EE 443 Optical Fiber Communications
Dr. Donald Estreich
Fall Semester

Lecture 4

http://www.wiretechworld.com/the-future-of-optical-fibres/
Continuing With The Optical Fiber

Silicon Dioxide – Crystalline vs. Amorphous

Glass is both a super-cooled liquid & an amorphous solid.

https://www.jagranjosh.com/articles/cbse-class-12th-chemistry-notes-solid-state-1467032622-1
Some Comments on Fused Silica

Fused silica is a high-purity, non-crystalline material manufactured through oxidation of raw silica in a flame hydrolysis process, whereas fused quartz is fabricated by the melting of naturally occurring quartz.

Fused silica is a common glass type used in the optics industry to manufacture optical components such as lenses, windows, mirrors, prisms, and beam-splitters. Fused silica is often a preferred material for precision optics due to its consistent and repeatable optical performance. Additionally, fused silica demonstrates a low thermal expansion coefficient that provides high thermal stability and resistance to thermal shocks, which are often critical characteristics in specific applications. Fused silica also has a high chemical resistance and minimal fluorescence. There are many types of fused silica, the most common include UV grade fused silica and IR grade fused silica.

https://www.edmundoptics.com/resources/application-notes/optics/uv-vs.-ir-grade-fused-silica/
Optical Fiber Manufacturing

https://www.techrepublic.com/article/3d-printing-is-helping-create-complex-fiber-optics/
Vertical Drawing in Optical Fiber Manufacturing


https://www.fibresystems.com/supplier/nextrom

http://www.patentsencyclopedia.com/imgfull/20090126408_04
Index of Refraction versus Wavelength for Silica Glass

Refractive index versus wavelength for common silica glass fiber

Fused Silica

Wavelength \( \lambda \) (microns)

<table>
<thead>
<tr>
<th>Wavelength (microns)</th>
<th>Refractive Index (n)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.6</td>
<td>1.4442</td>
</tr>
<tr>
<td>0.7</td>
<td>1.4470</td>
</tr>
<tr>
<td>0.8</td>
<td>1.4527</td>
</tr>
<tr>
<td>0.9</td>
<td>1.4470</td>
</tr>
<tr>
<td>1.0</td>
<td>1.4442</td>
</tr>
</tbody>
</table>

Selected Properties of Transparent Fused Silica

- Density: 2.203 g/cm³
- Hardness: 5.3...6.5 (Mohs scale), 8.8 GPa
- Tensile strength: 48.3 MPa
- Compressive strength: >1.1 GPa
- Bulk modulus: ~37 GPa
- Young's modulus: 71.7 GPa
- Coefficient of thermal expansion: 5.5 × 10⁻⁷/K (average from 20...320 °C)
- Thermal conductivity: 1.3 W/(m·K)
- Specific heat capacity: 45.3 J/(mol·K)
- Softening point: ≈1665 °C
- Annealing point: ≈1140 °C
- Electrical resistivity: >10¹⁸ Ω·m
- Dielectric constant: 3.75 at 20 °C & 1 MHz
- Index of refraction: n = 1.4585 (at 587.6 nm)
- Change of refractive index with temperature (0...700°C): 1.28 × 10⁻⁵/K (between 20...30 °C)

https://en.wikipedia.org/wiki/Fused_quartz
### Early History of Optical Fiber System Development

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1966</td>
<td>Kao &amp; Hackham identify glass impurities as primary cause of optical loss.</td>
</tr>
<tr>
<td>1970</td>
<td>Corning breaks the 20 dB/km loss attenuation milestone.</td>
</tr>
<tr>
<td>1973</td>
<td>First diode end-pumped fiber laser demonstrated.</td>
</tr>
<tr>
<td>1975</td>
<td>First commercial optical fiber link installed by Dorset (UK) police.</td>
</tr>
<tr>
<td>1977</td>
<td>First telephone signals using optical fiber in Long Beach, CA (USA)</td>
</tr>
<tr>
<td>1978</td>
<td>Single polarization optical fiber demonstrated.</td>
</tr>
<tr>
<td>1986</td>
<td>Erbium-doped fiber amplifier (EDFA) pioneered by David Payne (UK).</td>
</tr>
<tr>
<td>1995</td>
<td>Output power from optical fiber laser exceeds 10 watts.</td>
</tr>
<tr>
<td>1999</td>
<td>Output power from optical fiber laser exceeds 100 watts.</td>
</tr>
<tr>
<td>2009</td>
<td>Charles K. Kao awarded Nobel Prize in Physics for driving lower attenuation in fiber.</td>
</tr>
<tr>
<td>2009</td>
<td>Output power from optical fiber laser exceeds 10 kilowatts.</td>
</tr>
</tbody>
</table>

Charles Kao Receives 2009 Nobel Prize in Physics

Charles Kuen Kao is known as the “father of fiber optic communications” for his discovery in the 1960s of certain physical properties of glass, which laid the groundwork for high-speed data communication in the Information Age. Before Kao’s pioneering work, glass fibers were widely believed to be unsuitable as a conductor of information because of excessively high signal loss from light scattering. Kao realized that, by carefully purifying the glass, bundles of thin fibers could be manufactured that would be capable of carrying huge amounts of information over long distances with minimal signal attenuation and that such fibers could replace copper wires for telecommunication.

