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FULAS: HIGH ENERGY LASER SOURCE FOR FUTURE LIDAR APPLICATIONS

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I. INTRODUCTION

For atmospheric LIDAR instruments in space, a manifold of scientific applications exists. But due to the lack of high energy laser sources providing the performance, reliability and lifetime necessary to operate such instruments in space, realization is currently seen as still very critical in the community.

To overcome this, the FULAS (Future LASer Technology) project has been initiated by ESA in cooperation with the German space agency (DLR), to develop and built a technology demonstrator and to verify its suitability for potential space missions. In order to cover the common need of possible future lidar missions, requirements for a generic laser source had been defined to achieve maximum usability of the laser concept and technology for future LIDAR missions.

For definition of the baseline requirements, requirements of different potential LIDAR missions for Earth Observation have been evaluated. Depending on the mission, different types of lidar principles, e.g. Doppler wind lidar, backscatter lidar or DIAL, are required which need different kinds of laser transmitters (e.g. emitting single or double pulse, operating in burst mode, operating at different wavelength and pulse energy). Common for most of them is the need of a stabilized high quality and high energy laser source which can be based on a common solid state laser platform, if necessary in combination with suitable external frequency conversion to provide the required wavelength.

The main goal of the design concept of FULAS is to get versatile technology building blocks. Therefore, beside the predefined nominal operation requirements (close to the specifications of the ATLID Atmospheric LIDAR of the Earth Care mission), the flexibility of the design to be adapted and customized for manifold potential future LIDAR missions will be demonstrated.

One of the main issues with respect to lifetime and reliability for high energy lasers in space is the risk of degradation of optical coatings. The main focus here is on effects by Laser-Induced-Contamination (LIC) wherefore LIC risk mitigation is a major design criterion, demanding development of several innovative technology solutions to reach the design goal to reduce the amount of organic materials to close to zero.

Currently, the presented FULAS technology demonstrator is in construction phase, to be operable and ready for extensive testing begin of 2015. The technology will also be the heart of the Methane Remote Sensing Lidar Mission (MERLIN) [3],[4] (DLR/CNES, currently in Phase B).

II. OVERAL SYSTEM DESIGN

A. System overview

The FULAS laser is built as a pressurized and hermetically sealed housing of about 500 x 200 x 300 mm³, with an isostatic mounting I/F for accommodation. As shown in Fig. 1, the housing central main frame provides several hermetical feedthroughs for electrical and optical connectors, thermal-hydraulic feedthroughs for the miniature loop heat pipes (LHP) and a beam exit window.

An external cold plate attached to the central frame of the housing serves as condenser for the LHPs and as overall system thermal I/F.

The mounting of the laser optical bench is optimized for decoupling from the surrounding structure. By isostatic mounting inside the housing central frame, the optical bench is insulated from stress induced by the instrument environment. Particularly, it features a maximum tolerance with respect to mechanical deformation due to environmental pressure changes.

The compliance of the basic optical concept to the requirements, using conventional mounting technology and components, is currently validated in air-borne LIDAR applications, operated by DLR. To achieve space compatibility, the design is optimized with special attention on LIC issues introducing several new technologies.

To reduce LIC effects, a hermetically sealed housing provides lifetime atmospheric pressure conditions for the laser optical system. Use of innovative soldering techniques for optics alignment and glue free mounting, new concepts for the electrical harness avoiding plastic insulation, a newly developed friction stir welding (FSW) process for the pressurized housing and other details enable the realization of the design goal of an "all metallic, ceramic or glass design" by very few exceptions only.

