Fiber lasers and amplifiers
Optical fibers - losses

3 low loss windows for telecommunication
850 nm, 1300 nm, 1550 nm.
Optical fibers - dispersion
Motivation

- The development of optical fibers doped with rare earth ions has been initially pushed by the optical telecommunication field.

in-line optical amplification

Diagram:

Transmitter

DL  AM

Transmitter

TX  A  A  RX

Receiver

1 1 0 1
Electro-optical regeneration

- Until years ‘80: electrical regeneration

Long distance transmission:

- TX -> RX -> TX -> RX
- Conv. O/E -> Conv. E/O
Electro-Optical regeneration

Drawbacks:

• expensive
• limited bit-rate
• the optical link cannot be upgraded in terms of:
  wavelength
  bit rate
  signal format
Optical amplification

• Semiconductor optical amplifier (SOA):
  – low compatibility with optical fibers
  – performances not optimized for in-line amplification
Doped Fibers

- Doped fibers (‘80) with rare earths ions
  - Erbium (Er$^{3+}$) 1550 nm
  - Praseodimium (Pr$^{3+}$) 1300 nm
  - Neodimium (Nd$^{3+}$)

- Silica matrix completely compatible with in-line optical fibers
- Low cost
**Rare earths**

- Electronic configuration
  \[[\text{Xe}] \, 6s^2 \, 4f^N \] with \(0 < N < 14\)

Ion \(3^+\): the dopant loses 2 electrons \(s\) and 1 electron \(f\)

Optical transitions involve levels of the \(f\) orbital:
- Internal orbitals: the influence of the external local fields is minimised
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*Mass atomic weight calculated with respect to the mass atomic weight of oxygen (O) = 12.*

[From Pure and Applied Chemistry Vol. 17, No. 4 - (1914)]
Doping

dopant concentration: \(~100\) ppm

Importance of maintaining the properties of passive optical fibers

- Low loss
- NA
- Compatibility of the silica matrices

PROBLEM: Low solubility - clustering

**Trade off:**

- concentration → low amplification
- concentration → crystallization (loss)
- clustering - gain quenching (nonradiative disexcitation)

- First optimized doped fiber (1985): **Erbium**
  Univ. Southampton + Pirelli Cables (Milan)
Erbium doped fiber

Intensity Gain \( \alpha(\nu) = \sigma_{21}N_2 - \sigma_{12}N_1 \)

\[ \Phi(z) = \Phi_0 e^{\alpha(\nu)z} \]
Gain

\[
\alpha(\nu) \propto \sigma_{21} N_2 - \sigma_{12} N_1
\]

Gain shape depends on population inversion

\[
n_2 = \frac{N_2}{N_t}
\]
**Gain bandwidth**

30 nm bandwidth

the broadening is due to the host field

Problem: gain flattening
Codopants lead to a spectral change of the amplification band

Aluminum doping leads to gain broadening and flattening
**Amplification in the fiber**

Optimal length depends on doping level and pump power. Pump and signal **monomode**: good spatial overlap. Standard fibers, Pump 150-200 mW, $L_{\text{opt}}$ 10-15 m.
Optical amplifiers (EDFA) scheme

Counter propagating scheme

Alternative schemes: co- and counter propagating pump
**Optical components**

**WDM** wavelength division multiplexer
- fused fibers
- micro-optics

**Isolator** light can be transmitted only in one direction
Amplification regime

\[ P_{\text{out}} = \alpha P_P = P_{\text{ase}} + GP_s \]

- Quantum efficiency: \( \eta = \frac{h\nu_s}{h\nu_p} \)
- Absorption cross section

When \( P_s \) increases

GAIN SATURATION

\[ G = G_0/(1+P_s/P_{\text{sat}}) \]
Performances

- Gain 30-40 dB ($10^3$-$10^4$) with pump 100-400 mW
- Output power up to 23 dBm
- Bandwidth 30-40 nm

The in-line amplifiers usually work in the saturated regime:
- the output power is almost constant independently from the input power
- the ASE power is reduced
EDFA applications

- in line amplifier

- booster

- optical preamplifier

- loss compensation
New generation fibers

New optical amplifiers

RAMAN amplification

C-band 1530 – 1570 nm
L-band 1570 – 1635
S-band
L-band amplifiers

The long wavelength band (L-band) is defined approximately as 1570 nm to 1605 nm. This wavelength range encompasses only the tail of the erbium gain band.