"for groundbreaking achievements concerning the transmission of light in fibers for optical communication."

Charles K. Kao Receives 2009 Nobel Prize in Physics

From Nobel lecture:

“I cannot think of anything that can replace fiber optics.”

“In the next 1000 years, I can’t think of a better system.”

“But don’t believe what I say, because I didn’t believe what experts said either.”

https://www.researchgate.net/figure/The-young-scientist-Charles-Kao-doing-an-early-experiment-on-optical-fibers-at-the_fig12_325025838
The Wave Equation (derived from Maxwell’s Equations)

A signal propagating down a transmission line is governed by the wave equation,

\[ \nabla^2 E(x, y, z; t) + n^2(\omega)k^2 E(x, y, z; t) = 0 \]

where

\[ k = \frac{\omega}{(c / n)} = \frac{2\pi}{\lambda} \quad \text{and} \quad 2\pi f = \omega = \frac{(c / n)}{\lambda} \]

Solution:

\[ E(x, y, z; t) = \Re\{E(x, y)\} \cdot \exp\{j(kz - \omega t)\} \]

The solutions are of the form of complex exponentials where the phase of the traveling waves is

\[ \exp\{j(kz - \omega t)\} \Rightarrow \phi = (kz - \omega t) \]
The Wave Equation Solutions

The solutions are Fourier wave packets of multiple frequencies [Remember the Fourier series and Fourier integrals].

A single sinusoidal waveform has a phase velocity (point of constant phase) given by

$$\nu_{ph} = \frac{dz}{dt} = \frac{\omega}{k}$$

A wave packet (signal) moves with group velocity

$$\nu_{gr} = \frac{d\omega}{dk}$$

Group velocity is the speed of the waveform’s centroid as the signal propagates – it is equal to the speed of signal’s energy flow.
Some Useful Relationships

Wave propagation constant or wave vector $k$:

$$k = \frac{2\pi}{\lambda} = \frac{2\pi n}{\lambda_o} = \frac{2\pi nf}{c} = \frac{n\omega}{c} \quad \text{[radians/meter]}$$

Frequency $f$:

$$f = \frac{c}{\lambda_o} = \frac{c}{n\lambda} = \frac{kc}{2\pi n} = \frac{\omega}{2\pi} \quad \text{[1/seconds]}$$

Wavelength $\lambda$:

$$\lambda = \frac{c}{nf} = \frac{\lambda_o}{n} = \frac{2\pi}{k} = \frac{2\pi c}{n\omega} \quad \text{[meters]}$$
First Higher Order $\text{TE}_{11}$ Mode in a Coaxial Cable

Fig. 5. Electromagnetic field distributions for TEM mode (a) and $\text{TE}_{11}$ mode

https://www.semanticscholar.org/paper/Influence-of-Higher-order-Modes-in-Coaxial-on-of-Petrov-Rozanov/0e7ab9872e20f0eabac699b91bd5be8b3e42c309
$\omega - k$ or $\omega - \beta$ Diagram for Coaxial Line

For a TEM wave the group velocity is equal to the phase velocity.

Cylindrical Waveguide Modes

There are no TEM modes in single conductor waveguides or dielectric waveguides.

https://csttutorial.blogspot.com/2016/06/circular-waveguide-we-simulated-and.html
Optical Fiber Structure Classifications

- Optical Fiber
  - Multimode
    - Step-Index
    - Graded Index
  - Single Mode
Single Mode Fiber versus Multimode Fiber

\[ n_2 \text{ (core)} > n_j \text{ (cladding)} \]

Representative Cross Section of Optical Fibers

Some representative dimensions

Multimode Optical Fiber

Single-mode Optical Fiber

https://www.pcmag.com/encyclopedia/term/43125/fiber-optics-glossary
Step Index and Graded Index

\[ n_1 \text{ (core)} > n_2 \text{ (cladding)} \]

1. Multimode, Step-index
2. Multimode, Graded Index
3. Singlemode

https://www.thefoa.org/tech/ref/basic/fiber.html
Guiding an Optical Signal in Graded Index Optical Fiber

Path Of Light In Core

Index Profile Of Fiber

https://www.thefoa.org/tech/ref/basic/fiber.html
Single Mode Fiber versus Multimode Fiber

- Higher cost optical sources
  - ✓ 1310 + nm lasers (1 & 10 Gbps)
  - ✓ 1 Gbps with DWDM
  - ✓ Precision packaging
- Higher cost connectors needed
- Higher installation cost
- Higher system cost
- Lower transmission loss & higher BW
- Distances to 60 km and beyond

Best for
WAN, SAN, Data Center and CO

- Lower cost optical sources
  - ✓ 850 nm & 1310 nm lasers
  - ✓ 850 nm lasers (1 & 10 Gbps)
  - ✓ Low precision packaging
- Lower cost connectors needed
- Lower installation cost
- Lower system cost
- Higher transmission loss & lower BW
- Distances up to 2 km

