Chapter 3: Optical Devices

Optical Fibers

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Brief History of Optical Fiber Technology (1 of 2)

• Mid-1960s: Attenuation in bulk glass was \( \sim 500\text{dB/km} \)
  - Attempted guiding structures included surface-wave devices
    ◦ Metallic tubes and hollow dielectric tubes
  - Kao and Hockham pointed out what had to be done to reduce attenuation
    ◦ Reduce concentration of transition-metal ions (Fe, Cu, Cr, Ni, Mn, Co) to less than 1 part per billion
    ◦ Increase purity of SiO2 to make attenuation mostly scattering loss
  - In 1971 Kapron et al. at Corning made a fiber with \( \alpha \approx 20\text{dB/km} \)
    ◦ Used outside chemical vapor deposition
  - By 1977, experimental fibers had \( \alpha < 0.5 \text{ dB/km at } \lambda = 1.2 \mu\text{m} \)
Brief History of Optical Fiber Technology (2 of 2)

• Dispersion produces pulse broadening and limits bit rate
  - Unclad fiber was widely used for imaging and short-distance transmission
    ◦ Very rapid pulse broadening → not suitable for communications
  - Core-cladding fibers were named “weakly guiding fibers” in 1971 (Gloge)
    ◦ Essential for achieving low dispersion
Optical Fiber Types for Communications (1 of 3)

• Unclad fiber
  - Not used for communications because of very rapid pulse spreading due to high intermodal dispersion

• Multimode clad fiber (used in LANs and for short-haul applications)
  - Core refractive index > cladding refractive index
  - Usually the core refractive-index profile is graded quadratically to reduce pulse spreading due to intermodal dispersion
  - The most widely installed type has a core diameter of 62.5 μm and a cladding diameter of 125 μm
Optical Fiber Types for Communications (2 of 3)

- Single-mode clad fiber (used for long-haul applications)
  - Step-index: Core refractive index is a constant
  - Profiled index: Core refractive index is designed to achieve favorable group-velocity-dispersion characteristics
  - Core diameter $\sim 10 \, \mu m$
Optical Fiber Types for Communications (3 of 3)

Index Profile

Fiber Cross Section and Ray Paths

Typical Dimensions

Monomode step-index fiber

125 μm (cladding)

8–12 μm (core)

Multimode step-index fiber

125–400 μm (cladding)

50–200 μm (core)

Multimode graded-index fiber

125–140 μm (cladding)

50–100 μm (core)
Optical Fiber Waveguide Modes (1 of 2)

- Analysis involves Bessel functions and a lot of vector calculus
  - In a step-index fiber there are only two media, the core (refractive index $n_1$) and the cladding (refractive index $n_2$)
  - The mode that has a cutoff frequency equal to 0 is a hybrid electric mode ($HE_{11}$), in which both $E_z$ and $H_z$ are non-zero
    - There are two polarizations with the same frequency and propagation constant (degenerate $HE_{11}$ modes with different polarizations)
    - For $0 < V < 2.405$ the $HE_{11}$ mode is the only mode that can propagate (all others are below the cutoff frequency)
    - This is called “single-mode” operation, despite the fact that there are two degenerate modes
Optical Fiber Waveguide Modes (2 of 2)

- Assume $a$ is the core radius, then the normalized frequency and normalized propagation constant are

$$V = k_0 a \sqrt{n_1^2 - n_2^2}$$

$$b = \frac{\beta}{n_1 k_0} - \frac{n_2}{n_1} \frac{1 - n_2}{n_1}$$
Overview of Optical Fiber Manufacturing

