ATTENUATION AND NONLINEAR EFFECTS IN WAVEGUIDES

CHAPTER OUTLINE

7.1 Introduction
7.2 Intrinsic Absorption Loss
7.3 Rayleigh Scattering
7.4 Optical Fiber Manufacture
7.5 Mechanical Losses
7.6 Nonlinear Effects in Dielectrics
7.7 Stimulated Raman Scattering
7.8 Amplification Using Stimulated Raman Scattering
7.9 Stimulated Brillouin Scattering
7.10 Self-phase Modulation
7.11 Optical Solitons
7.12 Summary
Sources of attenuation

Attenuation arises from several different physical effects. In an optical waveguide, one must consider 1) intrinsic material absorptions, 2) absorptions due to impurities, 3) Rayleigh scattering, 4) bending and waveguide scattering losses, and 5) microbending loss. In terms of priority, intrinsic material absorption and Rayleigh scattering are the most serious causes of power loss for long-distance systems. Impurity absorption has become less of a problem as improved material

Intrinsic absorption and Rayleigh scattering is the most important attenuation mechanisms.
Intrinsic material absorptions

- Follows the Beer’s law: $P_{out} = P_{in}e^{-\alpha z}$

- Dictated by resonance responses from electronic states or vibrational states.

- Absorption edges are not sharp and rather smeared out.
Intrinsic material absorptions (contd..)

- **Electronic transition:**

\[
\begin{array}{c}
\text{Energy} \\
\text{Conduction Band} \\
8.9 \text{ eV} \\
\text{Valence Band}
\end{array}
\]

- **Vibrational transition:**

\[\sim 9 \text{ µm and their overtones.}\]

**Table 7.1** Energy bandgaps and absorption edges of various materials [1]

<table>
<thead>
<tr>
<th>Material</th>
<th>(E_g) (300 K)</th>
<th>(\lambda_{\text{min}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbS</td>
<td>0.37 eV</td>
<td>3.34 (\mu)m</td>
</tr>
<tr>
<td>GaAs</td>
<td>1.42</td>
<td>0.87</td>
</tr>
<tr>
<td>Si</td>
<td>1.12</td>
<td>1.10</td>
</tr>
<tr>
<td>Ge</td>
<td>0.67</td>
<td>1.85</td>
</tr>
<tr>
<td>InAs</td>
<td>0.35</td>
<td>3.54</td>
</tr>
<tr>
<td>Diamond</td>
<td>5.5</td>
<td>0.23</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>8.9</td>
<td>0.14</td>
</tr>
</tbody>
</table>

**Figure 7.3** The three fundamental vibrational modes of the triatomic SiO\(_2\) molecule are the bending mode, an asymmetric stretch, and a symmetric stretch.
Rayleigh Scattering

Rayleigh scattering is the scattering of light off random density fluctuations that exist in a dielectric material. When the index fluctuations occur over a dimension that is small compared to the wavelength of light, the density fluctuation can be viewed as a small dielectric particle which is uniformly excited by the field. The

\[
\Delta p(t) = \Delta \varepsilon E(t)
\]

\[
P_{\text{rad}} = \frac{\omega^4 p^2}{12 \pi \varepsilon_0 c^3} = \frac{\omega^4 (\Delta \varepsilon)^2 E^2}{12 \pi \varepsilon_0 c^3}
\]

Rayleigh Scattering is thermodynamic and hence fundamental and cannot be removed
Rayleigh Scattering (contd..)

Data courtesy Corning, Inc.

Figure 7.4  The total attenuation in fused silica consists of Rayleigh scattering, impurity absorption, and intrinsic absorption. Minimum loss occurs at $\lambda = 1.55\mu m$. 
Bending losses

**Figure 7.7** The plane wavefront in a bent waveguide is pivoted about the center of radius of curvature of the bend. At some critical radius, the phase velocity must exceed the velocity of light, and breaks away.

**Figure 7.9** Bending loss is calculated from Equation 7.10 for three different fibers. The cutoff wavelength for the fiber is set at 1.2μm, and the operating wavelength is 1.5μm.
Nonlinear effects

\[
\frac{P}{\varepsilon_0} = \chi^{(1)} \cdot E \quad \text{Linear optics}
\]
\[
+ \chi^{(2)} \cdot EE \quad \text{Sum and difference frequency generation, Pockels effect}
\]
\[
+ \chi^{(3)} \cdot EEE \quad \text{Third-harmonic generation, self-phase modulation, \ldots}
\]
\[
+ \cdots
\]

- Large power density in fibers can lead to harmonic generations.

