Lecture 20 #  Introduction to Dielectric Waveguide: Optical fibers

Younès Messaddeq
Centre d’optique, Photonique et laser, Québec, Canada
(younes.messaddeq@copl.ulaval.ca)
Spring 2015

Lectures available at:
www.lehigh.edu/imi

Sponsored by US National Science Foundation (DMR-0844014)
Outline

• Introduction & Useful References
• Basic of Optical Fibers
  a) Mode $LP_{lm}$
  b) Optical fibers Parameters
  c) Dispersion
  d) Attenuation
• Fabrication Method
• Properties of Optical fibers
• Special fibers
USEFUL REFERENCE


ISBN-10: 0133081753
Second Edition Version 1.056
Introduction
Optical Fiber Chronology

- Light guiding in water jet, *Tyndall (1878)*
- Dielectric waveguide analysis, *Hondros & Debye (1910)*
- Early experiments with silica fibers, *Lamb (1930)*
- Image trans. by fiber bundles, *van Heel, Kapany (1951)*
- Mode analysis of optical fiber, *Snitzer (1961)*
- 1st. semiconductor lasers, *various groups (1962)*
- 1st. POF, *DuPont (1963)*
- Fiber Lasers proposed & analyzed, *Snitzer (1964)*
Introduction
Optical Fiber Chronology

• FO proposed for long distance communication, Kao & Hockman (1966)

• First fiber with < 20dB/Km loss, Corning (1970)

• Record low loss of 0.2dB/Km @ 1.55um (1979)

• Er fiber amplifier, Payne & Desurvire (1987)

• Holey fibers first proposed, Russell (1991)

• Fist solid-core PCF fiber made (1996)

• Bend-insensitive fiber introduced, Corning (2007)
Theodore Maiman, working at Hughes Research Laboratories in Malibu, California, produced the first laser (Rubi).

The attenuation of glass is due largely to the presence of impurities, and if a glass can be developed with attenuation of only 20 dB / km, then optical communication could become a reality.

Charles Kao (1933)
Basic of Optical Fibers
A. Types Of Optical Fiber

- Single-mode step-index Fiber
- Multimode step-index Fiber
- Multimode graded-index Fiber

Light ray

\[ n_{\text{Core}} > n_{\text{cladding}} \]
B. Numerical Aperture (NA)

Maximum acceptance angle $\alpha_{\text{max}}$ is that which just gives total internal reflection at the core-cladding interface, i.e. when $\alpha = \alpha_{\text{max}}$ then $\theta = \theta_c$. Rays with $\alpha > \alpha_{\text{max}}$ (e.g. ray B) become refracted and penetrate the cladding and are eventually lost.

$$\sin \alpha_{\text{max}} = \frac{(n_1^2 - n_2^2)^{1/2}}{n_o} = \frac{\text{NA}}{n_o}$$

$$\text{NA} = (n_1^2 - n_2^2)^{1/2}$$

$$2\alpha_{\text{max}} = \text{total acceptance angle}$$

$\text{NA}$ is an important factor in light launching designs into the optical fiber.
Modes in Optical Fibers

Mode $LP_{lm}$ (linearly Polarized)

Weakly guiding modes in fibers

$\Delta \ll 1$ weakly guiding fibers

$$E_{LP} = E_{lm}(r, \phi) \exp(j(\alpha t - \beta_{lm}z))$$

Field Pattern

Traveling wave

$E$ and $B$ are $90^\circ$ to each other and $z$
Fundamental Mode is the $LP_{01}$ mode: $l = 0$ and $m = 1$

(a) Electric field of the fundamental mode
(b) Intensity in the fundamental mode $LP_{01}$

The electric field distribution of the fundamental mode, $LP_{01}$, in the transverse plane to the fiber axis $z$. The light intensity is greatest at the center of the fiber.
The electric field distribution of the fundamental mode in the transverse plane to the fiber axis $z$. The light intensity is greatest at the center of the fiber. Intensity patterns in $\text{LP}_{01}$, $\text{LP}_{11}$ and $\text{LP}_{21}$ modes. (a) The field in the fundamental mode. (b)-(d) Indicative light intensity distributions in three modes, $\text{LP}_{01}$, $\text{LP}_{11}$ and $\text{LP}_{21}$.
$E_{LP} = E_{lm}(r, \phi) \exp(j(\omega t - \beta_{lm}z))$

