Optical Microfibers and Nanofibers
Fabrication, Properties and Applications

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Outline

- Introduction
- 1. Fabrication
- 2. Optical Properties
- 3. Potentials and Applications
- Summary
Outline

- **Introduction**

1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary
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
Introduction

Optical fibers

Linear Optics
Guide light/photons linearly

When the light is powerful enough

Nonlinear Optics
Absorb & Generate new light/photons

Basiclly
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
Miniaturization of optical fibers

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

Fiber-optic technology

- Higher sensitivity
- Faster response
- Higher density
- 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., \( D_{fiber} \approx \lambda \) or \( D_{fiber} < \lambda \)
Introduction

Optical micro/nanofiber

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

i.e., \( D_{\text{fiber}} \approx \lambda \) or \( D_{\text{fiber}} < \lambda \)

sometimes it is called

“Subwavelength-diameter wires”/ “Microfiber” / “Nanofiber” / “Nanotaper”/ “Nanowire”/ “Fiber taper”/“Ultrathin optical fiber”…
Subwavelength-diameter silica wires for low-loss optical wave guiding

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1Department of Physics and Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
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Optical microfiber loop resonator

M. Sumetsky, a) Y. Dulashko, J. M. Fini, and A. Hale
OPS Laboratories, 19 Schoolhouse Road, Somerset, New Jersey 08873
(Received 4 November 2004; accepted 8 March 2005; published online 13 April 2005)

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

Ultra-low-loss optical fiber nanotapers

Gilberto Brambilla, Vittoria Finazzi, and David J. Richardson
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Nanotapers with a waist size larger than 1 µm are impractical due to difficulties associated with the required degree of nanofiber uniformity. In this paper we present a novel fabrication technique for making low-loss optical fiber nanotapers with a waist size down to 100 nm.

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

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1Department of Applied Physics and Chemistry, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

Mach-Zehnder interferometers assembled with optical microfibers or nanofibers

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Zhejiang University, Hangzhou 310027, China

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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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PRL 99, 163602 (2007)

New Journal of Phys

The open-access journal for physics

Single atoms on an optical nanofibre

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Department of Applied Physics and Chemistry, University of Electro-Communications, Chofu, Tokyo 182-8585, Japan

December 2004

PHYSICAL REVIEW LETTERS

19 OCTOBER 2007

week ending

003 (pps)
In this talk for simplicity

Micro/nanofiber

Optical microfiber loop resonator

M. Sumetsky, a) Y. Dulashko, J. M. Fini, and A. Hale
OPS Laboratories, 19 Schoolhouse Road, Somerset, New Jersey 08873
(Received 4 November 2004; accepted 8 March 2005; published online 13 April 2005)

We experimentally demonstrate an optical microfiber loop resonator. The resonator is formed in free space by creating a loop from the subwavelength-diameter waist of an optical fiber.
Introduction

What does an optical microfiber look like?

Microfibers under an electron microscope

4-μm diameter

150-nm diameter

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

What does an optical microfiber look like?

Scale of a microfiber

Single-mode fiber

Hair

microfiber
Introduction

What does an optical microfiber look like?

Scale of a microfiber

Single-mode fiber

125 μm

60 μm

500 nm

Hair

microfiber
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)

**Introduction**

What’s new of guiding light with a microfiber?

Low-loss optical waveguiding with microfibers

(D=360 nm, λ= 633 nm)

- Very small mode area
- Tight optical confinement
- High fraction of evanescent fields
- Enhanced field intensity on surface
- Large waveguide dispersion

What’s new of guiding light with a microfiber?