Best for
LAN, MAN, Access and Campus

Acceptance Angle $\alpha$ to an Optical Fiber

Numerical Aperature $NA = n \cdot \sin \alpha$

Numerical Aperature of Fiber

Start with Snell’s Law which is \( n \cdot \sin \alpha = n_1 \cdot \sin \theta \)

From figure on prior slide, \( \phi = \frac{\pi}{2} - \theta \) and \( \phi > \theta_{\text{critical}} \)

Thus, \( n \cdot \sin \alpha = n_1 \cdot \cos \phi = n_1 \cdot \sqrt{1 - \sin^2 \phi} \) because \( \sin^2 \phi + \cos^2 \phi = 1 \)

As \( \phi \to \theta_{\text{critical}} \) then when they are equal, \( n \cdot \sin \alpha = \sqrt{n_1^2 - n_2^2} \)

The numerical aperature (NA) is defined as \( \text{NA} = \sqrt{n_1^2 - n_2^2} \)

Let \( \Delta \) be the relative refractive index difference between core and cladding.

Define it to be \( \Delta = \frac{n_1^2 - n_2^2}{2n_1^2} \) where \( \Delta << 1 \)

Then \( \Delta = \frac{n_1 - n_2}{n_1} \) because \( n_1 \) and \( n_2 \) are nearly equal.

And \( \text{NA} = n_1 \sqrt{2\Delta} \)

Pages 18 & 19 of Senior.
Example for Acceptance Angle

Only light falling in this angle is guided along the fiber.

\[ \sin \alpha = \sqrt{(1.5)^2 - (1.485)^2} = \sqrt{2.2500 - 2.2052} = \sqrt{0.0448} \]

\[ \sin \alpha = 0.2116 \quad \Rightarrow \quad \alpha = \sin^{-1}(0.2116) = 12.22^\circ \]

Acceptance angle is twice \( \alpha = 24.44^\circ \)

From: Jeff Hecht, *Understanding Fiber Optics*, 3rd edition, Chapter 4, Figure 4.2, page 58.
Numerical Aperature

In optics, the **numerical aperture (NA)** of an optical system is a dimensionless number that characterizes the range of angles over which the system can accept or emit light.

https://en.wikipedia.org/wiki/Numerical_aperture

Effective Numerical Aperture $\text{NA}_{e^2}$

https://www.sukhamburg.com/effNumAperture.html
Skew Waves in Optical Fiber Core

- Meridional rays are not the only type of ray which propagate in a fibre.
- Skew rays do not pass through the fibre centre axis.
- Skew rays greatly outnumber meridional rays.
- Skew rays follow a helical path within the fibre.

- Skew ray propagation is difficult to visualise, but looking at the fibre end on we see a 2d projection of the rays. Seen in this way reflection takes place with an angle $\gamma$ to the radius.
- With meridional rays at the fibre output the angle depends on the input angle. For skew rays this is not so, instead the output angle depends on the number of reflections undergone. Thus skew rays tend to make the light output from a fibre more uniform.

https://slideplayer.com/slide/4666113/
The component of the phase propagation constant in the z-direction is \( \beta_z = n_1 k \cos \theta \)

Figure 2.8 (page 26) in Senior.
Three Lower Modes Showing Ray Propagation & Electric Field

Integer $m$ denotes number of zeros in transverse Pattern.

Figure 2.9 (page 28) in Senior.
Step-Index Multimode Fiber Modes

Different Modes

Multimode Fiber

Single Mode Fiber

Core: So small that only one mode is present

$l = 0, m = 0$
$l = 1, m = 1$
$l = 2, m = 1$
$l = 0, m = 2$

$l = 3, m = 1$
$l = 1, m = 2$
$l = 4, m = 1$
$l = 2, m = 2$

$l = 0, m = 3$
$l = 5, m = 1$
$l = 3, m = 2$
$l = 1, m = 3$

https://www.slideshare.net/fiberoptics4sale/multimode-fiber
Linearily Polarized (LP) Modes

- These *linearly polarized* (LP) modes, designated as $\text{LP}_{lm}$, are *good approximations* formed by exact modes TE, TM, HE and EH.

- The mode subscripts $l$ and $m$ describe the electric field intensity profile. There are $2l$ field maxima around the fiber core circumference and $m$ field maxima along the fiber core radial direction.

https://www.slideshare.net/tossus/waveguiding-in-optical-fibers
LP_{01} and LP_{11} Modes in the Core of an Optical Fiber

When light is launched into a fiber, modes are excited to varying degrees depending on the conditions of the launch — input cone angle, spot size, axial centration, etc. The distribution of energy among the modes evolves with distance as energy is exchanged between them. Energy can be coupled from guided to radiation modes by perturbations such as microbending and twisting of the fiber.

[Image: LP_{01} Mode Distribution]  [Image: LP_{11} Mode Distribution]

https://www.newport.com/t/fiber-optic-basics
QUESTIONS
COMMENTS
CONCERNS

https://mystonehavenfontanahoa.com/contact/