EE 443 Optical Fiber Communications
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Fall Semester

Lecture 6

http://www.wiretechworld.com/the-future-of-optical-fibres/
Pulse Spreading & Attenuation Caused by Dispersion

https://www.researchgate.net/figure/Pulse-Spread-and-Attenuation-due-to-Dispersion_fig1_277014078
Dispersion Mechanisms in Optical Fibers

MMF = Multi-Mode Fiber; SMF = Single Mode Fiber

https://www.intechopen.com/books/current-developments-in-optical-fiber-technology/multimode-graded-index-optical-fibers-for-next-generation-broadband-access
Chromatic Dispersion

Consists of material dispersion plus waveguide dispersion

Material Dispersion (Largest Contribution to Chromatic Dispersion)

Dispersion occurs when the phase velocity of a plane wave propagating in the medium varies nonlinearly with wavelength. In material dispersion when the second derivative of the refractive index is nonzero \((d^2n/d\lambda^2 \neq 0)\). Pulse spreading is estimated using the group delay (inverse of group velocity). We make use of

\[
v_{gr} = \frac{d\omega}{d\beta} \quad (2.37) \quad \text{and} \quad v_{gr} = \frac{c}{n_1 - \lambda \frac{dn_1}{d\lambda}} \quad (2.40)
\]

Then we can write for group delay.

\[
\tau_{gr} = \frac{d\beta}{d\omega} = \frac{1}{c} \left( n_1 - \lambda \frac{dn_1}{d\lambda} \right)
\]

where \(n_1\) is the index of refraction for the core of the fiber.

Ref. Section 3.9.1, pp. 110 to 111 in Senior
Material Dispersion (continued)

The pulse delay $\tau_m$ for fiber length $L$ is given by

$$\tau_m = \frac{L}{c} \left( n_1 - \lambda \frac{dn_1}{d\lambda} \right)$$

For a light source with rms spectral width $\sigma_\lambda$ and mean wavelength $\lambda$, the rms pulse broadening from the material dispersion is calculated by expanding the equation above in a Taylor’s series.

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \frac{\sigma_\lambda^2}{2} \frac{d^2\tau_m}{d\lambda^2} + \ldots$$

Generally the first term dominates, especially for wavelengths around 0.8 to 0.9 $\mu$m,

Therefore,

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda}$$
Material Dispersion (continued)

The pulse spread can be evaluated by considering the dependence of \( \tau_m \) upon \( \lambda \). Taking the derivative of  

\[
\frac{d\tau_m}{d\lambda} = \frac{L\lambda}{c} \left( \frac{dn_1}{d\lambda} - \lambda \frac{d^2n_1}{d\lambda^2} - \frac{dn_1}{d\lambda} \right) = -\frac{L\lambda}{c} \left( \frac{d^2n_1}{d\lambda^2} \right)
\]

Combining the last two equations gives the rms pulse broadening \( \sigma_m \) from material dispersion.

\[
\sigma_m = \left. \frac{\sigma_L L}{c} \right| \lambda \frac{d^2n_1}{d\lambda^2}
\]

The value generally given for material dispersion is a value for 
\[ \lambda^2 \frac{d^2n_1}{d\lambda^2} \] or \[ \frac{d^2n_1}{d\lambda^2} \]

The material dispersion coefficient is

\[
M = D_m = \frac{1}{L} \frac{d\tau_m}{d\lambda} = \frac{\lambda}{c} \left. \frac{d^2n_1}{d\lambda^2} \right|
\]

Senior (Section 3.9.1; pp. 110-111 of Senior) uses \( M \), but other references use \( D_m \) or \( D_\lambda \).
Material Dispersion (Conclusion)

The temporal width of an optical impulse of spectral width $\sigma_\lambda$ [nm], after traveling a distance $L$, is the response time (material dispersion):

$$\sigma_m = |D_m| \sigma_\lambda L$$

where $D_m = \frac{\lambda}{c} \left| \frac{d^2 n_1}{d\lambda^2} \right|$

**Interpretation:** A negative material dispersion coefficient $D_m$ means that long wavelengths travel faster than short wavelengths. And vice versa.
Chromatic Dispersion Characteristic

\[ \lambda = 1.312 \mu m \]

\[ \lambda = 0.87 \mu m; \quad D_m = -80 \text{ ps/nm-km} \]

\[ \lambda = 1.55 \mu m; \quad D_m = +17 \text{ ps/nm-km} \]

\[ \lambda = 1.31 \mu m; \quad D_m \approx 0 \text{ ps/nm-km} \]

Pulse Broadening From Material Dispersion

From the prior slide, at a wavelength $\lambda = 870$ nm the material dispersion coefficient $D_m = -80$ ps/(nm-km) for a silica glass optical fiber.