Low-loss optical waveguiding with microfibers \( (D=360 \text{ nm}, \lambda = 633 \text{ nm}) \)

- Very small mode area
- Tight optical confinement
- High fraction of evanescent fields
- Enhanced field intensity on surface
- Large waveguide dispersion

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
Introduction

Next Generation Fibers


Nanofibers 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-
Outline

- Introduction

1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary
1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

First work was reported in the 19th century

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

“On the production, properties, and some suggested uses of the finest threads”
1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

First work was reported in 19th century


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

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 \( \mu m \)

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

Low dimension

Uniform diameter

Large length

Circular cross section


OPN, April 2004

D = 50 nm

D = 450 nm

D = 260 nm

D = 480 nm
1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

Taper drawing of bulk glasses heated by flame or laser

1. Fabrication of Microfibers

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Taper drawing of bulk glasses heated by flame or laser

1. Fabrication of Microfibers

1.1 How to fabricate a microfiber?

Taper drawing of bulk glasses heated by flame or laser

1. Fabrication of Microfibers

SEM images

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

1. Fabrication of Microfibers

TEM images

D = 240 nm

D = 80 nm

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**

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^2 k^2 - \beta^2 \) \bar{e} = 0, \]
\[ \nabla^2 + n^2 k^2 - \beta^2 \) \bar{h} = 0. \]

Boundary conditions

\[ n(r) = \begin{cases} 
  n_1, & 0 \leq r < \rho \\
  n_2, & \rho \leq r < \infty 
\end{cases} \]

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

\[ \text{[1]} \text{ A. W. Snyder and J. D. Love, } \text{Optical waveguide theory, Chapman and Hall, New York, 1983.} \]
<table>
<thead>
<tr>
<th>$HE_{vm}$, $EH_{vm}$</th>
<th>$0 \leq r &lt; \rho$</th>
<th>$\rho \leq r &lt; \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_r$</td>
<td>$- \frac{a_1 J_{v-1}(UR) + a_2 J_{v+1}(UR)}{J_v(U)} f_v(\phi)$</td>
<td>$- \frac{U a_1 K_{v-1}(WR) - a_2 K_{v+1}(WR)}{W K_v(W)} f_v(\phi)$</td>
</tr>
<tr>
<td>$e_\phi$</td>
<td>$- \frac{a_1 J_{v-1}(UR) - a_2 J_{v+1}(UR)}{J_v(U)} g_v(\phi)$</td>
<td>$- \frac{U a_1 K_{v-1}(WR) + a_2 K_{v+1}(WR)}{W K_v(W)} g_v(\phi)$</td>
</tr>
<tr>
<td>$e_z$</td>
<td>$- \frac{i U J_v(UR)}{\rho \beta J_v(U)} f_v(\phi)$</td>
<td>$- \frac{i U K_v(W)}{\rho \beta K_v(W)} f_v(\phi)$</td>
</tr>
<tr>
<td>$h_r$</td>
<td>$\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{kn_1^2 a_3 J_{v-1}(UR) - a_4 J_{v+1}(UR)}{\beta J_v(U)} g_v(\phi)$</td>
<td>$\left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{kn_1^2 U a_5 K_{v-1}(WR) + a_6 K_{v+1}(WR)}{\beta W K_v(W)} g_v(\phi)$</td>
</tr>
<tr>
<td>$h_\phi$</td>
<td>$- \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{kn_1^2 a_3 J_{v-1}(UR) + a_4 J_{v+1}(UR)}{\beta J_v(U)} f_v(\phi)$</td>
<td>$- \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{kn_1^2 U a_5 K_{v-1}(WR) - a_6 K_{v+1}(WR)}{\beta W K_v(W)} f_v(\phi)$</td>
</tr>
<tr>
<td>$h_z$</td>
<td>$- \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{UF_2 J_v(UR)}{k\rho J_v(U)} g_v(\phi)$</td>
<td>$- \left(\frac{\varepsilon_0}{\mu_0}\right)^{1/2} \frac{UF_2 K_v(W)}{k\rho K_v(W)} g_v(\phi)$</td>
</tr>
</tbody>
</table>

$$f_v(\phi) = \begin{cases} \cos(v\phi) & \text{even} \\ \sin(v\phi) & \text{odd} \end{cases}$$

