Optical communications

Lecture 14 – Introduction to Amplifiers

Frantisek Urban
Introduction

- Where are we?
- Fibre based amplifiers
- EDFAs
- PDFA’s
- Raman Amplifiers
- Actual amplifier specification
Last Time

• Why do we need amplifiers?
• Easier ways of dealing with power.
• Calculations for simple fibre links.
• Gain behaviour:
  – Small signal gain.
  – Gain saturation.
• Noise figures
• Amplified Spontaneous Emission (ASE)
Erbium doped fibre amplifier (EDFA)

- Remember we want an all optical amplifier scheme.
- Such an amplifier exists for the 3rd telecommunications window.
- This is the Erbium Doped Fibre Amplifier or EDFA.
- Erbium ions are included in the core of a section of optical fibre.
- Pump energy provided by 980nm or 1480nm radiation – ideal for laser diodes.
- Invented in the UK at the University of Southampton in 1987.
- The enabling technology for modern telecommunications networks.
Why Erbium?

Erbium Amplification Spectrum

Minimum Fibre Loss

Erbium Amplification Spectrum

Optical-fiber attenuation (dB/km)

Optical-amplifier gain (dB)

Wavelength (nm)

1200 1300 1400 1500 1600 1700

1 0.4 0.2

3 THz 25 THz

WDM channels
How does this work?

Energy

980nm Pump

1480nm Pump

Stimulated Emission 1500nm→1600nm

Spontaneous Emission 1500nm→1600nm

Fast, non-radiative decay
Co-doping the fibre can shift slightly the emission spectrum.
Erbium Absorption Spectrum
Erbium Absorption

- Erbium has many possible pump bands.
- 980 and 1480nm are most suitable – shorter wavelengths suffer excited state absorption (ESA.)
- However, transition is quasi three-level.
- Too little pump power can result in loss at signal wavelength.
- Must consider the pumping geometry.
Pumping EDFA’s

Optimum fibre length 20-50m!
Pumping EDFA’s II

- Can pump the amplifier in two directions.
- Co-propagating travels in the same direction as the signal.
- Counter-propagating travels in the opposite direction.
- Pump absorption is non-linear, so a variable gain is seen along the length of the fibre.
- Must ensure that enough pump remains at the end of the amplifier to achieve ‘transparency’ across the amplified wavelengths.
- Often use both a co- and counter propagating pump to achieve this condition.
- Care is required with counter propagating pump due to noise considerations
Pumping EDFAS III – The directional coupler.

- Wavelength selective coupler is used to couple the pump light into the active fibre.
- Can also couple unused pump out after the amplifier section.
Gain Flattening and Gain Bands

- The emission spectrum of Er is not flat.
- Different wavelengths experience different amplifications.
- May need to introduce gain flattening filters to produce constant gain.
- Also shift gain with glass composition.
- High gain is available around the peak of the Erbium gain (~1535nm), so amplifiers operating in 1520-1560nm need relatively short fibre amplifiers.
- Operating at longer wavelengths 1570-1620nm requires much longer amplifiers.
- 1530-1565nm – C (conventional) Band.
- 1570–1620nm – L (Long) Band.
- 5nm gap allows signal to be split and sent through parallel amplifiers.
Amplifying at Other Wavelengths

- What about other wavelengths?
- Er operates around 1550nm. (3rd Telecomms window.)
- What about 1300nm (2nd Telecomms window)?
  - One solution is to look for another ‘Er’ like dopant with a broad emission spectrum around 1300nm.

<table>
<thead>
<tr>
<th>Band Name</th>
<th>Meaning</th>
<th>Wavelengths (nm)</th>
<th>Amplification Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>Original</td>
<td>1260-1360</td>
<td>Praesedodymium ?</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-Fibre ?</td>
</tr>
<tr>
<td>C</td>
<td>Conventional</td>
<td>1530-1565</td>
<td>Erbium-Fibre</td>
</tr>
<tr>
<td>L</td>
<td>Long</td>
<td>1565-1625</td>
<td>Erbium-Fibre</td>
</tr>
<tr>
<td>U</td>
<td>Ultra-long</td>
<td>1625-1675</td>
<td></td>
</tr>
</tbody>
</table>
PDFA’s

- Praeseodymium doped amplifiers have been developed for 1300nm operation.
- Performance significantly worse than comparable Er amplifiers operating around 1500nm.
- Pumping can be difficult.
- Often have to use Fluoride based glasses for the fibre – EXPENSIVE!
Raman Amplifiers

