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TDE

“LOW DISTORTION THICK DISK AMPLIFIER at > 400 mJ”

ESR

(Executive Summary Report)

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Summary of revisions

Revision	Names	Date	Description
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0001			
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1. TDE Project Executive Summary

1.1 Context

In order to improve understanding of climate science, more complete datasets of wind distribution over the whole globe are required. Data collection cannot be done with terrestrial instruments over the oceans, so ESA has built a project of LIDAR wind measurements that is part of the Living Planet program. The first AEOLUS satellite was launched in August 2018 and has provided precious results for better weather forecasts since its first days in Low Earth Orbit (LEO).

The source in the Doppler LIDAR instrument called ALADIN reaches its output power after amplification in a 2-stage optical amplifier. This amplifier is a very sensitive element which development has caused sever al years of delay to the AEOLUS mission. ESA seeks improved solutions for the amplification in order to avoid some of the difficulties encountered in the first system iteration.

In a previous TRP project, CILAS has developed and demonstrated a 400-mJ amplifier that satisfies the characteristics listed by ESA, with features that avoid previous difficulties (minute thermal lensing effect). The key objective of the current activity is to materialize the experience acquired from the Breadboard of the Previous Activity and start work on an Engineering Qualification Model that could be fully developed at a possible future activity.

1.2 Objectives

The project had 3 axes of development. The goals were to:

- improve on an optical element that had shown failure when the operation repetition rate went from 50 to 100 Hz.
- flatten stage 2 disks wavefront distortion further in order to enhance the beam spatial characteristics
- design an elegant breadboard CAD model and initiate a vibration and shock analysis in order to comply with the requirements for spaceborne equipment.

The 400-mJ breadboard showed top tier characteristics at 50 Hz, but operation could not be demonstrated at 100 Hz because of the failure of a multizone mirror. The first part of the project addressed the question of this failure, by analyzing the past damage, mitigating the coating vulnerability, and showing adequate performance at 100 Hz with a revisited mirror.

The multizone mirror is produced through a photolithographic process where a photoresist is applied during a first IBS coating step. The photolack is then removed for the second coating. The damaged mirror coatings were tested at the Deutsches Zentrum für Luft- und Raumfahrt or German Aerospace Center (DLR) for Laser Induced Damage Threshold (LIDT). Values measured were greater than 20 J/cm², typical for IBS-coatings, and 10 times greater than the fluences expected in the amplifier (< 2 J/cm²). The damages observed (Figure 1) appear very distinct: they are quite wide spread on the multizone mirror that failed in the amplifier, and the likely carbon deposit suggests the occurrence of a thermal effect linked to the failure.

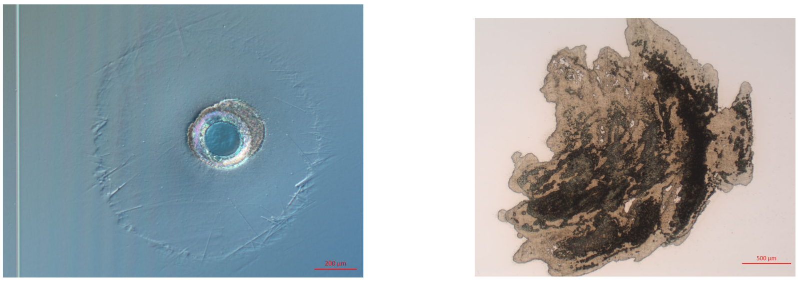

Figure 1 : Micrograph of a HR zone of the multizone mirror tested for LIDT (left), and damaged during operation at 100 Hz (right)

We verified that hotspots did not appear in the beam as repetition rate and thermal load were raised, and that the temporal shape did not evolve either. For the same laser fluence, the mirror ran for hours at 50 Hz, but failed after a few seconds at 100 Hz.
The most likely explanation for the damage is the existence of a resin residue after imperfect cleaning of the photolack. These traces are not sufficient to lower the LIDT, but as the average power increases on the mirror, the weak absorption is sufficient to cause burning and damage the coating.
An improved iteration of the mirror was purchased, with special attention given to the cleaning step.
The mirror was tested. The amplifier was operated at 400 mJ, 100 Hz, showing good beam quality (M^2~3 with a uniform energy distribution). The amplifier was operated over an extended period of time (100 hours) without failure. This confirms that the new mirror provisioned is more resistant than the first lot, and that adequate cleaning of the photomask can be done to avoid laser beam absorption.

