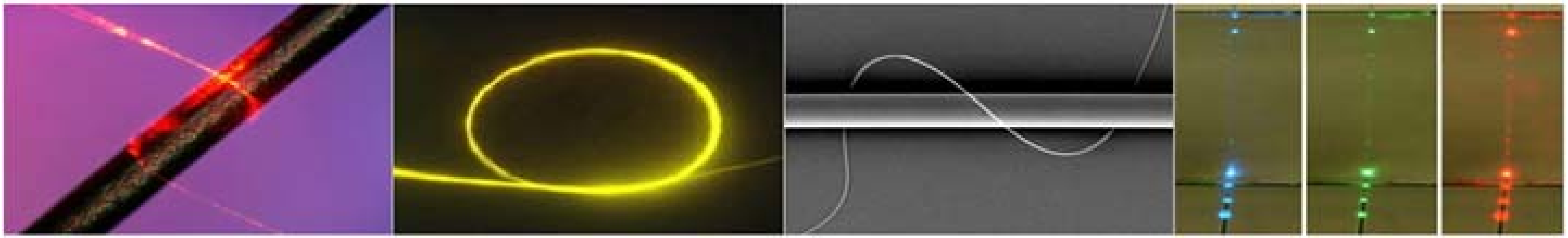
ECI Functional Glasses: Properties and Applications for Energy and Information
Siracusa, Sicily, Italy

Microfiber and Nanofiber Photonics



Limin Tong

State Key Laboratory of Modern Optical Instrumentation
Department of Optical Engineering
Zhejiang University
Hangzhou, China

2013-01-10

Outline

- Introduction

1. Fabrication

2. Optical Properties

3. Photonic Applications

- Summary

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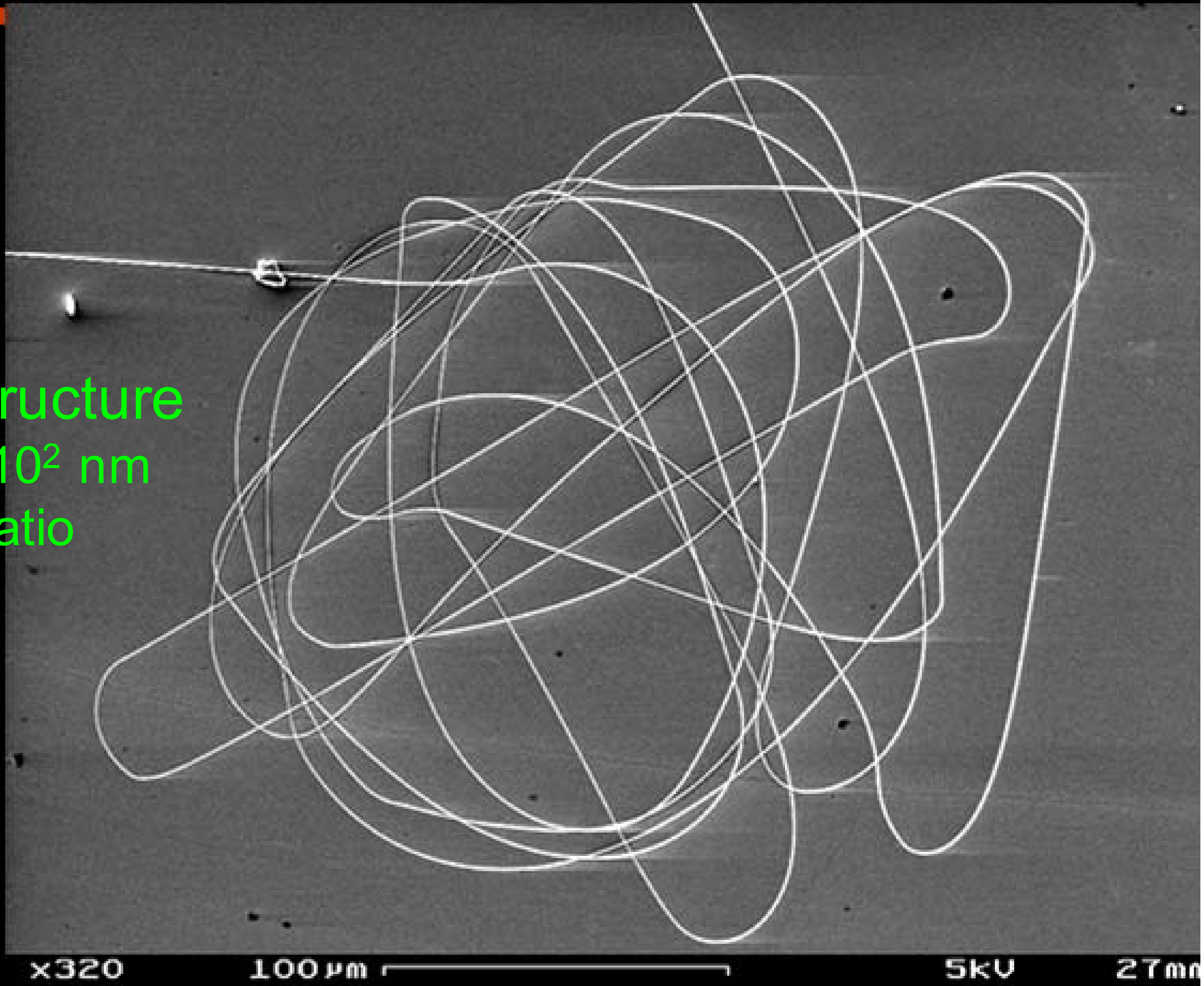
1.Introduction

Nanofiber

1-D glass structure

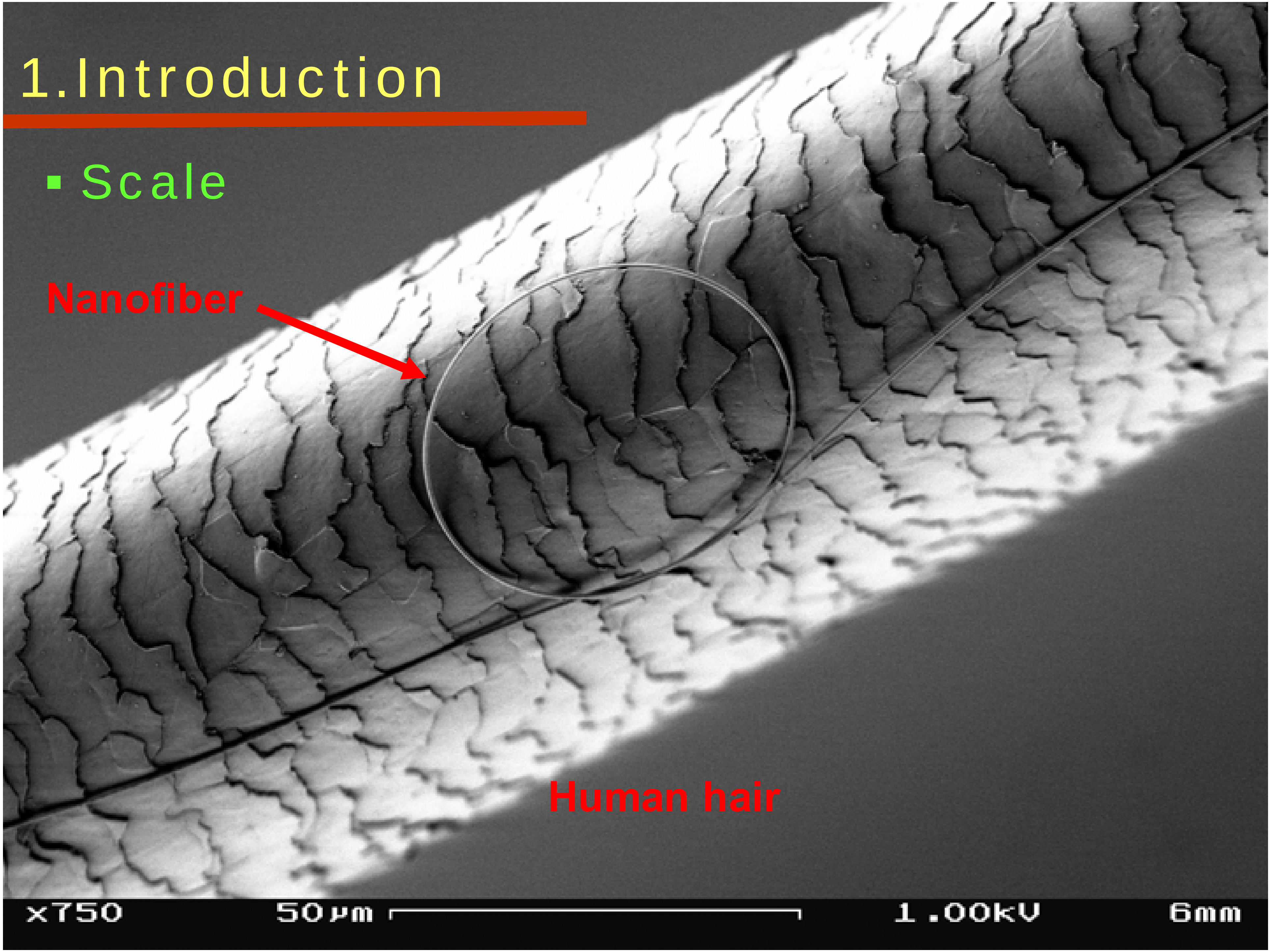
diameter 10^0-10^2 nm

large aspect ratio



1.Introduction

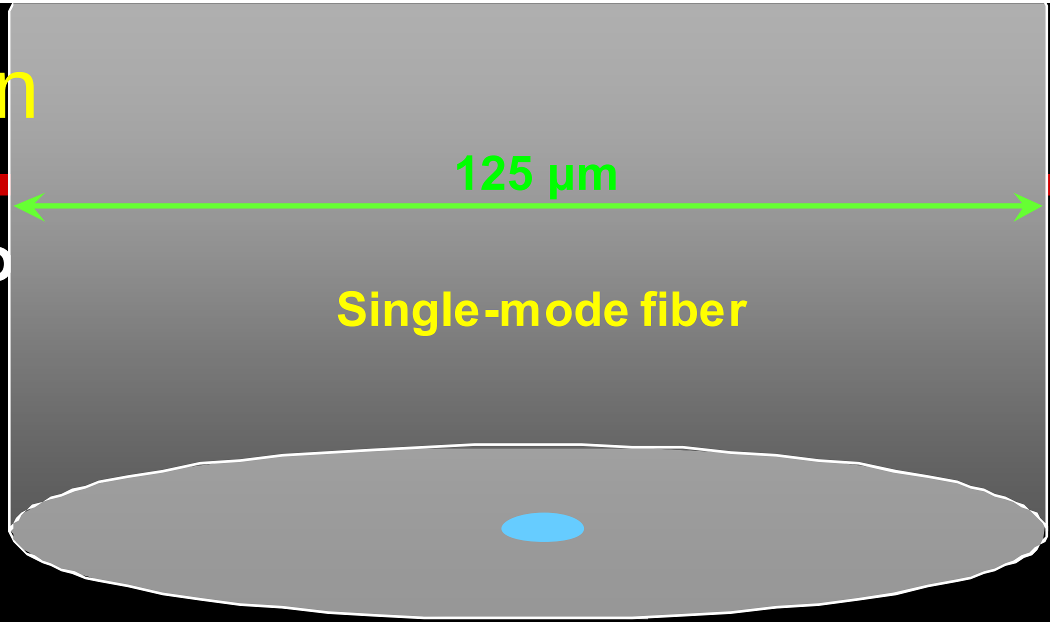
- Scale

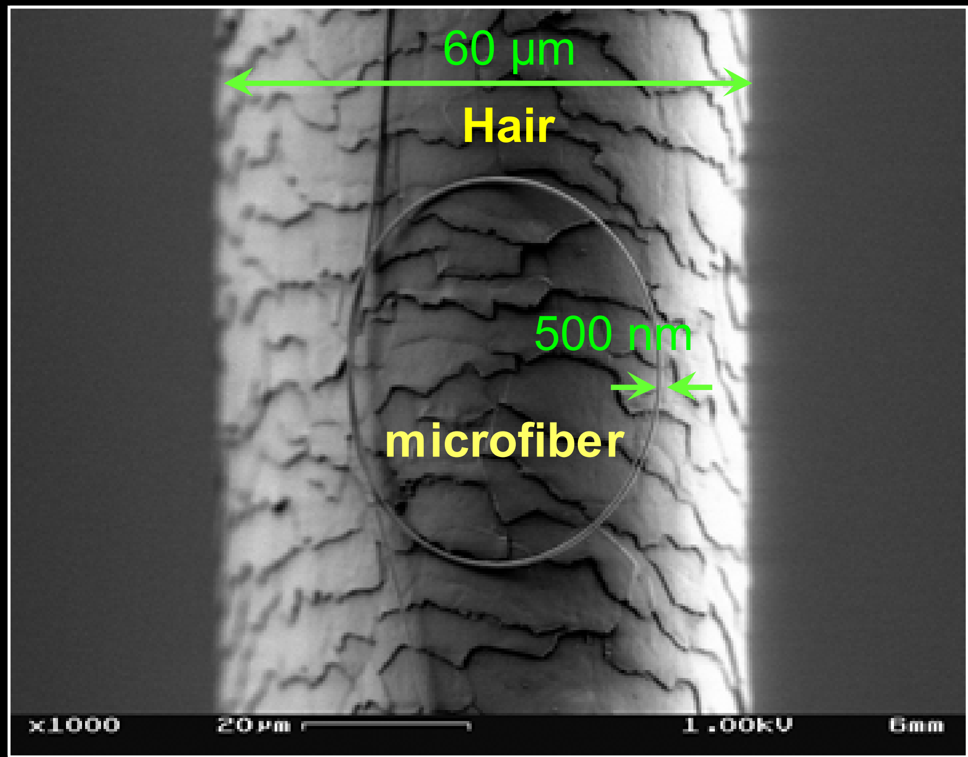


▫ Introduction

- **What does an o**

Scale of a microfiber





1.Introduction

- Why it is attractive to Photonics ?

Favorable properties of nanofibres/nanowires for photonics

• Sub-wavelength dimension • Tight optical confinement	Miniaturization of photonic devices, enhancement of optical nonlinear effects
• Large surface-to-volume ratio • Engineerable surface states	Photonic engineering for light absorption, conversion and emission
• Strong evanescent fields	Strong and high-efficiency near-field interaction
• Free-standing and low-mass	Response to photon momentum for opto-mechanics
• High mechanical strength • Optically visible	Easy micro/nanomanipulation

1.Introduction

- Why it is attractive to Photonics ?

Micro/Nanofiber

Fascinating 1-D structure for manipulating ↓

Electrons, photons, phonons, atoms
on the subwavelength or nano-scale

Intrigue a variety of opportunities for ↓

Fundamental study and **technological applications**

1.Introduction

J. Giles, Nature 441, 265 (2006)

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TOP FIVE IN PHYSICS

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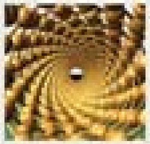
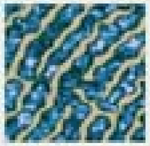
12.85 Carbon nanotubes



Super-strong materials and blisteringly fast electronic circuits: the potential applications of these tiny carbon tubes, discovered in 1991, are so enticing that everyone is pouring money into the field.

8.75 Nanowires



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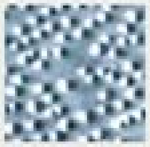
7.84 Quantum dots



Another nanotechnology with a huge range of potential applications. These tiny specks of semiconductor material, measuring as little as a few nanometres across, have already been used to create dyes for cell biologists and new kinds of laser. Physicists hope they might one day form the basis of a quantum computer.

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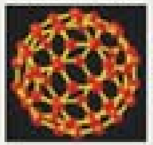
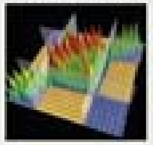


These spheres of carbon atoms are attracting significant research interest. But the latest ranking rewards newness, so the topic may have slipped down the list because it predates nanotubes by around six years. The discovery of fullerenes earned a Nobel prize and spawned studies of numerous potential uses, such as drug delivery agents.

6.82 Giant magnetoresistance



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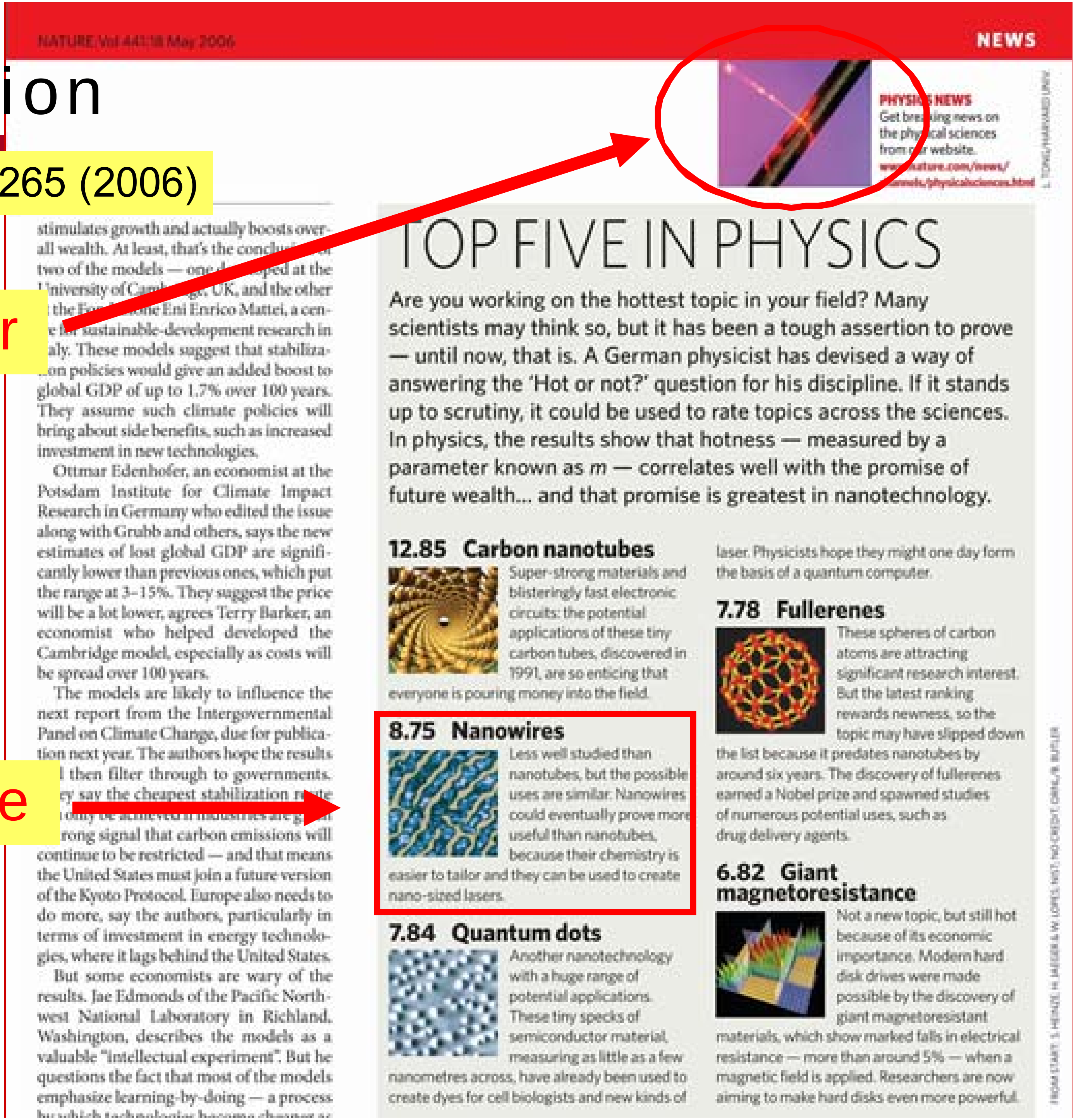
FROM START: S. HEINZE, H. JAEGER & W. LOPES; NIST; NO CREDIT; ORNL/R. BUTLER

1.Introduction

J. Giles, Nature 441, 265 (2006)

Nanofiber

Nanowire



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NATURE|Vol 441|18 May 2006

NEWS

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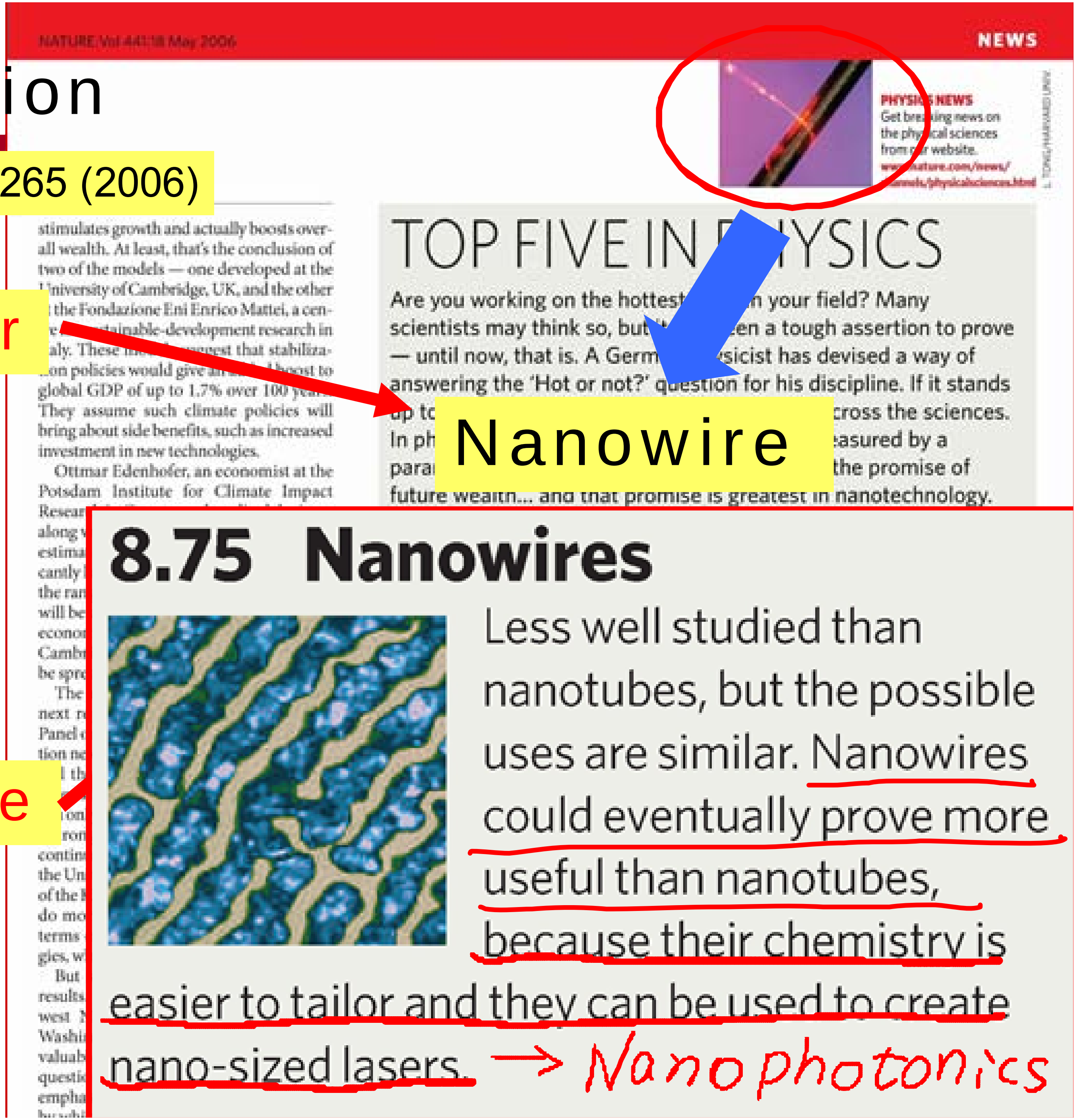

NATURE|Vol 441|18 May 2006

NEWS

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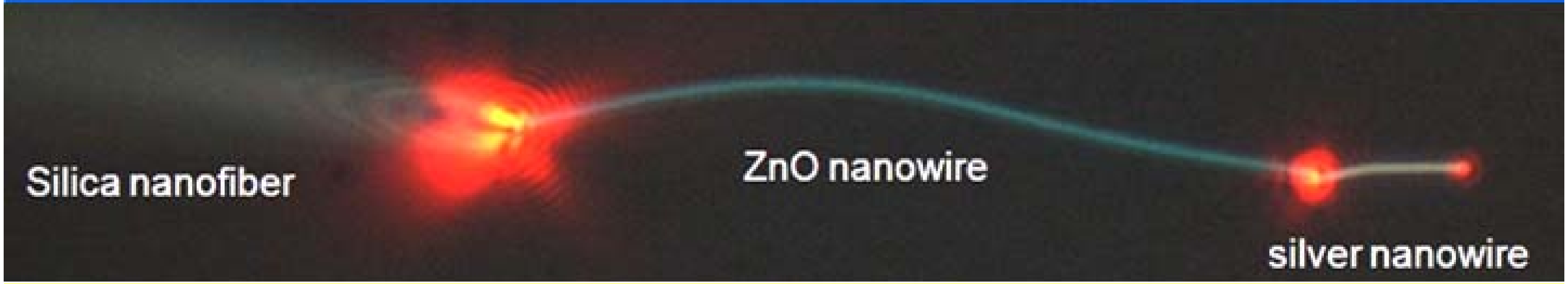
Typical nanowires studied in my group



Glass micro/nanofiber

e.g., Silica, phosphate micro/nanofiber

Polymer nanofiber

e.g., PMMA nanofiber, PS nanofiber

Semiconductor nanowire

e.g., ZnO nanowire, CdS nanowire

Metal nanowire

e.g., Silver nanowire, gold nanowire

Typical nanowires studied in my group

Nanofiber

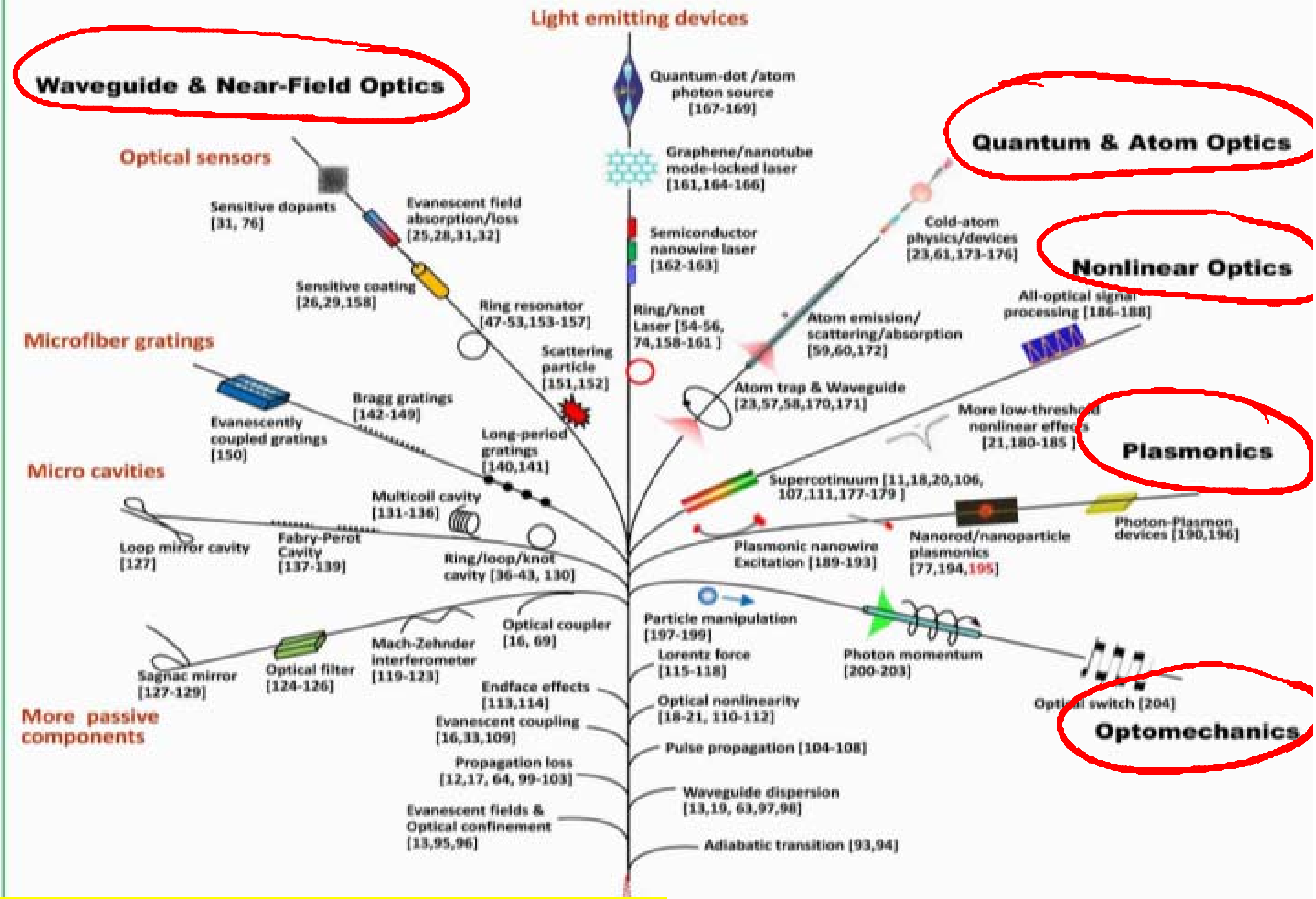
Glass nanofibers
e.g., Silica, phosphate

+

Optics

- Near-field optics
- Guide wave optics
- Optoelectronics
- Nonlinear optics
- Plasmonics
- Quantum optics
- Optomechanics

Plenty of opportunities for nanophotonics



Applications of optical micro/nanofibers

L. Tong et al., *Opt. Commun.* **285**, 4641 (2012)

Outline

- Introduction

1. Fabrication

2. Optical Properties

3. Photonic Applications

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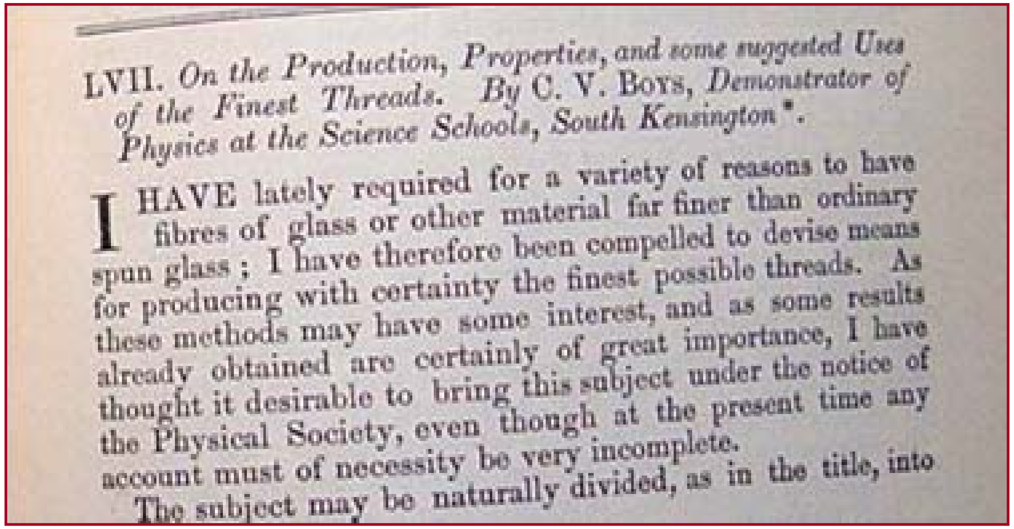
1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

First work was reported in 19th century

C. V. Boys, *Phil. Mag.* **23**, 489 (1887).

"On the production, properties, and some suggested uses of the finest threads"



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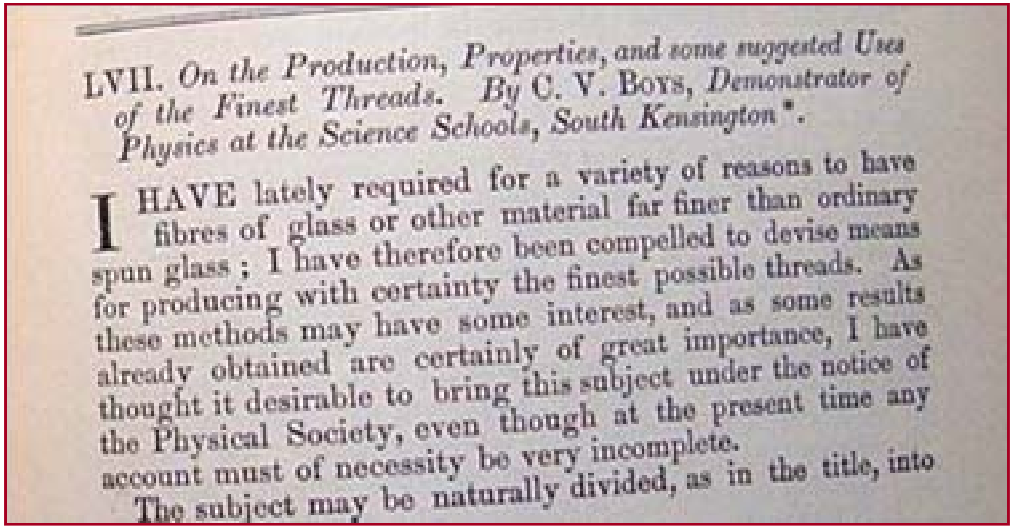

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Flame-heated drawing of molten glass → Finest threads

→ **D ~ μm** (They did not really know, no electron microscope at that time)

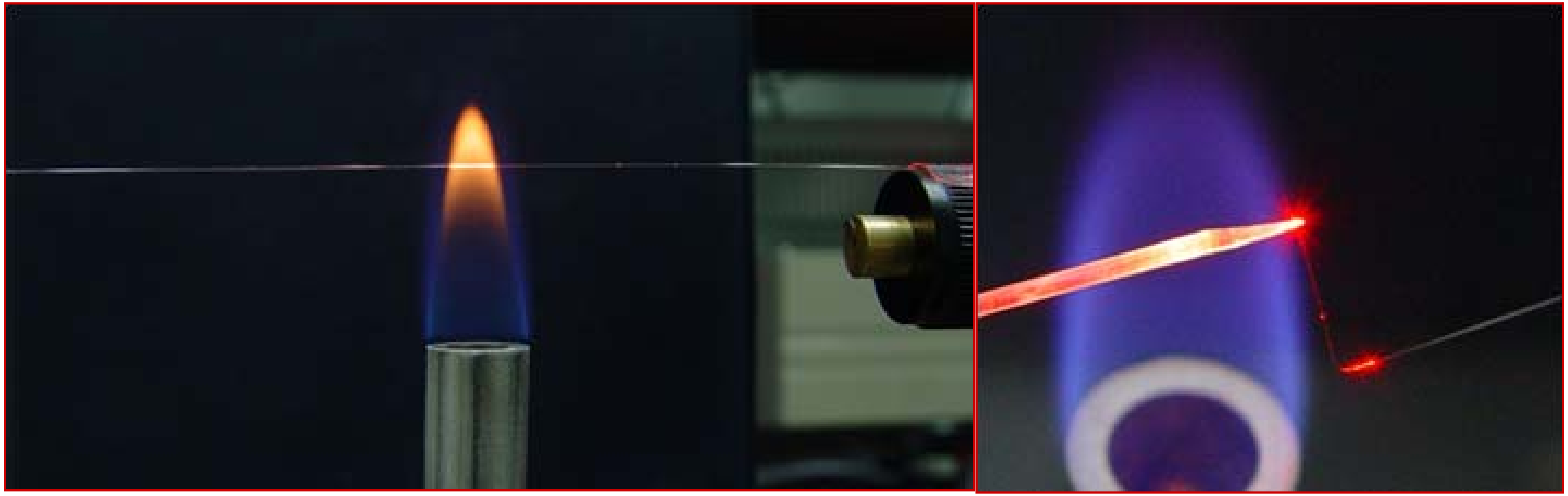
Applications

19th century: "Finest threads" → Elasticity → Spring for galvanometer

1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

Taper drawing fibers heated by flame, electric heater or laser



Taper drawing glass fibers to diameter **< 1 μm**

F. P. Payne et al., *SPIE* 1504, 165 (1991)
J. Bures et al., *J. Opt. Soc. Am. A* **16**, 1992 (1999)
L. Tong et al., *Nature* **426**, 816 (2003)
…

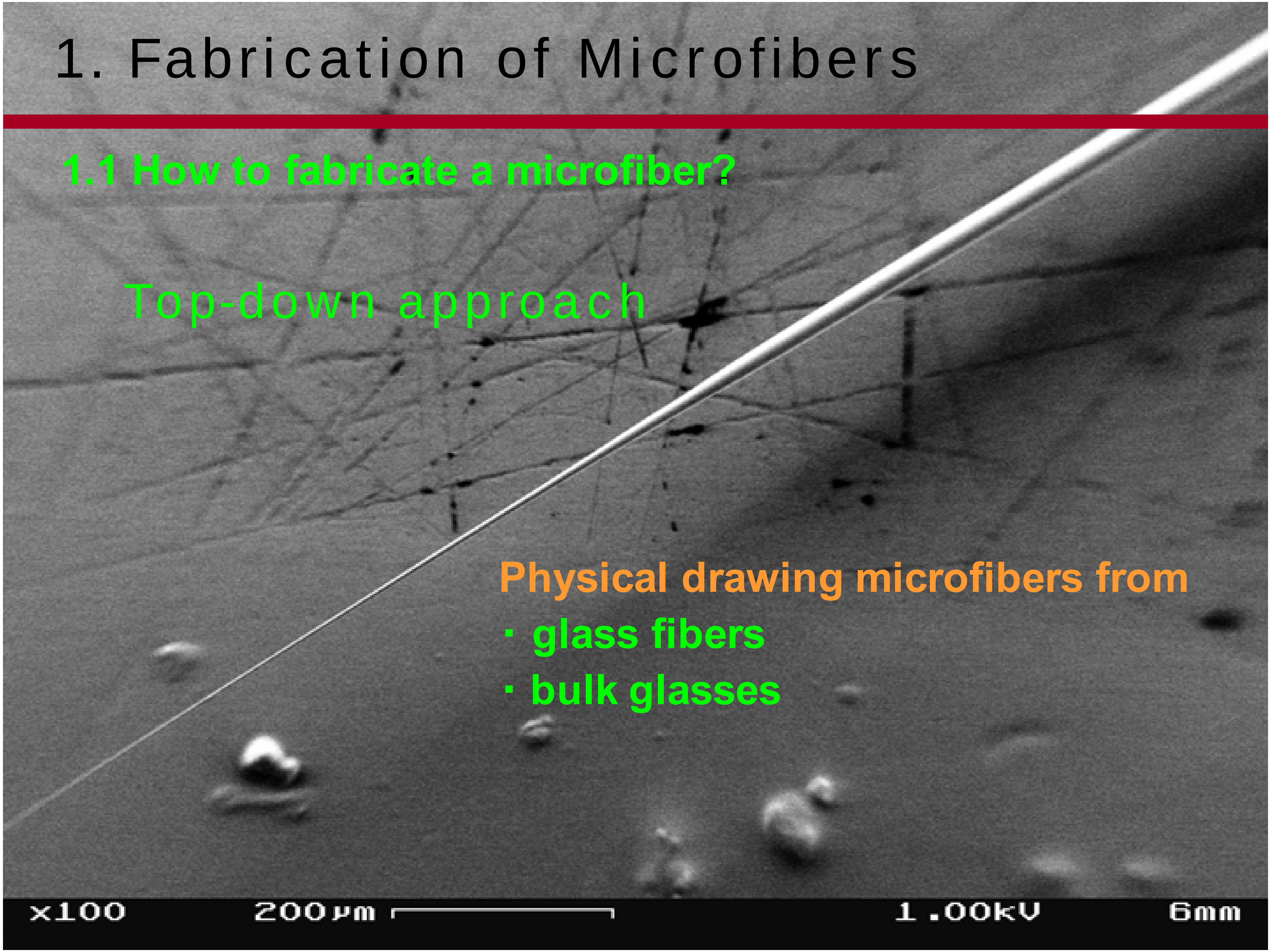
1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

Top-down approach

Physical drawing microfibers from

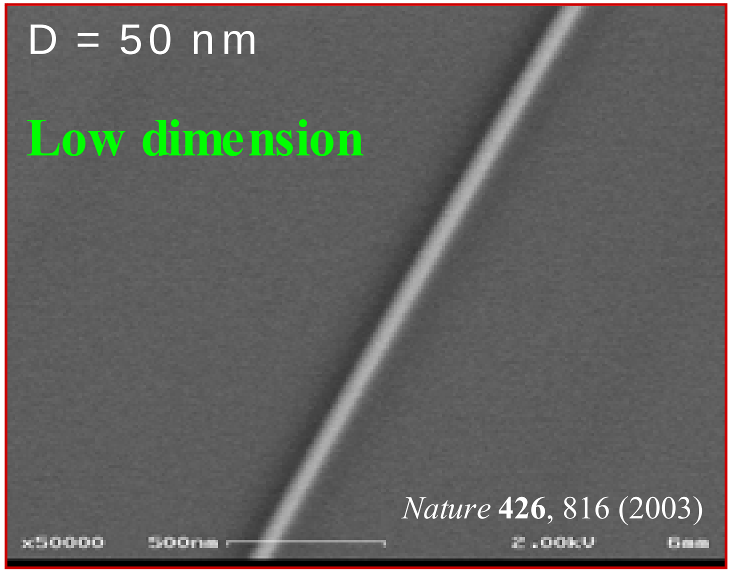
- **glass fibers**
- **bulk glasses**

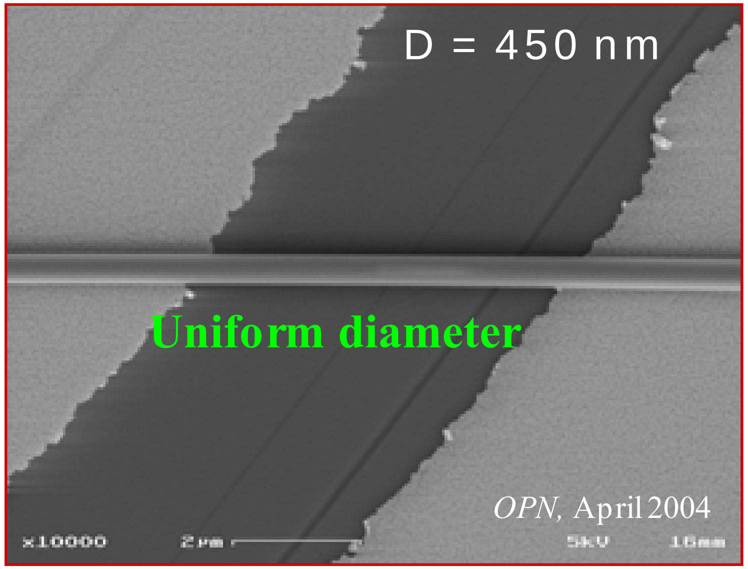


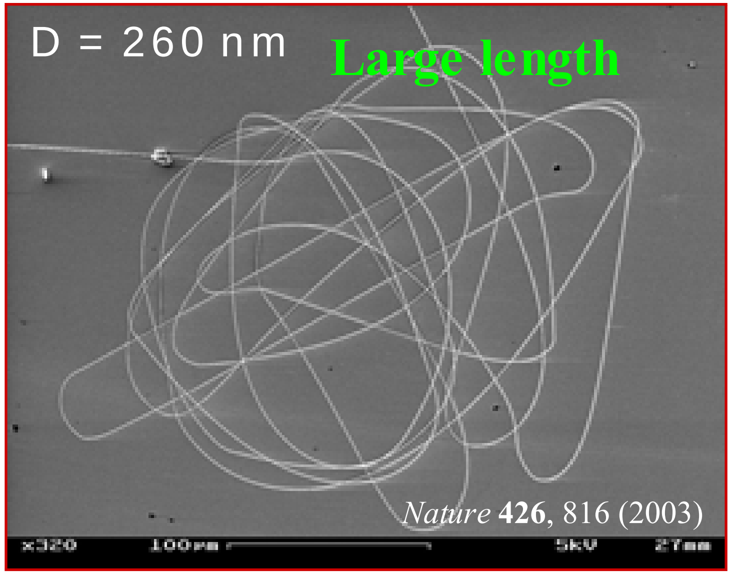
1. Fabrication of Microfibers

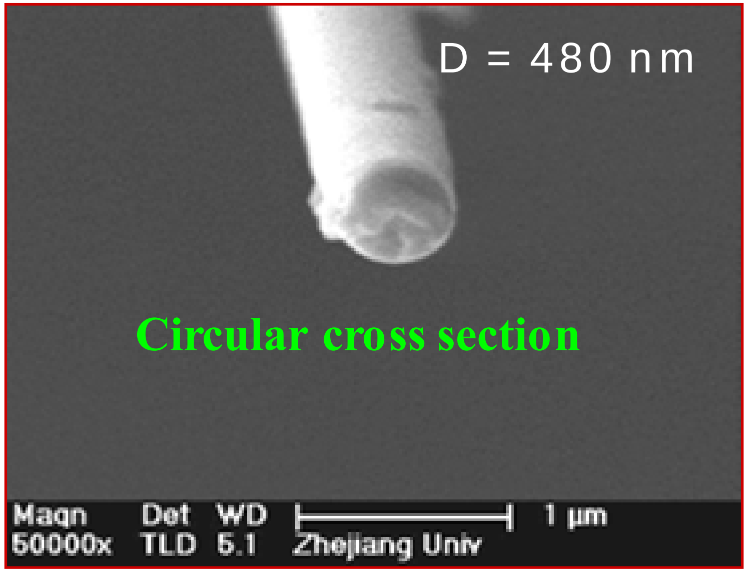
SEM images

Silica fibers









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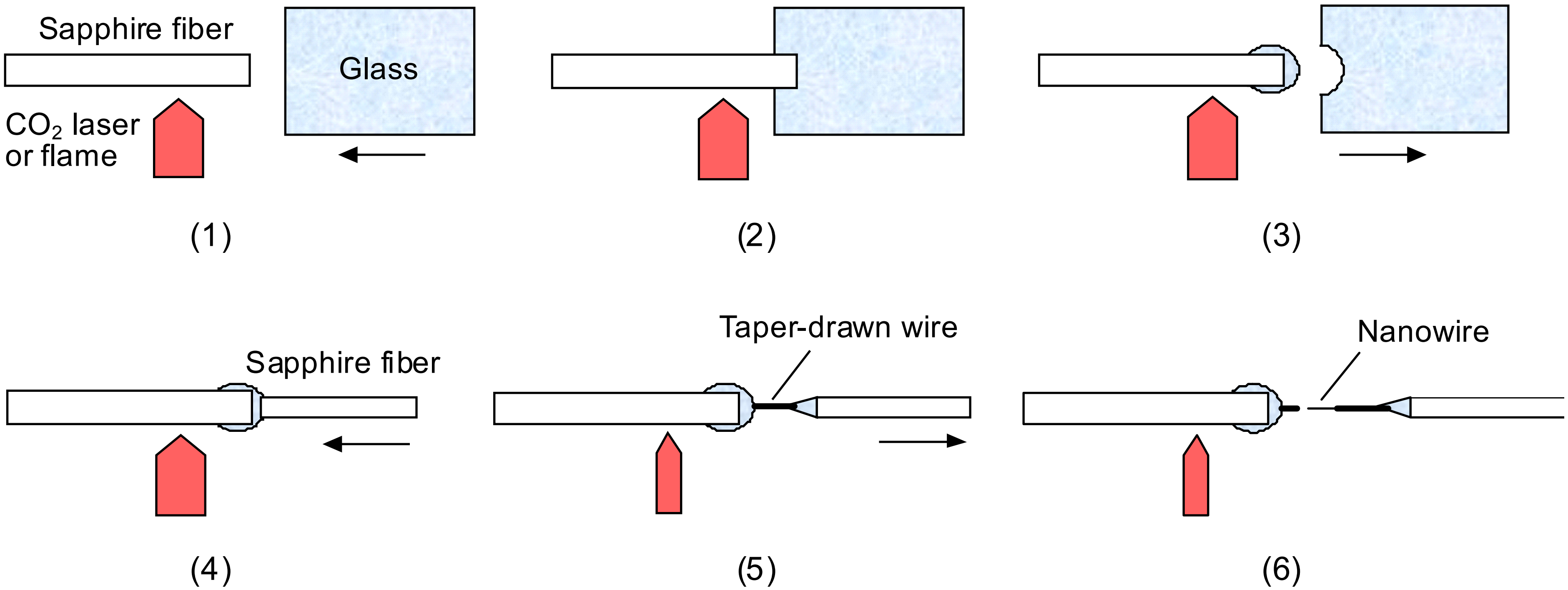
1.1 How to fabricate a microfiber?

