High stability single-frequency Yb fiber amplifier for Next Generation Gravity Missions

O. Fitzau¹*, M. Herper¹, M. Giesberts¹, K. Nicklaus², G. P. Barwood³, R.A. Williams³, P. Gill³, H. Koegel⁴, H.-D. Hoffman¹

¹Fraunhofer Institute for Laser Technology, ²SpaceTech GmbH, ³National Physical Laboratory UK, ⁴Airbus Defence & Space

ABSTRACT

In scope of the ESA funded “High stability Laser” activity, a single-mode and single-frequency fiber power amplifier with 500 mW output power at 1064 nm wavelength has been developed. It is part of an elegant breadboard (EBB) which consists additionally of an ultra-stable Fabry-Perot reference for frequency stabilization. The monolithic fiber amplifier is seeded by a non-planar ring oscillator (NPRO) with a linewidth below 10 kHz. The amplifier is stabilized in power via pump diode modulation and achieves a RIN performance of < 0.01/sqrt(Hz) in the range from 10⁻³ Hz to 10 Hz and a polarization extinction ratio of >30 dB.

Keywords: single-frequency, fiber amplifier, RIN, relative intensity noise, Yb fiber, high stability, NPRO, linear spectral density

1. INTRODUCTION

The potential ESA Next Generation Gravity Mission (NGGM) aims at the measurement of Earth’s gravitational field. Unlike its predecessors, GRACE and GOCE, NGGM will employ a narrow-linewidth laser as a signal source for the satellite to satellite interferometric ranging. Since the satellites will travel at an approximate distance of 100 km, a high spatial coherence of the laser source is required. To achieve high measurement accuracy the laser output power and frequency have to be extremely stable.

In this context, an elegant breadboard design of a laser source and frequency stabilization scheme has been developed by our consortium, comprising a non-planar ring oscillator (NPRO) as a seed source, a fiber-based power amplifier and a Fabry-Perot reference cavity for the frequency stabilization.

Since the final setup will be used on a satellite, thermal load, power consumption and overall efficiency as well as the susceptibility of the components to vibration, shock and to cosmic irradiation had to be considered.

In this paper, the current results on design and performance, especially of the fiber amplifier, will be presented.

2. SYSTEM REQUIREMENTS

Within the NGGM activity, the laser will be used as a signal source for a ranging interferometer between two satellites that are orbiting Earth in a tandem arrangement with a distance of around 100 km. The basic idea is that local variations in the earth’s gravitational field will lead to a change in the distance between the satellites, which can be measured by the interferometer. Since the changes in the gravitational field will be fairly small, distance changes between the satellites due to the gravity field are expected to be in the µm range. Therefore, the output signal of the laser needs to be extremely stable to make sure that variations in the interferometer signal result from distance variations and not from the

*Mail: oliver.fitzau@ilt.fraunhofer.de
fluctuations of the laser. To this end, the stability requirements are given in terms of the laser’s relative intensity noise (RIN)

\[ RIN \leq \frac{10^{-3}}{\sqrt{Hz}} \sqrt{1 + \left(\frac{10 mHz}{f}\right)^4} \text{ for } 10^{-4} Hz < f < 1 Hz \]

and its frequency noise

\[ \sqrt{S_y} \leq \frac{40 Hz}{\sqrt{Hz}} \sqrt{1 + \left(\frac{10 mHz}{f}\right)^2} \text{ for } 10^{-4} Hz < f < 1 Hz. \]

Further requirements define the maximum available seed power which amounts to 25 mW, as this is similar to the output power of commercially available, space-qualified NPROs.

Next to available space and electric power, additional requirements are an output power of 500 mW, an M² no greater than 1.2 and a polarization extinction ratio (PER) above 20 dB

Figure 1 shows the actual setup. The system consists of a frequency reference with Pound-Drever-Hall (PDH) stabilization scheme that was developed at the National Physical Laboratory in the UK and the Laser head itself, which is presented here and was developed at the ILT. SpaceTech was responsible for the overall system design while the final tests are being performed at Airbus Defence & Space. An overview of the complete system design is given in [1].
3. DESIGN CONSIDERATIONS

Available space qualified laser sources with the required frequency stability do not provide the required average power of 500 mW, therefore a Master Oscillator Power Amplifier (MOPA) concept is chosen. This approach also provides flexibility regarding possible sources for the narrow-linewidth signal. This way, the output power can be regulated by adjusting the pump power for the amplifier while letting the seed source operate at constant power to ensure maximum stability of its output signal properties. Due to its intrinsically stable narrow-linewidth and proven space qualification, an NPRO is chosen as a seed source for the fiber amplifier.