An alternate technology for this delicate element was also proposed. It relies on assembly of separate pieces with standard IBS-coating. This type of optical component has already been qualified for space applications (by WinLight & CILAS for µCarb mission), so there is a fall back solution if removing all traces of residue from the masking step of the multizone mirror production proved to be too difficult.

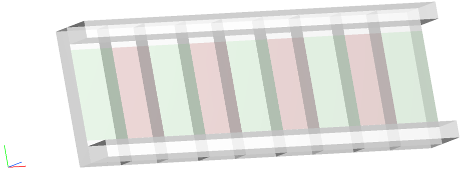

Figure 2 : Possible realization of an assembled multizone mirror with input from WinLight

Besides the optics that were damaged at 100 Hz, a second shortcoming of the 400-mJ amplifier realized in the first TRP was a leftover deformation of the beam due to insufficient wavefront distortion compensation in the large stage 2 disks. A few changes were identified in part 2 of the TDE that could possibly help in reducing the distortions, so a redesign of the system was done using the models previously validated.
First, the disks thickness was slightly decreased in order to reduce the temperature excursion between the front face of the disks and the bounded face. The temperature has a detrimental effect on the amplifier gain that curtails efficiency at 100 Hz. The amplifier dimensions were adjusted to optimize the amplifier performance.

A new epoxy adhesive was also identified that cures at room temperature in order to avoid the slight bimetallic effect that was observed with the first bonded disks. The new epoxy is NASA qualified and presents very low outgassing, so it is space compatible. A Laser Induced Contamination (LIC) test at 355 nm is still required to validate its use in a spaceborne high-energy amplifier.

The functionalization process was also ameliorated, with a compensation of the distortion on the fly, enabling fine control of the wavefront and correction of the astigmatism observed.

The results were characterized with a set-up including a Phasics SID4 sensor, which enables phase measurements with ~0.01λ accuracy.

Typical wavefront distortion shown Figure 3 were measured for 2 11-mm diameter, stage-2 disks under pumping before functionalization. An overt curvature is observable, which is the root of thermal lensing in standard lasers.

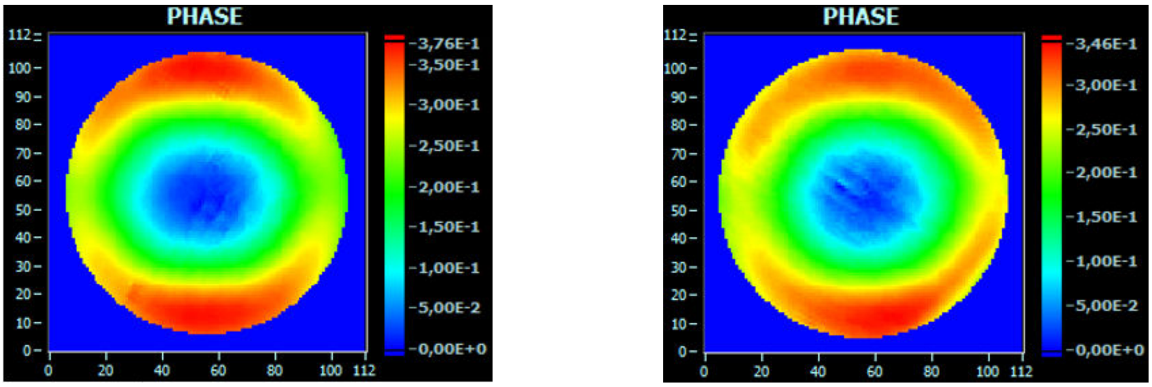

Figure 3 : Wavefront for 2 11 mm disks under pumping without functionalization

The associated profiles are plotted Figure 4 for all 11-mm diameter disks measured, and we note some astigmatism, induced by the hexagonal shape of the pump beam. After going twice through the 4 disks of stage 2, the total phase distortion acquired by the beam is almost 3□ when the laser is warmed-up. The wavefront being asymmetrical, this curvature is not easy to correct, and it varies during warm-up, generating a substantial risk of damage for optical elements on the high energy beam path.