Taper drawing of bulk glasses heated by flame or laser

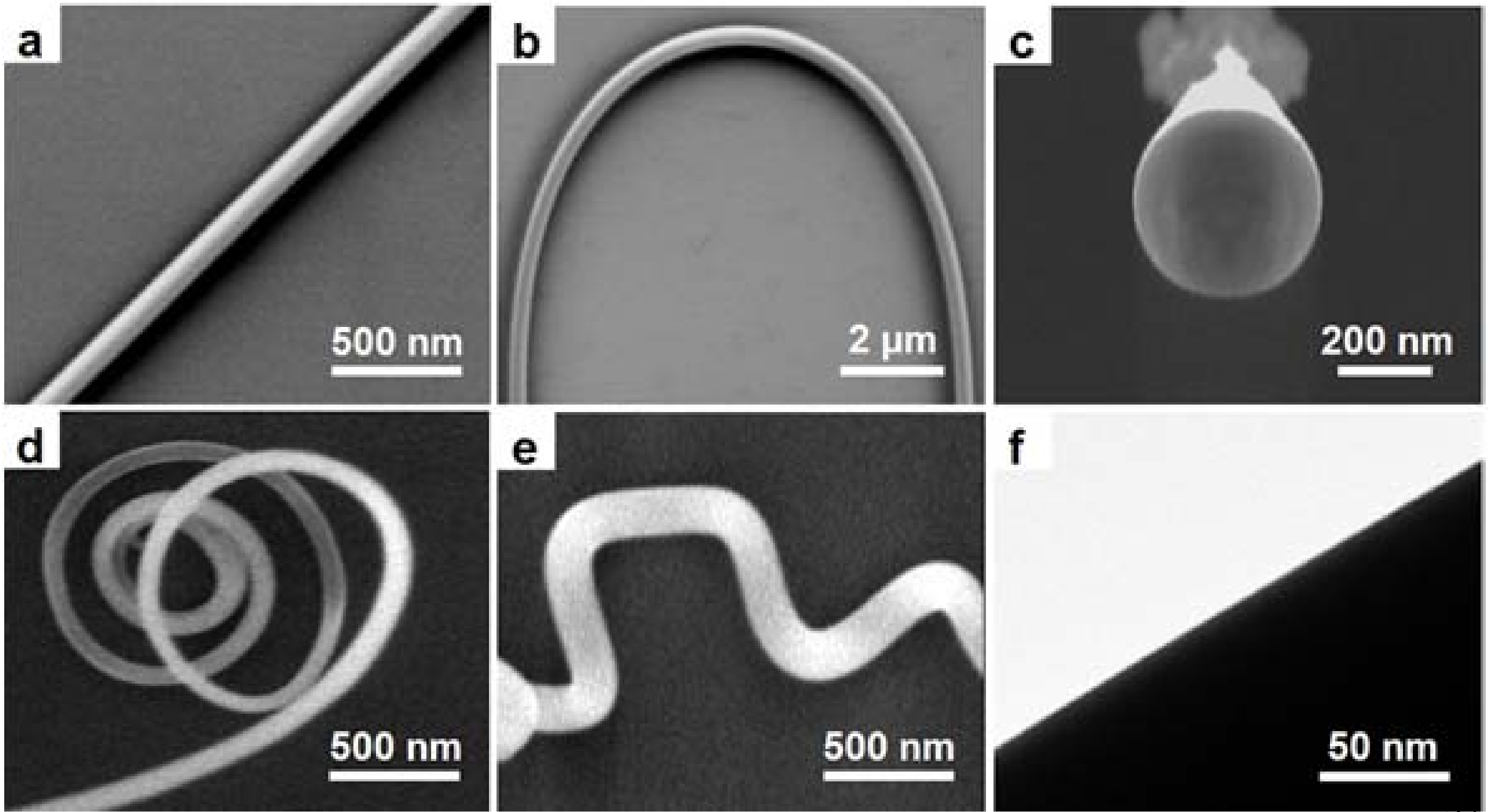


L. Tong et al., *Opt. Express* **14**, 82 (2006)

1. Fabrication of Microfibers

SEM images

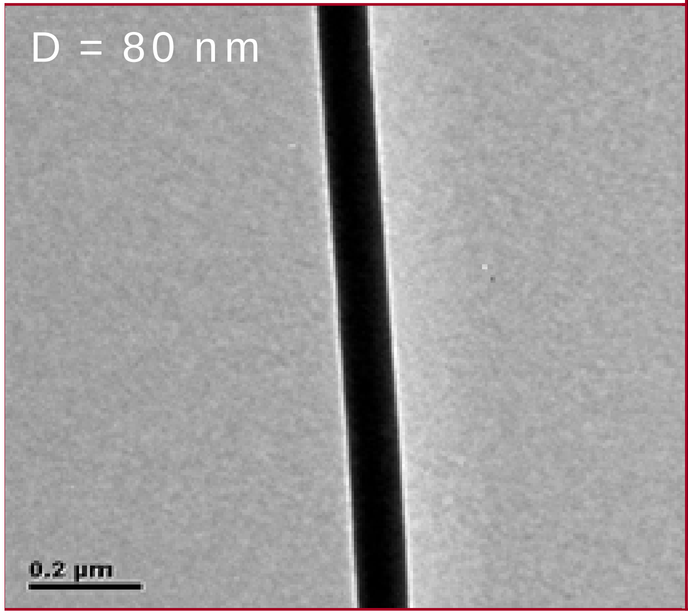
Other materials a, e: tellurite b: silicate c, d, f : phosphate

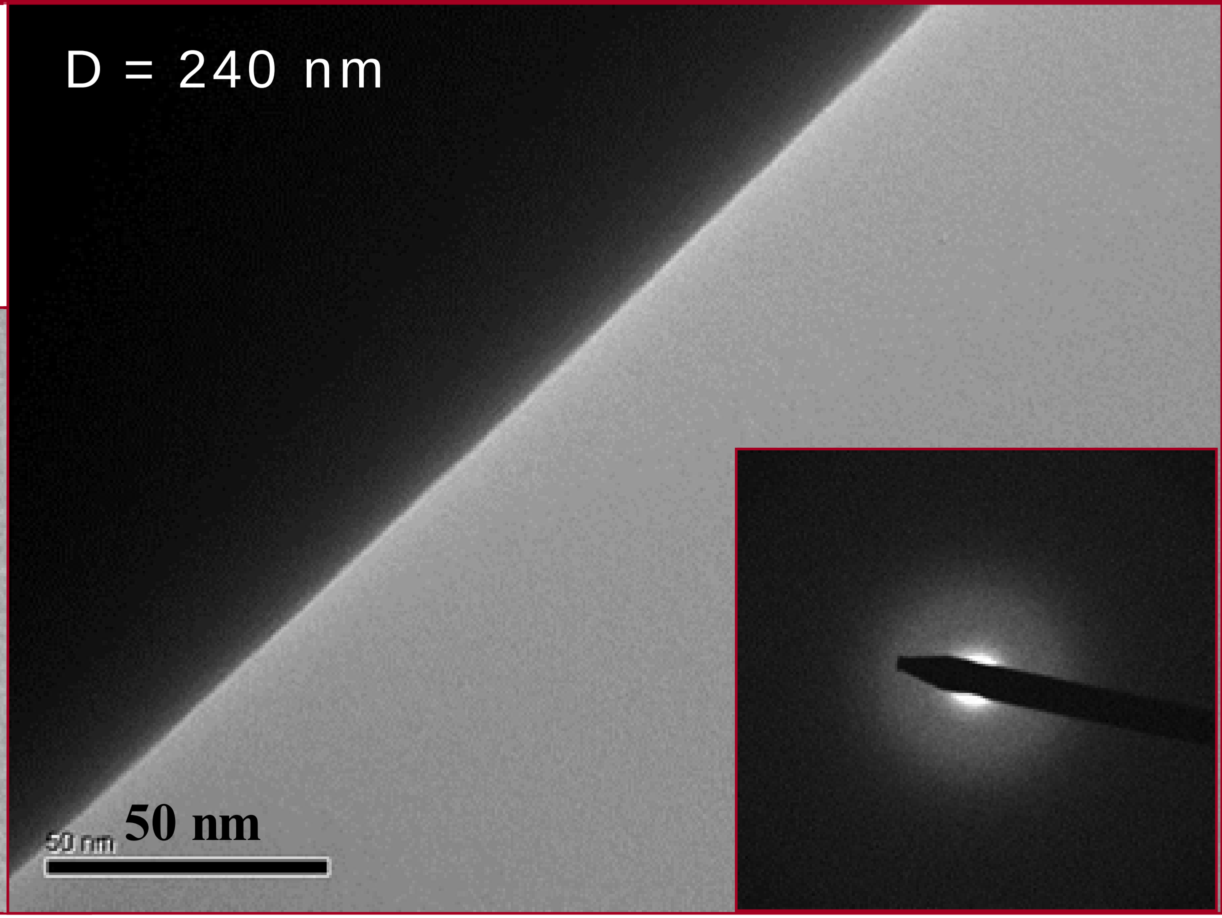


L. Tong et al., *Opt. Express* **14**, 82 (2006)

1. Fabrication of Microfibers

TEM images



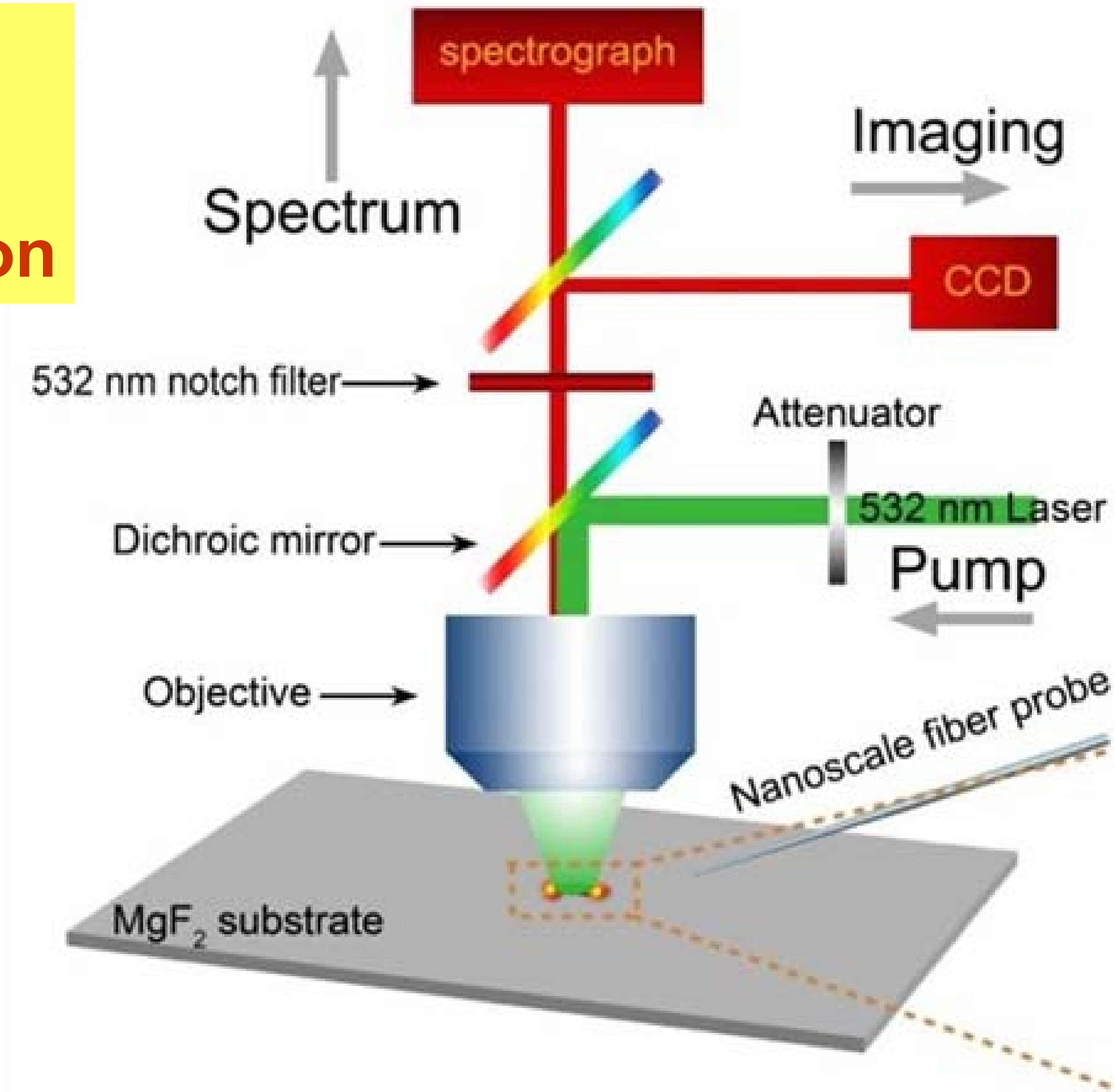


Very smooth surface with sidewall roughness (RMS) lower than 0.3 nm

Favorite for low-loss optical wave guiding

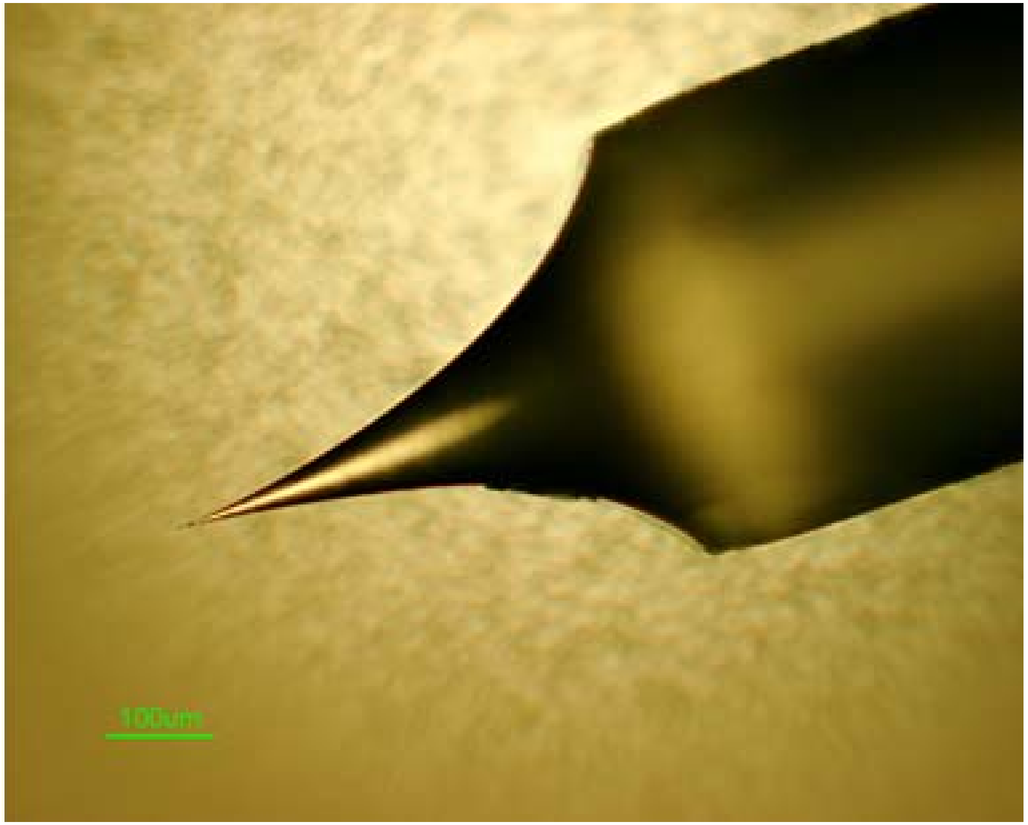
1. Fabrication: micromanipulation

Typical setup for micromanipulation and characterization



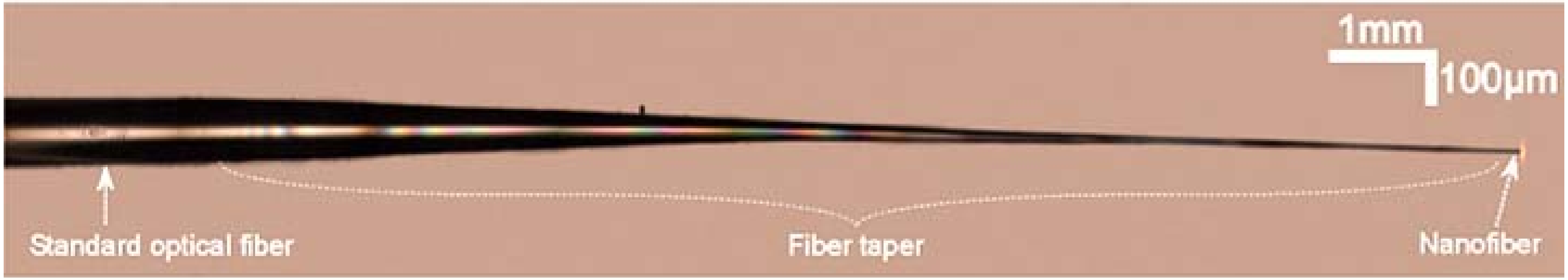
Y. Xiao et al., *Nano Lett*. **11**, 1112 (2011)

Nanoprobes



Tungsten STM probe
Cut, push, drag

Silica fiber probe
Push, light in/out-coupling



X. Guo et al., *Nano Lett*. **9**, 4515 (2009)

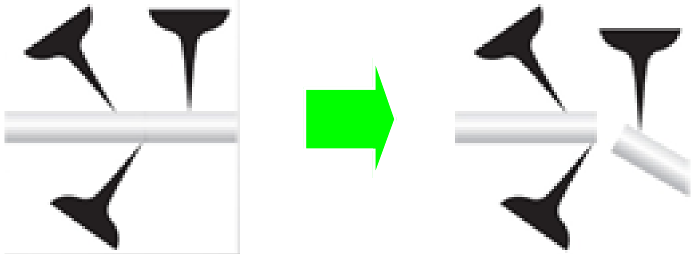
1. Fabrication: micromanipulation

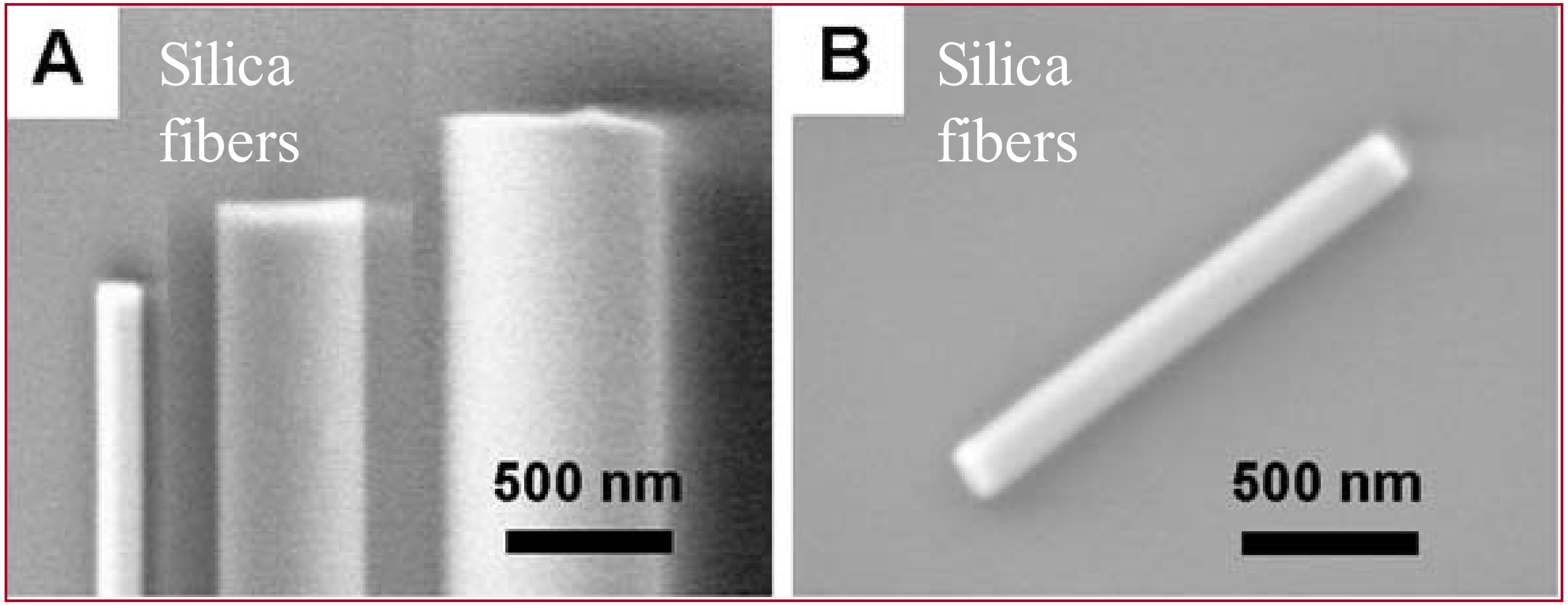
Micromanipulation

Tailoring through micro/nanomanipulation

- **Cut**

Bend-to-fracture approach to cut fibers with flat endfaces





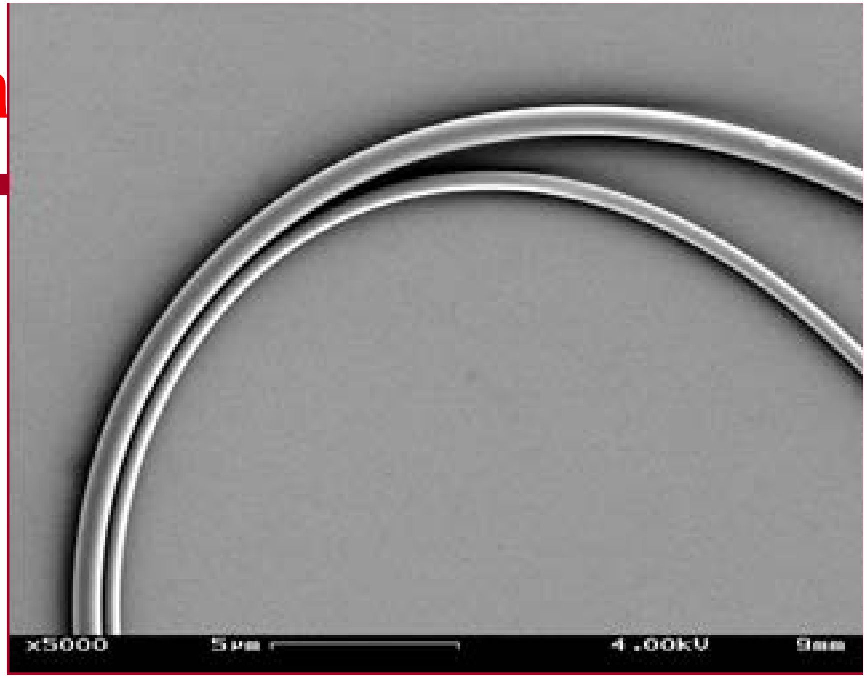
L. M. Tong et al., *Nano Lett.* **5**, 259 (2005)

1. Fabrication: microma

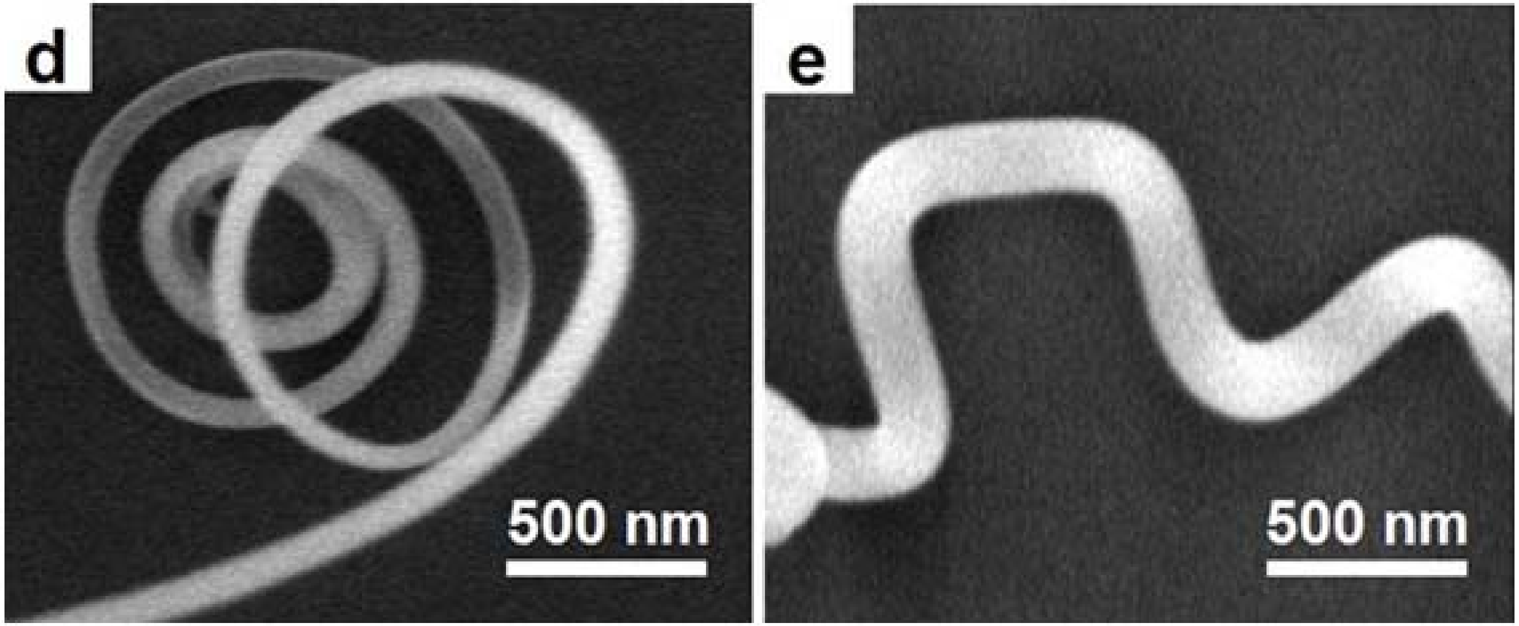
- **Plastic bend**

Annealing-after-bending method

Silica nanofibers



Tellurite nanofibers



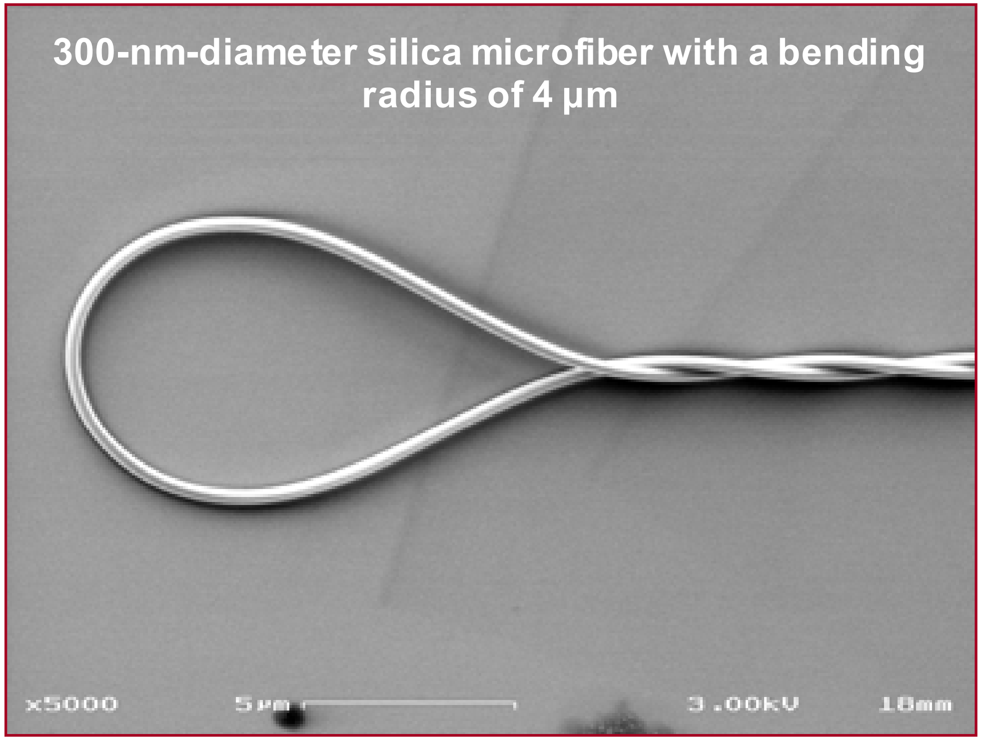
L. M. Tong et al., *Opt. Express* 14, 82 (2006)

1. Fabrication: micromanipulation

Micromanipulation

Tailoring through micro/nanomanipulation

- **Twist**



Typical tensile strength > 5 GPa (@ RT)

Mechanically robust & flexible

Critical for practical applications

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

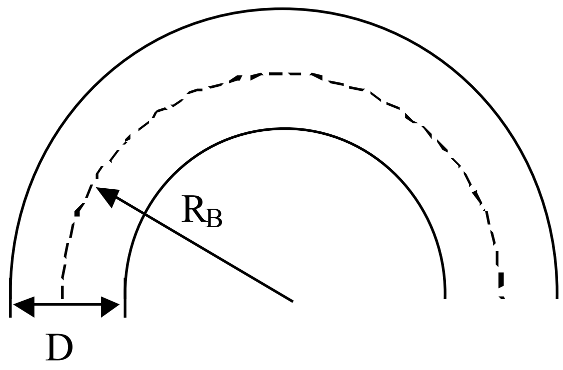
Tensile strength

$$\sigma = \frac{ED}{2R_B}$$

E : Young's modulus,
D : wire diameter,
R_B : bending radius,
Nonlinear Young's modulus [1]

$$E(\varepsilon) = E_0(1 + \alpha\varepsilon + \beta\varepsilon^2),$$

where ε is strain, $E_0 = 72.2\ GPa$, $\alpha = 3.2$, and $\beta = 8.48$.



Bending model of a silica wire

1. J. T. Krause, L. R. Testardi, and R. N. Thurston, "Deviations from linearity in the dependence of elongation upon force for fibers of simple glass formers and of glass optical lightguides", *Phys. Chem. Glasses* **20**, 135-139 (1979).

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

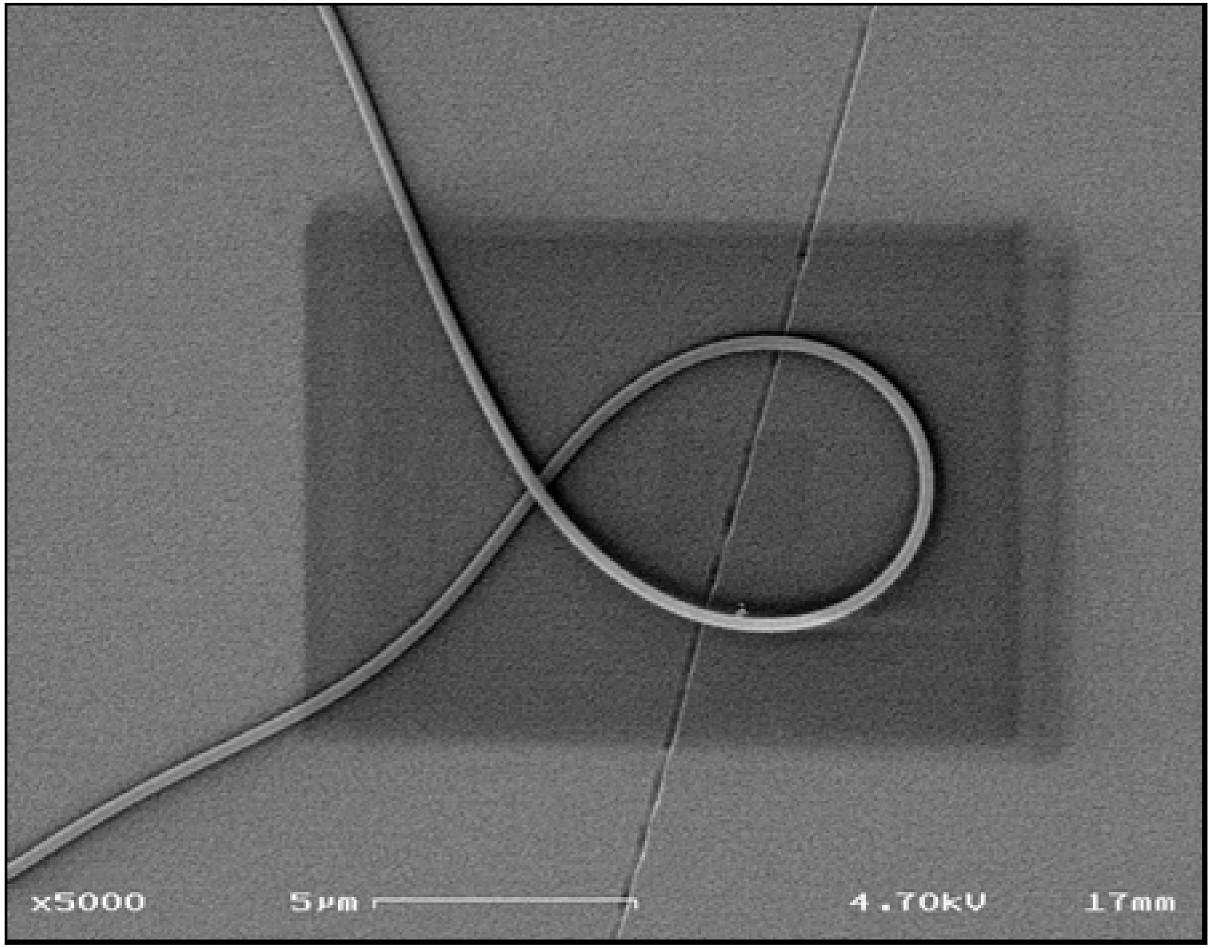
Tensile strength

Silica nanofiber

D=280 nm

R_B=2.7 μm

σ> 4.5 GPa

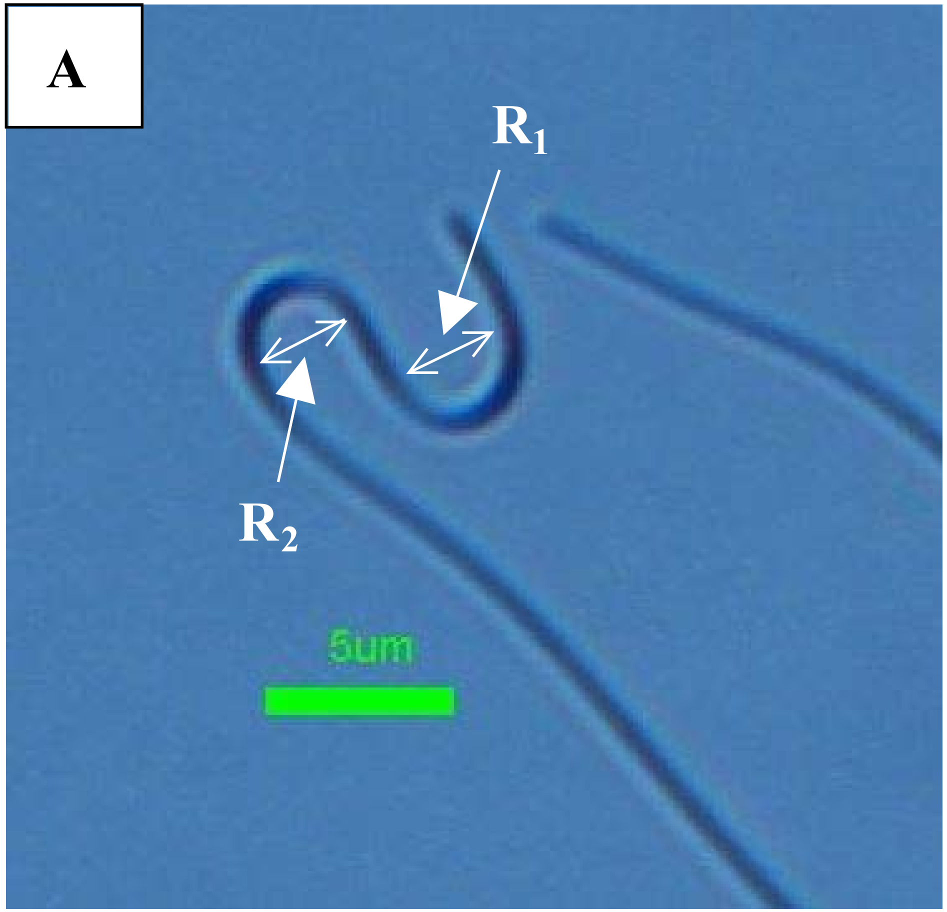


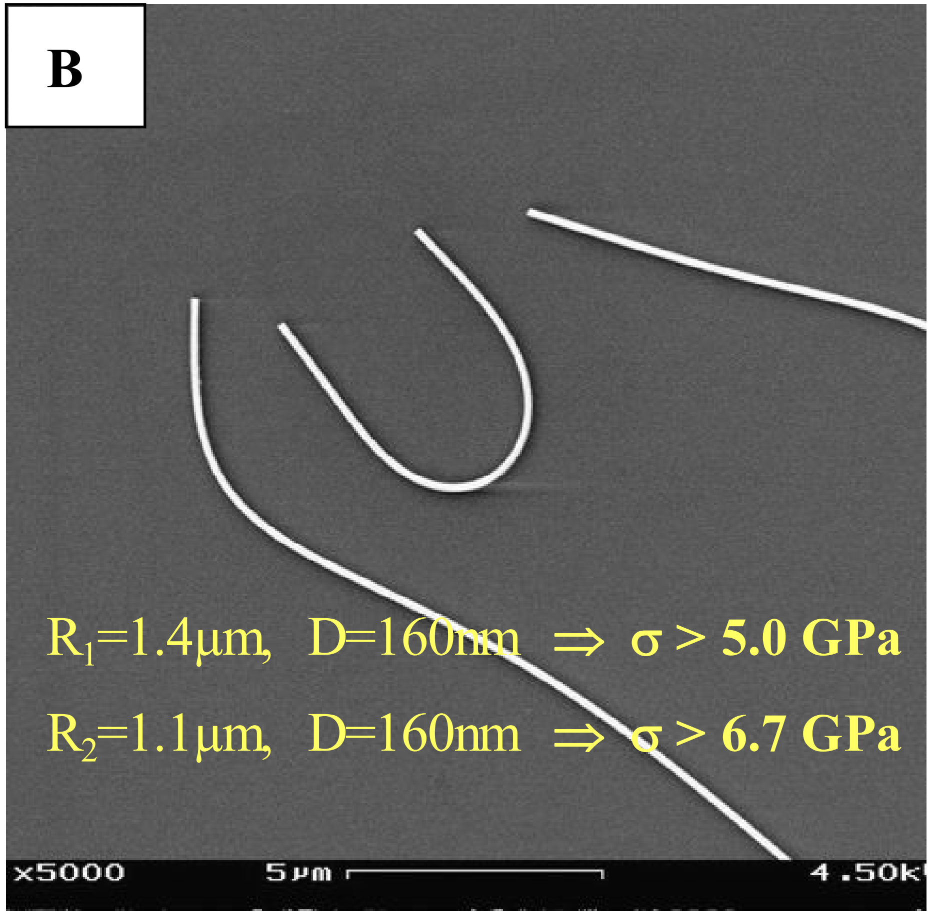
L. M. Tong et al., *Nature* **426**, 816 (2003)

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

Tensile strength bending-to-fracture test





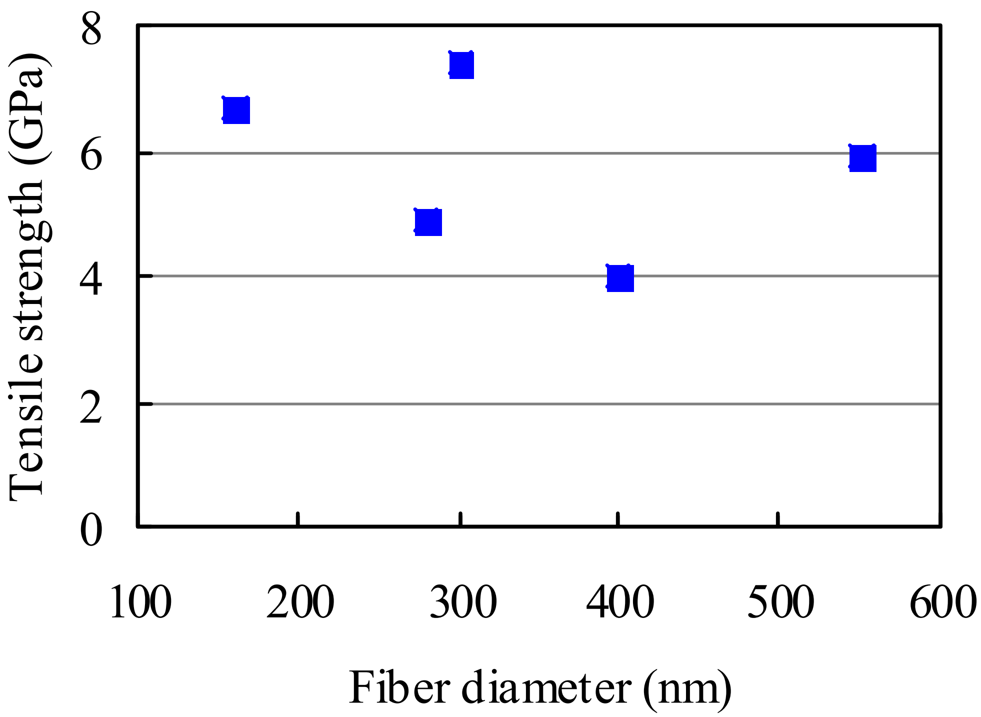
Optical microscope and SEM images of a bent 160-nm-diameter silica wire before (A) and after (B) fracture.

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

Tensile strength

Tensile strength of silica nanofiber measured by bending-to-fracture process (L ~ 10 μm)



Tensile strength of micrometer-diameter fibers (@ room temperature, medium humidity):

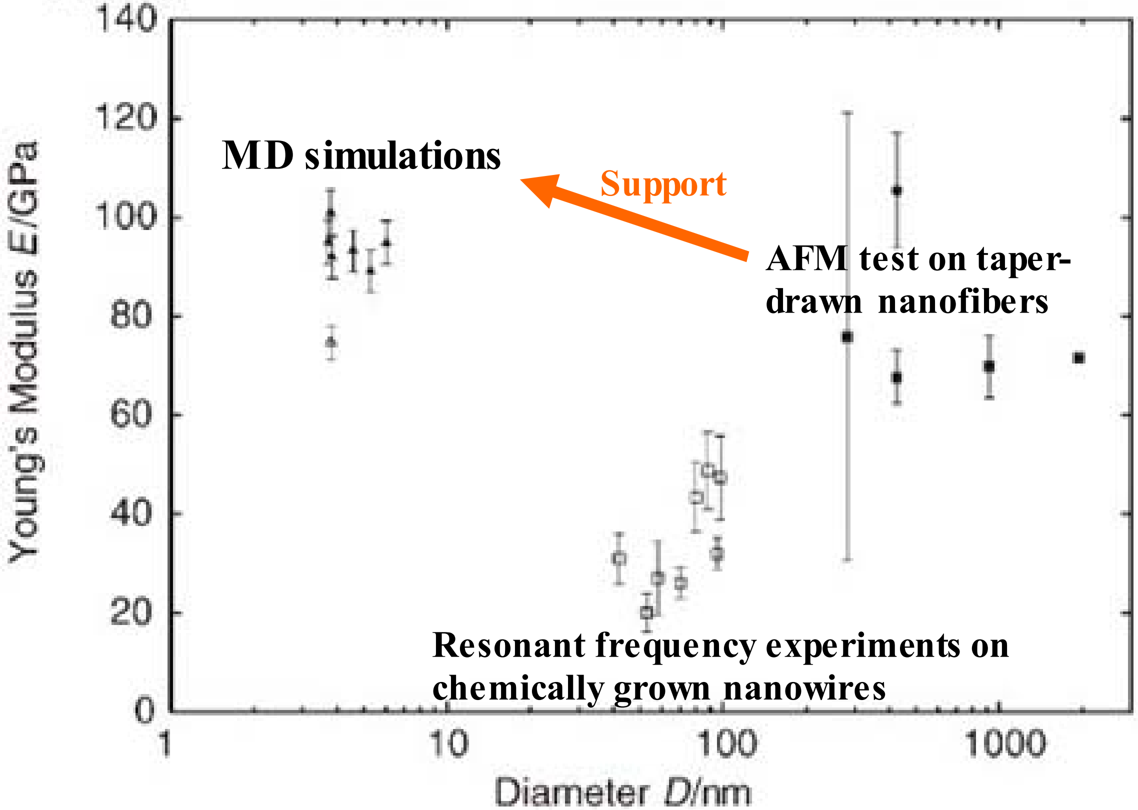
Spider silk (D~ 5μm)
σ : 0.5-1.5 Gpa

Silica fiber (D=125μm)
σ : 2-3 GPa

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

Young's modulus of silica nanofiber measured by AFM

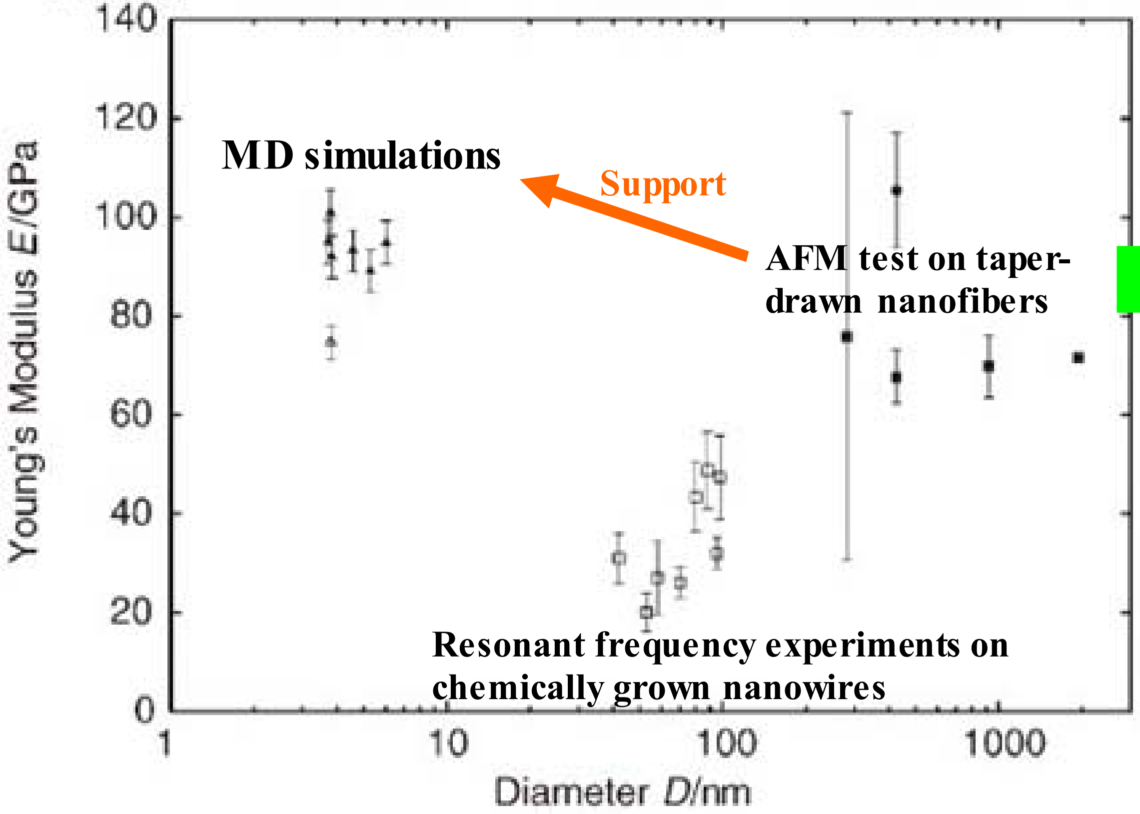


E. C. C. M. Silva et al., *Small* 2, 239 (2006)

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

Young's modulus of silica nanofiber measured by AFM



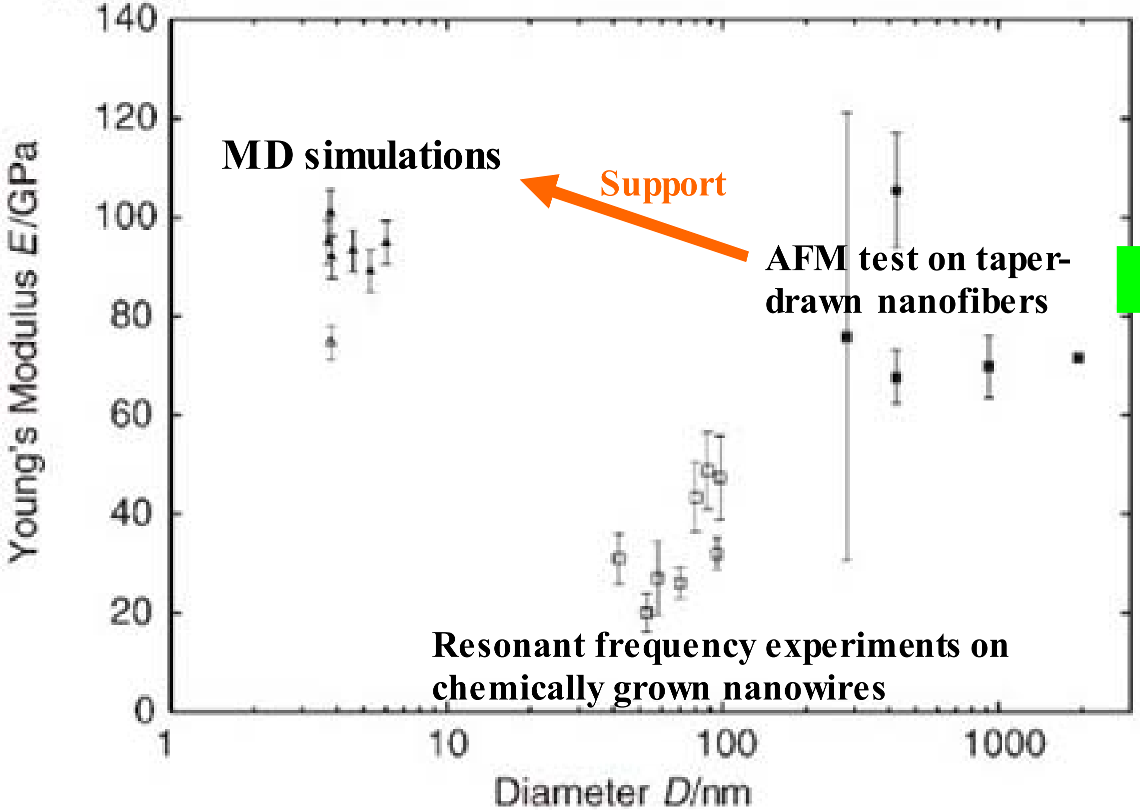
Taper-drawn nanofibers are better for mechanical research

E. C. C. M. Silva et al., *Small* 2, 239 (2006)

1. Fabrication: micromanipulation

Micromanipulation → Mechanical properties

Young's modulus of silica nanofiber measured by AFM



Taper-drawn nanofibers are better for mechanical research

Better uniformity than chemically grown nanowires

E. C. C. M. Silva et al., *Small* 2, 239 (2006)

Outline

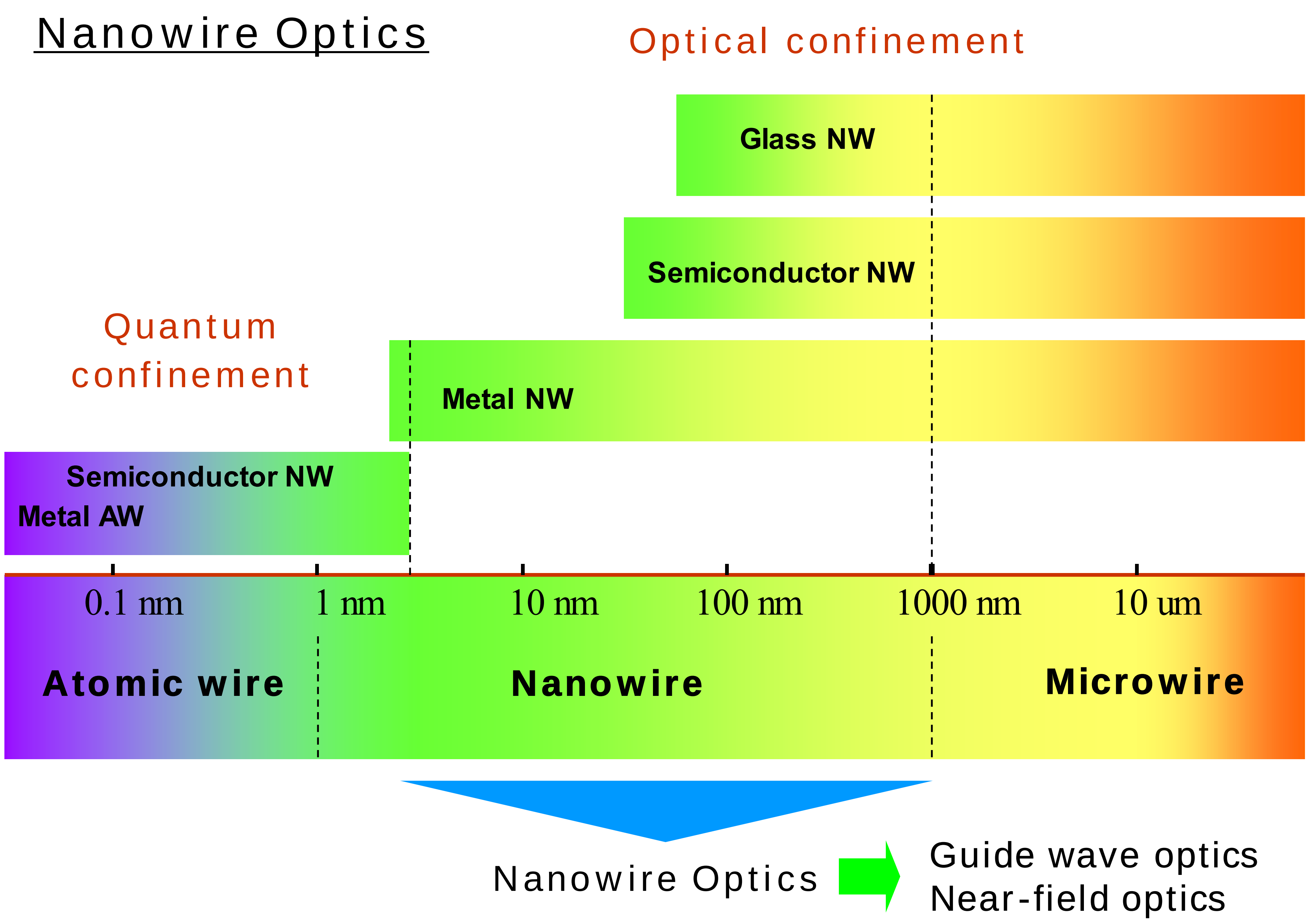
- Introduction

1. Fabrication

2. Optical Properties

3. Photonic Applications

- Summary


Nanowire Optics
Optical confinement
Glass NW
Semiconductor NW
Quantum confinement
Metal NW
Semiconductor NW
Metal AW
0.1 nm
1 nm
10 nm
100 nm
1000 nm
10 um
Atomic wire
Nanowire
Microwire
Nanowire Optics
Guide wave optics
Near-field optics

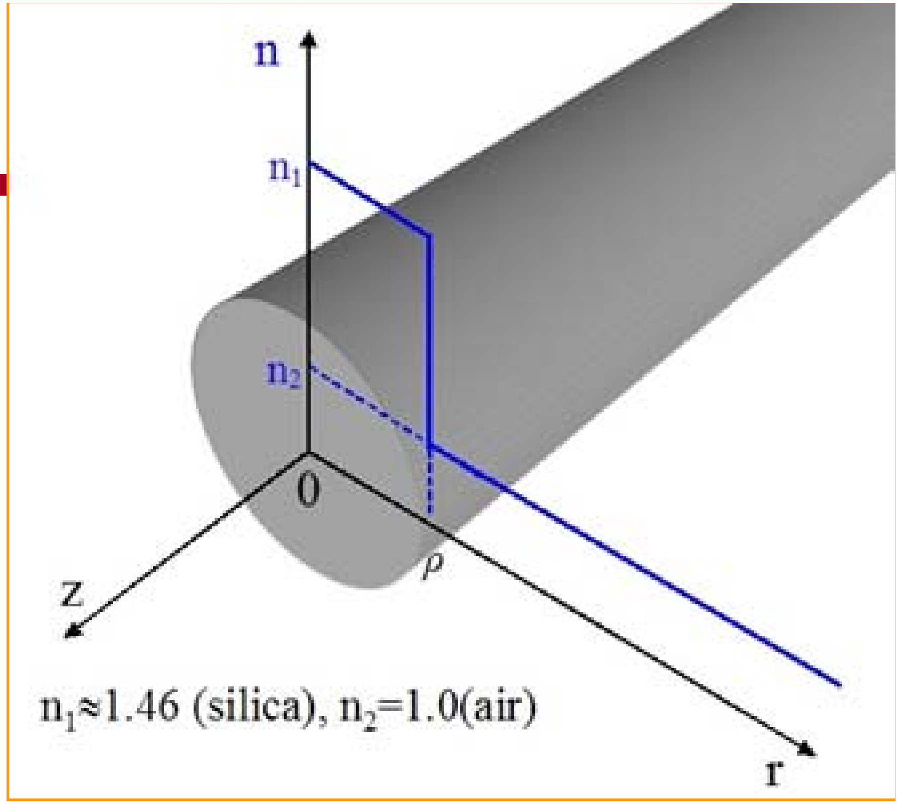
2. Nanofiber Optics

- **Basic model for**

  Guide wave optics

  Near-field optics

Cylindrical symmetry



Helmholtz Equations

$$(\nabla^2 + n^2k^2 - \beta^2)\vec{e} = 0,$$
$$(\nabla^2 + n^2k^2 - \beta^2)\vec{h} = 0.$$

+

Boundary conditions

$$n(r) = \begin{cases} n_1, & 0 \le r < \rho \\ n_2, & \rho \le r < \infty \end{cases}$$

Analytical solutions of guided modes supported by the fiber [1]

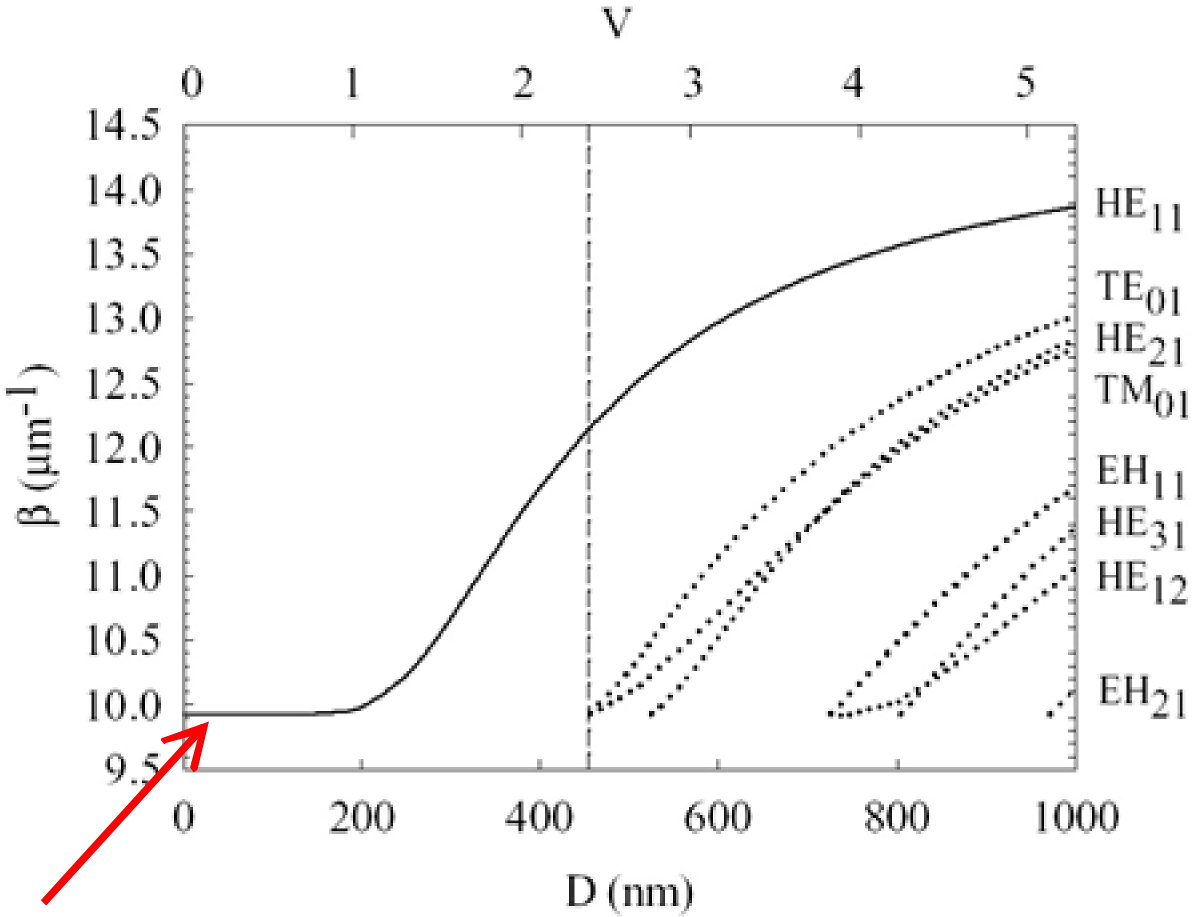
[1] A. W. Snyder and J. D. Love, *Optical waveguide theory*, Chapman and Hall, New York, 1983.

2. Nanofiber Optics

· **Basic model**

Propagation constants (*β*)

Air-clad silica microfibers
Wavelength: 633 nm



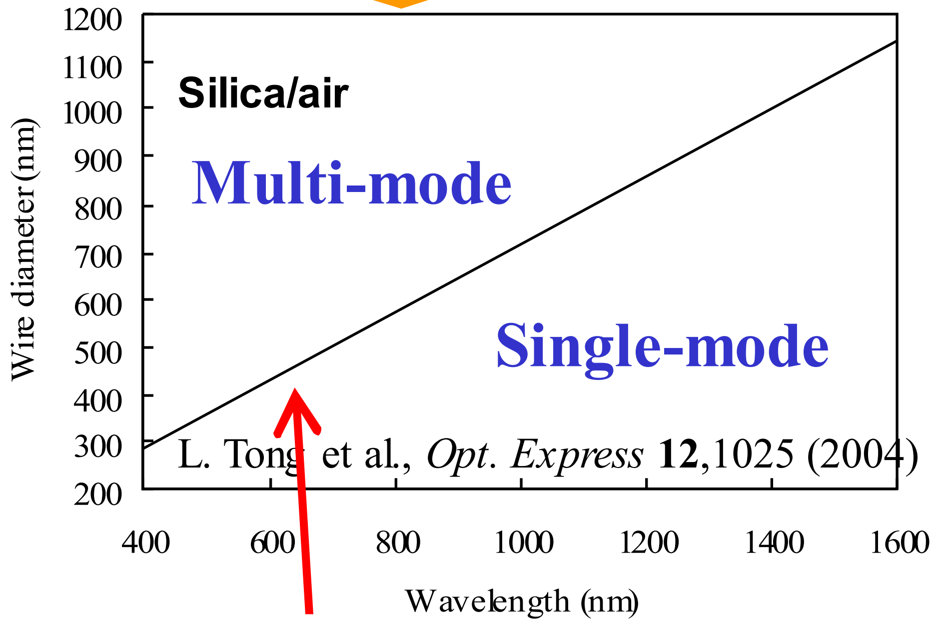
no cutoff of the fundamental modes

L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Nanofiber Optics

· **Single-mode condition**

$$V = \pi \cdot \frac{D}{\lambda_0} \cdot \left(n_1^{\ 2} - n_2^{\ 2}\right)^{1/2} \approx 2.405$$

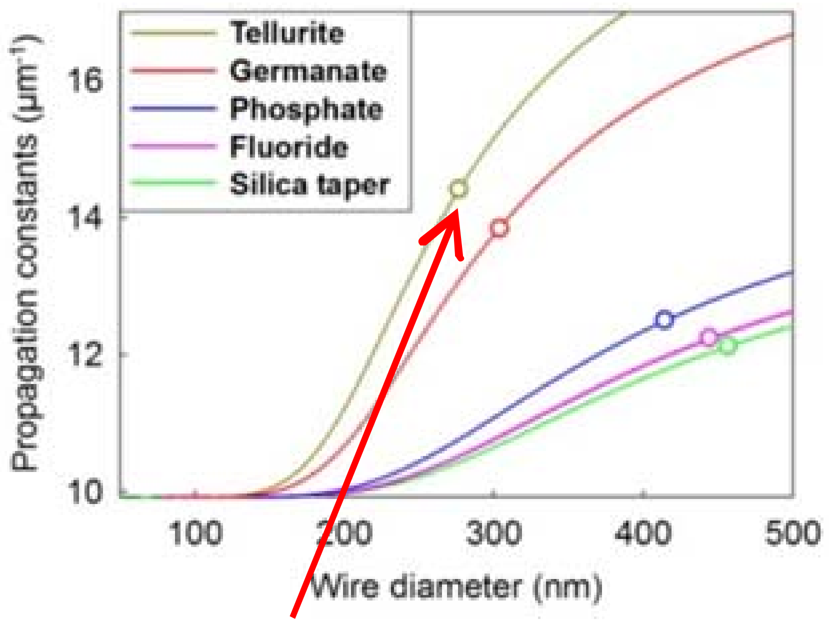


L. Tong et al., *Opt. Express* **12**,1025 (2004)

The shorter the wavelength

β for HE_{11} mode of several glass nanofibers

L. Tong et al., *Opt. Express* **14**, 82 (2006)



the higher the refractive index

L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

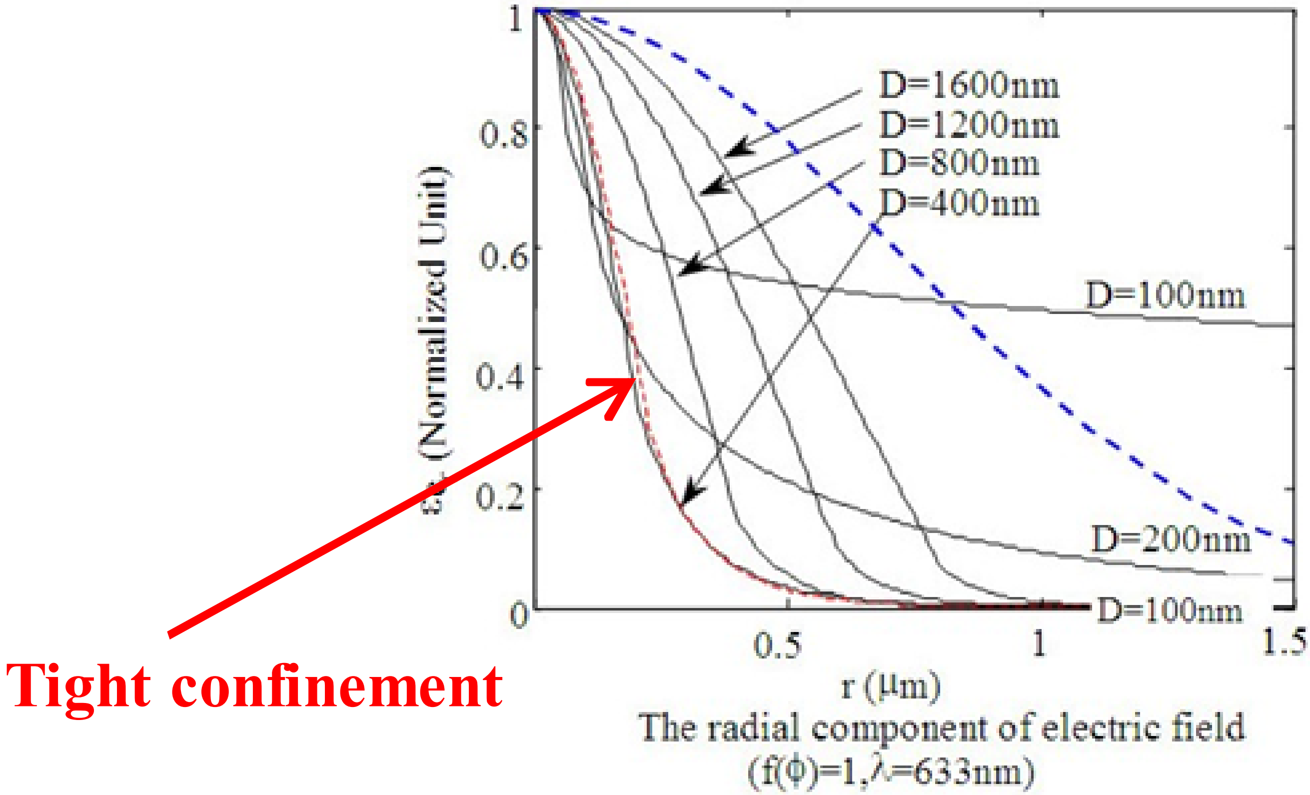
the smaller the single-mode cutoff diameter

2. Nanofiber Optics

2.3 Electric fields of HE_{11} mode

For the fundamental mode (HE_{11})

Normalized electric fields in a air-clad silica fiber operated at 633-nm wavelength

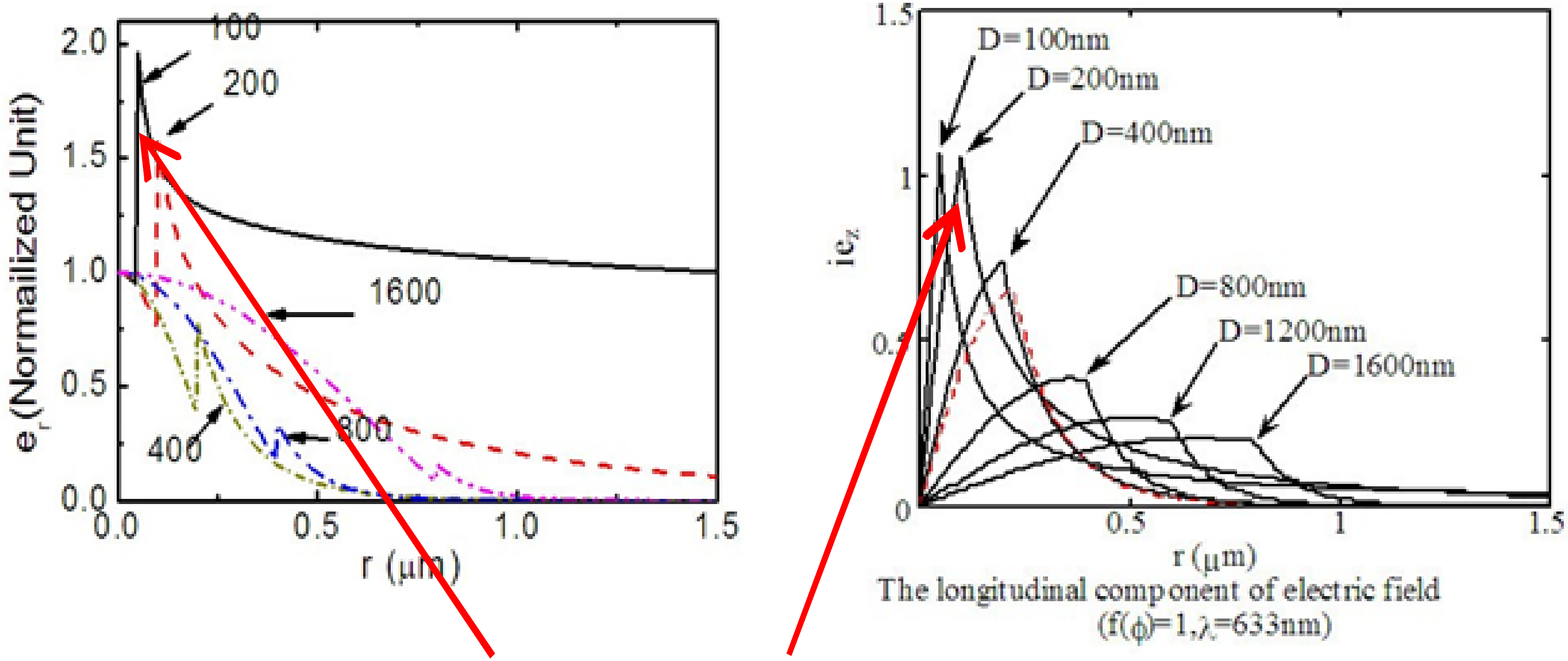


The radial component of electric field
(f(ϕ)=1, λ=633nm)

L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

For the fundamental mode (HE_{11})

Normalized electric fields in a air-clad silica fiber operated at 633-nm wavelength



The longitudinal component of electric field
($f(\phi)=1, \lambda=633$nm)

On the surface, x- and z-component → Maximum
→field enhancement on surface

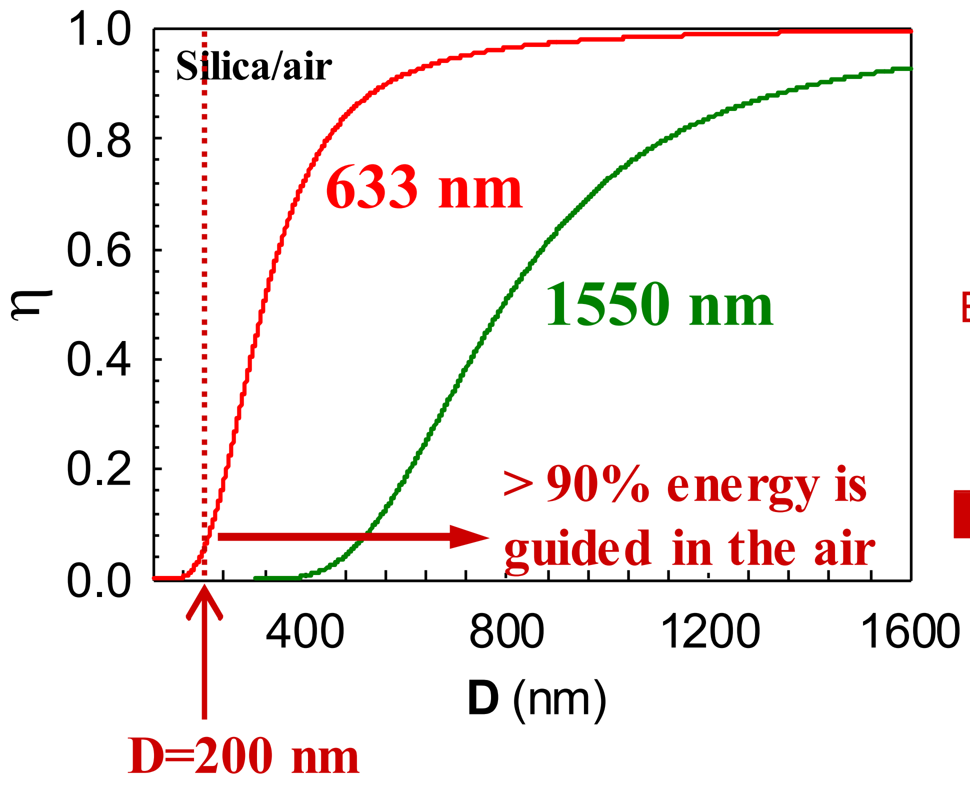
e.g., when a 1-mW 780-nm-wavelength light sent into a 340-nm-diameter silica nanofiber, it generate a 2kW/mm^2 power density on the nanofiber surface.

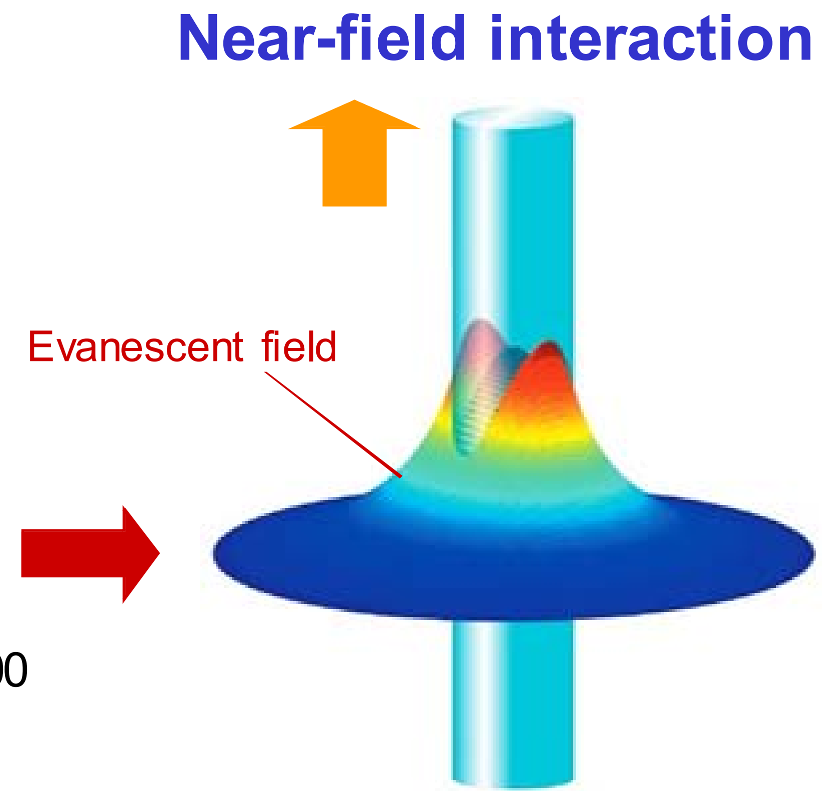
J. Bures et al., J. Opt. Soc. Am. A **16**, 1992-1996 (1999)
L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Nanofiber Optics

· **Evanescent field of HE_{11} mode**

Fractional power inside the core



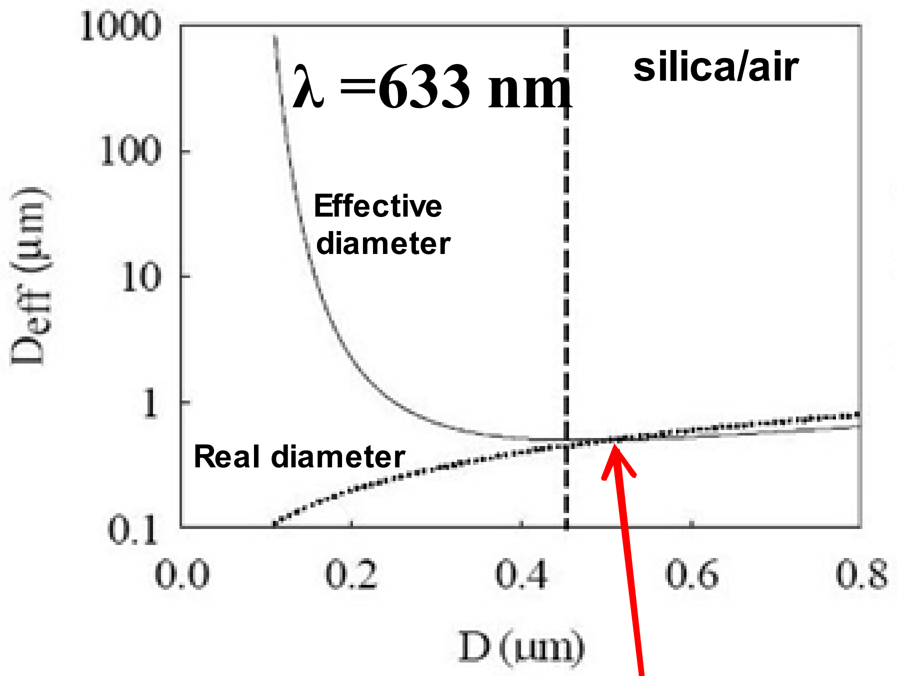


L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Nanofiber Optics

・Optical confinement of HE_{11} mode

Effective Diameter: Mode area for optical confinement of 86.5%



Small mode area → **Nonlinear effects**

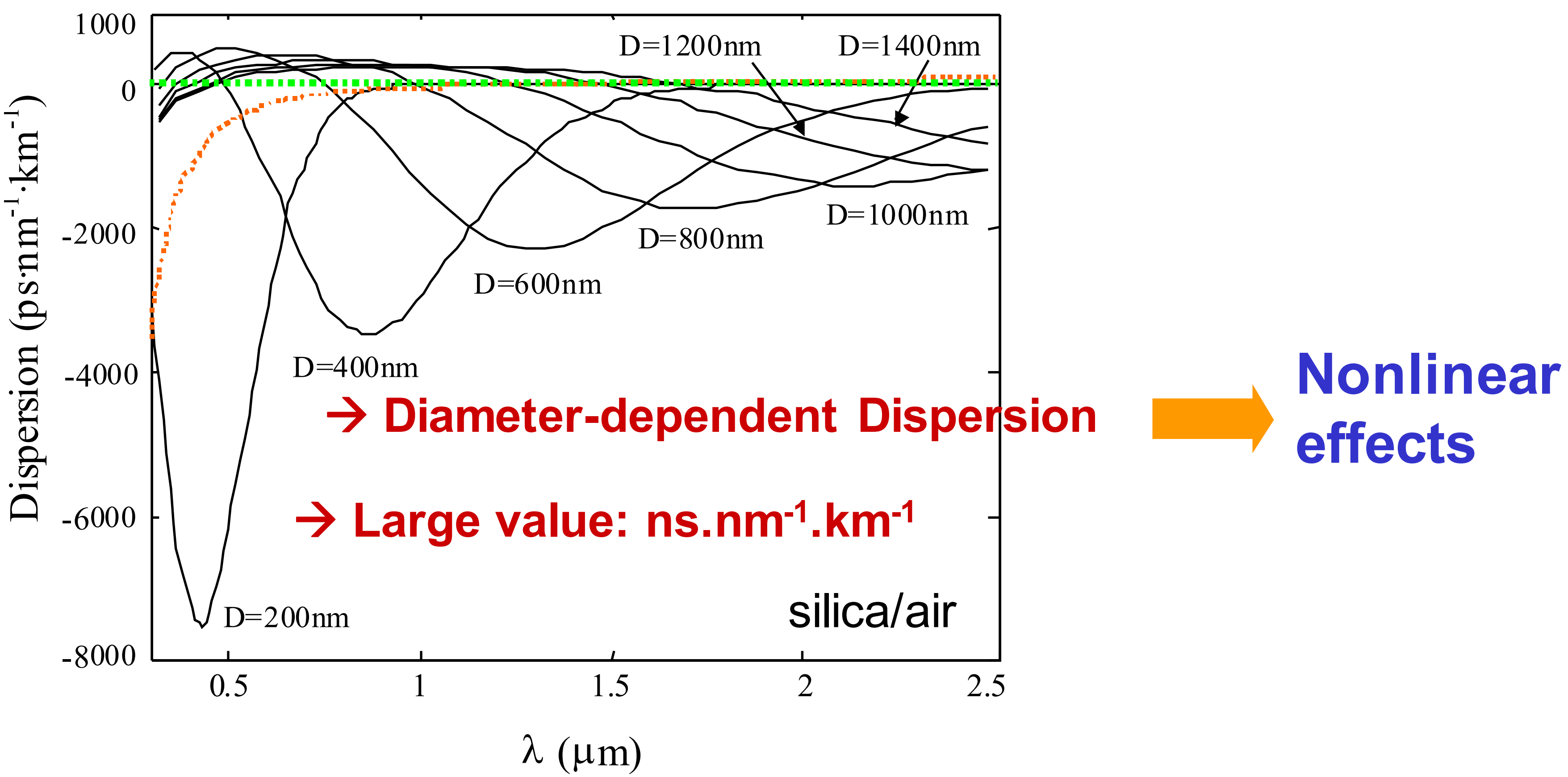
Minimum usable Effective Diameter ～510 nm

L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Nanofiber Optics

- **Waveguide dispersion of HE_{11} mode**

Waveguide dispersion in air-clad silica fibers

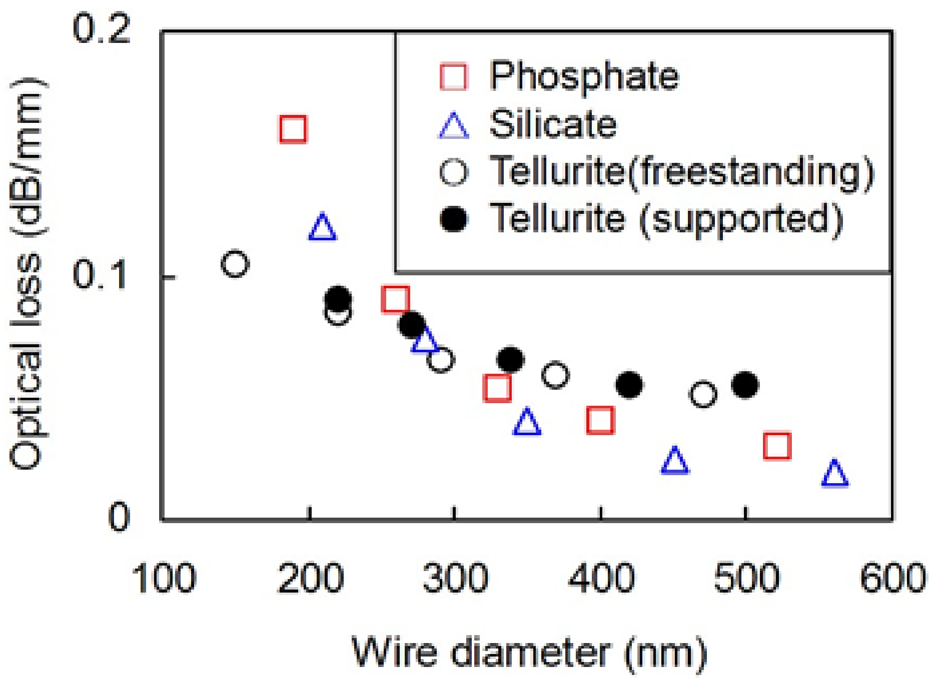


L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Nanofiber Optics

· Optical loss in real nanofibers

Measured losses for single-mode glass fibers are typically < 0.1 dB/mm



L. M. Tong et al., *Opt. Express* **12**,1025 (2004)

Lowest optical losses @RT

Silica nanofibers:

$\alpha \sim 0.001$ dB/mm

S. G. Leon-Saval et al., *Opt. Express* 12, 2864 (2004)

PMMA nanowires:

$\alpha \sim 0.01$ dB/mm

F. X. Gu et al., *Nano Lett.* 8, 2757-2761 (2008)

ZnO nanowires:

$\alpha \sim 0.1$ dB/mm

Ag nanowires:

$\alpha \sim 0.4$ dB/um

Y. G. Ma et al., *Opt. Lett.* 35, 1160 (2010)

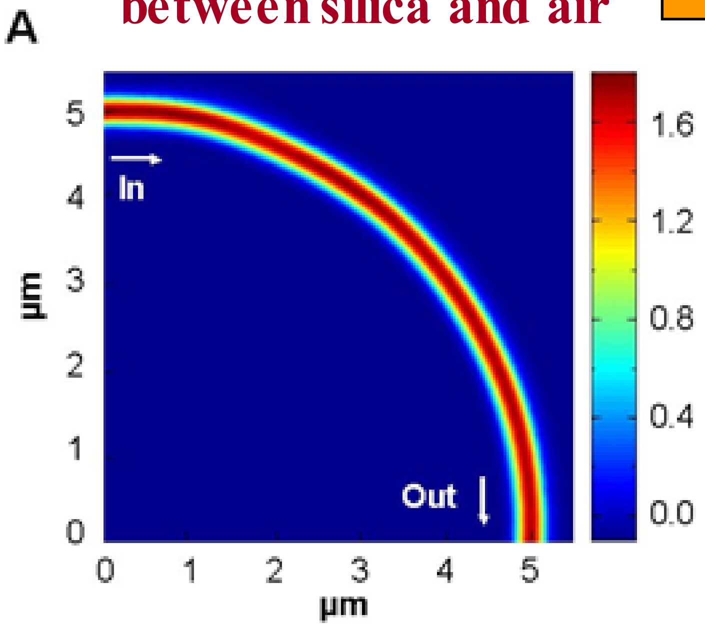
2. Nanofiber Optics

・Optical loss in real nanofibers

Bending loss

High index contrast between silica and air

Light can be guided through sharp bend with low optical loss



3D-FDTD simulations of the intensity of a 633-nm-wavelength light guided in 5-μm-radius-bend 450-nm-diameter silica fiber.

