ICSO 2016

International Conference on Space Optics

Biarritz, France

18–21 October 2016

FULAS: high energy laser source for future lidar applications

S. Hahn

M. Bode

J. Luttmann

H.-D. Hoffmann

FULAS: HIGH ENERGY LASER SOURCE FOR FUTURE LIDAR APPLICATIONS

S. Hahn[1], M. Bode[1], J. Luttmann[2], H.-D. Hoffmann[2].
[1]*Airbus DS GmbH, 81663 Munich, Germany, Email: sven.hahn@airbus.com*
[2]*Fraunhofer Institute for Laser Technology, Steinbachstraße 15, 52074 Aachen, Germany*

I. INTRODUCTION

For space-borne atmospheric LIDAR instruments, 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 seen by the community as still very critical.

To overcome this, the FULAS (Future LASer Technology) project had been initiated by ESA supported by 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 had been evaluated. Depending on the mission, different types of lidar principles, e.g. Doppler wind lidar, backscatter lidar or DIAL, are applicable, requiring 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 of 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 of reducing the amount of used organic materials to close to zero.

The design was already presented at ICSO 2014 [1]. Since then it had been built and demonstrated its capabilities. As the technology will be the heart of the Methane Remote Sensing Lidar Mission (MERLIN) [4],[5] (DLR/CNES, Phase C in preparation), the test plan of FULAS was adjusted to support the MERLIN development needs. Therefore in the first instance only the Oscillator and Amplifier section, without UV-conversion stage, of the presented FULAS laser, which is very similar to the one in preparation for MERLIN, had been assembled within the last year and integrated into the hermetical and pressurized housing. The optical performance in the IR had been demonstrated followed by successful operational thermal vacuum tests during Summer 2016 at the Airbus DS Test facilities.

The UV-section will be implemented next and further extensive testing, including vibrational and 6 month endurance testing, will be performed in 2017.

II. OVERAL SYSTEM DESIGN

II.A. Major design requirements

Beside the typical space instrument requirements to deal with the very limited power and mass budgets, 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 thermoelastic deformations.

II.B. 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 central frame of the housing provides several hermetical feedthroughs for electrical and optical connectors, thermal-hydraulic feedthroughs for the miniature loop heat pipes (LHP) and a beam exit window. Furthermore two connectors for purging and pressurizing the Housing before final sealing are implemented.

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 mechanical 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, the design 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, had been validated before 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, the 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, 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.
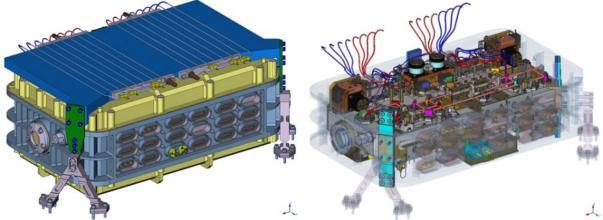

Fig. 1: FULAS pressurized housing with top-mounted cold plate (left) and internal optical bench (right)

II.C. "Clean" Pressurized housing

Due to the need of a lightweight design while providing the thermal conductivity to support thermal balancing, Aluminium is 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 isostatic mounted optical bench (Fig. 1). The frame is closed by two symmetric 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. A

mechanical Friction Stir Welding (FSW) process was optimized in the frame of the project, using a special welding effector developed by Airbus Group.

II.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 of efficient control of the conductivity by active derating using an attached inhibition heater. By constant powering the heater of one LHP out of the redundant pair with typically a maximum of 1.5 W, the inhibition is suitable to completely disable the relevant LHP and therewith realize the cold-redundancy design.

