Optical Communications Systems

Attenuation in Optical Fibres

Attenuation limits the optical power which can reach the receiver, limiting the operating span of a system.

Attenuation has dropped from 20 dB/Km (1973) to 0.2 dB/Km (1993)

Units of attenuation are dB/Km

Simple formula relates received power $P_r$ and transmitted power $P_t$

$$P_r = P_t 10^{-AL}$$

A is attenuation in dB/km
L is fibre span in km

There are a number of major causes of attenuation in fibre:
- Absorption loss
- Scattering loss
- Bending loss

A receiver in an optical system requires a minimum optical input power to operate with a specified error probability.

Attenuation reduces the optical power available, degrading the error probability.

Most system specifications allow a maximum error probability of $1E-9$

Effect of attenuation

Types of Attenuation

Absorption Loss:
Caused by the fibre itself or by impurities in the fibre, such as water and metals.

Scattering Loss:
Intrinsic loss mechanism caused by the interaction of photons with the glass itself.

Bending loss:
Loss induced by physical stress on the fibre.
Material Absorption Losses

- Material absorption is caused by absorption of photons within the fibre.
  - When a material is illuminated, photons can make the valence electrons of an atom transition to higher energy levels
  - Photon is destroyed, and the radiant energy is transformed into electric potential energy. This energy can then
    - Be re-emitted (scattering)
    - Frees the electron (photoelectric effects) (not in fibers)
    - Dissipated to the rest of the material (transformed into heat)
- In an optical fibre Material Absorption is the optical power that is effectively converted to heat dissipation within the fibre.
- Two types of absorption exist:
  - Intrinsic Absorption, caused by interaction with one or more of the components of the glass
  - Extrinsic Absorption, caused by impurities within the glass

Intrinsic Absorption 1

Less significant than extrinsic absorption. For a pure (no impurities) silica fibre a low loss window exists between 800 nm and 1600 nm.

- Graph shows attenuation spectrum for pure silica glass.
- Intrinsic absorption is very low compared to other forms of loss
- It is for this reason that fibres are silica and optical communications systems work between about 800 to 1600 nm.

Intrinsic Absorption 2

- Intrinsic absorption in the ultraviolet region is caused by electronic absorption bands. Basically, absorption occurs when a light particle (photon) interacts with an electron and excites it to a higher energy level.
- The main cause of intrinsic absorption in the infrared region is the characteristic vibration frequency of atomic bonds. In silica glass, absorption is caused by the vibration of silicon-oxygen (Si-O) bonds. The interaction between the vibrating bond and the electromagnetic field of the optical signal causes intrinsic absorption. Light energy is transferred from the electromagnetic field to the bond.

Extrinsic Absorption (metallic ions)

- Extrinsic absorption is much more significant than intrinsic
- Caused by impurities introduced into the fiber material during manufacture
  - Iron, nickel, and chromium
- Caused by transition of metal ions to a higher energy level
- Modern fabrication techniques can reduce impurity levels below 1 part in \(10^{10}\).
- For some of the more common metallic impurities in silica fibre the table shows the peak attenuation wavelength and the attenuation caused by an impurity concentration of 1 in \(10^9\).

<table>
<thead>
<tr>
<th>Peak wavelength (nm)</th>
<th>One part in (10^9) (dB km(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cr(^{3+})</td>
<td>625</td>
</tr>
<tr>
<td>Cr(^{2+})</td>
<td>685</td>
</tr>
<tr>
<td>Cu(^{2+})</td>
<td>850</td>
</tr>
<tr>
<td>Fe(^{2+})</td>
<td>1100</td>
</tr>
<tr>
<td>Fe(^{3+})</td>
<td>400</td>
</tr>
<tr>
<td>Ni(^{2+})</td>
<td>650</td>
</tr>
<tr>
<td>Mn(^{3+})</td>
<td>460</td>
</tr>
<tr>
<td>V(^{4+})</td>
<td>725</td>
</tr>
</tbody>
</table>
Extrinsic Absorption (OH ions)

- Extrinsic absorption caused by dissolved water in the glass, as the hydroxyl or OH ion.
- In this case absorption due to the same fundamental processes (between 2700 nm and 4200 nm) gives rise to so called absorption overtones at 1380, 950 and 720 nm.
- Typically a 1 part per million impurity level causes 1 dB/km of attenuation at 950 nm. Typical levels are a few parts per billion.

