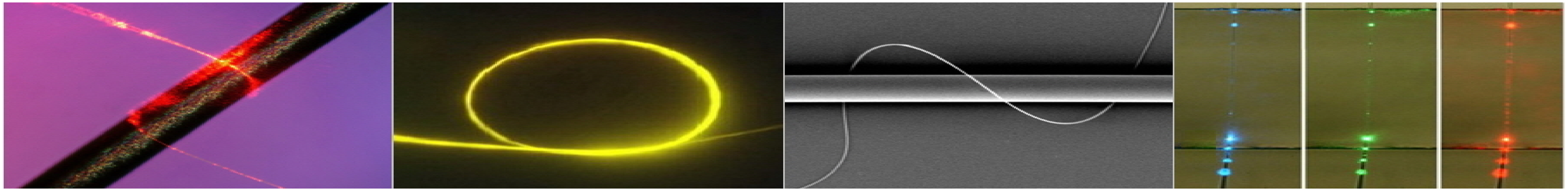
US-China Winter School on New Functionalities in Glass

Optical Microfibers and Nanofibers

Fabrication, Properties and Applications



Limin Tong

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

2010-01-12

Outline

- Introduction

1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary

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- Introduction

1. Fabrication

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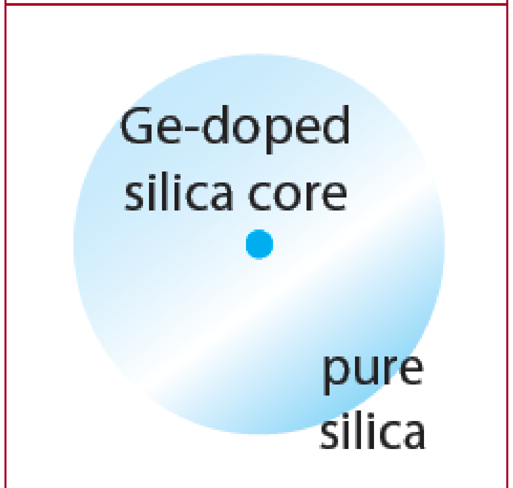
▫ Introduction

Optical fibers



In the past 40 years, optical fibers have been finding successful applications in

- **Optical communications**
- **Optical sensing**
- **Power delivery**
- **Nonlinear fiber optics**

⬇

Nobel Prize in Physics 2009

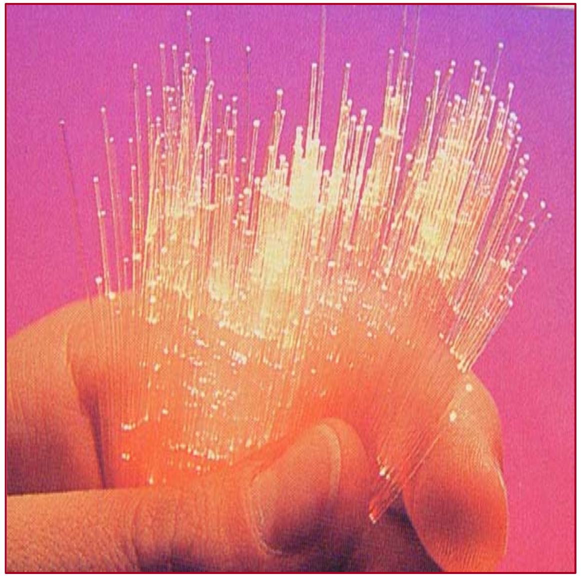
▫ Introduction

- **Optical fibers**

  Basically

  Linear Optics

  Guide light/photons linearly



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- **Optical fibers**

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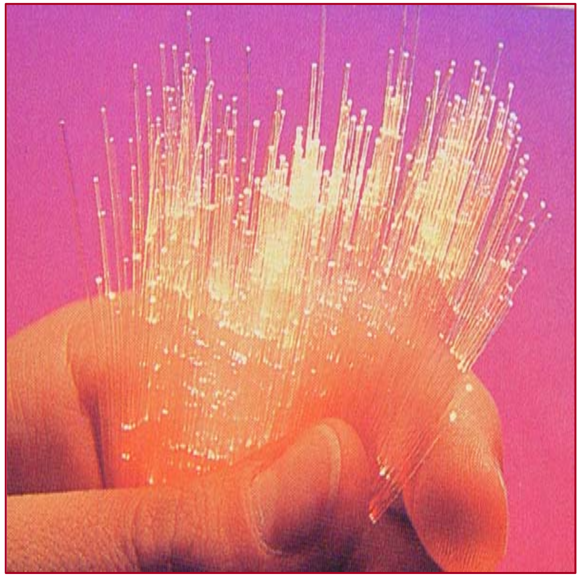
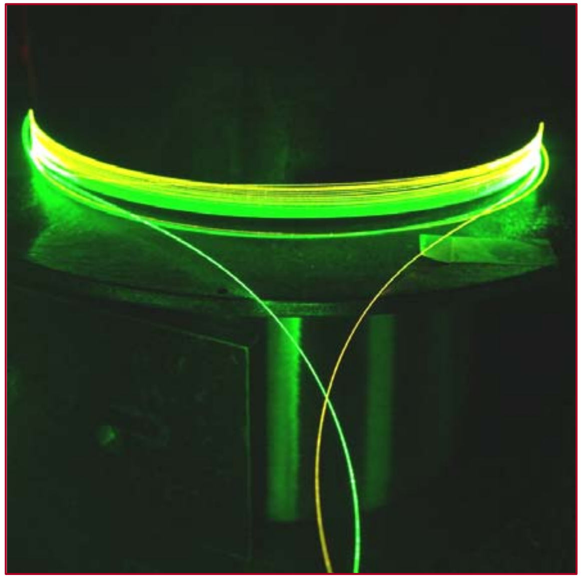


When the light is powerful enough

Nonlinear Optics

Absorb & Generate new light/photons



▫ Introduction

Miniaturization of optical fibers

Fiber-optic technology

- **Rapid development of nanotechnology**
- **Fiber optic devices with higher performances**

e.g., Higher sensitivity
Faster response
Higher density
Smaller footprint

▫ Introduction

● Miniaturization of optical fibers

Fiber-optic technology

- **Rapid development of nanotechnology**
- **Fiber optic devices with higher performances**

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Smaller footprint

It is desired to miniaturize optical fibers

◻ Introduction

- **Miniaturization of optical fibers**

  Also, it is always interesting to explore new opportunities of an optical fiber

Introduction

- **Miniaturization of optical fibers**

Also, it is always interesting to explore new opportunities of an optical fiber

For example

- **Besides the photon, can it guide something else?**
  e.g., an atom, a molecules, or a dust

Introduction

Miniaturization of optical fibers

Also, it is always interesting to explore new opportunities of an optical fiber

For example

- **Besides the photon, can it guide something else?**
  e.g., an atom, a molecules, or a dust

- **As electromagnetic waves, can the photons in a glass fiber behavior like the electrons in a copper wire?**
  e.g., making a connection by a simple touch

Introduction

- **Miniaturization of optical fibers**

The answer: Yes, if the fiber is thin enough

Optical microfiber or nanofiber

Therefore, the motivation of shrinking optical fibers is:

Explore new opportunities on new dimensions

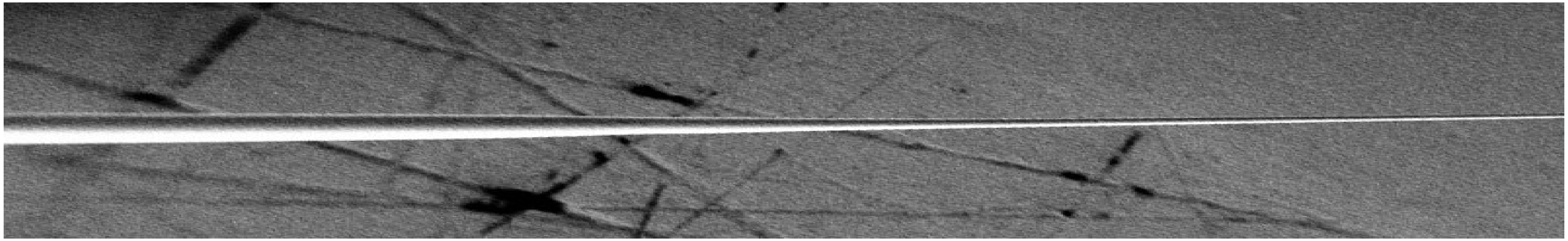
▫ Introduction

● Miniaturization of optical fibers

For this purpose

One of the simplest approach

Drawing a standard optical fiber to micro or nanometer scale



▫ Introduction

■ Optical micro/nanofiber

an optical fiber with diameter close to or thinner than the wavelength of the light it guided

i.e., $D_{fiber} \approx \lambda \quad or \quad D_{fiber} < \lambda$

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Optical micro/nanofiber

an optical fiber with diameter close to or thinner than the wavelength of the light it guided

i.e., $D_{fiber} \approx \lambda \quad or \quad D_{fiber} < \lambda$

sometimes it is called

"Subwavelength-diameter wires"/ "Microfiber" / "Nanofiber" / "Nanotaper"/ "Nanowire"/

"Fiber taper"/"Ultrathin optical fiber"…

letters to nature

Subwavelength-diameter silica wires for low-loss optical wave guiding

Limin Tong[1,2], Rafael R. Gattass[1], Jonathan B. Ashcom[1]*, Sailing He[2], Jingyi Lou[2], Mengyan Shen[1,3], Iva Maxwell[1] & Eric Mazur[1]

[1]*Department of Physics and Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA*
[2]*Centre for Optical and Electromagnetic Research and Department of Physics,*

APPLIED PHYSICS LETTERS 86, 161108 (200

Optical microfiber loop resonator

M. Sumetsky,[a)] Y. Dulashko, J. M. Fini, and A. Hale
OFS Laboratories, 19 Schoolhouse Road, Somerset, New Jersey 08873

(Received 4 November 2004; accepted 8 March 2005; published online 13

We experimentally demonstrate an optical microfiber loop resonator. The r
free space by creating a loop from the subwavelength-diameter waist of a

Ultra-low-loss optical fiber nanotapers

Gilberto Brambilla,Vittoria Finazzi, and David J. Richardson
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gb2@orc.soton.ac.uk
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PHYSICAL REVIEW A 73, 013819 (2006)

Scattering of an evanescent light field by a single cesium atom near a nanofiber

Fam Le Kien,[1,*] V. I. Balykin,[1,2] and K. Hakuta[1]
[1]*Department of Applied Physics and Chemistry, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan*

February 15, 2008 / Vol. 33, No. 4 / OPTICS LETTERS

Mach–Zehnder interferometers assembled with optical microfibers or nanofibers

Yuhang Li and Limin Tong*
State Key Laboratory of Modern Optical Instrumentation, and Department of Optical Engineering, Zhejiang University, Hangzhou 310027, China
*Corresponding author: phytong@zju.edu.cn

New Journal of Physi
The open-access journal for physics

Single atoms on an optical nanofibre

K P Nayak and K Hakuta[1]
Department of Applied Physics and Chemistry, University of
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003 (9pp)

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PRL 99, 163602 (2007) PHYSICAL REVIEW LETTERS week ending 19 OCTOBER 2007

Cold-Atom Physics Using Ultrathin Optical Fibers: Light-Induced Dipole Forces and Surface Interactions

G. Sagué, E. Vetsch, W. Alt, D. Meschede, and A. Rauschenbeutel*
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In this talk ⇩ for simplicity

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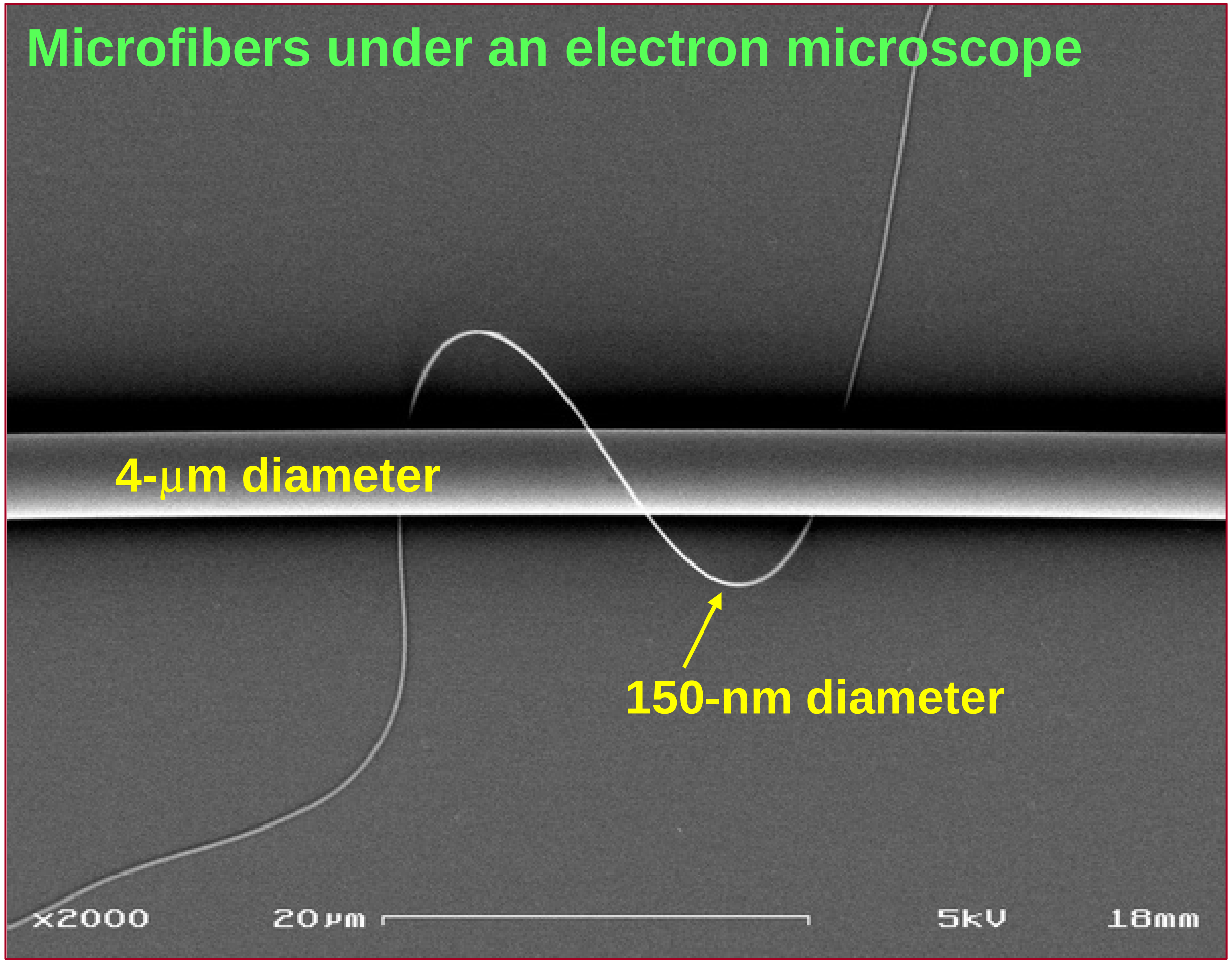
▫ Introduction

- **What does an optical microfiber look like ?**

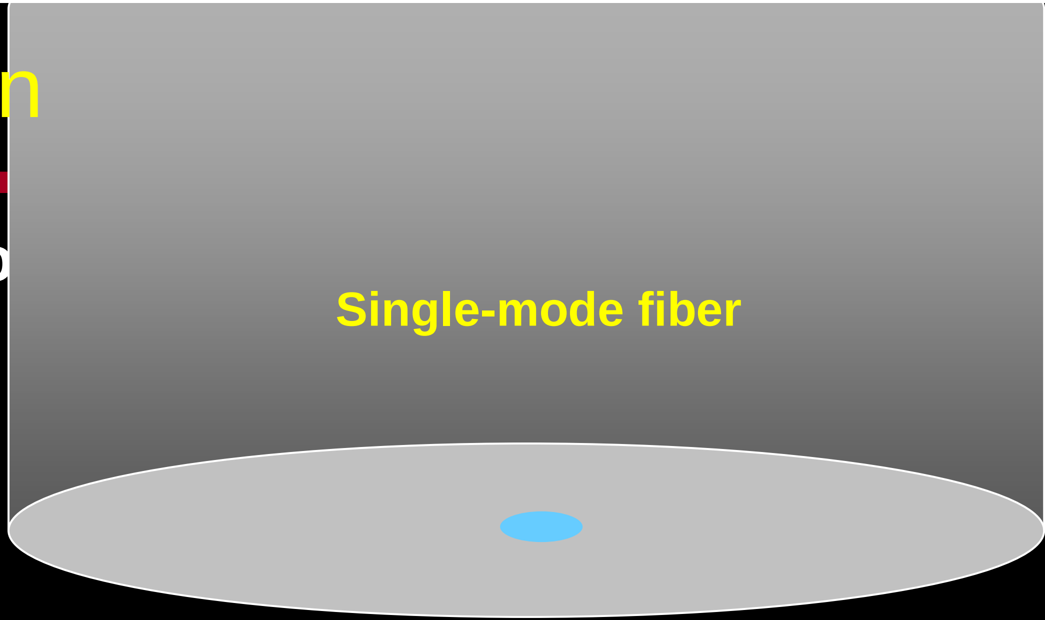


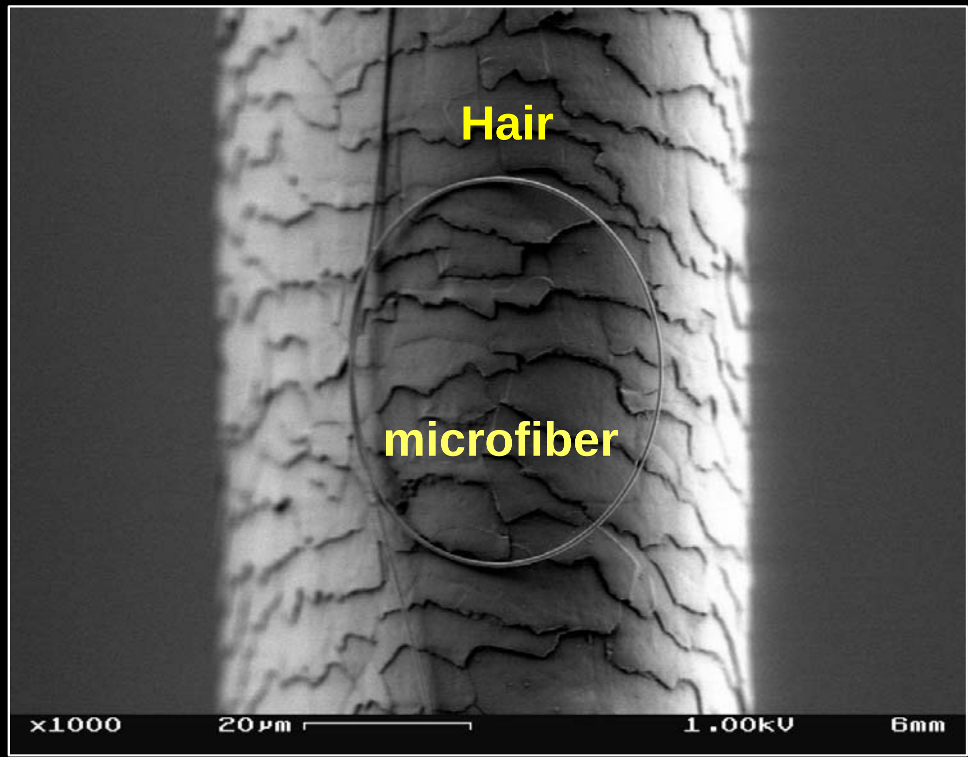
L. Tong et al., *Nanotechnology* **16,** 1445 (2005)

▫ Introduction

- **What does an o**

Scale of a microfiber





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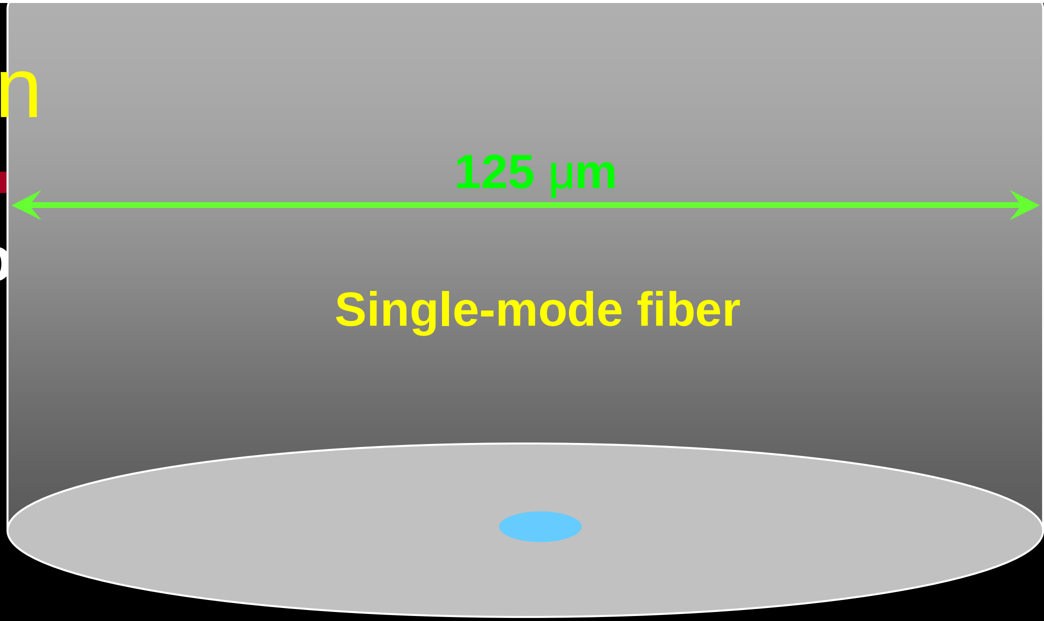

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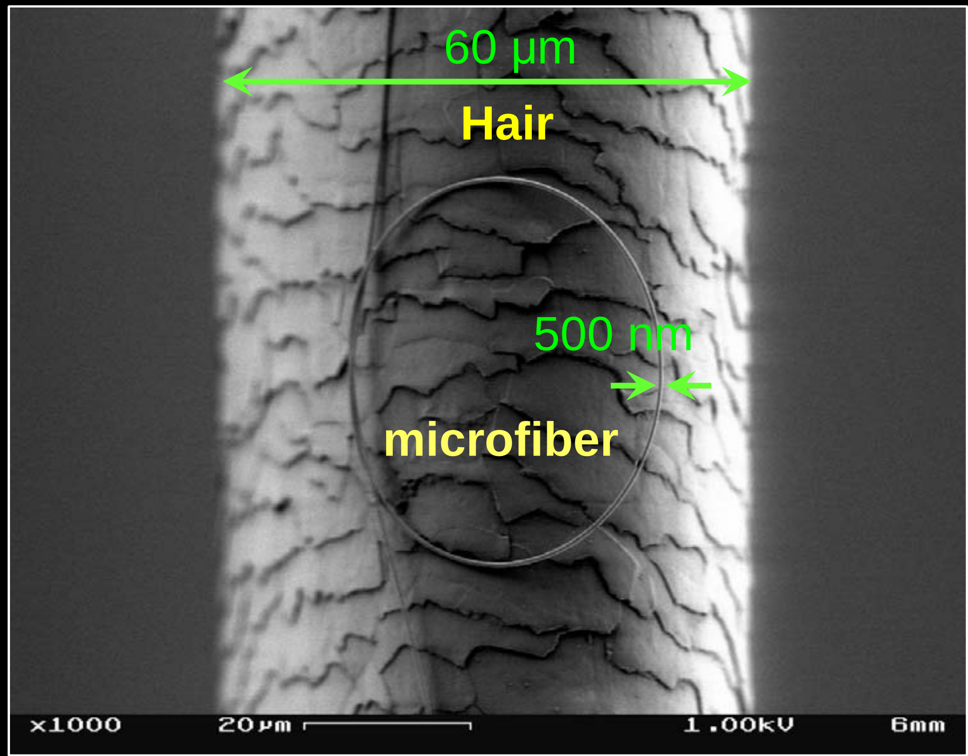


▫ Introduction

● **What does an optical microfiber look like ?**

Due to its large length, despite of its thin diameter, a microfiber is visible to the naked eye.

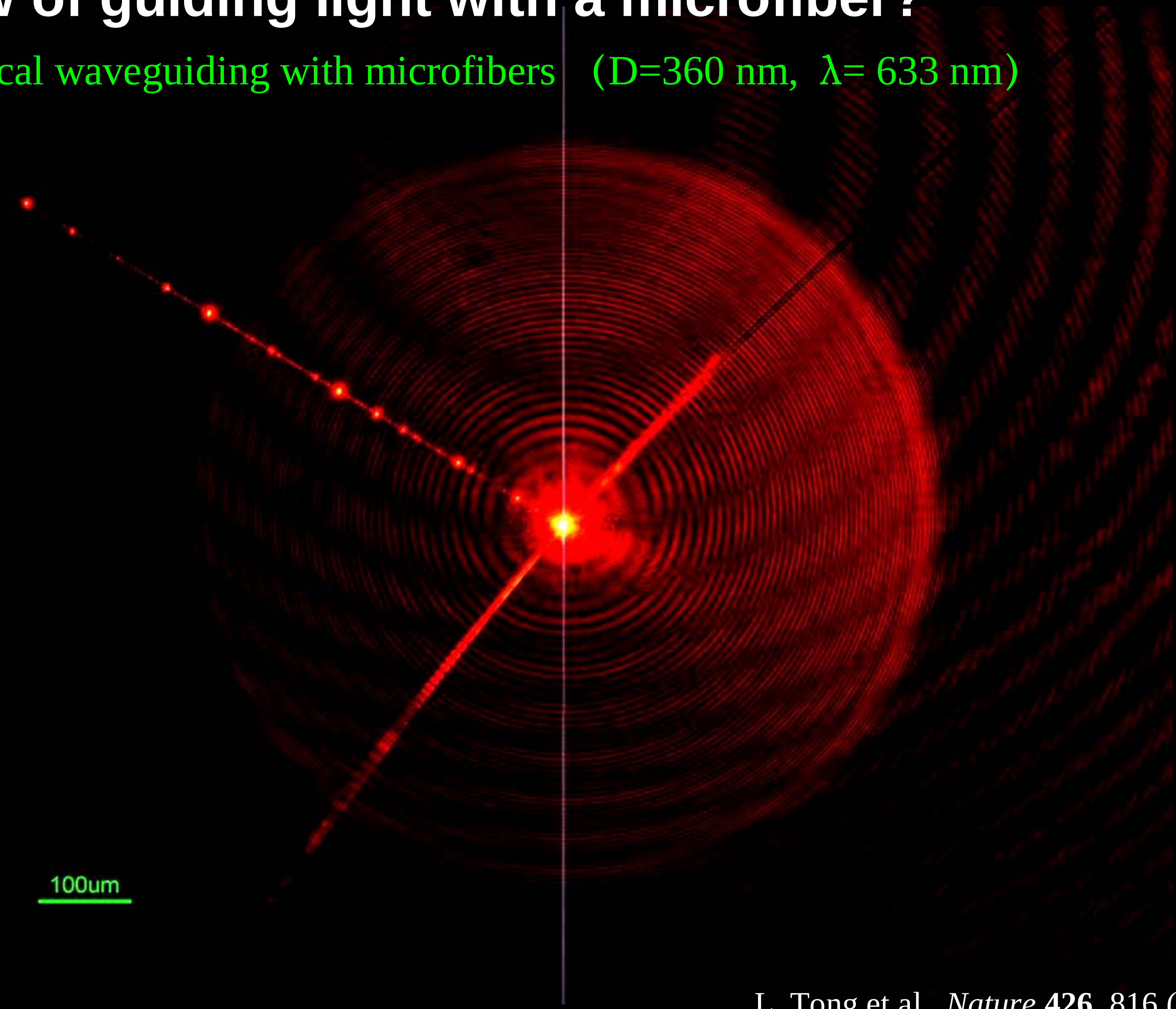
Nanoscale glass

Movie 0-1: A 350-nm-diameter nanofiber captured by a digital camera using close-up mode, the fiber is illuminated by a 633-nm-wavelength light guided along it

Introduction

- **What's new of guiding light with a microfiber?**

Low-loss optical waveguiding with microfibers (D=360 nm, λ= 633 nm)



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

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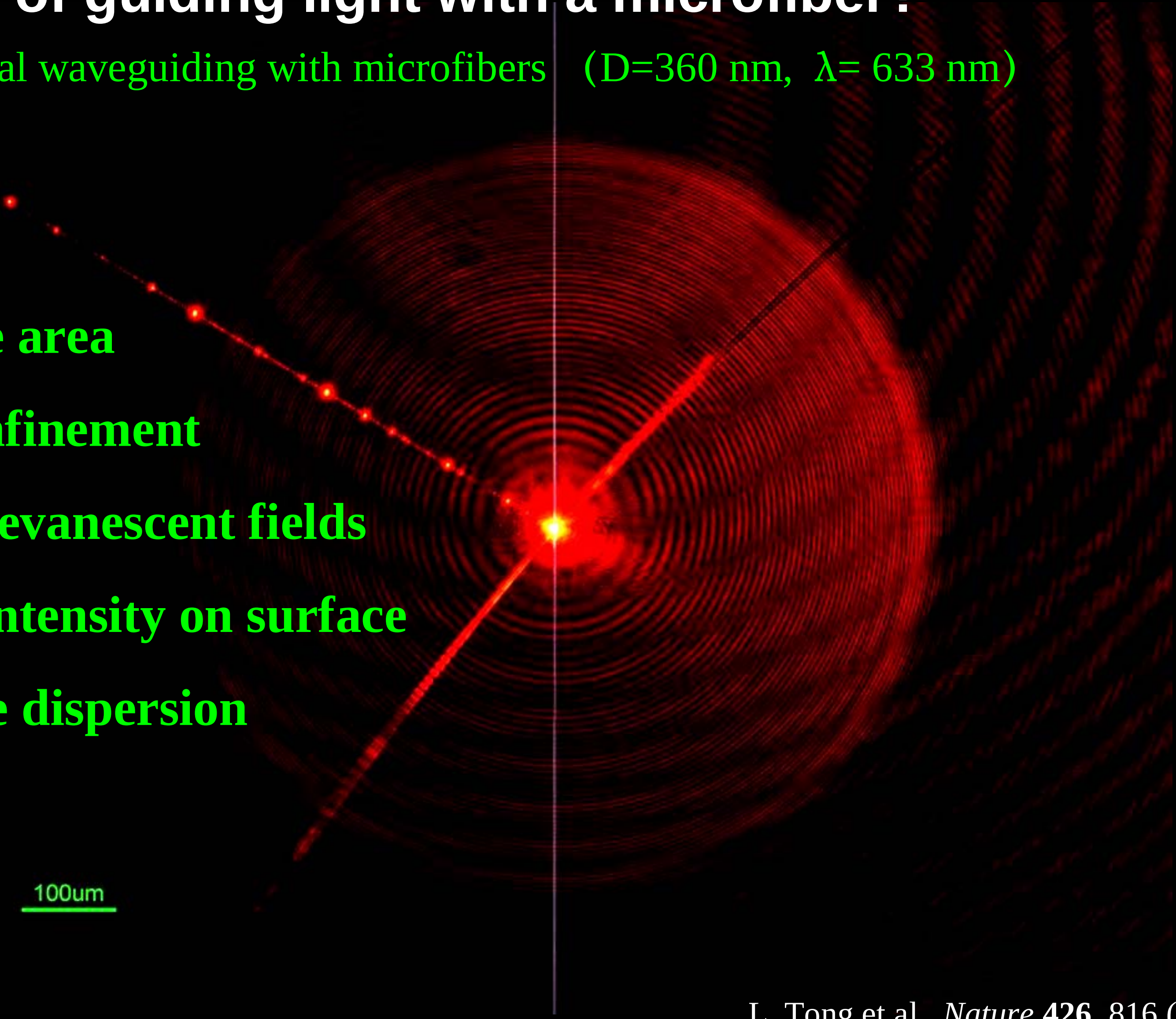

Very small mode area

Tight optical confinement

High fraction of evanescent fields

Enhanced field intensity on surface

Large waveguide dispersion

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

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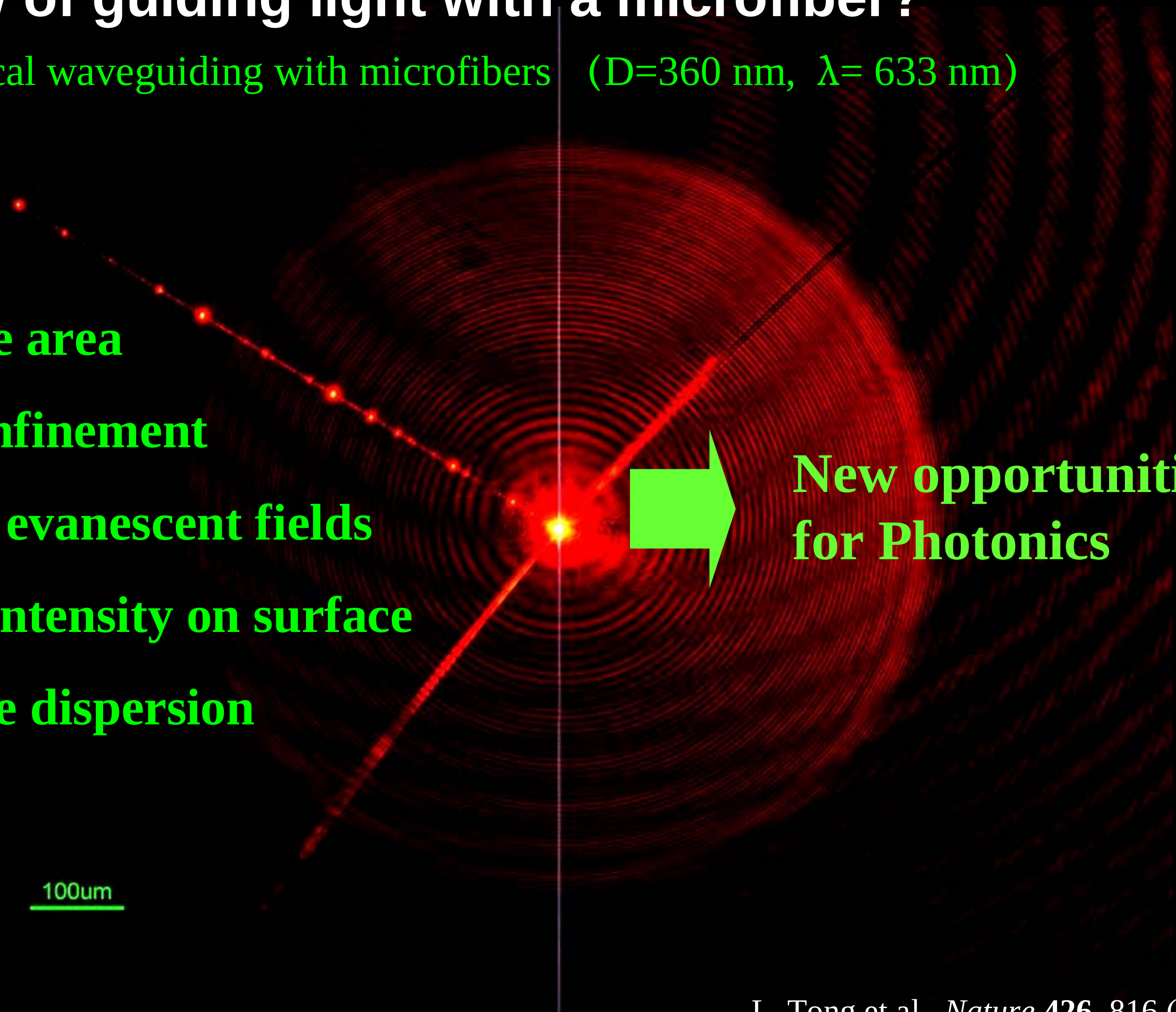

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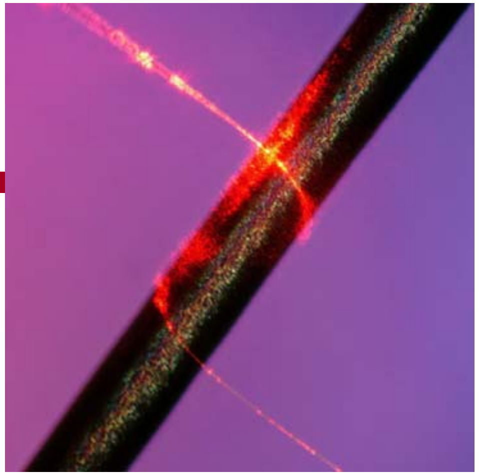
⇒ **New opportunities for Photonics**

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

▫ Introduction



● **Motivation for working on microfibers**

which makes it possible to combine **fiber optics** with **near-field optics**, **nonlinear optics**, **plasmonics** and **quantum optics** on micro/nanoscale, for both fundamental research and technological applications

---

Optical communication

Optical sensing

Optical computing

Quantum information

...

▫ Introduction

■ Next Generation Fibers

G. Brambilla, “**Next generation fibers: Optical fibers go nano**”, *Laser Focus World*, October 2007, p85-88.

Optical fibers go nano

GILBERTO BRAMBILLA

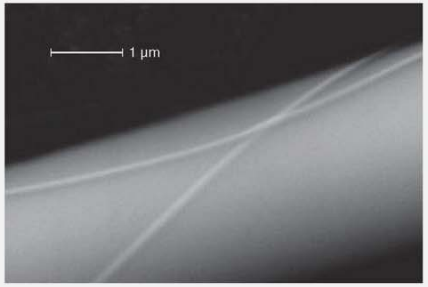


FIGURE 1. Two nanowires with radii of 30 and 50 nm manufactured from standard telecom optical fibers (around which they are entwined) are shown in a scanning-electron micrograph. (*Courtesy of the University of Southampton*)

Nanoscience and nanotechnology have attracted much interest in recent years because materials exhibit novel properties when structured at nanometer dimensions. In the last two decades, nanowires and subwavelength wires have been fabricated from a variety of materials using a wide range of techniques, including electron-beam lithography, laser ablation, templates, vapor-liquid-solid techniques, physical- or chemical-vapor deposition, and sol-gel.

Although optical nanowires have previously been fabricated from silica, most have exhibited an irregular profile along their length. Surface roughness and length inhomogeneity appear to have limited the loss levels that could be reliably achieved, and thus their usefulness for optical applications.