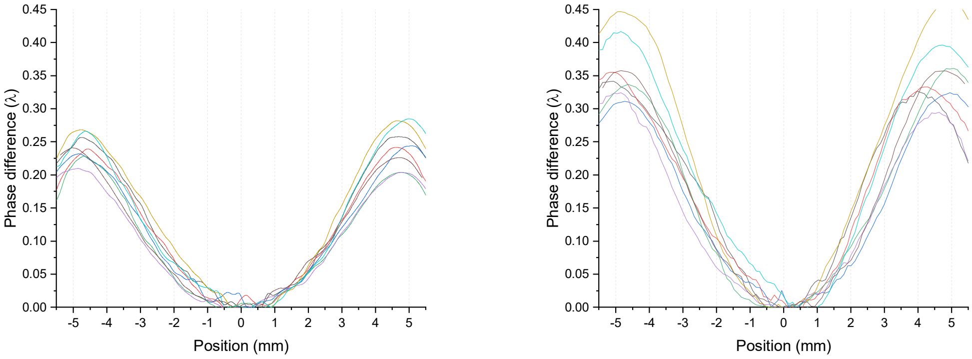

Figure 4 : Profiles of the wavefronts for all 11 mm disks under pumping without coating

In order to avoid the detrimental effects of thermal lensing, we seek to compensate the phase distortions caused by pump absorption. To that end, the disks are functionalized so that phase distortion is flattened.

Figure 5 shows the result of phase compensation characteristic of CILAS amplifier for 2 separate large stage 2 disks. We observe that the wavefront under pumping appears almost uniform over practically the whole disk, eliminating the strong curvature seen in Figure 3 that is the signature of thermal lensing.

By fine tuning the compensation, we also managed to reduce greatly the astigmatism caused by the pump beam shape (hexagonal shape, noticeable on Figure 3).

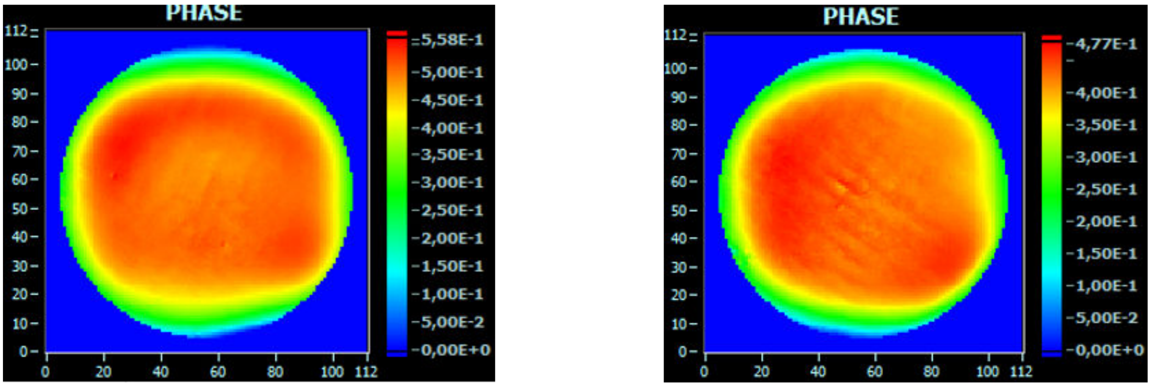

Figure 5 : Wavefront for 2 11 mm disks under pumping after functionalization

Because phase distortion only matters over the area of the amplified beam at the center of the disks, we plot the profiles associated to the wavefront measurement above over the beam diameter before and after functionalization (Figure 6).