$m = \text{number of maxima along } r \text{ starting from the core center. Determines the reflection angle } \theta$

$2l = \text{number of maxima around a circumference}$

$l = \text{radial mode number}$

$l = \text{extent of helical propagation, i.e. the amount of skew ray contribution to the mode.}$
Optical Fiber Parameters

\[ n = \frac{(n_1 + n_2)}{2} = \text{average refractive index} \]
\[ \Delta = \text{normalized index difference} \]
\[ \Delta = \frac{(n_1 - n_2)}{n_1} \approx \frac{(n_1^2 - n_2^2)}{2} \]

\[ V = \frac{2\pi a}{\lambda} \left( n_1^2 - n_2^2 \right)^{1/2} = \frac{2\pi a}{\lambda} \left( 2n_1 n\Delta \right)^{1/2} \]

\( V < 2.405 \) only 1 mode exists. Fundamental mode

\( V < 2.405 \) or \( \lambda > \lambda_c \) Single mode fiber (SMF).

\( V > 2.405 \) Multimode fiber

Number of modes

\[ M \approx \frac{V^2}{2} \]
a) Intermode (Intermodal) Dispersion: Multimode fibers

b) Materials Dispersion
   Group velocity depends on $N_g$ and hence on $\lambda$

c) Waveguide Dispersion
   Group velocity depends on waveguide structure

d) Chromatic Dispersion
   Material dispersion + Waveguide Dispersion
a) Intermode Dispersion (MMF)

\[ \pi_c \approx \frac{c}{n_1} \sin \theta_c = \frac{c}{n_1} \left( \frac{n_2}{n_1} \right) \]

\[ \Delta \tau = \frac{L}{v_{\text{gmin}}} - \frac{L}{v_{\text{gmax}}} \]

\[ \frac{\Delta \tau}{L} \approx \frac{n_1 - n_2}{c} \]

\[ \frac{\Delta \tau}{L} = \frac{(n_1 - n_2)}{c} \frac{n_1}{n_2} \]

\[ \Delta \tau / L \approx 10 - 50 \text{ ns / km} \]

Depends on length!
Intramode Dispersion (SMF)
Dispersion in the fundamental mode

Group Delay \( \tau = \frac{L}{v_g} \)

Group velocity \( v_g \) depends on

- **Refractive index** = \( n(\lambda) \)
  - **Material Dispersion**

- **V-number** = \( V(\lambda) \)
  - **Waveguide Dispersion**

\[ \Delta = \frac{n_1 - n_2}{n_1} = \Delta(\lambda) \]

- **Profile Dispersion**
Emitter emits a spectrum $\Delta \lambda$ of wavelengths.

Waves in the guide with different free space wavelengths travel at different group velocities due to the wavelength dependence of $n_1$. The waves arrive at the end of the fiber at different times and hence result in a broadened output pulse.

$$\frac{\Delta \tau}{L} = D_m \Delta \lambda$$

$D_m = \text{Material dispersion coefficient, ps nm}^{-1} \text{ km}^{-1}$
Material Dispersion

Group velocity: \( v_g = \frac{c}{N_g} \)

Depends on the wavelength

\[
\frac{\Delta \tau}{L} = D_m \Delta \lambda
\]

\( D_m = \text{Material dispersion coefficient, ps nm}^{-1} \text{ km}^{-1} \)

\[
D_m \approx -\frac{\lambda}{c} \left( \frac{d^2 n}{d\lambda^2} \right)
\]
c) Waveguide dispersion

\[ b \text{ hence } \beta \text{ depends on } V \text{ and hence on } \lambda \]

\[ V = \frac{2\pi a}{\lambda} \left( n_1^2 - n_2^2 \right)^{1/2} \]