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

| $a_1 = \frac{(F_2 - 1)}{2}$; $a_3 = \frac{(F_1 - 1)}{2}$; $a_5 = \frac{(F_1 - 1 + 2\Delta)}{2}$ | 
|---|---|
| $b_1 = \frac{1}{2U} \left( \frac{J_{v-1}(U)}{J_v(U)} - \frac{J_{v+1}(U)}{J_v(U)} \right)$ | 
| $b_2 = -\frac{1}{2W} \left( \frac{K_{v-1}(W)}{K_v(W)} + \frac{K_{v+1}(W)}{K_v(W)} \right)$ | 

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

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

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

42
\[
\begin{array}{|c|c|c|}
\hline
TE_{0m} & 0 \leq r < \rho & \rho \leq r < \infty \\
\hline
\begin{align*}
e_\phi &= -\frac{J_1(UR)}{J_1(U)} \\
h_r &= \left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \frac{\beta J_1(UR)}{k J_1(U)} \\
h_z &= i\left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \frac{U J_0(UR)}{k \rho J_1(U)}
\end{align*}
& \begin{align*}
e_\phi &= -\frac{K_1(WR)}{K_1(W)} \\
h_r &= \left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \frac{\beta K_1(WR)}{k K_1(W)} \\
h_z &= -i\left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \frac{W K_0(WR)}{k \rho K_1(W)}
\end{align*}
\hline
\end{array}
\]

\[e_r = e_z = h_\phi = 0\]

\[
\begin{array}{|c|c|c|}
\hline
TM_{0m} & 0 \leq r < \rho & \rho \leq r < \infty \\
\hline
\begin{align*}
e_r &= \frac{J_1(UR)}{J_1(U)} \\
e_z &= iU \frac{J_0(UR)}{\rho \beta J_1(U)} \\
h_\phi &= \left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \frac{kn_1^2 J_1(UR)}{\beta J_1(U)}
\end{align*}
& \begin{align*}
e_r &= \frac{n_1^2 K_1(WR)}{n_2^2 K_1(W)} \\
e_z &= -i n_1^2 \frac{W K_0(WR)}{n_2^2 \rho \beta K_1(W)} \\
h_\phi &= \left(\frac{\varepsilon_0}{\mu_0}\right)^{\frac{1}{2}} \frac{kn_1^2 K_1(WR)}{\beta K_1(W)}
\end{align*}
\hline
\end{array}
\]

\[e_\phi = h_r = h_z = 0\]
2. Optical Properties

2.1 Basic model

Solve the eigenvalue equations numerically

\[
\begin{align*}
HE_{vm} & \left\{ \frac{J_v'(U)}{UJ_v(U)} + \frac{K_v'(W)}{WK_v(W)} \right\} \left\{ \frac{J_v'(U)}{UJ_v(U)} + \frac{n_2^2 K_v'(W)}{n_1^2 WK_v(W)} \right\} = \left( \frac{v \beta}{kn_1} \right)^2 \left( \frac{V}{UW} \right)^4 \\
EH_{vm} & \left\{ \frac{J_v'(U)}{UJ_v(U)} + \frac{K_v'(W)}{WK_v(W)} \right\} = 0 \\
TE_{0m} & \frac{J_1(U)}{UJ_0(U)} + \frac{K_1(W)}{WK_0(W)} = 0 \\
TM_{0m} & \frac{n_1^2 J_1(U)}{UJ_0(U)} + \frac{n_2^2 K_1(W)}{WK_0(W)} = 0
\end{align*}
\]
2. Optical Properties

- Basic model

Propagation constants (\( \beta \))