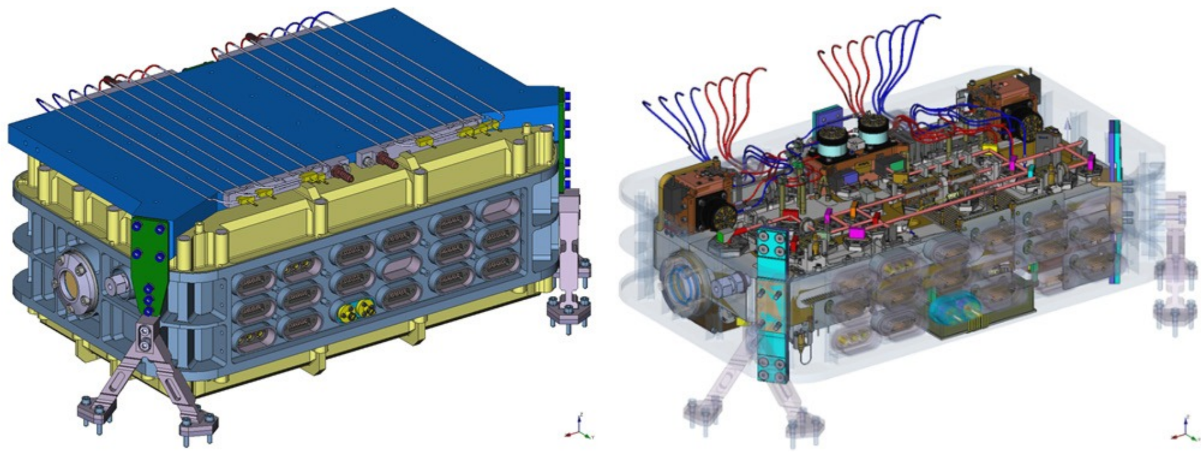

Fig. 1. FULAS pressurized housing with top-mounted cold plate and internal optical bench

B. Major design requirements

Beside the typical space instrument requirements to deal with the very limited power and mass budgets and to tolerate high vibrational loads and large thermal range, as well as the high stiffness and extraordinary geometrical stability requirements typical for optical instruments, a laser transmitter like FULAS is driven by further, application specific critical requirements.

One of the most critical design aspects to operate a high energy laser in space is the risk of degradation of optical coatings due to high energy laser radiation. The lessons learned from former programs have focused the attention on effects by Laser-Induced-Contamination (LIC). Hence for optical components exposed to high energy laser radiation, extraordinary cleanliness even on molecular level is mandatory. This is in particular valid for instruments in the UV spectral range, as given for FULAS. Therefore the avoidance of outgassing organic substances like glues and plastics, even in variants labeled as "low outgassing", is a major design requirement.

One well-known measure to mitigate the LIC criticality is the presence of an Oxygen containing atmosphere, which demands a hermetically sealed and pressurized housing for operation in space. Furthermore, a pressurized environment also is beneficial for the damage threshold of some optical coatings, thus increasing the reliability and durability of the system. Consequently, a pressurization requirement for the whole laser housing, including necessary feedthroughs and the exit window, has been established. Starting from 1 bar initial pressure, a pressure drop in space/vacuum of not more than 0.1 bar over lifetime (3 years) is specified to guarantee stable conditions.

Further design driver is the need for efficient extraction of the thermal loads, independent from the mechanical I/F, and active stabilization of the temperature of the main heat sources (laser diodes), while limiting the overall thermal gradients and resulting thermo elastic deformations.

C. "Clean" Pressurized housing

Due to the need of a lightweight design while providing the thermal conductivity to support thermal balancing, Aluminium was the material of choice for the housing. To provide access to both sides of the double sided optical bench, a symmetrical open frame is used, carrying the optical bench (Fig. 1). This frame is closed by two symmetrically bolted covers, primary-sealed by special metallic gaskets, enabling easy reopening and resealing during assembly and testing. For final life-time sealing, the covers are designed to be welded, providing a reliable redundant secondary sealing.

The challenging part of the design is the need of a multitude of various feedthroughs (electrical, thermal and fibre-optical) to operate such a system, as well as a high quality optical beam exit window. To fulfil the cleanliness and lifetime requirements, only thermal joining methods as welding, brazing or glass/ceramic potting are applicable. For brittle materials like glass a CTE-matched joint is necessary, which typically leads to low CTE metals like Steel or Titanium, not compatible with an Aluminium housing and conventional joining technology.

The special modular design realized for FULAS is based on different feedthrough modules in similar geometry and with Titanium or Stainless Steel body. To overcome the incompatibility of conventional welding methods to join this materials with an aluminium housing, a special joining process is applied. This mechanical FSW process was optimized in the frame of the project, using a special effector developed by Airbus Group.

D. Active thermal management

To allow an efficient rejection of about 100 W of thermal load inside the pressurized housing and minimize thermal gradients across the optical bench, mini Loop Heat Pipes (LHP) are directly attached to the major heat sources inside the laser housing, as illustrated in Fig. 2.

Four pairs, each operated in one-out-of-two cold-redundancy configuration, are connected with their evaporators directly to the main heat sources on the optical bench, enabling selective cooling directly at the source. By its semi rigid tubing combined with dedicated housing feedthroughs the heat is efficiently transported out of the housing towards the external cold plate. Due to the low mechanical stiffness of the tubes, the optical alignment and the mechanical decoupling of the optical bench is conserved and not affected by the thermal I/F.

