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# Development of a highly-efficient amplifier system for 10-channel satellite laser communication in the context of the HydRON project

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## ABSTRACT

We present the development of a fiber-based high-efficiency laser amplifier (HELA) as a demonstrator for future high throughput satellite communication systems operating in the 1 µm wavelength range. The work is conducted in the context of ESA's ARTES ScyLight framework programme (SeCure and Laser Communication Technology) and more specifically within its HydRON project. Combining the experiences of in-house manufactured optical fiber components and of laser developments for space applications, an all-fiber amplifier solution was designed. The realized laboratory testbed simultaneously amplifies a 10-channel seed input from the mW-level up to a total output power of 100 W. Leveraging the benefits of advanced fiber technology, an enhanced wall-plug efficiency of about 29% has been achieved.

**Keywords:** Fiber amplifier, laser communication, WDM, HydRON

## 1. INTRODUCTION

The demand for optical technologies in the context of space applications has increased in the recent decades. Especially, the utilization of particular laser systems enables innovative spaceborne techniques, such as the monitoring of the Earth's atmospheric processes (e.g. wind speed) by means of the lidar method. In the domain of optical telecommunication, the role of the laser has to be assessed even higher. It is a game changer to improve the performance of established space applications and paves the way for expanding the corresponding capabilities of such systems. As an example, the optical satellite communication platform as developed by the European Space Agency (ESA) can directly benefit from such specially designed laser systems. Since the start of the deployment of the European Data Relay System (EDRS) in 2016, satellite laser communication technology has demonstrated its capability of reliably providing quasi-real-time data services. In a next step to integrate satellite and terrestrial networks, a high throughput optical network in space (HydRON) shall be established, with the goal to provide optical interconnections with Terabit per second data rates [1].

The high-bandwidth ground/satellite optical interconnections will be based on wavelength division multiplexing (WDM) laser terminals with 10 (or more) optical channels with a minimum individual data rate capability of 10 Gbps and approximately 1 nm channel spacing. For the incoming weak laser signals on each HydRON space node, sub-units of the laser communication chain have to amplify the optical signal. Next to many power consuming units of satellite communication systems, an enhanced wall-plug efficiency of the core laser amplifier sub-unit is a crucial point regarding the feasibility and competitiveness of the all-optical approach to a Tbps coherent communication network. Other space applications such as in the domain of lidar and scientific metrology can also benefit from corresponding developments in the 1 µm wavelength range.

In this context, we present the development status of a continuous-wave (CW) fiber amplifier for the use in WDM optical communication systems with a total output power level of 100 W. A focus was placed on the simultaneous multichannel amplification in a single fiber as well as on enhancing the wall-plug efficiency (WPE) to a level of around 30%. In this context, the WPE of this high-efficiency laser amplifier (HELA) is defined as the ratio of the amplifier's overall optical output power and its electrical input power, including laser pump sources as well as drive and control electronics. For the realization of such comparably high WPEs and after the comparison of different laser amplifier concepts, a fiber amplifier architecture showed the highest potential to fulfill all requirements for the HELA design. Especially in the 1 µm wavelength range, current developments in optical technologies allow for the realization of amplifier schemes with enhanced WPEs.

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# 2. HELA SYSTEM ARCHITECTURE

The baseline design of the HELA system is conceptualized as a two-stage fiber amplifier architecture and is shown in Figure 1. The system is designed to increase an input power level of a 10-channel seed signal from 1 to 10 mW per channel to an optical output power of 10 W per channel. In order to demonstrate the specific capabilities of the amplifier system especially regarding output power and gain flatness across the seed spectrum, a corresponding seed laser system has been developed which is briefly described Section 2.1. The actual fiber amplifier system is presented in Section 2.2.