Air-clad silica microfibers
Wavelength: 633 nm

no cutoff of the fundamental modes

2. Optical Properties

- Single-mode condition

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

\( \beta \) for HE_{11} mode of several glass nanofibers

- 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

\[
\begin{aligned}
&\left\{ \frac{J_1'(U)}{UJ_1(U)} + \frac{K_1'(W)}{WK_1(W)} \right\} \left\{ \frac{J_1'(U)}{UJ_1(U)} + \frac{n_2^2 K_1'(W)}{n_1^2 WK_1(W)} \right\} = \left( \frac{\beta}{kn_1} \right)^2 \left( \frac{V}{UW} \right)^4
\end{aligned}
\]

Solve $\beta$ numerically

Electromagnetic fields

\[
\begin{aligned}
\vec{E}(r, \phi, z) &= (e_r \hat{r} + e_\phi \hat{\phi} + e_z \hat{z}) e^{i\beta z} e^{i\omega t}, \\
\vec{H}(r, \phi, z) &= (h_r \hat{r} + h_\phi \hat{\phi} + h_z \hat{z}) e^{i\beta z} e^{i\omega t}
\end{aligned}
\]
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

Tight confinement

For the fundamental mode \((\text{HE}_{11})\)

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

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

\[ \text{e} = \text{(Normalized Unit)} \]
\[ r (\mu \text{m}) \]

1.5
1.0
0.5
0.0

490
200
1600
400

1.5
1.0
0.5
0.0

D=100nm
D=200nm
D=400nm
D=800nm
D=1200nm
D=1600nm

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

\[ r (\mu \text{m}) \]

780-nm-wavelength light sent into a 340-nm-diameter silica nanofiber, it generate a 2 kW/m m² power density on the nanofiber surface.

e.g., when a 1-mW 780-nm-wavelength light sent into a 340-nm-diameter silica nanofiber, it generate a 2 kW/m m² power density on the nanofiber surface.


2. Optical Properties

- Evanescent field of HE_{11} mode

Z-components of Poynting vector

\[
S_z = \begin{cases} 
\frac{|a|^2}{2} \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \frac{kn_i^2}{\beta J_i^2(U)} \left\{ a_1 a_3 J_0^2(UR) + a_2 a_4 J_2^2(UR) + \frac{1-F_1 F_2}{2} J_0(UR) J_2(UR) \cos(2\phi) \right\}, & \text{core} \\
\frac{|a|^2}{2} \left( \frac{\varepsilon_0}{\mu_0} \right)^{1/2} \frac{kn_i^2}{\beta K_i^2(W)} \frac{U^2}{W^2} \left\{ a_1 a_3 K_0^2(WR) + a_2 a_4 K_2^2(WR) - \frac{1-2\Delta-F_1 F_2}{2} K_0(WR) K_2(WR) \cos(2\phi) \right\}, & \text{cladding}
\end{cases}
\]

Fractional power inside the core

\[
\eta = \frac{P_1}{P_1 + P_2}
\]

where

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

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

2. Optical Properties

- Evanescent field of HE\textsubscript{11} mode

Fractional power inside the core

![Graph showing fractional power inside the core for different wavelengths and core sizes.]

2. Optical Properties

- Evanescent field of HE$_{11}$ mode

Fractional power inside the core

![Graph showing optical properties with silica/air and evanescent field interaction.](image)

2. Optical Properties

- Optical confinement of HE\textsubscript{11} mode

Effective Diameter: Mode area for optical confinement of 86.5%

Minimum usable Effective Diameter $\sim 500$ nm

2. Optical Properties

- Optical confinement of HE$_{11}$ mode

Effective Diameter: Mode area for optical confinement of 86.5%

Minimum usable Effective Diameter $\sim$ 510 nm

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

2. Optical Properties

- Optical loss in real microfibers

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

Lower loss reported in silica fibers:

\[ \alpha \sim 0.01 \text{ dB/mm} \] \[ \text{(2)} \]


Lowest loss reported:

\[ \alpha \sim 1 \text{ dB/m} \] \[ \text{(3)} \]


Lower loss may be possible

\[ \alpha < 0.1 \text{ dB/m} \]
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

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)

**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**

PS nanofiber (n=1.59)
633-nm wavelength
2-μm bending radius
Bending loss ~ 1 dB/90°

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.

