Wrapping light around a hair:
manipulating light at the nanoscale

University of Washington
Seattle, WA, 10 October 2005
and also....

at Harvard:

Jonathan Aschom
Mengyan Shen
Iva Maxwell
James Carey
Brian Tull
Dr. Yuan Lu
Dr. Richard Schalek
Prof. Federico Capasso
Prof. Cynthia Friend

and elsewhere:

Xuewen Chen (Zhejiang University)
Zhanghua Han (Zhejiang University)
Dr. Sailing He (Zhejiang University)
Prof. Igor Khruschev (Aston University)
Dr. Jingyi Lou (Zhejiang University)
Dr. Ray Mariella (LLNL)
Liu Liu (Zhejiang University)
“I managed to illuminate the interior of a stream in a dark space. I have discovered that this strange arrangement offers one of the most beautiful, and most curious experiments that one can perform in a course on Optics.”

Daniel Colladon, Comptes Rendus, 15, 800–802 (1842)
D. Colladon, *La Nature*, 325 (1884)
• waveguiding
• nanowire fabrication
• optical properties
Waveguiding

two crossed planar waves...
Waveguiding

...cause an interference pattern
$E = 0$ on the nodal lines
Waveguiding

...satisfying boundary conditions for planar-mirror waveguide
Waveguiding

transverse standing wave, traveling along axis
Waveguiding

transverse standing wave, traveling along axis
Waveguiding

change angle of incident waves...
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change angle of incident waves...
boundary conditions only satisfied for certain $\theta$

standing wave in $y$-direction, traveling in $z$-direction
consider wave incident at angle $\theta$
Waveguiding

twice-reflected wave
self consistency:

\[ AC - AB = 2d \sin \theta = m\lambda \quad (m = 1, 2, \ldots) \]
self consistency:

\[ AC - AB = 2d \sin \theta = m \lambda \quad (m = 1, 2, \ldots) \]

so:

\[ \sin \theta_m = m \frac{\lambda}{2d} \]
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so:

\[ \sin \theta_m = m \frac{\lambda}{2d} \]
number of modes:

\[ M = \frac{2d}{\lambda} \]
now consider a planar dielectric waveguide
rays incident at angle $\theta > \pi/2 - \theta_c$ are unguided
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided
rays incident at angle $\theta < \pi/2 - \theta_c$ are guided
self consistency:

\[ AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m\lambda \quad (m = 0, 1, 2\ldots) \]
self consistency:

\[ AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m\lambda \quad (m = 0, 1, 2 \ldots) \]

so:

\[ \tan \left( \frac{\pi d}{\lambda} \sin \theta - m \frac{\pi}{2} \right) = \left( \frac{\sin^2 \left( \frac{\pi}{2} - \theta_c \right)}{\sin^2 \theta} - 1 \right)^{1/2} \]
self consistency:

\[ AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m\lambda \quad (m = 0, 1, 2\ldots) \]

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Waveguiding

**self consistency:**

\[ AC - AB = 2d \sin \theta - \frac{\varphi_r}{\pi} \lambda = m\lambda \quad (m = 0, 1, 2\ldots) \]

**so:**

\[
\tan \left( \frac{\pi d}{\lambda} \sin \theta - m \frac{\pi}{2} \right) = \left( \frac{\sin^2(\frac{\pi}{2} - \theta_c)}{\sin^2 \theta} - 1 \right)^{1/2}
\]
number of modes:

\[ M = \frac{\sin\left(\frac{\pi}{2} - \theta_c\right)}{\lambda/2d} \]
number of modes:

\[ M = \sin\left(\frac{\pi}{2} - \theta_c\right) \frac{\sin(\pi/2 - \theta_c)}{\lambda/2d} \]

or:

\[ M = 2 \frac{d}{\lambda} \left(n_1^2 - n_2^2\right)^{1/2} \]
propagation constant of guided wave:

\[ \beta_m^2 = k^2 - k_y^2 = k^2 - \frac{m^2 \pi^2}{d^2} \]

group velocity:

\[ v_m = c \cos \theta_m \]
single mode condition for 600-nm light:

planar mirror

\[ M = \frac{2d}{\lambda} \quad \text{300} < d < 600 \text{ nm} \]

dielectric

\[ M = 2 \frac{d}{\lambda} (n_1^2 - n_2^2)^{1/2} \quad d < 268 \text{ nm} \]
Waveguiding