A very important feature of the LHP technology, contrary to classical heat pipes, is the possibility to control the conductivity by active derating using an attached inhibition heater. Powered with $\ll$ 1 W, the necessary precise, but effective active temperature control is possible. By powering the heater of one LHP out of the redundant pair with about 1 W, the inhibition is suitable to completely disable the relevant LHP and therewith realize the cold-redundancy design.

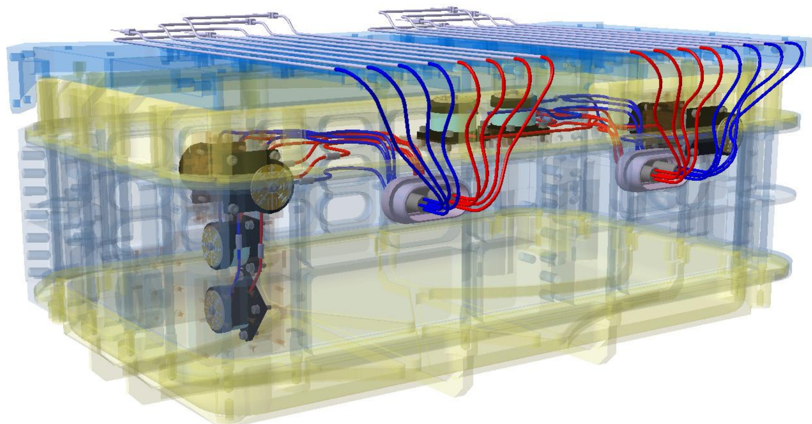

Fig. 2. Housing with LHP – Thermal management Sub-System

III. LASER OPTICAL DESIGN

A. Operation principle

The FULAS system as presented is a high power laser system using solid state laser technology which is state of the art for industrial applications. The laser optical design consists of a frequency stabilized Nd:YAG Master Oscillator - Power Amplifier (MOPA) configuration with external frequency tripling by non-linear third harmonic generation (THG). The main nominal laser parameters are shown in Tab. 1.

The master oscillator includes a Nd:YAG crystal rod as gain medium, end-pumped from both sides by fiber coupled laser diode modules. For pulsed operation, the resonator is q-switched by use of a pockels cell. To achieve single longitudinal mode operation and to fulfill the stringent requirements on the pulse quality, the oscillator is injection seeded and cavity controlled by a piezo driven end mirror. The reference laser source for seeding is placed outside of the housing and transmitted via polarization maintaining optical fiber and dedicated hermetical housing feedthrough.

For the amplifier, the InnoSlab concept, developed by the Fraunhofer Institute for Laser Technology (ILT), is applied. This concept is ideal for high energy and high efficiency single mode power amplifiers [2]. The Nd:YAG slab crystal is end pumped from both sides by use of high power diode stacks and appropriate beam shaping optics as shown schematically in Fig. 3. The signal beam is folded 7 times through the amplifier crystal in a single pass configuration. By choosing appropriate mirror radii and signal beam divergence the beam is widened with every pass to keep the fluence constant. Hence the fluence can be kept high enough for efficient amplification while remaining away from the damage threshold. With an input signal of about 9 mJ, the presented FULAS amplifier is designed to generate output pulse energy of up to 90 mJ at 1064 nm. The design is easily scalable in its output power by adapting the slab crystal width and number of folds or by sequential operation of multiple amplifier stages. Both variants are already demonstrated with more conventional laser designs, e.g. in the 2nd generation of the ALADIN Air-borne Demonstrator (A2D2G), to be delivered to DLR in Q3-2014, and the two CharmF systems [5],[6] operational at DLR since end 2013, providing up to twice the FULAS IR pulse energy.

Tab. 1. Laser major parameter

Parameter	Required	Target
Wavelength	355 ± 1 nm	
Energy per pulse	27 mJ	36 mJ
Pulse repetition frequency	100 Hz	
Optical-optical efficiency	> 7%	> 9%
Energy short term stability	< ± 10%	< ± 5%
Spatial mode / beam quality	Gaussian / M² < 2	
Full beam divergence	< 300 µrad	
Pulse duration	< 50 ns	
Longitudinal mode	Single	
Pulse linewidth / spectral purity	< 50 MHz / 99% within 100 MHz	
Frequency stability	< 4 MHz rms	< 1 MHz rms