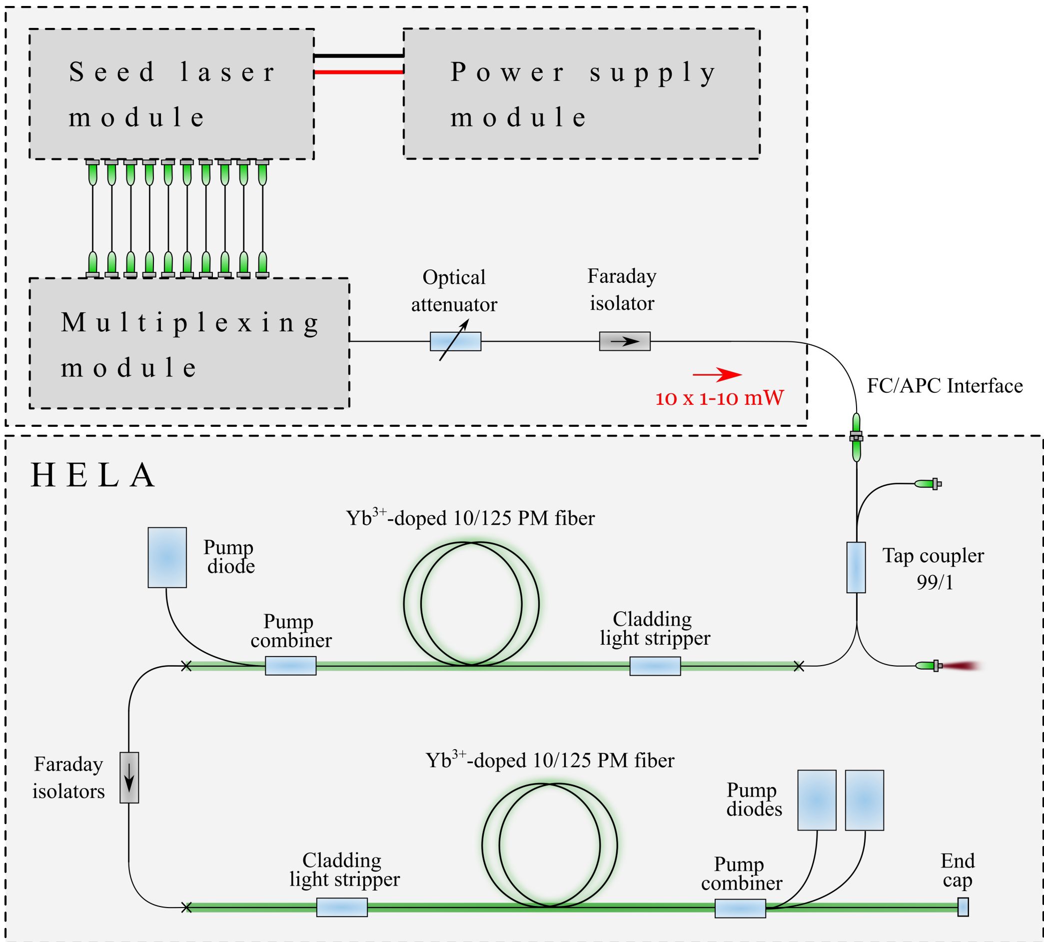


Figure 1: Setup of the HELA design based on a two-stage amplifier architecture including in-house manufactured fiber components. A corresponding seed laser system with 10 optical channels guided inside a single-mode fiber was developed in order to demonstrate the capabilities of the amplifier system.

## 2.1 HELA seed laser concept

The corresponding 10-channel seed laser system is designed as an auxiliary ground support equipment to operate the fiber amplifier and is composed of three modules:

a) The power supply module containing both a 5 V power supply for the laser diode drivers as well as a 24 V power supply driving the automation control system inside the seed laser module.

b) The seed laser module containing 10 diode drivers together with the narrow-linewidth distributed feedback (DFB) laser diodes and an automation control system.

c) The multiplexing module based on cascaded volume Bragg gratings (VBGs).

The output signals of the 10 DFB diodes are multiplexed into a polarization-maintaining (PM) single-mode fiber by means of setup based on VBGs and free-space fiber coupling. Offering a narrow bandwidth with a FWHM of only 0.6 nm, each VBG is precisely aligned in order to reflect the signal wavelength of its corresponding DFB diode. At the same time, the VBGs efficiently filter out most of the ASE background of the seed laser diodes. An optical isolator is included at the output of the seed laser system in order to protect the DFB diodes from any backward traveling signal originating from the amplifier modules.