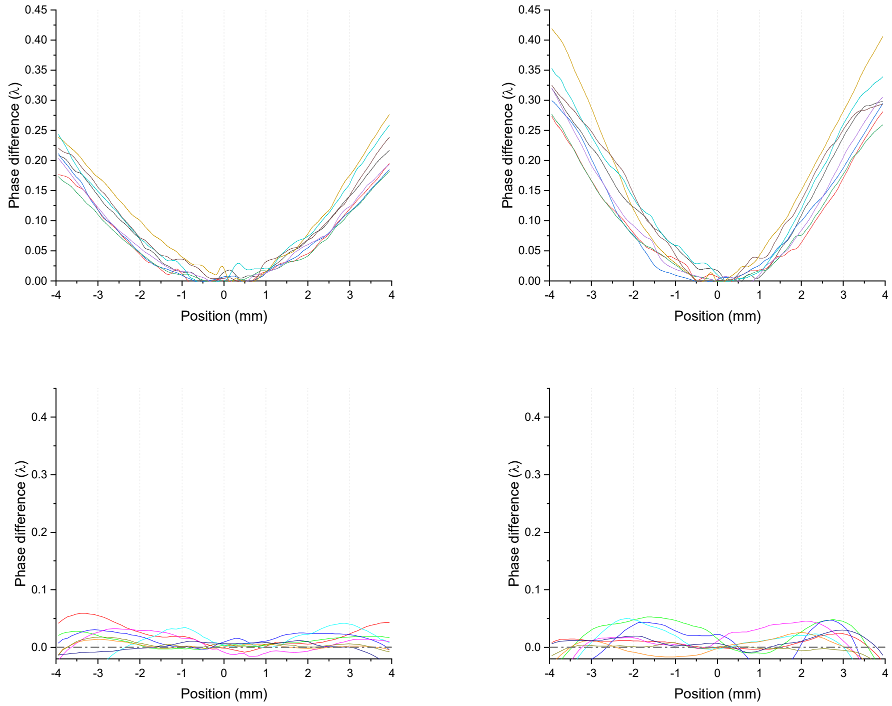

Figure 6 : Profiles of the wavefronts for all 11 mm disks under pumping over the beam area. Top: before functionalization; bottom: after functionalization

The results are indisputable: the functionalization enables a flattening of the wavefront distortion even during pumping. This flattening was shown to occur whatever the pump power absorbed: CILAS 400-mJ amplifier is not subject to thermal lensing, as it is passively compensated.

The results achieved are excellent and quite repeatable, as we see that for most 11-mm disks, the wavefront distortion measured have less than 0.02λ RMS (Figure 7). Similar results are achieved with the smaller stage 1 disks:

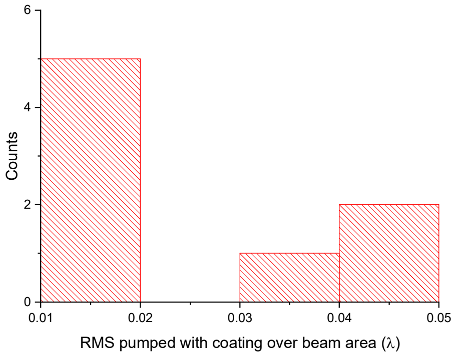

Figure 7 : Histogram of RMS value for all 11 mm disks under pumping after functionalization, over the beam area

In conclusion to part 2 of the TDE, the project was highly successful, as the large stage-2 disks wavefront distortion have been much reduced, at rest (with the new space qualified epoxy adhesive), and under pumping, using an improved functionalization process.

A third part of the TDE project aimed at preparing the future of the 400-mJ amplifier by designing a CAD model of an elegant breadboard, and analyzing it for thermal and vibration behavior.

Some input data were incompletely defined, so arbitrary choices were made to produce the model shown Figure 8.

