Outline

- Introduction - Review of WDM and TDM Issues
  - Light Property - The modes
- Dispersion
  - Modal Dispersion
  - Chromatic Dispersion
- Polarization
  - State of Polarization - Principal States of Polarization
  - Polarization Mode Dispersion
    - First Order PMD
    - Second Order PMD
  - Measurement and Uncertainty
  - Standards Issues
  - Examples of Test Results and Issues

Data and Transport Capacity Evolution

- More Bandwidth Means
  - Increasing the Channel Bit Rate
  - Increasing the Number of Channels

Light Property

- Electromagnetic wave composed of
  - Electric Field Vector E
  - Magnetic Field Vector H
- Both 90° out of phase to each other and orthogonal
- Propagating in time with optical frequency ω and in space with propagation constant k in the z direction
- Oscillating in the x-z and y-z planes

TDM Limitations at 10 Gbit/s and higher

- Expensive electronic components
- Transmitter chirp (change of frequency inside its bandwidth)
- Chromatic Dispersion effect is 16 times greater at 10 Gb/s than at 2.5 Gb/s
- PMD increase BER
Waveguiding in Optical Fiber

Snell's Law

Total Internal Reflection Condition:

\[ n_1 > n_2 \]

\[ \theta > \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \]

Note: Strictly true only for multimode fiber

Conventional Single-Mode Fiber Loss

<table>
<thead>
<tr>
<th>Wavelength (µm)</th>
<th>OH Rayleigh Scattering</th>
<th>Lattice Vibrations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>1.4</td>
<td>1.0</td>
<td>1.4</td>
</tr>
<tr>
<td>1.6</td>
<td>1.0</td>
<td>1.6</td>
</tr>
<tr>
<td>1.8</td>
<td>1.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Light Property

- For a system, such as in an optical fiber, where
  - a refractive index \( n_1 \) exists over the fiber core radius "a"; and
  - a refractive index \( n_2 < n_1 \) exists in the cladding

**Guided modes (HE11 or LP01, LP11, ...) if**

\[ (2\pi/\lambda)n_2 < \beta \leq (2\pi/\lambda)n_1 \]

Light Properties - Propagation Conditions

- Solving the Maxwell equations:
  - \( E_{xy}, H_x, \) and \( H_z = \text{Transverse Electric TE modes} \)
  - \( H_{zx}, E_{xy}, \) and \( E_z = \text{Transverse Magnetic TM modes} \)

- Sinusoidal variation along x,y axis if
  - \( (2\pi/\lambda)n_1 > \beta \)

Oscillating field, in the core

Light Properties vs. Index

- Mode propagation vs. index profile
  - Multimode Fiber
  - Step Index
Light Properties vs. Index
- Mode propagation vs. index profile
  - Singlemode dispersion unshifted fiber G.652
  - Depressed Clad is more bending resistant

Light Properties - Modes
- Number of guided modes:
  - Multimode Fibers
    - Step index:
      \[ N = \Delta \left( \frac{2\pi a}{\lambda} \right)^2 \]
      \[ \Delta = \frac{(n_1 - n_2)}{n_1} \] and \( a \) = core radius
      Typically \( \Delta = 0.5\% \), \( n_1 = 1.46 \), \( a = 25-50 \mu m \), \( \lambda = 0.85-1.3 \mu m \)
    - Graded index: \( N = 1/4 \) of \( N_{\text{step}} \)
  - Singlemode Fibers:
    \[ N = 1 \text{ when } a/\lambda < 0.27/(n_1\Delta^{1/2}) \]

Dispersion
Interaction of Light Properties with Material Properties
- Three Kinds
  - Multimode Dispersion or Modal Dispersion
  - Chromatic Dispersion
  - Birefringence Dispersion or PMD

Dispersion Effects
- **Single-channel effects**: (All Bad)
  - Distorts pulses
  - Interacts with single-ch nonlinear TX effects
- **Multiple channel effects (WDM)**: (All Good)
  - Data in adjacent channels "walk-off"
  - Inhibits crosstalk effects between channels
  - So can use smaller channel spacing,
  - And higher per-channel power

Multimode Dispersion
- In step index MM fiber, the numerical aperture \( \theta \) and the number of modes \( N \) make the modes travelling different paths and arriving at different times

Multimode Dispersion
- A pulse transmitted in such medium suffers a broadening, a dispersion, limiting the signal transmission bandwidth
  - In step index fiber, limited modal BW = 20-40 MHz
  - In graded index fiber, limited modal BW = 400-600 MHz
Chromatic Dispersion

- The speed of light in optical fiber is slightly wavelength dependent.
- Optical channels carrying data signals have finite bandwidth.
- Therefore, the spectral components of a signal are delayed in the fiber,
- This results in pulse shape distortion.
- This “DISPERSION” can be “compensated” or “managed”.