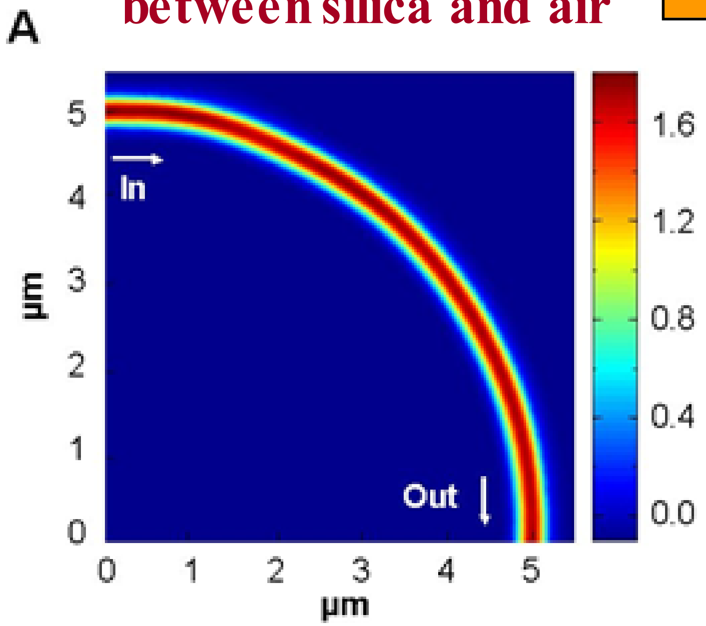
L. M. Tong et al., *Nano Lett.* **5**, 259 (2005)

2. Nanofiber Optics

- **Optical loss in real nanofibers**

Bending loss

High index contrast between silica and air



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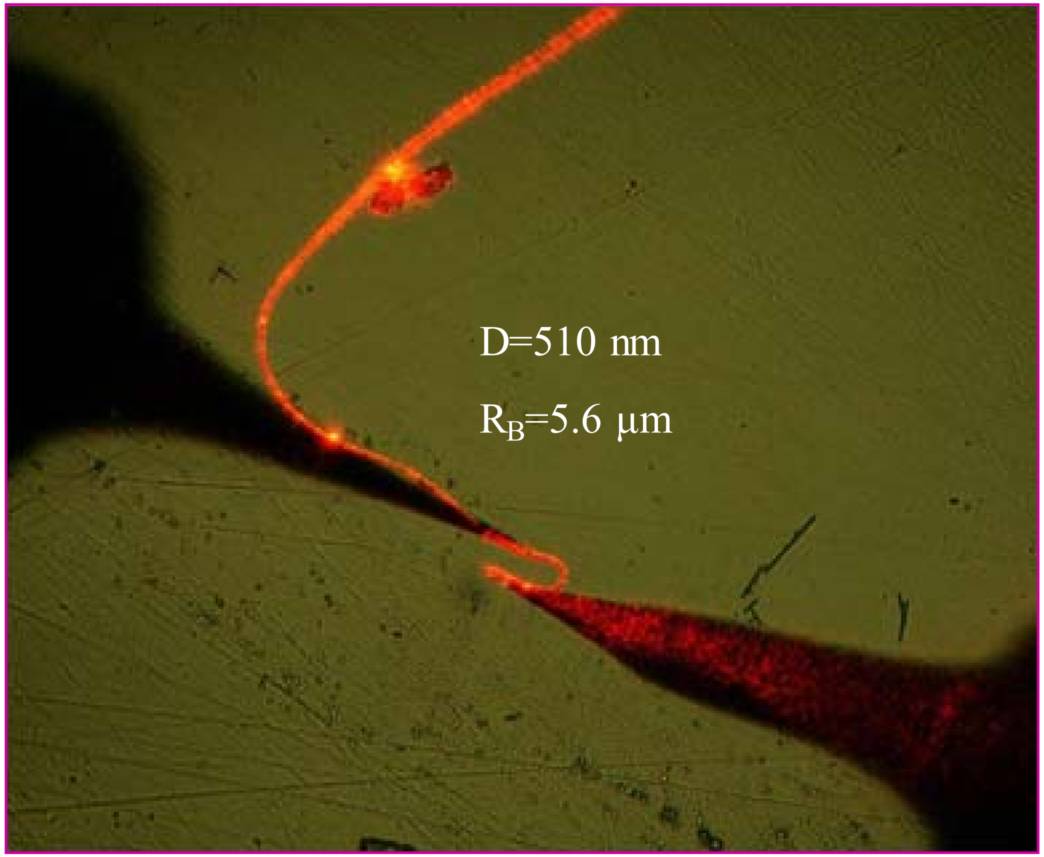


Optical microscope image of a 633-nm-wavelength light guided in 5.6-µm-radius-bend 510-nm-diameter silica fiber.

L. M. Tong et al., *Nature* **426**, 816 (2003)

Bending loss

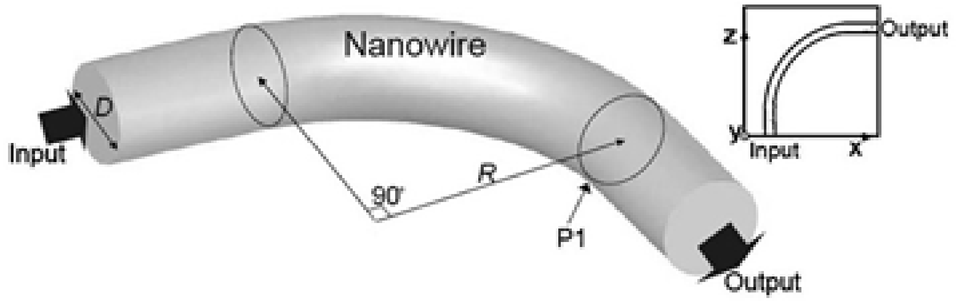


Fig. 1. Mathematical model for 3D-FDTD simulation of a circular 90° bent nanowire. Inset, topography profile of the bent nanowire.

3D-FDTD simulations

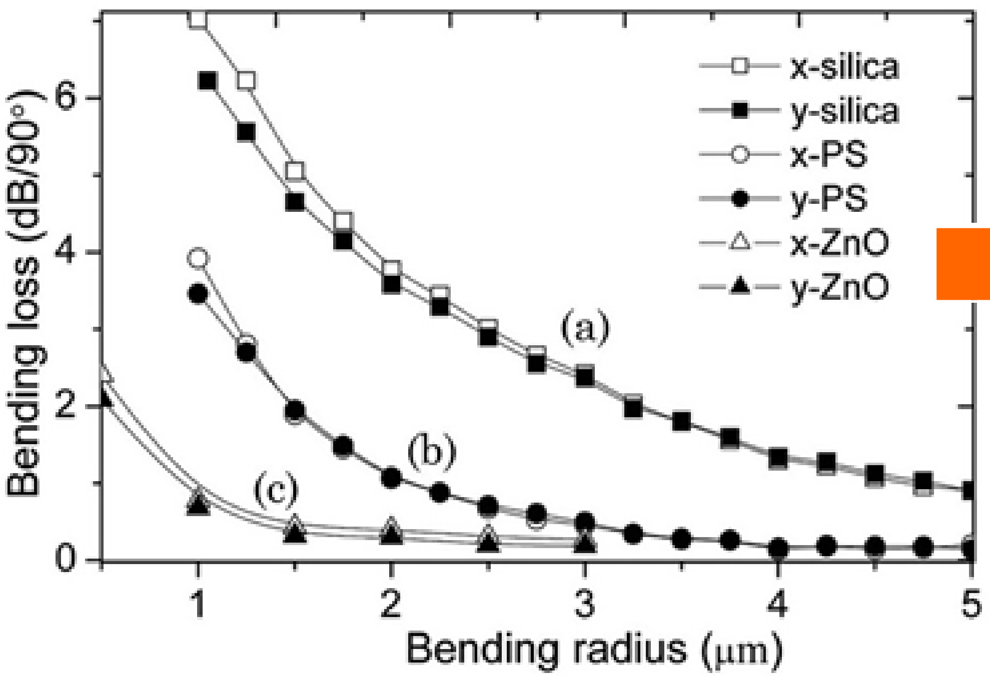


Fig. 3. Bending-radius-dependent bending losses of (a) a 350 nm diameter silica nanowire, (b) a 350 nm diameter PS nanowire, and (c) a 270 nm diameter ZnO nanowire with a 633 nm wavelength source.

PS nanofiber (n=1.59)

633-nm wavelength

2-μm bending radius

Bending loss ~ 1 dB/90°

H. K. Yu et al., *Appl. Opt.* 48, 4365 (2009)

2. Nanofiber Optics

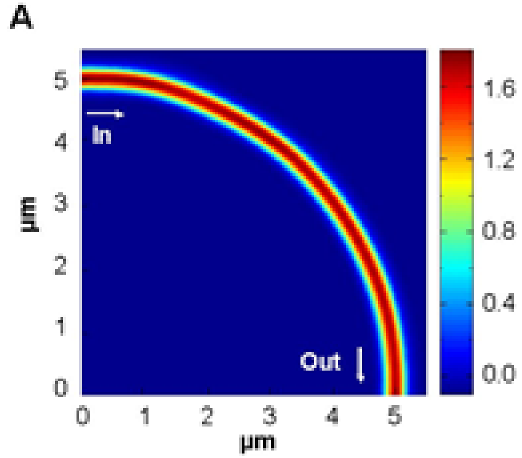
■ What's New ?

Small

2. Nanofiber Optics

■ **What's New ?**

Small **1** **High *Δn* for SM → Sharper bend with shorter optical length**



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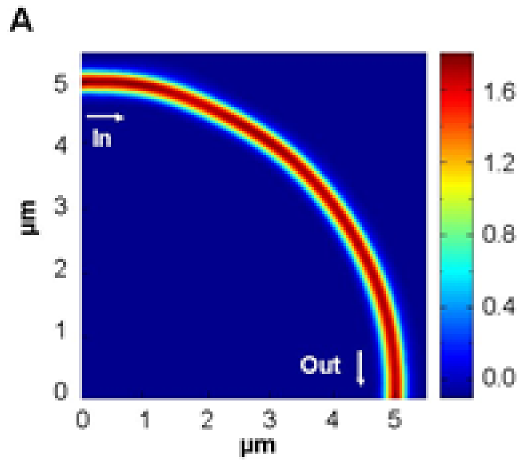


Light travels through with less time

e.g., consider the minimum allowable bending radius

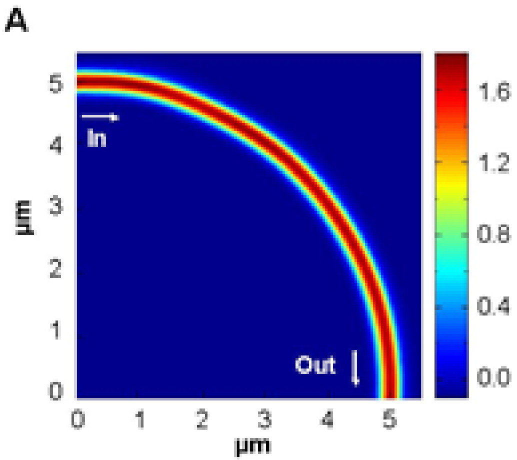
SMF ~1 cm → ~ 30 ps

Nanofiber ~ 10 µm NF → ~30 fs **1000 times faster**

2. Nanofiber Optics

■ **What's New ?**

Small **1** → **High *Δn* for SM → Sharper bend with shorter optical length**



Light travels through with less time

e.g., consider the minimum allowable bending radius
SMF ~1 cm → ~ 30 ps
Nanofiber ~ 10 µm NF → ~30 fs **1000 times faster**

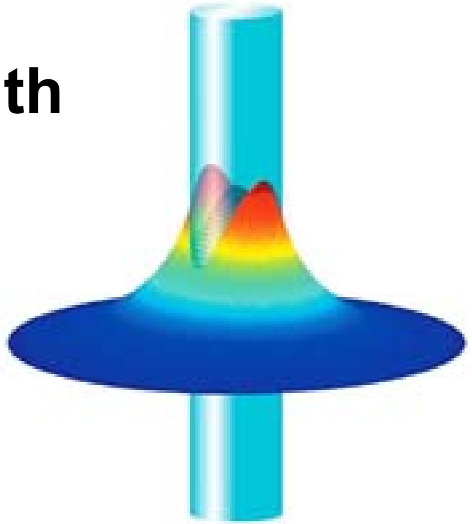
Faster & compacter interconnects

2. Nanofiber Optics

■ **What's New ?**

Small 2 **Core diameter < wavelength**

High fraction of evanescent fields
Steep field gradient



2. Nanofiber Optics

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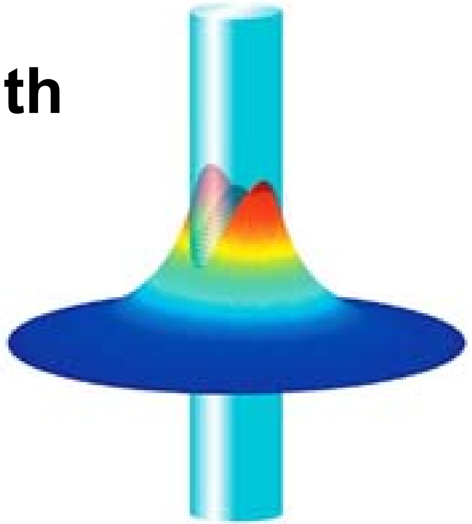


High fraction of evanescent fields
Steep field gradient

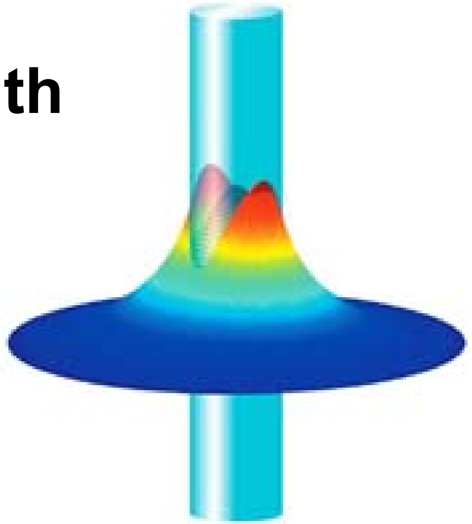
Stronger near-field interaction

Higher-sensitivity sensing
Photonic-plasmonic nanowavguide coupling

2. Nanofiber Optics

■ **What's New ?**

Small 2 **Core diameter < wavelength**



High fraction of evanescent fields
Steep field gradient

Stronger near-field interaction

Larger optical gradient force

Higher-sensitivity sensing
Photonic-plasmonic nanowavguide coupling

Atom trapping and waveguiding

2. Nanofiber Optics

■ What's New ?

Small → 3 **Smaller mode area**

e.g., **SMF** ~ 100 μm^2
Nanofiber ~ 1 μm^2

2. Nanofiber Optics

■ What's New ?

Small → 3 **Smaller mode area**

e.g., SMF ~ 100 μm^2
Nanofiber ~ 1 μm^2

Thinner Beam

Higher-sensitivity optical sensing

2. Nanofiber Optics

■ **What's New ?**

Small ➌ **Smaller mode area**

e.g., SMF ~ 100 μm^2
Nanofiber ~ 1 μm^2

Thinner Beam

Higher-sensitivity optical sensing

Higher effective nonlinearity

Lower-threshold optical nonlinear effects

2. Nanofiber Optics

■ **What's New ?**

Small → 4 **Tight confinement with small mode area**

Modify vacuum states around the nanofiber

2. Nanofiber Optics

■ What's New ?

Small 4 **Tight confinement with small mode area**

Modify vacuum states around the nanofiber

Modify spontaneous
rate of an atom nearby

2. Nanofiber Optics

■ What's New ?

Small 4 **Tight confinement with small mode area**

Modify vacuum states around the nanofiber

Modify spontaneous rate of an atom nearby

Couple distant atoms through the fiber

2. Nanofiber Optics

■ **What's New ?**

Small ⇒ 5 **Extremely light in mass**

⇓

e.g., Mass of a 200-nm-diameter 10-um-length nanofiber is
~ 10^{-15} kg / ~10 pN (in weight)
comparable to the pressure of light with power of 10 mW

2. Nanofiber Optics

■ **What's New ?**

Small **5** **Extremely light in mass**

e.g., Mass of a 200-nm-diameter 10-um-length nanofiber is
~ 10^{-15} kg / ~10 pN (in weight)
comparable to the pressure of light with power of 10 mW

Feel the momentum of light guided through

2. Nanofiber Optics

■ What's New ?

Small ⇨ (5) **Extremely light in mass**

⇩

e.g., Mass of a 200-nm-diameter 10-um-length nanofiber is
~ 10^{-15} kg / ~10 pN (in weight)
comparable to the pressure of light with power of 10 mW

⇩

Feel the momentum of light guided through

⇩

Photon-momentum-induced effect

2. Nanofiber Optics

■ What's New ?

Small ⇨ **Extremely light in mass**

⇩

e.g., Mass of a 200-nm-diameter 10-um-length nanofiber is
~ 10^{-15} kg / ~10 pN (in weight)
comparable to the pressure of light with power of 10 mW

⇩

Feel the momentum of light guided through

⇩ Photon-momentum-induced effect

⇩ Fundamental research in photonics

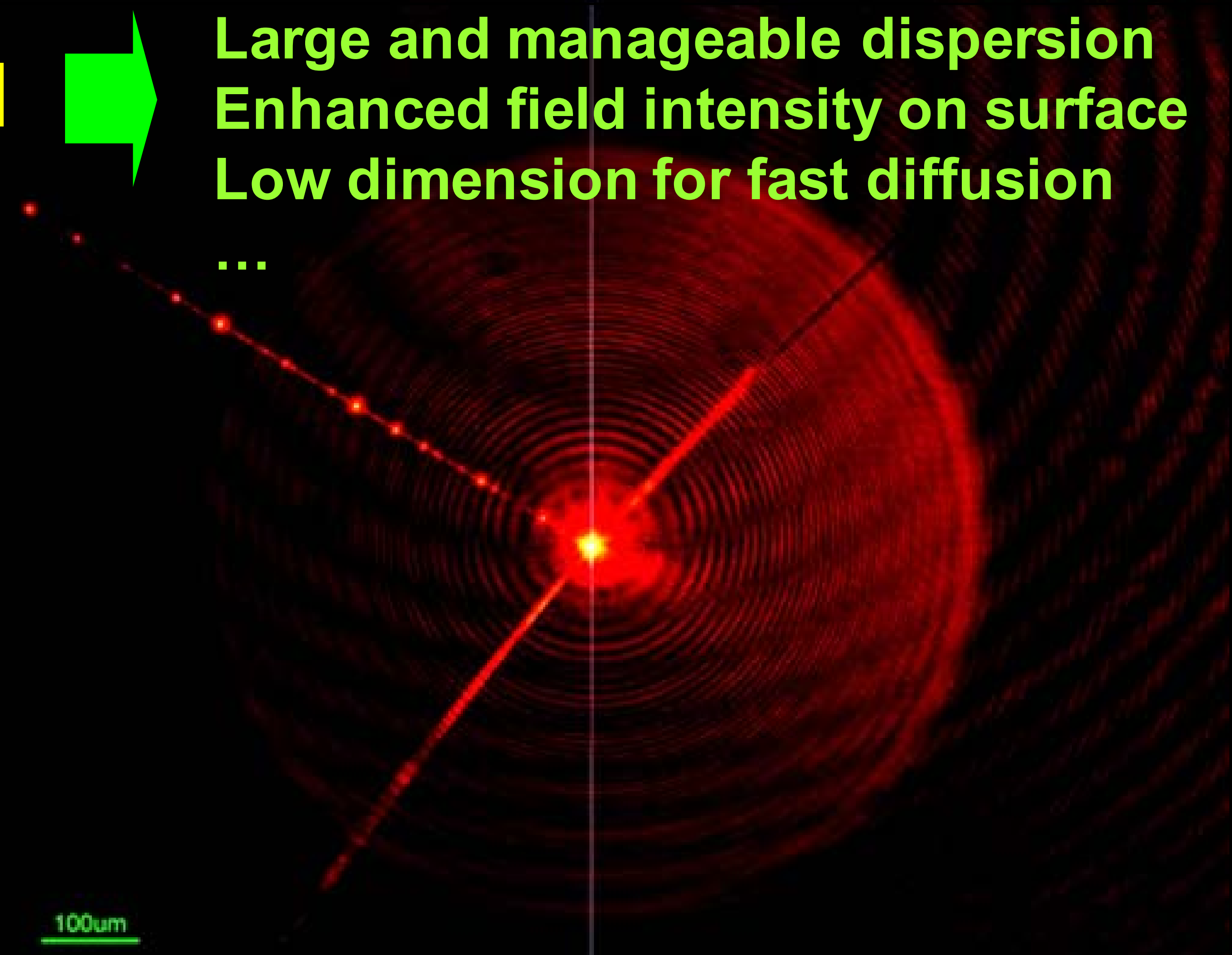
2. Nanofiber Optics

- **What's New ?**

Small ➡

More :

Large and manageable dispersion
Enhanced field intensity on surface
Low dimension for fast diffusion
…



L. M. Tong et al., *Nature* **426**, 816 (2003)

2. Nanofiber Optics

■ **What's New ?**

Small ➡

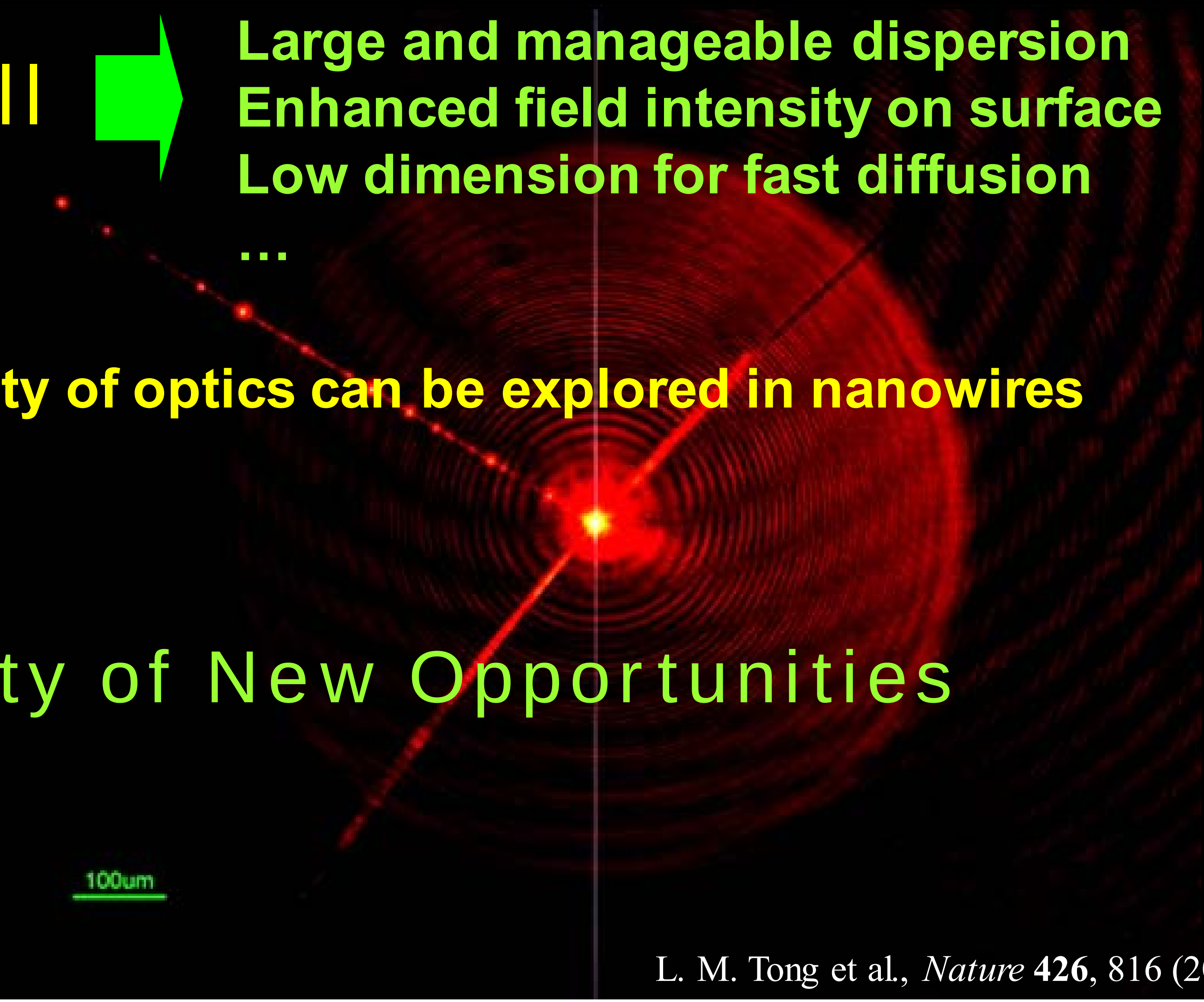
More :

Large and manageable dispersion
Enhanced field intensity on surface
Low dimension for fast diffusion
…

Plenty of optics can be explored in nanowires

⬇

Plenty of New Opportunities



L. M. Tong et al., *Nature* **426**, 816 (2003)

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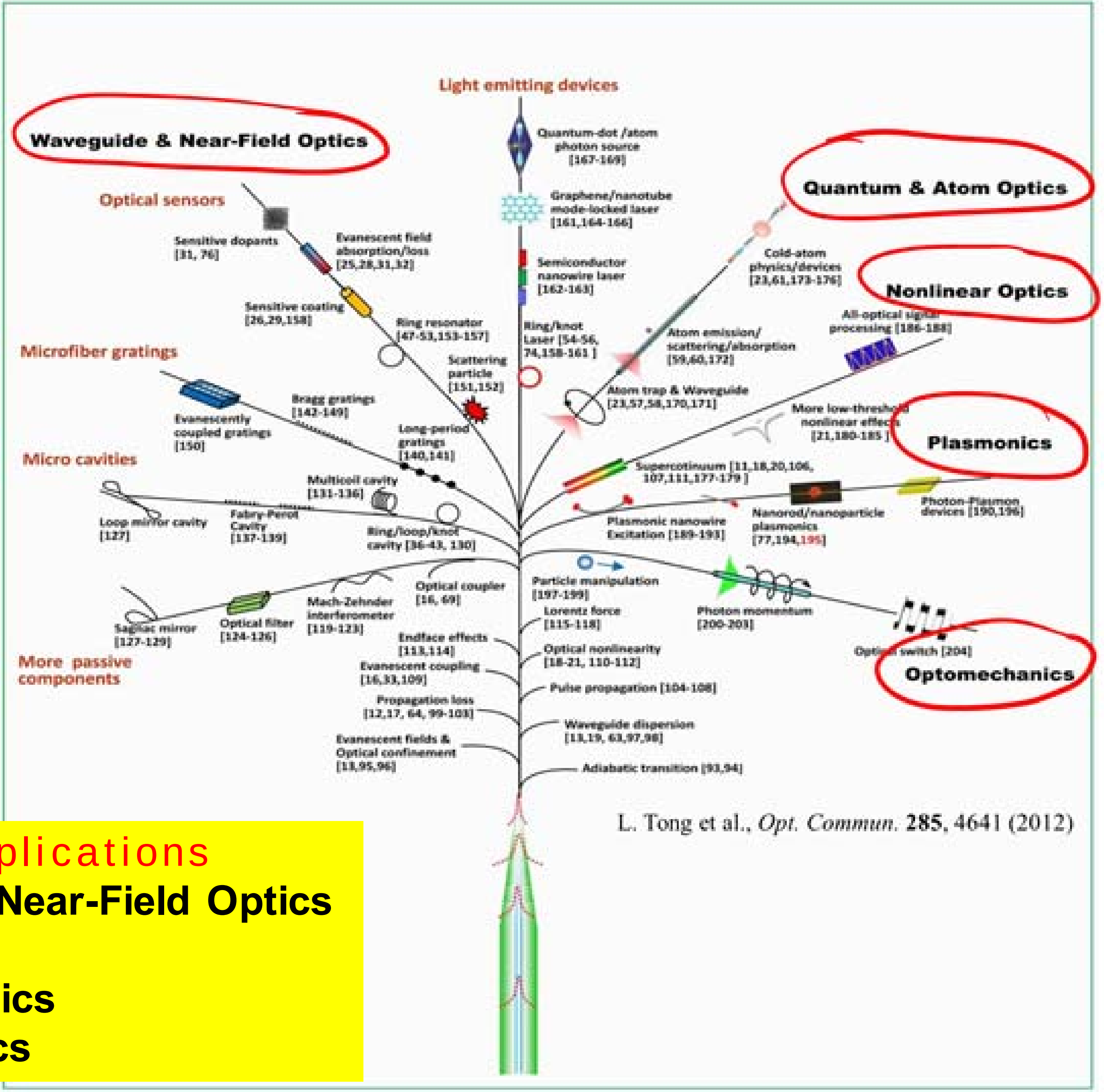


L. Tong et al., *Opt. Commun.* **285**, 4641 (2012)

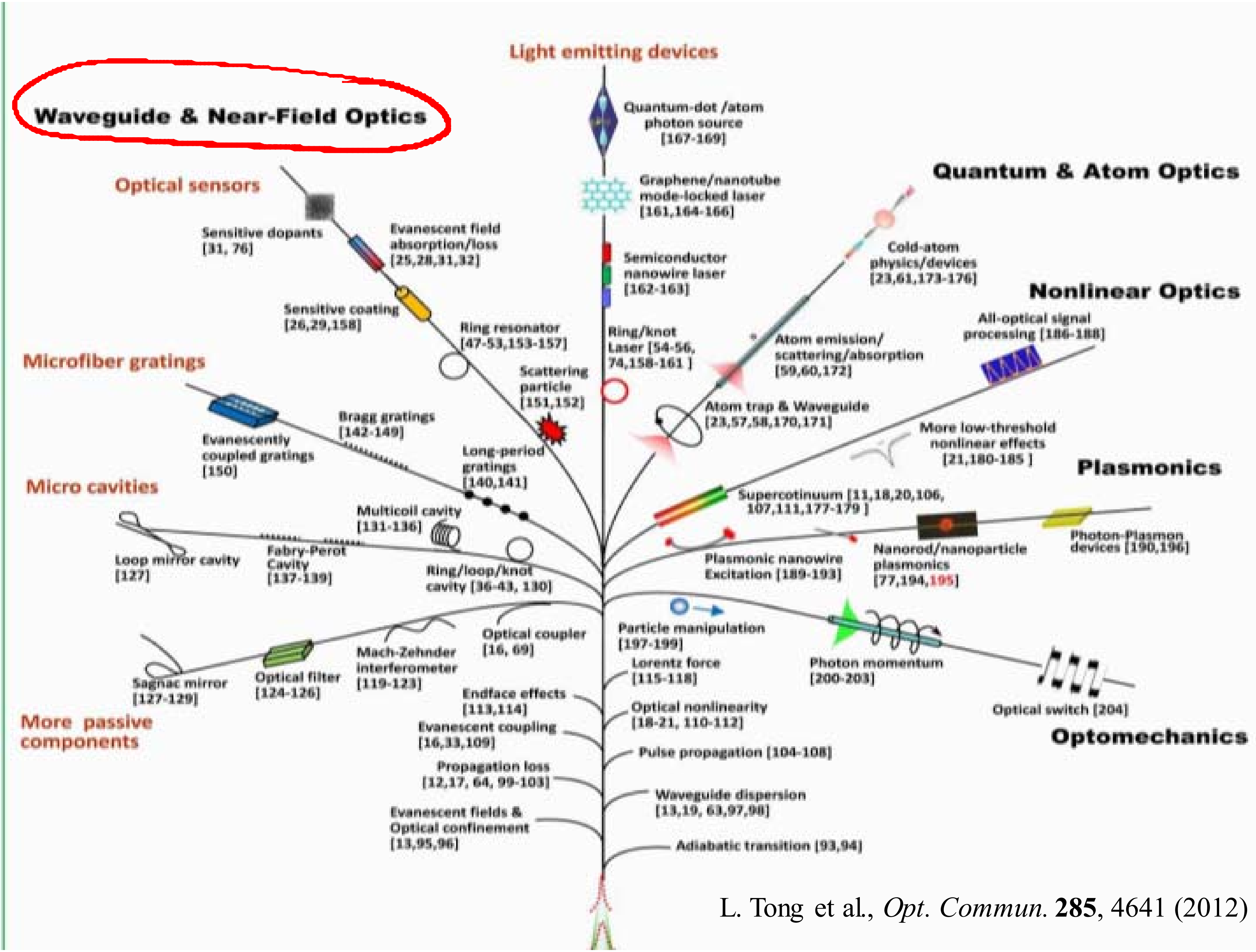
3. Photonic Applications

(1) Waveguide & Near-Field Optics

(2) Plasmonics

(3) Nonlinear Optics

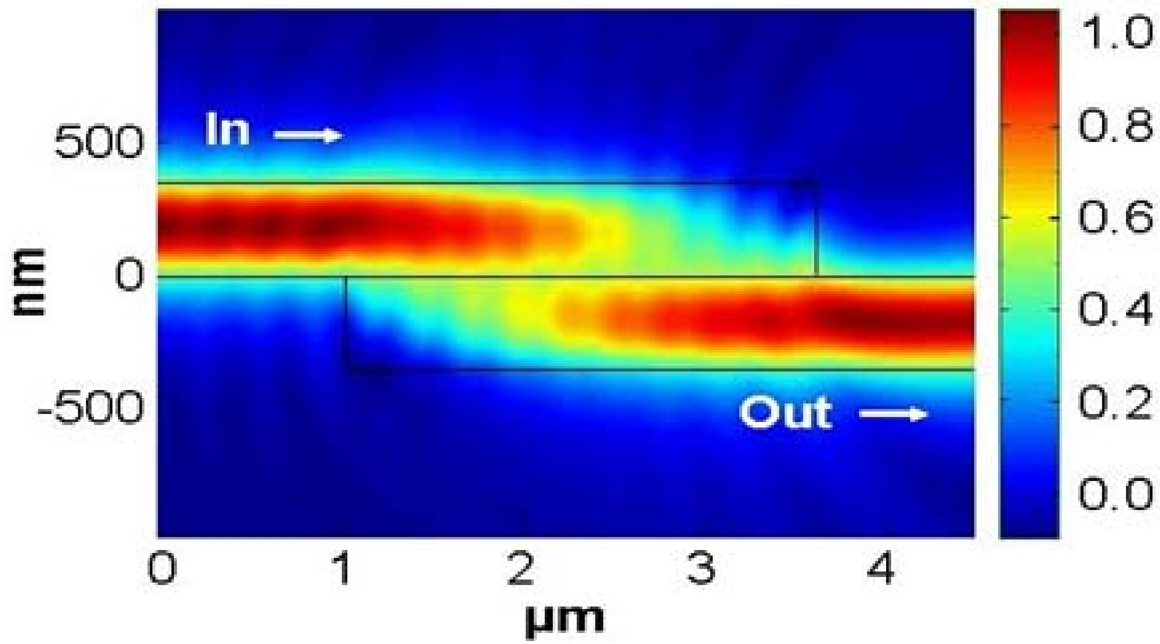
(4) Optomechanics



L. Tong et al., *Opt. Commun.* **285**, 4641 (2012)

Near-field coupling between two nanofibers

High fraction of evanescent field → Strong near-field interaction



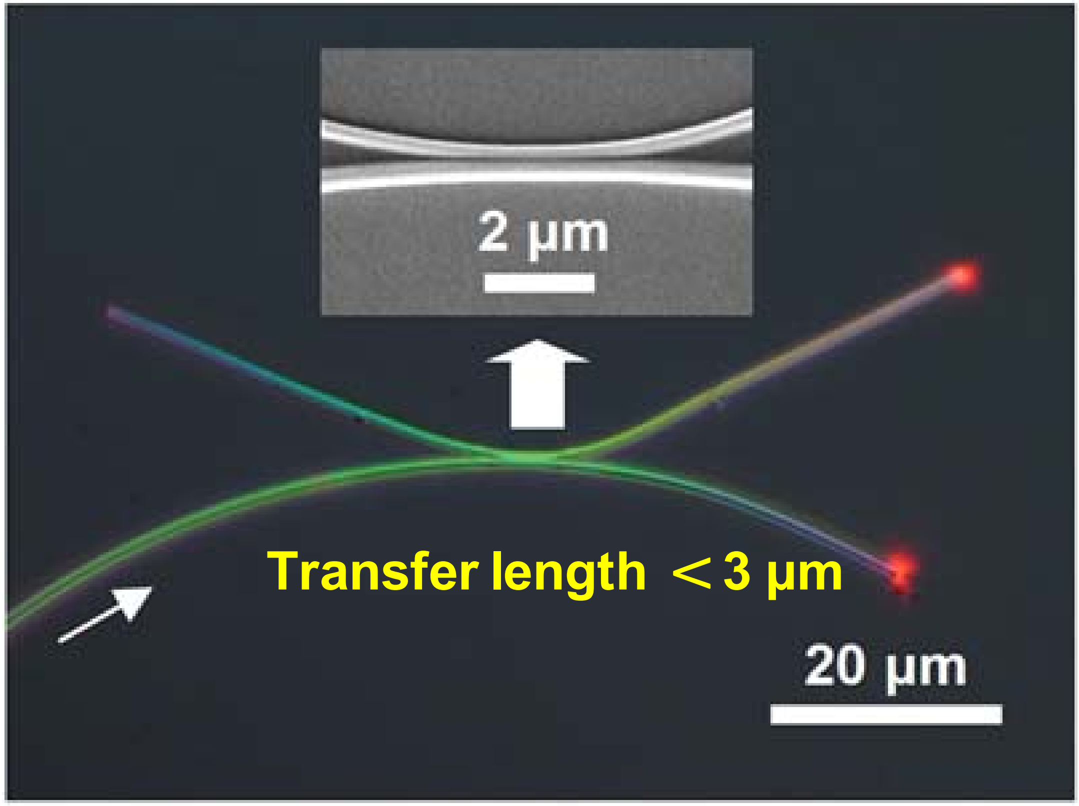
3D-FDTD simulation of two closely contacted silica microfibers
(D1=D2=350 nm)

L. M. Tong et al., *Nano Lett.* **5**, 259 (2005); K. J. Huang et al., *Appl. Opt.* **46**,1249 (2007)

Near-field coupling between two nanofibers

- Micro-coupler

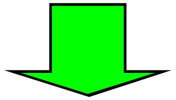
Micro-coupler assembled with two tellurite nanofibers on a silica wafer



Fiber diameter： 350/450 nm

Working wavelength: 633 nm

Overlapping ＜3 μm



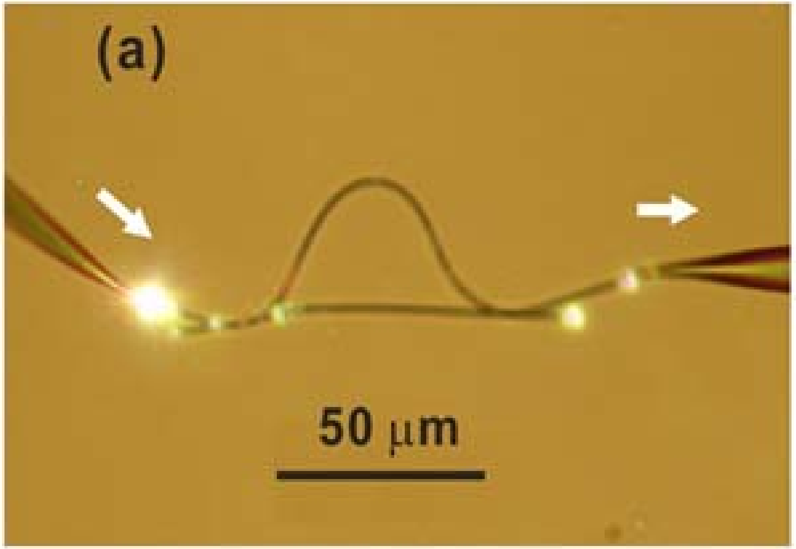
3-dB splitter

L. M. Tong et al., *Opt. Express* 14, 82 (2006)

Near-field coupling between two nanofibers

- Tiny Mach-Zehnder interferometer

When two micro-couplers are assembled in



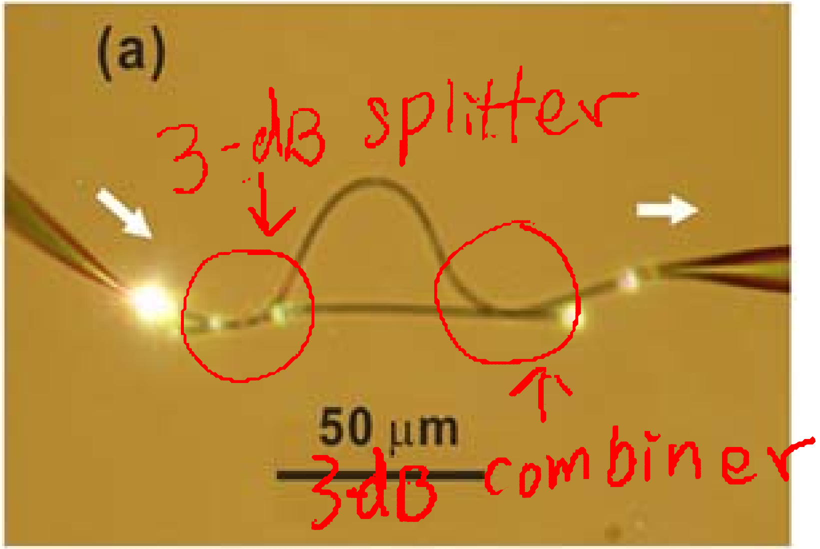
MZI assembled with two 480-nm-diameter tellurite nanofibers on a MgF_2 substrate

Y. H. Li et al., *Opt. Lett.* **33**, 303 (2008)

Near-field coupling between two nanofibers

- Tiny Mach-Zehnder interferometer

When two micro-couplers are assembled in



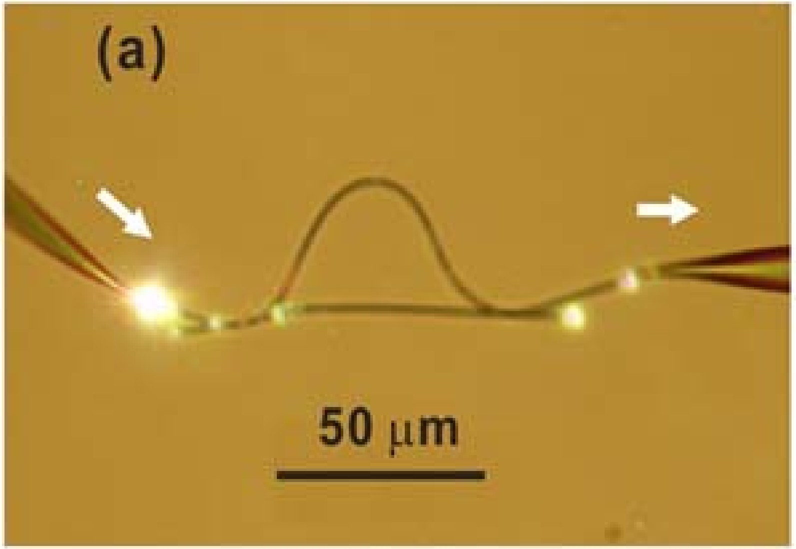
MZI assembled with two 480-nm-diameter tellurite nanofibers on a MgF_2 substrate

Y. H. Li et al., *Opt. Lett.* **33**, 303 (2008)

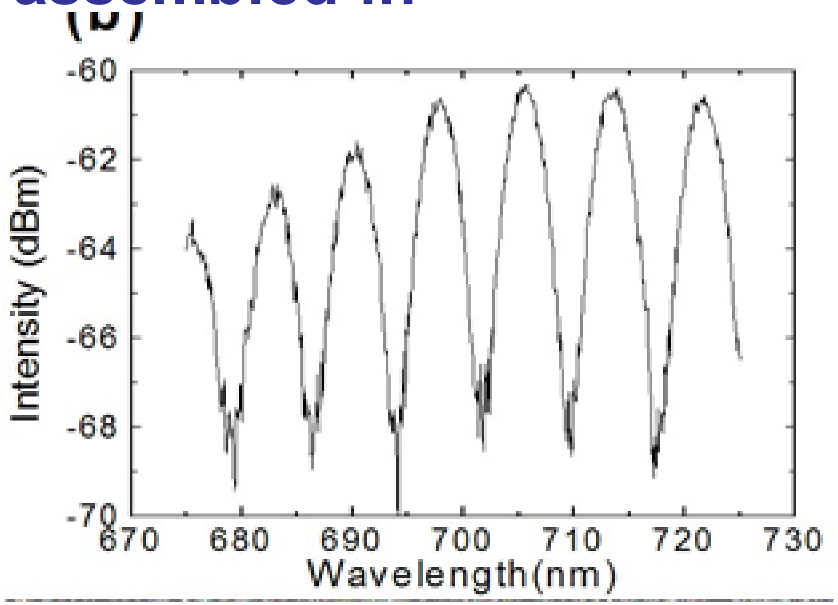
Near-field coupling between two nanofibers