Nanowires can also be drawn from optical fibers; this process results in very low surface roughness and high homogeneity. The low optical loss of these nanowires opens the way to a host of new optical devices for communications, sensing, biology, and chemistry.

Optical-fiber nanowires are fabricated by adiabatically stretching optical fibers, preserving the original fiber dimensions at the input and output ends and allowing ready splicing to standard fibers and fiber components. These fiber pigtails have macroscopic dimensions and allow the manipulation of a single nanowire without the expensive instrumentation typical of the nano world.

With large evanescent fields and high optical nonlinearity, nanofibers drawn from optical fiber are well suited for optical sensors and other devices. Their standard-size fiber ends allow for easy coupling of light in and out.

Flame brushing

In the last four years, the manufacture of nanowires from optical fibers has been established as a methodology to reliably produce structures with a transmission loss low enough to be used for optical devices. Among the top-down techniques, the “flame-brushing” technique provides the longest and most uniform nanowires with the lowest measured loss. Originally developed for the manufacture of fiber tapers and couplers, flame brushing is based on a small flame moving under an optical fiber that is being stretched. The control of the flame movement and the fiber stretch can be used to define the taper shape to an extremely high degree of accuracy.

Although taper diameters in the range of 1 µm can be eas-

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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"

> LVII. *On the Production, Properties, and some suggested Uses of the Finest Threads.* *By* C. V. Boys, *Demonstrator of Physics at the Science Schools, South Kensington**.
>
> I HAVE lately required for a variety of reasons to have fibres of glass or other material far finer than ordinary spun glass; I have therefore been compelled to devise means for producing with certainty the finest possible threads. As these methods may have some interest, and as some results already obtained are certainly of great importance, I have thought it desirable to bring this subject under the notice of the Physical Society, even though at the present time any account must of necessity be very incomplete.
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> The subject may be naturally divided, as in the title, into

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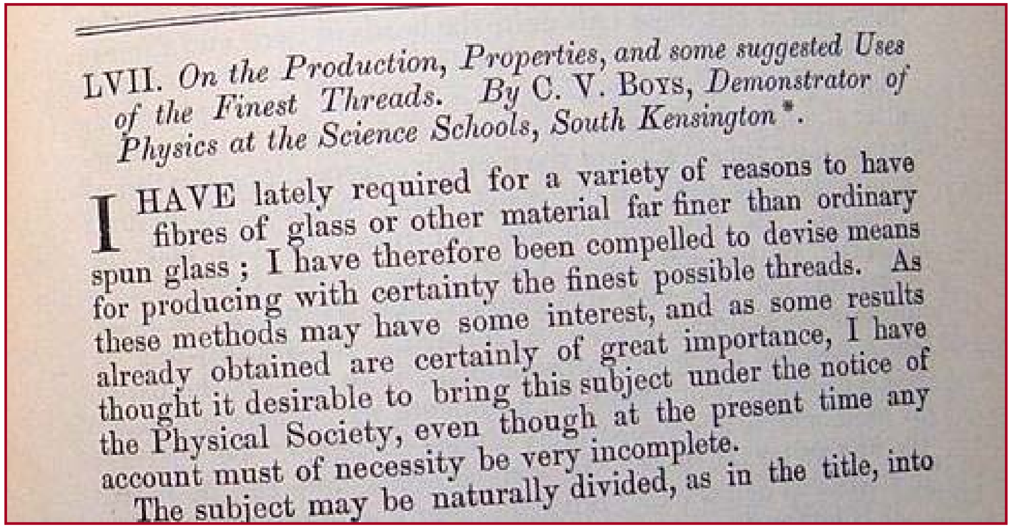
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The subject may be naturally divided, as in the title, into

Flame-heated drawing of molten glass → Finest threads

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

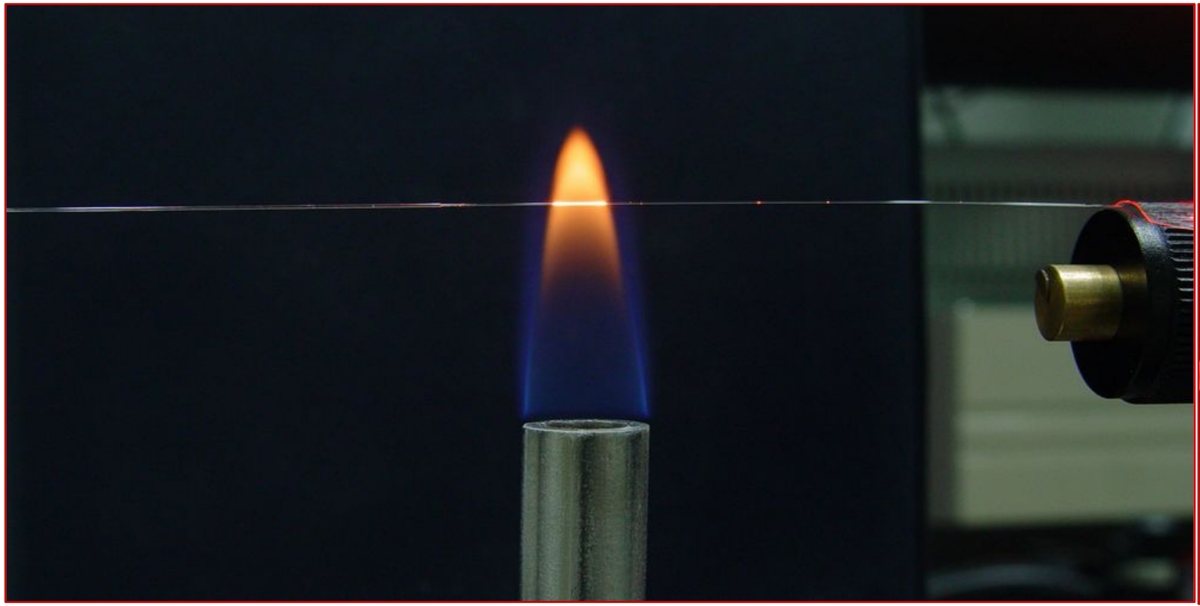
Applications

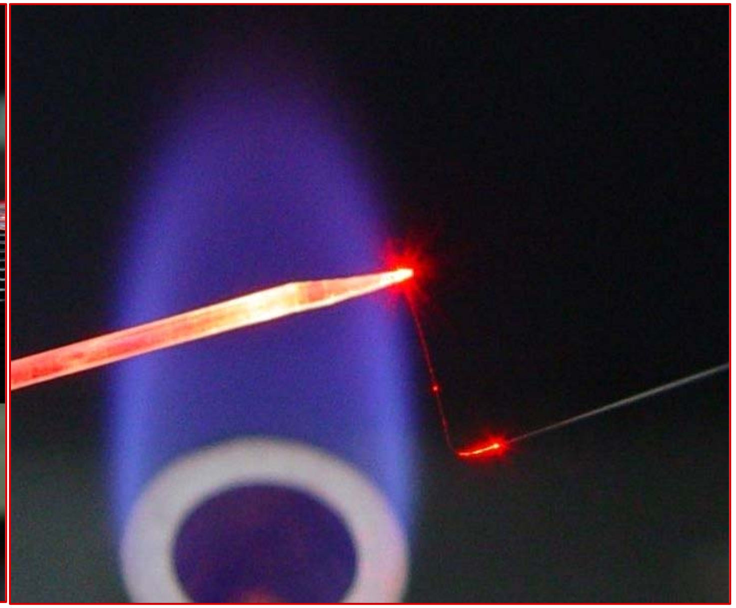
19th century: "Finest threads" → Elasticity → Spring for galvanometer

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?

Movie 1-1: Taper drawing a glass fiber heated by a flame

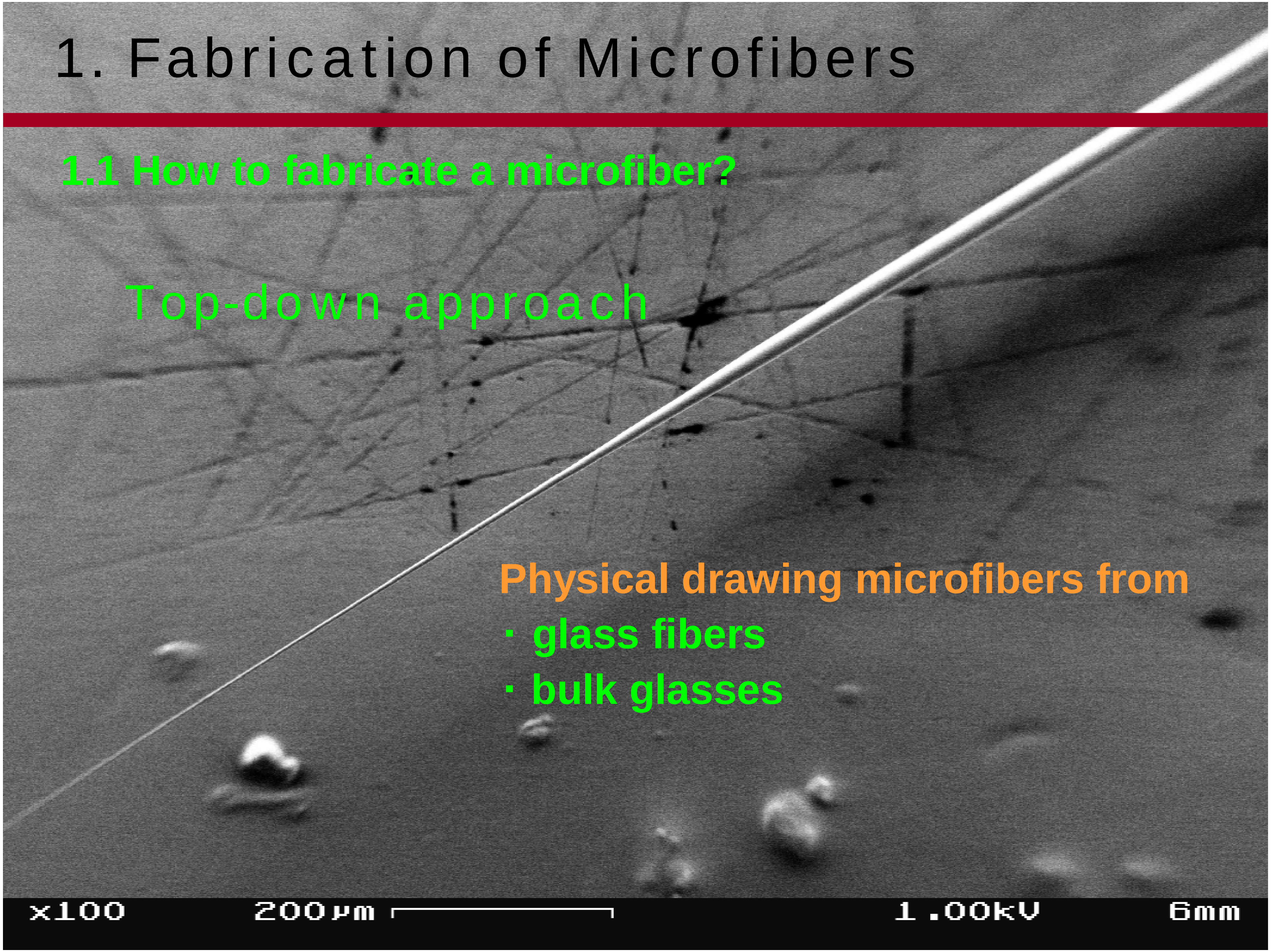
1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

Top-down approach

Physical drawing microfibers from

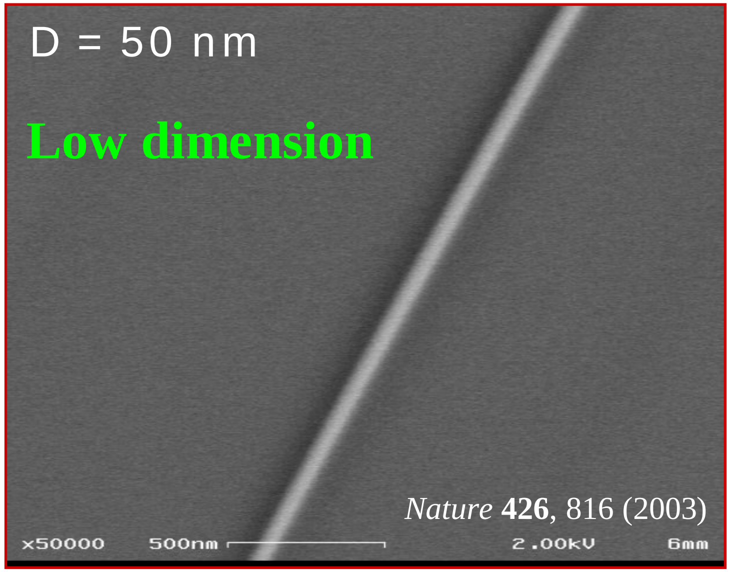
- **glass fibers**
- **bulk glasses**

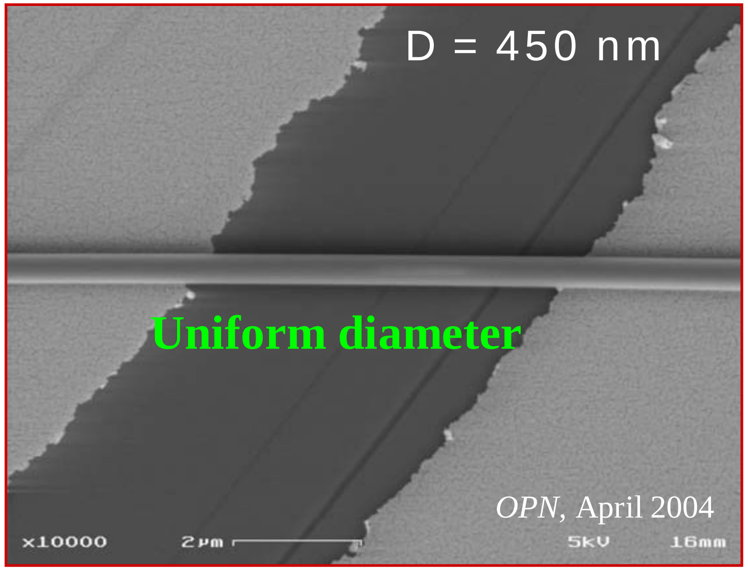


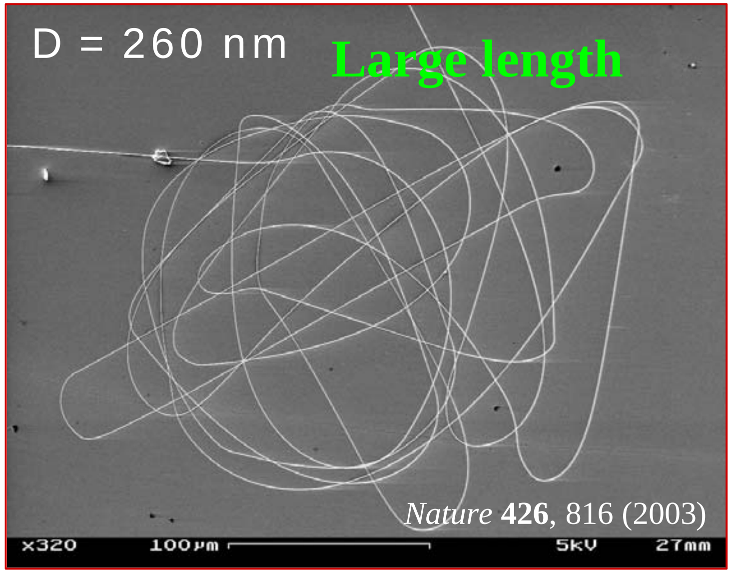
1. Fabrication of Microfibers

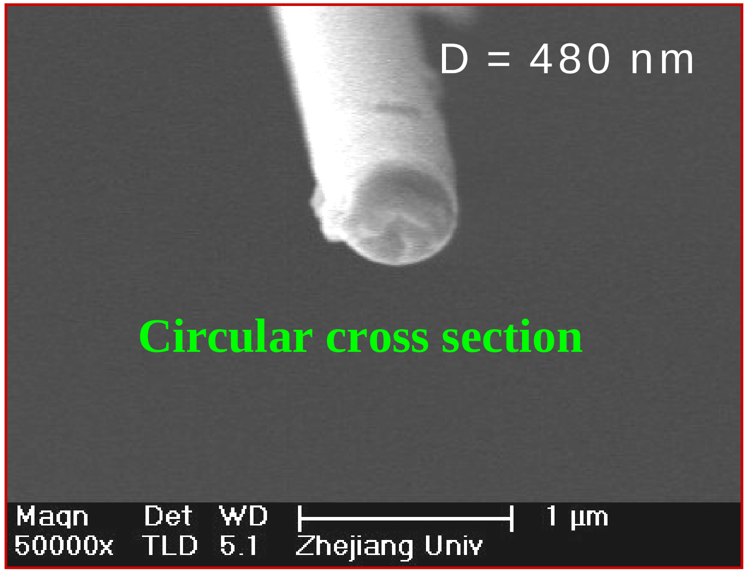
SEM images

Silica fibers





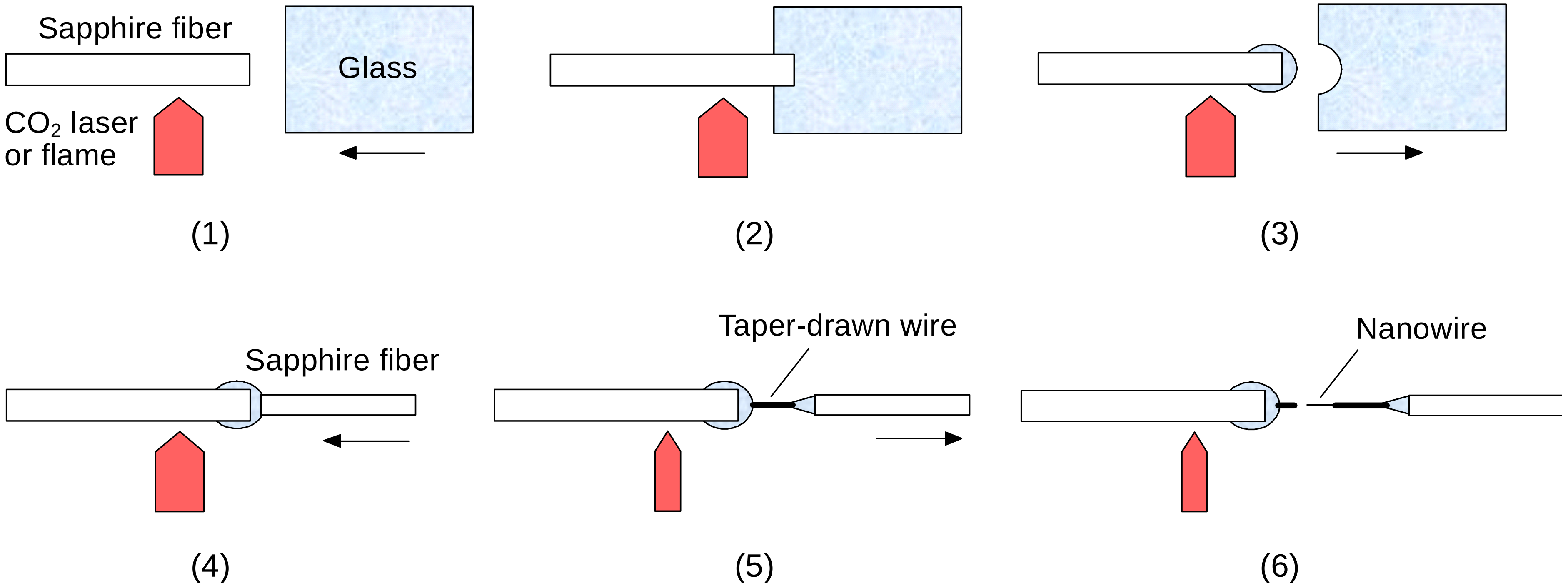




1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

Taper drawing of bulk glasses heated by flame or laser

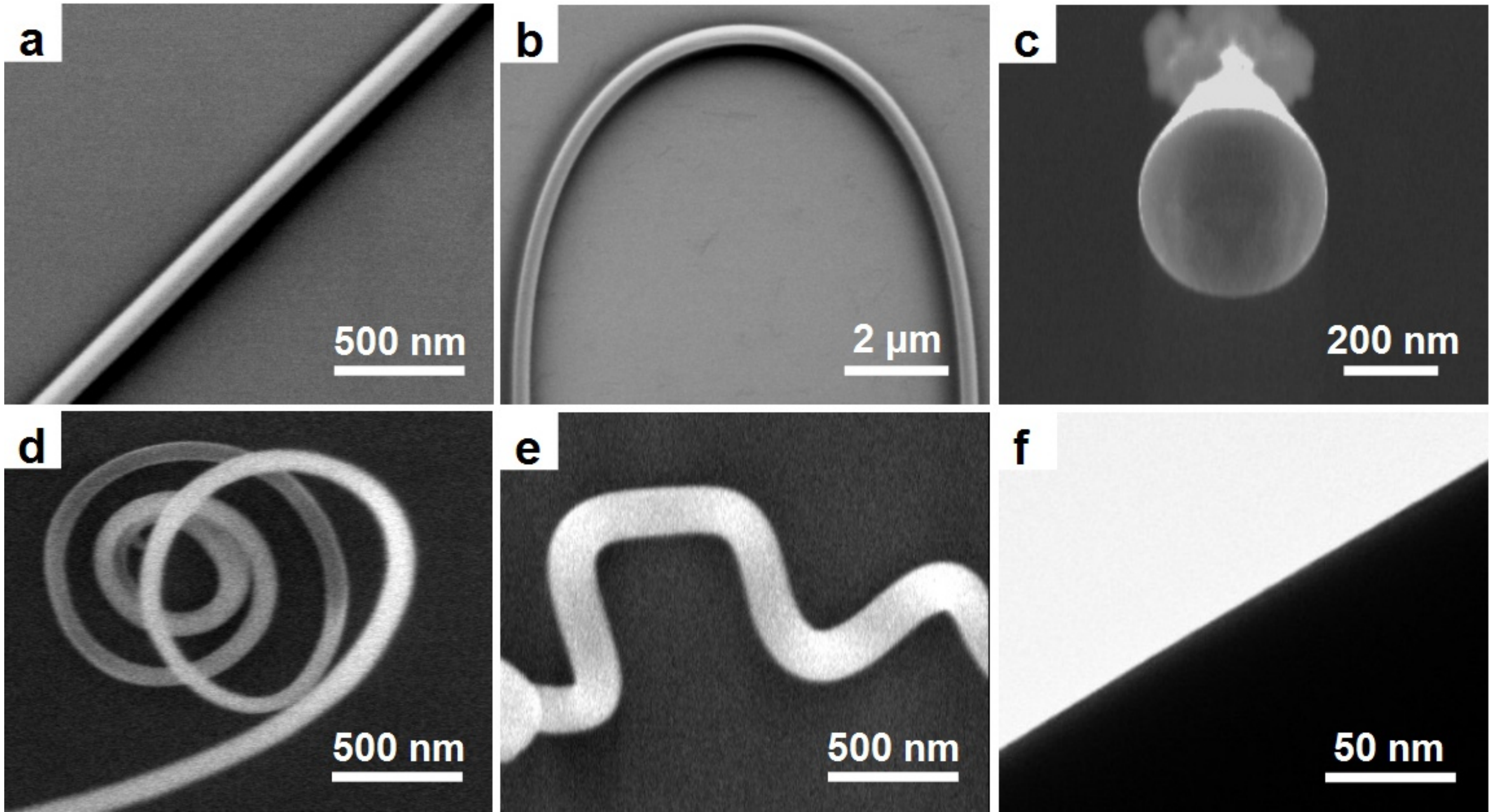


L. Tong et al., *Opt. Express* **14**, 82 (2006)

1. Fabrication of Microfibers

SEM images

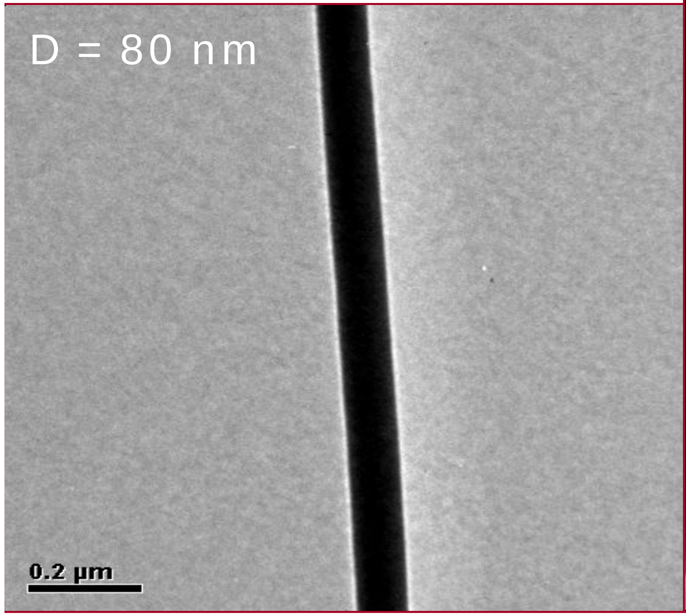
Other materials a, e: tellurite b: silicate c, d, f : phosphate

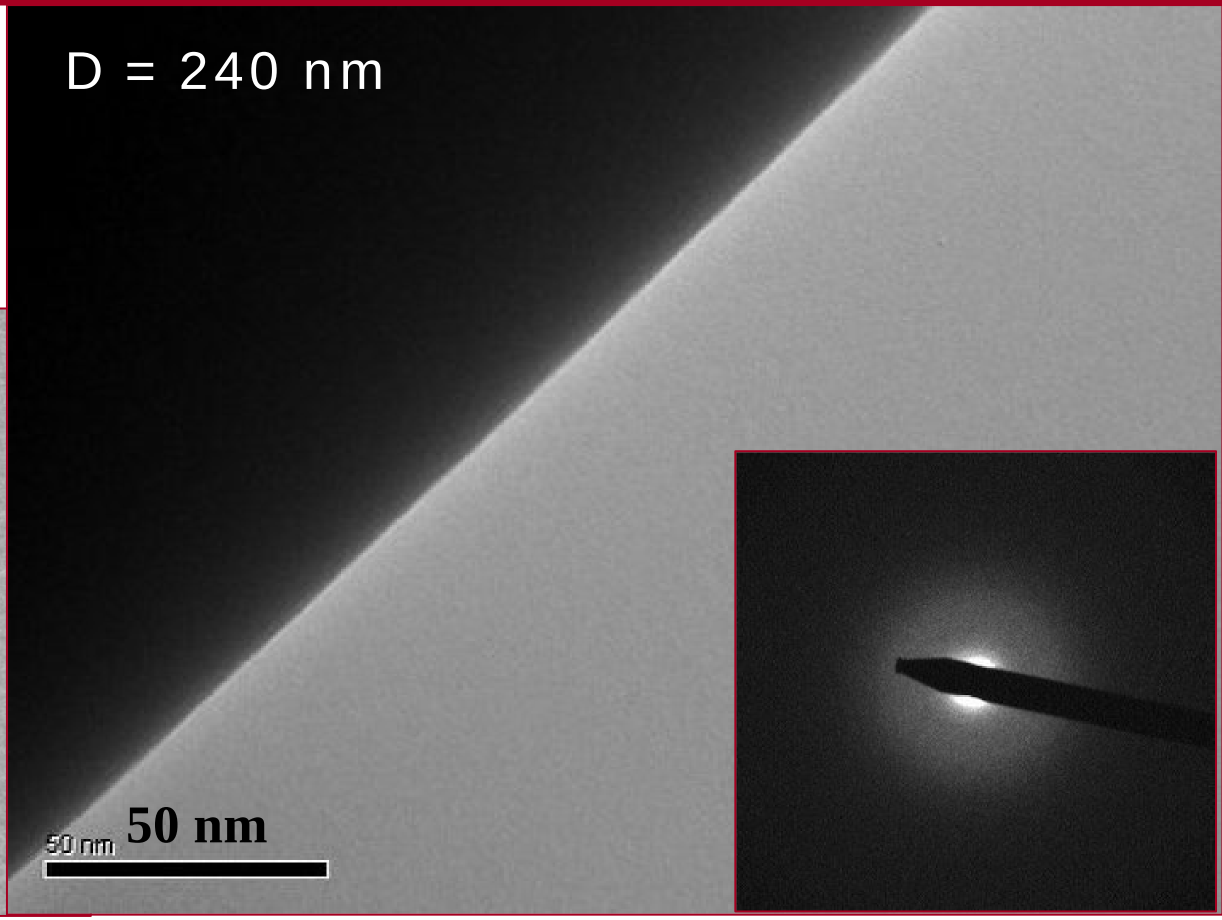


L. Tong et al., *Opt. Express* **14**, 82 (2006)

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

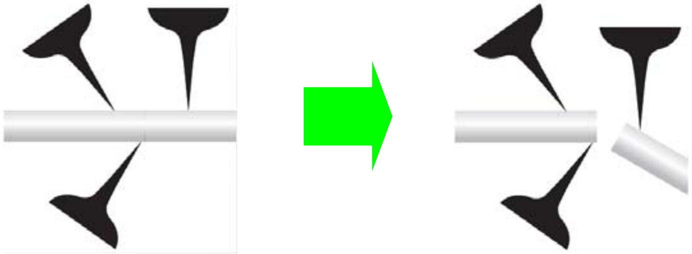
1. Fabrication of Microfibers

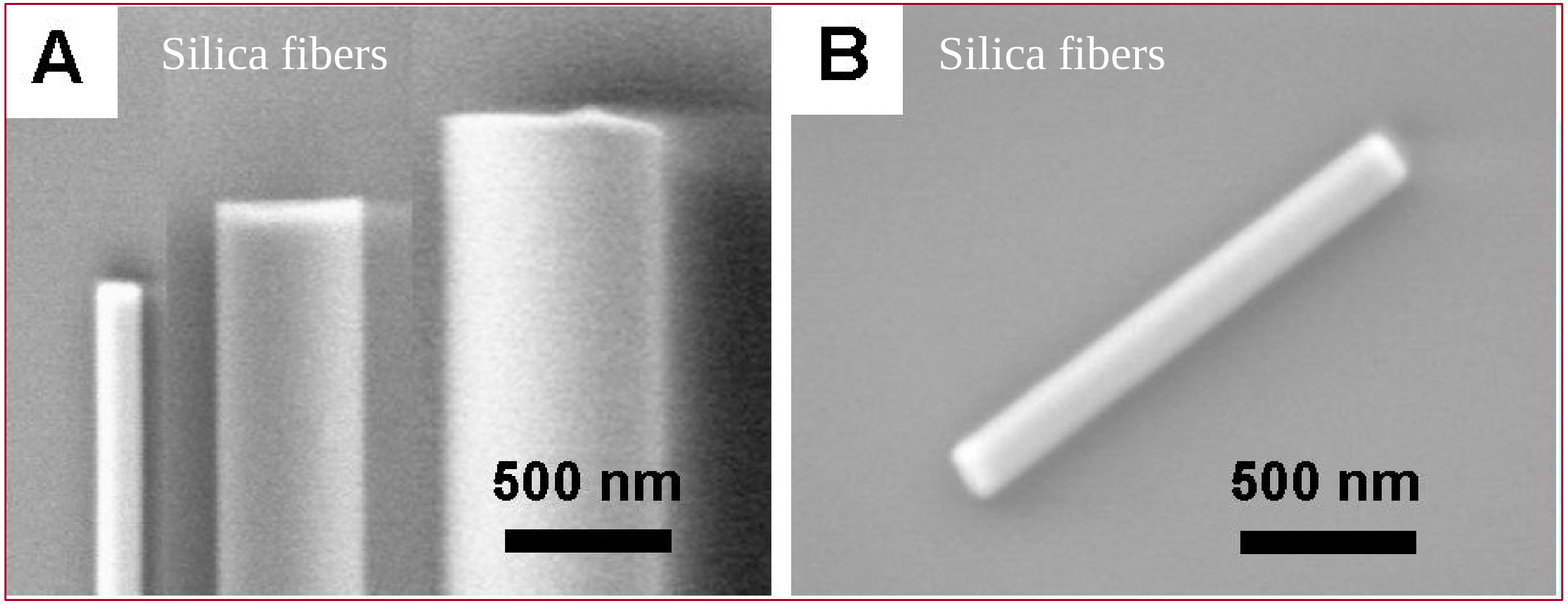
1.2 Micromanipulation

Tailoring through micro/nanomanipulation

- **Cut**

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





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

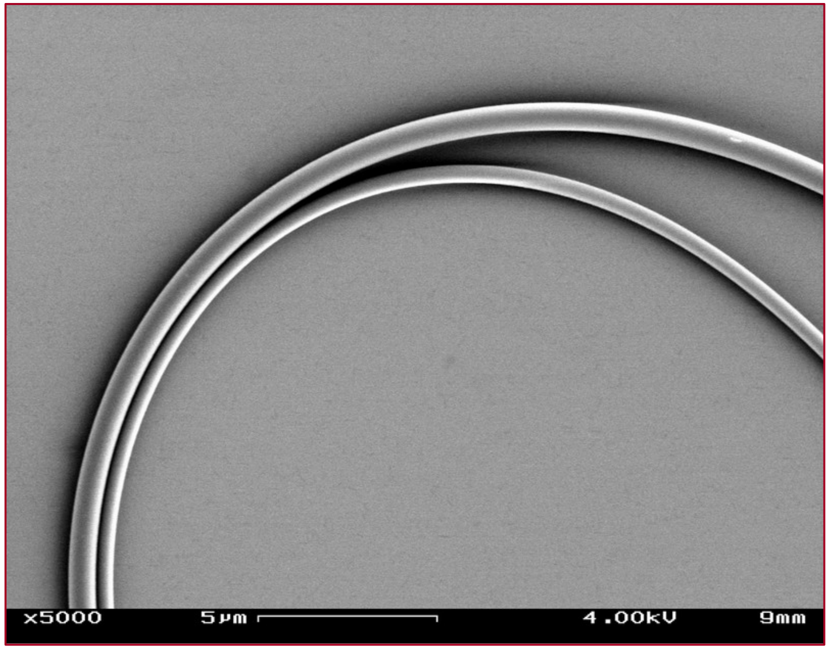
1. Fabrication of Microfibers

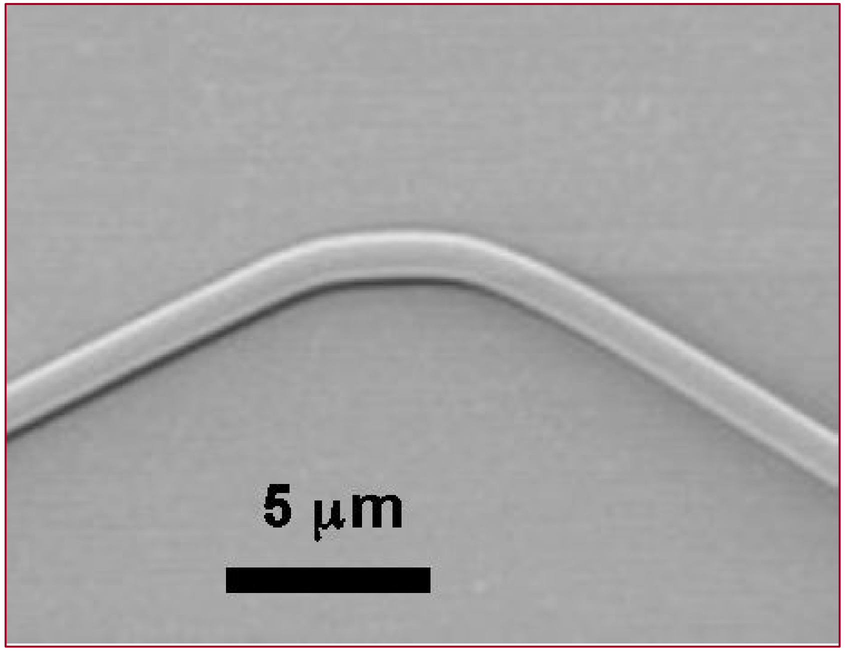
1.2 Micromanipulation

Tailoring through micro/nanomanipulation

- **Plastic bend**

Annealing-after-bending method





Silica fibers

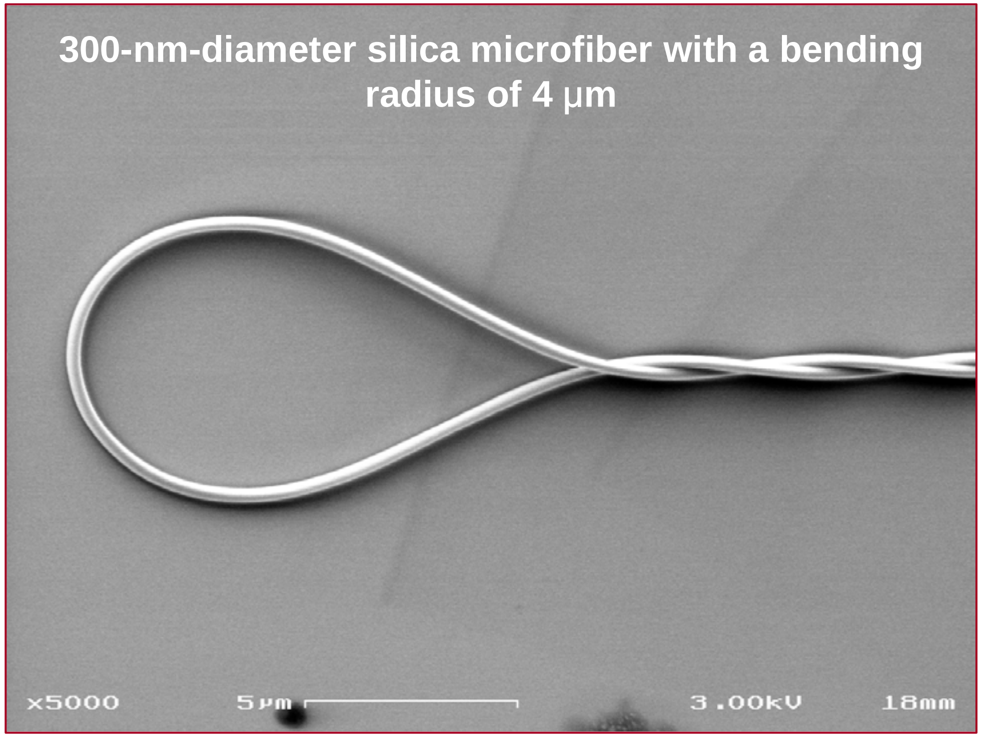
L. Tong et al., *Nano Lett.* **5**, 259 (2005)

1. Fabrication of Microfibers

1.2 Micromanipulation

Tailoring through micro/nanomanipulation

- **Twist**



300-nm-diameter silica microfiber with a bending radius of 4 μm

Mechanically robust & flexible

Critical for practical applications

Typical tensile strength > 5 GPa (@ RT)

Outline

- Introduction

1. Fabrication

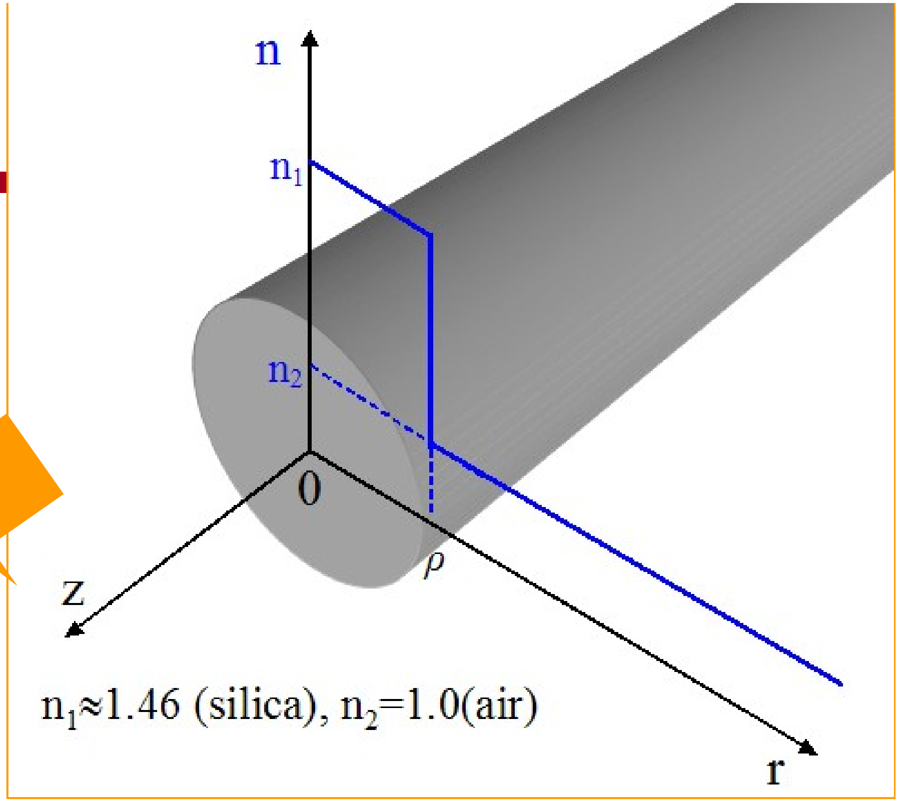
2. Optical Properties

3. Potentials and Applications

- Summary

2. Optical Properties

- **Basic model**



Perfect 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.

