Optical Fibre Amplifiers

Stavros Iezekiel
Department of Electrical and Computer Engineering
University of Cyprus
SYSTEM CONSIDERATIONS
Attenuation & dispersion

- Reduction in pulse energy
- Pulse spreading

\[ L = \frac{c\tau}{n_g} \]
At low bit rates, the maximum transmission distance is limited by attenuation, while at high bit rates the distance is limited by dispersion:

**Attenuation-limited**

**Dispersion-limited**

FP = Fabry-Perot laser diode
DFB = distributed feedback laser diode
REGENERATION
Optical Signal Regeneration

- It is necessary to re-amplify and reshape the pulses at regular intervals using regeneration:

**Diagram:**
- **Optical source** → **FIBRE** → **3R** → **Regenerator** → **Photoreceiver** → **Fibre output**
- **3R**:
  - retiming
  - reshaping
  - re-amplification

**Regenerator**:
- **Photoreceiver** → **Electronics**: Clock recovery, pulse reshaping → **Laser transmitter**
ECE 455 Lecture 08

Optical regenerators are classified into three categories by the 3-R's scheme.

1R: re-amplification of the data pulse alone is carried out.
2R: in addition to re-amplification, pulse reshaping is carried out.
3R: in addition to re-amplification and reshaping, retiming of data pulse is done.

- Advantages:
  - Clock recovery
  - Pulse reshaping

- Disadvantages:
  - O/E & E/O conversion needed
  - Bit rate is "locked in" — no upgrades
  - Single wavelength only
OPTICAL AMPLIFICATION
Optical Amplifiers

• All-optical components (i.e. optical input/output). Fibre-based amplifiers also contain lasers, but this is to create a population inversion in the gain medium.

• Have replaced electronics-based regenerators, in which optical signals had to be hotodetected, amplified electronically and then applied to optical source.

• Have revolutionised optical communications
  – used in wavelength division multiplexed (WDM) systems
  – allow the use of soliton transmission at ultra high bit rates (1000s of Gb/s) over thousands of km
  – Have removed the speed and wavelength bottleneck associated with all-electronic regeneration.
- An optical amplifier provides gain over a useful spectral range, as shown here for an erbium-doped fibre amplifier:

![Graph showing fibre attenuation and optical amplifier gain over a spectral range.](image-url)
This broad spectral range enables a number of wavelengths to be multiplexed onto a fibre, thus increasing the bit rate that can be transmitted.
• Advantages:
  – Optical input & output
  – Photons in – more photons out
  – Transparent to both bit rate & modulation format
  – Supports many wavelengths
    • WDM: Wavelength division multiplexing

• Disadvantages:
  • No pulse reshaping
  • \therefore Needs dispersion compensation
  • Adds noise to output signal
Ideal amplifier:

- Flat gain response
- Linear phase response
Real amplifier:

- Input
- Output
- Gain + Noise

- Gain saturation
- Nonlinearity
TYPES OF OPTICAL AMPLIFIER
Types of optical amplifier

- Semiconductor optical amplifiers (SOAs)
- Fibre amplifiers
  1. Making use of nonlinear effects, such as stimulated Raman scattering (these are also known as distributed fibre amplifiers).
  2. Rare earth doped fibres: most common type is erbium-doped (1.55\,\mu m central wavelength), but praseodymium-doped also available (1.3\,\mu m).

In this course, we will only consider erbium-doped fibre amplifiers (EDFA).
EDFAs are used in all modern long-distance optical links, but usually the regeneration is 1R. EDFAs have replaced the approach taken with early generation links that used all-electronic 3R regenerators. EDFAs are used in all modern long-distance optical links, but usually the regeneration is 1R.
Packaged erbium-doped fibre amplifier (EDFA)
Other doped fibre amplifiers

<table>
<thead>
<tr>
<th>Band name</th>
<th>Meaning</th>
<th>Wavelength (nm)</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Original</td>
<td>1260-1360</td>
<td>Praseodymium</td>
</tr>
<tr>
<td>E</td>
<td>Extended</td>
<td>1360-1460</td>
<td></td>
</tr>
<tr>
<td>S</td>
<td>Short</td>
<td>1460-1530</td>
<td>Thulium</td>
</tr>
<tr>
<td>C</td>
<td>Conventional</td>
<td>1530-1565</td>
<td>Erbium</td>
</tr>
<tr>
<td>L</td>
<td>Long</td>
<td>1565-1625</td>
<td>Erbium</td>
</tr>
<tr>
<td>U</td>
<td>Ultra-long</td>
<td>1625-1675</td>
<td></td>
</tr>
</tbody>
</table>
APPLICATIONS OF OPTICAL AMPLIFIERS
Application 1: As in-line amplifiers in long-haul links to compensate for attenuation in the 1550 nm window. Mostly EDFAs and Raman.

Optical amplifiers boost the signal at regular intervals (e.g. between 30 km to 80 km) to make sure power level in link does not drop below the required receiver sensitivity.
Optical amplifiers compensate for loss, but they also introduce noise:

Hence a low noise figure is important, as well as saturation power (being able to handle medium power levels)
The other problem is that for standard single-mode fibre, the 1550 nm window offers low loss, but minimal chromatic dispersion is at 1310 nm. Hence some kind of “dispersion management” or dispersion compensation is required, e.g. by using dispersion-shifted fibre (DSF).
Application 2: As power amplifiers to increase source power (post-amplifiers):

\[ P_{S} \text{ (dBm)} \quad G(\text{dB}) \]

\[ \text{Output power (dBm)} = P_{S} + G \]

- Most laser diodes used in optical transmitters have powers of a few mW, but fibre can handle of the order of 100 mW before optical nonlinear effects occur. So a power amplifier can be used to boost signal immediately after the source.

- SOAs are useful because they can be integrated with lasers, but EDFA power amplifiers are also available with output powers around 100 mW.

- Amplifier adds noise, but this is attenuated by the fibre

- Important that the amplifier is not saturated by the transmitter
Application 3: As pre-amplifiers to improve receiver sensitivity:

- Optical amplifier is placed immediately before the optical receiver in order to improve sensitivity.

- At this point the signal is weak, so good gain is required, but even more important is the fact that the amplifier must not add a lot of noise, so a low noise figure is required (typically less than 5 dB).
Star coupler: splits into $N$ fibres; has insertion and splitting loss
FIGURES OF MERIT FOR OPTICAL AMPLIFIERS
Important figures of merit & considerations for an amplifier

- Include:
  - Gain
  - Bandwidth
  - Gain saturation
  - Noise
Properties of Ideal Optical Amplifiers

• Provide high gain
  – (30 dB or more)
• Have a wide spectral bandwidth
  – to allow several wavelengths to be transmitted
• Provide uniform (i.e. flat) gain vs. $\lambda$
  – to maintain relative strength of spectral components
• Allow bi-directional operation
  – i.e. gain in both directions
• Have low insertion loss
  – to maximise benefits of amplifier gain
• Have no crosstalk
  – i.e. no interference between different spectral components
• Have wide dynamic range
  – gain should not saturate with high input powers
• Have a good conversion efficiency
  – pump power converted to amplifier gain
High gain over a wide spectral bandwidth, but the gain profile is not flat.
ASE: Amplified spontaneous emission noise
Typical gain versus power profile for optical amplifier: