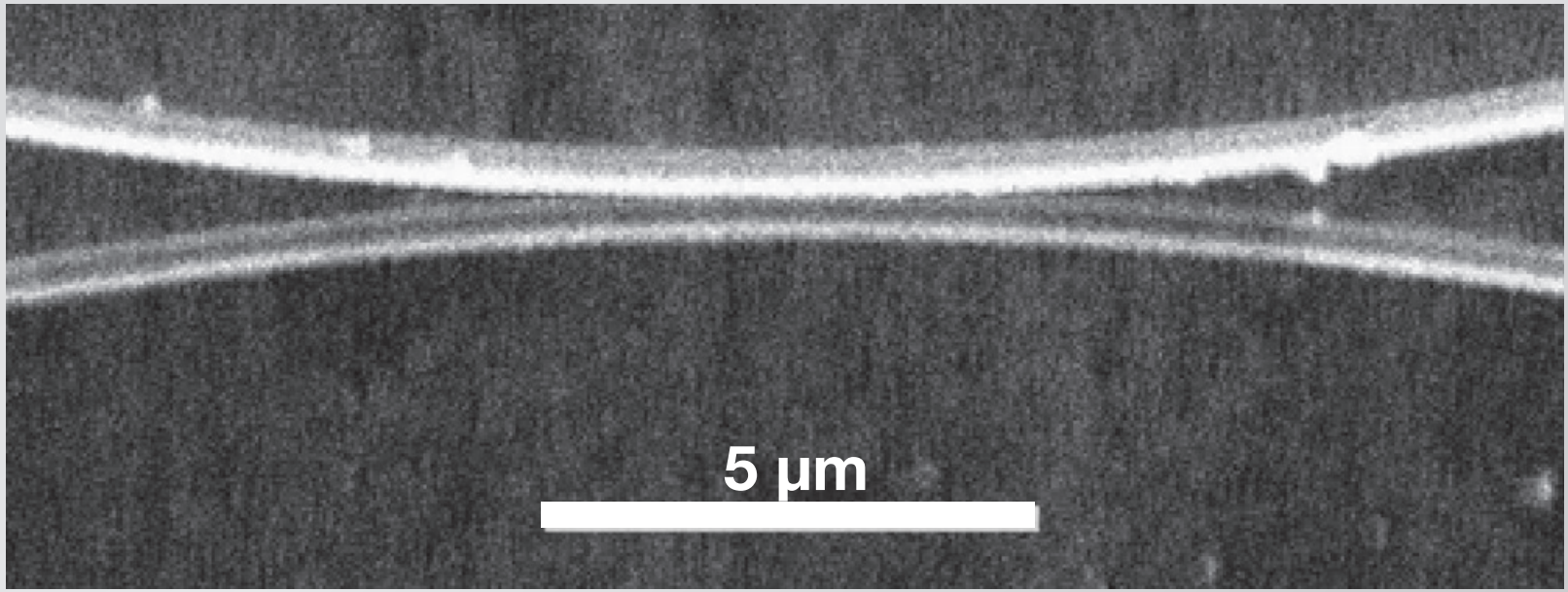



*Nanoletters*, 5, 259 (2005)

# Manipulating light at the nanoscale

Points to keep in mind:

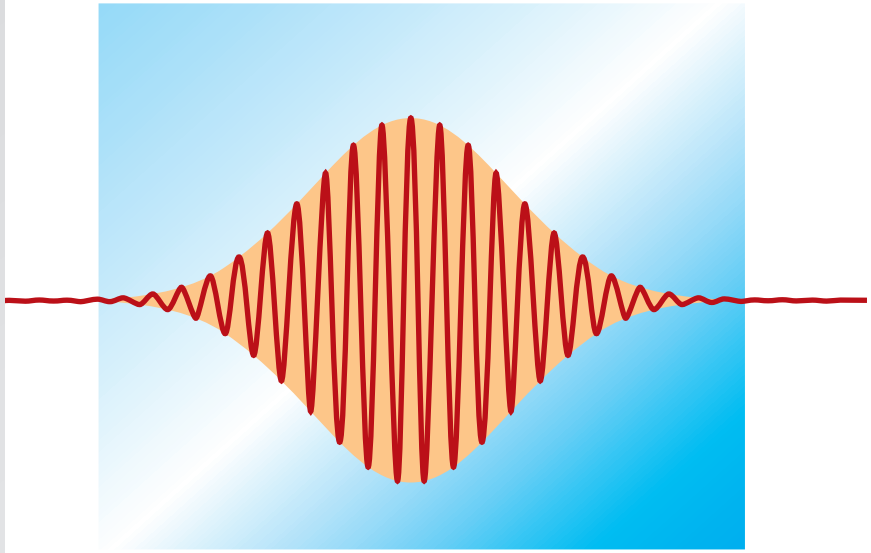
- low-loss guiding
- convenient evanescent coupling
- attached to ordinary fiber

# Outline

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

# Supercontinuum generation

**nonlinear dispersion:** $n = n_o + n_2 I$



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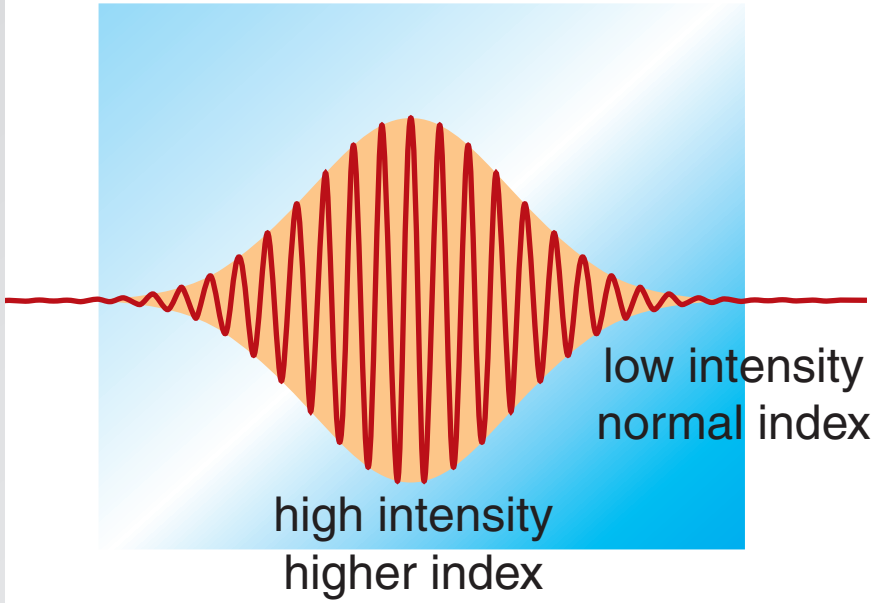

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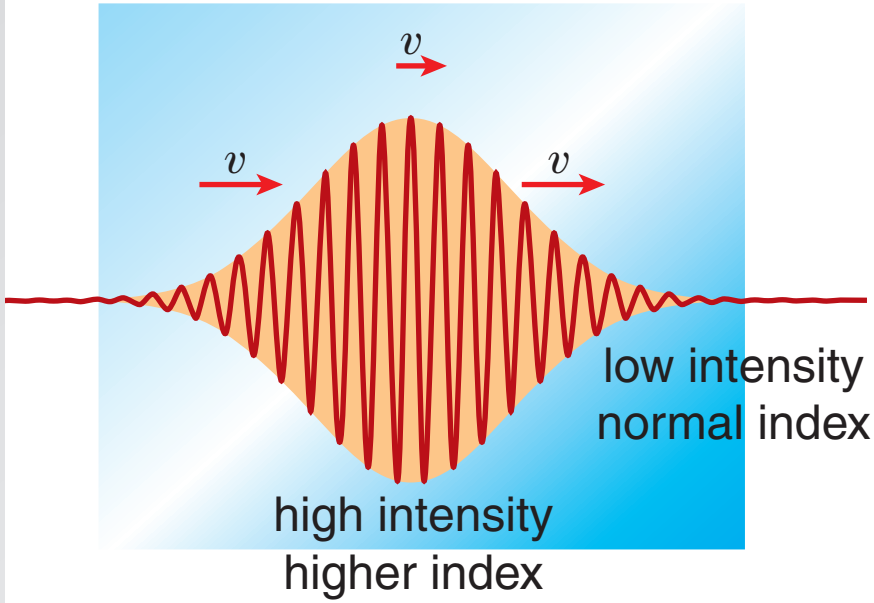

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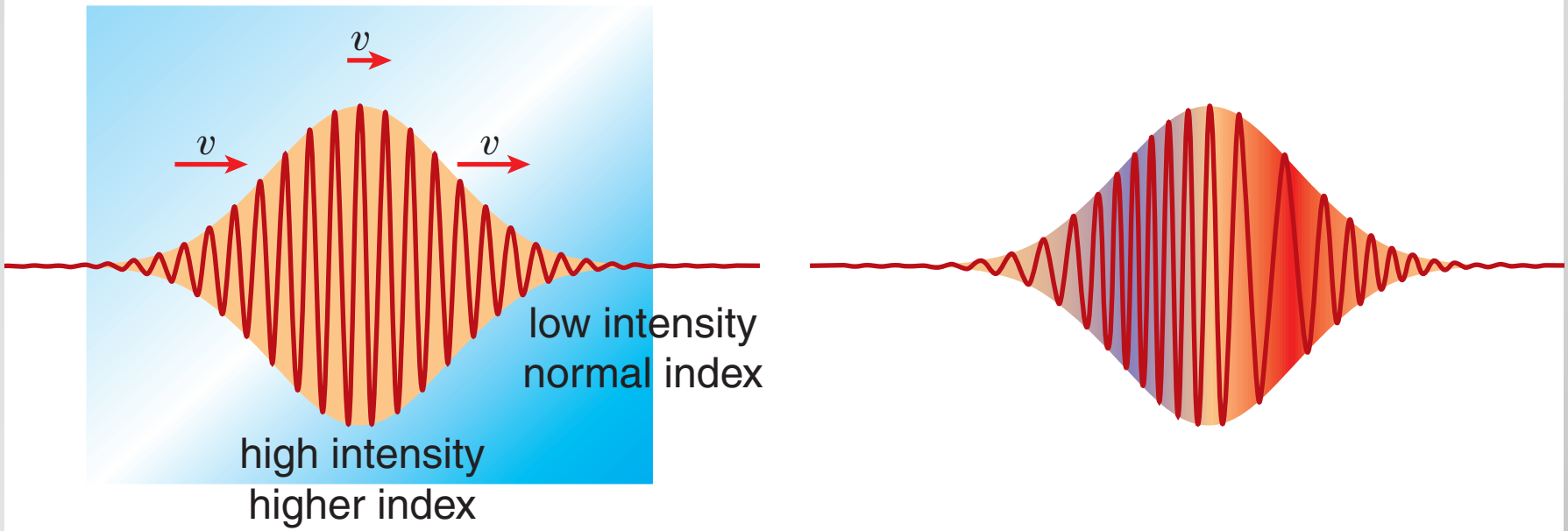

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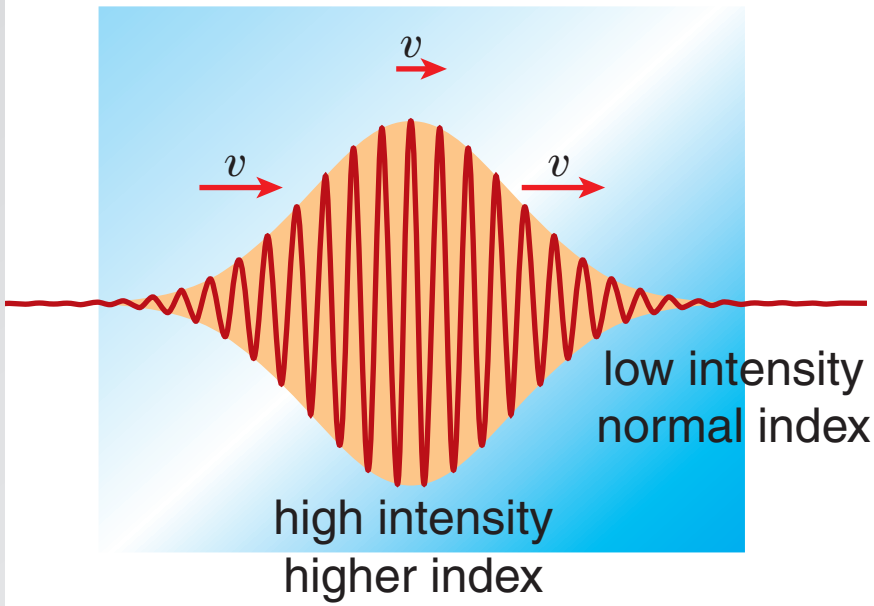
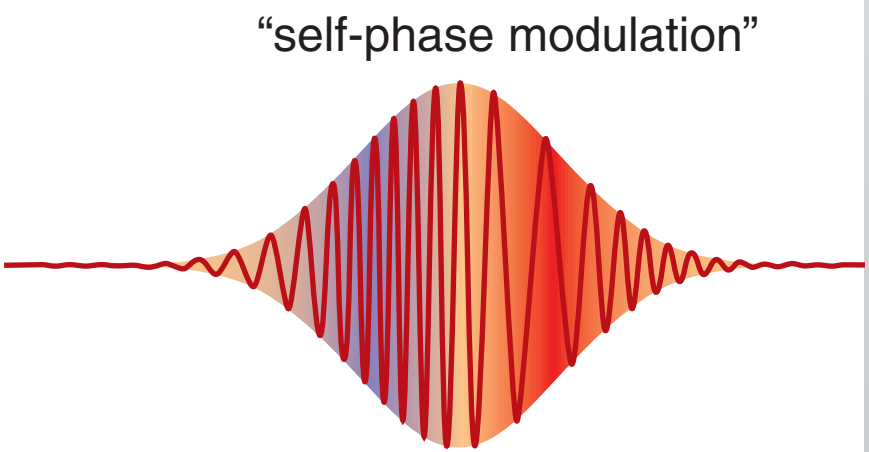
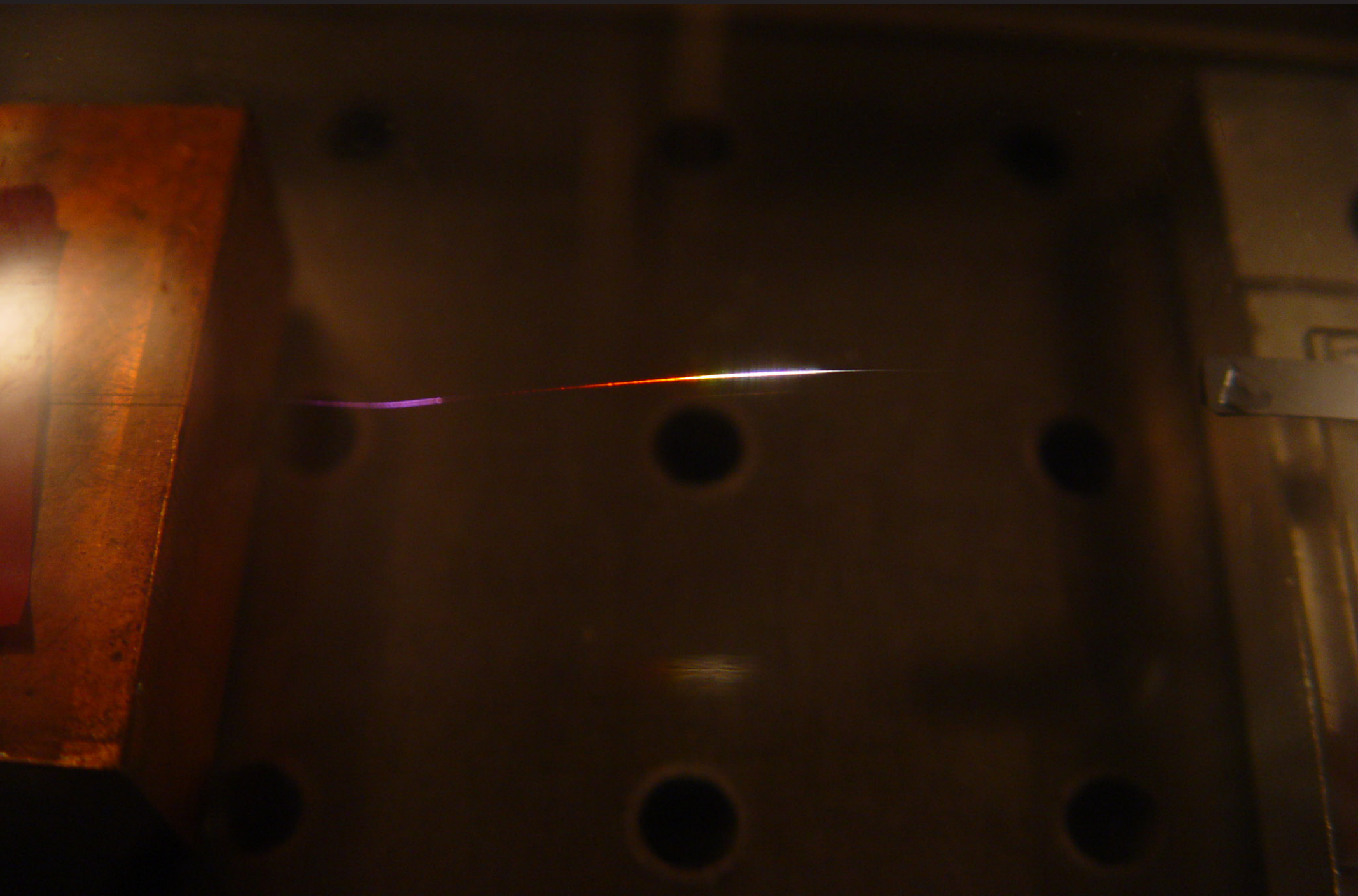


# Supercontinuum generation

strong confinement $\longrightarrow$ high intensity

# Supercontinuum generation



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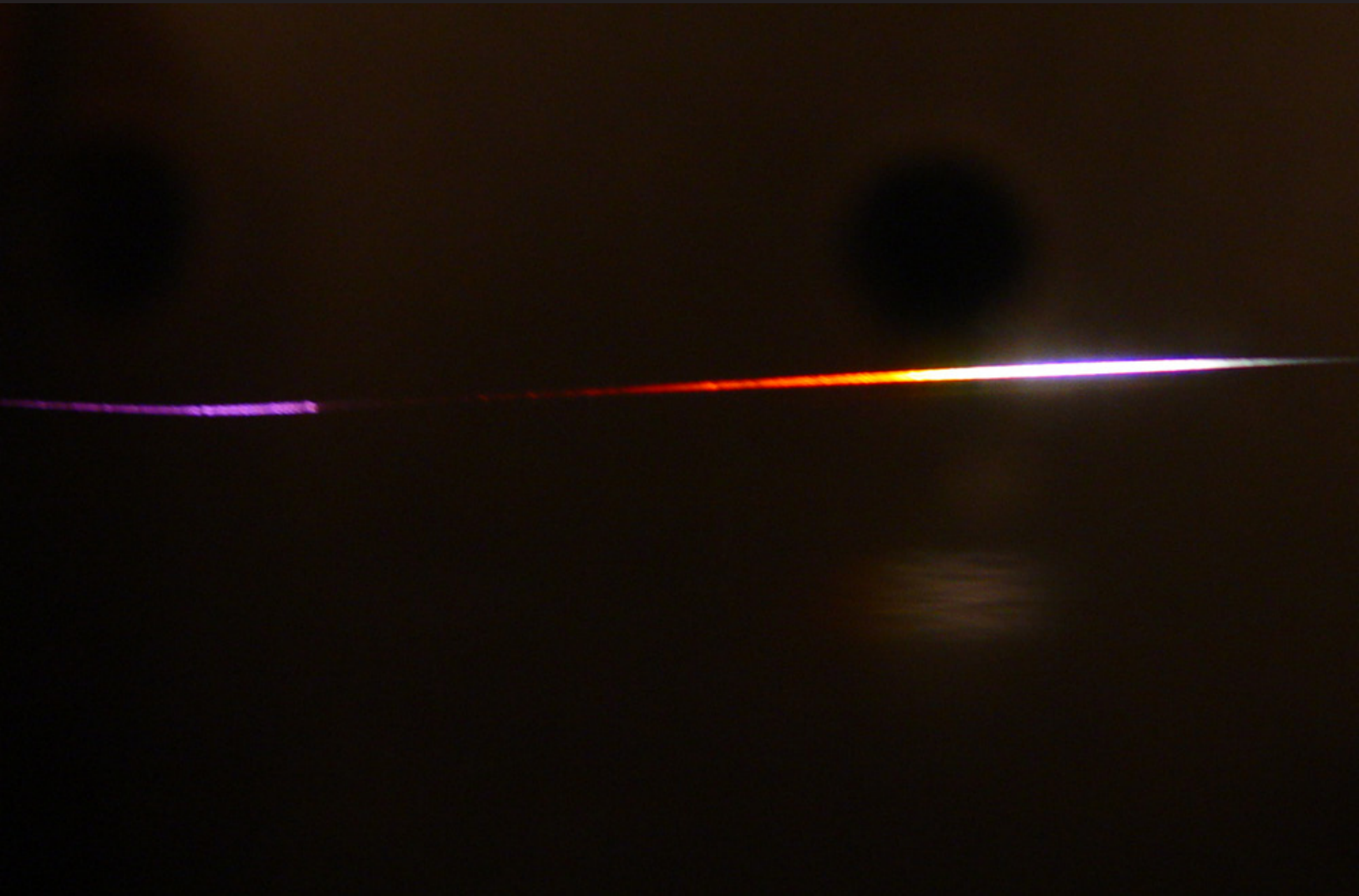
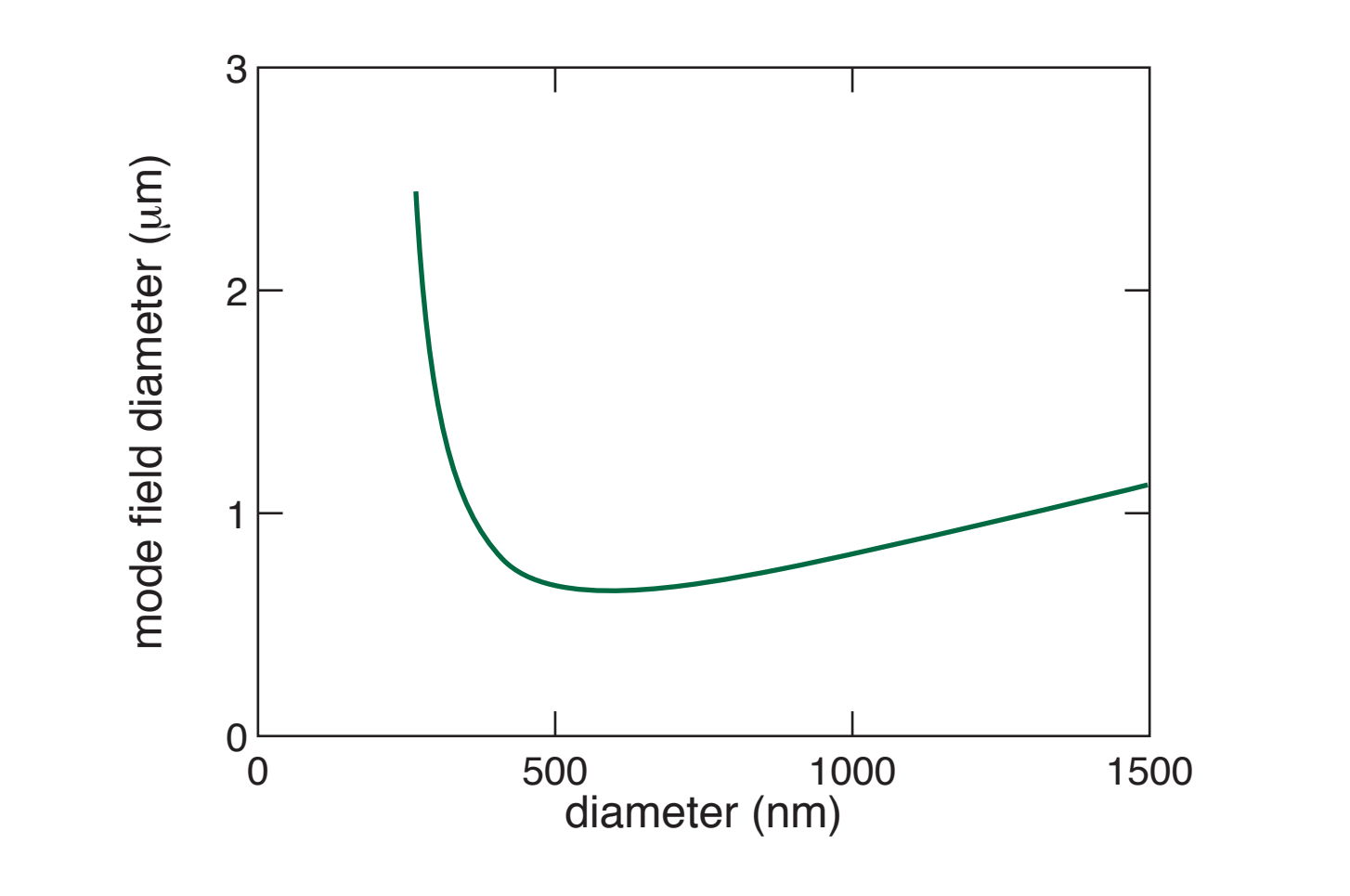