HE_{vm}, EH_{vm}	$0 \le r < \rho$	$\rho \le r < \infty$
e_r	$-\dfrac{a_1 J_{v-1}(UR) + a_2 J_{v+1}(UR)}{J_v(U)} f_v(\phi)$	$-\dfrac{U}{W}\dfrac{a_1 K_{v-1}(WR) - a_2 K_{v+1}(WR)}{K_v(W)} f_v(\phi)$
e_ϕ	$-\dfrac{a_1 J_{v-1}(UR) - a_2 J_{v+1}(UR)}{J_v(U)} g_v(\phi)$	$-\dfrac{U}{W}\dfrac{a_1 K_{v-1}(WR) + a_2 K_{v+1}(WR)}{K_v(W)} g_v(\phi)$
e_z	$\dfrac{-iU}{\rho\beta}\dfrac{J_v(UR)}{J_v(U)} f_v(\phi)$	$\dfrac{-iU}{\rho\beta}\dfrac{K_v(WR)}{K_v(W)} f_v(\phi)$
h_r	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2}\dfrac{kn_1^2}{\beta}\dfrac{a_3 J_{v-1}(UR) - a_4 J_{v+1}(UR)}{J_v(U)} g_v(\phi)$	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2}\dfrac{kn_1^2}{\beta}\dfrac{U}{W}\dfrac{a_5 K_{v-1}(WR) + a_6 K_{v+1}(WR)}{K_v(W)} g_v(\phi)$
h_ϕ	$-\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2}\dfrac{kn_1^2}{\beta}\dfrac{a_3 J_{v-1}(UR) + a_4 J_{v+1}(UR)}{J_v(U)} f_v(\phi)$	$-\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2}\dfrac{kn_1^2}{\beta}\dfrac{U}{W}\dfrac{a_5 K_{v-1}(WR) - a_6 K_{v+1}(WR)}{K_v(W)} f_v(\phi)$
h_z	$-i\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2}\dfrac{UF_2}{k\rho}\dfrac{J_v(UR)}{J_v(U)} g_v(\phi)$	$-i\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2}\dfrac{UF_2}{k\rho}\dfrac{K_v(WR)}{K_v(W)} g_v(\phi)$

$$f_v(\phi) = \begin{cases}\cos(v\phi) \\ \sin(v\phi)\end{cases}; \qquad g_v(\phi) = \begin{cases}-\sin(v\phi) & even \\ \cos(v\phi) & odd\end{cases}$$

$$a_1 = \frac{(F_2 - 1)}{2}; \quad a_3 = \frac{(F_1 - 1)}{2}; \quad a_5 = \frac{(F_1 - 1 + 2\Delta)}{2}$$

$$a_2 = \frac{(F_2 + 1)}{2}; \quad a_4 = \frac{(F_1 + 1)}{2}; \quad a_6 = \frac{(F_1 + 1 - 2\Delta)}{2}$$

$$F_1 = \left(\frac{UW}{V}\right)^2 \frac{b_1 + (1 - 2\Delta)b_2}{v}; F_2 = \left(\frac{V}{UW}\right)^2 \frac{v}{b_1 + b_2}$$

$$b_1 = \frac{1}{2U}\left\{\frac{J_{v-1}(U)}{J_v(U)} - \frac{J_{v+1}(U)}{J_v(U)}\right\}$$

$$b_2 = -\frac{1}{2W}\left\{\frac{K_{v-1}(W)}{K_v(W)} + \frac{K_{v+1}(W)}{K_v(W)}\right\}$$

TE_{0m}	$0 \le r < \rho$	$\rho \le r < \infty$
e_ϕ	$-\dfrac{J_1(UR)}{J_1(U)}$	$-\dfrac{K_1(WR)}{K_1(W)}$
h_r	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{\beta}{k} \dfrac{J_1(UR)}{J_1(U)}$	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{\beta}{k} \dfrac{K_1(WR)}{K_1(W)}$
h_z	$i\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{U}{k\rho} \dfrac{J_0(UR)}{J_1(U)}$	$-i\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{W}{k\rho} \dfrac{K_0(WR)}{K_1(W)}$
	$e_r = e_z = h_\phi = 0$	
TM_{0m} e_r	$\dfrac{J_1(UR)}{J_1(U)}$	$\dfrac{n_1^{\ 2}}{n_2^{\ 2}} \dfrac{K_1(WR)}{K_1(W)}$
e_z	$\dfrac{iU}{\rho\beta} \dfrac{J_0(UR)}{J_1(U)}$	$\dfrac{-in_1^{\ 2}}{n_2^{\ 2}} \dfrac{W}{\rho\beta} \dfrac{K_0(WR)}{K_1(W)}$
h_ϕ	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{kn_1^{\ 2}}{\beta} \dfrac{J_1(UR)}{J_1(U)}$	$\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \dfrac{kn_1^{\ 2}}{\beta} \dfrac{K_1(WR)}{K_1(W)}$
	$e_\phi = h_r = h_z = 0$	

2. Optical Properties

2.1 Basic model

Solve the eigenvalue equations numerically

HE_{vm}, EH_{vm}

$$\left\{\frac{J_v'(U)}{UJ_v(U)}+\frac{K_v'(W)}{WK_v(W)}\right\}\left\{\frac{J_v'(U)}{UJ_v(U)}+\frac{n_2^2K_v'(W)}{n_1^2WK_v(W)}\right\}=\left(\frac{v\beta}{kn_1}\right)^2\left(\frac{V}{UW}\right)^4$$

TE_{0m}

$$\frac{J_1(U)}{UJ_0(U)}+\frac{K_1(W)}{WK_0(W)}=0$$

TM_{0m}

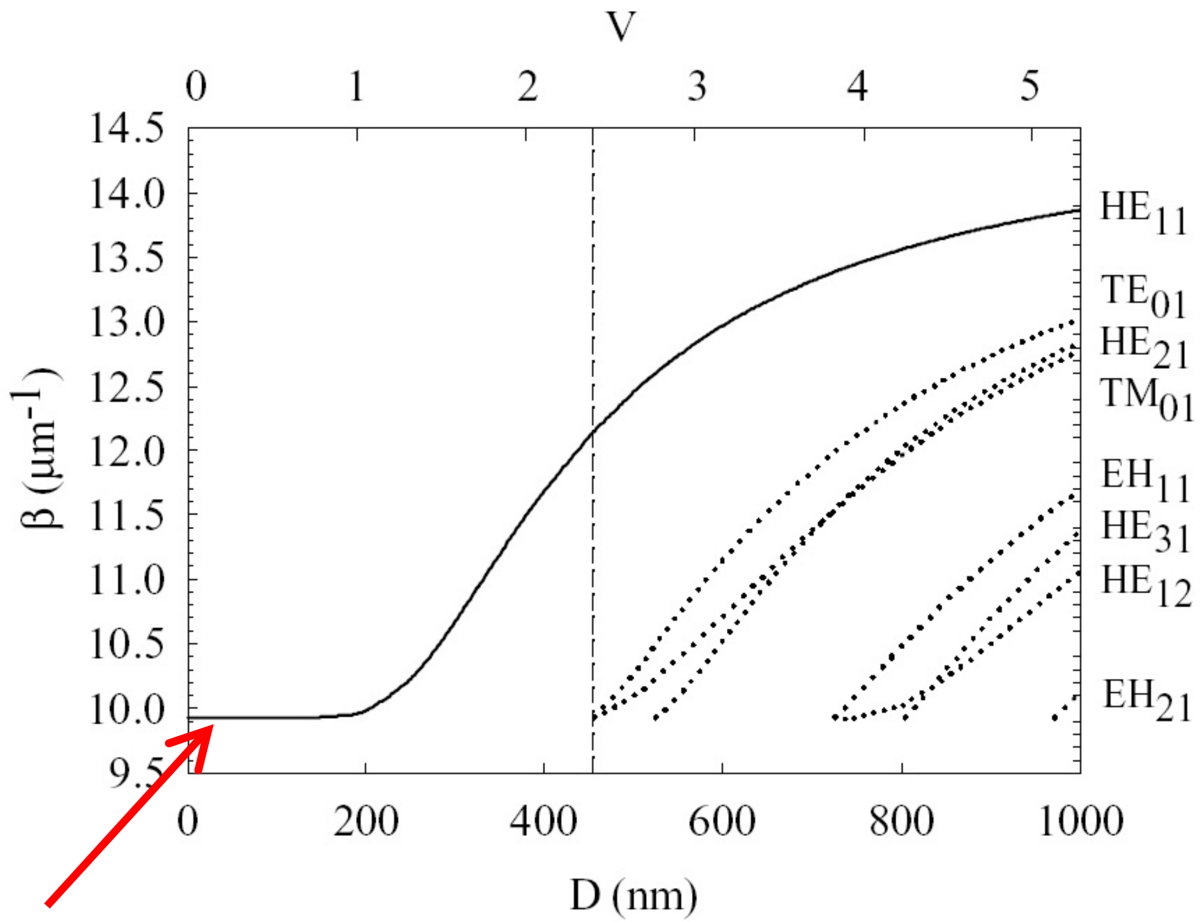
$$\frac{n_1^2J_1(U)}{UJ_0(U)}+\frac{n_2^2K_1(W)}{WK_0(W)}=0$$

2. Optical Properties

- **Basic model**

Propagation constants (β)

Air-clad silica microfibers
Wavelength: 633 nm



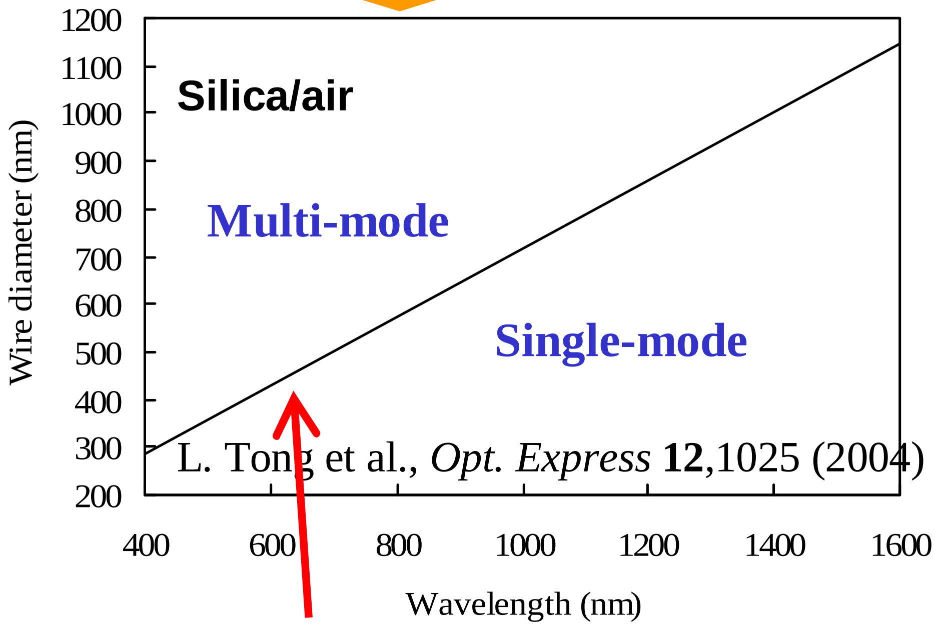
no cutoff of the fundamental modes

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

2. Optical Properties

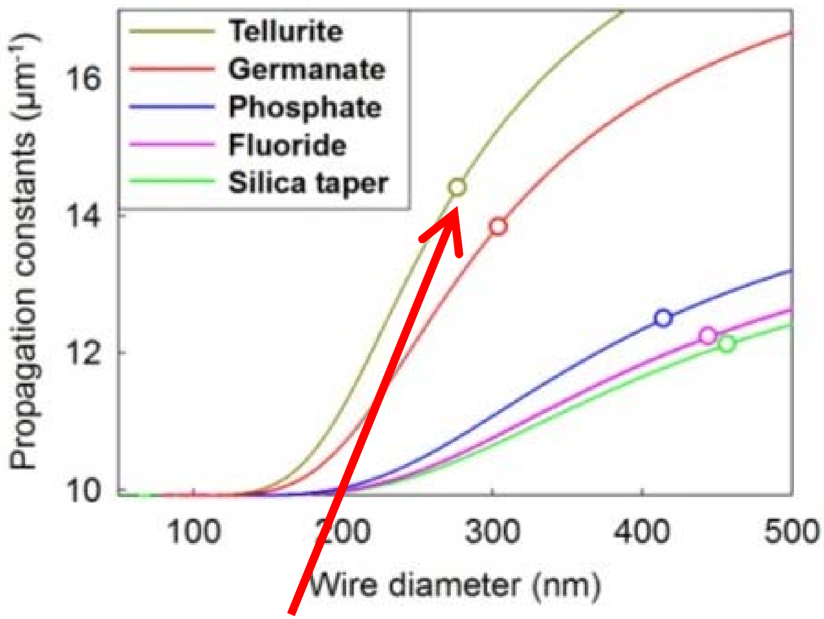
· **Single-mode condition**

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



β for HE_{11} mode of several glass nanofibers

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



The shorter the wavelength **the higher the refractive index**

the smaller the single-mode cutoff diameter

2. Optical Properties

- **Electric fields of HE_{11} mode**

For the fundamental mode (HE_{11})

Eigenvalue equations

$$\left\{\frac{J_1^{'}(U)}{UJ_1(U)}+\frac{K_1^{'}(W)}{WK_1(W)}\right\}\left\{\frac{J_1^{'}(U)}{UJ_1(U)}+\frac{n_2{}^2K_1^{'}(W)}{n_1{}^2WK_1(W)}\right\}=\left(\frac{\beta}{kn_1}\right)^2\left(\frac{V}{UW}\right)^4$$

Solve β numerically

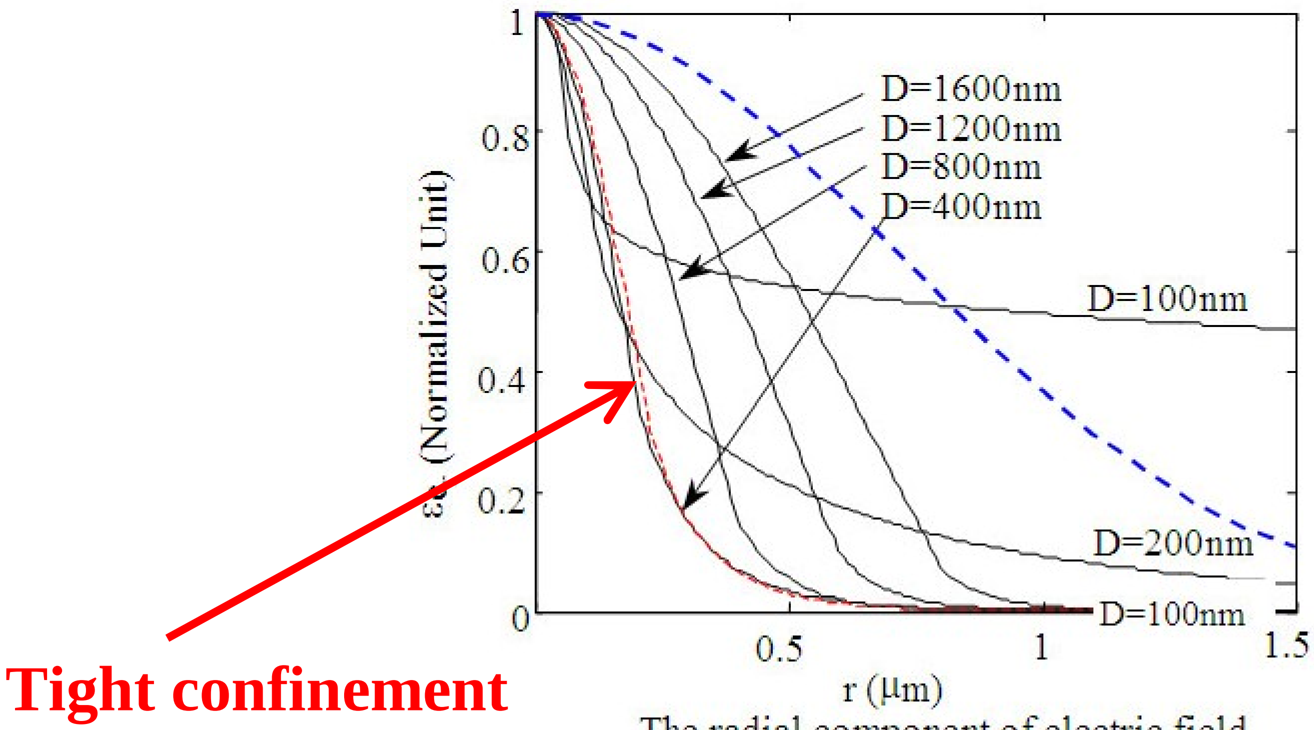
Electromagnetic fields
$$\begin{cases}\vec{E}(r,\phi,z)=(e_r\hat{r}+e_\phi\hat{\phi}+e_z\hat{z})e^{i\beta z}e^{i\omega t}, \\ \vec{H}(r,\phi,z)=(h_r\hat{r}+h_\phi\hat{\phi}+h_z\hat{z})e^{i\beta z}e^{i\omega t}\end{cases}$$

2. Optical Properties

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

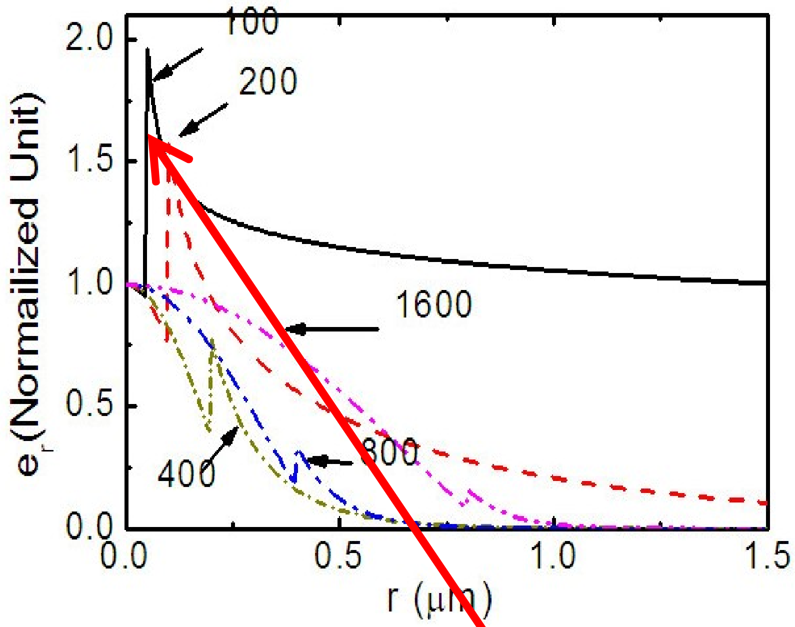


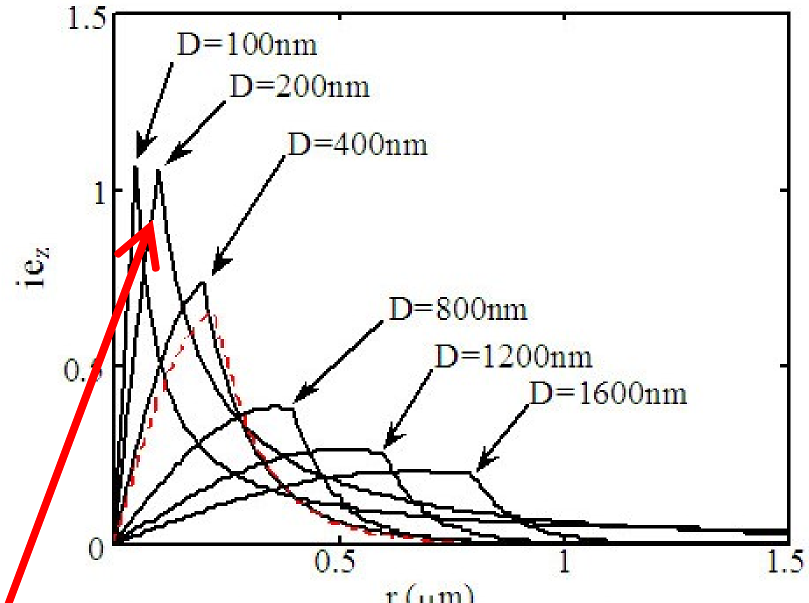
The radial component of electric field
($f(\phi)=1, \lambda=633nm$)

L. 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(ϕ)=1,λ=633nm)

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/mm² power density on the nanofiber surface.

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

2. Optical Properties

· Evanescent field of HE$_{11}$ mode

Z-components of Poynting vector

$$S_z = \begin{cases} \dfrac{|a|^2}{2}\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2} \dfrac{kn_1^2}{\beta J_1^2(U)}\left\{a_1 a_3 J_0^2(UR) + a_2 a_4 J_2^2(UR) + \dfrac{1-F_1F_2}{2} J_0(UR) J_2(UR)\cos(2\phi)\right\}, & core \\ \dfrac{|a|^2}{2}\left(\dfrac{\varepsilon_0}{\mu_0}\right)^{1/2} \dfrac{kn_1^2}{\beta K_1^2(W)} \dfrac{U^2}{W^2}\left\{a_1 a_5 K_0^2(WR) + a_2 a_6 K_2^2(WR) - \dfrac{1-2\Delta-F_1F_2}{2} K_0(WR) K_2(WR)\cos(2\phi)\right\}, & cladding \end{cases}$$

Fractional power inside the core

$$\eta = \frac{P_1}{P_1 + P_2}$$

where

$$P_1 = \int_0^a S_{z1} dA, \quad P_2 = \int_a^\infty S_{z2} dA,$$

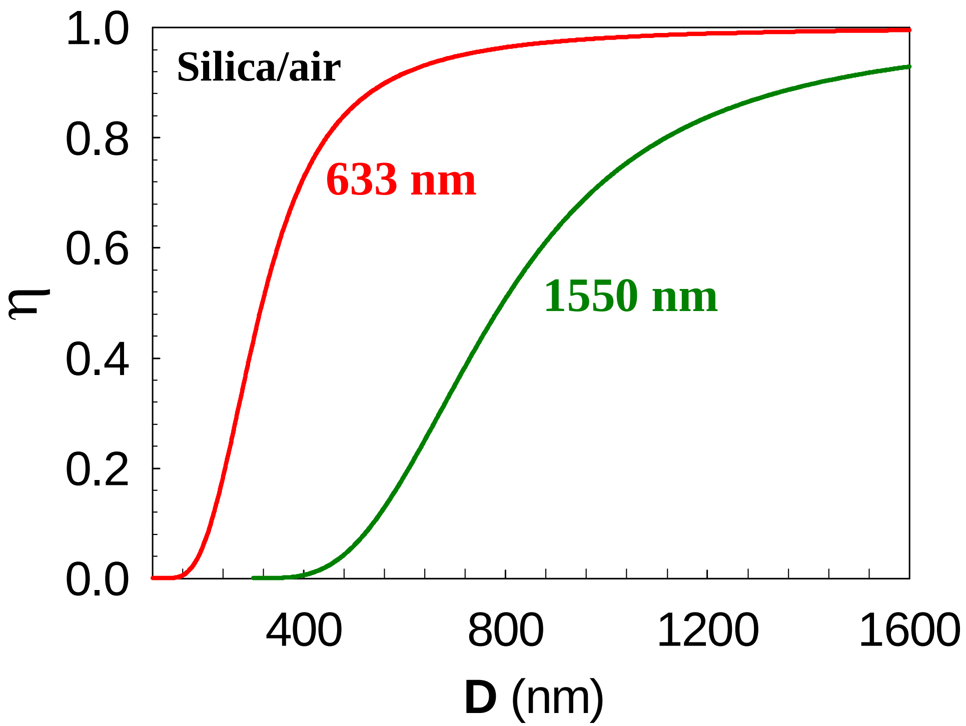
$$dA = \rho^2 R \cdot dR \cdot d\phi = r \cdot dr \cdot d\phi.$$

A.W. Snyder and J. D. Love, Optical waveguide theory, Chapman and Hall, New York, 1983.
L. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Optical Properties

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

Fractional power inside the core

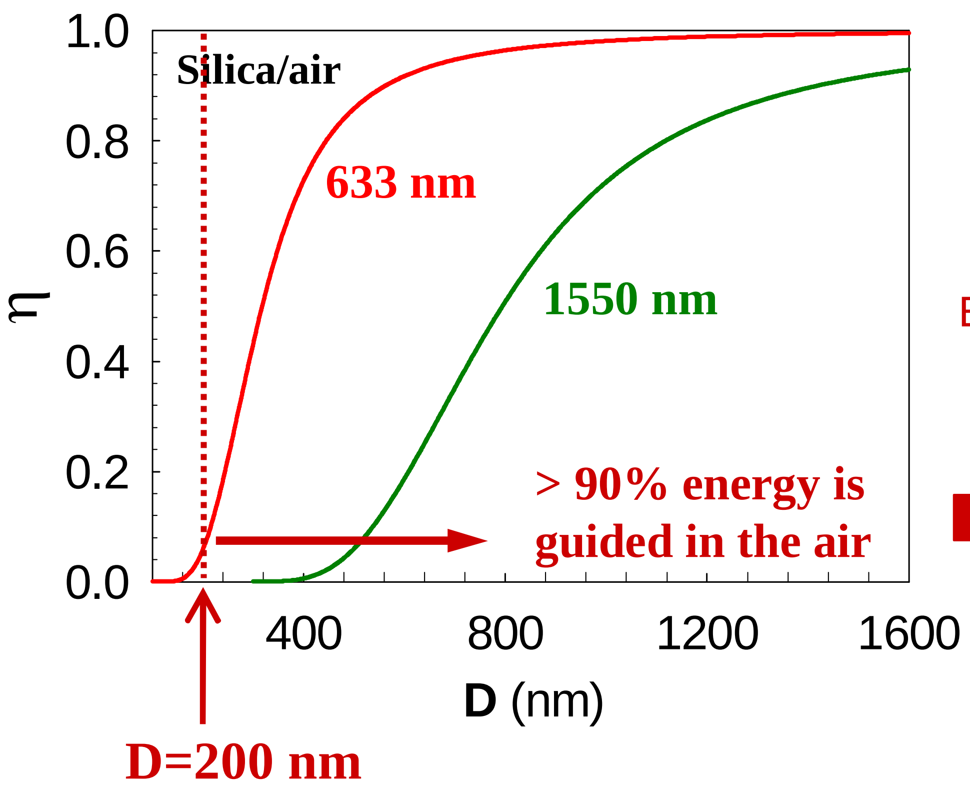


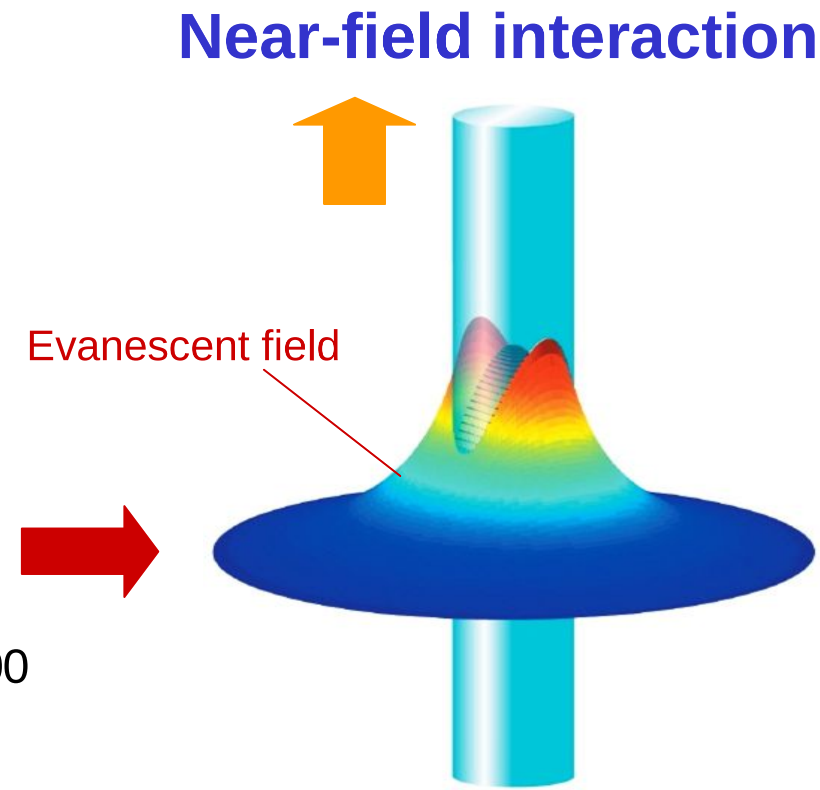
L. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Optical Properties

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

Fractional power inside the core



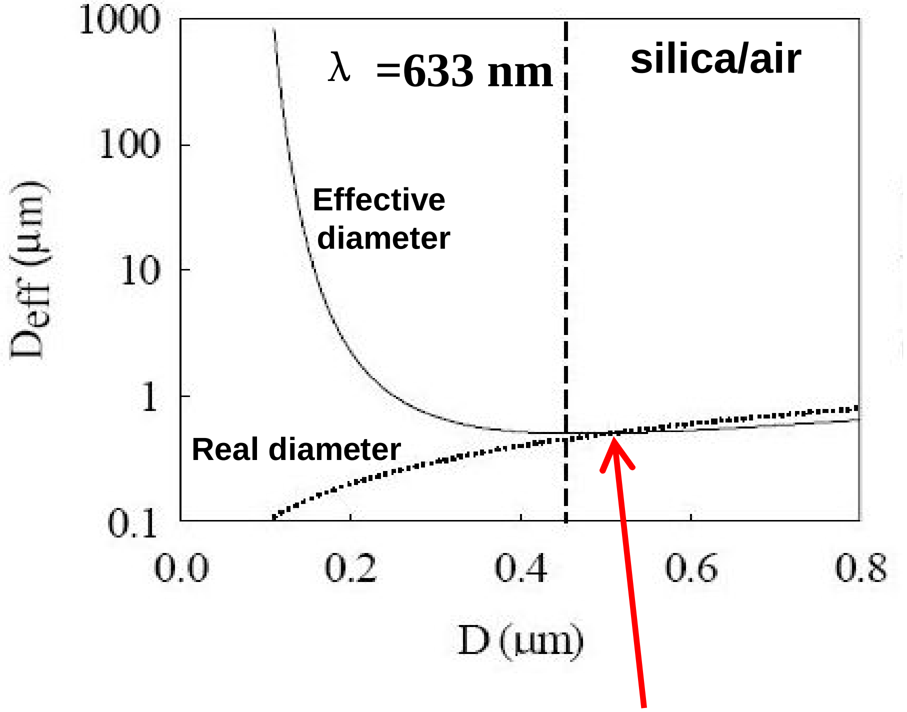


L. Tong et al., *Opt. Express* **12**,1025 (2004)

2. Optical Properties

· **Optical confinement of HE_{11} mode**

Effective Diameter: Mode area for optical confinement of 86.5%



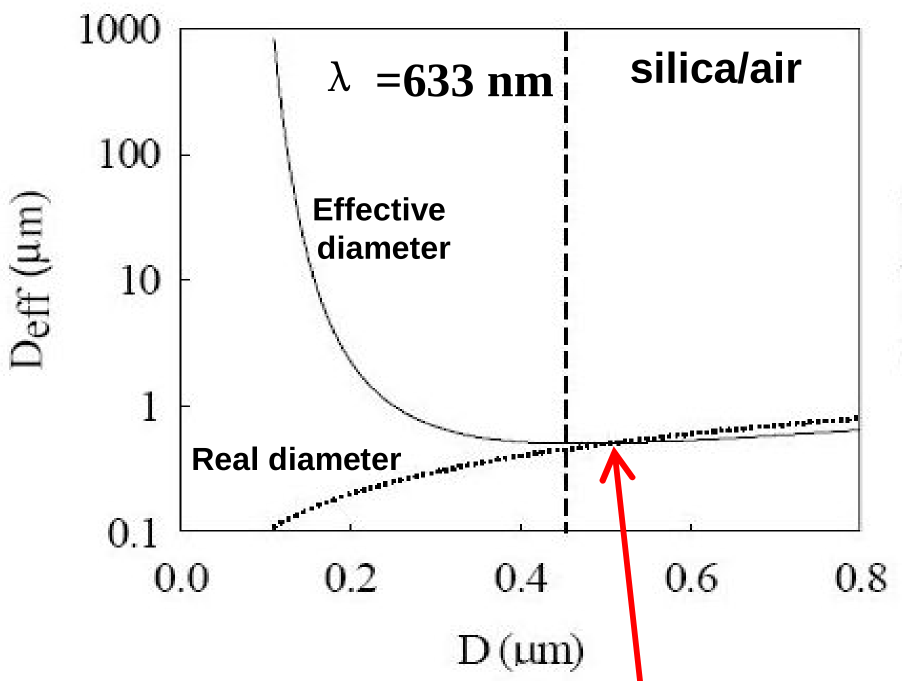
Minimum usable Effective Diameter ～500 nm

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

2. Optical Properties

- **Optical confinement of HE_{11} mode**

Effective Diameter: Mode area for optical confinement of 86.5%



Small mode area → **Nonlinear effects**

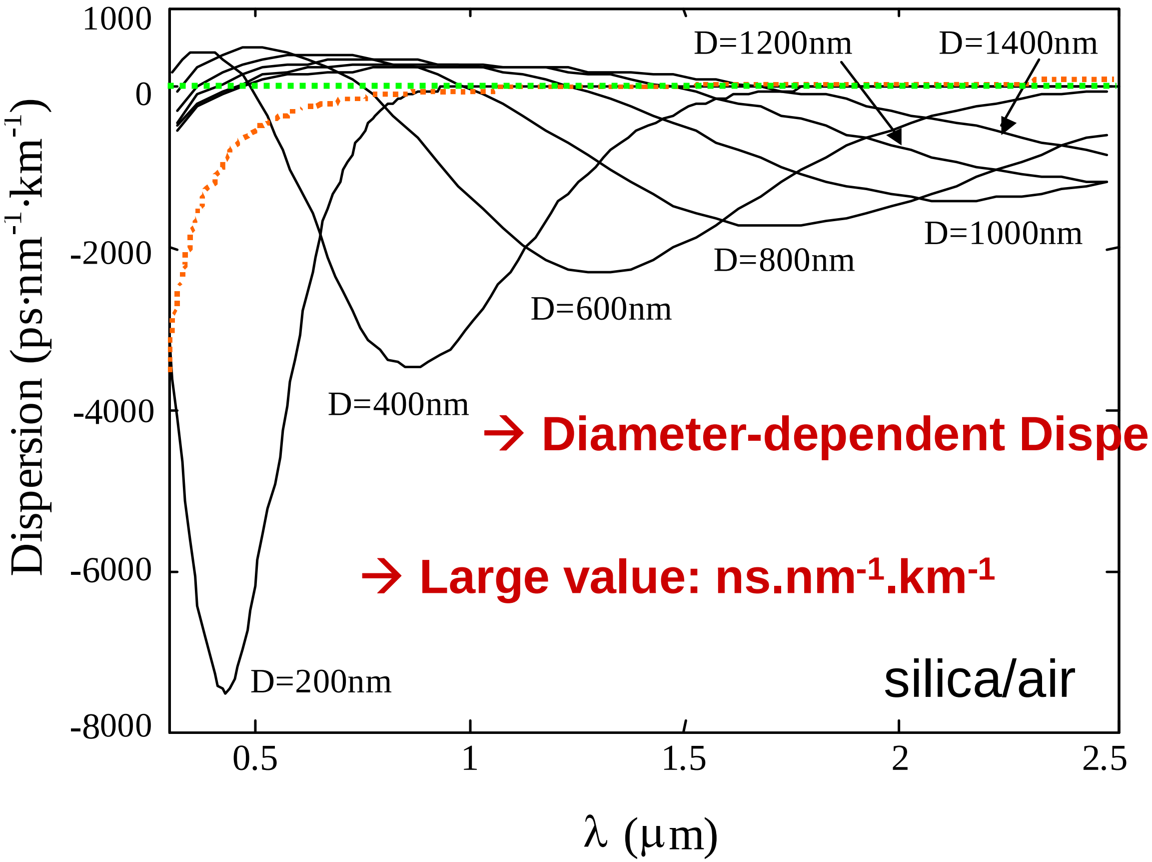
Minimum usable Effective Diameter ～510 nm

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

2. Optical Properties

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

Waveguide dispersion in air-clad silica fibers



→ **Diameter-dependent Dispersion**

→ **Large value: ns.nm^{-1}.km^{-1}**

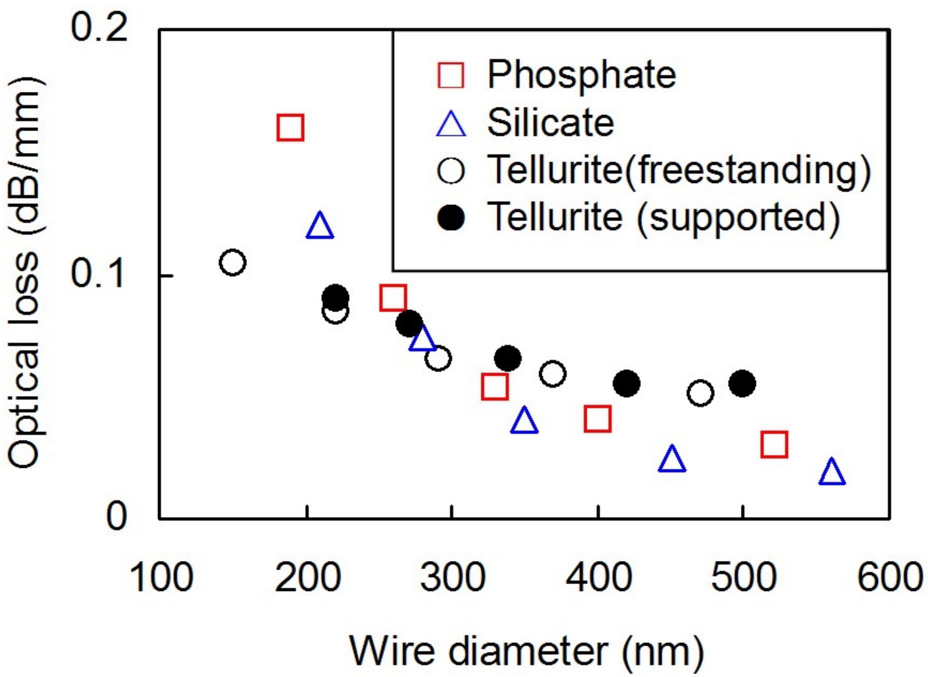
⇒ **Nonlinear effects**

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

2. Optical Properties

· Optical loss in real microfibers

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



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

Lower loss reported in silica fibers:

α ~ 0.01 dB/mm [2]

[2] G. Brambilla et al., *Opt. Express* **12**, 2258 (2004)

Lowest loss reported:

α ~ 1 dB/m [3]

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

Lower loss may be possible

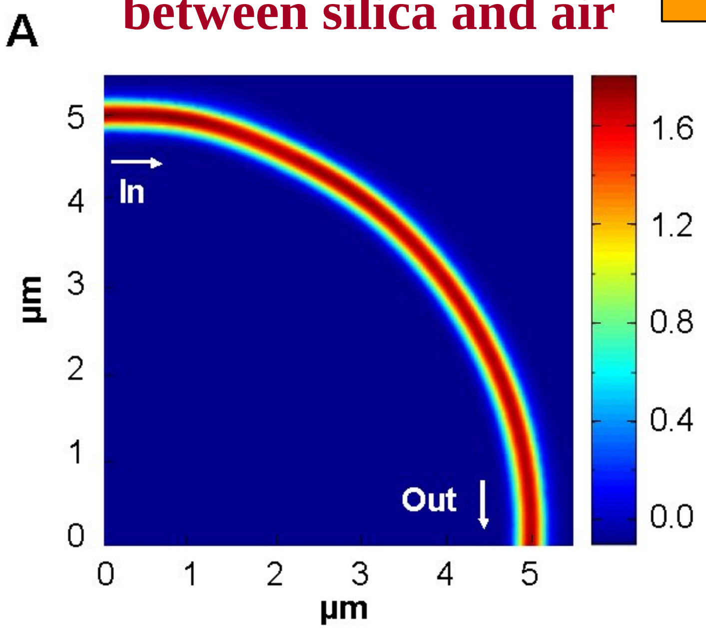
α < 0.1 dB/m

2. Optical Properties

· Optical loss in real microfibers

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.