- Tiny Mach-Zehnder interferometer

When two micro-couplers are assembled in



MZI assembled with two 480-nm-diameter tellurite nanofibers on a MgF_2 substrate



Transmission spectrum of the MZI

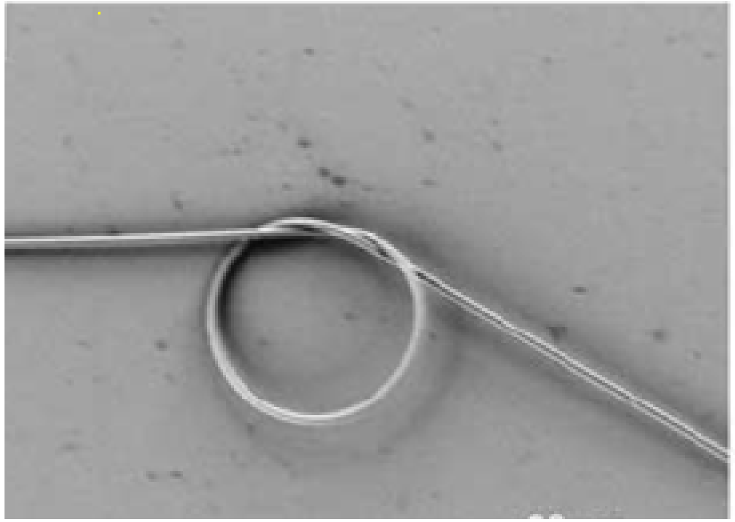
Small footprint and high flexibility

Y. H. Li et al., *Opt. Lett.* **33**, 303 (2008)

Near-field coupling between two nanofibers

- Micro resonator

Tie a microfiber into a loop or knot → ring resonator

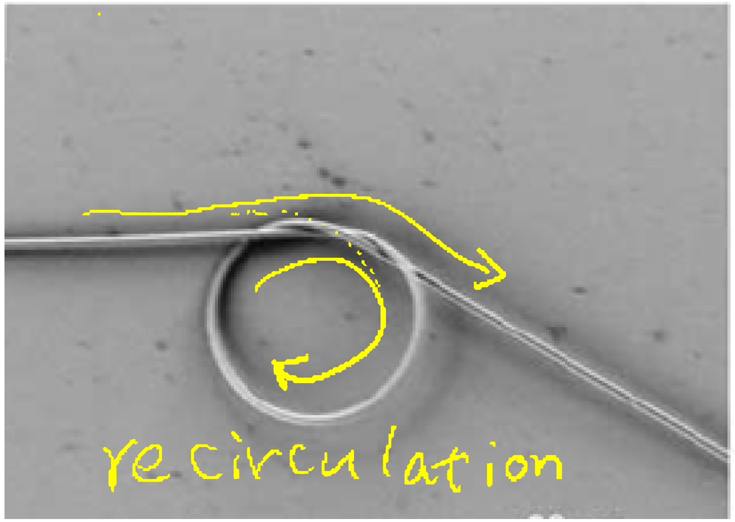


X. S. Jiang et al., *Appl. Phys. Lett.* **88**, 223501(2006)

Near-field coupling between two nanofibers

- Micro resonator

Tie a microfiber into a loop or knot → ring resonator



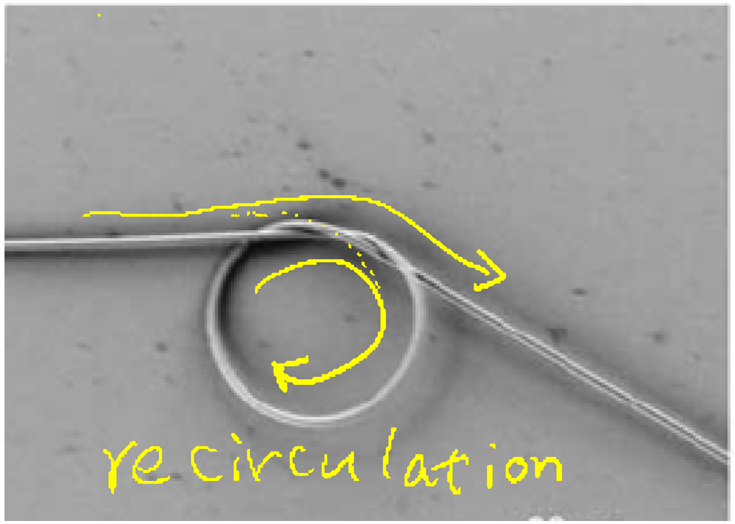
X. S. Jiang et al., *Appl. Phys. Lett.* **88**, 223501(2006)

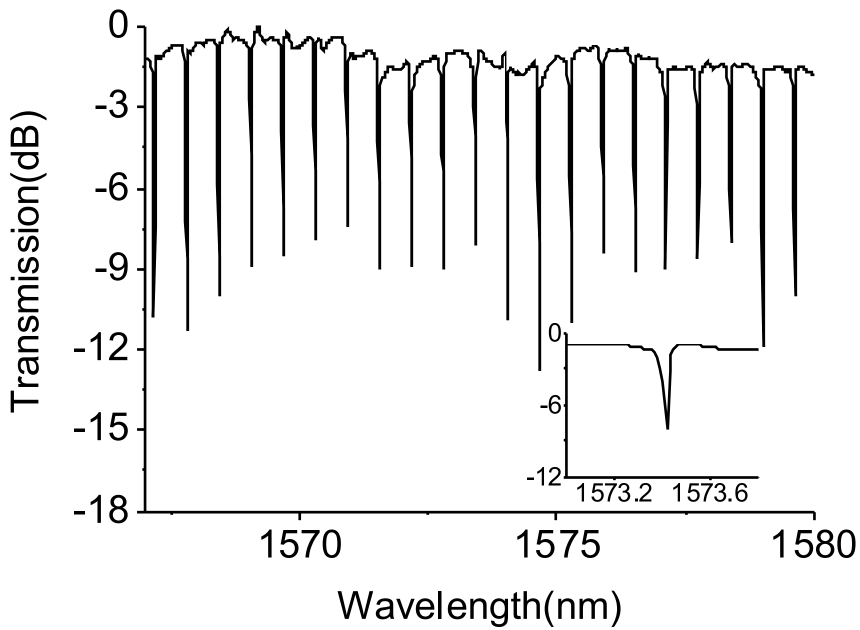
(1) Waveguide & Near-field Optics

Near-field coupling between two nanofibers

- Micro resonator

Tie a microfiber into a loop or knot → ring resonator





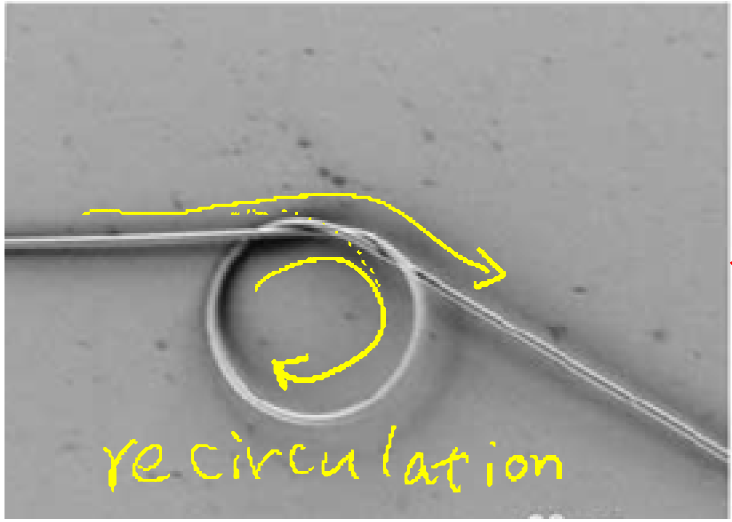
X. S. Jiang et al., *Appl. Phys. Lett.* **88**, 223501(2006)

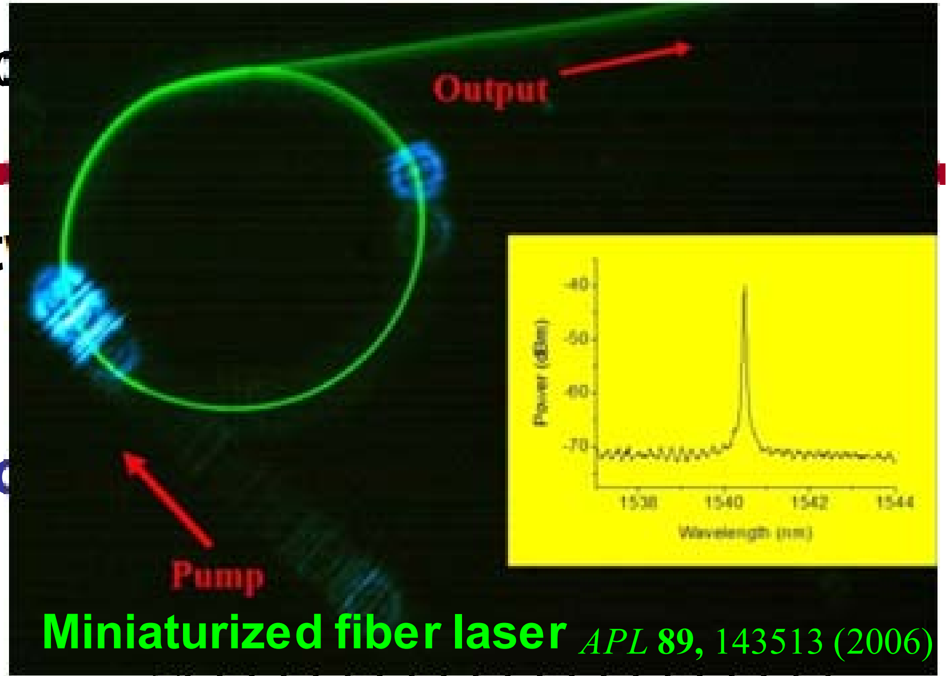
(1) Waveguide & Near-field

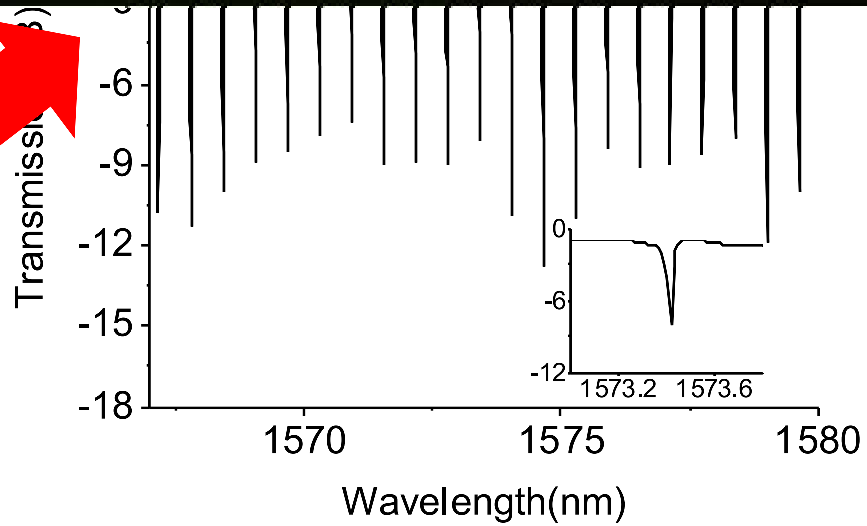
Near-field coupling between t

- Micro resonator

Tie a microfiber into a loop c







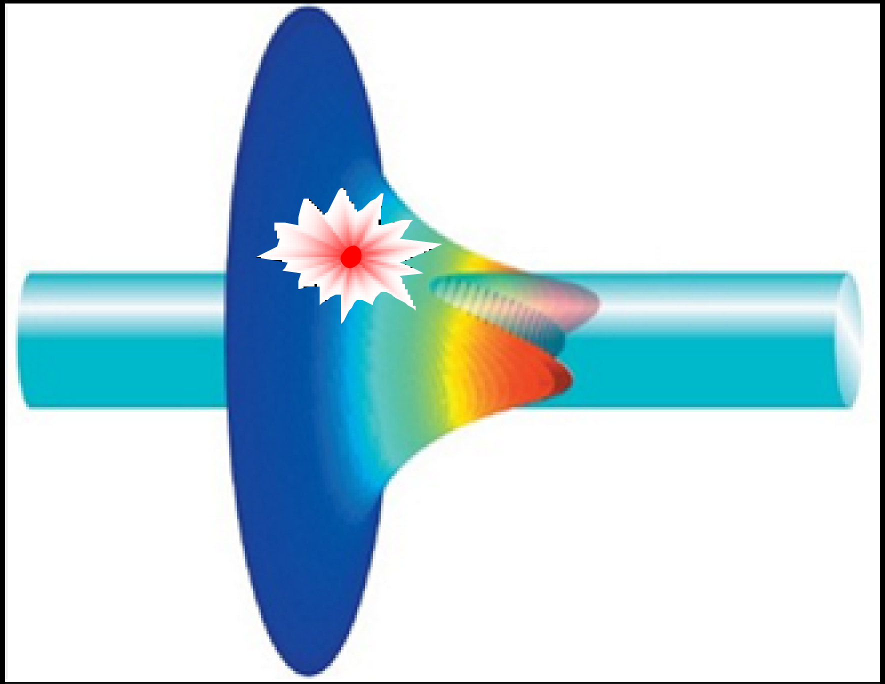
X. S. Jiang et al., *Appl. Phys. Lett.* **88**, 223501(2006)

X. S. Jiang et al., *Appl. Phys. Lett.* **89**, 143513(2006)

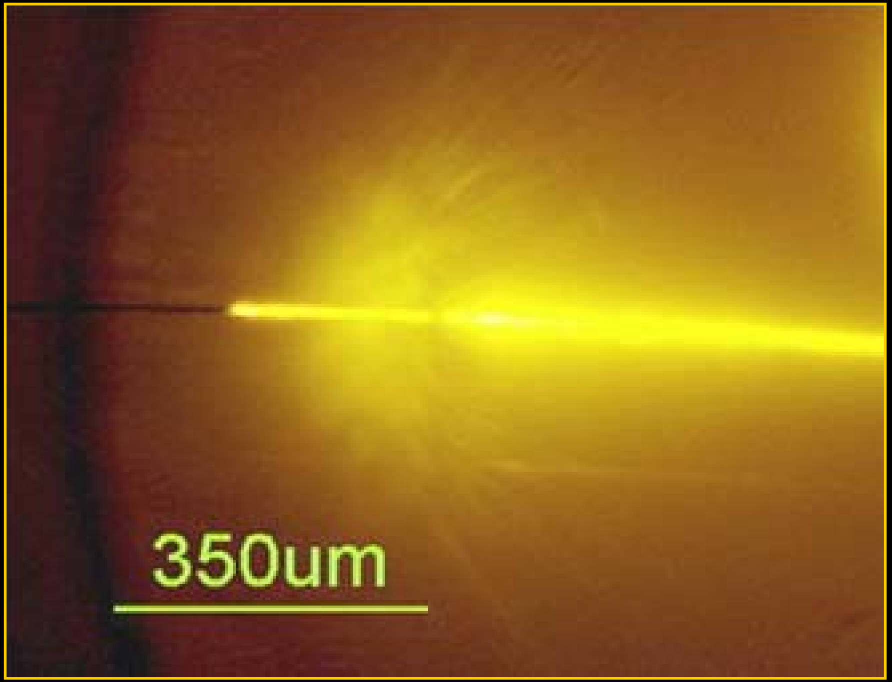
(1) Waveguide & Near-field Optics

- Micro Lasers : **Microfiber dye laser**

(1) silica microfiber – laser dye molecules



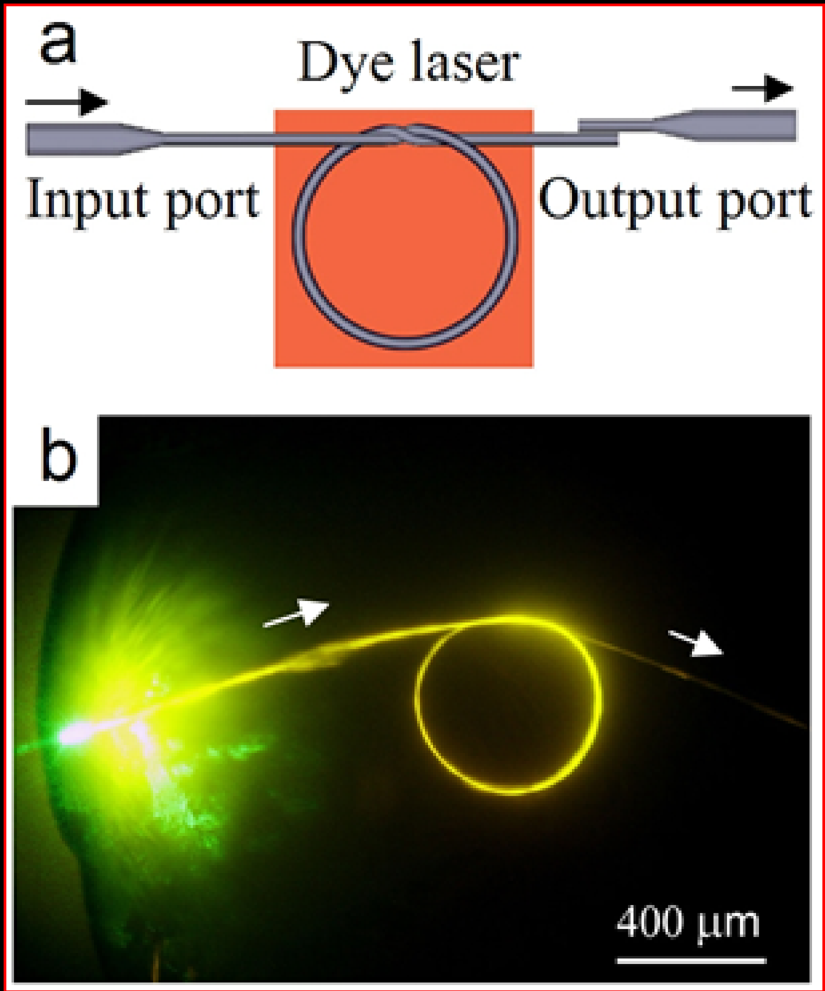
Near-field excitation of dye molecules



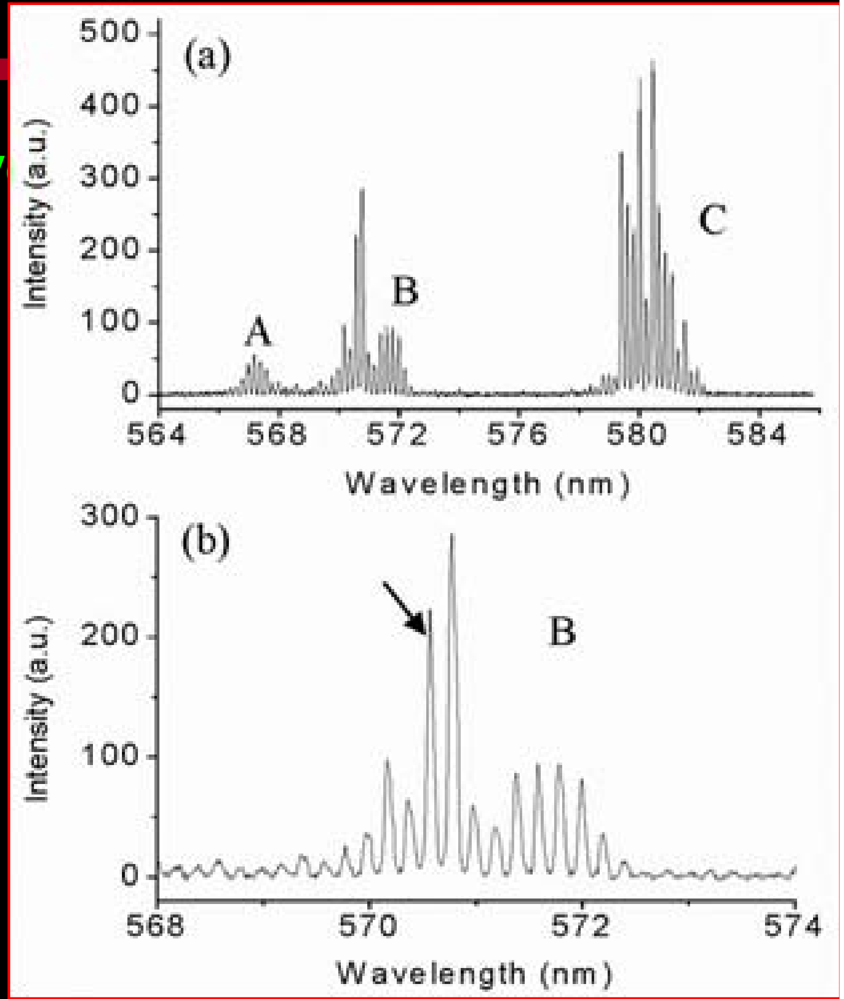
R6G dye solution excited by a 532-nm-wavelength light guided along a 3-um-diameter silica microfiber

(1) Waveguide & Near-field Optics

- Micro Lasers : **Microfiber dy**



Silica microfiber knot dye laser:
(R6G) solution: 5 mM/l, Pump wavelength: 532 nm

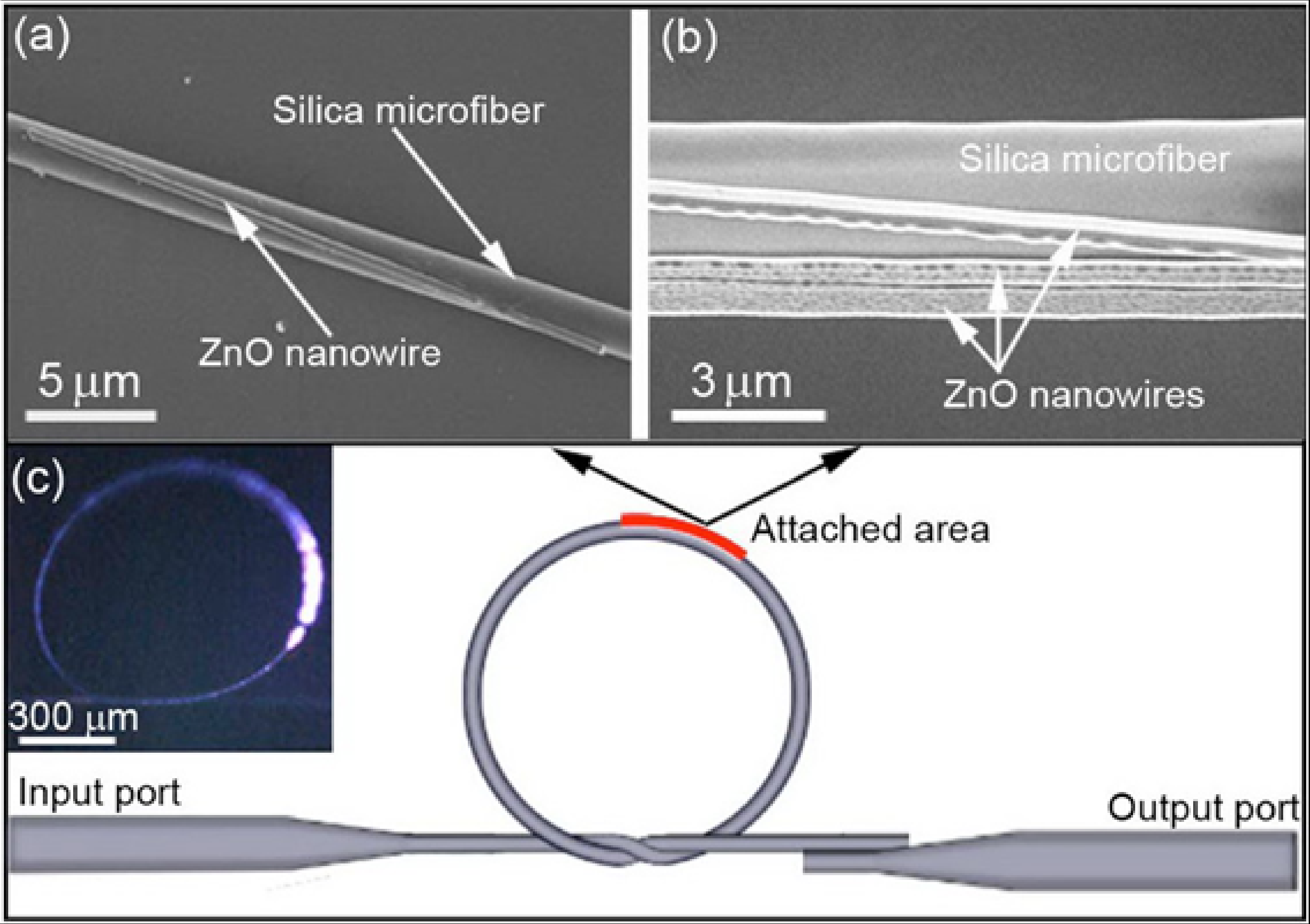


Laser emission from a 350-μm-diameter microfiber knot dye laser (fiber diameter ~ 3.9 μm) . Threshold 10 μJ/pulse, Q 10,000

X. Jiang et al., *Appl. Phys. Lett.* **90,** 233501 (2007)

(1) Waveguide & Near-field Optics

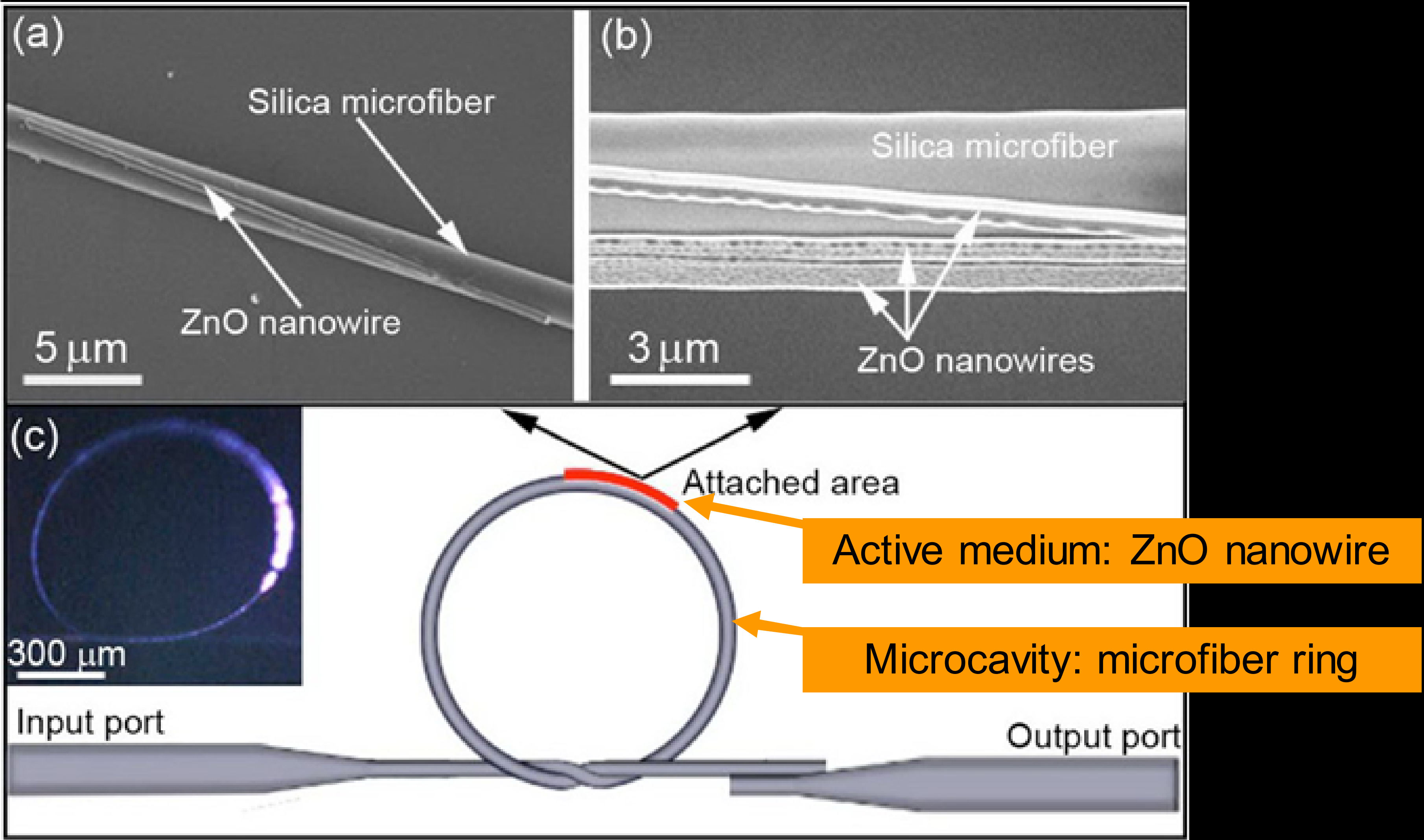
• Micro Lasers : **Microfiber–ZnO-nanowires laser**



Q. Yang et al., *Appl. Phys. Lett.* **94**, 101108 (2009)

(1) Waveguide & Near-field Optics

- Micro Lasers : **Microfiber–ZnO-nanowires laser**



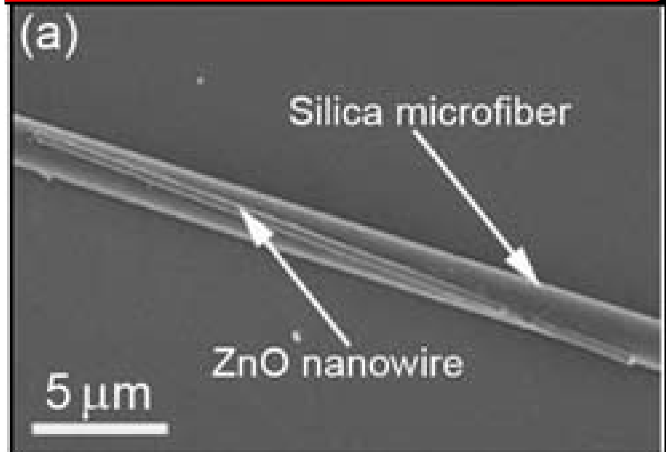
Q. Yang et al., *Appl. Phys. Lett.* **94**, 101108 (2009)

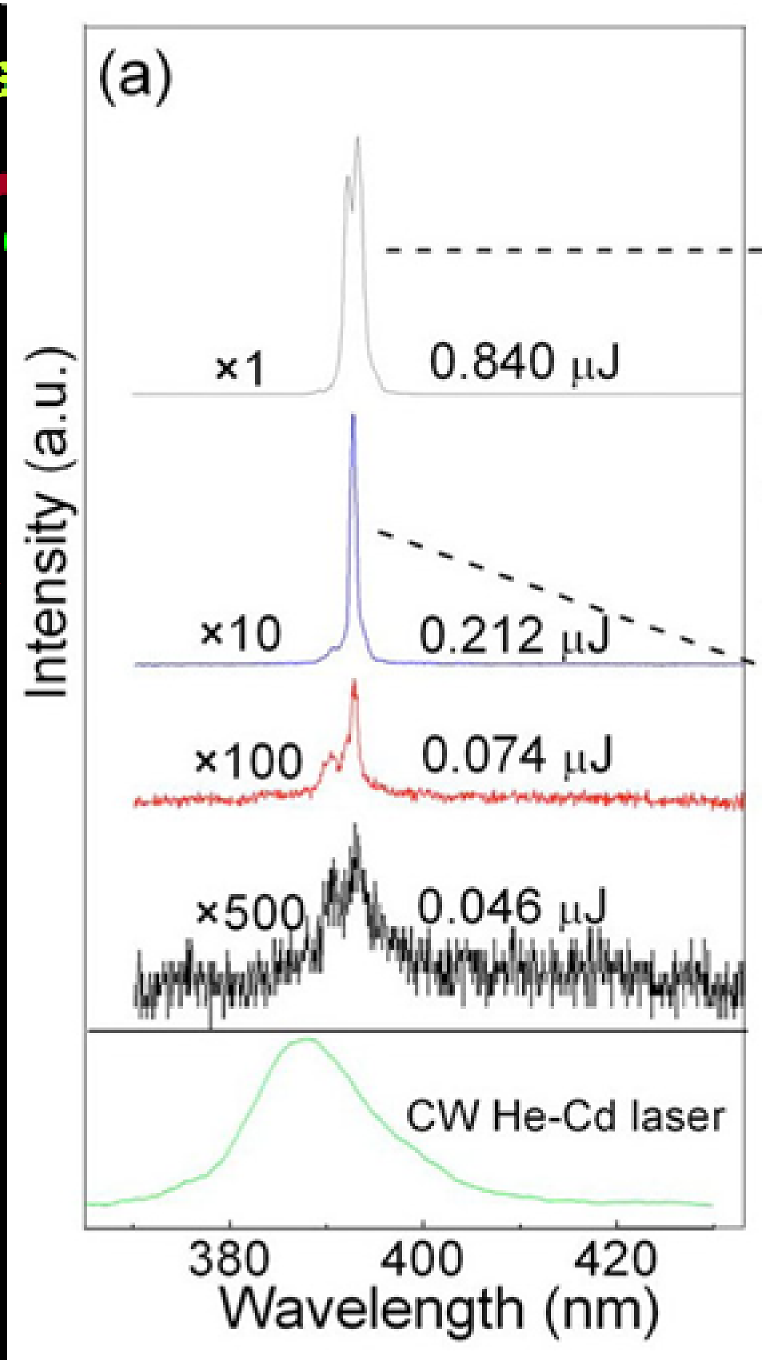
(1) Near-field Optics

- Micro Lasers : **Mi** ... **laser**

Pump pulses:
355 nm, 6 ns, 10 Hz

Hybrid nanowire lasers





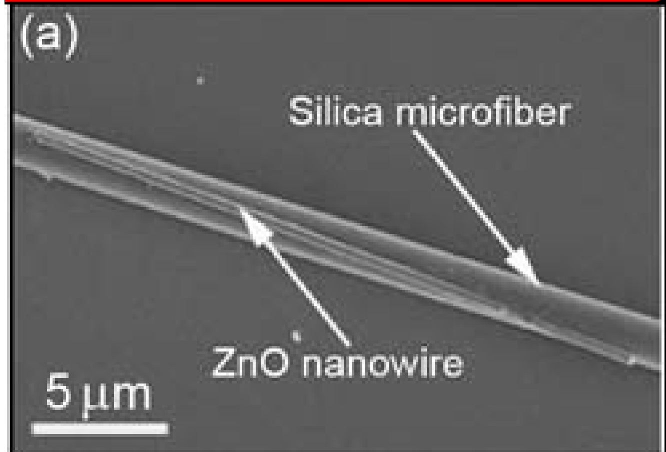
Q. Yang et al., *Appl. Phys. Lett.* **94**, 101108 (2009)

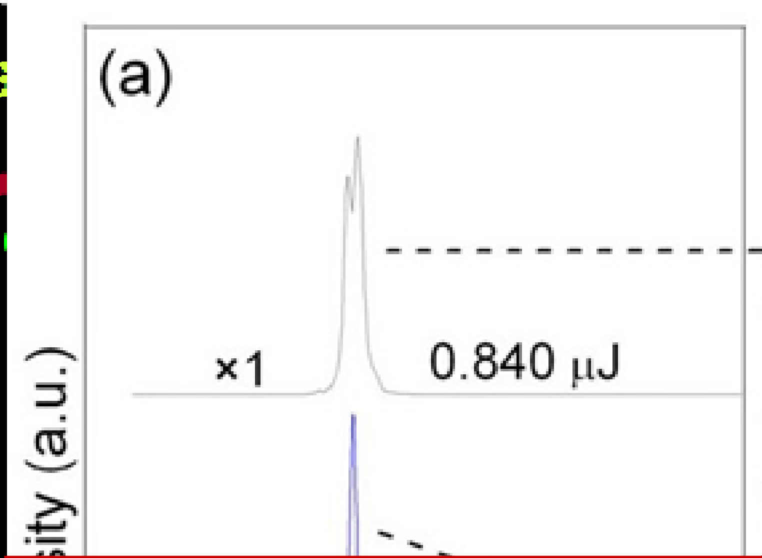
(1) Near-field Optics

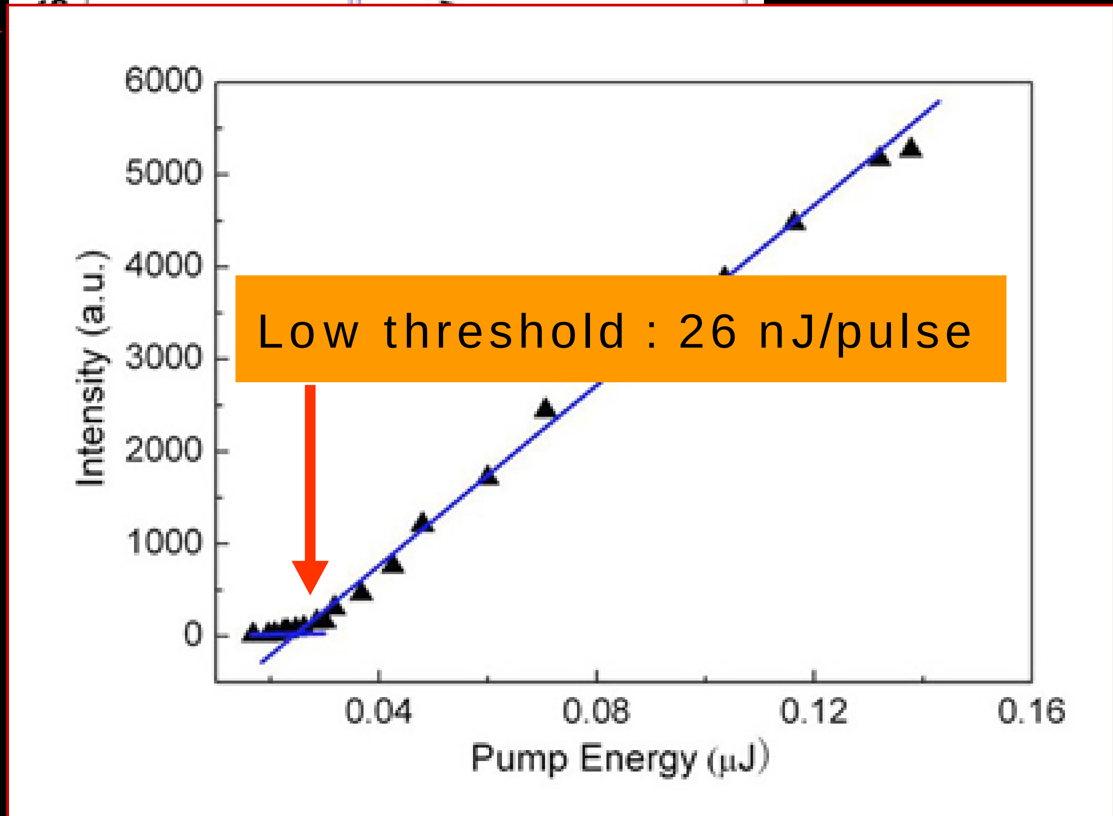
- Micro Lasers : **Mi laser**

Pump pulses:
355 nm, 6 ns, 10 Hz

Hybrid nanowire lasers





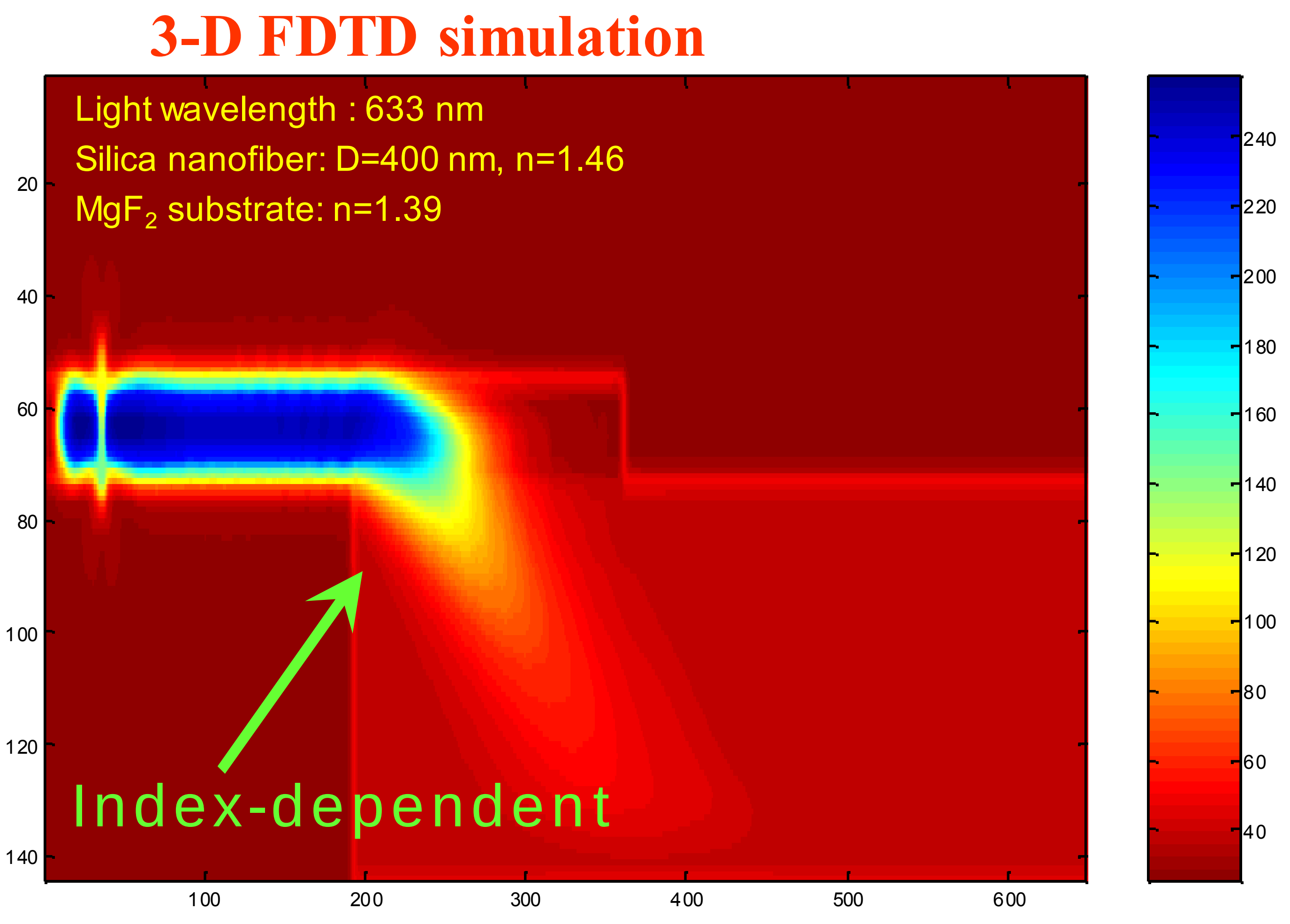


Low threshold : 26 nJ/pulse

Q. Yang et al., *Appl. Phys. Lett.* **94**, 101108 (2009)

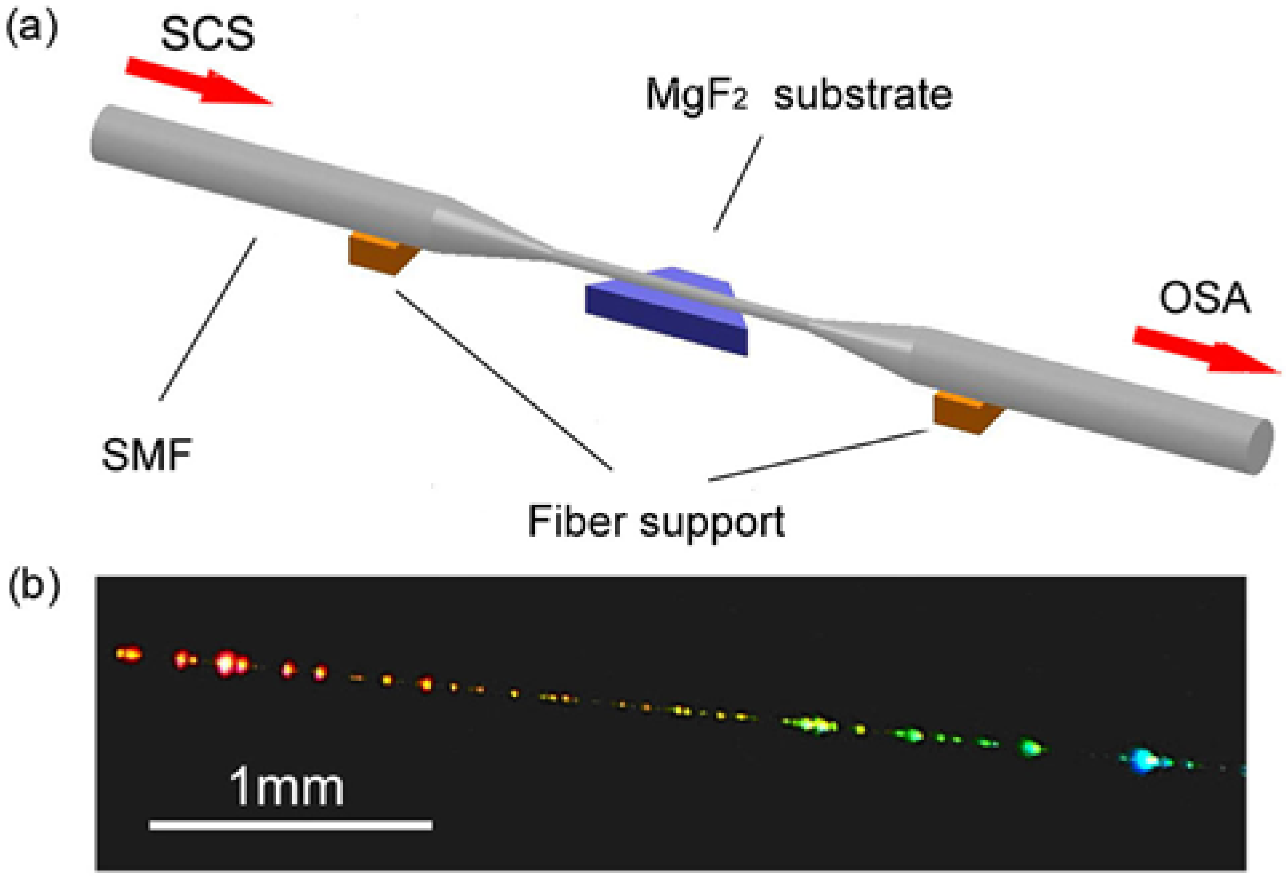
(1) Waveguide & Near-field Optics

- Substrate induced leakage



(1) Waveguide & Near-field Optics

- Micro filters
  silica micro/nanofiber – MgF_2 substrate



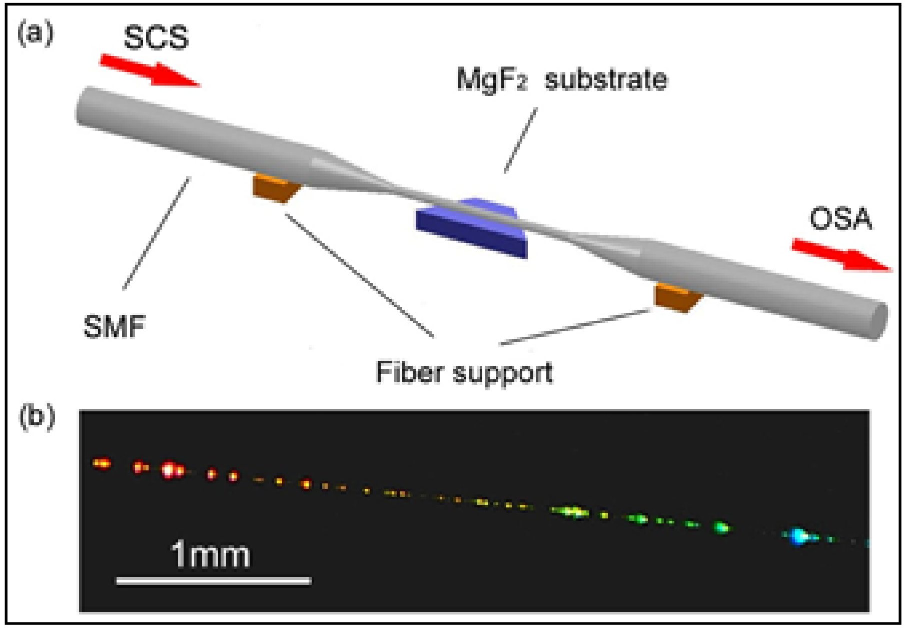
wavelength-dependent leakage

Y. Chen et al., *Opt. Lett.* **33**, 2565 (2008)

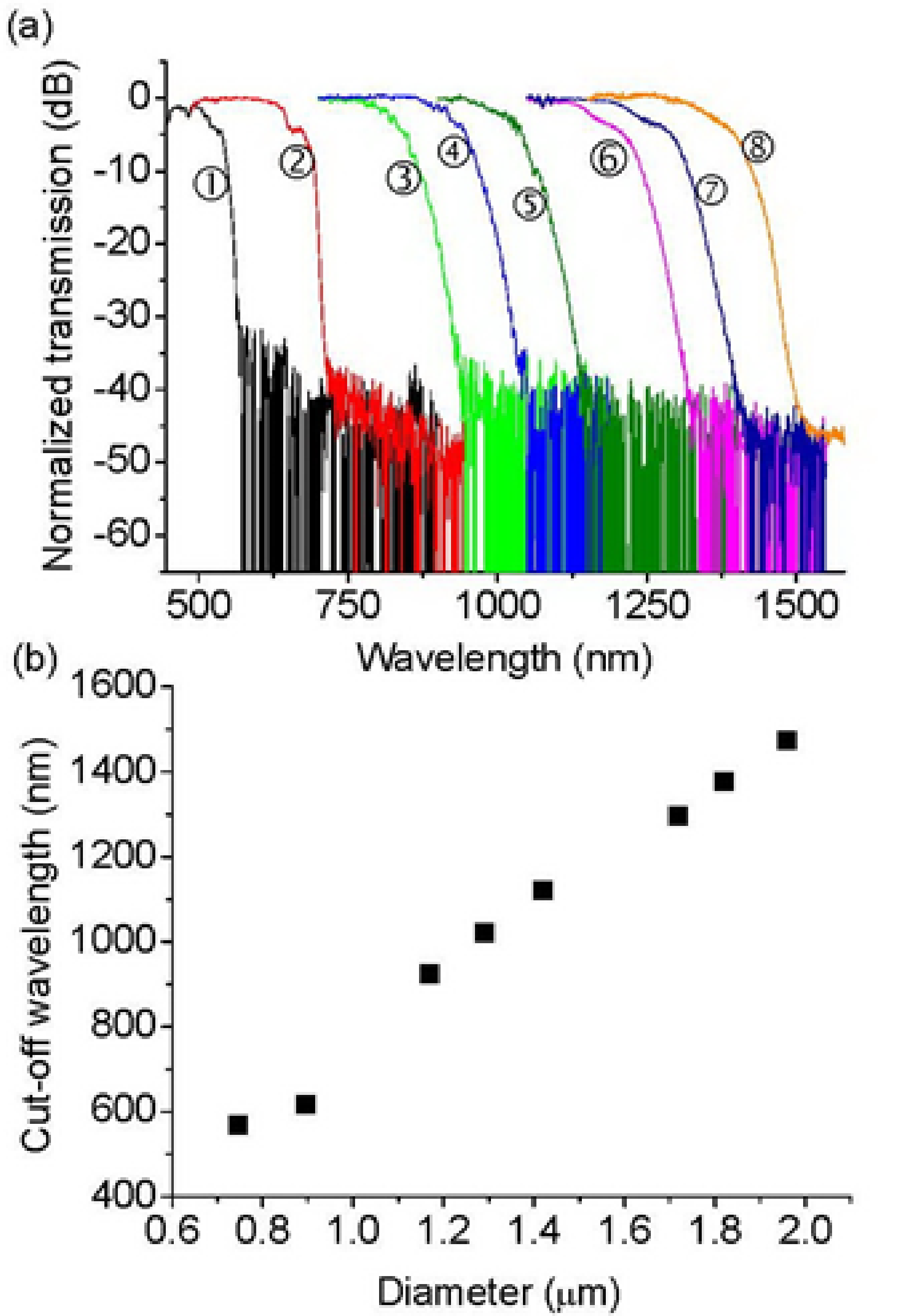
(1) Waveguide & Near-fiel

- Micro filters

  Short-pass filter



(a) Normalized transmission spectra with microfiber diameters of ①0.75, ②0.88, ③1.17, ④1.29, ⑤1.42, ⑥1.72, ⑦1.82, ⑧1.96 μm. The interaction length is 1.1 mm. (b) Cutoff wavelength versus microfiber diameter.



