Fiber loss or attenuation is a limiting factor in transmission distance. Attenuation can be described by the general relationship
\[ \frac{dP}{dz} = -\alpha P \]
solving this differential equation gives
\[ P_{out} = P_{in} e^{-\alpha L} \]

The power budget is the difference between the transmission power and the minimum detectable power

Power budget is
\[ PB = \frac{P_{tx}}{P_{min}} \]

Example:
\[ P_{tx} = 10 \text{mw} \]
\[ P_{min} = 1 \text{mw} \]

\[ 10^{-6} = 10^{-2} e^{-\alpha L} \]

\[ \ln(10^{-8}) = -\alpha L \]

\[ L = \frac{\ln(10^{-8})}{-\alpha} \]

Rather than work with \( \ln \) and dividing it is faster to work with dB

\[ PB (\text{dB}) = 10 \log_{10} \left( \frac{P_{tx}}{P_{min}} \right) \]

For our example
\[ PB = 10 \log_{10} \left( \frac{10^{-6}}{10^{-2}} \right) = 80 \text{dB} \]

We need (1) Power in dB
(2) Attenuation in dB
(3) dB is a relative unit
To get power in dB we calculate it relative to 1mw and call it dBm

\[ P_{dBm} = 10 \log_{10} \left( \frac{P}{1 \text{mw}} \right) \]

10 mw = 10 \log_{10} (10) = 10 \text{dBm}
(2) To get attenuation in dB

\[ P_{\text{out}} = P_{\text{in}} e^{-\alpha L} \]

\[
10 \log_{10} (P_{\text{out}}) = 10 \log_{10} \left( P_{\text{in}} e^{-\alpha L} \right)
\]

\[
= 10 \log_{10} (P_{\text{in}}) + 10 \log_{10} e^{-\alpha L}
\]

\[
= 10 \log_{10} (P_{\text{in}}) + (10)(-\alpha L) \log_{10} e
\]

\[
= 10 \log_{10} (P_{\text{in}}) - \frac{10 \alpha \log_{10} e}{\alpha_{\text{dB}} L}
\]

\[ \alpha_{\text{dB}} = 4.34 \alpha \]

Examples

BYU liquid core ARROWS: \( \alpha = 0.3 \text{ cm}^{-1} \)

Metal coated micro-fluidic waveguides: \( 0.5 \text{ cm}^{-1} \)
Example: Minimum detectable power

\[ P_{\text{min}} = 0.1 \, \text{mW} \]

Laser power

\[ P_{\text{laser}} = 10 \, \text{mW} \]

Coupling loss at transmitter and receiver

\[ \alpha_{\text{coupling}} = 1 \, \text{dB each} \]

Splice required every 10 km

\[ \alpha_{\text{splice}} = 0.3 \, \text{dB each} \]

What is the maximum transmission length at \( \lambda = 1550 \, \text{nm} \)?

Look up transmission loss in spec.

\[ \alpha = 0.19 \, \text{dB/km} \]

\[ P_{\text{min}} (\text{dBm}) = 10 \log_{10} \left( \frac{0.1 \times 10^{-6}}{1 \times 10^{-3}} \right) = 40 \, \text{dBm} \]

\[ P_{\text{laser}} (\text{dBm}) = 10 \log_{10} \left( \frac{10}{1} \right) = 10 \, \text{dBm} \]

Power Budget = 10 - (-40) = 50 dB

\[ = P_{\text{coupling}} + P_{\text{splice}} + \alpha L \]

\[ 50 = (2)(1) + (0.3)N + 0.19 L \]
First assume $N=0$

$50 = 2 + 0.19L$

$L = \frac{48}{0.19} = 252.6 \text{ km}$

$L = \frac{L}{10} = 25.3 \text{ segments}$

$N = 26 - 1 = 25$

$L = 50 - 2 - (25)(3) + 0.19L$

$L = \frac{50 - 2 - (25)(3)}{0.19} = 213.2$

$L = 21.3$

Now $N = 22 - 1$

$L = 50 - 2 - (22)(3) = 219.5$

$L = 21.9 \text{ km}$

$N$ is still 21

So $L = 219.5 \text{ km}$

What about at other wavelengths?