# Supercontinuum generation

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




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

# Supercontinuum generation

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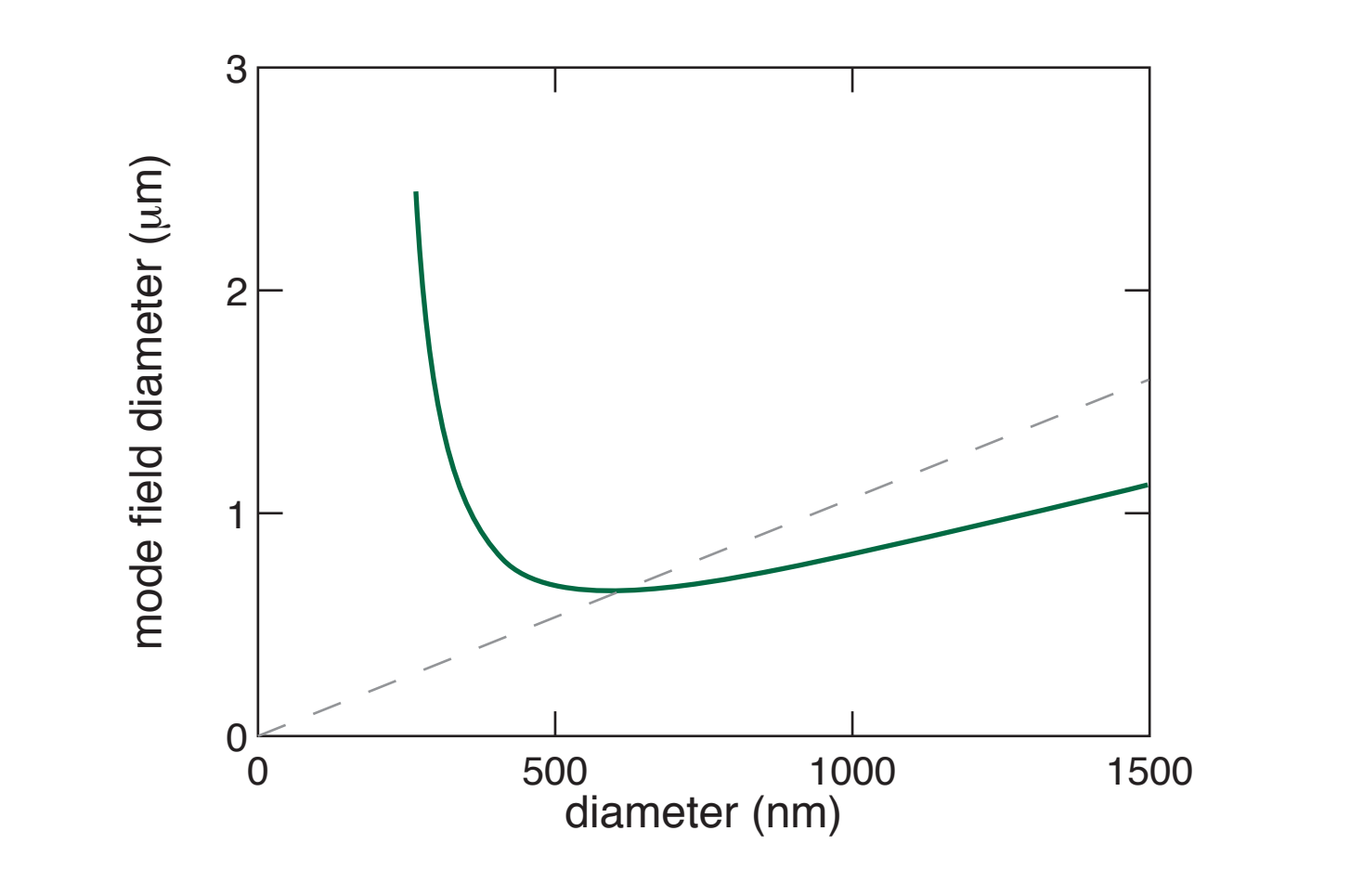


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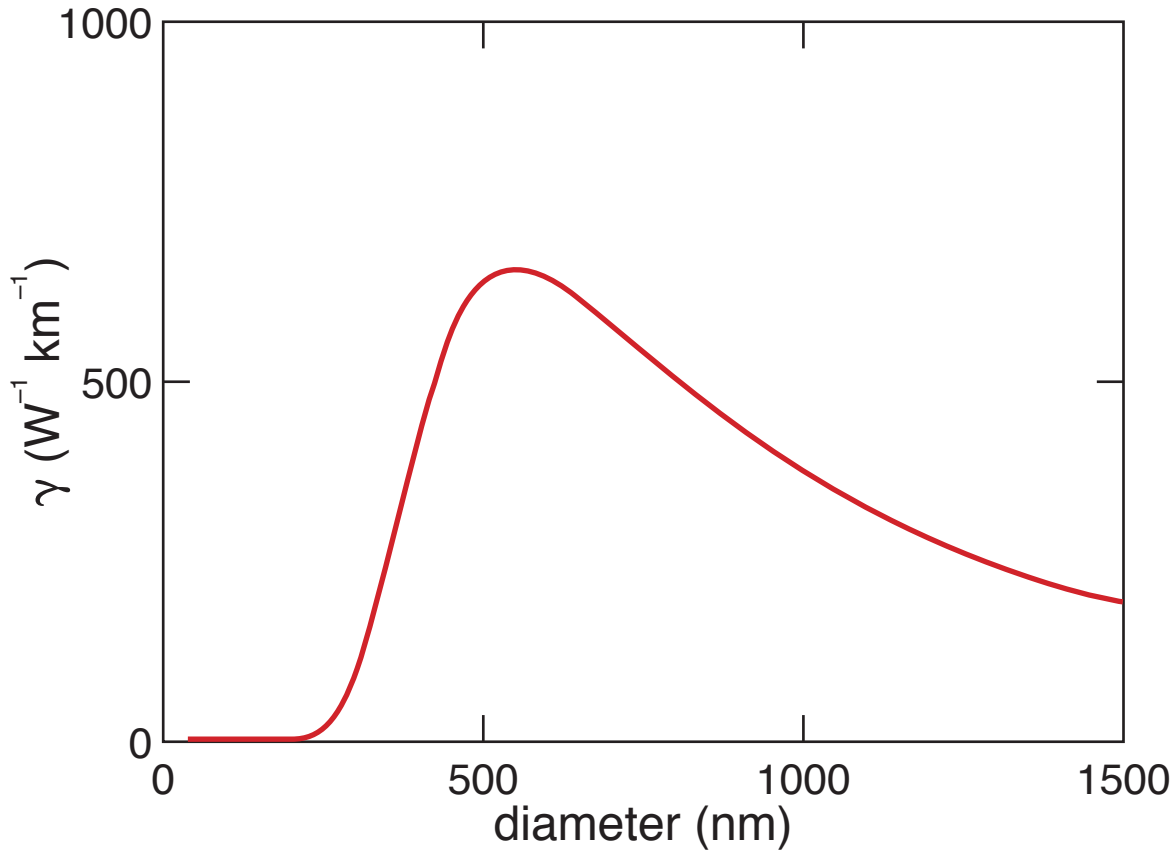
# Supercontinuum generation

## nonlinear parameter



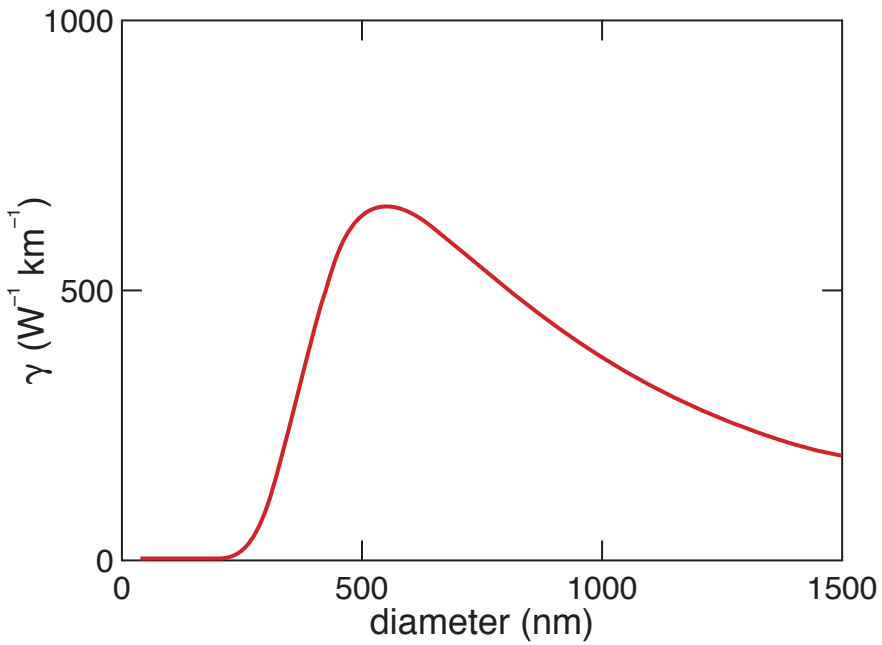

M.A. Foster, *et al.*, *Optics Express*, 12, 2880 (2004)

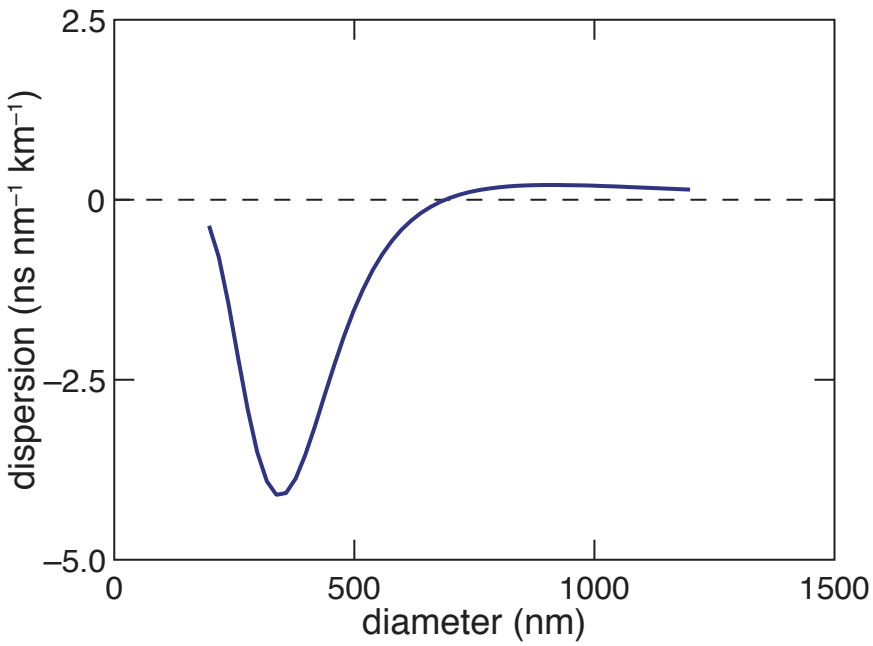
# Supercontinuum generation

**dispersion important!**

# Supercontinuum generation

## waveguide dispersion

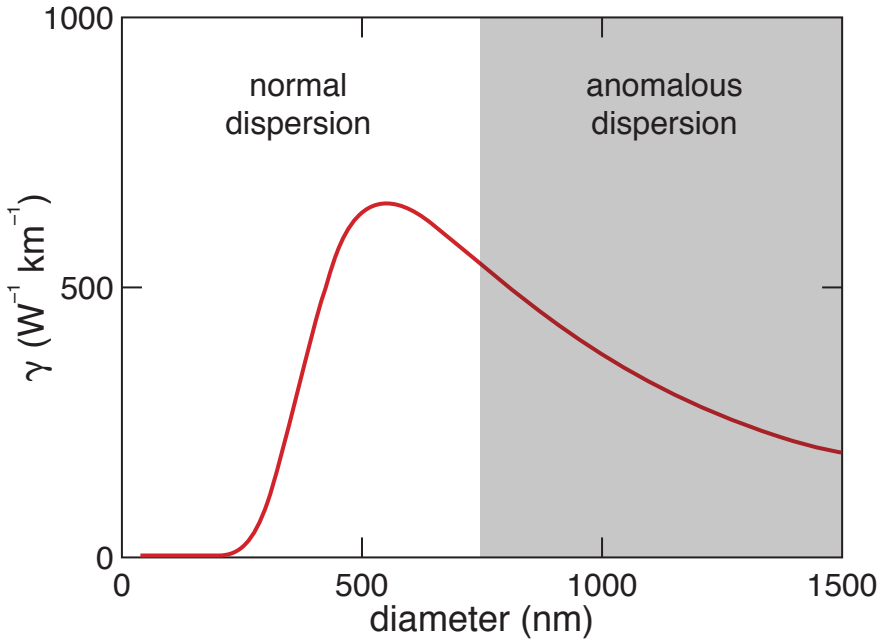


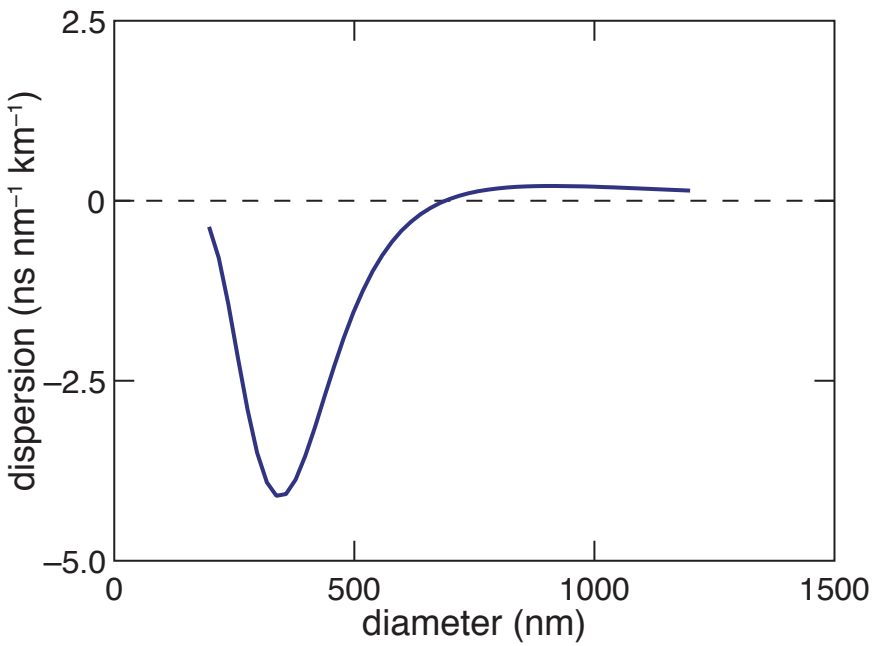




*Optics Express*, 12, 1025 (2004)

# Supercontinuum generation

## waveguide dispersion

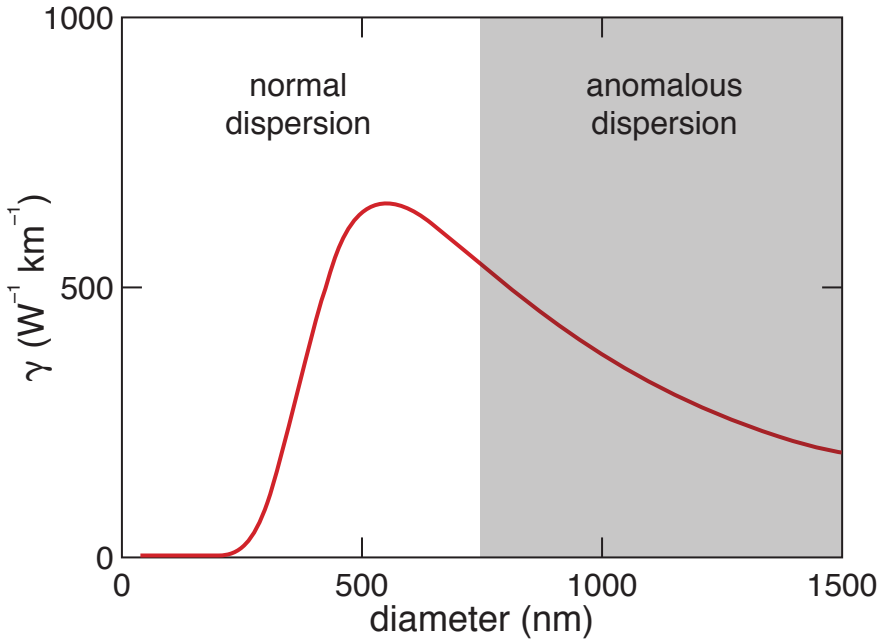


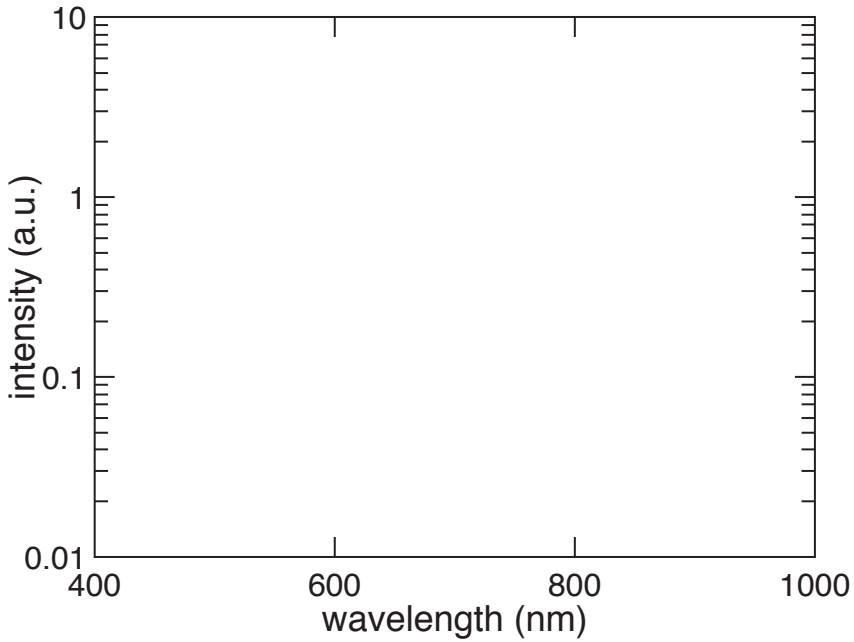




*Optics Express*, 12, 1025 (2004)

# Supercontinuum generation

## nanowire continuum generation



# Supercontinuum generation

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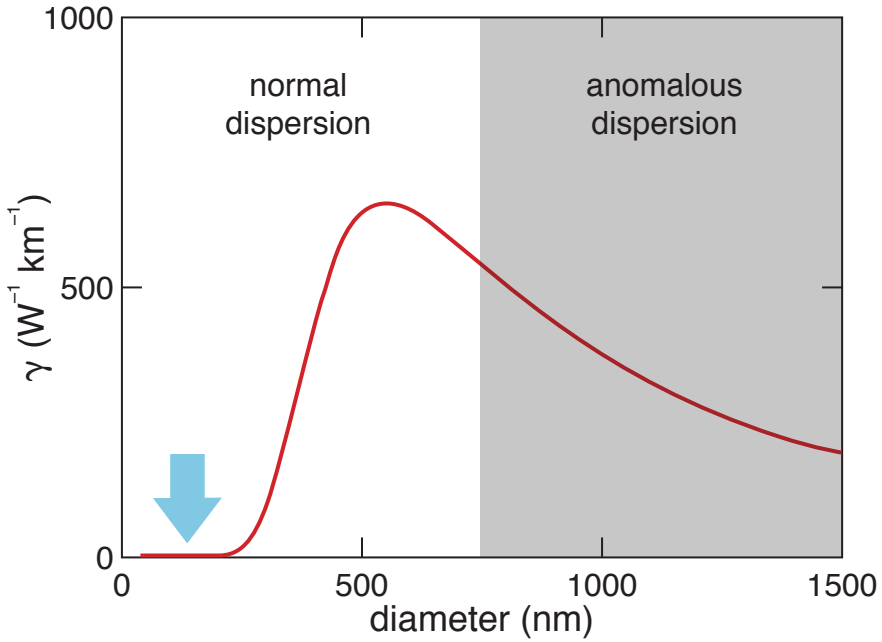
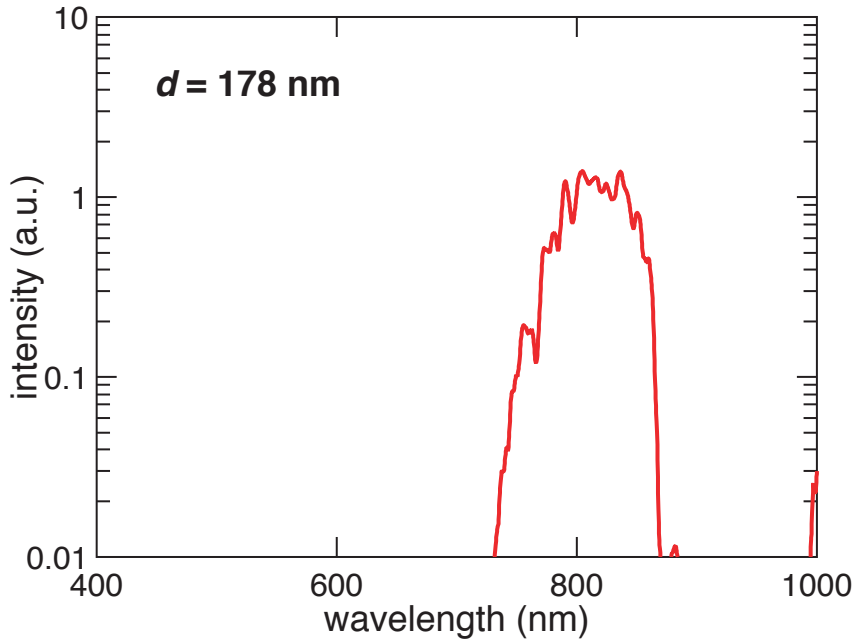
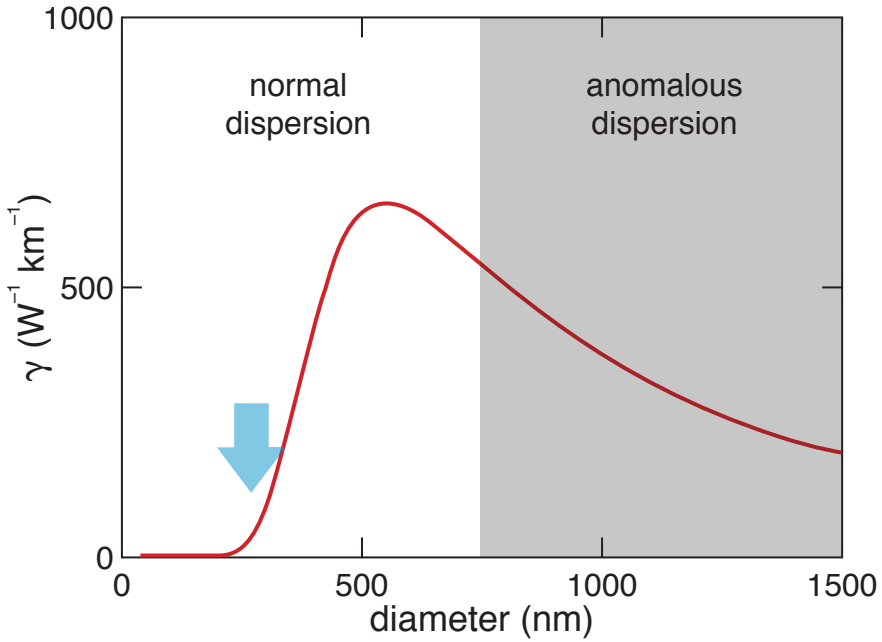


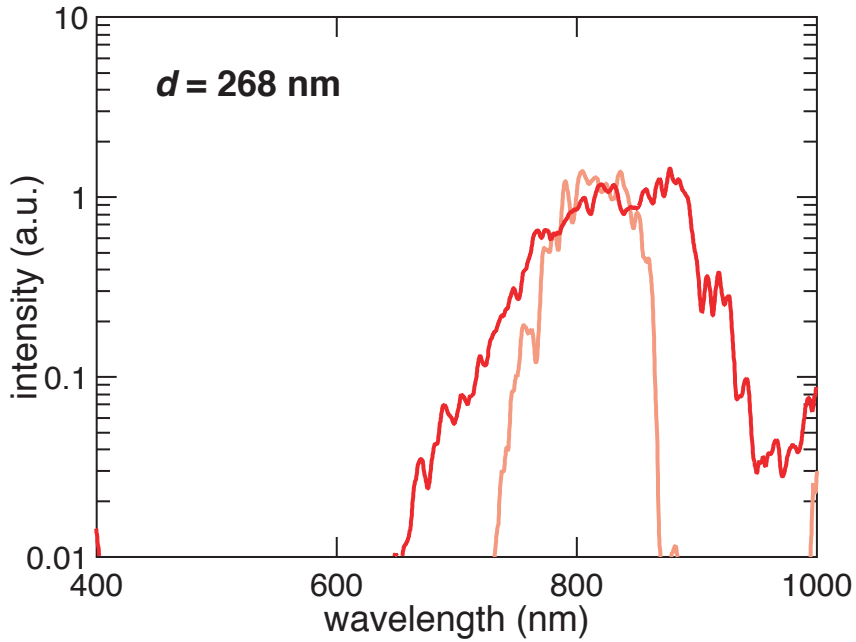




*Optics Express*, 14, 9408 (2006)

# Supercontinuum generation

## nanowire continuum generation

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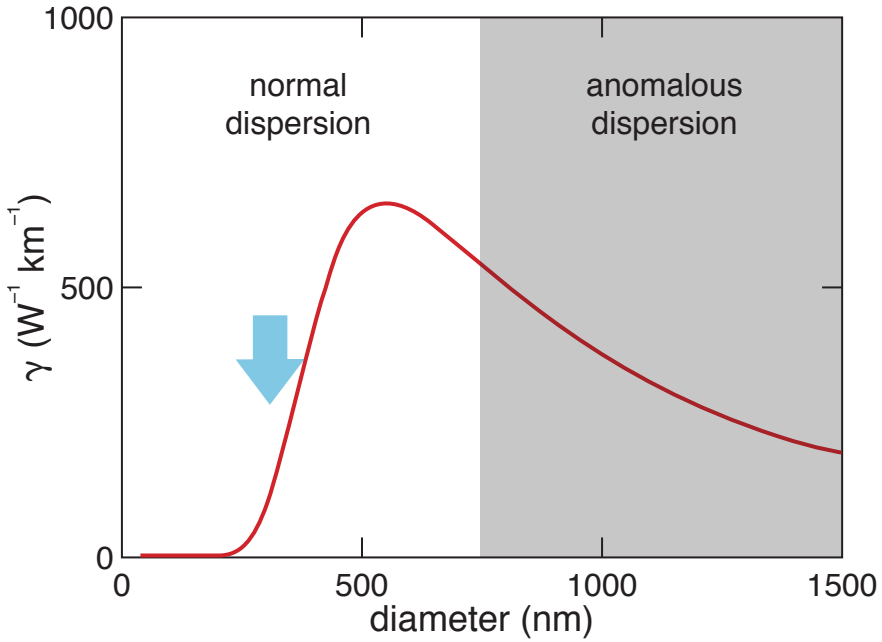