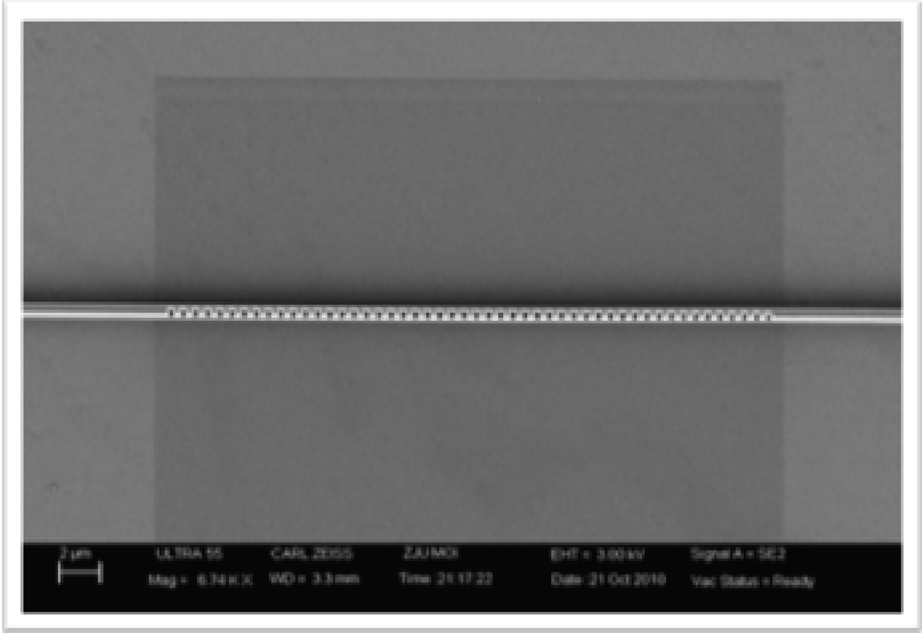
Y. Chen et al., *Opt. Lett.* **33**, 2565 (2008)

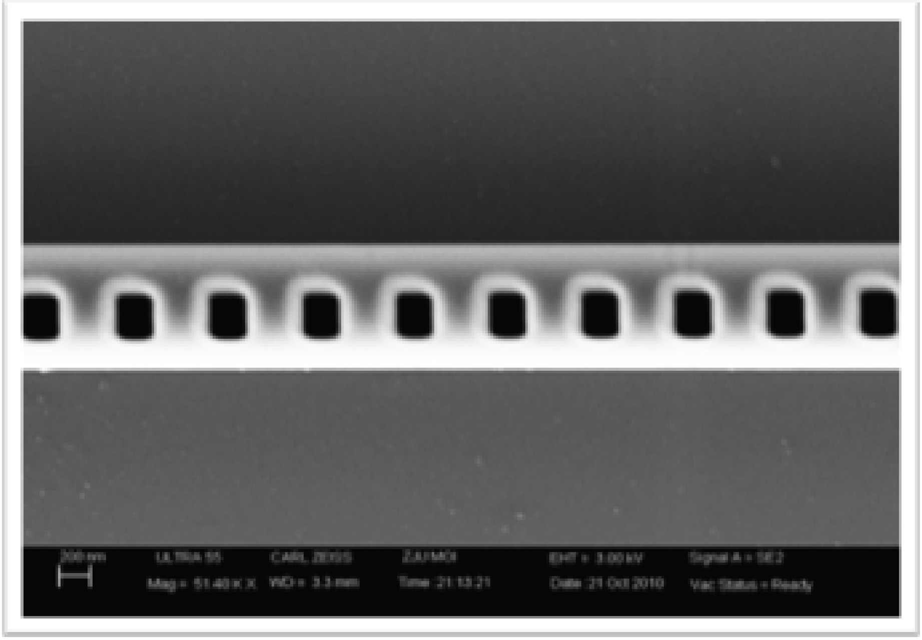
MNF Bragg Gratings

Ultra-compact microfiber Bragg gratings

Fabrication: Focused ion beam milling of an as-drawn microfiber

Fabricate nanoholes or grooves on single nanofibers



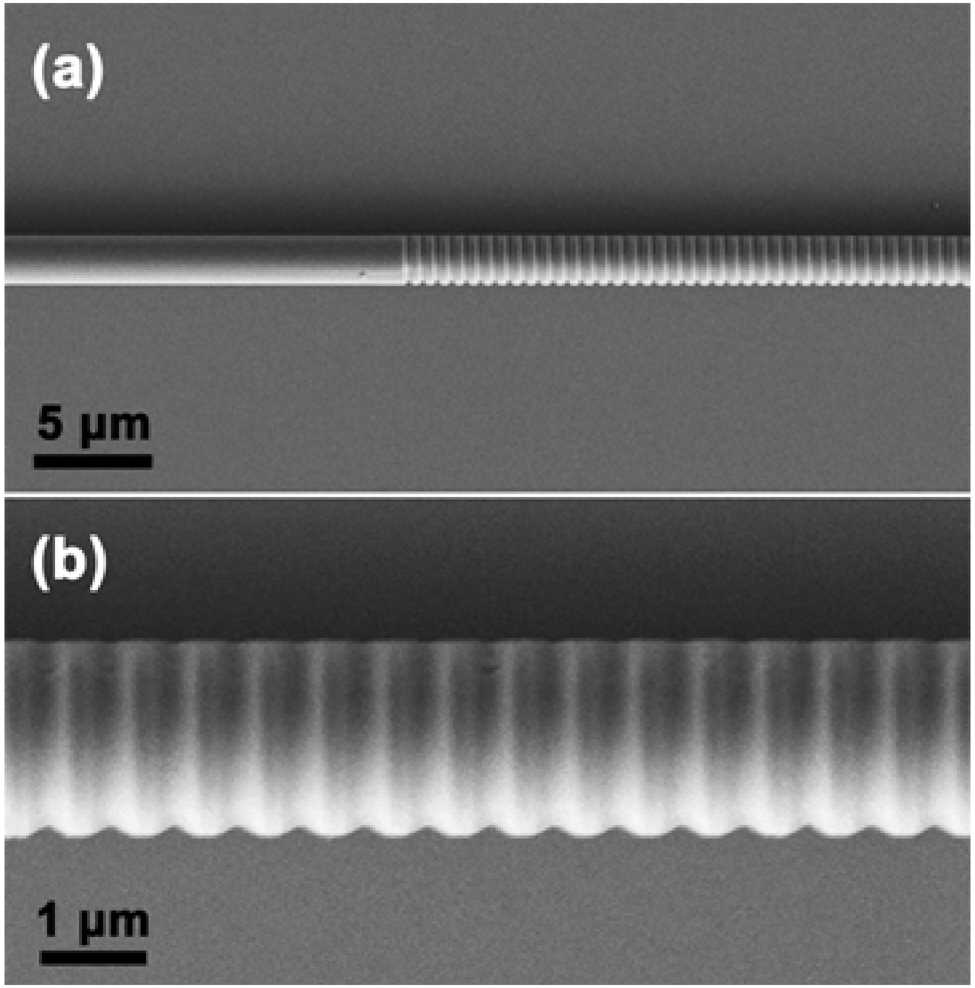


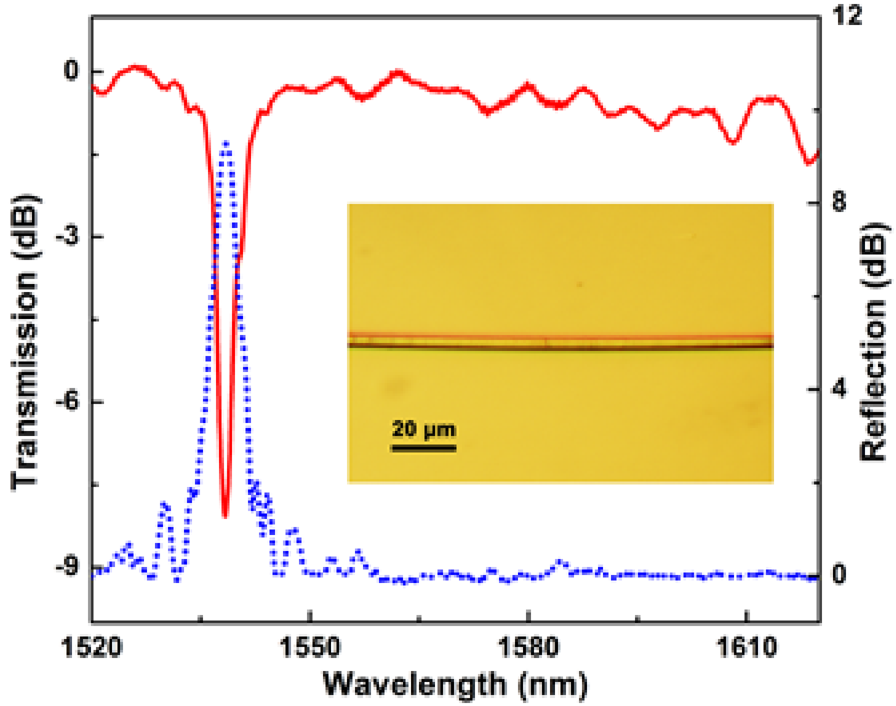
Y. X. Liu et al., Opt. Lett. 36, 3115-3117 (2011)

MNF Bragg Gratings

Ultra-compact microfiber Bragg gratings

Periodical grooves





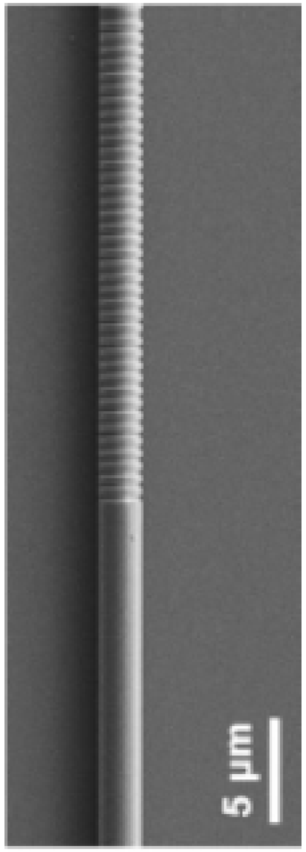
Fiber Diameter: 1.8 μm
Groove depth: 100 nm
Grating period: 578 nm
Grating length: 550 μm

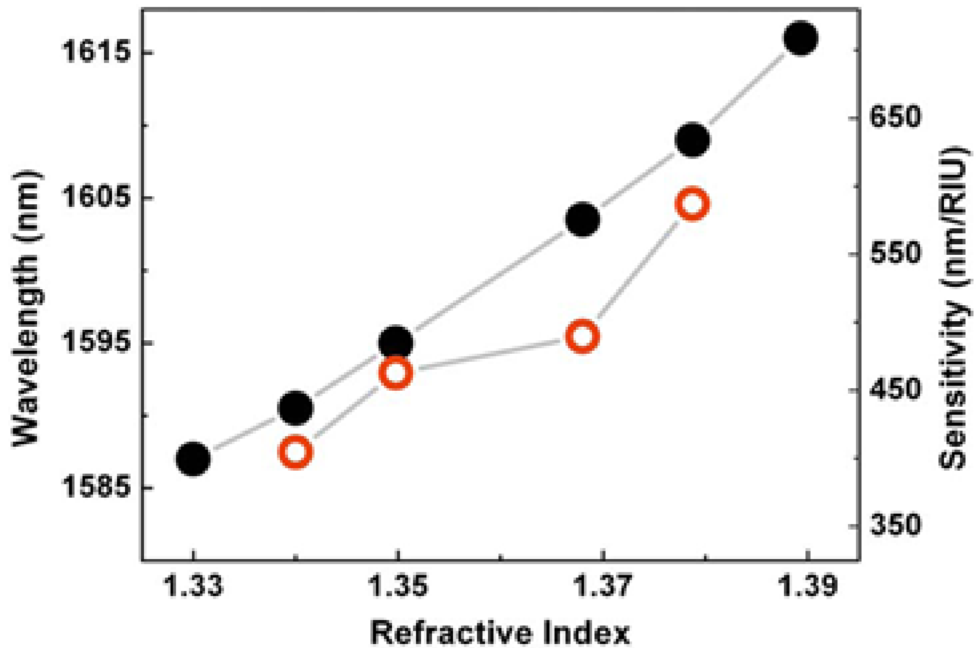
Y. X. Liu et al., Opt. Lett. 36, 3115-3117 (2011)

MNF Bragg Gratings

Microfiber optical sensors
with high sensitivity and compactness

Refractive index sensing in a glycerin solution





Sensitivity ~ 500nm/RIU

Y. X. Liu et al., Opt. Lett. 36, 3115-3117 (2011)

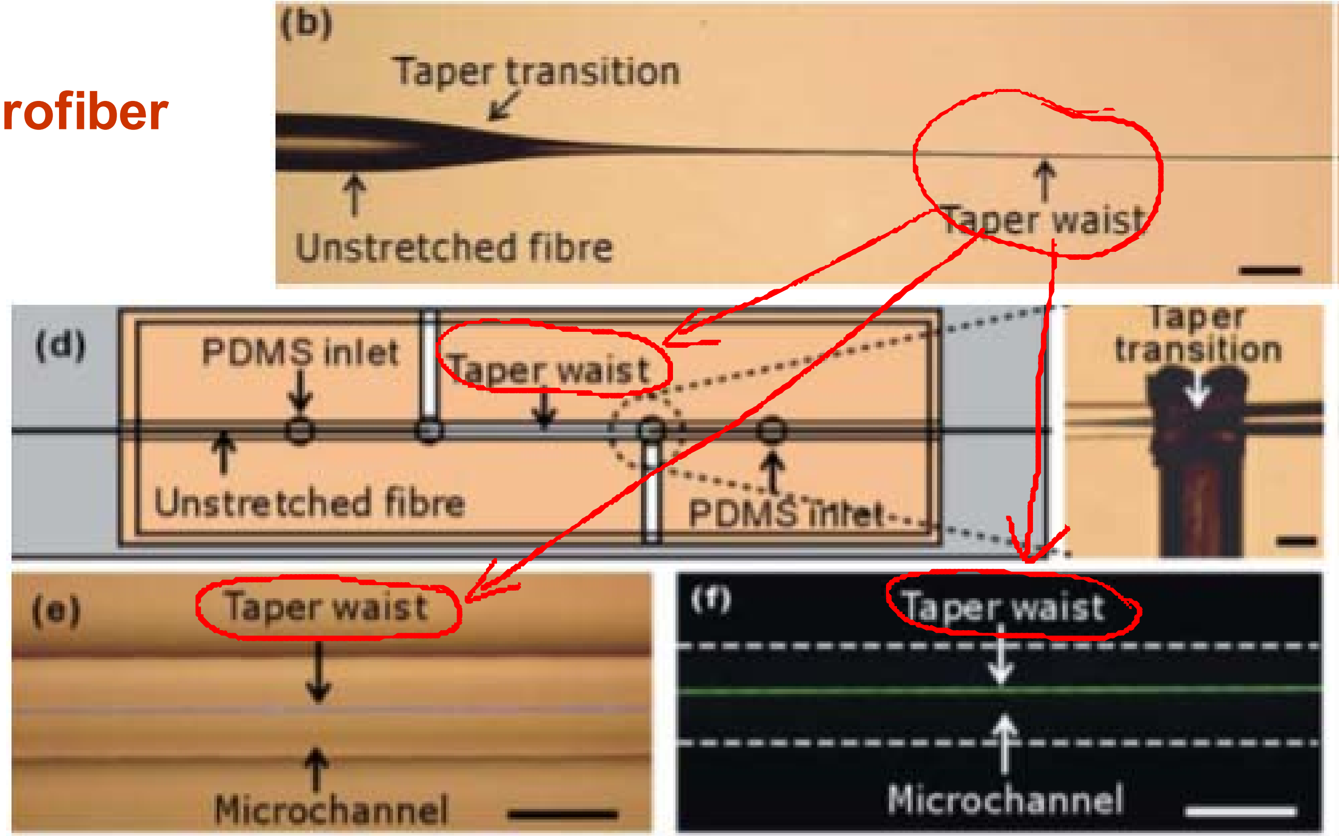
Microfiber–Microfluidic Optical sensors

Recently, by embedding microfibers in microfluidic chips, we have realized ultra-sensitive optical sensing based on waveguiding properties of microfibers

Biconical optical microfiber

embedding

Microfluidic chips



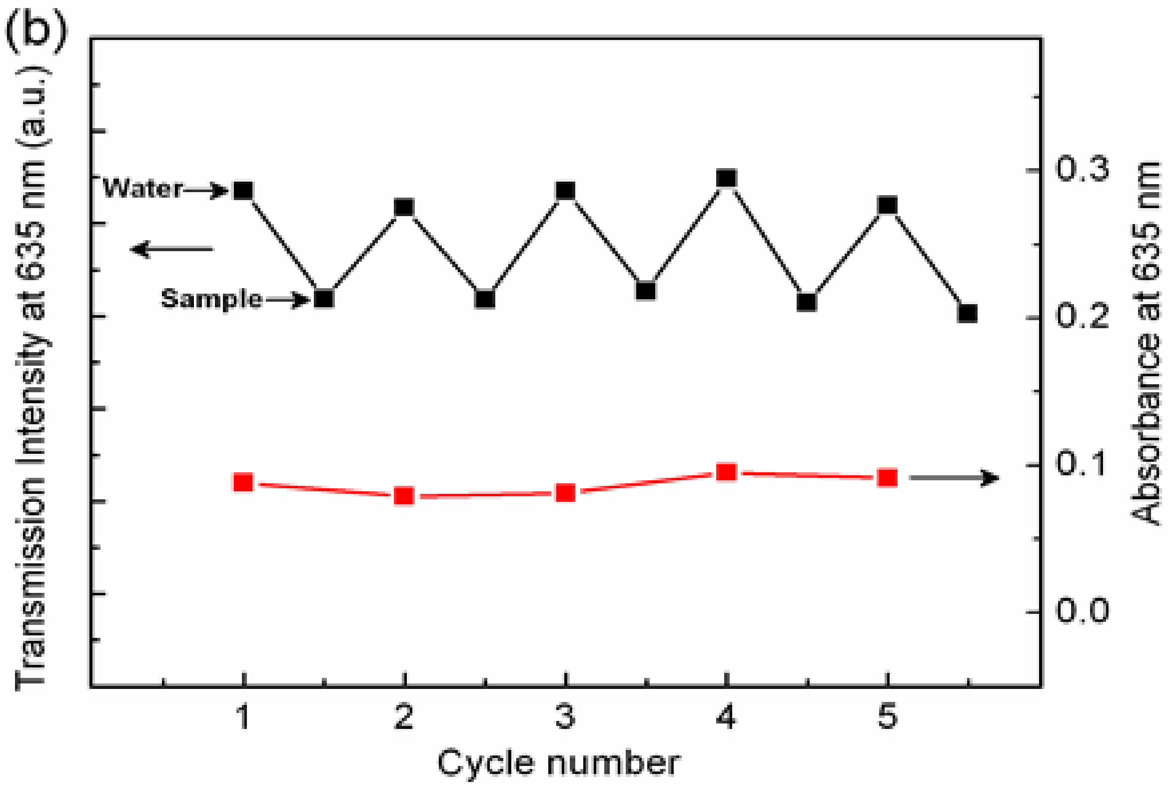
L. Zhang et al., *Lab Chip* 11, 3720-3724 (2011)

MNF-Microfluidic Optical sensors

Microfiber Optical Sensing in Microfluidic Chips

Cycling measurement:

900-nm-diameter silica microfiber @ 633 nm wavelength
500 pM Methylene blue solutions



Excellent reversibility @ low concentration

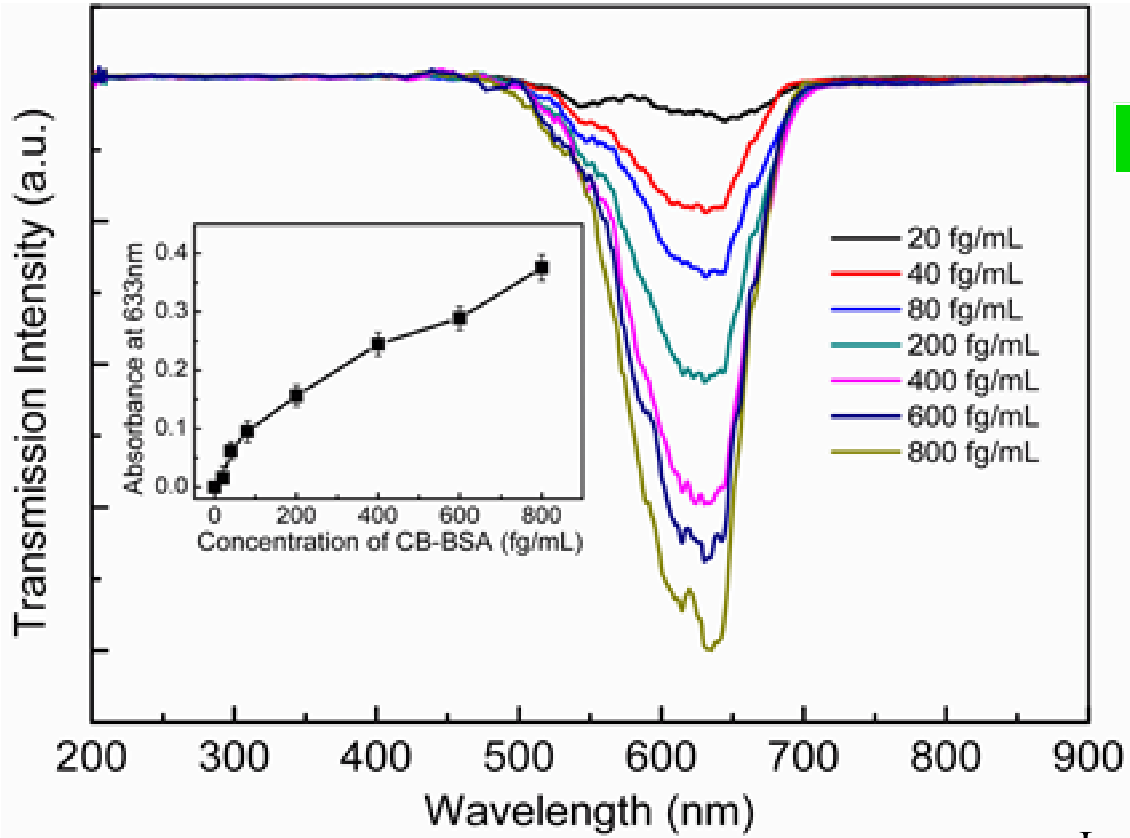
L. Zhang et al., *Lab Chip* 11, 3720-3724 (2011)

MNF-Microfluidic Optical sensors

Microfiber Optical Sensing in Microfluidic Chips

Detection limit:

900-nm-diameter silica microfiber @ 633 nm wavelength
CB-BSA concentrations



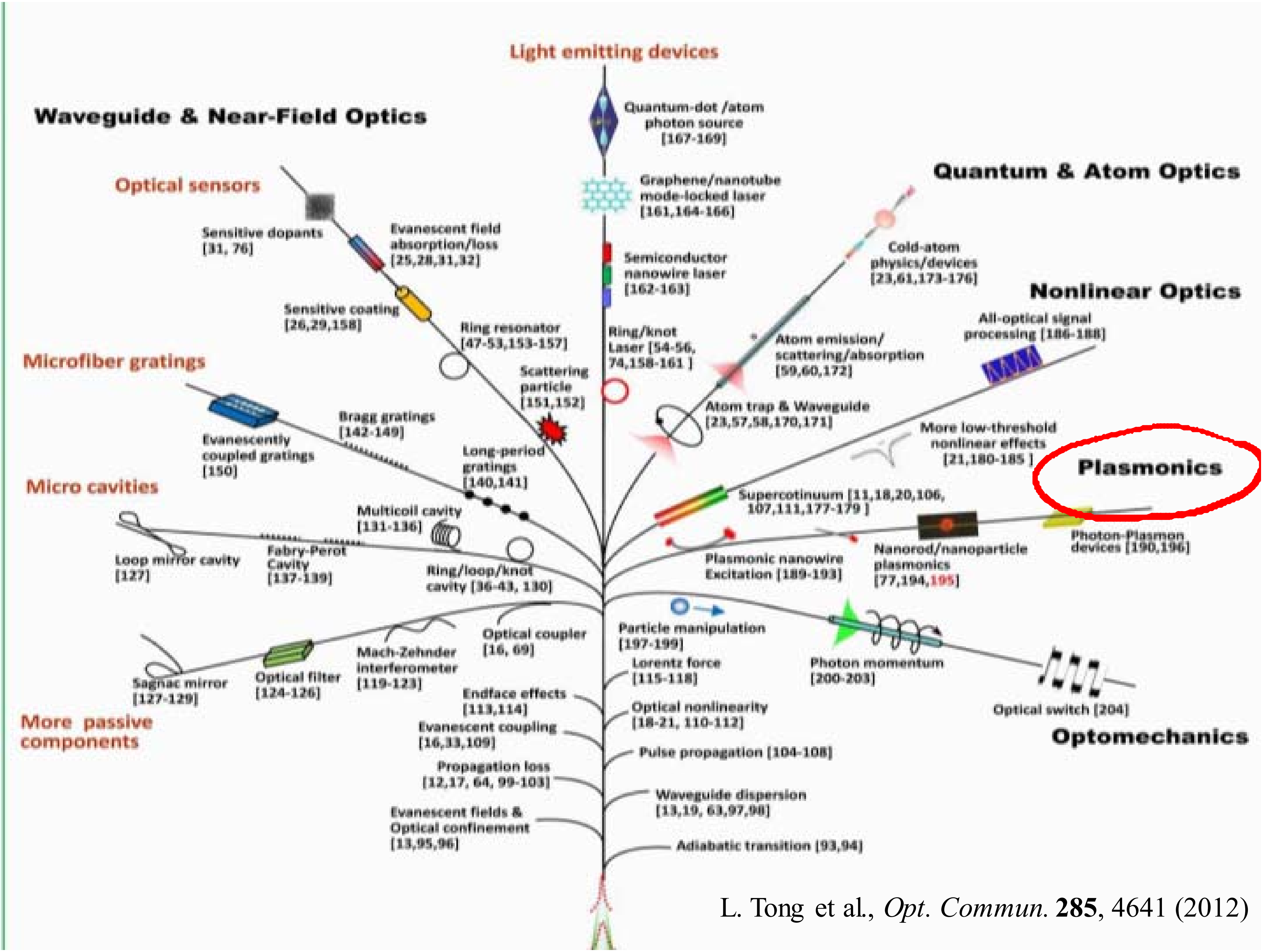
Detection limit → 10 fg/ml

Optical power: 150 nW

promising for

Safe detection of single or a few molecules of biological specimens

L. Zhang et al., *Lab Chip* 11, 3720-3724 (2011)



L. Tong et al., *Opt. Commun.* **285**, 4641 (2012)

(2) Plasmonics

	Photonic	v.s.	Plasmonic
Confinement	Less than λ/5		Better than λ/10
Loss	Low		Very high

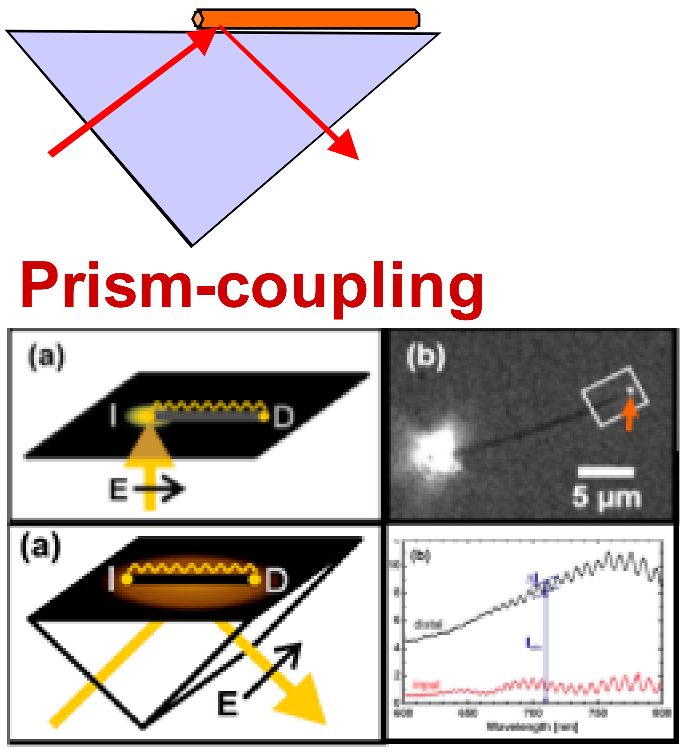
Challenges for using tightly confined palsmonic nanowires

- **Efficient excitation of propagation SPP in nanowires**
- **Balance between loss and confinement**

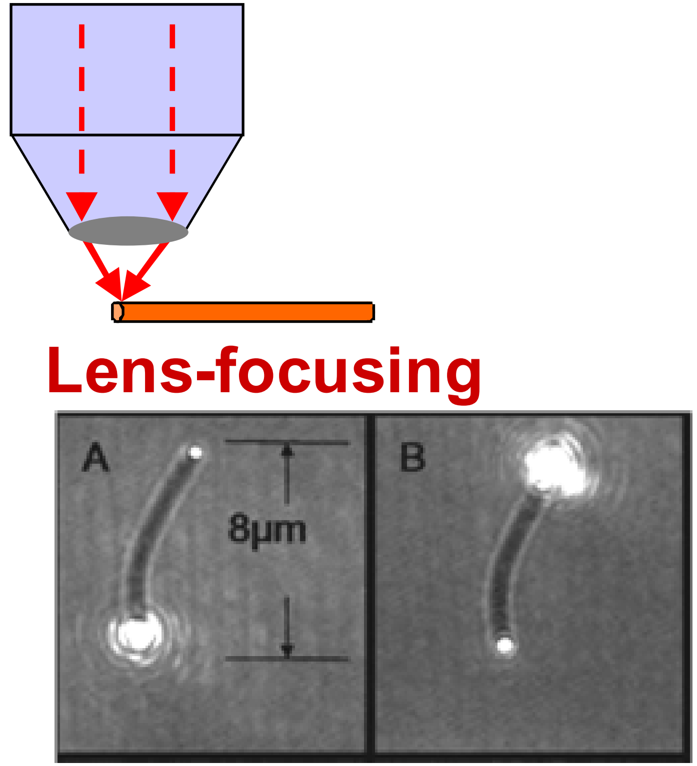
etc.

Plasmonic Nanowires

Excitation of propagation SPP in nanowires



H. Ditlbacher et al., Phys. Rev. Lett. **95**, 257403 (2005).



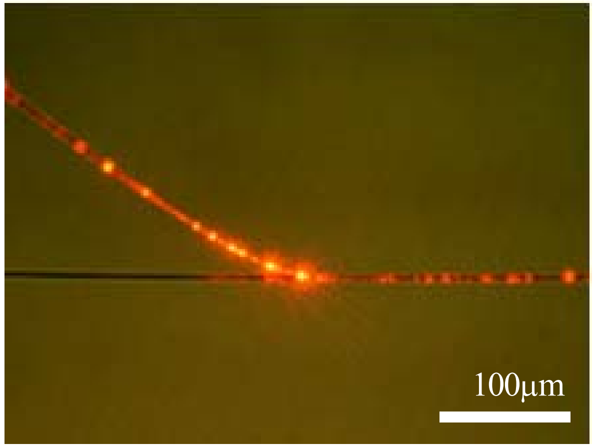
A. W. Sanders et al., Nano Lett. 6, 1822 (2006).

Require bulk component

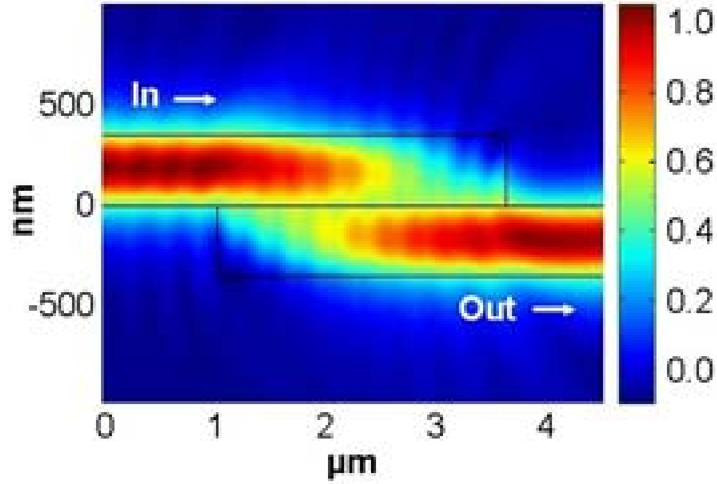
Efficiency is not very high

Optical Coupling

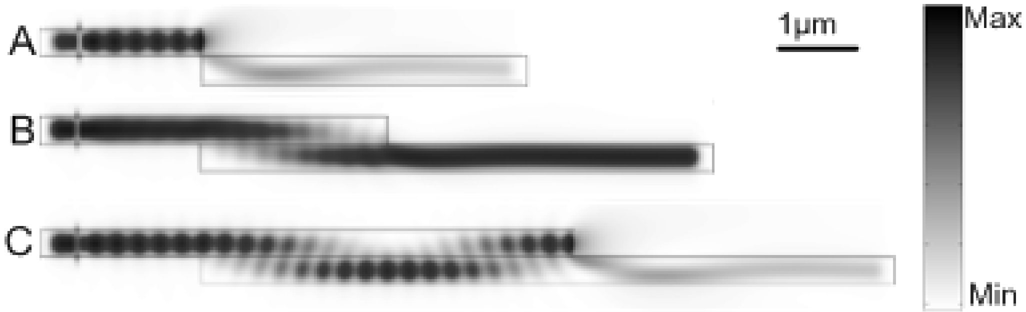
Near-field optical coupling between photonic nanowires
is well studied



L. Tong et al., *Nature* **426**, 816 (2003)



L. Tong et al., *Nano Lett.* **5**, 259 (2005)

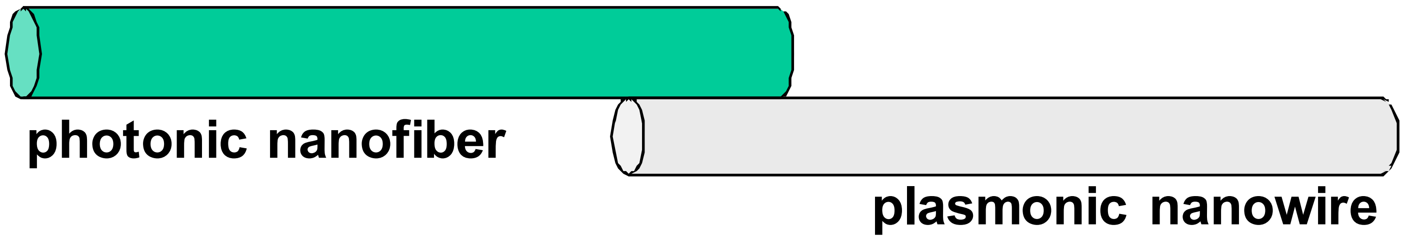


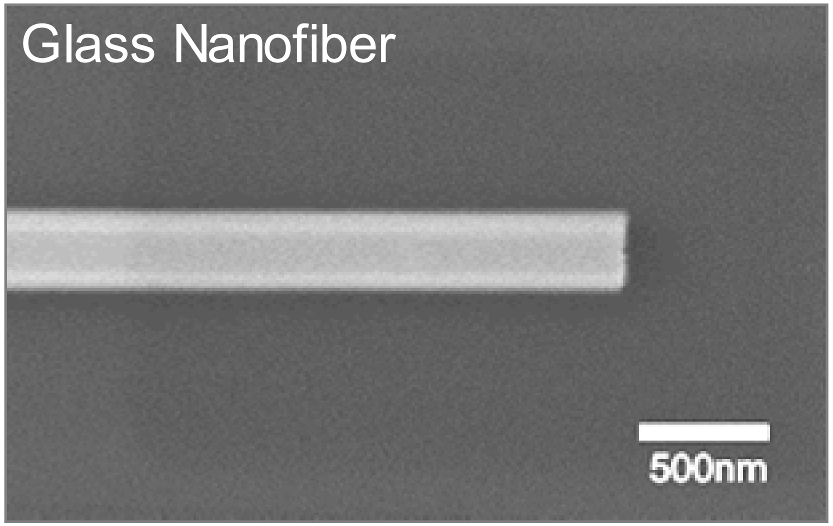
K. Huang et al., *Appl. Opt.* **46**,1249 (2007)

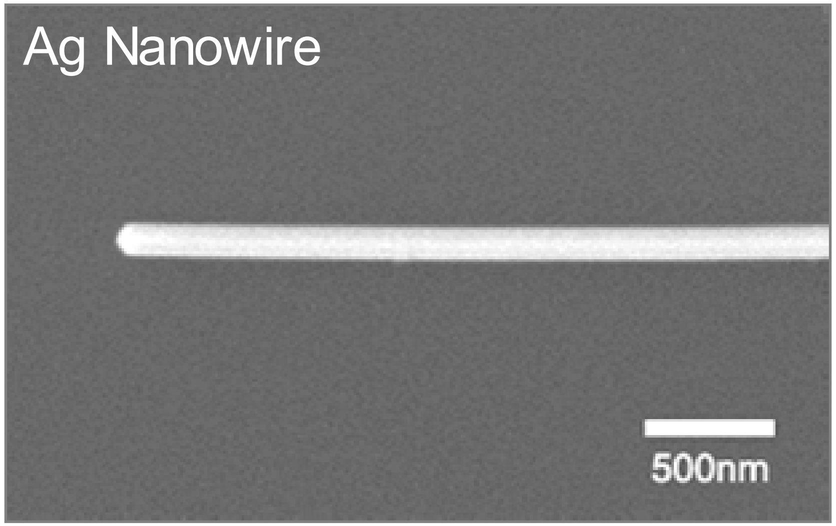
Compact & high efficiency

Nanowire Coupling

Can we coupling of plasmonic and photonic nanowires in similar way?