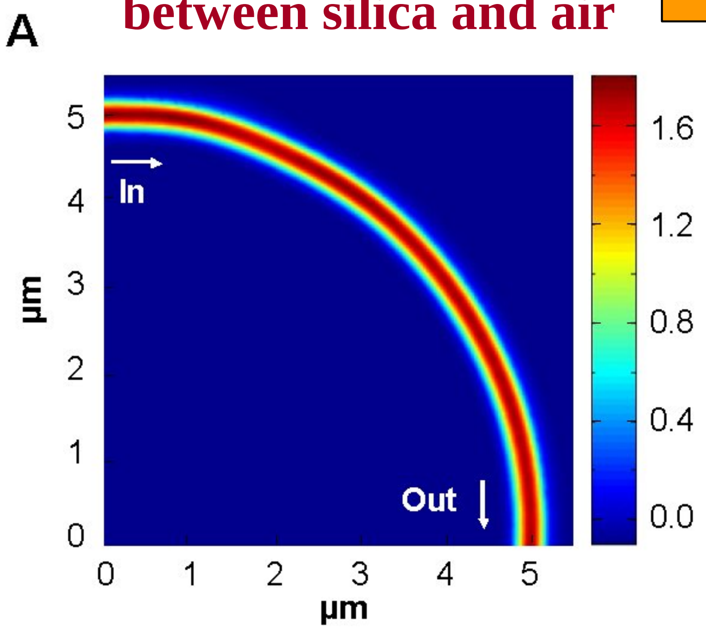
L. Tong et al., *Nano Lett.* **5**, 259 (2005)

2. Optical Properties

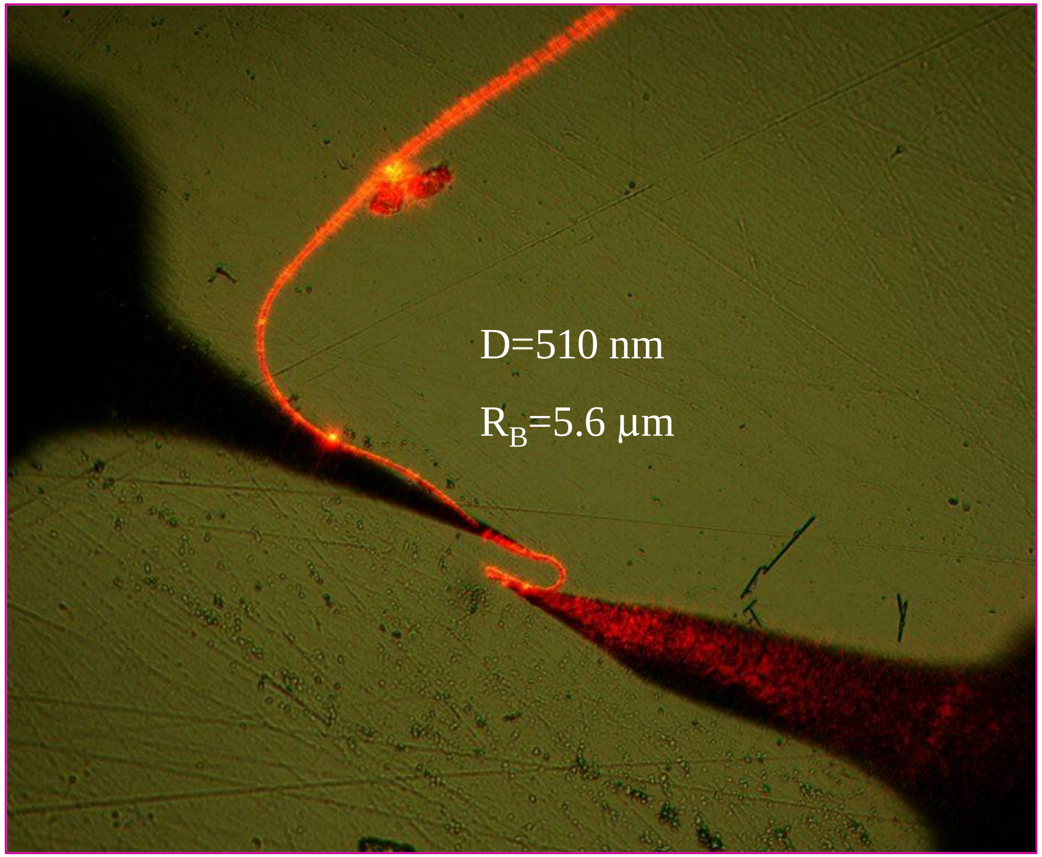
· Optical loss in real microfibers

Bending loss

High index contrast between silica and air



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



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

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

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

Bending loss

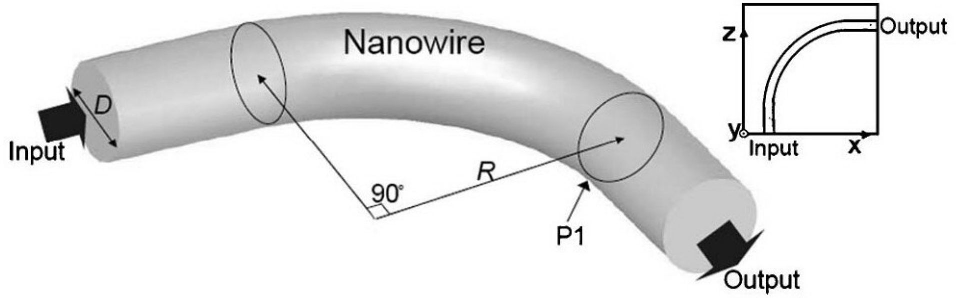


Fig. 1. Mathematical model for 3D-FDTD simulation of a circular 90° bent nanowire. Inset, topography profile of the bent nanowire.

3D-FDTD simulations

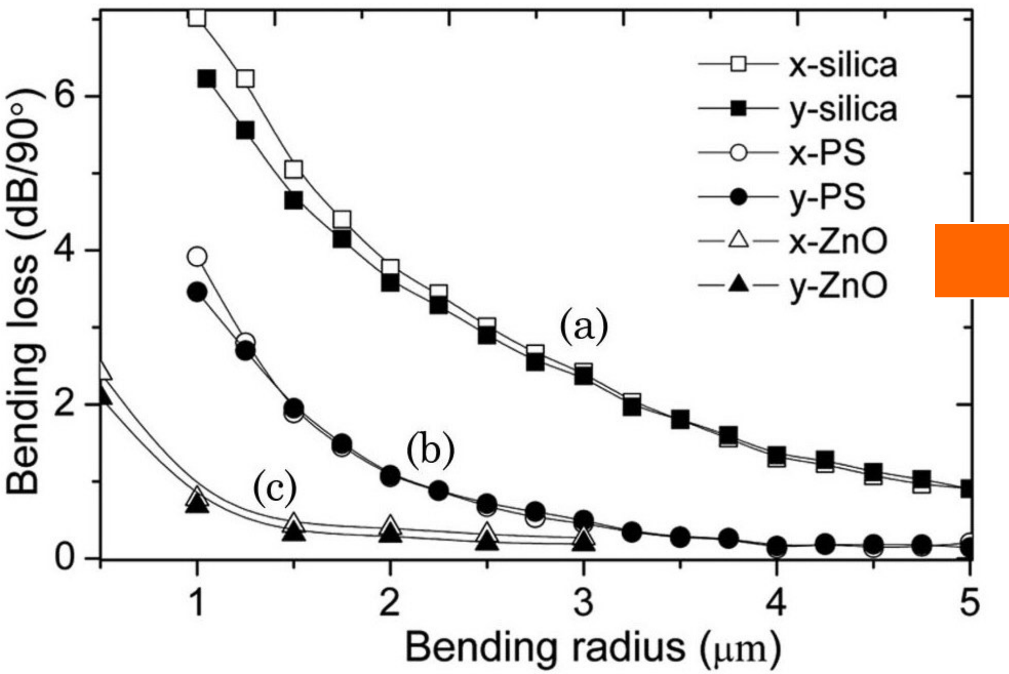


Fig. 3. Bending-radius-dependent bending losses of (a) a 350 nm diameter silica nanowire, (b) a 350 nm diameter PS nanowire, and (c) a 270 nm diameter ZnO nanowire with a 633 nm wavelength source.

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. Optical Properties

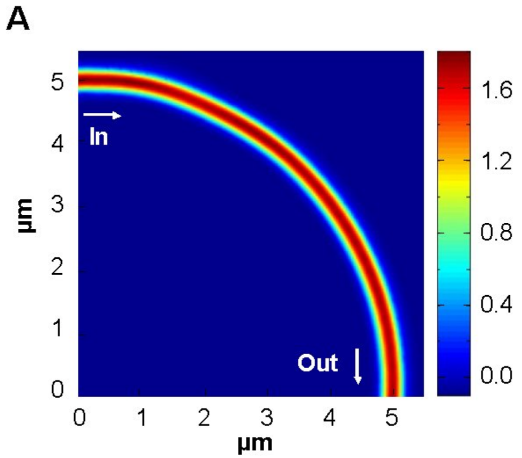
■ **What's New ?**

Small

2. Optical Properties

■ **What's New ?**

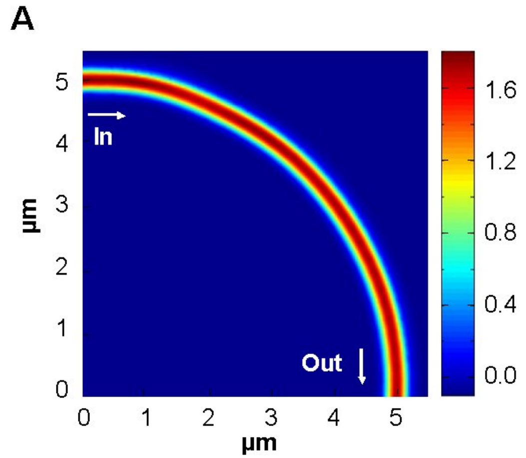
Small **1** **High Δn for SM → Sharper bend with shorter optical length**



2. Optical Properties

■ **What's New ?**

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



Light travels through with less time

e.g., consider the minimum allowable bending radius

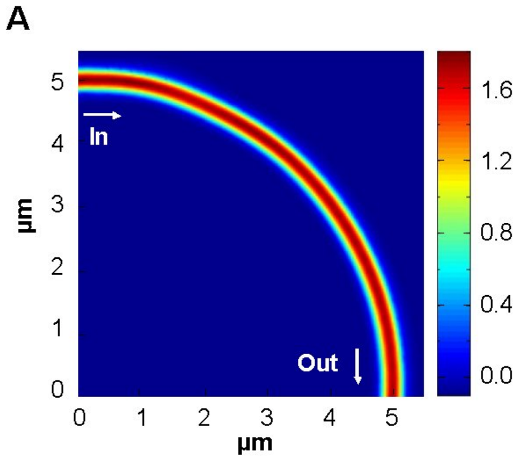
SMF ~1 cm → ~ 30 ps

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

2. Optical Properties

■ **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**

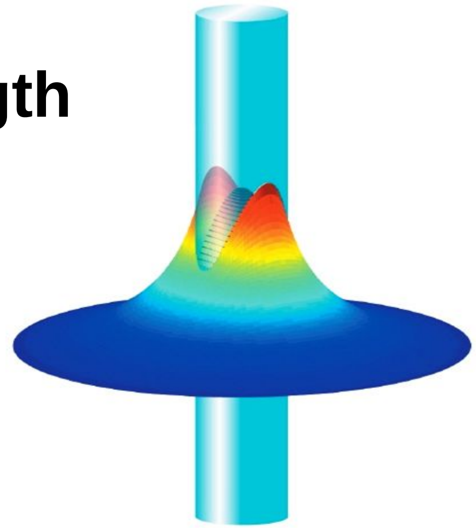
Faster operation

2. Optical Properties

■ **What's New ?**

Small 2 **Core diameter < wavelength**

High fraction of evanescent fields
Steep field gradient



2. Optical Properties

■ **What's New ?**

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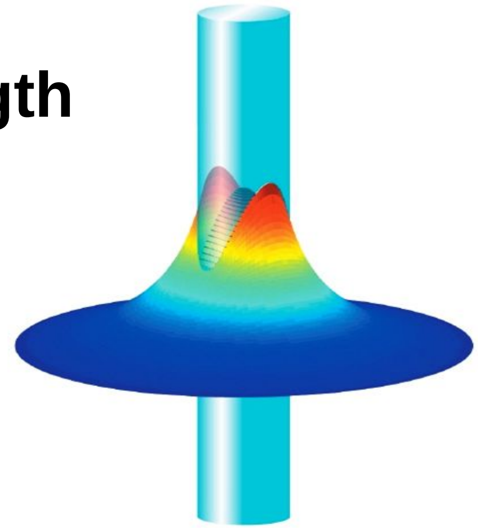


Stronger near-field interaction

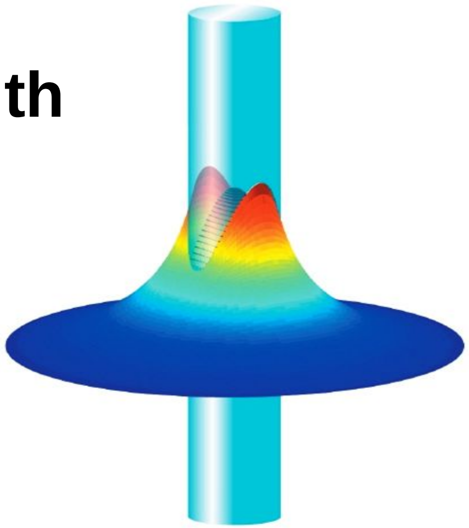
Higher-sensitivity optical sensing

2. Optical Properties

■ **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 optical sensing

Atom trapping and waveguiding

2. Optical Properties

■ **What's New ?**

Small **3** **Smaller mode area**

e.g., SMF ~ 100 μm²

Nanofiber ~ 1 μm²

2. Optical Properties

■ 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. Optical Properties

■ What's New ?

Small → 3 **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. Optical Properties

■ **What's New ?**

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

Modify vacuum states around the nanofiber

2. Optical Properties

■ 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. Optical Properties

■ **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. Optical Properties

■ **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. Optical Properties

■ **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. Optical Properties

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

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↓

Feel the momentum of light guided through

↓

Photon-momentum-induced effect

2. Optical Properties

■ 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

↓ Fundamental research in photonics

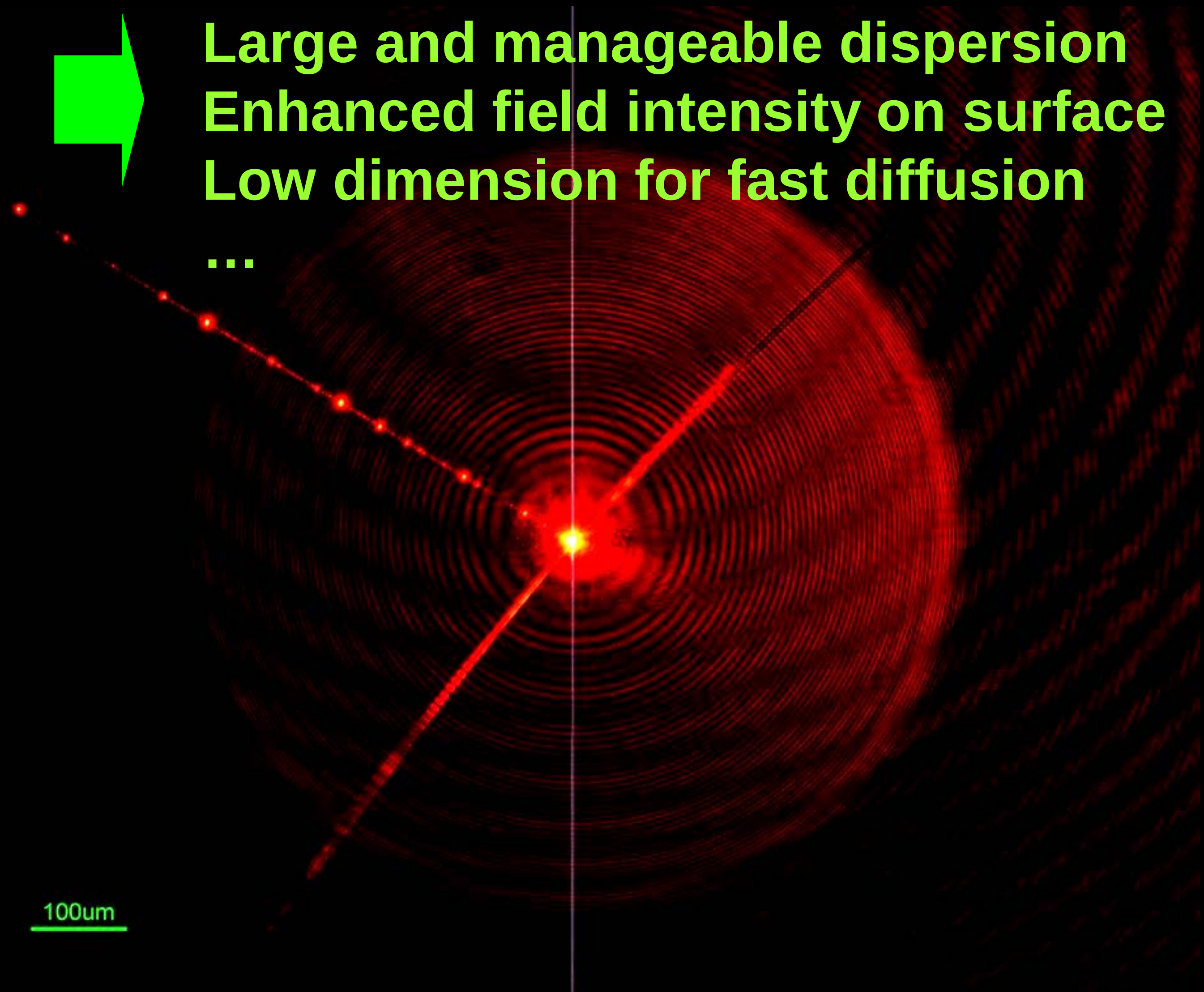
2. Optical Properties

■ **What's New ?**

Small ➡

More :

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



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

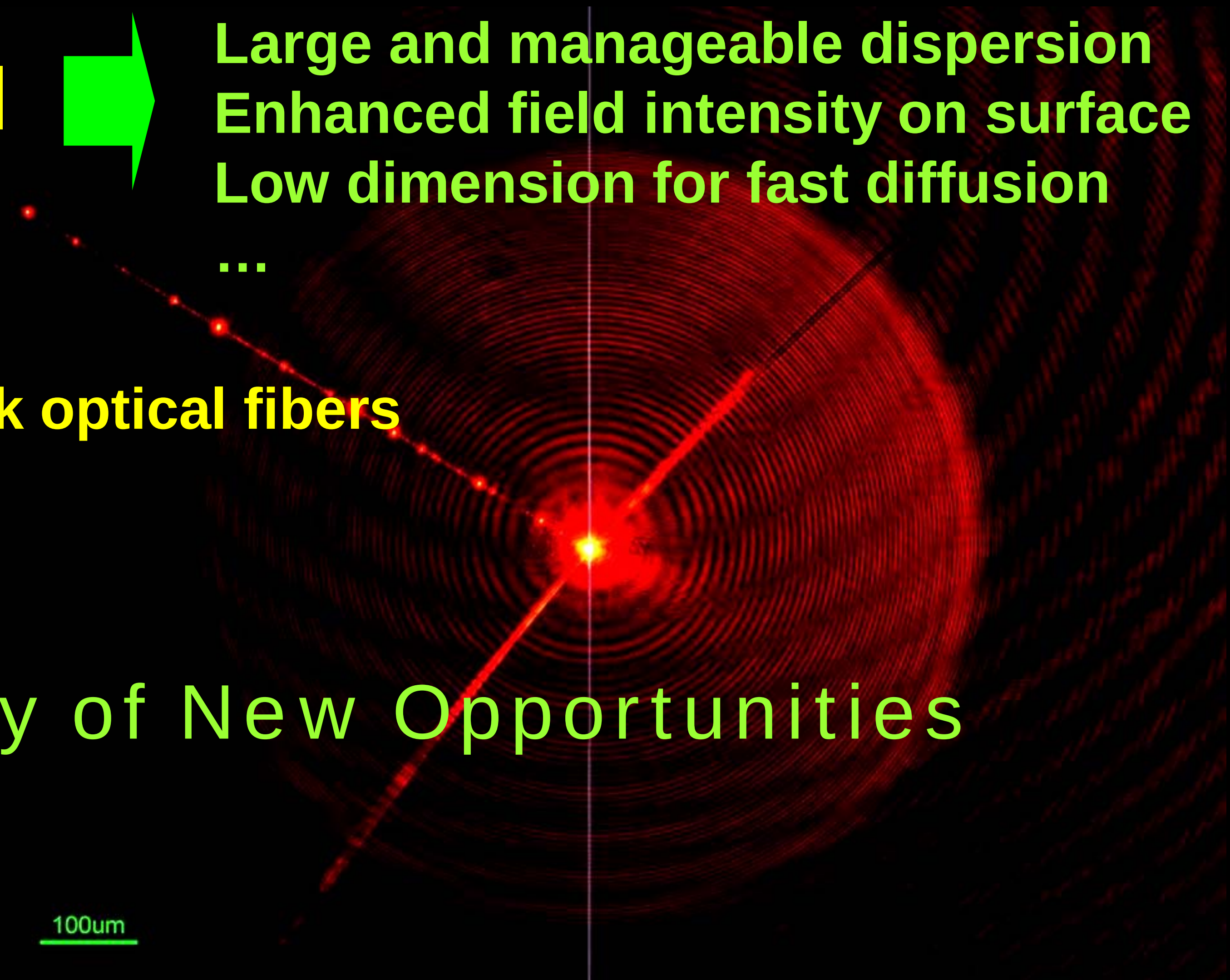
2. Optical Properties

■ **What's New ?**

Small ➡ **More :**

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

⬇ **Shrink optical fibers**



Plenty of New Opportunities

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

Outline

- Introduction

1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary

Outline

3. Potentials and Applications

(1) Near-Field Optics

(2) Plasmonics

(3) Nonlinear Optics

(4) Quantum Optics\Atom Optics

(5) Photon Momentum

Outline

3. Potentials and Applications

(1) Near-Field Optics

(2) Plasmonics

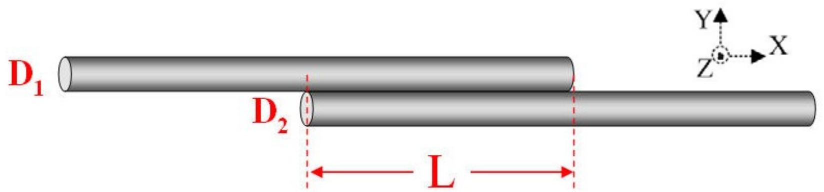
(3) Nonlinear Optics

(4) Quantum Optics\Atom Optics

(5) Photon Momentum

2.1 Near-field coupling between two nanofibers

High fraction of evanescent field → Strong near-field interaction



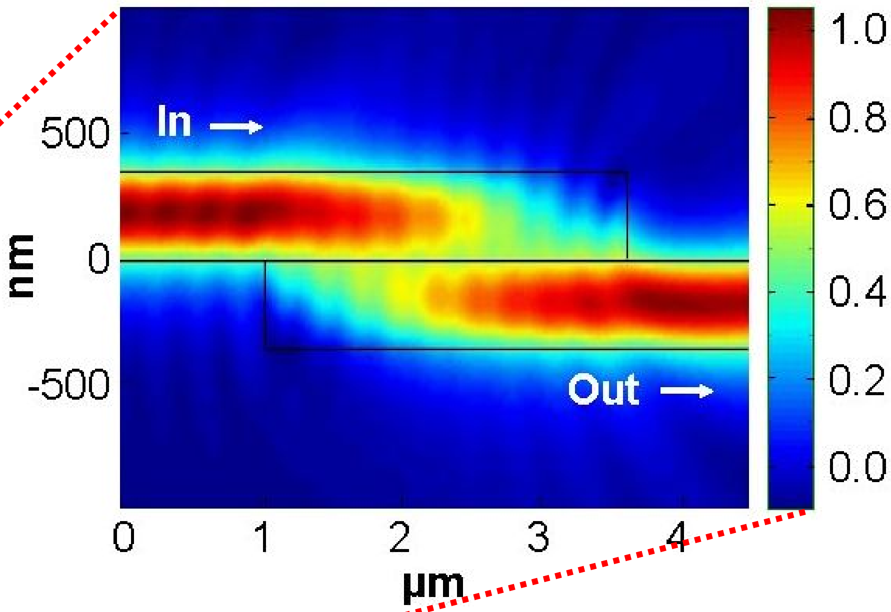
3D-FDTD simulation of two closely contacted silica microfibers (D1=D2=350 nm)

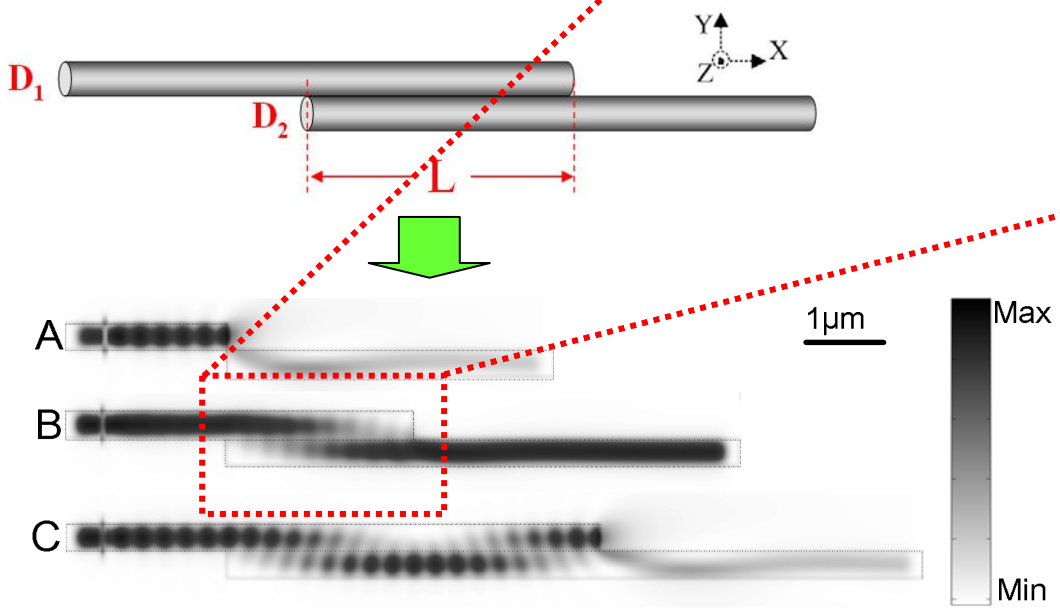
3D-FDTD power maps at 633-nm wavelength with overlapping length of (A) 0, (B) 2.4 μm, and (C) 4.8 μm. The source is *z* polarized with wavelength of 633 nm.

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

2.1 Near-field coupling betwee

High fraction of evanescent field →





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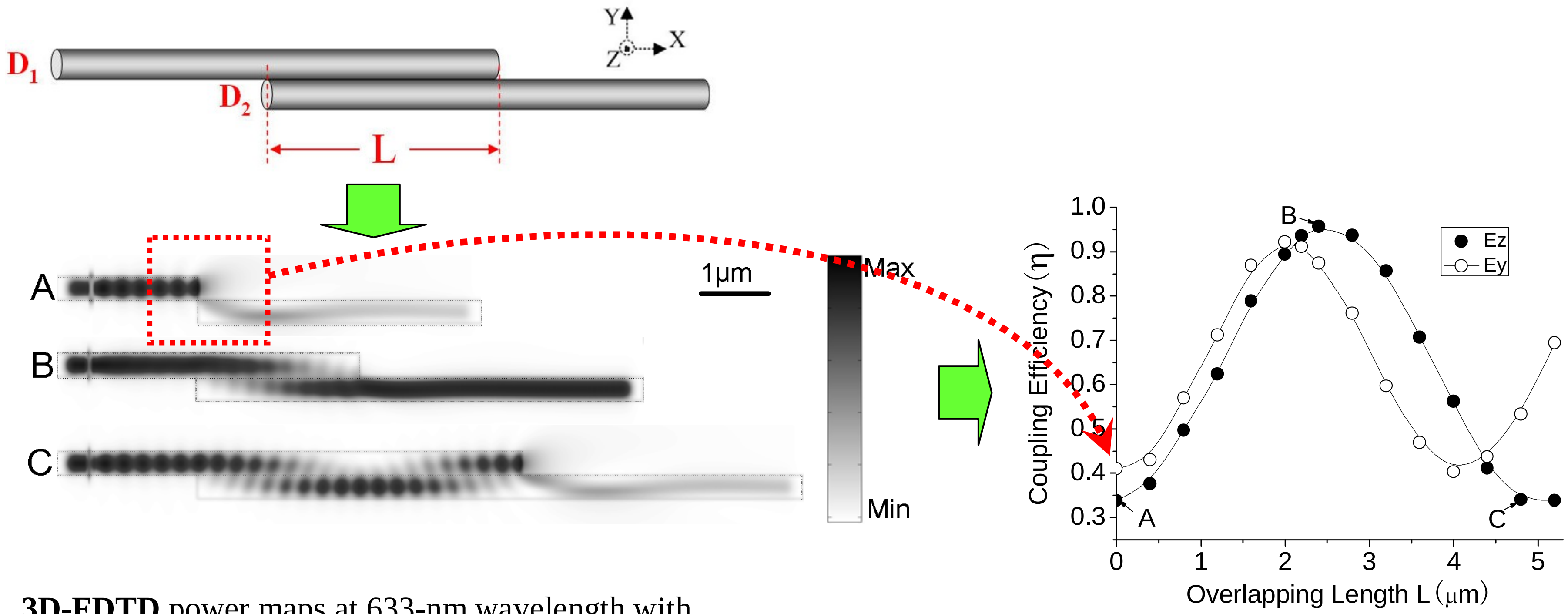


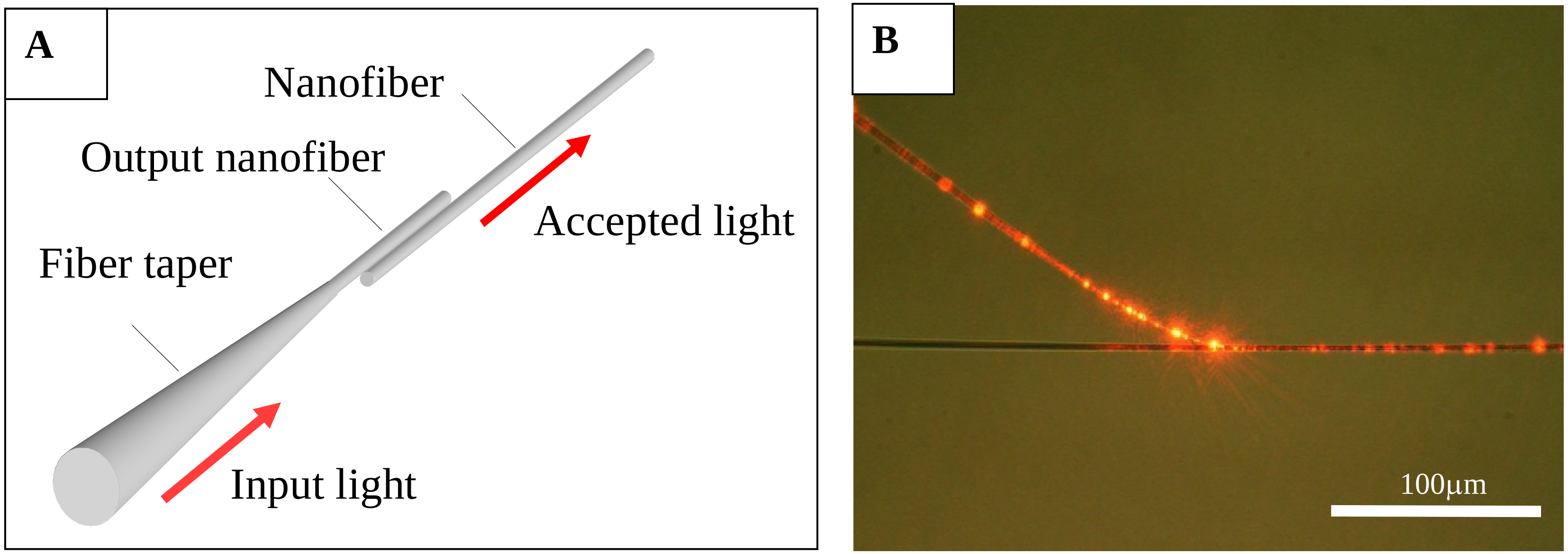
3D-FDTD power maps at 633-nm wavelength with overlapping length of (A) 0, (B) 2.4 μm, and (C) 4.8 μm. The source is *z* polarized with wavelength of 633 nm.