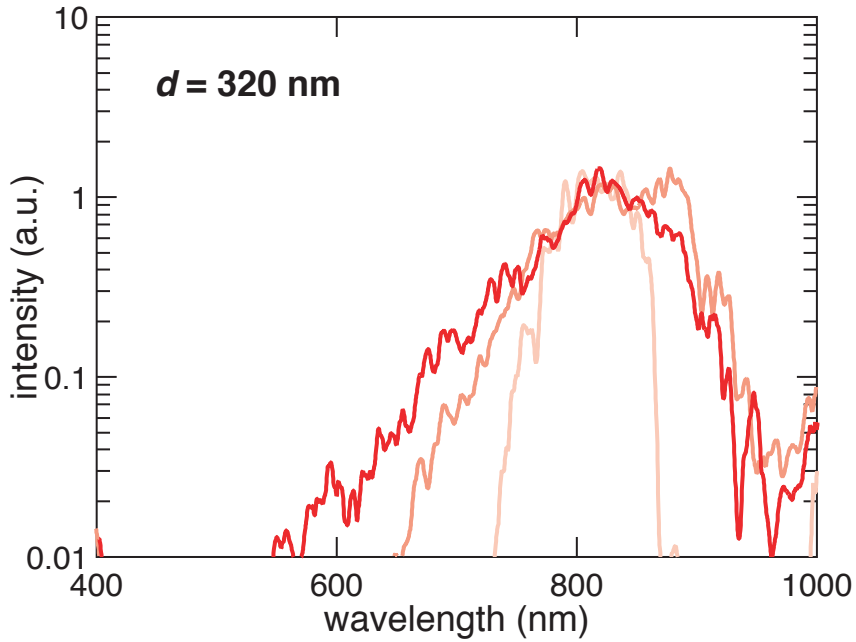


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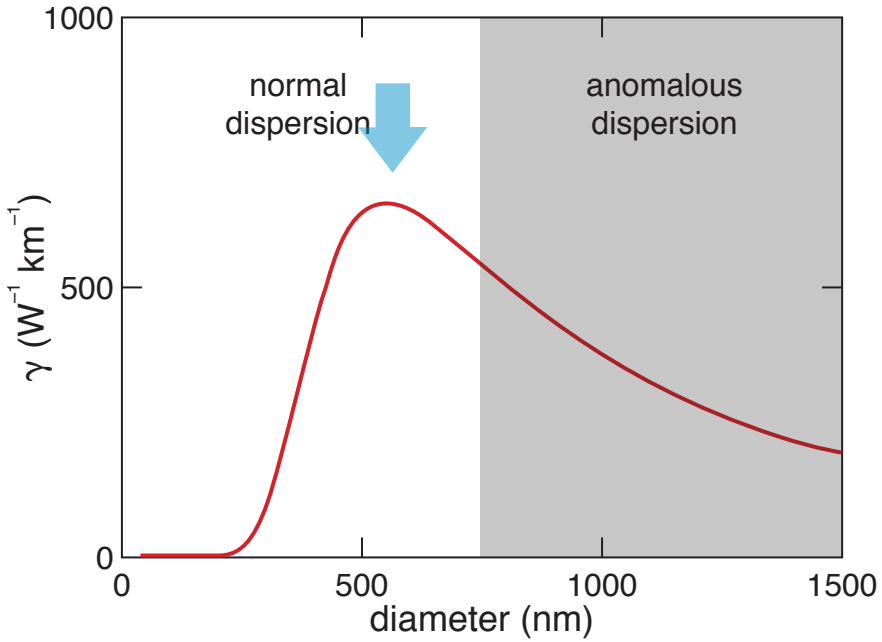


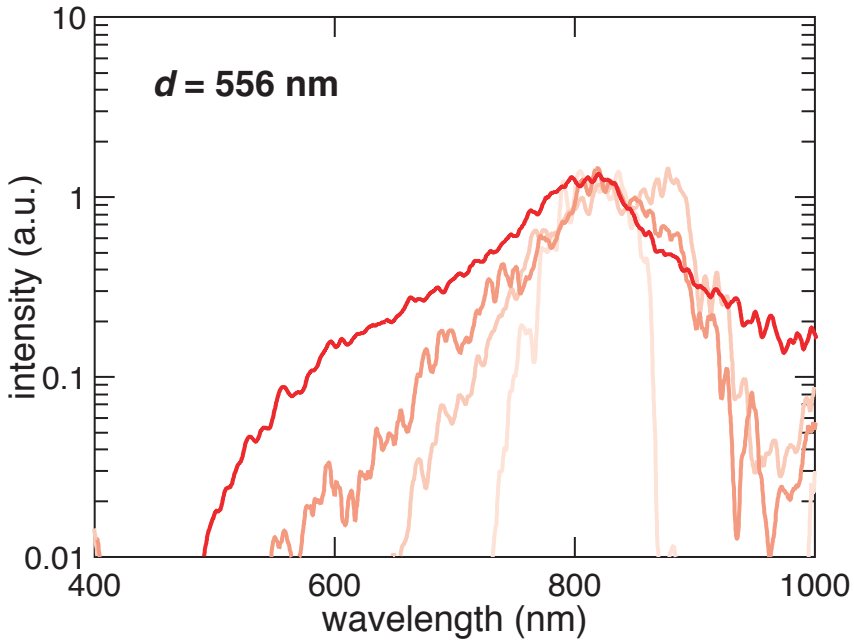


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# Supercontinuum generation

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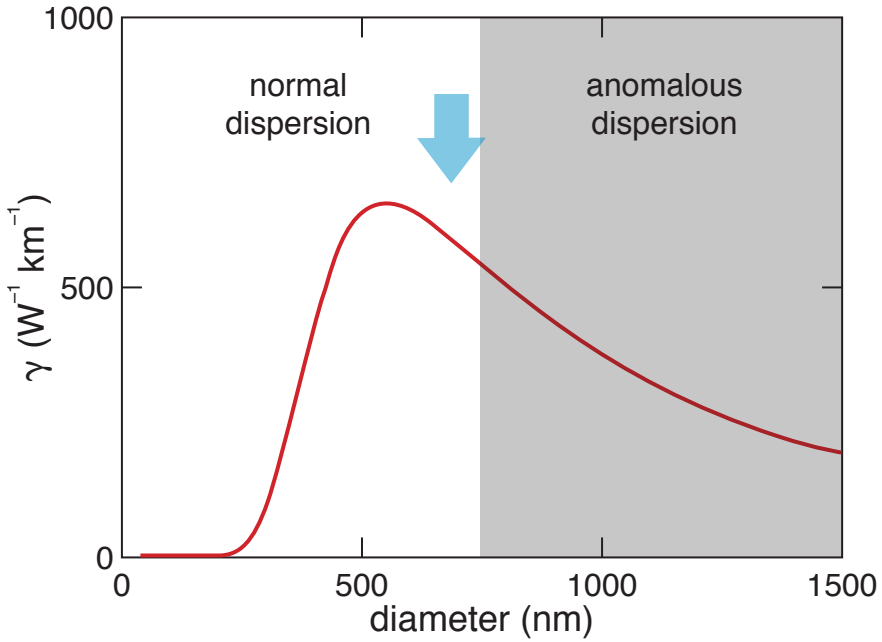


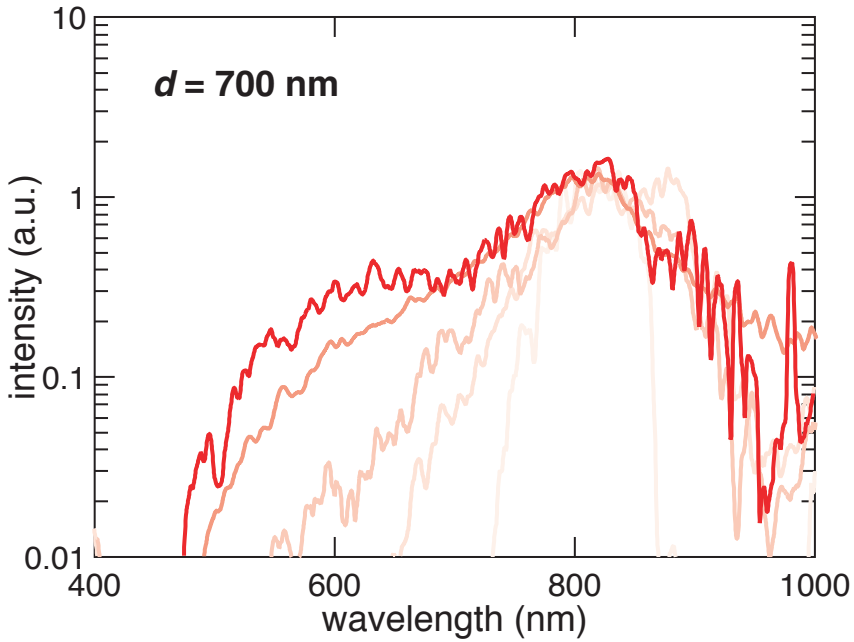


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# Supercontinuum generation

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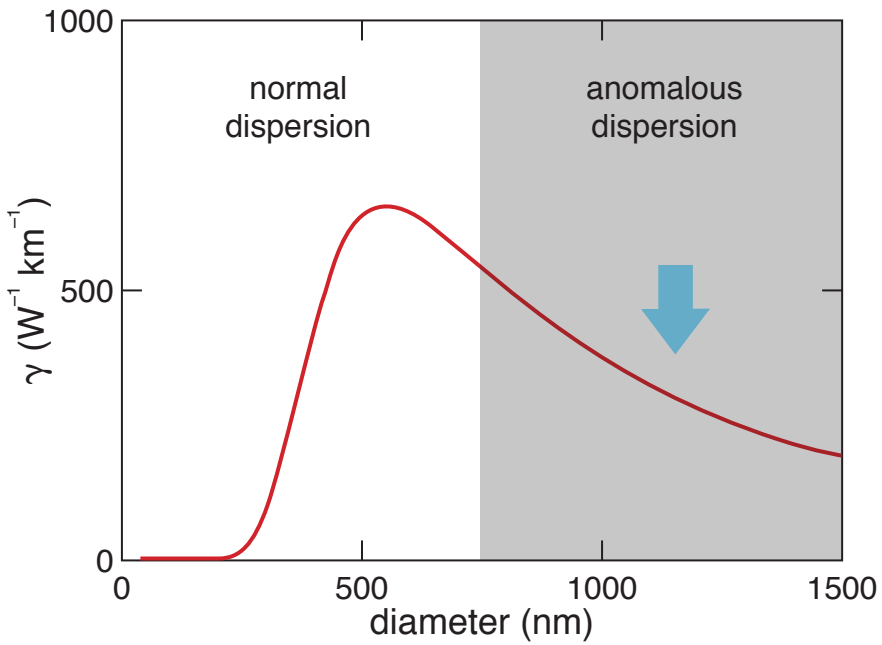


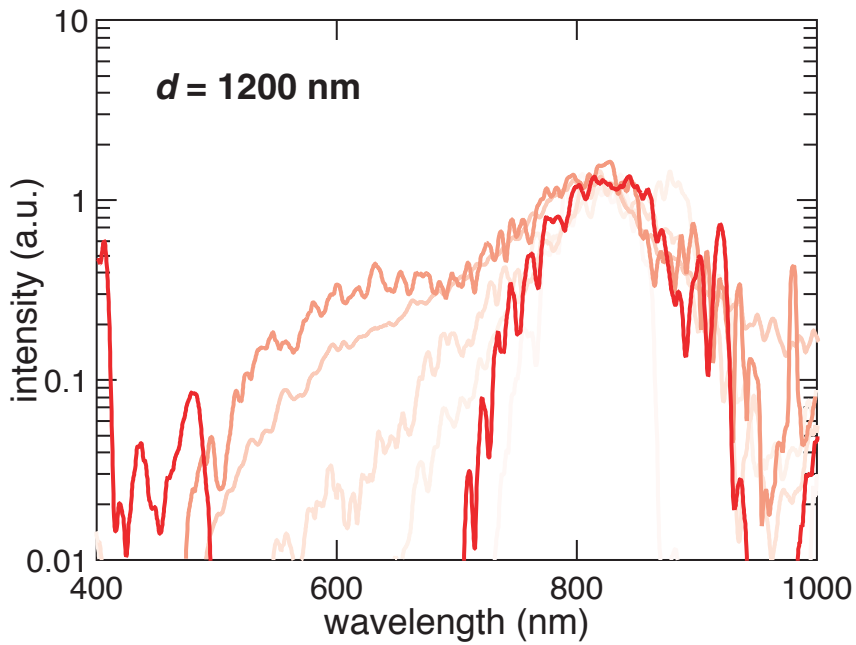


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# Supercontinuum generation

energy in nanowire < 100 pJ!

# Supercontinuum generation

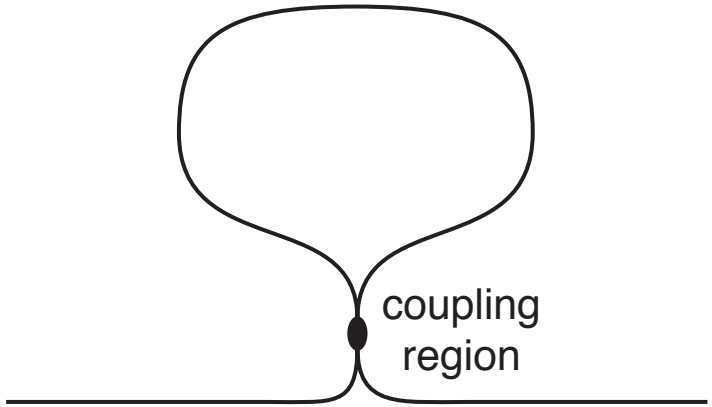
- picojoule nonlinear optics
- optimum diameter for silica 500–600 nm
- low dispersion

# Outline

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

# Optical logic gates

## nanowire Sagnac interferometer



# Optical logic gates

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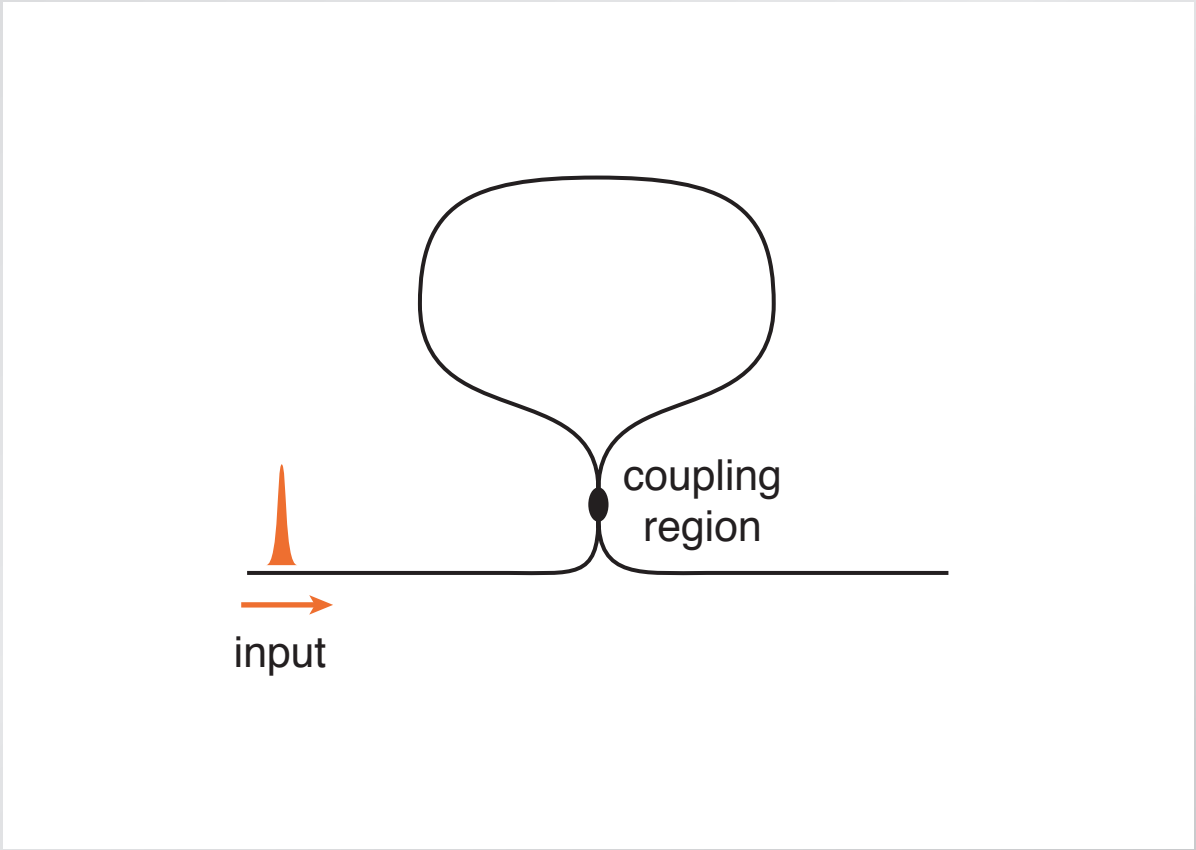

# Optical logic gates

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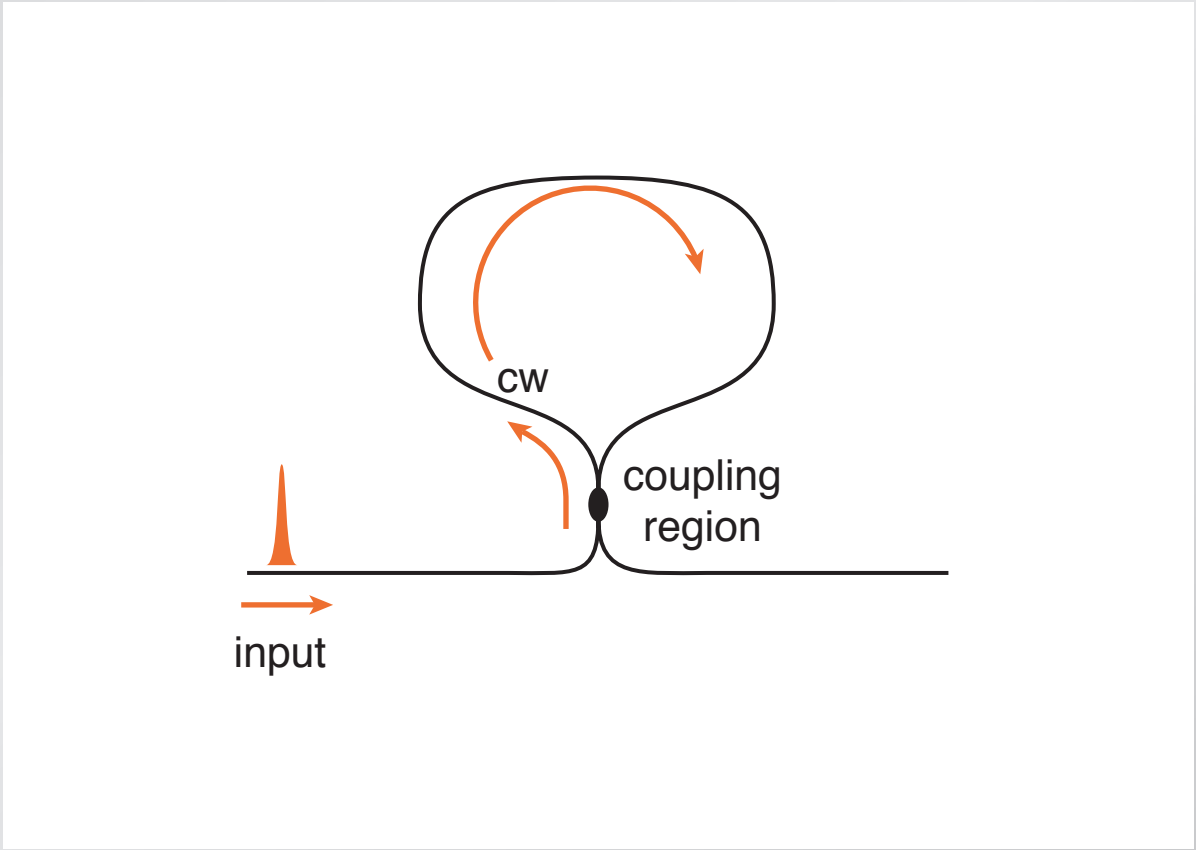

# Optical logic gates

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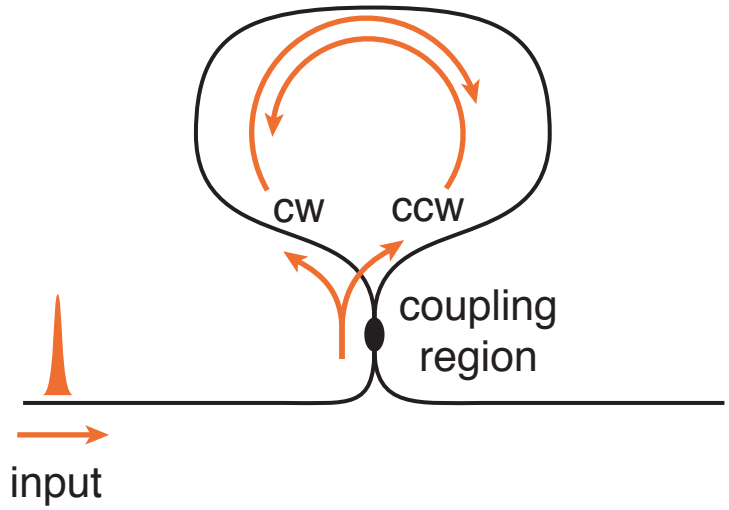

# Optical logic gates

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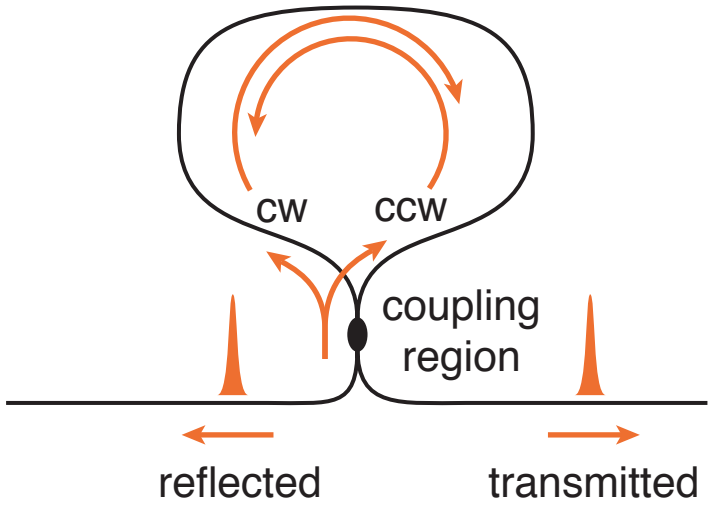
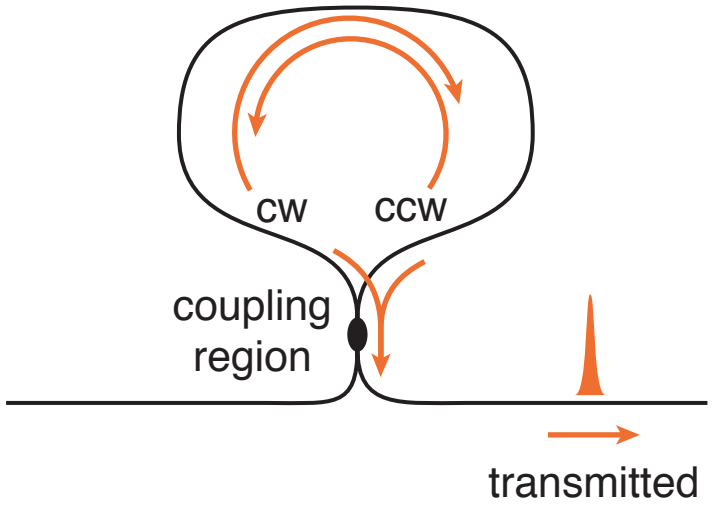