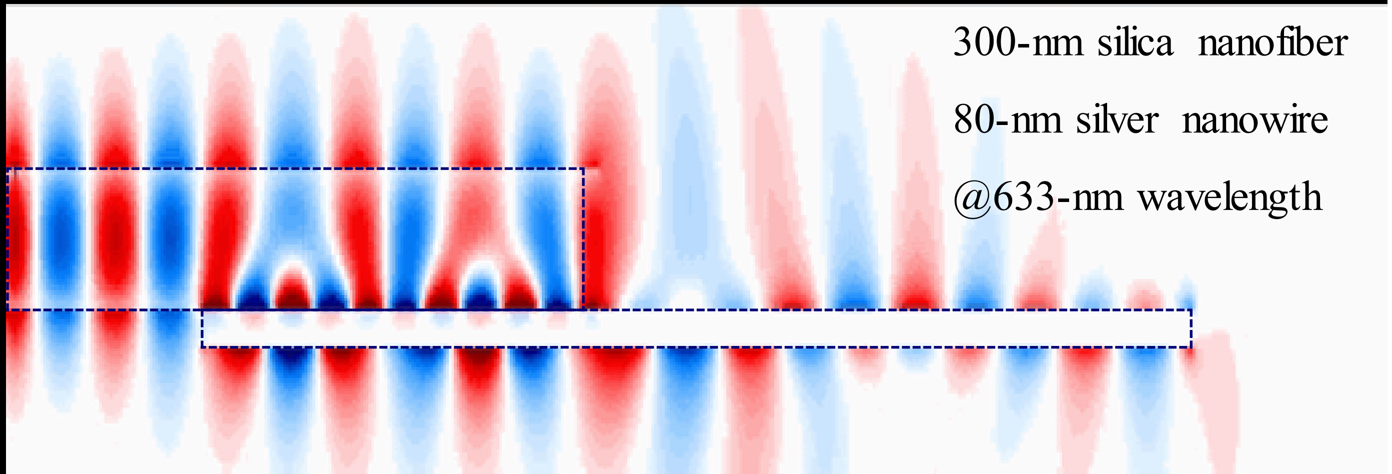


Nanowire Coupling

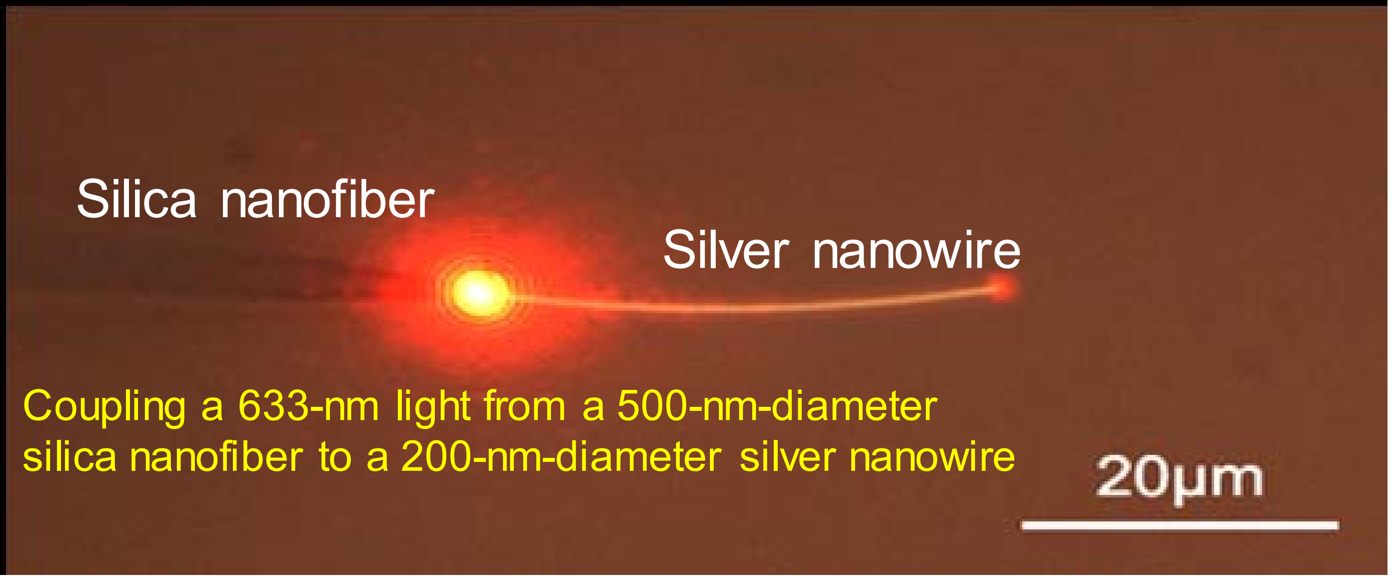
Can we coupling of plasmonic and photonic nanowires in similar way?

Yes

Simulation

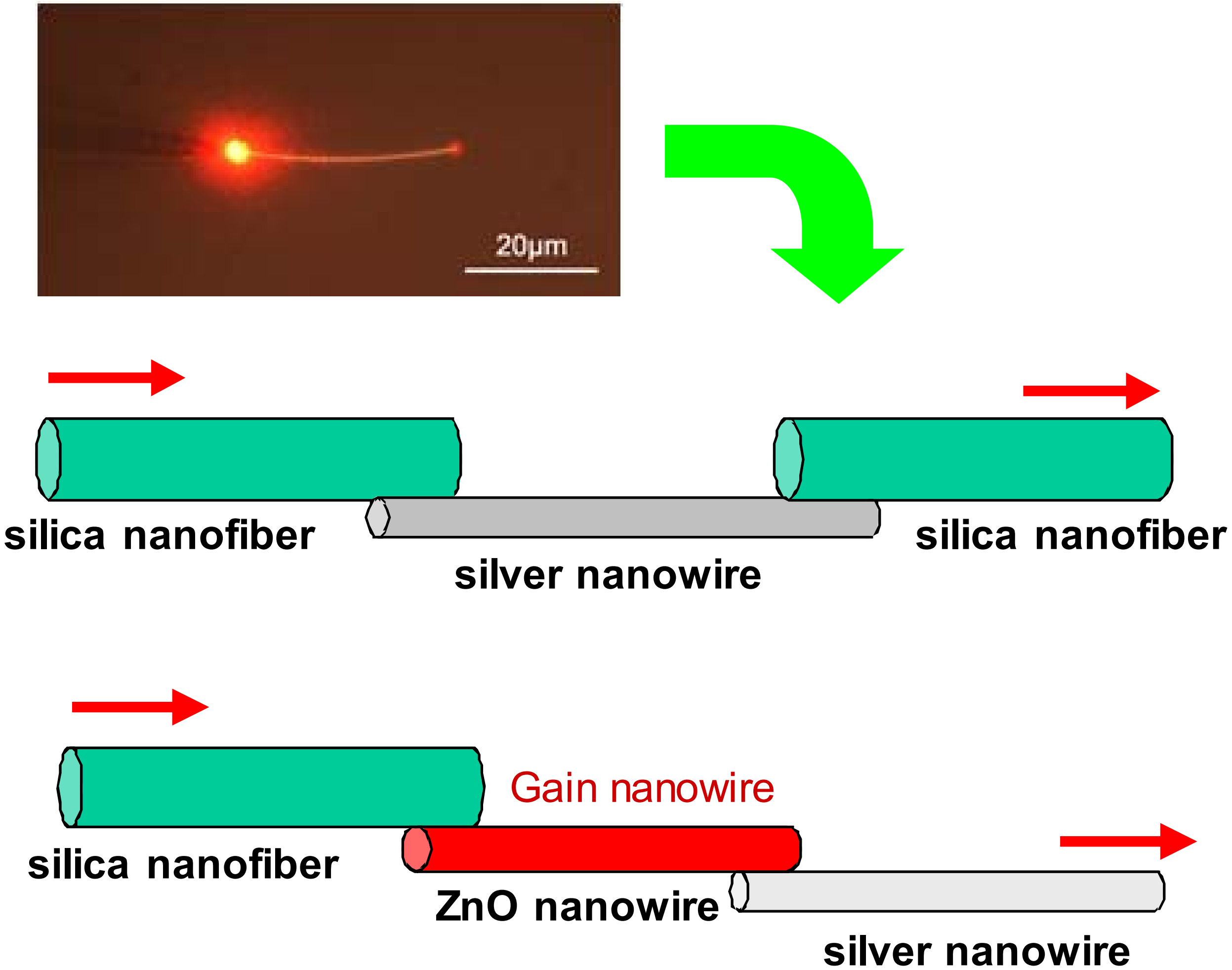


Experiments



Coupling a 633-nm light from a 500-nm-diameter silica nanofiber to a 200-nm-diameter silver nanowire

Hybrid nanofiber-nanowire structure



Advantages

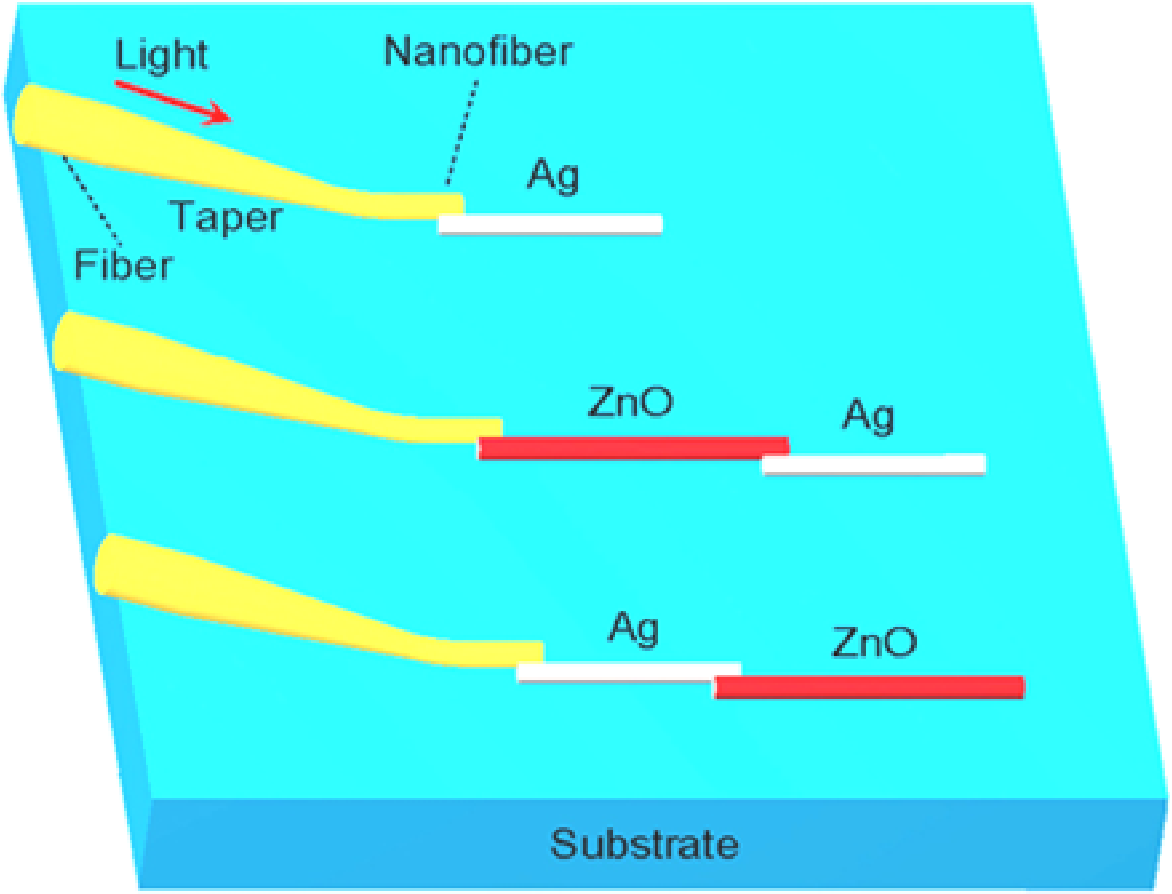
- Convenient and efficient input/output
- Loss reduction/ compensation by dielectric/gain nanowire
- Compatible with optical fiber system

X. Guo et al., *Nano Lett*. 9, 4515-4519 (2009)

Nanowire Coupling

Near-field coupling of photonic and plasmonic nanowires

Basic configuration for nanowire coupling

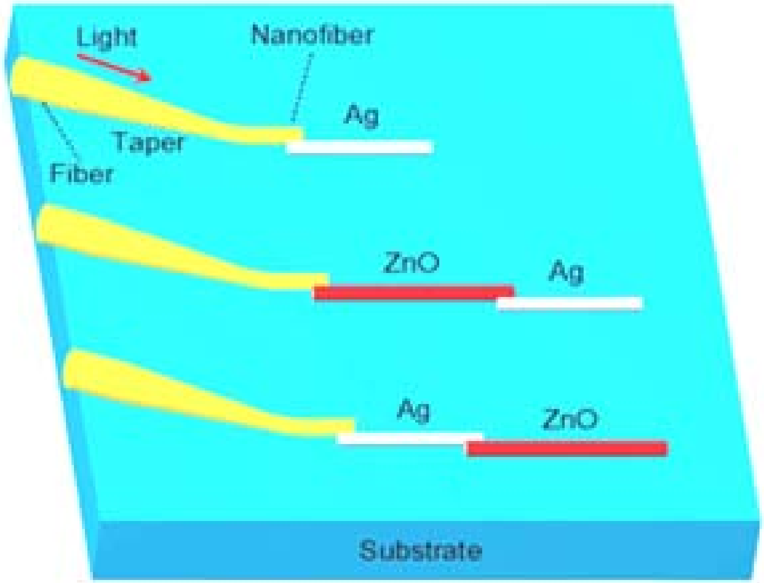


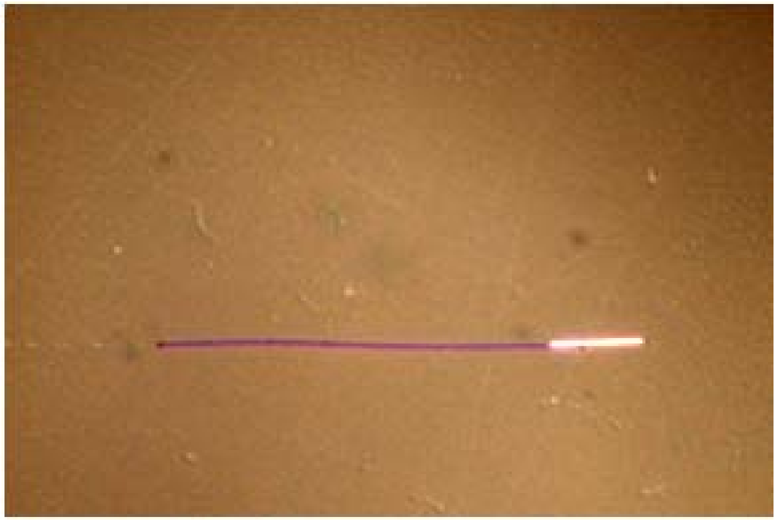
X. Guo et al., *Nano Lett*. **9**, 4515 (2009)

Nanowire Coupling

Near-field coupling of photonic and plasmonic nanowires

Basic configuration for nanowire coupling





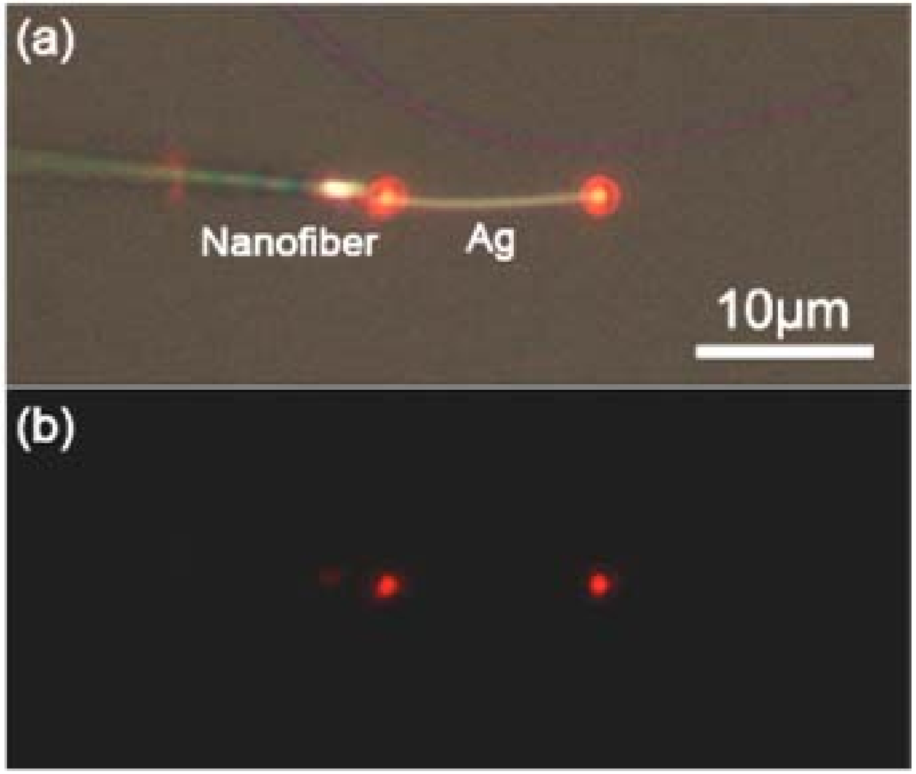
Assembly process of a hybrid coupler with ZnO and Ag nanowires

X. Guo et al., *Nano Lett*. **9**, 4515 (2009)

Nanowire Coupling

Near-field coupling of photonic and plasmonic nanowires

Coupling efficiency



Silica nanofiber: D=500 nm

Ag nanowire: D=240 nm L=12μm

Fractional output from the Ag nanowire: 49%

Deducting the guiding loss[1,2]:

Ag about 0.43 dB/μm

ZnO lower than 0.001dB/μm

Coupling efficiency ~75%

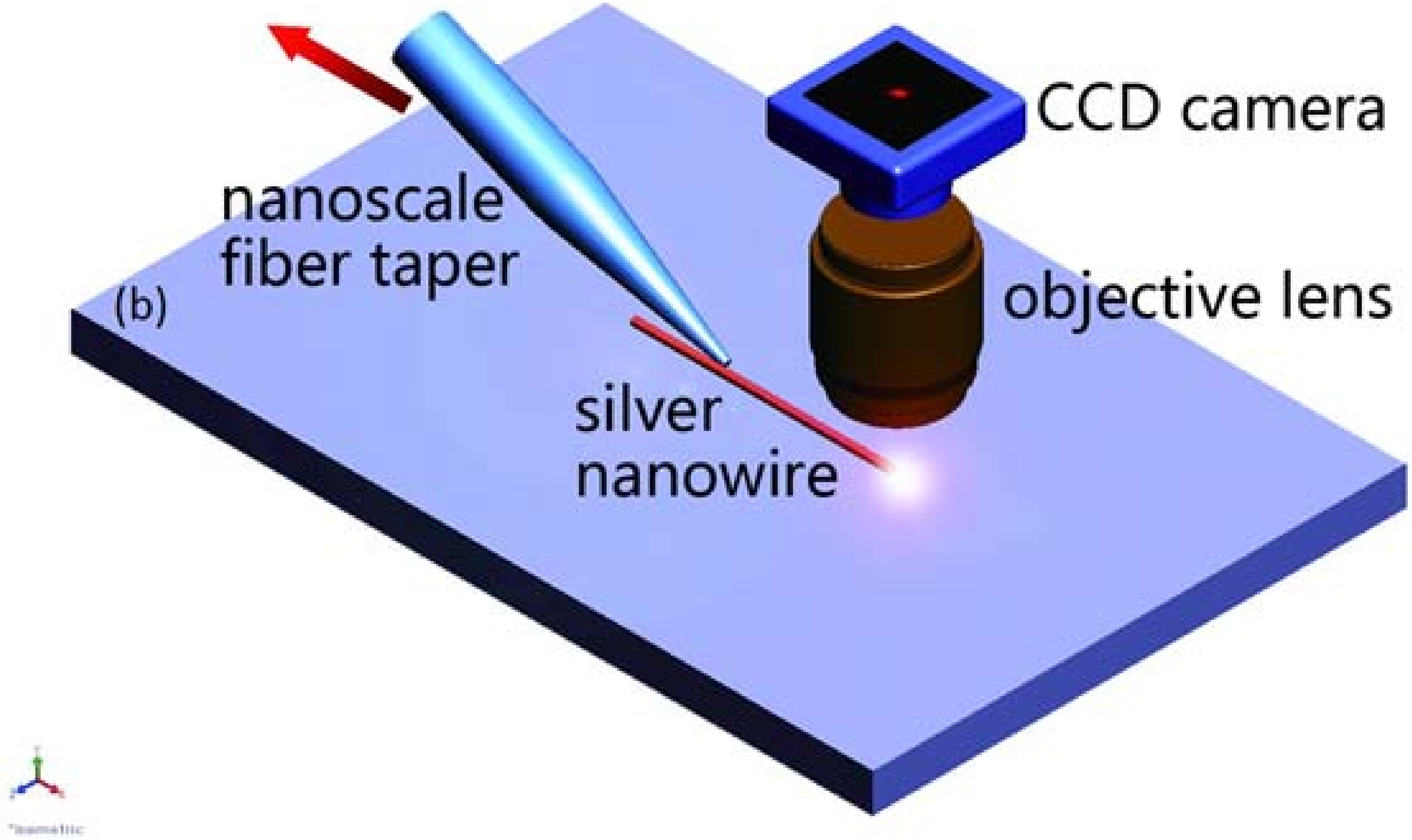
[1] H. Ditlbacher et al., *Phys. Rev. Lett.* **95**, 257403 (2005).

[2] A. L. Pyayt et al., *Nature Nano*.**3**, 660 (2008).

Nanowire Coupling

Direct loss measurement of plasmonic nanowires

Relying on high-efficiency (high repeatability) coupling

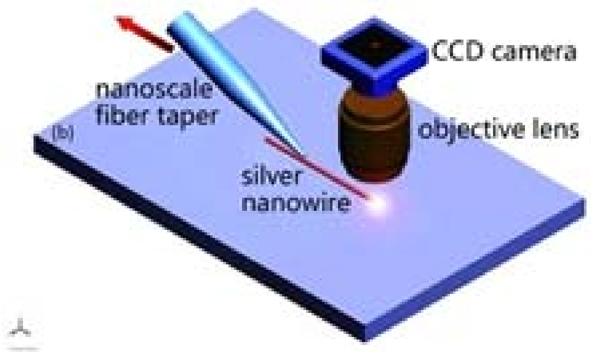


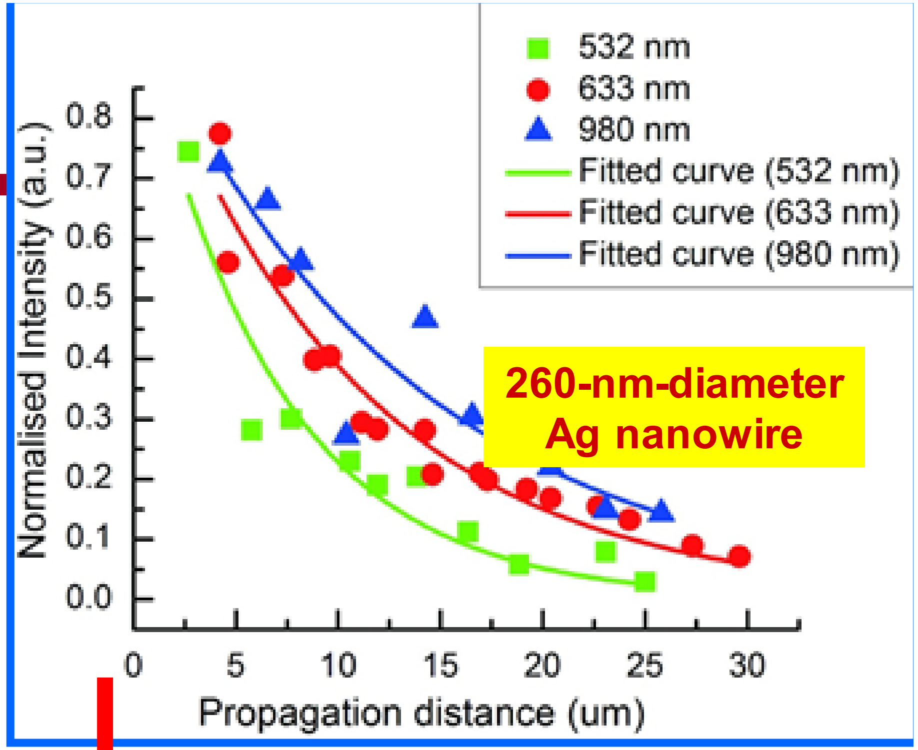
Y. G. Ma et al., *Opt. Lett.* **35**, 1160 (2010)

Nanowire Coupling

Direct loss measurement

Relying on high-efficiency (high





Typical propagation loss: ~ 0.41 dB/um @ 633 nm

Y. G. Ma et al., *Opt. Lett.* **35**, 1160 (2010)

Nanowire Coupling

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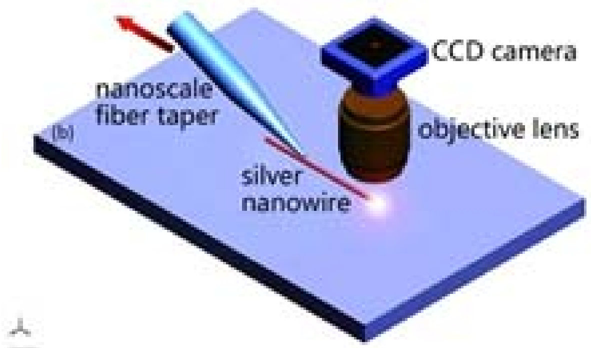
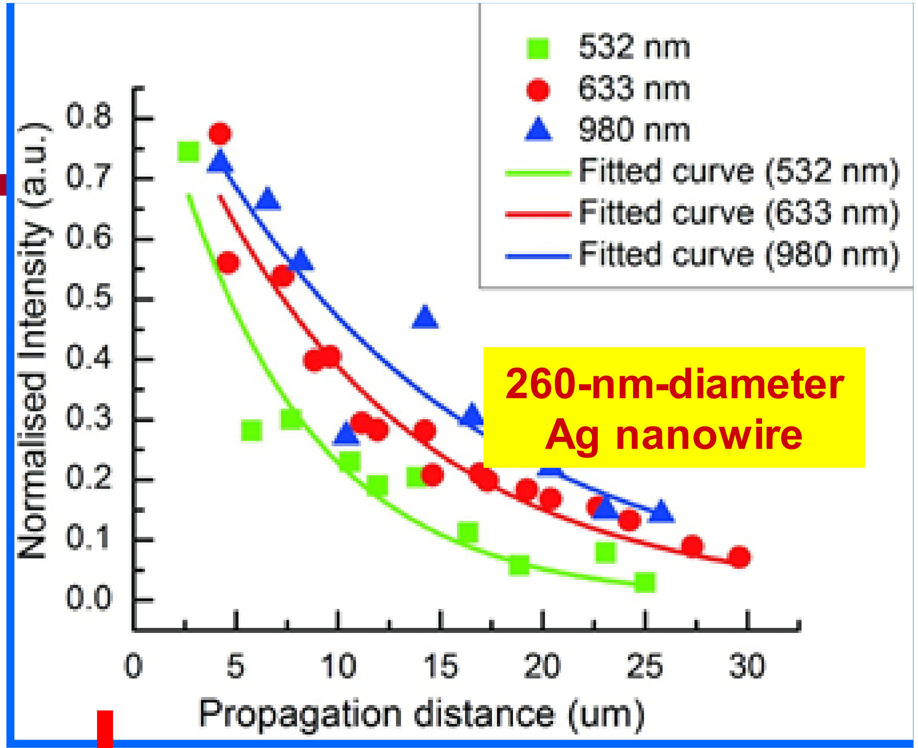


Y. G. Ma et al., *Opt. Lett.* **35**, 1160 (2010)



Typical propagation loss: ~ 0.41 dB/um @ 633 nm

(1) Loss of a Ag nanowire could be lower than previous indirect experimental results

e.g., measured using F-P resonance: 0.43 dB/um @ 633 nm

→ H. Ditlbacher et al., *Phys. Rev. Lett.* **95**, 257403 (2005)

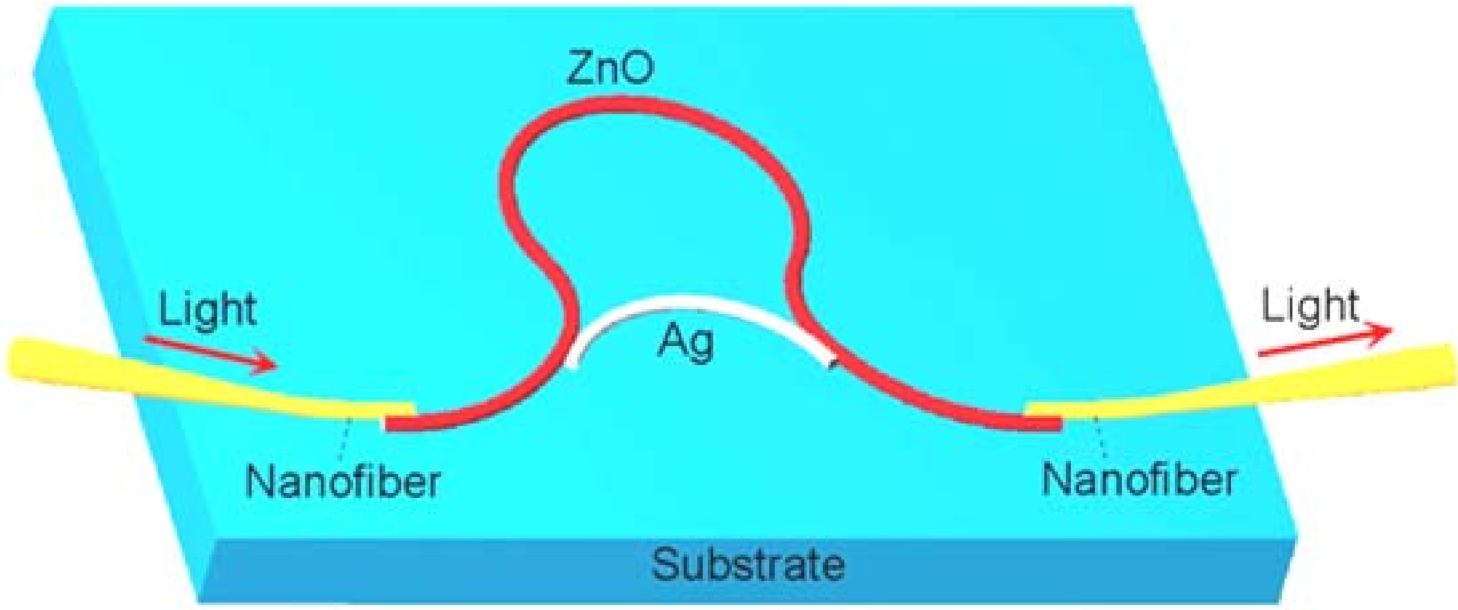
(2) Should be much lower than those obtained by theoretical calculations

e.g., 328-nm diameter: 0.72dB/um@ 633nm →X. Chen et al.,*Nano Lett.* **9**, 3756 (2009)

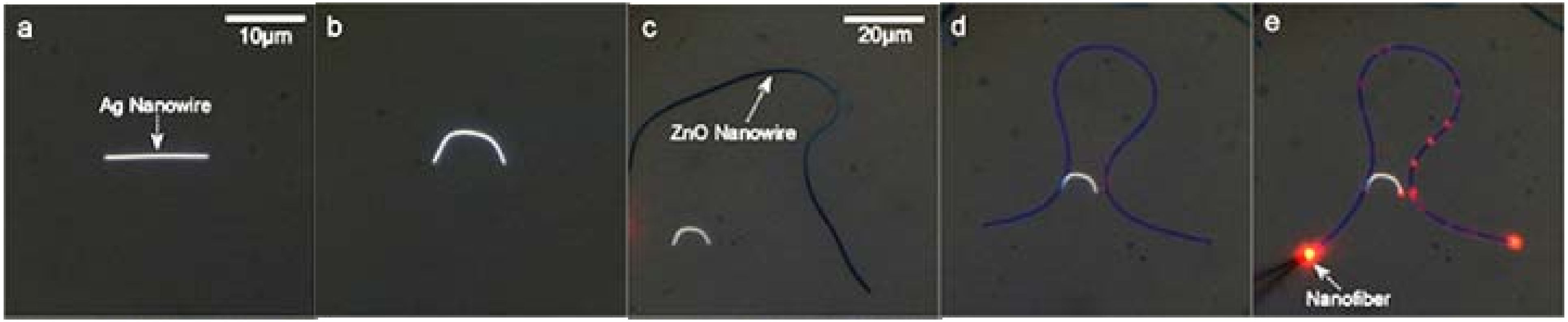
Applications

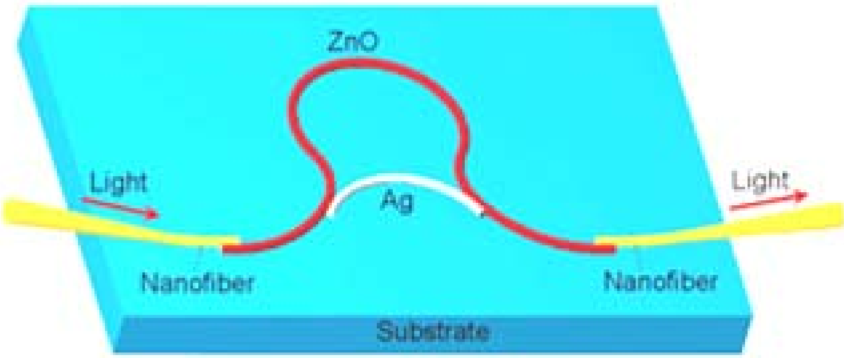
Hybrid “Photon-Plasmon” circuits and devices

Mach-Zehnder Interferometer

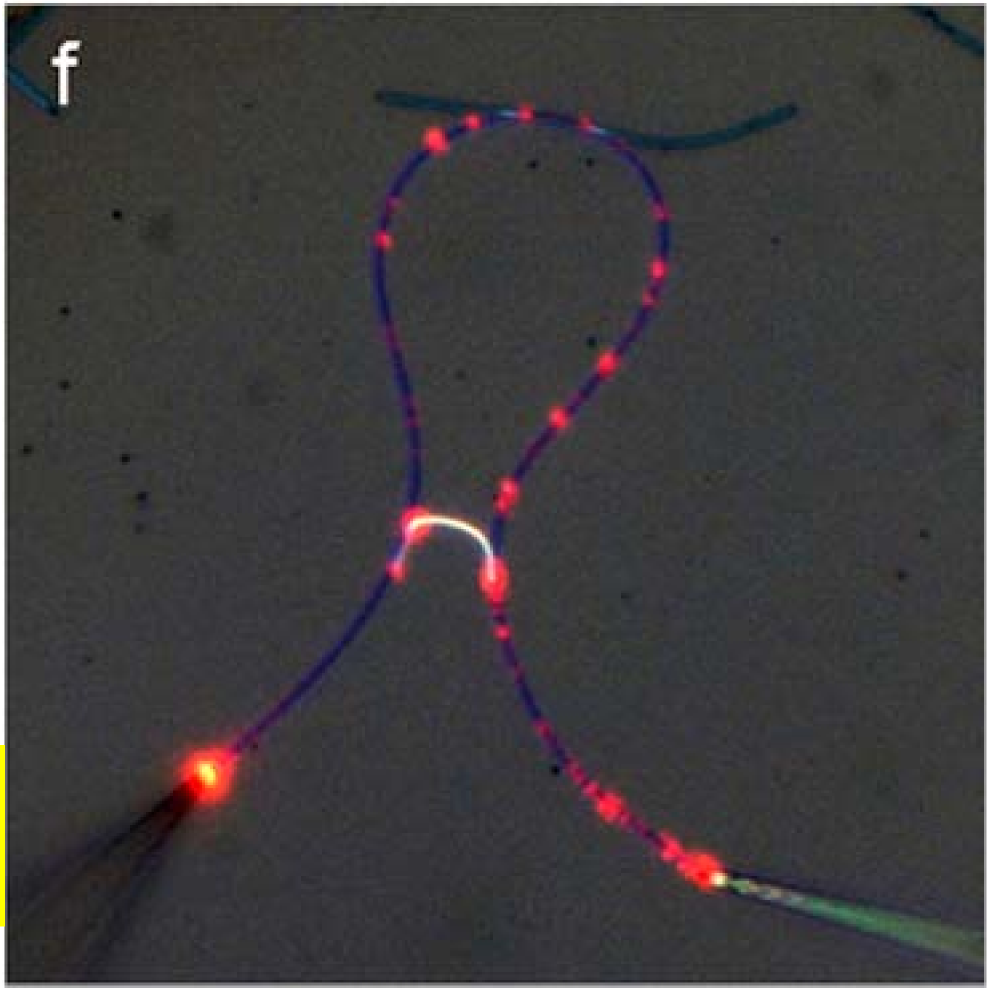


X. Guo et al., *Nano Lett.* **9**, 4515 (2009)





As-assembled MZI



ZnO Nanowire: D 330 nm, L 89 μm

Ag Nanowire: D 120 nm, L 6.5 μm

X. Guo et al., *Nano Lett.* **9**, 4515 (2009)

Hybrid "Photon-Plasmon" circuits and devices

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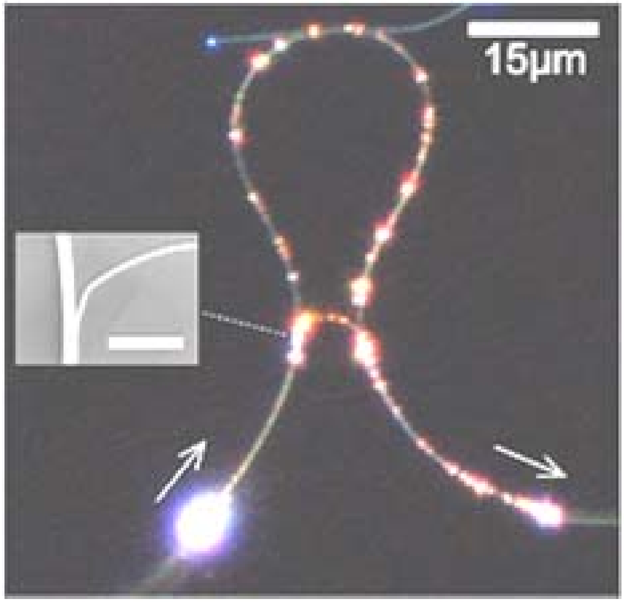

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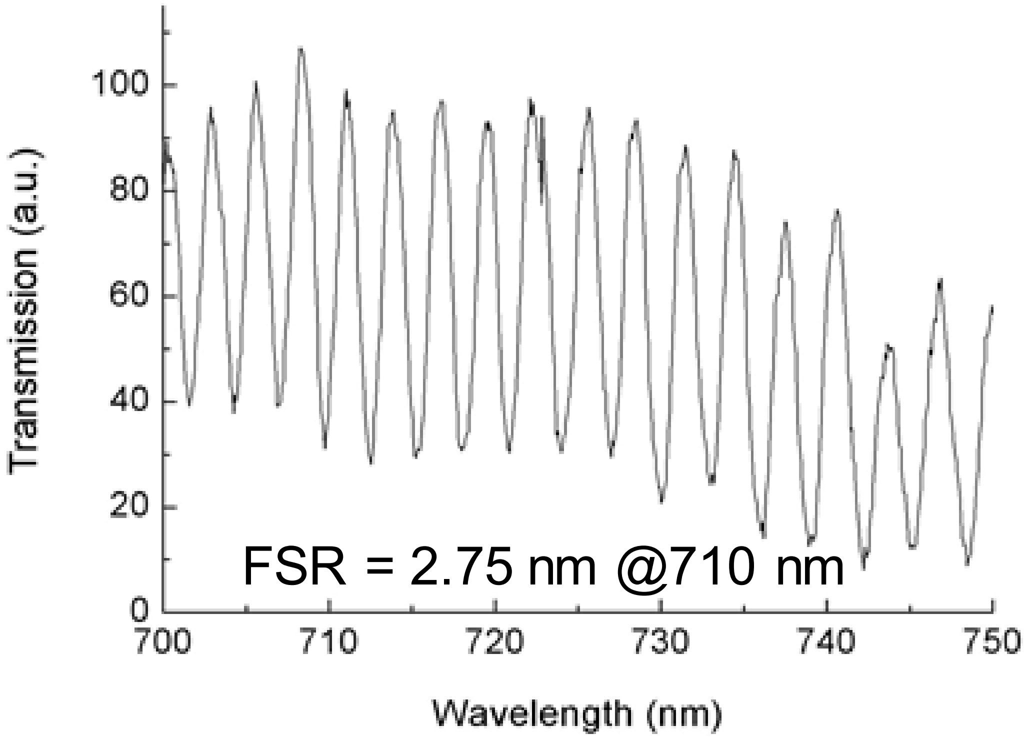
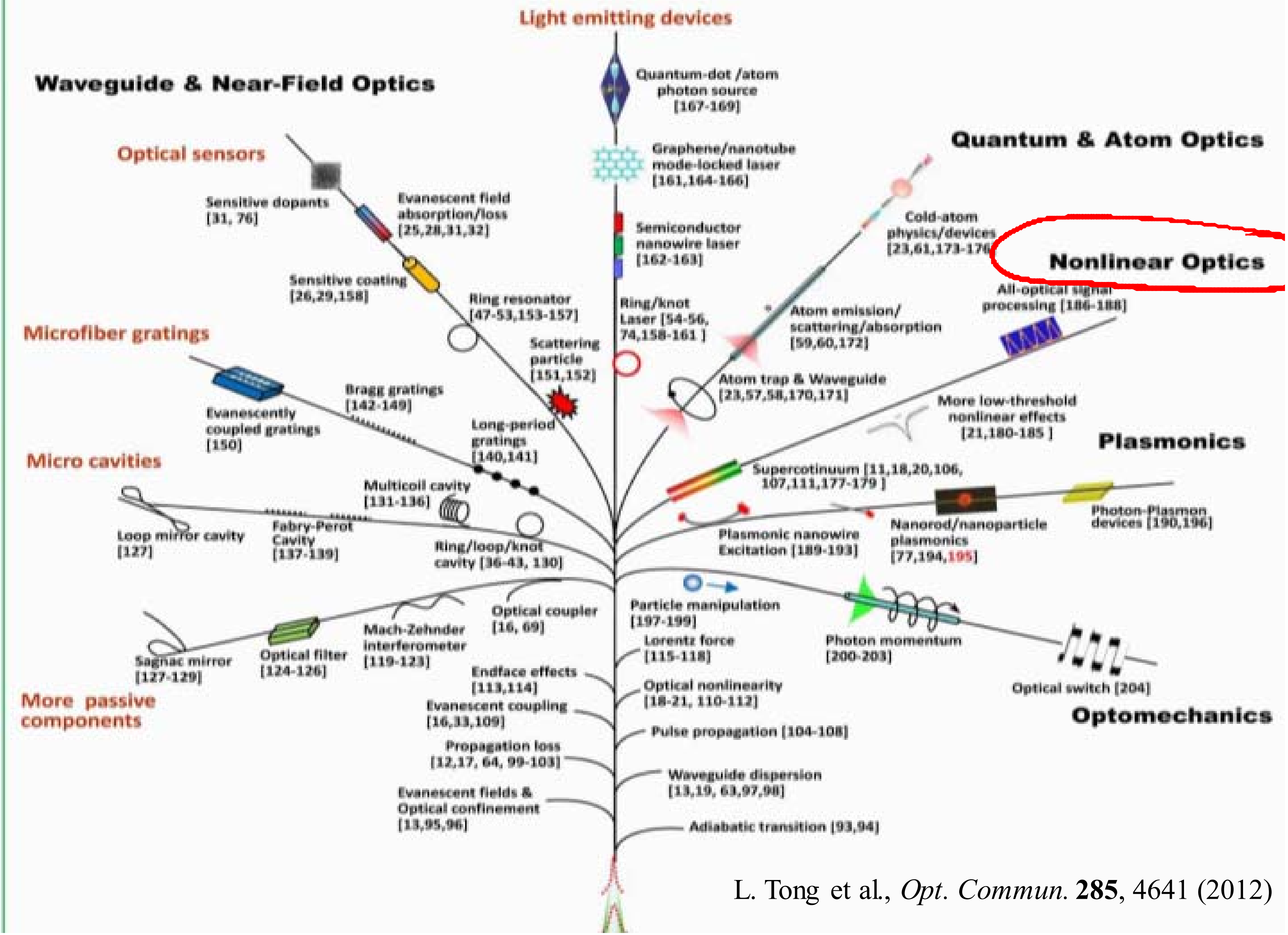


Potential device applications: sensors, modulators etc.