Normalized propagation constant

\[ b = \frac{(\beta / k)^2 - n_2^2}{n_1^2 - n_2^2} \]

\[ k = \frac{2\pi}{\lambda} \]

\[ b \approx \left( 1.1428 - \frac{0.996}{V} \right)^2 \]
Chromatic Dispersion

Material dispersion coefficient ($D_m$) for the core material (taken as SiO$_2$), waveguide dispersion coefficient ($D_w$) ($a = 4.2$ μm) and the total or chromatic dispersion coefficient $D_{ch}$ ($= D_m + D_w$) as a function of free space wavelength, $\lambda$

$$\Delta \tau = \frac{(D_m + D_w)}{L} \Delta \lambda$$
Attenuation

\[ \text{Attenuation} = \text{Absorption} + \text{Scattering} \]

**Attenuation coefficient** \( \alpha \) is defined as the *fractional decrease in the optical power per unit distance*. \( \alpha \) is in m\(^{-1}\).

\[ P_{\text{out}} = P_{\text{in}} \exp(-\alpha L) \]

\[ \alpha_{\text{dB}} = \frac{10}{L} \log_{10} \left( \frac{P_{\text{in}}}{P_{\text{out}}} \right) \]

\[ \alpha_{\text{dB}} = \frac{10}{\ln(10)} \alpha = 4.34 \alpha \]
Attenuation

Absorption and Scattering Loss

[Graph showing attenuation in dB/km vs. wavelength (μm) with labels for Rayleigh scattering, OH⁻ absorption peaks, UV absorption, 1310 nm, 1550 nm, and Infrared absorption.]
1) **Losses (Material):**

a) **Intrinsic Absorption**

**UV Region**

- “Urbach tail”: \[ \alpha = \alpha_o \exp \left( \frac{\sigma \hbar}{k_B T} (\omega - \omega_o) \right) \]

- \( \text{SiO}_2 \): \( \lambda_o \approx 140 \text{ nm} \)
- \( \text{GeO}_2 \): \( \lambda_o \approx 185 \text{ nm} \)

**IR Region**

- \( \alpha_{IR} = 7.81 \times 10^{11} \exp \left( - \frac{48.48}{\lambda} [\mu \text{m}] \right) \) [dB/km]
b) **Absorption due to impurities:**

**Transition Metal:** Cr, Mn, Cu, Fe, Ni, etc

- 1-10 dB/km @ 1-5 ppm

**hydroxyl ions (OH⁻)**

- $\nu_{OH}$ (fundamental) $\rightarrow$ 2.73 $\mu$m
  
  $2\nu_{OH} \rightarrow$ 1.38 $\mu$m
  
  $3\nu_{OH} \rightarrow$ 0.95 $\mu$m
  
  $2\nu_{OH} + \nu_1 \rightarrow$ 1.24 $\mu$m
c) Rayleigh scattering:

- Microscopic variations (sub-\(\lambda\)) density of Material.
- \(\alpha_R \cong (0.75 + 66 \Delta n_{Ge}) \lambda^{-4} \) [\(\text{dB/km}\)]
  
  \[ \text{où } \Delta n_{Ge} : \text{n variation due to Ge.} \]
- Main factor losses in the visible and near infrared
  
  (\(\rightarrow 1.6 \ \mu m\))
2) Guide Loss:

a) Guide Imperfection:

- Irregularities of the interface Core-cladding;
- Mie Diffusion (defects $>> \lambda$)
- $< 0.05$ dB/km for silice.

b) Bending Loss:

- Distortion mode: Distortion of indice profil.

\[ n'(r) = n(r) \left( 1 + \frac{r}{R} \cos \varphi \right) \]

$R$ : Rayon de courbure
Optical Loss Mechanisms

\[ \alpha_c = \frac{A_c}{\sqrt{R(m)}} e^{-KR(m)} \text{ [dB/m]} \]

où : 
\[ A_c = \frac{1}{2} \left( \frac{\pi}{aw^3} \right)^{1/2} \left[ \frac{u}{wK_1(w)} \right]^2 \approx \frac{30(\Delta n)^{1/4}}{\sqrt{\lambda(m)}} \left( \frac{\lambda_c}{\lambda} \right)^{3/2} \left[ \frac{\text{dB}}{\sqrt{\text{m}}} \right] \]

\[ K = \frac{4\Delta nw^3}{3aV^2n_2} \equiv 0.705 \frac{(\Delta n)^{3/2}}{\lambda(m)} \left( 2.748 - 0.996 \frac{\lambda}{\lambda_c} \right)^3 \left[ \text{m}^{-1} \right] \]