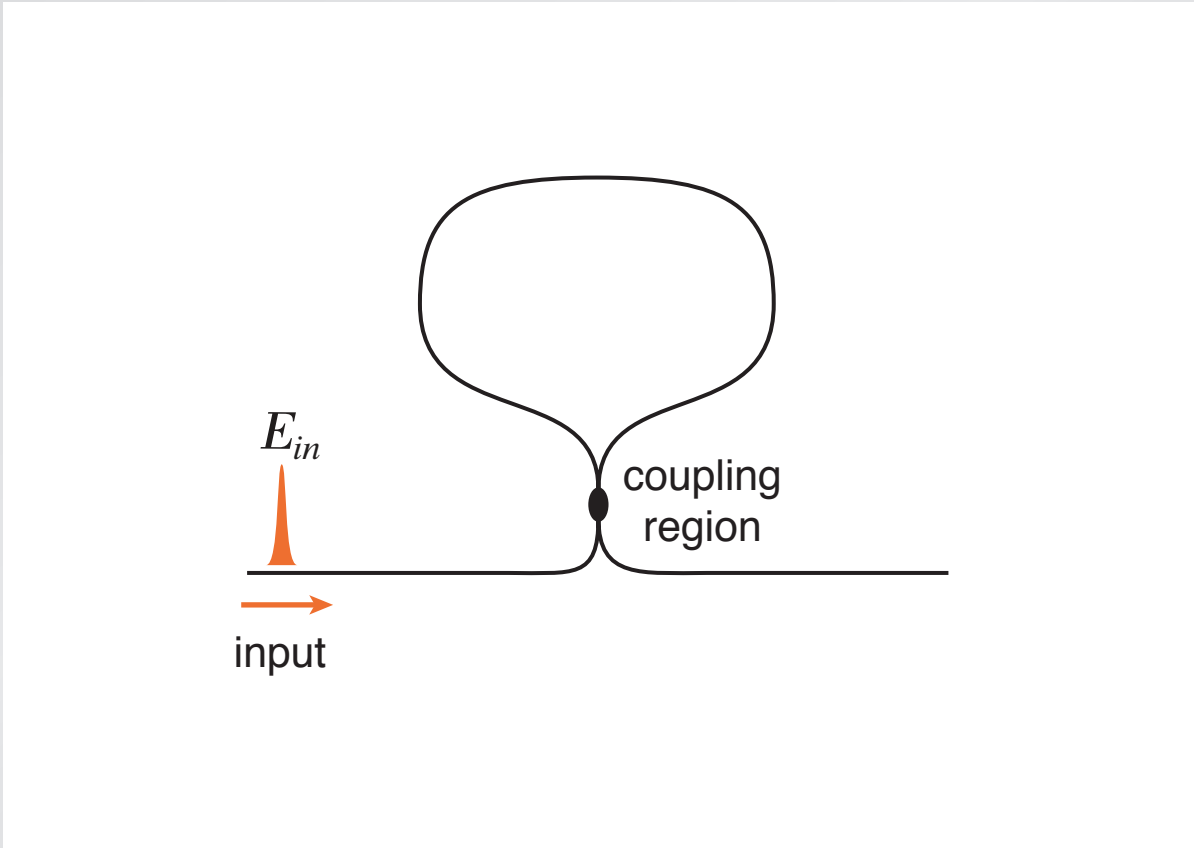
# Optical logic gates

**output = transmitted cw + ccw power**



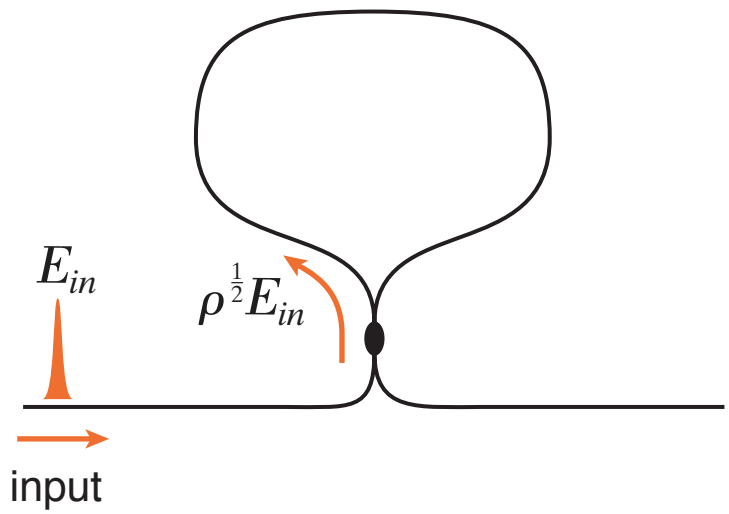
# Optical logic gates

**input electric field amplitude $E_{in}$**



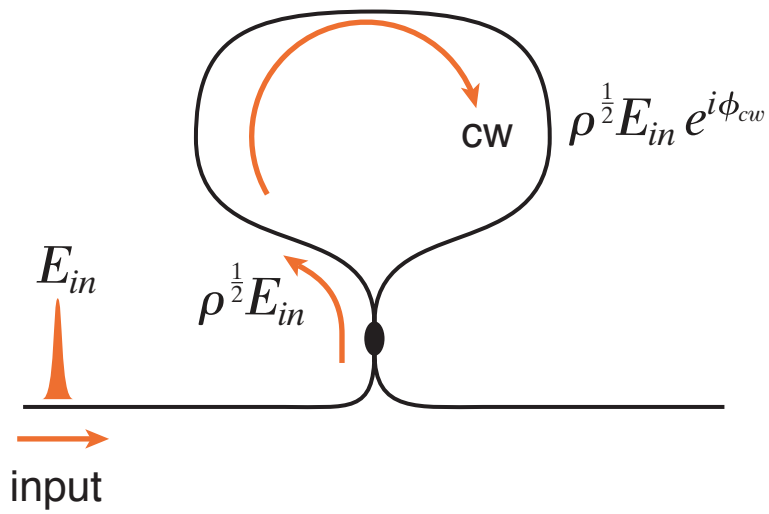
# Optical logic gates

**coupling parameter: ρ**



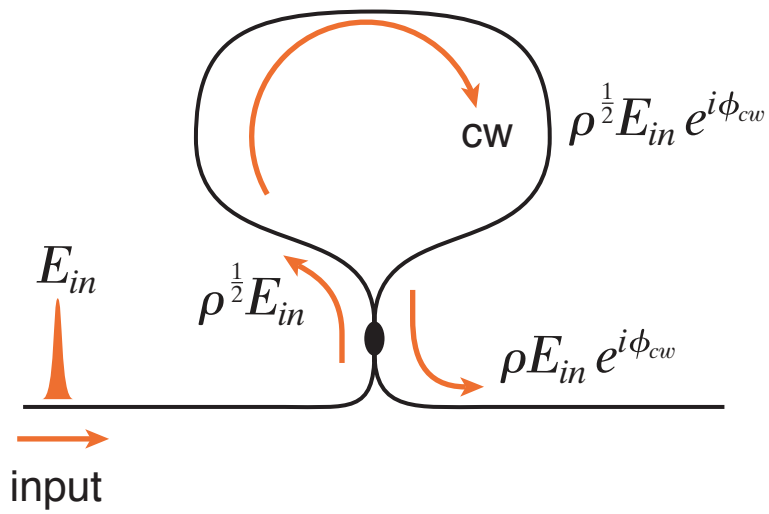
# Optical logic gates

phase accumulation over path length of loop $L$



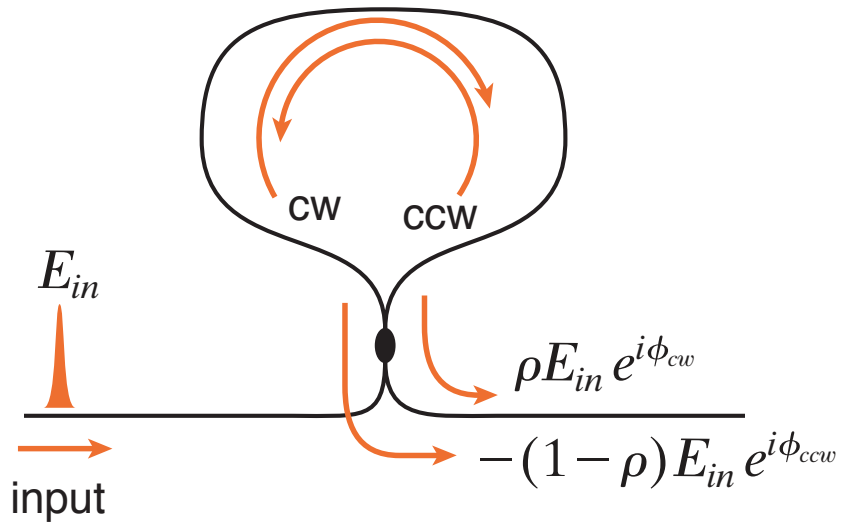
# Optical logic gates

**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

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

# 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:**

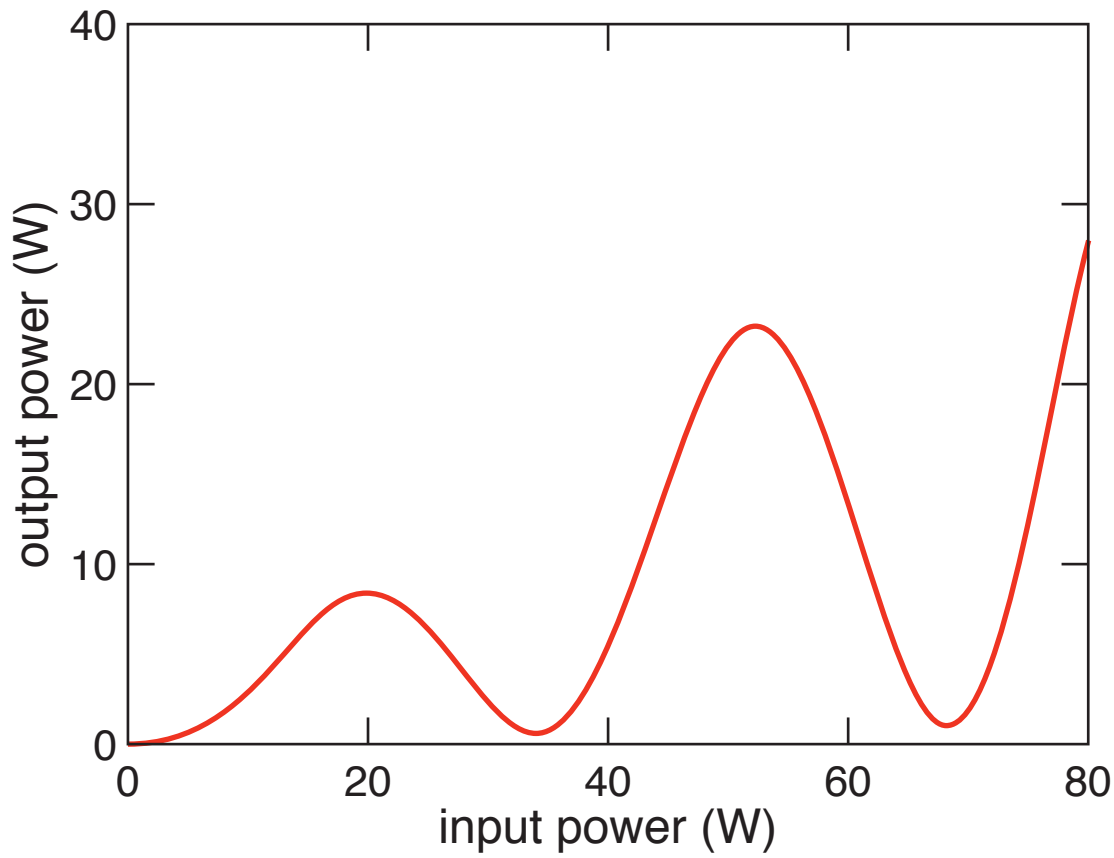
$$\rho = 0.5$$

**no transmission:**

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

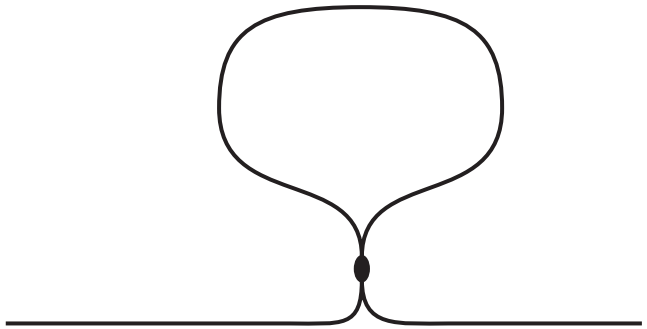
# Optical logic gates

**when $\rho \neq 0.5$:**



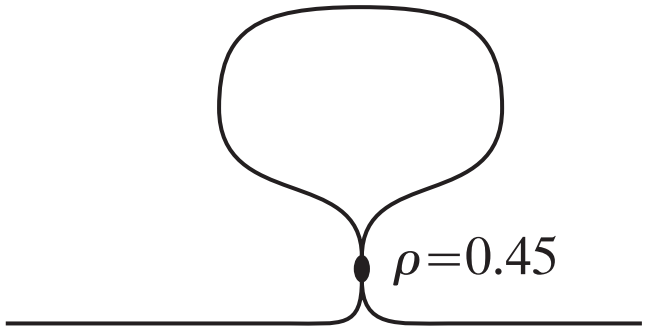
# Optical logic gates

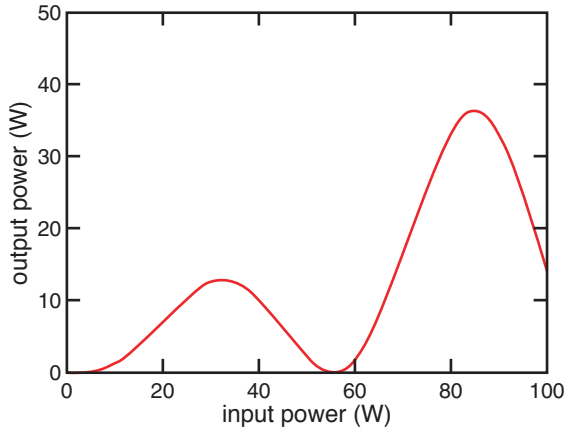
## nonlinear nanogate



# Optical logic gates

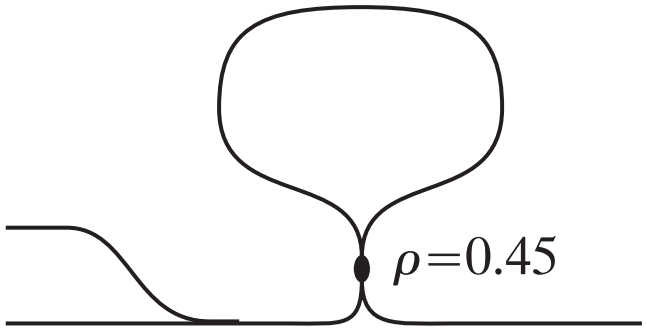
## nonlinear nanogate

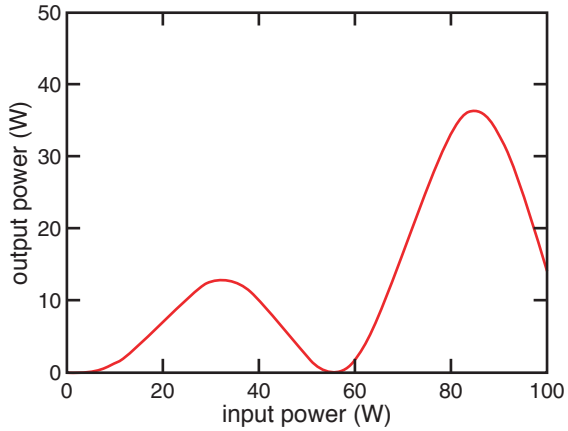


# Optical logic gates

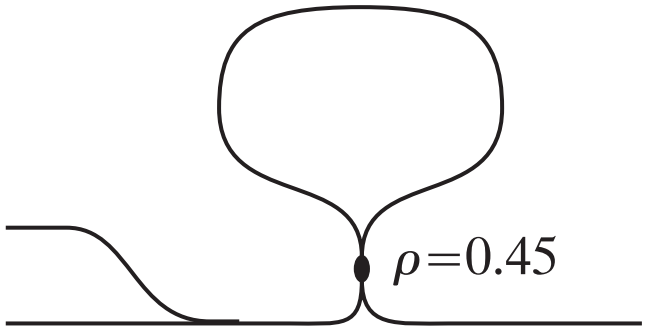
## nonlinear nanogate

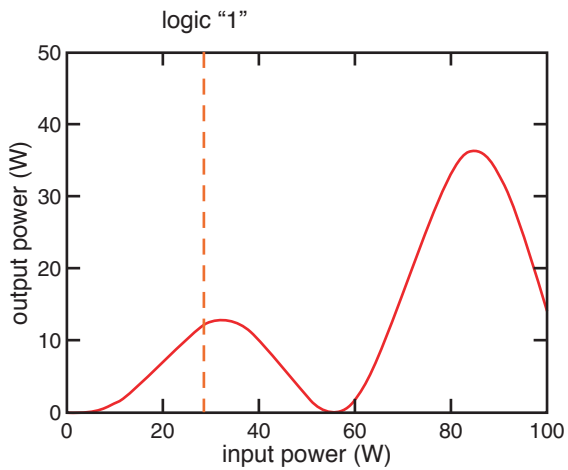


# Optical logic gates

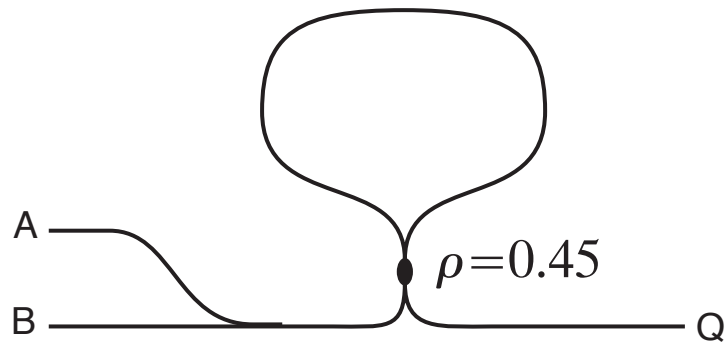
## nonlinear nanogate

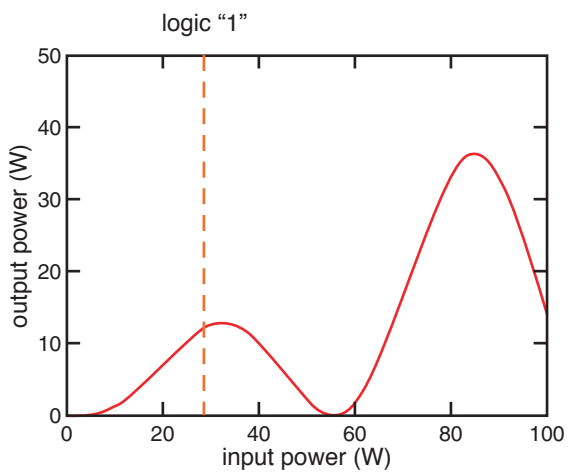


# Optical logic gates

## nonlinear nanogate

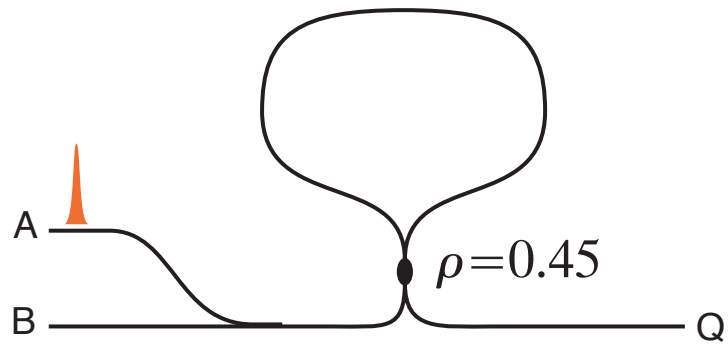


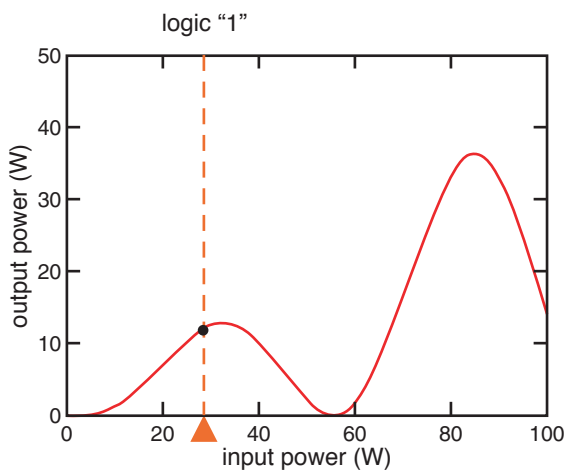




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |

# Optical logic gates

## nonlinear nanogate

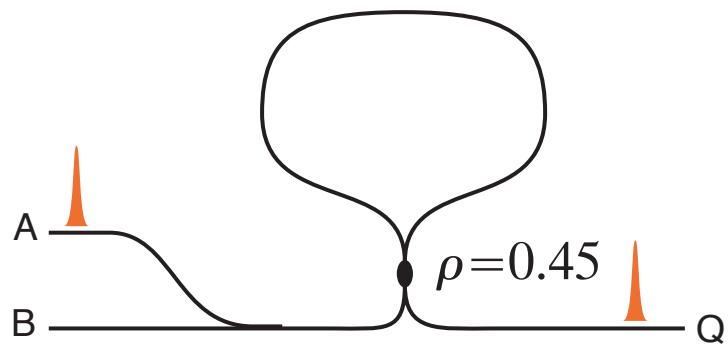


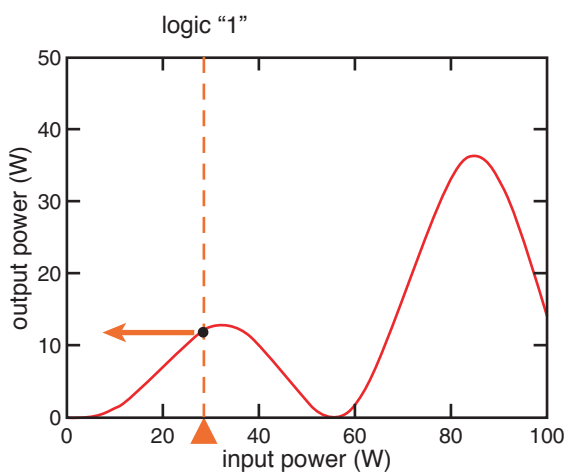




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |

# Optical logic gates

## nonlinear nanogate

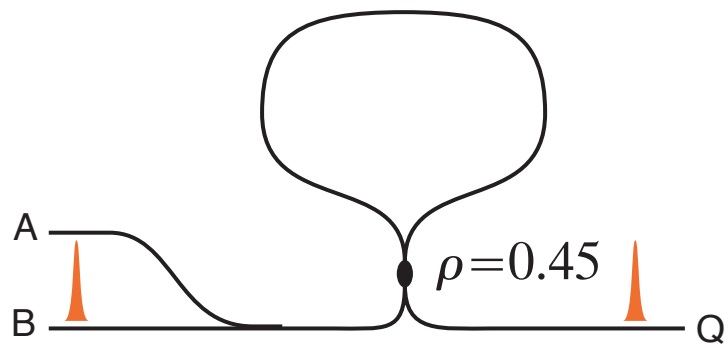


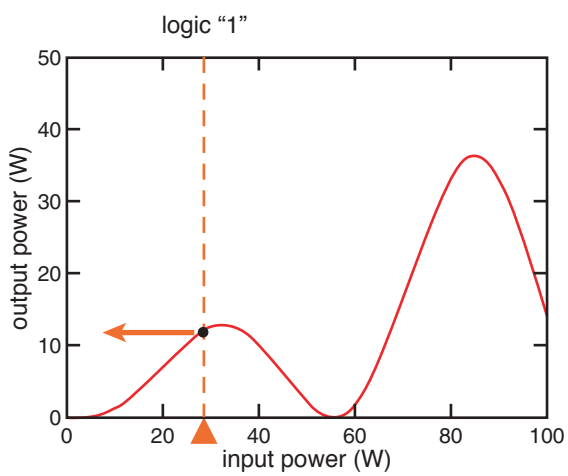




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |

# Optical logic gates

## nonlinear nanogate

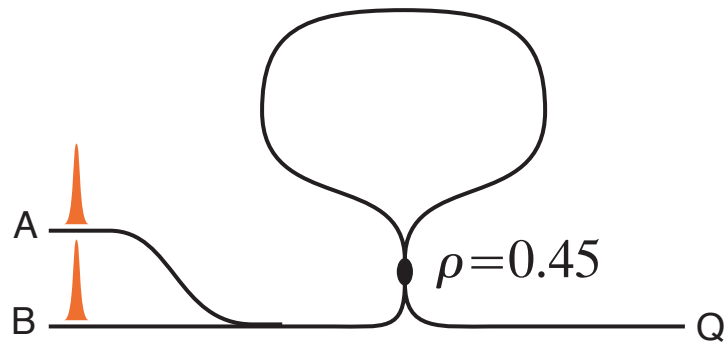


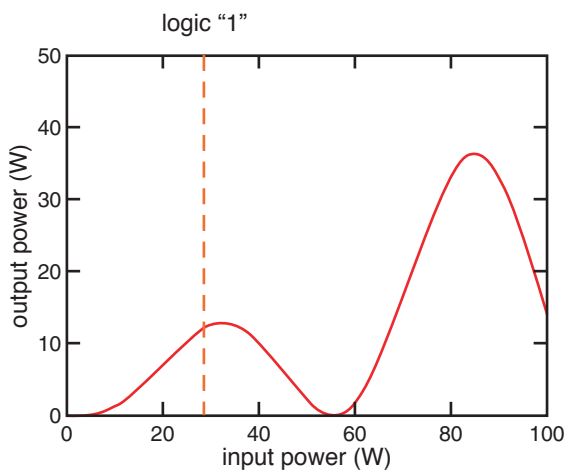




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |

# Optical logic gates

## nonlinear nanogate




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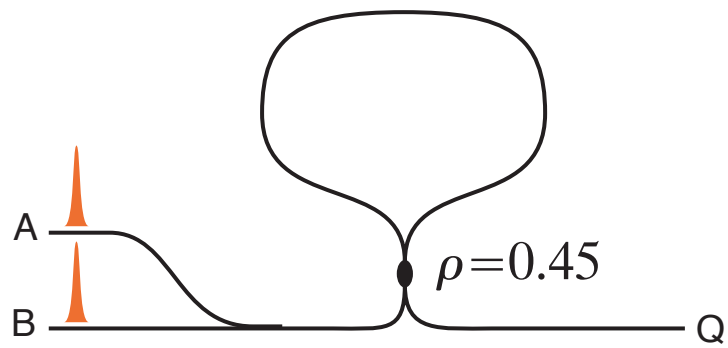
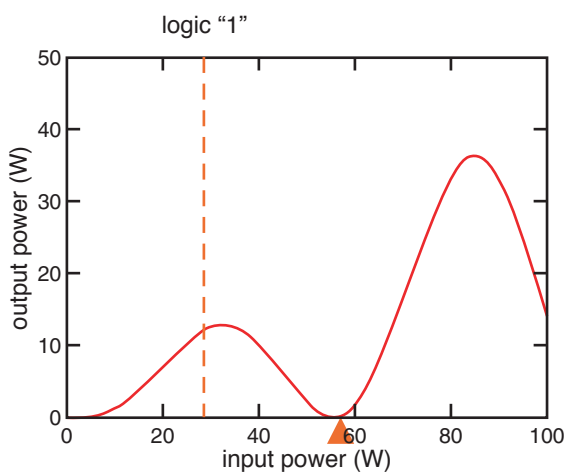
| 0 | 0 | 0 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |

