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Characterization of the 3F4 – 3H6 Transition in Thulium-doped Silica Fibres and Simulation of a 2µm Single Clad Amplifier

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Abstract We report measurements of absorption, gain and lifetime for two commercially available Tm-doped single clad silica fibres for the transition 3H6 – 3F4. Comparison of simulation and experimental results for a single stage amplifier at 1952 nm yields good agreement.

Introduction
With the recent progress in transmission system experiments in the 2 µm band, physical measurements and software tools for the simulation and design of Thulium-doped fibre amplifiers (TDFAs) are becoming increasingly important. Precise and accurate measurement of the absorption, gain spectra, and lifetime of the 3F4 – 3H6 transition in silica-doped Tm fibres are required to compare and simulate active fibres from different manufacturers. The precision of the measurements directly impacts the accuracy of the model. We selected two commercially available fibres for characterization, OFS TmDF200 and iXBlue IXF-TDF-4-125-v2, whose main characteristics are listed in Table 1. Using our physical measurements and simulation tool, we compared our simulation with experimental data for an amplifier at 1952 nm. Good agreement was found between the simulation and experimental results. Our model can be used to design CW or pulsed amplifiers for telecommunications or LIDAR applications.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>OFS</th>
<th>iXBlue</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Ø (µm)</td>
<td>4</td>
<td>5.3</td>
</tr>
<tr>
<td>NA (u.a.)</td>
<td>0.26</td>
<td>0.17</td>
</tr>
<tr>
<td>Abs @ 793 nm (dB.m⁻¹)</td>
<td>175</td>
<td>370</td>
</tr>
<tr>
<td>Co-dopant</td>
<td>Al, La</td>
<td>Al, Ge</td>
</tr>
<tr>
<td>Doping level (m⁻³)</td>
<td>8.4x10²⁵</td>
<td>/</td>
</tr>
</tbody>
</table>

Table 1: OFS and iXBlue fibre specifications according to manufacturer and literature⁷.

Fibre characterization
The transition lifetime was measured using an in-band pulsed source. The fibre under test (a few centimeters long) was in-band pumped around 1560 nm through a WDM. This pumping wavelength allowed us to totally invert the population. The pump power was increased until the backward fluorescence didn’t change as a function of pump power (Pₚₑₐ₉ > Pₚₑₐ₉ sat). The observed spectrum was corrected for the transmission of the setup. Because of back scattering, the pump light wasn’t negligible. Thus the usable data were fitted with a sum of Gaussians.

The small signal absorption was measured using a tunable laser and an ASE source using a cut-back method. Multiple cut-backs were performed with sample lengths of a few centimeters to multiple meters in order to measure the full spectrum. The data were fitted using a sum of Gaussians as shown in Fig. 2.

Fig. 1: Measured 3F4 lifetime curve with its two exponentials fit for the OFS and iXBlue fibres.

The small signal gain coefficient of the fibres was measured and calculated using three different methods.

The first method relies on the saturated fluorescence technique³. The fibre under test (a few centimeters long) was in-band pumped around 1560 nm through a WDM. This pumping wavelength allowed us to totally invert the population. The pump power was increased until the backward fluorescence didn’t change as a function of pump power (Pₚₑ₉ > Pₚₑ₉ sat). The observed spectrum was corrected for the transmission of the setup. Because of back scattering, the pump light wasn’t negligible. Thus the usable data were fitted with a sum of Gaussians.

The second method relies on launching a small
signal at 2050 nm through the previous setup and measuring its amplification. When the pump is off, the signal only sees the absorption through the sample. When the pump saturates the sample, the signal sees only the gain. The difference between the two states gives us the small signal gain since we already know the small signal absorption at the signal wavelength. This method is expected to give the most accurate results.

The third method uses McCumber theory on the fitted absorption coefficient. Here the calculation is done assuming room temperature at 25 °C. The wavelength at which the gain and the absorption cross \( (\alpha' = g'(\lambda')) \) is determined using the intersection of the fitted absorption and the fitted gain.

Differences between the iXBlue and OFS fibres can be observed as listed in Table 2. The iXBlue fibre has a shorter lifetime and a higher doping level (absorption \( \approx 2.6 \) times greater) than the OFS fibre, which can be explained by the core composition, co-dopants, and co-doping ratios.