Owing to its large interaction length and small modal cross sections (high intensity), fiber lasers are generally susceptible to nonlinear effects. As the linewidth of the signal needs to be below 10 kHz, stimulated Brillouin scattering (SBS) can become an issue, even at the low output power level. The relevance of SBS in this context can be estimated by looking at the threshold power $T_{SBS}$, at which already half of the laser output power is converted into Brillouin-scattered light. This power depends on the mode field area, as indicated by $A_{eff}$, the effective fiber length $L_{eff}$, which takes the actual power into account, as well as the signal linewidth $\Delta \nu_p$. The constants $\xi$, $g_B$ and $\Delta \nu_S$ depend on the properties of the host material and the polarization of the signal. Of course, it is important to stay well below this power level. Therefore, $L_{eff}$ needs to be kept as short as possible while $A_{eff}$ needs to be as large as possible.

$$T_{SBS} = \frac{21\xi A_{eff}}{g_B L_{eff}} \left(1 + \frac{\Delta \nu_p}{\Delta \nu_S}\right)$$  

(1)

To this end, a 10/125 $\mu$m fiber is chosen as the gain medium. Firstly, because its larger core size as compared to standard 6/125 $\mu$m fibers leads to a larger mode field area and, secondly, because the larger core-to-cladding area ratio leads to a higher absorption, thus allowing for a shorter piece of fiber to be used. In order to further increase the absorption and keep the fiber length short, a pump at 976 nm is used. Since pumping at this wavelength can lead to strong fluctuations in the absorption when the output wavelength of the pump changes, e.g. due to temperature changes, a grating-stabilized diode is chosen as the pump source.

To achieve good signal-to-noise ratio (SNR), a co-directional pumping scheme should be used in which the pump light is travelling in the same direction as the amplified signal. However, this leads to a greater effective fiber length than a contra-directional pumping scheme which therefore is preferred in our setup, keeping in mind the threshold for SBS. To still ensure a good SNR, a bandpass filter is introduced into the setup at the signal exit.

A modular design is chosen which consists of three individual boxes, housing the pump diode, the fiber amplifier and the control electronics. This design allows for the separation of the strong heat sources, which is mainly the pump diode, from the most heat sensitive elements and also the possibility of conveniently placing the modules in different positions within the satellite. Furthermore, the separated pump diode allows fulfilling a redundancy concept.

For the stabilization of the output central wavelength as well as the output power, two feedback loops are introduced into the setup (Figure 2). A small fraction of the seed signal is coupled out of the seed path via a tap coupler and routed into the reference cavity to create the signal for the PDH frequency stabilization, which uses a piezo actuator as well as a feedback to the NPRO’s crystal temperature to modulate its output wavelength. For the power regulation feedback loop, a small fraction of the output power is delivered to a photodiode, again by way of a tap coupler. The photodiode signal is used as a power reference and the attached electronics allow for the regulation of the output power by adjusting the pump power for the amplifier.
Figure 2: Schematic of the implemented feedback loops. The first loop ensures the high frequency stability of the seed light. The second loop controls the laser output power by monitoring the current output power and regulating the pump diode current.

The main part of the laser head is the fiber amplifier module which contains all fiber components (Figure 3). On its way to the amplifier, the seed signal passes two tap couplers, the first one for the PDH frequency stabilization, the second one for the ‘seeder on’ safety interlock, and an isolator.

Figure 3: Schematic of the fiber amplifier.

The multi-mode pump combiner couples the pump light contra directionally into the active, Yb-doped, 10/125 µm fiber. Behind the band pass filter a subsequent tap coupler provides the feedback loop signal for the power regulation.

All functions of the amplifier, e.g. thermal stabilization of the pump diode, readout of the photodiodes or power regulation, are controlled by an electronics board with a 16 bit readout circuit, which was specially designed for this project, especially taking into account that the implemented circuits can be converted into a space-proof design.

Component tests and simulation

Since the major part of the project is to find a design suitable for operation in the expected environment of a later space mission, the thermal and mechanical properties needed to be investigated with respect to thermal load and its impact on the components’ properties and also the mechanical stresses that all components need to be able to withstand.
Therefore, each component was investigated regarding its criticalities, e.g. radiation-induced effects on the active fibers, changes in the tap couplers coupling ratio when exposed to temperature changes or the individual losses and heat dissipation created by each component.