• An optical fiber is drawn from a *preform*
  - Dimensions are ~ 1 meter in length by 2 cm in diameter
  - Refractive-index profile is the same (relative to the outside diameter) as in the finished fiber
    ◦ The core is doped with GeO$_2$ or P$_2$O$_5$ to increase the refractive index
    ◦ B$_2$O$_3$ and F can be used in the cladding to decrease the refractive index
• Methods for preparing the preform all use some form of vapor deposition
  - It is very difficult to purify silica adequately in a bulk melt
  - In the vapor-deposition methods, SiO$_2$ is obtained by reacting SiCl$_4$ with O$_2$ to produce a porous “soot” of silica
Drawing an Optical Fiber
Methods for fabricating a preform (1 of 3)

• Modified chemical vapor deposition (MCVD)
  - The cladding and core are deposited on the inside of a fused silica tube
  - The refractive-index profile is controlled by adding various dopants as deposition progresses
  - At the end, the tube is heated and collapses into a solid rod
• Outside vapor deposition (OVD)
  - The layers of the preform are deposited on the outside of a rotating mandrel using flame hydrolysis
  - The mandrel’s thermal expansion coefficient is larger than that of the preform, so the mandrel drops out after cooling
  - This process produces a central dip in the refractive index
Methods for fabricating a preform (2 of 3)

MCVD process for fabricating a preform
Methods for fabricating a preform (3 of 3)

- Vapor axial deposition (VAD)
  - Deposition occurs on the end of a rotating rod
Coating and Cabling

• Coating
  - Deposited immediately after the fiber is pulled
  - Purpose: Protection from abrasion
  - Surface flaws cause cracks to form
    ◦ Protection from H$_2$O
  - Exposure to H$_2$O would promote growth of crystallites $\rightarrow$ fracture

• Cable
  - Jacket contains one to many fiber bundles, each inside a buffer tube
  - Purposes:
    ◦ Mechanical strength
    ◦ Protection from H$_2$O and other environmental chemicals
    ◦ Prevention of micro bending losses
Properties of Fibers for Communications (1 of 2)

• Numerical aperture
  - Useful only for multimode fibers and incoherent sources (e.g. LEDs)
• Attenuation
  - Imperfect light coupling into the fiber
  - Absorption
  - Scattering
• Dispersion
  - Modal Dispersion: different modes propagate at different group velocities; Meaningful only for multimode fibers
  - Chromatic Dispersion
• Group-velocity dispersion
  - Important only for single-mode fibers
Properties of Fibers for Communications (2 of 2)

• **Birefringence**  (Or **Double refraction**, is the decomposition of a ray of light into two rays (the **ordinary ray** and the **extraordinary ray**) when it passes through certain types of material, depending on the polarization of the light. This effect can occur only if the structure of the material is **anisotropic** (directionally dependent). If the material has a single axis of anisotropy or optical axis, (i.e. it is **uniaxial**) birefringence can be formalized by assigning two different refractive indices to the material.

(See the double refraction in Calcite)

- Polarization-maintaining fiber
- Polarization-mode dispersion in non-polarization-maintaining fiber

• **Fiber Non-linearities**
  - Stimulated Raman Scattering (SRS)
  - Stimulated Brillouin Scattering (SBS)
  - Self phase modulation (SPM)
  - Polarisation mode dispersion (PMD)
  - Cross phase modulation (XPM)
  - Four wave mixing
Numerical Aperture (1 of 2)

- It is defined as

\[ NA = \sin(\theta_m) = \sqrt{n_1^2 - n_2^2} \equiv n_1 \sqrt{2\Delta}, \quad \Delta = \frac{n_1 - n_2}{n_1} \]

where \( \theta_m \) is the system’s maximum acceptance half-angle and \( n \) is the refractive index of the outside material.
Numerical Aperture (2 of 2)

• If \( n = 1 \), then \( 0 \leq NA \leq 1 \)
  - 0 means that no light gets into the system
  - 1 means that all of the light propagating towards the system gets in
  - Power into system \( \propto (NA)^2 \)
• Typically, \( NA = 0.15 \) for single mode fiber and \( 0.3 \) for MMF
Attenuation (1 of 3)