Overlapping-length-dependent coupling efficiency

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

2.1 Near-field coupling between two nanofibers

Launch light into a nanofiber



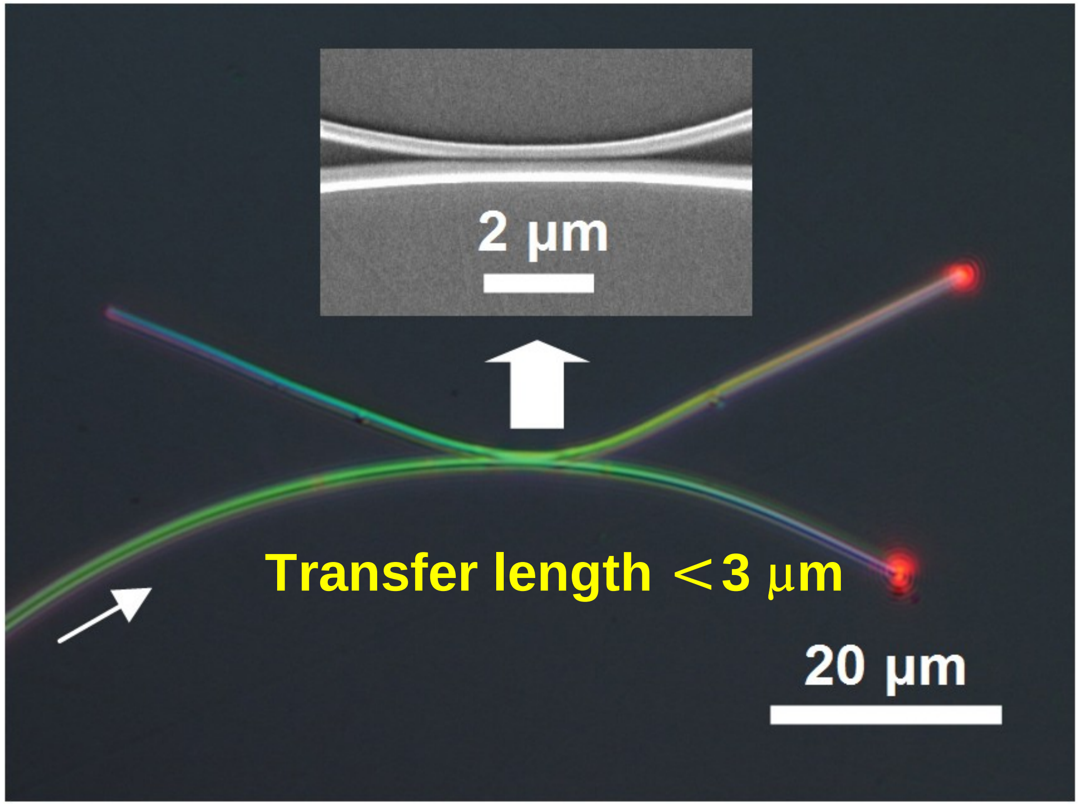
Launching light into microfibers. (A) Schematic diagram for launching light into a silica microfiber using evanescent coupling. (B) Optical microscope image of coupling light from a 390-nm-diameter fiber to a 450-nm-diameter fiber.

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

2.1 Near-field coupling between two nanofibers

• Micro-coupler

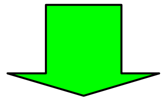
Micro-coupler assembled with two tellurite fibers on a silica substrate



Fiber diameter：350/450 nm

Working wavelength：633 nm

Overlapping ＜3 µm



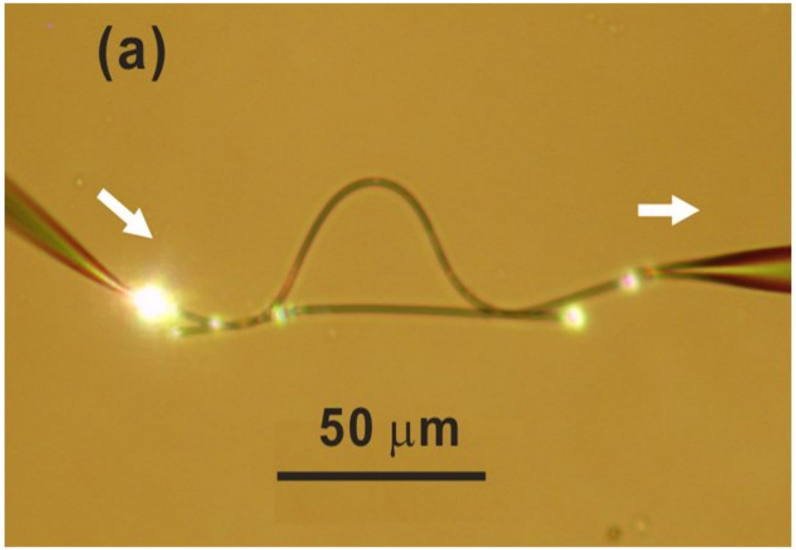
3-dB splitter

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

2.1 Near-field coupling between two nanofibers

- Tiny Mach-Zehnder interferometer

When two micro-couplers are assembled in cascade → MZI



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

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

2.1 Near-field coupling between two nanofibers

- Tiny Mach-Zehnder interferometer

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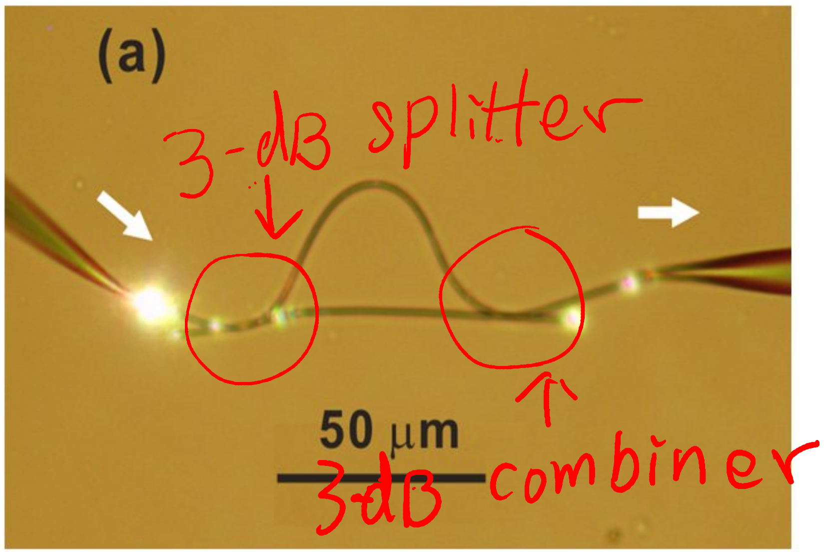

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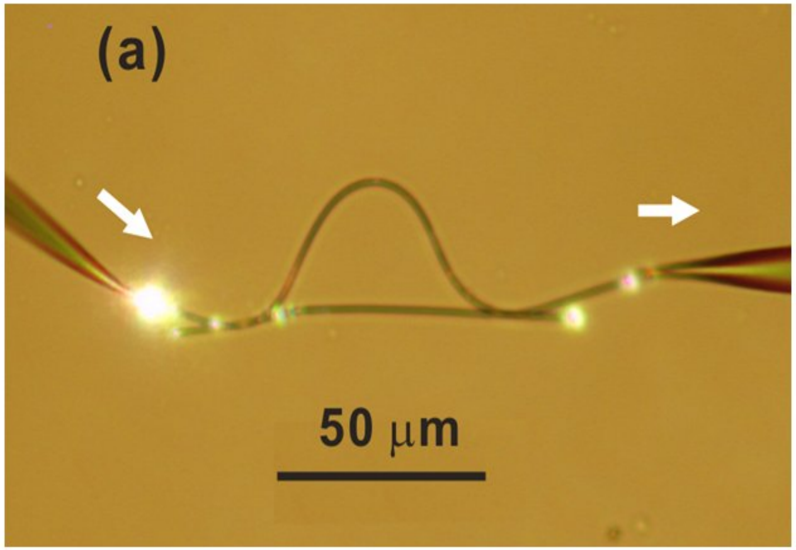
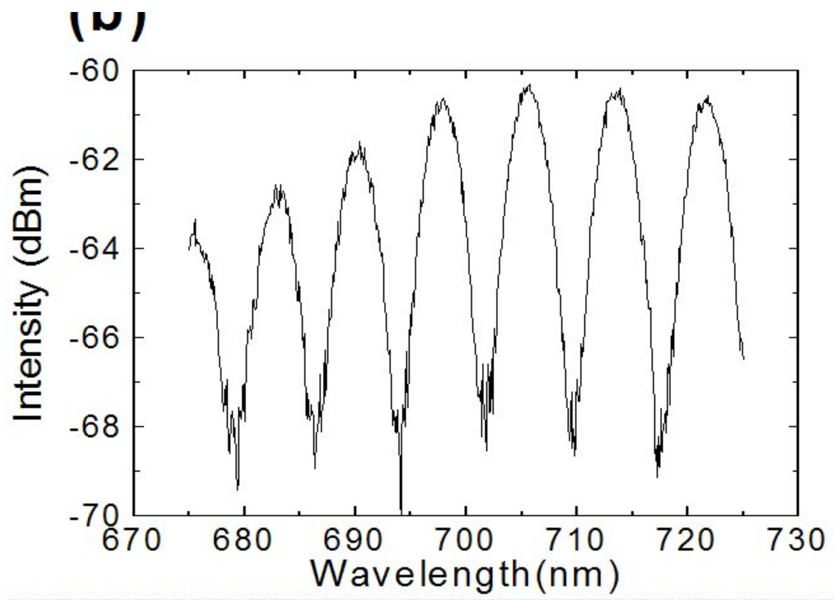


MZI assembled with two 480-nm-diameter tellurite fibers on a MgF_2 substrate



Transmission spectrum of the MZI

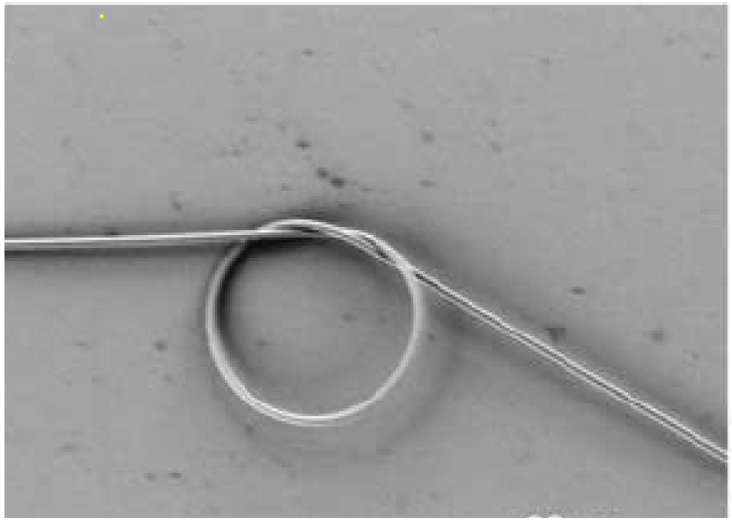
Small footprint and high flexibility

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

2.1 Near-field coupling between two nanofibers

- Micro resonator

Tie a microfiber into a loop or knot → ring resonator



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

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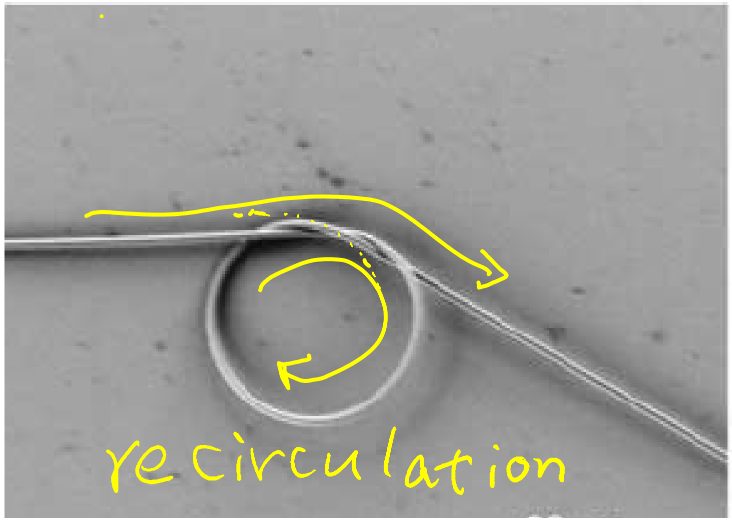

X. Jiang et al., *Appl. Phys. Lett.* **88**, 223501(2006)

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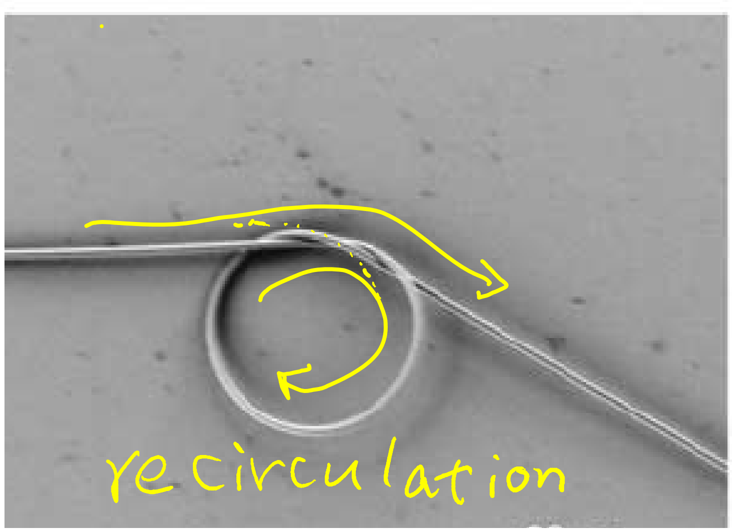
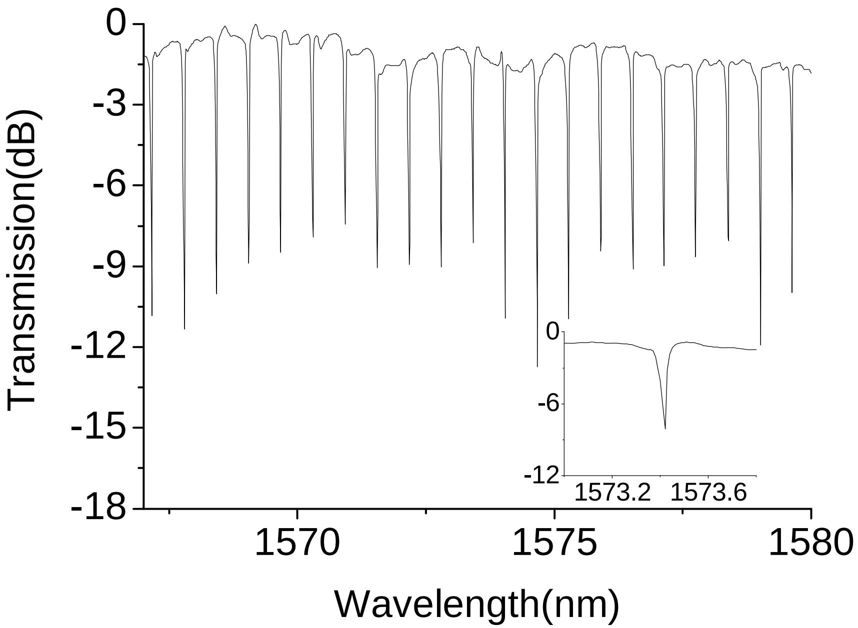


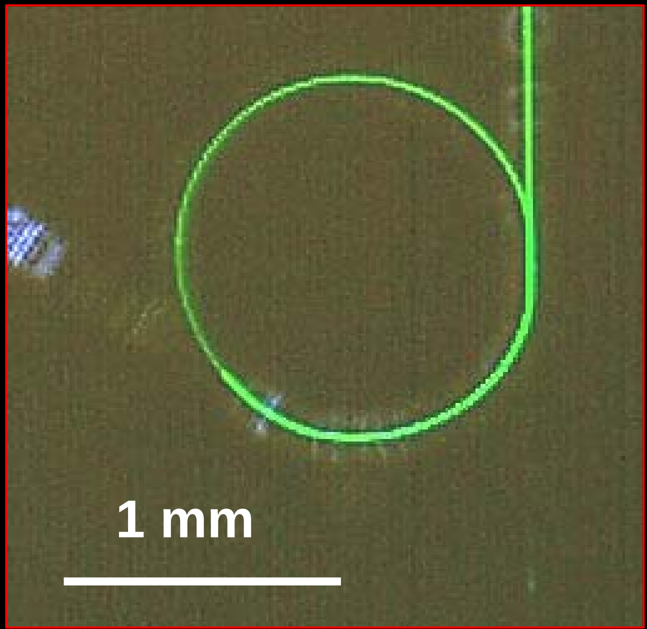


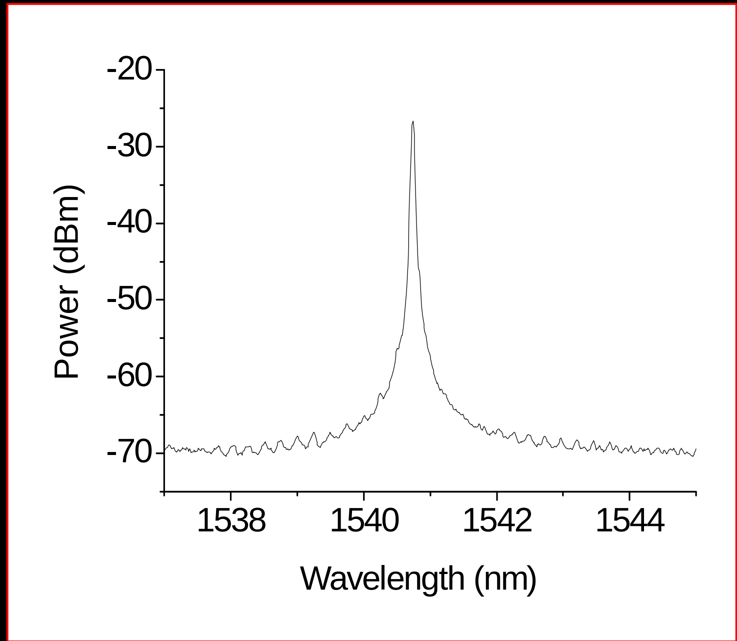
X. Jiang et al., *Appl. Phys. Lett.* **88**, 223501(2006)

(1) Near-field Optics

• Micro Lasers : **Rare-earth-doped microfiber laser**

Microfiber knot resonator + doped with active ions → Microfiber knot laser





Fiber material: (Er,Yb) codoped phosphate glass
Fiber diameter ~ 3.8 μm
Knot diameter ~ 2 mm
Pump wavelength ~ 975 nm

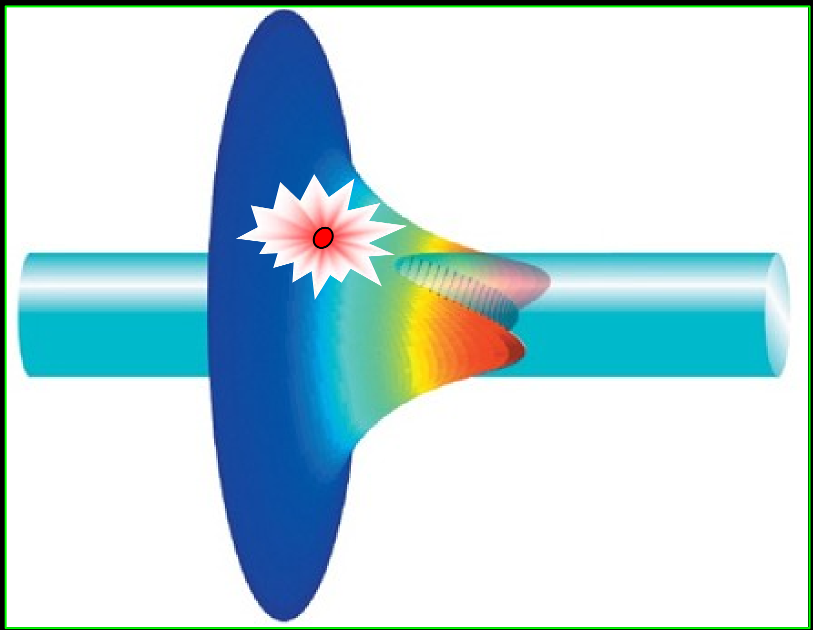
Laser output ~ 1.54 μm, power > 8 μW

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

(1) Near-field Optics

- Micro Lasers : **Microfiber dye laser**

（1） silica microfiber – laser dye molecules

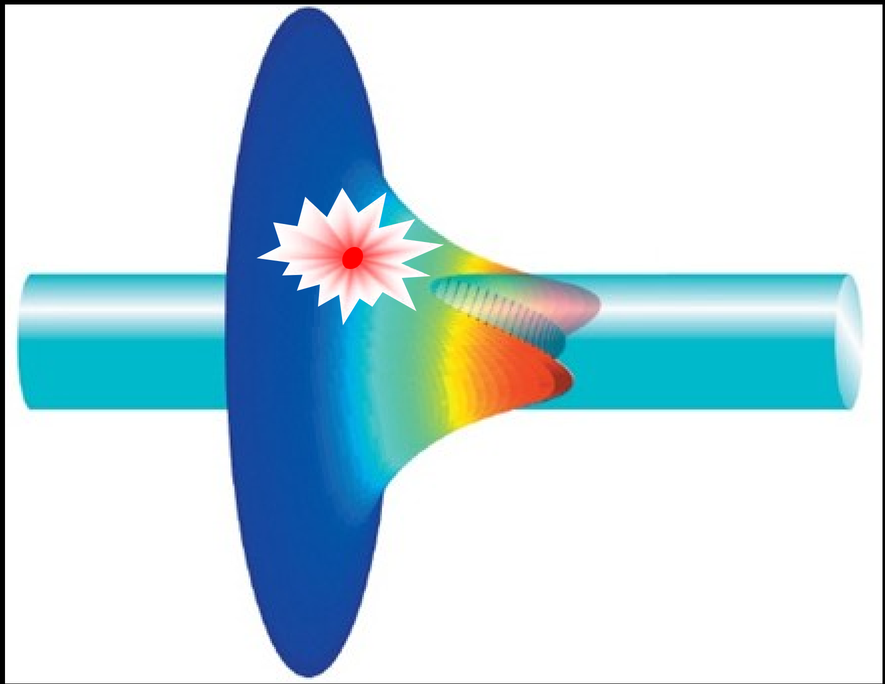


Near-field excitation of dye molecules

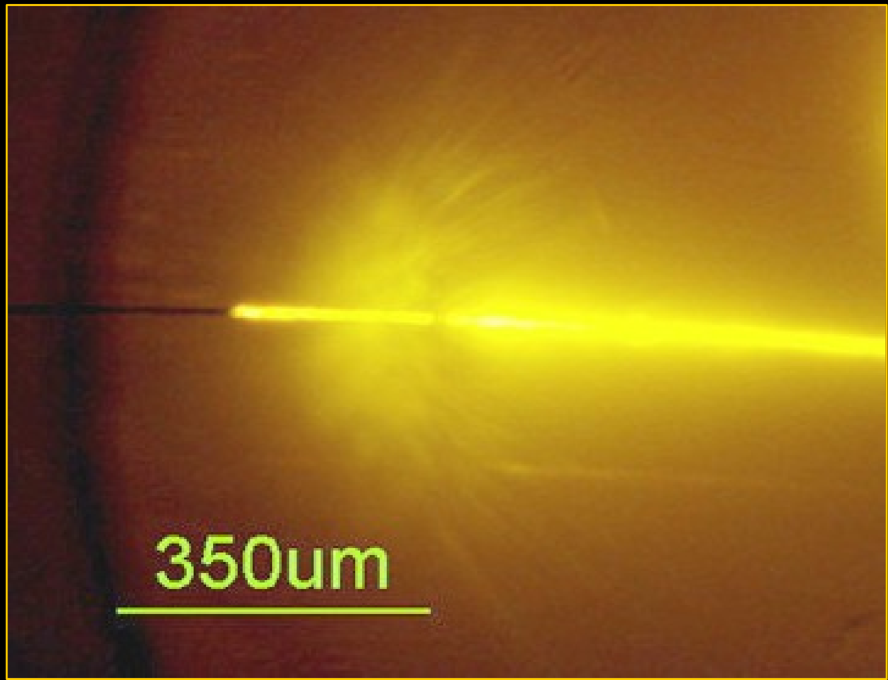
(1) Near-field Optics

- Micro Lasers : **Microfiber dye laser**

（1） silica microfiber – laser dye molecules



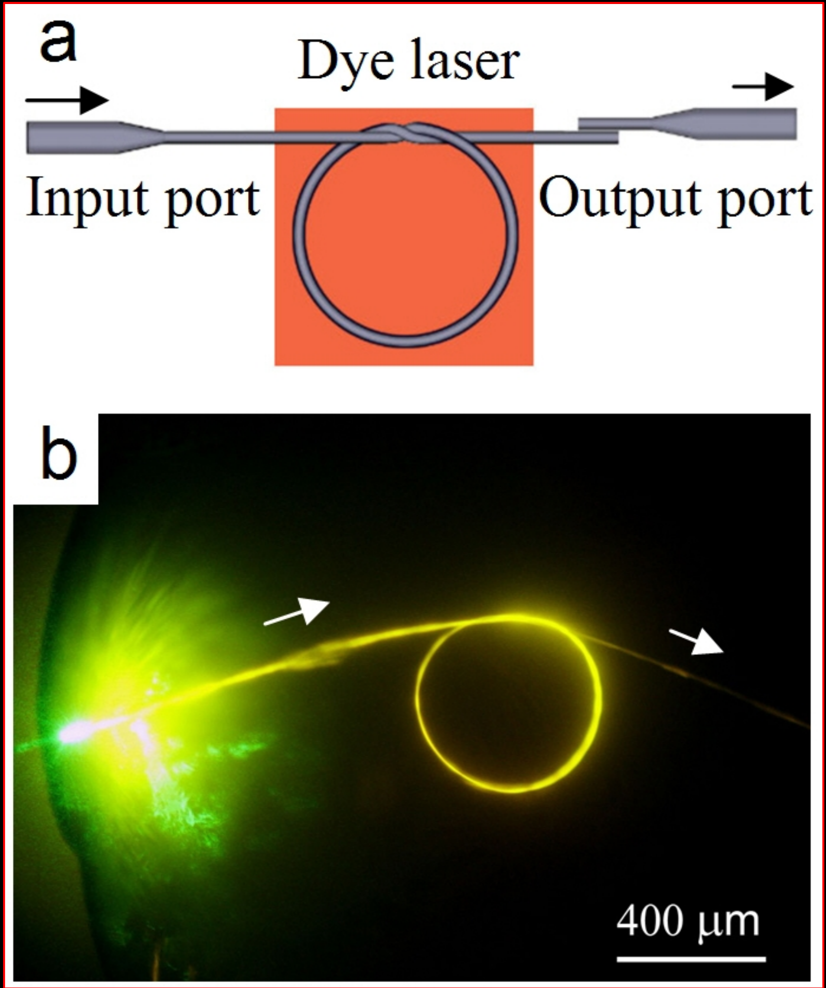
Near-field excitation of dye molecules

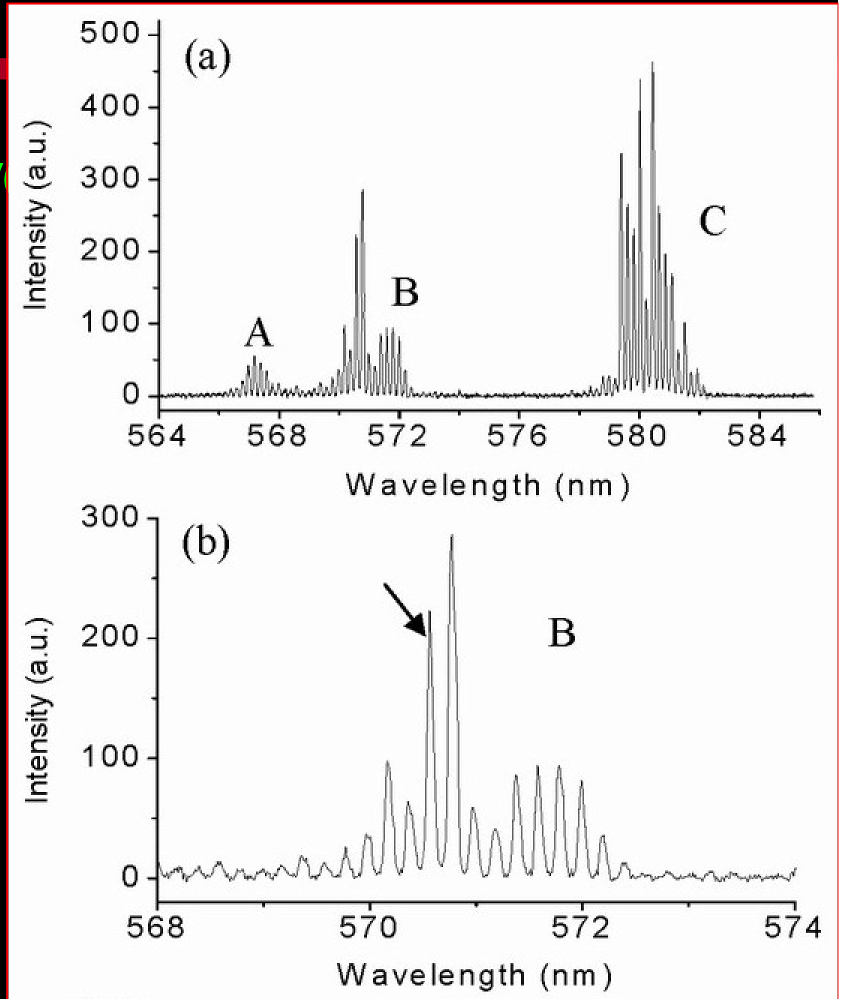


R6G dye solution excited by a 532-nm-wavelength light guided along a 3-um-diameter silica microfiber

(1) Near-field Optics

- Micro Lasers : **Microfiber dy**





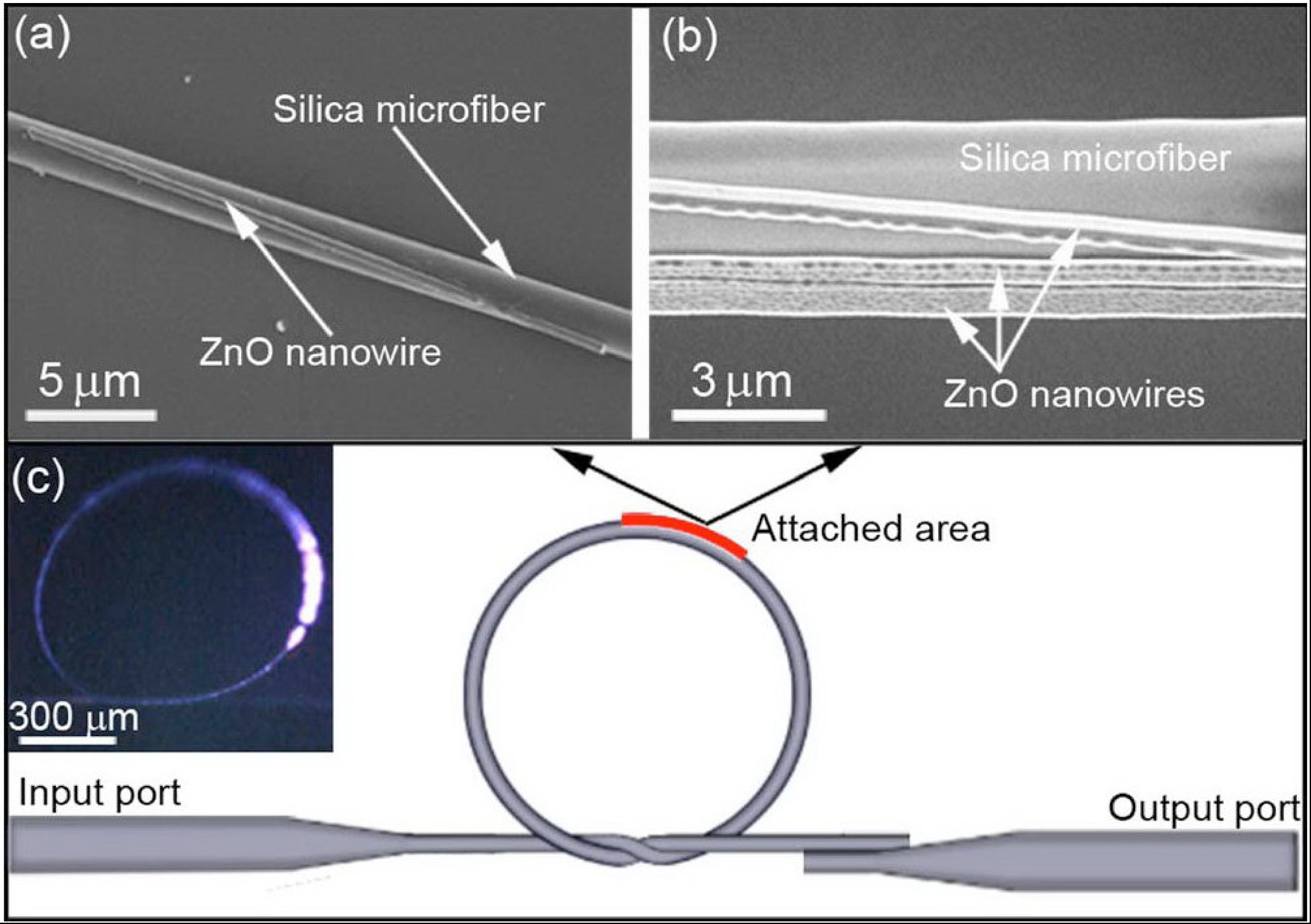
Silica microfiber knot dye laser:
(R6G) solution: 5 mM/l, Pump wavelength: 532 nm

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) Near-field Optics

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



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

(1) Near-field Optics

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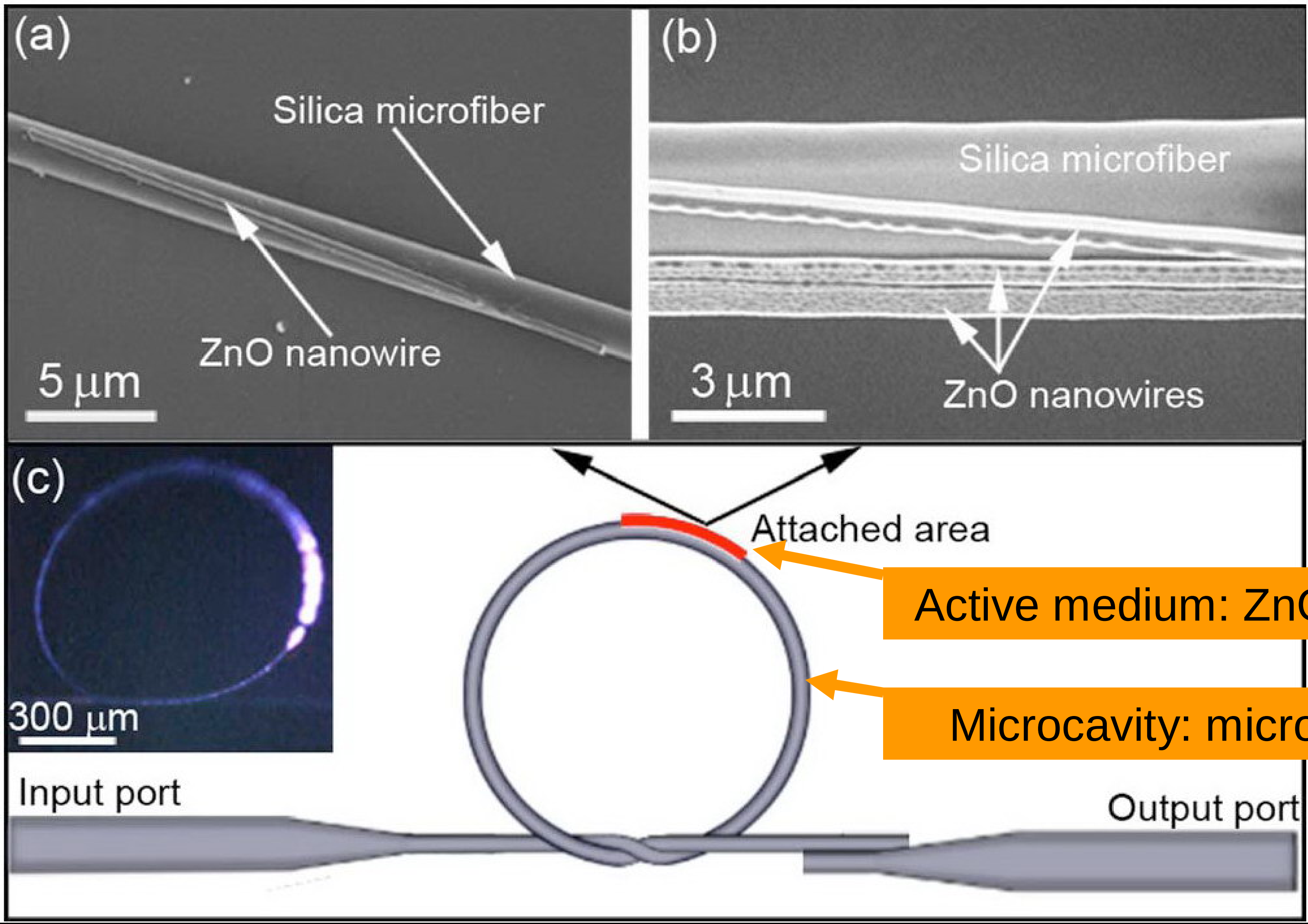


Active medium: ZnO nanowire

Microcavity: microfiber ring

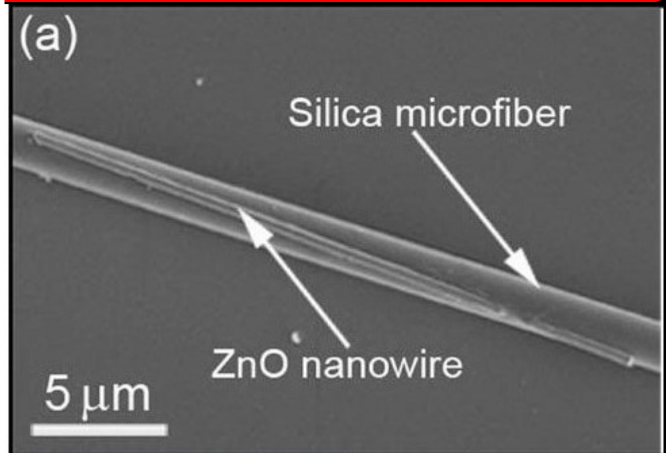
Q. Yang et al., *Appl. Phys. Lett.* **94**, 101108 (2009)