Absorption Spectrum for OH in Silica

Narrow windows circa 800, 1300 nm and 1550 nm exist which are unaffected by this type of absorption.

Scattering Losses in Fibre

- Scattering is a process whereby all or some of the optical power in a mode is transferred into another mode.
- Frequently causes attenuation, since the transfer is often to a mode which does not propagate well. (also called a leaky or radiation mode).

Rayleigh Scattering (I)

- Dominant scattering mechanism in silica fibres
- Scattering causes by inhomogeneities in the glass, of a size smaller than the wavelength.
- Inhomogeneities manifested as refractive index variations, present in the glass after manufacture.
- Difficult to eliminate with present manufacturing methods
- Rayleigh loss falls off as a function of the fourth power of wavelength:

\[
\alpha_r = \frac{A_r}{\lambda^4} \quad \text{dB per km}
\]

- \(\lambda\) in this empirical formula is expressed in microns (\(\mu\)m)
- The Rayleigh scattering coefficient \(A_r\) is a constant for a given material.
- For 1550 nm the loss is approximately 0.18 dB per km.

Types of Scattering Loss in Fibre

- Two basic types of scattering exist:
  - Linear scattering: Rayleigh and Mie
  - Non-linear scattering: Stimulated Brillouin and Stimulated Raman.

- Rayleigh is the dominant loss mechanism in the low loss silica window between 800 nm and 1700 nm.
- Raman scattering is an important issue in Dense WDM systems.
Rayleigh Scattering (II)

- The Rayleigh scattering coefficient $A_T$ depends:
  - The fibre refractive index profile
  - The doping used to achieve a given core refractive index
- For a step index germanium doped fibre $A_T$ is given by:
  $$A_T = 0.63 + 2.06 \cdot NA \text{ dB/km}$$
- For a graded index near-parabolic profile fibre $A_T$ is given by:
  $$A_T = 0.63 + 1.75 \cdot NA \text{ dB/km}$$

Exercise: Show that for a graded index fibre with a numerical aperture of 0.275 operating at 1330 nm the Rayleigh scattering loss is approximately 0.36 dB/km.

Total Fibre Attenuation and Developments

Empirical formulas from Harold Hughes, *Telecommunications Cables*, Wiley

Total Fibre Attenuation

- Measured total attenuation characteristic shows that the loss is dominated by extrinsic absorption loss and scattering.
- Attenuation falls with increasing wavelength, so that the loss at 1550 nm is only about 0.25 dB/km, compared to about 2.5 dB/km at 850 nm

Transmission Windows

- Three low loss transmission windows exist circa 850, 1320, 1550 nm
- Earliest systems worked at 850 nm, latest systems at 1550.
Broadband Fibre: Lucent Allwave Fibre

- Traditional manufacturing methods leave residual OH ions in the glass, result is absorption peaks, "locking-off" sections of the available spectrum
- New process virtually removes all residual OH ions
- Process involves a new way of making the optical fibre preform
- Opens up the spectrum circa 1383 nm, the OH peak
- Loss at 1383 nm is < 0.31 dB/km
- Important implications for Dense Wavelength Division Multiplexing

Ultra-low Attenuation Fibre

- Minimum attenuation circa 1550 nm is 0.2 dB/km at present.
- Corning SMF28 ULL (Ultra low loss) is 0.17-0.18 dB/km at 1550nm
- Future moves to longer wavelengths are being researched, 0.01 dB/KM possible in future (2500 nm).
- Present state of the art at longer wavelengths is greater than ten times the theoretical value.

ZBLAN=Zirconium-Fluoride Barium-Fluoride Lanthanum-Fluoride Aluminium-Fluoride Sodium-Fluoride