D. Marcuse, JOSA, 66(3), 1976

\[ \text{e.g. } \Delta n = 5 \times 10^{-3} \quad \lambda = 1.0 \mu\text{m} \quad \lambda_c = 900 \text{ nm} \]

\[ \alpha_{2\text{cm}} = 1 \text{ dB/km} \quad \alpha_{1\text{cm}} = 10^4 \text{ dB/km} \]
Optical Loss Mechanisms

U.V. ABSORPTION
RAYLEIGH SCATTERING
IR ABSORPTION
TOTAL ATTENUATION

Attenuation dB/Km

Wavelength μm
Optical Loss for different Materials

Transmission Window:
Optical Loss for Different Fiber Materials

![Graph showing optical loss for different materials](image)
Fabrication Methods
Optical Fiber Fabrication Methods

• **Glass**
  – CVD preform → fiber drawing
  – Rod-in-tube prefrom → fiber drawing
  – Cast preform → fiber drawing
  – Double crucible → direct draw
  – Sol gel preform → fiber drawing
  – Stack and draw → PCFs

• **Polycrystalline**
  – Extrusion
  – Hot rolling

• **Monocrystalline**
  – Seed crystal growth from melt
  – Zone melting

• **Polymer**
  – Extrusion
  – Cast prefrom → fiber drawing

MCVD—Modified Chemical Vapor Deposition
PMCVD—RF Plasma Enhanced MCVD
PCVD—Microwave Plasma CVD
OVD—Outside Vapor Deposition
VAD—Axial Vapor Deposition
Optical Fiber Fabrication Methods

OVD  MCVD  AVD
MCVD system
MCVD Process
Typical Glass Fiber Compositions

Multimode

\[
\begin{align*}
\text{GeO}_2 \cdot \text{B}_2\text{O}_3 \cdot \text{SiO}_2 \\
\text{GeO}_2 \cdot \text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{GeO}_2 \cdot \text{SiO}_2
\end{align*}
\]

\[
\begin{align*}
\text{B}_2\text{O}_3 \cdot \text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{B}_2\text{O}_3 \cdot \text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{F} \cdot \text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{SiO}_2 \\
\text{F} \cdot \text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{SiO}_2 \\
\text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{F} \cdot \text{SiO}_2 \\
\text{F} \cdot \text{P}_2\text{O}_5 \cdot \text{SiO}_2 \\
\text{F} \cdot \text{SiO}_2
\end{align*}
\]

Singlemode

\[
\begin{align*}
\text{GeO}_2 \cdot \text{SiO}_2 \\
\text{SiO}_2
\end{align*}
\]
Dopant Effects in Silica Glass

<table>
<thead>
<tr>
<th></th>
<th>INDEX n</th>
<th>EXPANSION α</th>
<th>VISCOSITY η</th>
<th>STABILITY</th>
<th>DURABILITY</th>
<th>DISPERSION λd</th>
<th>RAYLEIGH SCATTERING</th>
<th>IR LOSS</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>GeO₂</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>⬤</td>
<td>↑</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>↑</td>
<td>↑</td>
<td>↓₂</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>⬤</td>
<td>↑</td>
</tr>
<tr>
<td>B₂O₃</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>⬤</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>↓</td>
<td></td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>⬤</td>
<td></td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>↑</td>
<td>↑</td>
<td>?</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
<td>⬤</td>
<td></td>
</tr>
</tbody>
</table>
Image BSE of the GRIN preform
Other Method: Rotational Casting

Rotational Preform Casting Process
Optical Fiber Coatings

• Environmental Protection
  – Abrasion
  – Moisture ingress
  – Hydrogen diffusion
  – Chemical attack
  – Temperature resistance
  – Mechanical bending

• Sensing
  – Fluorescence
  – Swelling
  – Chem/Bio reactive
  – Magnetic
  – Acoustic
  – Piezoelectric
Coatings Materials

-100°C  0  100  200  300  400  500°C

- Metal
- Polyimide
- Silicone
- Polyetherimide
- Epoxy Resin
- Acrylate
Evanescent-Wave Sensor Principle
Chemically-Induced Cladding Change

- Presence of chemical agent in cladding region changes optical properties
- Light propagating through sensor waveguide is affected by changes in exposed region
Fiber Drawing Process
Mechanical Properties
Optical fibers behave as an elastic material up to the point of failure.