single mode condition for 600-nm light:

planar mirror

\[ M = \frac{2d}{\lambda} \quad 300 < d < 600 \text{ nm} \]

dielectric

\[ M = 2 \frac{d}{\lambda} (n_1^2 - n_2^2)^{1/2} \quad d < 268 \text{ nm} \]

can make \( d \) larger by making \( n_1 - n_2 \) smaller!
Vector potential obeys:

$$\nabla^2 \mathbf{A} + \omega^2 \mu_0 \epsilon \mathbf{A} = -i \omega \mu_0 \nabla \epsilon \Phi$$
Waveguiding

Vector potential obeys:

\[ \nabla^2 \vec{A} + \omega^2 \mu_0 \epsilon \vec{A} = 0 \]
Waveguiding

Vector potential obeys:

\[ \nabla^2 \vec{A} + \omega^2 \mu_0 \epsilon \vec{A} = 0 \]

Substituting

\[ \vec{A} = \hat{y}u(x,y)e^{-i\beta z} \]
Waveguiding

Vector potential obeys:

\[ \nabla^2 \vec{A} + \omega^2 \mu_0 \epsilon \vec{A} = 0 \]

Substituting \[ \vec{A} = y u(x,y) e^{-i\beta z} \]

yields:

\[ \nabla_T^2 u + [-\beta^2 + \omega^2 \mu \epsilon(r)] u = 0 \]
Waveguiding

Vector potential obeys:

$$\nabla^2 \vec{A} + \omega^2 \mu_0 \varepsilon \vec{A} = 0$$

Substituting

$$\vec{A} = \hat{y} u(x,y) e^{-i\beta z}$$

gives:

$$\nabla_T^2 u + [-\beta^2 + \omega^2 \mu \varepsilon(r)] u = 0$$

Compare to time-independent Schrödinger equation:

$$\nabla^2 \psi + \frac{2m}{\hbar^2} [E - V(r)] \psi = 0$$
Waveguiding
Waveguiding

\[ m = 1 \]

\[ d \]
Waveguiding
Waveguiding
Waveguiding
Waveguiding
Waveguiding
Waveguiding
Waveguiding

single mode condition for 600-nm light:

\[ M = 2 \frac{d}{\lambda} (n_1^2 - n_2^2)^{1/2} \]

without cladding: \( d < 268 \text{ nm} \)

Add cladding with 0.4% index difference:

\( d < 5 \mu\text{m} \)
commercial single-mode fiber (Corning Titan®)

<table>
<thead>
<tr>
<th></th>
<th>core</th>
<th>cladding</th>
</tr>
</thead>
<tbody>
<tr>
<td>index</td>
<td>$n_1 = 1.468$</td>
<td>$n_2 = 1.462$</td>
</tr>
<tr>
<td>diameter:</td>
<td>8.3 $\mu$m</td>
<td>125.0 ± 1.0 $\mu$m</td>
</tr>
<tr>
<td>operating wavelength:</td>
<td>$\lambda = 1310$ nm/1550 $\mu$m</td>
<td></td>
</tr>
</tbody>
</table>
Waveguiding

drawbacks of clad fibers:

- weak confinement
- no tight bending
- coupling requires splicing
Waveguiding
Outline