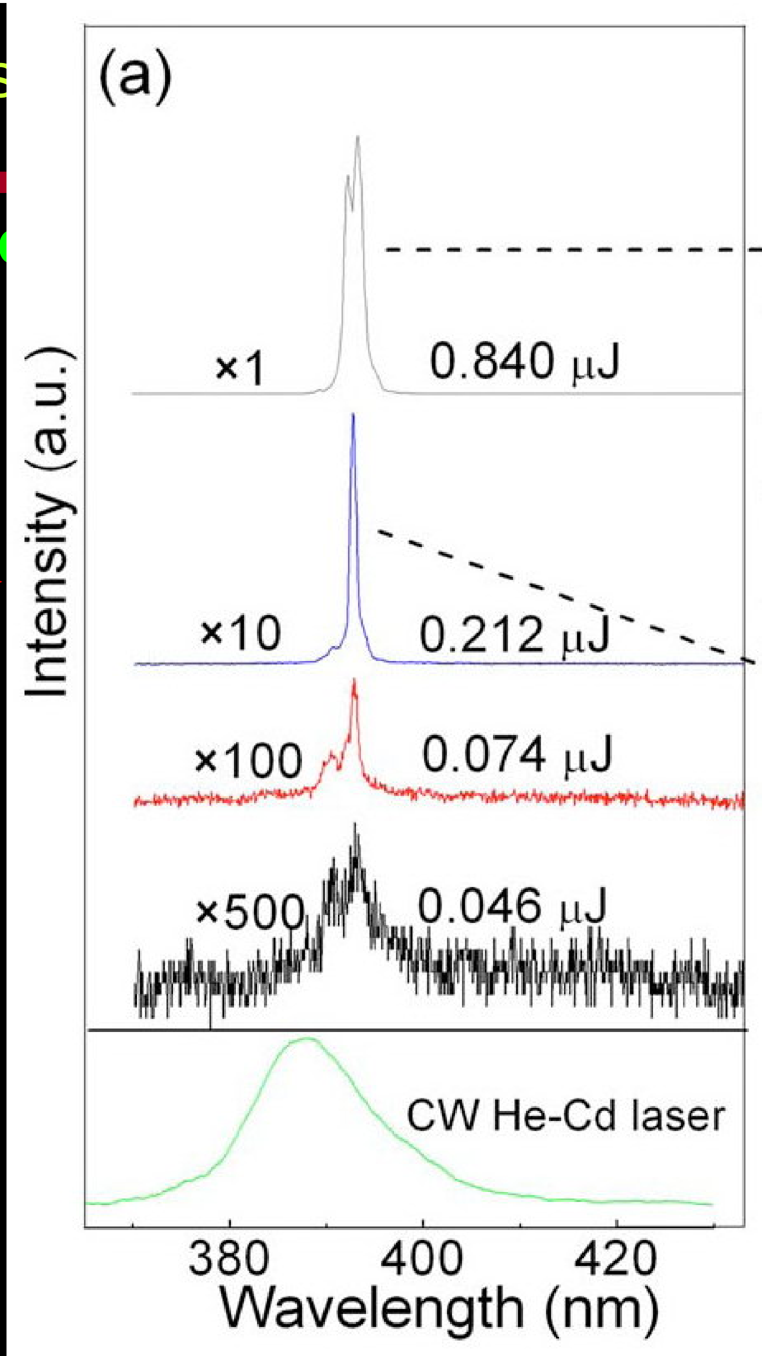
(1) Near-field Optics

• 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

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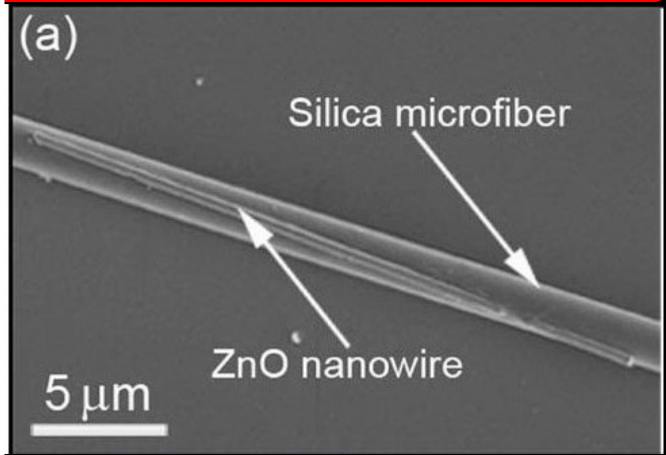
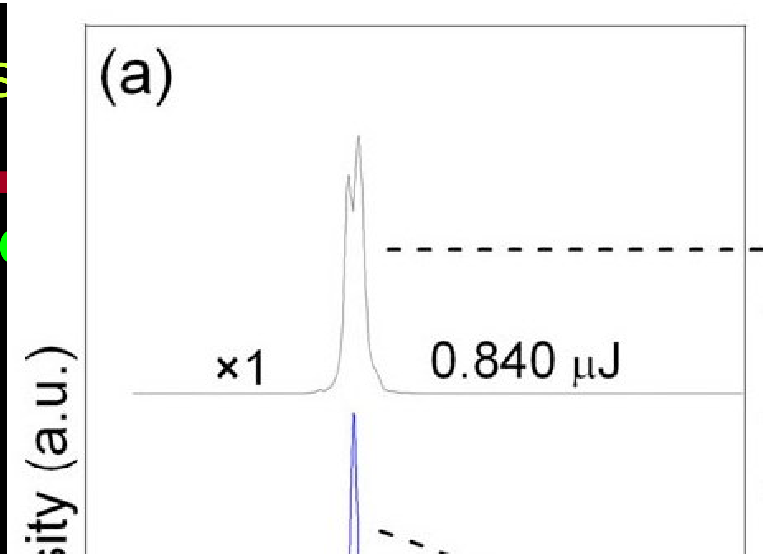
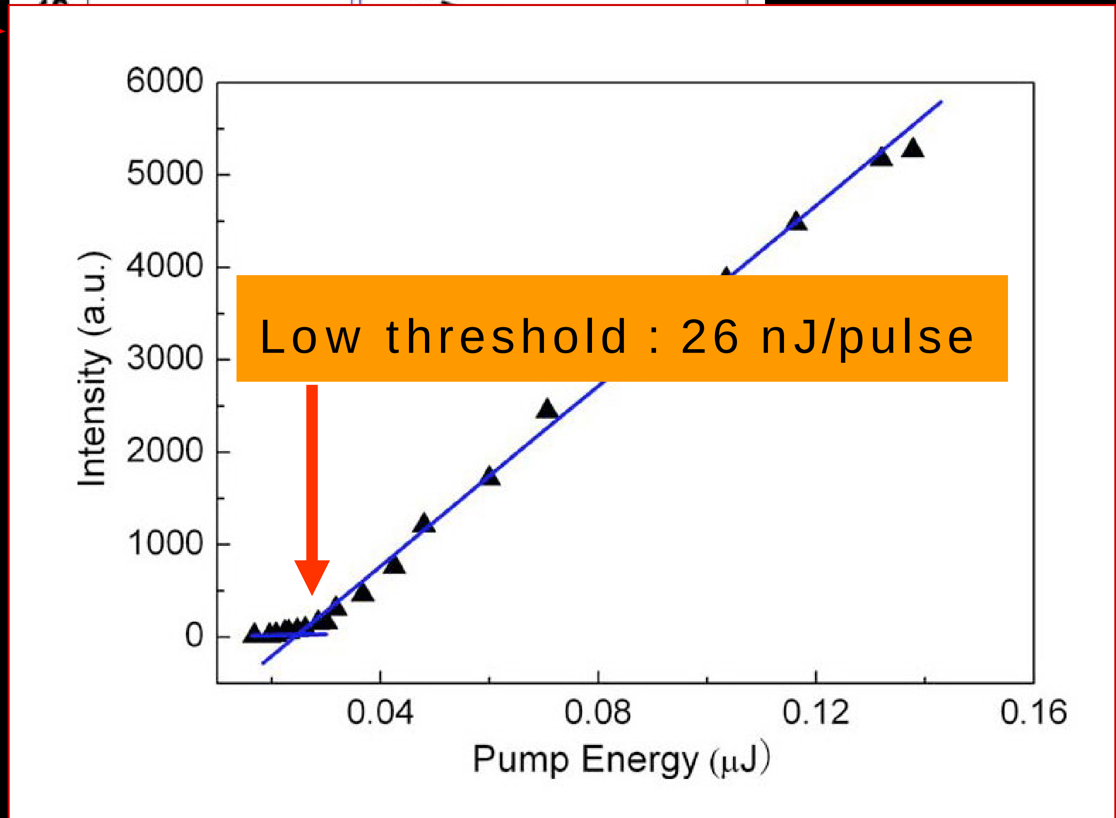




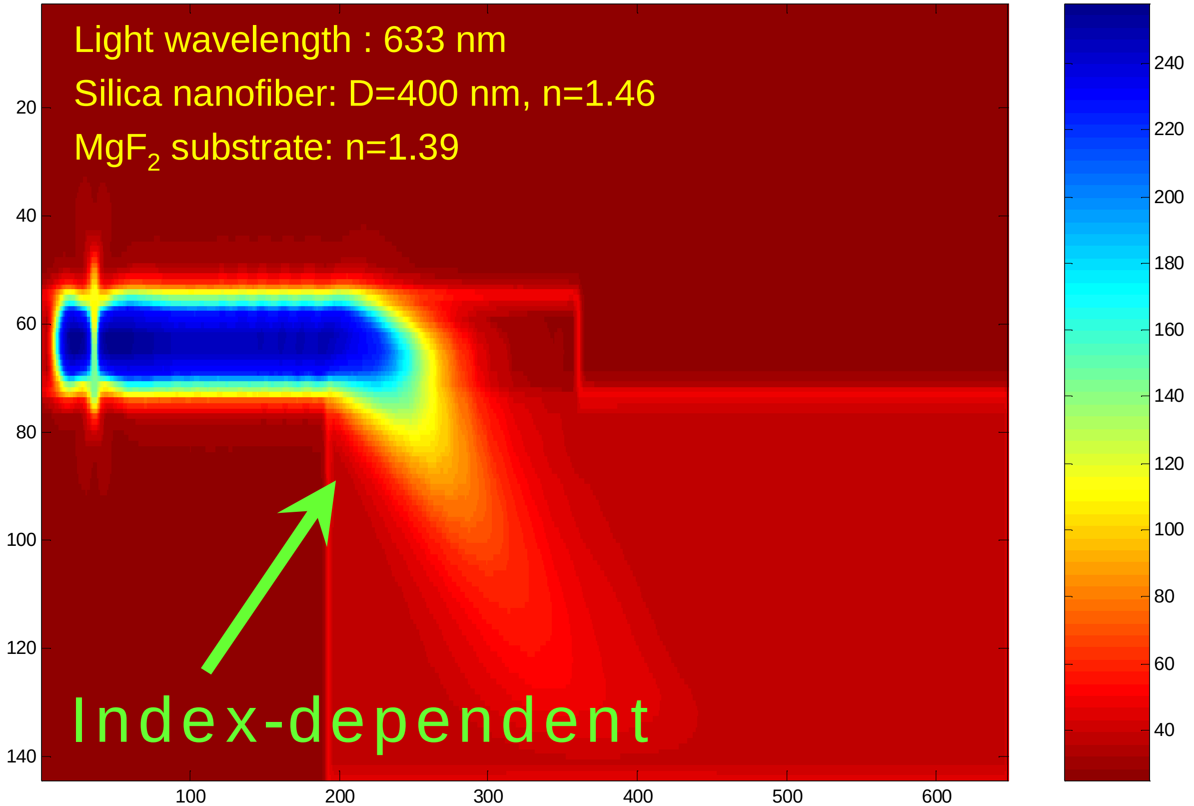


Q. Yang et al., *Appl. Phys. Lett.* **94**, 101108 (2009)

2.2 Near-field coupling for optical sensing

- Substrate induced leakage

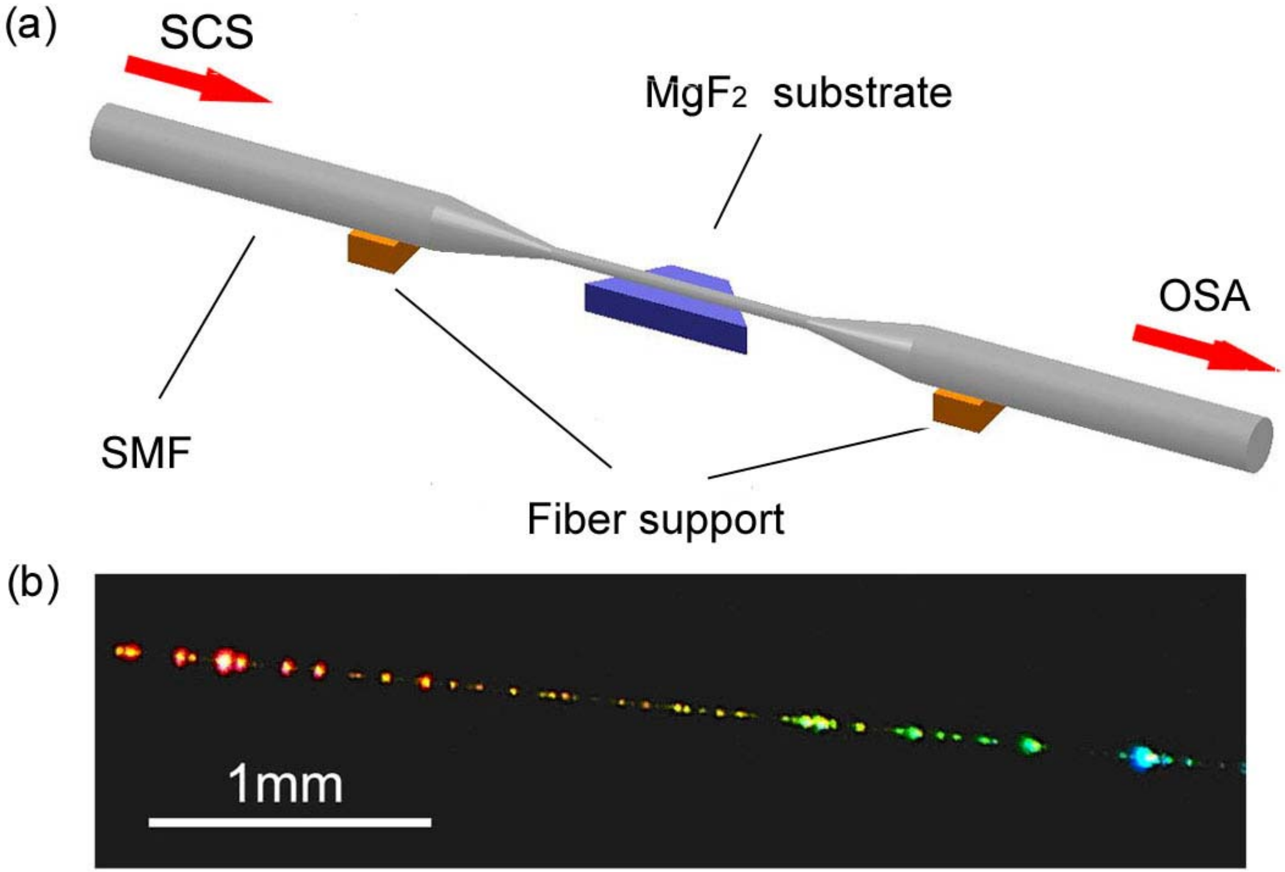
3-D FDTD simulation



(1) Near-field Optics

- Micro filters

silica microfiber – MgF_2 substrate



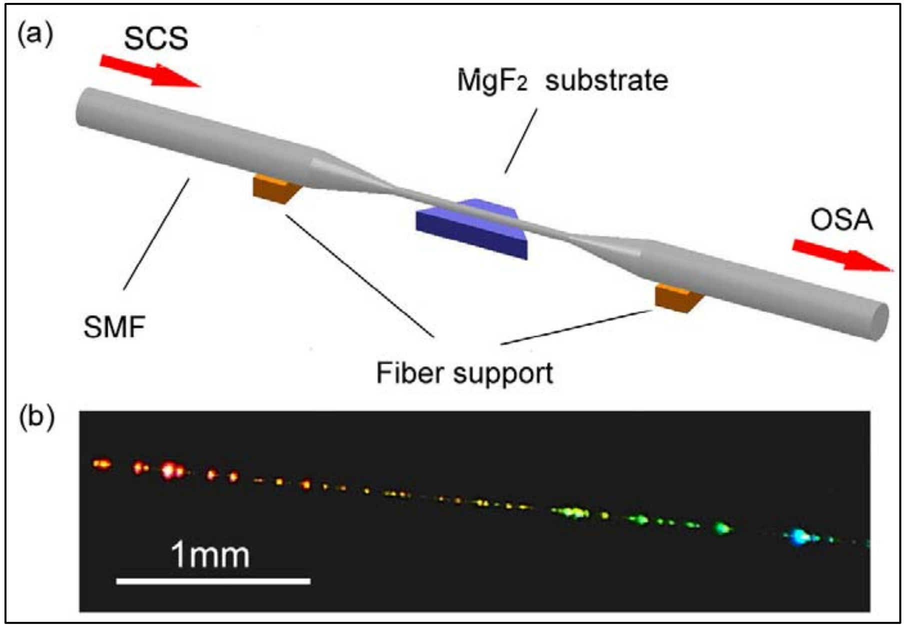
wavelength-dependent leakage

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

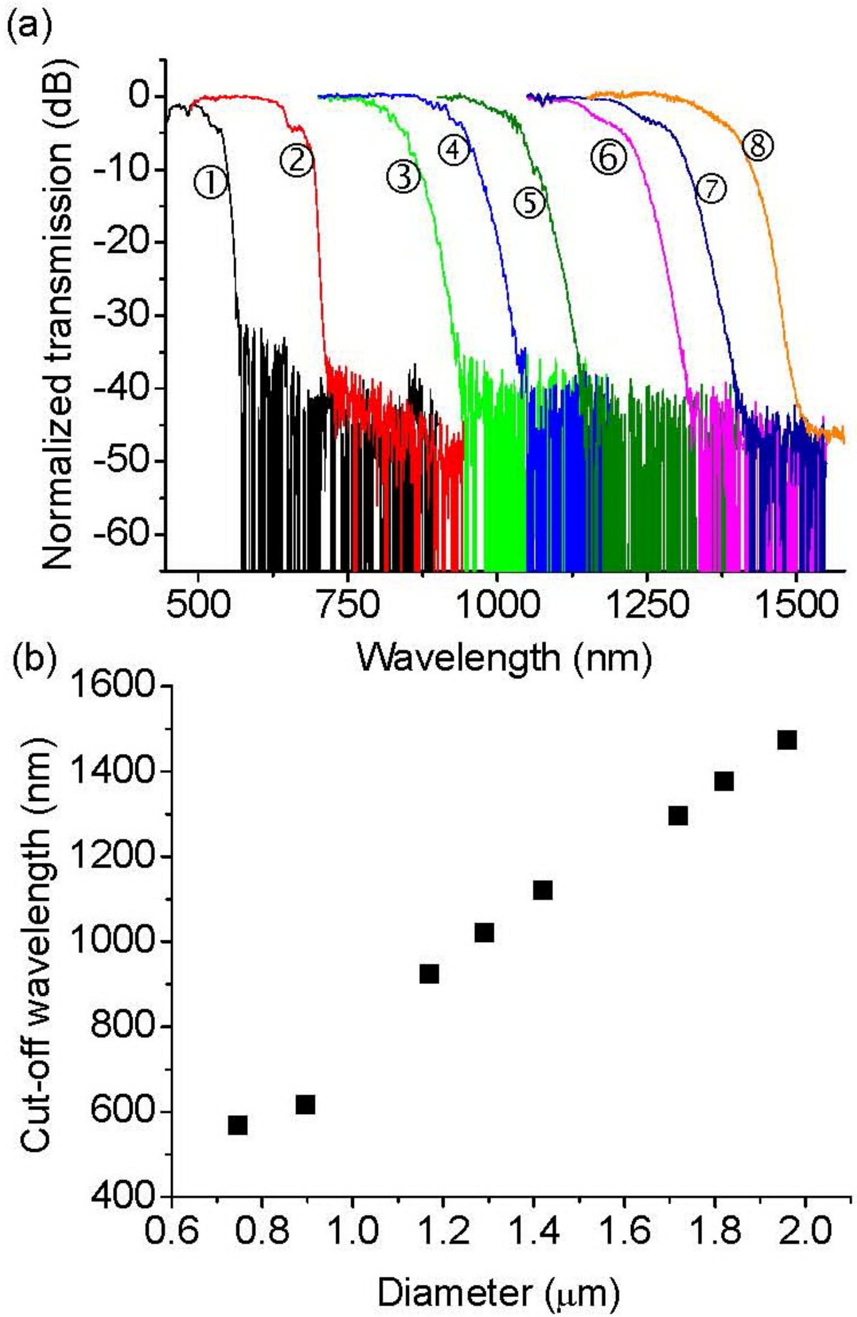
(1) Near-field Optics

- 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.

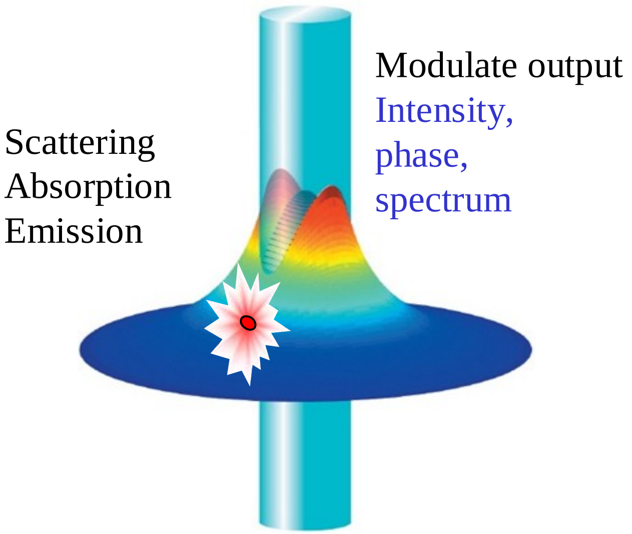


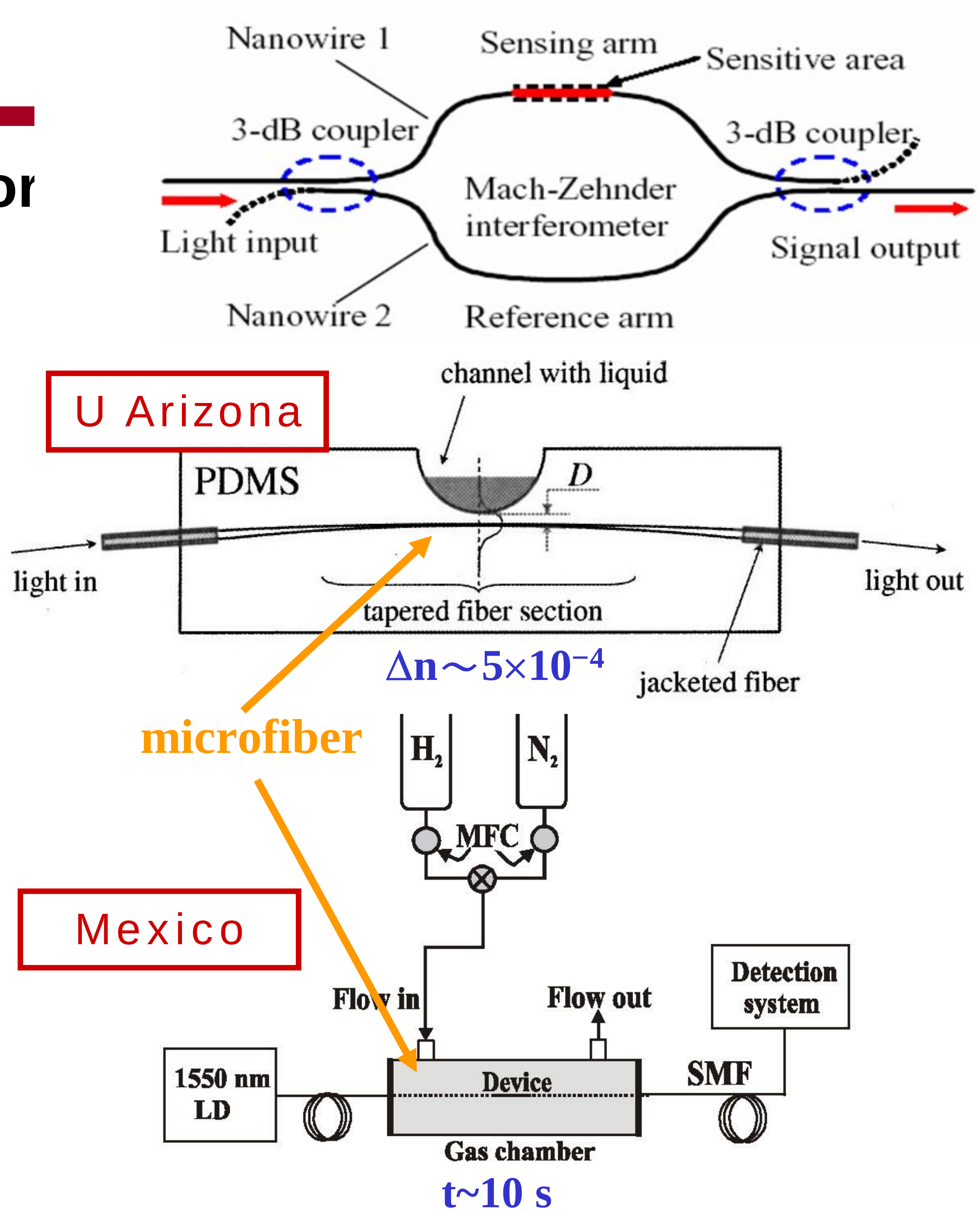
Y. Chen et al., *Opt. Lett.* **33**, 2565 (2008)

(1) Near-field Optics

2.2 Near-field coupling for

- Nanofiber sensors





Small footprint
High sensitivity
Fast response

[9] J. Lou et al., *Opt. Express* **13**, 2135 (2005)
[10] P. Polynkin et al., *Opt. Lett.* **30**, 1273 (2005)
[11] J. Villatoro et al., *Opt. Express* **13**, 5087 (2005)

Outline

3. Potentials and Applications

(1) Near-Field Optics

(2) Plasmonics

(3) Nonlinear Optics

(4) Quantum Optics\Atom Optics

(5) Photon Momentum

(2) Plasmonics

- Plasmonics

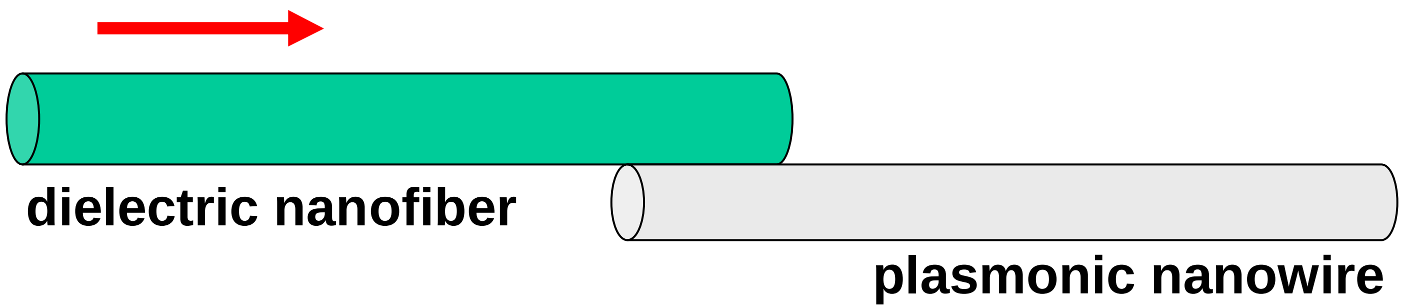
	Dielectric	v.s.	Plasmonic
Confinement	**$< \lambda/5$**		**$\sim \lambda/10$**
Loss	**Low**		**Very high**

Two questions: (1) loss – confiement

(2) high efficient launching

Hybrid nanofiber-nanowire structure

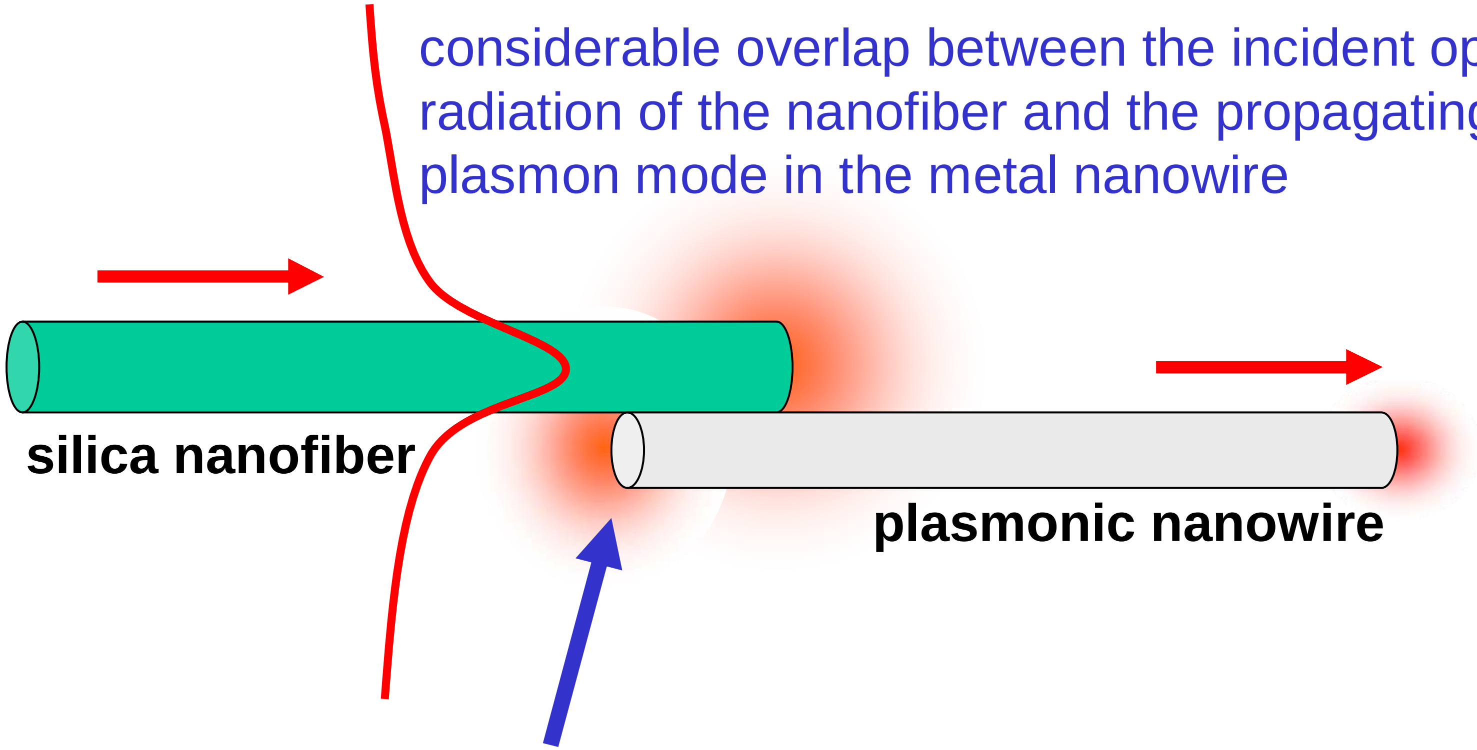
Direct coupling of silica nanofibers and silver nanowires



Hybrid nanofiber-nanowire structure

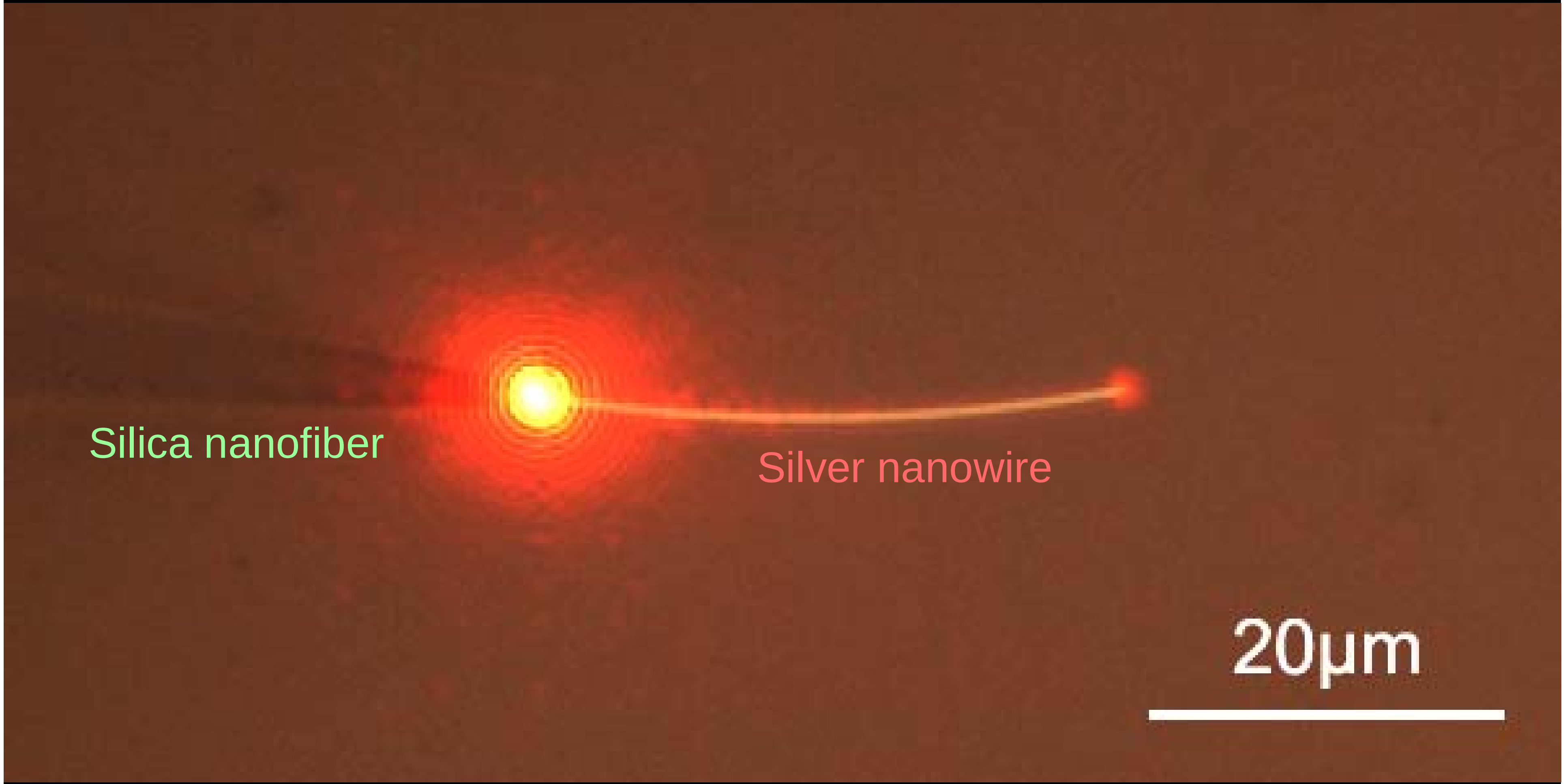
Can we couple a dielectric nanowire and a plasmonic nanowire?

considerable overlap between the incident optical radiation of the nanofiber and the propagating plasmon mode in the metal nanowire



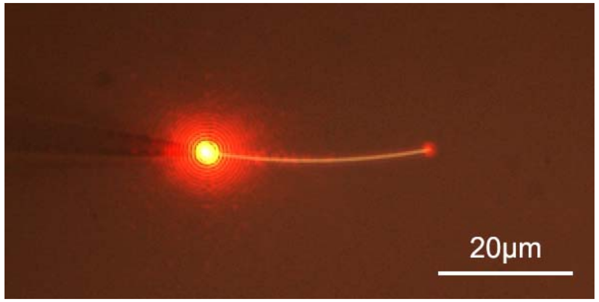
the small end of the silver nanowire scatters evanescent waves for compensating momentum mismatch between the dielectric and the plasmonic waveguides

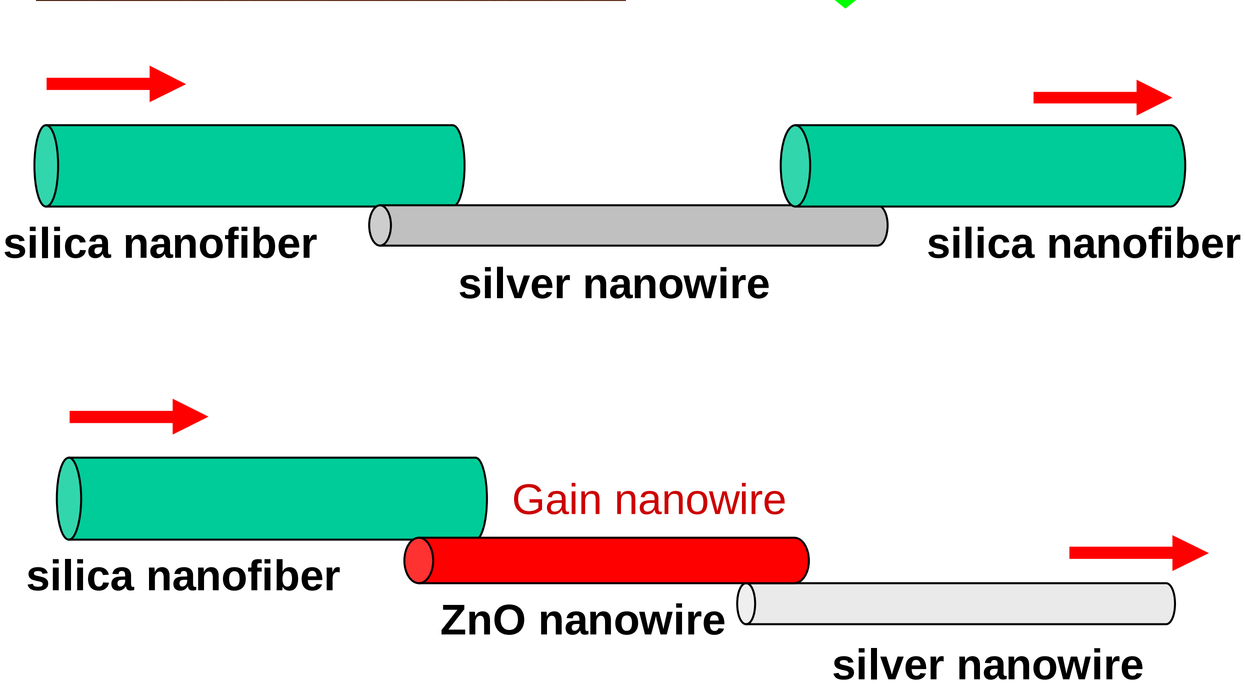
Coupling a 633-nm-wavelength light from a 500-nm-diameter silica nanofiber to a 200-nm-diameter silver nanowire