• Basic formula:

\[
\frac{\text{Power received at a distance } L \text{ from the transmitter}}{\text{Power transmitted}} = e^{\alpha L}
\]

- \(\alpha\) is the *attenuation coefficient* (units are \(\text{cm}^{-1}\) or \(\text{m}^{-1}\))
- Loss in dB = \(10(\log_{10} e)\alpha L \approx 4.343 \alpha L\)
- Practical units of the attenuation coefficient are dB/km or dB/m
• Origins of attenuation in silica fibers in the 1.2 - 1.6 \(\mu\text{m}\) region
  - Absorption
    - Mostly due to residual water in silica fiber
    - 1st overtone of stretching mode of \(\text{H}_2\text{O}\) is at 1.4 \(\mu\text{m}\), 2nd at 0.945 \(\mu\text{m}\)
    - Because H may occur at the end of a O-Si-O chain, an H-O vibration can be coupled to an Si-O vibration (as at 1.24 \(\mu\text{m}\))
Attenuation (2 of 3)

- Rayleigh scattering (same basic mechanism as makes the sky blue)
  - caused by small variations in the density of glass as it cools
  - Causes a change in direction which usually causes light to escape from the core
  - Attenuation coefficient: $\alpha_R = C\lambda^{-4}$ where $C \approx 0.7–0.9$ (dB/km)(μm)$^{-4}$
  - Important for $\lambda < 1.2\mu$m
Attenuation (3 of 3)

- Attenuation of light in silica fiber in the near-infrared region:
  \( \nu_1 \): O–Si–O bending mode, \( \nu_3^1 \): O–H stretching mode
Bending Loss (1 of 2)
**Bending Loss (2 of 2)**

![Bending Loss Graph](image)

**Bend loss versus bend radius**
Dispersion (1 of 2)

- Dispersion is the property that the velocity of light depends on the optical frequency or the mode of propagation in a waveguide.
- Dispersion causes the duration and shape of an optical pulse to change in the course of propagation, causing bit errors in reception.
- Causes of dispersion:
  - Material dispersion: Frequency dependence of the refractive index.
  - Waveguide dispersion: Frequency dependence of the propagation constant in a fiber mode.
  - Intermodal dispersion: Different fiber modes have different propagation constants at the same frequency, making pulses launched simultaneously in different modes arrive at the receiver at different times.
Dispersion (2 of 2)

- Group-velocity dispersion: A single pulse in a single fiber mode contains a range of frequencies, each of which propagates at a different velocity
Intermodal dispersion in multimode fibers (1 of 5)

- Different modes of propagation in a waveguide correspond to different E and H field patterns
  - For a fiber with a sufficiently small core radius, there is only one propagating mode
- Different modes propagate at different speeds because some modes take a longer path through a fiber than others
- Also called multipath dispersion
- The differential mode delay for step-index fiber

\[ \frac{L_1}{v_c} - \frac{L_2}{v_c} \]  

(Units: μs, ns or ps)

is the difference in arrival times of two pulses launched into different modes
  - \( v_c \approx \frac{c}{n_{core}} \) is the propagation velocity of a monochromatic wave in the core of the fiber
Intermodal dispersion in multimode fibers (2 of 5)

- Differential mode delay is important for LAN technologies
- \( l = s / \sin \theta_c \) where \( \theta_c \) = critical angle and \( \sin \theta_c = n_{\text{clad}} / n_{\text{core}} \)
- For a fiber of length \( L \), the difference in arrival times of a pulse that travels along an axial ray and one that travels along a meridional ray at the critical angle is

\[
\Delta t = \frac{n_{\text{core}} L}{c} \left( 1 - \frac{1}{\sin \theta_c} \right)
\]

\[
= \left( \frac{n_{\text{core}} L}{c} \right) \left( \frac{n_{\text{core}}}{n_{\text{clad}}} \right) \Delta
\]

where \( \Delta = \frac{n_{\text{core}} - n_{\text{clad}}}{n_{\text{core}}} \)
Intermodal dispersion in multimode fibers (3 of 5)