- Theoretical strength of silica glass determined by cohesive bond strength of constituent atoms > 20 GPa (3-5Mpsi)!
- Glass fiber strengths are on the order of 4-6 GPa (~800Kpsi).
- Actual strength is limited by surface flaw distribution.
Effective fiber strength is a function of:
- Length
- Strain rate
- Temperature
- Relative Humidity
- Chemical or mechanically induced flaws

Strength Kpsi
Proof-Testing

• Fiber is subjected to a short-term tensile strain during or subsequent to production. Applied load is the proof-stress value.
• Establishes minimum strain capability: fiber will break for large cracks larger than the proof-stress value.
• Typical proof-stress levels: 50Kpsi & 100Kpsi
Reducing the mode field diameter

Depressing the cladding

Adding a low index trench

Symmetric holes within the cladding

NanoStructures Ring

Corning (2007)
Special Optical Fibers
In contrast to solid core glass fibers, hollow core fibers can propagate light by:

- Hollow-core fiber
- Metallic Cladding
- Multilayer Dielectric Mirror
- 2D Photonic Crystal cladding
Hollow Core Optical Fibers

Waveguide probes are currently being developed for applications in: beam delivery, trace gas detection, signal collection, and IR imaging.

Jason M. Kriesel, SPIE defence, April (2011)
Fluoride Glasses

- 1974- Fluoride glasses (M. Poulain)
Fiber Amplifier

Nd$^{3+}$ doped fiber and amplification at 1060nm.

E. Snitzer, Appl. Optics, 3, 10 (1964)

Potential λ Regions for Systems Expansion

Weak signal

1 Amplified signal

Transmitting Fiber (Km)  Fiber amplifier Fiber (Km) (m)

1300 1400 1525 1550 1600

Fiber Loss
# Fiber Laser

<table>
<thead>
<tr>
<th>Dopant(s)</th>
<th>Host glass</th>
<th>Pump $\lambda$ (µm)</th>
<th>Laser $\lambda$ (µm)</th>
<th>Transition</th>
<th>Output power (W)</th>
<th>Slope efficiency (%)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Er$^{3+}$, Yb$^{3+}$</td>
<td>Silicate</td>
<td>0.975</td>
<td>1.5</td>
<td>$^4I_{15/2} \rightarrow ^4I_{15/2}$</td>
<td>297</td>
<td>19</td>
<td>21</td>
</tr>
<tr>
<td>Tm$^{3+}$, Ho$^{3+}$</td>
<td>ZBLAN</td>
<td>0.792</td>
<td>1.94</td>
<td>$^3F_4 \rightarrow ^3H_6$</td>
<td>20</td>
<td>49</td>
<td>33</td>
</tr>
<tr>
<td>Tm$^{3+}$</td>
<td>Silicate</td>
<td>0.793</td>
<td>2.05</td>
<td>$^3F_4 \rightarrow ^3H_6$</td>
<td>1,050</td>
<td>53</td>
<td>22</td>
</tr>
<tr>
<td>Tm$^{3+}$, Ho$^{3+}$</td>
<td>Silicate</td>
<td>0.793</td>
<td>2.1</td>
<td>$^5I_7 \rightarrow ^5I_8$</td>
<td>83</td>
<td>42</td>
<td>34</td>
</tr>
<tr>
<td>Ho$^{3+}$</td>
<td>Silicate</td>
<td>1.950</td>
<td>2.14</td>
<td>$^5I_7 \rightarrow ^5I_8$</td>
<td>140</td>
<td>55</td>
<td>23</td>
</tr>
<tr>
<td>Tm$^{3+}$</td>
<td>ZBLAN</td>
<td>1.064</td>
<td>2.31</td>
<td>$^3H_4 \rightarrow ^3H_6$</td>
<td>0.15</td>
<td>8</td>
<td>35</td>
</tr>
<tr>
<td>Er$^{3+}$</td>
<td>ZBLAN</td>
<td>0.975</td>
<td>2.8</td>
<td>$^4I_{15/2} \rightarrow ^4I_{15/2}$</td>
<td>24</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td>Ho$^{3+}$, Pr$^{3+}$</td>
<td>ZBLAN</td>
<td>1.1</td>
<td>2.86</td>
<td>$^5I_6 \rightarrow ^5I_7$</td>
<td>2.5</td>
<td>29</td>
<td>25</td>
</tr>
<tr>
<td>Dy$^{3+}$</td>
<td>ZBLAN</td>
<td>1.1</td>
<td>2.9</td>
<td>$^6H_{15/2} \rightarrow ^6H_{15/2}$</td>
<td>0.275</td>
<td>4.5</td>
<td>36</td>
</tr>
<tr>
<td>Ho$^{2+}$</td>
<td>ZBLAN</td>
<td>1.15</td>
<td>3.002</td>
<td>$^5I_6 \rightarrow ^5I_7$</td>
<td>0.77</td>
<td>12.4</td>
<td>26</td>
</tr>
<tr>
<td>Ho$^{3+}$</td>
<td>ZBLAN</td>
<td>0.532</td>
<td>3.22</td>
<td>$^5S_2 \rightarrow ^5F_5$</td>
<td>0.011</td>
<td>2.8</td>
<td>27</td>
</tr>
<tr>
<td>Er$^{3+}$</td>
<td>ZBLAN</td>
<td>0.653</td>
<td>3.45</td>
<td>$^4F_9/2 \rightarrow ^4I_{15/2}$</td>
<td>0.008</td>
<td>3</td>
<td>28</td>
</tr>
<tr>
<td>Ho$^{3+}$</td>
<td>ZBLAN</td>
<td>0.89</td>
<td>3.95</td>
<td>$^5I_6 \rightarrow ^5I_6$</td>
<td>0.011</td>
<td>3.7</td>
<td>29</td>
</tr>
</tbody>
</table>