X. Guo et al., *Nano Lett.* **9**, 4515 (2009)



L. Tong et al., *Opt. Commun.* **285**, 4641 (2012)

Nanofibers for nonlinear optics

For nonlinear effects, nanofibers present advantages including:

- **Small mode area :** $D_{eff} < \lambda$
- **Effective nonlinearity :** $\gamma = (2\pi/\lambda) n_2 / A_{eff}$ **→ Large γ**
- **Dispersion : Diameter-dependent → manageable**

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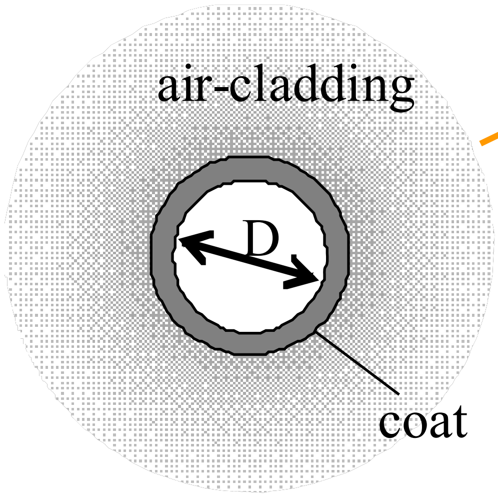

J. Y. Lou et al., *Opt. Express* **14**, 6993 (2006)

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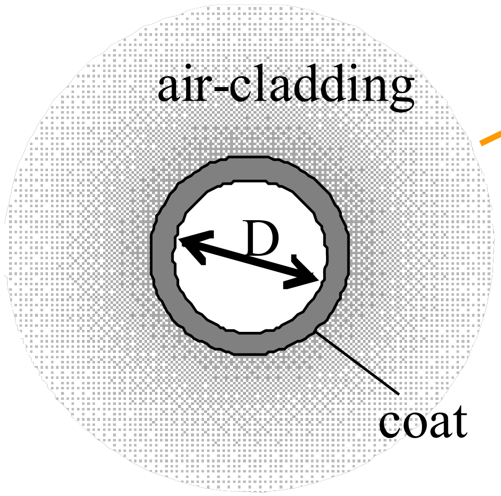
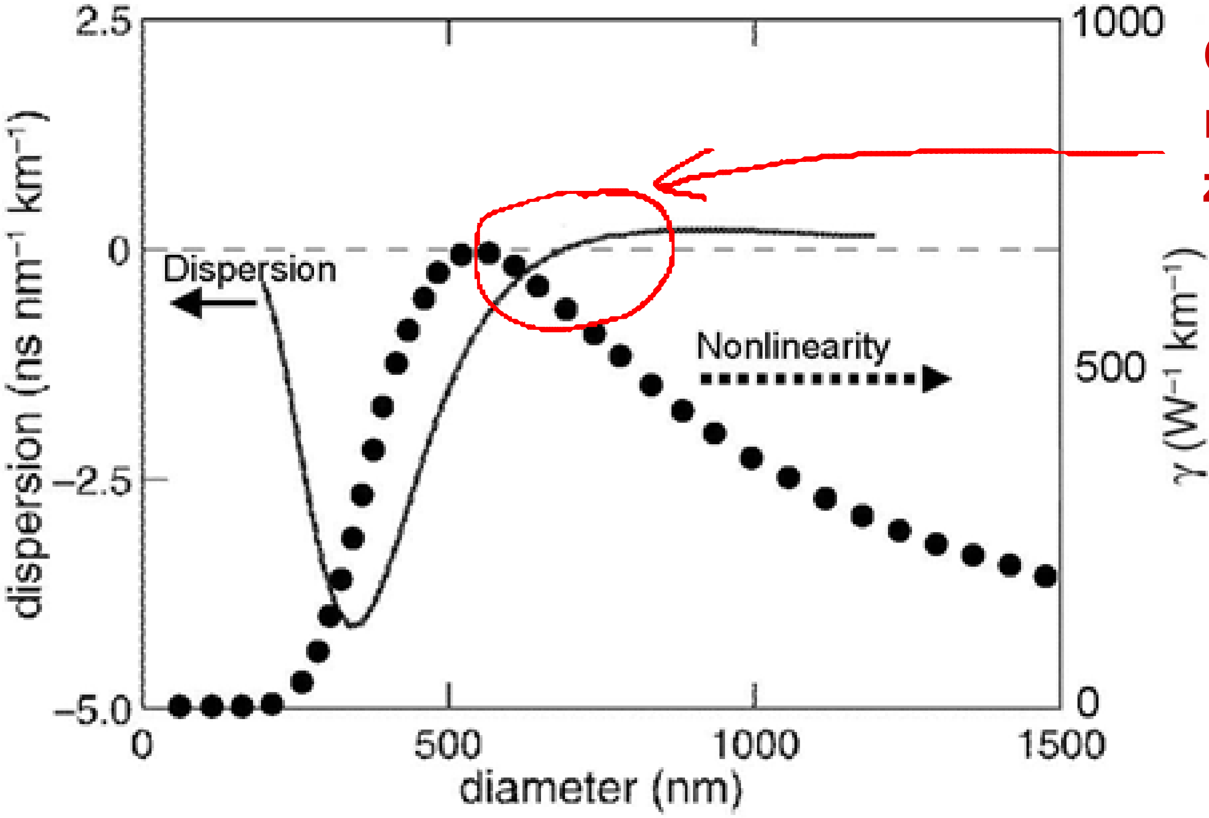


- **Low threshold**
- **Short interaction length**
- **possible to work with very small quantity of samples**

J. Y. Lou et al., *Opt. Express* **14**, 6993 (2006)

Nanofibers for nonlinear optics

Diameter-dependent dispersion and nonlinearity of an air-cladding silica nanofiber at 800-nm wavelength



Considerably high nonlinearity around zero dispersion

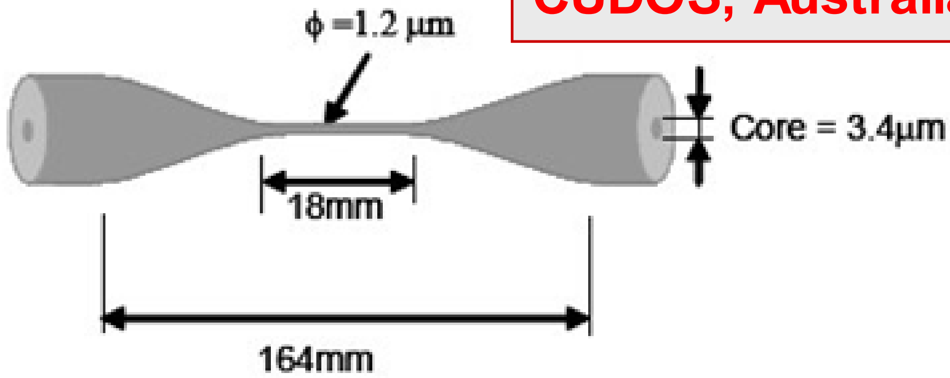
L. Tong et al., *Opt. Express* **12**,1025 (2004)

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

Optical Nonlinearity in high nonlinear microfibers

CUDOS, Australia

Enhanced nonlinearity in sub-wavelength-diameter As_2Se_3 fibers



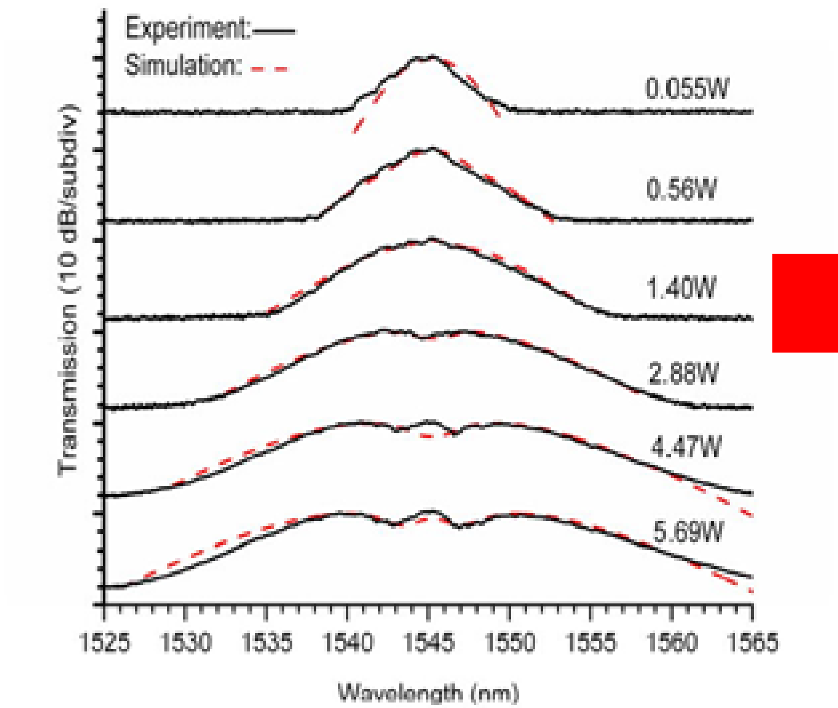


Fig. 5. SPM spectra under different incident peak power in the As_2Se_3 fiber

Enhanced nonlinearity of 68 $W^{-1}m^{-1}$

v.s. SMF28: $\gamma \sim 1 \times 10^{-3}$ W^{-1} m^{-1}

62,000 times larger
(500 times larger n_2 and 125 times smaller effective mode area)

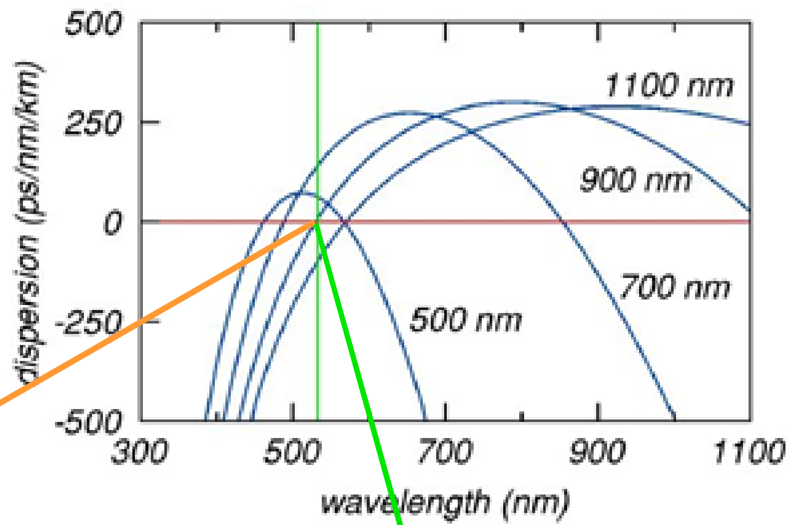
E. C. Mägi et al., *Opt. Express* 12, 10324 (2007)

(3) Nonlinear Optics

Supercontinuum generation

- with ns pulses [12]

U Bath (UK)



Silica fiber

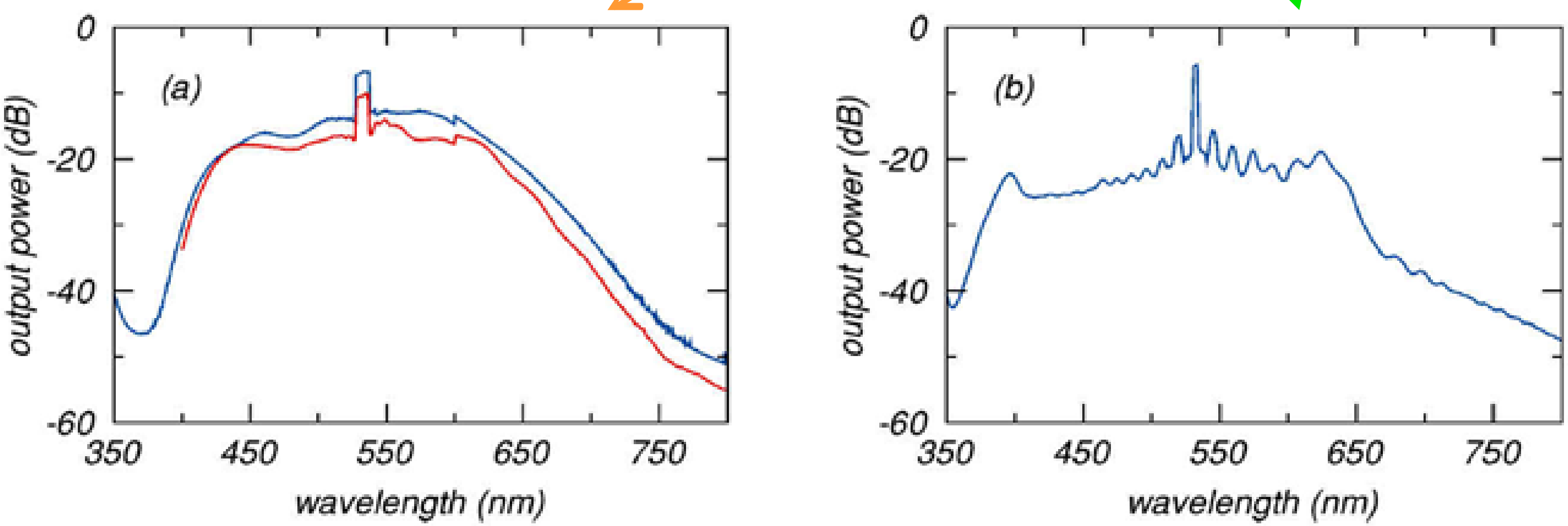


Fig. 4. SC spectra generated by taper waists for diameter, length and average laser power of (a) 920 nm, 90 mm and ~3 mW, and (b) 510 nm, 20 mm and ~1.5 mW, respectively. The red curve is for a sample made from Nufern 630-HP fibre instead of Corning SMF-28.

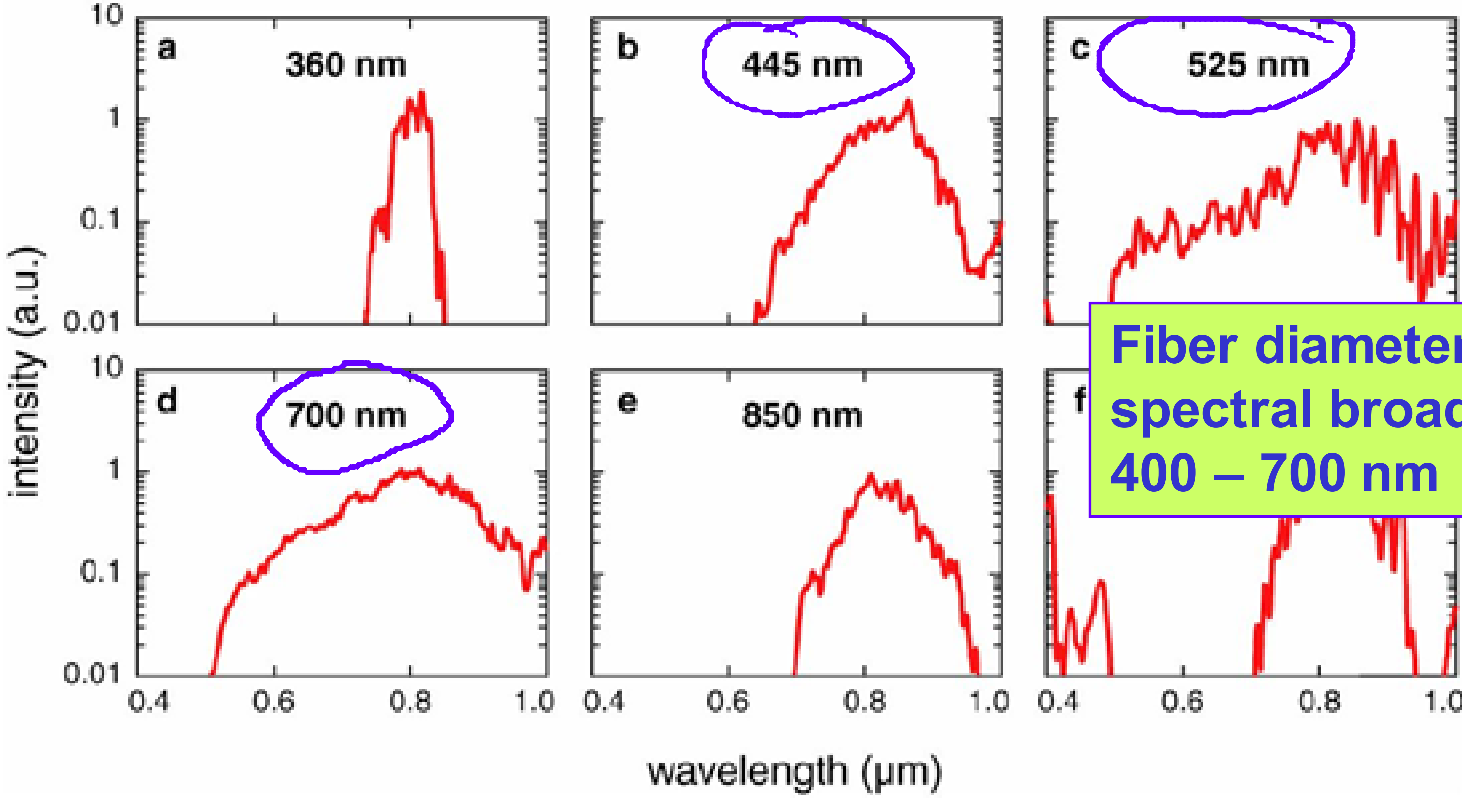
[12] S. G. Leon-Saval et al., *Opt. Express* **12**, 2864 (2004)

(3) Nonlinear Optics

Supercontinuum generation

- with fs pulses

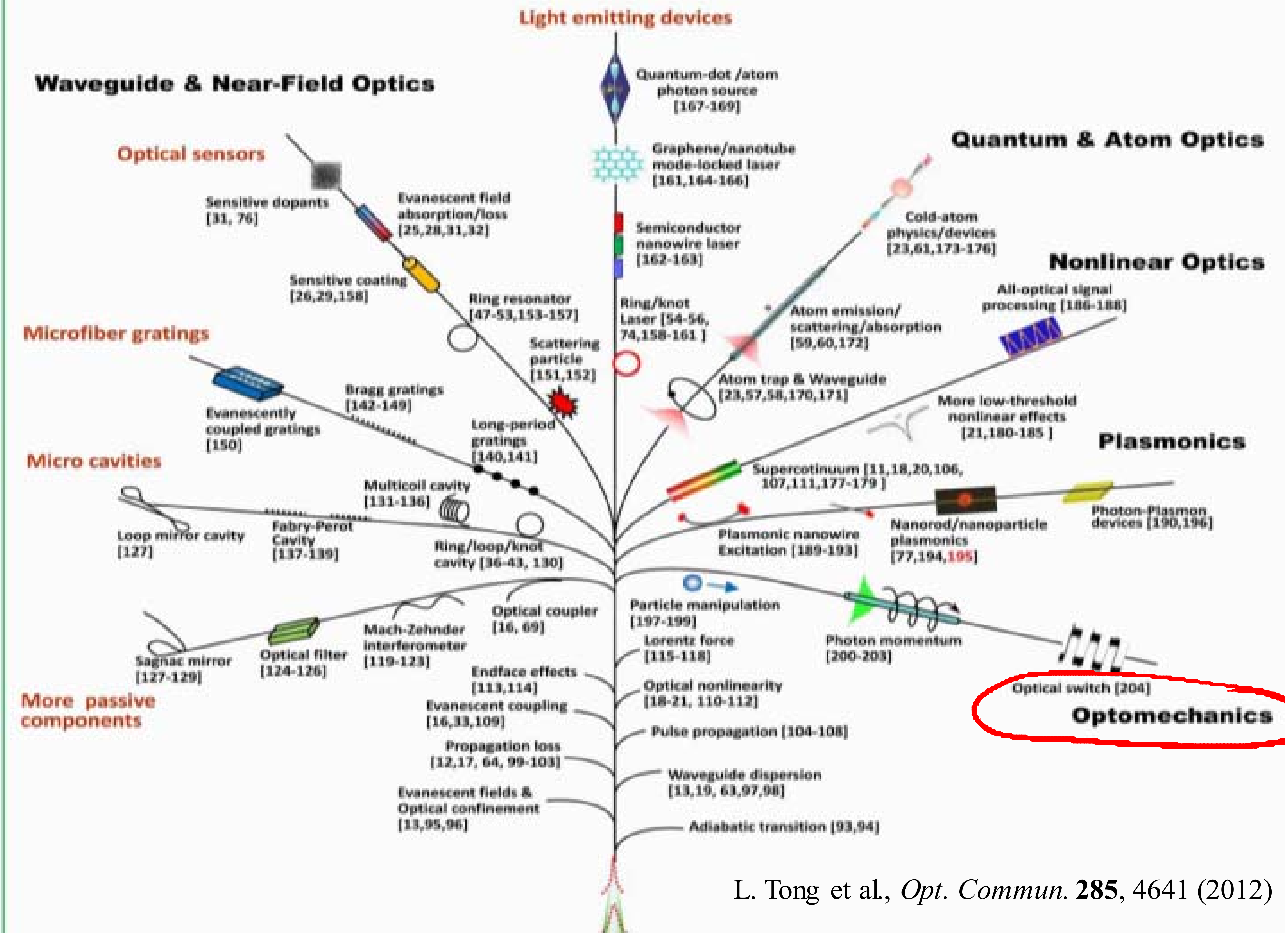
Pumping light : $\lambda\sim$800 nm, $\tau\sim$100 fs



Fiber diameter good for spectral broadening : 400 – 700 nm

Fig. 2. Supercontinuum spectra for the six fibers of Fig. 1. The transmitted pulse energies are: (*a*) 0.3 nJ, (*b*) 4 nJ, (*c*) 6 nJ, (*d*) 4 nJ, (*e*) 7 nJ and (*f*) 2.5 nJ.

[13] R. R. Gattass et al., *Opt. Express* **14**, 9408 (2006)



L. Tong et al., *Opt. Commun.* **285**, 4641 (2012)

(4) Optomechanics

Feel momentum of light

Sun Yat-Sen Univ (China) 中山大学

Extremely light in mass

↓

Weight & elastic bending force
of a silica nanofiber is comparable to the force caused by
momentum change of light

↓

Feel the momentum of light guided through

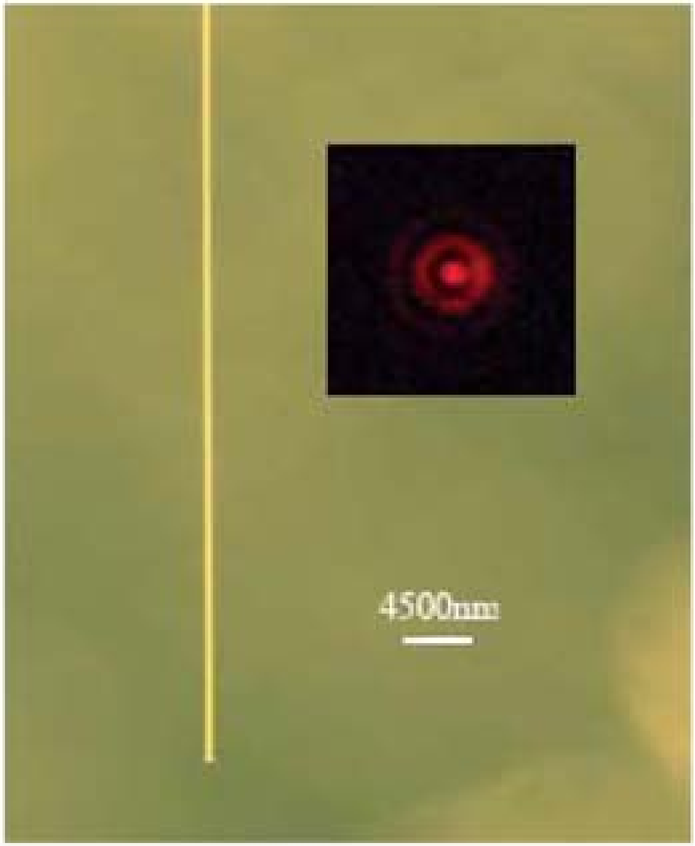


FIG. 1 (color online). The stationary micrograph of the tip of the SF, showing that the diameter of the SF tip is about 450 nm. The inset is the enlarged profile of a weak red light beam outgoing from the SF end face.

W. L. She et al., *Phys. Rev. Lett.* 101, 243601 (2008)

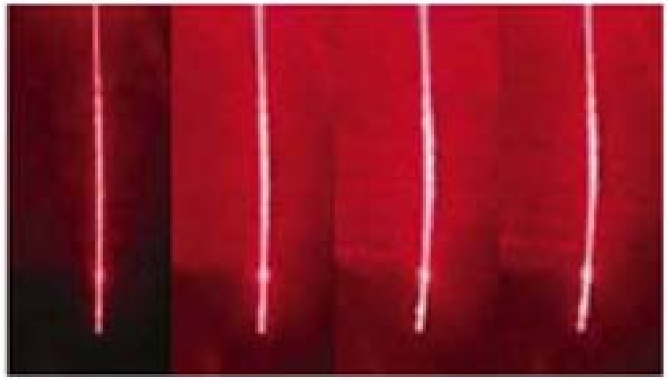
Phys. Rev. Lett. **101**, 243601
(issue of 12 December 2008)
Title and Authors

10 December 2008

Light Bends Glass

Light gives a push rather than a pull when it exits an optical fiber, according to experiments reported in the 12 December *Physical Review Letters*. The observations address a 100-year-old controversy over the momentum of light in a transparent material: Is it greater or smaller than in air? In the experiments, a thin glass fiber bends as light shines out the end, apparently a recoil in response to the light gaining momentum as it passes from glass to air. But the many experimental subtleties mean that the issue is unlikely to be settled soon.

Light moves slower inside a material than it does in air or vacuum. In 1908



Phys. Rev. Lett. **101**, 243601 (2008)

Recoil action. A thin glass fiber goes from straight (far left) to bent (far right) after a laser pulse shoots out the fiber's tip. The effect suggests that light gains momentum as it exits the fiber and supports one side in a century-long

43601 (2008)

Physical Review Focus

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Light moves slower inside a material than it does in air or vacuum. In 1908

Observed a push force on the endface of a nanofiber exerted by outgoing light

Suggested Abraham's momentum in transparent dielectrics

$$P=E/(nc)$$

Phys. Rev. Lett. 101, 243601 (2008)

Recoil action. A thin glass fiber goes from straight (far left) to bent (far right) after a laser pulse shoots out the fiber's tip. The effect suggests that light gains momentum as it exits the fiber and supports one side in a century-long

43601 (2008)

(4) Optomechanics

Feel momentum of light

There was a debate on She's results [*PRL* 101, 243601(2008)], on the fractional momentum and mechanical momentum of photons [PRL103, 019301 (2009)].

Lorentz force density $\mathbf{f} = (\mathbf{P}\cdot\nabla)\mathbf{E} + \frac{\partial \mathbf{P}}{\partial t}\times \mu_0 \mathbf{H}$

Longitudinal component $\mathbf{f}_z = (\mathbf{P}\cdot\nabla)\mathbf{E}_z + (\frac{\partial \mathbf{P}}{\partial t}\times \mu_0 \mathbf{H})_z$

Mechanical momentum $\boldsymbol{p}^z_{\mathbf{mech}} = \Delta \mathrm{v}\int_0^T \mathbf{f}_z dt$

For continuous wave → $p^z_{\mathrm{mech}}=0$

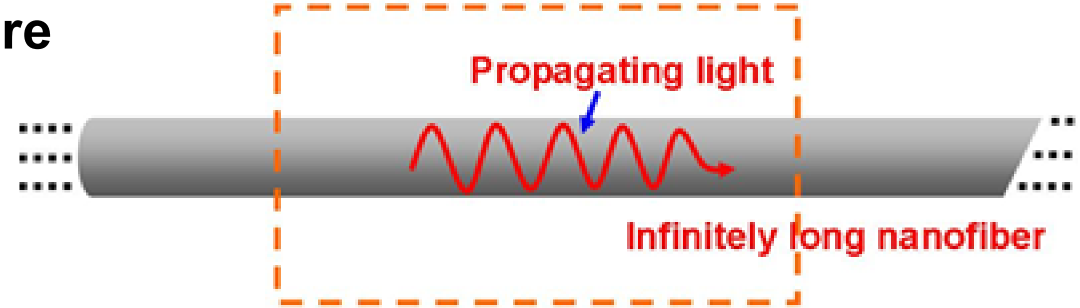
$P^z/P > 90\%$

H. K. Yu et al., arXiv:0907.4618

(4) Optomechanics

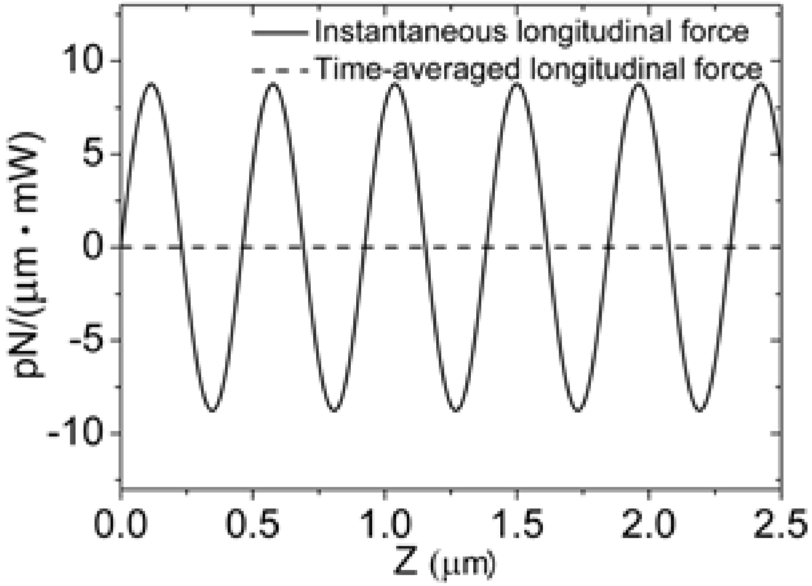
Longitudinal Lorentz force

(1) in a infinitely long nanofibre



Longitudinal Lorentz force density

$$\mathbf{f}_z = \rho_b \mathbf{E}_z + (\mathbf{J}_b \times \mu_0 \mathbf{H})_z$$



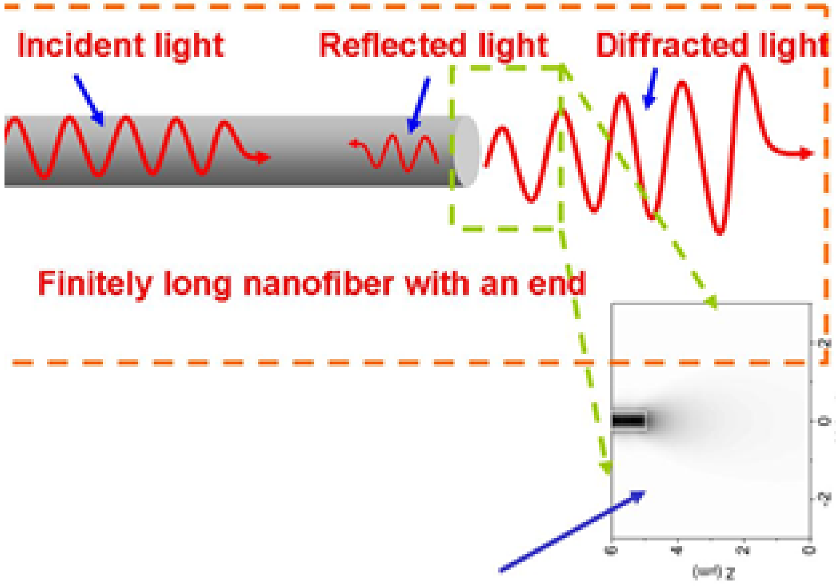
Silica nanofibre D=450 nm
Light wavelength = 980 nm

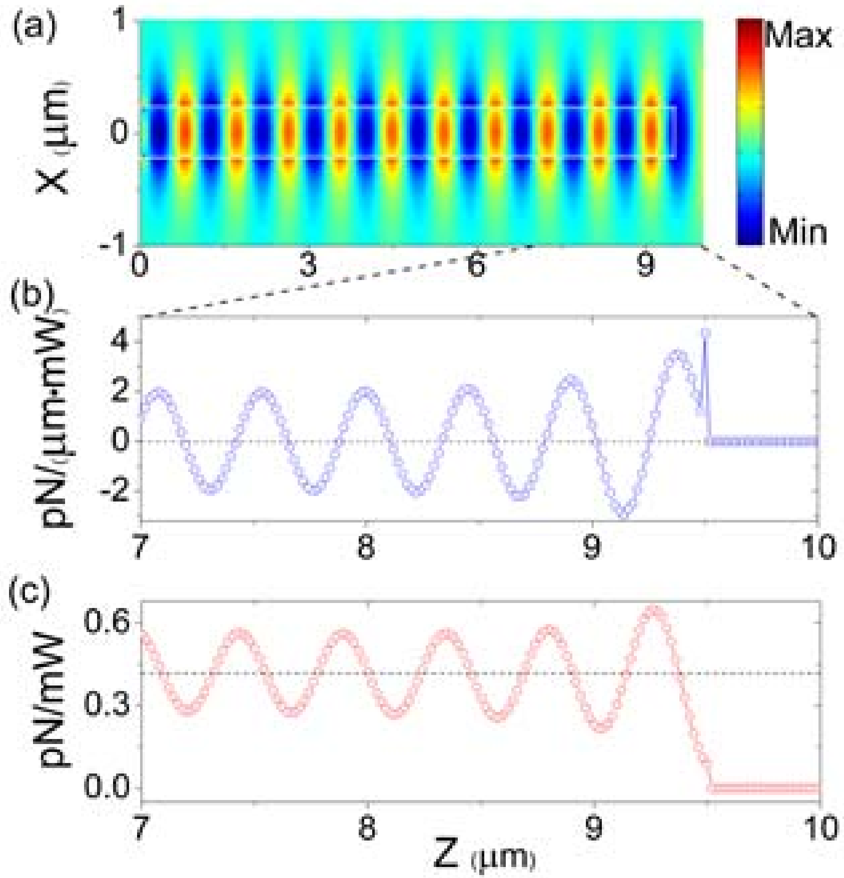
H. K. Yu et al., *Phys. Rev. A* **83**, 058380 (2011)

(4) Optomechanics

Longitudinal Lorentz force

(2) in a nanofibre with endface





Silica nanofibre D=450 nm
Light wavelength = 980 nm

Precisely determined Lorentz force can be used for intriguing nanofibre optomechanical devices

H. K. Yu et al., *Phys. Rev. A* **83**, 058380 (

Outline

- Introduction

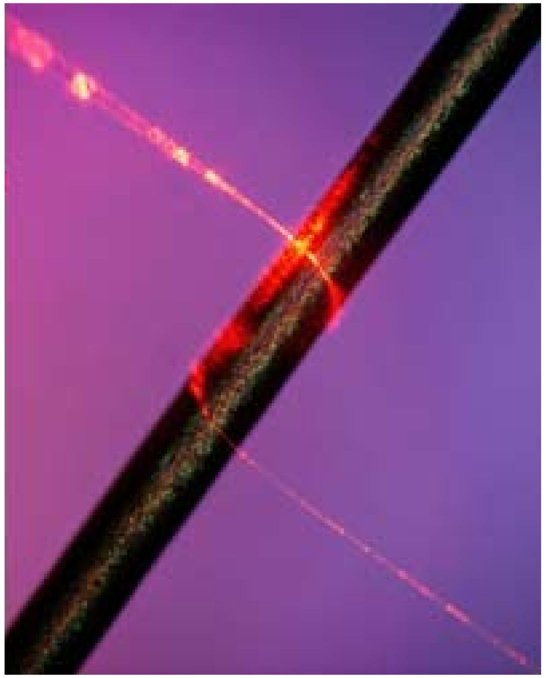
1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary

Summary



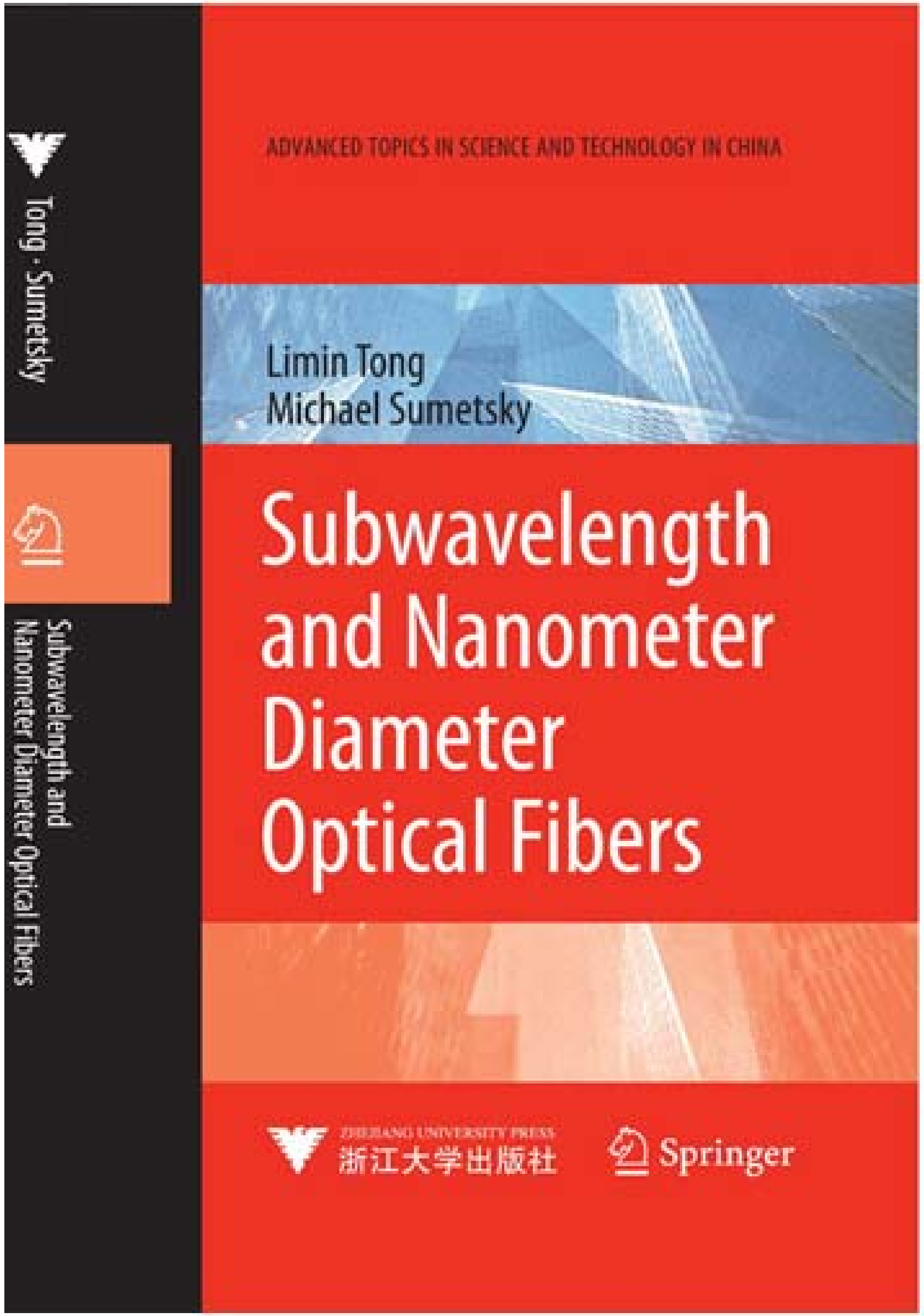
Glass micro/nanofibres offer favorable properties for manipulating light on the nanoscale.

When incorporated with guide wave optics, near-field optics, nonlinear optics, plasmonics and optomechanics, these 1-D glass nanostructures may bring new opportunities for both fundamental research and technological applications.

Summary

More details on nanofibre

Limin Tong, Michael Sumetsky, *Subwavelength and Nanometer Diameter Optical Fibers*, Zhejiang University Press, Springer, 2009.



Outlook

For nanofiber photonics

How far can we go ?

— depends on —

How well can we confine and transport the light

Outlook

For nanofiber photonics

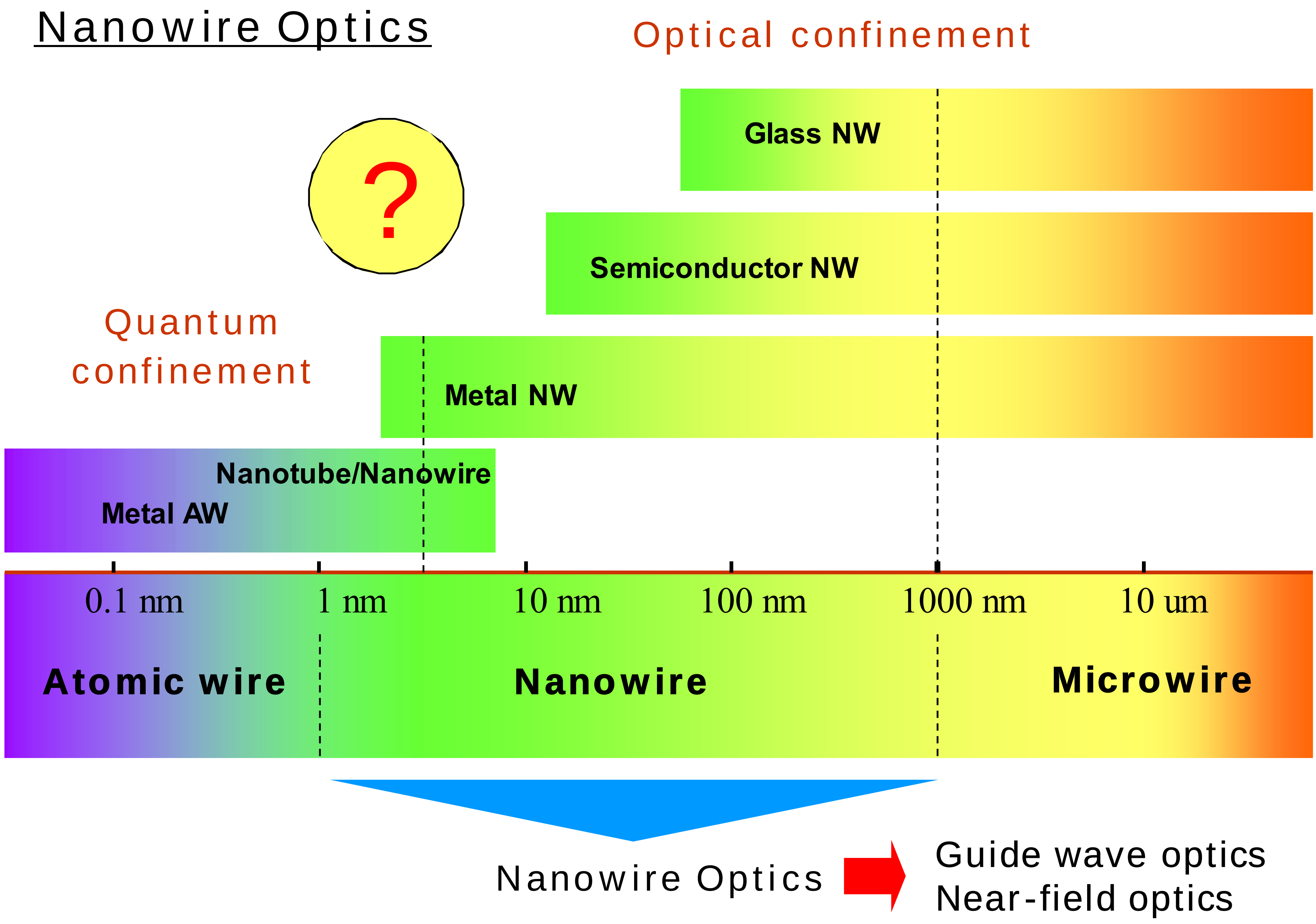
How far can we go ?

— depends on —

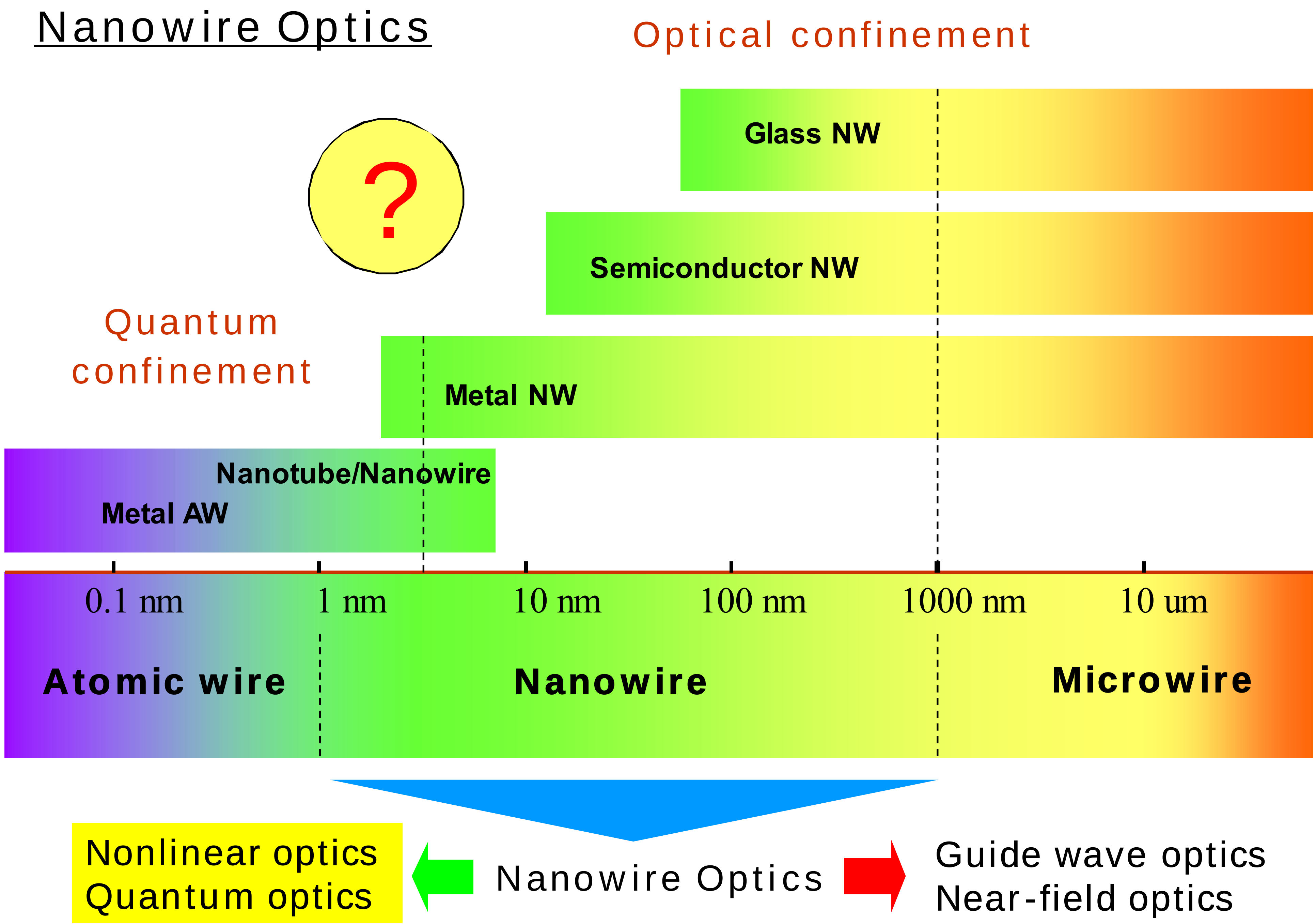
How well can we confine and transport the light

Dielectric Semiconductor Plasmonic

What's the next ?



Nanowire Optics
Optical confinement
Glass NW
?
Semiconductor NW
Quantum confinement
Metal NW
Nanotube/Nanowire
Metal AW
0.1 nm
1 nm
10 nm
100 nm
1000 nm
10 um
Atomic wire
Nanowire
Microwire
Nanowire Optics
Guide wave optics
Near-field optics


Nanowire Optics
Optical confinement
Glass NW
Semiconductor NW
?
Quantum confinement
Metal NW
Nanotube/Nanowire
Metal AW
0.1 nm
1 nm
10 nm
100 nm
1000 nm
10 um
Atomic wire
Nanowire
Microwire
Nonlinear optics
Quantum optics
Nanowire Optics
Guide wave optics
Near-field optics

Contributed by many colleagues and students of our Nanophotonics Research Group

Group photo 2012-06

Nanophotonics Research Group @ ZJU

www.nanophotonics.zju.edu.cn

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Collaborators

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KTH (Sweden)
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etc.

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