The Speed of Light in Fiber

\[ v(\lambda) = \frac{c_o}{n(\lambda)} = \frac{c_o}{n_0(\lambda_0)} + n(\lambda_0) \Delta \lambda + n(\lambda_0) \Delta \lambda^2 \]

Units of Dispersion:
\[ D = 17 \text{ ps/(nm km)} \] at 1550nm in SMF

- After travelling \( L = 1 \text{ km} \),
- Signals separated by \( \Delta \lambda = 1 \text{ nm} \) are delayed by \( \Delta \tau = 17 \text{ ps} \) (3 mm)

Dispersion translates \( \Delta \) wavelength into time delay

Chromatic Dispersion

- Any light source has a finite spectral power distribution
- The source wavelengths are not propagating with the same velocity (group velocity) as they see different material and index structure and are arriving at different times

Dispersion

A pulse transmitted in such medium suffers a broadening, a dispersion, limiting the signal transmission bandwidth
- In SM fiber, limited Chromatic Dispersion
  - \( D = 0.1 \text{ ps/mm-km} \) to 10 ps/mm-km

Dispersion

Pulse spreading can be minimized by operating at the fiber’s zero dispersion wavelength (linear regime)
- However non-linear effects arising from EDFAs can affect the performance (non-linear regime)
Chromatic Dispersion

Effect of Dispersion Slope

Long and Short λ, Channels Experience Different Average Dispersion

Dispersion Causes Channel “Walk-off”...
A good thing.

Blue pulse passes through the red pulse

\[ L = \frac{T}{2 \Delta \lambda} = \frac{200 \text{ps}}{0.8 \text{nm} \cdot D} \]

10 Gb/s NRZ in SMF: Eye Diagrams

Evolution of Fiber Types

But for single ch. @1550nm, \( D = 17 \text{ ps/nm/km} \)

2) So let’s get rid of dispersion completely!

\( \rightarrow \) Dispersion Shifted Fiber (DSF) \( D = 0 \text{ ps/nm/km} @1550\text{nm} \)

3) But for multi-channel WDM @1550nm:

Four Wave Mixing! Better add a little dispersion.

\( \rightarrow \) Non-Zero DSF (NZDSF) “classic” \( D = 2 \text{ ps/nm/km} \)

4) Higher data rates = higher power, more FWM so try:

Add some more dispersion, larger core area, reduced slope:

\( \rightarrow \) Premium NZDSF (TW-DS, LEAF etc.) \( D = 4 \text{ ps/nm/km} \)

5) If more dispersion is good, let’s add some more...

\( \rightarrow \) Alcatel TeraLight \( D = 8 \text{ ps/nm/km} \)

6) Since we have DCF now, maybe...

Back to conventional SMF.
Dispersion Compensation Devices

- In the field today:
  - Dispersion Compensating Fiber
- In the systems lab:
  - Dispersion Slope Compensating Fiber
  - Chirped Fiber Bragg Gratings
- In the research labs:
  - Higher order Fiber Mode Devices
  - Virtually Imaged Phased Array

The Ideal Dispersion Compensator

- Large Negative Dispersion:
  - Wavelength-dependent delay
- Dispersion/Slope Ratio matched to your fiber
- Wide Optical Bandwidth
- Minimize:
  - Loss
  - Nonlinear Effects
  - Variation (ripple) in \(\lambda\)-dependent Delay
  - Polarization Dependence
- Small, Cheap

Dispersion Compensating Fiber (DCF)

- \(-65\) ps/nm\(\cdot\)km Dispersion (5 x SMF)
  - 16km to compensate 80km SMF
- \(-0.28\) ps/nm\(\cdot\)km Dispersion Slope (Lucent)
  - Can match SMF dispersion/slope ratio
- Wide optical bandwidth
- However,
  - Complicated layer structure
  - High loss (10dB for 16km DCF)
  - Small effective core area
    - \(\rightarrow\) high nonlinearity
  - Increased bending loss

DISPERSION COMPENSATING FIBER

- Dispersion is nearly constant across a band
- Any dispersion amount possible by changing fiber length
- Commercially available, field proven and passive
- Corrects to the center wavelength, causing long wavelengths to be overcompensated and short wavelengths to be undercompensated
- Not tunable, fixed dispersion only
- To achieve the negative dispersion, use a small effective area for fiber core. This introduces noise, the higher powers in the core causing more non-linear effects.
- DCF has a high loss (0.6 dB/km)

A Simple Dispersion Map:

10Gb/s over 5 Spans of 80km SMF

The Bottom Line on Dispersion

- Dispersion slope compensation will be required for 40 Gb/s transmission
- In addition, per channel dispersion compensation will probably also be necessary
- Tunable dispersion compensation becomes critical:
  - For per-band DC, to reduce the number of codes for different span lengths and fiber types
  - For per-channel DC, to reduce the number of codes
- Adaptive dispersion compensation may be necessary for 40 Gb/s as well
  - Temperature changes in the fiber plant can cause the dispersion to move outside the tight limit
Polarization

Is a property of light being affected by the cabled fiber and other system component (MUX/DeMUX, EDFA, OADM, OXC, Router, etc.)