A schematic of the corresponding setup is shown in Figure 2 together with an image of the realized breadboard setup. Through an automation control system and its corresponding software, each of the DFB diodes can be individually adjusted regarding diode current and housing temperature in order set the required output power and wavelength. At nominal diode current, the seed laser system can deliver an optical output power of up to ~20 mW per channel.

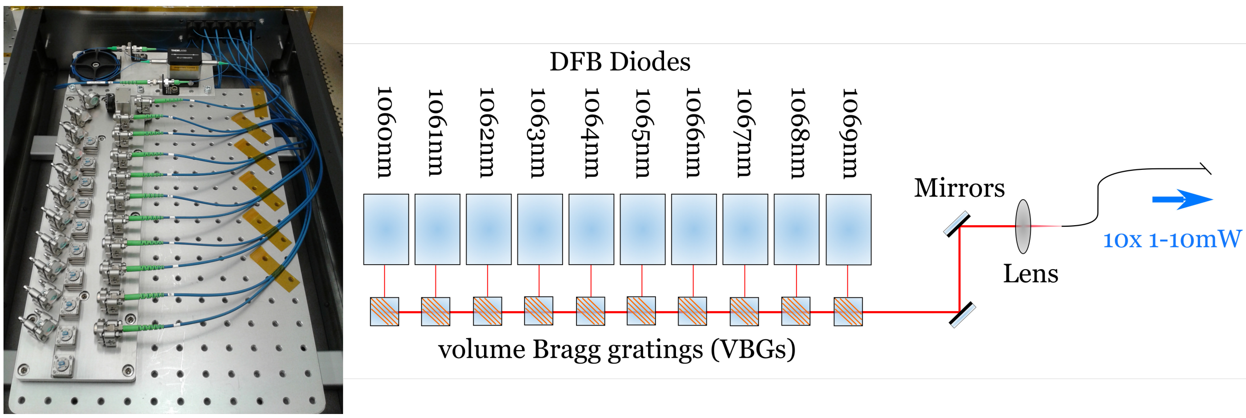


Figure 2: Concept of the HELA seed laser system based on volume Bragg gratings and a free-space coupling into a polarization-maintaining single-mode output fiber.

Additionally, a fiber optical attenuator is integrated at the output of the seed laser system, allowing to arbitrarily modify the total seed power between 10 mW and 100 mW. Thus, the seed can be operated with output powers between 1 mW and 10 mW per signal channel, which is the required range for the characterization of the HELA system. The corresponding output spectrum of the combined 10-channel seed signal is represented in Figure 3. Here, the power levels between the channels and the final signal wavelengths were adjusted via the pump current and the temperature of each individual DFB diode. After the optimization, peak-to-peak power variations of less than 2% were achieved.

With this signal, the following HELA amplifier modules were seeded and the performance of the system was characterized.

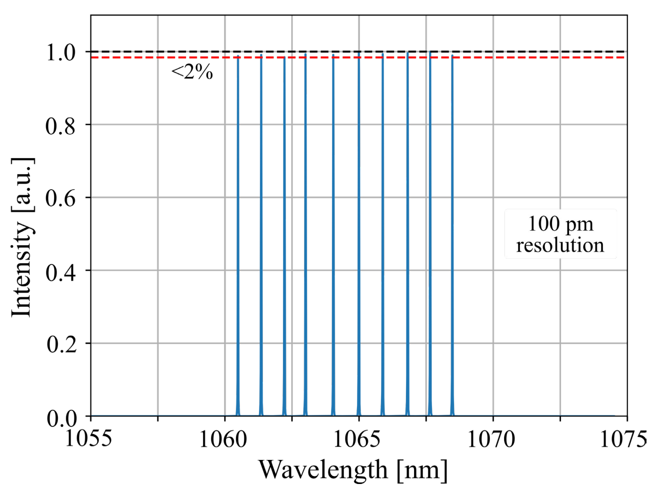


Figure 3: Optical spectrum of the 10 seed laser channels with peak-to-peak power variations <2%.

