Polarization Mode Dispersion
Its meaning and impact on high data rate transmission

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Outline

• What is PMD?
• Fiber PMD Specification
• PMD Specification on a Transmission Link
• How to Mitigate PMD Penalty
What is PMD?

Single mode transmission actually consists of two orthogonal polarization states (or modes) traversing down the fiber (known as Principle State of Polarization, or PSP).

Delay between two orthogonal states of polarization is DGD.

DGD = Differential Group Delay
Causes of PMD

Birefringence
Polarized state (or “mode”) in axis A is different from that in axis B
Present because of asymmetry of fiber core

Stress
Lateral stress

Bend
Twist
Differential Group Delay (DGD) and PMD

DGD is not deterministic, and varies wildly with wavelengths and time.

PMD is RMS time average of DGD.

From experiments, statistical variation of DGD over wide wavelengths is a short time is equivalent to the statistical variation at a given wavelength over a long period of time.

\[ \text{RMS} (\text{DGD}) = \sqrt{\frac{3\pi}{8}} \times \langle \text{DGD} \rangle \]
DGD follows Maxwellian Distribution, so does PMD

PMD (in ps/\text{vkm})

DGD (in ps)
DGD of a Fiber Link is also Maxwellian

- Concatenated link DGD distribution is also Maxwellian
  - Characterized by \( \text{PMD}_{\text{Link}} \)
  - Related to individual PMD elements

\[
\text{PMD}_{\text{Link}} = \frac{1}{L_{\text{Link}}^{1/2}} \times \left[ \text{PMD}_1^2 L_1 + \text{PMD}_2^2 L_2 + \ldots + \text{PMD}_N^2 L_N \right]^{1/2}
\]
How is PMD of Optical Fiber Specified?

### Optical Specifications

<table>
<thead>
<tr>
<th>Fiber Attenuation</th>
<th>Cable Cutoff Wavelength ($\lambda_{ccf}$)</th>
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<tbody>
<tr>
<td>Maximum Attenuation</td>
<td>$\lambda_{ccf} \leq 1260$ nm</td>
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</table>

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Maximum Value* (dB/km)</th>
</tr>
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<tbody>
<tr>
<td>1310</td>
<td>0.33 – 0.35</td>
</tr>
<tr>
<td>1383 ± 3**</td>
<td></td>
</tr>
<tr>
<td>1490</td>
<td></td>
</tr>
<tr>
<td>1550</td>
<td></td>
</tr>
<tr>
<td>1625</td>
<td></td>
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</tbody>
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*Maximum specified attenuation value available
**Attenuation post-hydrogen aging according to Section C.5 for B.1.3 fibers.
Alternate attenuation offerings available through Corning.

### Mode-Field Diameter

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>MFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1285 – 1330</td>
<td></td>
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<tr>
<td>1310</td>
<td></td>
</tr>
<tr>
<td>13525 – 1375</td>
<td></td>
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<tr>
<td>1550</td>
<td></td>
</tr>
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</table>

### Attenuation vs. Wavelength

<table>
<thead>
<tr>
<th>Range (nm)</th>
<th>Ref, ( \lambda ) (nm)</th>
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<tbody>
<tr>
<td>1285 – 1330</td>
<td>1310</td>
</tr>
<tr>
<td>13525 – 1375</td>
<td>1550</td>
</tr>
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### Polarization Mode Dispersion (PMD)

- **PMD Link Design Value**: ≤0.06*
- **Maximum Individual Fiber**: ≤0.1


The PMD link design value is a term used to describe the PMD of concatenated lengths of fiber (also known as PMD$_Q$). This value represents a statistical upper limit for total link PMD. Individual PMD values may change when cabled.

Extract from Corning’s SMF-28e+ Fiber Specification Sheet
Maximum Individual Fiber PMD Specification: \( \text{PMD}_{\text{max}} \)

- This is the maximum PMD for individual fibers manufactured
  - 100% fiber have PMD values < \( \text{PMD}_{\text{max}} \)
Why using PMD_{max} for network design is overly conservative?