2. Optical Properties

What’s New?

Small
2. Optical Properties

What’s New?

**Small**

High $\Delta n$ for SM $\rightarrow$ Sharper bend with shorter optical length

![Graph showing optical properties with labels and scale]
2. Optical Properties

What’s New?

- Small

High $\Delta n$ for SM $\rightarrow$ Sharper bend with shorter optical length

Light travels through with less time

e.g., consider the minimum allowable bending radius

- SMF $\sim$ 1 cm $\rightarrow$ $\sim$ 30 ps
- Nanofiber $\sim$ 10 $\mu$m NF $\rightarrow$ $\sim$ 30 fs 1000 times faster
2. Optical Properties

What’s New?

Small

High $\Delta n$ for SM $\rightarrow$ Sharper bend with shorter optical length

Light travels through with less time

e.g., consider the minimum allowable bending radius

SMF $\sim 1 \text{ cm} \rightarrow \sim 30 \text{ ps}$

Nanofiber $\sim 10 \mu\text{m NF} \rightarrow \sim 30 \text{ fs}$ 1000 times faster

Faster operation
2. Optical Properties

What’s New?

- **Small**
  - Core diameter < wavelength
  - High fraction of evanescent fields
  - Steep field gradient
2. Optical Properties

- **What’s New?**
  - **Small**
  - Core diameter < wavelength
  - High fraction of evanescent fields
  - Steep field gradient
  - Stronger near-field interaction
  - Higher-sensitivity optical sensing
2. Optical Properties

What’s New?

- **Small**
- 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

Smaller mode area

e.g., SMF $\sim 100 \ \mu m^2$
Nanofiber $\sim 1 \ \mu m^2$
2. Optical Properties

- What’s New?

- **Small**
  - Smaller mode area
  - e.g., SMF ~ 100 μm²
  - Nanofiber ~ 1 μm²

- Thinner Beam

- Higher-sensitivity optical sensing
2. Optical Properties

■ What’s New?

Small

3. Smaller mode area

e.g., SMF $\sim 100 \ \mu m^2$
Nanofiber $\sim 1 \ \mu m^2$

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

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

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
\[ \sim 10^{-15} \text{ kg} / \sim 10 \text{ pN (in weight)} \]
comparable to the pressure of light with power of 10 mW
2. Optical Properties

What’s New?

Small

Extremely light in mass

- e.g., Mass of a 200-nm-diameter 10-um-length nanofiber is ~ 10^{-15} \text{ kg} / ~ 10 \text{ 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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Feel the momentum of light guided through

Photon-momentum-induced effect
2. Optical Properties

What’s New?

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  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

...
2. Optical Properties

- What's New?
- Small
- Large and manageable dispersion
- Enhanced field intensity on surface
- Low dimension for fast diffusion
- Shrink optical fibers

More:

Plenty of New Opportunities

Outline

- Introduction

1. Fabrication

2. Optical Properties

3. Potentials and Applications

- Summary
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
(1) Near-field Optics

2.1 Near-field coupling between two nanofibers

High fraction of evanescent field $\rightarrow$ 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 $\mu$m, and (C) 4.8 $\mu$m. The source is $z$ polarized with wavelength of 633 nm.

2.1 Near-field coupling between two nanofibers

High fraction of evanescent field →

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Overlapping-length-dependent coupling efficiency

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.