### 2.2 HELA fiber amplifier concept

The detailed setup of the HELA fiber amplifier concept is presented in Figure 1. An FC/APC connector is used as the HELA input interface. The following tap coupler serves as a monitor port for the optical seed power. This signal is used for an integrated interlock system, which can shutdown the system in a case of a seed system failure.

A pre-amplifier integrated to minimize the ASE fluctuations at high gain factors contains both a pump combiner (PC) as well as a cladding light stripper (CLS). Based on the in-house experience with fiber optical technology, these components were developed and manufactured at LZH. An integration of both PC and CLS directly into the active $Yb^{3+}$-doped fiber allowed to avoid any critical fusion splices within the amplifier stages.

Based on a side-pumping technology, each PC consists of an $Yb^{3+}$-doped signal fiber and two multi-mode (MM) 105/125 input fibers which transfer the pump light from the laser diodes into the system. The key advantage of this pumping technology is the uninterrupted signal core, eliminating the need for an additional fusion splice in conjunction with signal mode matching. For the optimization of the coupling efficiency of the pump light from the MM-fibers into the actual signal fiber, coreless MM-fibers were spliced to the 105/125 input fibers. For each of the realized PCs, an optical coupling efficiency of the pump light into the signal fiber of approx. 85% has been achieved.

Any residual pump light that is not absorbed during the amplification process inside the active $Yb^{3+}$-doped fiber is removed by a CLS manufactured with a $CO_2$-laser [2]. The physical design of the CLS interrupts the guidance properties of the fiber's cladding. As a result, the pump light is extracted from the cladding and directly guided into the housing of the component, which serves as a beam dump in this case. The resulting heat load is dissipated in a controlled manner via the thermal interface of the HELA system, which is composed of a thermally well-conducting baseplate water-cooled to approx. 18 °C. The latter also serves as a heat sink for the VBG-stabilized laser diodes operating at 976 nm that are employed to pump the HELA system.

The main-amplifier is systematically designed in the same way as the pre-amplifier. In contrast to the pre-amplifier, the optical components of the main-amplifier have to fulfill high-power requirements. Both pre-amplifier and main-amplifier are operated in a counter-pumped configuration in order to reduce non-linear effects such as four-wave mixing and to increase the optical output power. Furthermore, two Faraday isolators are implemented for an optimum isolation between both amplifier stages.

Due to the 10 µm core diameter of the employed fibers, a high intensity occurs at the fiber end facet at the output of the main-amplifier. Such high intensities can irreversibly damage the fiber end or the entire amplifier system. Therefore, an end cap was fused to the output fiber in order to decrease the intensity at the transition to the air. For the HELA laboratory testbed, a ½"-diameter fused silica substrate with a thickness of 6 mm and an anti-reflective coating on the output surface was used.

## 3. PERFORMANCE OF THE HELA SYSTEM

### 3.1 Optical slope

The measured optical output power of the HELA system versus the injected optical pump power is shown in Figure 4. In order to optimize the performance of the system, fiber cut-back experiments have been performed with both amplifier stages. In Figure 4a), the performance of the pre-amplifier with 2.2 m of active fiber is presented. This particular fiber length has been chosen as a trade-off between the amplifier efficiency on the one hand and the required gain flatness across the seed spectrum on the other hand. At a seed input power of 10 mW per channel, an output power of 1.40 W was achieved from an optical input pump power of 3 W. At 1 mW per channel, the pre-amplifier delivered an output power of 1.13 W. This corresponds to optical-to-optical efficiencies of ~47% and ~38%. A potential explanation for this rather low efficiency is the low optical saturation in the 10 µm fiber core with a seed input power in the mW-regime.

The optical slopes of the main-amplifier module are shown in Figure 4b). Here, the pre-amplifier was operated at the maximum available output power. Compared to the performance of the pre-amplifier, the relative output power variations of the main-amplifier between different seed input powers are smaller. At an optimized fiber length of 2.2 m and a total pump power of approx. 160 W, the desired output power level of 100 W was obtained. This corresponds to an optical-to-optical efficiency of ~63%.