# Optical logic gates

## nonlinear nanogate

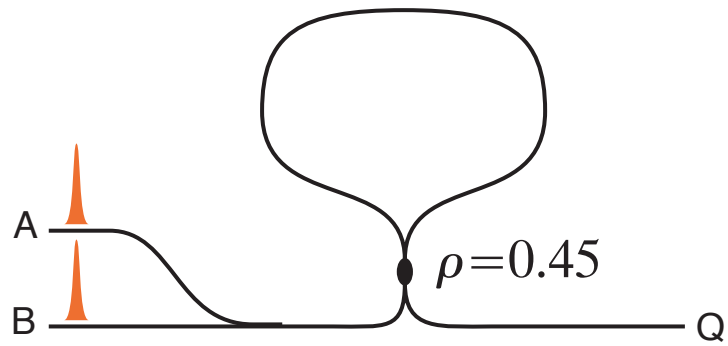


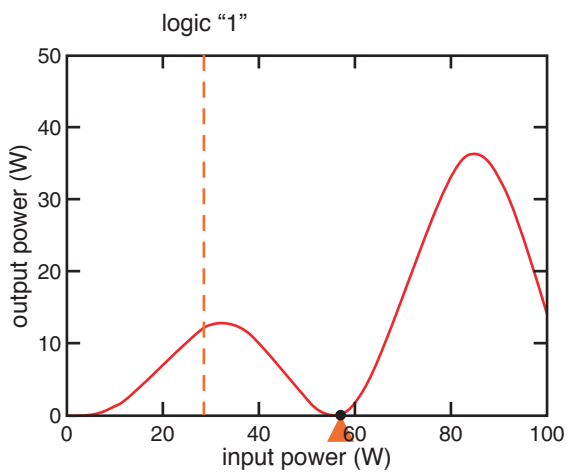




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |

# Optical logic gates

## nonlinear nanogate

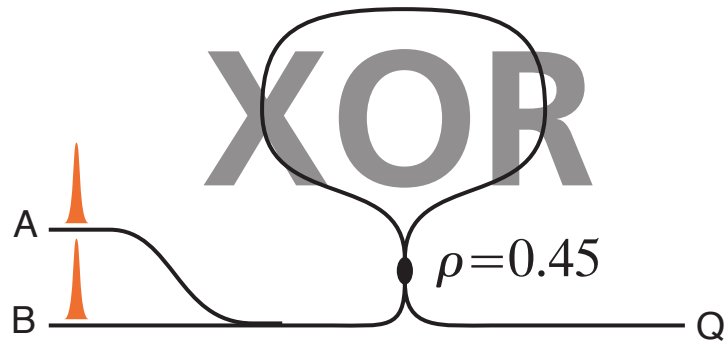


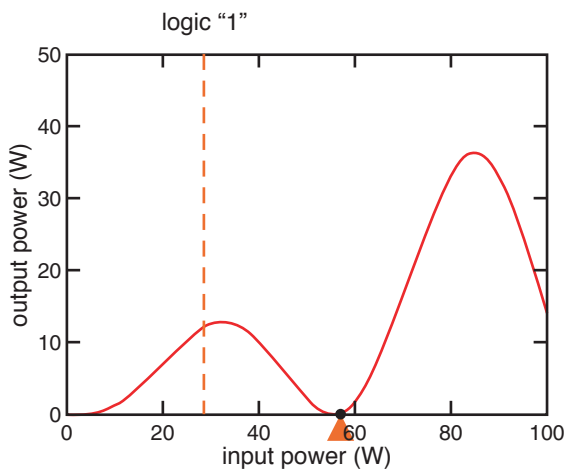




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 1 | 0 |

# Optical logic gates

## nonlinear nanogate

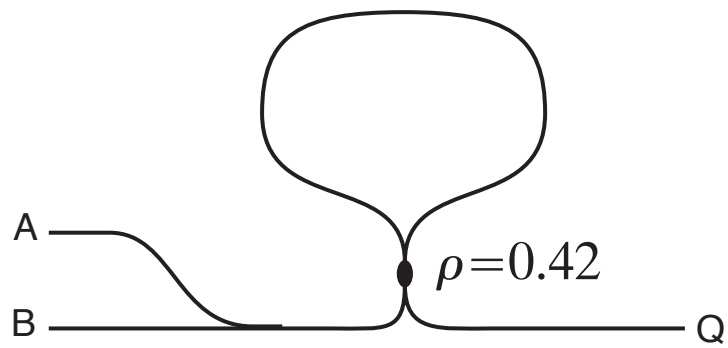


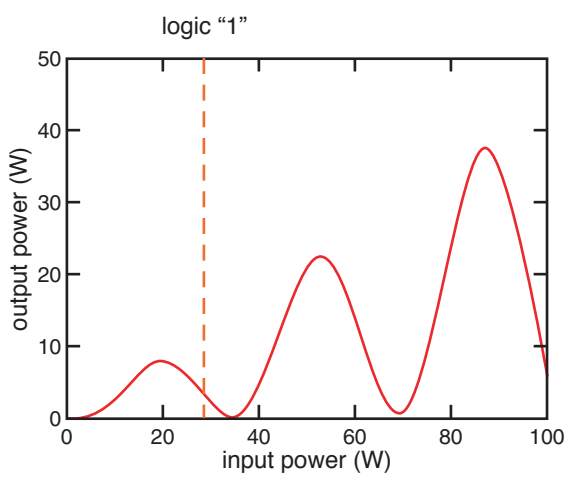




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 1 | 0 |

# Optical logic gates

## nonlinear nanogate

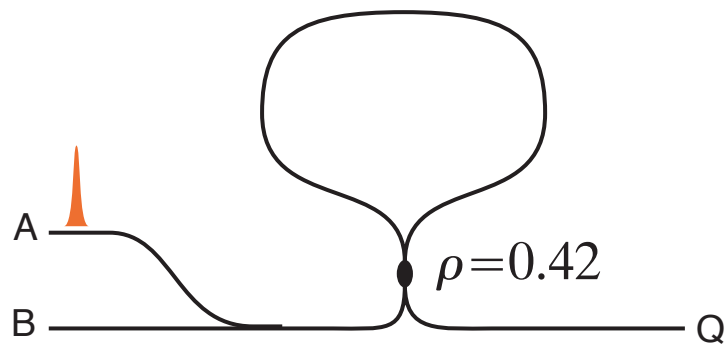


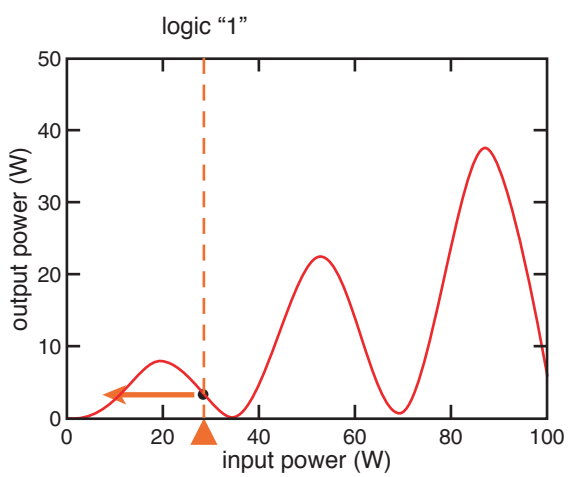




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |

# Optical logic gates

## nonlinear nanogate

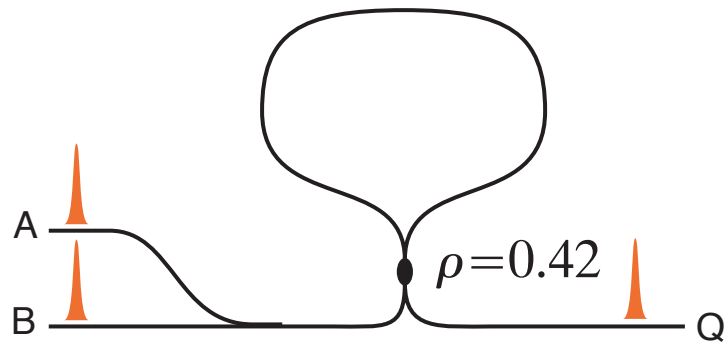


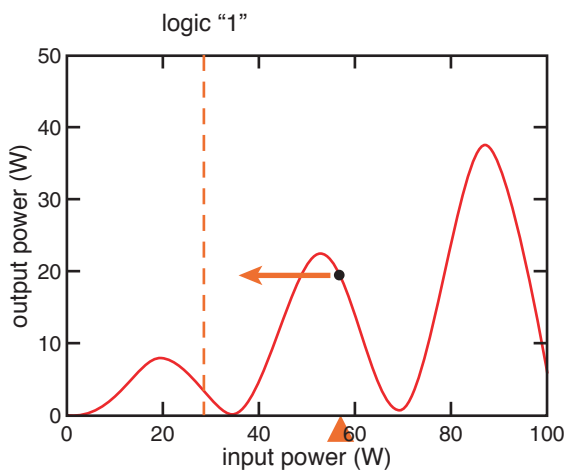




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 0 |
| 0 | 1 | 0 |

# Optical logic gates

## nonlinear nanogate

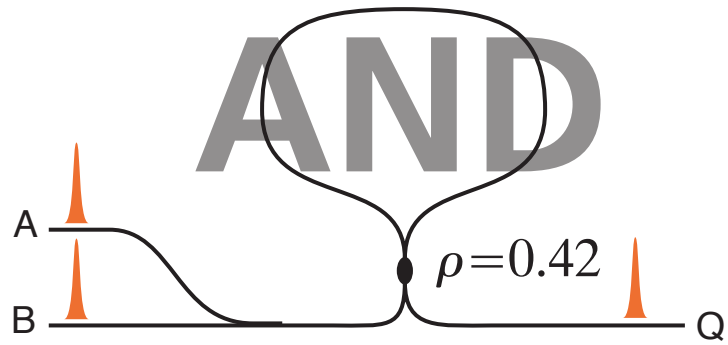


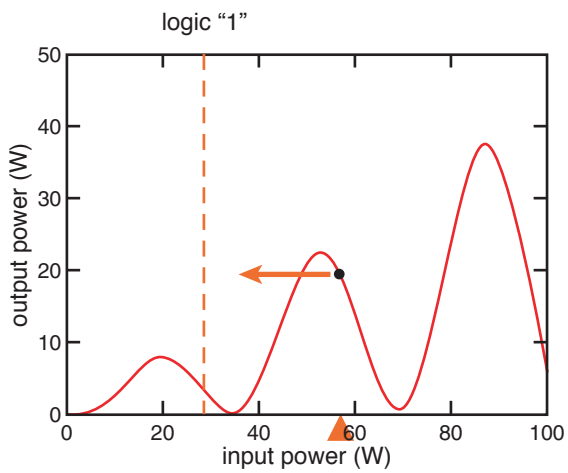




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 1 | 1 |

# Optical logic gates

## nonlinear nanogate

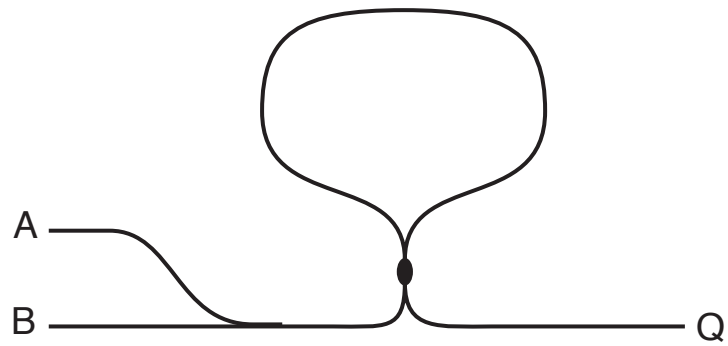


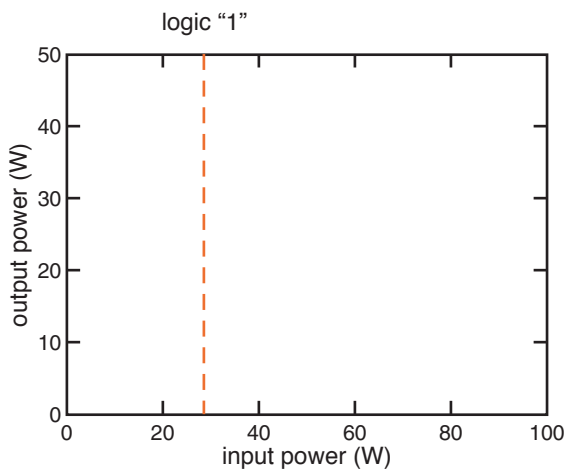




| A | B | Q |
|---|---|---|
| 0 | 0 | 0 |
| 1 | 0 | 0 |
| 0 | 1 | 0 |
| 1 | 1 | 1 |

# Optical logic gates

## for NAND gate need ouput with no input

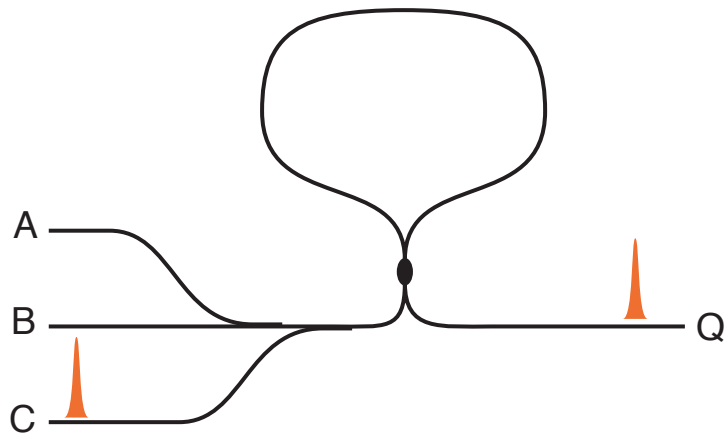


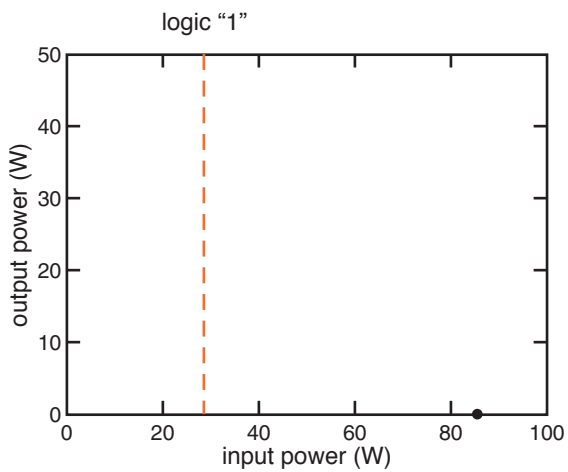




| A | B | Q |
|---|---|---|
| 0 | 0 | 1 |

# Optical logic gates

## for NAND gate need ouput with no input

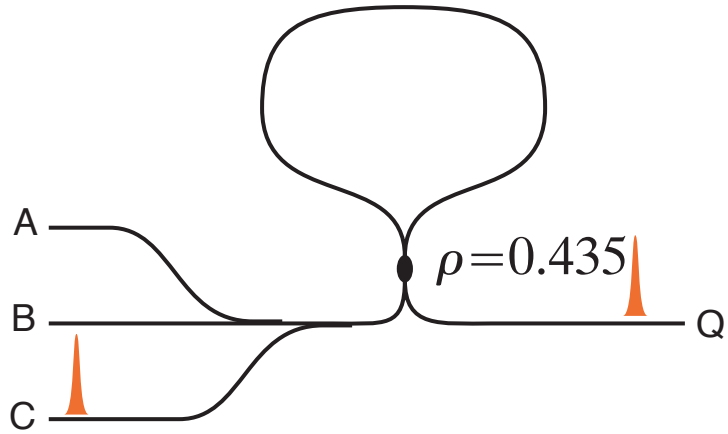


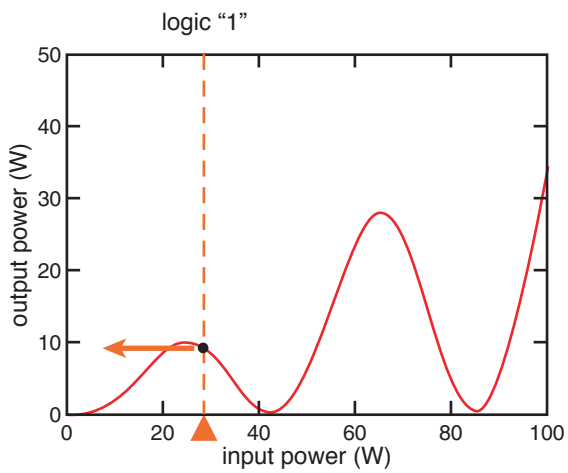




| A | B | Q |
|---|---|---|
| 0 | 0 | 1 |

# Optical logic gates

## for NAND gate need ouput with no input

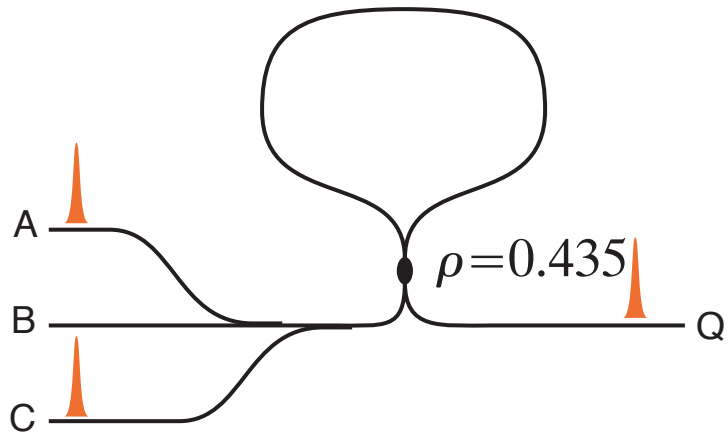


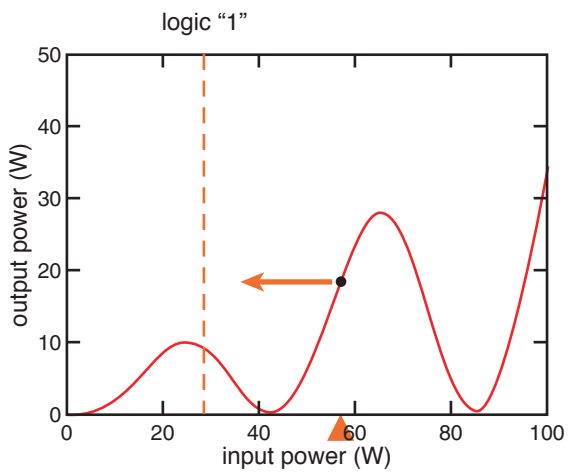




| A | B | Q |
|---|---|---|
| 0 | 0 | 1 |

# Optical logic gates

## universal NAND gate

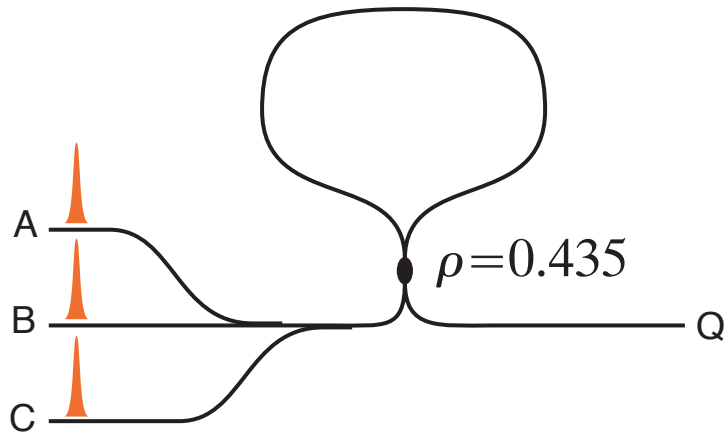


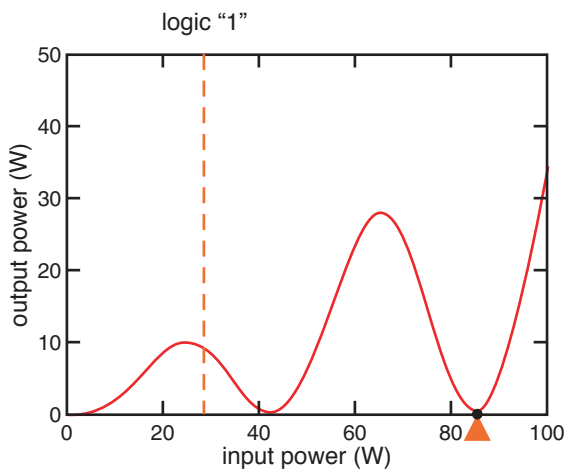




| A | B | Q |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |

# Optical logic gates

## universal NAND gate

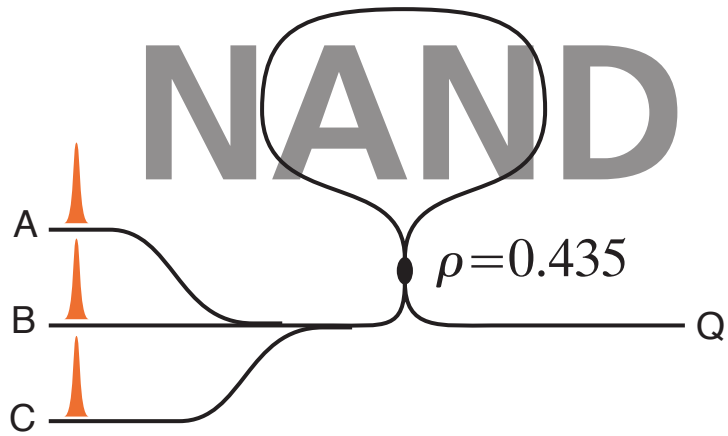


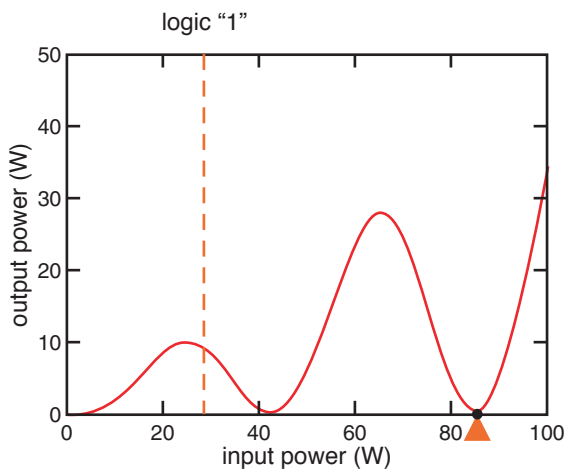




| A | B | Q |
|---|---|---|
| 0 | 0 | 1 |
| 1 | 0 | 1 |
| 0 | 1 | 1 |
| 1 | 1 | 0 |

# Optical logic gates

## universal NAND gate




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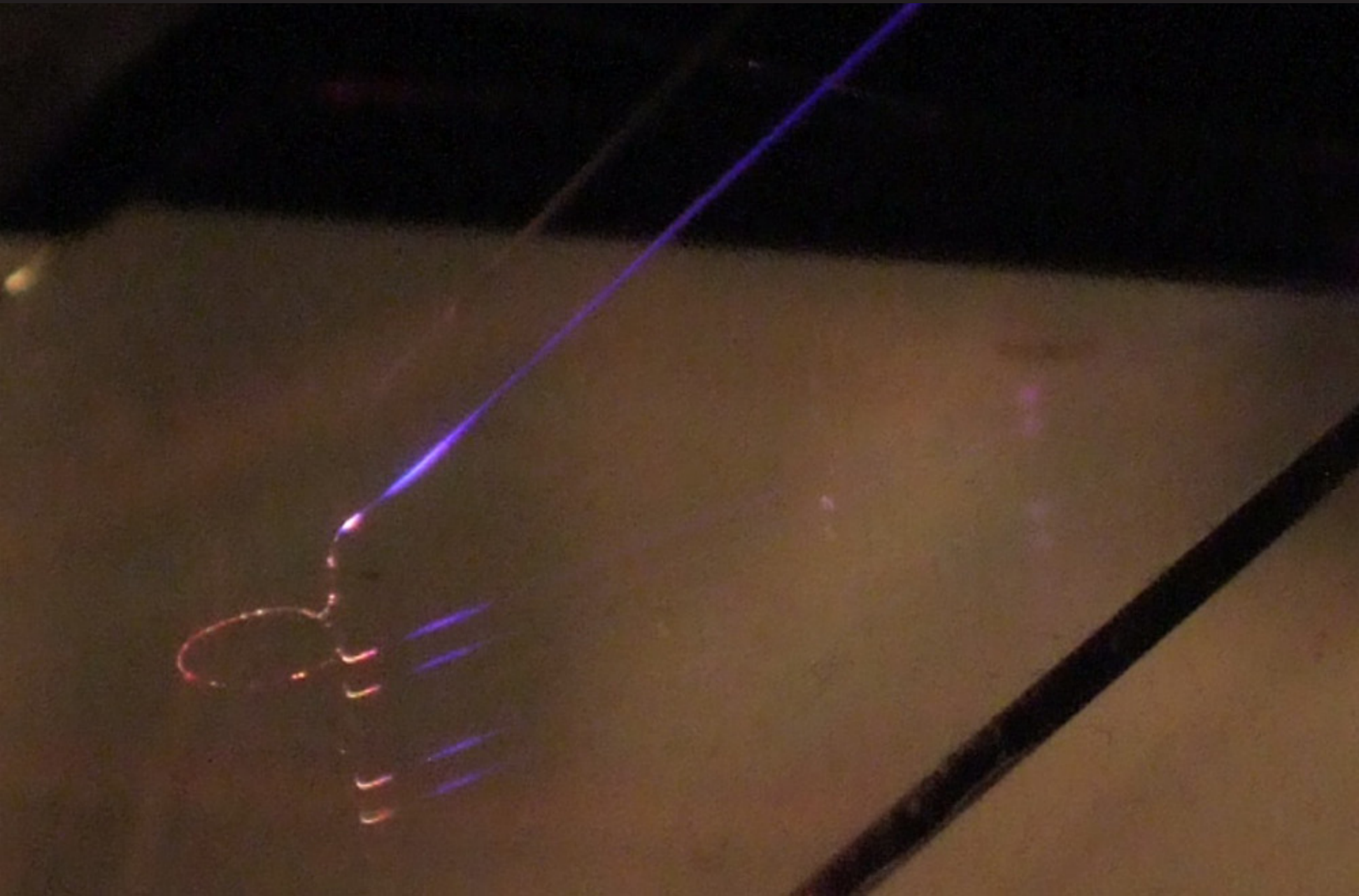
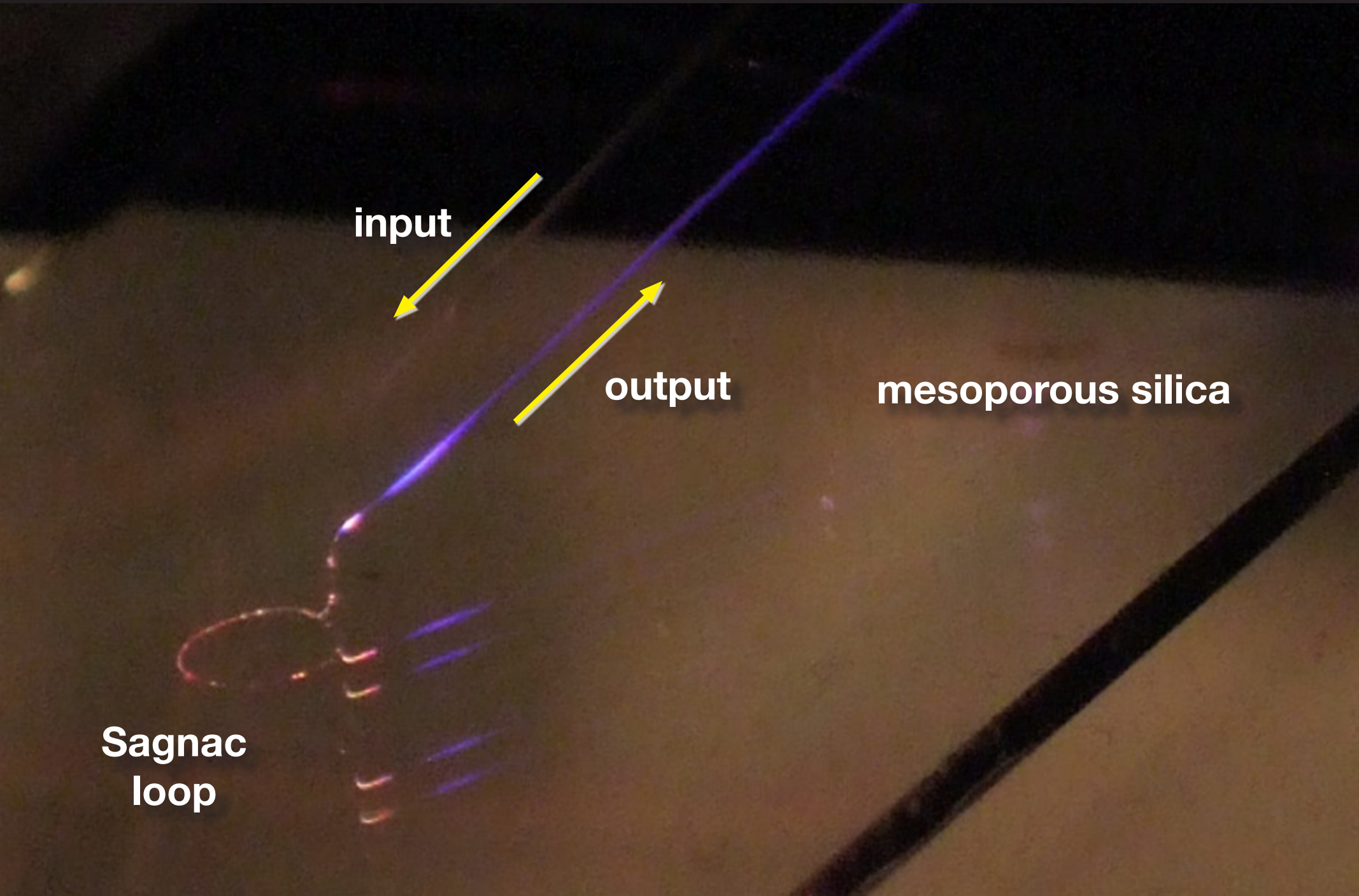
# Optical logic gates