<table>
<thead>
<tr>
<th>$\lambda$ (nm)</th>
<th>$\alpha$ (dB/km)</th>
<th>$L$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>1.8</td>
<td>26</td>
</tr>
<tr>
<td>1310</td>
<td>0.34</td>
<td>130</td>
</tr>
<tr>
<td>1383</td>
<td>0.50</td>
<td>90</td>
</tr>
<tr>
<td>1550</td>
<td>0.19</td>
<td>219</td>
</tr>
</tbody>
</table>
Environmental Specifications

<table>
<thead>
<tr>
<th>Environmental Test Condition</th>
<th>Induced Attenuation</th>
</tr>
</thead>
<tbody>
<tr>
<td>-60°C to +85°C C*</td>
<td>≤0.05 (dB/km)</td>
</tr>
</tbody>
</table>
| Temperature-Humidity Cycling| 10°C to +85°C C*,  
                             up to 98% RH        | ≤0.05                |
| Water Immersion, 23°C ± 2°C | ≤0.05                |
| Heat Aging, 85°C ± 2°C      | ≤0.05                |

*Reference temperature = +23°C

Operating Temperature Range
-60°C to +85°C

Dimensional Specifications

Length (km/reel): fiber lengths available up to 50.4*
* Longer spliced lengths available at a premium.

Glass Geometry

Fiber Curl: ≥ 4.0 m radius of curvature
Cladding Diameter: 125.0 ± 0.7 μm
Core-Clad Concentricity: ≤ 0.5 μm
Cladding Non-Circularity: ≤ 1.0%

Defined as: \[ \frac{1 - \text{Min. Cladding Diameter}}{\text{Max. Cladding Diameter}} \times 100 \]

Coating Geometry

Coating Diameter: 245 ± 5 μm
Coating-Cladding Concentricity: <12 μm

Mechanical Specifications

Proof Test
The entire fiber length is subjected to a tensile proof stress ≥ 100 kpsi (0.7 GN/m²)*.
* Higher proof test levels available at a premium.

Performance Characterizations

Characterized parameters are typical values.

Core Diameter: 8.2 μm

Numerical Aperture: 0.14
NA is measured at the one percent power level of a one-dimensional far-field scan at 1310 nm.

Zero Dispersion Wavelength (λ₀): 1313 nm

Zero Dispersion Slope (S₀): 0.086 ps/(nm²-km)

Refractive Index Difference: 0.36%

Effective Group Index of Refraction,
(Neff @ nominal MFD):
  1.4677 at 1310 nm
  1.4682 at 1550 nm

Fatigue Resistance Parameter (nₐ): 20

Coating Strip Force:
  Dry: 0.6 lbs. (3N)
  Wet, 14-day room temperature: 0.6 lbs. (3N)

Rayleigh Backscatter Coefficient
(for 1 ns pulse width):
  1310 nm: -77 dB
  1550 nm: -82 dB
Material Absorption

- Material absorption
  - Intrinsic: caused by atomic resonance of the fiber material
    - Ultra-violet
    - Infra-red: primary intrinsic absorption for optical communications
  - Extrinsic: caused by atomic absorptions of external particles in the fiber
    - Primarily caused by the O-H bond in water that has absorption peaks at $\lambda=2.8, 1.4, 0.93, 0.7 \, \mu m$
    - Interaction between O-H bond and SiO$_2$ glass at $\lambda=1.24 \, \mu m$
    - The most important absorption peaks are at $\lambda=1.4 \, \mu m$ and $1.24 \, \mu m$
Scattering Loss

- There are four primary kinds of scattering loss
  - Rayleigh scattering is the most important

\[ \alpha_r = c_R \frac{1}{\lambda^4} \quad (dB/km) \]

where \( c_R \) is the Rayleigh scattering coefficient and is the range from 0.8 to 1.0 \((dB/km)\cdot(\mu m)^4\)

- Mie scattering is caused by inhomogeneity in the surface of the waveguide
  - Mie scattering is typically very small in optical fibers

- Brillouin and Raman scattering depend on the intensity of the power in the optical fiber
  - Insignificant unless the power is greater than 100mW
Figure 4.4  Intrinsic attenuation in optical fibers.
Historical Progression of Attenuation vs Wavelength

Bhattacharya, (after Kaiser), Figure 1.19

- Early 1970s
- Mid 1970s
- Early 1980s

Attenuation (dB/km) vs Wavelength (nm)
External Losses

• Bending loss
  – Radiation loss at bends in the optical fiber
  – Insignificant unless \( R < 1 \text{mm} \)
  – Smaller curvature become significant if there are accumulated bending losses over a long distance

• Coupling and splicing loss
  – Misalignment of core centers
  – Tilt
  – Air gaps
  – End face reflections
  – Mode mismatches
Fig. 4.26 The three possible types of misalignment which may occur when jointing compatible optical fibers [Ref. 58]: (a) longitudinal misalignment; (b) lateral misalignment; (c) angular misalignment.