The total efficiency of the HELA amplifier module is primarily influenced by the efficiency of the pump diodes and the slope efficiency of each amplifier stage including the optical losses of the fiber-based components. The WPE at an output power of 100 W was determined based on the required electrical input power, which was calculated by the pump diodes voltages and currents and an assumed optimized flight electronics efficiency. By this, a final WPE of 29.0% was obtained.

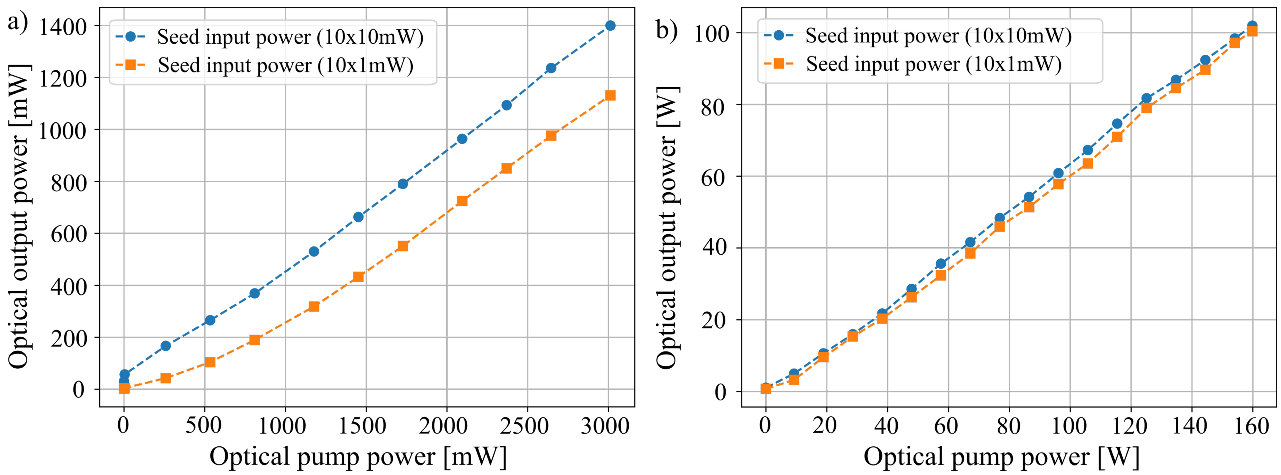


Figure 4: Optical slope at different injected optical pump powers of the pre-amplifier in a) and of the main-amplifier in b). The performance was tested with seed input powers of 10 mW and 1 mW per channel.

### 3.2 Optical spectrum

Another important aspect besides the slope efficiency is the equal amplification of all signal channels. A final optical spectrum is shown in Figure 5, which has been acquired at the nominal output power of 100 W when seeding the HELA system with 10x10 mW of input power. Here, the peak-to-peak power variations between the channels were below 1 dB. This small difference between the individual signals was achieved by means of an optimized length of the active fiber in both of the amplifier modules.

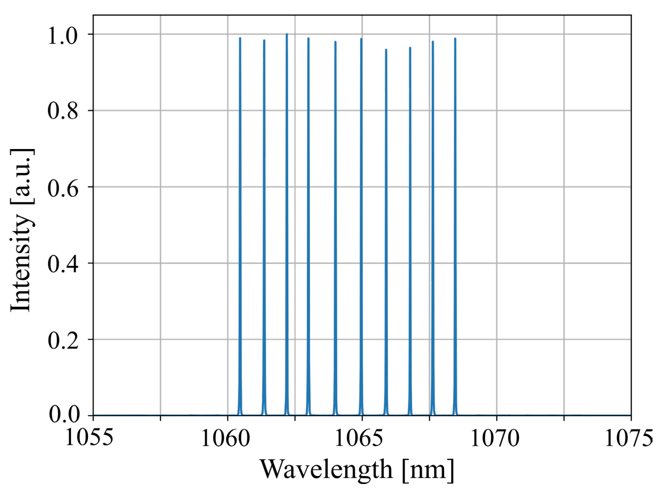


Figure 5: Optical spectrum after the main-amplifier at a total output power level of 100 W (10x10 mW of seed input power).