- A further option is to exploit the non-linear effects of the fibre.
- Can use the forward generated Stokes wave in SRS to provide gain in a particular bandwidth.
- Possible to obtain gain across a very broad wavelength range.
- Can be used in conjunction with EDFA to give extended and/or flattened composite gain curves.
- Relatively high pump power required - ~1W. Difficult to achieve in semiconductor lasers.
- Distributed gain can reduce FWM problems.
- No special fibre required.
Raman Gain

![Graph showing Raman Gain with wavelength in nm and pump power in W on the x-axis, and gain in dB on the y-axis. The graph includes curves for 980 mW, 590 mW, and 350 mW.]
Composite Amplifier

Gain vs. Wavelength

- Composite Gain
- Er Gain
- Raman Gain

1530nm to 1600nm
A real fibre amplifier
## Amplifier Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range</td>
<td>1530 to 1563nm</td>
</tr>
<tr>
<td>Input power range</td>
<td>-29 to 0 dBm</td>
</tr>
<tr>
<td>Saturated output power</td>
<td>17.3 ±0.3 dBm</td>
</tr>
<tr>
<td>Noise figure</td>
<td>&lt;6.0 dB</td>
</tr>
<tr>
<td>Nominal gain</td>
<td>+17 dB</td>
</tr>
<tr>
<td>Gain flatness</td>
<td>&lt;1.5 dB</td>
</tr>
<tr>
<td>Settable variable gain</td>
<td>17 dB to 7 dB (gain flatness is &lt;1.5 dB for 17 to 13 dB; &lt;2.0 dB for 7 to 13 dB)</td>
</tr>
<tr>
<td>Automatic gain control accuracy</td>
<td>±1.0 dB</td>
</tr>
<tr>
<td>Transient suppression response time</td>
<td>50 microseconds</td>
</tr>
<tr>
<td>Backward amplified spontaneous emission</td>
<td>&lt;25 dB</td>
</tr>
<tr>
<td>PMD</td>
<td>&lt;0.6 ps</td>
</tr>
<tr>
<td>Mode of operation</td>
<td>Unidirectional</td>
</tr>
<tr>
<td>Optical return loss</td>
<td>&gt;27 dB</td>
</tr>
<tr>
<td>Input and output isolation</td>
<td>&gt;30 dB</td>
</tr>
<tr>
<td>Polarization sensitivity</td>
<td>&lt;0.5 dB</td>
</tr>
</tbody>
</table>
Conclusions

- Fibre amplifiers are a key enabling technology.
- Best fibre amplifiers work in 3rd Telecomms windows and are based on Erbium.
- Other wavelengths regimes possible, though much more difficult. Pr for 1.3µm.
- Can also make use for Raman Effect for amplification.
- Gain and loss behaviour of Er amplifiers.
- Example of a real amplifier.
Optical communications

Lecture 15 – Semiconductor Optical Amplifiers and OTDR

Frantisek Urban
Introduction

- Where are we?
- Using semiconductors as amplifiers.
- Amplifier geometry
- Cross talk
- Polarisation dependence
- Gain clamping
- Real amplifier performance
- Introduction to real networks
Last time

- Fibre amplifiers are a key enabling technology
- Best fibre amplifiers work in 3rd Telecomms window and are based on Erbium.
- Other wavelength regimes possible, but much more difficult. Pr for 1.3µm.
- Can also make use of the Raman effect for amplification.
- Gain and loss behaviour of Er amplifiers.
- Example of a real amplifier.
• A different approach is to use a semiconductor gain element rather than a fibre.
• Wide range of amplification wavelengths available.
• Cost is increased complexity coupling in and out of the amplifier.
• Electrical gain switching is possible allowing modulation to be integrated within the amplifier.
• Need to ensure that amplifier does not generate its own waves!
• Fabry – Perot Amplifier
• Incoming beam is reflected in the amplifier.
• Often just use endface reflections of the substrate.
SOA Geometries

- Travelling wave amplifier – TWA.
- Endfaces are AR coated or waveguide is tilted with respect to endfaces.
- Gain extracted is the single pass gain for the amplifier. Exponential dependence on device length.
Gain Versus Frequency for SOA devices

\[ G_{\text{FPA}}^{\text{Max}} = \frac{G_S (1 - R)^2}{(1 - RG_S)^2} \]

\[ G_S = \text{Single Pass (TWA) Gain} \]