Stimulated Raman, Stimulated Brillouin and Self-Phase modulation.
Raman Scattering

Molecular polarizability:

\[ \alpha(x) = \alpha_0 + \left. \frac{\partial \alpha}{\partial x} \right|_{x_0} \delta x \]

\[ \delta x(t) = \delta x_0 e^{\pm j \omega_p t} \]

\[ p(t) = \alpha(t)E(t) \]

\[ = \left( \alpha_0 + \left. \frac{\partial \alpha}{\partial x} \right|_{x_0} \delta x_0 e^{\pm j \omega_p t} \right) E_0 e^{j \omega_1 t} \]

\[ = \alpha_0 E_0 e^{j \omega_1 t} + \left. \frac{\partial \alpha}{\partial x} \right|_{x_0} \delta x_0 E_0 e^{j(\omega_1 \pm \omega_p) t} \]
Stimulated Raman Scattering

\[ p(t)_{\omega_1 \pm \omega_p} = \frac{\delta \alpha}{\delta x} \delta x_0 E_0 e^{i(\omega_1 \pm \omega_p)t} \]

Signal gain:

\[ \frac{dI_2}{dz} = G_r I_2 I_1 \]

\[ I_2(z) = I_2(0) e^{G_r \cdot I_1 \cdot z} \]

Table 7.4  Raman frequencies and gain coefficients [14] (\(\lambda = 0.694\mu m\))

<table>
<thead>
<tr>
<th>Material</th>
<th>Frequency shift (cm(^{-1}))</th>
<th>Raman gain (m/W)</th>
<th>Linewidth (\Delta v) (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiNbO(_3)</td>
<td>258</td>
<td>(28.7 \times 10^{-13})</td>
<td>7</td>
</tr>
<tr>
<td>Benzene</td>
<td>992</td>
<td>(2.8 \times 10^{-13})</td>
<td>2.2</td>
</tr>
<tr>
<td>SiO(_2)</td>
<td>467 (peak)</td>
<td>(0.9 \times 10^{-13})</td>
<td>200</td>
</tr>
</tbody>
</table>

\(~4\%\) gain in Raman shifted light every kilometre in fused silica

SRS can generate a bandwidth under strong pump conditions
Stimulated Brillouin Scattering

Brillouin scattering is similar to Raman scattering, except acoustic phonons are involved instead of optical phonons. Acoustic phonons consist of collective vibrations of the atoms in a solid, while optical phonons tend to involve vibrations only between a few individual atoms [10]. Acoustic vibrations occur at a much lower frequency than optical phonons, being on the order of 1 cm$^{-1}$ ($\approx 30$ GHz). Bril-

SBS can cause back-reflection of the pump beam.

$$\delta \nu = 2nV_s/\lambda$$

SBS gain:

$$G_B \approx G_0(\Delta \nu_B/\Delta \nu_p)$$
Self Phase Modulation

\[ E(z, t) = E_0 e^{i(\omega_0 t - k_0 z)} = E_0 e^{i\phi} \]
\[ \phi = \omega_0 t - \frac{\omega_0}{c} nz \]

Intensity dependent refractive index

\[ n(I) = n_0 + n_2 \cdot I \]

Self phase modulation

\[ \phi = \omega_0 t - \frac{\omega_0 z}{c} [n_0 + n_2 I(t)] \]

Instantaneous frequency of the field

\[ \omega(t) = \frac{d\phi}{dt} = \omega_0 \left[ 1 - \frac{z}{c} \frac{dn}{dt} \right] \]

Generation of a time varying phase shift
Self Phase Modulation (contd.)

Frequency up shifted  Frequency down shifted

\[ \omega(t) = \frac{d\phi}{dt} = \omega_0 \left[ 1 - \frac{z}{c} n_2 \frac{d}{dt} I(t) \right] \]

\[ \delta\omega = \Delta k L = \frac{2\pi L}{\lambda} \frac{d\delta n}{dt} \quad \Delta \phi = \frac{2\pi L}{\lambda} \delta n_{max} \]

Additional chirp increases dispersion
Optical Solitons

optical solitons [16, 17]. A soliton, by definition, is a solution to a wave equation that propagates without distortion. As we know, when we launch a pulse in a real

\[ D = -\frac{\lambda}{c} \frac{d^2 n}{d\lambda^2} \]

Figure 7.16 In a graph of the dispersion in SiO₂, the region above 1.3 μm is called the negative dispersion region.
Optical Solitons (contd..)

Frequency up shifted  Frequency down shifted

Chirped Pulse  Compressed Pulse

shape as it propagates. It represents a pulse with just the right amplitude so that the pulse-spreading dispersion effects are exactly canceled by the pulse-narrowing effects of the nonlinearity. For higher-order solitons, the input-pulse amplitude must