### 3.3 Long-term output power stability

For the HELA system a stable long-term operation is required, with peak-to-peak power variations of <2% over 24 hours. For the characterization of this parameter, the optical output power of the HELA system was logged with a thermal power sensor (*Ophir 1000W-BB-V3)* for more than 25 hours. The long-term test was performed with the maximum available output power of the pre-amplifier and the nominal total power of 100 W provided by the main-amplifier, which corresponds to approx. 10 W per optical channel. After both amplifier stages reached their targeted working point, the output power was stable for more than 25 hours as shown in Figure 6. The resulting peak-to-peak variations of the total power were in the range of 0.95%.

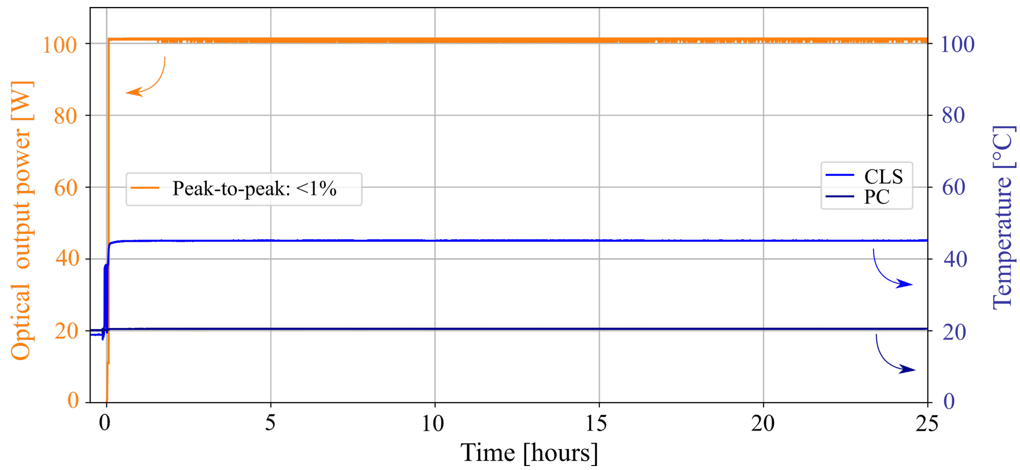


Figure 6: Long-term measurement of the optical output power of the HELA system in orange. The temperatures of the key components of the main amplifier (CLS: cladding light stripper, PC: pump combiner) are shown in blue.

In addition to the optical power, the temperatures of the key components of the main amplifier were monitored during the aforementioned long-term test. On top of the housings of both PC and CLS, PT1000 temperature sensors were installed. Especially inside the CLS, the residual pump light extracted from the active fiber is directly converted into heat, which has to be transferred out of the system via the water-cooled thermal interface. During the long-term operation, the housing of the CLS reached a stable temperature of around 45°C (see Figure 6, blue line). From experience, this value is not critical for the reliability of the component.
The heating of the PC was due to the typical power leakages inside this component. Compared to the CLS, the temperature of the PC was significantly lower and reached ~20°C. This does not compromise the long-term operation of the HELA system either.
Another important optical parameter is the polarization extinction ratio (PER) of the output beam which is required to be >20 dB for the HELA system. At the nominal output power of 100 W, a stable PER of >23 dB was achieved, which can be attributed to the spliceless configuration of both amplifier stages.

## 4. CONCLUSION

In this contribution, we presented the design of a laser amplifier for a WDM optical communication system operating in the 1 µm wavelength range. Due to the employed fiber technology, an enhanced wall-plug efficiency of about 29% was demonstrated. Combining the experiences of in-house manufactured optical fiber components such as specially designed pump combiners and cladding light strippers, and of laser developments for space applications, an all-fiber amplifier solution was designed. Taking advantage of a spliceless configuration in both amplifier modules of the system, an optimum amplifier performance with a total output power of 100 W and a PER of >23 dB was achieved. A stable laser operation was demonstrated with peak-to-peak power fluctuations <1% measured during a 25-hour long-term test. While this development is driven by the needs and specifications of the HydRON mission concept, it can also benefit other space applications in the domain of lidar and scientific metrology.

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