- waveguiding
- nanowire fabrication
- optical properties
Nanowire fabrication

two-step drawing process

standard fiber

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Nanowire fabrication

two-step drawing process

standard fiber
Nanowire fabrication

two-step drawing process

standard fiber

1-µm silica wire

drawing
Nanowire fabrication

two-step drawing process

standard fiber

1-μm silica wire

sapphire taper
Nanowire fabrication

two-step drawing process

standard fiber

1-μm silica wire

drawing

sapphire taper

silica wire
Nanowire fabrication

two-step drawing process

1-\mu\text{m} silica wire

standard fiber

drawing

flame

sapphire taper

silica wire
Nanowire fabrication

two-step drawing process

standard fiber

drawing

1-μm silica wire

flame

sapphire taper

silica wire
Nanowire fabrication

two-step drawing process

standard fiber

drawing

1-μm silica wire

flame

sapphire taper

drawing

silica wire
Nanowire fabrication
Nanowire fabrication

1 µm

Nanowire fabrication
Nanowire fabrication

1000 µm
Nanowire fabrication

500 µm
Nanowire fabrication

200 µm
Nanowire fabrication
Nanowire fabrication

50 µm
Nanowire fabrication

20 µm
Nanowire fabrication

10 µm
Nanowire fabrication

6 μm
Nanowire fabrication
Nanowire fabrication
Nanowire fabrication

312 nm

1 µm
Specifications

**diameter** $D$: down to 20 nm

**length** $L$: up to 90 mm

**aspect ratio** $D/L$: up to $10^6$

**diameter uniformity** $\Delta D/L$: $2 \times 10^{-6}$
Nanowire fabrication

\[ d = 260 \text{ nm} \]
\[ L = 4 \text{ mm} \]
Nanowire fabrication

240-nm wire
Nanowire fabrication

RMS roughness < 0.5 nm

20 nm
Nanowire fabrication

20 nm
Nanowire fabrication

measure tensile stress at breaking point
Nanowire fabrication

bend to breaking point

50 µm
Nanowire fabrication

bend to breaking point

50 µm
Nanowire fabrication

bend to breaking point

50 µm
minimum bending radius $R_{EB}$ gives tensile stress:

$$\sigma = \frac{ED}{2R_{EB}}$$

$E$ = Young’s modulus
$D$ = wire diameter
Waveguiding

tensile strength

![Graph showing the relation between tensile stress (GPa) and nanowire diameter (nm). The graph includes data points for bending and pulling.]
Nanowire fabrication

2 µm
Nanowire fabrication

20 µm
Nanowire fabrication

20 µm
Outline

- waveguiding
- nanowire fabrication
- optical properties
Optical properties

coupling light into nanowires
Optical properties

coupling light into nanowires
Optical properties

coupling light into nanowires
Optical properties

280-nm nanowire

360 nm

450 nm
Optical properties
Optical properties

Poynting vector profile for 800-nm nanowire
Optical properties

Poynting vector profile for 800-nm nanowire
Optical properties

Poynting vector profile for 800-nm nanowire

evanescent wave
Optical properties

Poynting vector profile for 600-nm nanowire
Optical properties

Poynting vector profile for 500-nm nanowire
Optical properties

Poynting vector profile for 400-nm nanowire
Optical properties

Poynting vector profile for 300-nm nanowire
Optical properties

Poynting vector profile for 200-nm nanowire
Waveguiding

fraction of power carried in core

![Graph showing fraction of power carried in core as a function of diameter. The graph includes two curves, one for 633 nm and another for 1550 nm wavelengths.]
Optical properties

coupling light between nanowires
Optical properties

coupling light between nanowires
Optical properties

coupling light between nanowires
Optical properties

50 µm
Optical properties
Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss a single-mode diameter < 0.1 dB/mm

Optical properties

100 µm
Optical properties

minimum bending radius: 5.6 \( \mu m \)
Optical properties

virtually no loss through 5 µm corner!
Optical properties

dispersion:

- modal dispersion
- material dispersion
- waveguide dispersion
- nonlinear dispersion
Optical properties

waveguide dispersion

Optics Express, 12, 1025 (2004)
Optical properties

waveguide dispersion

Optics Express, 12, 1025 (2004)
Optical properties

waveguide dispersion

Optics Express, 12, 1025 (2004)
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waveguide dispersion

**Optics Express**, 12, 1025 (2004)
Optical properties

nonlinear dispersion: \( n = n_0 + n_2 I \)
Optical properties

nonlinear dispersion: \( n = n_0 + n_2 I \)
Optical properties

nonlinear dispersion: \( n = n_0 + n_2 I \)
Optical properties

nonlinear dispersion:  \[ n = n_0 + n_2I \]
Optical properties

**nonlinear dispersion:** \( n = n_o + n_2 I \)
Optical properties
Optical properties
Summary

- strong confinement
- very tight bending
- large evanescent wave
Outlook

microphotonic components
microphotonic components
Outlook

microphotonic components
Outlook
Outlook
Outlook

Aerogel

density: 1.9 kg/m$^3$

index of refraction: 1.03–1.08
Outlook

loss measurement @ 633 nm

Nanoletters, in press (2005)
Outlook

530 nm

10 μm
Outlook

bending loss @ 633 nm

Nanoletters, in press (2005)
Outlook
Outlook
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