S.D. Jackson, Nature Photonics, 6,423 (2012)
Fiber Laser
Fiber Laser
Optical fiber constructed with a lattice of voids (air holes) along its length → provide unique optical properties impossible to obtain with solid fibers.

Very large index of refraction differences
– 1.0 (air) to 1.45 (undoped silica): $\Delta n \sim 0.45$
– Doped silica fiber: $\Delta n \sim 0.03$

Voids can be filled with functional materials allowing dynamic properties
– Control local index with temperature, electrical field, magnetic field, etc.

Photonic bandgap operation
– Periodic structure creates resonance, like a 2-D gratings.
Microstructure Fibers

Overall terms:
- Photonic Crystal Fibre (PCF)
- Micro structured Fiber (MSF)
- Micro structured Optical Fiber (MOF)

Main classes:
- High-Index Core
  - Hole
  - Hole-assisted
- Photonic Band Gap (PBG)
  - Bandgap Guiding

Subclasses:
- High NA
- Large Mode Area
- Highly Nonlinear
- Low-index Core
- Air Guiding Hollow Core
Un-doped silica glass is used for both core and cladding regions. Core is solid.

Placement of air channels \((n = 1)\) in the cladding creates an “effective” index below that of the solid core region. Light is confined and guided by total internal reflection. NA can approach 1.

Different designs can be achieved by varying index delta, channel spacing, size & diam.
Un-doped silica glass is used for both core and cladding regions. **Core is hollow** (air).

Placement of air channels \((n = 1)\) in the cladding creates a 2-D photonic bandgap structure.

Constructive interference is produced by scattered light refracted at the core/cladding interfaces of the periodic lattice structure.

Light can only propagate in specific regions.
Special Fibers

PCF Fabrication:
Stack-and-Draw Process
Special Fibers

PCF Applications

• Telecommunications
  – Dispersion compensation
  – Transmission fibers
  – Broadband SM fibers

• Lasers
  – Double Clad fibers (laser cavity)
  – Large Area fibers (high power transmission)
  – White Light Sources

• Sensing
• Metrology
• Medical
  – Optical Coherence Tomography
Special Fibers

PCF Applications

Gas Sensor

laser drilled gas inlet hole  laser drilled PCF (cross section)
Special Fibers

PCF Applications

Ultra-Broad White Light Source

Ranka, J. K., Windeler, R. S., and Stentz, A. J.,
Special Fibers

Electrical Resistance: $6-26 \Omega$
Instability of the driver medium

Special Fibers

Fiber Designs at COPL