Wrapping light around a hair

AP298r Lecture
Harvard University
Cambridge, MA, 16 March 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

at Zhejiang University:

Dr. Sailing He
Dr. Jingyi Lou
Xuewen Chen
Liu Liu
Zhanghua Han

Dr. Ray Mariella (LLNL)
“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)
W. WHEELER.

APPARATUS FOR LIGHTING DWELLINGS OR OTHER STRUCTURES.

No. 247,229.

Patented Sept. 20, 1881.

Fig. 1

Fig. 2

Inventor:
William Wheeler

Witnesses:
J. W. Rock

US Patent 247, 229 (1881)
Outline

- waveguiding
- nanowire fabrication
- optical properties
Waveguiding

two crossed planar waves...
Waveguiding

...cause an interference pattern
Waveguiding

$E = 0$ 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...
Waveguiding

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Waveguiding

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

standing wave in $y$-direction, traveling in $z$-direction
Waveguiding

consider wave incident at angle $\theta$
twice-reflected wave
self consistency:

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

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

so:

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

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\]
number of modes:

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

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

or:

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

propagation constant of guided wave:

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

group velocity:

\[ v_m = c \cos \theta_m \]
Waveguiding

single mode condition for 600-nm light:

planar mirror

\[ M = \frac{2d}{\lambda} \]

\[ 300 < d < 600 \text{ nm} \]

dielectric

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

\[ d < 268 \text{ nm} \]
single mode condition for 600-nm light:

- Planar mirror:
  \[ M = \frac{2d}{\lambda} \]
  \[ 300 < d < 600 \text{ nm} \]

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

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

\[ \nabla^2 \vec{A} + \omega^2 \mu_0 \epsilon \vec{A} = -i \omega \mu_0 \nabla \epsilon \Phi \]
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

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

$$\nabla^2 \mathbf{A} + \omega^2 \mu_0 \epsilon \mathbf{A} = 0$$

Substituting

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

yields:

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

Vector potential obeys:

\[ \nabla^2 \vec{A} + \omega^2 \mu_o \varepsilon \vec{A} = 0 \]

Substituting

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

yields:

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

Compare to time-independent Schrödinger equation:

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

commercial single-mode fiber (Corning Titan®)

<table>
<thead>
<tr>
<th>Description</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 µm</td>
<td>125.0 ± 1.0 µm</td>
</tr>
</tbody>
</table>

operating wavelength: $\lambda = 1310$ nm/1550 nm
Waveguiding

drawbacks of clad fibers:

• weak confinement

• no tight bending

• coupling requires splicing
Outline

• waveguiding
• nanowire fabrication
• optical properties
Nanowire fabrication

two-step drawing process

standard fiber
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

drawing

sapphire taper
Nanowire fabrication

two-step drawing process
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

silica wire
Nanowire fabrication

two-step drawing process

standard fiber

1-μm silica wire

flame

sapphire taper

silica wire
drawing
Nanowire fabrication
Nanowire fabrication
Nanowire fabrication
Nanowire fabrication

500 µm
Nanowire fabrication

200 \mu m
Nanowire fabrication

100 µm
Nanowire fabrication

50 µm
Nanowire fabrication

20 µm
Nanowire fabrication
Nanowire fabrication

6 µm

6 µm
Nanowire fabrication
Nanowire fabrication

312 nm

1 μm
Waveguiding

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

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
Nanowire fabrication

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

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

$E = \text{Young’s modulus}$
$D = \text{wire diameter}$
Waveguiding

tensile strength

![Graph showing tensile stress vs. nanowire diameter (nm). The graph includes two data sets: one for bending (diamonds) and one for pulling (squares).]
Nanowire fabrication

2 µm
Nanowire fabrication
Nanowire fabrication

20 μm
Outline

- waveguiding
- nanowire fabrication
- optical properties
Optical properties

coupling light into nanowires
Optical properties

coupling light into nanowires

objective

fiber taper

nanowire
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 in core versus diameter for 633 nm and 1550 nm wavelengths. The red line represents 633 nm, and the black line represents 1550 nm.](image-url)
Optical properties
Optical properties

coupling light between nanowires
Optical properties

coupling light between nanowires
Optical properties

coupling light between nanowires
Optical properties

coupling light between nanowires
Optical properties

coupling light between nanowires
Optical properties

“tunneling” of light
Optical properties

50 µm
Optical properties

50 µm
Optical properties

intensity distribution

![Intensity Distribution Graph](image)
Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

Optical properties

loss measurement

Optical properties

loss measurement

Optical properties

loss a single-mode diameter < 0.1 dB/mm

Optical properties
Optical properties

minimum bending radius: 5.6 µm
Optical properties

virtually no loss through 5 μm corner!
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

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waveguide dispersion

![Graph showing waveguide dispersion](image)

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

waveguide dispersion

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Optical properties

nonlinear dispersion: \[ n = n_0 + n_2 I \]
nonlinear dispersion:  \( n = n_o + n_2I \)
Optical properties

**nonlinear dispersion:**  \[ n = n_0 + n_2 I \]
Optical properties

nonlinear dispersion: $n = n_0 + n_2 I$
Optical properties

nonlinear dispersion: \[ n = n_o + n_2 I \]
Optical properties
Optical properties
Optical properties

self-phase modulation

![Graph](image-url)
Optical properties

self-phase modulation

![Graph showing self-phase modulation](image_url)
Optical properties

self-phase modulation

![Graph showing optical properties with self-phase modulation.](image)
Summary
• strong confinement
• very tight bending
• large evanescent wave
Outlook

microphotonic components
Outlook

microphotonic components
Outlook

microphotonic components
Outlook
Outlook
Outlook

350 nm

450 nm

10 µm
Outlook
Outlook

loss measurement @ 633 nm

Nanoletters, in press (2005)
Outlook

10 µm

530 nm

10 µm
Outlook

bending loss @ 633 nm

Nanoletters, in press (2005)
Outlook

420 nm

aerogel

420 nm
biosensor
Outlook

biosensor

receptor
Outlook

biosensor

![Diagram of a biosensor with an input and output arrow, and a receptor area in the middle.](image-url)
Outlook

biosensor
Outlook

biosensor
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