Very low gain can be obtained. Long spans of fibers are needed.
Prototype optical amplifiers

- EDFA: Erbium-doped fiber amplifier (1530–1565 nm)
- GS-EDFA: Gain-shifted EDFA (1570–1610 nm)
- EDTFA: Tellurium-based gain-shifted TDFA (1530–1610 nm)
- GS-TDFA: Gain-shifted thulium-doped fiber amplifier (1490–1530 nm)
- TDFA: Thulium-doped fluoride-based fiber amplifier (1450–1490 nm)
- RFA: Raman fiber amplifier (1420–1620 nm or more)

Tellurium: TeO₂
Thulium commonly a compound of thulium and fluoride TmF₃
# Standard optical amplifier

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* λ = C- or L-
Bench top amplifier

- Unique choice of 0.5W to 5W output power
- 1530 to 1570 nm or 1575 to 1610nm operational bandwidth
- Low noise figure
- Extremely low PMD
- APC and ACC controls
- Dispersion compensation option
- Excellent performance to cost ratio
- Two year warranty
High power amplifiers

WDM systems

Splitter 1× N
High power amplifiers

Issues: higher power levels for optical communication
       high power systems (lasers)

Outline:
   - Yb$^{3+}$ and Er$^{3+}$ Yb$^{3+}$ doped fibers
   - Novel fiber structures
Yb$^{3+}$ fiber

- Highly efficient amplification system in silica host (no concentration quenching)
- 2 level system

Non radiative decay

900 nm 980 nm 1100 nm

Cross-sections

absorption
emission
Er Yb fiber

resonant transfer

Yb: high absorption cross section
improved pumping efficiency

Fiber length reduction!

Clustering reduction
Problem: high power pumping

- To obtain high power output (several Watts) high pump powers are needed

Available lasers: solid state lasers
  - low efficiency
  - very cumbersome
  - not tunable

  semiconductor lasers or array
  - High efficiency
  - Wavelength selectable
  - High output power (> 100 W)

Problem: coupling to a single mode fiber
Coupling

• Coupling is optimized when the beam is spatially single mode, has gaussian shape and divergence similar to the fiber NA

Good optical coupling
Good matching between the beam and the mode profile

High power semiconductor lasers:
spatially multimodal, high divergence, astigmatic beam. Coupling can be of the order of a few %
Cladding pumped fibers

The pump is efficiently coupled in the multimodal internal cladding and it progressively transferred in the doped core.
Optimized geometries

- Maximum superposition between the core and the pump fields

low pump absorption

Fiber stretching: optical modes scrambling
High power Er Yb amplifiers

Main Features:

✓ Unique choice of 0.5W to 5W output power
✓ 1530 to 1570 nm or 1575 to 1610nm operational bandwidth
✓ Low noise figure
✓ Extremely low PMD
✓ APC and ACC controls
✓ Dispersion compensation option
✓ Excellent performance to cost ratio
✓ Two year warranty

Applications:

✓ Fiber Optic Communications
✓ Wireless Communications
✓ Power Booster for Tunable Sources
✓ Photonics Switching
✓ Sensorics
✓ Components Testing
## High power Er Yb amplifiers

### Typical Specifications

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<tr>
<td>Saturated Output Power</td>
<td>W</td>
<td>0.6</td>
<td>1</td>
<td>2</td>
<td>5</td>
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<tr>
<td>Polarization</td>
<td>random</td>
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<tr>
<td>Mode of Operation</td>
<td>single channel</td>
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<tr>
<td>Optical Bandwidth</td>
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<tr>
<td>C-band</td>
<td>nm</td>
<td>1535-1557</td>
<td>1535-1567</td>
<td>1535-1567</td>
<td>1540-1570</td>
</tr>
<tr>
<td>L-band</td>
<td>nm</td>
<td>1570-1605</td>
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<td>1570-1605</td>
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<tr>
<td>Optical Input Power</td>
<td>dBm</td>
<td>-3 to +3</td>
<td>-3 to +3</td>
<td>0 to +3</td>
<td>0 to +3</td>
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<tr>
<td>Typical Noise Figure</td>
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<tr>
<td>C-band</td>
<td>nm</td>
<td>5.5</td>
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<tr>
<td>L-band</td>
<td>nm</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>6.5</td>
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<tr>
<td>Output Power Stability (over 8 hours, APC mode)</td>
<td>dB</td>
<td>0.1-0.2</td>
<td>0.1-0.2</td>
<td>0.1-0.2</td>
<td>0.1-0.2</td>
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<tr>
<td>Polarization Dependand Loss (PDL)</td>
<td>dB</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
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<tr>
<td>Polarization Mode Dispersion (PMD)</td>
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<td>0.7</td>
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<tr>
<td>Input/Output Optical Isolation</td>
<td>dB</td>
<td>40/30</td>
<td>40/30</td>
<td>40/30</td>
<td>40/25</td>
</tr>
</tbody>
</table>
1300 nm amplifiers