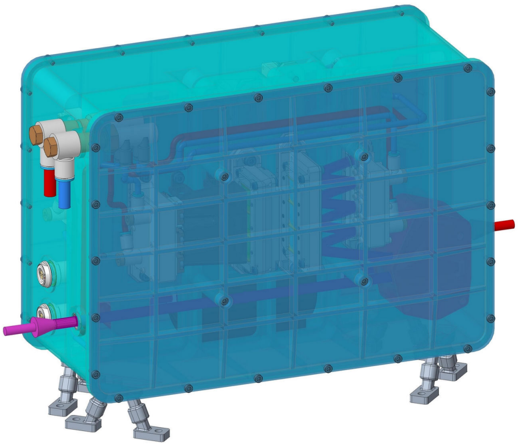

Figure 8: CAD model of vertical compact housing

In this design, the 2 stages are placed on either side of a structural plate, so that all optics holders are easily accessible. The casing is closed by 2 cover plates.

The case, made of 6061 T6 aluminum in this model version, is not airtight to allow good pressure balancing.
The optical mounts were conceived after a sensitivity analysis was conducted to determine the degrees of freedom that are critical for alignment. Innovative approach enables a very rugged system.
An optical isolator is required between the 2 amplification stages to avoid feedback and instabilities. The isolator integrated in the CAD model is the one used in the TRP breadboard, for laboratory applications. It is not space qualified, its size and particularly its mass, seriously penalize the current design.
In summary, the CAD model is compact, rugged, and weighs less than 5 kg (4.8 kg if made of Aluminum, with 820 g for the isolator alone), with a footprint of 290 mm x 131 mm, and total height of 235 mm.

Thermal analysis of the elegant breadboard designed makes it possible to dimension the cooling system required to operate the amplifier in the laboratory. At 100 Hz, 210 W have to be extracted from the amplifier. The definitive cooling system will involve loop heatpipe and will be integrated in an EQM.
We have also verified that transitions between operational and non-operational temperatures are not expected to cause components slippage or hysteresis effects, which is an important requisite for a spaceborne system.

Shock and vibration analysis of the Aluminum elegant breadboard was also initiated, with some optimization steps taken. The requirements listed by the agency correspond to typical launcher vibration spectra for sine and random excitation, and for shocks.
After adding stiffeners and modifying some elements implantation in order to eliminate the lowest frequency eigenmodes, it was possible to almost comply with all requirements (random vibrations generated stress values close to material yield strength, mostly around flexures fixations)
Because some elements of the CAD model are not the definitive ones (optical isolator, diode stacks, fixtures), and because the design has to be agreed upon with the end-user before making an EQM, a final optimization was not realized at this stage. Calculations for a system made of Beralcast show that the system can be compliant for all requirements.

As a conclusion, the project addressed the question of space compatibility of the developed amplifier, and the recommendations for follow-up activities in order to reach a fully tested EQM.
Elements that were of concern for space compatibility in the first breadboard assembled were eliminated in the new design, and the substitutes, which are space qualified, were validated for use in the amplifier. LIC tests at 355 nm are still required for the particular application of ALADIN.
Discussions were initiated with manufacturers of space-qualified components (diode stacks, optical isolator, coatings). These elements, although they are not currently integrated in the breadboard, can be developed with low risk of failure during integration.
The overall assembly is almost compatible with launch conditions. Some optimization will be necessary once the surroundings specifications are given and design is finalized.

One major advantage of CILAS 400-mJ amplifier for space applications, is the possibility to duplicate the pump source without having to modify the 3D layout, or to add components. Table 1-1 shows the mass gain sustained because of diode duplication via the “smart packaging” option developed for CILAS amplifier. We see that the amplifier mass remains below specification even with the commercial isolator integrated and no mass optimization done on the design.

Table 1-1: Summary of elegant Aluminum breadboard mass gain for pump source duplication (values in g)

	Single diode source		Duplication via “smart packaging”	
Optics+holders	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
	582	718	621	730
Casing	1485		1575	
Isolator	810		810	
Casing stiffeners	0		20	
Total	4815		4975	

Table 1-2 recapitulates the status of the different amplifier components with regards to space compatibility, and the remaining steps required to increase their TRL. Further activities will necessitate exchange of information with the end-user in order to integrate at its best the amplifier in the overall equipment.