2.1 Near-field coupling between two nanofibers

• **Micro-coupler**

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

- **Transfer length**: $<3 \ \mu m$
- **Overlapping**: $<3 \ \mu m$
- **Fiber diameter**: 350/450 nm
- **Working wavelength**: 633 nm
- **3-dB splitter**

(1) Near-field Optics

2.1 Near-field coupling between two nanofibers

- Tiny Mach-Zehnder interferometer

When two micro-couplers are assembled in cascade $\rightarrow$ MZI

MZI assembled with two 480-nm-diameter tellurite fibers on a MgF$_2$ substrate

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 MgF₂ substrate
(1) Near-field Optics

2.1 Near-field coupling between two nanofibers

- **Tiny Mach-Zehnder interferometer**

  When two micro-couplers are assembled in cascade → MZI

![Image](a)

MZI assembled with two 480-nm-diameter tellurite fibers on a MgF$_2$ substrate

Transmission spectrum of the MZI

---

(1) Near-field Optics

2.1 Near-field coupling between two nanofibers

- **Micro resonator**

  Tie a microfiber into a loop or knot $\rightarrow$ ring resonator

(1) Near-field Optics

2.1 Near-field coupling between two nanofibers

• Micro resonator

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(1) Near-field Optics

2.1 Near-field coupling between two nanofibers

- **Micro resonator**

  Tie a microfiber into a loop or knot \(\rightarrow\) ring resonator

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

(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

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 dye laser

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

(1) Near-field Optics

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

**Near-field Optics**

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

![Diagram](image)

- **Active medium**: ZnO nanowire
- **Microcavity**: microfiber ring

Pump pulses: 355 nm, 6 ns, 10 Hz

Hybrid nanowire lasers

(1) Near-field Optics

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

**Pump pulses:**
- 355 nm, 6 ns, 10 Hz

**Hybrid nanowire lasers**

---

(1) Near-field Optics

2.2 Near-field coupling for optical sensing

- **Substrate induced leakage**

![3-D FDTD simulation](image)

- Light wavelength: 633 nm
- Silica nanofiber: D=400 nm, n=1.46
- MgF$_2$ substrate: n=1.39

*Index-dependent*
(1) Near-field Optics

- **Micro filters**
  silica microfiber – MgF$_2$ substrate

(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.

2.2 Near-field coupling for

- **Nanofiber sensors**

  - Modulate output: intensity, phase, spectrum

Small footprint
High sensitivity
Fast response

---

3. Potentials and Applications

(1) Near-Field Optics
(2) Plasmonics
(3) Nonlinear Optics
(4) Quantum Optics\Atom Optics
(5) Photon Momentum
(2) Plasmonics

- Plasmonics

<table>
<thead>
<tr>
<th></th>
<th>Dielectric</th>
<th>v.s.</th>
<th>Plasmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confinement</td>
<td>&lt; $\lambda/5$</td>
<td></td>
<td>$\sim \lambda/10$</td>
</tr>
<tr>
<td>Loss</td>
<td>Low</td>
<td></td>
<td>Very high</td>
</tr>
</tbody>
</table>

Two questions: (1) loss – confinement
                (2) high efficient launching
(2) Plasmonics

Hybrid nanofiber-nanowire structure

Direct coupling of silica nanofibers and silver nanowires
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)
(2) Plasmonics

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)
(2) Plasmonics

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)
(2) Plasmonics

Hybrid nanowire resonators

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

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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**

- **Silica nanofiber**
- **Silver nanowire**
  - $D \sim 260 \text{ nm, } L \sim 24 \text{ um}$
- **ZnO nanowire**
  - $D \sim 400 \text{ nm, } L \sim 90 \text{ um}$

- **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
3. Potentials and Applications

(1) Near-Field Optics
(2) Plasmonics
(3) Nonlinear Optics
(4) Quantum Optics\Atom Optics
(5) Photon Momentum
(3) Nonlinear Optics

2.2 Nanofibers for nonlinear optics

For nonlinear effects, nanofibers present advantages including:

- Small mode area: $D_{\text{eff}} < \lambda$

- Effective nonlinearity: $\gamma = \left(\frac{2\pi}{\lambda}\right)n_2/A_{\text{eff}} \rightarrow \text{Large } \gamma$

- Dispersion: Diameter-dependent $\rightarrow \text{manageable}$
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(3) Nonlinear Optics

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- Effective nonlinearity: $\gamma = \frac{(2\pi/\lambda)n_2}{A_{\text{eff}}} \rightarrow \text{Large } \gamma$
- Dispersion: Diameter-dependent $\rightarrow$ manageable

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

(3) Nonlinear Optics

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

Optical Nonlinearity in high nonlinear microfibers

Enhanced nonlinearity in sub-wavelength-diameter As$_2$Se$_3$ fibers

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)

(3) Nonlinear Optics

Supercontinuum generation

- with ns pulses \[^{[12]}\]

U Bath (UK)

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.