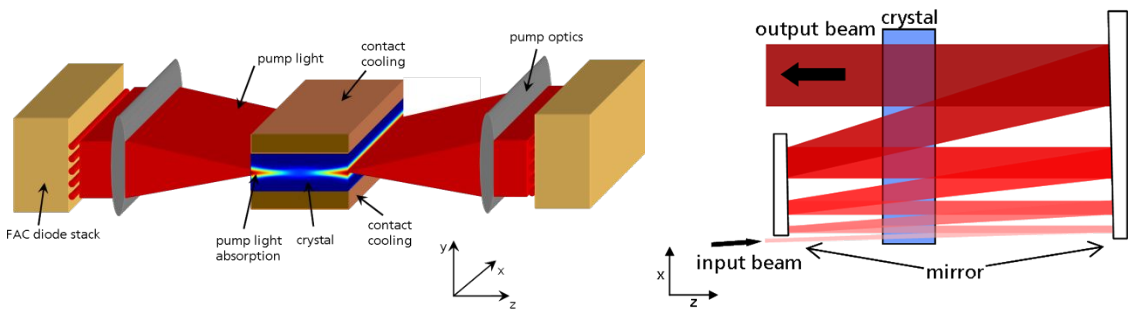

Fig. 3. Schematic of InnoSlab Pump configuration (left) and folded signal beam path (right)

After the amplifier, the beam caustic has to be adjusted to fit to the optimum beam diameter for the frequency conversion. To triple the laser frequency, two LBO crystals are used in critical phase-matching configuration. The first one with type I process (oo→e) for second harmonic generation (green, 532 nm) and the second one with type II process (oe→o) for third harmonic generation (UV, 355 nm). In favour for high life time of the freuqency conversion stage, the fluence on its optical surfaces is designed to rather low levels. With the resulting very conservative conversion efficiency of at least 30% [7][8], which has been verified in many operational laser system, the requested output pulse energy of about 27 mJ at 355 nm wavelength is generated.

B. Optomechanical design

The laser optical bench is mounted inside the pressurized housing central frame by use of three isostatic mounts. The laser is assembled on both sides of the bench, as shown in Fig. 4. The lower side carries the oscillator, while the power amplifier and the frequency conversion are situated on the upper side.

To realize an efficient and compact laser system meeting the stringent mechanical and cleanliness requirements for a reliable and stable space-borne operation, new mounting technologies are introduced. This technology has been developed at Fraunhofer ILT in the frame of a DLR funded research project. Compact, precise, stable and glue free mounting of all optical laser components is realized by use of a soldering technology. Temperature cycling tests of soldered mirrors demonstrated stability of better than 10 µrad, as required for adjustment sensitive components like resonator mirror mounts. A reflow soldering process is applied to less sensitive components like pump optics, where the position accuracy is dominated by the mechanical tolerances, while an innovative active alignment technique is used for components requiring high alignment accuracy. The so called "Pick & Align" process enables active high precision 6-axis alignment of the optics during soldering. Adjustment by repeated melting of the solder is possible multiple times, thus enabling the alignment of the laser oscillator end mirrors directly on the optical bench, without need for additional mechanical alignment capabilities.

Further examples of the efforts to avoid contaminating materials are the two high energy optical isolators implemented to avoid feedback from the oscillator into the seed fiber and from the amplifier into the oscillator. Typically the necessary permanent magnets are assembled by gluing. For FULAS a newly developed, glue free isolator design is introduced.