Extensive data on radiation-induced losses in optical fibers is available, e.g. in [2], however, mainly for passive setups. Since the final application will be a constantly running laser, we decided to do the measurements of the radiation-induced absorption in an active setup, since the laser operation can cause annealing effects to take place. Therefore, we built two amplifiers with an output power comparable to the required power of the breadboard setup. Different types of commercially available active and passive fibers were introduced into this setup and exposed to gamma radiation up to a total dose of 20 krad, which represents the expected dose for this low earth orbit application. The radiation-induced absorption was determined and, according to the results, one commercial fiber was chosen for the actual setup since it exhibited a significantly lower susceptibility to irradiation than the other candidates. The measured values for the radiation-induced absorption in the fiber that was chosen for our setup are summarized in Table 1.

<table>
<thead>
<tr>
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<th>RIA after 20 krad gamma dose in dB/m</th>
<th>Signal</th>
<th>pump</th>
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<tr>
<td>active fiber</td>
<td>0.4298</td>
<td>0.0821</td>
<td></td>
</tr>
<tr>
<td>passive fiber</td>
<td>0.0477</td>
<td>0.0019</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: End of lifetime (EOL) results for the fiber that is chosen for the actual setup.

Since the results show only a small effect in passive fibers, the remaining fiber-optical components did not have to be tested for radiation-induced effects. However, the performance of the VBG stabilized pump diode under irradiation was still unclear, so it also had to undergo radiation tests, in this case with both gamma and proton irradiation.

In order to quantify the diode’s performance, we defined the locking factor $F_{lock}$ as the ratio of output power within the desired wavelength range to the total output power.

$$F_{lock} = \int_{975 \text{ nm}}^{977 \text{ nm}} \frac{P_\lambda \, d\lambda}{P_{tot}}$$  \hfill (2)

Figure 4 shows the performance of the pump diode in terms of frequency locking and output power before and after gamma and proton irradiation. The total gamma dose was 20 krad, the same as for the fiber tests, additionally, the diode was exposed to $4\times10^{10}$ protons/cm² at 36 MeV for 10 minutes which represents the expected dose for the unshielded diode as worst-case scenario. While the output power after irradiation remained virtually unchanged, the locking factor decreased significantly, especially the proton radiation led to a strong effect. Thus, the pump diode is operated at an increased temperature.
Based on the components tests, the amplifier performance could be simulated for the initial properties as well as for the end-of-lifetime (EOL) case, taking all the radiation-induced effects of both active and passive fibers, as well as the pump diode, into account.

4. Results

Figure 5 shows the output power of the laser head vs. pump current. At 3.5 A, the power amounts to 500 mW, the linear behavior indicates that there is no significant influence of non-linear effects, especially SBS, which could be expected at linewidths below 10 kHz. Also, no thermal rollover was observed up to this power level.

Figure 6 shows a comparison between the normalized spectrum of the NPRO seed signal and the output signal, measured with an optical spectrum analyzer and a resolution of 50 pm. Apart from a low ASE noise level below 60 dB in the amplified signal, both spectra are very similar.
The RIN performance of $< 0.02$/sqrt(Hz) in the range from $10^{-4}$ Hz to 10 Hz can be seen in Figure 7. Over the complete range, the RIN performance is at least one order of magnitude lower than the requirement.

Stabilizing the seed frequency by an external high finesse reference cavity the amplified output achieved a frequency noise $< 40$ Hz/sqrt(Hz)xNFS(f) in the range from $10^{-4}$ Hz to 1 Hz (Figure 8) in thermal environment similar to the expected environment of a later mission.
Figure 8: Preliminary results of the frequency stabilization of the NPRO seed source with fiber amplifier that were performed by the NPL.

The output polarization was measured to be \( > 30 \text{ dB} \), which is well above the requirement of a PER better than 20 dB. The total electrical power consumption of the fiber amplifier including the pump diode and its temperature stabilization is lower than 20 W.

5. SUMMARY AND OUTLOOK

In order to achieve the relative intensity noise requirement defined by ESA, the active stabilization of the amplifier is achieved via pump diode power modulation and it results in a value that is more than one order of magnitude lower than the requirement in the frequency range of \( 10^4 \) to 10 Hz. Further on, the linear spectral density of the output frequency is measured and shows also a match to the required values in a frequency range of \( 10^{-2} \) to 1 Hz.

The achieved output power amounts to 500 mW at a center wavelength of 1064.5 nm and a PER of 30 dB.

For the development of the amplifier and the design of all components, we took into account structural and thermal analyses and a pre-selection of off-the-shell components regarding thermal behavior to achieve the RIN and frequency-LSD performance with respect to the boundary conditions in a satellite given by ESA.

6. ACKNOWLEDGMENT

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7. REFERENCES