- Actual fiber PMD values hardly come close to PMD_{max} value
  - Actual PMD measured is always around the average RMS value

- PMD_{max} value is measured based on individual continuous length of fiber
  - In real life network, link is always made up of different segments of fiber spliced or jointed together
  - Thus, PMD of a link (PMD link value) is averaged down through multiple individual segments of fiber PMD

- PMD_{max} tells you nothing about the statistical distribution of the PMD values
  - Different fiber PMD distributions can give same PMD_{max} value
Good and Bad Fiber PMD Distributions can give same $PMD_{max}$

Good Fiber PMD Distribution

Bad Fiber PMD Distribution

Same $PMD_{max}$ value
Thus, PMD Link Design Value

Definition according to IEC 60794-3:2001 Section 5.5, Method 1

PMD Link Design Value ($\text{PMD}_Q$) is the PMD of a concatenated link of $M$ segments of 20km individual fibers (thus 400km reference link), based on a $Q\%$ upper confident statistical level

Normally $M = 20$ segment and $Q = 0.01\%$
M = 20 Segments, Q = 0.01%, PMD_Q

Define PMD_Q (Link Design Value) as an upper-bound so that less than 0.01% of Monte-Carlo distributions - using M random concatenated sections - exceed PMD > PMD_Q
PMD Link Design Value (PMD\textsubscript{Q}) Is A Better Estimate Of Concatenated Link PMD

- PMD\textsubscript{max} is an overly conservative estimate of the PMD of a link consisting of concatenated fibers
- Smaller PMD\textsubscript{Q} value corresponds to a tighter manufacturing distribution

PMD\textsubscript{Q} (99.99\% upper limit)
Properties of a Maxwellian Distribution

P(x) = \frac{\sqrt{2}}{\pi} \frac{x^2 e^{-x^2/(2a^2)}}{a^3}

P(DGD > DGD_{\text{max}}) = 4 \times 10^{-5}

"3" is the Maxwellian Adjustment Factor, can be up to 3.78 to adjust for other component’s PMD and probability.
PMD Tolerance for High Bit Rate Transmission

\( \text{DGD}_{\text{max}} \) should be less than 30% of the bit period of transmission (for equal mode splitting between two Principle States of Polarization PSPs)

\( \text{DGD}_{\text{ave}} \) is therefore specified as 10% of bit period

<table>
<thead>
<tr>
<th>Bit rate</th>
<th>Bit period</th>
<th>( \text{DGD}_{\text{ave}} ) allowed</th>
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<tbody>
<tr>
<td>2.5 Gbps</td>
<td>400 ps</td>
<td>40 ps</td>
</tr>
<tr>
<td>10 Gbps</td>
<td>100 ps</td>
<td>10 ps</td>
</tr>
<tr>
<td>40 Gbps</td>
<td>25 ps</td>
<td>2.5 ps</td>
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According to ITU FO211-98-01-TD12
### ITU-T G.652 A, B, C, D Specifications, major difference is in PMD specifications

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<tbody>
<tr>
<td>Attenuation @1310nm</td>
<td>0.4 dB/km</td>
<td>0.4 dB/km</td>
<td>0.4 dB/km</td>
<td>0.4 dB/km</td>
</tr>
<tr>
<td>Attenuation @1383nm</td>
<td>Not specified</td>
<td>Not specified</td>
<td>Less than attenuation at 1310nm</td>
<td>Less than attenuation at 1310nm</td>
</tr>
<tr>
<td>Attenuation @1550nm</td>
<td>0.3 dB/km</td>
<td>0.3 dB/km</td>
<td>0.3 dB/km</td>
<td>0.3 dB/km</td>
</tr>
<tr>
<td>Max PMD&lt;sub&gt;Q&lt;/sub&gt; (M=20, Q=0.01%)</td>
<td>0.5 ps/√km</td>
<td>0.2 ps/√km</td>
<td>0.5 ps/√km</td>
<td>0.2 ps/√km</td>
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