Frequency

Gain / AU
Gain Bandwidth for FPA & TWA

• Fabry-Perot amplifier exhibits strong Fabry-Perot features.
• Gain ripple with frequency is evident.
• Decreasing reflectivity of FP reduces the gain ripple and the gain.
• In the limit of $R=0$, the response of the FPA is that of the TWA.
• Key point: FPA’s have a higher gain, but a narrower bandwidth than TWA’s.
• $G_{FPA\text{ BW}} = \sim 0.01\text{nm}$ (Depends on reflectivity). $G_{TWA\text{ BW}} = \sim 60\text{nm}$.
• In practise only TWA amplifiers are used as they can support a much wider bandwidth.
• Requires precise and expensive control of the AR coatings on the end face of the amplifier.
Crosstalk

• If an amplifier is used to amplify more than one wavelength channel, cross talk can occur.
• Crosstalk arises through two main mechanisms – four wave mixing and cross saturation.
• Four wave mixing causes a reduction of amplification at the signal wavelengths and may also interfere with adjacent signal channels.
• Cross saturation occurs when the amplifier is operating in a saturated regime. Changing one channel from off to on can have a serious effect of the gain of another channel.
Cross saturation

- Saturating the gain from one channel can effect another channel.
- Places the lower limit on the amplifier bit rate.
- If bits rate $< 1/\tau_{sp}$ then gain changes with input signal.
- $BR_{\text{min}}$ SOA $\sim 1$ GBit/s
- $BR_{\text{min}}$ EDFA $\sim 100$ kHz
Polarisation Dependent Gain

- Due to their assymetric shapes, SOA waveguides produce a polarisation dependent gain.
- Gain can vary by 5-7dB for TE and TM polarisations.
- Particular problem after signals have been transmitted down standard optical fibre – not polarisation maintaining.
- Solutions involve double passing signal through the SOA after rotating the polarisation.
- Commercial SOA’s have reduced polarisation dependent loss to <0.5dB.
## A real SOA

<table>
<thead>
<tr>
<th></th>
<th>Standard SOA module</th>
<th>Gain-clamped SOA module</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength of maximum gain</td>
<td>1540 nm</td>
<td>1540 nm</td>
</tr>
<tr>
<td>Fiber-to-fiber gain at $P_{in}=-25$ dBm</td>
<td>25 dB</td>
<td>17 dB</td>
</tr>
<tr>
<td>Gain ripple</td>
<td>0.5 dB</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Polarization sensitivity</td>
<td>0.5 dB</td>
<td>0.5 dB</td>
</tr>
<tr>
<td>Noise figure nsp/C1</td>
<td>7 dB</td>
<td>7 dB</td>
</tr>
<tr>
<td>Saturation output power at 3 dB gain compression</td>
<td>3 dBm</td>
<td>10 dBm</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>10 dBm</td>
<td>11 dBm</td>
</tr>
<tr>
<td>3 dB optical bandwidth</td>
<td>40 nm</td>
<td>40 nm</td>
</tr>
<tr>
<td>Lasing wavelength</td>
<td>NA</td>
<td>1510 nm</td>
</tr>
<tr>
<td>Driving current</td>
<td>150 mA</td>
<td>150 mA</td>
</tr>
</tbody>
</table>
## Amplifier Roles

<table>
<thead>
<tr>
<th>Amplifier Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Booster Amplifier</strong></td>
<td>Provides maximum power into fibre link.</td>
</tr>
<tr>
<td><strong>Inline Amplifier</strong></td>
<td>Amplifies signal along fibre. Good gain flatness required as many amplifiers may be cascaded.</td>
</tr>
<tr>
<td><strong>Pre-Amplifier</strong></td>
<td>Amplifies weak signal before receiver. High gain and low noise performance is essential.</td>
</tr>
</tbody>
</table>
Optical Amplifiers Summary

- Optical amplifiers have revolutionised telecommunications.
- The development of the EDFA for 1550nm transmission allowed unrepeatered fibre optic cables to be deployed across trans-oceanic distances.
- Optical amplifiers can introduce noise into a system through ASE.
- Amplification at other wavelengths is more difficult although some solutions are in place.
- Semiconductor Optical Amplifiers show great promise although care must be taken to ensure optimum system performance.
Building a fibre link

Losses: Attenuation
Splices
Connectors

Power: Source
Amplifier

Fibre Splices
Fibre Connectors
20km Fibre Lengths
Amplifier
Receiver
Conclusions

- Semiconductor optic amplifiers
- FP and TW designs
  - Bandwidth considerations
  - Gain ripple
- Cross talk and cross saturation
- Polarisation dependent gain
- Gain clamping
- Real amplifiers
- Introduction to real world networks