Assume we have an LED optical source with a linewidth $\sigma_\lambda$ of 50 nm. Note: All optical sources have a spectral linewidth by their nature. The pulse spreading rate in a single-mode fiber is given by

$$\text{pulse spreading rate} = |D_m| \sigma_\lambda$$

$$= \frac{80 \text{ps}\times50 \text{nm}}{\text{nm-km}} = 4 \text{ ns/km}$$

If the pulse traveling $L = 100$ km, then the time spreading width $\sigma_\tau$ is given by

$$\sigma_\tau = |D_m| \sigma_\lambda L = 0.4 \mu\text{sec}$$
Waveguide Dispersion

10% to 20% of light is in the cladding while 90% to 80% of light is in the core of the optical fiber cable when pulse is propagating down the fiber.

Waveguide Dispersion

Waveguide dispersion is the result of the field distribution of the traveling signal overlapping in both the core and cladding (it depends upon the ratio of the fiber’s core radius to the wavelength).

Waveguide dispersion is very important to single-mode optical fibers (where modal dispersion is essentially absent).

The pulse spreading width $\sigma_{WG}$ over the range of wavelengths can be found from the derivative of the group delay with respect to $\lambda$.

$$
\sigma_{WG} = \left| \frac{d\tau_{WG}}{d\lambda} \right| \sigma_{\lambda} = \left| D_{WG}(\lambda) \right| \sigma_{\lambda} L
$$

where

$$
D_{WG} = \frac{1}{2\pi c} \left[ V^2 \frac{d^2 \beta}{dV^2} \right]
$$

$D_{WG}$ is the waveguide dispersion coefficient. Note: 

$$
V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}
$$
Dispersion in Optical Fibers

When several different categories of dispersion are present in a fiber, then we add the dispersion coefficients of each source of dispersion, namely,

$$D_{\text{eff}} = \sum_{\text{all } k} D_k$$

And the spectral width is

$$\sigma_{\tau,\text{eff}} = \left| \sum_{\text{all } k} D_k(\lambda) \right| \sigma_{\lambda} L$$
Polarization Mode Dispersion (PMD)

PMD in single-mode optical fiber originates with non-circularity of the core (see next slide). Fiber birefringence has two components. Birefringence is a basic characteristic of all oval waveguide. Stress birefringence — it is generally dominant — is induced by the mechanical stress field set up when a fiber is drawn to other than a perfectly circular shape. Over short lengths, fiber birefringence splits the input pulse into linear slow and fast polarization modes, behaving like a linearly birefringent crystal. The corresponding difference in propagation time is called the differential group delay (DGD) and expressed in picoseconds. Together, the differential group delay and the orthogonal polarization modes are the fundamental manifestations of first-order PMD.

In practice, only relatively short, straight, undisturbed lengths of transmission fiber behave as simple, uniform birefringences.

https://www.photonics.com/Articles/Polarization_Mode_Dispersion_Concepts_and/a25153
Polarization Mode Dispersion (PMD)

Cross-section of optical fiber

Ideal → Practical

Cladding
Core

Fast axis
Slow axis

1st-order PMD

- Well defined, frequency independent eigenstates
- Deterministic, frequency independent Differential Group Delay (DGD)
- DGD scales linearity with fiber length

Δτ: Differential Group Delay (DGD)

https://slideplayer.com/slide/750009/
Polarization Mode Dispersion (PMD)

Vertically polarized (fast mode)

Horizontally polarized (Slow mode)

Oval Fiber

Delay difference

Distance L(km)

PMD is most important at higher data rates.

Keysight 86038B Photonic Dispersion and Loss Analyzer

Features:
- Full characterization of dispersion and loss, dependent on wavelength and polarization
- Determination of spectral GD, CD, DGD, PMD, IL, PDL and analysis for 2nd-order PMD, GD ripple, zero-dispersion wavelength and CD slope, and accurate determination of fiber or device length
- Fast swept-wavelength measurements for all parameters
- Widest available wavelength range with options covering 1260-1640nm and up to 200nm sweep range with a single option

Is that all there is to dispersion?
(or just when you thought it was safe to relax)

Answer: No
Mode Coupling (or Mode Mixing)

As an optical signal propagates down a fiber, pulse distortion increases less rapidly because of mode coupling.

Mode coupling occurs when energy from one mode couples to other modes. Thus, energy is transferred to these other modes. Mode coupling averages out the propagation delays associated with the modes – it reduces modal dispersion. However, there is an added penalty, attenuation losses increase from the shifting between modes.

Causes of mode coupling:
- Fiber structural imperfections and perturbations
- Fiber diameter variations
- Refractive index variations
- Microbending of fiber
- Fiber splices
- At connectors such as at passive optical component connections
Two Causes of Mode Coupling (or Mode Mixing)

Fiber core-to-cladding irregularity

Fiber microbending

From: Section 2.4.3 (Figure 2.20) on page 43 of Senior.
Let $h$ (dB/km) be the additional loss from mode coupling.

Let $L_c$ be the distance where mode coupling becomes significant.

Then for distances $L$ beyond $L_c$, pulse dispersion assumes a dependence.

$$\text{pulse dispersion time} \sim \sqrt{L \cdot L_c}$$

Loss $h$ must be determined by experiment.

From: Figure 3-21 (page 122) of Keiser, Optical Fiber Communications (3rd edition), McGraw-Hill.
Dispersion-Modified Single-Mode Fibers

As an optical fiber’s dispersion characteristic can be modified by tailoring the specific fiber’s parameters.

To do this the parameters that are available are

- Change the core diameter
- Modify the relative fractional index difference $\Delta$
- Modify the profile of the index of refraction (core & cladding)

The net slide illustrates three approaches in engineering dispersion properties of optical fibers.

Step-index single-mode fibers have lowest dispersion near 1300 nm, but have lower attenuation near 1550 nm. How do we deal with this?

\[
\Delta = \frac{n_2^2 - n_1^2}{2n_1^2} \quad (2.9)
\]
One Solution: Dispersion-Engineered Optical Fibers

For example:

Dispersion Shifting Index Profile

Dispersion Flattening Index Profile

Dispersion Compensating Index Profile
Dispersion Optimized Optical Fibers

There are two popular optimized fibers near 1300 nm. These are
(a) Matched cladding fiber
(b) Depressed cladding fiber

From: Figure 3-22 (page 124) of Keiser, Optical Fiber Communications (3rd edition), McGraw-Hill.
Dispersion Shifted Optical Fibers

The addition of material and wavelength dispersion can shift the zero dispersion point at longer wavelengths.

These are

(a) Step index dispersion shifted fiber, and
(b) Triangular dispersion shifter fiber

As shown above in index cross-section view.

From: Figure 3-22 (page 124) of Keiser, Optical Fiber Communications (3rd edition), McGraw-Hill.
Dispersion Shifted Optical Fibers (continued)

Material, Waveguide & Total Dispersion Characteristics

From: Section 3.12.1 (Figure 3.21) on page 134 of Senior.
Dispersion Flattened Optical Fibers

Dispersion flattening fibers are much more complex to design. However, they do offer a broader span of wavelengths for operation.

These are
(a) Step index dispersion shifted fiber, and
(b) Triangular dispersion shifter fiber
As shown above in index cross-section view.

From: Figure 3-22 (page 124) of Keiser, Optical Fiber Communications (3rd edition), McGraw-Hill.
Dispersion Flattened Optical Fibers (continued)

This figure gives the total resultant dispersion flattened characteristic.

From: Figure 3-24 (page 126) of Keiser, Optical Fiber Communications (3rd edition), McGraw-Hill.
Large Effective Area (LEA) Fiber Designs

The motivation for LEA fiber design is to reduce the effects of fiber non-linearities and the limitations they set in large networks. We have not yet discussed such fiber non-linearities, but they include nonlinear inelastic scattering processes (i.e., stimulated Raman scattering and stimulated Brillouin scattering).