For the presented System, the necessary precise and efficient temperature control is realized by applying less than 0.5 W of control power to the respective LHP evaporator. Reliable suppression of the redundant LHP is achieved applying constantly 0.7 W to each redundant LHP evaporator.
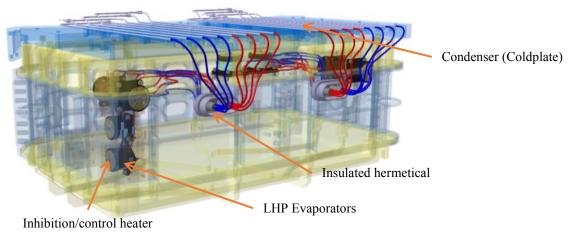

Condenser (Coldplate)

Insulated hermetical

LHP Evaporators

Inhibition/control heater

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

III. LASER OPTICAL DESIGN

I.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 laser parameters for IR and UV are listed in Tab. 1, including also the values already demonstrated in the IR during the past test campaign.

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 [3]. 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, demonstrated during the past test campaign. 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), built for DLR, and the two CharmF systems [6],[7] operational at DLR since end 2013, providing up to twice the FULAS IR pulse energy. Another up scaled version of the laser design had been built as laboratory bread board, demonstrating more than 500 mJ at 1064 nm by using two sequential amplifier stages [10].

Tab. 1. Laser major parameter specifications (IR, UV) and Measurements (IR)

Parameter	IR		UV	
	Specification	Measured	Specification	Target
Wavelength	1064 ± 1 nm		355 ± 1 nm	
Puls Repetition Frequency	100 Hz			
Energy per pulse	> 85 mJ	90 mJ	> 27 mJ	36 mJ
Energy short term stability (p. to p. over 1.4 sec)	< ± 3 %	< ± 2 %	< ± 10 %	< ± 5 %
Optical-optical Efficiency	> 20 %	19.2 % [(*)]	> 7 %	> 9 %
Pulse duration	< 50 ns	26 ns	< 50 ns	
Spatial Mode / Beam quality	Gaussian / M^2 < 2	Gaussian / M^2 1.54	Gaussian / M^2 < 2	
Longitudinal Mode	Single	Single	Single	
Pulse linewidth	--	19.6 MHz	< 50 MHz	
Frequency stability over 1.4 s	< 1.33 MHz rms	< 1 MHz over 10 s	< 4 MHz rms	< 1 MHz rms
Boresight stability – short term (p. to p. over 1.4 sec)	< ±75 μrad	< ± 20 μrad (p-p over 10 min)	< ±75 μrad	
Boresight stability – long term (p. to p. at T = 21±2 °C)	< ± 150 μrad.	< ± 50 μrad [(**)]	< ±150 μrad	

(*) Reduced efficiency mainly due to non-optimal selection of Pump diodes.
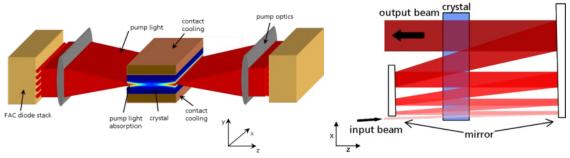(**) Measured over 5 days operation during thermal vacuum cycling within the operational Temperature range

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

After the amplifier, the IR beam caustic is 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 frequency 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% [8][9], which has been verified in many operational laser system, the requested output pulse energy of about 27 mJ at 355 nm wavelength is generated.

I.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. For components requiring high alignment accuracy, an innovative active alignment technique is used. 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.
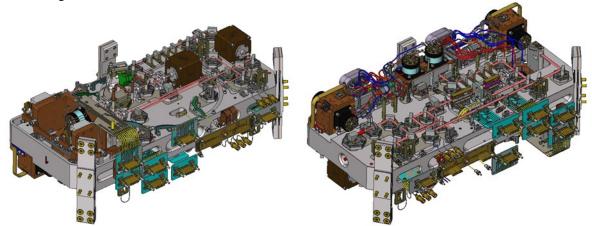

Fig. 4: Two sided optical bench, showing Oscillator side (left) and Amplifier/THG side (right).