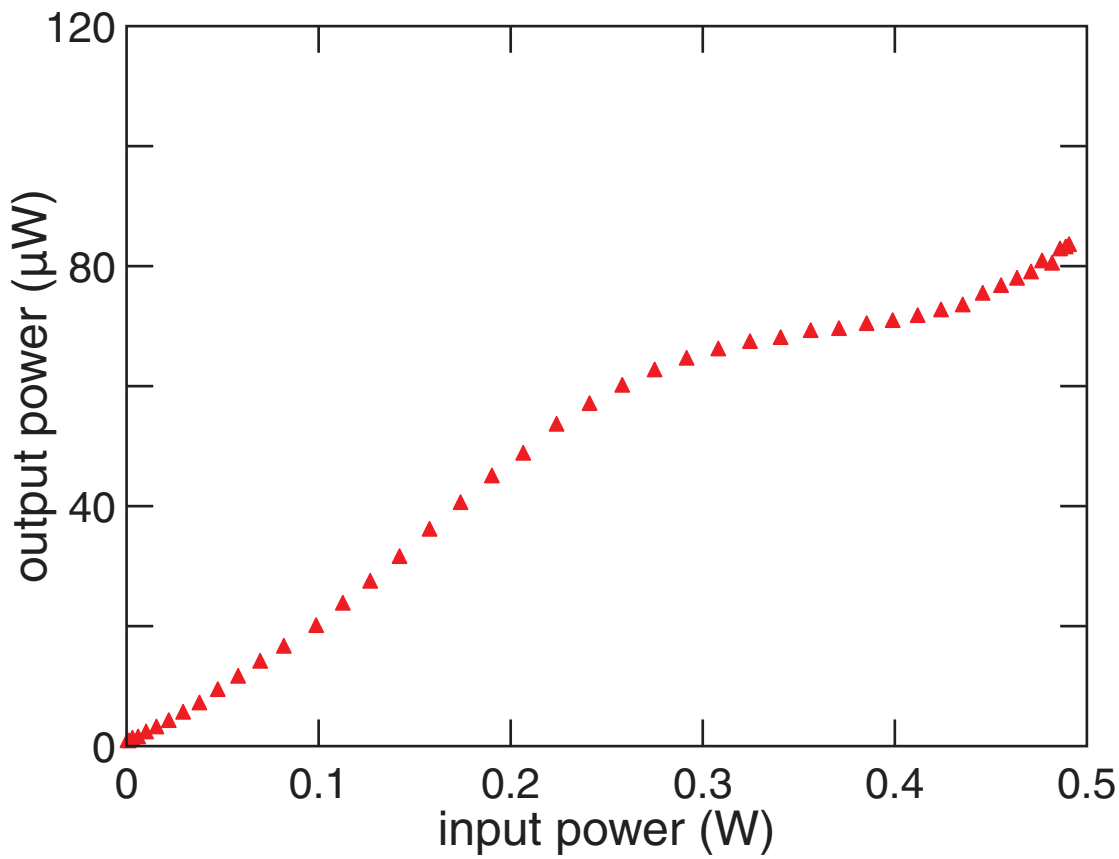
# Optical logic gates

# Optical logic gates



# Optical logic gates

## very preliminary data

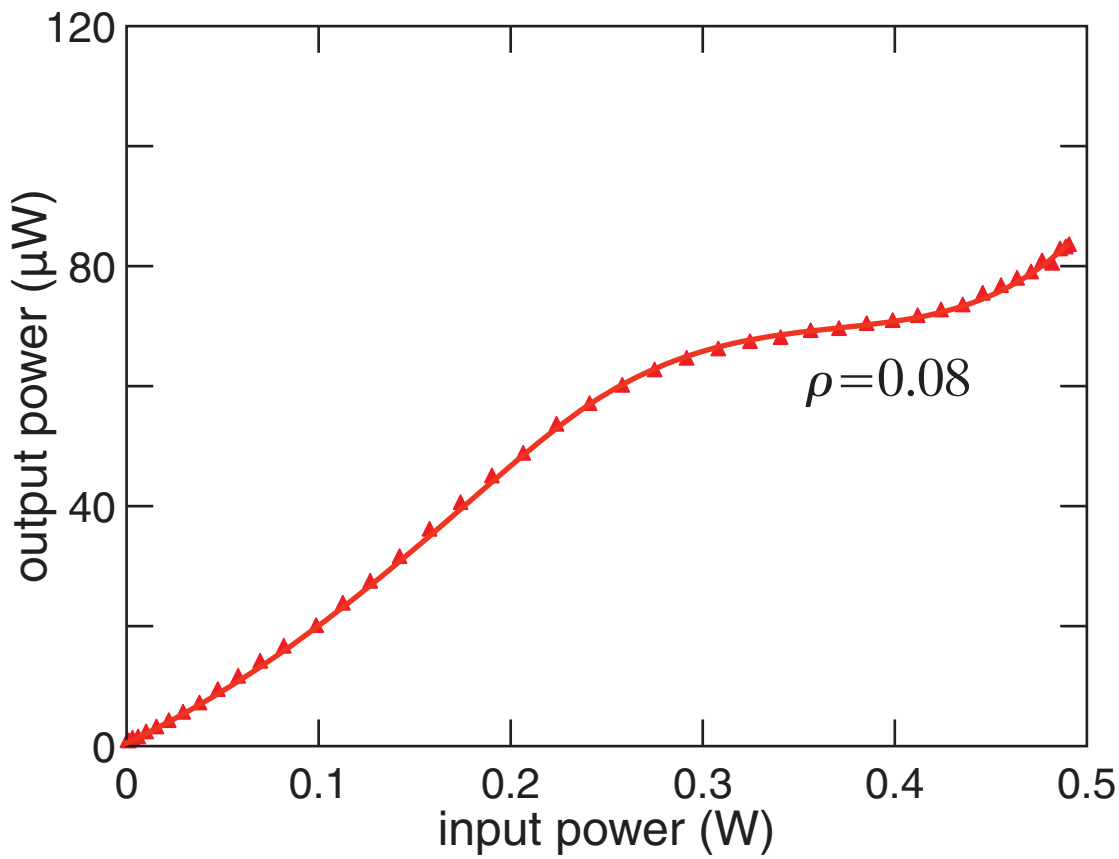


# Optical logic gates

**light-by-light modulation!**

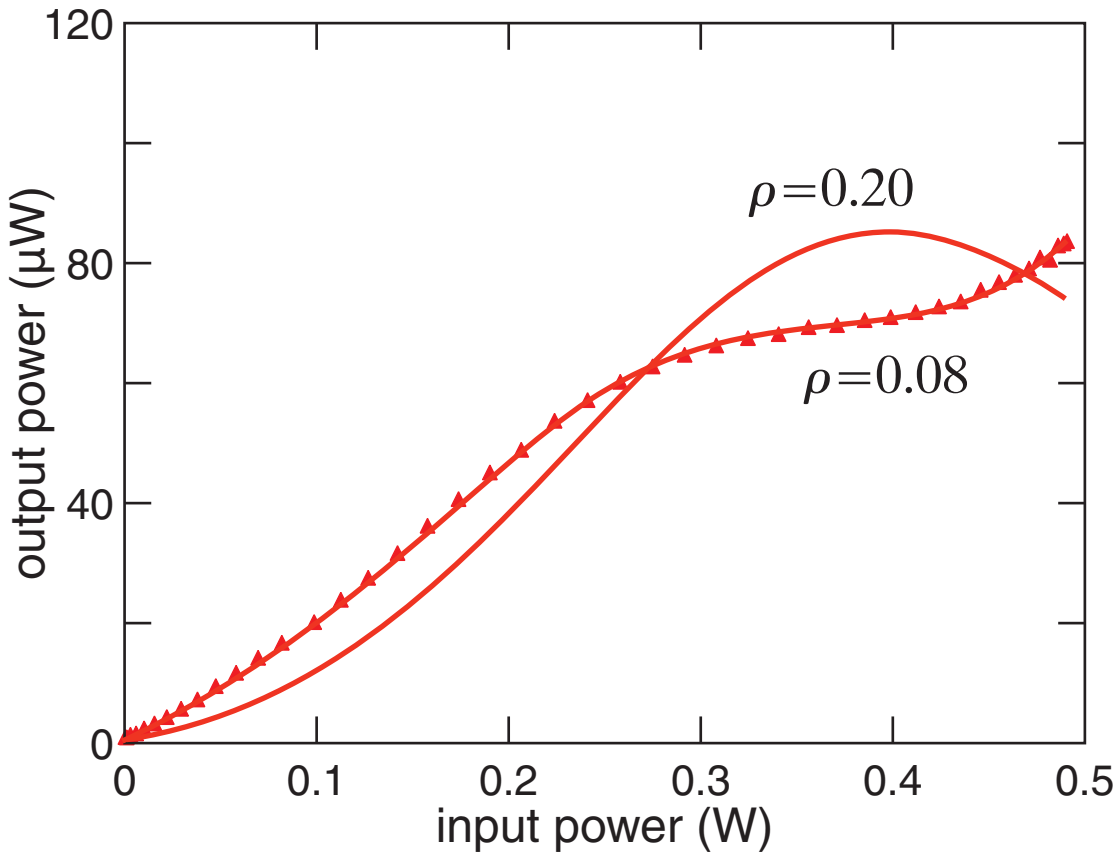
# Optical logic gates

## very preliminary data



# Optical logic gates

## very preliminary data



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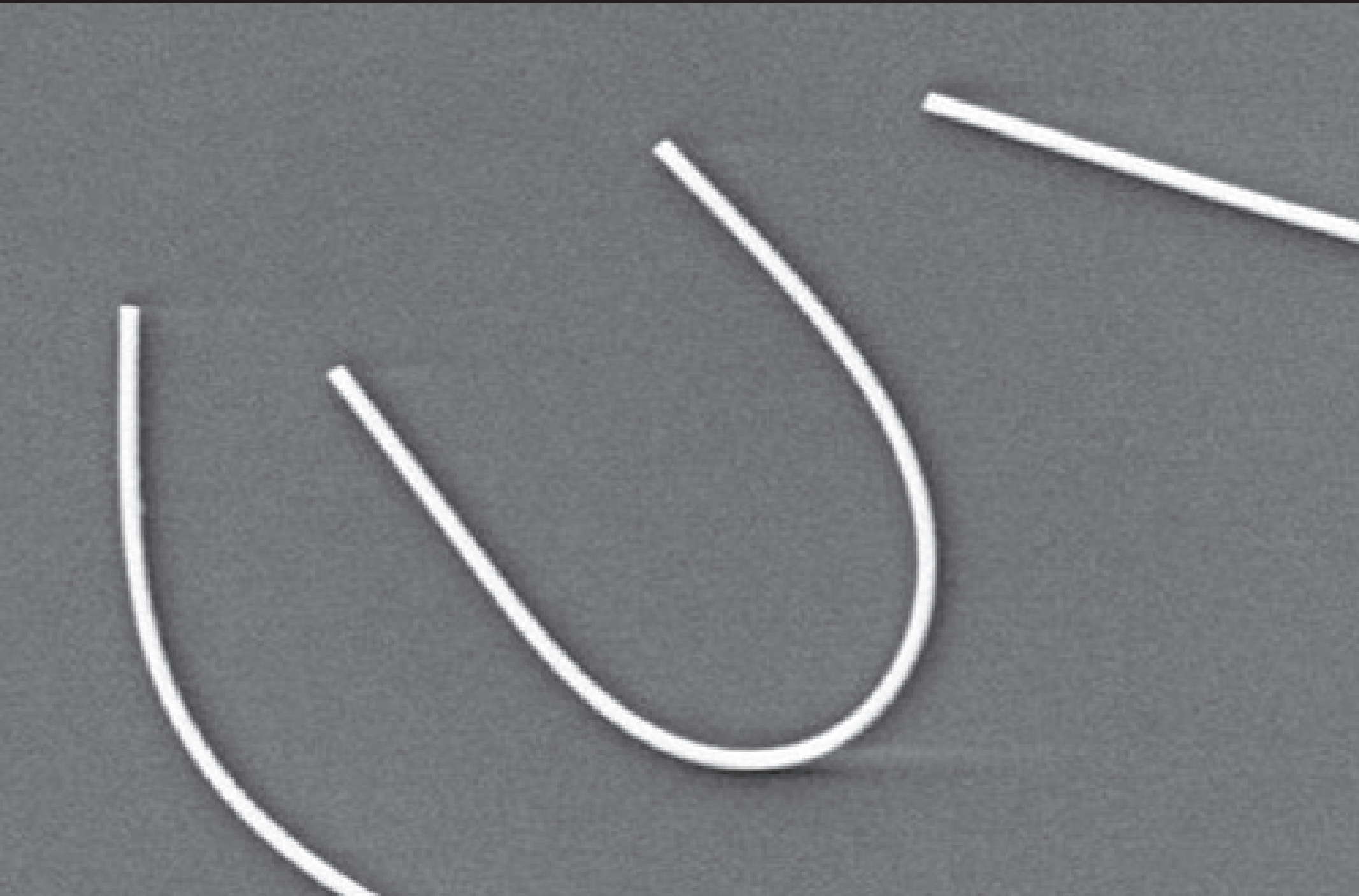


# Optical logic gates

**need a different approach!**

# Optical logic gates

need a different approach!

- lithographic fabrication

# Optical logic gates

need a different approach!

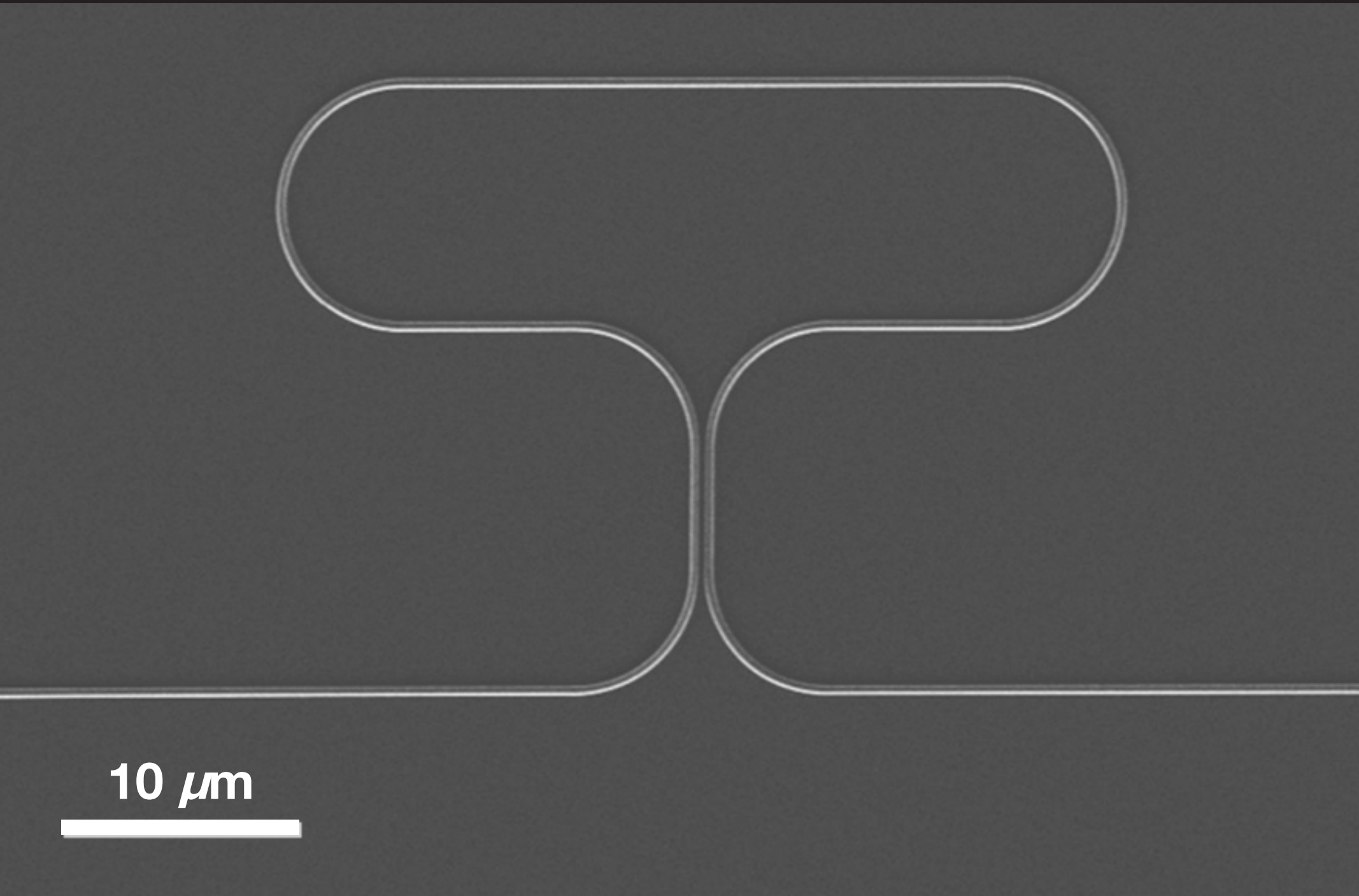
- lithographic fabrication
- greater index

# 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 $W^{-1}$ $km^{-1}$ |

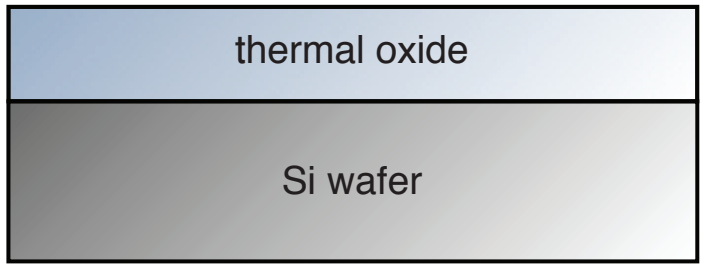
# Optical logic gates

reactive sputtering of titanium with oxygen

*Optics Express*, 20, 23821 (2012)

# Optical logic gates

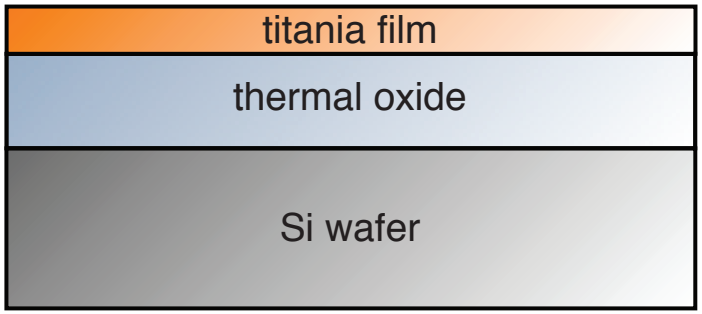
**begin with silicon wafer with thermal oxide**




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

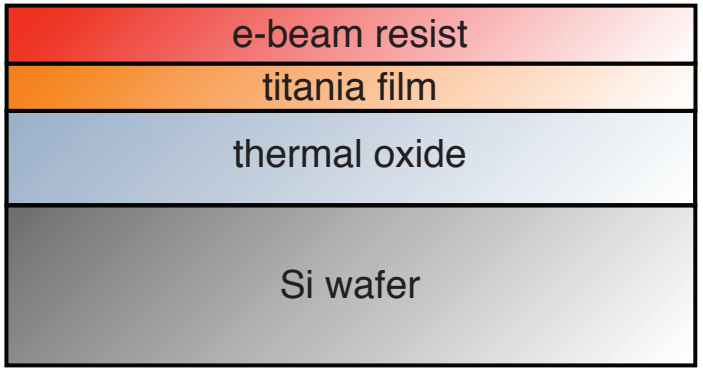
**deposit titania using reactive sputtering**




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

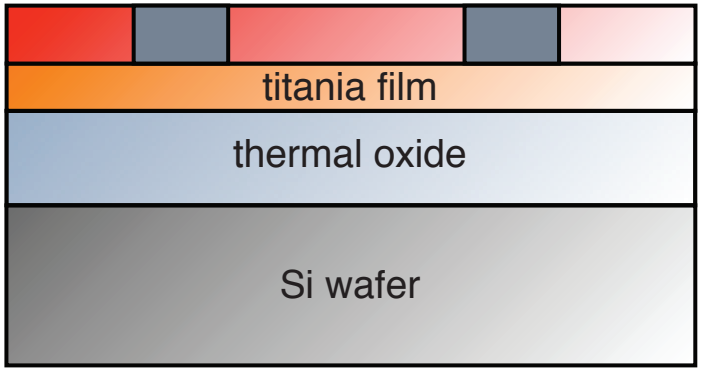
## spin on e-beam resist




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

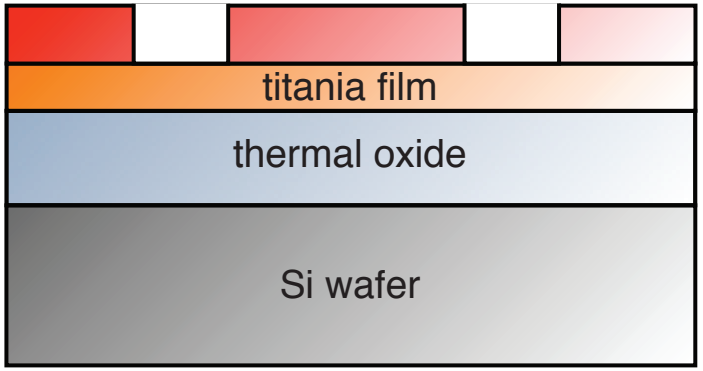
**write pattern using e-beam**




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

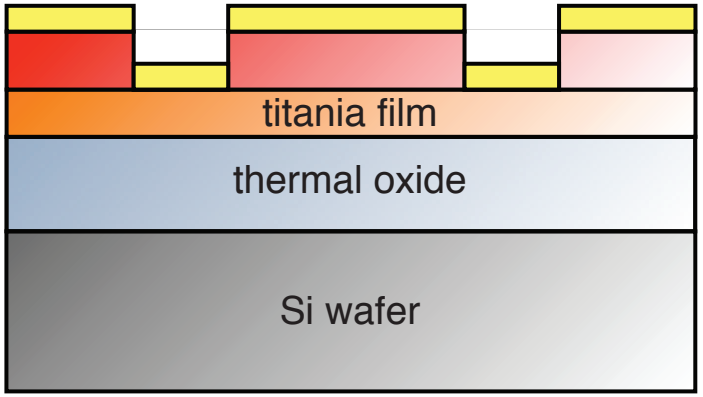
develop to remove exposed regions




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

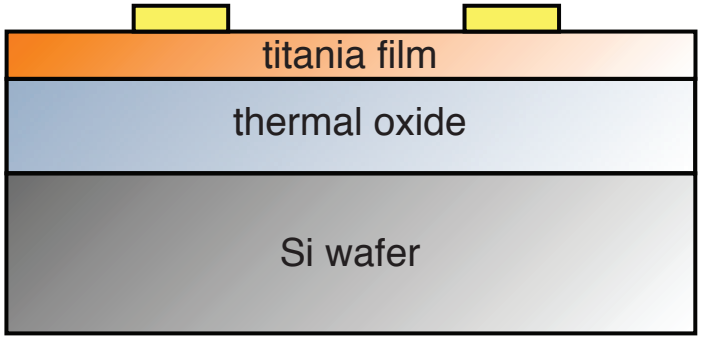
deposit thin metal film




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

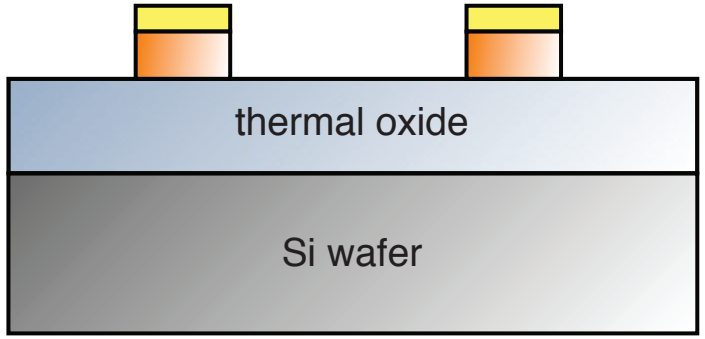
**dissolve resist, lift off metal film**




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

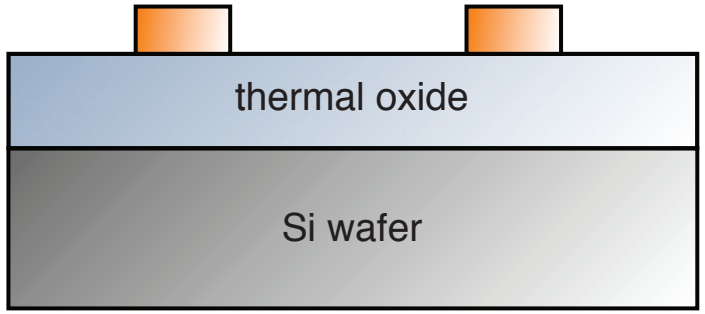
reactive ion etch through titania film




*Optics Express*, 20, 23821 (2012)

# Optical logic gates

remove remaining metal




*Optics Express*, 20, 23821 (2012)

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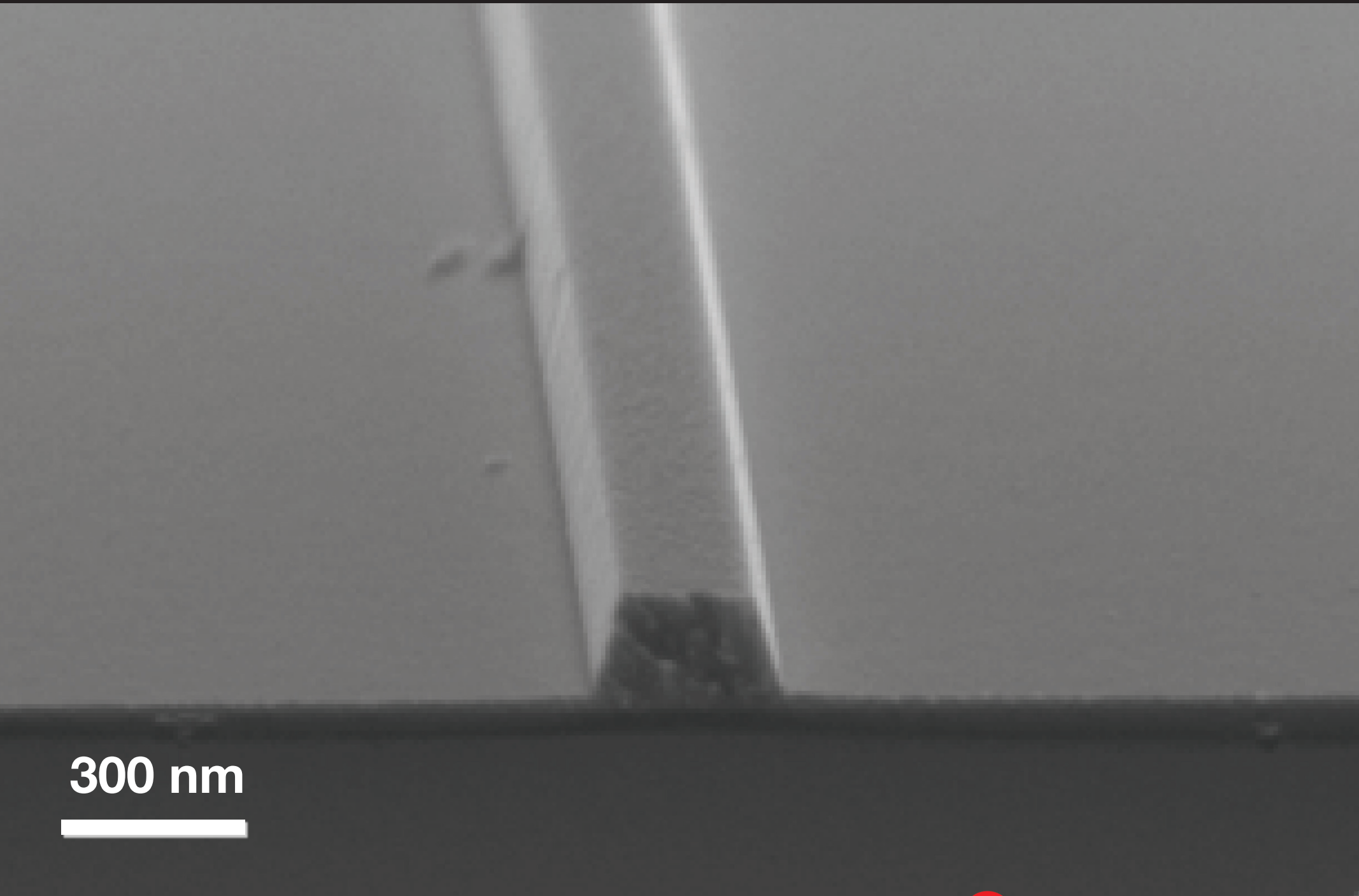