- Numerical value for clad, weakly guiding fiber ($n_{\text{core}} \approx n_{\text{clad}} \approx 1.5$ and $\Delta \approx 3 \times 10^{-3}$)
  \[ \Delta t/L \approx 15 \text{ns/km} \]
- Requirement for minimal inter symbol interference:
  \[ B\Delta t < 1 \quad \text{where } B = \text{bit rate} \]
- Maximum length bit-rate product for weakly guiding step-index fiber:
  \[ BL < \frac{n_{\text{clad}}}{n_{\text{core}}} \frac{c}{\Delta} \]
- Numerical values for weakly guiding fiber, for which $n_{\text{core}} \approx n_{\text{clad}} \approx 1.5$:
  - Step-index multimode ($\Delta \approx 3 \times 10^{-3}$): $BL < 67 \text{ Mb-km/s (MHz-km)}$
Intermodal dispersion in multimode fibers (4 of 5)

• Unclad multimode ($\Delta \approx 0.33$): $BL < 0.4$ Mb-km/s (MHz-km)
  - Because $90^\circ - \theta_{c,\text{unclad}} >> 90^\circ - \theta_{c,\text{clad}}$ the path difference per km of fiber between an axial ray and a ray that bounces back and forth at the critical angle is much greater for unclad fiber than for clad, weakly guiding fiber

• Graded-index multimode fiber can have higher values of $BL$ than step-index multimode fiber
  - The $\alpha$-profile used to model graded-index fiber is
  
  \[
  n(\rho) = \begin{cases} 
  n_1 \left[1 - \Delta \left(\rho / a\right)^\alpha\right], & \text{if } \rho \leq a \\
  n_2, & \text{if } \rho > a 
  \end{cases}
  \]

  where $a =$ core radius and $\Delta = (n_1 - n_2)/n_1$
Intermodal dispersion in multimode fibers (5 of 5)

- The value $\alpha = 2$ produces zero intermodal dispersion in the paraxial approximation of geometrical optics
  
  ° The actual bit-rate limit that can be achieved with $\alpha = 2$ is
  
  \[ BL < \frac{8c}{n_1 \Delta^2} \]
  
  ° The graded-index core acts like a distributed lens, approximately equalizing the optical path lengths traveled by different rays
Group Velocity Dispersion (1 of 2)

- Group-velocity dispersion in a single fiber mode
  - The phase velocity of a wave, \( v_p = \frac{\omega}{\beta} \), is the velocity at which a monochromatic wave travels
  - The group velocity, \( v_g = \frac{d\omega}{d\beta} \), is the velocity of a pulse
    - A pulse is a superposition of many frequencies, by Fourier analysis
      - If \( \omega \) is not a linear function of \( \beta \), then \( v_g \neq v_p \)
  - The differential group delay, \( d(L/v_g) \), is the difference in arrival times of two pulses centered at different wavelengths
    - Chromatic dispersion:
      \[
      D = \frac{d\left(\frac{1}{v_g}\right)}{d\lambda} \quad \text{(units: ps per nm-km)}
      \]
Group Velocity Dispersion (2 of 2)

- The high-wavelength and low-wavelength parts of a single pulse

\[
\frac{1}{L} \frac{d \left( \frac{L}{v_g} \right)}{d\lambda} = DGD
\]

per unit distance, per unit wavelength difference
Group Velocity Dispersion in Single Mode Fiber (1 of 4)

• Difference in arrival times of waves at wavelengths $\lambda$ and $\lambda + \Delta \lambda$:

$$\Delta t = L \frac{d}{d\lambda} \left( \frac{1}{v_g} \right) \Delta \lambda = LD \Delta \lambda$$

$$D = D_M + D_W$$

- Material dispersion: $D_M = \frac{1}{c} \frac{dn_{2g}}{d\lambda} = -\frac{2\pi}{\lambda^2} \frac{dn_{2g}}{d\omega}$