I.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 utilize 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, visible on the photograph in Fig. 6.
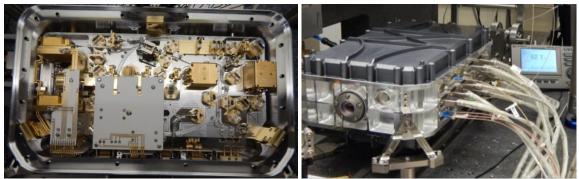
II. ASSEMBLY AND TEST CAMPAIGN

II.A. Assembly and Integration

The FULAS design including all subassemblies and developed processes had been realized and verified within the last two years. After individual subassembly tests, including e.g. environmental testing (vibrational and Thermal Vacuum) of a representative structural model of the housing, the complete Housing was successfully manufactured, assembled (see Fig. 5) and tested. Extensive testing had been performed with the integrated LHP thermal subsystem. The performance and active thermal control capability of the LHP system was operationally verified before integration of the sensitive optical system. In parallel, the optomechanical assembly had been performed. After successful test of the individual components and subassemblies, the optical bench had been equipped and the Oscillator as well as the Amplifier aligned.

After wedding of the aligned optical bench with the Housing frame and the LHP thermal management system, the Housing was closed (Fig. 6) and the IR performance of the Laser system successfully demonstrated (see Tab. 1 for results).

Fig. 5: *Left:* LHP-Thermal subsystem ready for integration into the Housing frame. *Right:* Pre assembled pressurized Housing, ready for Thermal Subsystem testing and Integration of Laser optical bench.

Fig. 6: Oscillator side, including Pockels-Cell HV-switch of the Optical bench after integration into the pressurized Housings central frame (left) and closed Laser with Housing during first performance test.

II.B. Thermal Vacuum Test campaign

In Summer 2016, the FULAS Laser system had been testes under thermal vacuum conditions (see Fig. 7). In the frame of this test campaign, the temperature and pressure related performance parameters had been verified.

The insensitivity of the optomechanical design against externa pressure changes had been proven by operation of the pressurized laser monitoring its performance during facility evacuation and by comparison of the Performance measured in laboratory environment and under vacuum. Therefore the major performance parameters (Pulse energy, beam profile, puls width and beam pointing) had been measured and recorded whenever the laser was operational. Also the housing internal pressure was monitored during the vacuum test campaign, demonstrating the capabilities of the (primary) hermetical sealing concept to withstand the applicable temperature range of -20 °C to +50 °C.

Fig. 7: *Left:* Laser in preparation for Thermal Vacuum testing; *Right:* test facility with integrated laser and external test setup for online laser performance measurement

During the first part of the test campaign, the laser was operated continuously under vacuum conditions for about one week, while varying its I/F temperatures. According to the requirements, the laser demonstrated full

performance with variation of the thermal I/F temperature in a 4 °C range and variation of the mechanical I/F temperature in a 10 °C range.

One of the most important test results is the demonstration of the required pointing stability of the laser beam. By use of a customized Autocollimator Setup with in-house data acquisition and evaluation software and a mirror mounted on an isostatic frame close to the beam exit window of the housing, the pointing of the beam was measured directly with respect to the laser mechanical I/F.

III. OUTLOOK

After finalization of the thermal vacuum test campaign, successfully demonstrating the laser optical performance under representative thermal and pressure conditions, the laser system will be modified by implementing the frequency tripling section. Once the performance is demonstrated in its final UV-configuration, further test campaigns are foreseen, including vibrational testing and a 6 month operational endurance test.

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 instrument 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 [4],[5], using a downscaled IR-section of the seeded Nd:YAG MOPA for pumping an integrated OPO operating at about 1640 nm. The A2D2G air-borne Doppler LIDAR instrument currently in final preparation will provide more than 60 mJ at 355 nm.

IV. 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.

Beside the successful operational verification of the FULAS design within the test campaigns in summer 2016, the capabilities of the laser optical design have been proven in the past 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, 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.

V. ACKNOWLEDGEMENT

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