- Interesting materials:
  - Neodimium
  - Disprosium
  - Praseodimium → best results in ZBLAN

Silica host is not suitable:
phononic interaction: non radiative disexcitation

New hosts: **Fluoride glasses** (ZBLAN Zirconium Barium, Lanthanum, Alluminium, Nitrogen)
**Chalcogenide glasses** LaGaS, GeGaS.
Fiber lasers

• First motivation:
  Transmitter for optical communication

NOW:
• CW high power lasers
• pulsed laser for laboratory applications
Fiber cavities

Advantages with respect to solid state lasers:
Compact, low cost, high efficiency
Mode locked ring cavities

- Active and passive mode locked laser are commercially available for laboratory applications
- Too expensive for TLC
- The stability is not sufficiently optimised

- very compact, efficient
Fiber Bragg gratings

- Fundamental break-through

The light is reflected when constructive interference occurs

\[ \lambda = 2n_{\text{eff}}\Lambda \]

wavelength selective mirrors

Bandwidth 0.1 - 2 nm

R up to 100%
Bragg gratings fabrication

- Refractive index of germanium-doped silica core can be changed by exposure to UV light
- A refractive index change $\Delta n$ $10^{-3}$ - $10^{-6}$ can be obtained
- The physical phenomena is not completely understood - phorefractivity
Fibre sensitisation

• Low refractive index change in standard silica fibers.
• To enhance photosensitivity:
  – increase of germanium concentration. The fibre become incompatible with standard ones -
    • losses - different field diameters- lossy splices
  – different co-dopants have been tried with varying success
  – best results: diffusion of molecular hydrogen into the fiber core at high pressure. $\Delta n > 10^{-2}$ has been obtained
High power fiber lasers

- Fiber gratings + cladding pumped fibers
- Most efficient laser \(\rightarrow\) Ytterbium doped fiber
- Pumping with diode array diode

Big break-through:
- high efficiency (low power consumption)
- 70-80 % against a few % in solid state lasers
- air cooling: very high value of the ratio surface/volume
Amplification in Yb fiber

3 level system

920 nm 980 nm

4 level system

920 nm 1020 nm

High quantum efficiency

Broad pumping band (800 - 1064) - Semiconductor lasers
**Yb fiber laser**

- Prototype models: up to 100 W power output.
- Commercially available up to 15 W

- Important feature: the output is spatially single mode

The laser is pumped at 920 nm by semiconductor array diode lasers. The output wavelength is selected by the Bragg gratings.
Yb fiber lasers

**Main Features:**
- Up to 100W output optical power
- Beam quality $M^2<1.1$
- 1030 to 1120nm fixed wavelength
- Up to 20m SM fiber delivery
- Compact rugged package
- >50,000 hrs pump diodes lifetime
- Air Cooled
- 24V DC power line
- >100,000 hrs pump diodes lifetime
- Linear polarization option

**Applications:**
- Engraving
- Marking
- Micro Welding
- Micromachining
- Cutting
- Graphic Art Imaging
- Nonlinear Converters Pumping
Yb fiber lasers

**YLR-HP Series**

1 to 50kW CW Ytterbium Fiber Laser Systems

**Industrial Grade Systems**

**Main Features:**

- Excellent Beam Parameter Product
- Over 25% Wall-Plug Efficiency
- >100khrs Estimated Pump Diode MTBF
- Maintenance Free Operation
- Extremely Compact
- 2 Year Warranty
- Up to 200m Fiber Delivery
- Up to 50kW Output Available

**Applications:**

- Direct and Remote Welding
- High Speed Cutting
- Brazing
- Rock and Concrete Drilling
- Hardening