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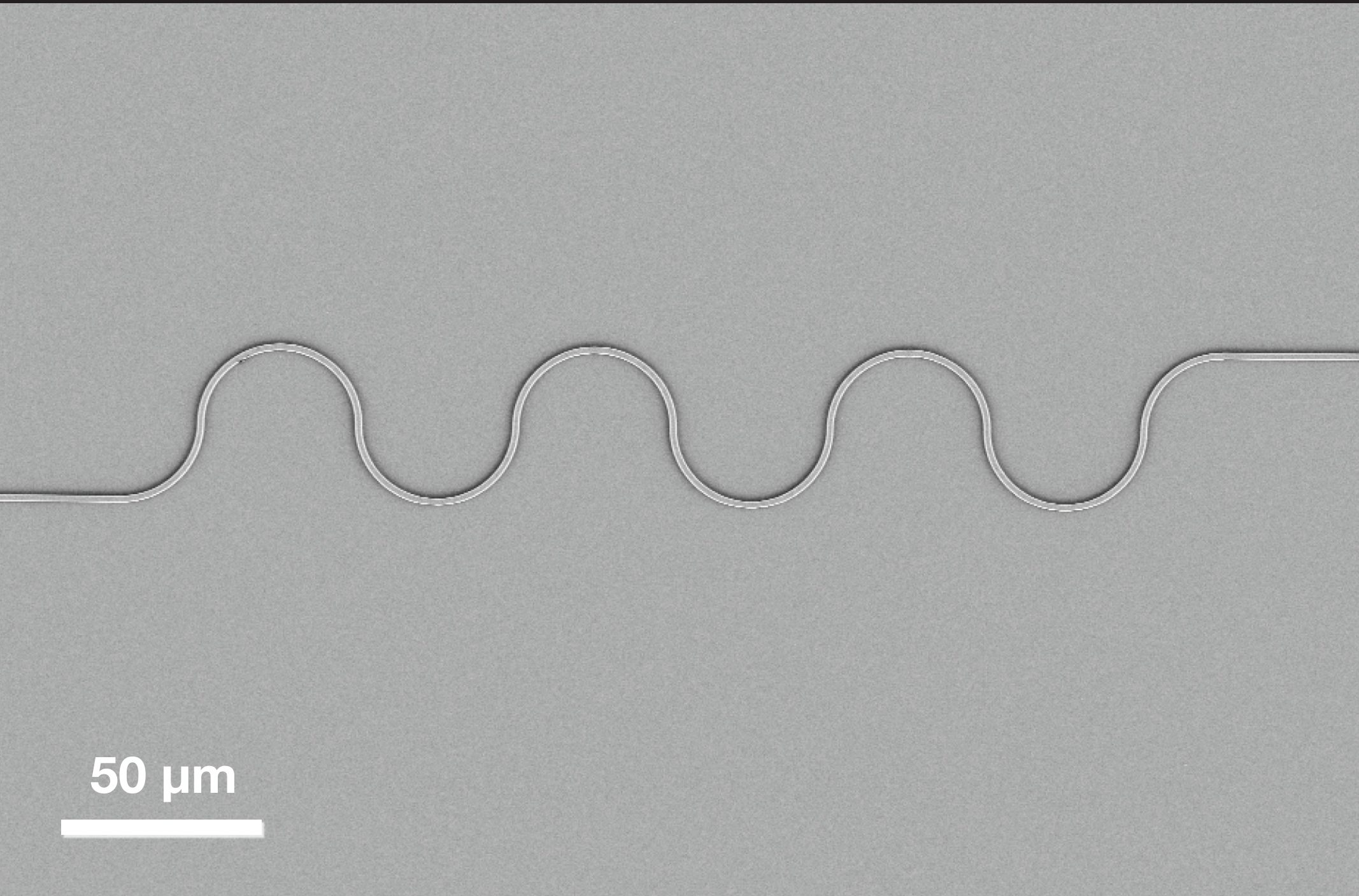

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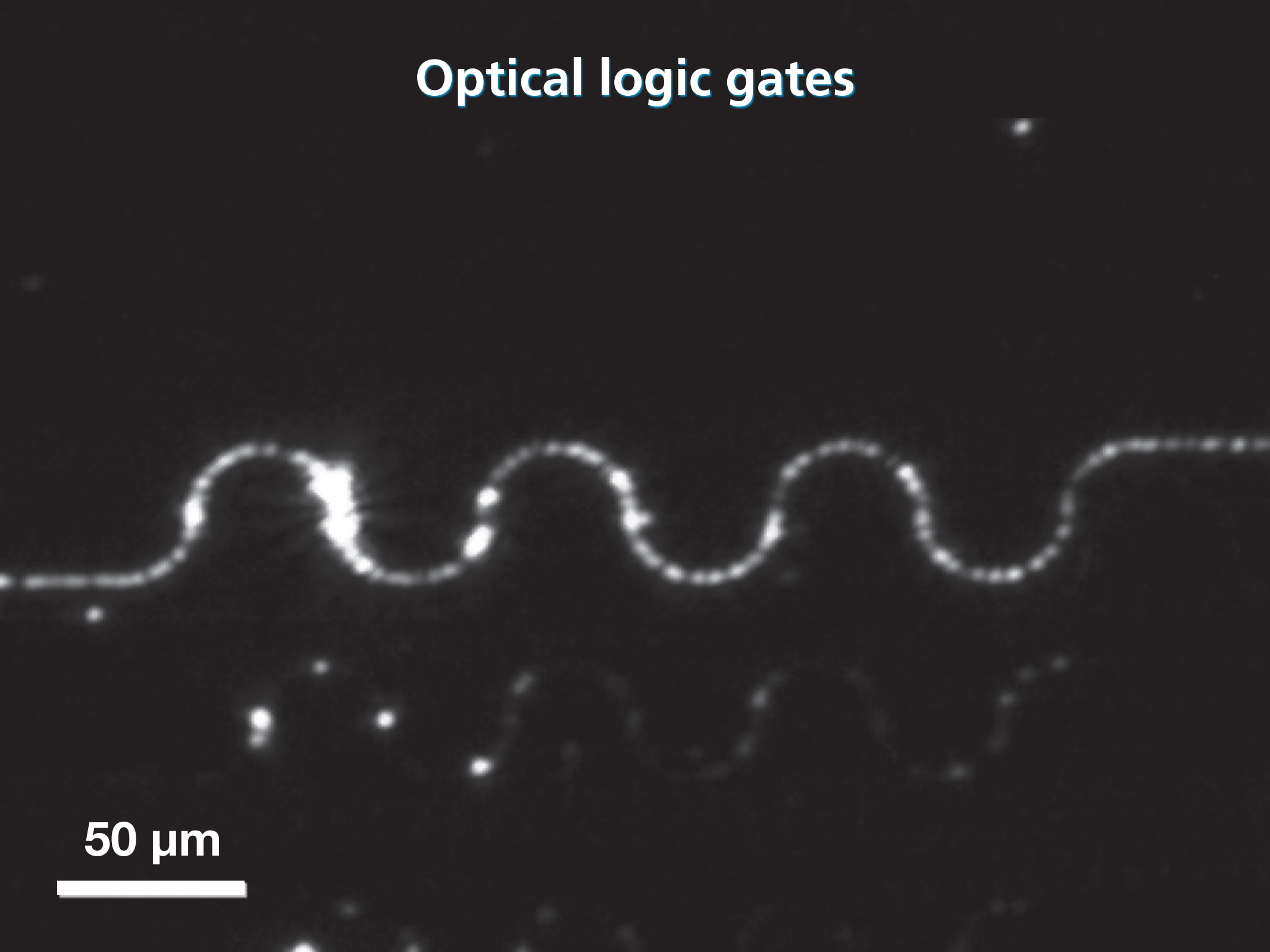

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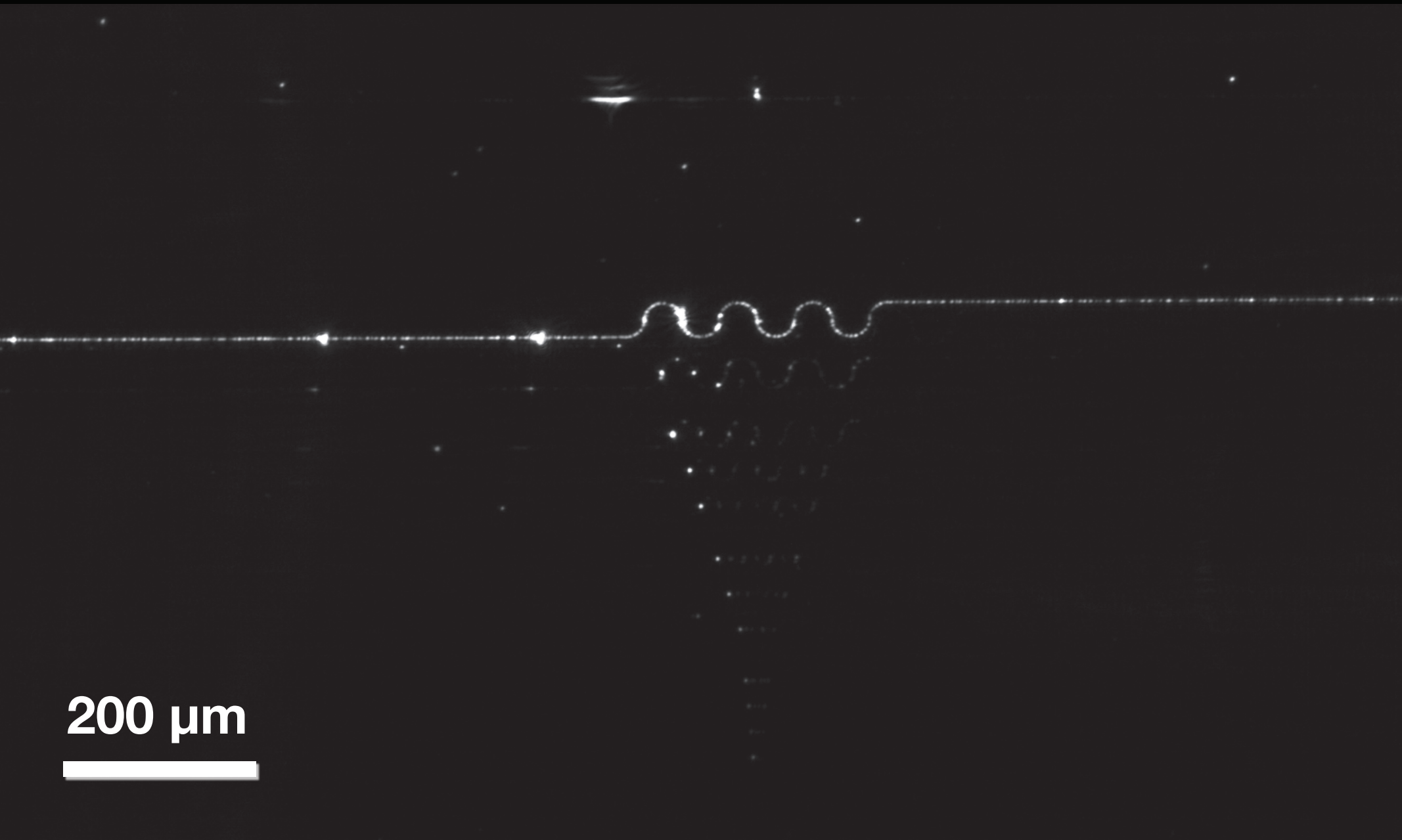

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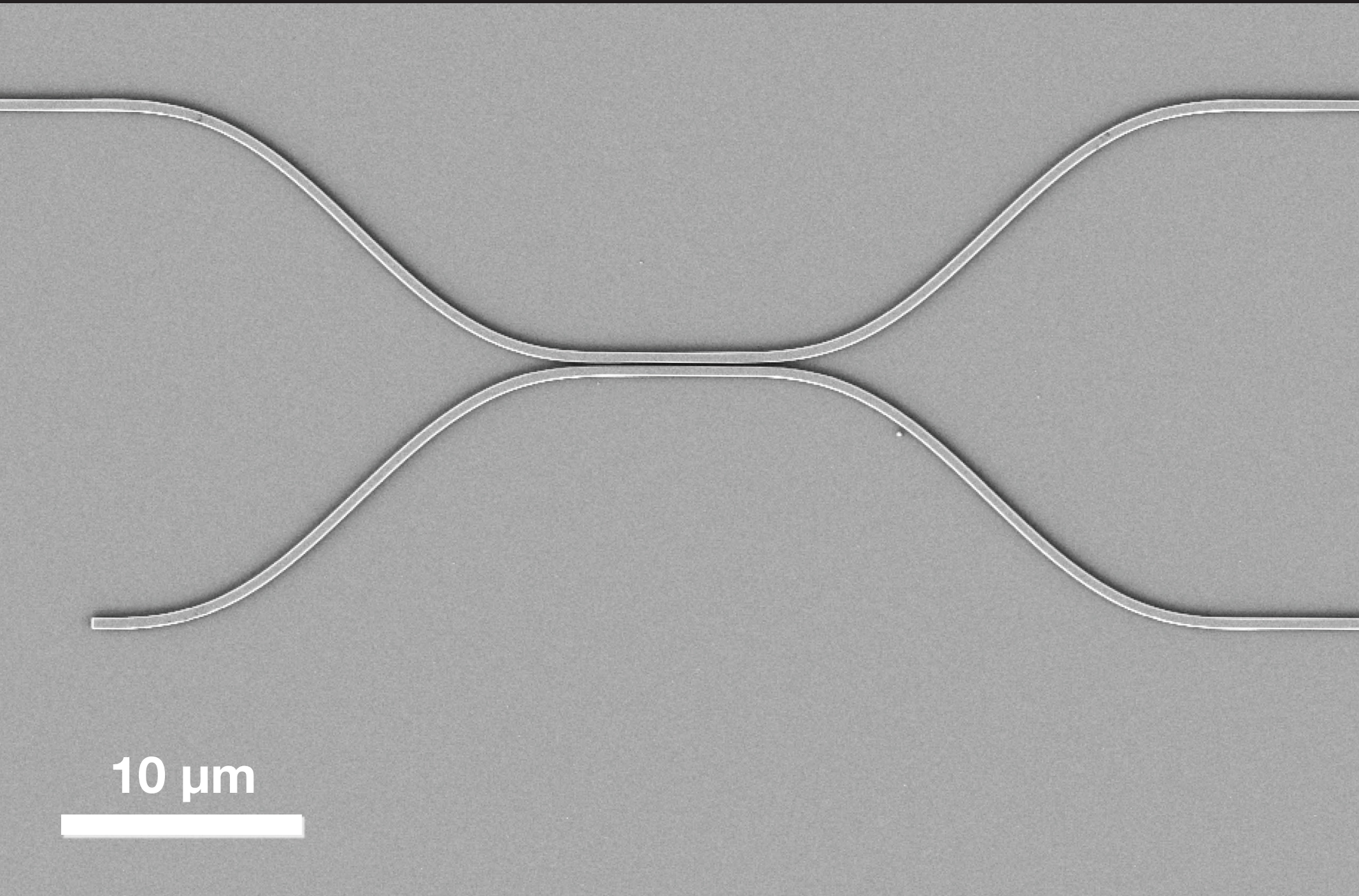

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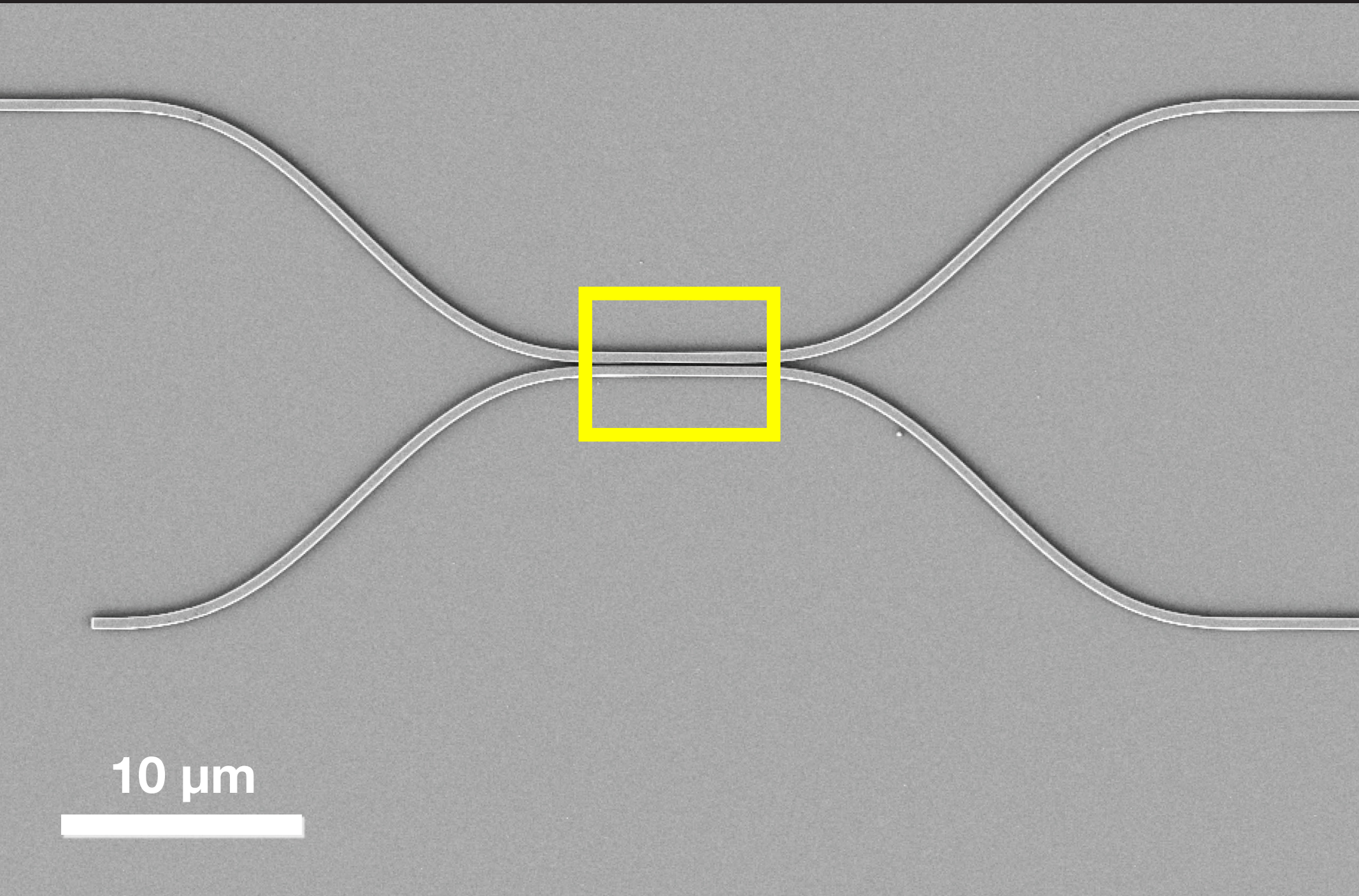

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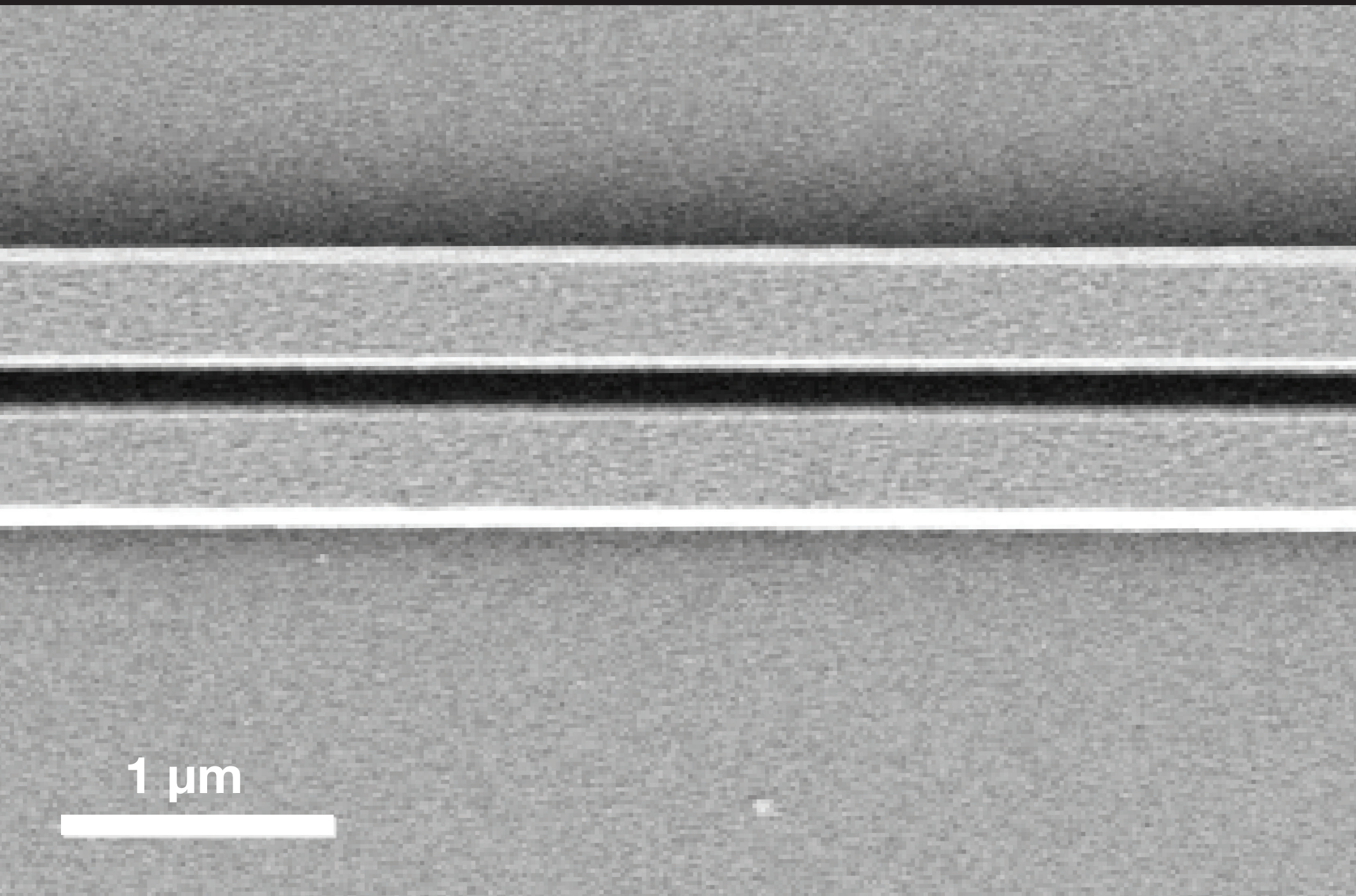

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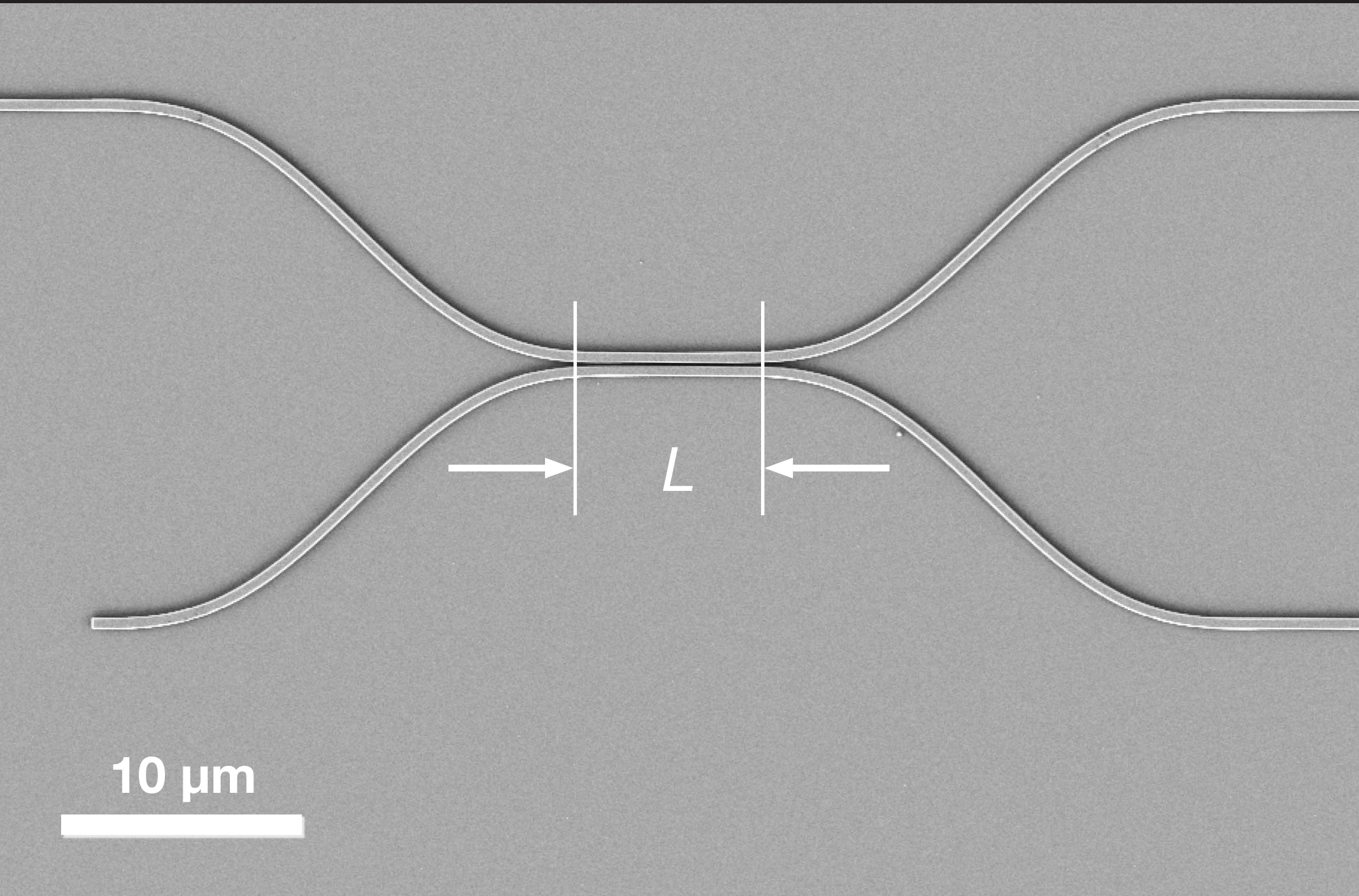