From: Figure 3-22 (page 124) of Keiser, Optical Fiber Communications (3rd edition), McGraw-Hill.
**Spectral Linewidth for LED and Laser Sources \( \sigma_\lambda \)**

<table>
<thead>
<tr>
<th>Source</th>
<th>Linewidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEDs</td>
<td>20 nm to 100 nm</td>
</tr>
<tr>
<td>Semiconductor laser diodes</td>
<td>1 nm to 5 nm</td>
</tr>
<tr>
<td>Nd:YAG solid-state lasers</td>
<td>0.1 nm</td>
</tr>
<tr>
<td>NeHe gas laser</td>
<td>0.002 nm</td>
</tr>
<tr>
<td>Single Mode Laser</td>
<td>( 10^{-4} ) nm</td>
</tr>
</tbody>
</table>

For an LED if center frequency is 850 nm, then a 50 nm spectral spread is 6% linewidth.
LED Spectral Emission by Color LED

Multi-Mode Laser Spectrum

Polymeric or Plastic Optical Fibers (POF)

Plastic Optical Fibers are fabricated from organic polymers (both core & cladding) which have large diameter cores & cladding. They are much cheaper and easier to handle than silica fibers. Also, their transmission in the infrared (IR) region is poor and their loss mechanisms are similar to those of silica fibers.

Structure data:
- Core diameter: 125 to 1880 μm
- Cladding diameter: 1250 to 2000 μm
- Numerical, aperture: 0.3 to 0.6

Performance characteristics:
- Attenuation: 50 to 1000 dB/km at \( \lambda = 650 \text{ nm} \)
- Bandwidth: Up to 10 MHz-km
- Applications: Useful only for short-haul (such as “in-house”) low cost links. However, fiber coupling and termination are quite easy and do not require sophisticated techniques or skills.

From: Section 4.5.5 (Plastic optical fibers), page 191 to 194 of Senior.
Attenuation in PMMA Optical Fiber

Polymethyl Methacrylate

$n = 1.495$

In plastics, the major source of attenuation is due to overtones of C-H vibrations.

http://photonicswiki.org/index.php?title=Dispersion_and_Attenuation_Phenomena
Attenuation in PMMA and Polystyrene (PS) GI Optical Fiber

https://www.semanticscholar.org/paper/Low-Loss-and-High-Bandwidth-Polystyrene-Based-Index-Makino-Akimoto/db37d8c10360ca0e691321fc700fda7a325f0bd6
ZBLAN Glasses Give Superior Attenuation Performance

ZBLAN – Heavy Metal Fluoride Glasses

Heavy metal fluoride glasses were accidentally discovered in 1975 by Poulain and Lucas at the University of Rennes in France, including a family of glasses ZBLAN with a composition $\text{ZrF}_4\text{-BaF}_2\text{-LaF}_3\text{-AlF}_3\text{-NaF}$.

The advantages of ZBLAN over other glasses, such as silica, is superior infrared transmittance. Their drawbacks are fragility and sensitivity to acids.

$\text{ZrF}_4$, $\text{BaF}_2$, $\text{LaF}_3$, $\text{AlF}_3$ and $\text{NaF}$ is abbreviated as “ZBLAN.”

[Link to definition](http://acronymsandslang.com/definition/6139215/ZBLAN-meaning.htm)

[Further information](https://en.wikipedia.org/wiki/ZBLAN)
Submarine Optic Fiber Cable on Ocean Floor

Microsoft, Facebook, and the telecoms infrastructure company Telxius have completed the highest capacity subsea cable to ever cross the Atlantic Ocean. The cable is capable of transmitting 160 terabits of data per second, and 16 million times faster than an average home internet connection, Microsoft. The cable became operational in February 2018. Called Marea, the 4,100 mile long subsea cable lies 17,000 feet below the ocean surface and extends between Virginia Beach, Virginia and the city of Bilbao in Spain.

https://www.submarinenetworks.com/systems/trans-atlantic/marea
Submarine Optical Fiber Cable

Note: Environment is ocean salt water.

https://www2.telegeography.com/submarine-cable-faqs-frequently-asked-questions

http://seranggapeloncatpat.annauniv pw/ocean-floor-fiber-optic-cable
Operational Submarine Optical Fiber Cables

As of February 2019, there were 378 submarine cables totaling greater than 1.2 million kilometers.

Ship for Laying Submarine Optical Fiber Cable

https://www.wired.com/story/google-cramming-more-data-new-atlantic-cable/
https://www.venusclubs.co.nz/02/provide-your-clients-with-answers-before-they-ask-their-questions/

Next: Submarine cables