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.

(3) Nonlinear Optics

2.4 More potentials and applications

Pulse compression
Two photon absorption
Enhanced Kerr nonlinearity
All-optical signal processing
Nonlinear interaction in atom vapor

3. Potentials and Applications

(1) Near-Field Optics
(2) Plasmonics
(3) Nonlinear Optics
(4) Quantum Optics\Atom Optics
(5) Photon Momentum
(4) Quantum Optics

2.5 Atom trap and manipulation

• Atom trap and guide using optical waveguides $^{[15,16]}$

![Diagram of atom trap and guide using optical waveguides]

E.g. Hollow waveguide

(4) Quantum Optics

2.5 Atom trap and manipulation

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

Advantages

• Deep potential for trapping/guiding of neutral atoms
• Trap atoms in open space outside the nanofiber
• Couple atom emission back into the nanofiber
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** $D_{\text{fiber}} < \sim \lambda /2$

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

---

• Atom trap and guide using optical microfiber \[18\]

Two-color scheme

\[ F_{\text{blue}} \]
\[ F_{\text{red}} \]
trapped atom

optical fiber
two-color light waves

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

• Atom trap and guide using optical microfiber \cite{18}

Two-color scheme

400-nm-diameter silica fiber, Cesium atom

Red-detune: 30-mW 1.06-\(\mu\)m, \(P_{\text{Circular}}\)

Blue-detune: 29-mW 700-nm, \(P_{\text{Circular}}\)

\(P_{\text{Linear}}\) → Linear trap is possible!

(4) Quantum Optics

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
(4) Quantum Optics

2.6 Light-atom interaction without cavity

Enhance spontaneous decay

Modify vacuum modes around the nanofiber

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.

Enhance spontaneous decay

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!

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.

Light-atom interaction without cavity

Couple two distant atoms through guided modes of a nanofiber

![Diagram](image)

U Electro-Communications (Japan)

Radiative exchange between two distant atoms

Coupling two distant atoms

Quantum information

Nonradiative Förster energy transfer range $\sim 10$ nm

3. Potentials and Applications

(1) Near-Field Optics
(2) Plasmonics
(3) Nonlinear Optics
(4) Quantum Optics\Atom Optics
(5) Photon Momentum
(5) Photon Momentum

Feel momentum of light

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.

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
Light Bends Glass

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Light moves slower inside a material than it does in air or vacuum. In 1908, W. L. She et al., Phys. Rev. Lett. 101, 243601 (2008)

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

Suggested Abraham’s momentum in transparent dielectrics

\[ P = E/(nc) \]

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
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)].
(5) Photon Momentum

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

\[ f = (P \cdot \nabla)E + \frac{\partial P}{\partial t} \times \mu_0 H \]

Longitudinal component

\[ f_z = (P \cdot \nabla)E_z + \left( \frac{\partial P}{\partial t} \times \mu_0 H \right)_z \]

Mechanical momentum

\[ P_{\text{mech}}^z = \Delta V \int_0^T f_z dt \]

For continuous wave

\[ P_{\text{mech}}^z = 0 \]

\[ P^z / P > 90\% \]
Feel momentum of light

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\[ p^z_{\text{mech}} = \Delta v \int_0^T f_z dt \]

For continuous wave

\[ p^z_{\text{mech}} = 0 \]

\[ p^z / P > 90\% \]

Support She’s results and Abraham’s momentum

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

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Summary

For more details:

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