**Table 2: Spectral characteristics of the OFS and iXBlue fibres.**

<table>
<thead>
<tr>
<th>Fiber</th>
<th>iXBlue</th>
<th>OFS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abs ( \lambda_{peak} ) (nm)</td>
<td>1643</td>
<td>1645</td>
</tr>
<tr>
<td>FWHM (nm)</td>
<td>195</td>
<td>180</td>
</tr>
<tr>
<td>Gain ( \lambda_{peak} ) (nm)</td>
<td>1801</td>
<td>1818</td>
</tr>
<tr>
<td>FWHM (nm)</td>
<td>301</td>
<td>298</td>
</tr>
</tbody>
</table>

**Single stage amplifier simulation**

Our simulation software models the Thulium ion as a three level (\( ^{3}H_{5}, ^{3}F_{4} \) & \( ^{3}H_{4} \)) system and can also take into account the ion interactions, the so-called “two-for-one” effect and its opposite. We assume the active fibre to be step index and the input signal spectrum to be monochromatic. The background loss is considered independent of the wavelength and set to 100 dB.km\(^{-1}\). Using the parameters we measured on the OFS fibre and other relevant values, we simulated and evaluated a core-pumped amplifier operating at 1952 nm. The doping level, the \( ^{3}H_{4} \) lifetime (12 \( \mu \)s) and the ion-ion parameters values \( k_{130}=2.4x10^{-24} \text{ m}^{3}\text{s}^{-1} \) & \( k_{201}=3x10^{-23} \text{ m}^{3}\text{s}^{-1} \) were taken from the literature. This single stage is composed of a 7 m long active fibre co and counter-pumped at 1550 nm by two DFB diodes, each delivering around 200 mW into the active fibre. The input and output are both isolated to prevent spurious lasing. Data displayed are relative to the active fibre. Three simulation cases are considered: with or without the ion-ion interactions for the doping level from the literature and then with ion-ion interactions for a doping level adjusted to get better agreement with the experimental data.
could be extracted from this amplifier at full pump power for an input signal power of 2.1 dBm at 1952 nm.

![Signal gain as a function of the input signal power at 1952 nm and full co- and counter-propagating pump powers.](image)

The amplifier was then run at full pump power and the input signal power varied. Up to 40 dB of signal gain was demonstrated for an input signal power of -35 dBm as shown in Fig. 4. The difference between simulation and experiment is found to be again less than 0.7 dB for the best fit and is independent of the input signal power. The noise figure was also simulated and measured, and found to be 3 to 3.5 dB on average below -10 dBm input signal power.

**Discussion**

Our measurements demonstrate our ability to precisely characterize a Tm doped fibre, and also confirm Agger’s and Povlsen’s data on the OFS fibre for the absorption coefficient and the lifetime decay. We observe a peak emission to peak absorption ratio of less than 1, according to both the saturated fluorescence method and the McCumber method. Overall, reasonable agreement is found between the two methods, but some differences at higher and lower wavelengths need to be explained. We also observe a good agreement between the saturated fluorescence method and the small signal amplification at 2050 nm, confirming the gain measured using the saturated fluorescence. Using our physical measurements of the OFS fibre and a value of \( N = 8.4 \times 10^{25} \text{ m}^{-3} \), our preliminary simulation results of the 7 m OFS amplifier was within 0.8 dB of experiment, when ion-ion interaction is taken into account. These results are encouraging but suffer from inaccuracies in parameters such as the doping level and the background loss. As an illustration, by adjusting the doping parameter from 8.4x10^{26} m^{-3} to 9.1x10^{25} m^{-3} we obtained simulation results that were within 0.5 dB of experimental results. Therefore, a better knowledge of the fiber parameters is needed in order to simulate the fiber in a more accurate and precise way. We intend to expand our simulations to the full Thulium transmission band in order to more fully evaluate our simulation software.

**Summary**

In this paper we established a characterization method for measuring three important parameters in commercially available OFS and IXBlue Tm-doped fibres. These parameters are the absorption, the gain, and the lifetime of the \( ^2F_4 \leftrightarrow ^2H_6 \) transition. Our measurements produced precise and reliable data that can be used in a simulation tool to model single clad Tm-doped fibre amplifiers. In particular, we validated the use of our parameters by simulating an amplifier made with 7 meters of the OFS fibre pumped at 1550 nm. The simulation at 1952 nm signal wavelength showed agreement to within 0.5 dB of the experimental output power data. In addition, both the simulation of small signal gain and the experimental data showed up to 40 dB of internal small signal gain. Simulation and measurement of the small signal internal noise figure yielded values close to the quantum limit of 3 dB.

**Acknowledgements**

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**References**