State of Polarization (SOP) Linear Vertical

State of Polarization (SOP) Linear Horizontal

State of Polarization (SOP) Linear +/- 45°

State of Polarization (SOP) Circular LH, RH

Dispersion

Polarization Mode Dispersion (PMD)
The Phenomenon

- Interaction between light and material properties
- Polarization vs. Birefringence
- Different polarization states
  - travel at different velocities
  - have different arrival time (Differential Group Delay)
  - cause pulse broadening
- PMD can also be called Birefringence Dispersion
Polarization Mode Dispersion (PMD)

The Effects
- Digital transmissions
  - BER increase and bandwidth limitation
- Analog transmissions:
  - Distortion (CSO) and channel number limitation

The Causes
- Asymmetries in fiber core geometry and/or stress distribution create fiber local birefringence affecting polarization
- A "real" fiber is a randomly distributed addition of these local birefringent portions

Polarization Mode Coupling

Negligible Coupling Random Coupling

<table>
<thead>
<tr>
<th>Definition</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low level of energy exchange</td>
<td>High level of energy exchange</td>
</tr>
<tr>
<td>between the PSPs</td>
<td>between the PSPs</td>
</tr>
<tr>
<td>PMD = DGD = constant</td>
<td>PMD = mean value of variation of DGD as a function of wavelengths</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Phenomenon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deterministic for components</td>
<td>Stochastic for long fibers,</td>
</tr>
<tr>
<td>and short fibers</td>
<td>Unstable</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Units</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>pm/km for short fibers</td>
<td>ps/km for long fibers</td>
</tr>
<tr>
<td>ps for components</td>
<td>ps/km for long fibers</td>
</tr>
</tbody>
</table>

Example: Isolators (<2 ps), couplers (<0.02 ps) PMF (hibi) fibers, connectors (<0.01 ps)

Second Order PMD

Birefringence
  ⇒ Spatial change of index of refraction
  ⇒ \( \lambda \), Dependent

PMD is also \( \lambda \), dependent ⇒ 2nd order PMD

2nd order PMD ⇒ rate of change of DGD vs \( \lambda \)
  ⇒ change of direction of PSPs

2nd order PMD ⇒ units = chromatic dispersion
Second order PMD coefficient

2\textsuperscript{nd} order PMD coefficient : ps / (nm.km)

1\textsuperscript{st} order PMD coefficient = 0.5 ps/km

2\textsuperscript{nd} order PMD coefficient ≅ 0.15 ps/(nm.km)

Proposed standard specifications ⇒ 2\textsuperscript{nd} order PMD coefficient ≤ 0.2 ps/nm.km

Why Measuring PMD?

- PMD is created during fiber manufacturing
- PMD is affected during cable manufacturing
- PMD is affected during cable installation (field)
- PMD is affected by the environment (field)

It is essential to measure PMD at every stage of the fiber life

PMD Measurement Characteristics

- Ability to measure pulse broadening at the receiver end (in the time domain).
- Ability to determine the variation of the DGD as a function of wavelengths (in the frequency/wavelength domain).
- PMD is the mean value of the DGDs
  - fixed/constant for components and short fibers,
  - statistical in nature for long fibers
    averaging procedure
- \( \text{PMD}_{\text{TOT}} = \sqrt{\sum_{n} (\text{PMD}_n)^2} \)

Variation of the DGD as a Function of wavelength

PMD Issues

- Increases with increase of:
  - Channel Bit Rate
  - Number of Spans
  - Launched Power (indirectly - only if results in longer span length - also ignoring impact of nonlinear PMD)
  - Channel Count (more channels increases the chance that any one channel is unavailable)
- Not significantly influenced by increase of:
  - Channel Spacing
- Decreases with:
  - Better Control over Fiber Geometry, or Increased Mode Coupling
  - The Use of Dispersion Compensation has an unclear impact on PMD
- More an issue for old G.652 Fibers than for newer G.652, G.653 and G.655 Fibers in WDM (but watch out for the environment)

Methods for dealing with high PMD fibers

- AM Analog systems:
  - use low chirp lasers
  - choose sub-carrier frequencies within one octave
  - transmit over shorter distances
  - transmit fewer video channels per wavelength
- Digital systems:
  - active optical and electronic compensation techniques have been demonstrated in the laboratory
  - use low chirp lasers
  - transmit over shorter distances
  - transmit at lower bit rates per wavelength
Proposed PMD Coefficient for a 99.994% probability that the power penalty will be less than 1 dB for 0.1 of the bit period

<table>
<thead>
<tr>
<th>Bit Rate (Gb/s)</th>
<th>Maximum PMD (ps)</th>
<th>PMD Coefficient 400km fiber (ps/km^{1/2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5</td>
<td>40</td>
<td>≤ 2.0</td>
</tr>
<tr>
<td>10</td>
<td>10</td>
<td>≤ 0.5</td>
</tr>
<tr>
<td>20</td>
<td>5</td>
<td>≤ 0.25</td>
</tr>
<tr>
<td>40</td>
<td>2.5</td>
<td>≤ 0.125</td>
</tr>
</tbody>
</table>

Among the oldest of 80 million km of fiber cables installed in the 80’s

\( \lambda = 1550 \text{ nm} \)

Cable length = 27.55 km

PMD = 108 ps

PMD Coefficient = 20.57 ps/ km^{1/2}