- Waveguide dispersion:

$$D_W = -\frac{2\pi\Delta}{\lambda^2} \left[ \frac{n_{2g}^2}{n_2 \omega} - V \frac{d^2 (Vb)}{dV^2} + \frac{dn_{2g}}{d\omega} \frac{d(Vb)}{dV} \right]$$
Group Velocity Dispersion in Single Mode Fiber (2 of 4)

- Requirement for minimal inter symbol interference:

\[ B \Delta t < 1 \Rightarrow BL|D|\Delta \lambda < 1 \]
Nonlinear Optics

• Comprises some of the most striking effects in physics
  - Light of a single color enters a transparent substance
  - Different colors emerge on the other side
• Examples:
  - Second harmonic generation: $\omega_{\text{in}}$, $2\omega_{\text{out}}$
  - Stimulated Raman scattering: $\omega_{L_{\text{in}}}$, $\omega_{S} = \omega_{L} - \omega_{v_{\text{out}}}$
  - Stimulated Brillouin scattering: $\omega_{L_{\text{in}}}$, $\omega_{B} = \omega_{L} - \omega_{a_{\text{out}}}$
Nonlinear Optical Effects in Fibers (1 of 2)

• When an optical electric field is stronger than about $10^{-5}$ to $10^{-6}$ of a typical electric field inside an atom ($\sim 10^{11}$ V/m), there are small but measurable departures of the linear relation between electric field and induced dipole moment per unit volume, even in “ordinary” materials such as silica glass.

• Single-mode fibers in long-haul telecommunication systems have all the right conditions for producing nonlinear optical effects:
  - High power/unit area in the core $\rightarrow$ high optical electric field
  - Long propagation distance at high power/unit area
Nonlinear Optical Effects in Fibers (2 of 2)

- Important nonlinear effects for optical communications include:
  - Changes in the refractive index which are proportional to optical power
    - Self-phase modulation broadens the signal spectrum
    - Dispersion then increases the pulse duration and bit error rate
  - Four-wave mixing: The optical analog of intermodulation distortion
  - Optical gain, pumped by optical power
Questions
Group Velocity Dispersion in Single Mode Fiber (3 of 4)

- Wavelength spread $\Delta \lambda$ for a pulse
  
  $$ \frac{|\Delta \lambda|}{\lambda} = \frac{|\Delta v|}{v} \Rightarrow |\Delta \lambda| = \frac{\lambda^2}{v} |\Delta v| $$

  - The Fourier integral theorem (applied to a Gaussian waveform) says that: $|\Delta v| \cdot |\Delta t| \approx 1$.
  
  Then, for a bandwidth-limited pulse, $|\Delta v| \approx B$

  - For a non-bandwidth-limited pulse,
    
    $$ |\Delta v| > B \Rightarrow |\Delta \lambda| > B \frac{\lambda^2}{v} $$

- Requirement for minimal inter symbol interference:
  
  $$ BL < \frac{1}{|D||\Delta \lambda|} < \frac{v}{B |D| \lambda^2} \Rightarrow B^2 L < \frac{v}{|D| \lambda^2} $$
Group Velocity Dispersion in Single Mode Fiber (4 of 4)

• Which criterion should one use to determine the maximum bit rate $B$ that an optical channel can carry,

$$BL < \frac{1}{D|\Delta\lambda|} \quad \text{or} \quad B^2L < \frac{v}{D|\lambda^2|}$$

- The first criterion (on $BL$) should be applied when the source is a broadband laser or an LED.
- The second criterion (on $B^2L$) should be applied when the laser source is narrowband, and the signal is created by externally modulating the laser light (using on-off keying).
  ◦ The frequency width of a pulse may change as the pulse propagates, as a result of self-phase modulation