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

Hybrid nanofiber-nanowire structure





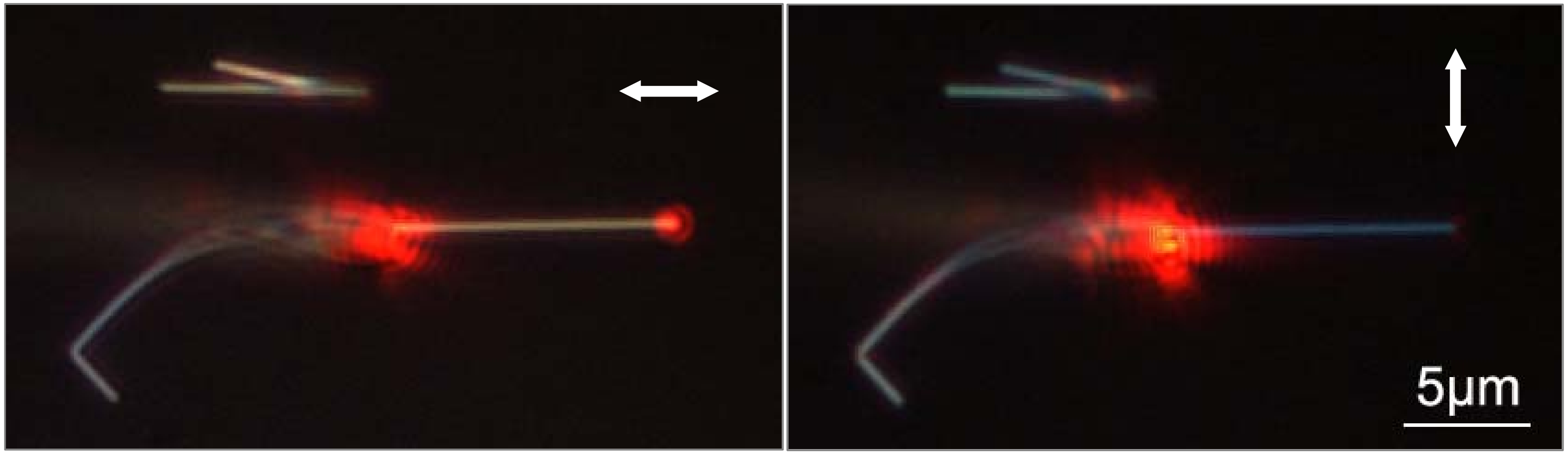
Advantages

- **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)

Hybrid nanofiber-nanowire structure

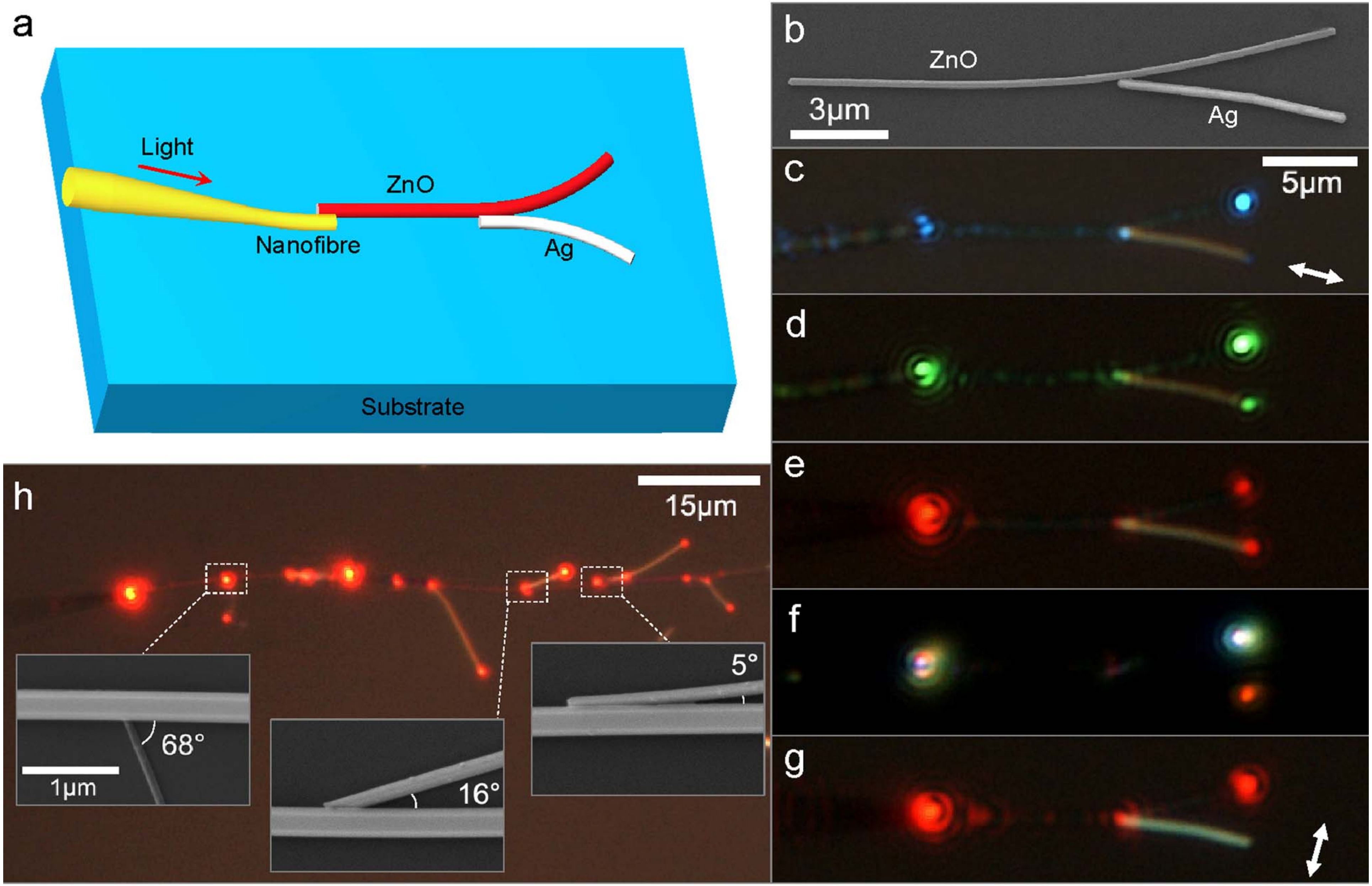
Polarization-dependent coupling efficiency



Polarization splitters

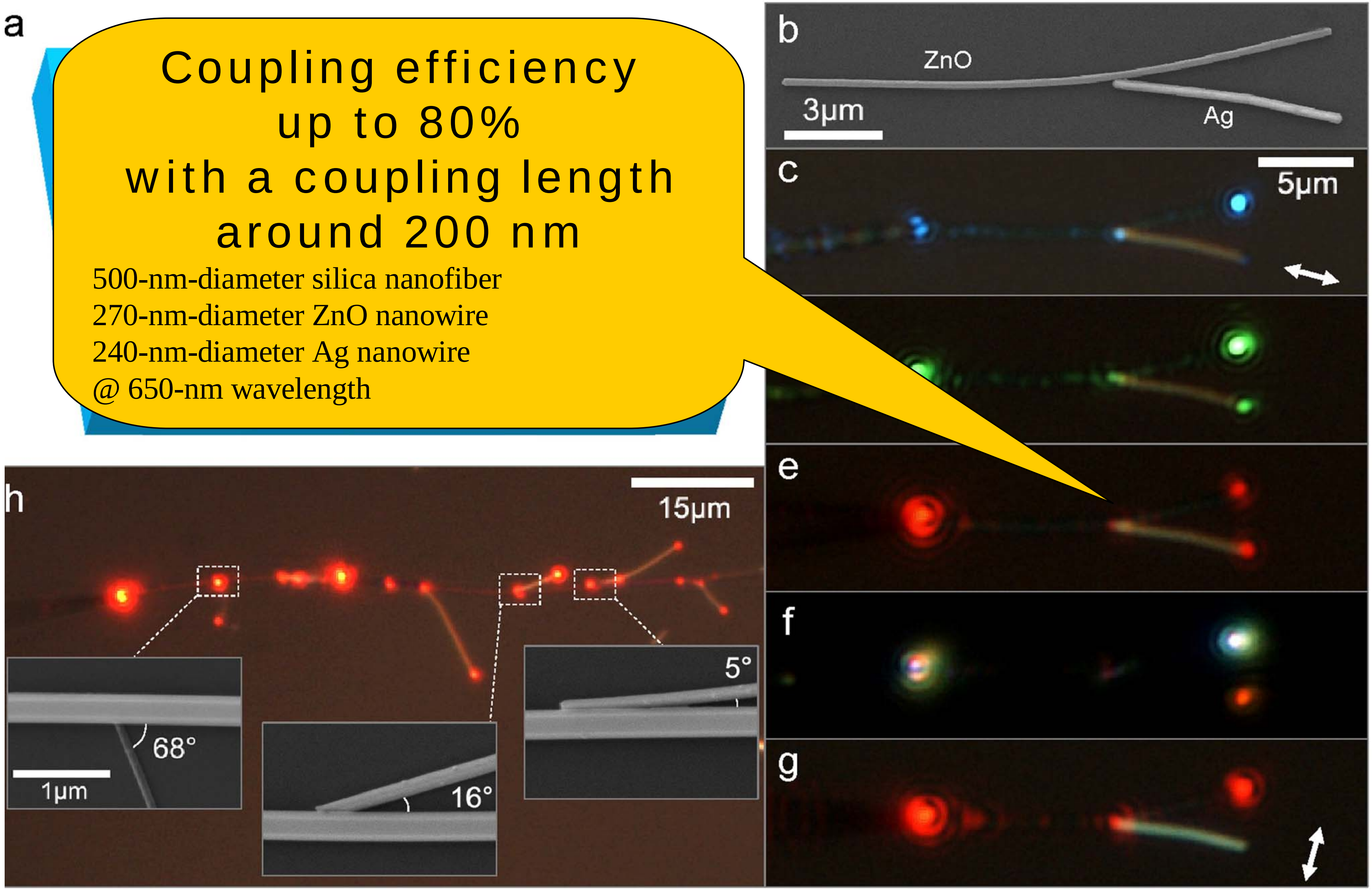
X. Guo et al., *Nano Lett*. 9, 4515-4519 (2009)

Branch couplers



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

Branch couplers

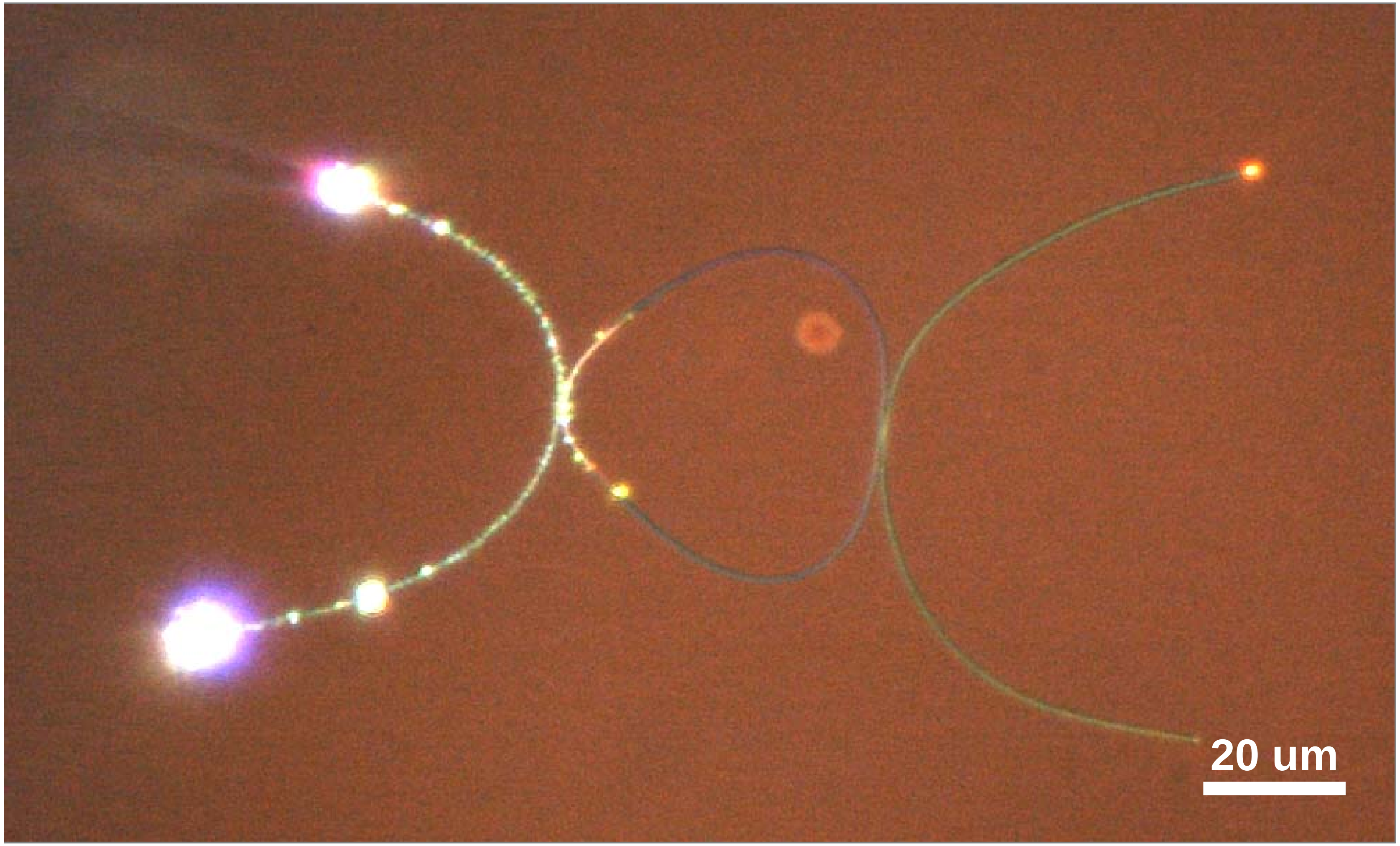


Coupling efficiency
up to 80%
with a coupling length
around 200 nm

500-nm-diameter silica nanofiber
270-nm-diameter ZnO nanowire
240-nm-diameter Ag nanowire
@ 650-nm wavelength

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

Hybrid nanowire resonators



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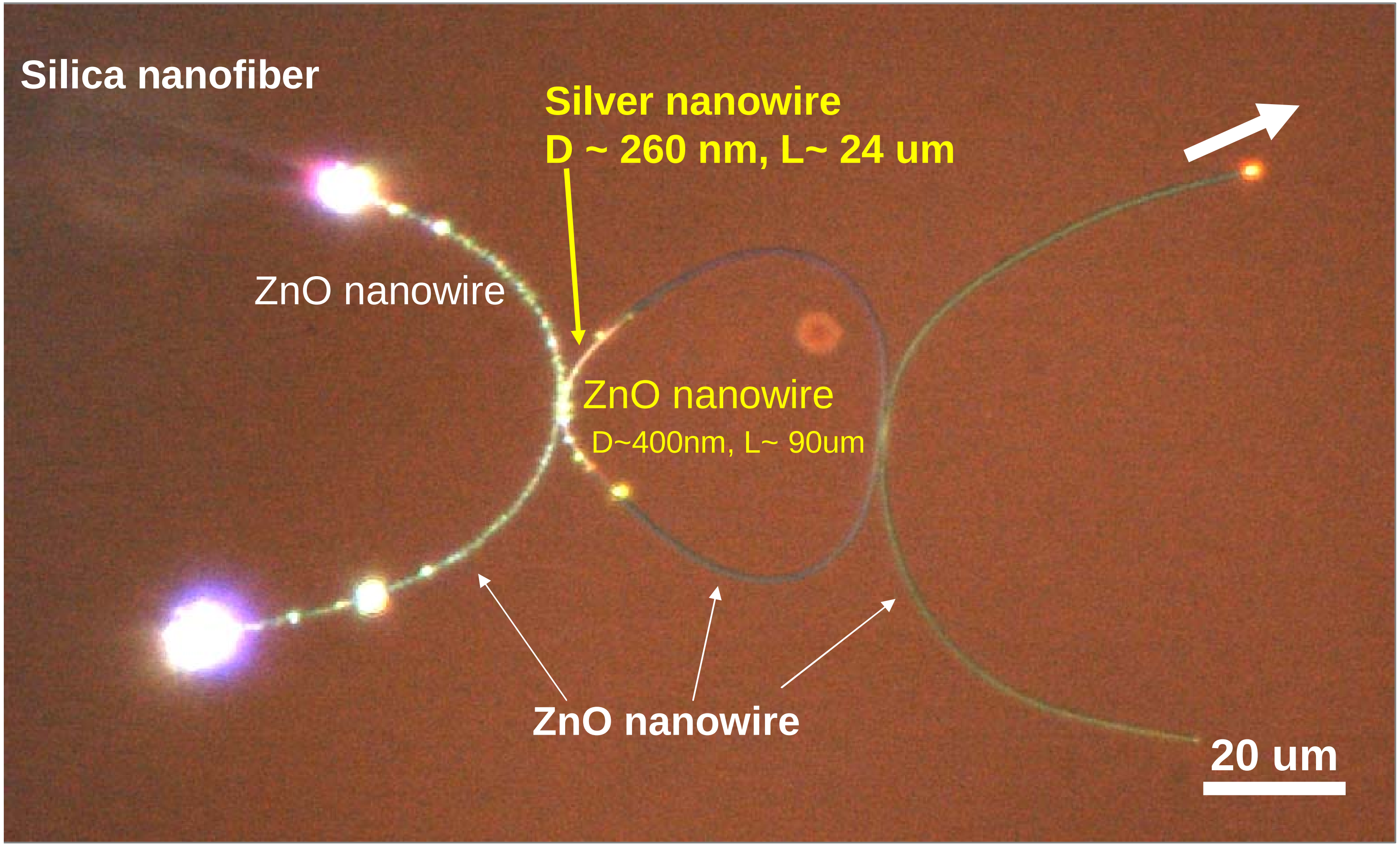
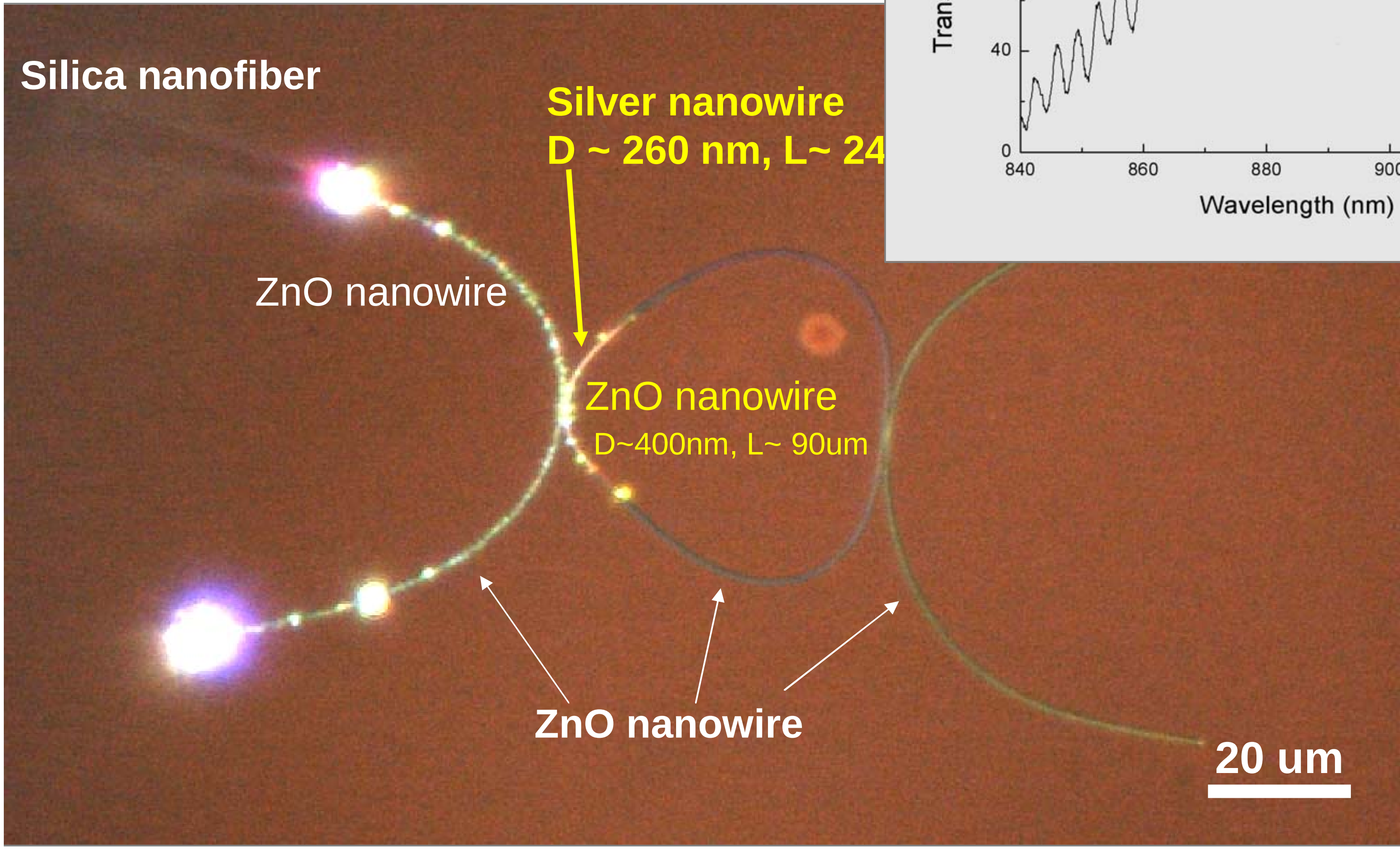
Hybrid nanowire resonators

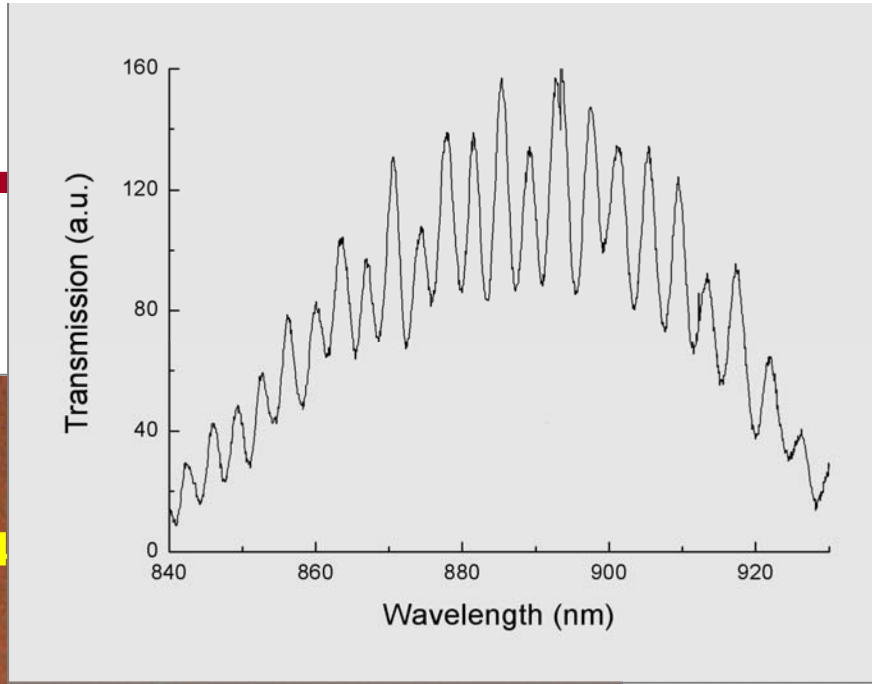


X. Guo et al., *Nano Lett*. 9, 4515-4519 (2009)

(2) Plasmonics

Hybrid nanowire resonators

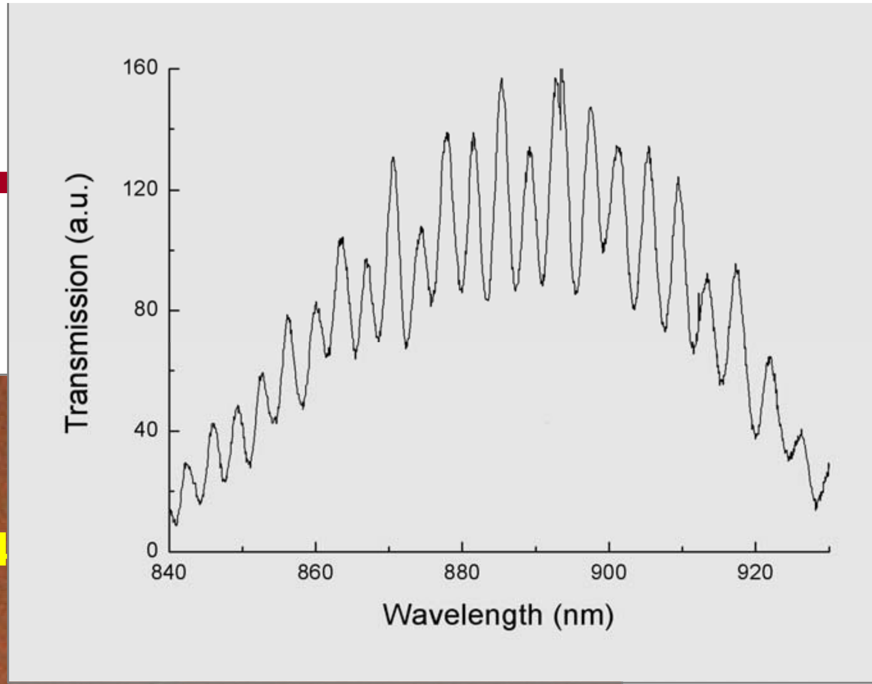


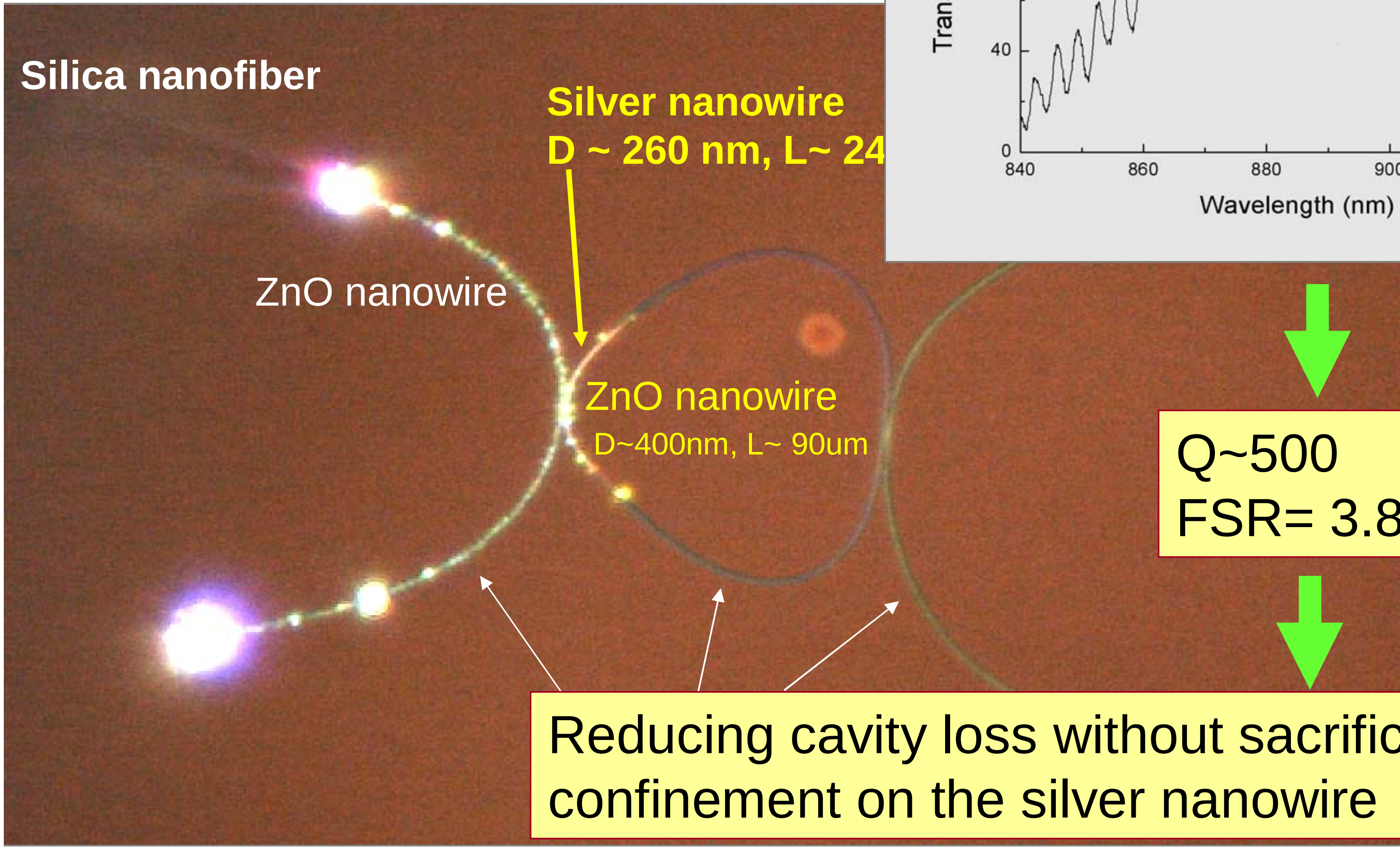


X. Guo et al., *Nano Lett*. 9, 4515-4519 (2009)

(2) Plasmonics

Hybrid nanowire resonators





Q~500
FSR= 3.8 nm

Reducing cavity loss without sacrificing confinement on the silver nanowire

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

Outline

Outline

3. Potentials and Applications

(1) Near-Field Optics

(2) Plasmonics

(3) Nonlinear Optics

(4) Quantum Optics\Atom Optics

(5) Photon Momentum

2.2 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 ɣ**
- **Dispersion : Diameter-dependent** → **manageable**

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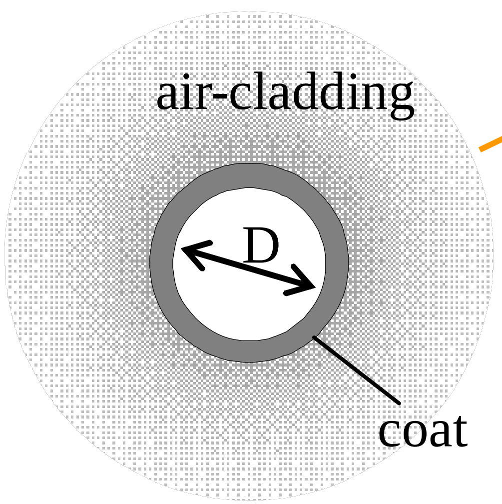

J. Y. Lou et al., *Opt. Express* **14**, 6993 (2006)

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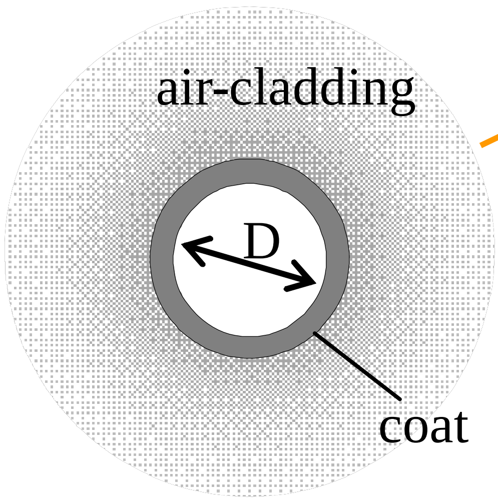
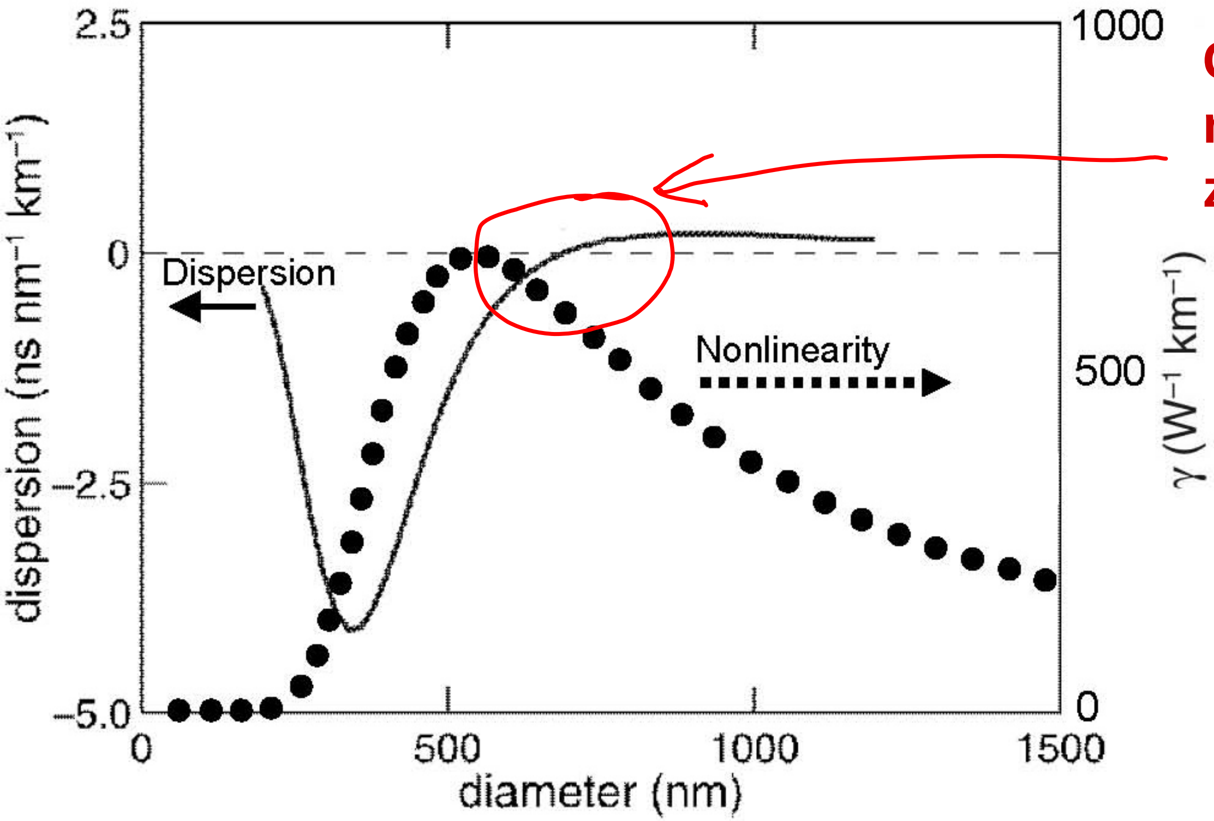


- **Low threshold**
- **Short interaction length**
- **possible to work with very small quantity of samples**

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

2.2 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

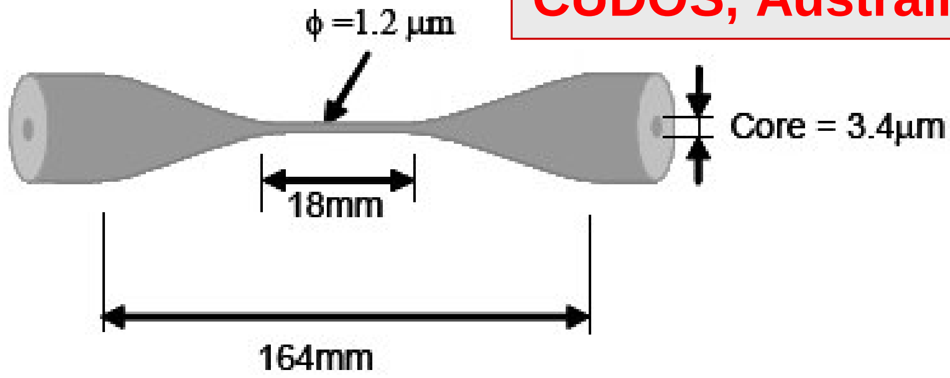
L. Tong et al., *Opt. Express* **12**,1025 (2004)

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



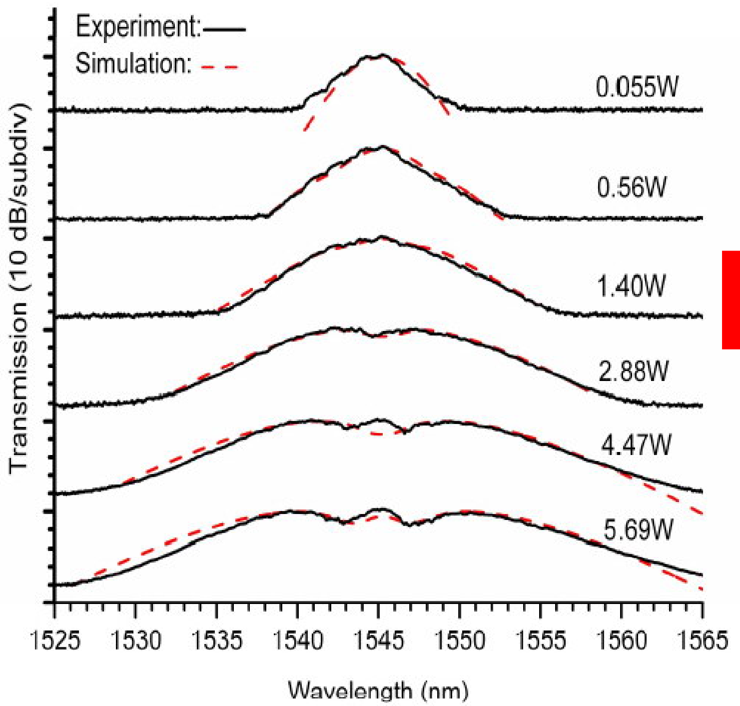


Fig. 5. SPM spectra under different incident peak power in the As_2Se_3 fiber

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)

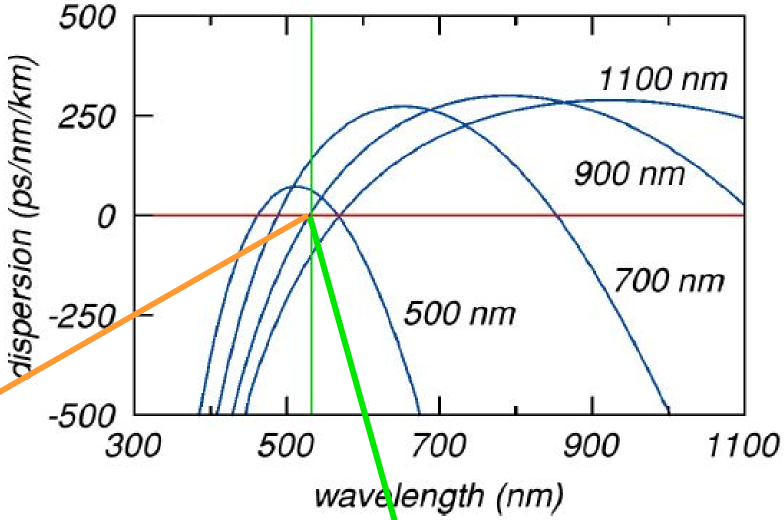
E. C. Mägi et al., *Opt. Express* 12, 10324 (2007)

(3) Nonlinear Optics

Supercontinuum generation

- with ns pulses [12]

U Bath (UK)



Silica fiber

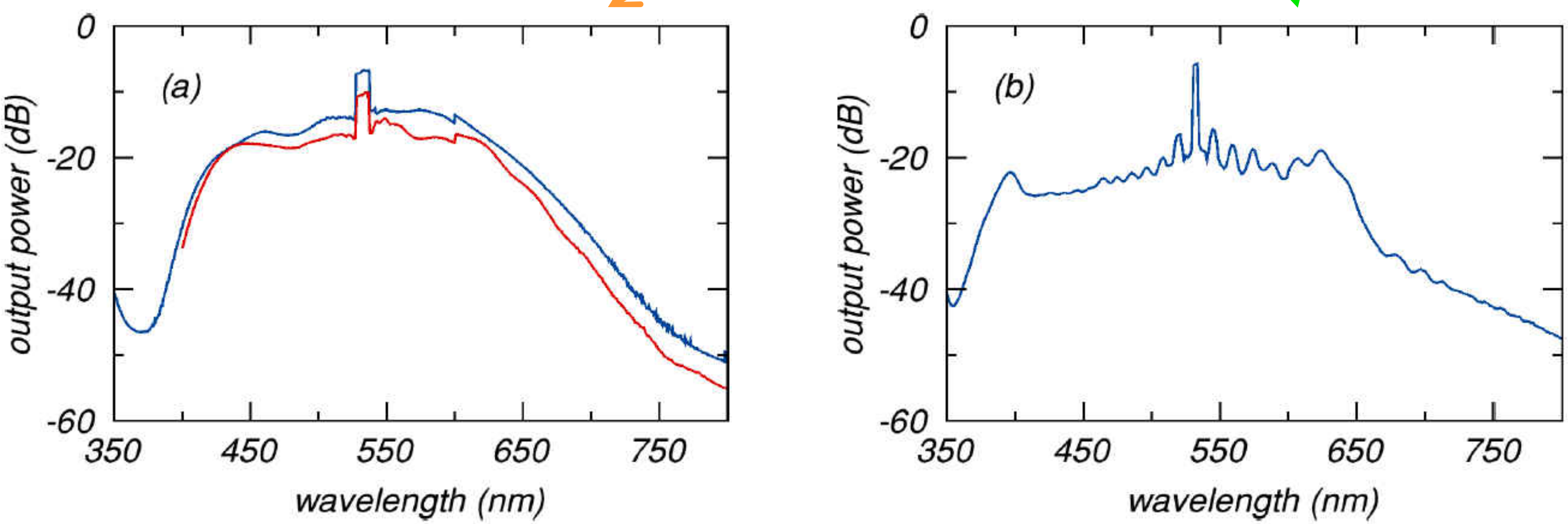


Fig. 4. SC spectra generated by taper waists for diameter, length and average laser power of (a) 920 nm, 90 mm and ~3 mW, and (b) 510 nm, 20 mm and ~1.5 mW, respectively. The red curve is for a sample made from Nufern 630-HP fibre instead of Corning SMF-28.