Table 1-2: Recapitulation of space compatibility for each amplifier element

Component	Current TRL	Required steps to increase TRL	Risk of failure
Diode stacks	4	Decide on pump source redundancy requirement or not Identify a stack packaging Harden the packaging Qualify the packaging	medium
Isolator	4	Develop a wider aperture isolator Qualify the isolator	low
ASE absorptive coating	5	Qualify the coating in a space environment (LIC at 355 nm)	low
Disk adhesive	5	Qualify the adhesive in a space environment (LIC at 355 nm)	low
Optical coatings:			
general	9	NA	Null
multizone mirror	4	Qualify the multizone mirror in a space environment	Medium
Microlens array	5	Qualify the array in a space environment	low
Optical mounts	3	Fabricate the CAD models and qualify them in a space environment	low
Housing	3	Finalize the complete system definition Optimize for resistance to vibration Manufacture, assemble, and qualify in space environment	low

1.3 Outreach activities

In the course of this project, we have contacted Lumibird as a diode stack manufacturer. With their support, we have narrowed down the choice of diode packages compatible with our configuration, in particular with the smart “packaging option” identified for pump source duplication.

We have also communicated with the Deutsches Zentrum für Luft- und Raumfahrt (DLR) regarding LIC measurements. Indeed, we did collaborate on the first TRP for LIDT characterization of the amplifier optics. The DLR laboratory is also set-up to carry out LIC measurements at different wavelengths, and in particular at 355 nm. They will be able to perform the LIC test in the UV to confirm compatibility of the new adhesive and coating for use in CILAS amplifier when frequency conversion is realized.

Discussions with LaserOptik are on-going to achieve a reliable multizone mirror that sustains operation at 400 mJ, 100 Hz.

SpaceTech GmbH has developed a TRL8 optical isolator with a small beam aperture. They have suggested to us that they did not see an obstacle to the development of a wider beam aperture element.

During the course of the project, we have been invited to present at OSA Laser Congress – LAC in October 2020. We did an oral presentation at ESA Workshop XI WLMLA'2021 and submitted the results for ESA ICSO’2022**.**

1.4 Conclusions and lessons learnt

Major advancement has been made on the 400-mJ thick-disk amplifier. An elegant breadboard CAD model has been designed and analyzed in terms of resistance to shocks and vibration. Some optimization of the casing demonstrated how to reduce the lowest frequency eigenmodes. Before the system is made flight compliant, the configuration has to be finalized, and an optical isolator similar to the one used in Merlin but with wider free aperture, should be developed.

The wavefront distortions have been remarkably reduced for disks in both stages. The disks have been redesigned to improve operation at 100 Hz, and experimental results confirm the models once again.

The components used in the latest breadboard are low outgassing, and qualified by either CNES or NASA.

A considerable advantage of the amplifier is that we can achieve pump source redundancy at almost no cost to the amplifier performance. This makes it possible to double the laser longevity, which is critical for space applications.

The multizone mirror has been improved and operation at 400 mJ, 100 Hz over 100 hours has been demonstrated. An alternate solution has also been presented that could substitute for this element in case the masking / cleaning technology involved could not be made reliable.

Recommendations have been given for follow up activities to be performed in order to reach a fully tested EQM.

1.5 Future roadmap

Table 1-2 lists the various activities that need to be undertaken to increase the amplifier TRL and to reach fully tested EQM. Some can be done by CILAS, and some require collaboration with European companies.

CILAS 400-mJ amplifier offers unique features (almost inexistent thermal lensing effects, good beam quality with top-hat distribution, good efficiency, operation versatility, easy diode duplication) that could be of interest for an ALADIN booster replacement, or for other applications (Raman detection system source laser).

A 2-year program would enable to reach TRL6, and an additional 3-year program could attain TRL8.