Modes in Optical Fibers
Savera Tanwir

CSC-430 Fiber Optic Communication Systems

Topics

➢ Mode Theory
➢ Modes in planar waveguides
➢ Mode Condition
➢ TE and TM modes
➢ Single and Multi-mode Fibers
➢ Multimode Distortion
  – SI, GRIN and single mode fibers
Mode Theory

- The mode theory, along with the ray theory, is used to describe the propagation of light along an optical fiber.
- The mode theory uses electromagnetic wave behavior to describe the propagation of light along a fiber.

Modes in planar waveguide

- The optical wave is effectively confined within the guide and the electric field distribution in the x direction does not change as the wave propagates in z direction.
- The stable field distribution in the x direction with only a periodic z dependence is known as a mode.
- A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface has a particular value.
- Hence, the light propagating within the guide is formed into discrete modes, each typified by a distinct value of $\theta$. 
$\beta$ is the Longitudinal propagation factor $= n_1 k$
Mode Condition

- The component of plane wave in the x-direction is reflected at the interface between the higher and lower refractive index media.
- The component of wave in x-direction gives constructive interference to form standing wave patterns across the guide when the following condition is met
  \[ \Delta \Phi = m \cdot 2\pi \text{, where } m \text{ is an integer} \]
- The next slide shows examples of such rays for \( m = 1, 2, 3 \) together with the electric field distributions in the x direction.

Modes in a Planar Guide
TE and TM Modes

- Maxwell's equations describe electromagnetic waves or modes as having two components.
- The two components are the electric field, \( E(x, y, z) \), and the magnetic field, \( H(x, y, z) \). The electric field, \( E \), and the magnetic field, \( H \), are at right angles to each other.
- Modes traveling in an optical fiber are said to be transverse. The transverse modes propagate along the axis of the fiber.
- In TE modes, the electric field is perpendicular to the direction of propagation.
- In TM modes, the magnetic field is perpendicular to the direction of propagation. The electric field is in the direction of propagation.

TE Modes

![Diagram showing TE modes in a fiber optic cable](image)
High and Low order Modes

Multi-mode Fiber

- Multimode fiber is best designed for short transmission distances, and is suited for use in LAN systems and video surveillance.
- Modes result from the fact that light will only propagate in the fiber core at discrete angles within the cone of acceptance.
- Multi-mode fibers have large core diameters and they can support applications from 10 Mbit/s to 10 Gbit/s over link lengths of up to 550 meters, more than sufficient for the majority of premises applications.
Single Mode Fibers

- Fiber supporting only one mode is called single-mode or mono-mode fiber.
- Single-mode fiber allows for a higher capacity to transmit information because it can retain the fidelity of each light pulse over longer distances, and it exhibits no dispersion caused by multiple modes.
- The most common type of single-mode fiber has a core diameter of 8 to 10 µm. The smaller core diameter makes coupling light into the core more difficult.
- Data rates of up to 10 gigabits per second are possible at distances of over 60 km with commercially available transceivers.

Modal Dispersion

- Step Index Fiber
- Graded Index Fiber
- Singlemode Fiber
Distortion in SI Fibers

- Distortion is caused by material and waveguide dispersion and multi mode pulse spreading
- Multimode pulse spreading is given by the formula

\[ \frac{\Delta \tau}{L} = \frac{NA^2}{2cn_1} \]

- Find the pulse spread for glass fiber over 1 km with \( n_1 = 1.48 \) and \( n_2 = 1.46 \)?
- The measured value is 10 – 50 ns/km. Why?

Distortion in SI Fibers

- Reduction in pulse spreading
  - Mode mixing
    - Due to bends and scattering
  - Attenuation of higher ordered modes

- Total pulse spreading

\[ (\Delta \tau)^2 = (\Delta \tau)^2_{\text{mod}} + (\Delta \tau)^2_{\text{dis}} \]

- Which of the material dispersion or multimode spreading is greater?
  - We can reduce material and waveguide dispersion using a source with smaller line width like laser but since modal distortion is much greater, it is in effective and it will be cheaper to use an LED
Distortion in Single Mode Fibers

- Only material and waveguide dispersion
- Pulse Spread is smaller for longer wavelengths and narrower line widths. Why?
- Which source is preferable in this case??
- Can the sum of material and waveguide dispersion become zero?

Distortion in Graded-Index Fibers

- Much Less multi-mode distortion. Why?
- Typical pulse spread is just a few nano sec per km
- Modal Spread in GRIN Fiber
  \[ \Delta \tau / L = n_1 \Delta^2 / 2c \]
- Pulse spread decreases by a factor of \(2/\Delta\) by using GRIN instead of SI
- What is the pulse spread for GRIN fiber with \(n_1 = 1.48\) and \(n_2 = 1.46\)?
Length Dependence of Pulse Spread

- The pulse broadening does not occur linearly with fiber length.
- It is proportional to the square root of the length
- Why?

Mode Mixing

- Over shorter paths, the mixing is incomplete so the pulse broadening is linear
- After further travel an equilibrium modal power distribution is reached. After this $L^{1/2}$ dependency is observed
- This length is called equilibrium length

$$\Delta\tau = L\Delta\tau/L \quad \text{for } L \leq L_e$$
$$\Delta\tau = \sqrt{L_e\Delta\tau/L} \quad \text{for } L \geq L_e$$

- What happens in fiber with no mode mixing? And a lot of mode mixing?
- How can we find optical 3-dB bandwidth if modal distortion $\gg$ material and waveguide dispersion?