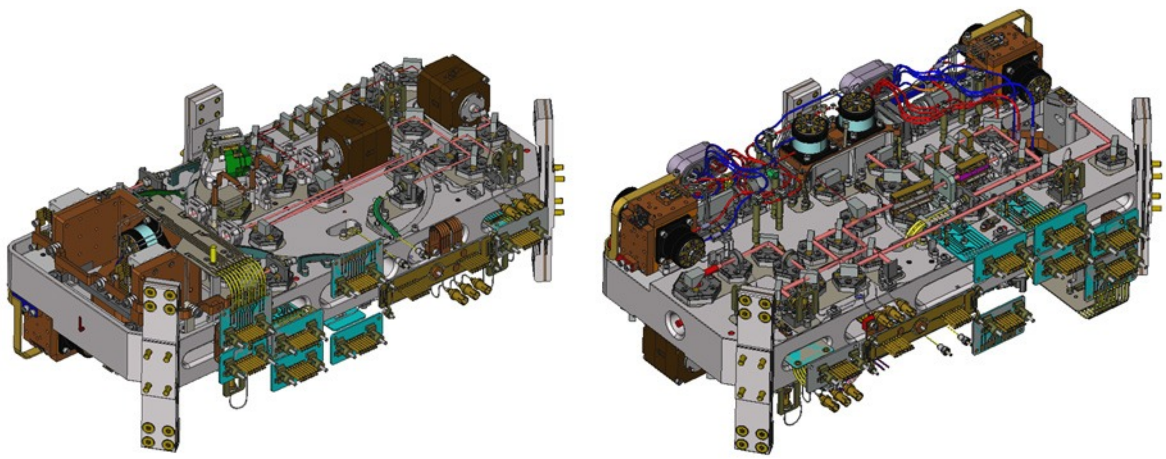

Fig. 4. Two sided optical bench, showing Oscillator side (left) and Amplifier/THG side (right)

C. "Clean" internal Harness and Electrical Design

For operation of FULAS more than 90 different electrical connections are necessary, covering low power control and monitoring signals, coaxial cabling as well as high current power supply (>100 A). One major contributor for the mentioned critical LIC issue is the pollution due to outgassing of organic and plastic materials as used for electrical insulation. Hence an electrical design is realized, avoiding any kind of plastic insulation. The main harness for distribution of the signals at the optical bench is realized by ceramic printed circuit boards manufactured in thick film technique. For high current power supply of the pump diodes, copper current bars are used, also to minimize electrical losses. To reduce the amount of electrical wiring nearby the optical components, parts of the main harness are embedded in tunnels machined through the centre of the optical bench. For connecting the individual electrical components, bare wires are used, fixed by insulating ceramic brackets. All connector assemblies use ceramic or glass for insulation, which is also valid for the sealing of the electrical housing feedthroughs.

To avoid the need of high voltage signals guided over long path and through the housing wall, the driving electronics for the pockels cell, operating at 4.6 kV with about 10 ns rise/fall time, is placed close to the cell inside the housing. For contamination reasons, the tailored electronic is built-up inside a separate hermetically sealed box.

IV. OUTLOOK

After final integration and successful verification of the relevant performance parameters, the complete system will undergo a set of environmental tests to demonstrate the laser optical performance under representative environmental conditions. This test campaign to be started begin of 2015 will include vibrational testing as well as operational and non-operational thermal vacuum testing. Afterwards a 6 month operational endurance test is foreseen.

In nominal operation mode, the system will provide single frequency laser pulses of about 30 mJ pulse energy at a wavelength of 355 nm. Delivered with 100 Hz repetition rate and tailored pulse duration in the range of 20 ns to 50 ns, this is suitable for e.g. atmospheric cloud and aerosol observation.

To show the versatility and flexibility of the presented laser design concept, so called "advanced operation modes" will be verified. One of these is the verification of high frequency doubling efficiency to make the system suitable e.g. as 532 nm pump source for an OPO for Water Vapour LIDAR application. Another option to be demonstrated is the stable double-pulse operation as necessary for DIAL applications like the MERLIN insrument and the efficient (without preheating) stable burst mode operation, preferred for wind LIDAR applications.

Further demonstration of the versatility and energy scalability of the FULAS platform is in progress. A modified version of FULAS is currently in preparation for the MERLIN DIAL instrument, using a downscaled IR-section of the seeded Nd:YAG MOPA for pumping an integrated OPO operating at about 1640 nm. Beside the mentioned A2D2G air-borne Doppler LIDAR instrument, providing more than 60 mJ at 355 nm, another upscaled version of the laser is currently prepared as laboratory bread board to demonstrate up to 500 mJ at 1064 nm, using two sequential amplifier stages.

V. CONCLUSION

The presented laser system provides a flexible, highly efficient laser technology platform, fundamental for a multitude of future space-borne LIDAR missions. The most important asset of this technology is the scalability and versatility of the laser optical concept, which is realized by the modular design approach.

The capabilities of the laser optical design have been proven already in several projects, ranging from laboratory bread boards up to operational air-borne LIDAR applications: Stable single frequency operation in single and double pulse mode at variable repetition rate in continuous or burst mode, covering a demonstrated pulse energy range from single mJ up to 500 mJ in the NIR, capable for high efficiency frequency conversion to the green or UV by frequency doubling/tripling as well as conversion within NIR spectral range by use of an OPO.

In combination with the newly developed pressurized housing technology and the "clean" organic-free design, the high potential of FULAS as enabling technology for powerful Earth observation and scientific applications is obvious.

ACKNOWLEDGEMENT

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