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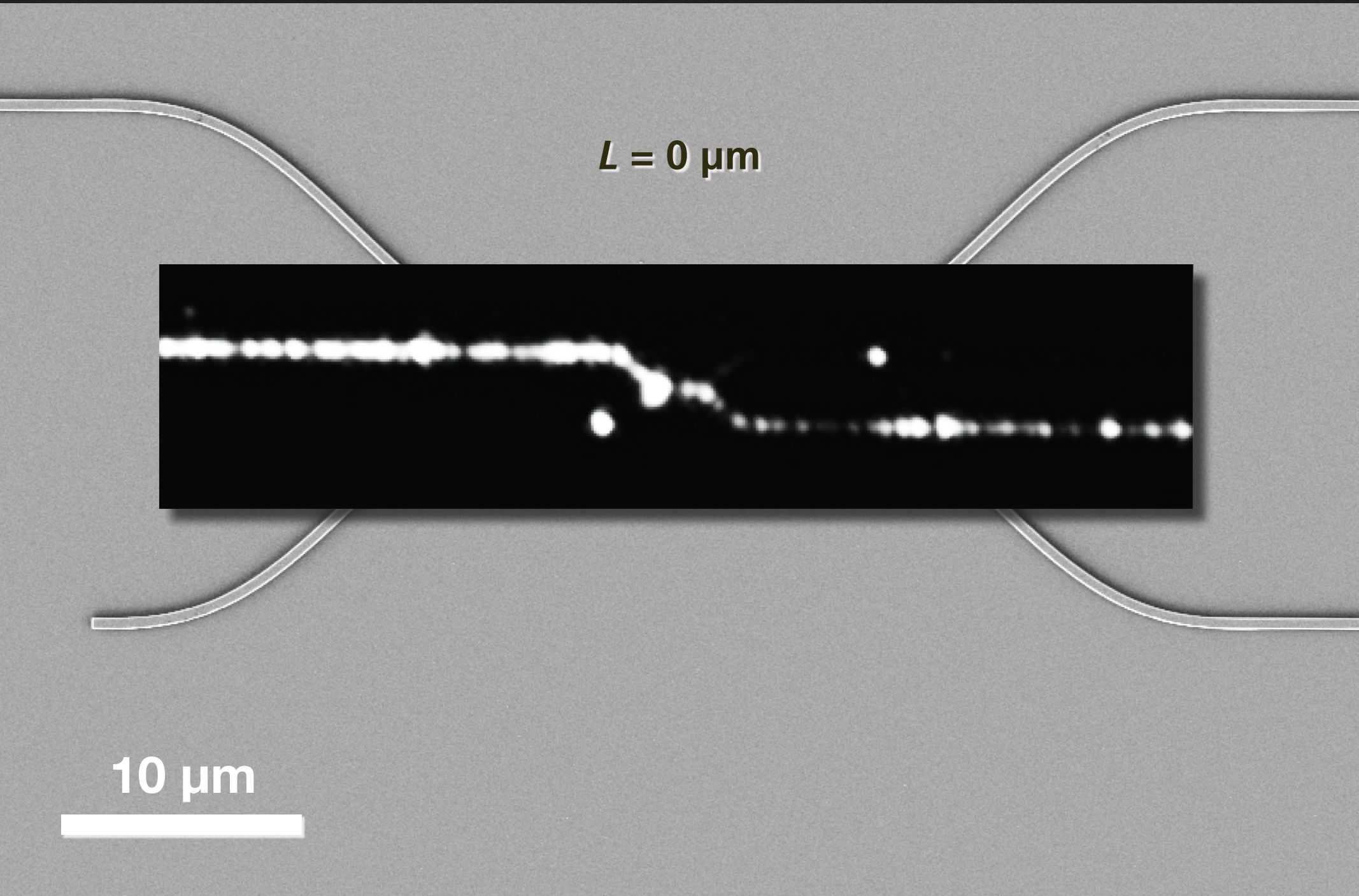

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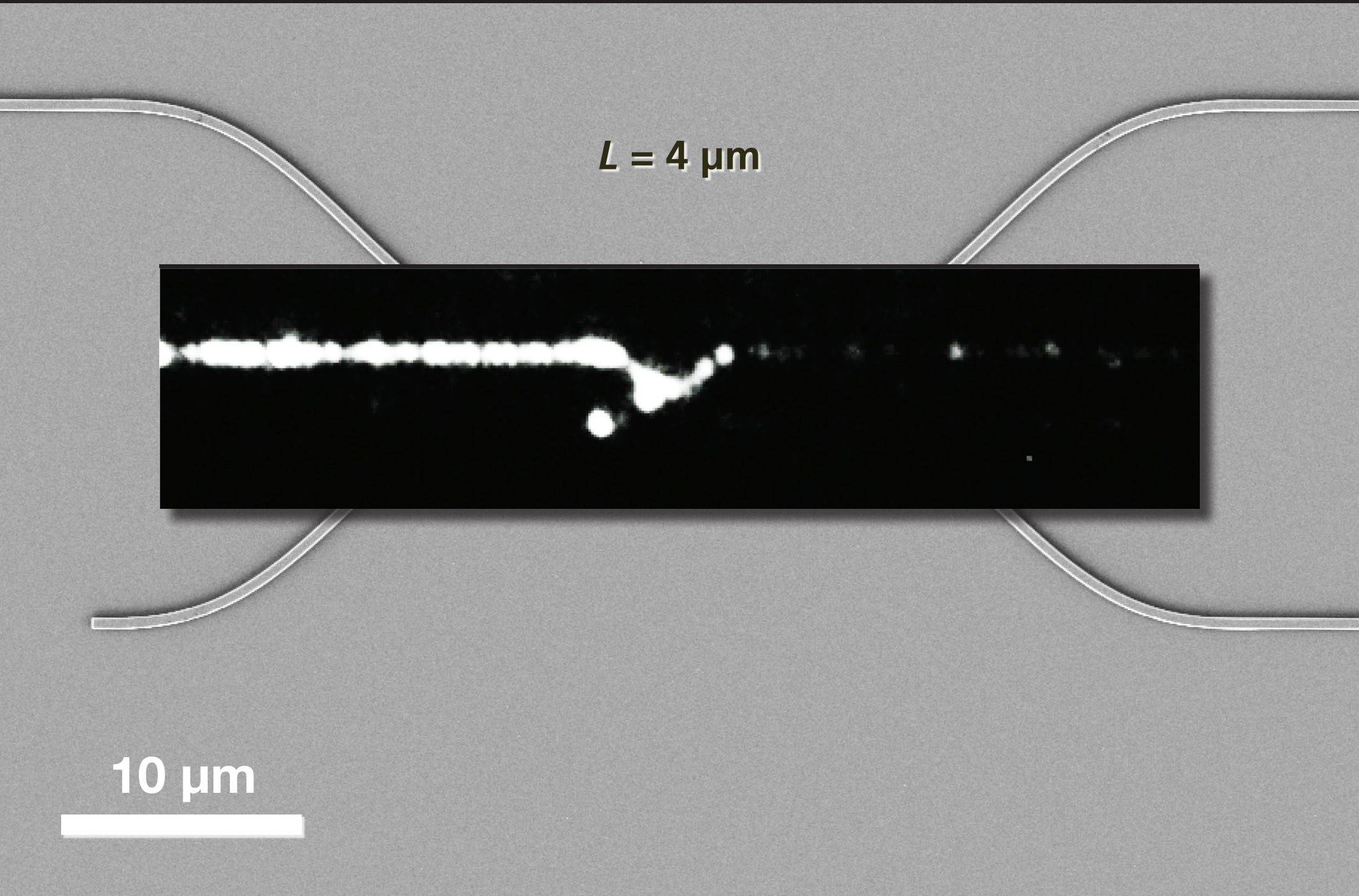

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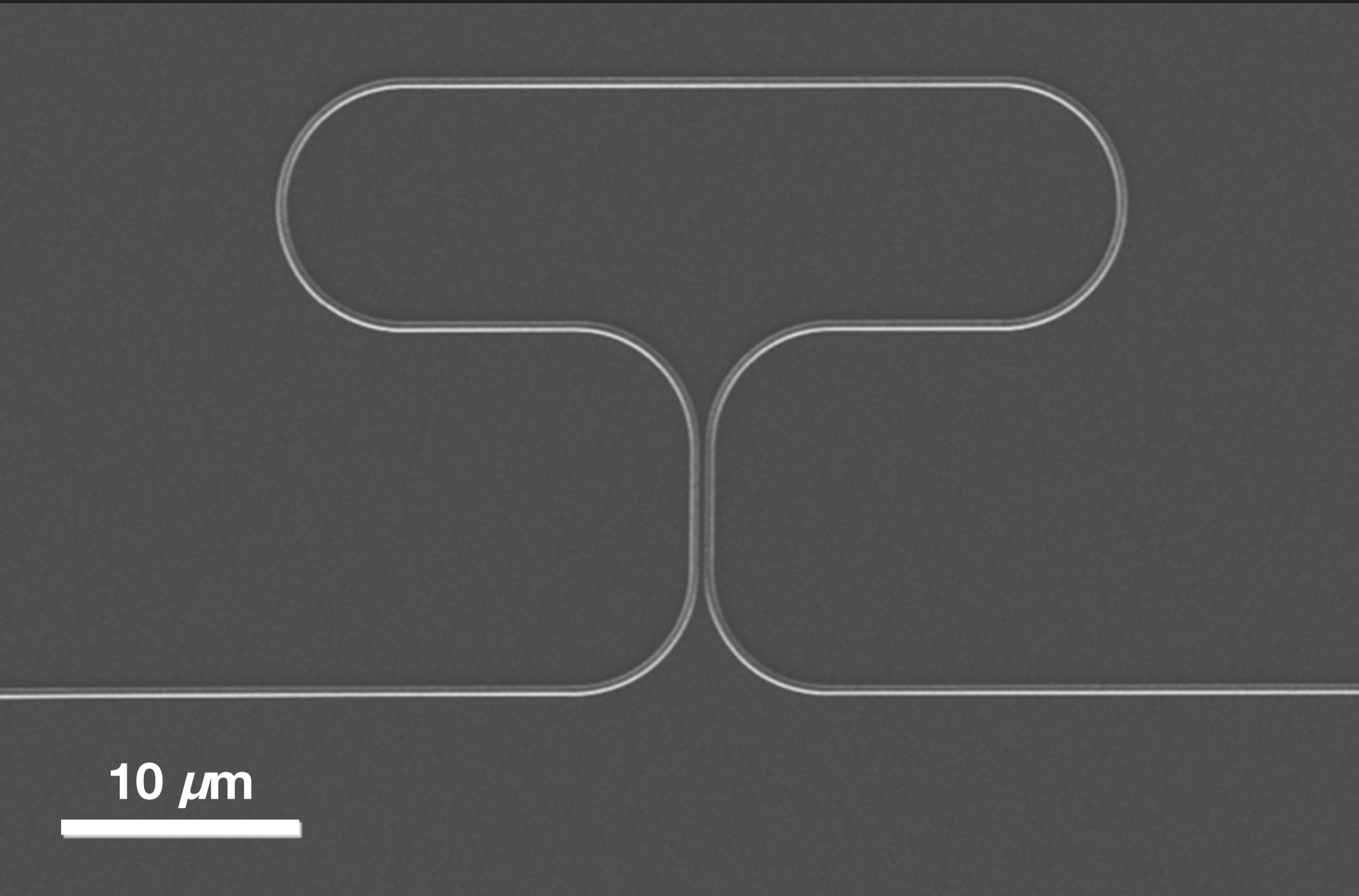

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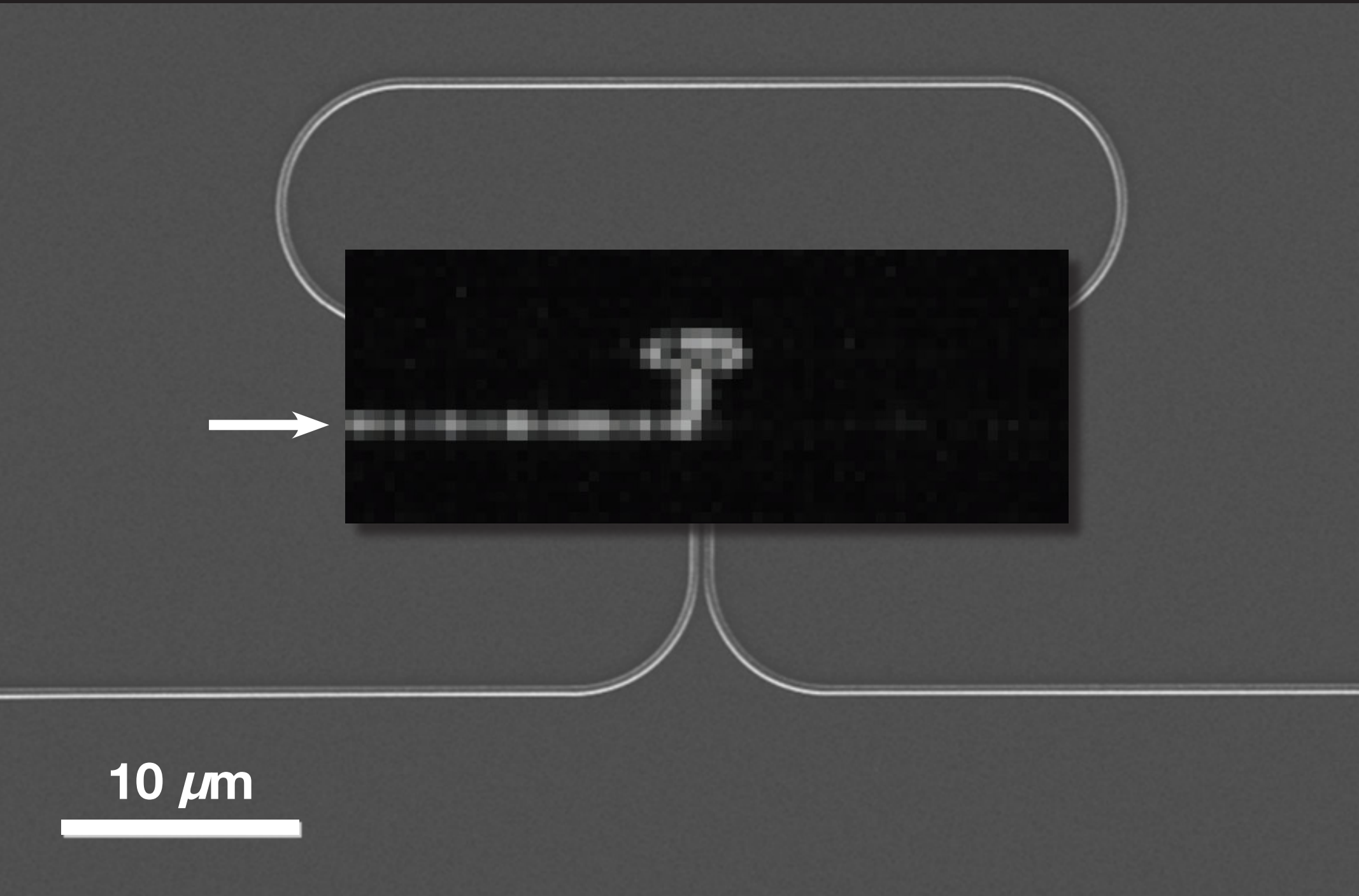
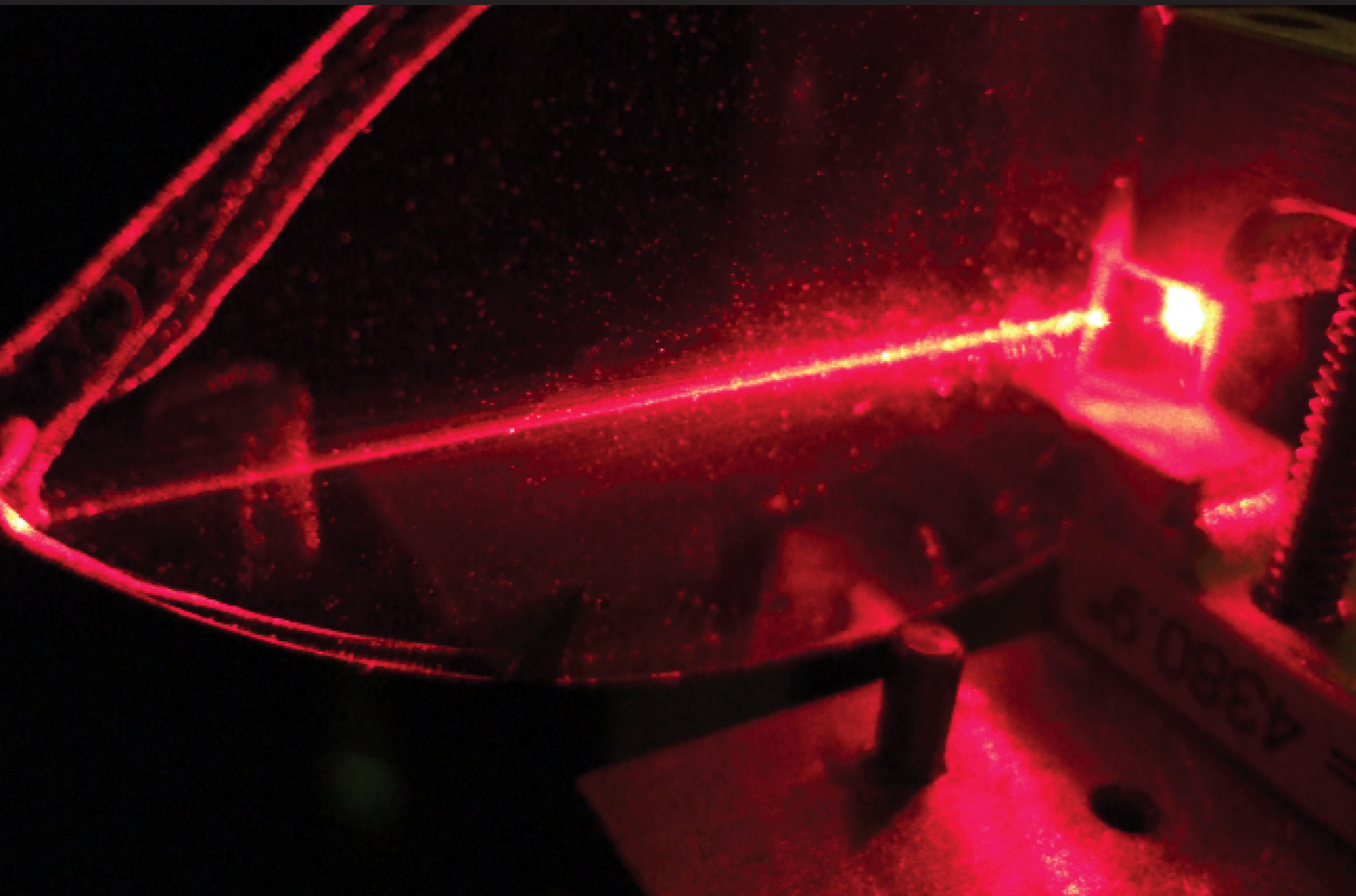


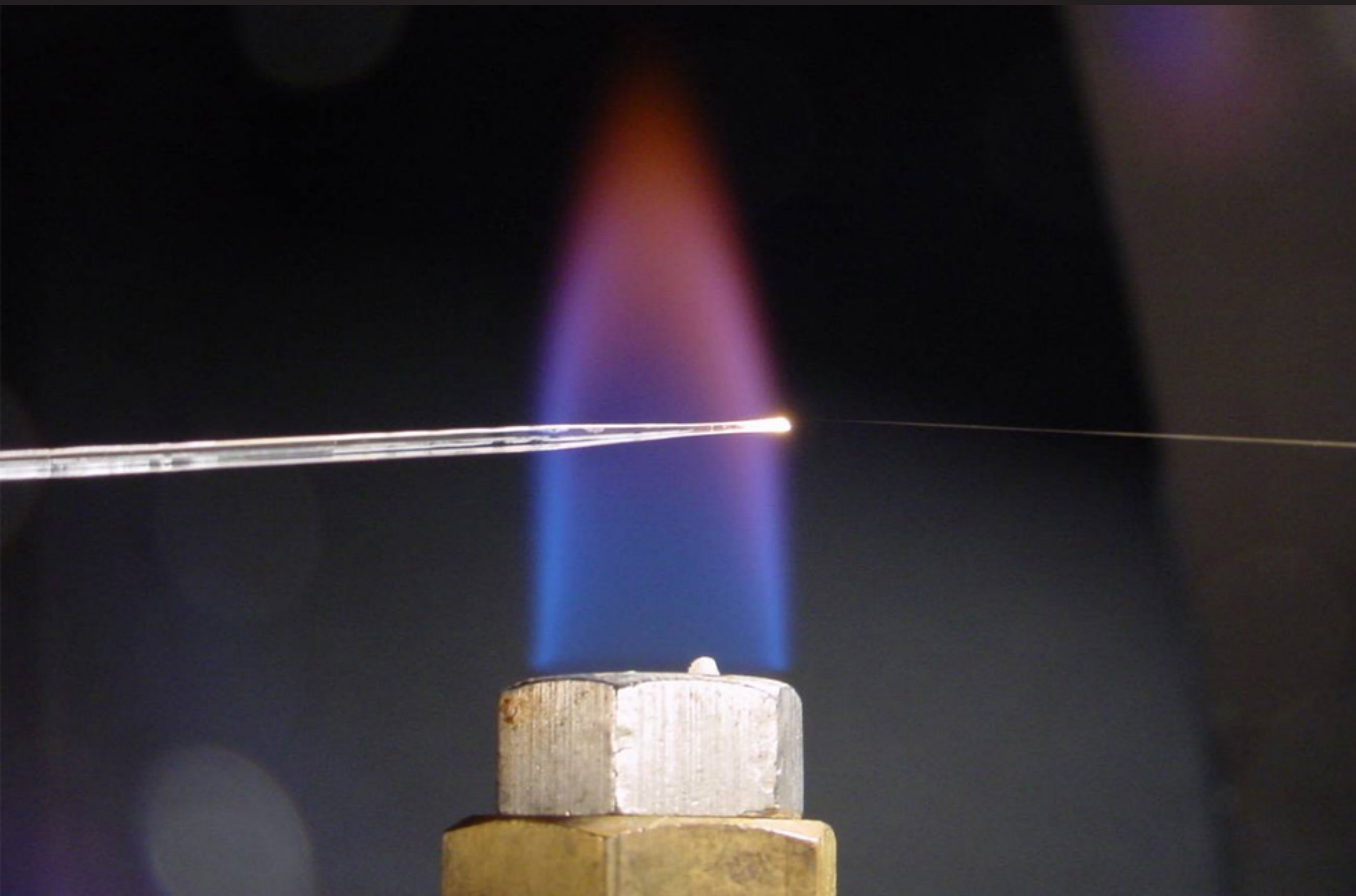
# Summary



# Summary

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

# Summary



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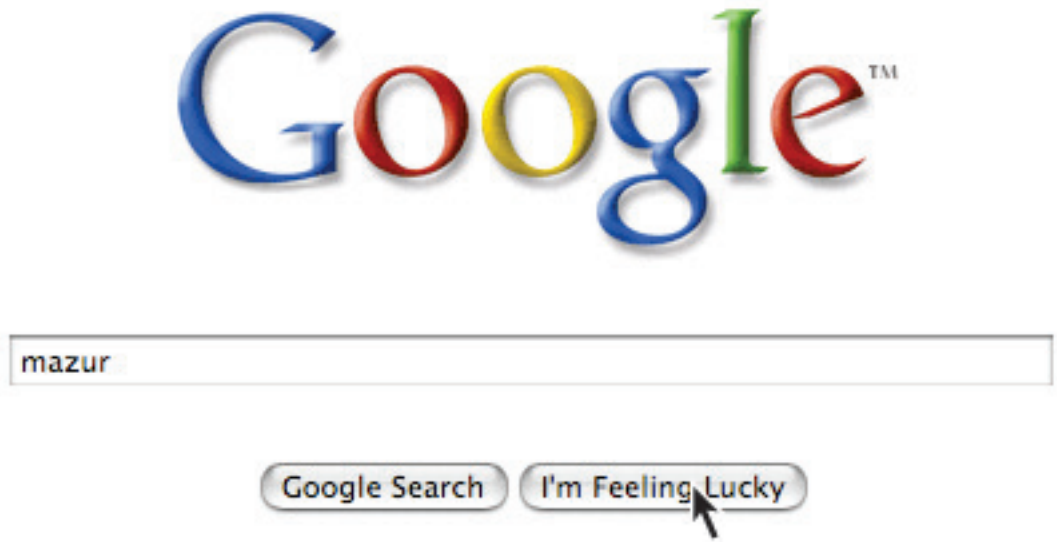
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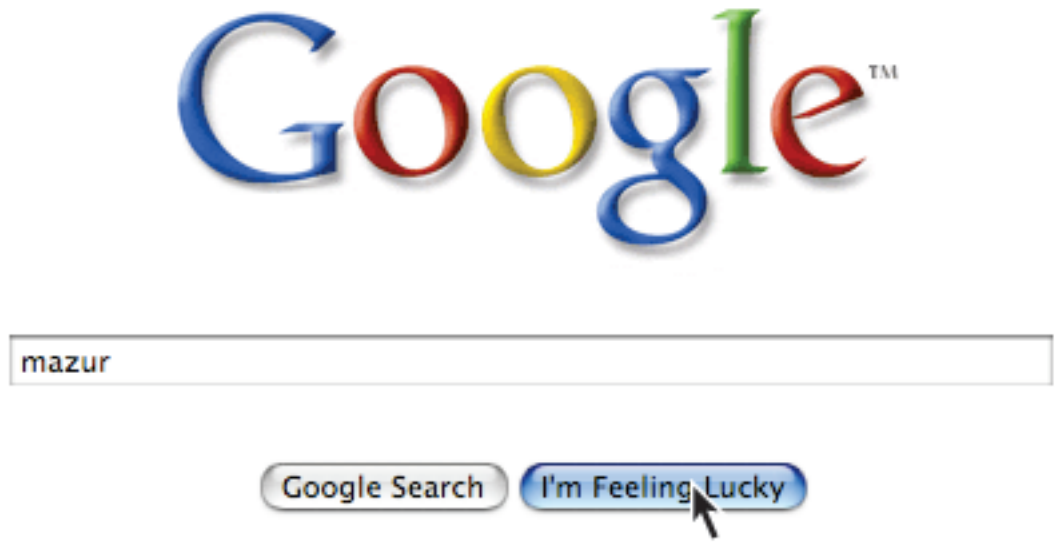
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