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

2.3 Supercontinuum generation

- with fs pulses

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

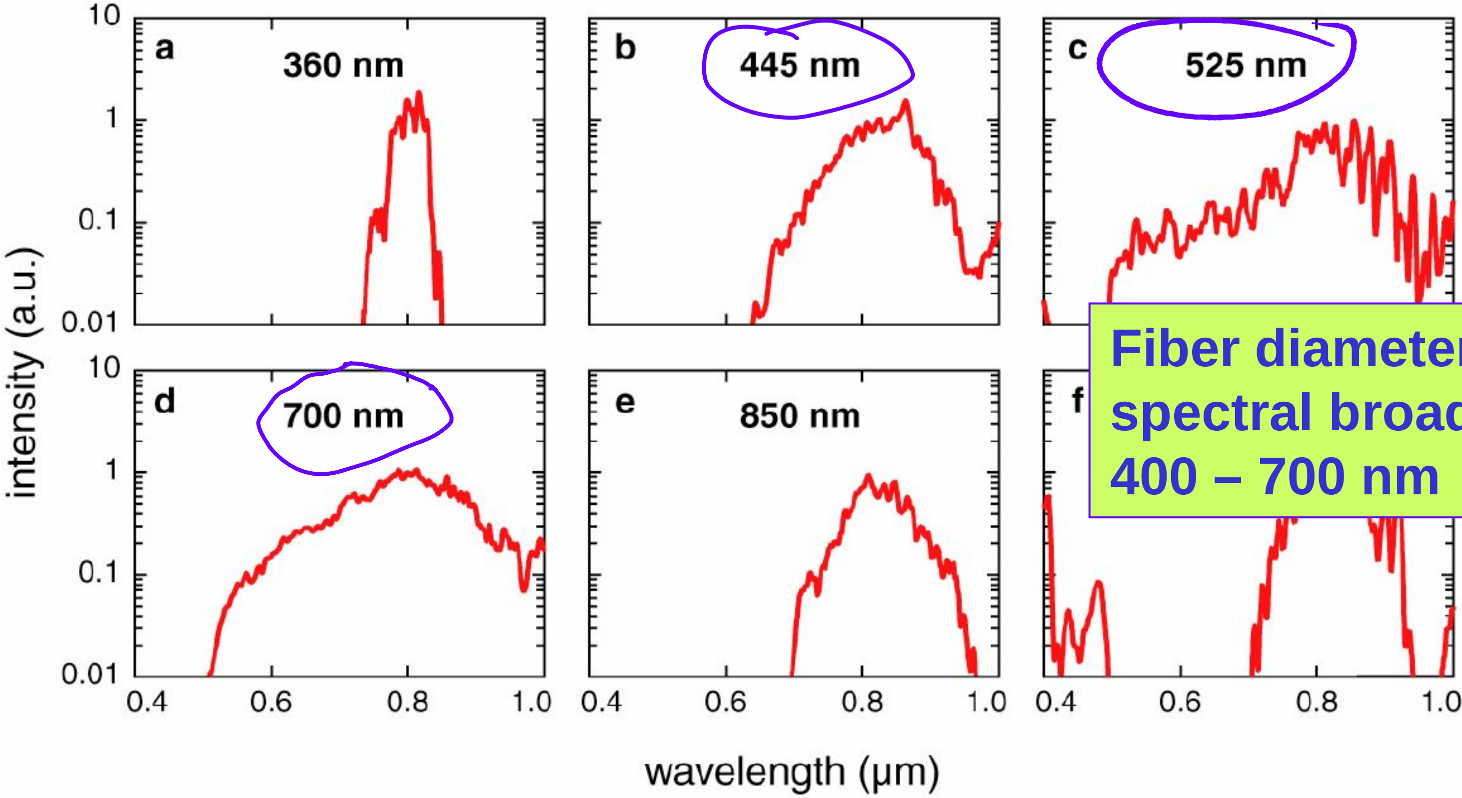


Fig. 2. Supercontinuum spectra for the six fibers of Fig. 1. The transmitted pulse energies are: (*a*) 0.3 nJ, (*b*) 4 nJ, (*c*) 6 nJ, (*d*) 4 nJ, (*e*) 7 nJ and (*f*) 2.5 nJ.

Fiber diameter good for spectral broadening : 400 – 700 nm

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

2.4 More potentials and applications

Pulse compression

Two photon absorption

Enhanced Kerr nonlinearity

All-optical signal processing

Nonlinear interaction in atom vapor

M. A. Foster et al., *Opt. Express* 13, 6848 (2005)
L. Shi et al., *Opt. Express* 14, 5055 (2006)
H. You et al., Phys. Rev. A78, 053803(2008)
E. C. Magi et al., *Opt. Express* 15, 10324 (2007)
M .D. Pelusi et al., *Opt. Express* 16, 1506 (2008)
M. A. Foster et al., *Opt. Express* 16, 1300-1320 (2008)
S. M. Spillane et al., *Phys. Rev. Lett.* 100, 233602 (2008)

Outline

3. Potentials and Applications

(1) Near-Field Optics

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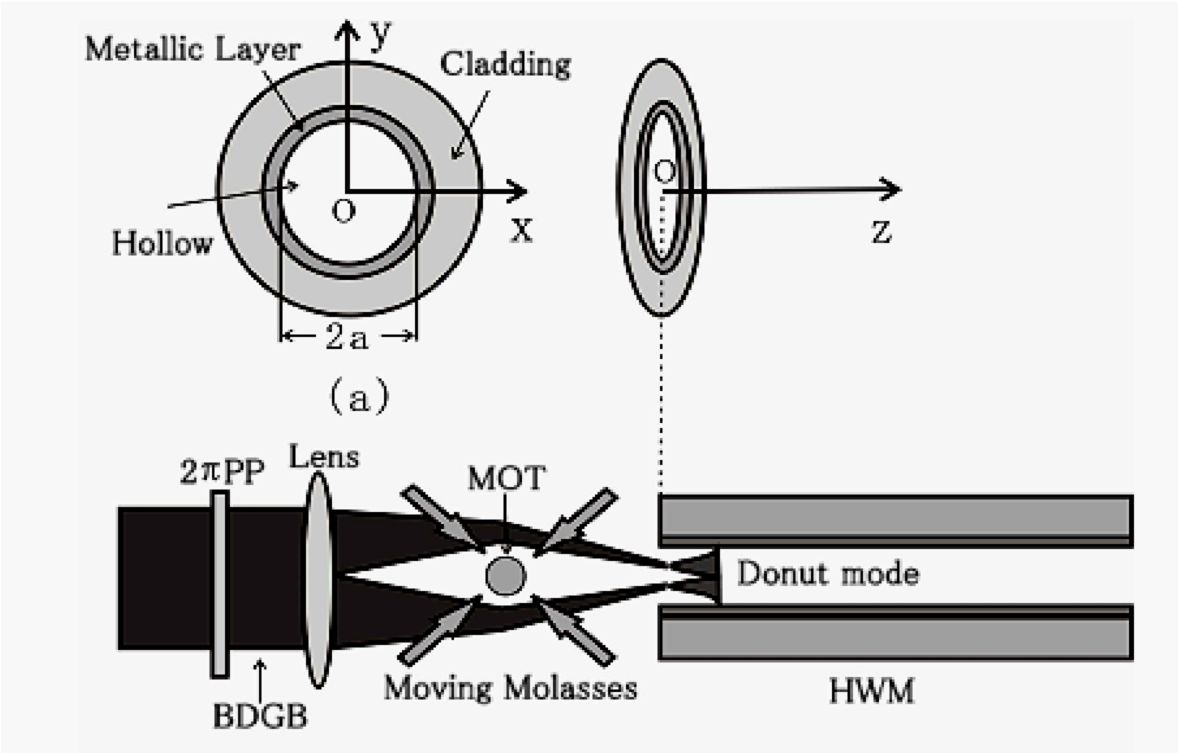
2.5 Atom trap and manipulation

- Atom trap and guide using optical waveguides [15,16]

e.g. Hollow waveguide



[15] A. H. Barnett *et al.*, *Phys. Rev.* **A61**, 023608 (2000)
[16] Z. Wang, *et al.*, *Opt. Express* **13**, 8406 (2005)

2.5 Atom trap and manipulation

- Atom trap and guide using optical nanofiber [17-20]

U Electro-Communications (Japan)

Advantages

- **Deep potential for trapping/guiding of neutral atoms**
- **Trap atoms in open space outside the nanofiber**
- **Couple atom emission back into the nanofiber**

2.5 Atom trap and manipulation

- Atom trap and guide using optical nanofiber [17-20]

U Electro-Communications (Japan)

Basic idea

Using the gradient force of a red/blue-detuned evanescent-wave to balance/serve as the centrifugal/centripetal force to store, move, and manipulate cold atoms in a controlled manner, and **this is possible only when $D_{fiber} < \sim \lambda /2$**

Due to the spatial distribution of the evanescent fields of a nanofiber

[17] V. I. Balykin et al., *Phys. Rev.* **A70**, 11401 (2004)

[18] F. L. Kien et al., *Phys. Rev.* **A70**, 11401 (2004)

[19] F. L. Kien et al., *Phys. Rev.* A**73**, 13819 (2006)

[20] K. P. Nayak et al., *Opt. Express* **15**, 5431 (2007)

- Atom trap and guide

using optical microfiber [18]

U Electro-Communications (Japan)

Two-color scheme

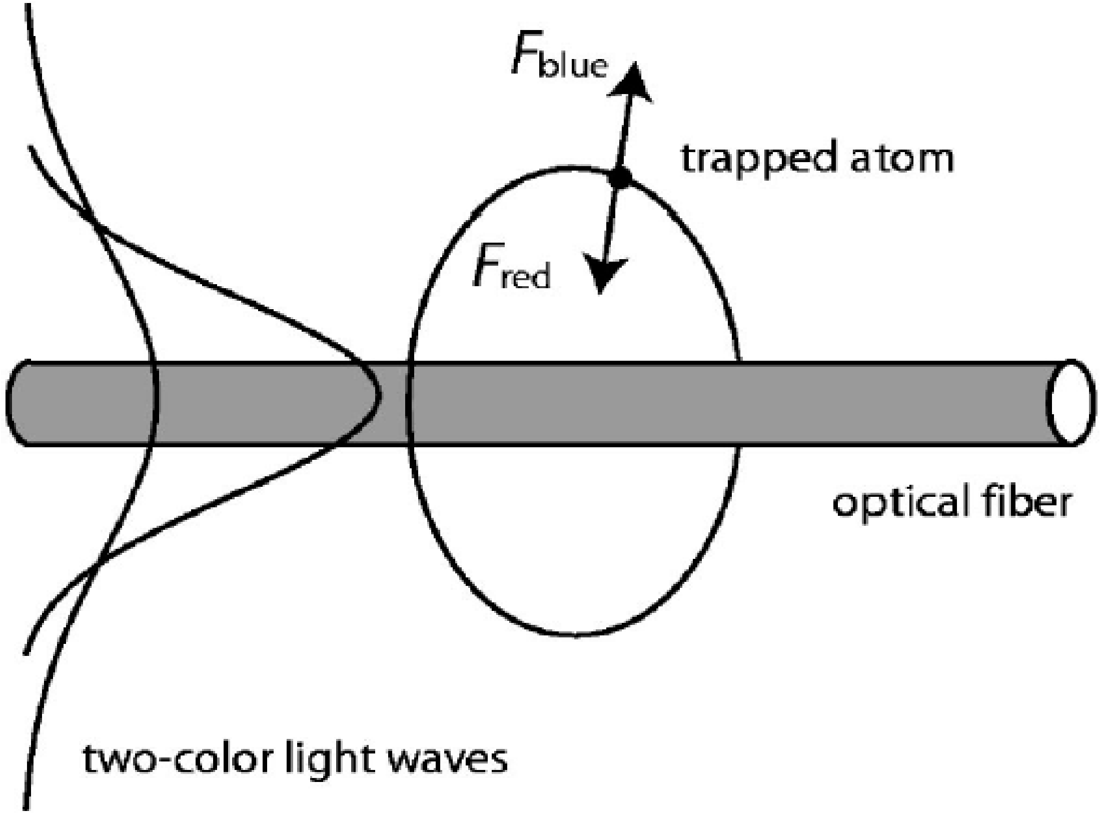


FIG. 1. Schematic of atom trapping and guiding around an optical fiber.

[18] F. L. Kien et al., *Phys. Rev.* **A70**, 11401 (2004)

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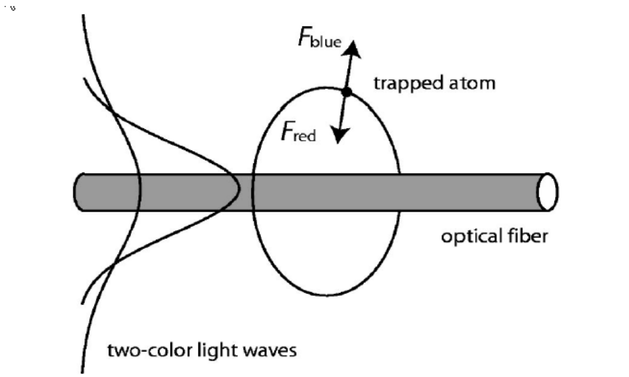
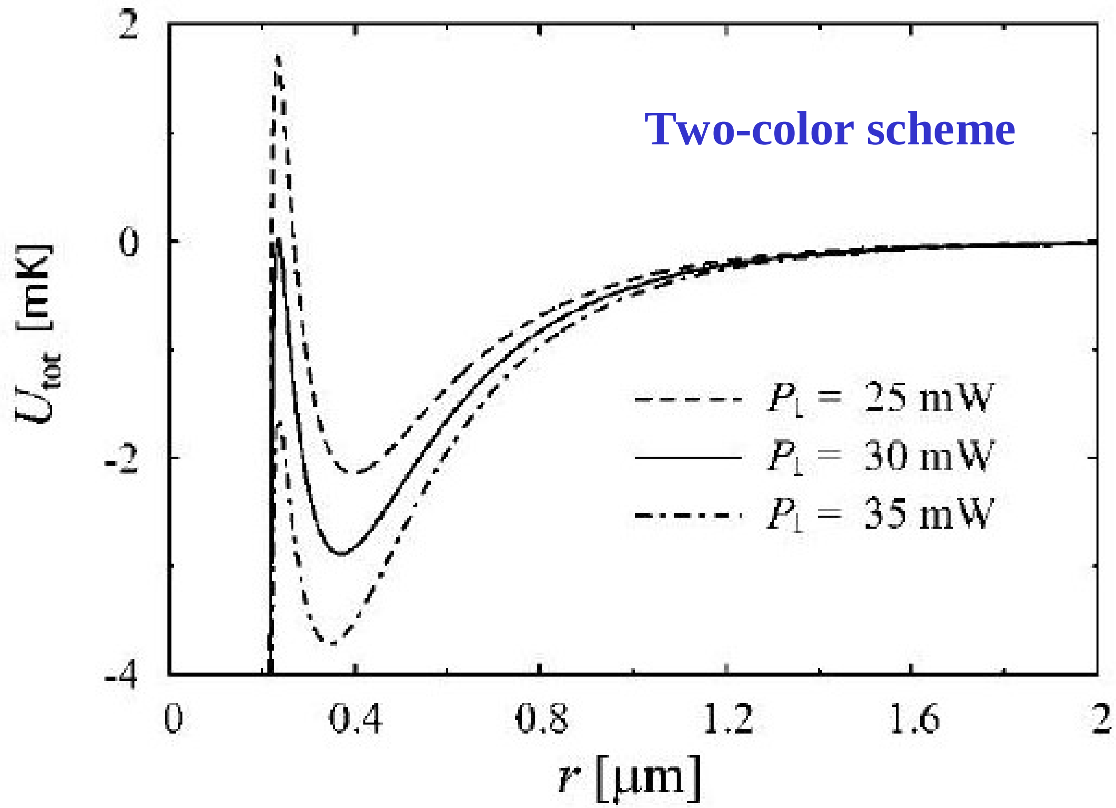


FIG. 1. Schematic of atom trapping and guiding around an optical fiber.



400-nm-diameter silica fiber，Cesium atom
Red-detune: 30-mW 1.06-μm, $P_{-Circular}$
Blue-detune: 29-mW 700-nm, $P_{-Circular}$

Trap depth → ～3 mK
Coherence time → ～ 32 ms

$P_{-Linear}$ → Linear trap is possible !

[18] F. L. Kien et al., *Phys. Rev.* **A70**, 11401 (2004)

2.6 Light-atom interaction without cavity

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

↓

Modify vacuum states around the nanofiber

↓ Modify spontaneous rate of an atom nearby

↓ Couple distant atoms

2.6 Light-atom interaction without cavity

Enhance spontaneous decay

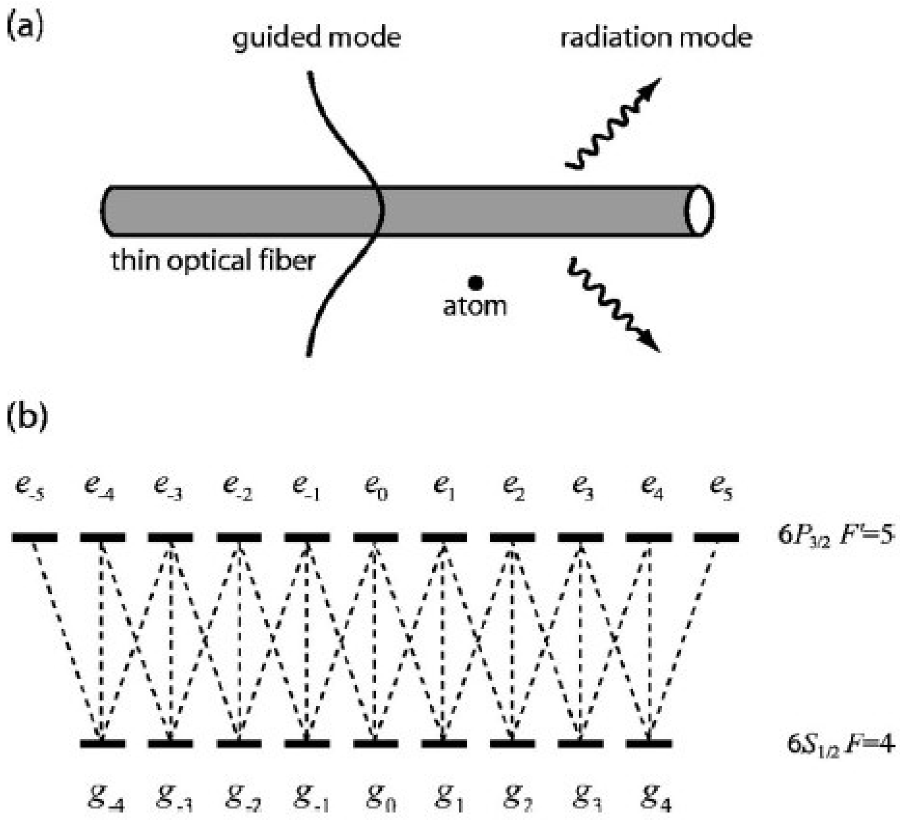


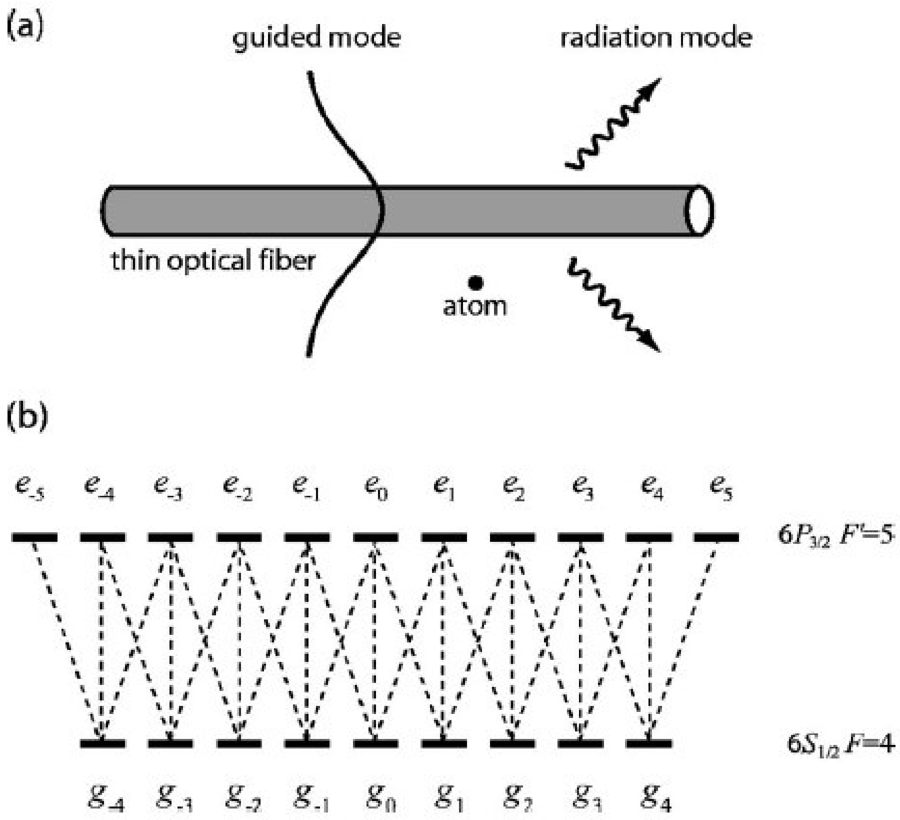
FIG. 1. (a) An atom interacting with guided and radiation modes in the vicinity of a thin optical fiber. (b) Schematic of the $6P_{3/2}F'=5$ and $6S_{1/2}F=4$ hfs levels of a cesium atom.

Modify vacuum modes around the nanofiber

[21] Fam Le Kien et al., *Phys. Rev.* A **72**, 032509 (2005).
[22] G. Sague et al., *Phys. Rev. Lett.* **99**, 163602 (2007).

2.6 Light-atom interaction without cavity

Enhance spontaneous decay



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Theoretically proposed by researchers in Japan (U Electro-Communications) [21]

and experimentally observed by researchers in Germany (U of Bonn) [22]

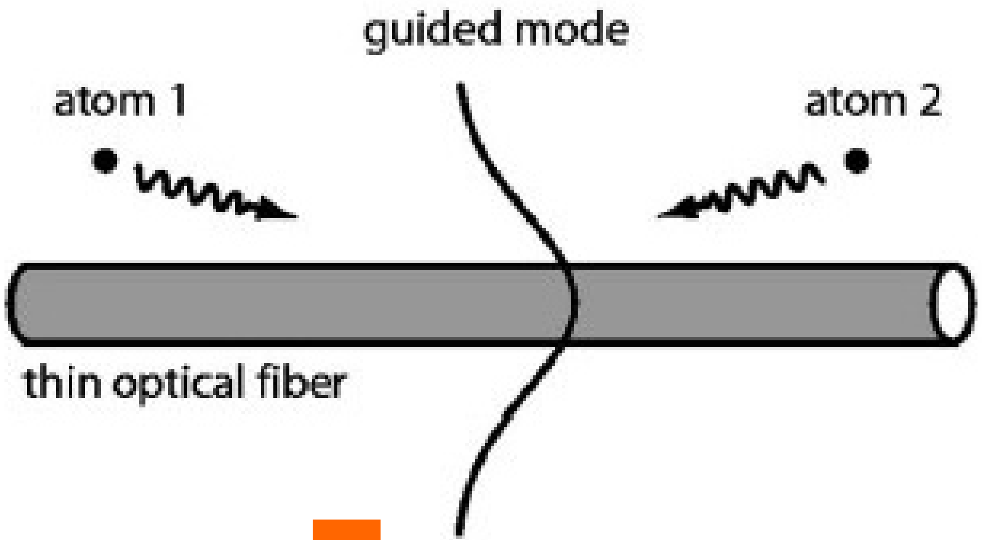
Modify spontaneous rate without cavity !

[21] Fam Le Kien et al., *Phys. Rev.* A **72**, 032509 (2005).
[22] G. Sague et al., *Phys. Rev. Lett.* **99**, 163602 (2007).

Light-atom interaction without cavity

Couple two distant atoms through guided modes of a nanofiber

U Electro-Communications (Japan)



Radiative exchange between two distant atoms

Coupling two distant atoms ⟺ v.s. Nonradiative Förster energy transfer range ～ 10 nm

Quantum information

Fam Le Kien et al., *Phys. Rev.* A **72**, 063815 (2005).

Outline

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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

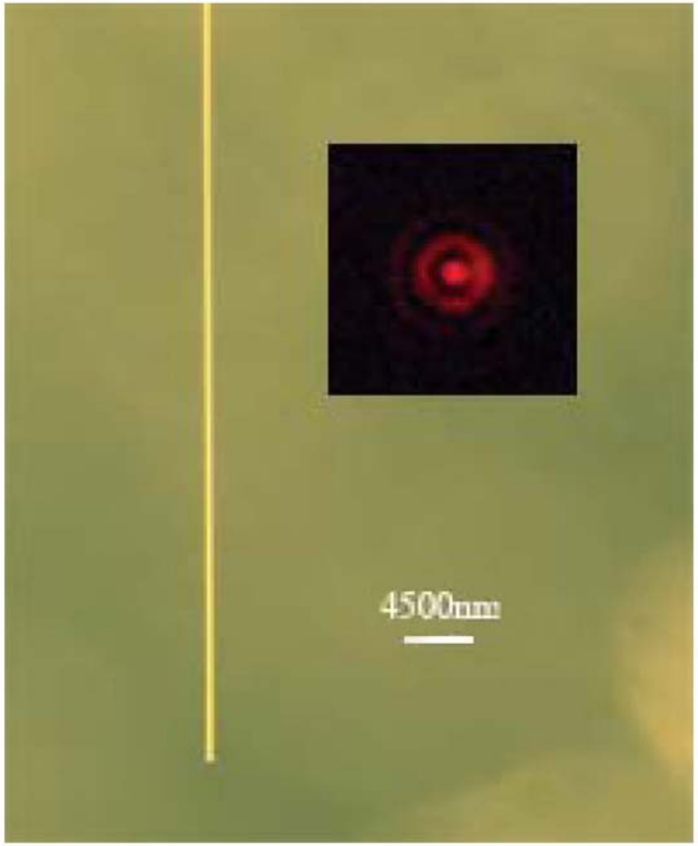

FIG. 1 (color online). The stationary micrograph of the tip of the SF, showing that the diameter of the SF tip is about 450 nm. The inset is the enlarged profile of a weak red light beam outgoing from the SF end face.

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

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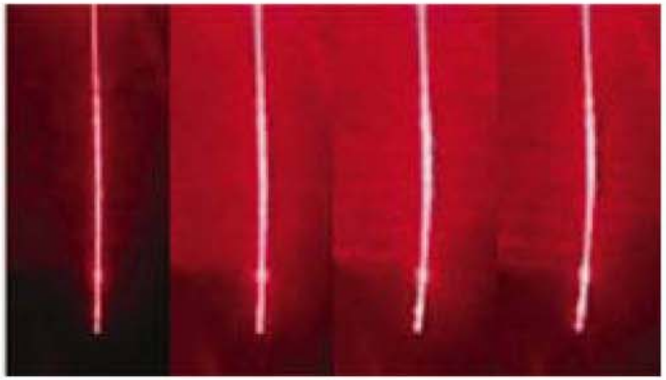
Phys. Rev. Lett. **101**, 243601
(issue of 12 December 2008)
Title and Authors

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.



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

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

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Phys. Rev. Lett. **101**, 243601
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10 December 2008

Light Bends Glas

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

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)

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)].

Feel momentum of light

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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

Feel momentum of light

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For continuous wave →

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$P^z/P > 90\%$

→ **Support She's results and Abraham's momentum**

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

Outline

- Introduction

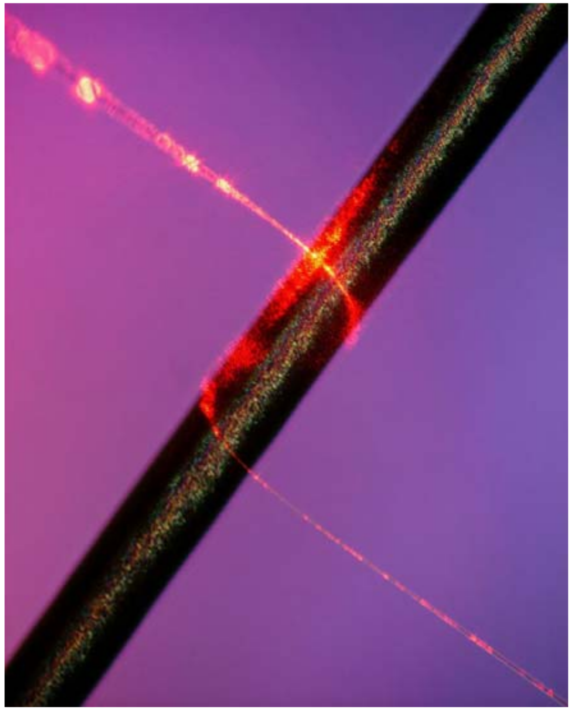
1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary

Summary



High-uniform glass microfibers and nanofibers can be fabricated using taper-drawing technique.

These fibers present interesting properties that may not existed in conventional optical fibers.

They are promising for connecting fiber optics with near-field optics, nonlinear optics, and quantum optics on the micro/nanoscale, and bringing new opportunities for both fundamental research and technological applications.

Shrink optical fibers to wavelength/ subwavelength scale

bring new opportunities for

Fundamental research **Technological applications**

Optics research on micro/nanoscale

- Fiber optics
- Near-field optics
- Nonlinear optics
- Plasmonics
- Quantum optics
- …

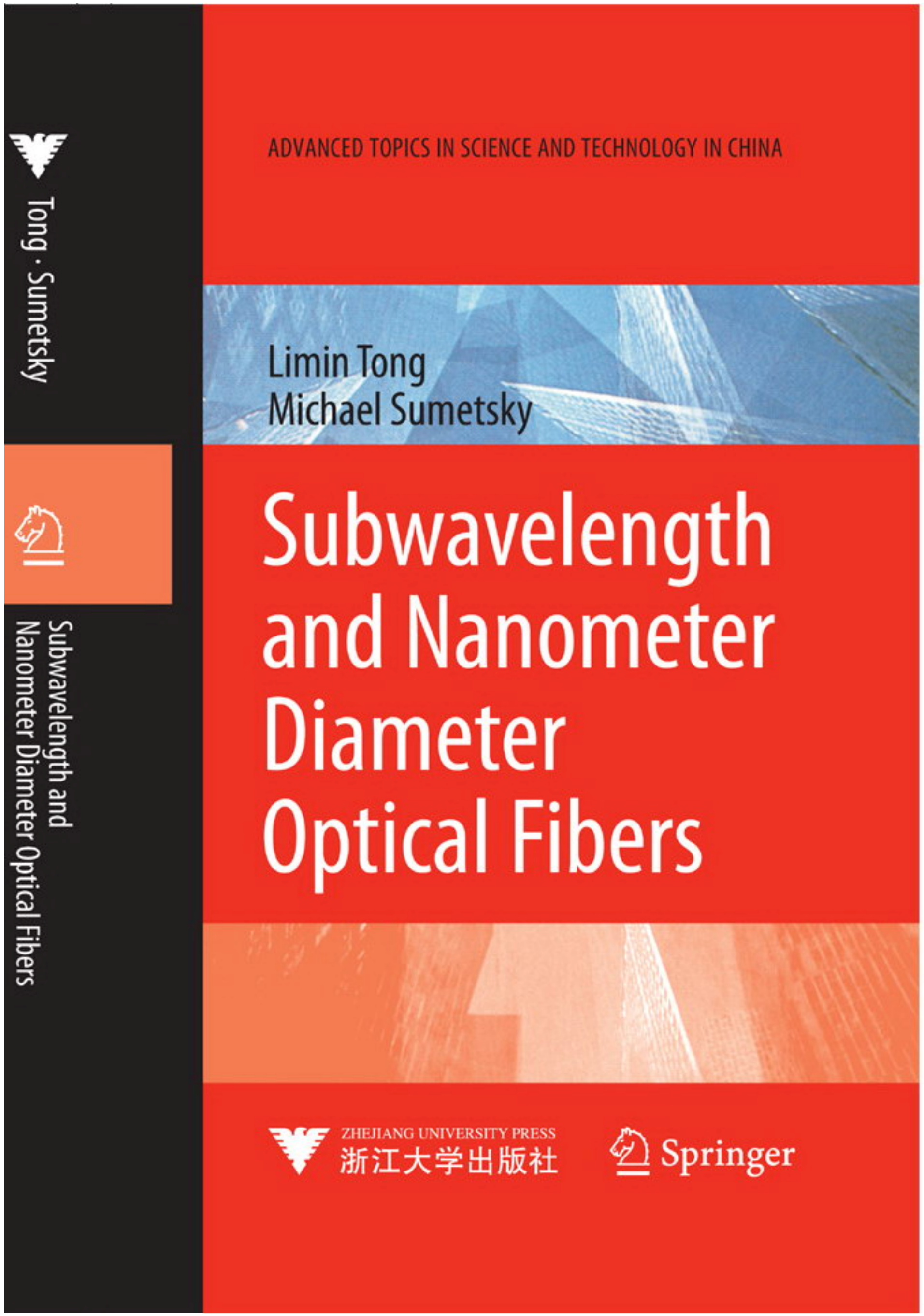
Photonic devices on micro/nanoscale

- Filters
- Resonators
- Interferometers
- Lasers
- Sensors
- …

Summary

For more details:

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



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SIOM (China)

Lili Hu, Junjie Zhang

University of Houston (USA)

Jiming Bao

Fudan Univ (China)

Lei Xu

KTH (Sweden)

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www.nanophotonics.zju.edu.cn

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